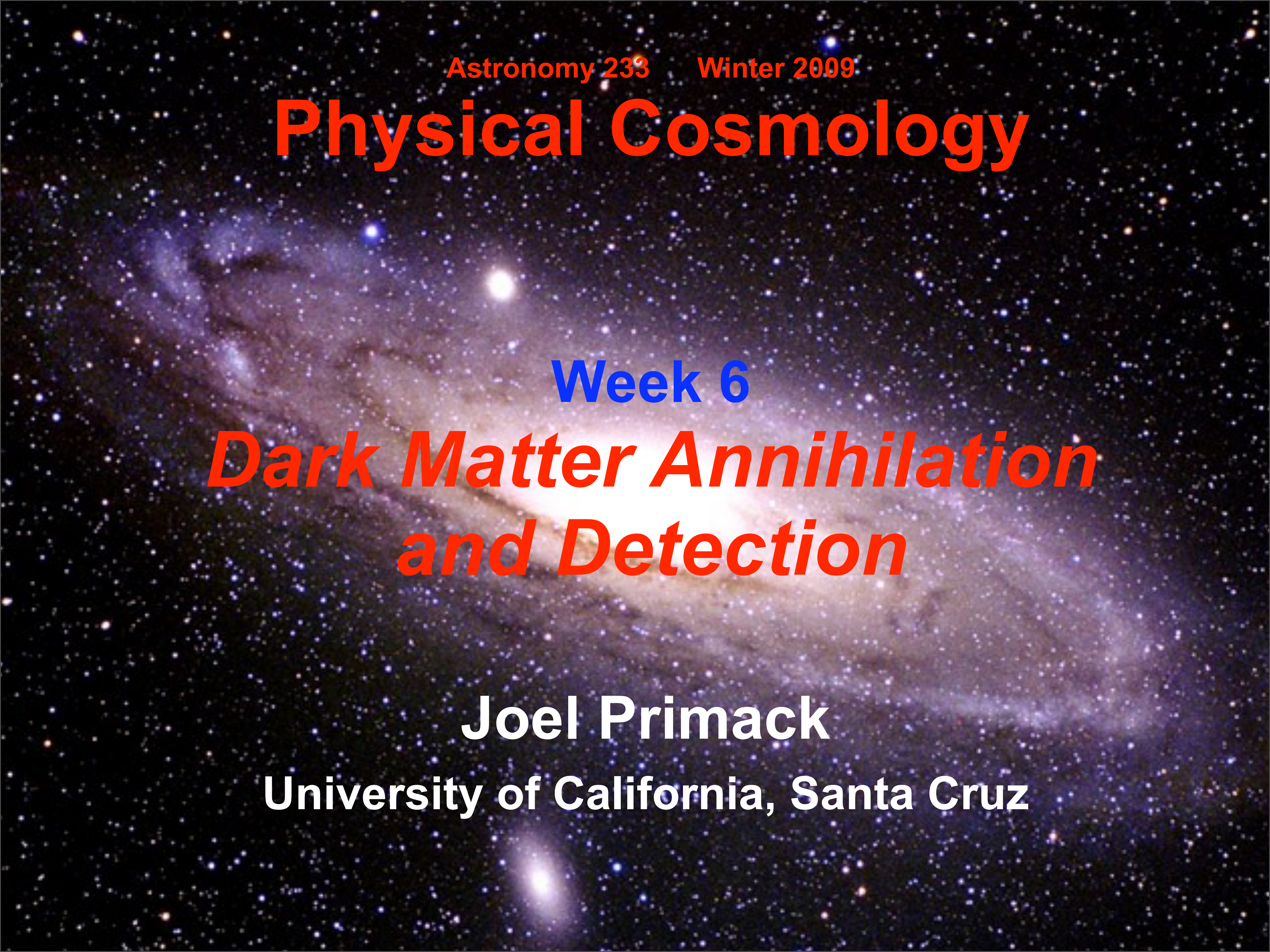


Astronomy 233 Winter 2009

Physical Cosmology

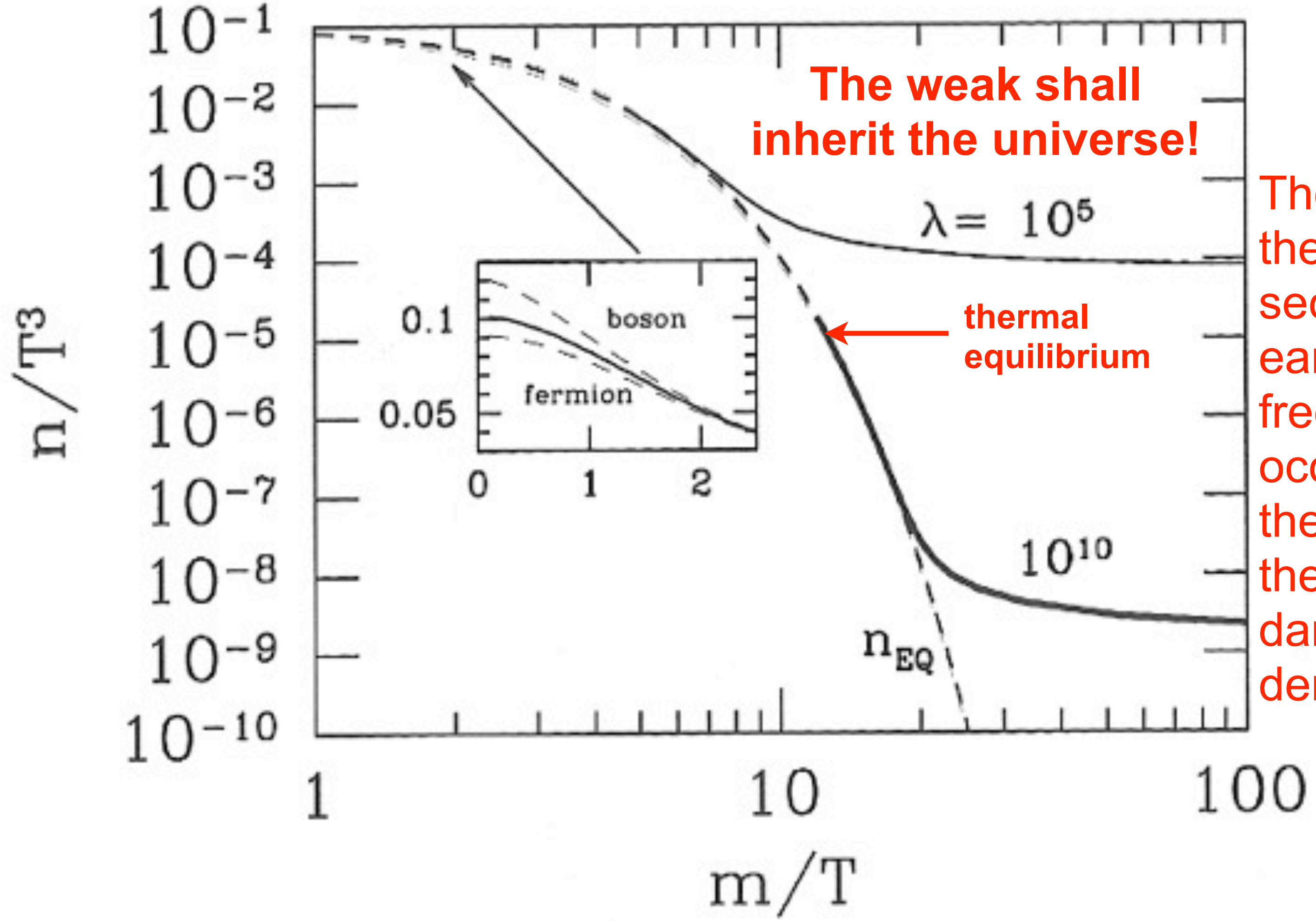
Week 6

Dark Matter Annihilation and Detection

Joel Primack

University of California, Santa Cruz

Dark Matter Annihilation



The weak shall inherit the universe!

thermal equilibrium

The weaker the cross section, the earlier freezeout occurs, and the larger the resulting dark matter density.

Figure 3.5. Abundance of heavy stable particle as the temperature drops beneath its mass. Dashed line is equilibrium abundance. Two different solid curves show heavy particle abundance for two different values of λ, the ratio of the annihilation rate to the Hubble rate. Inset shows that the difference between quantum statistics and Boltzmann statistics is important only at temperatures larger than the mass.

Dodelson, *Modern Cosmology*, p. 76

Dark Matter Annihilation

The abundance today of dark matter particles X of the WIMP variety is determined by their survival of annihilation in the early universe. Supersymmetric neutralinos can annihilate with each other (and sometimes with other particles: “co-annihilation”). Dark matter annihilation follows the same pattern as the previous discussions: initially the abundance of dark matter particles X is given by the equilibrium Boltzmann exponential $\exp(-m_X/T)$, but as they start to disappear they have trouble finding each other and eventually their number density freezes out. The freezeout process can be followed using the Boltzmann equation, as discussed in Kolb and Turner, Dodelson, Mukhanov, and other textbooks. For a detailed discussion of Susy WIMPs, see the review article by Jungman, Kamionkowski, and Griest (1996). The result is that the abundance today of WIMPs X is given in most cases by (Dodelson’s Eqs. 3.59-60)

$$\Omega_X = \left[\frac{4\pi^3 G g_*(m)}{45}\right]^{1/2} \frac{x_f T_0^3}{30\langle\sigma v\rangle \rho_{cr}} = 0.3h^{-2}\left(\frac{x_f}{10}\right)\left(\frac{g_*(m)}{100}\right)^{1/2} \frac{10^{-39}\mathrm{cm}^2}{\langle\sigma v\rangle}.$$

Here $x_f \approx 10$ is the ratio of m_X to the freezeout temperature T_f, and $g_*(m_X) \approx 100$ is the density of states factor in the expression for the energy density of the universe when the temperature equals m_X

$$\rho = \frac{\pi^2}{30}T^4\left[\sum_{i=\text{bosons}} g_i + \frac{7}{8}\sum_{i=\text{fermions}} g_i\right] \equiv g_*\frac{\pi^2}{30}T^4.$$

The sum is over relativistic species *i* (see the graph of *g*(*T*) on the next slide). Note that more X’s survive, the weaker the cross section σ. For Susy WIMPs the natural values are $\sigma \sim 10^{-39}$ cm^2, so $\Omega_X \approx 1$ naturally.

http://dmtools.brown.edu/DMWiki/index.php/

Dark Matter for Beginners

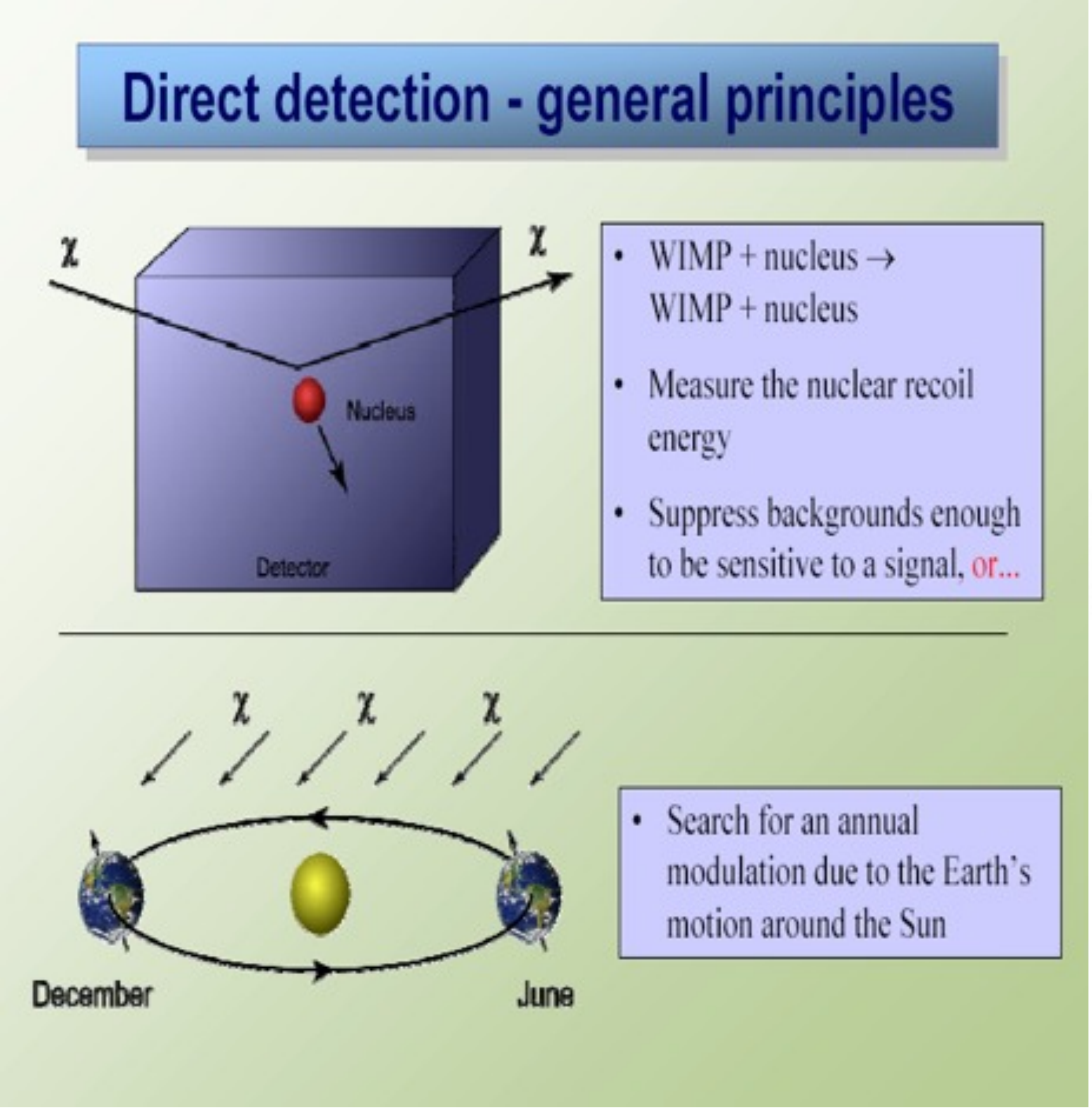
So what’s it made of?

Because of its relatively inert nature, the physical makeup of dark matter remains a mystery. Some likely candidates are Massive Compact Halo Objects (MACHOs) and Weakly Interacting Massive Particles (WIMPs), each of which describes a number of theoretical particles. Our research is designed to detect the latter of these possibilities. Right now, the most probable candidate for a dark matter WIMP is a particle called the neutralino. The neutralino is one of the particles whose existence is predicted by the theory of supersymmetry, which attempts to unite the four natural forces under a single theory.

So why should we care what dark matter is?

Science began as the human quest for knowledge and understanding. On a short-term scale, scientific research tells us what, when, where, and how. But as part of the big picture, the purpose of scientific inquiry is and always has been to answer the biggest question of all: why? Insight about dark matter may provide us with an answer to this question. Once we know what constitutes 85% of the matter in the universe, we will be able to more deeply understand its origins. Only then will we be able to comprehend our own.

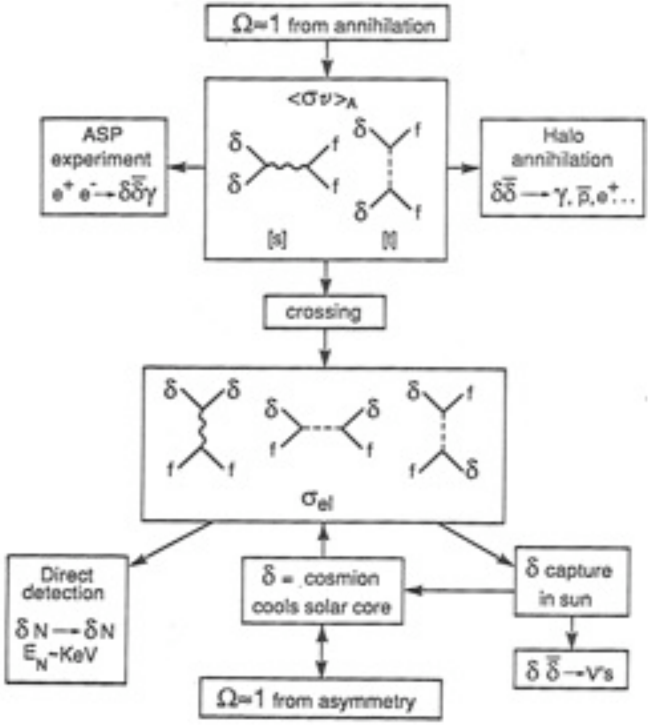
Experiments are Underway for Detection of WIMPs

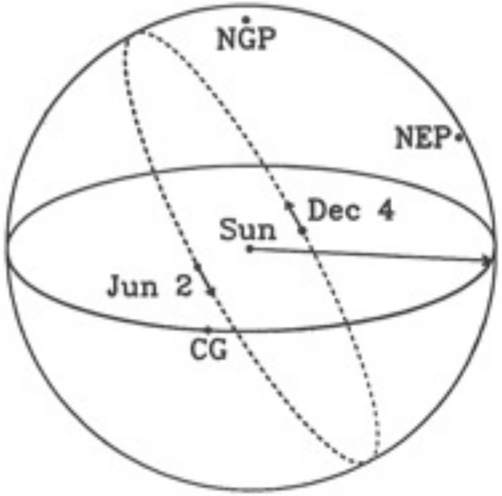


Direct detection - general principles

- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...

- Search for an annual modulation due to the Earth's motion around the Sun

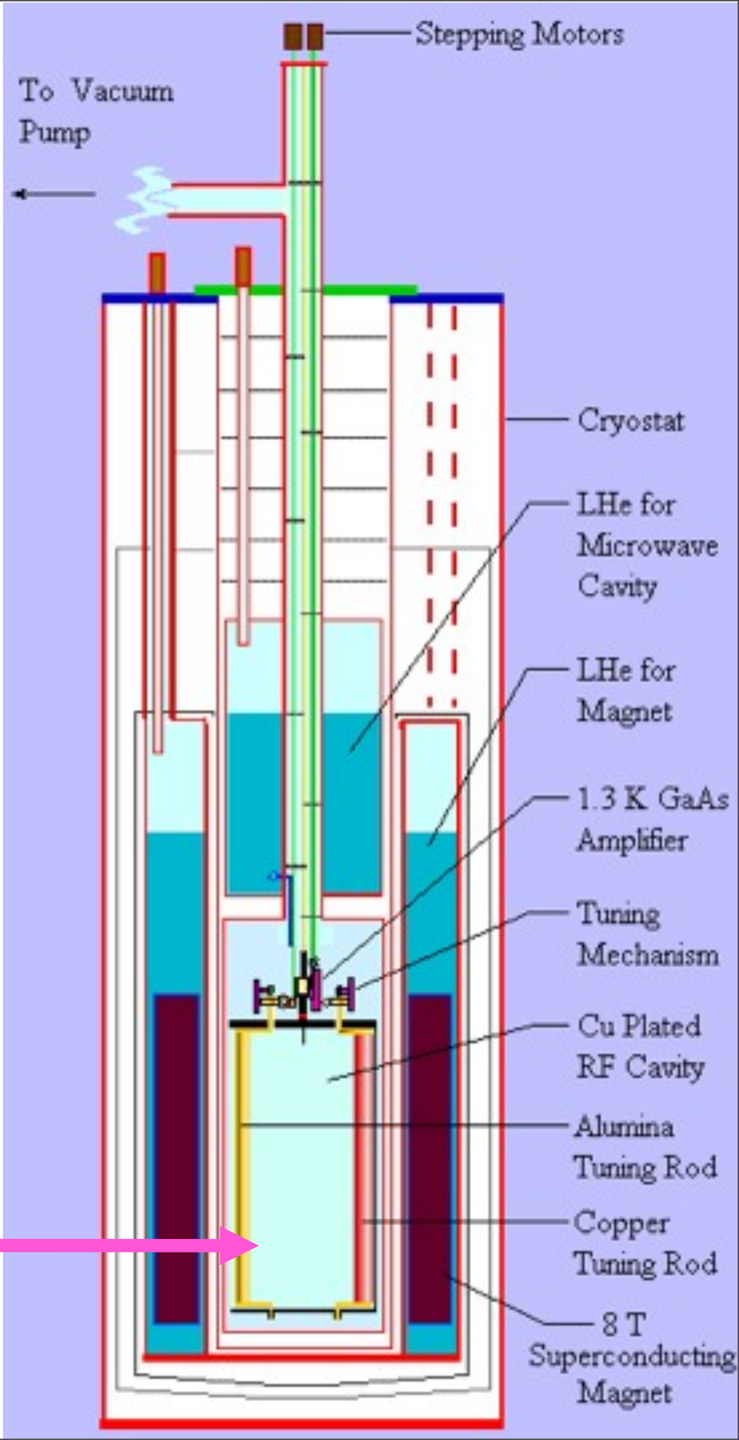




Primack, Seckel, & Sadoulet (1987)

and also AXIONs

The diagram at right shows the layout of the axion search experiment now underway at the Lawrence Livermore National Laboratory. Axions would be detected as extra photons in the Microwave Cavity.



WHAT IS THE DARK MATTER?

Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many upcoming experiments

- Production at Large Hadron Collider
- Better CMB data from PLANCK
- Direct Detection
  - Spin Independent - CDMS-II, XENON50, LUX
  - Spin Dependent - COUPP, PICASSO
- Indirect detection via
  - GLAST and larger ACTs
  - PAMELA and ATIC

-- there could well be a big discovery in the next year or two!

Four roads to dark matter: *catch it, infer it, make it, weigh it*

Direct:

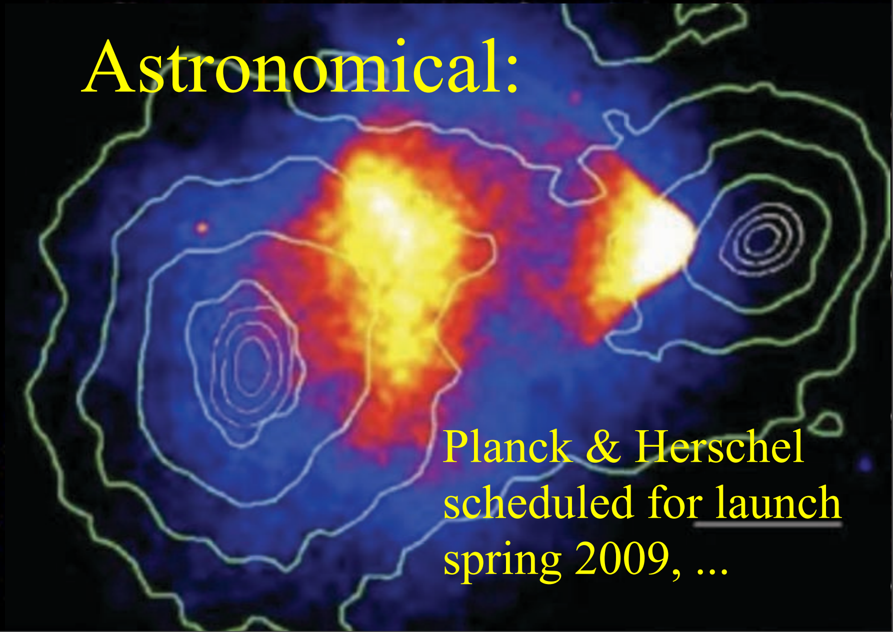
Production:

LHC

With all
these
upcoming
experiments,
the next
few years
will be very
exciting!

Indirect:

Fermi (GLAST)
launched
June 11, 2008



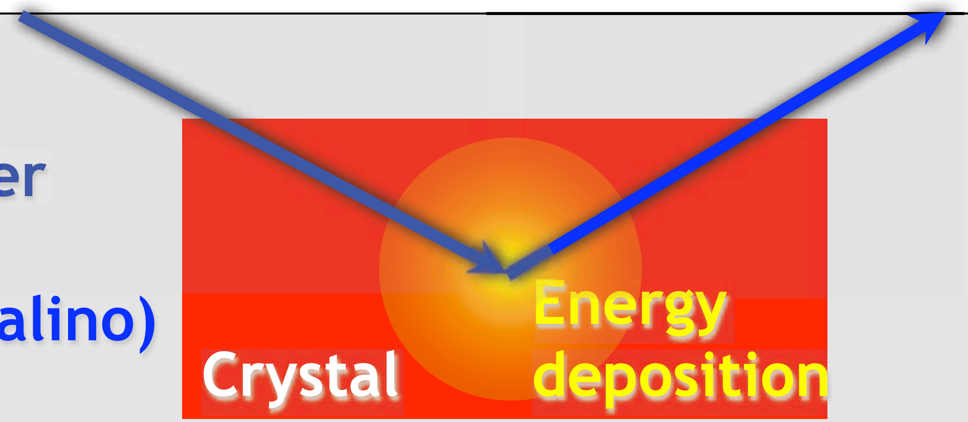
Astronomical:

Planck & Herschel
scheduled for launch
spring 2009, ...

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)

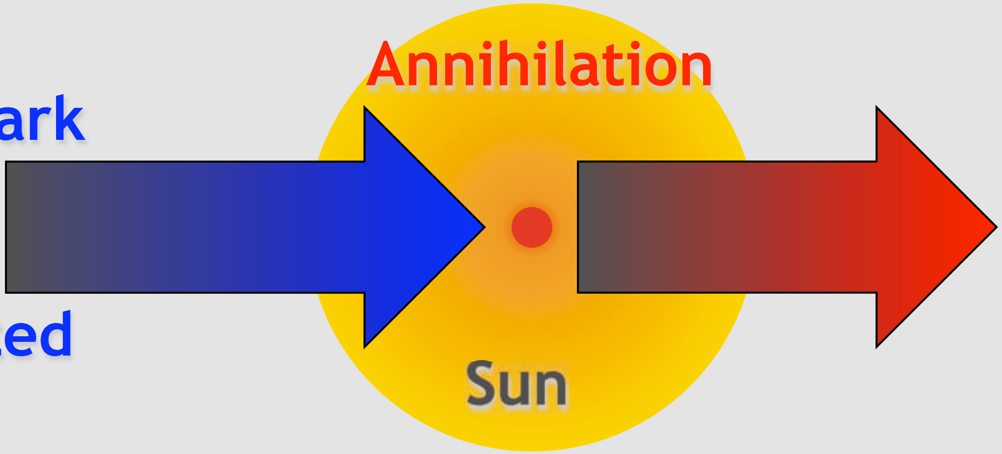


Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

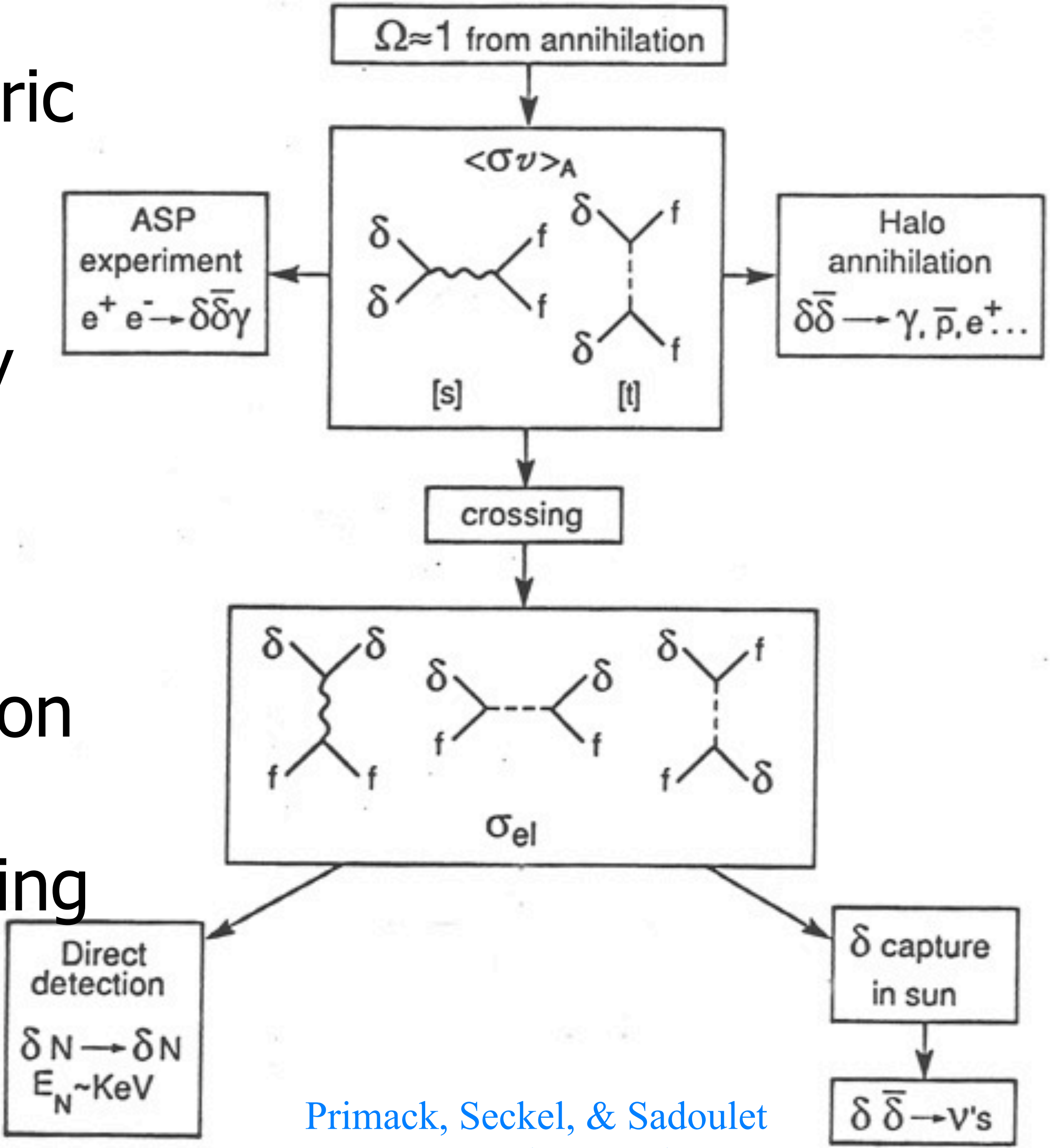
Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



High-energy neutrinos (GeV-TeV) can be measured

Supersymmetric WIMP (δ) annihilation is related by crossing to WIMP Direct Detection by Elastic Scattering



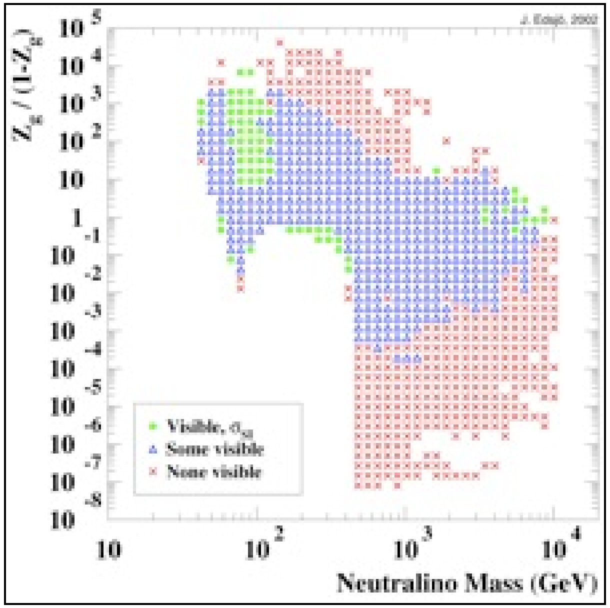
Primack, Seckel, & Sadoulet
Ann Rev Nucl Part Sci 1988

Future WIMP Sensitivities

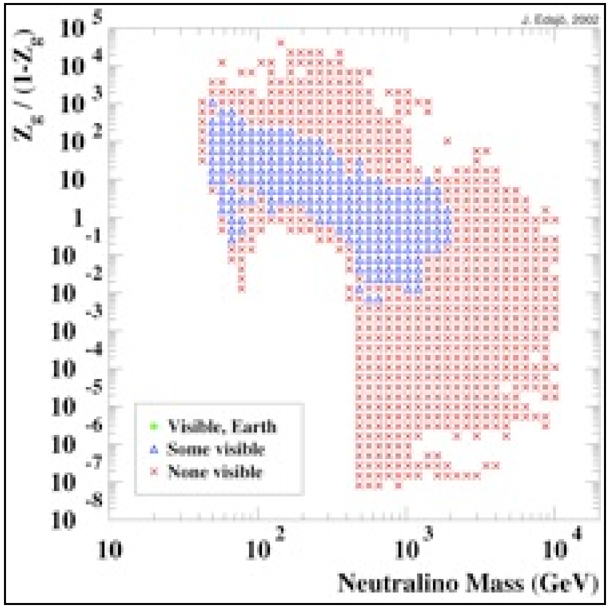
Direct Detection

Indirect, km^3 Detector

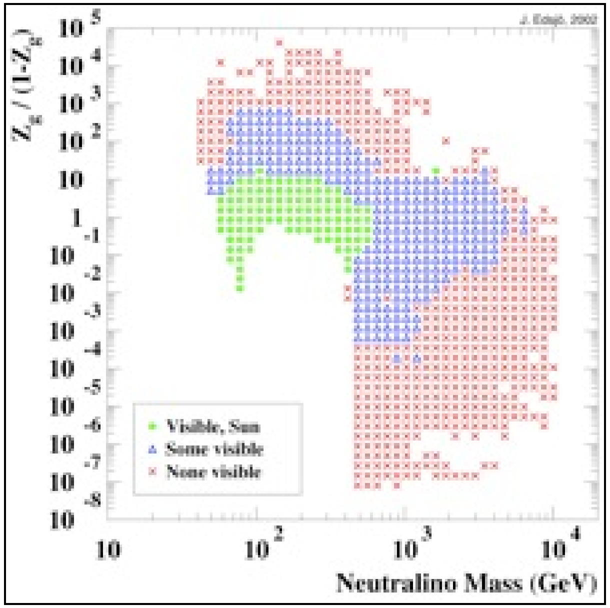
Genius/CRESST

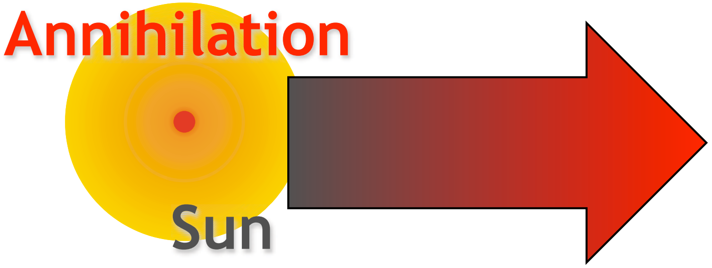


Earth



Sun





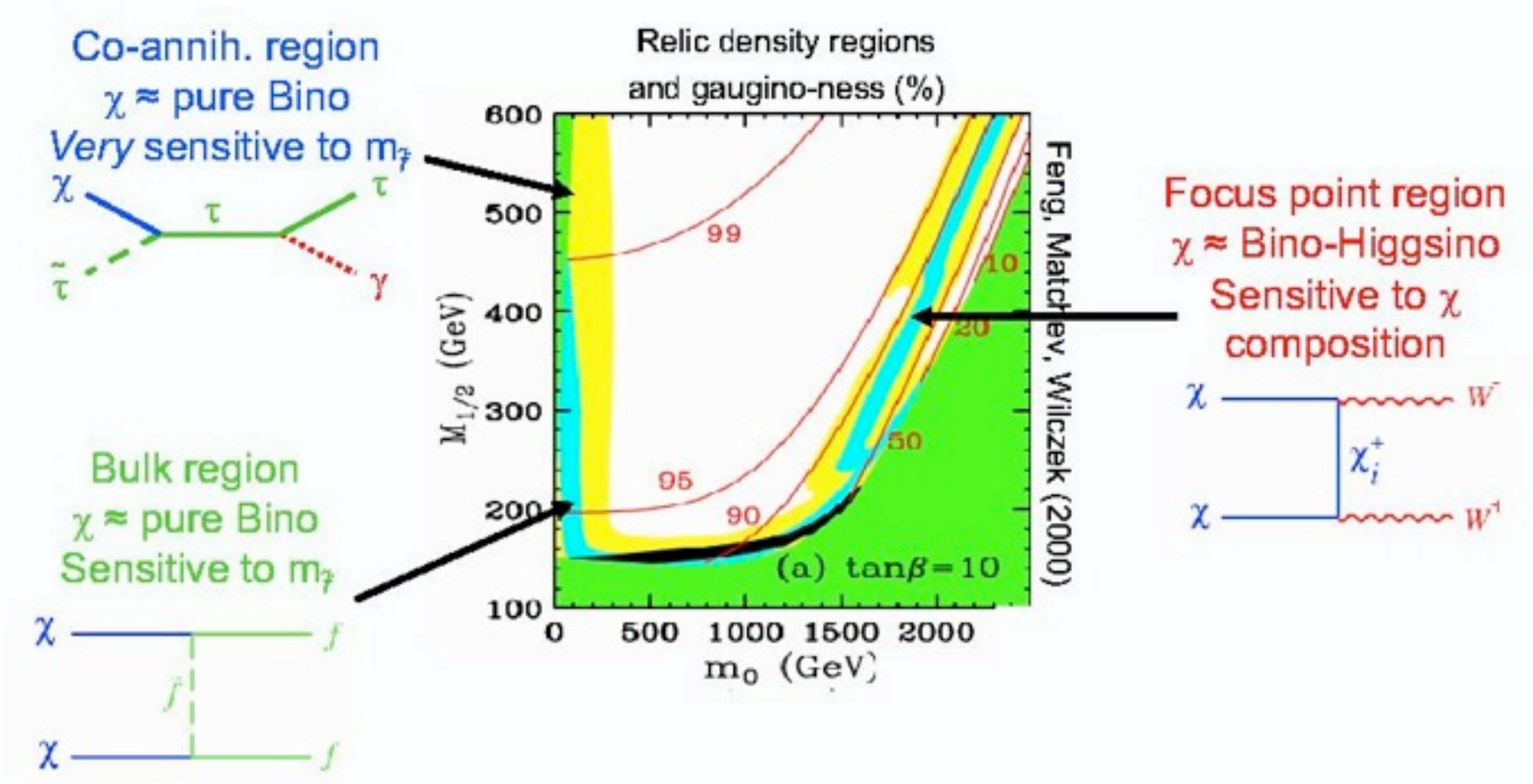
Annihilation

Sun

High-energy
neutrinos
(GeV-TeV)
can be measured

Relic Density

- Cosmology: $\Omega_{DM} = 0.23 \pm 0.04$.   What can HEP tell us?



Co-annih. region
$\chi \approx$ pure Bino
Very sensitive to $m_{\tilde{\tau}}$

Bulk region
$\chi \approx$ pure Bino
Sensitive to $m_{\tilde{f}}$

Relic density regions and gaugino-ness (%)

Focus point region
$\chi \approx$ Bino-Higgsino
Sensitive to χ composition

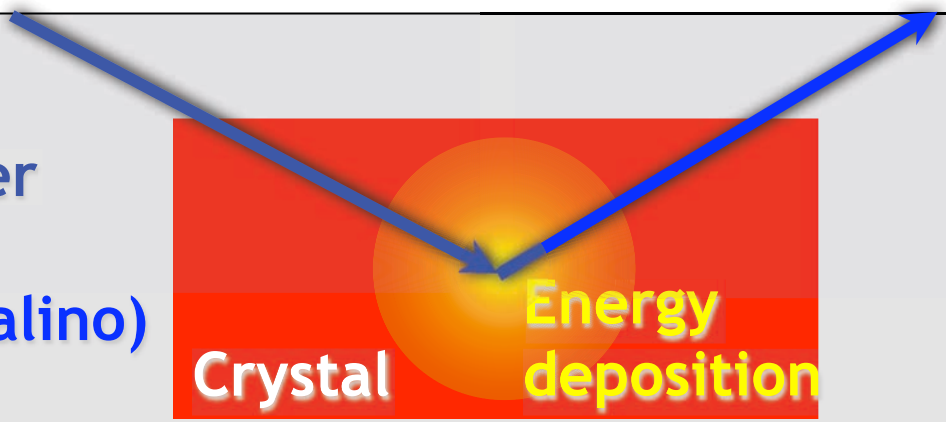
Feng, Matchev, Wilczek (2000)

Jonathan Feng, SLAC Summer School 2003

Search for Neutralino Dark Matter

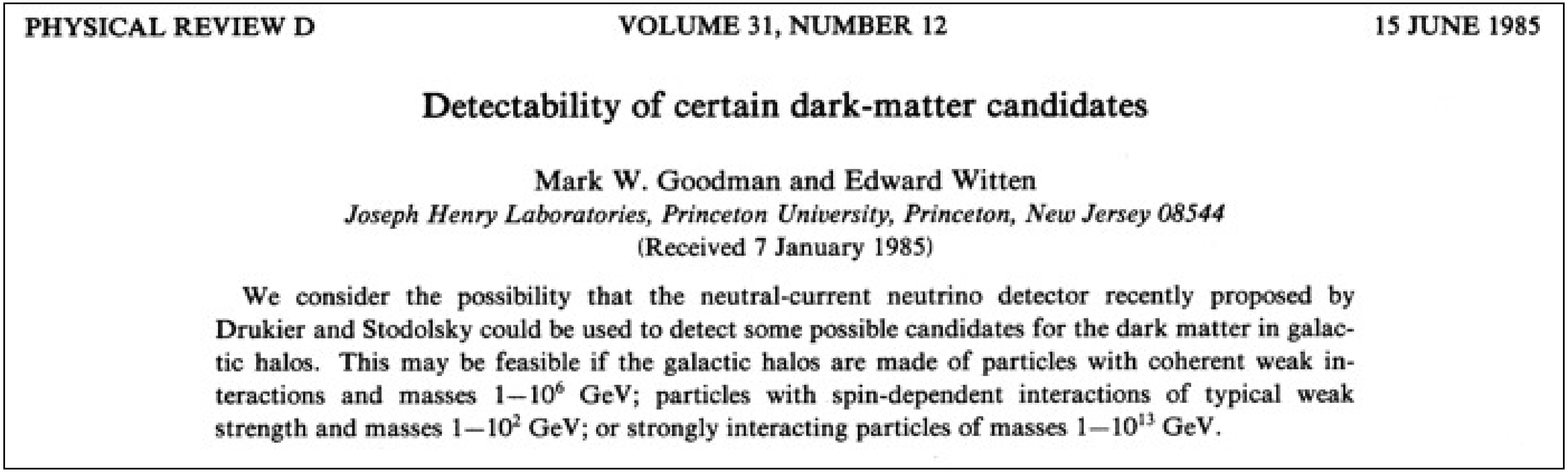
Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)



Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

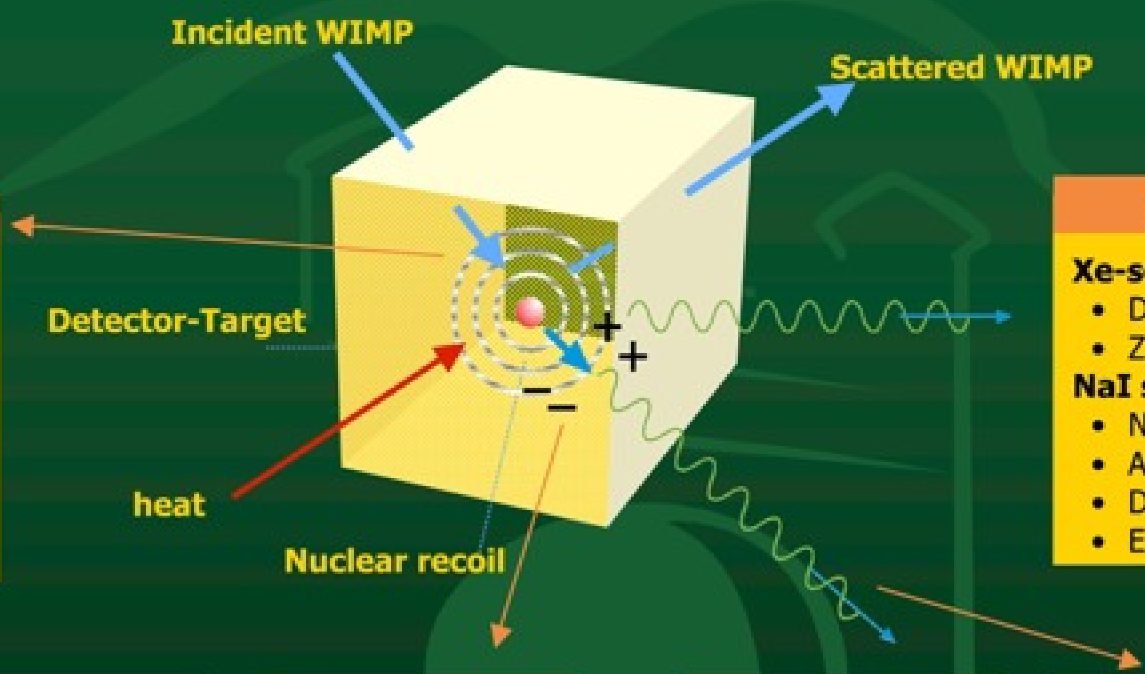
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^{6}$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^{2}$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Direct Detection Methods



HEAT

Bolometers:
- MiDBD
- ROSEBUD-I
- CRESST-I
- CUORICINO

Metastable p.det:
- SSD Micrograins
- SDD Droplets

LIGHT

Xe-scintillators:
- DAMA-Xe
- ZEPLIN-I

NaI scintillators:
- NAIAD
- ANAIS
- DAMA, LIBRA
- ELEGANTS

HEAT+CHARGE

- CDMS
- EDELWEISS

CHARGE

Ge-experiments:
- H/M
- IGEX
- GENIUS-TF

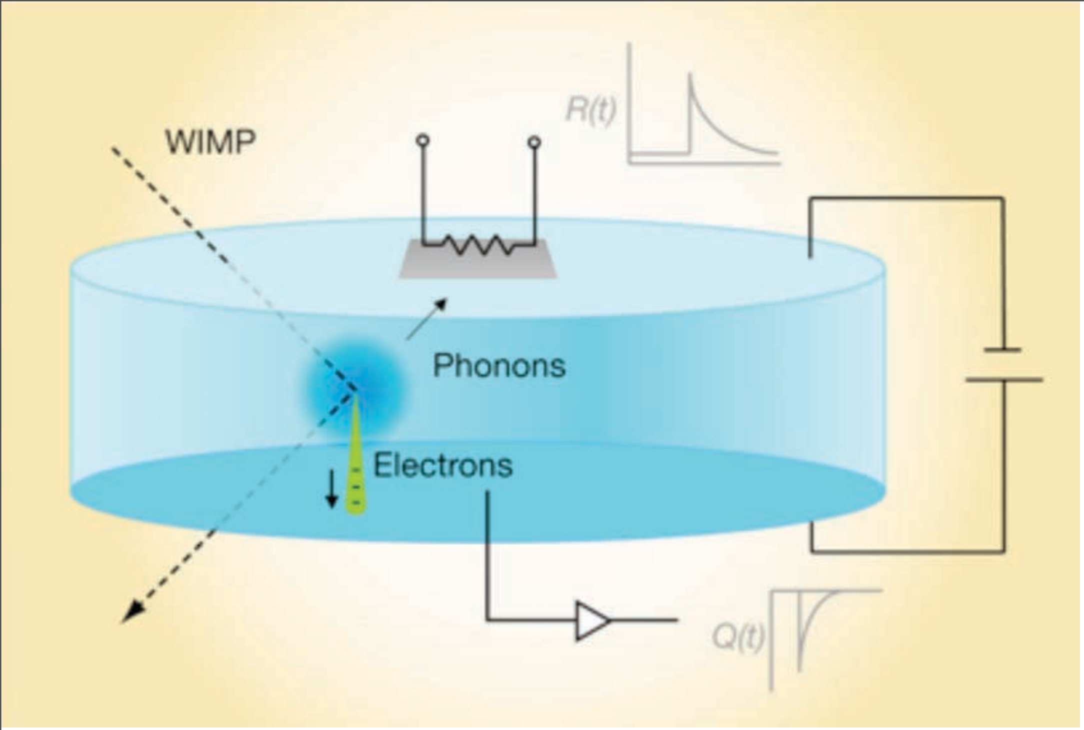
Tracking Chambers:
- DRIFT

HEAT+LIGHT

- ROSEBUD-II
- CRESST-II

LIGHT+CHARGE

- ZEPLIN-II
- X-MASS



CDMS - Cryogenic DM Search

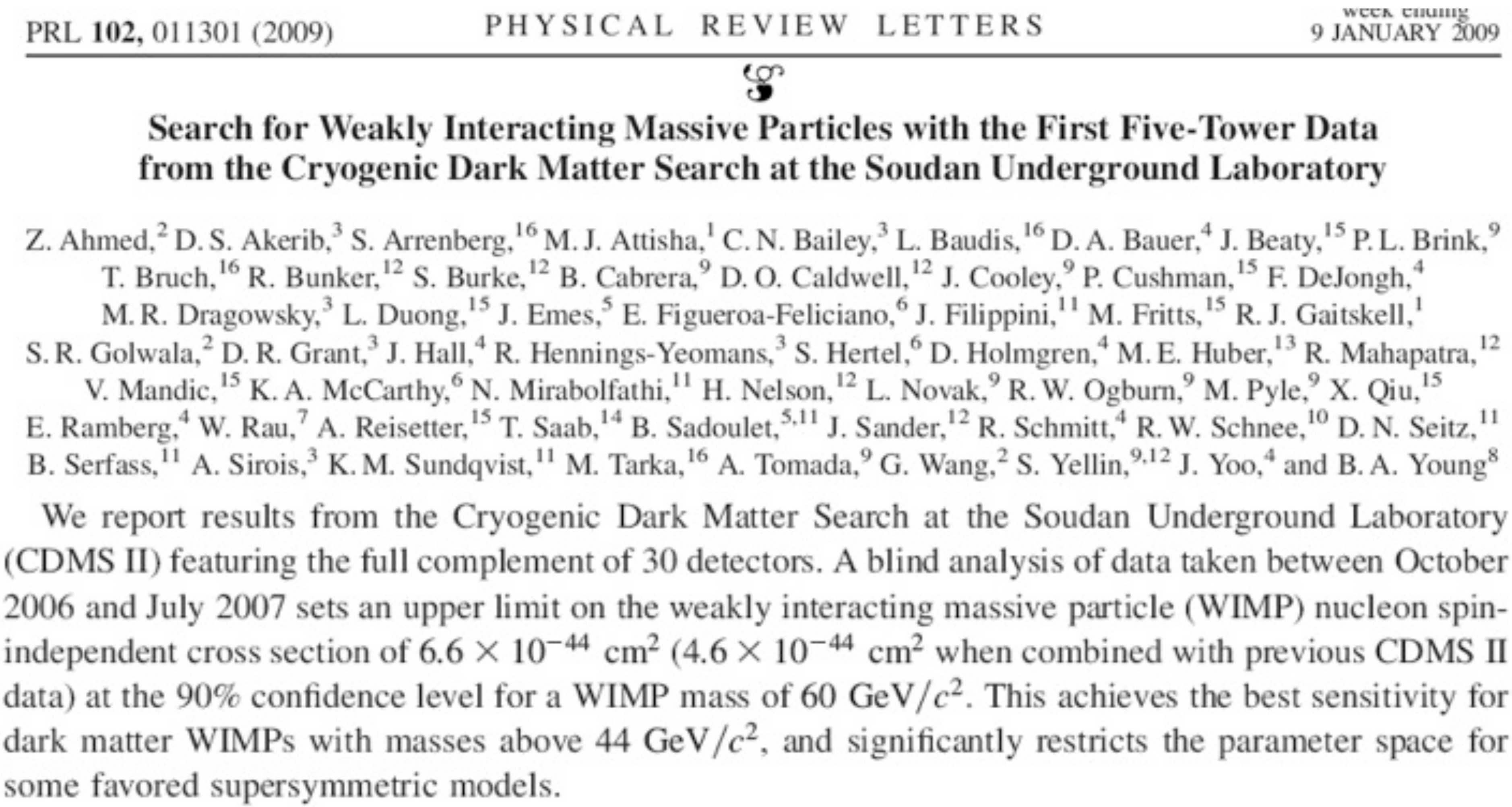
Berkeley-Stanford-led experiment has been at forefront

Figure from: Perspective by Karl van Bibber http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.011301 on Z. Ahmed et al. CDMS Collaboration, “Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory,” Phys. Rev. Lett. 102, 011301 (2009) – Published January 05, 2009

Schematic of an individual detector within CDMS. A WIMP scattering from a germanium nucleus produces a low-energy nuclear recoil, resulting in both ionization and athermal phonons. Charge carriers drift out to one face of the detector under the influence of a small electric field, and are detected with a sensitive amplifer [signal shown as Q(t)]. Phonons reaching the other face break Cooper pairs in a thin superconducting aluminum layer; the resulting quasiparticles heat a transition-edge sensor (TES) bonded to the aluminum layer, causing a measurable momentary change in its resistance R(t). In reality, the readout elements on both sides are highly segmented, and the relative timing of the ionization and phonon signals recorded, to provide good event localization.

CDMS - Cryogenic DM Search

Berkeley-Stanford-led experiment
has been at forefront



PRL 102, 011301 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory

Z. Ahmed,[2] D. S. Akerib,[3] S. Arrenberg,[16] M. J. Attisha,[1] C. N. Bailey,[3] L. Baudis,[16] D. A. Bauer,[4] J. Beaty,[15] P. L. Brink,[9] T. Bruch,[16] R. Bunker,[12] S. Burke,[12] B. Cabrera,[9] D. O. Caldwell,[12] J. Cooley,[9] P. Cushman,[15] F. DeJongh,[4] M. R. Dragowsky,[3] L. Duong,[15] J. Emes,[5] E. Figueroa-Feliciano,[6] J. Filippini,[11] M. Fritts,[15] R. J. Gaitskell,[1] S. R. Golwala,[2] D. R. Grant,[3] J. Hall,[4] R. Hennings-Yeomans,[3] S. Hertel,[6] D. Holmgren,[4] M. E. Huber,[13] R. Mahapatra,[12] V. Mandic,[15] K. A. McCarthy,[6] N. Mirabolfathi,[11] H. Nelson,[12] L. Novak,[9] R. W. Ogburn,[9] M. Pyle,[9] X. Qiu,[15] E. Ramberg,[4] W. Rau,[7] A. Reisetter,[15] T. Saab,[14] B. Sadoulet,[5,11] J. Sander,[12] R. Schmitt,[4] R. W. Schnee,[10] D. N. Seitz,[11] B. Serfass,[11] A. Sirois,[3] K. M. Sundqvist,[11] M. Tarka,[16] A. Tomada,[9] G. Wang,[2] S. Yellin,[9,12] J. Yoo,[4] and B. A. Young[8]

We report results from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory (CDMS II) featuring the full complement of 30 detectors. A blind analysis of data taken between October 2006 and July 2007 sets an upper limit on the weakly interacting massive particle (WIMP) nucleon spin-independent cross section of 6.6×10^{-44} cm^2 (4.6×10^{-44} cm^2 when combined with previous CDMS II data) at the 90% confidence level for a WIMP mass of 60 GeV$/c^2$. This achieves the best sensitivity for dark matter WIMPs with masses above 44 GeV$/c^2$, and significantly restricts the parameter space for some favored supersymmetric models.

Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory

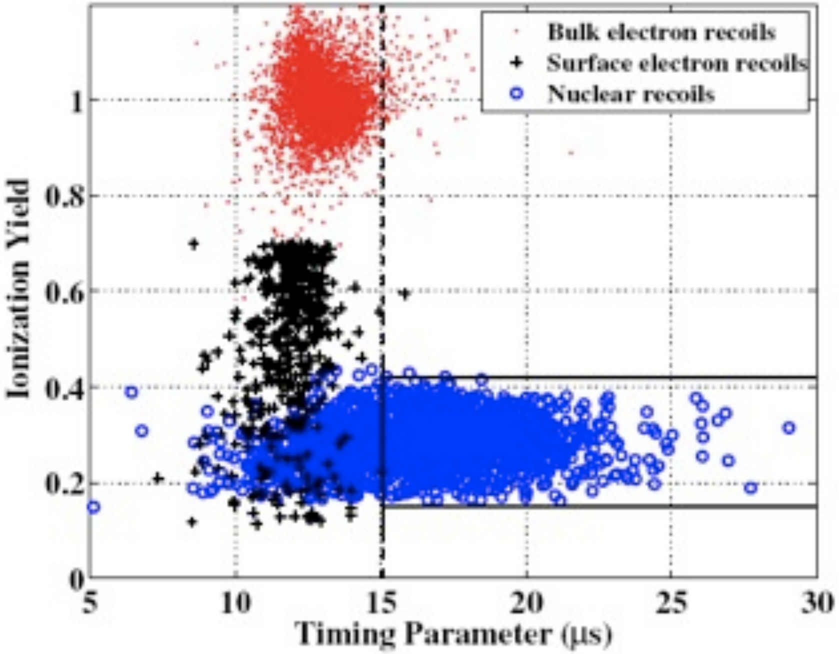


FIG. 1 (color online). Ionization yield versus timing parameter (see text) for calibration data in one of our Ge detectors. The yield is normalized to unity for typical bulk-electron recoils (dots; from ^{133}Ba γ-rays). Low-yield ^{133}Ba events (+), attributed to surface electron recoils, are discriminated from neutron-induced nuclear recoils from ^{252}Cf (○), based on timing parameter values. The vertical dashed line indicates the minimum timing parameter allowed for candidate dark matter events in this detector, and the box shows the approximate signal region, which is in fact weakly energy dependent.

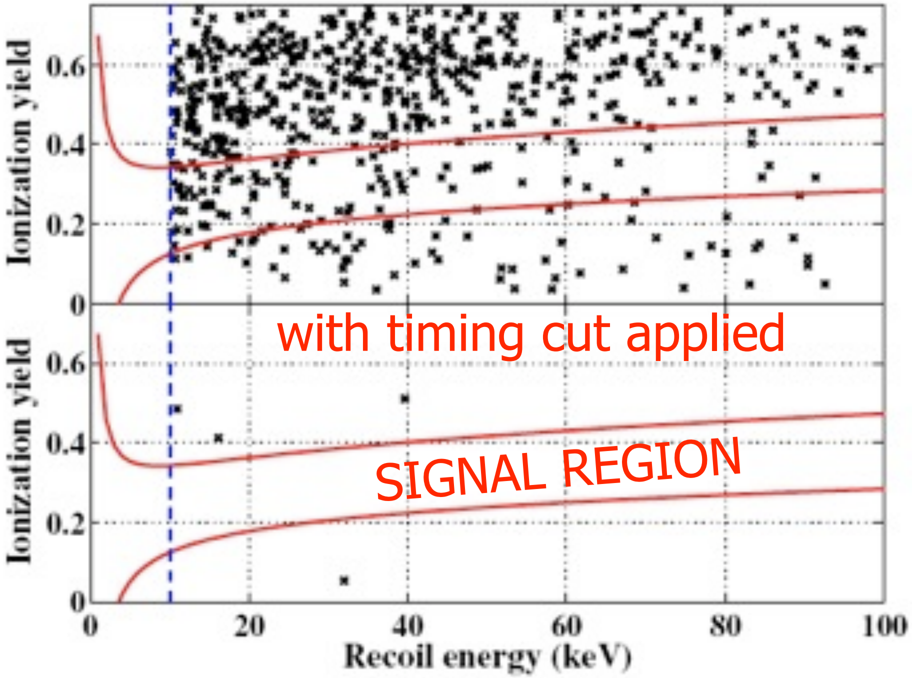
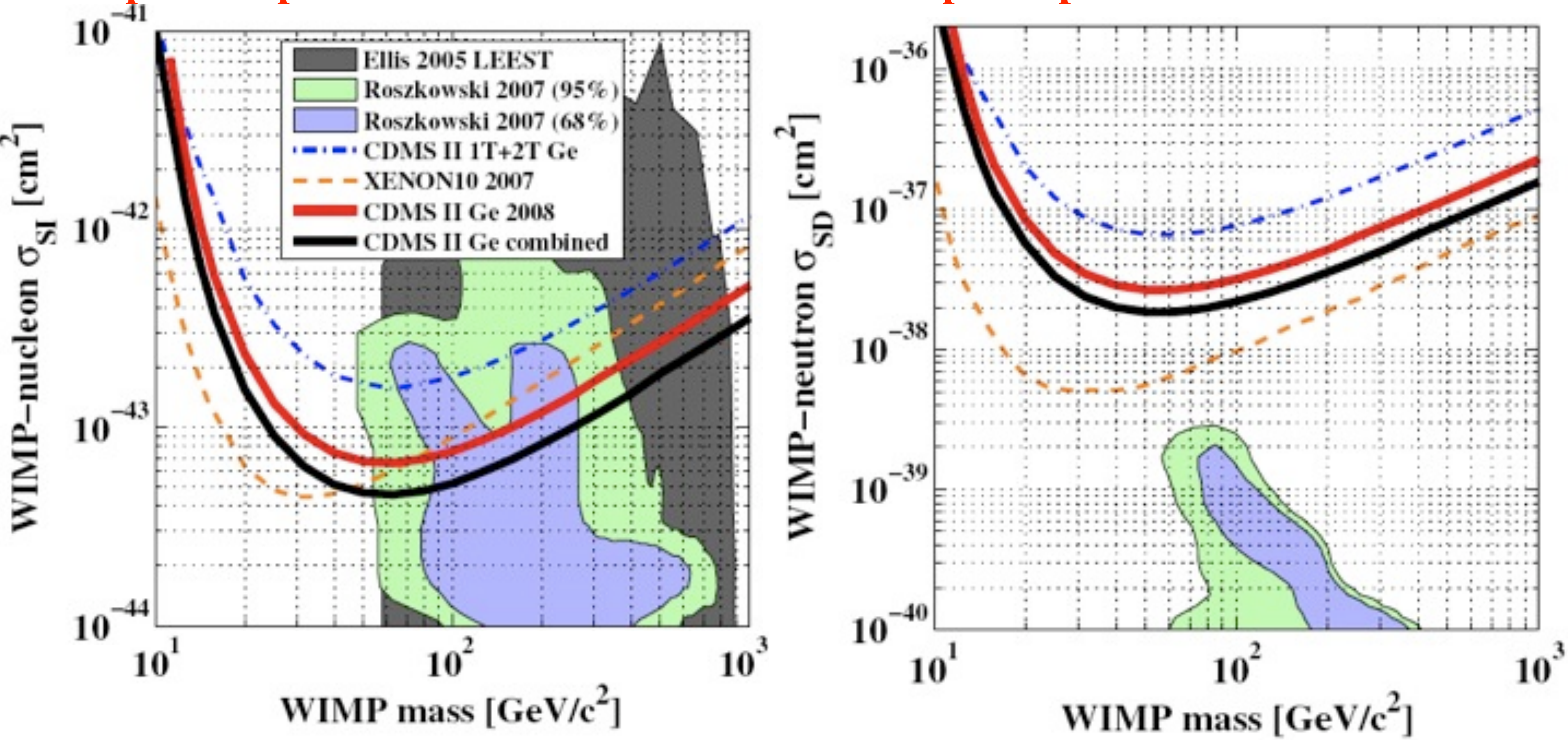


FIG. 2 (color online). Top: Ionization yield versus recoil energy in all detectors included in this analysis for events passing all cuts except the timing cut. The signal region between 10 and 100 keV recoil energies was defined using neutron calibration data and is indicated by the curved lines. Bulk-electron recoils have yield near unity and are above the vertical scale limits. Bottom: Same, but after applying the timing cut. No events are found within the signal region.



Spin-independent WIMP-nucleon σ **Spin-dependent WIMP-nucleon σ**

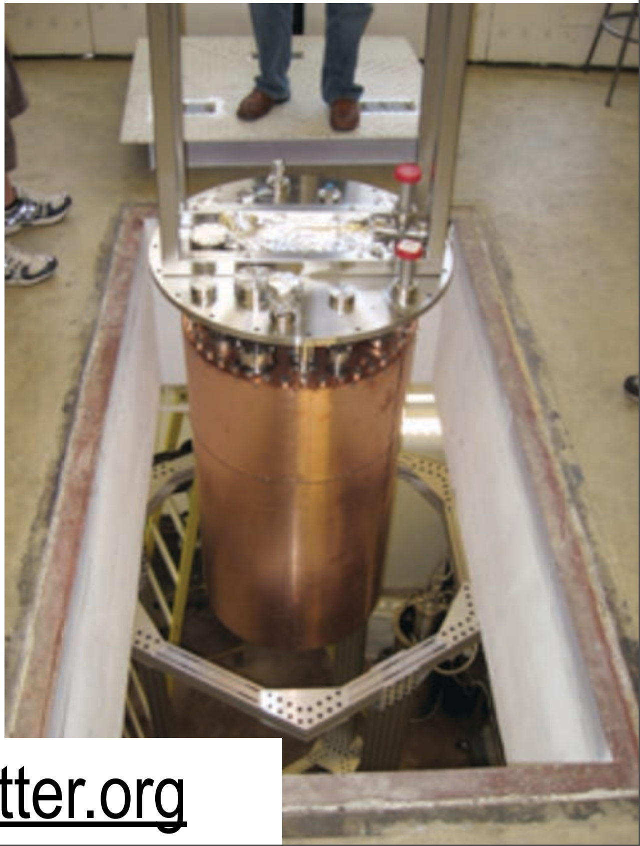
Spin-independent WIMP-nucleon (SI) and spin-dependent WIMP-neutron (SD) cross-section upper limits (90% C.L.) versus WIMP mass. In each panel, the curves represent 90% C.L. upper limits on the scattering cross section from this work and other recent experiments. Shaded regions represent parameter ranges expected from supersymmetric models described in [22,23].

[22] J. R. Ellis, K. A. Olive, Y. Santoso, and V. C. Spanos, Phys. Rev. D 71, 095007 (2005).
[23] L. Roszkowski et al., J. High Energy Phys. 07 (2007) 075.

LUX Dark Matter Experiment

- Brown [Gaitskell], Case [Shutt], LBNL [Lesko] , LLNL [Bernstein], Maryland [Hall], Rochester [Wolfs], Texas A&M [White], UC Davis [Svoboda/Tripathi], U South Dakota [Mei] , Yale [McKinsey]
  - XENON10,ZEPLIN II (US),CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - Also ZEPLIN III Groups in next phase
  - Co-spokespersons: Gaitskell (Brown) / Shutt (Case)
- 300 kg Dual Phase liquid Xe TPC with 100 kg fiducial
  - Using conservative assumptions: >99.4% ER background rejection for 50% NR acceptance, E>5 keVr (ER rejection is energy dependent)
    (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial
- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - Can achieve BG γ+β < $8\text{x}10^{-4}$ /keVee/kg/day, dominated by PMTs (Hamamatsu R8778).
    - Neutrons (α,n) & fission subdominant
  - External: large water shield with muon veto.
    - Very effective for cavern γ+n, and HE n from muons
    - Very low gamma backgrounds with readily achievable $<10^{-11}$ g/g purity.
- DM reach: $7\text{x}10^{-46}$ cm^2 in 10 months

In DUSEL
(Deep Underground Science and Engineering Laboratory)
Homestake Mine
Lead, South Dakota, USA
2009



www.luxdarkmatter.org

Dark Matter and Terascale Physics

V. Barger

The Gold Standard: mSUGRA

- SUSY stabilizes radiative corrections to the Higgs mass and realizes GUT unification of electroweak and strong couplings
- Weird quantum numbers of particles explained by 16 representation of SO(10)

- mSUGRA: SUSY broken by gravity
  - predictive--small number of parameters: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

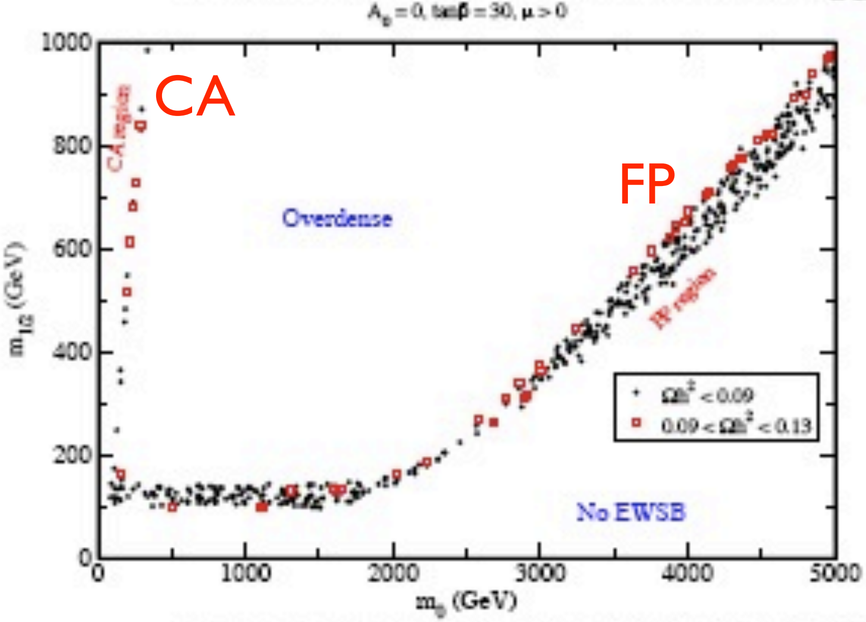
- Find well defined regions of parameter space consistent with the relic density from WMAP

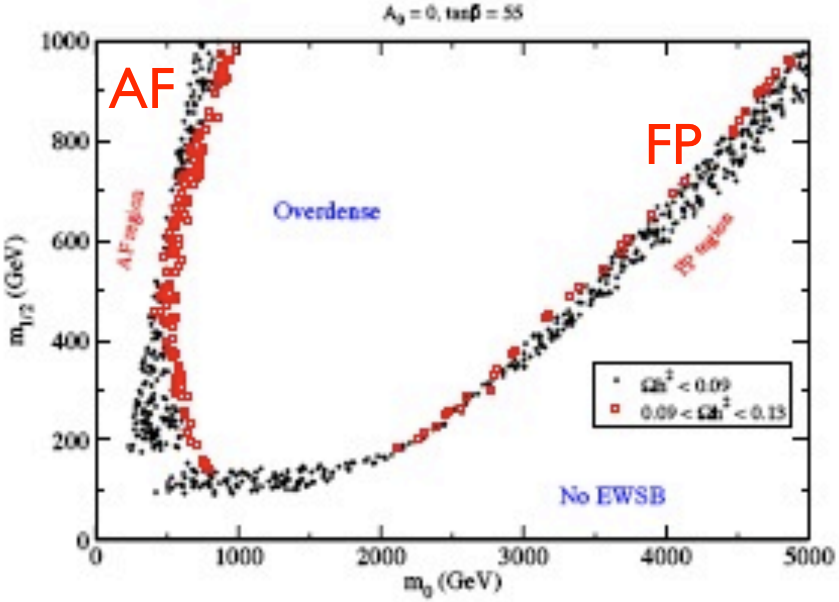
$$0.099 < \Omega_{DM} h^2 < 0.123 \ (2\sigma)$$

- DM is associated with EWSB
  - weak scale cross section naturally gives $\Omega_{\rm CDM}$

mSUGRA parameter space

- Representative regions in mSUGRA parameter space (red points fully account for $\Omega_{\rm CDM}$)

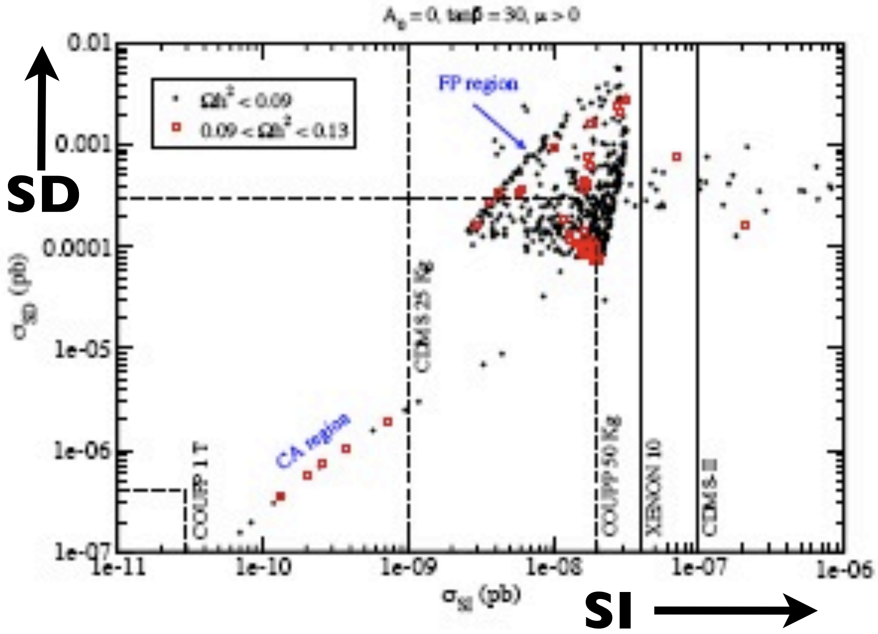


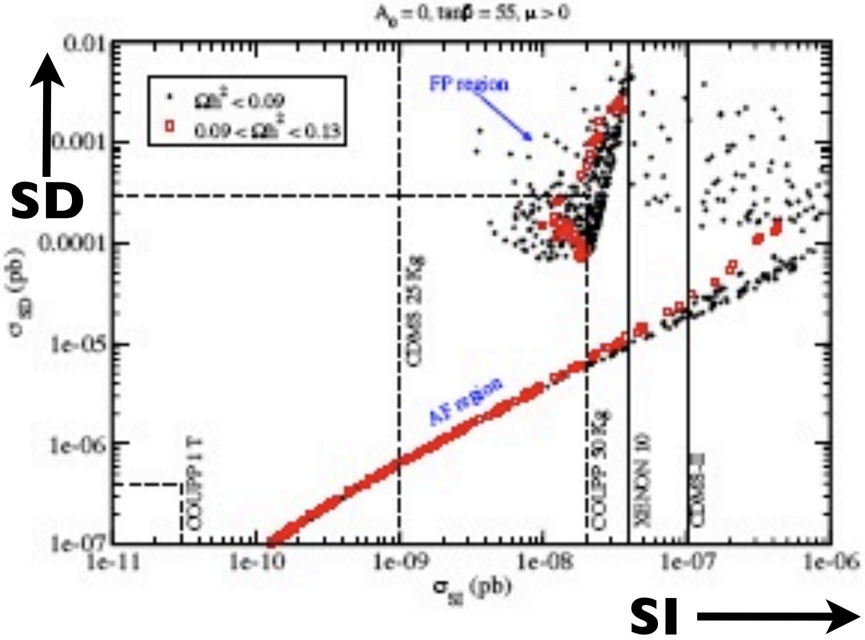


- Focus Point (FP) region: high mass scalar fermions
  - Preferred by $b-\tau$ unification
  - Solves SUSY FCNC and CP-violating problems
- A-funnel (AF) region: annihilation through CP-odd Higgs (A)
- $\tilde{\tau} - \chi_1^0$ coannihilation (CA) region
- Bulk region (BR) at low $m_0, m_{1/2}$ nearly excluded

Scattering rates in mSUGRA

- Different solutions to DM relic density populate different regions of σ_{SD} vs. σ_{SI} Spin Dependent vs. Spin Indenepdent

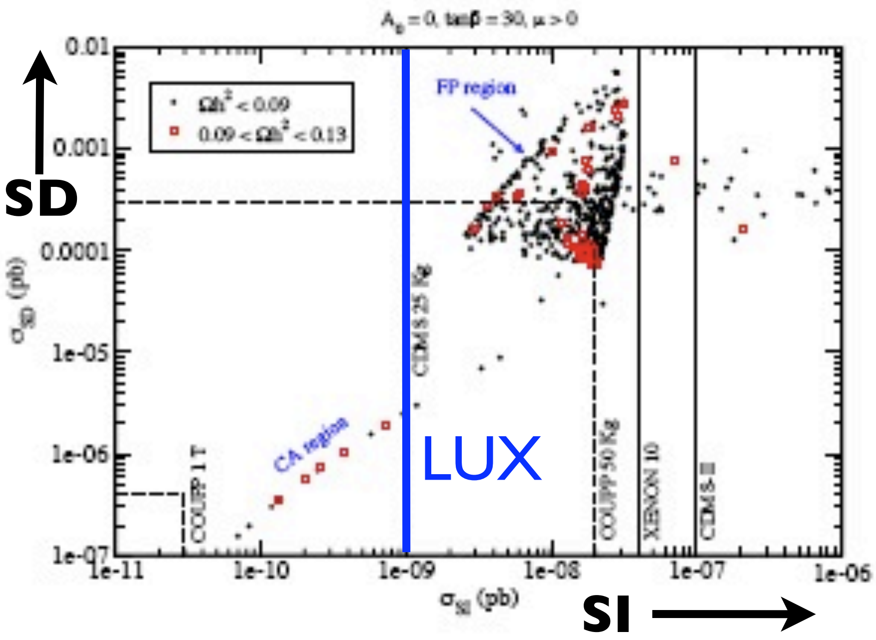


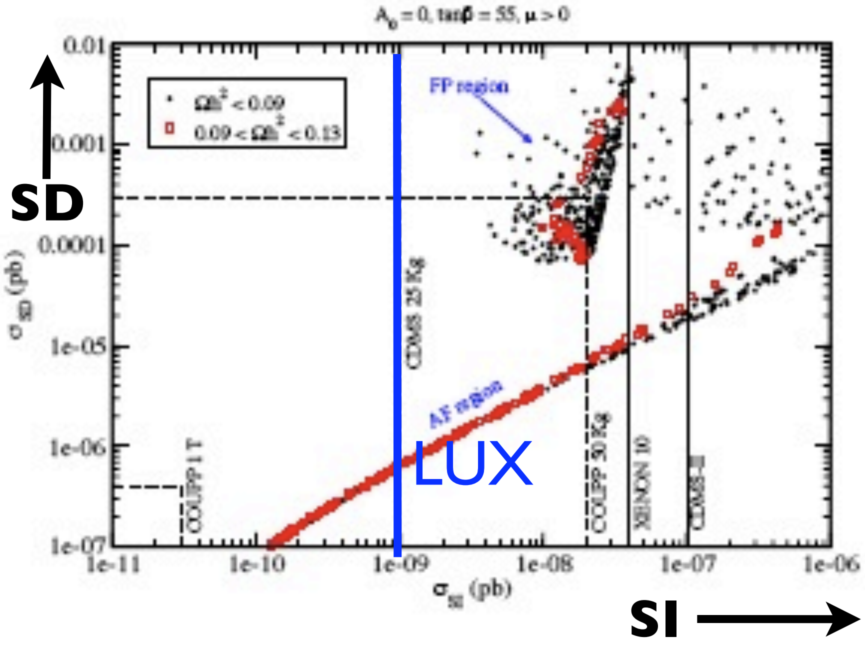


- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

Scattering rates in mSUGRA

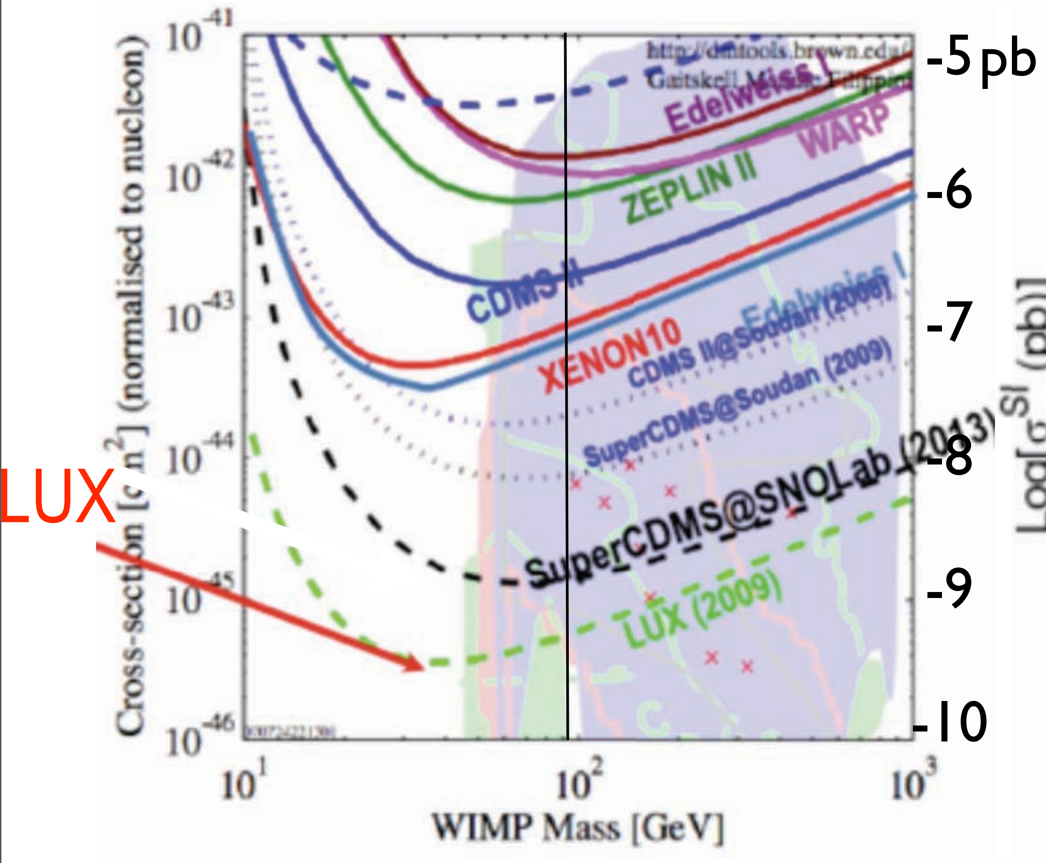
- Different solutions to DM relic density populate different regions of σ_{SD} vs. σ_{SI} Spin Dependent vs. Spin Indenepdent

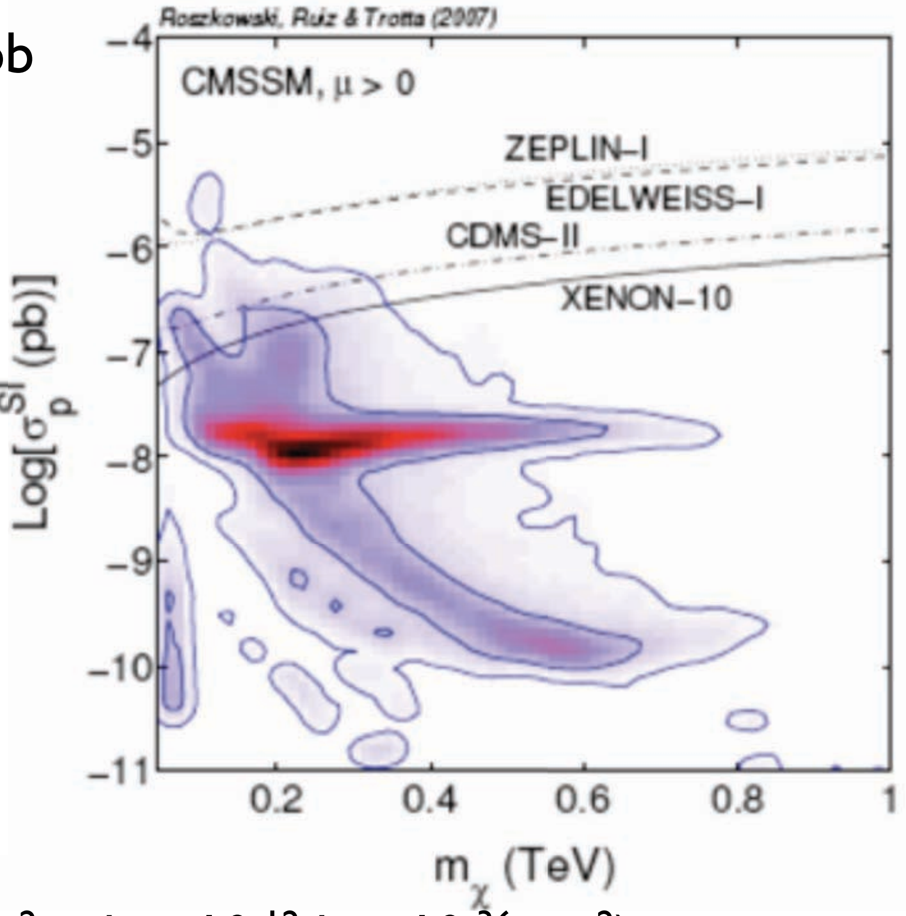




- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

By ~2009 Direct Detection could probe most of the CMSSM (constrained minimal supersymmetric standard model) and mSUGRA (minimal supergravity) WIMP parameter space! If LUX succeeds, it will leapfrog over CDMS and have great discovery potential during 2009.





10^{-8} pb = 10^{-44} cm^2 (barn=10^{-24} cm^2, pb = 10^{-12} b = 10^{-36} cm^2)

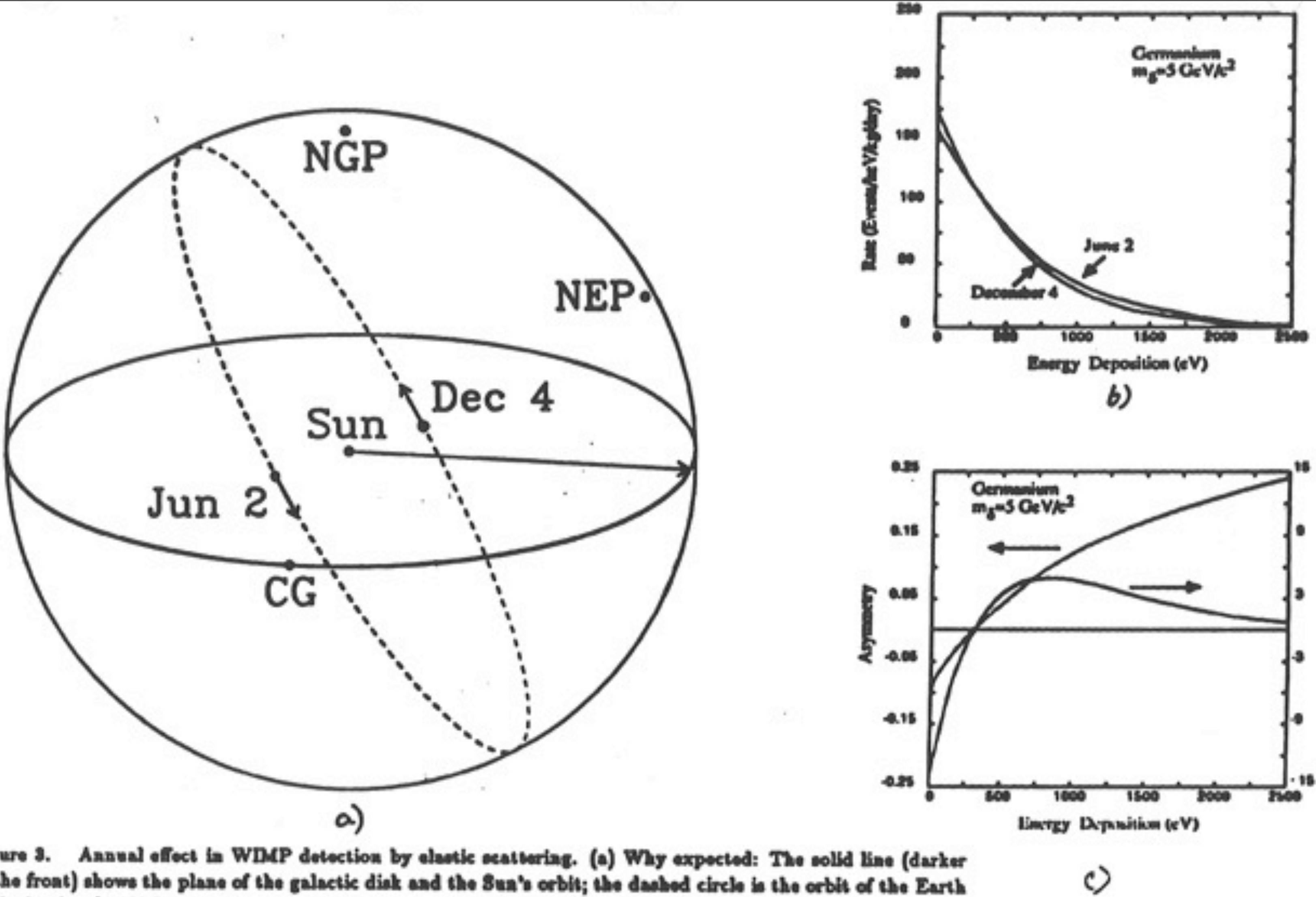
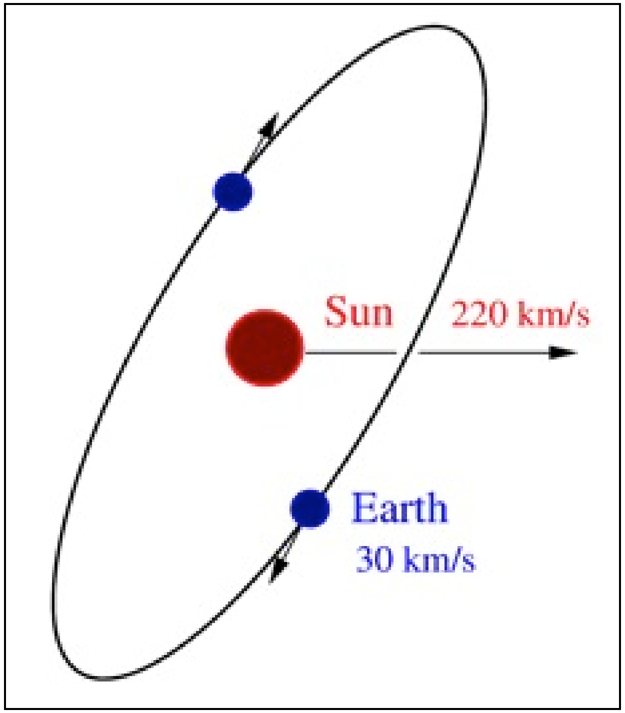


Figure 3. Annual effect in WIMP detection by elastic scattering. (a) Why expected: The solid line (darker in the front) shows the plane of the galactic disk and the Sun's orbit; the dashed circle is the orbit of the Earth (ecliptic plane). NGP and NEP are the north galactic and ecliptic poles. CG shows the direction toward the galactic center, and the long and short arrows show the Sun's and the Earth's velocities. The sum of the Sun's and Earth's velocities reaches its maximum on June 2 (248 km s^{-1}) and minimum on December 4 (219 km s^{-1}). (These velocities with respect to the galactic center are obtained neglecting the small eccentricity of the Earth's orbit, and assuming that the Sun's peculiar velocity is 16.5 km s^{-1} in the galactic direction $l = 53°$, $b = 25°$ with respect to the local standard of rest (cf. 118). Event rates in WIMP detectors actually depend on the Earth's velocity with respect to the DM halo, whose rotational velocity is uncertain.) (b) Rate for June 2 and December 4 vs. deposited energy. (c) June – December difference (right axis) and asymmetry (left axis) vs. deposited energy. Note that although the asymmetry increases with the energy deposition, the rate and therefore also the June – December rate difference both decrease at high energy deposition.

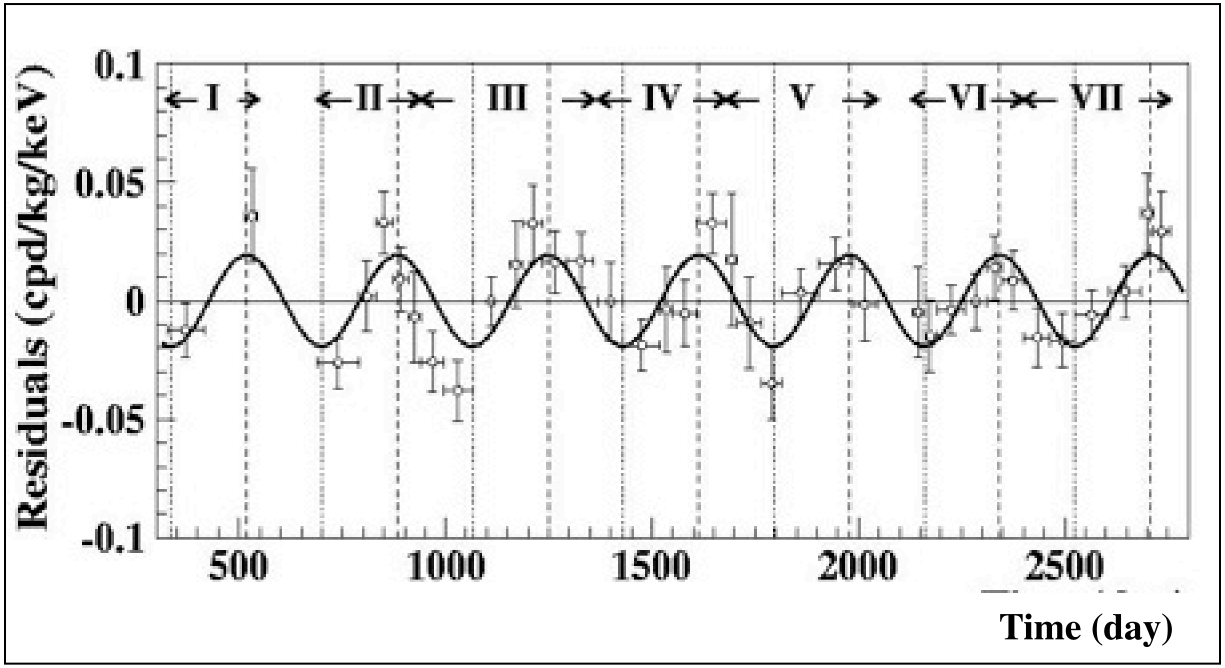
Primack, Seckel, & Sadoulet, Ann Rev Nucl Part Sci 1988

DAMA Evidence for WIMP detection



Annual modulation of WIMP signal a "smoking gun" signature

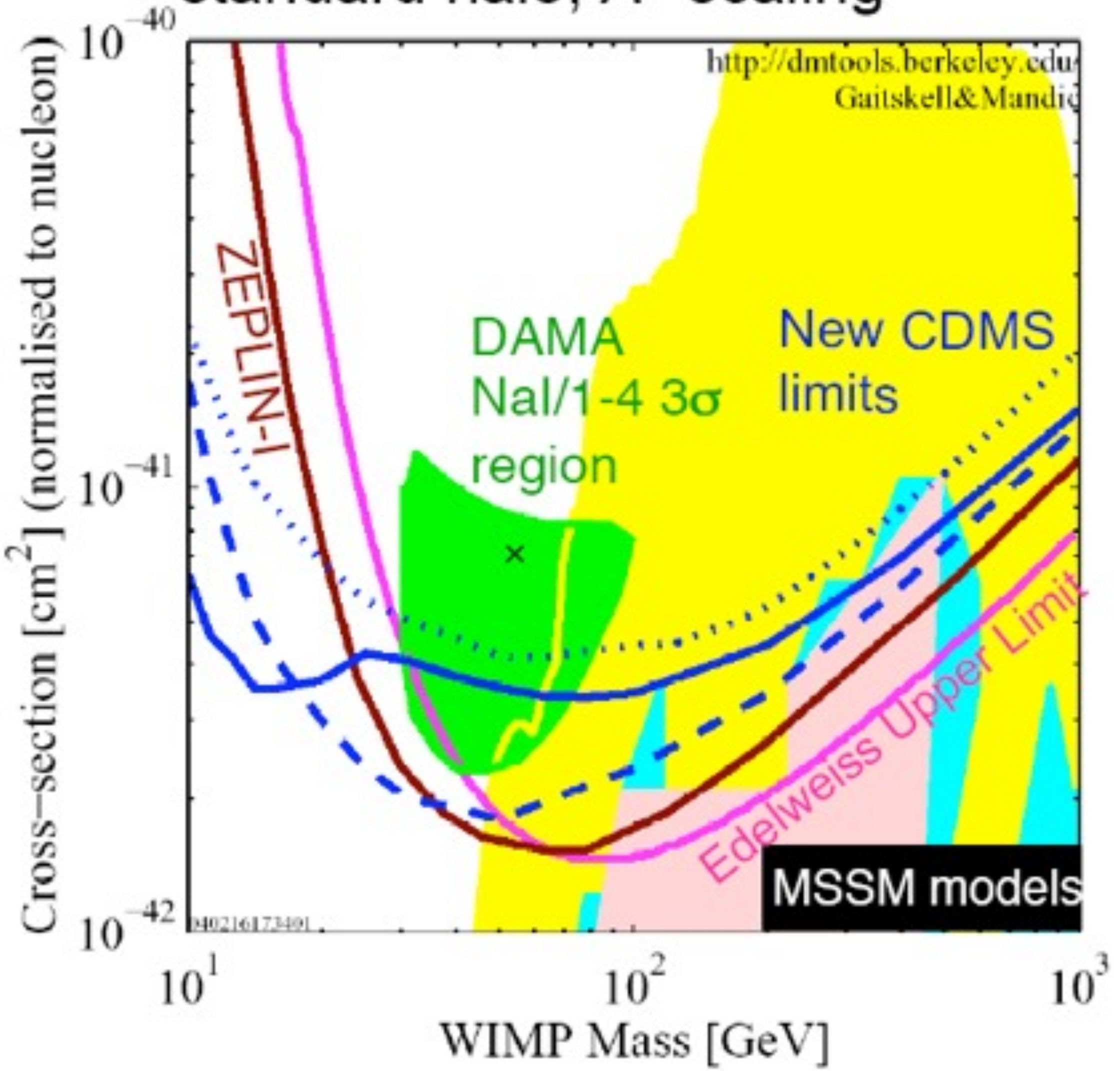
DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]



- Detector stability ?
- Background stability ?

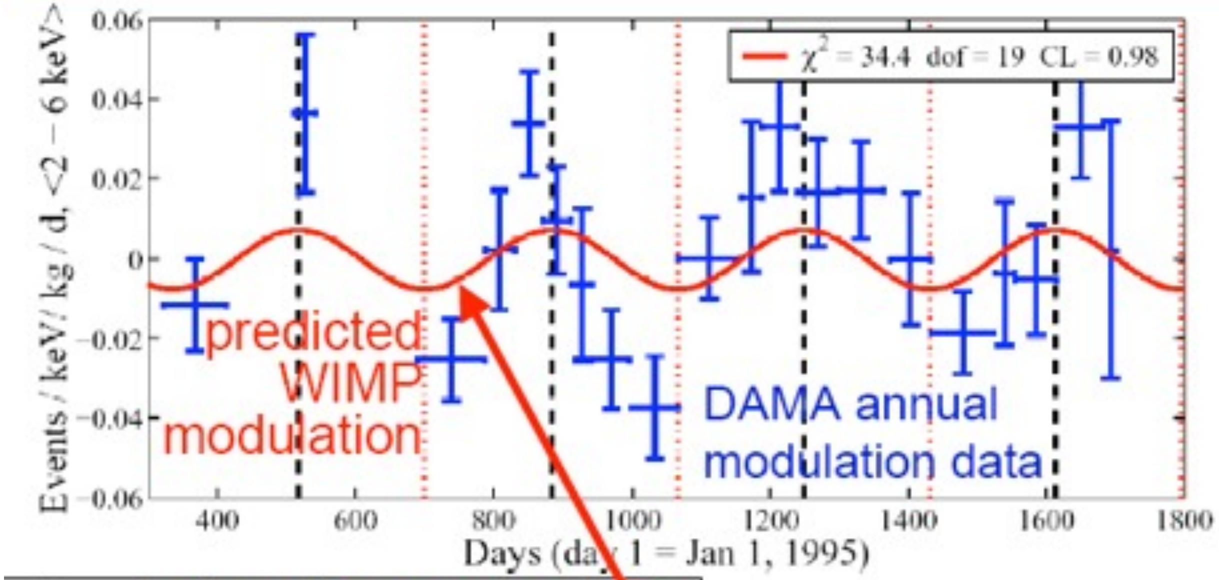
Resulting Experimental Upper Limits

90% CL upper limits assuming standard halo, A^2 scaling

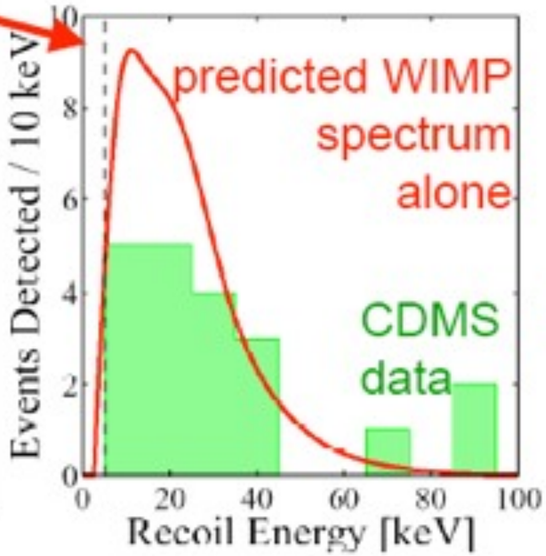


- Calculate allowed region using extension of "Feldman Cousins" method
  - Constrain neutron background based on neutron multiples, Si
- Limits slightly worse than expected sensitivity (dashes), slightly better than limits wo/ subtraction (dots)
- Exclude new parameter space for WIMP masses below 20 GeV
- Exclude a few interesting supersymmetry models
- Exclude DAMA most likely point (x) at 99.8% CL

Incompatibility with DAMA



Best **simultaneous fit** to CDMS and DAMA predicts too little annual modulation in DAMA, too many events in CDMS (even for **no** neutron background)

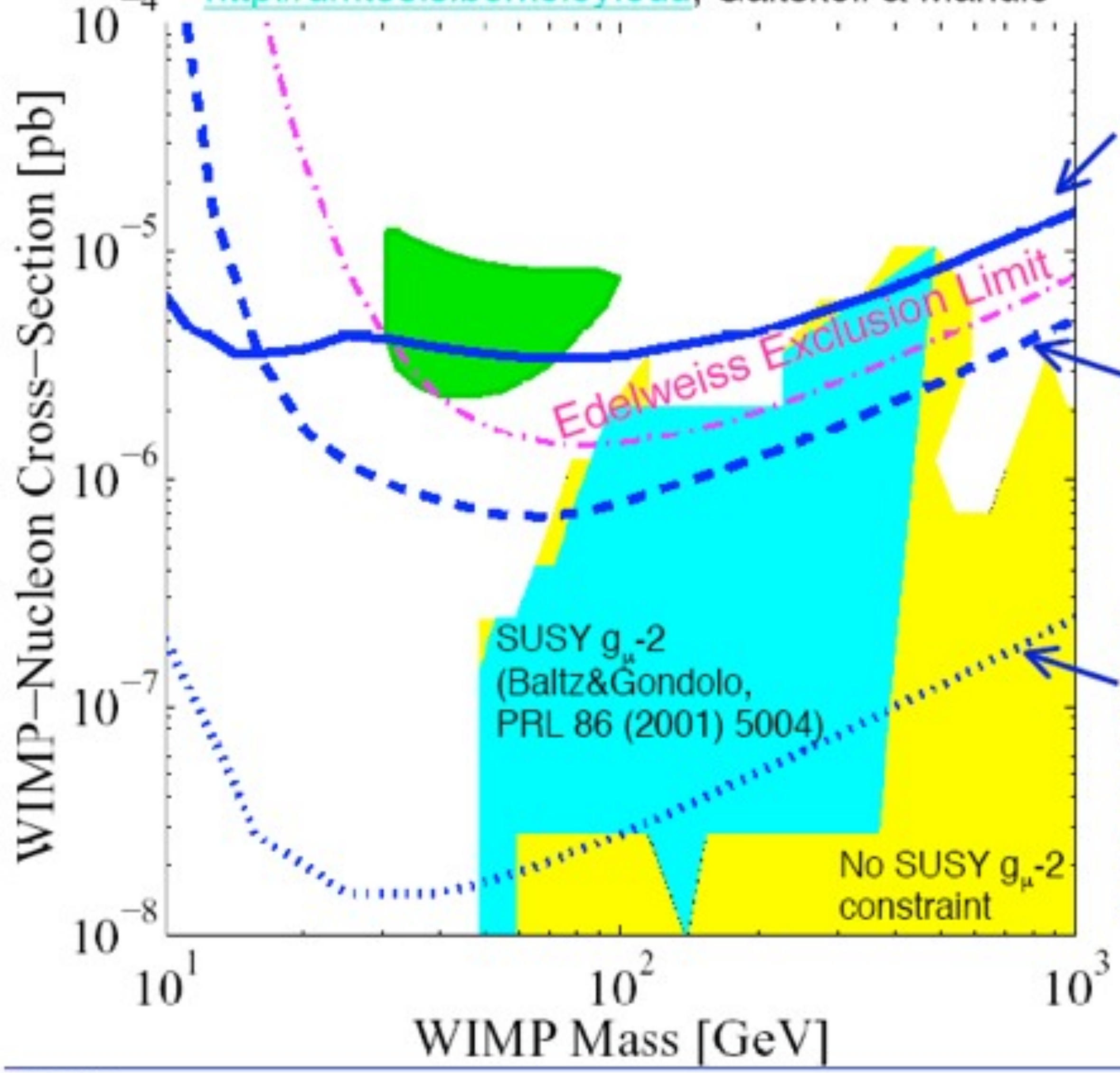


- Test under assumptions of
  - "standard" halo
  - standard WIMP interactions
- CDMS results incompatible with DAMA model-independent annual-modulation data (left) at > 99.8% CL even if all low-energy events are WIMPs

The 2009 limits are much stronger.

Current and Projected CDMS Sensitivity

For more limit curves, see
http://dmtools.berkeley.edu, Gaitskell & Mandic



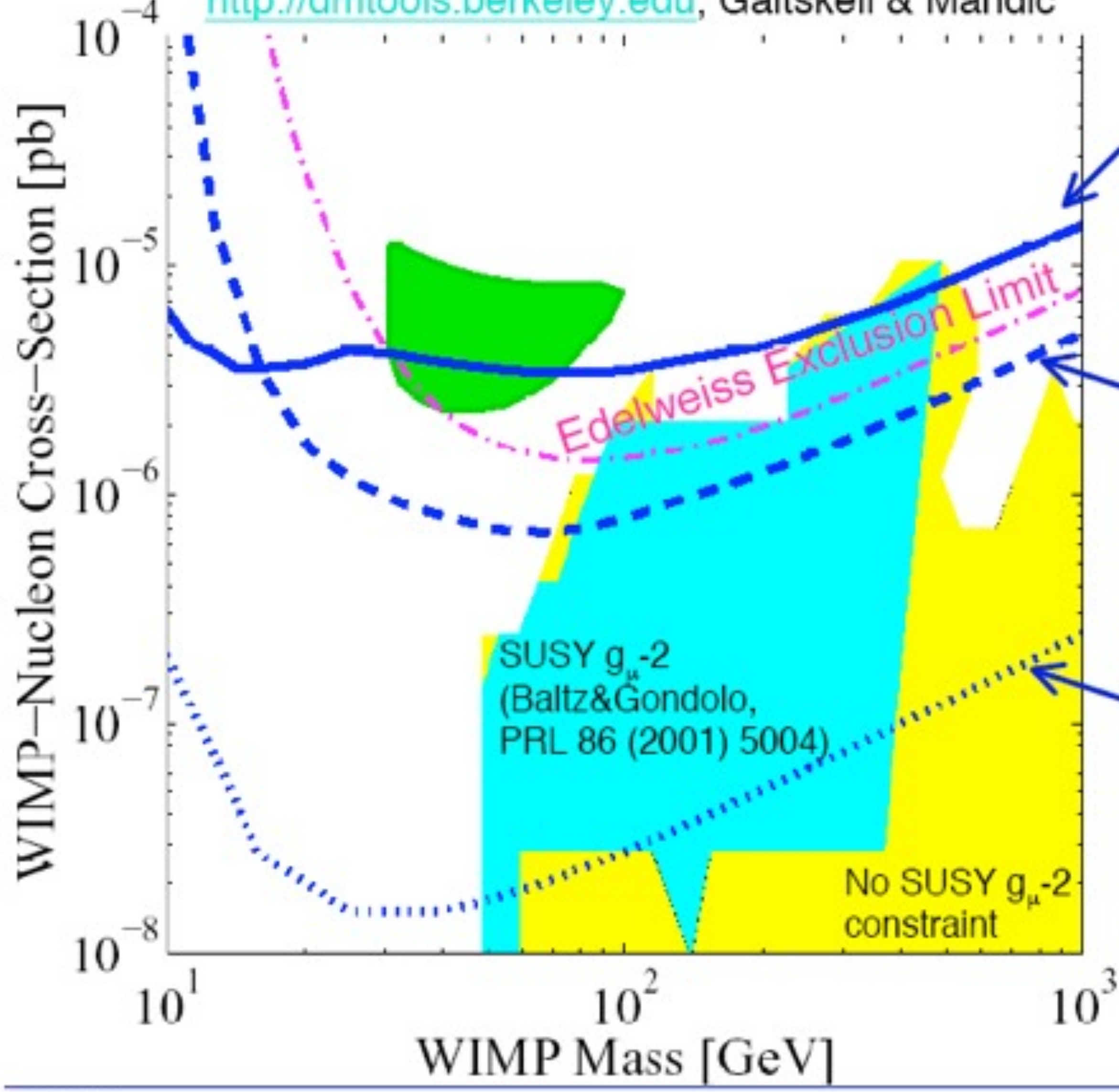
Current CDMS Limit

Expected sensitivity of data in hand from first CDMS run at Soudan (5x better than current limit).

Projected sensitivity for CDMS at Soudan, with 5 towers 4 kg Ge, 1.5 kg Si: 0.1 events/kg/keV/year (100x better than current limit).

Current and Projected CDMS Sensitivity

For more limit curves, see
http://dmtools.berkeley.edu, Gaitskell & Mandic



Current CDMS Limit 2003

Expected sensitivity of data in hand from first CDMS run at Soudan (5x better than current limit).

Projected sensitivity for CDMS at Soudan, with 5 towers 4 kg Ge, 1.5 kg Si: 0.1 events/kg/keV/year (100x better than current limit). This sensitivity has almost been reached now (early 2009). DAMA is excluded!

WHAT IS THE DARK MATTER?

Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many upcoming experiments

- Production at Large Hadron Collider
- Better CMB data from PLANCK
- Direct Detection
  - Spin Independent - CDMS-II, XENON50, LUX
  - Spin Dependent - COUPP, PICASSO
- **Indirect detection via**
  - **GLAST and larger ACTs**
  - **PAMELA and ATIC**

-- there could well be a big discovery in the next year or two!

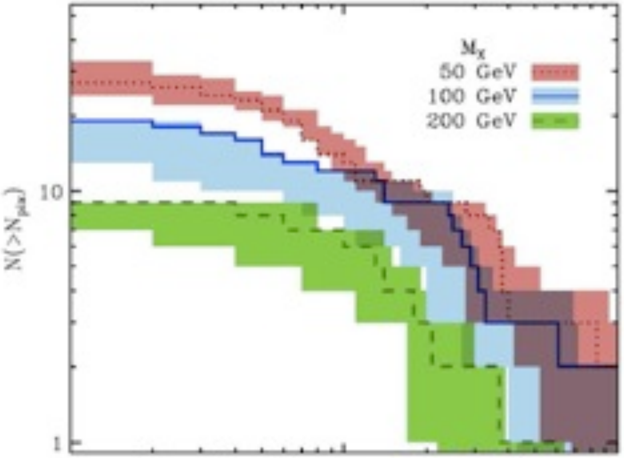
THE DARK MATTER ANNIHILATION SIGNAL FROM GALACTIC SUBSTRUCTURE: PREDICTIONS FOR GLAST

2008 ApJ 686, 262

Michael Kuhlen[1], Jürg Diemand[2,3], Piero Madau[2]

ABSTRACT

We present quantitative predictions for the detectability of individual Galactic dark matter subhalos in gamma-rays from dark matter pair annihilations in their centers. Our method is based on a hybrid approach, employing the highest resolution numerical simulations available (including the recently completed one billion particle Via Lactea II simulation) as well as analytical models for the extrapolation beyond the simulations' resolution limit. We include a self-consistent treatment of subhalo boost factors, motivated by our numerical results, and a realistic treatment of the expected backgrounds that individual subhalos must outshine. We show that for reasonable values of the dark matter particle physics parameters ($M_\chi \sim 50 - 500$ GeV and $\langle \sigma v \rangle \sim 10^{-26} - 10^{-25}$ cm^3 s^{-1}) GLAST may very well discover a few, even up to several dozen, such subhalos, at 5 σ significance, and some at more than 20 σ. We predict that the majority of luminous sources would be resolved with GLAST's expected angular resolution. For most observer locations the angular distribution of detectable subhalos is consistent with a uniform distribution across the sky. The brightest subhalos tend to be massive (median $V_{\max}$ of 24 km s^{-1}) and therefore likely hosts of dwarf galaxies, but many subhalos with $V_{\max}$ as low as 5 km s^{-1} are also visible. Typically detectable subhalos are 20 – 40 kpc from the observer, and only a small fraction are closer than 10 kpc. The total number of observable subhalos has not yet converged in our simulations, and we estimate that we may be missing up to 3/4 of all detectable subhalos.

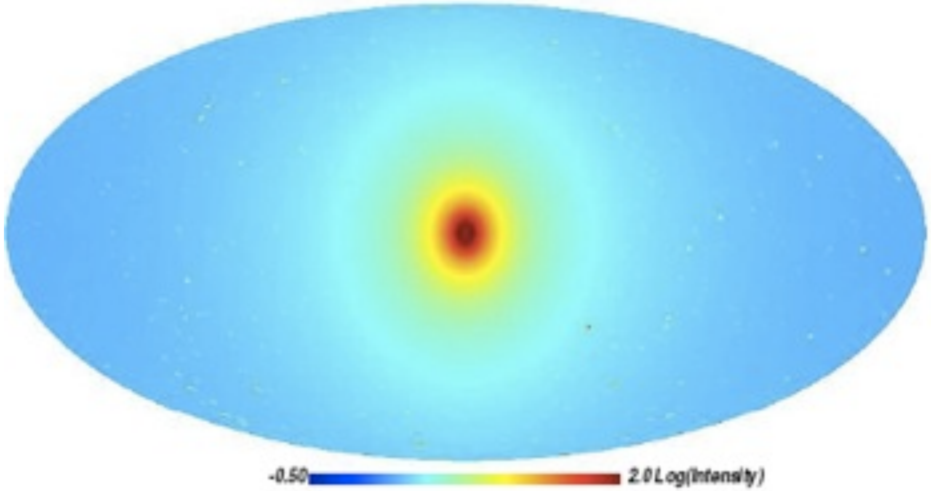


The number of detectable (S = 5) subhalos with more than N_{pix} detectable pixels versus N_{pix}, for three different choices of M(for <σv> = 3×10^{-26} cm^3 s^{-1}). The shaded regions show the range of N(>N_{pix}) for ten randomly chosen observer locations and the solid lines refer to an observer placed along the intermediate axis of the host halo ellipsoid.

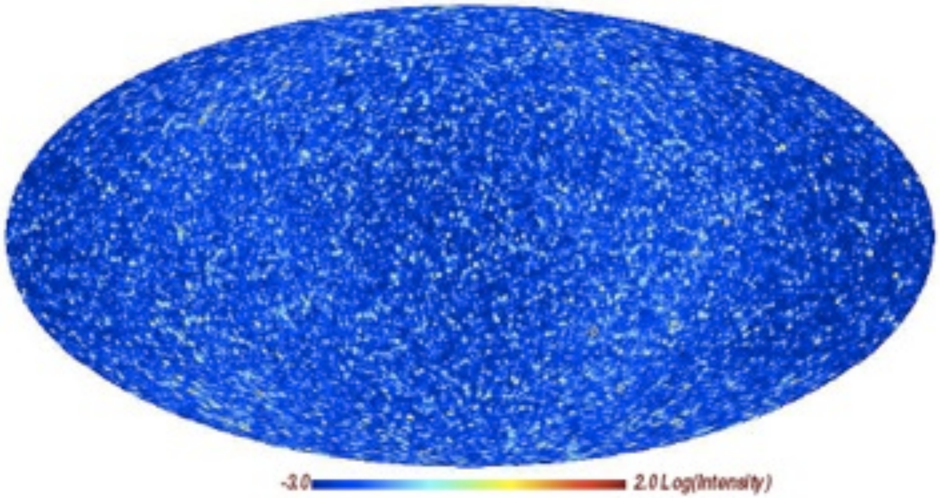
A blueprint for detecting supersymmetric dark matter in the Galactic halo

V. Springel et al. 2008 Nature 456, 73-76

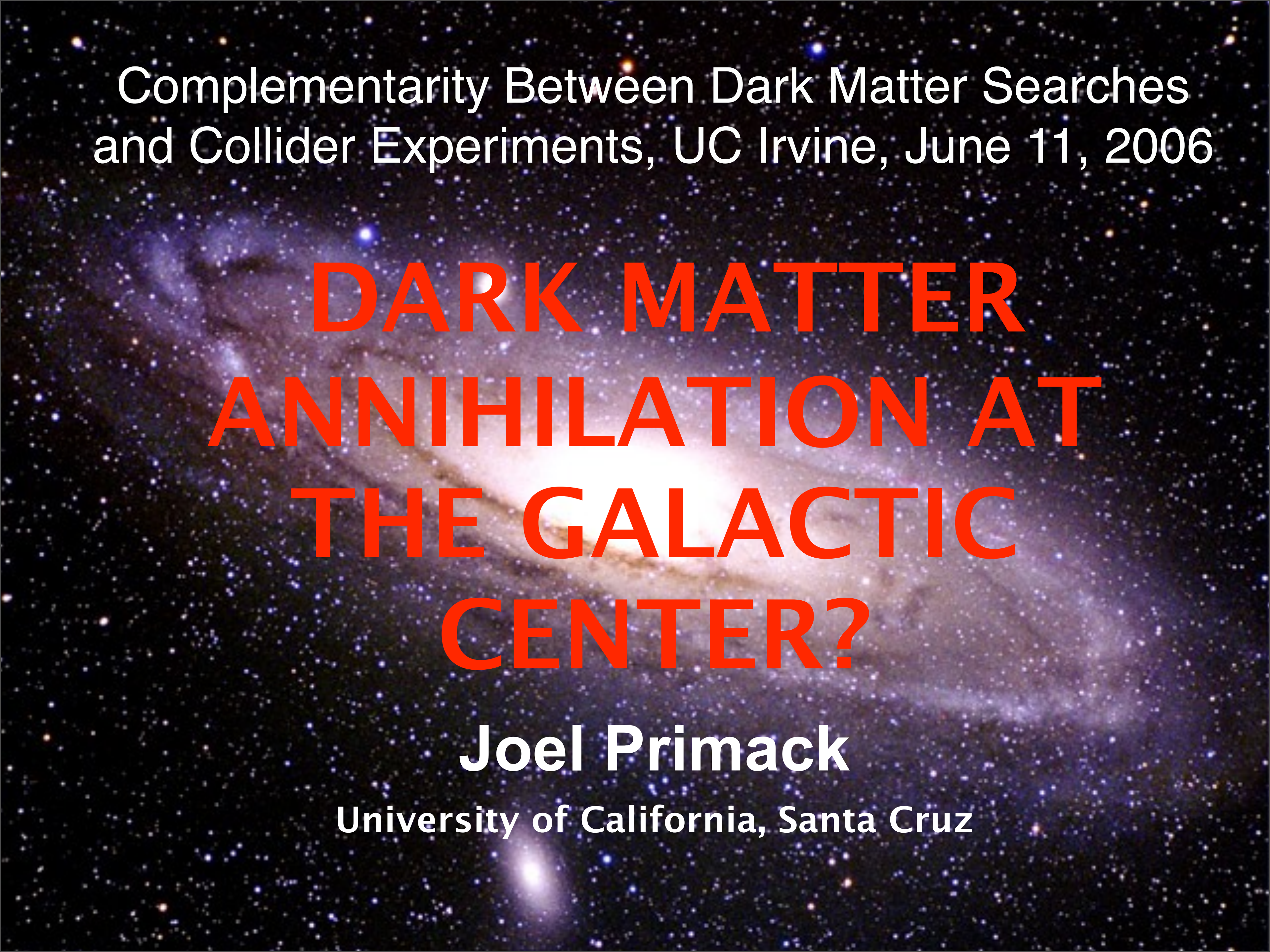
Dark matter is the dominant form of matter in the universe, but its nature is unknown. It is plausibly an elementary particle, perhaps the lightest supersymmetric partner of known particle species[1]. In this case, annihilation of dark matter in the halo of the Milky Way should produce g -rays at a level which may soon be observable[2,3]. Previous work has argued that the annihilation signal will be dominated by emission from very small clumps[4,5] (perhaps smaller even than the Earth) which would be most easily detected where they cluster together in the dark matter halos of dwarf satellite galaxies[6]. Here we show, using the largest ever simulation of the formation of a galactic halo, that such small-scale structure will, in fact, have a negligible impact on dark matter detectability. Rather, the dominant and likely most easily detectable signal will br produced by diffuse dark matter in the main halo of the Milky Way[7,8]. If the main halo is strongly detected, then small dark matter clumps should also be visible, but may well contain no stars, thereby confirming a key prediction of the Cold Dark Matter (CDM) model.



total emission



emission from resolved subhalos (SubSm+SubSub)



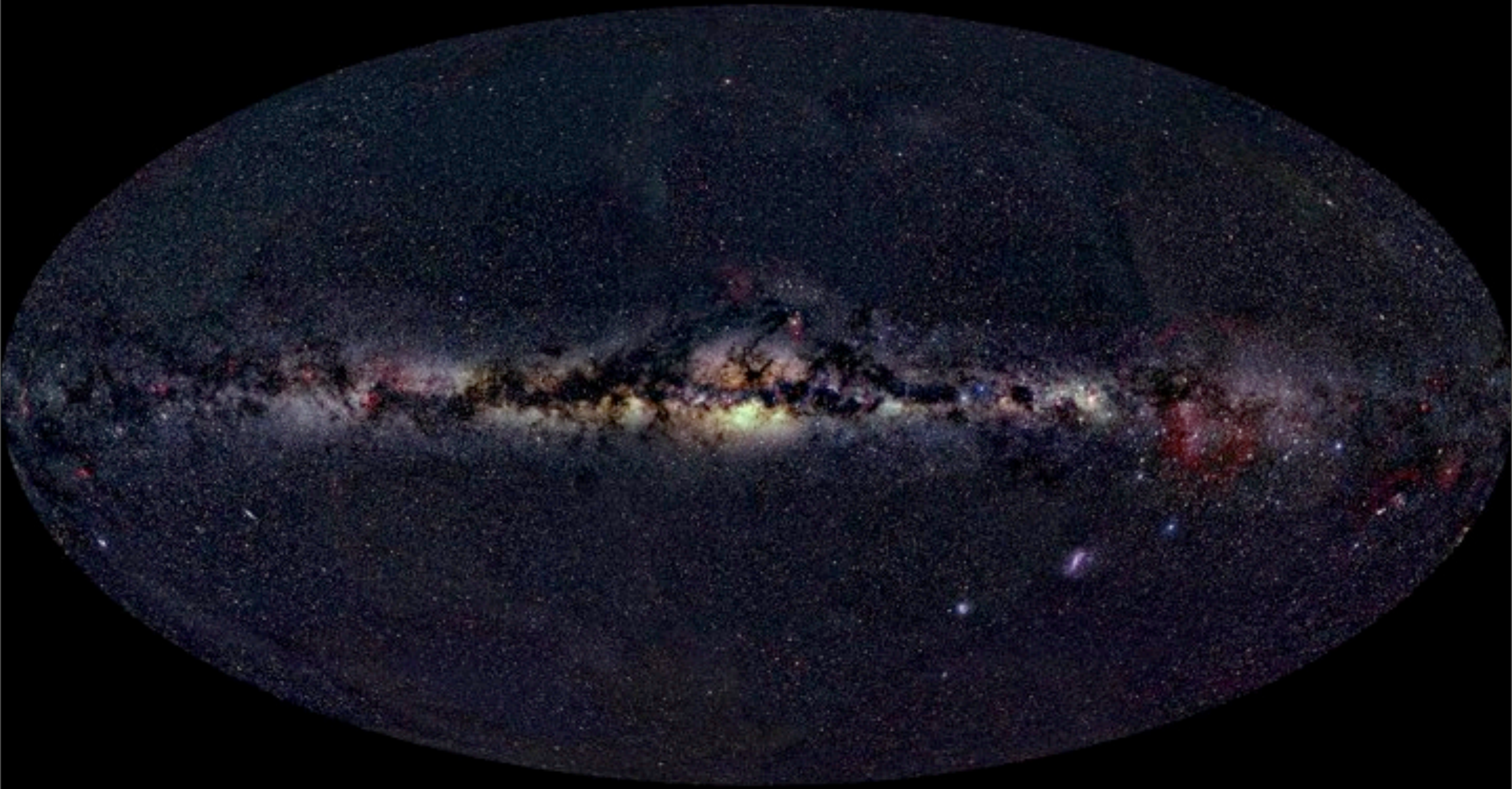
Complementarity Between Dark Matter Searches and Collider Experiments, UC Irvine, June 11, 2006

DARK MATTER ANNIHILATION AT THE GALACTIC CENTER?

Joel Primack

University of California, Santa Cruz

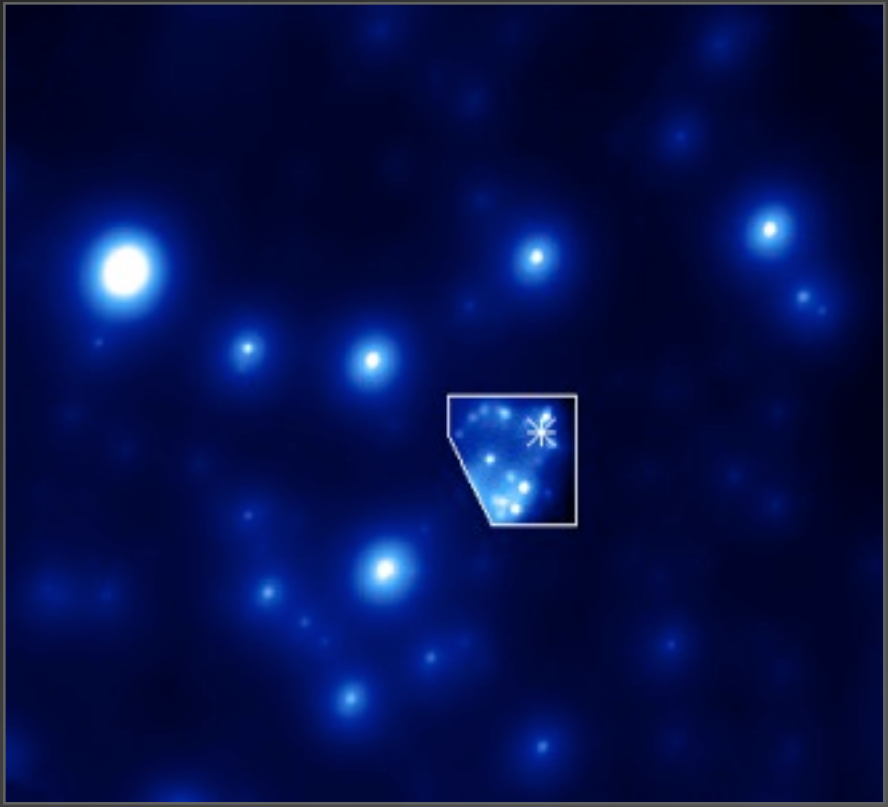
The Milky Way in the Sky



© 2000. Axel Mellinger

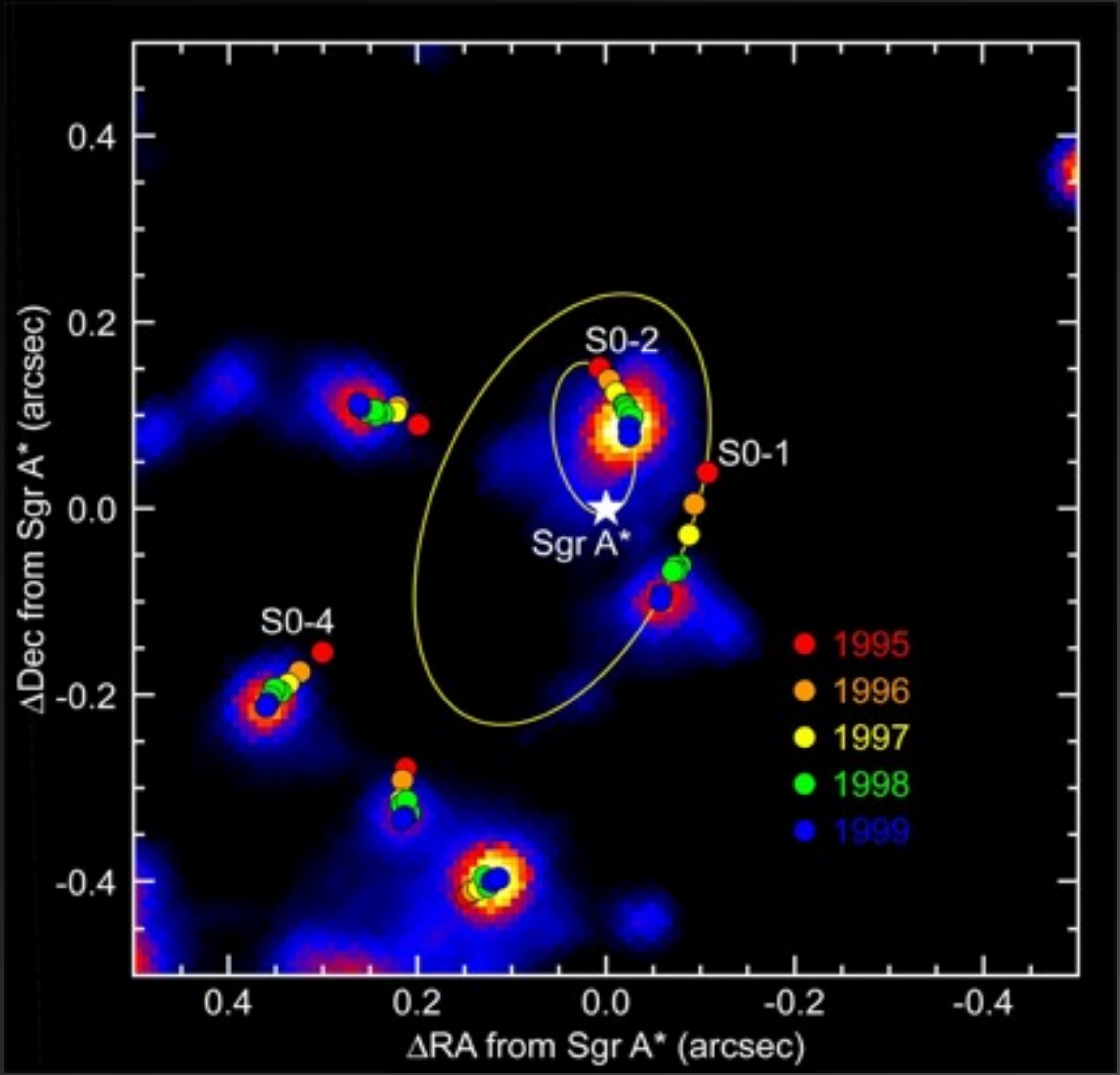
There's a supermassive black hole at the center of our galaxy…

- Modern large telescopes can track individual stars at galactic center
  - Need infrared (to penetrate dust).
  - Need very good resolution (use adaptive optics).
- and have been observing for past 10 years, with improving resolution…



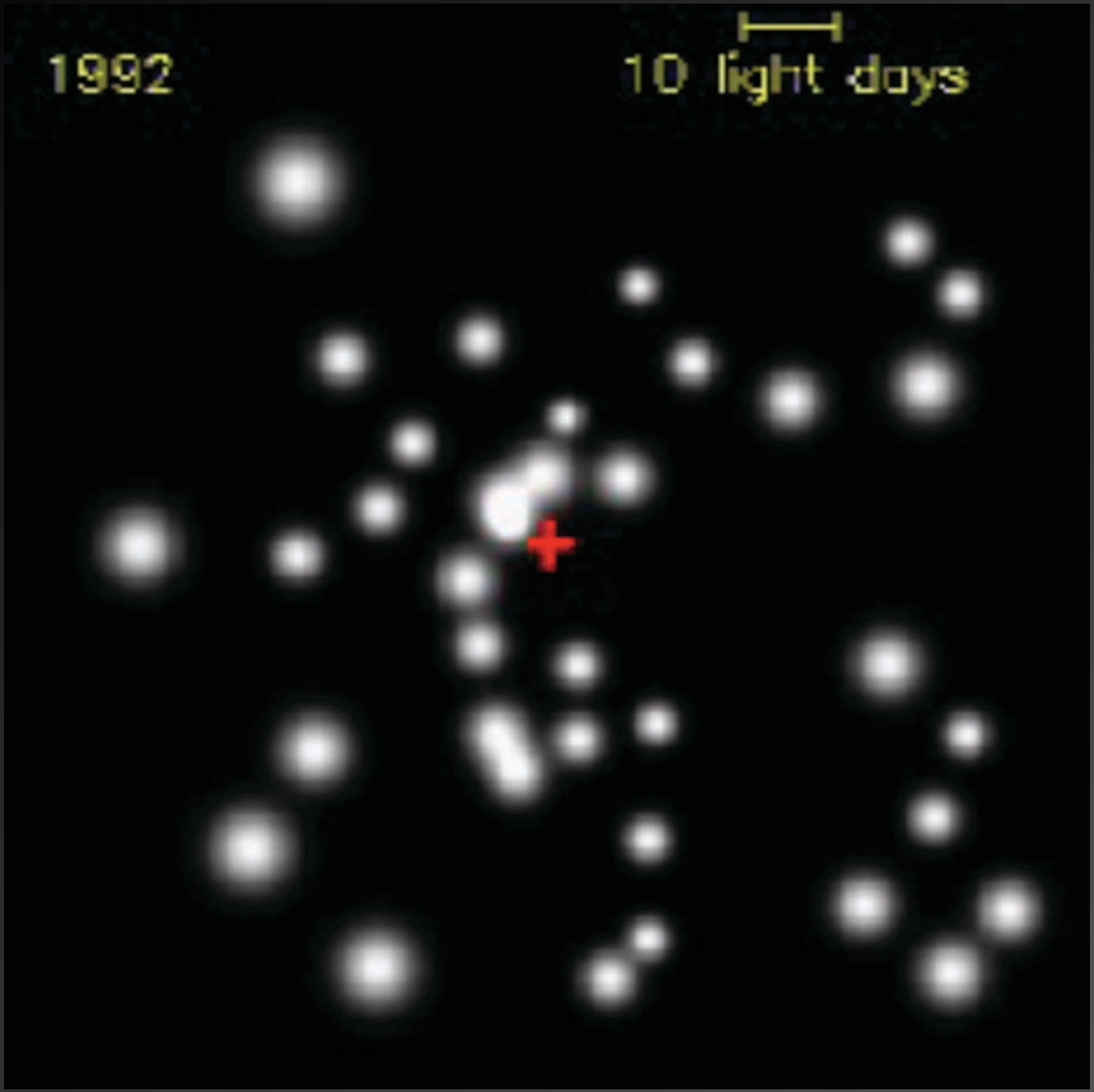
Keck, 2 μm

Ghez, et al.

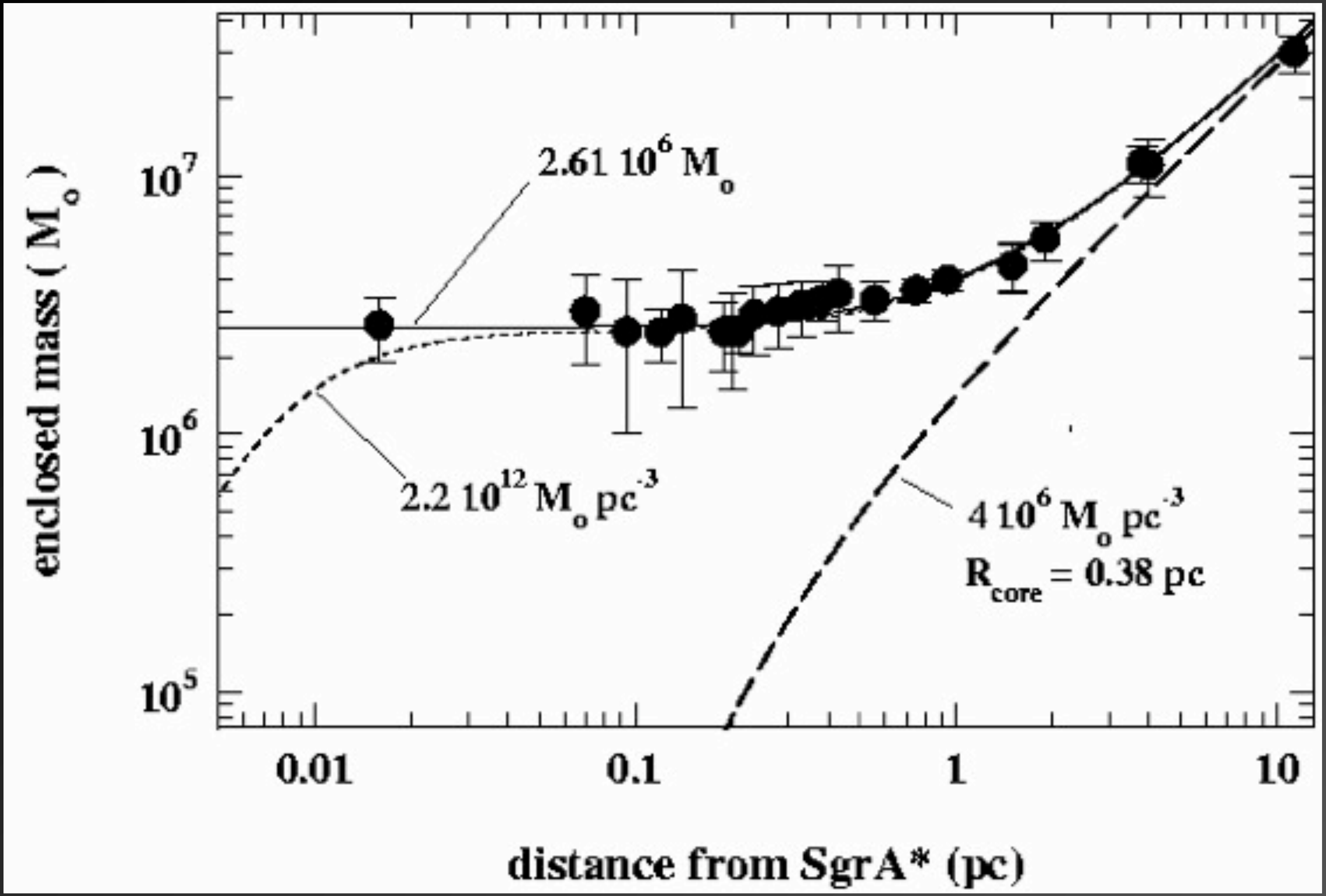


Motions of stars consistent with large, dark mass located at Sgr A…*

Ghez, et al.



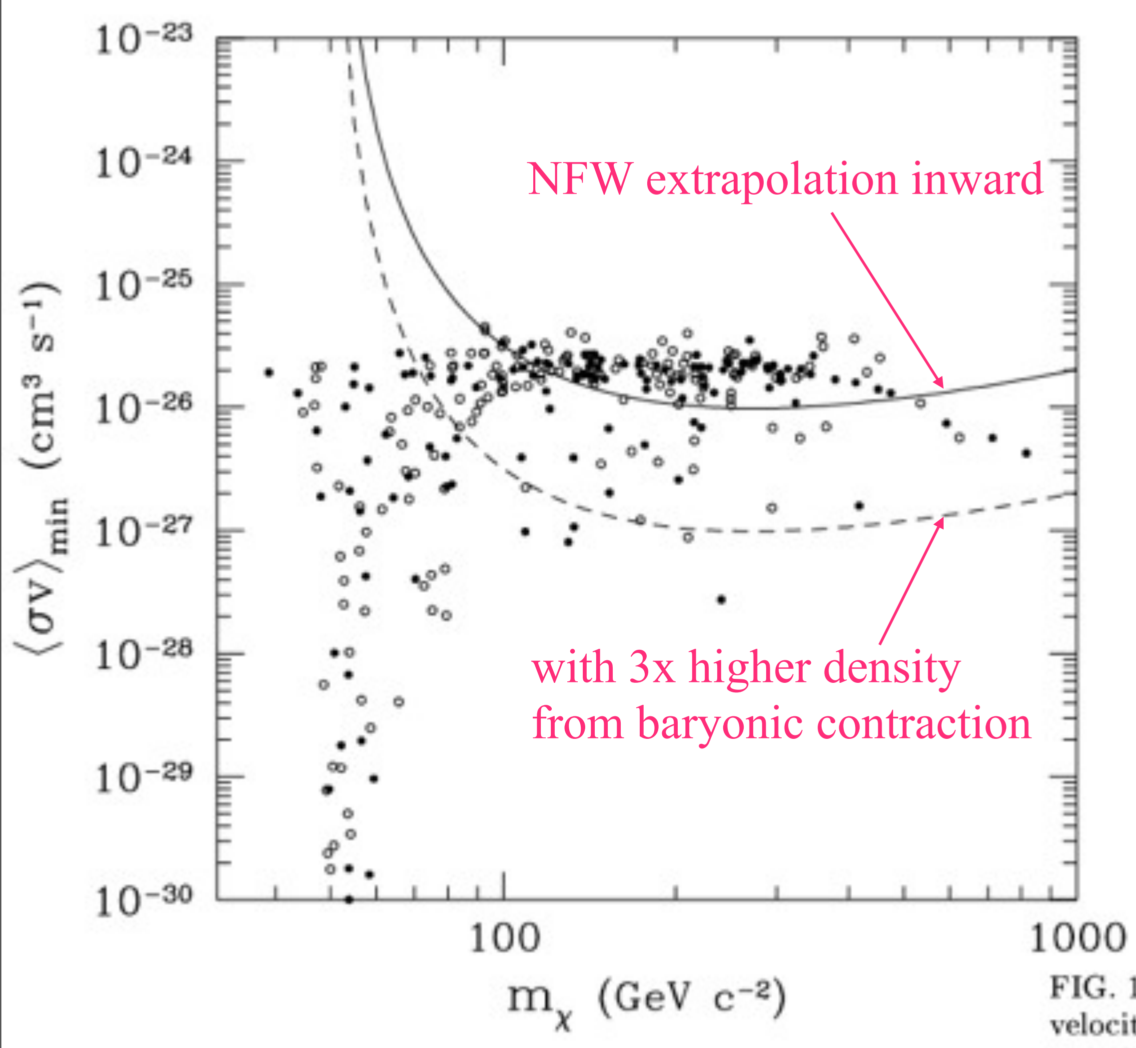
Schödel, Genzel, et al. 2004



Schödel et al. 2003

- **The central object at the center of the Milky Way is…**
  - Very dark – but now seen to flare in X-rays and IR.
  - Very massive (~3 million solar masses).
  - Must be very compact (star S0-2 gets within 17 light hours of the center).
- **Currently the best case for any supermassive black hole.**

γ rays from WIMP annihilation at the Galactic Center



NFW extrapolation inward

with 3x higher density from baryonic contraction

Scattering of WIMPs by star cluster around central supermassive black hole predicts WIMP density

$$\rho(r) \propto r^{-3/2}$$

in central pc. The annihilation rate ∝ ρ^2 so signal is modestly enhanced and centrally peaked.

FIG. 1: Minimum detectable annihilation cross section times velocity as a function of WIMP mass. The filled circles correspond to SUSY model WIMPs with $\Omega_\chi h^2 = 0.11 \pm 0.01$ [32] and the open circles correspond to SUSY models with $\Omega_\chi h^2$ between 1σ and 2σ away from the central value.

Gnedin & Primack, Phys Rev Lett 2004

Scattering off stars sets a universal profile.— The above considerations assumed that the phase-space density of dark matter particles is conserved. However, in addition to the supermassive black hole, the Galactic center harbors a compact cluster of stars, with density at least $\rho_* = 8 \times 10^8\, M_\odot\ \mathrm{pc}^{-3}$ in the inner 0.004 pc [18]. These stars frequently scatter dark matter particles and cause the distribution function to evolve towards an equilibrium solution. Both stars and dark matter experience two-body relaxation.

The idealized problem of a stellar distribution around a massive black hole in star clusters has been considered in the past (cf. [19] for a review). Stars driven inward towards the black hole by two-body relaxation try to reach thermal equilibrium with the stars in the core, but are unable to do so because of tidal disruption or capture by the black hole. Unlike core collapse in self-gravitating star clusters, however, the density of inner stars does not grow toward infinity. A steady-state solution is possible where the energy released by removal of the most bound stars is transported outward by diffusion. Because there is no special scale in the problem, the quasi-equilibrium distribution function is a power-law of energy, $f(E) \propto |E|^p$, and the density is a power-law of radius, $\rho \propto r^{-3/2-p}$ [20, 21]. The solution is unique and independent of the initial conditions.

The evolution of the dark matter distribution $f(E,t)$ in a two-component system of dark matter particles of mass m_χ and stars of mass m_* can be described by a collisional equation in the Fokker-Planck form:

$$\frac{\partial q}{\partial E}\frac{\partial f}{\partial t} = A\frac{\partial}{\partial E}\left[\frac{m_\chi}{m_*} f \int_E^\infty f_* \frac{\partial q_*}{\partial E_*} dE_* + \frac{\partial f}{\partial E}\left\{\int_E^\infty f_* q_* dE_* + q\int_{-\infty}^E f_* dE_*\right\}\right],$$

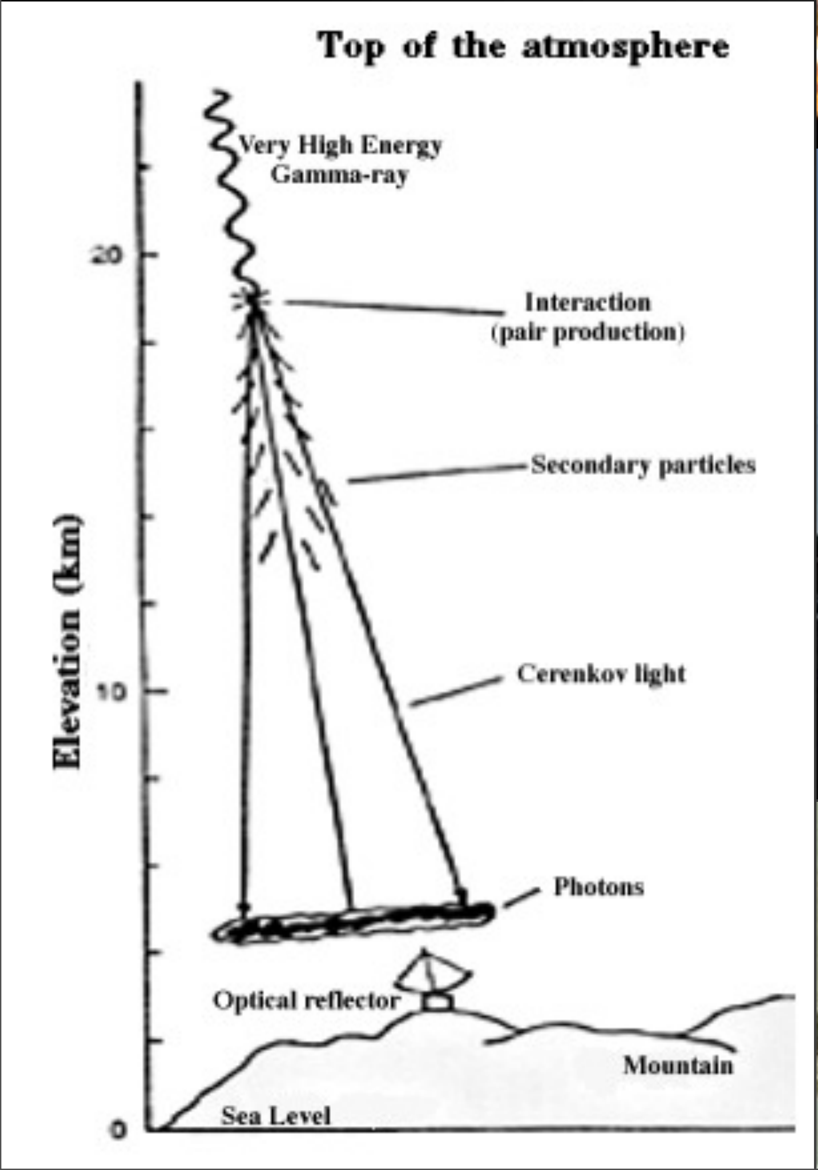
where $E = v^2/2 - GM_{\rm bh}/r$ is the energy within the sphere of influence of the black hole, $q(E) = (2^{3/2}/3)\pi^3 G^3 M_{\rm bh}^3 E^{-3/2}$, $A \equiv 16\pi^2 G^2 m_*^2 \ln\Lambda$, and $\ln\Lambda = \ln M_{\rm bh}/m_* \approx 15$ is the standard Coulomb logarithm. The equilibrium distribution function of stars is $f_*(E_*, t) \propto |E_*|^{1/4}$, i.e. $p = 1/4$. For dark matter particles, however, the first term in the square brackets vanishes since the particle mass is negligible compared to stellar mass. An equilibrium solution with no energy flux requires $\partial f/\partial E = 0$, or $p = 0$. The corresponding density profile is $\rho_{\rm dm} \propto r^{-3/2}$.

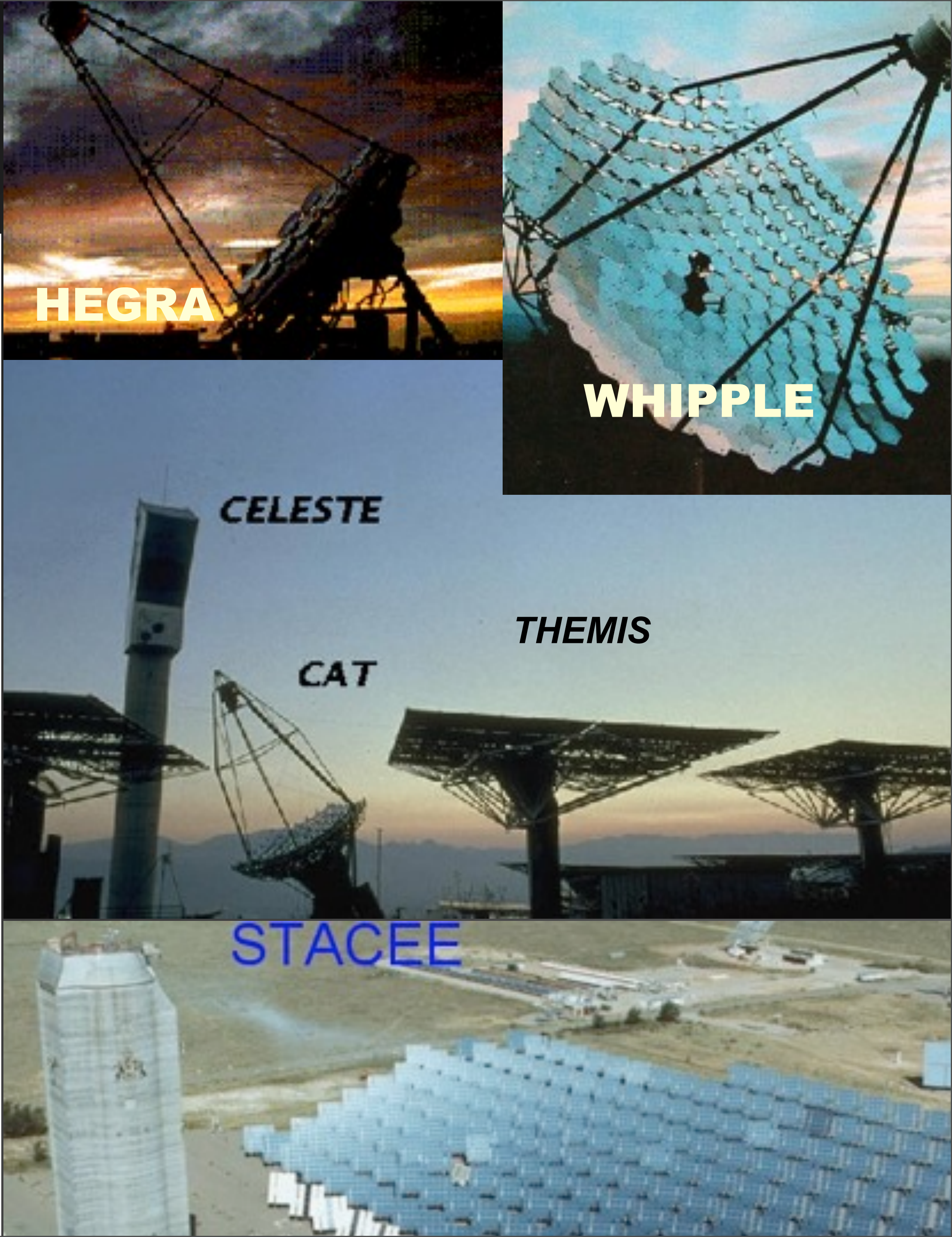
Implications for dark matter searches.— The dark matter density in the central region of the Galaxy is thus given by

$$\rho_{\rm dm}(r) = \begin{cases} \rho_0\,(r/r_{\rm bh})^{-3/2} & L < r \le r_{\rm bh}\ , \\ \rho_0\,(r/r_{\rm bh})^{-\alpha} & r_{\rm bh} \le r\ , \end{cases}$$

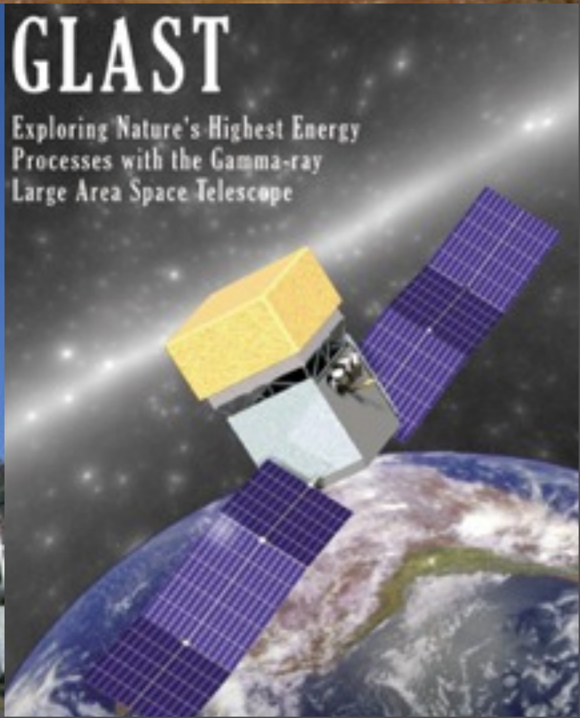
where $L \approx 10^{-3}$ pc, and we expect that $0 < \alpha < 1.5$.

Early Atmospheric Čerenkov Telescopes

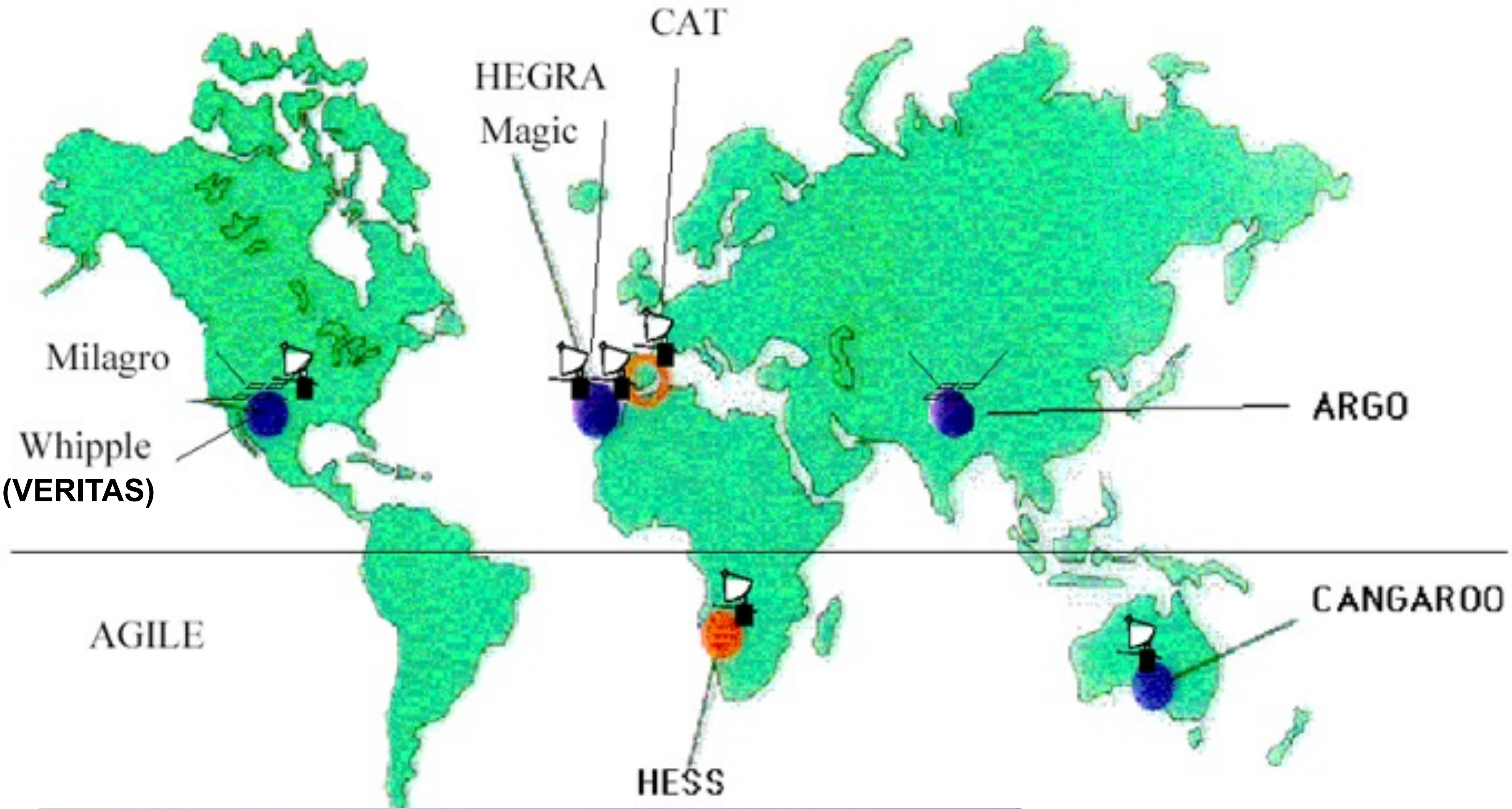




New Ground and Space Based Telescopes



Ground-based Gamma Ray Telescopes



Cerenkov telescope

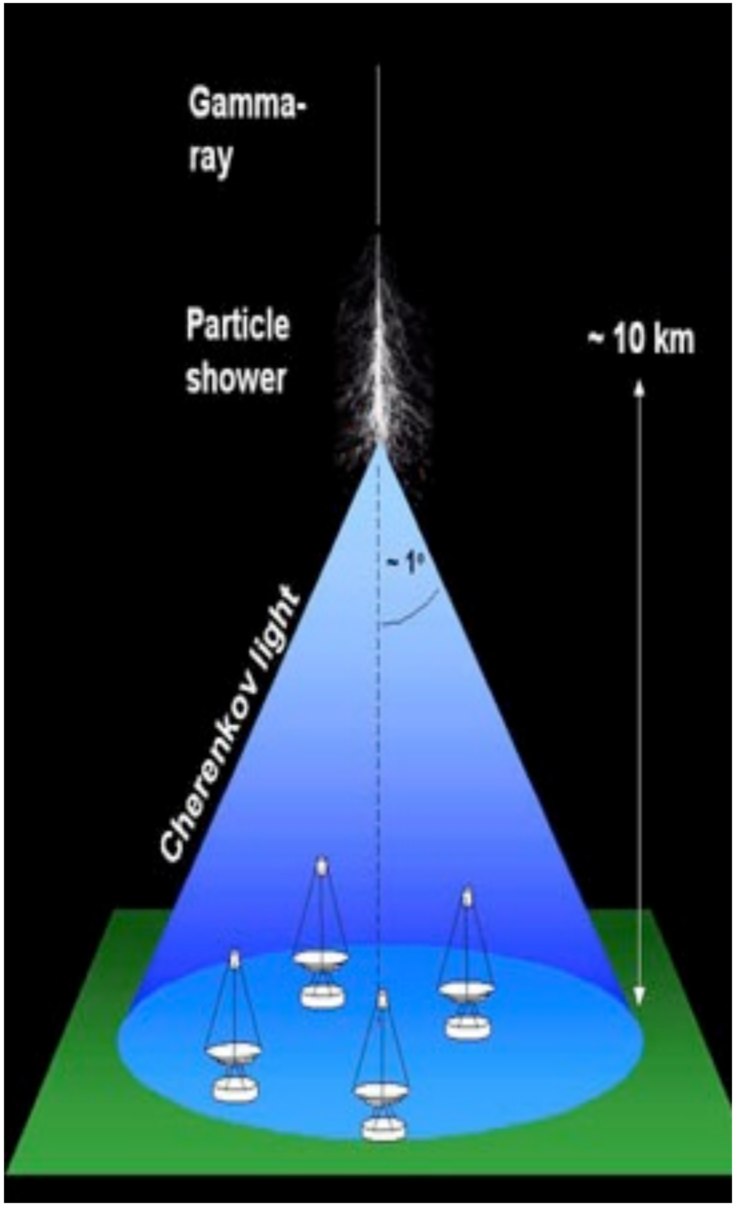
"all sky" monitors

Results from H.E.S.S. on MWy Center

H.E.S.S.: High Energy Stereoscopic System

- Array 4 telescopes, diameter ~12 m
- Field of view ~5°
- Angular resolution (single photon): ~ 6 '
  (with hard cuts): ~ 4 '
- Energy resolution ~15%
- Location: Namibia, 1800 m asl
  Coord.: 23°16' S, 16°30' E

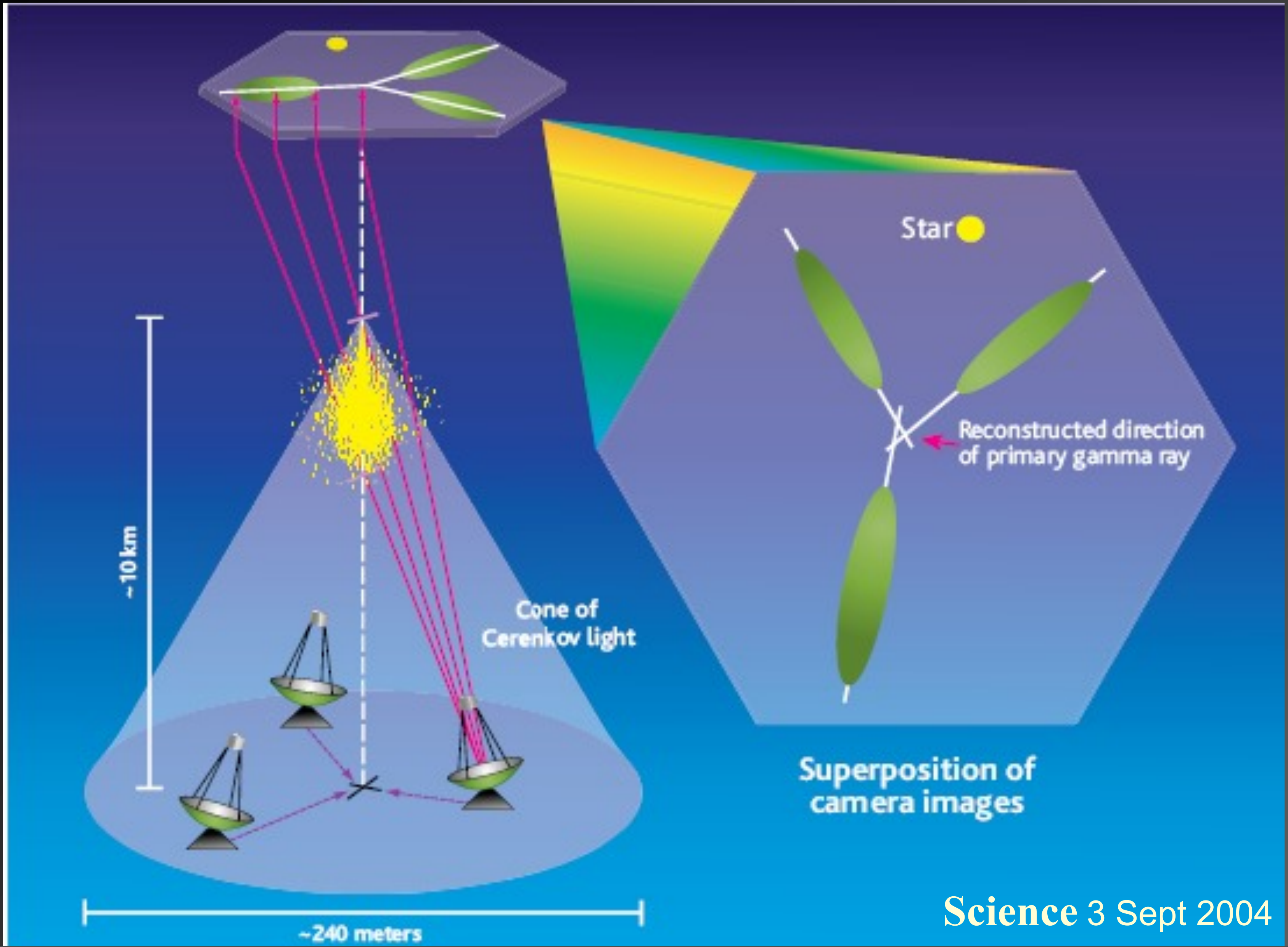
Energy Threshold (pre - post cuts):
0°: (105 GeV, 125 GeV)
20°: (115 GeV, 145 GeV)
45°: (265 GeV, 305 GeV)
60°: (785 GeV, 925 GeV)



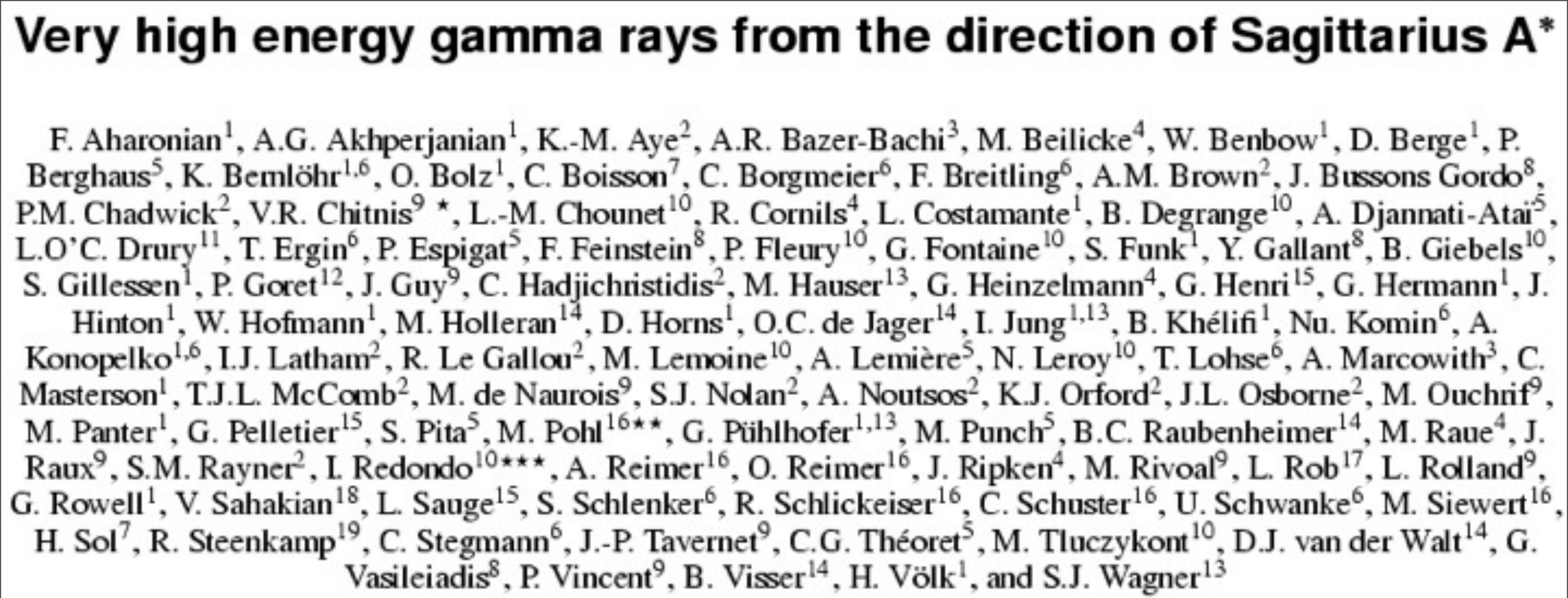
Victor Hess

1912 balloon flight to 6 km: "cosmic ray" intensity increased with altitude

H.E.S.S.: High Energy Stereoscopic System



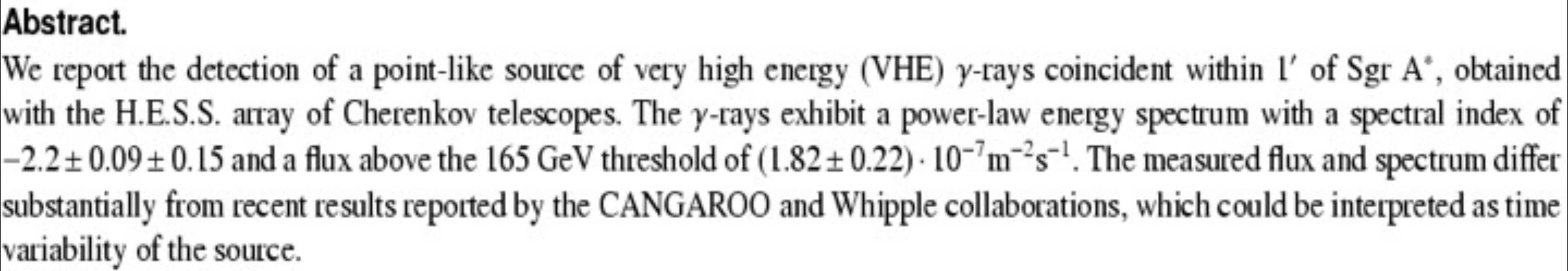
Science 3 Sept 2004



Very high energy gamma rays from the direction of Sagittarius A*

F. Aharonian[1], A.G. Akhperjanian[1], K.-M. Aye[2], A.R. Bazer-Bachi[3], M. Beilicke[4], W. Benbow[1], D. Berge[1], P. Berghaus[5], K. Bernlöhr[1,6], O. Bolz[1], C. Boisson[7], C. Borgmeier[6], F. Breitling[6], A.M. Brown[2], J. Bussons Gordo[8], P.M. Chadwick[2], V.R. Chitnis[9 ⋆], L.-M. Chounet[10], R. Cornils[4], L. Costamante[1], B. Degrange[10], A. Djannati-Atai[5], L.O'C. Drury[11], T. Ergin[6], P. Espigat[5], F. Feinstein[8], P. Fleury[10], G. Fontaine[10], S. Funk[1], Y. Gallant[8], B. Giebels[10], S. Gillessen[1], P. Goret[12], J. Guy[9], C. Hadjichristidis[2], M. Hauser[13], G. Heinzelmann[4], G. Henri[15], G. Hermann[1], J. Hinton[1], W. Hofmann[1], M. Holleran[14], D. Horns[1], O.C. de Jager[14], I. Jung[1,13], B. Khélifi[1], Nu. Komin[6], A. Konopelko[1,6], I.J. Latham[2], R. Le Gallou[2], M. Lemoine[10], A. Lemière[5], N. Leroy[10], T. Lohse[6], A. Marcowith[3], C. Masterson[1], T.J.L. McComb[2], M. de Naurois[9], S.J. Nolan[2], A. Noutsos[2], K.J. Orford[2], J.L. Osborne[2], M. Ouchrif[9], M. Panter[1], G. Pelletier[15], S. Pita[5], M. Pohl[16 ⋆⋆], G. Pühlhofer[1,13], M. Punch[5], B.C. Raubenheimer[14], M. Raue[4], J. Raux[9], S.M. Rayner[2], I. Redondo[10 ⋆⋆⋆], A. Reimer[16], O. Reimer[16], J. Ripken[4], M. Rivoal[9], L. Rob[17], L. Rolland[9], G. Rowell[1], V. Sahakian[18], L. Sauge[15], S. Schlenker[6], R. Schlickeiser[16], C. Schuster[16], U. Schwanke[6], M. Siewert[16], H. Sol[7], R. Steenkamp[19], C. Stegmann[6], J.-P. Tavernet[9], C.G. Théoret[5], M. Tluczykont[10], D.J. van der Walt[14], G. Vasileiadis[8], P. Vincent[9], B. Visser[14], H. Völk[1], and S.J. Wagner[13]

A&A Letters, **425L**, 13 (October 2004)



Abstract.

We report the detection of a point-like source of very high energy (VHE) γ-rays coincident within $1'$ of Sgr A*, obtained with the H.E.S.S. array of Cherenkov telescopes. The γ-rays exhibit a power-law energy spectrum with a spectral index of $-2.2 \pm 0.09 \pm 0.15$ and a flux above the 165 GeV threshold of $(1.82 \pm 0.22) \cdot 10^{-7}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$. The measured flux and spectrum differ substantially from recent results reported by the CANGAROO and Whipple collaborations, which could be interpreted as time variability of the source.

See also Dieter Horns' talk at Gamma2004, astro-ph/0408192, Phys Lett B; and HESS contributions to ICRC29 (2005) by Hinton, Ripkin, Rolland

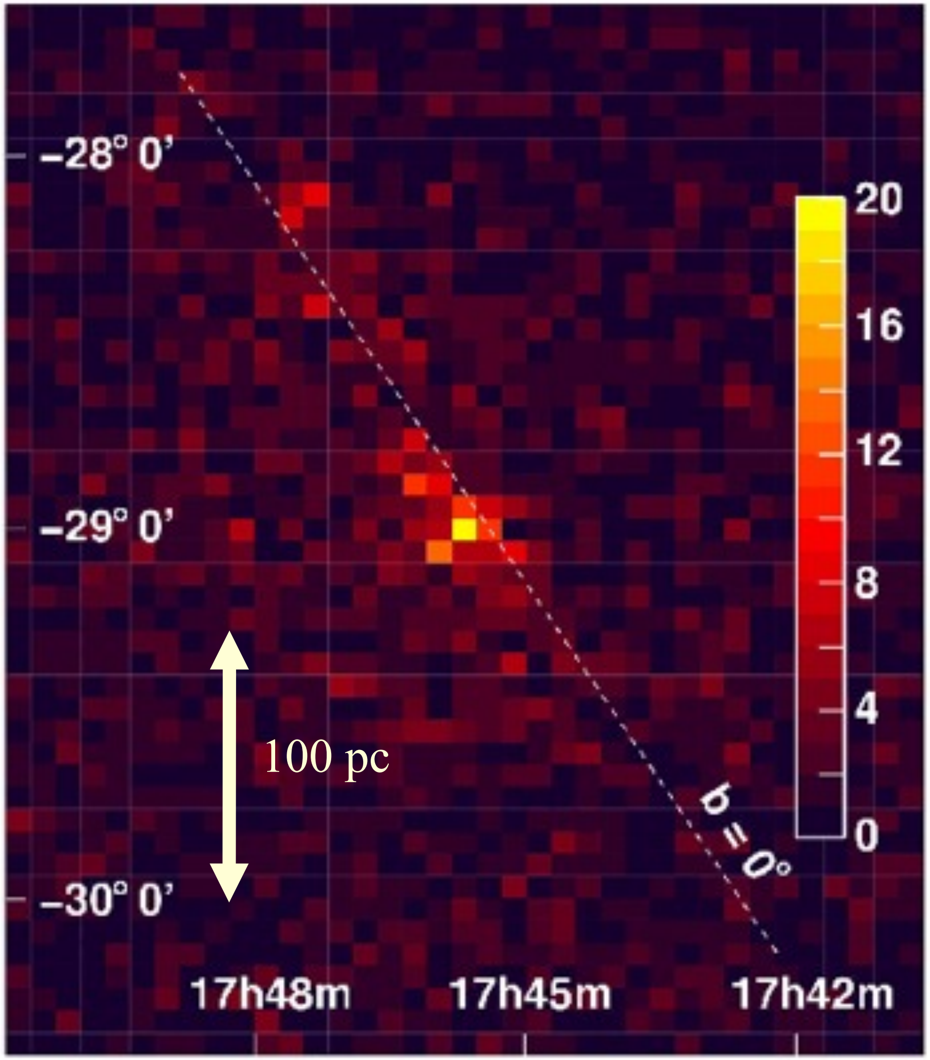


Fig. 1. Angular distribution of γ-ray candidates for a 3° field of view centred on Sgr A*. Both data sets ('June/July' and 'July/August') are combined, employing tight cuts to reduce the level of background. The significance of the feature extending along the Galactic Plane is under investigation.

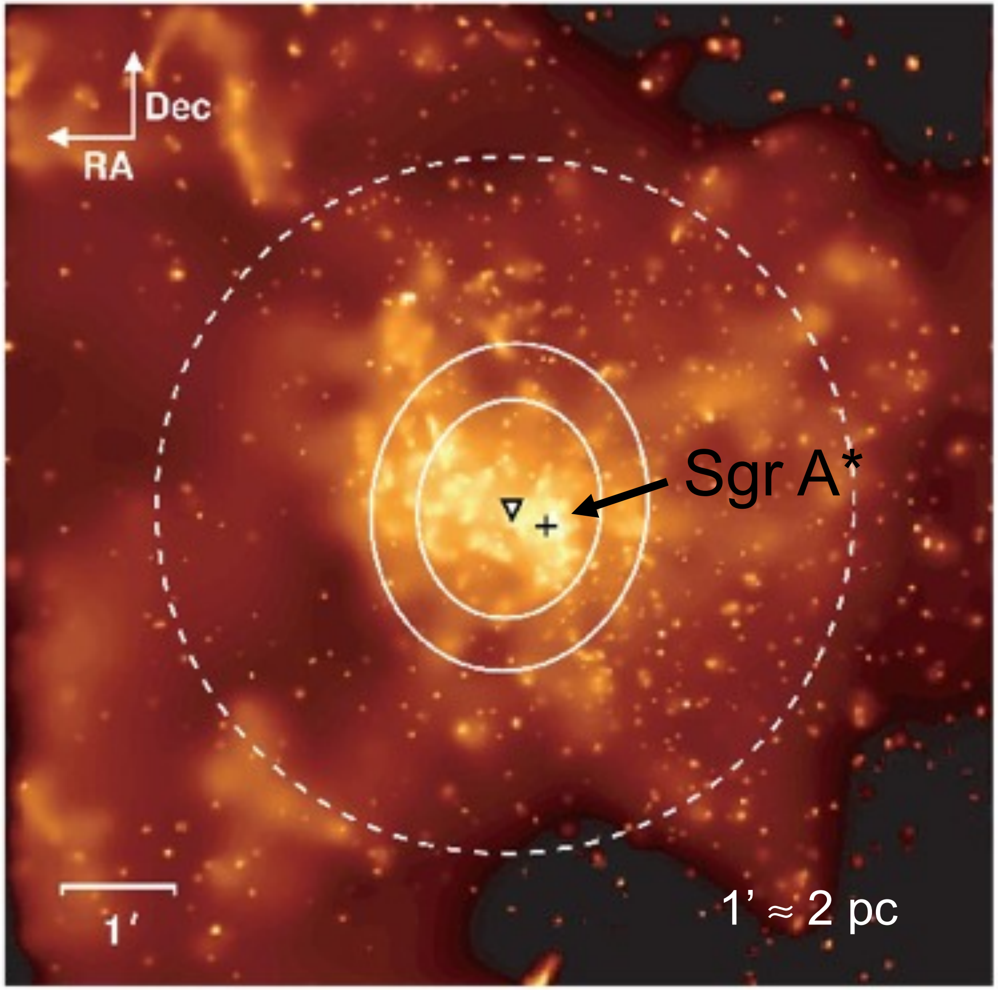
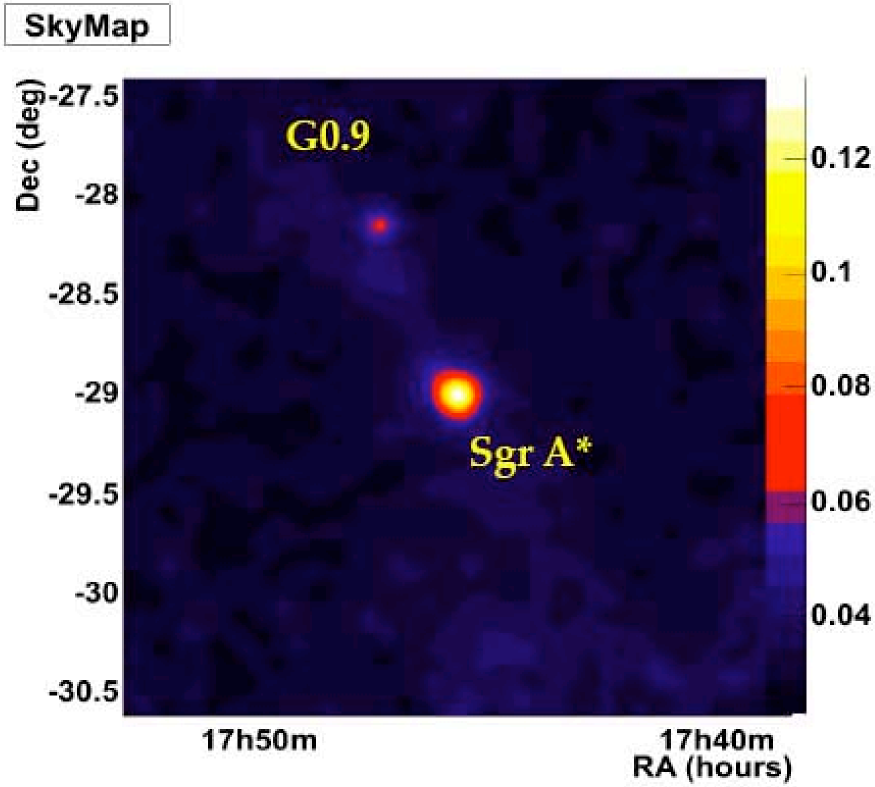
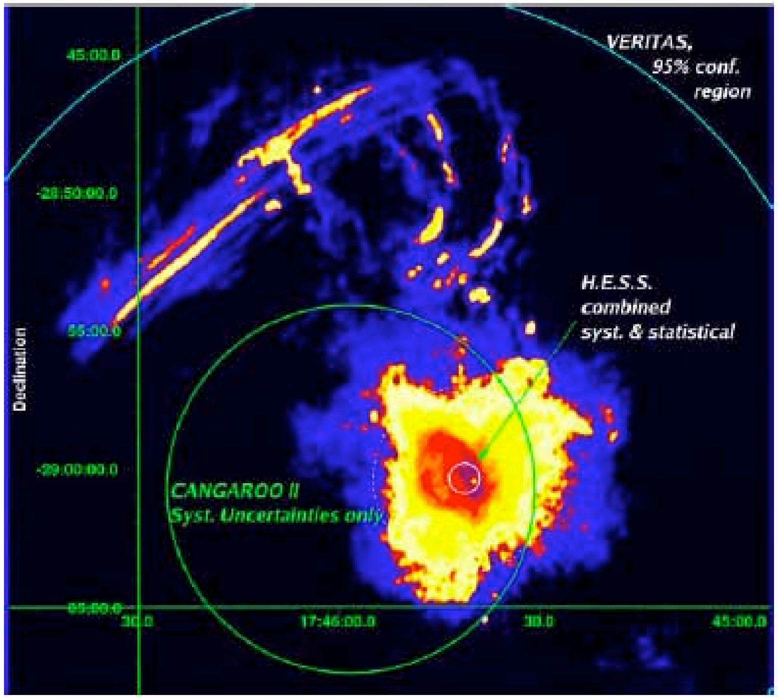


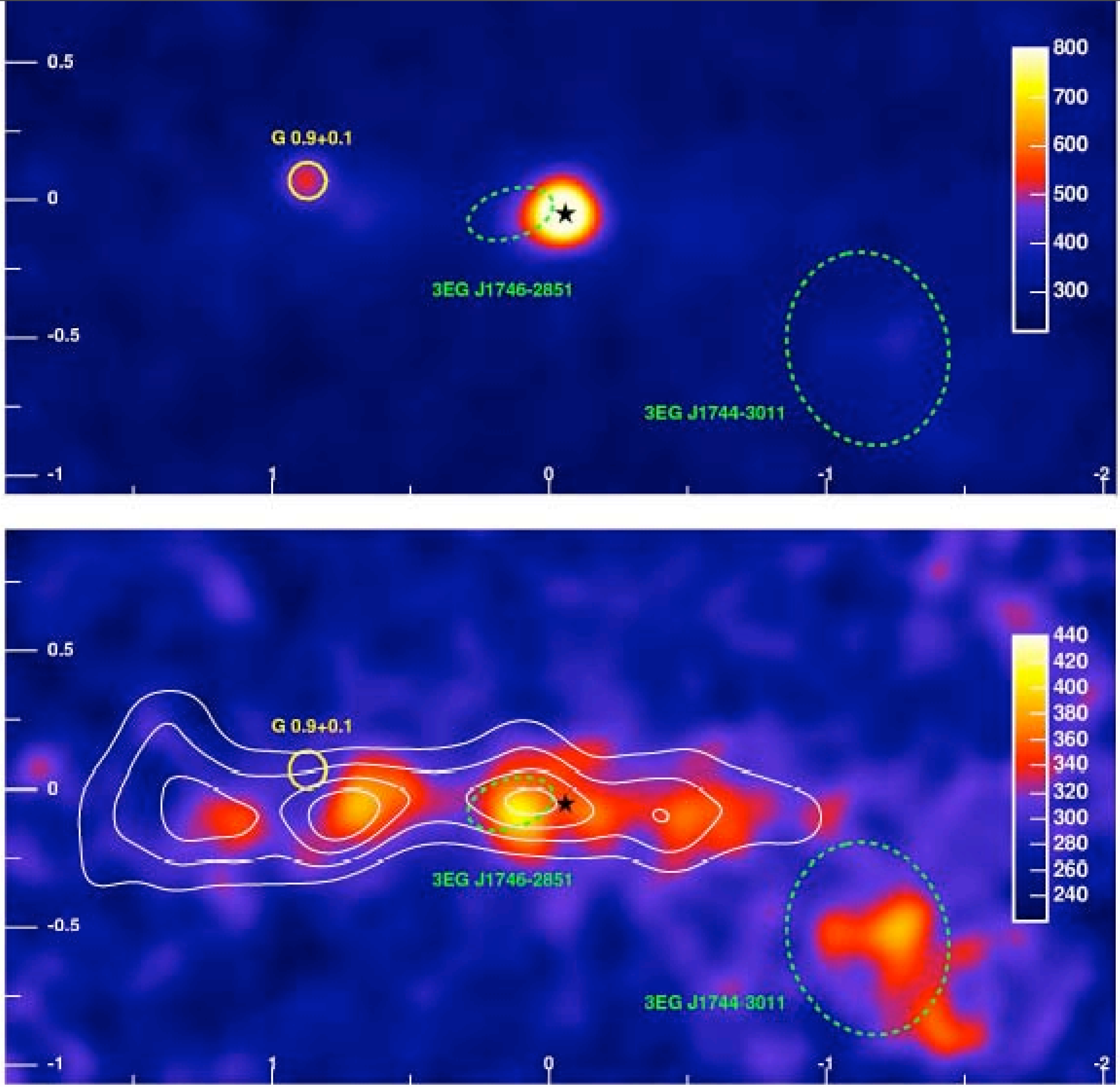
Fig. 2. Centre of gravity of the VHE signal (triangle), superimposed on a 8.5′ by 8.5′ Chandra X-ray map (Munro et al. 2003) of the GC. The location of Sgr A* is indicated by a cross. The contour lines indicate the 68% and 95% confidence regions for the source position, taking into account systematic pointing errors of 20″. The white dashed line gives the 95% confidence level upper limit on the rms source size. The resolution for individual VHE photons - as opposed to the precision for the centre of the VHE signal - is 5.8′ (50% containment radius).

Felix Aharonian's talk at Texas @ Stanford December 2004





if extended source - size less than 3' (7 pc)
if point-like source – position within 1' around Sgr A*

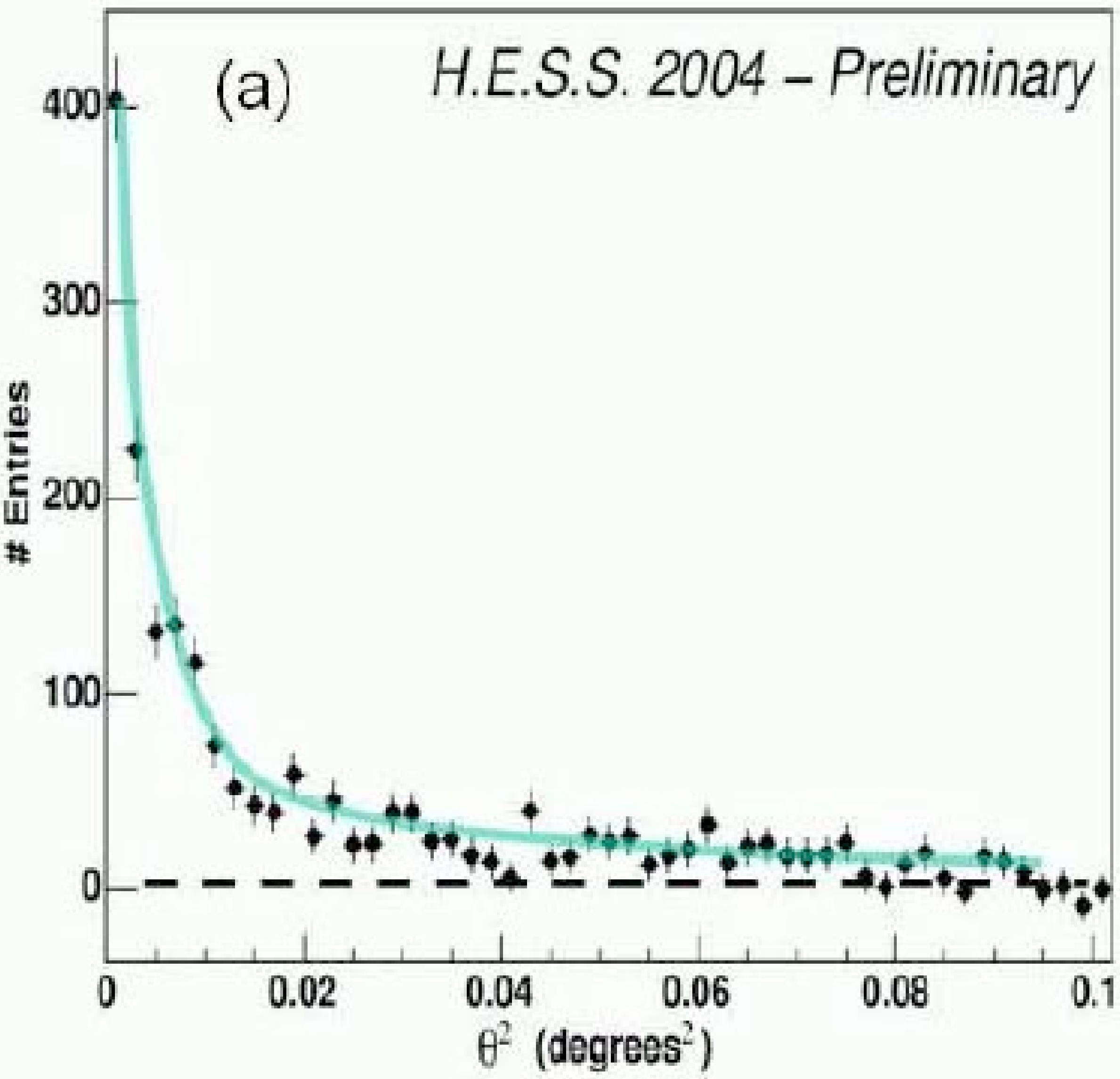


Discovery of Very-High-Energy Gamma-Rays from the Galactic Centre Ridge
Authors: The H.E.S.S. Collaboration: F. A. Aharonian, et al
Nature
Journal-ref: Nature 439 (2006) 695

Felix Aharonian's talk at Texas @ Stanford

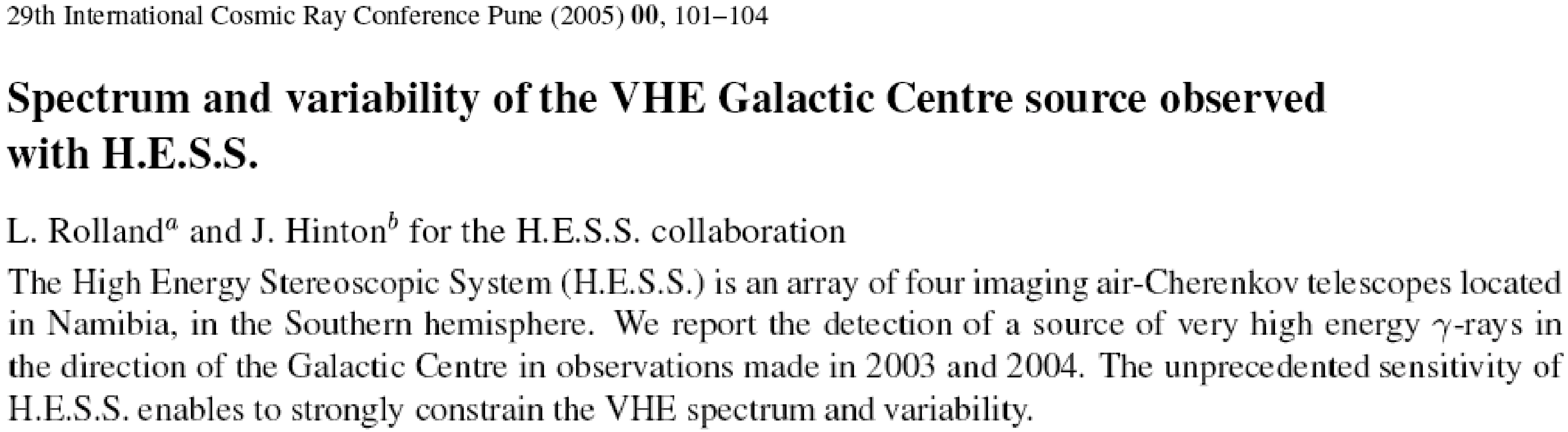
TeV Gamma-rays from central <10 pc region of GC

- Annihilation of DM ? *mass of DM particles > 12 TeV ?*
- *Sgr A** : $3\ 10^6 M_o$ BH ? *somewhat speculative but possible*
- SNR Sgr A East ? *why not ?*
- Plerionic (IC) source(s) *why not ?*
- Interaction of CRs with dense molecular gas (clouds) ? *easily*



Angular distribution of the gamma-ray emission from the Sgr A source.

W. Hoffman plenary talk at ICRC29 2005

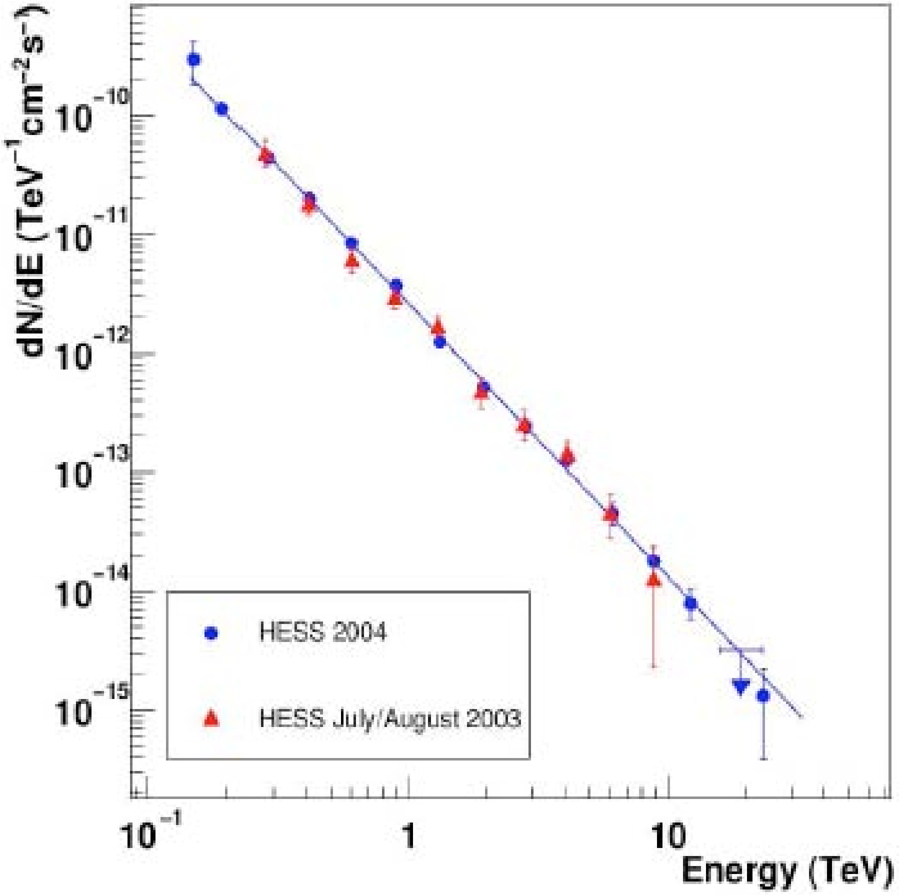


29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

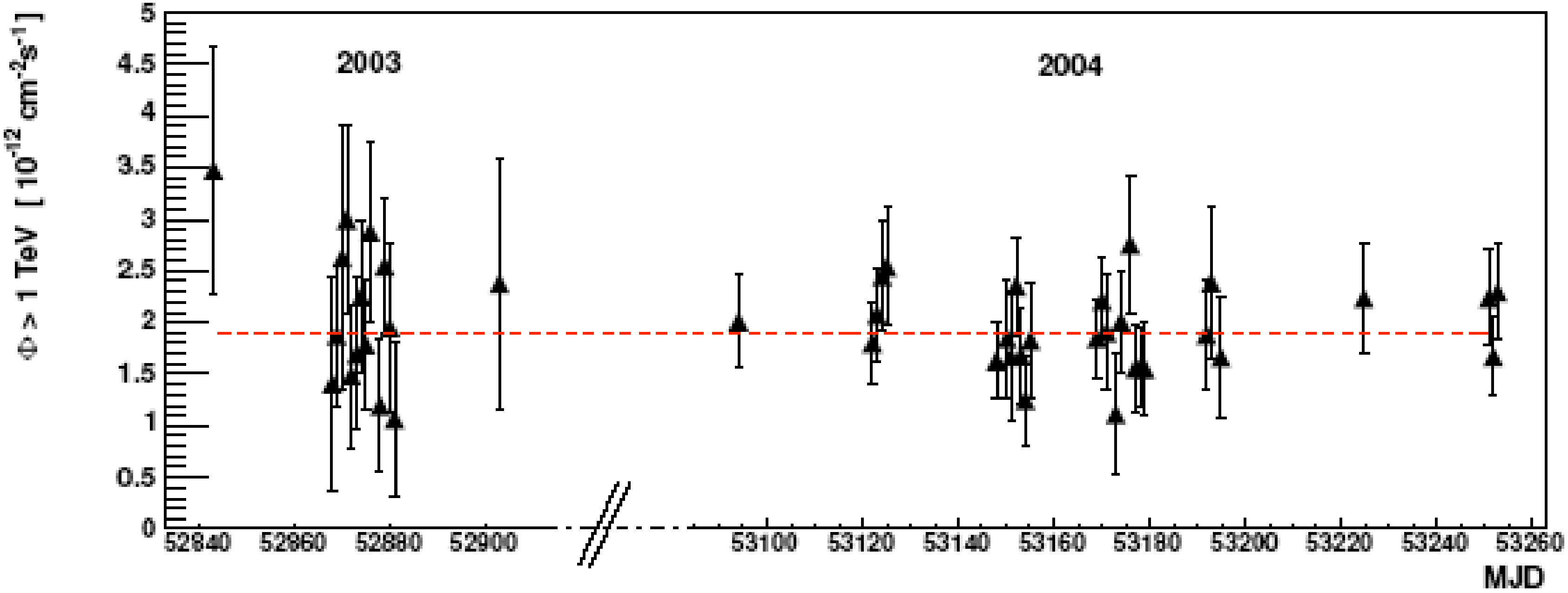
Spectrum and variability of the VHE Galactic Centre source observed with H.E.S.S.

L. Rolland[a] and J. Hinton[b] for the H.E.S.S. collaboration

The High Energy Stereoscopic System (H.E.S.S.) is an array of four imaging air-Cherenkov telescopes located in Namibia, in the Southern hemisphere. We report the detection of a source of very high energy γ-rays in the direction of the Galactic Centre in observations made in 2003 and 2004. The unprecedented sensitivity of H.E.S.S. enables to strongly constrain the VHE spectrum and variability.



Differential energy spectrum from the direction of the Galactic Center measured in 2003 (two telescopes) and 2004 (four telescopes).

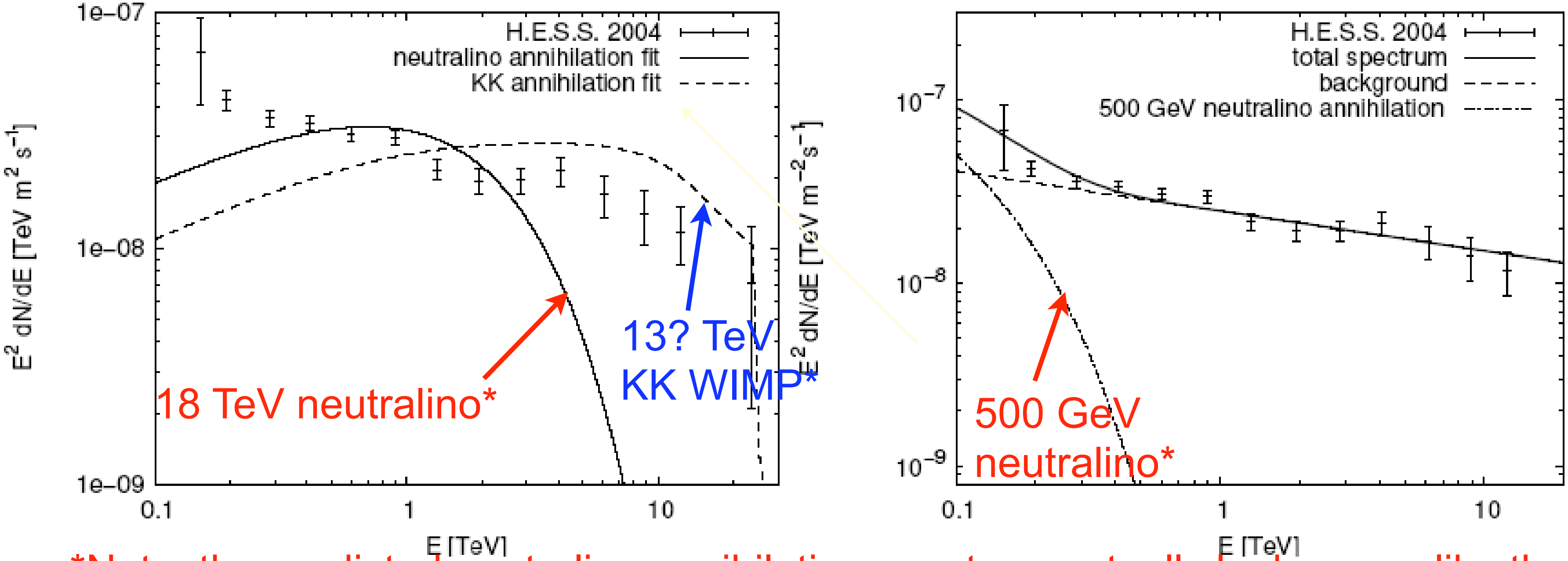


Galactic Centre source light curves. The integral nightly average flux above 1 TeV is given as function of time in modified Julian Days for both 2003 and 2004 observations. The Galactic Centre source flux is consistent with a constant flux at all probed time scales.

29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Dark matter annihilation as possible origin of the very high energy γ-radiation from the Galactic center measured by H.E.S.S.

J. Ripken[a], D. Horns[b], L. Rolland[c], J. Hinton[d] on behalf of the H.E.S.S. collaboration



18 TeV neutralino*

13? TeV KK WIMP*

500 GeV neutralino*

*Note: the predicted neutralino annihilation spectrum actually looks more like the observed one -- see Bergstrom et al. PRL 95 (2005) 241301

Figure 1. Left: Spectral energy distribution of the γ-radiation from Sgr A* as measured by H.E.S.S. together with fits of annihilation radiation only (hypothesis 1). The used neutralino annihilation spectrum is from [9] and the KK annihilation spectrum from [10]. For the $B^{(1)}$ such high masses are lager than anticipated. Right: Again the measured Sgr A* spectral energy distribution together with a power law plus an annihilation spectrum of a 500 GeV neutralino (hypothesis 2).

* 10 TeV KK annihilation spectrum is from Bergstrom et al. PRL 94 (2005) 131301

Gamma Rays from Kaluza-Klein Dark Matter

Phys.Rev.Lett. 94 (2005) 131301

Lars Bergström,* Torsten Bringmann,† Martin Eriksson,‡ and Michael Gustafsson§
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden

A TeV gamma-ray signal from the direction of the Galactic center (GC) has been detected by the H.E.S.S. experiment. Here, we investigate whether Kaluza-Klein (KK) dark matter annihilations near the GC can be the explanation. Including the contributions from internal bremsstrahlung as well as subsequent decays of quarks and τ leptons, we find a very flat gamma-ray spectrum which drops abruptly at the dark matter particle mass. For a KK mass of about 1 TeV, this gives a good fit to the H.E.S.S. data below 1 TeV. A similar model, with gauge coupling roughly three times as large and a particle mass of about 10 TeV, would give both the correct relic density and a photon spectrum that fits the complete range of data.

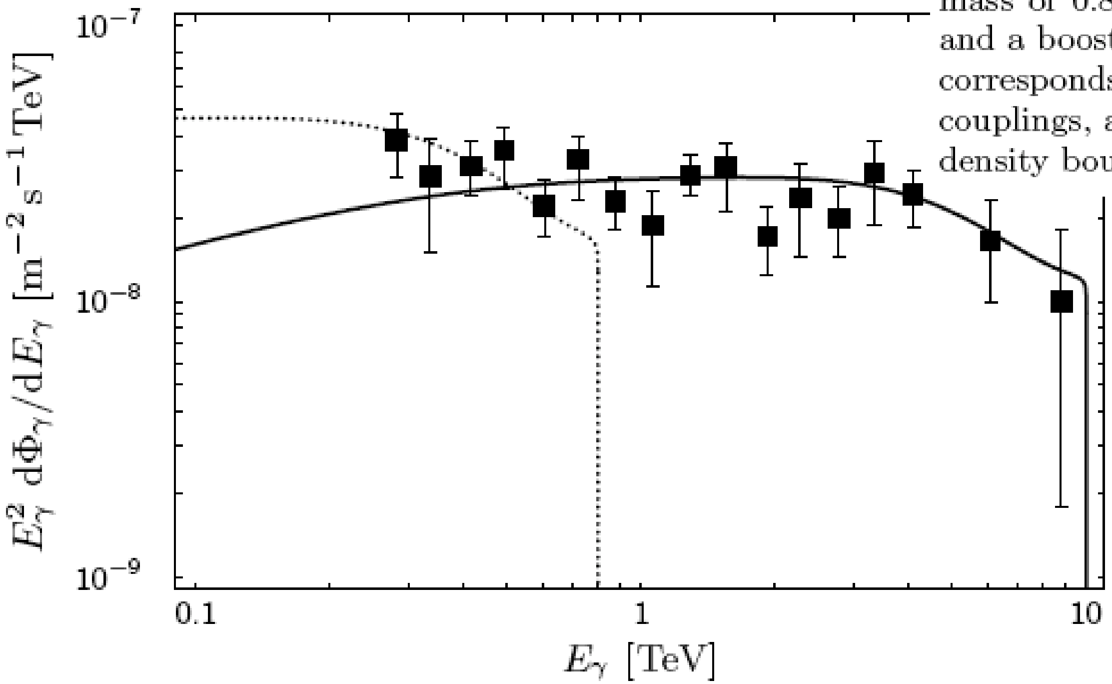


FIG. 3: The H.E.S.S. data [3] compared to the gamma-ray flux from a region of 10^{-5} sr encompassing the GC, for a $B^{(1)}$ mass of 0.8 TeV, a 5% mass splitting at the first KK level, and a boost factor b around 200 (dashed line). The solid line corresponds to a hypothetical 10 TeV WIMP with similar couplings, a total annihilation rate given by the WMAP relic density bound, and a boost factor around 1000.

Gamma Rays from Heavy Neutralino Dark Matter

Phys.Rev.Lett. 95 (2005) 241301

Lars Bergström,* Torsten Bringmann,† Martin Eriksson,‡ and Michael Gustafsson§
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden

We consider the gamma-ray spectrum from neutralino dark matter annihilations and show that internal bremsstrahlung of W pair final states gives a previously neglected source of photons at energies near the mass of the neutralino. For masses larger than about 1 TeV, and for present day detector resolutions, this results in a characteristic signal that may dominate not only over the continuous spectrum from W fragmentation, but also over the $\gamma\gamma$ and γZ line signals which are known to give large rates for heavy neutralinos. Observational prospects thus seem promising.

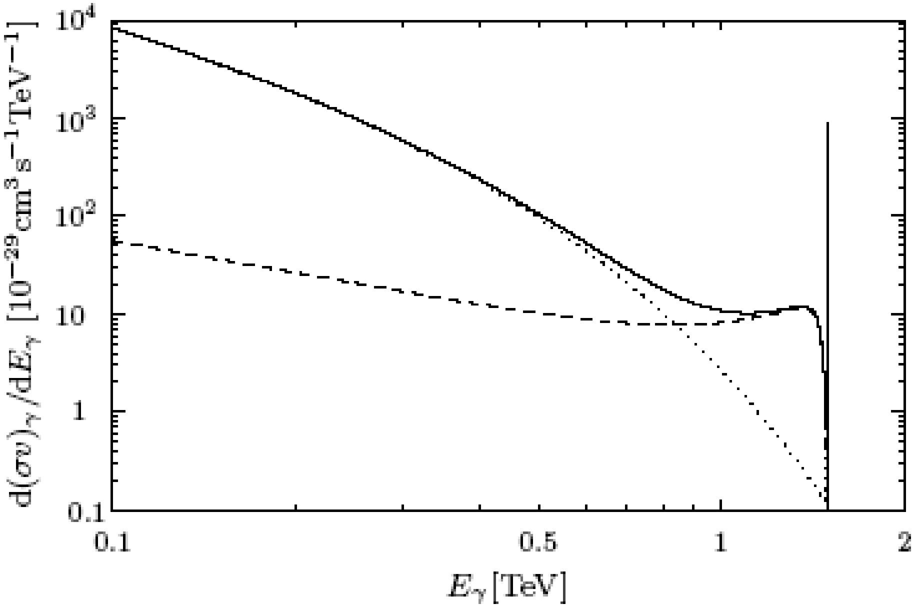


FIG. 3: The total differential photon distribution from $\chi\chi$ annihilations (solid line) for the MSSM model of Table I. Also shown separately is the contribution from radiative processes $\chi\chi \rightarrow W^+W^-\gamma$ (dashed), and the W fragmentation together with the $\chi\chi \rightarrow \gamma\gamma$, $Z\gamma$ lines (dotted).

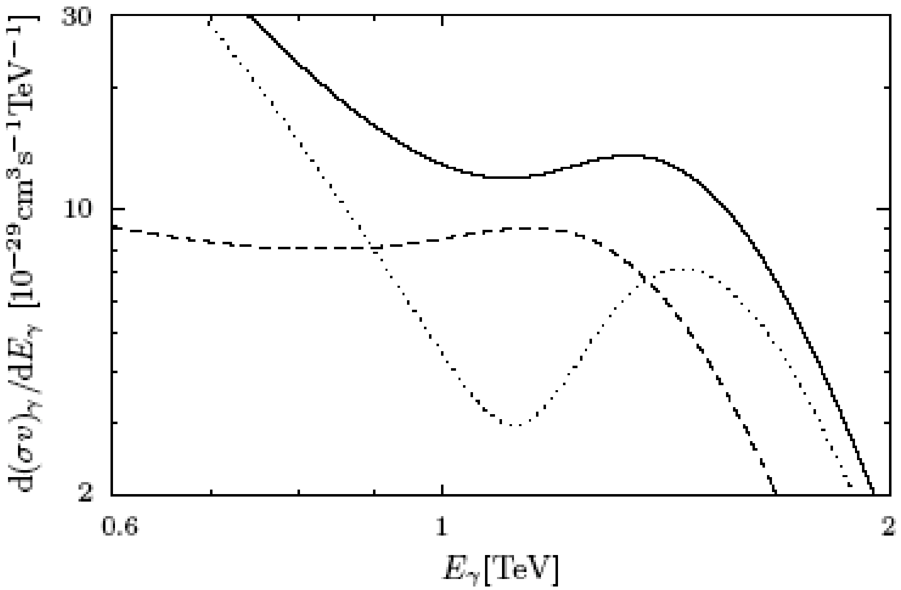


FIG. 4: The same spectra as in Fig. 3, as seen by a detector with an energy resolution of 15 percent.

Comments

- The H.E.S.S. galactic center signal could possibly be explained by a SN remnant, or by emission associated with accretion by the SMBH or dark matter annihilation near it, or a combination of sources
- A SN remnant is an extended source expected to produce a power-law energy spectrum offset from the SMBH, accretion is expected to be variable, while DM annihilation should produce a cuspy angular distribution with an energy spectrum cut off near the WIMP mass
- No time variability has been seen by H.E.S.S.

Comments, con’d

- The power law spectrum observed to ~12 TeV requires M_{WIMP} > 30 TeV -- can a SUSY WIMP that massive be consistent with unitarity and $\Omega_m \approx 0.25$? UCSC grad student Rudy Gilmore answers NO for usual SUSY neutralinos, but he is investigating whether WIMP annihilation through an s-channel Higgs could work
- The angular resolution of the 4-telescope H.E.S.S. array may allow determination of the angular distributions; MAGIC and VERITAS may also help measure the high energy spectrum and see if there is a roll-off

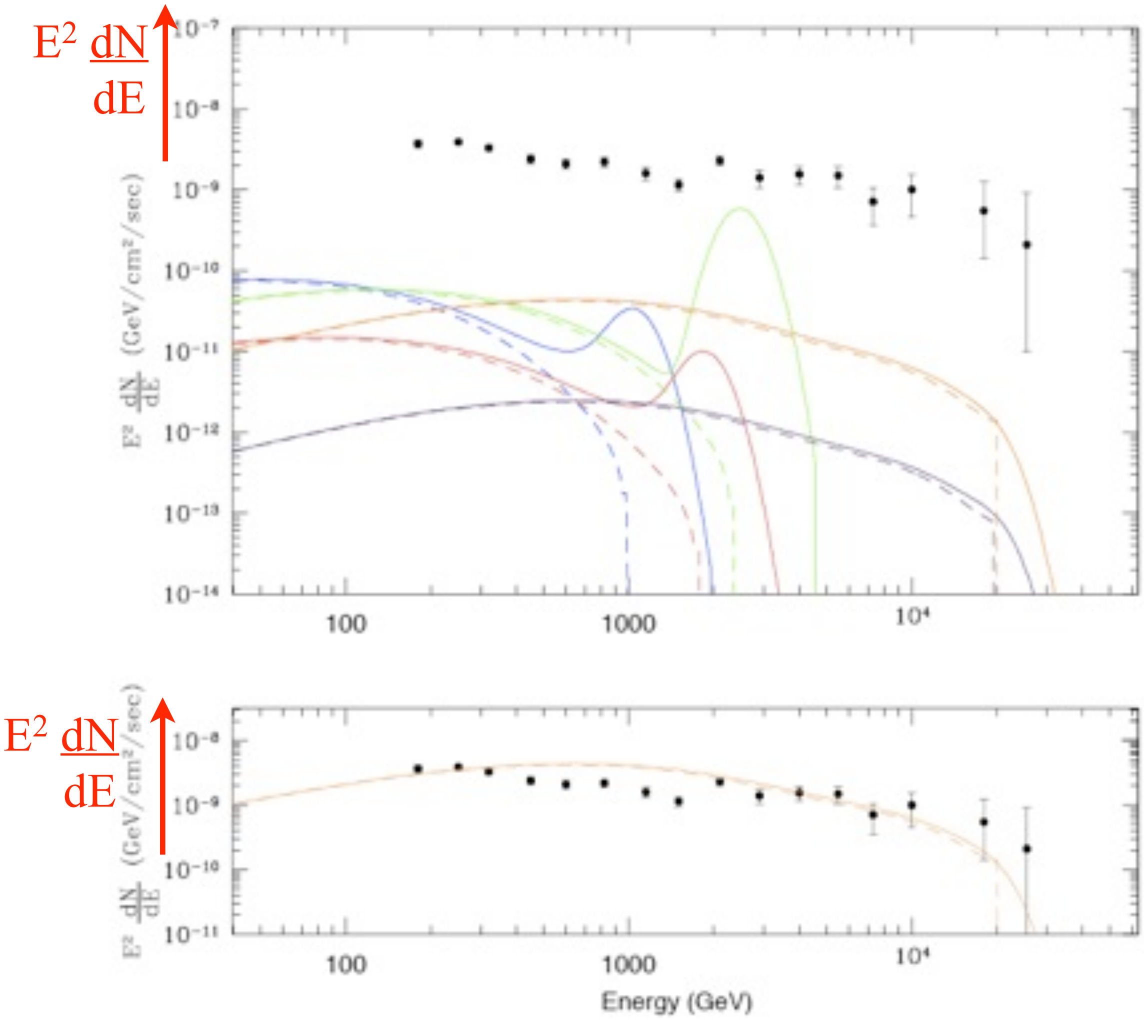
Rudy C. Gilmore, Mass Limits on Neutralino Dark Matter

Phys.Rev.D76:043520,2007

Abstract: We set an upper limit on the mass of a supersymmetric neutralino dark matter particle using the MicrOMEGAS and DarkSUSY software packages and the most recent constraints on relic density from combined WMAP and SDSS data. We explore several different possible scenarios within the MSSM, including coannihilation with charginos and sfermions and annihilation through a massive Higgs resonance, using low energy mass inputs. We find that no coannihilation scenario is consistent with dark matter in observed abundance with a mass greater than 2.5 TeV for a wino-type particle or 1.8 TeV for a Higgsino-type. Contrived scenarios involving Higgs resonances with finely-tuned mass parameters can allow masses as high as 34 TeV. The resulting gamma-ray energy distribution is not in agreement with the recent multi-TeV gamma ray spectrum observed by H.E.S.S. originating from the center of the Milky Way. Our results are relevent only for dark matter densities resulting from a thermal origin.

Rudy C. Gilmore, Mass Limits on Neutralino Dark Matter

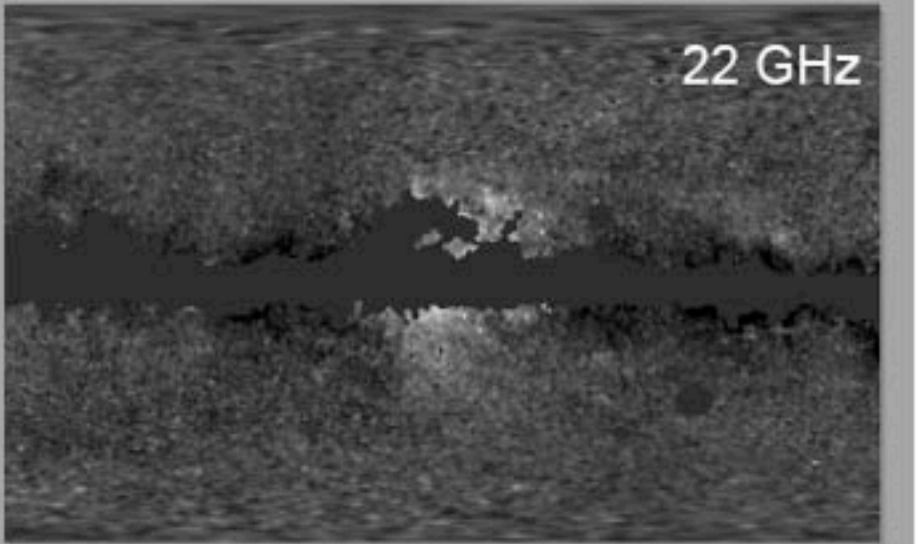
SUSY DM maximum mass is too low, spectrum shape is wrong, to account for Sag A* gamma rays



In the upper plot, we summarize our findings by showing the resulting local gamma–ray flux from the galactic center in several annihilation scenarios using the halo model of [12] with fiducial normalization (no baryonic compression), and compare to the latest observations of the H.E.S.S. experiment (black data points, [30]). The dashed lines show the true continuous distribution, while the solid lines show the total (continuous plus discrete) emission spectra as seen by a detector with an energy resolution of 15 percent. The blue line is a 1 TeV Higgsino, coannihilating with a nearly degenerate chargino and second Higgsino. The red line shows the same model with coannihilation from a 3rd generation squark, at a mass of 1.8 TeV. The green line is a 2.4 TeV wino. The purple and orange lines are both a mixed type neutralino annihilating through a heavy Higgs resonance. The orange model has been optimized by fine tuning of the resonance, so that the cross section and resulting flux are maximized, while the purple line shows a more typical model. The lower plot demonstrates an attempt to fit a Higgs resonance model to the H.E.S.S. data. A factor 10 density boost is applied, resulting in a 10^2 increase in flux above the fiducial value.

Dark Matter in the WMAP Sky

- In 2004, Doug Finkbeiner suggested that the WMAP Haze could be synchtrotron from electrons/positrons produced in dark matter annihilations in the inner galaxy (astro-ph/0409027)



- In particular, he noted that:

1) Assuming an NFW profile, a WIMP mass of 100 GeV and an annihilation cross section of 3×10^{-26} cm^3/s, the total power in dark matter annihilations in the inner 3 kpc of the Milky Way is
$\sim1.2\times10^{39}$ GeV/sec

2) The total power of the WMAP Haze is between
0.7×10^{39} and 3×10^{39} GeV/sec

Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

DM2008

Dark Matter in the WMAP Sky

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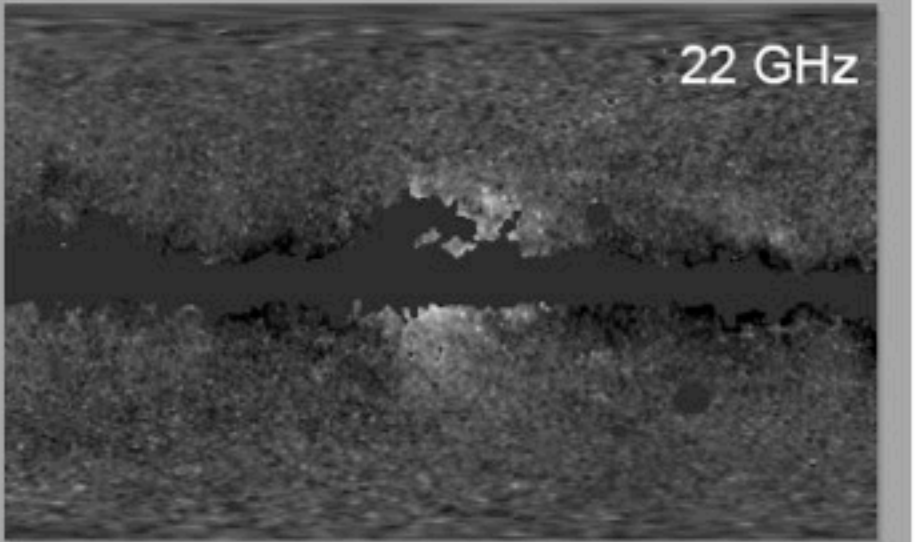


- In particular, he noted that:

1) Assuming an NFW profile, a WIMP mass of 100 GeV and an annihilation cross section of 3×10^{-26} cm^3/s, the total power in dark matter annihilations in the inner 2 kpc of the Milky Way is

~1.2×10^{39} GeV/sec

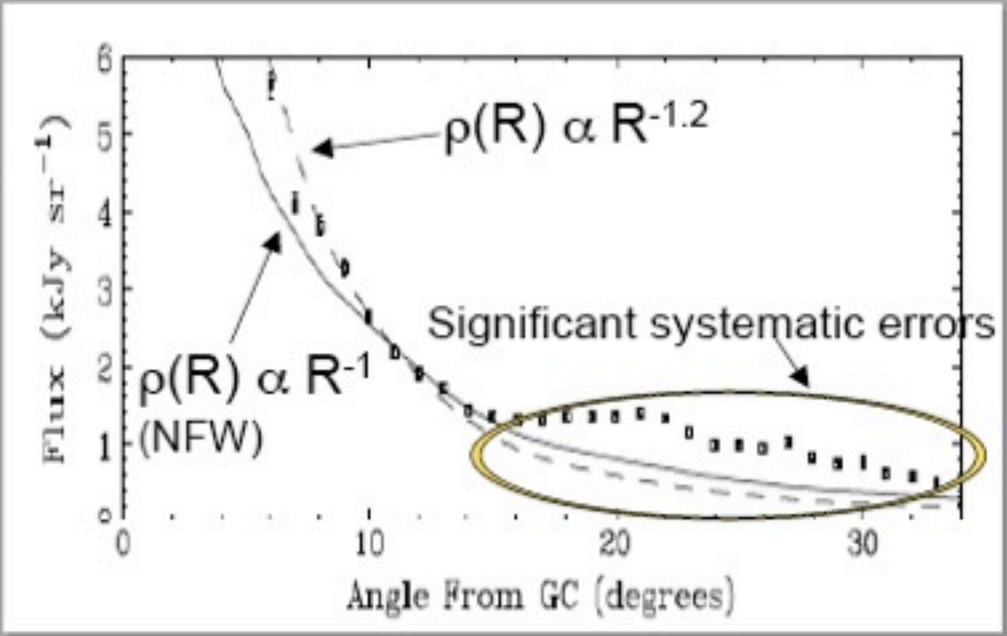
Coincidence?

2) The total power of the WMAP Haze is between

0.7×10^{39} and 3×10^{39} GeV/sec

Fitting The Haze To The Dark Matter Halo Profile

- When the effects of diffusion are accounted for, we find that an NFW halo profile ($\rho \propto R^{-1}$) under produces the WMAP haze at small angles
- Angular distribution of the haze matches that found for a profile, with $\rho \propto R^{-1.2}$

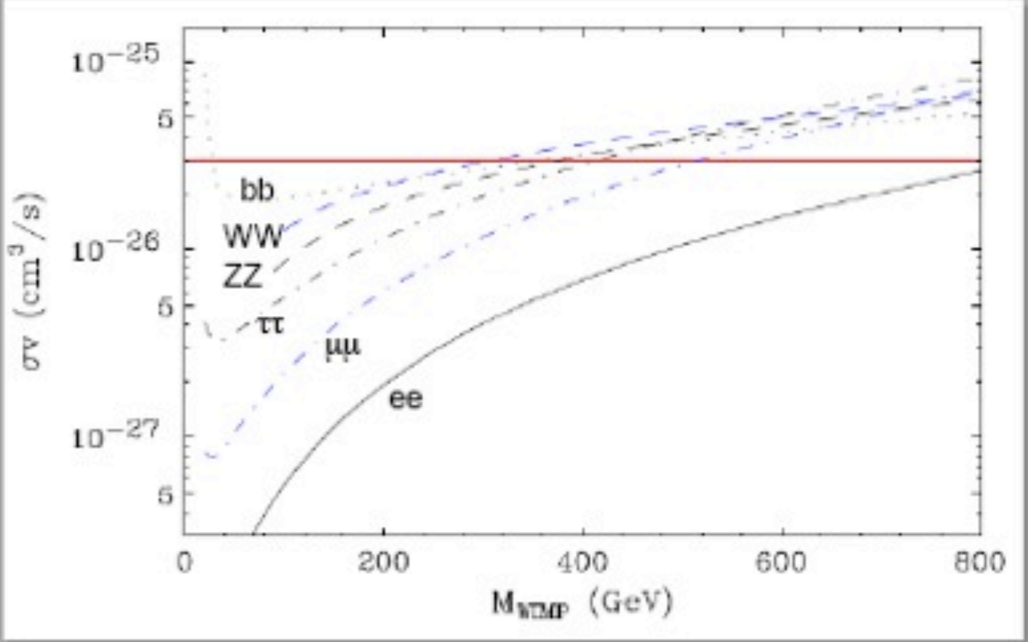


- Although the precise result of this fit depends on the diffusion parameters adopted (magnetic fields, starlight density, etc.), the approximate result (slope of -1.1 to -1.3) is fairly robust

Hooper, G. Dobler and D. Finkbeiner, PRD, arXiv:0705.3655

The Dark Matter Annihilation Cross Section

- For a given annihilation mode, diffusion parameters and halo profile, we can calculate the annihilation cross section needed to normalize to the observed intensity of the WMAP Haze



- For a typical 100-1000 GeV WIMP, the annihilation cross section needed is within a factor of 2-3 of the value needed to generate the density of dark matter thermally ($3\text{x}10^{-26}$ cm^3/s)

- ***No boost factors are required!***

Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

Hooper, G. Dobler and D. Finkbeiner, PRD, arXiv:0705.3655

The remarkable match of the WMAP Haze to the signal expected from Dark Matter

The Haze is consistent with dark matter annihilations with the following characteristics:

1. A dark matter distribution with $\rho \propto R^{-1.2}$ in the inner kiloparsecs of our galaxy
2. A dark matter particle with a ~100 GeV to several TeV mass, and that annihilates to typical channels (heavy fermions, gauge bosons, etc.)
3. An annihilation cross section within a factor of a few of 3×10^{-26} cm^3/s (the value required of a thermal relic)

A completely vanilla dark matter scenario!

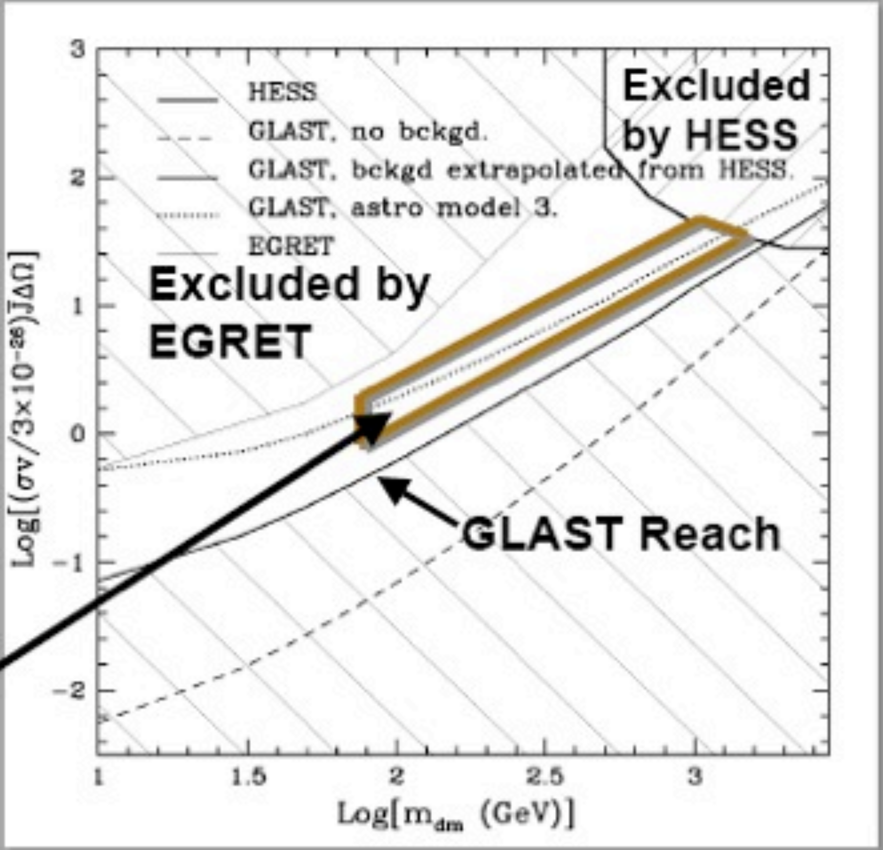
Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

Hooper, G. Dobler and D. Finkbeiner, PRD, arXiv:0705.3655

Gamma-Rays From The Galactic Center

- GLAST will extend the region of the cross section-mass plane excluded by EGRET and HESS considerably

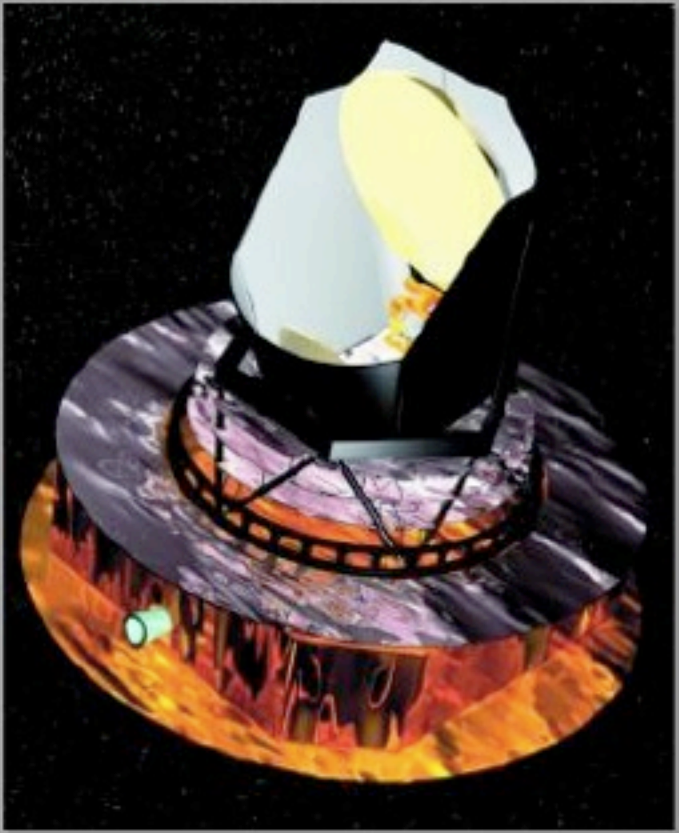
- If we normalize the annihilation rate to that needed to generate the observed intensity of the WMAP Haze, we find that the gamma ray flux is within the reach of GLAST



Range Predicted By the WMAP Haze

Hooper and G. Zaharijas, PRD, hep-ph/0603540

The WMAP Haze In Light Of Planck



Planck (launch in 2008) will represent a major step forward from WMAP:

- Improved frequency coverage
- Improved angular resolution

- At frequencies above ~100 GHz, all foregrounds other than emission from thermal dust are negligible; subtracting one foreground rather than the several (3 or 4) required at WMAP frequencies will enable for a much more robust confirmation of the hard synchrotron origin of the Haze
- Systematic uncertainties are expected to be reduced by more than an order of magnitude relative to WMAP

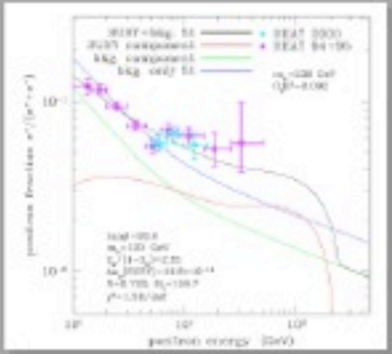
What About Other Claims of Evidence For Dark Matter Annihilation?

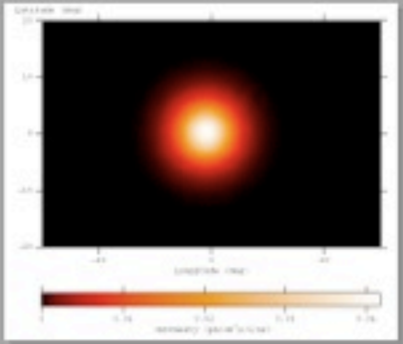
- The HEAT positron excess

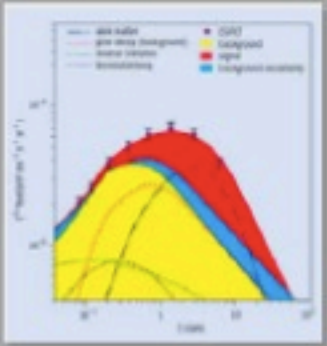
- 511 keV emission from the galactic bulge

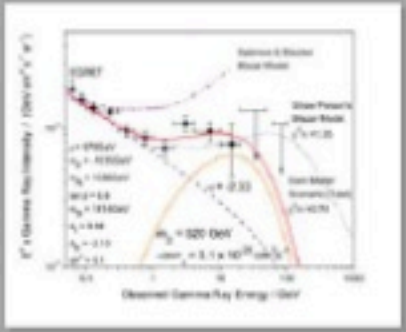
- EGRET's galactic gamma ray spectrum

- EGRET's extragalactic gamma ray spectrum









Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

Signal	Required Particle Physics	Required Astrophysics
WMAP Haze	100 GeV to multi-TeV WIMP, ~3×10^{-26} cm^3/s annihilation cross section	Cusped halo profile, standard diffusion, no boost factors
HEAT Positron Excess	50-1000 GeV WIMP; Either large (non-thermal) annihilation cross section OR …	Large boost factor (50 or more)
INTEGRAL 511 keV Emission	~MeV particle, p-wave annihilator with ~3×10^{-26} cm^3/s annihilation cross section	Mildly cusped halo profile
EGRET Diffuse Galactic	~50-300 GeV WIMP; Either large (non-thermal) annihilation cross section OR …	Large boost factors; two massive rings of dark matter in the galactic plane; non-standard, highly convective diffusion model
EGRET Diffuse Extragalactic	~500 GeV WIMP; Either large (non-thermal) annihilation cross section OR …	Large boost factors/highly cusped profiles; Conflict with Milky Way unless Galactic Center is exceptional

Signal	Required Particle Physics	Required Astrophysics
WMAP Haze	100 GeV to multi-TeV WIMP, ~$3x10^{-26}$ cm^3/s annihilation cross section	Cusped halo profile, standard diffusion, no boost factors
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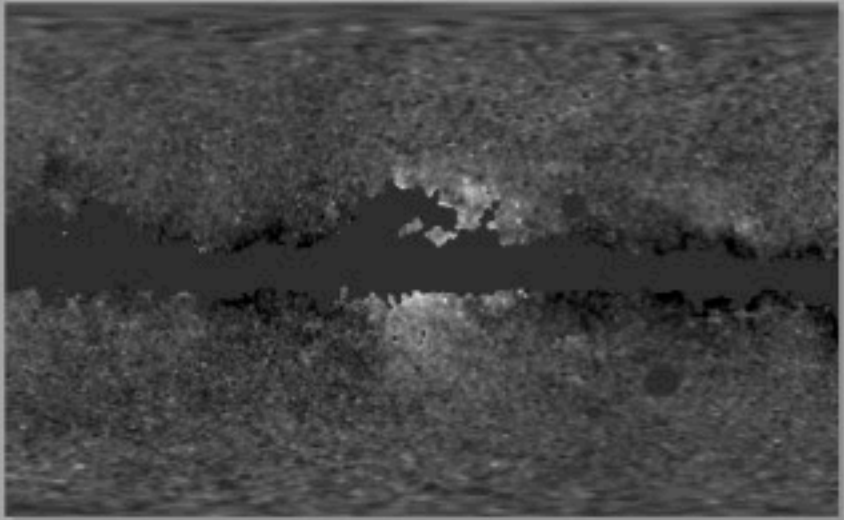
EGRET Diffuse Extragalactic	~500 GeV WIMP; Either large (non-thermal) annihilation cross section OR …	Large boost factors/highly cusped profiles; Conflict with Milky Way unless Galactic Center is exceptional

Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

Conclusions

- WMAP data, after the subtraction of known foregrounds, contains an excess from the region around the center of the Milky Way - The "WMAP Haze"



- Consistent with synchrotron emission from energetic electrons/positrons from dark matter annihilations with:
  - A cusped halo profile
  - A 100-1000 GeV WIMP
  - An annihilation cross section within a factor of 2-3 of the value required of a thermal relic (~3×10^{-26} cm^3/s)

A completely vanilla dark matter scenario!

highly relevant SCIPP Seminar

Date: Tuesday, February 10th

Time: 10:30am

Location: ISB 310

Speaker: Stefano Profumo (SCIPP)

Title: "Dissecting Pamela (and ATIC) with Occam's Razor: existing, well-known Pulsars naturally account for the "anomalous" Cosmic-Ray Electron and Positron Data"

Abstract: We argue that both **the positron fraction measured by PAMELA and the peculiar spectral features reported in the total differential electron-positron flux measured by ATIC have a very natural explanation in electron-positron pairs produced by nearby pulsars.** We show that the greatly improved quality of current data allow us to reverse-engineer the problem: given the regions of pulsar parameter space favored by PAMELA and by ATIC, are there known pulsars that naturally explain the data? We address this question by (1) outlining simple theoretical models for estimating the energy output, the diffusion setup and the injection spectral index of electron-positron pairs, and by (2) considering all known pulsars (as given in the ATNF catalogue). It appears unlikely that a single pulsar be responsible for both the PAMELA result and for the ATIC excess, although two sources are enough to naturally explain both of the experimental results. We list several candidate pulsars that can individually or coherently contribute to explain the PAMELA and ATIC data. We point out that Fermi-LAT will play a decisive role in the very near future, by (1) providing us with an exquisite measurement of the electron-positron flux that will make it possible to distinguish between various pulsar scenarios, and by (2) unveiling the existence of as yet undetected gamma-ray pulsars that can significantly contribute to the local electron-positron flux.

Four roads to dark matter: *catch it, infer it, make it, weigh it*

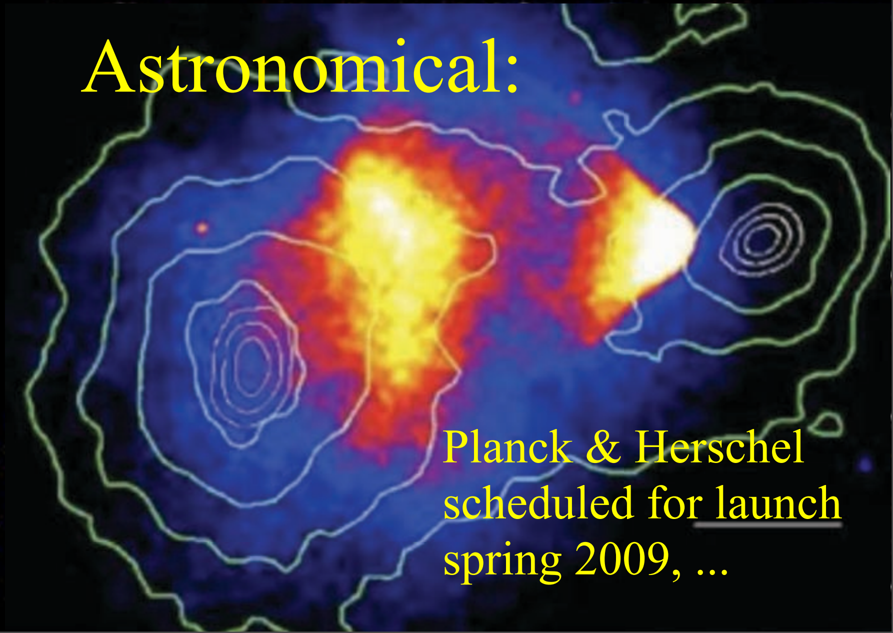

Direct:


Production:

With all
these
upcoming
experiments,
the next
few years
will be very
exciting!


Indirect:

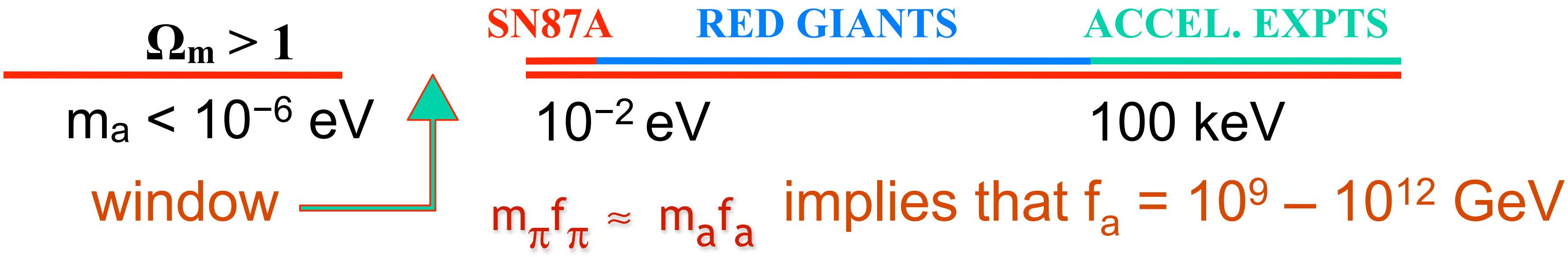
Fermi (GLAST)
launched
June 11, 2008


Astronomical:

Planck & Herschel
scheduled for launch
spring 2009, ...

Axion Physics in a Nutshell

Why axions? QCD with $m_{quarks} \neq 0$ violates **CP** and therefore **T** due to instantons, unless an undetermined parameter θ is very small – or the axion field absorbs the **CP**-violating phase. If this **CP** violation isn't avoided, the neutron gets an electric dipole moment 10^{10} times larger than the experimental upper bound!



$\Omega_m > 1$

$m_a < 10^{-6}$ eV

window

SN87A **RED GIANTS** **ACCEL. EXPTS**

10^{-2} eV

100 keV

$m_\pi f_\pi \approx m_a f_a$ implies that $f_a = 10^9 – 10^{12}$ GeV

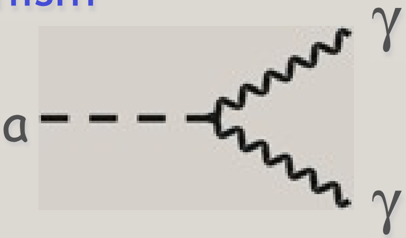
When the temperature T drops to $T \sim f_a$, the axion field gets a vacuum expectation value $f_a e^{i\theta}$, and then when T drops to $\Lambda_{QCD} \sim 100$ MeV QCD causes the axion to get mass m_a and density $\rho_a \propto 1/m_a$.

What? Axions are never relativistic, so there is no free streaming to erase fluctuations in their density. So they behave like Cold Dark Matter.

Axion Physics in a Nutshell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism



→ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$

For $f_a >> f_\pi$ axions are "invisible" and very light

Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production

- No excessive energy drain:

  $m_a < 10$ meV

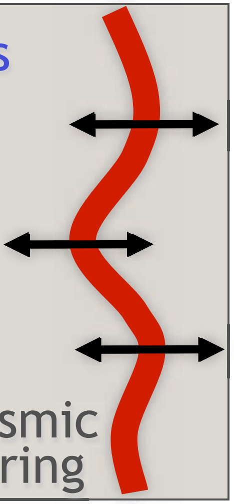
- Search for solar axions (CAST)

Cosmology

In spite of small mass, axions are born non-relativistically ("non-thermal relics")

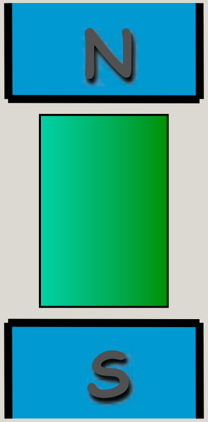
→ "Cold dark matter" candidate

$m_a \sim$ 1-1000 μeV

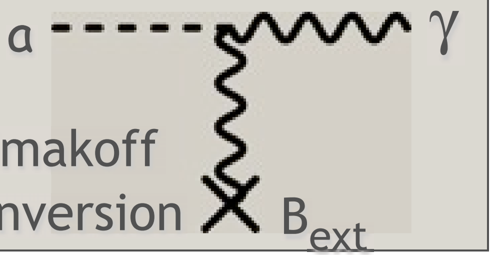


Cosmic String

Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



Primakoff conversion

Experimental Search for Axions

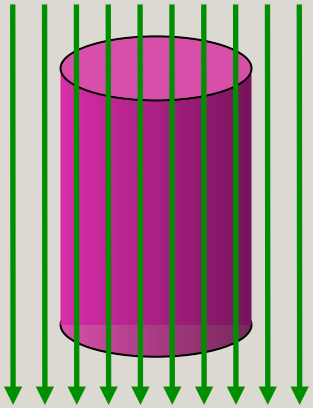
DM axions $m_a = 10\text{-}3000\ \mu\text{eV}$

Velocities in galaxy $v_a \approx 10^{-3}\ c$

Energies therefore $E_a \approx (1 \pm 10^{-6})\ m_a$

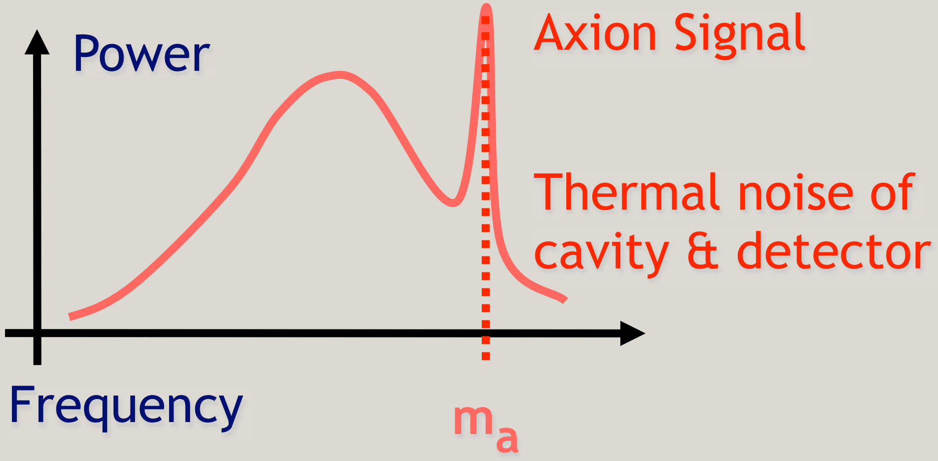
Microwave Energies
(1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

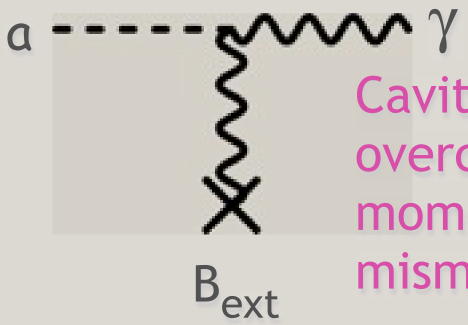


$B_{ext} \approx 8$ Tesla

Microwave Resonator
$Q \approx 10^5$



Primakoff Conversion



Cavity overcomes momentum mismatch

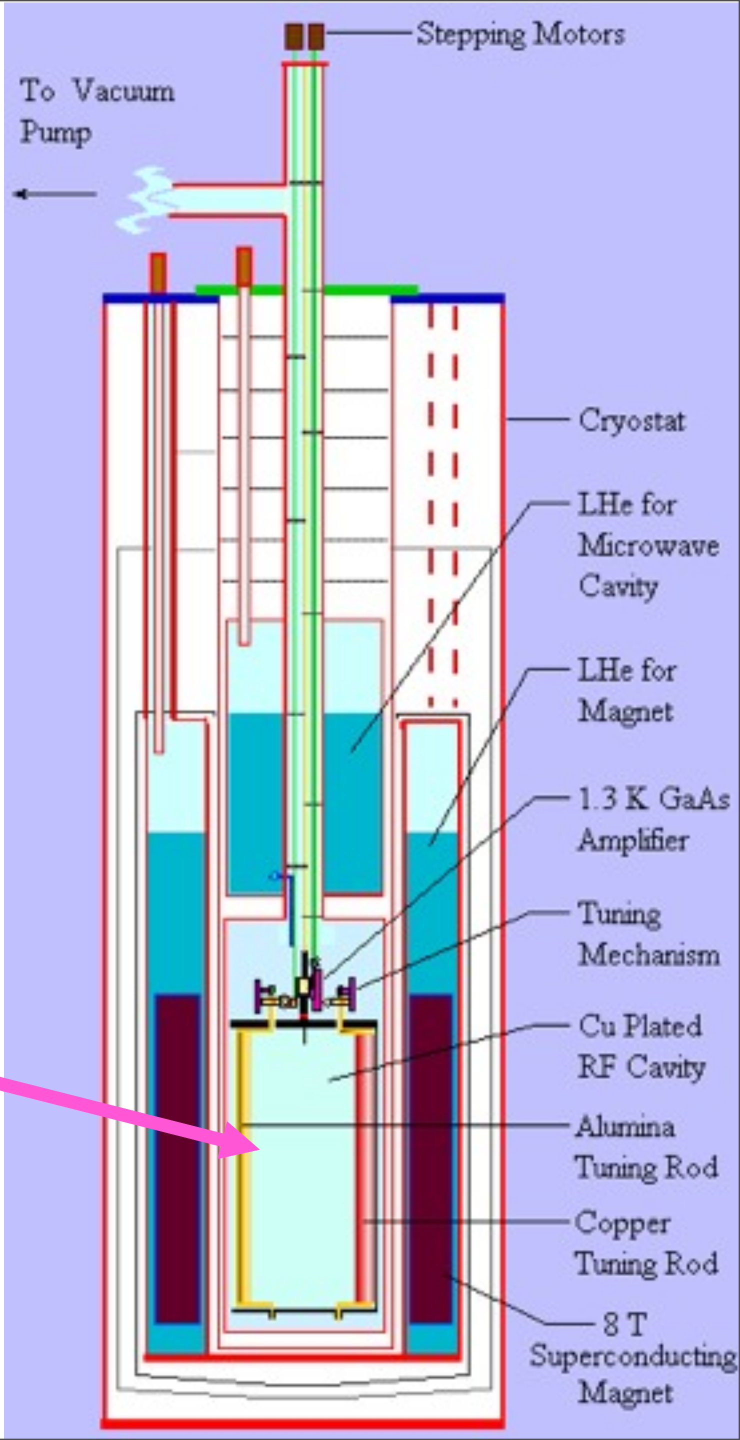
2 Experiments in Operation

- Axion Dark Matter Experiment (ADMX), Livermore, US
- CARRACK II, Kyoto, Japan

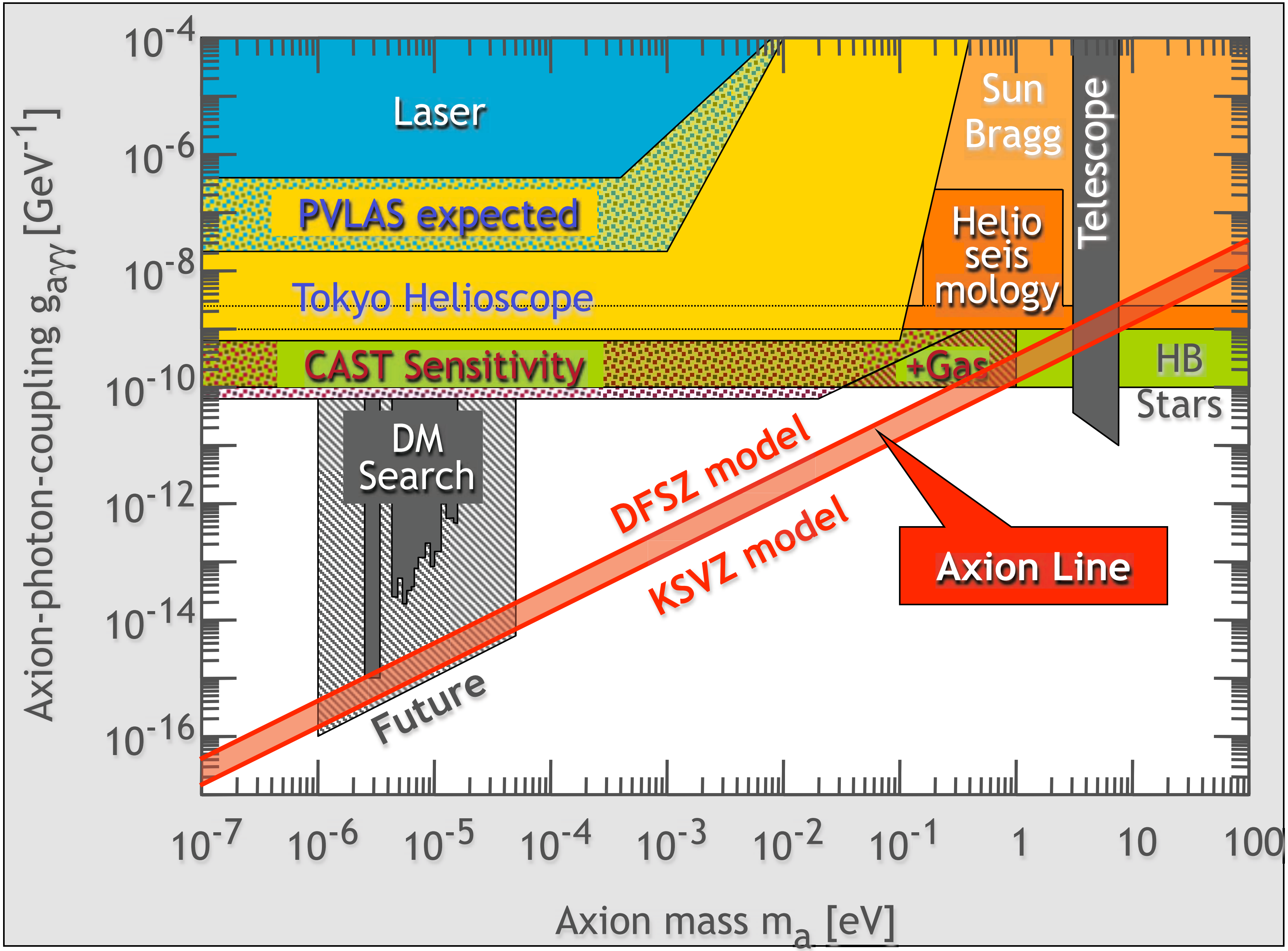
AXION search

The diagram at right shows the layout of the axion search experiment now underway at the Lawrence Livermore National Laboratory. Axions would be detected as extra photons in the Microwave Cavity.

An improved version of this experiment is moving to the University of Washington.



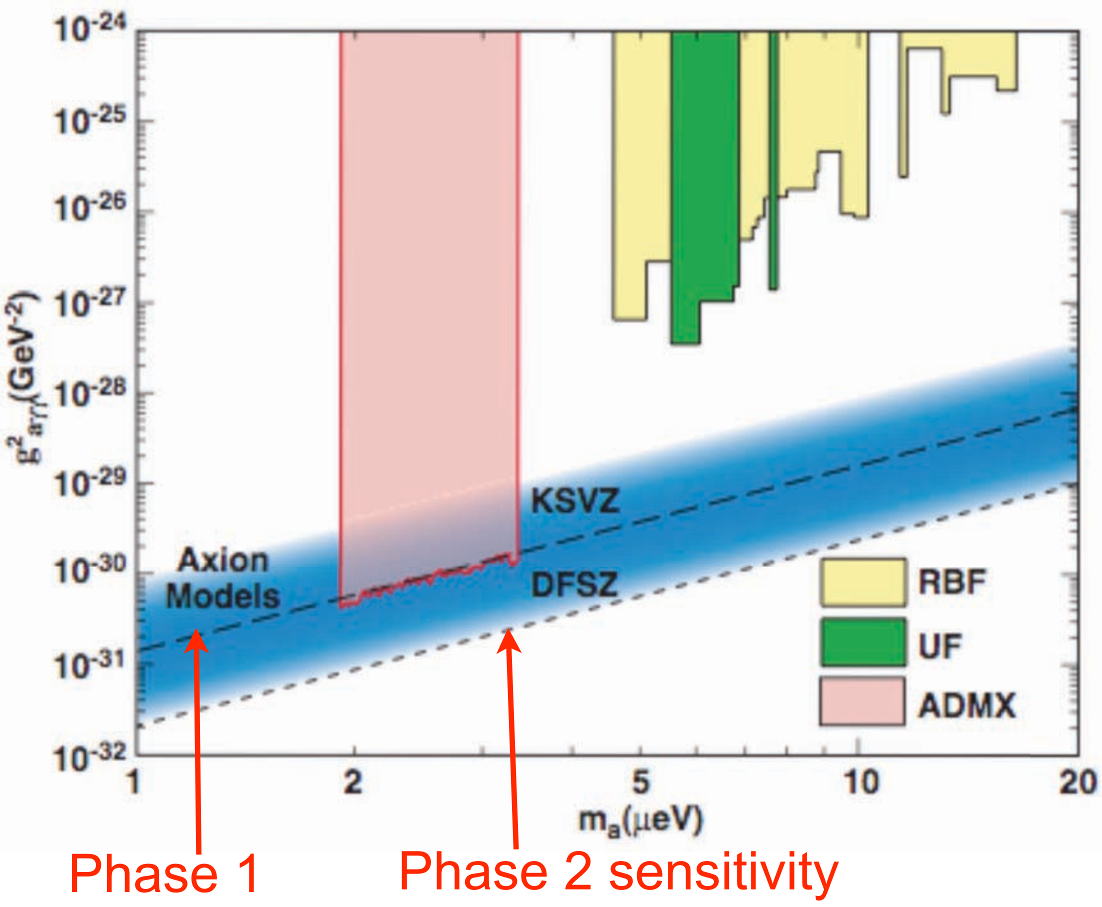
Limits on Axion-Photon-Coupling



AXION search

The Strong CP Problem. The standard SU(3) theory of the Strong force violates CP conservation, for example predicting that the neutron has an electric dipole moment 10^8 times bigger than the current upper limit, unless an uncalculable parameter is very small. The only elegant solution to this "Strong CP Problem" involves a new particle that interacts so weakly that it has never been detected before. This particle is the Axion. Fortunately this particle would interact with other particles just enough that if you went looking for it very carefully, you might be able to find it.

The **Axion DM Experiment (ADMX)** is designed to look into only a slice of the allowed mass range. The reason it's only a slice and not the whole range is simply due to the equipment. The frequency that is scanned by ADMX depends on the tuning rods and the resonant cavity. Making the apparatus able to scan a larger frequency range would have cost more and made the apparatus bigger, which makes cooling and transportation harder, among other things. As to why it is that particular slice, it's because it's the most convenient one to look in. There's no significant reason to believe that the Axion would be more likely to be in any particular range, so this one was chosen based on it being easiest to scan with current technology.



Phase 1

Phase 2 sensitivity

Types of Dark Matter

Ω_i represents the fraction of the critical density $\rho_c = 10.54\ h^2$ keV/cm^3 needed to close the Universe, where h is the Hubble constant H_0 divided by 100 km/s/*Mpc*.

Dark Matter Type	Fraction of Critical Density	Comment
Baryonic	$\Omega_b \sim 0.04$	about 10 times the visible matter
Hot	$\Omega_\nu \sim 0.001–0.1$	light neutrinos
Cold	$\Omega_c \sim 0.3$	most of the dark matter in galaxy halos

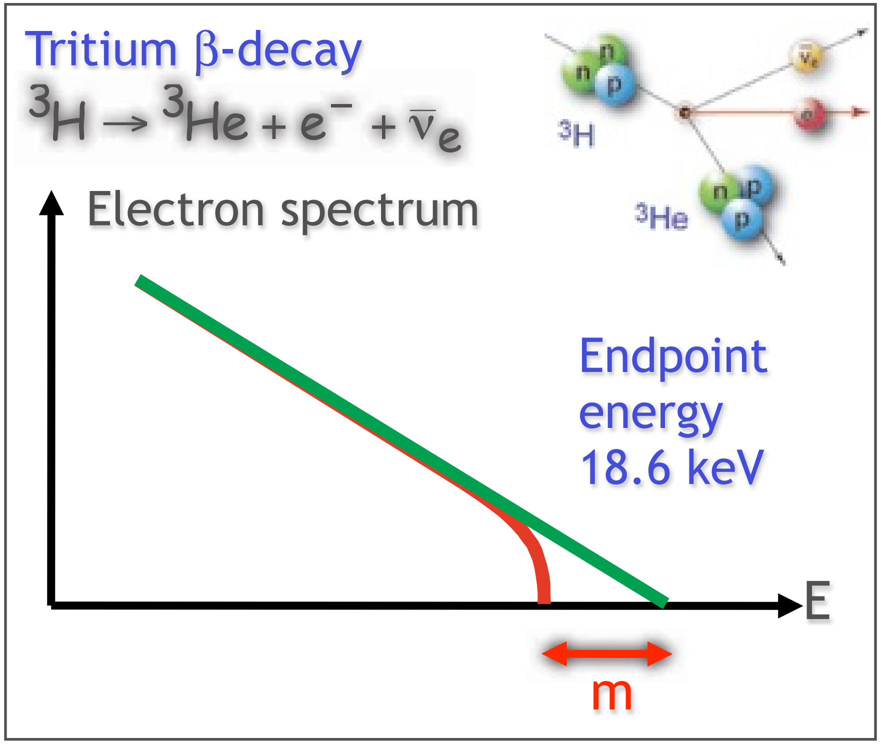
Dark Matter and Associated Cosmological Models

Ω_m represents the fraction of the critical density in all types of matter.
Ω_Λ is the fraction contributed by some form of "dark energy."

Acronym	Cosmological Model	Flourished
HDM	hot dark matter with $\Omega_m = 1$	1978–1984
SCDM	standard cold dark matter with $\Omega_m = 1$	1982–1992
CHDM	cold + hot dark matter with $\Omega_c \sim 0.7$ and $\Omega_\nu = 0.2–0.3$	1994–1998
ΛCDM	cold dark matter $\Omega_c \sim 1/3$ and $\Omega_\Lambda \sim 2/3$	1996–today

Joel Primack, *Beam Line*, Fall 2001

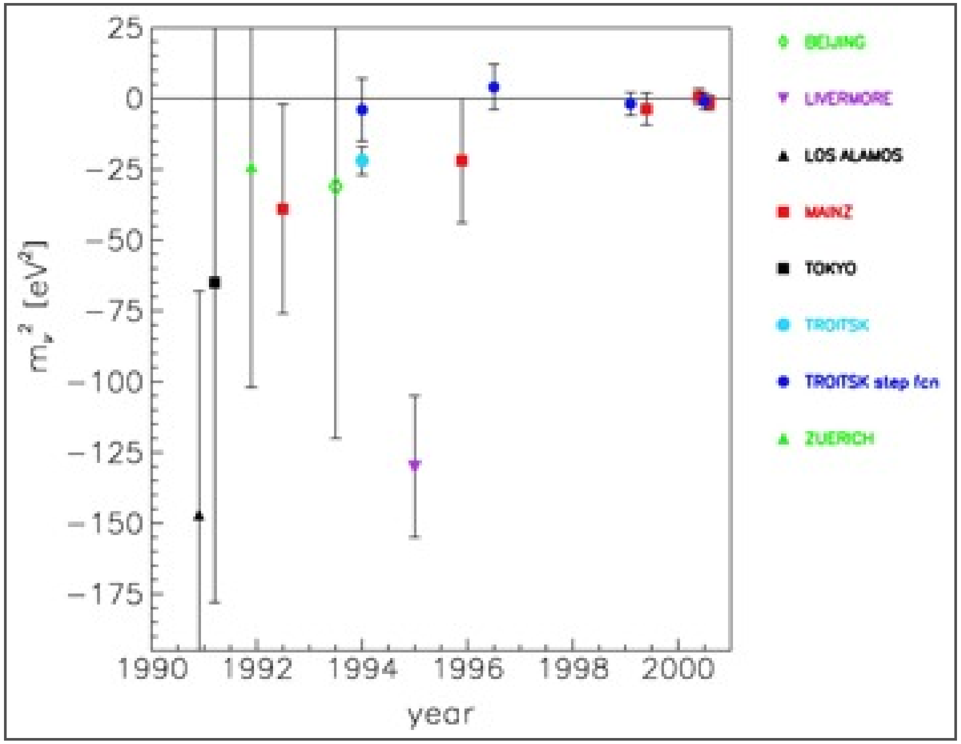
$m(\nu_e)$: Tritium Endpoint Spectrum



Tritium β-decay

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

Endpoint energy 18.6 keV



Currently best limits from Mainz and Troitsk experiments

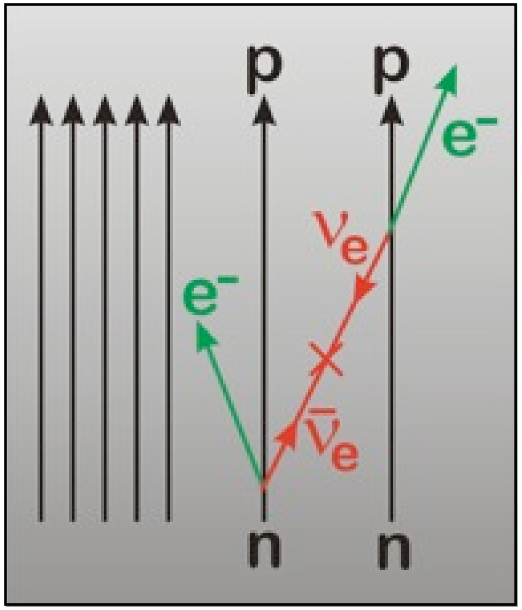
$m < 2.2$ eV (95% CL)

- Scaled-up spectrometer (KATRIN) should reach 0.2 eV
- Currently under construction
- Measurements to begin 2007

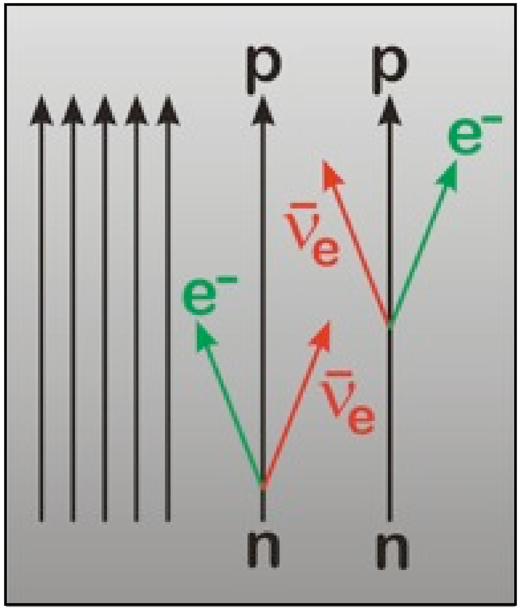
http://ik1au1.fzk.de/~katrin

Neutrinoless ββ Decay

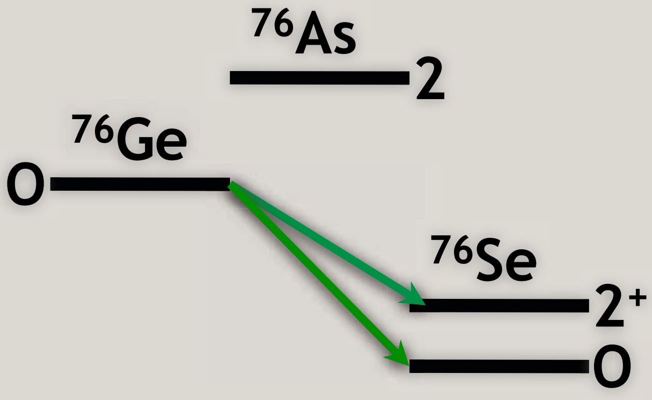
0ν mode, enabled by Majorana mass



Standard 2ν mode



Some nuclei decay only by the ββ mode, e.g.



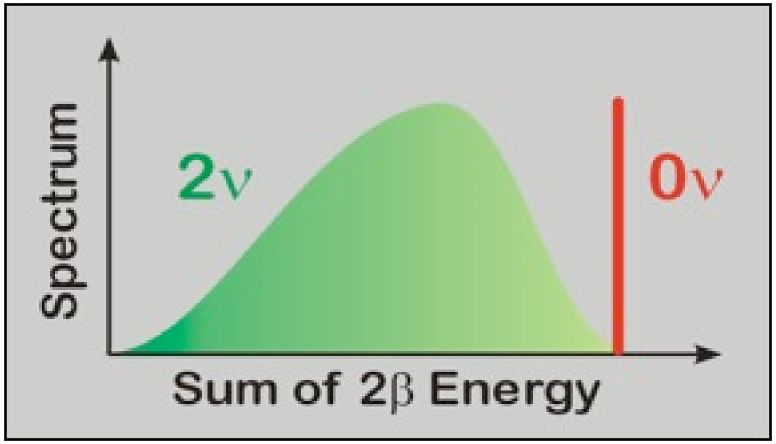
Half life ~ 10^{21} yr

Measured quantity

$$|m_{ee}| = \left|\sum_{i=1}^{N} \lambda_i |U_{ei}|^2 m_i\right|$$

Best limit from ^{76}Ge

$$|m_{ee}| < 0.35\,\mathrm{eV}$$



ν_e

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with e^+ or e^-. See the Note on "Electron, muon, and tau neutrino listings" in the Particle Listings.

Mass $m < 3$ eV Interpretation of tritium beta decay experiments is complicated by anomalies near the endpoint, and the limits are not without ambiguity.

Mean life/mass, $\tau/m_\nu > 7 \times 10^9$ s/eV [i] (solar)

Mean life/mass, $\tau/m_\nu > 300$ s/eV, CL = 90% [i] (reactor)

Magnetic moment $\mu < 1.0 \times 10^{-10}\ \mu_B$, CL = 90%

ν_μ

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with μ^+ or μ^-. See the Note on "Electron, muon, and tau neutrino listings" in the Particle Listings.

Mass $m < 0.19$ MeV, CL = 90%

Mean life/mass, $\tau/m_\nu > 15.4$ s/eV, CL = 90%

Magnetic moment $\mu < 6.8 \times 10^{-10}\ \mu_B$, CL = 90%

ν_τ

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with τ^+ or τ^-. See the Note on "Electron, muon, and tau neutrino listings" in the Particle Listings.

Mass $m < 18.2$ MeV, CL = 95%

Magnetic moment $\mu < 3.9 \times 10^{-7}\ \mu_B$, CL = 90%

Electric dipole moment $d < 5.2 \times 10^{-17}$ e cm, CL = 95%

Number of Neutrino Types and Sum of Neutrino Masses

Number $N = 2.994 \pm 0.012$ (Standard Model fits to LEP data)

Number $N = 2.92 \pm 0.07$ (Direct measurement of invisible Z width)

Neutrino Mixing

There is now compelling evidence that neutrinos have nonzero mass from the observation of neutrino flavor change, both from the study of atmospheric neutrino fluxes by SuperKamiokande, and from the study of solar neutrino cross sections by SNO (charged and neutral currents) and SuperKamiokande (elastic scattering). The flavor change observed in solar neutrinos has been confirmed by the KamLAND experiment using reactor antineutrinos.

Solar Neutrinos

Detectors using gallium ($E_\nu \gtrsim 0.2$ MeV), chlorine ($E_\nu \gtrsim 0.8$ MeV), and Cherenkov effect in water ($E_\nu \gtrsim 5$ MeV) measure significantly lower neutrino rates than are predicted from solar models. From the determination by SNO of the ^{8}B solar neutrino flux via elastic scattering, charged-current process interactions, and neutral-current interactions, one can determine the flux of non-ν_e active neutrinos to be $\phi(\nu_{\mu\tau}) = (3.41^{+0.66}_{-0.64}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, providing a 5.3 σ evidence for neutrino flavor change. A global analysis of the solar neutrino data, including the KamLAND results that confirm the effect using reactor antineutrinos, favors large mixing angles and $\Delta(m^2) \simeq (6\text{–}9) \times 10^{-5}\ \mathrm{eV}^2$. See the Note "Solar Neutrinos" in the Listings and the review "Neutrino Mass, Mixing, and Flavor Change."

Atmospheric Neutrinos

Underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected, and also a deficiency of upward going ν_μ compared to downward. This can be explained by oscillations leading to the disappearance of ν_μ with $\Delta m^2 \approx (1\text{–}3) \times 10^{-3}\ \mathrm{eV}^2$ and almost full mixing between ν_μ and ν_τ. The effect has been confirmed by the K2K experiment using accelerator neutrinos. See the review "Neutrino Mass, Mixing, and Flavor Change."

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

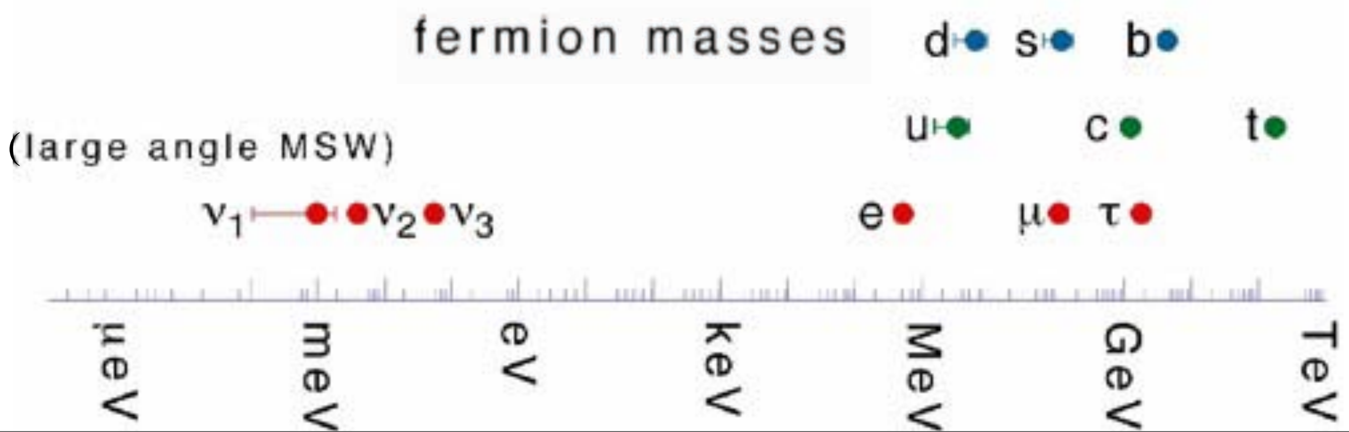
THE ATMOSPHERIC-NEUTRINO DATA from the Super-Kamiokande underground neutrino detector in Japan provide strong evidence of muon to tau neutrino oscillations, and therefore that these neutrinos have nonzero mass (see the article by John Learned in the Winter 1999 *Beam Line*, Vol. 29, No. 3). This result is now being confirmed by results from the K2K experiment, in which a muon neutrino beam from the KEK accelerator is directed toward Super-Kamiokande and the number of muon neutrinos detected is about as expected from the atmospheric-neutrino data (see article by Jeffrey Wilkes and Koichiro Nishikawa, this issue).

But oscillation experiments cannot measure neutrino masses directly, only the squared mass difference $\Delta m^2_{ij} = |m_i^2 - m_j^2|$ between the oscillating species. The Super-Kamiokande atmospheric neutrino data imply that $1.7\times10^{-4} < \Delta m^2_{\tau\mu} < 4\times10^{-3}$ eV² (90 percent confidence), with a central value $\Delta m^2_{\tau\mu} = 2.5\times10^{-3}$ eV². If the neutrinos have a hierarchical mass pattern $m_{\nu_e} << m_{\nu_\mu} << m_{\nu_\tau}$ like the quarks and charged leptons, then this implies that $\Delta m^2_{\tau\mu} \cong m^2_{\nu_\tau}$ so $m_{\nu_\tau} \sim 0.05$ eV.

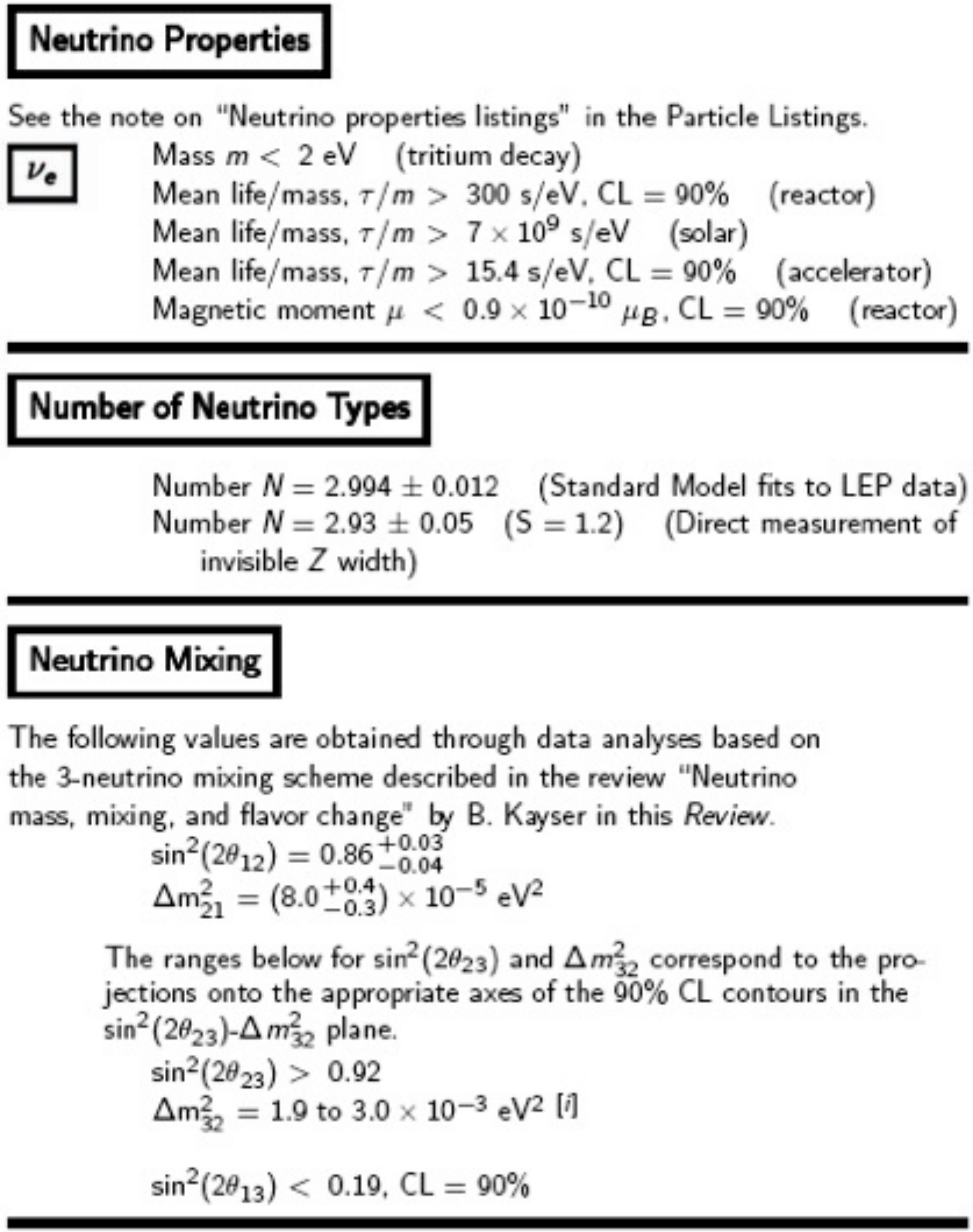
These data then imply a lower limit on the HDM (or light neutrino) contribution to the cosmological matter density of $\Omega_\nu > 0.001$—almost as much as that of all the stars in the disks of galaxies. There is a connection between neutrino mass and the corresponding contribution to the cosmological density, because the thermodynamics of the early Universe specifies the abundance of neutrinos to be about 112 per cubic centimeter for each of the three species (including both neutrinos and antineutrinos). It follows that the density Ω_ν contributed by neutrinos is $\Omega_\nu = m(\nu)/(93\ h^2\ \mathrm{eV})$, where $m(\nu)$ is the sum of the masses of all three neutrinos. Since $h^2 \sim 0.5$, $m_{\nu_\tau} \sim 0.05$ eV corresponds to $\Omega_\nu \sim 10^{-3}$.

This is however a lower limit, since in the alternative case where the oscillating neutrino species have nearly equal masses, the values of the individual masses could be much larger. The only other laboratory approaches to measuring neutrino masses are attempts to detect neutrinoless double beta decay, which are sensitive to a possible Majorana component of the electron neutrino mass, and measurements of the endpoint of the tritium beta-decay spectrum. The latter gives an upper limit on the electron neutrino mass, currently taken to be 3 eV. Because of the small values of both squared-mass differences, this tritium limit becomes an upper limit on all three neutrino masses, corresponding to $m(\nu) < 9$ eV. A bit surprisingly, cosmology already provides a stronger constraint on neutrino mass than laboratory measurements, based on the effects of neutrinos on large-scale structure formation.

Joel Primack, *Beam Line*, Fall 2001



Hitoshi Murayama



Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

ν_e

Mass $m < 2$ eV (tritium decay)
Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)
Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.9 \times 10^{-10}\ \mu_B$, CL = 90% (reactor)

Number of Neutrino Types

Number $N = 2.994 \pm 0.012$ (Standard Model fits to LEP data)
Number $N = 2.93 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino mass, mixing, and flavor change" by B. Kayser in this *Review*.

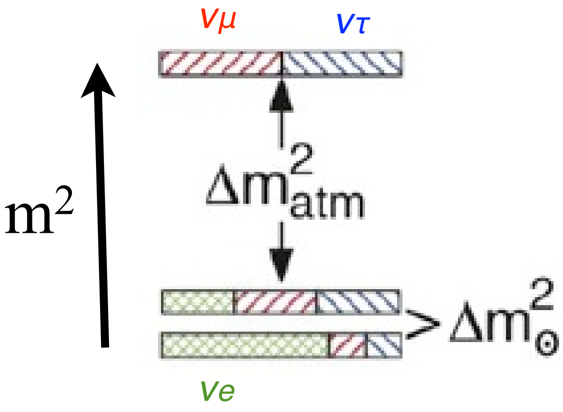
$$\sin^2(2\theta_{12}) = 0.86^{+0.03}_{-0.04}$$
$$\Delta m^2_{21} = (8.0^{+0.4}_{-0.3}) \times 10^{-5}\ \text{eV}^2$$

The ranges below for $\sin^2(2\theta_{23})$ and Δm^2_{32} correspond to the projections onto the appropriate axes of the 90% CL contours in the $\sin^2(2\theta_{23})$-Δm^2_{32} plane.

$$\sin^2(2\theta_{23}) > 0.92$$
$$\Delta m^2_{32} = 1.9 \text{ to } 3.0 \times 10^{-3}\ \text{eV}^2\ [i]$$

$$\sin^2(2\theta_{13}) < 0.19,\ \text{CL} = 90\%$$

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: http://pdg.lbl.gov)

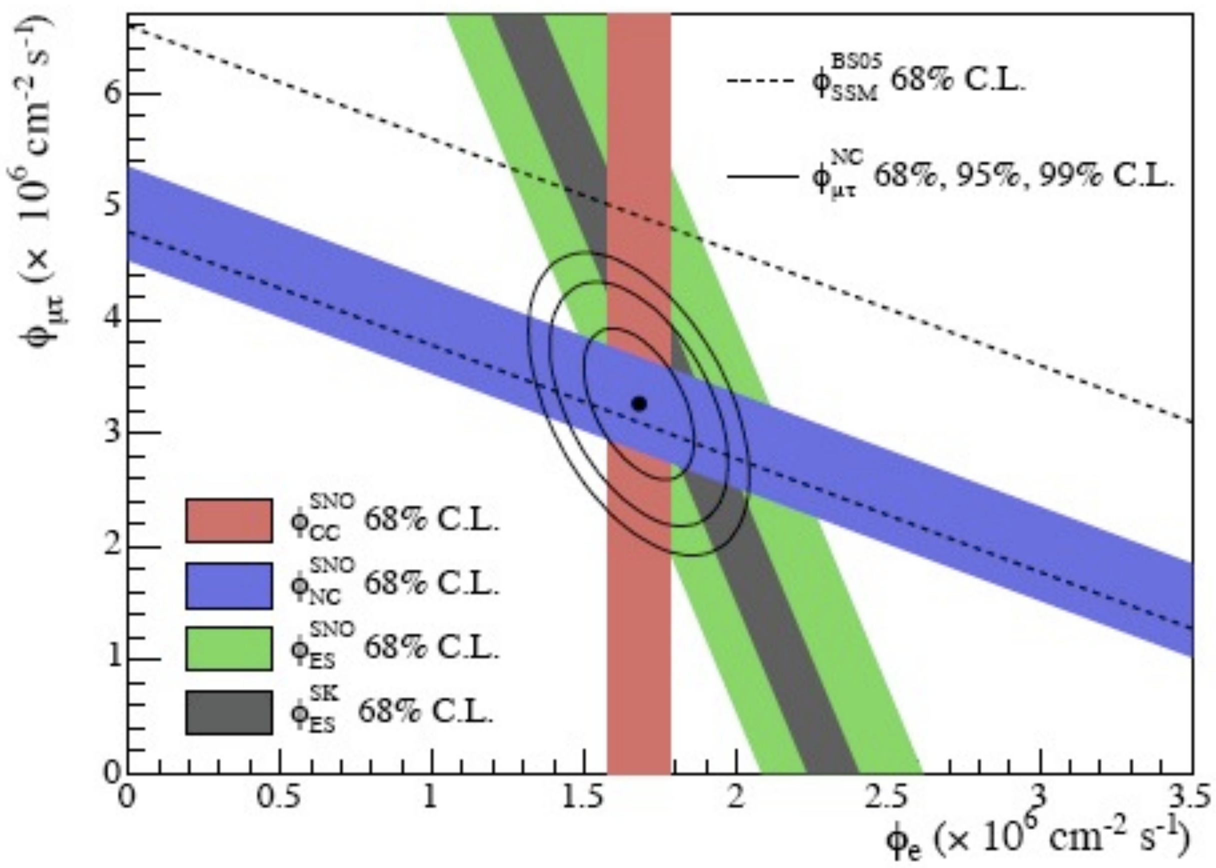


A three-neutrino squared-mass spectrum that accounts for the observed flavor changes of solar, reactor, atmospheric, and long-baseline accelerator neutrinos. The νe fraction of each mass eigenstate is crosshatched, the νμ fraction is indicated by right-leaning hatching, and the ντ fraction by left-leaning hatching. From B. Kaiser, http://pdg.lbl.gov/2007/reviews/

numixrpp.pdf

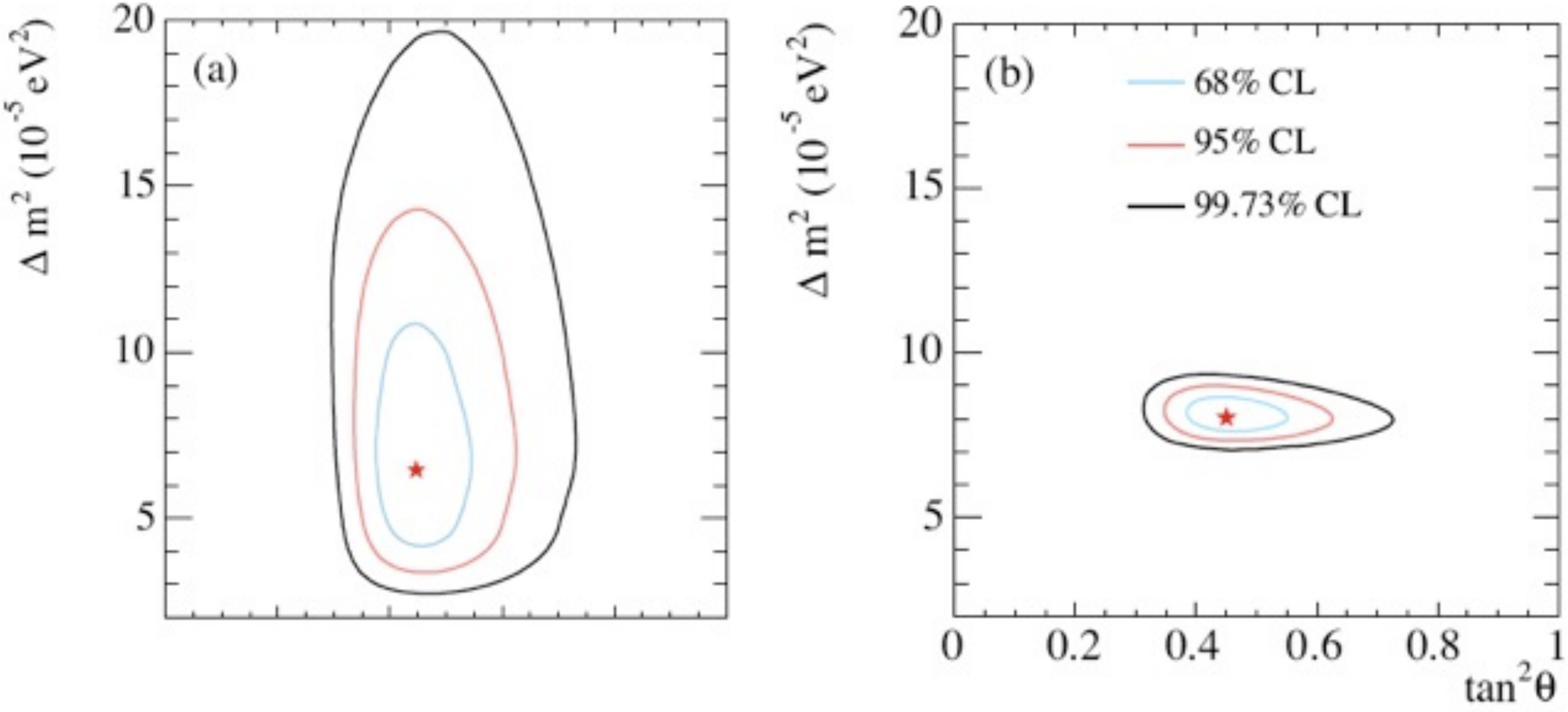
Sudbury Neutrino Observatory Confirms Solar Neutrinos Oscillate

$n \rightarrow p\, e^- \bar{\nu}_e$ must happen twice per ^{4}He, and then ~1/3 of the electron antineutrinos oscillate to mu or tau neutrinos



Fluxes of ^{8}B solar neutrinos, $\phi(\nu_e)$,and $\phi(\nu_{\mu \text{ or } \tau})$, deduced from the SNO's charged current (CC), ν_e elastic scattering (ES), and neutral-current (NC) results for the salt phase measurement. The Super-Kamiokande ES flux and the BS05(OP) standard solar model prediction are also shown. The bands represent the 1σ error. The contours show the 68%, 95%, and 99% joint probability for $\phi(\nu_e)$ and $\phi(\nu_{\mu \text{ or } \tau})$.

[From PDG 2005 review by K. Nakamura.]

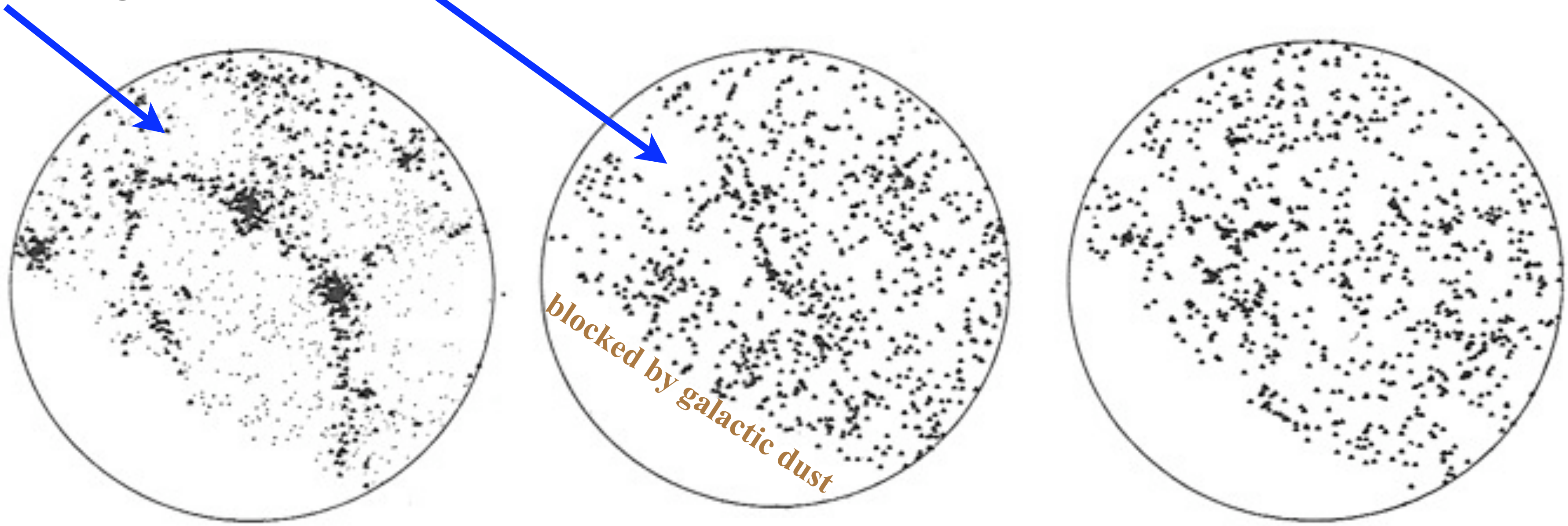


Update of the global neutrino oscillation contours given by the SNO Collaboration assuming that the ^{8}B neutrino flux is free and the *hep* neutrino flux is fixed. (a) Solar global analysis. (b) Solar global + KamLAND. [From PDG 2005 review by K. Nakamura.]

$$\Delta m_{12}{}^2 = 8\text{x}10^{-5}\ \text{eV}^2 \Rightarrow m_2 \geq 9\text{x}10^{-3}\ \text{eV}$$

Whatever Happened to Hot Dark Matter?

In ~1980, when purely baryonic adiabatic fluctuations were ruled out by the improving upper limits on CMB anisotropies, theorists led by Zel'dovich turned to what we now call the HDM scenario, with light neutrinos making up most of the dark matter. However, in this scheme the fluctuations on small scales are damped by relativistic motion ("free streaming") of the neutrinos until T becomes less than m_ν, which occurs when the mass entering the horizon is about 10^{15} solar masses, the supercluster mass scale. Thus superclusters would form first, and galaxies later by fragmentation. This predicted a galaxy distribution that would be much more inhomogeneous than observed.



HDM Observed Galaxy Distribution CDM

Simon White, in *Inner Space/Outer Space* (1986)

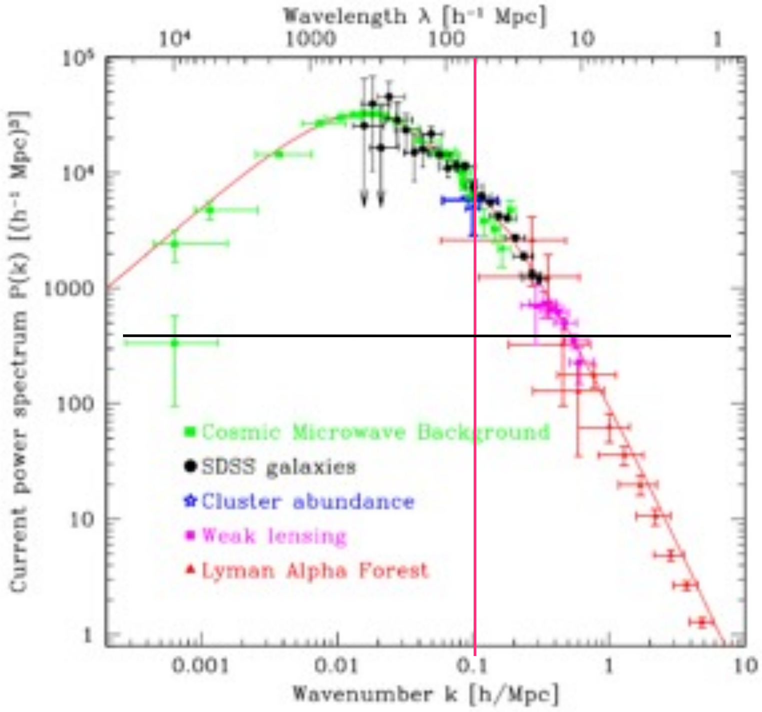
Whatever Happened to Hot Dark Matter?

Since 1984, the most successful structure formation scenarios have been those in which most of the matter is CDM. With the COBE CMB data in 1992, two CDM variants appeared to be viable: ΛCDM with $\Omega_m \approx 0.3$, and Ω_m=Cold+Hot DM with $\Omega_\nu \approx 0.2$ (Holtzman & Primack 1992, Wright et al. (COBE) 1992). Both cosmologies predicted a distribution of nearby galaxies in excellent agreement with observations.

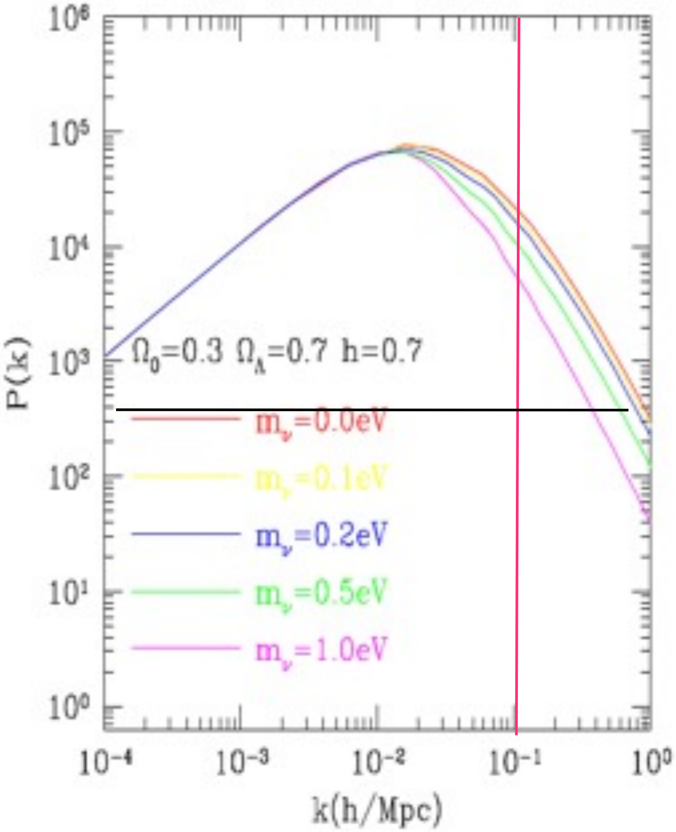
However, a potential problem with CHDM was that, like all $\Omega_m=1$ theories, it predicted rather late structure formation. By 1998, the evidence of early galaxy and cluster formation, the SN1a data showing that the expansion rate of the universe has been increasing, and the increasing evidence that $\Omega_m \approx 0.3$ had favored ΛCDM and doomed CHDM.

Now we also know from neutrino oscillations that neutrinos have mass. The upper limit is $\Sigma\, m_\nu < 1.3$ eV from CMB alone and $\Sigma\, m_\nu < 0.61$ eV from CMB + BAO + SN1a (Komatsu et al. 2008). There is a stronger but somewhat controversial constraint $\Sigma\, m_\nu < 0.17$ eV including Lyα forest data (Seljak et al. 2006).

Effect of Neutrino Mass on Predicted Power Spectrum P(k)



SDSS P(k) Tegmark+05

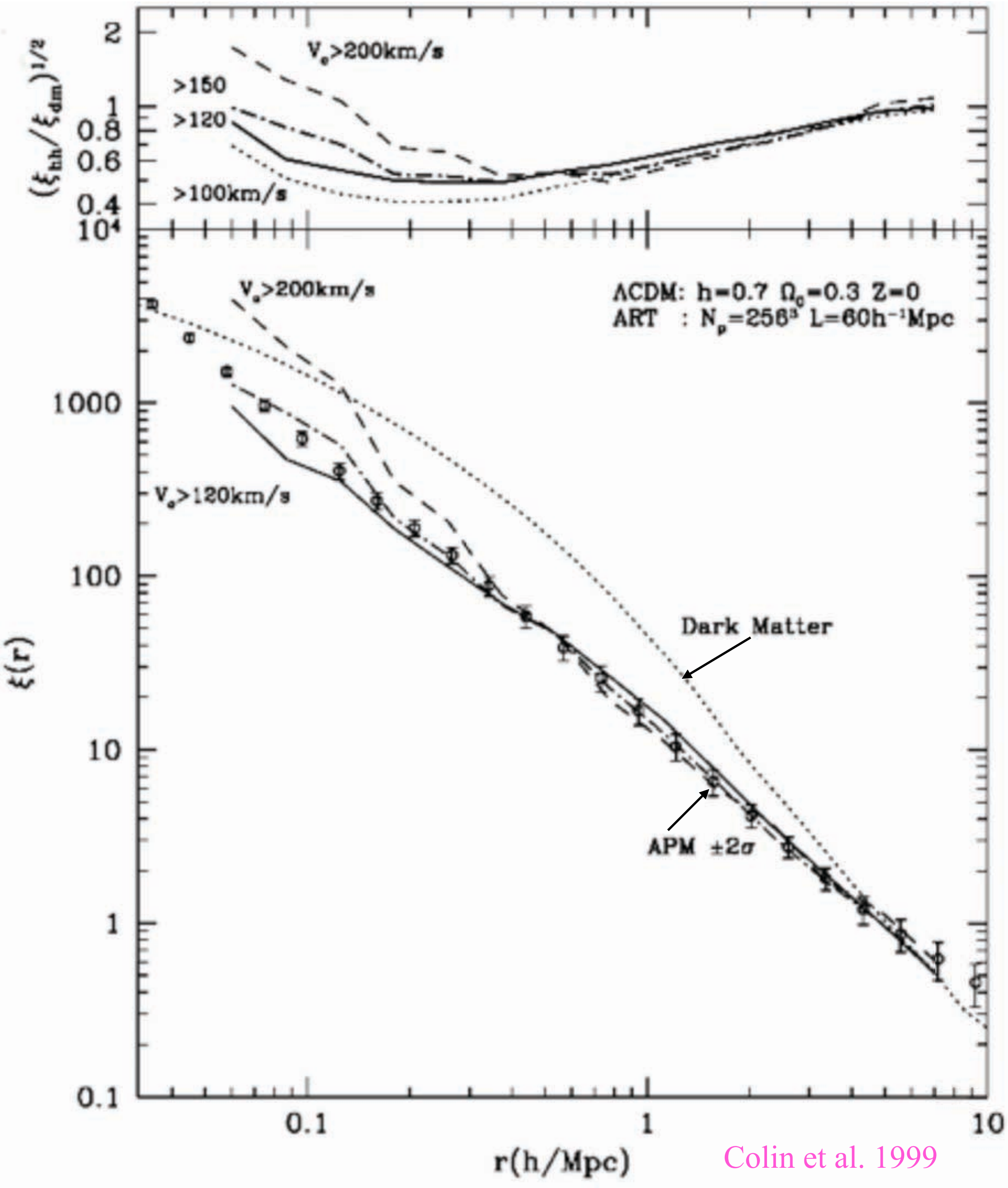


P(k) for LCDM with degenerate neutrino masses totaling 1.0 eV or less.

Masataka Fukugita, Massive Neutrinos in Cosmology
Plenary talk given at NuFact05, Frascati, 21-26 June 2005, **hep-ph/0511068**

ΛCDM Scale-Dependent Anti-Biasing

The dark matter correlation function ξ_{mm} for ΛCDM is ~$3\times\xi_{gg}$ at 1 Mpc. This disagreement between ξ_{mm} and ξ_{gg} was pointed out by Klypin, Primack, & Holtzman 1996. When simulations could resolve galaxy halos, it turned out that this needed "anti-biasing" arises naturally. This occurs because of destruction of halos in dense regions caused by merging and tidal disruption.



Colin et al. 1999