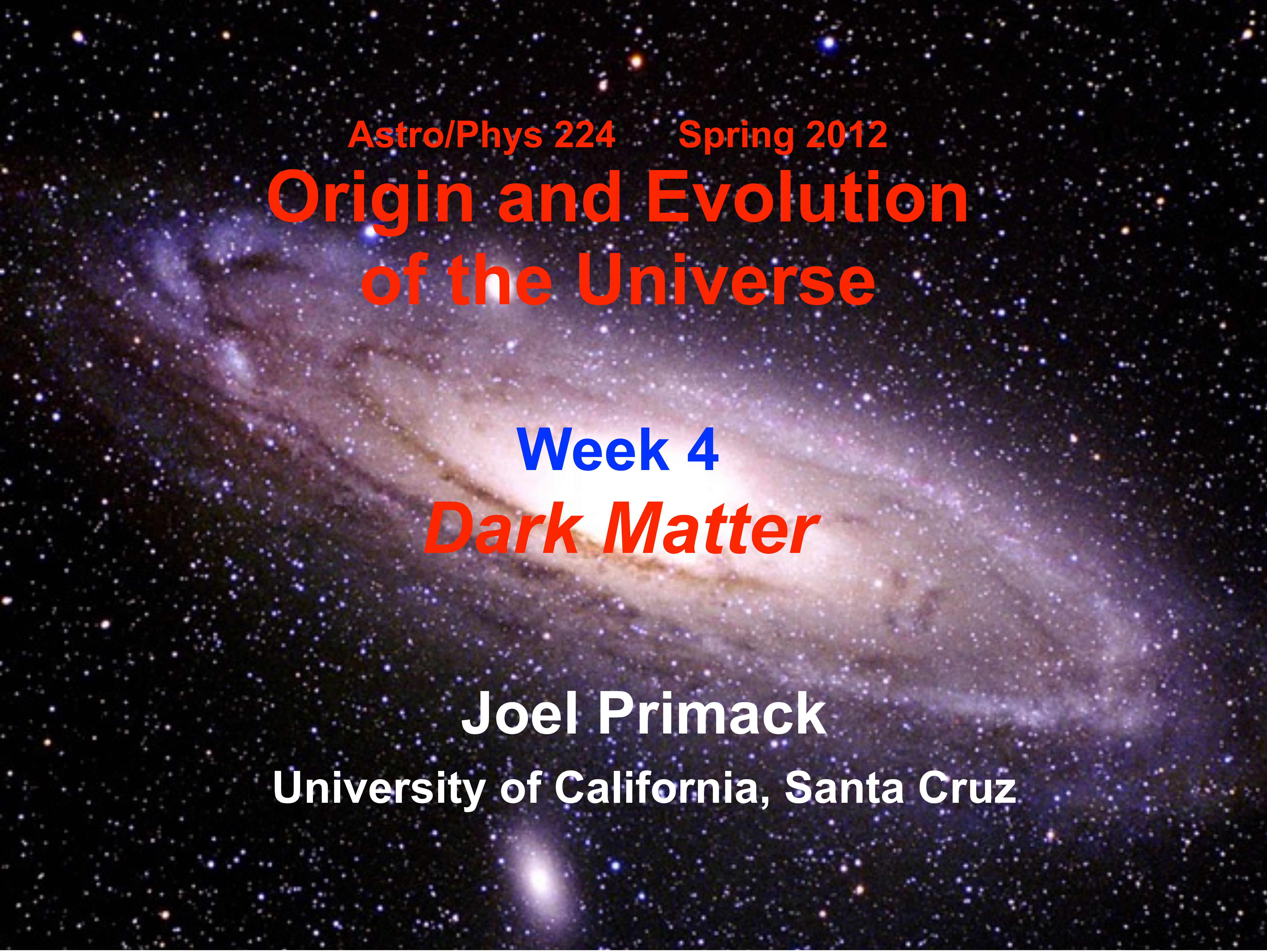


Astro/Phys 224 Spring 2012

Origin and Evolution of the Universe

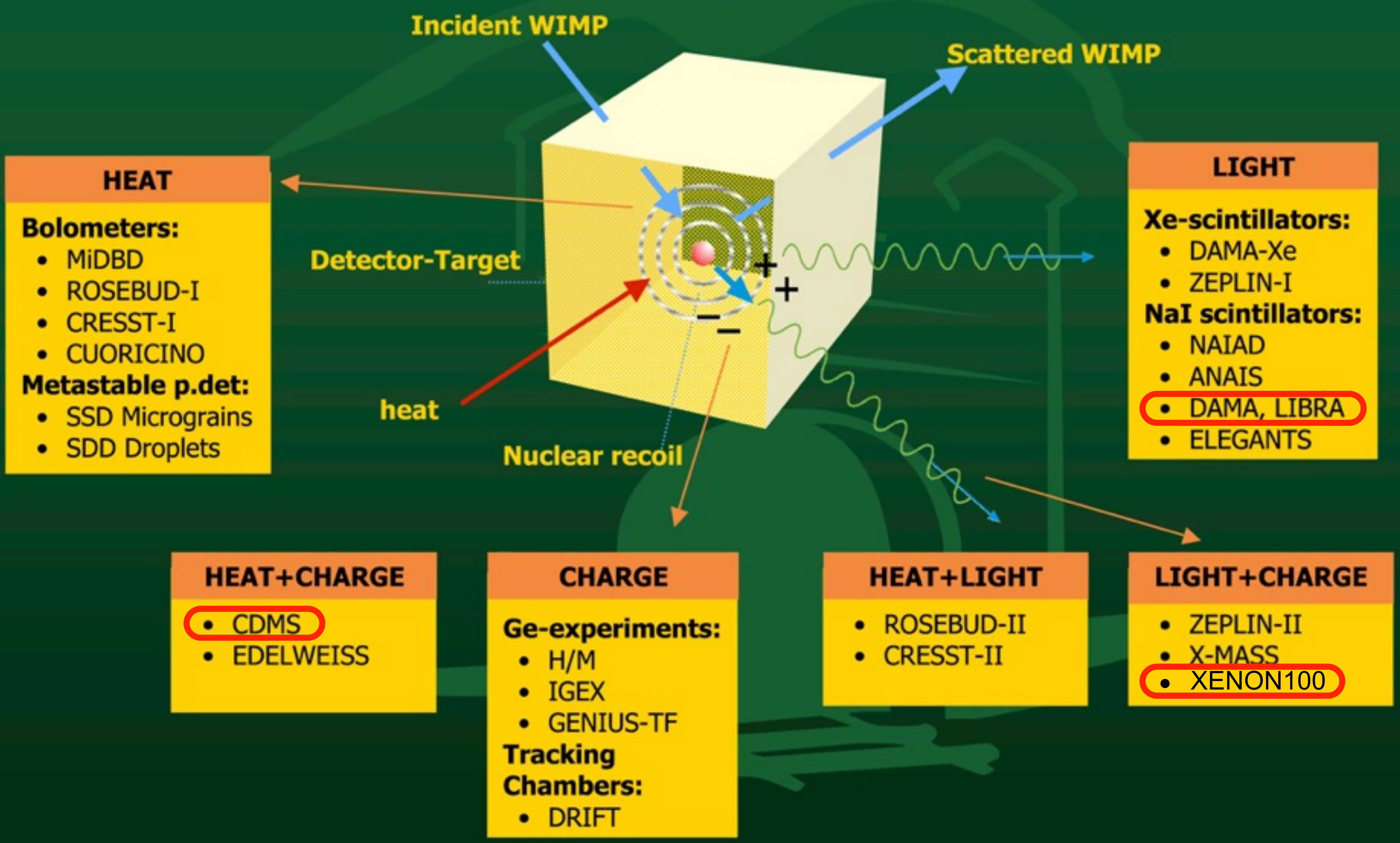
Week 4

Dark Matter

Joel Primack

University of California, Santa Cruz

Direct Detection Methods



CDMS - Cryogenic DM Search

Berkeley-Stanford-led experiment has been at the forefront

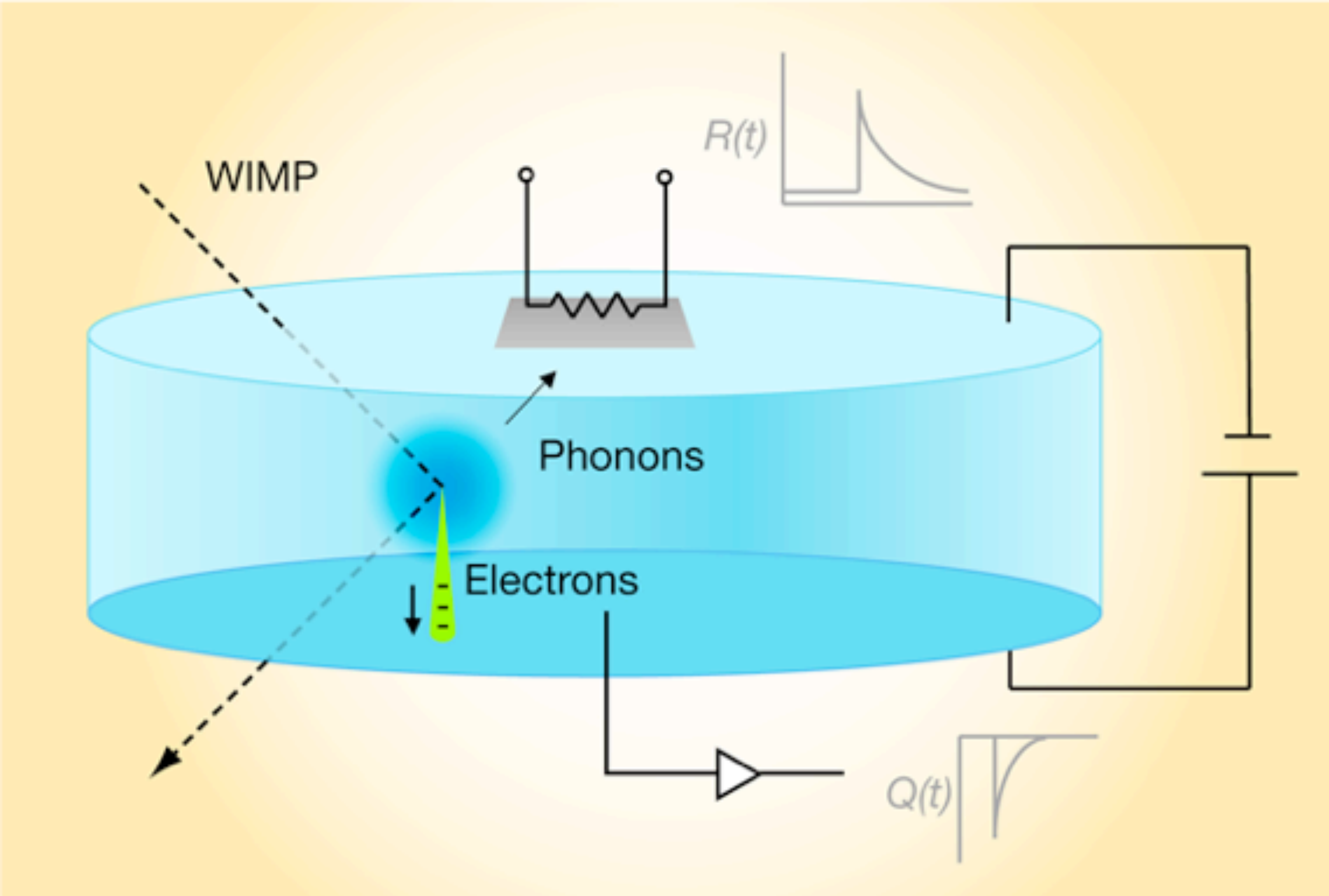
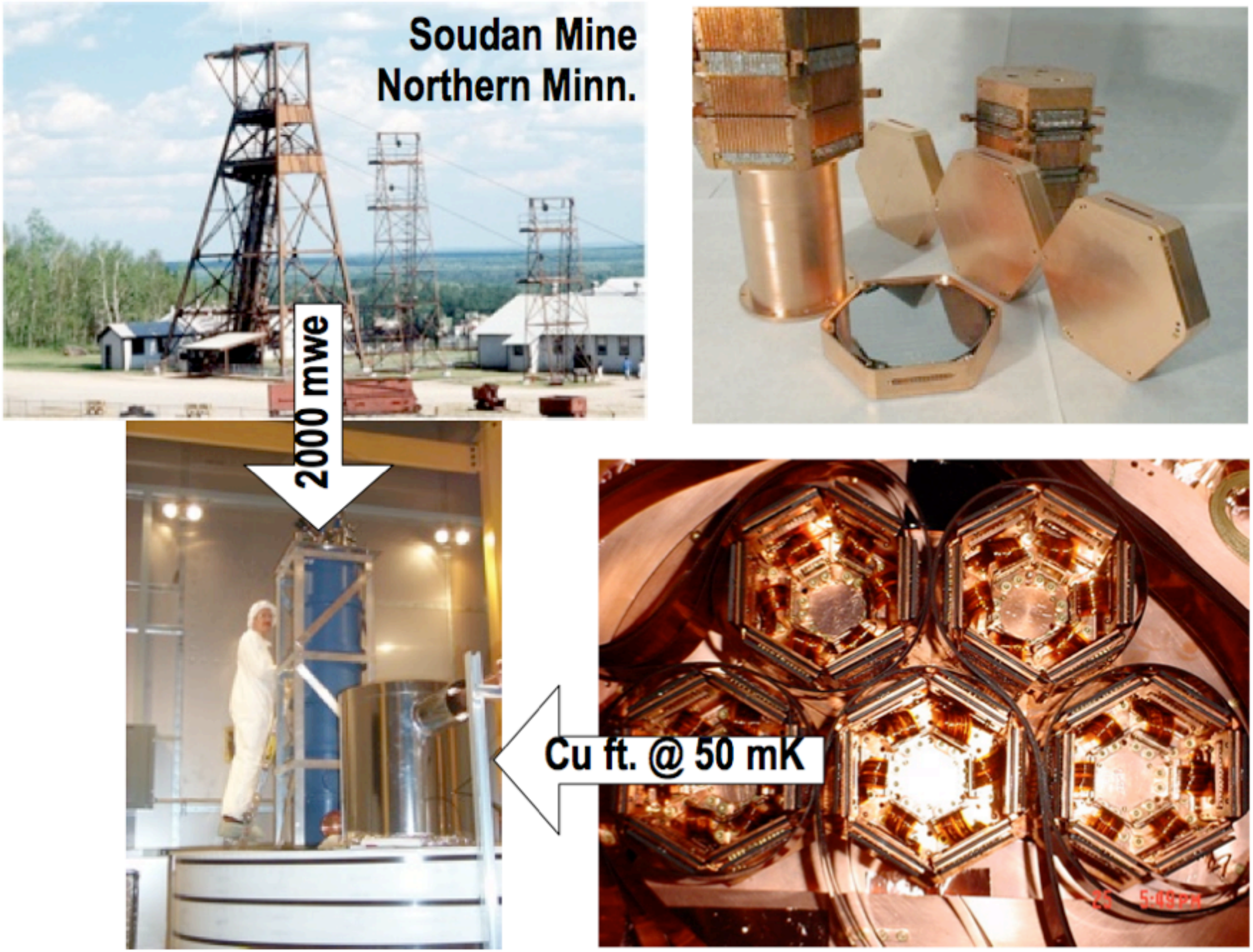


Figure from: Perspective by Karl van Bibber http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.011301 on Z. Ahmed et al. CDMS Collaboration, “Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory,” 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-II shielded underground detector array



From CDMS II to SuperCDMS and GEODM

CDMS II

⌀7.5cm x 1cm ZIP — 16 detectors = 4 kg

0.25 kg/detector — 2 yr, 1700 kg-d

SuperCDMS Soudan (G1)

⌀7.5cm x 2.5cm iZIP — 15 detectors = 10 kg*

0.64 kg/detector — 2 yr, 4000 kg-d

*iZIP has 2x larger fiducial efficiency than CDMS II ZIP

SuperCDMS SNOLAB (G2)

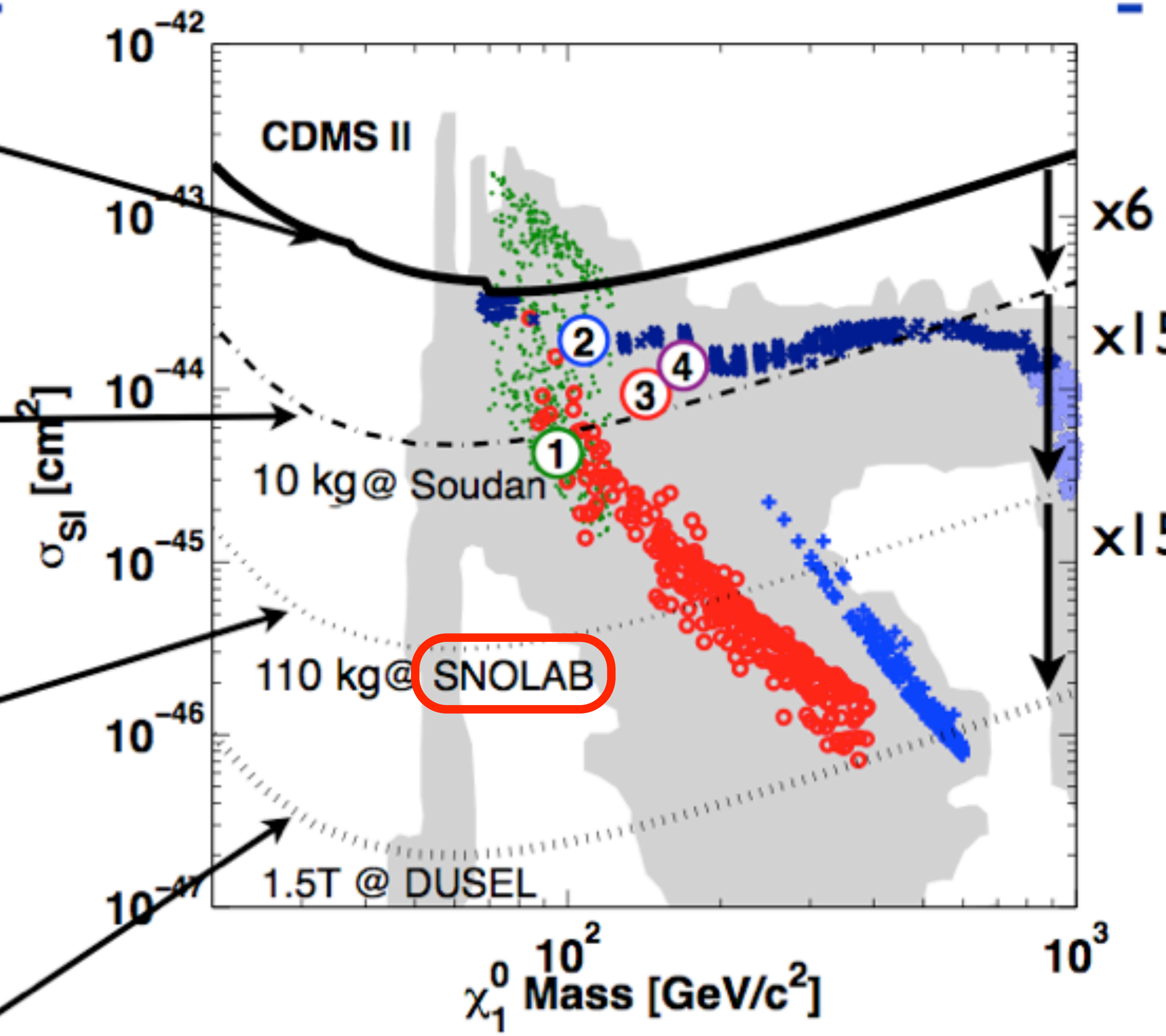
⌀10cm x 3.3cm iZIP — 72 detectors = 110 kg

1.5 kg/detector — 3 yr = 100,000 kg-d

GEODM (G3)

⌀15cm x 5cm iZIP — 300 detectors = 1.5 T

5.1 kg/detector — 3 yr, 1.5 M kg-d



Staged three-prong program to explore MSSM or study a signal:

- decreased backgrounds
- improved background rejection
- increase in mass/detector and decrease in cost/detector

< 1 event misid'd bgnd at each stage

SuperCDMS Future

Slide reformatted from Sunil Golwala

- SuperCDMS Soudan (G1)
  - 15 iZIP detectors being commissioned, science running to begin soon
  - 2 yrs, ~4000 kg-d raw exposure expected
  - sensitivity will be set by residual radiogenic neutron background:
    - 5 x 10^{-45} cm^2 (0 events) to 8 x 10^{-45} cm^2 (expected bgnd)
- SuperCDMS SNOLAB (G2)
  - 2 SuperCDMS Soudan detectors with ^{210}Pb sources will establish rejection needed for SuperCDMS SNOLAB (~10^{-5})
  - R&D toward 10 cm x 3.3 cm detectors funded, actively pushing development of:
    - crystal quality demonstration from vendors with ionization-only tests
    - phonon sensor design
    - cryogenic electronics and hardware and 300K electronics
    - shielding/cryostat design incl. possible neutron veot
  - Will propose to 2012 NSF and DOE solicitations, hope for construction start FY14
- GEODM
  - Planning to continue in parallel “G3 long-term R&D” on 15-cm diameter crystals, multiplexed and alternate forms of phonon and ionization readout, shielding and cosmogenic neutron studies.

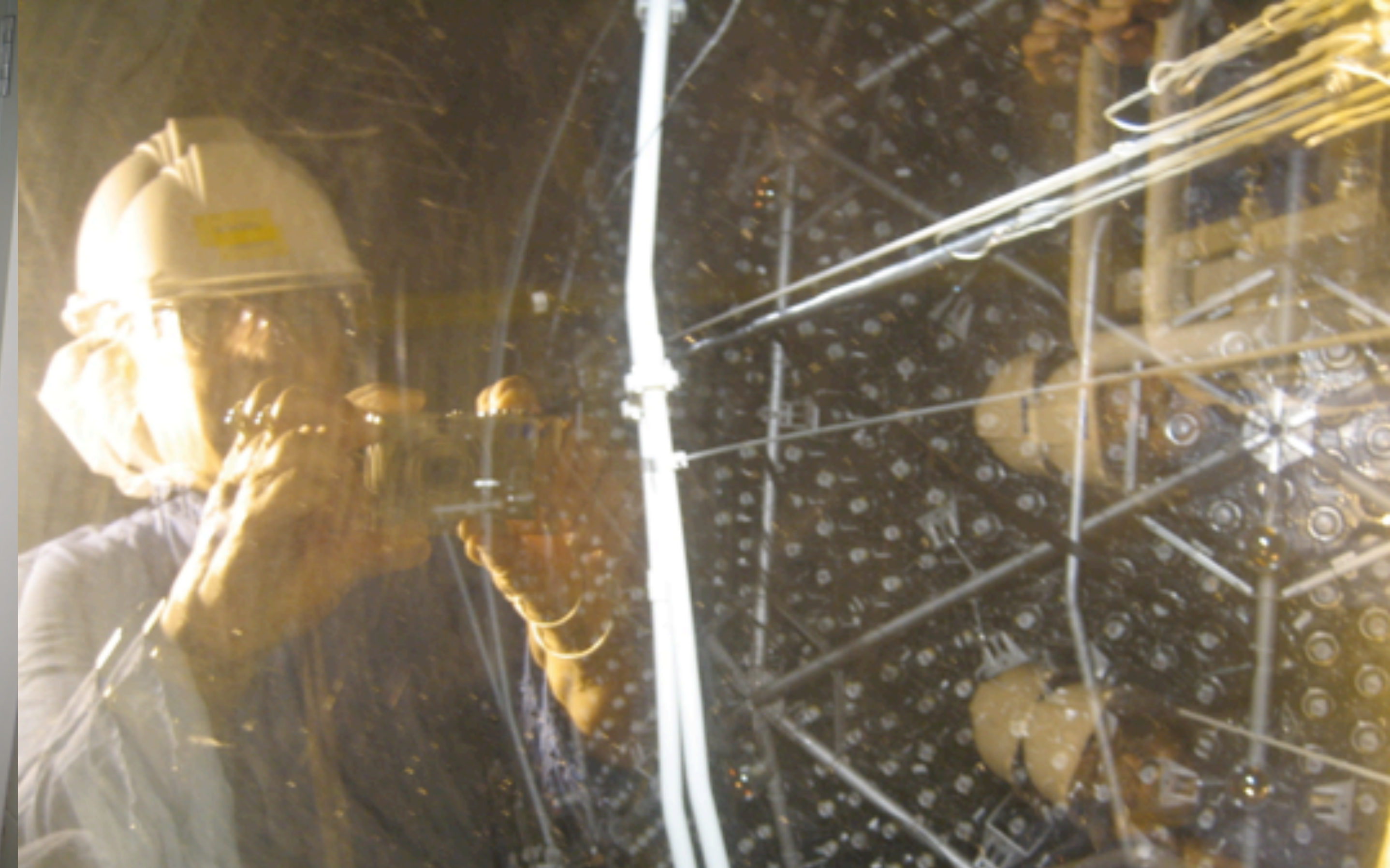

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE


4000 LBS MAX

AUG 9
SNO


USE AIR

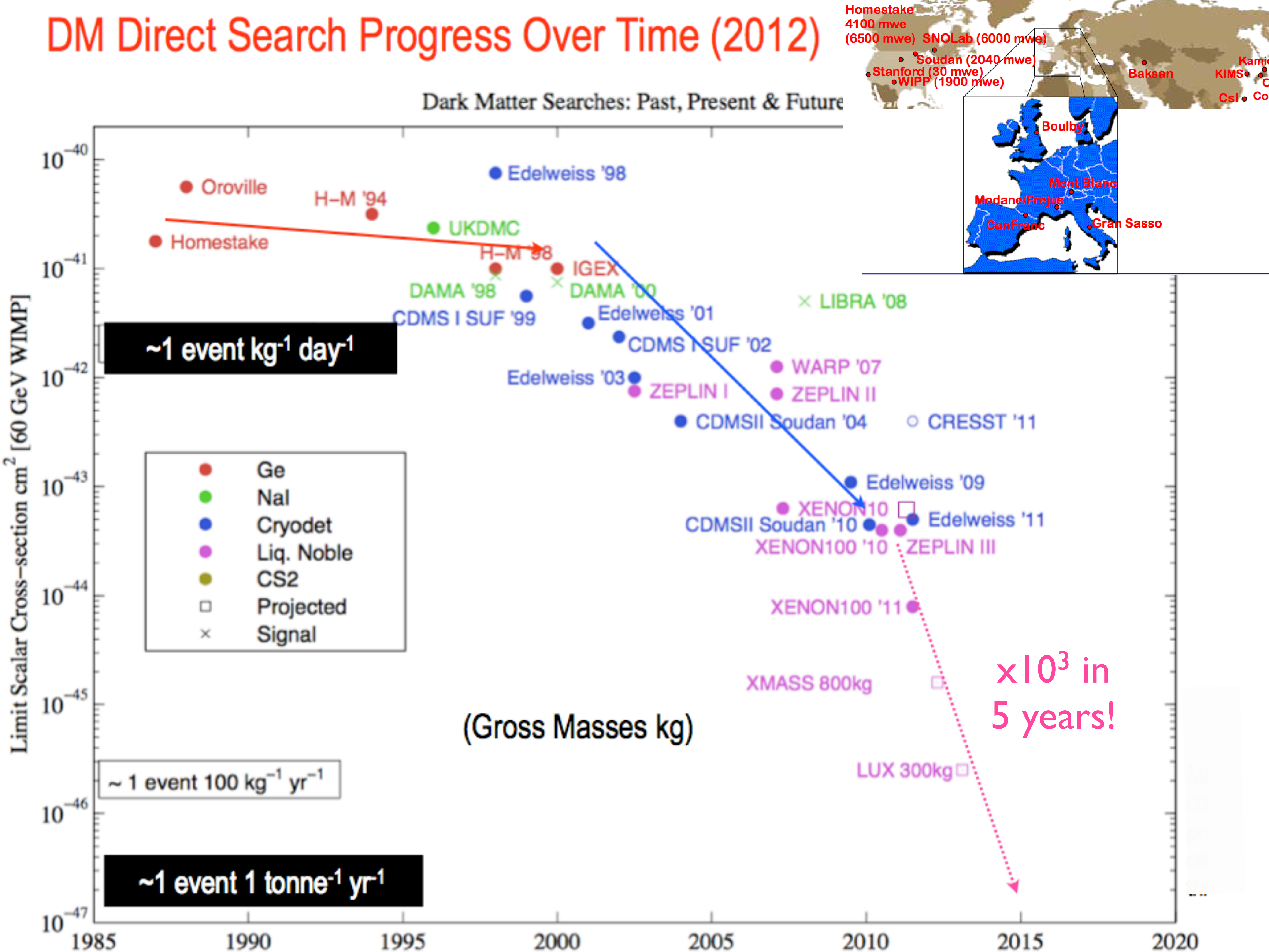

USE AIR SHOWER




SEARCH FOR DARK MATTER WITH
Picasso


Rushing
Frustration
Fatigue
Complacency
can cause or contribute to these critical errors...
Eyes not on Task
Mind not on Task
Line-of-Fire
Balance/Traction/Grip
...which increase the risk of injury.
I GUINNESS

DM Direct Search Progress Over Time (2012)

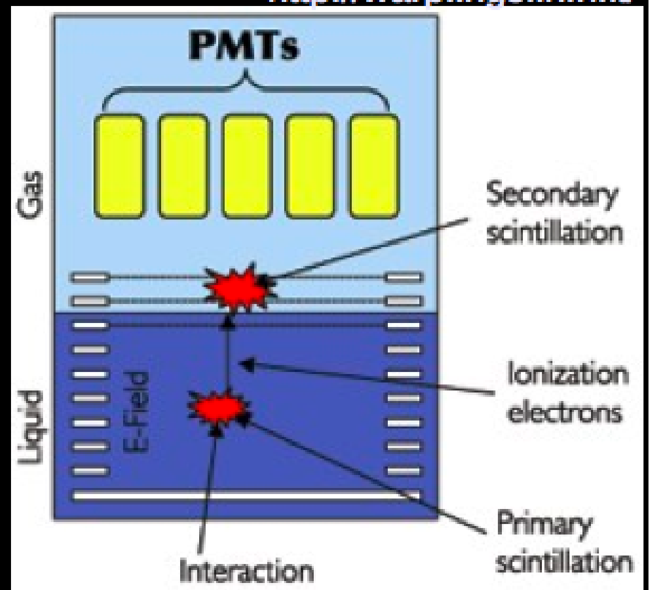


Thursday, April 26, 12

liquid noble detectors

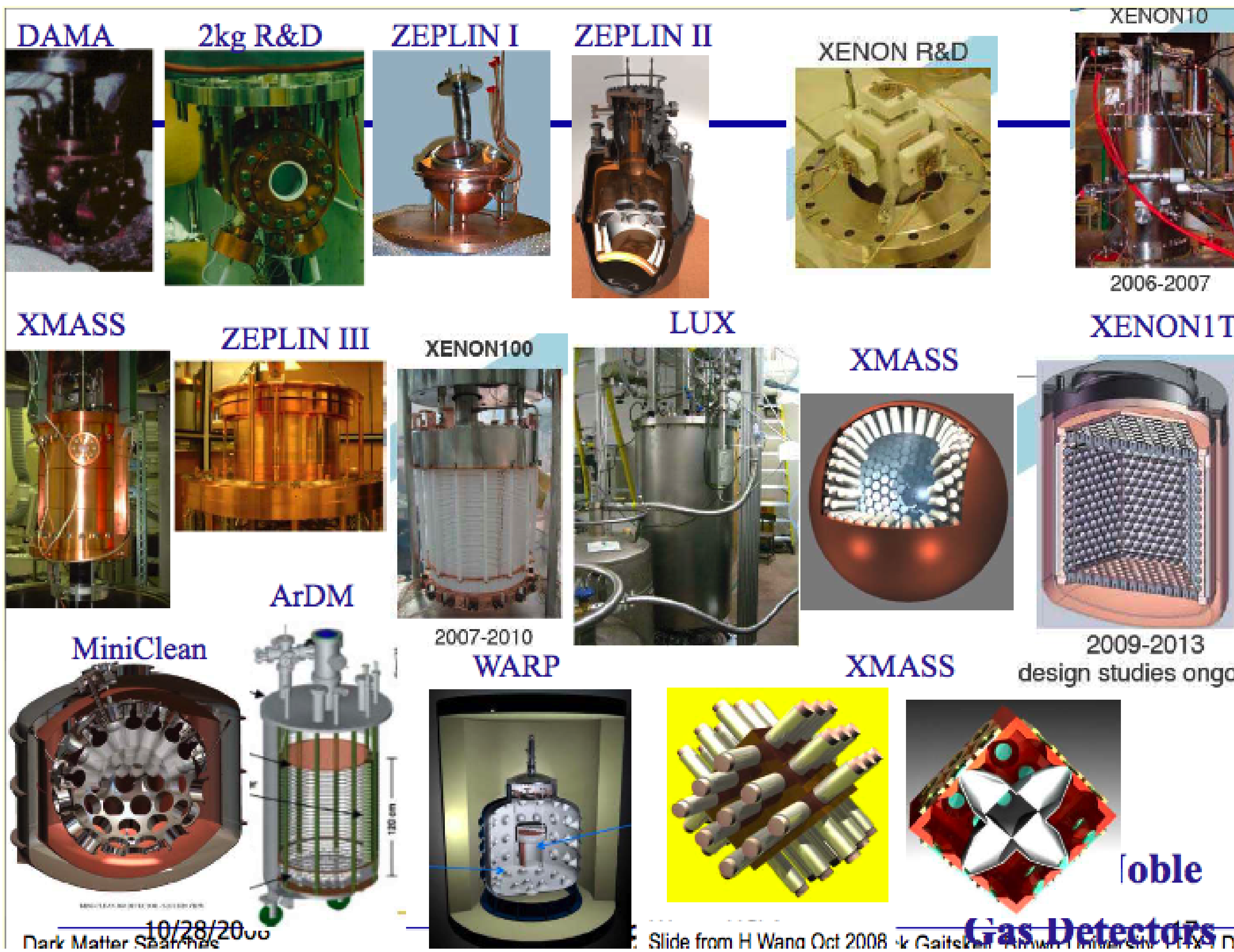
- WIMP-nucleus elastic scattering produces ionization electrons and photons.
- Photons (primary scintillation) are detected by PMTs
- Electrons are drifted (by E field) to gas region, where they are accelerated and collide with gas atoms, producing secondary scintillation
- Shape of primary and ratio of primary to secondary signal depend on ionizing particle (WIMP looks different from ex. beta decay electron)

http://warp.lngs.infn.it/



Noble Liquid Comparison (DM Detectors)

	Scintillation Light	Intrinsic Backgrounds	WIMP (100 GeV) Sensitivity vs Ge >10 keVr
Ne (A=20) $60/kg 100% even-even nucleus	85 nm Requires wavelength Shifter	Low BP (20K) - all impurities frozen out No radioactive isotopes	Scalar Coupling: Eth>50 keVr, 0.02x Axial Coupling: 0 (no odd isotope)
Ar (A=40) $2/kg (isotope separation >$1000/kg) ~100% even-even	125 nm Requires wavelength shifter	Nat Ar contains ~39Ar 1 Bq/kg == ~150 evts/keVee/kg/day at low energies. Requires isotope separation, low 39Ar source, or very good discrimination (~10^6 to match CDMS II)	Scalar Coupling: Eth>50 keVr, 0.10x Axial Coupling: 0 (no odd isotope)
Xe (A=131) $1000/kg 50% odd isotope	175 nm UV quartz PMT window	136Xe double beta decay is only long lived isotope - below pp solar neutrino signal. Relevant for DM search below ~10^{-47} cm^2. 85Kr can be removed by charcoal or distillation separation.	Scalar Coupling: Eth>5 keVr, 1.30x Axial Coupling: ~5x (model dep) Xe is 50% odd n isotope 129Xe, 131Xe



Future of Direct Detection

- Experiments under construction, to release results in 2009-2010
  - Target masses 10-300 kg
  - Expect 10-100x better reach than existing limits.
- Next Round, for results in 2011-2013
  - Target masses 1-3 tonne, 10^3 x better reach
  - Project cost $5-15M
- "Ultimate" Detectors, for results ~2014+
  - Target masses 3-50 tonne, 10^4 x better reach
  - Project cost $20-50M
- Labs with 1-20 tonne dm experiments on roadmap
  - Gran Sasso, Italy
  - Frejus, France
  - Canfranc, Spain
  - Kamioka, Japan
  - SNOLab, Canada
  - Sanford Lab/DUSEL (Homestake), US

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 $\gamma+\beta < 8\times10^{-4}$ /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: 7×10^{-46} cm^2 in 10 months

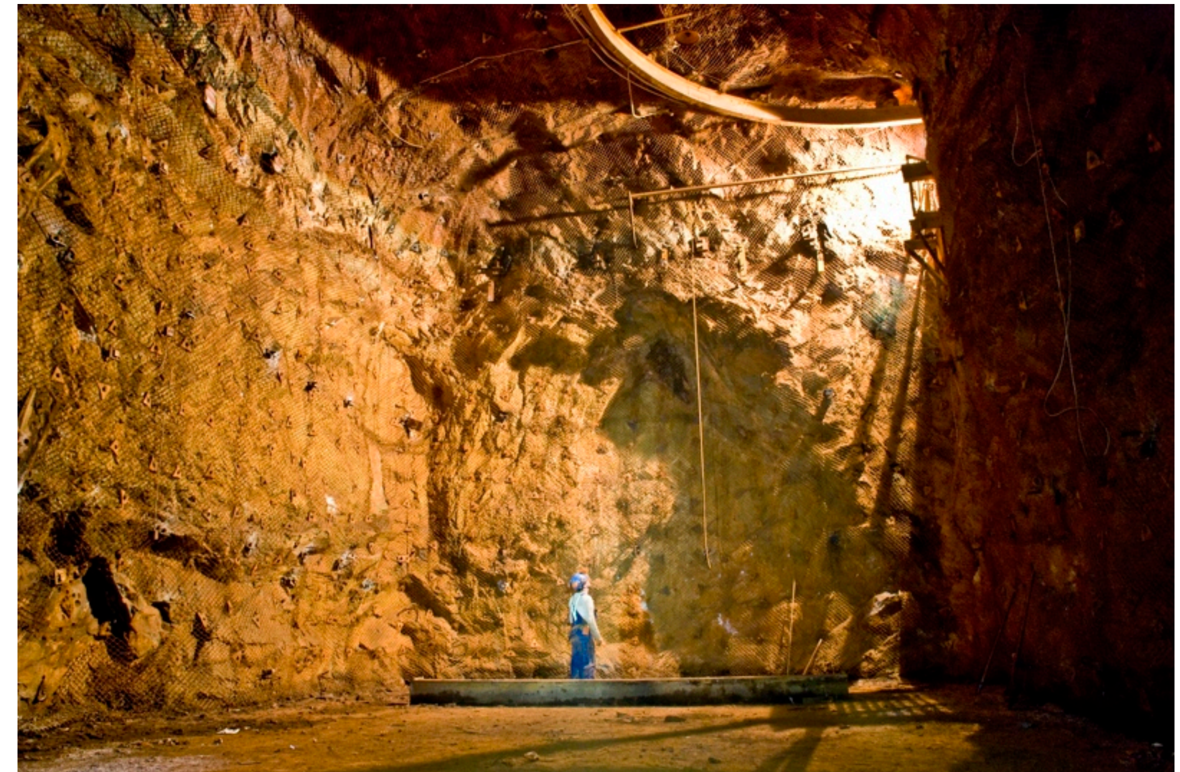
In DUSEL

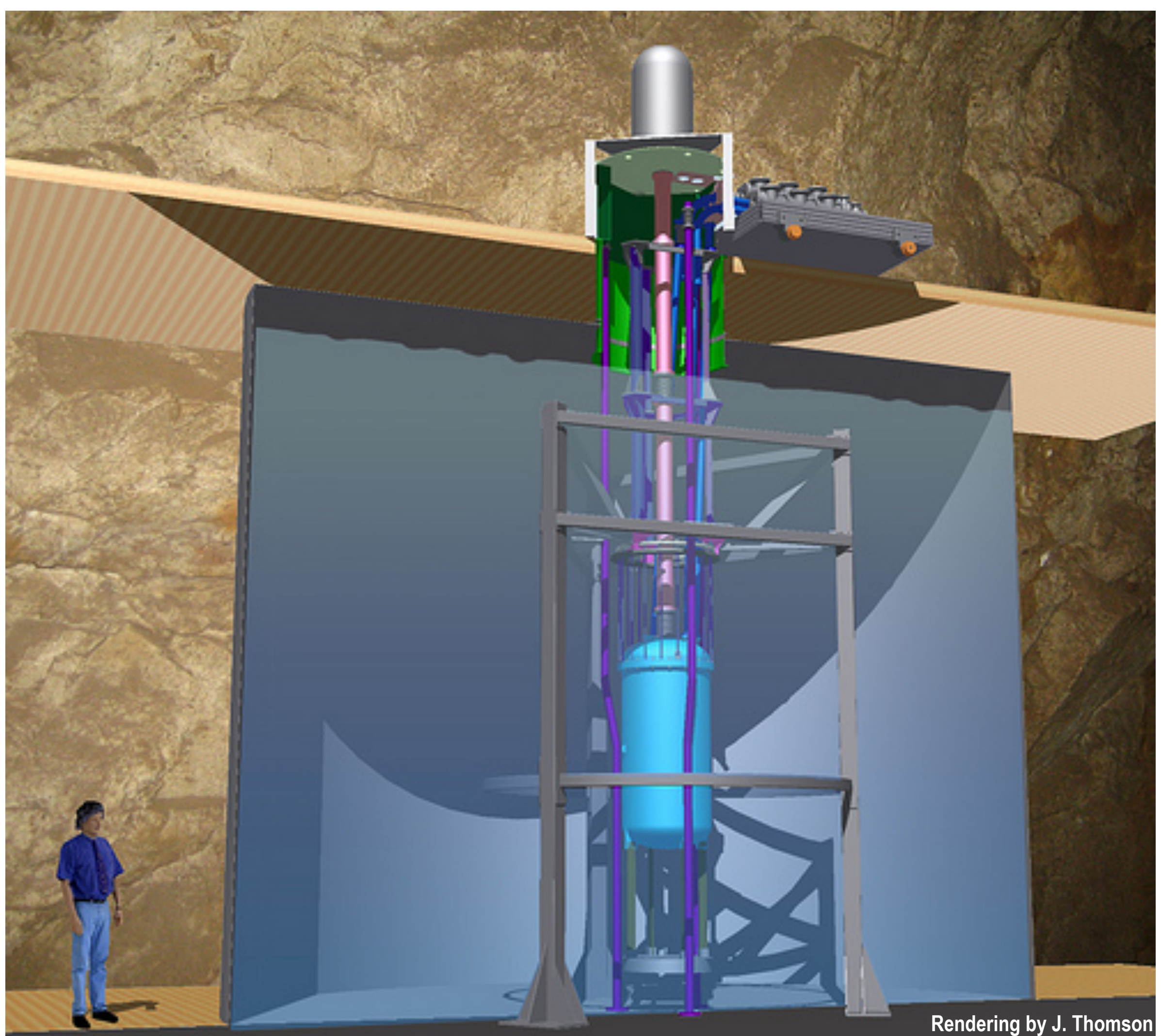
(Deep Underground Science and Engineering Laboratory)
Homestake Mine
Lead, South Dakota, USA
April 2012 - operation Sept 2012

www.luxdarkmatter.org

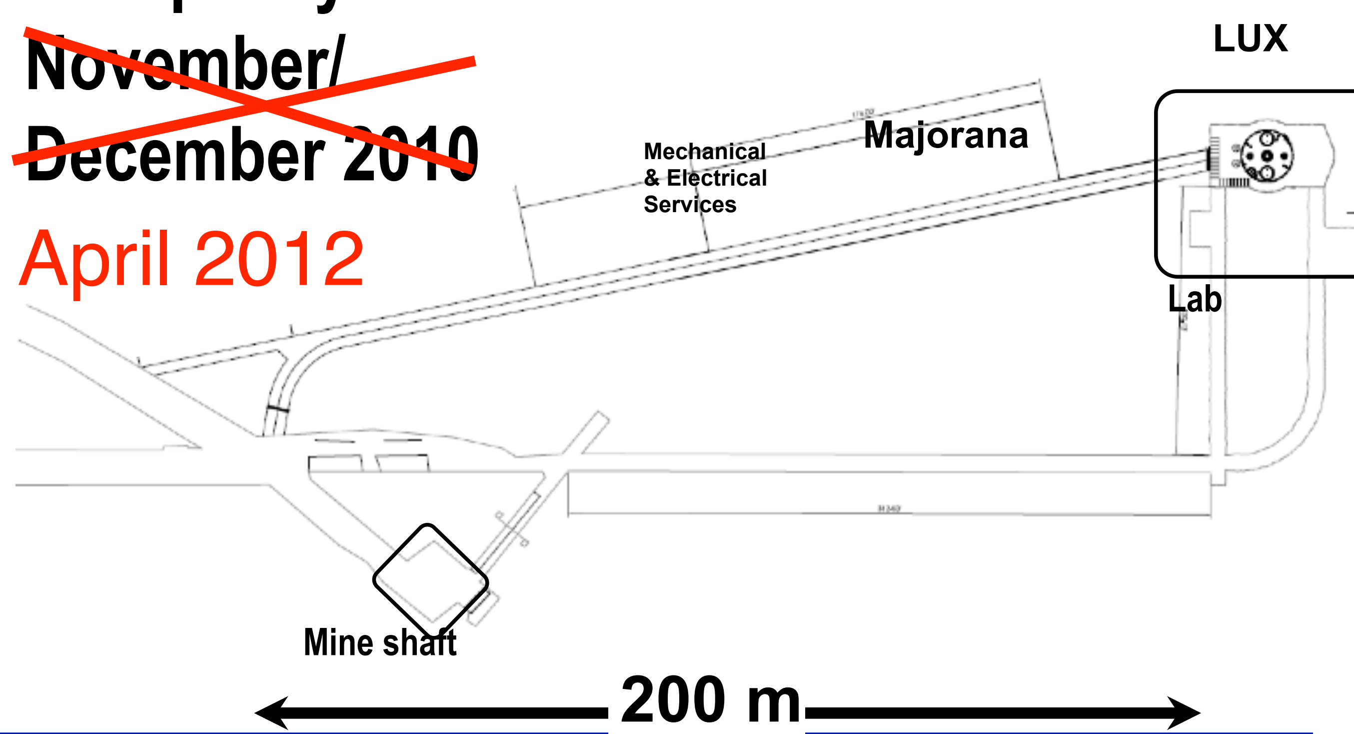
LUX in the Davis Laboratory at the Homestake Mine in South Dakota (4850L)

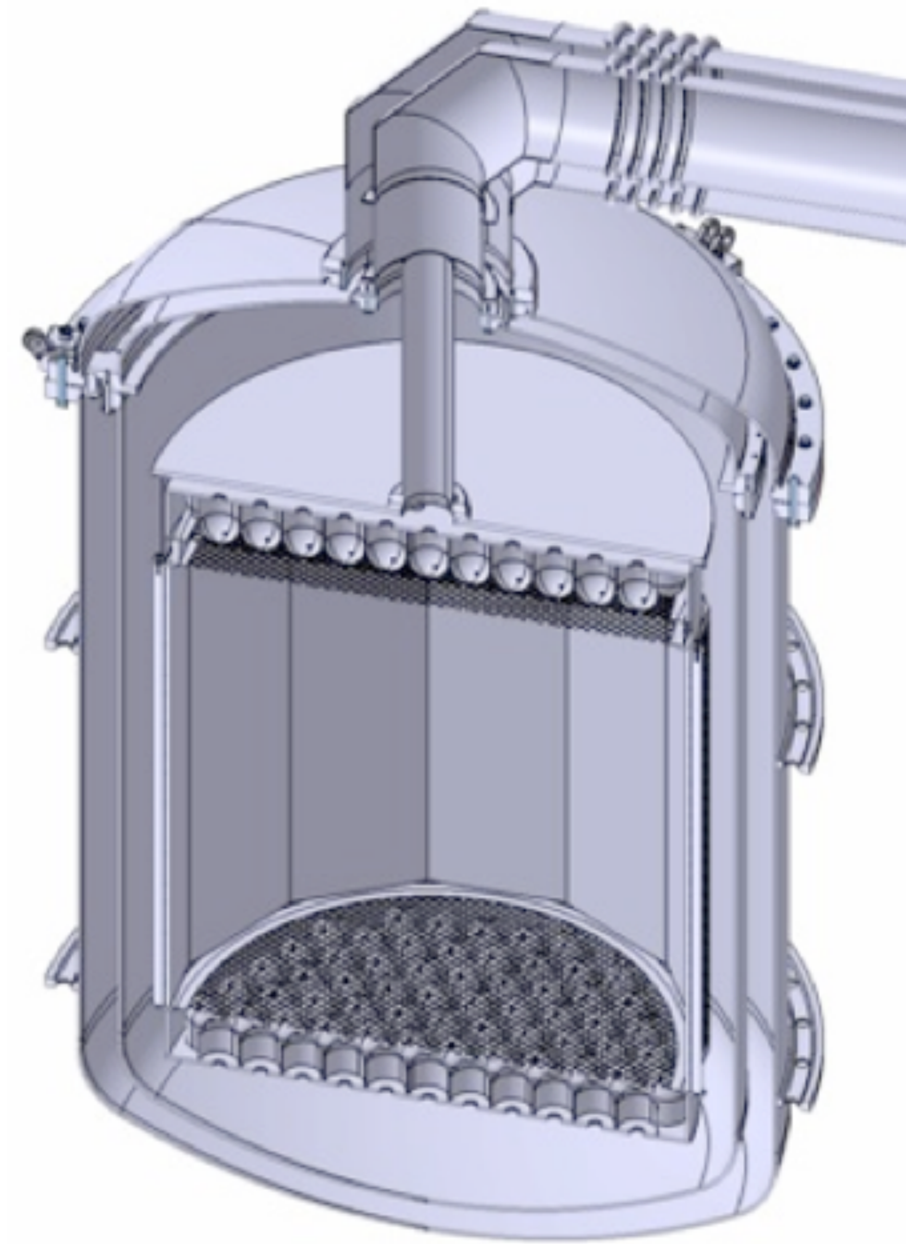
- Construction/excavation design completed
  - New 300’ access/safety tunnel being excavated
  - Shared with Majorana facility
- Two story, dedicated LUX 55’ x 30’ x 32’ facility being built now





- Beneficial occupancy: ~~November/December 2010~~ April 2012

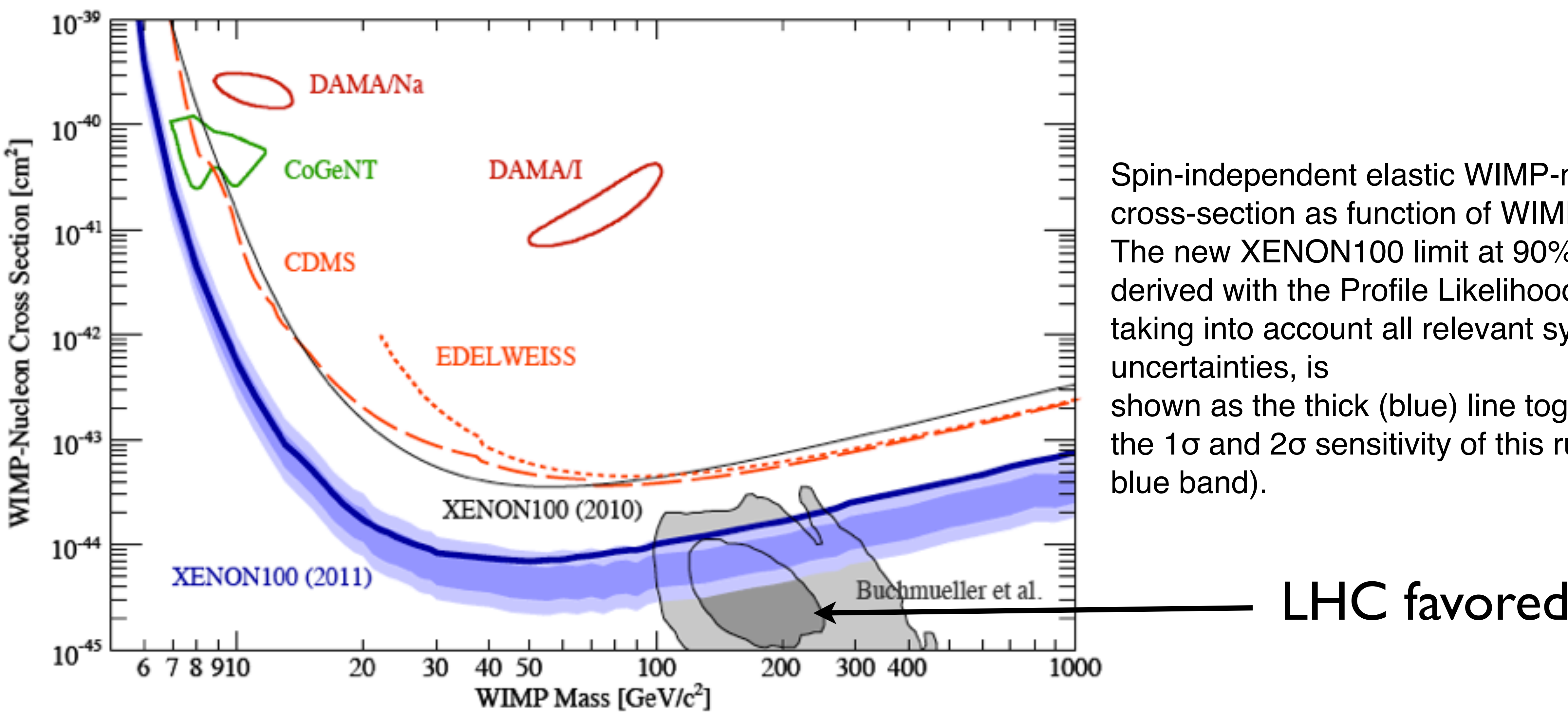


past (2005 - 2007)	current (2007-2012)	future (2012-2017)
		
XENON10	**XENON100**	**XENON1T**
Achieved (2007) $\sigma_{SI}=8.8 \times 10^{-44}$ cm^2	*Achieved (2011)* $\sigma_{SI}=7.0 \times 10^{-45}$ cm^2	Projected (2017) $\sigma_{SI} \sim 10^{-47}$ cm^2
Phys. Rev. Lett. **100**, 021303 (2008)	Projected (2012) $\sigma_{SI} \sim 2\times10^{-45}$ cm^2	
Phys. Rev. Lett. **101**, 091301 (2008		

Dark Matter Results from 100 Live Days of XENON100 Data

E. Aprile et al. 4/13/11

We present results from the direct search for dark matter with the XENON100 detector, installed underground at the Laboratori Nazionali del Gran Sasso of INFN, Italy. XENON100 is a two-phase time projection chamber with a 62 kg liquid xenon target. Interaction vertex reconstruction in three dimensions with millimeter precision allows to select only the innermost 48 kg as ultra-low background fiducial target. In 100.9 live days of data, acquired between January and June 2010, no evidence for dark matter is found. Three candidate events were observed in a pre-defined signal region with an expected background of (1.8 ± 0.6) events. This leads to the most stringent limit on dark matter interactions today, excluding spin-independent elastic WIMP-nucleon scattering cross-sections above 7.0×10^{-45} cm^2 for a WIMP mass of 50 GeV/c^2 at 90% confidence level.

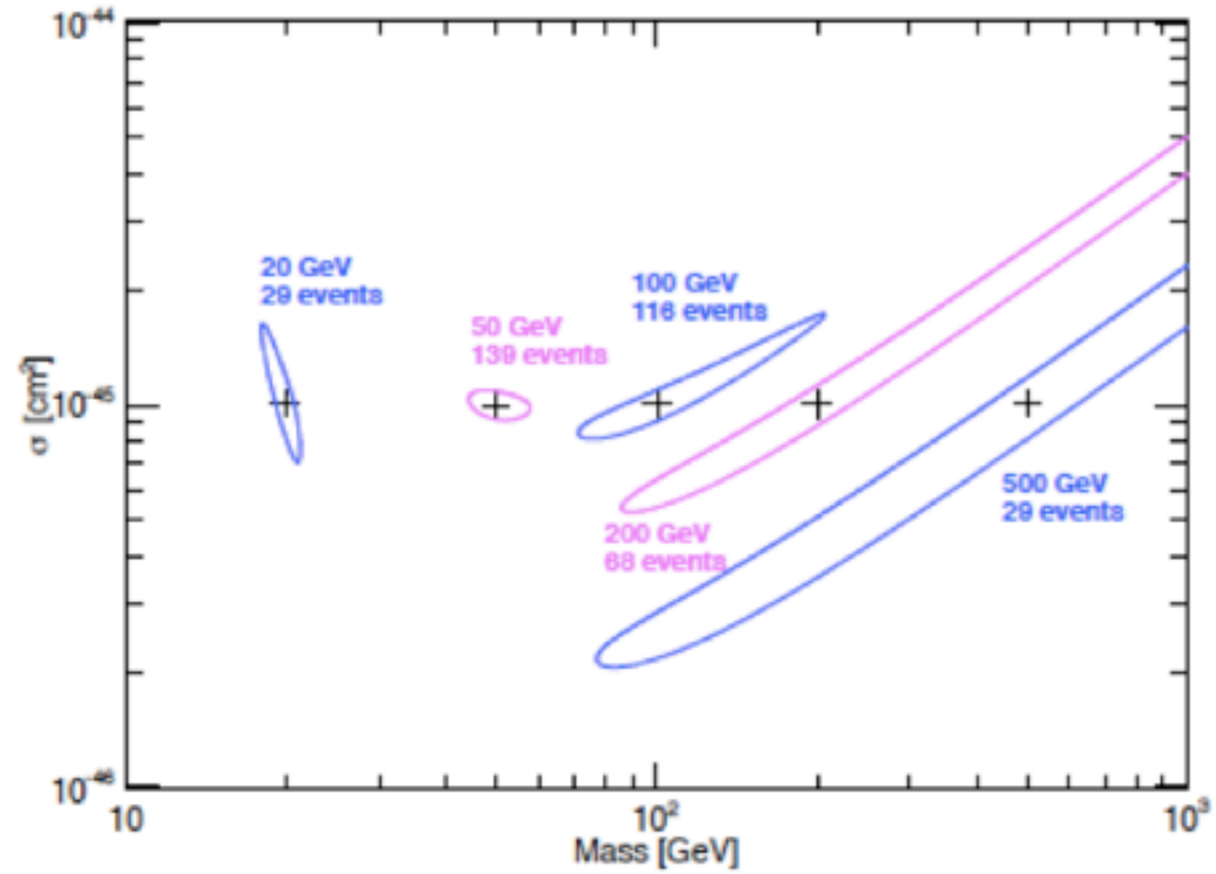


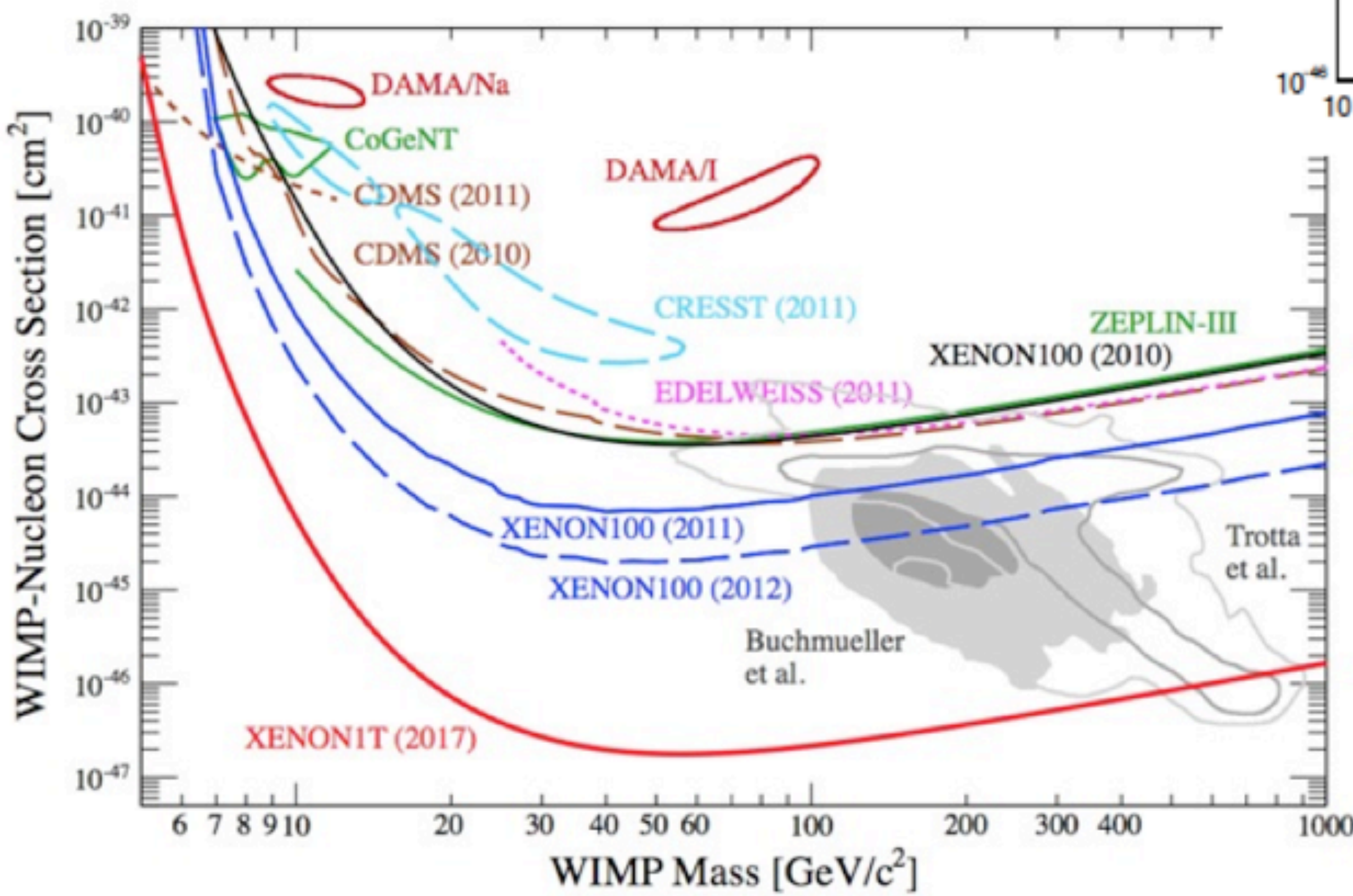
Spin-independent elastic WIMP-nucleon cross-section as function of WIMP mass. The new XENON100 limit at 90% CL, as derived with the Profile Likelihood method taking into account all relevant systematic uncertainties, is
shown as the thick (blue) line together with the 1σ and 2σ sensitivity of this run (shaded blue band).

The XENON1T Science Case

a statistically significant WIMP signal after 2.2 ton-years of data

~100 events if cross section at 10^{-45} cm^2

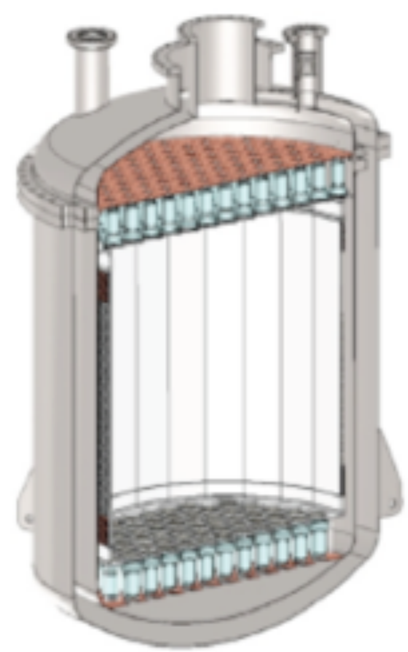




two orders of magnitude improvement in SI cross-section sensitivity w/r to XENON100

XENON1T: OVERVIEW

- Detector: 1m drift TPC with 2.2 ton LXe target
- Shield: ~10 m x 10 m Water Cherenkov Muon Veto
- Background: 0.01 mdru (100 lower than XENON100
- Location: approved by INFN for LNGS Hall B
- Capital Cost: ~11 M$ (50% US and 50% non-US)
- Status: Construction start in Fall 2012
- Science Run: projected to start in 2015
- Sensitivity: 2×10^{-47} cm^2 at 50 GeV with 2.2 ton-years



LNGS Underground Laboratory – Hall B

LNGS Underground Laboratory – Hall B

Dark Matter and Terascale Physics

V. Barger

The Gold Standard: mSUGRA

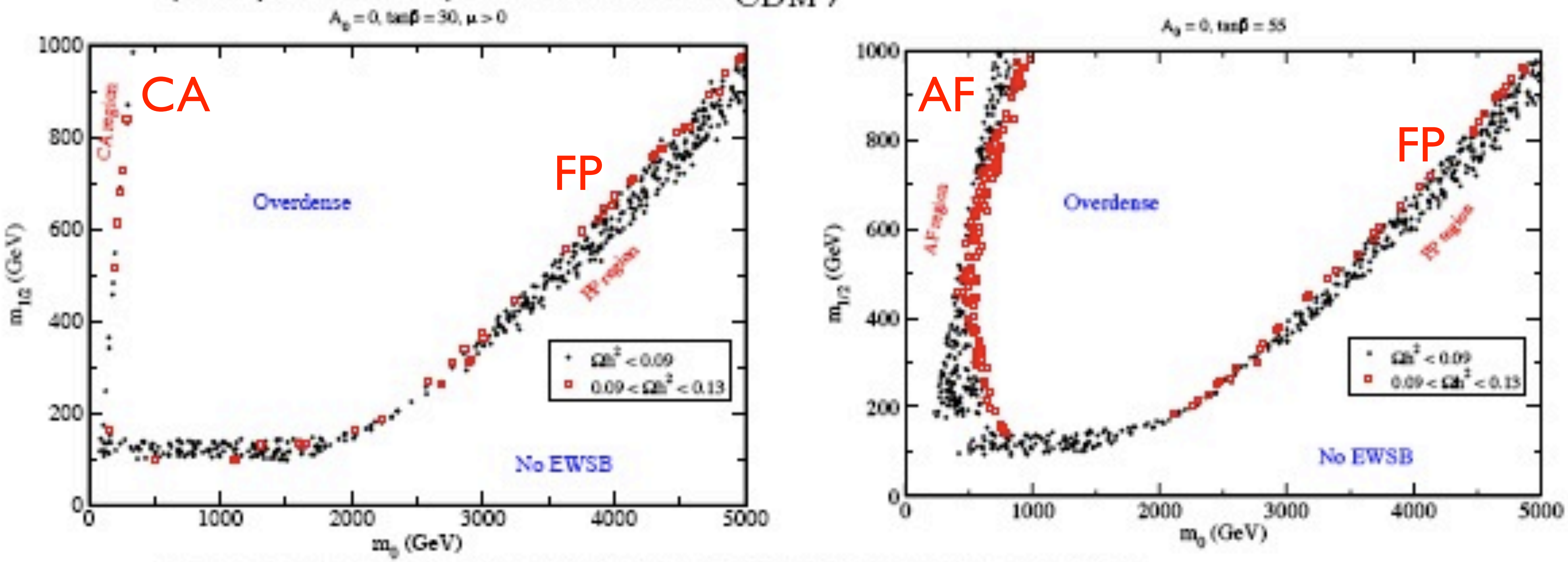
- SUSY stabilizes radiative corrections to the Higgs mass and realizes GUT unification of electroweak and strong couplings
- Weird quantum numbers of particles explained by 16 representation of SO(10)
- mSUGRA: SUSY broken by gravity
  - predictive--small number of parameters: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$
- 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 Ω_{CDM})



- Focus Point (FP) region: high mass scalar fermions

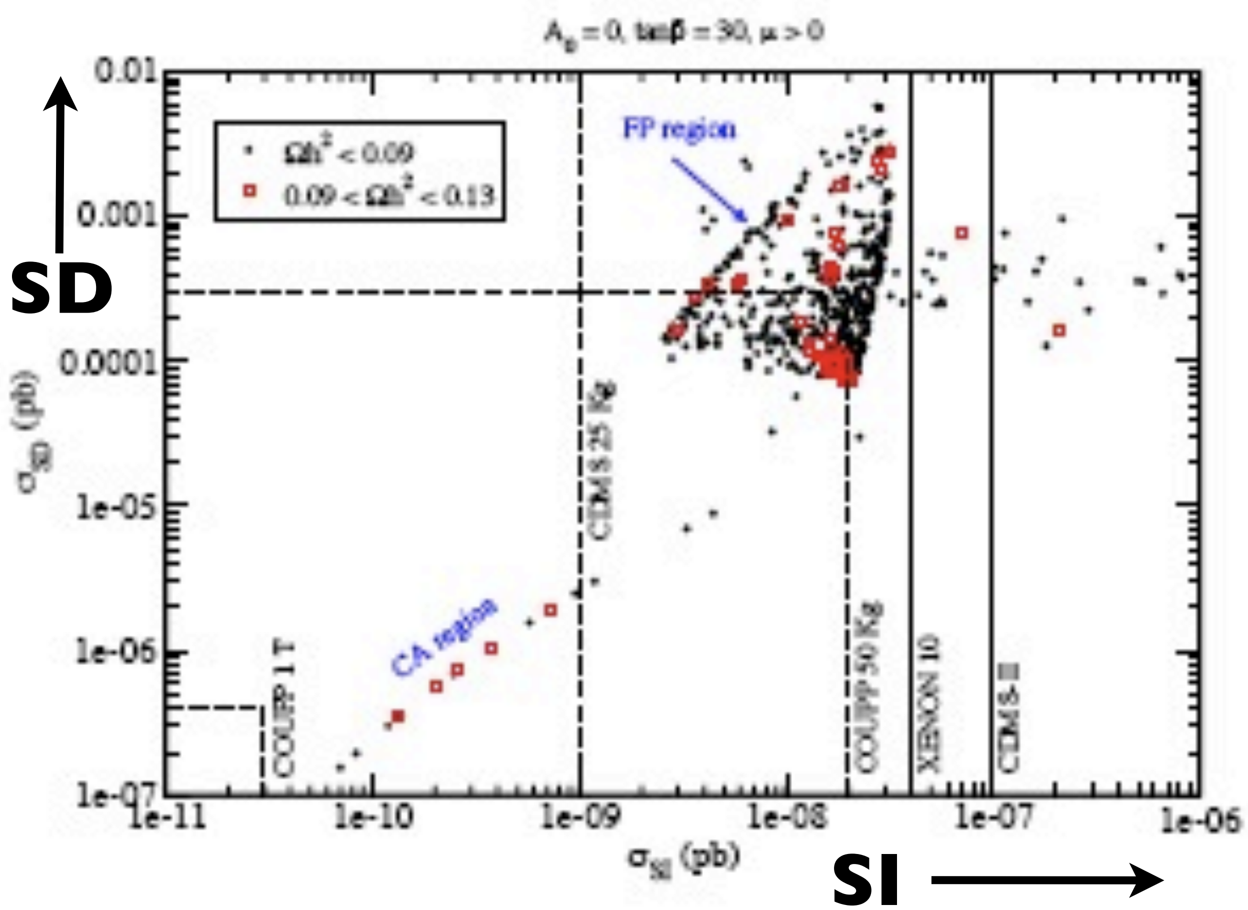
  Preferred by $b - \tau$ unification

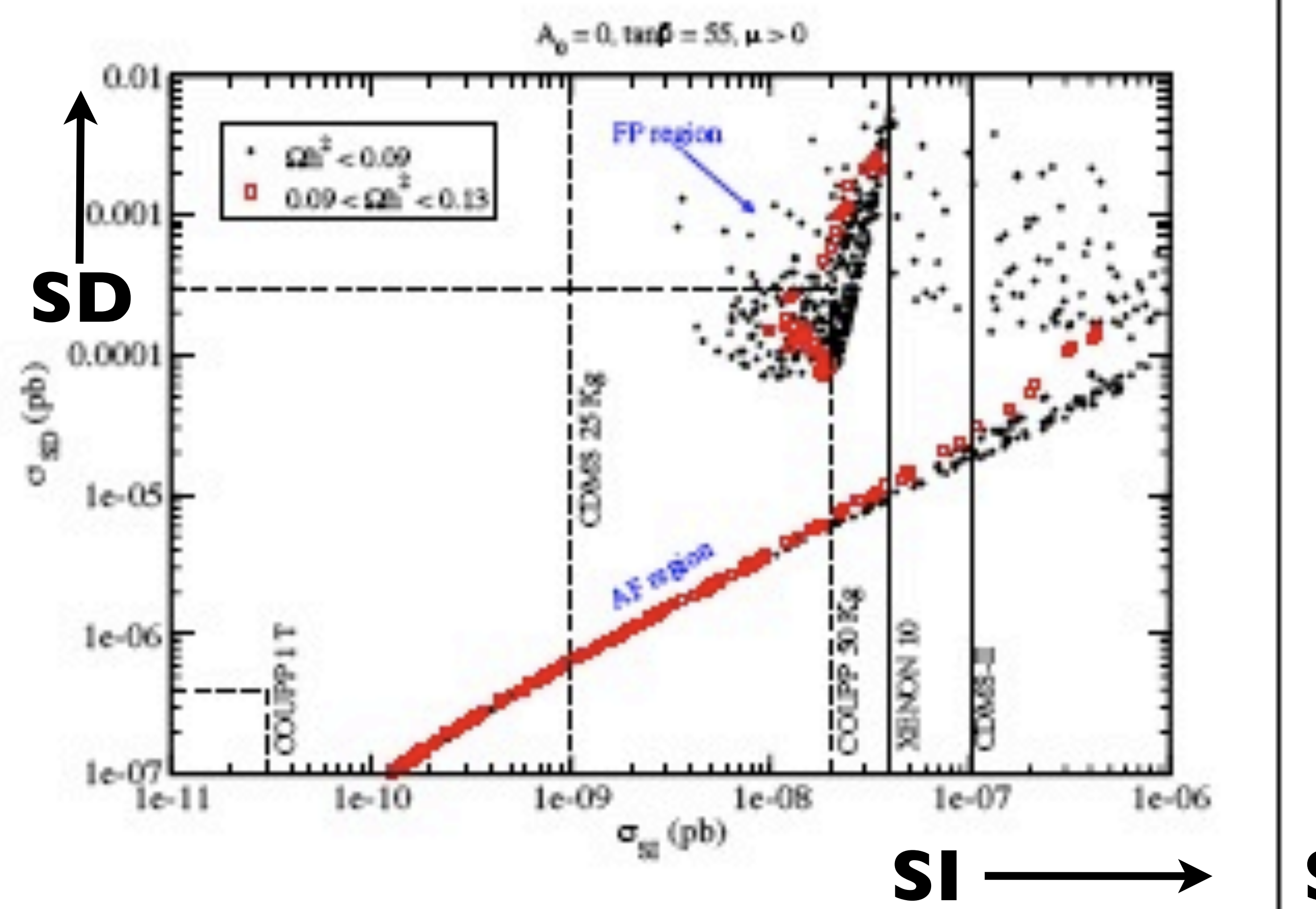
  Solves SUSY FCNC and CP-violating problems

- 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

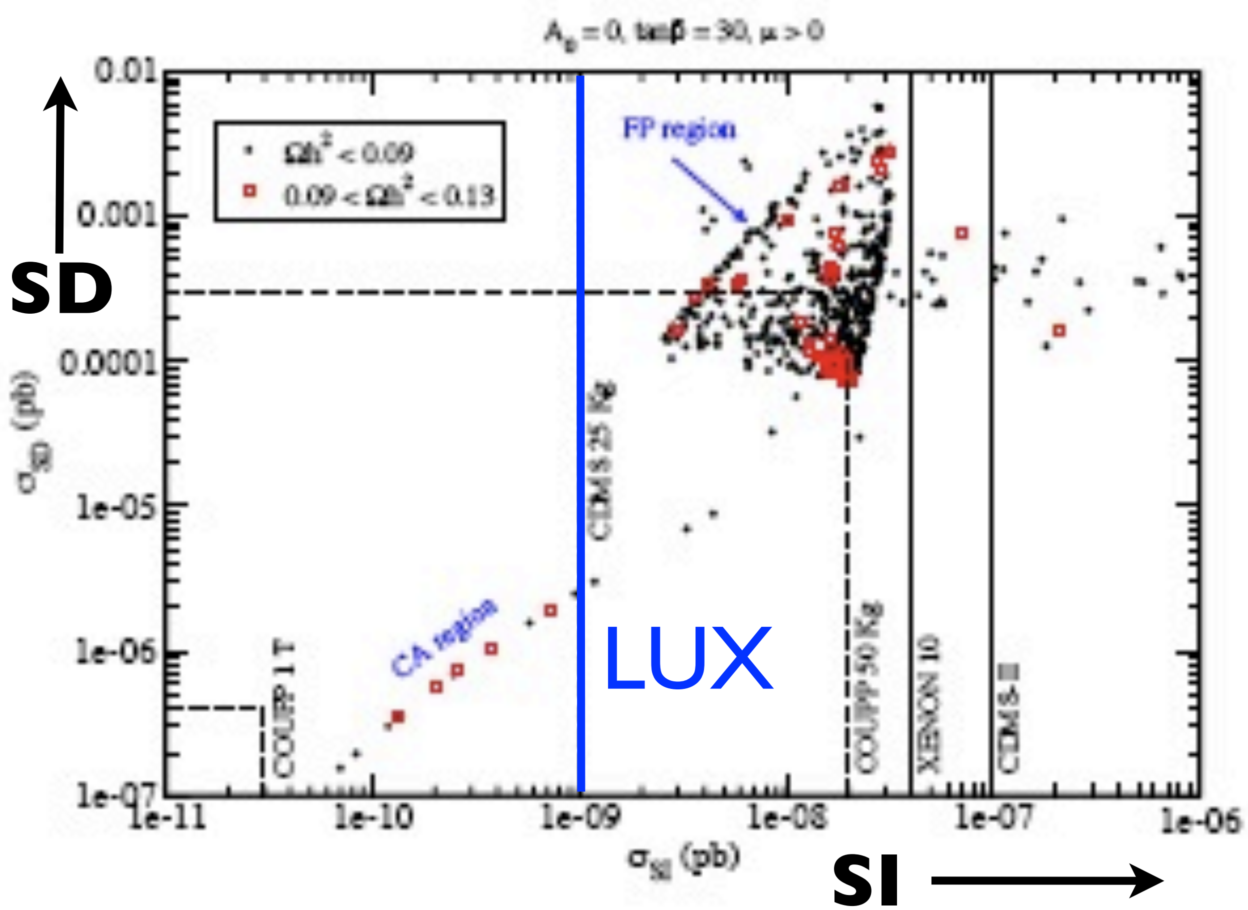


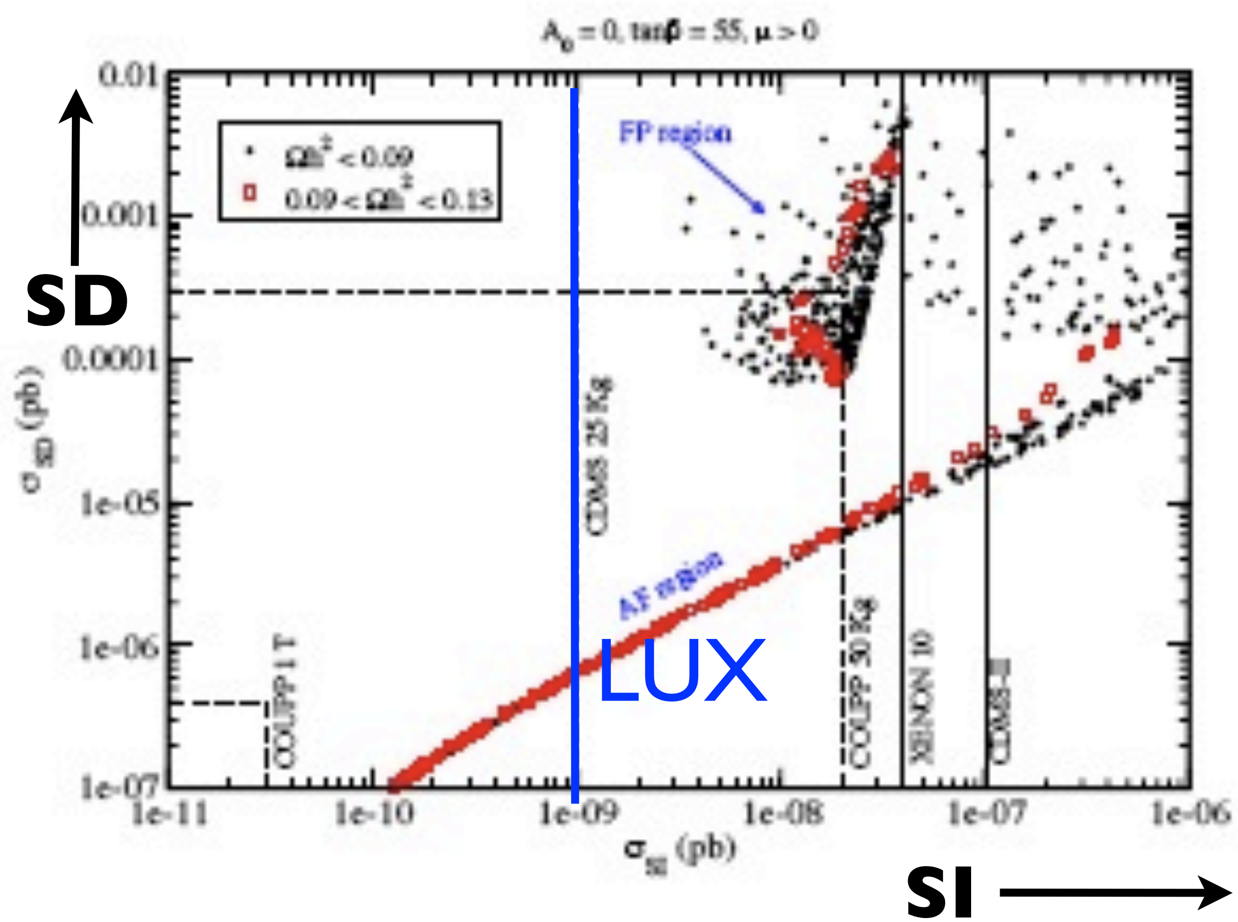


- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

Scattering rates in mSUGRA

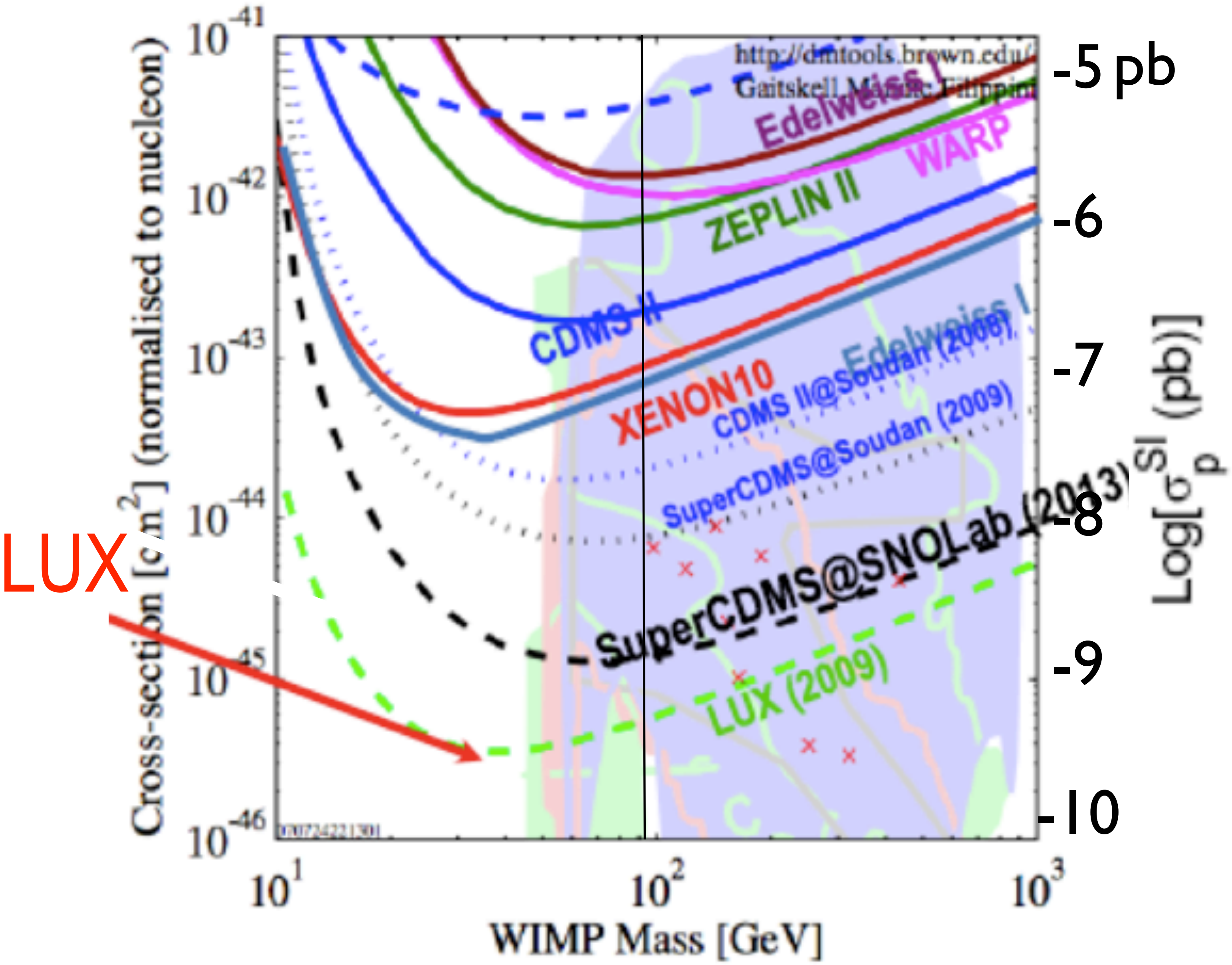
- Different solutions to DM relic density populate different regions of σ_{SD} vs. σ_{SI} Spin Dependent vs. Spin Indenepdent

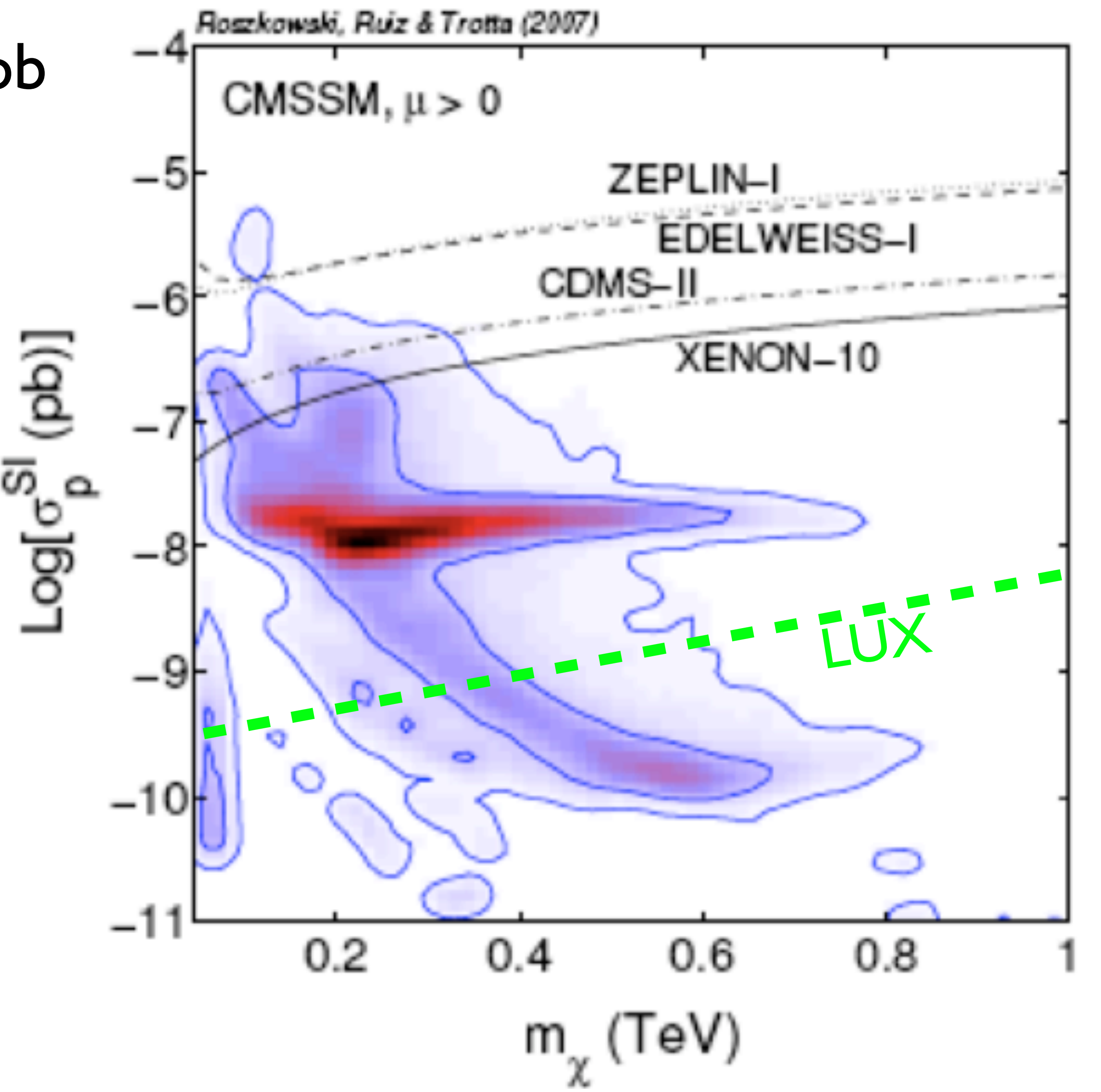




- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

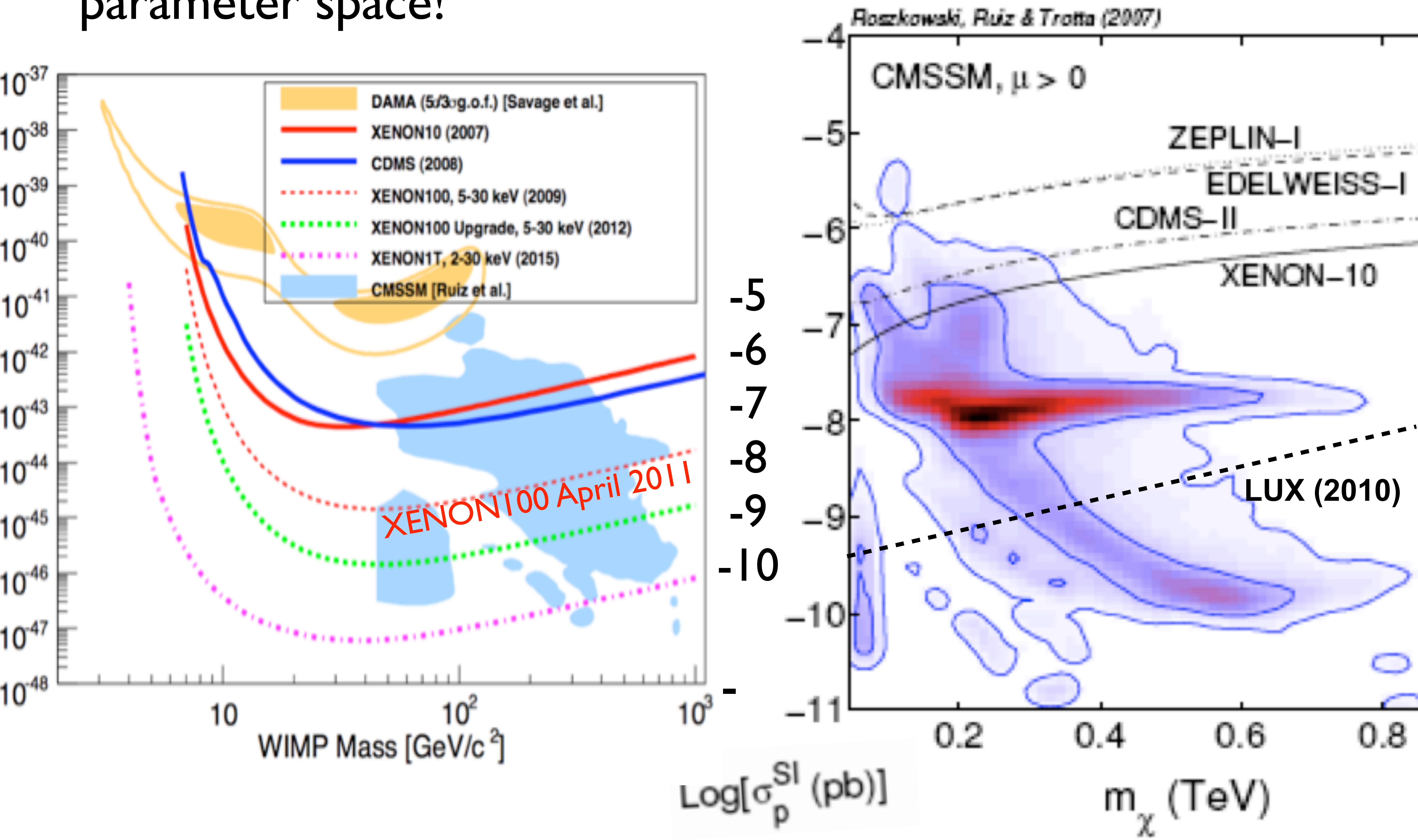
By ~2015 Direct Detection could probe most of the CMSSM (constrained minimal supersymmetric standard model) and mSUGRA (minimal supergravity) WIMP parameter space! If LUX and other large noble gas detectors succeed, they will leapfrog over CDMS and have great discovery potential during 2012-15.





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

By ~2015 Direct Detection could probe most of the CMSSM (constrained minimal supersymmetric standard model) and mSUGRA (minimal supergravity) WIMP parameter space!



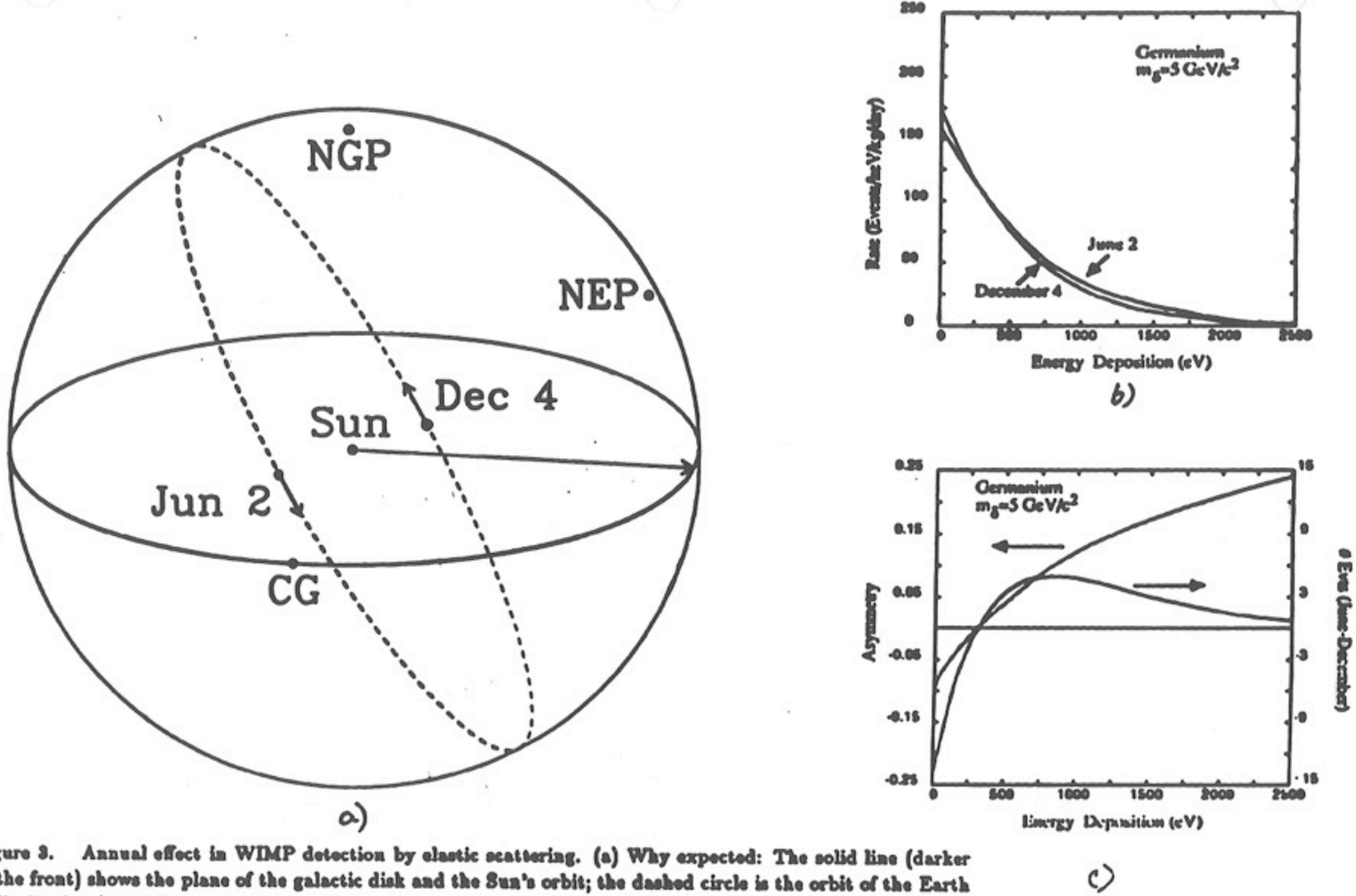
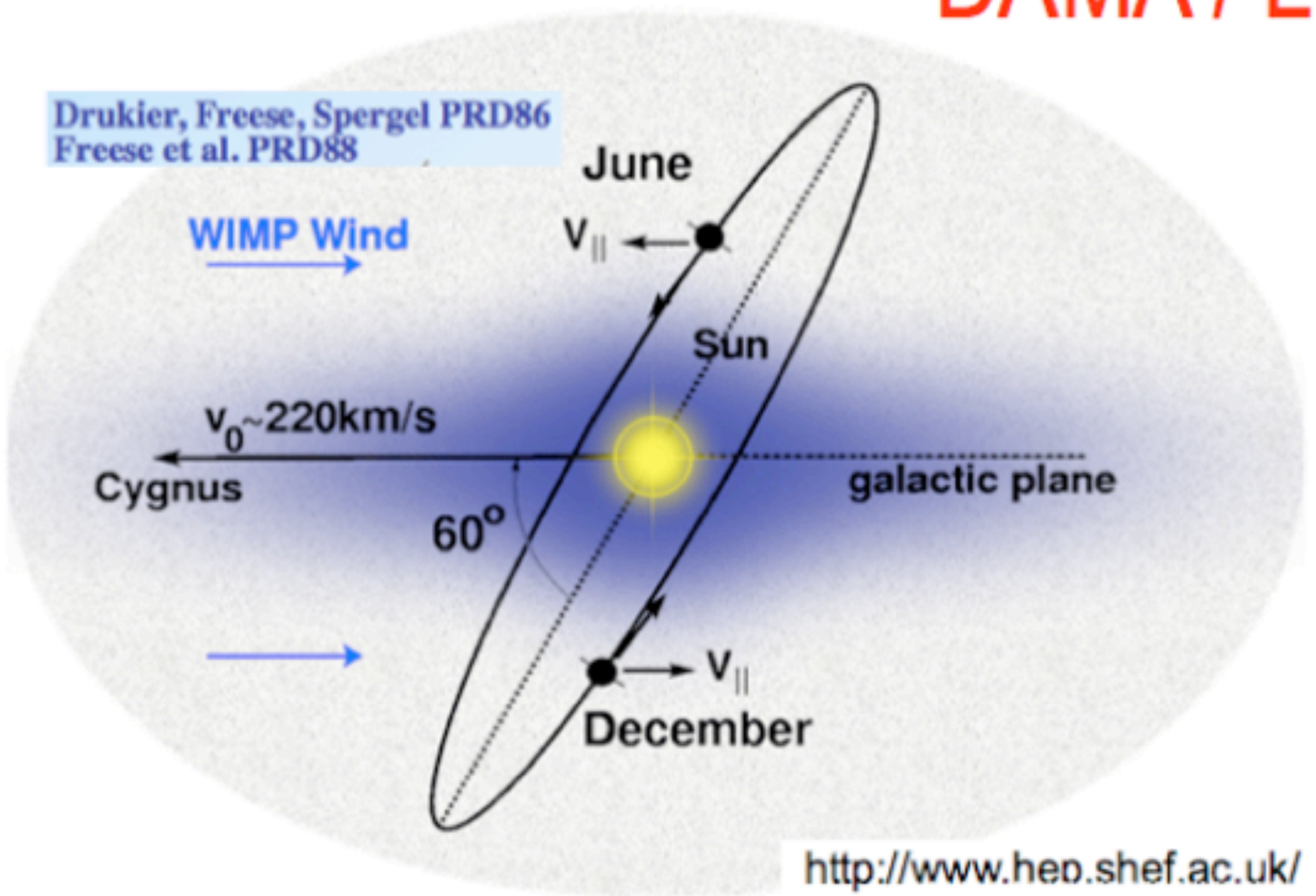


Figure 3. Annual effect in WIMP detection by elastic scattering. (a) Why expected: The solid line (darker in the front) shows the plane of the galactic disk and the Sun's orbit; the dashed circle is the orbit of the Earth (ecliptic plane). NGP and NEP are the north galactic and ecliptic poles. CG shows 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.

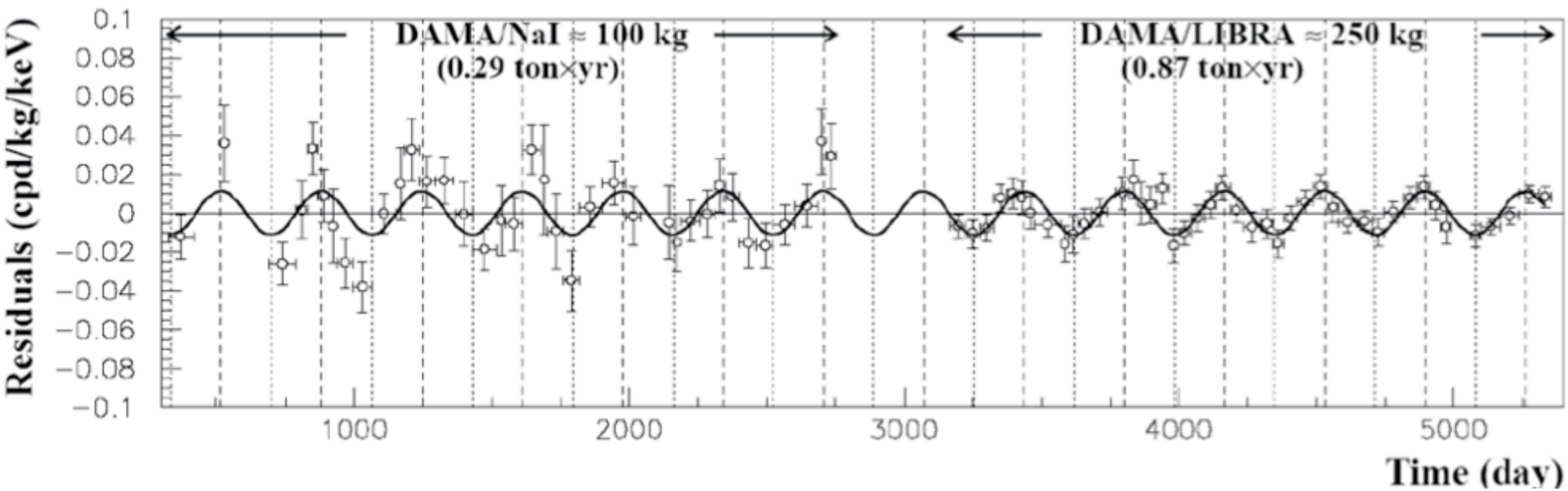
Primack, Seckel, & Sadoulet, Ann Rev Nucl Part Sci 1988

DAMA / LIBRA

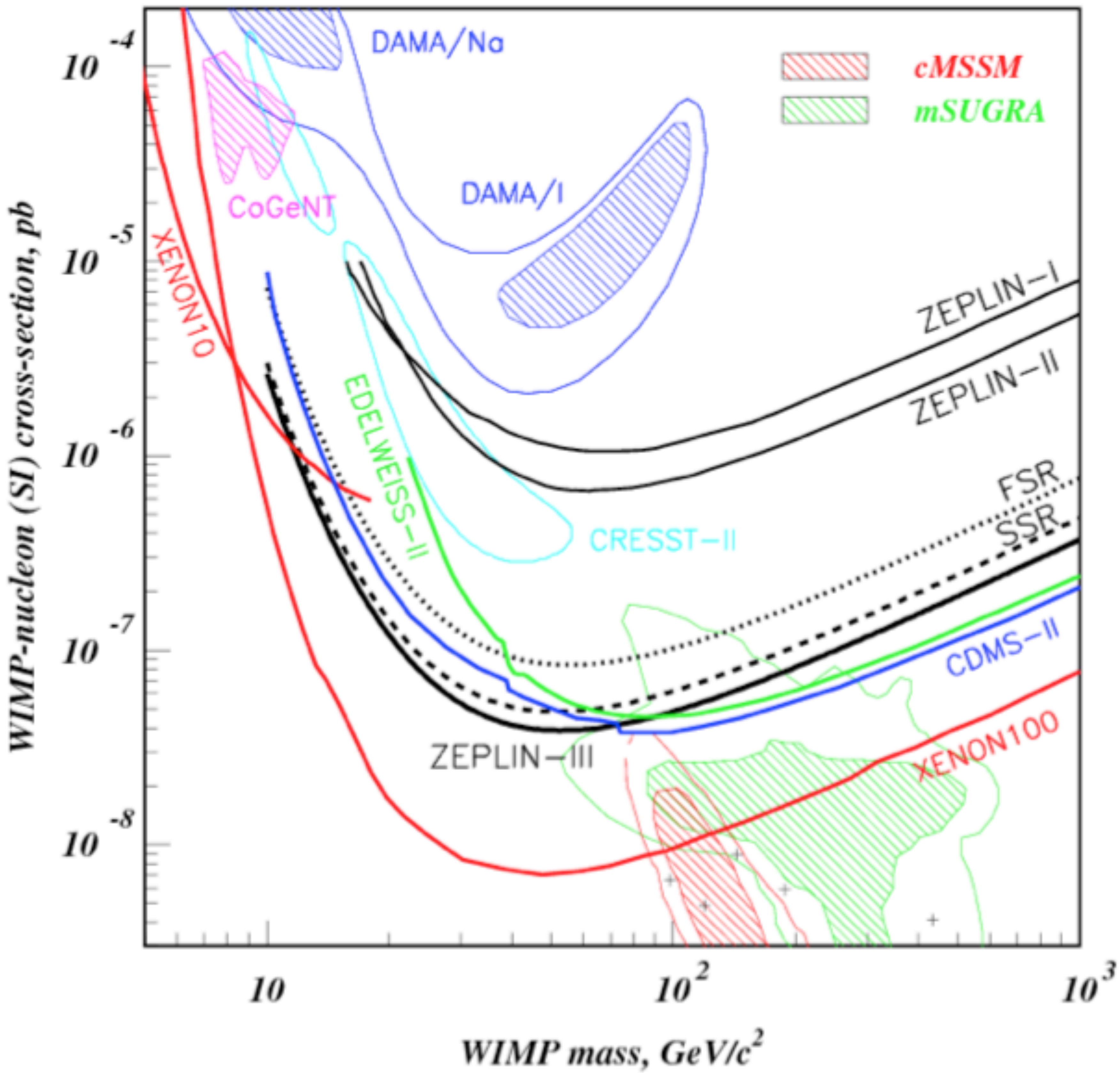


http://www.hep.shef.ac.uk/

- Annual Modulation
  - Significance is 8.9σ
  - 1-2% effect in bin count rate
  - Appears in lowest energy bins
  - Can another experiment observe this effect?



DAMA Interpretation and Current Limits



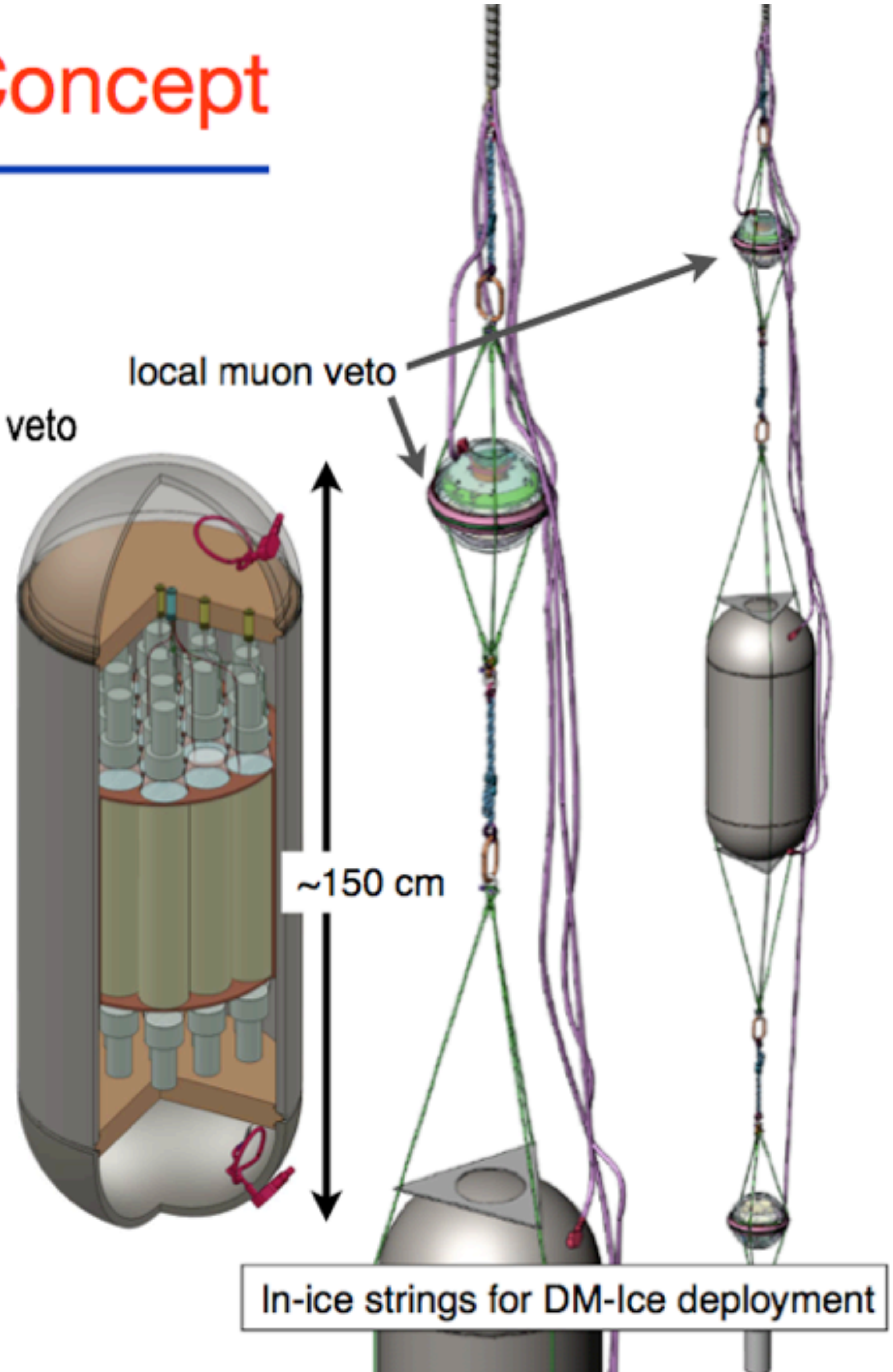
DM-Ice Concept

Detector
- 250–500 kg NaI(Tl)
- Closely-packed inside pressure vessel for coincidence veto
- Two PMTs/Crystal

Location
- South Pole, ~ 2500 m deep in the ice
- Near the center of IceCube for additional veto

Pressure vessel
- Withstand > 7000 psi of freeze-back pressure
- Low-background stainless steel
- Low background copper shielding where needed

Electronics
- Pulse digitization inside the vessel
- Power from SP Station or IceCube Counting Lab
- Remotely controllable

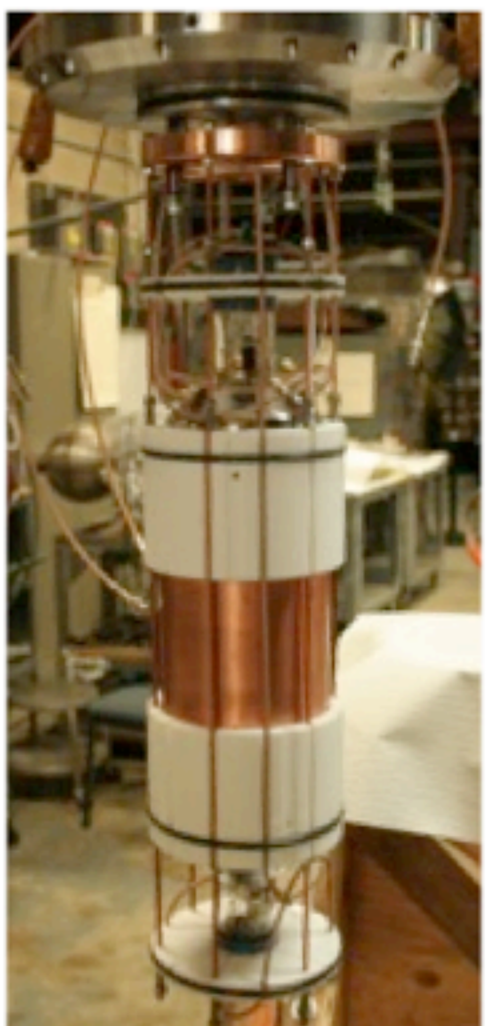


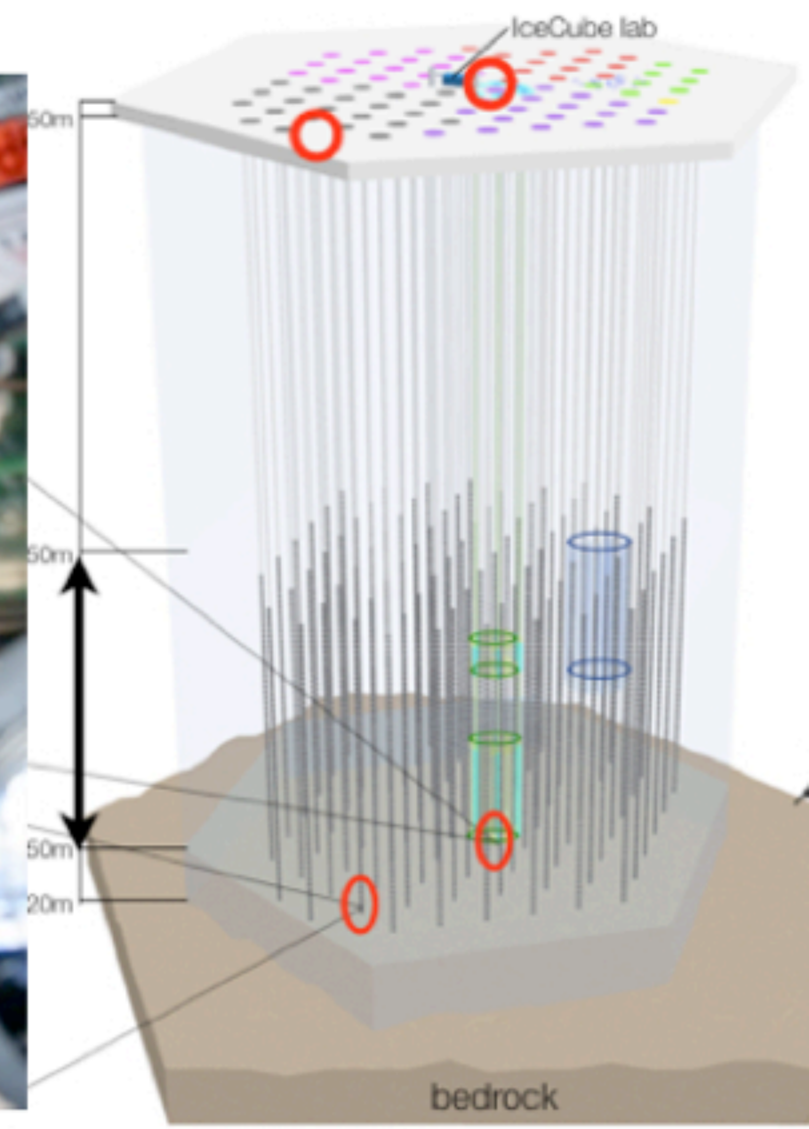
Slide from Reina Maruyma, DM2012

DM-Ice-17 (kg)

Slide reformatted from Reina Maruyma, DM2012

- 17 kg of NaI(Tl) (formerly part of NaIAD) deployed as a feasibility study at the South Pole Dec. 2010
- Continuous operation since Jan. 2011
- Data transmitted via satellite
- Analysis underway





WHAT IS THE DARK MATTER?

Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many ongoing and 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 few years. Whoever discovers the nature of the dark matter will surely win the Nobel prize!


DARK MATTER
ANNIHILATION AT
THE GALACTIC
CENTER?

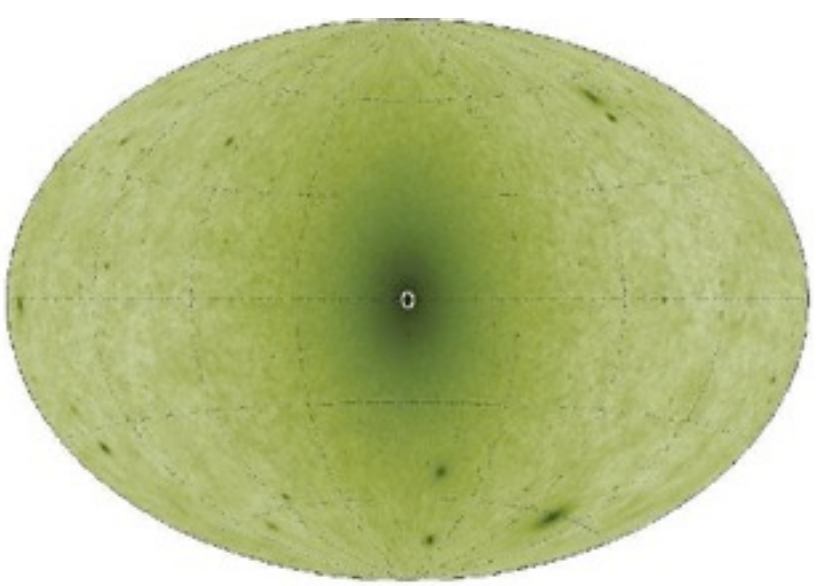
THE DARK MATTER ANNIHILATION SIGNAL FROM GALACTIC SUBSTRUCTURE: PREDICTIONS FOR GLAST

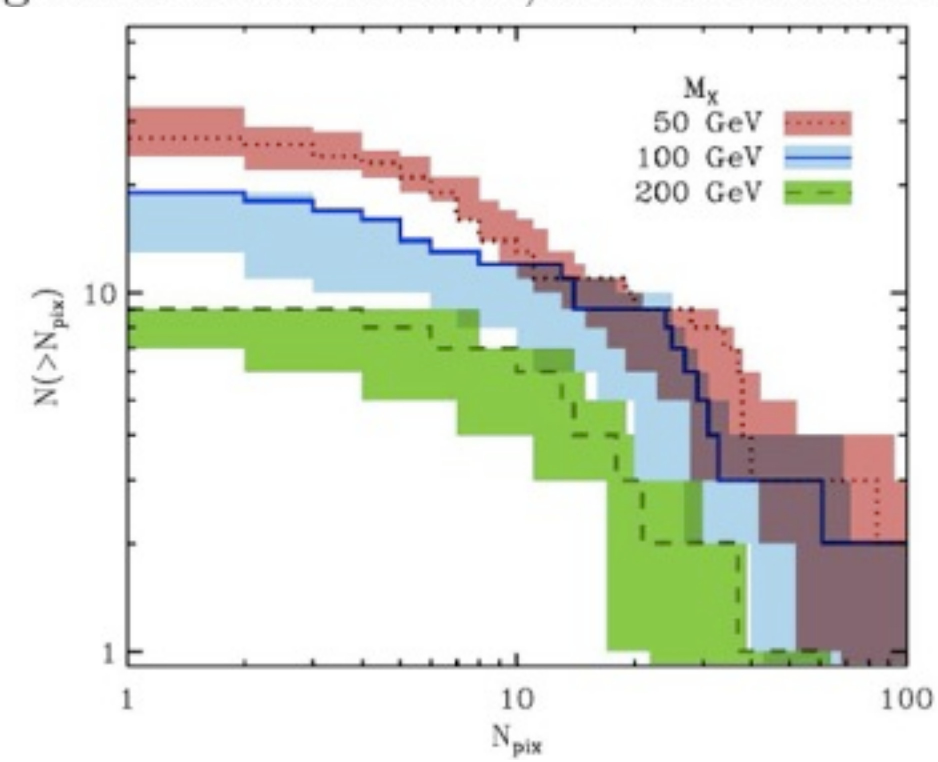
2008 ApJ 686, 262

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.



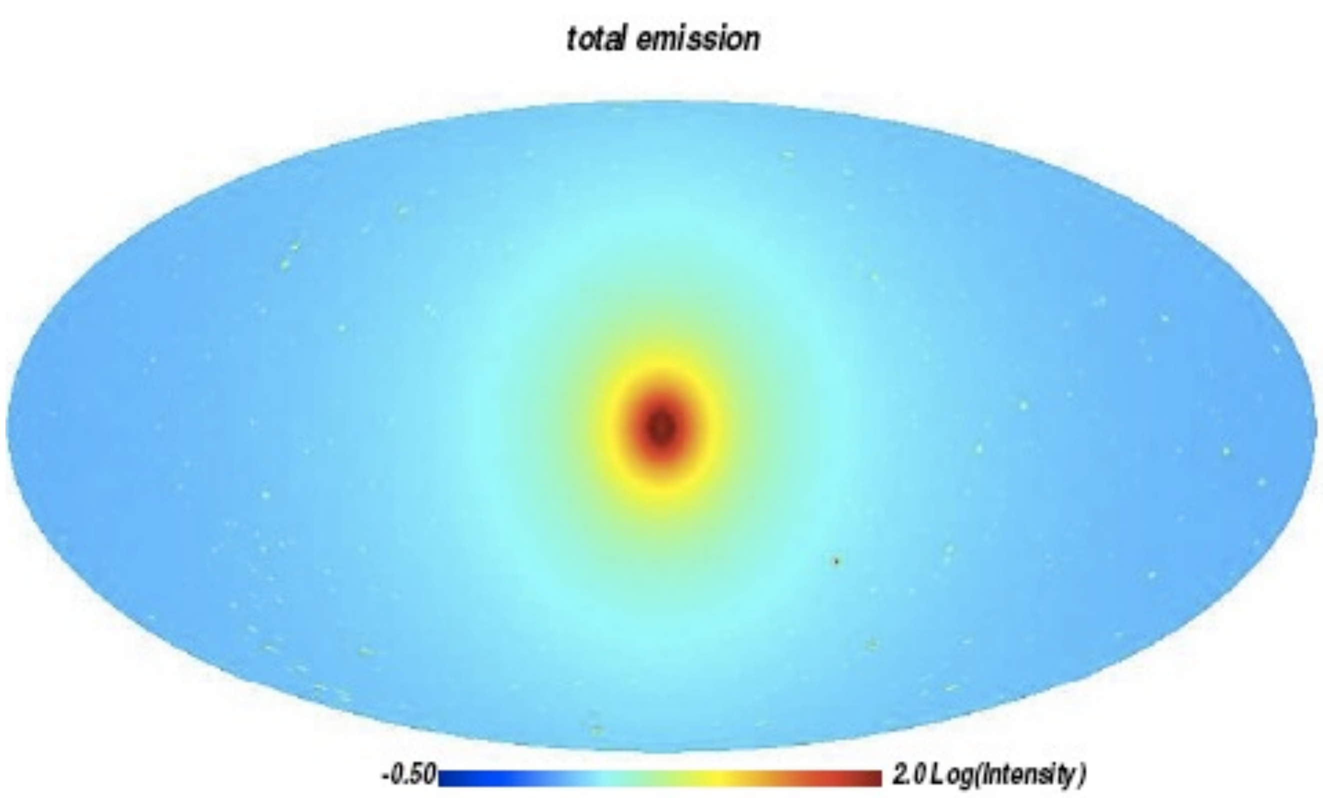


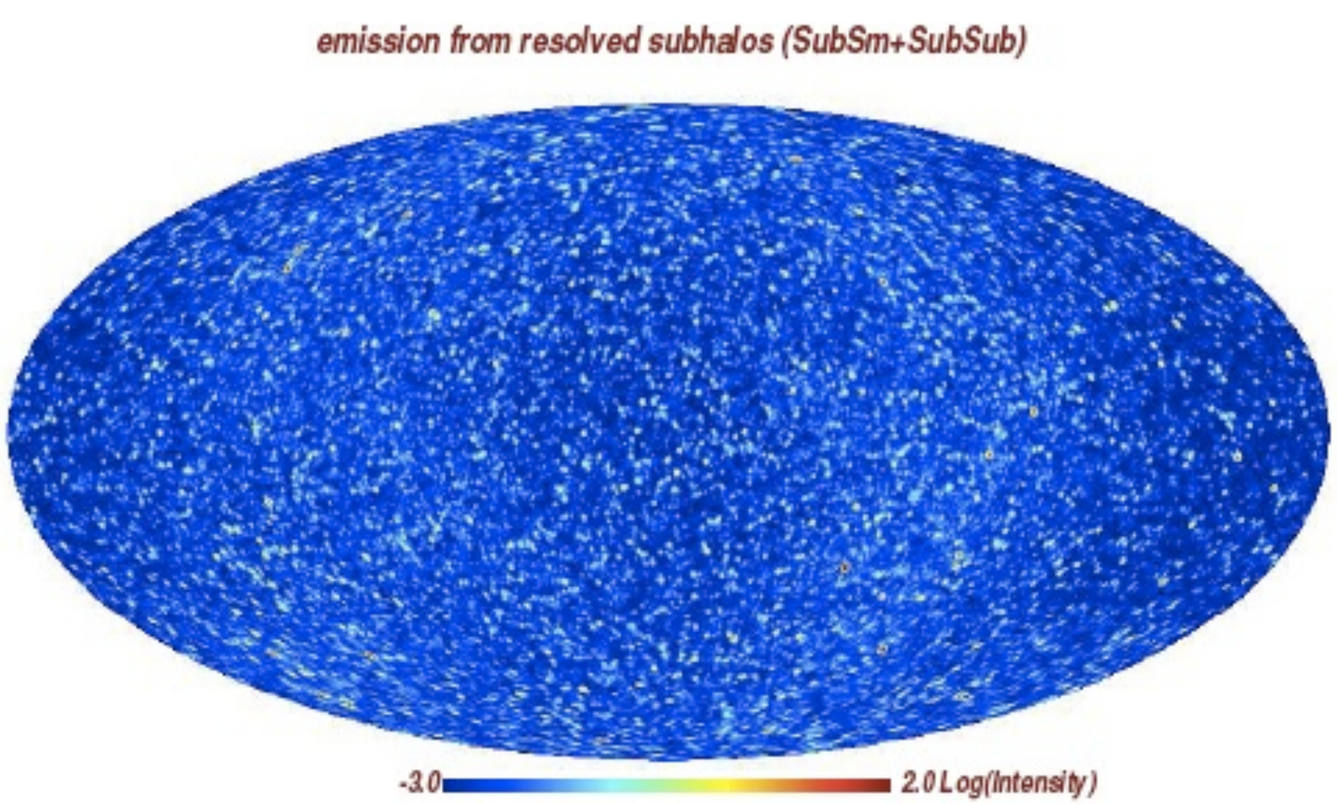
The number of detectable (S = 5) subhalos with more than N_{pix} detectable pixels versus N_{pix}, for three different choices of M(for $<\sigma v> = 3\times10^{-26}$ cm^3 s^{-1}). The shaded regions show the range of N(>Npix) for ten randomly chosen observer locations and the solid lines refer to an observer placed along the intermediate axis of the host halo ellipsoid.

A blueprint for detecting supersymmetric dark matter in the Galactic halo

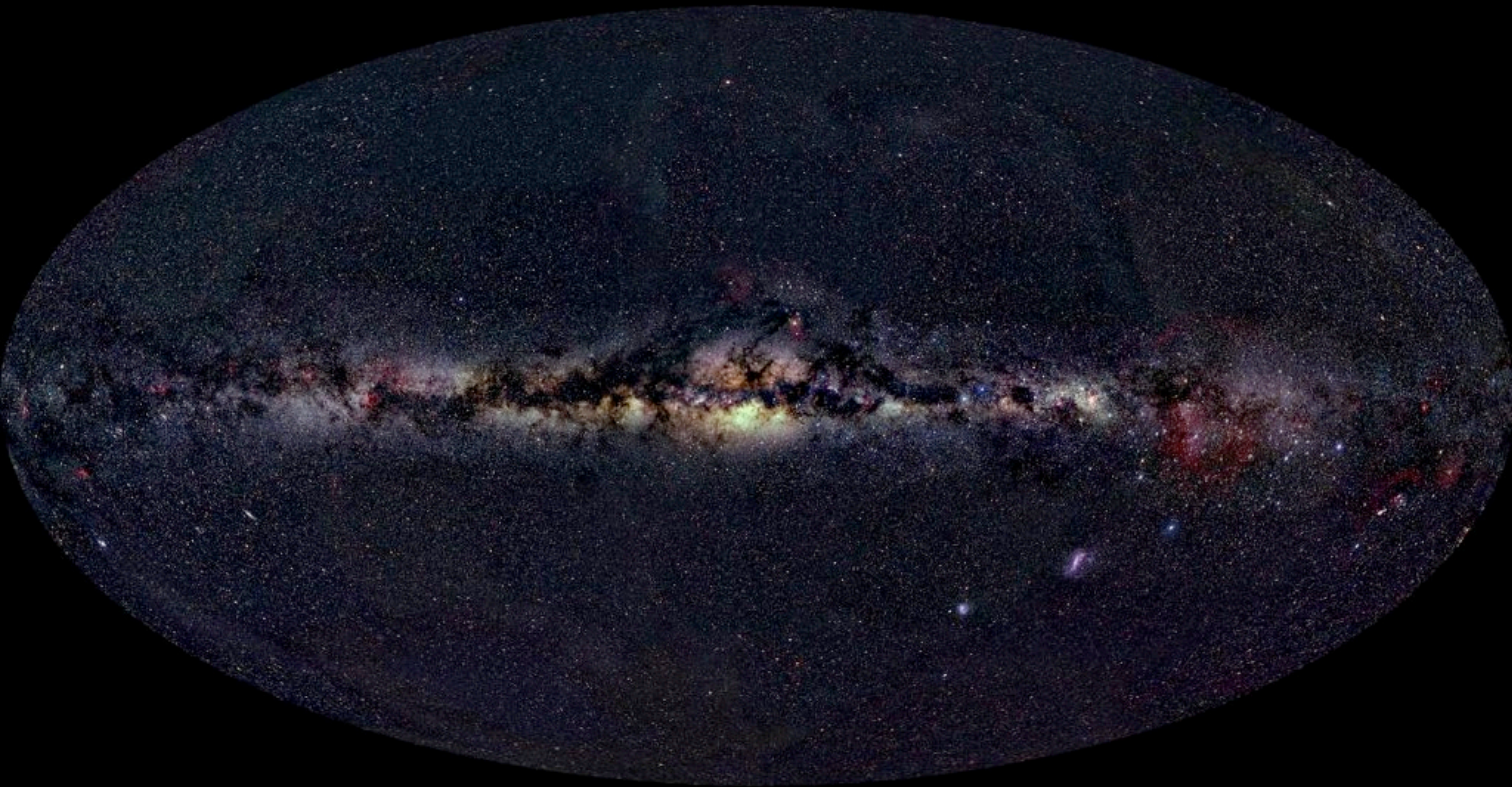
V. Springel et al. 2008 Nature 456, 73-76

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 be 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.



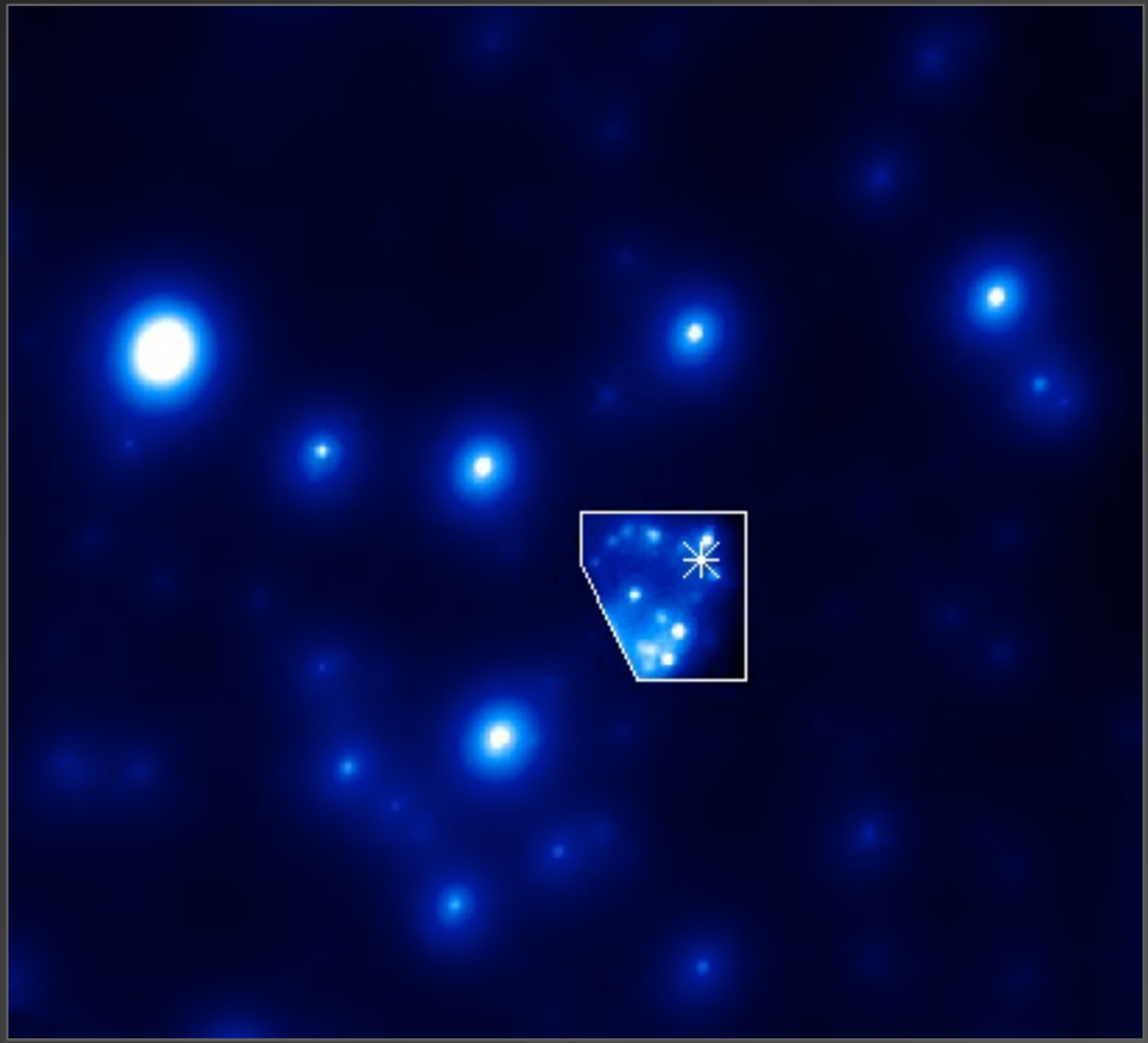


The Milky Way in the Sky

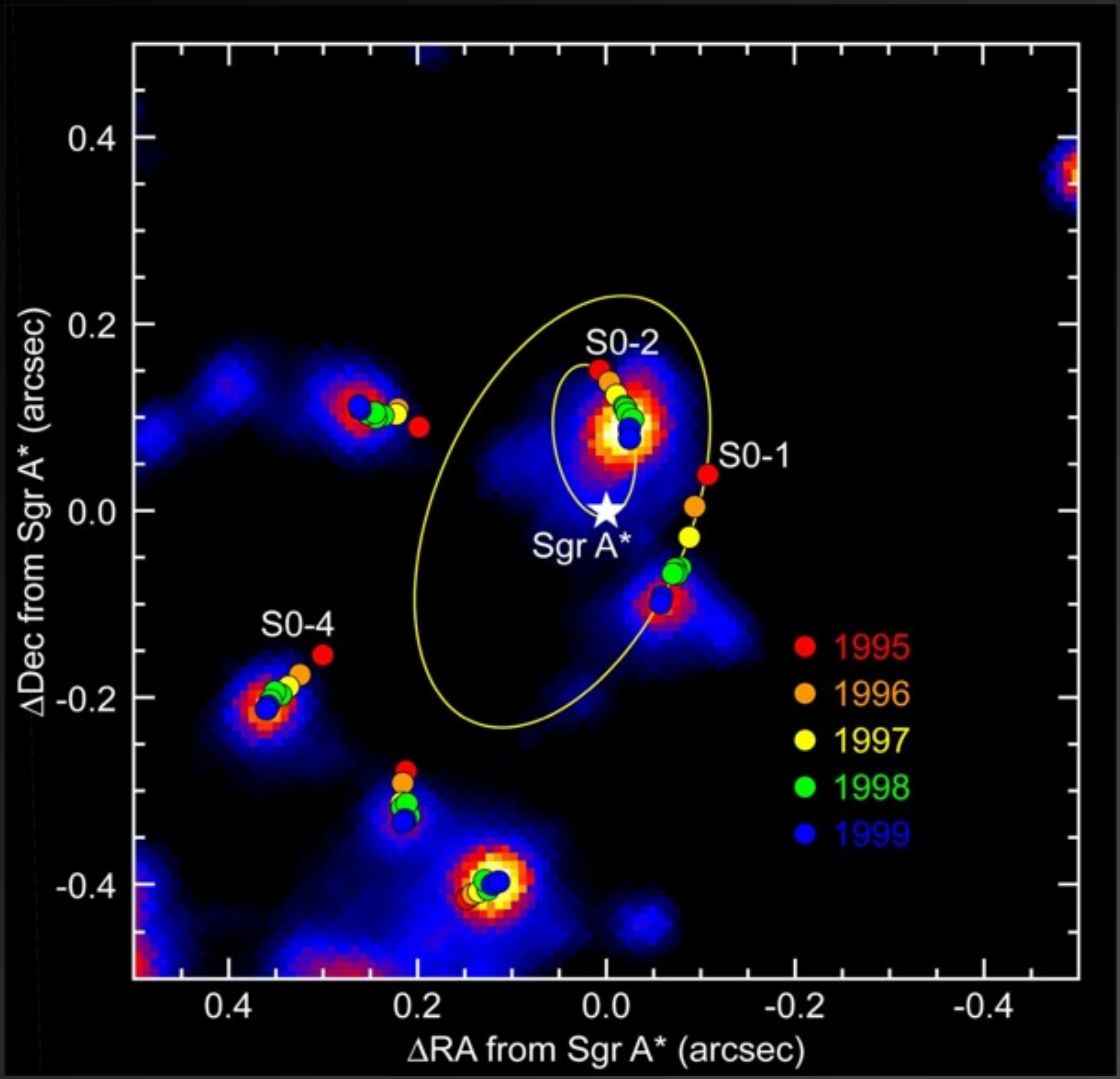


There's a supermassive black hole at the center of our galaxy…

- 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 15 years, with improving resolution…

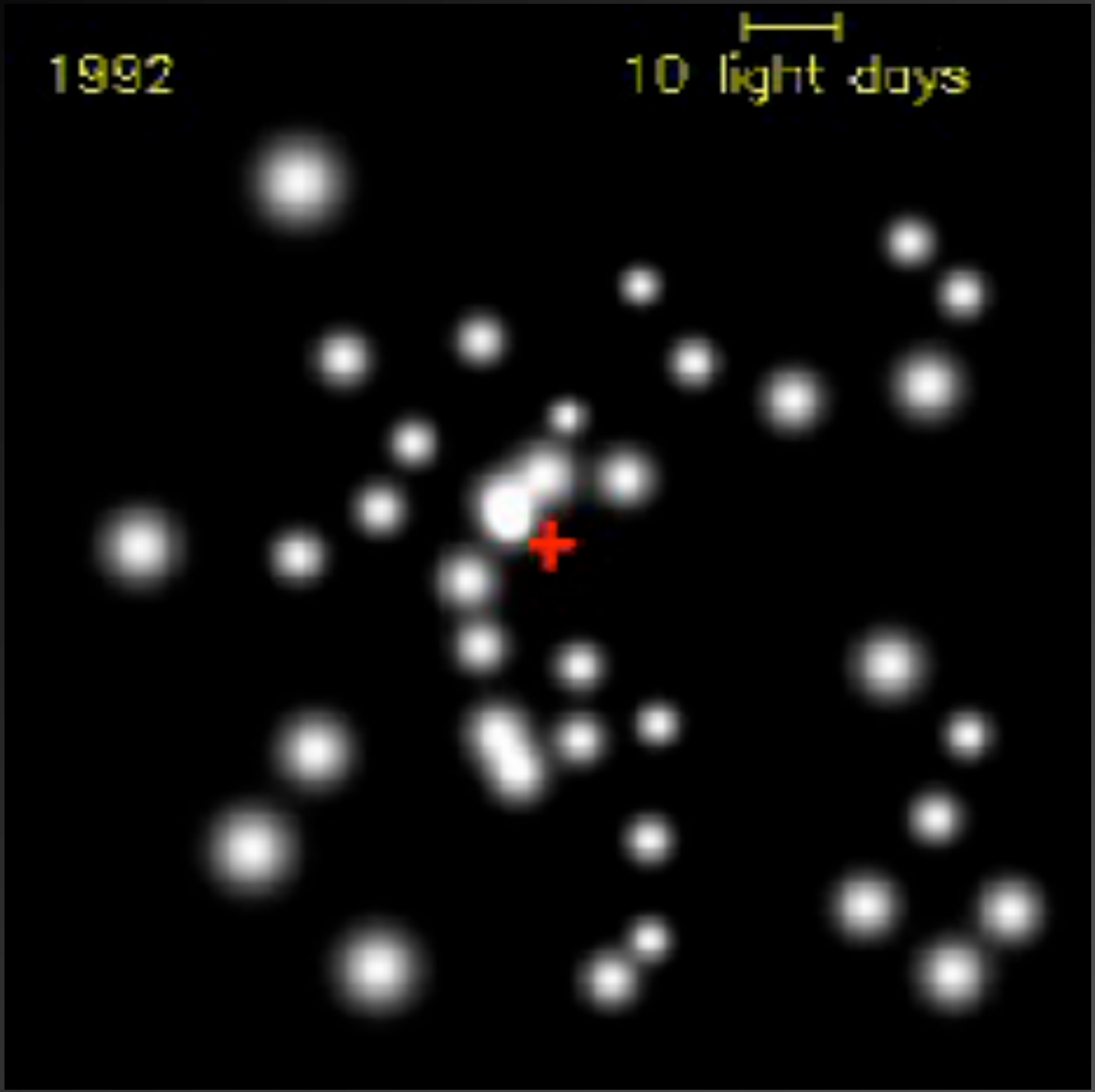


Keck, 2 μm *Ghez, et al.*

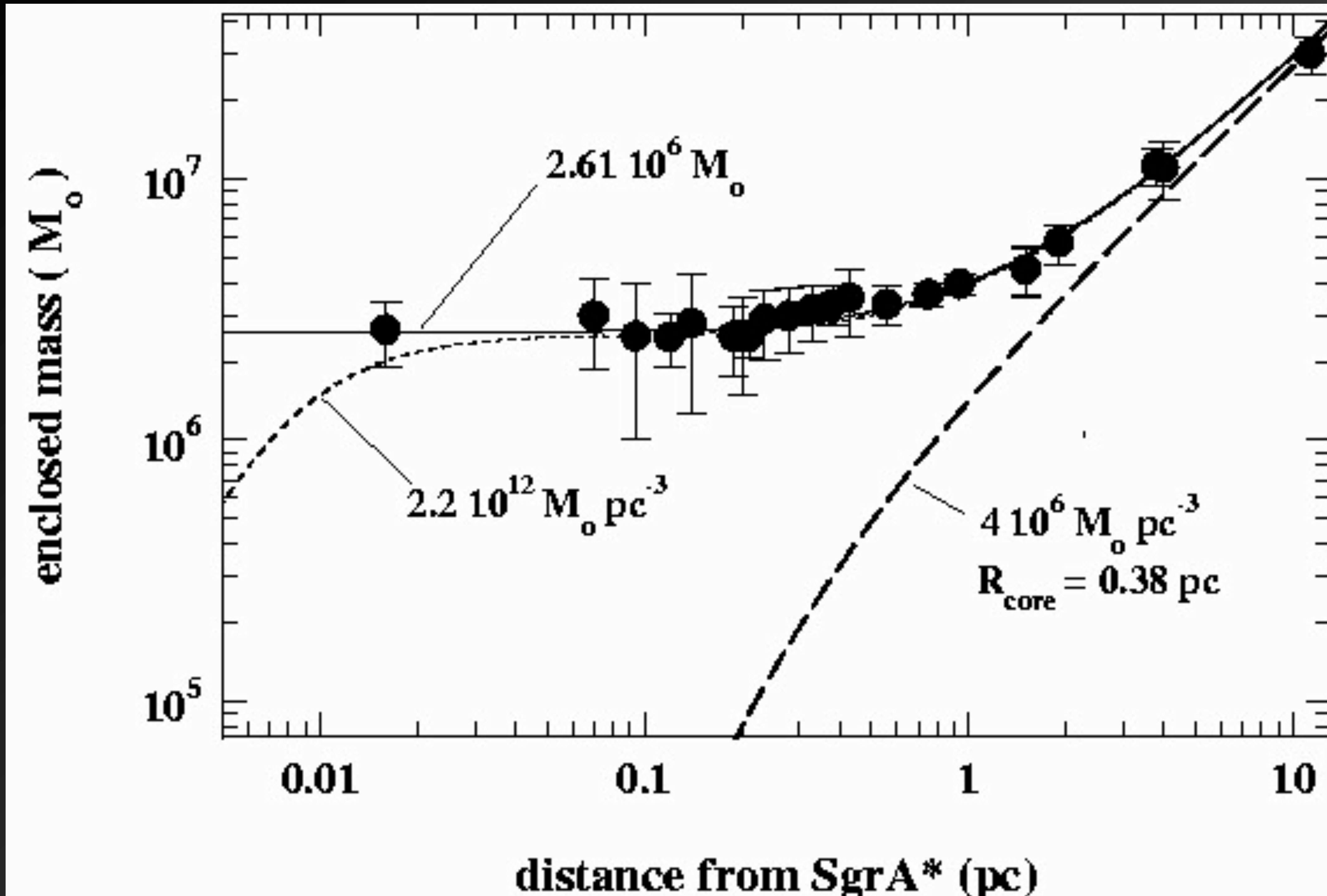


Motions of stars consistent with large, dark mass located at Sgr A…*

Ghez, et al.



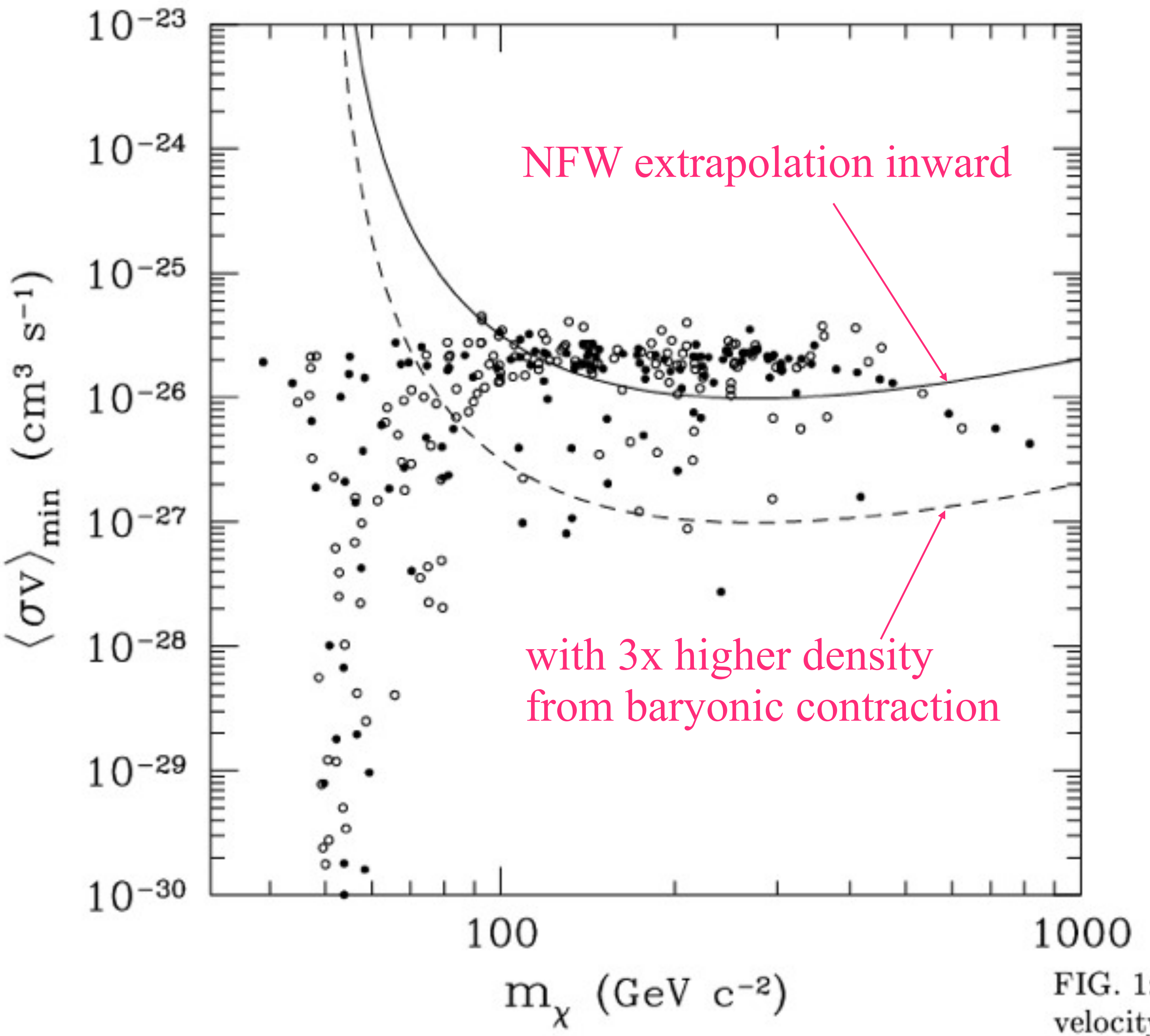
Schödel, Genzel, et al. 2004



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



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:

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

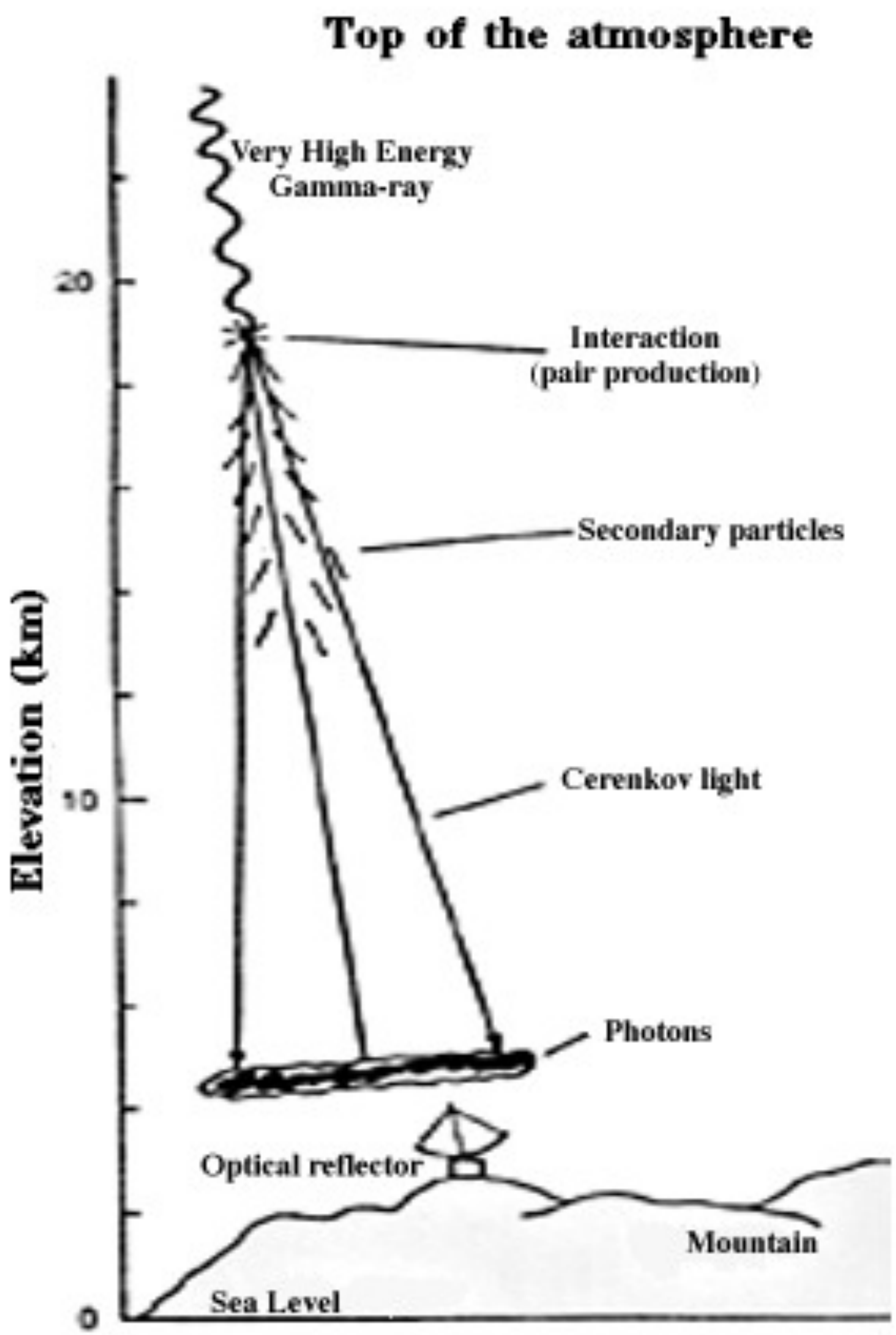
where $E = v^2/2 - GM_{\rm bh}/r$ is the energy within the sphere of influence of the black hole, $q(E) = (2^{3/2}/3)\pi^3 G^3 M_{\rm bh}^3 E^{-3/2}$, $A \equiv 16\pi^2 G^2 m_*^2 \ln\Lambda$, and $\ln\Lambda = \ln M_{\rm bh}/m_* \approx 15$ is the standard Coulomb logarithm. The equilibrium distribution 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 $\rho_{\rm dm} \propto r^{-3/2}$.

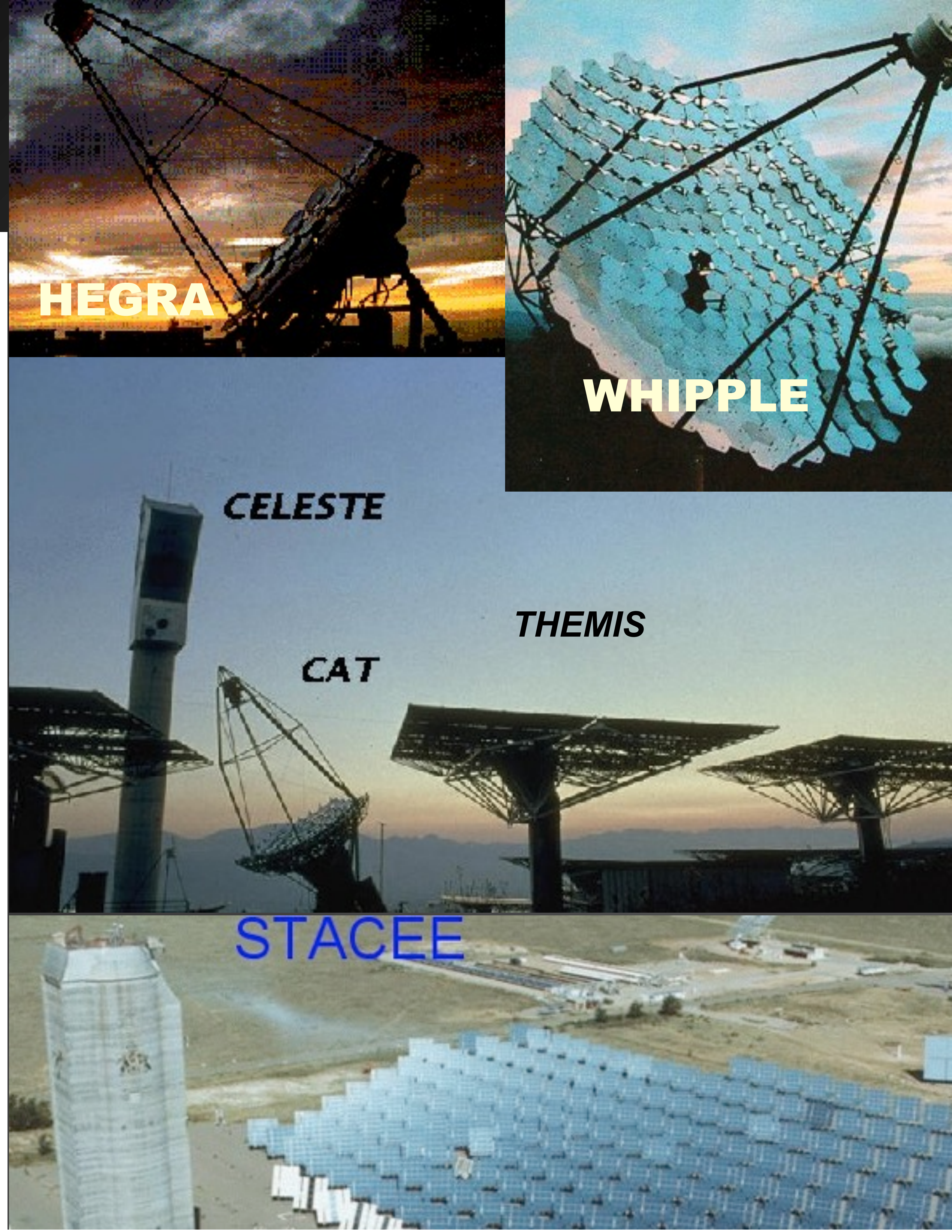
Implications for dark matter searches.— The dark matter density in the central region of the Galaxy is thus given by

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

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

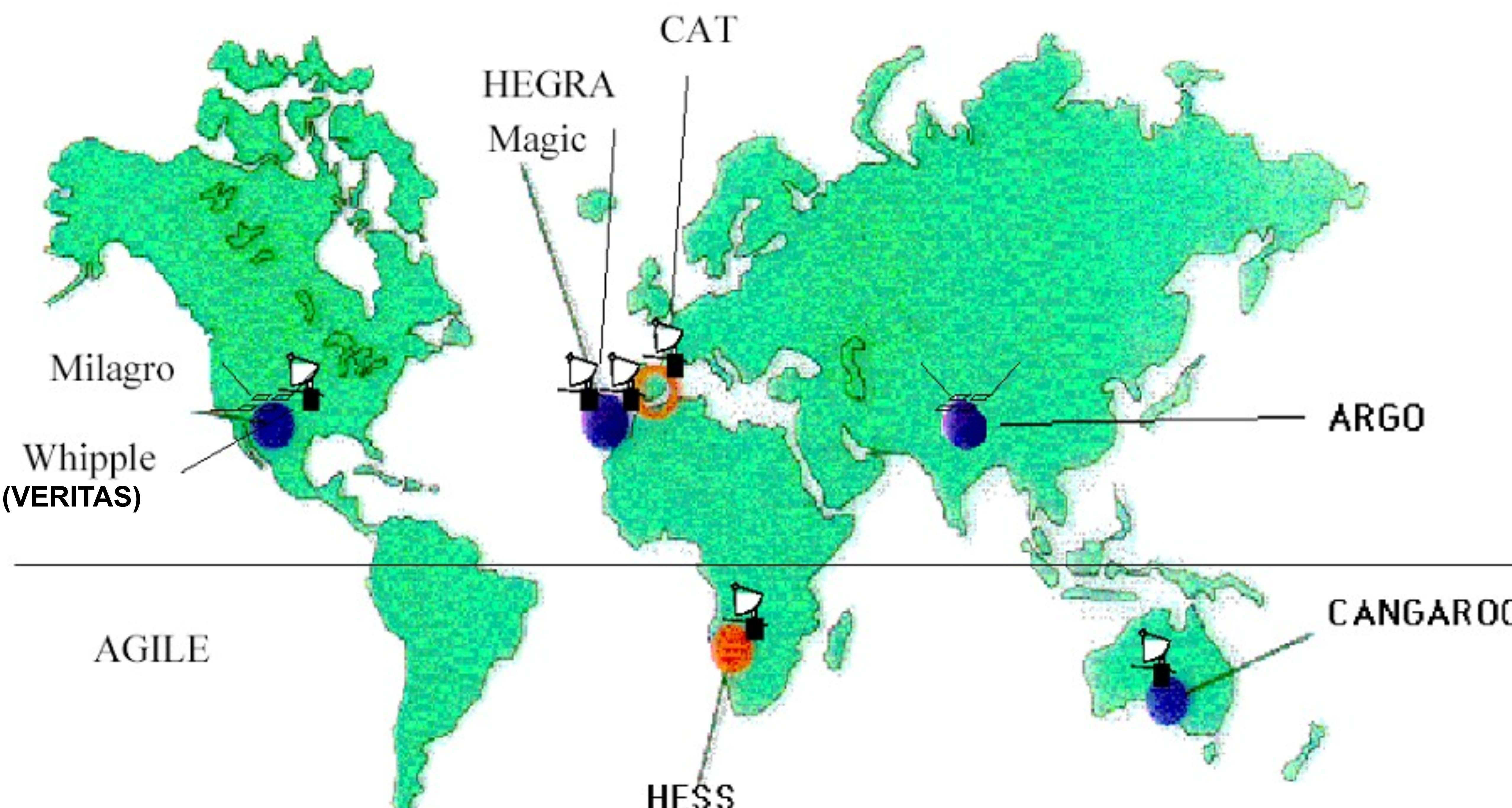
Early Atmospheric Čerenkov Telescopes

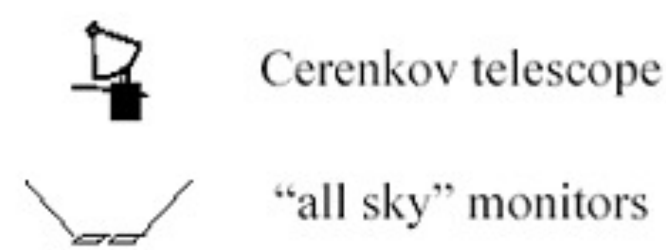




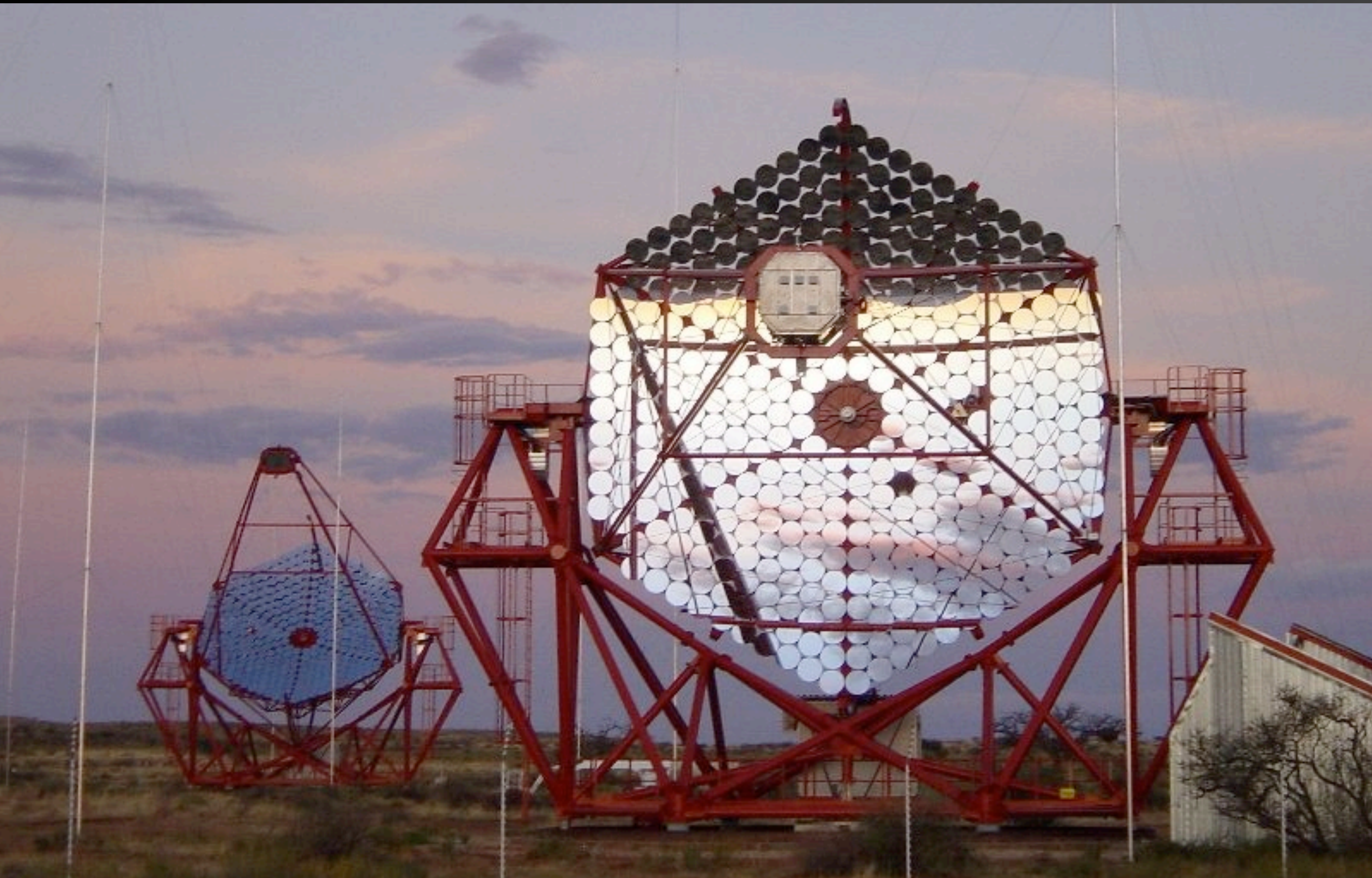
New Ground and Space Based Telescopes

Ground-based Gamma Ray Telescopes 2



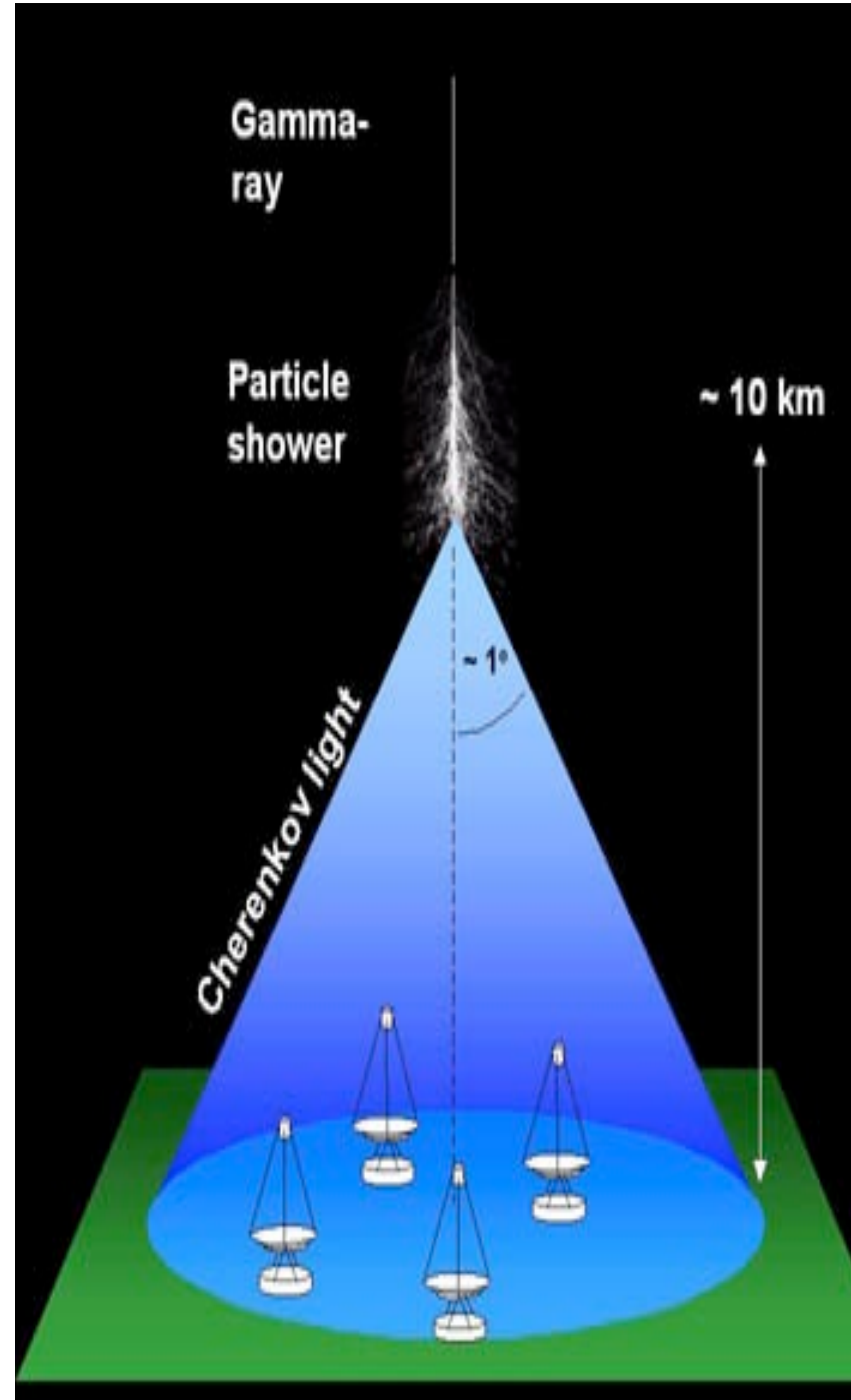


Results from H.E.S.S. on MWy Center



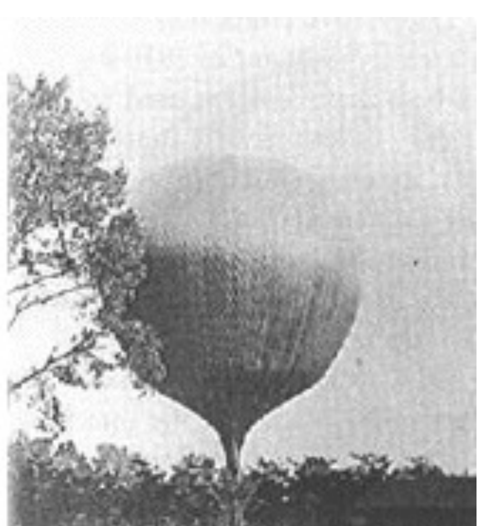
H.E.S.S.: High Energy Stereoscopic System

- 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



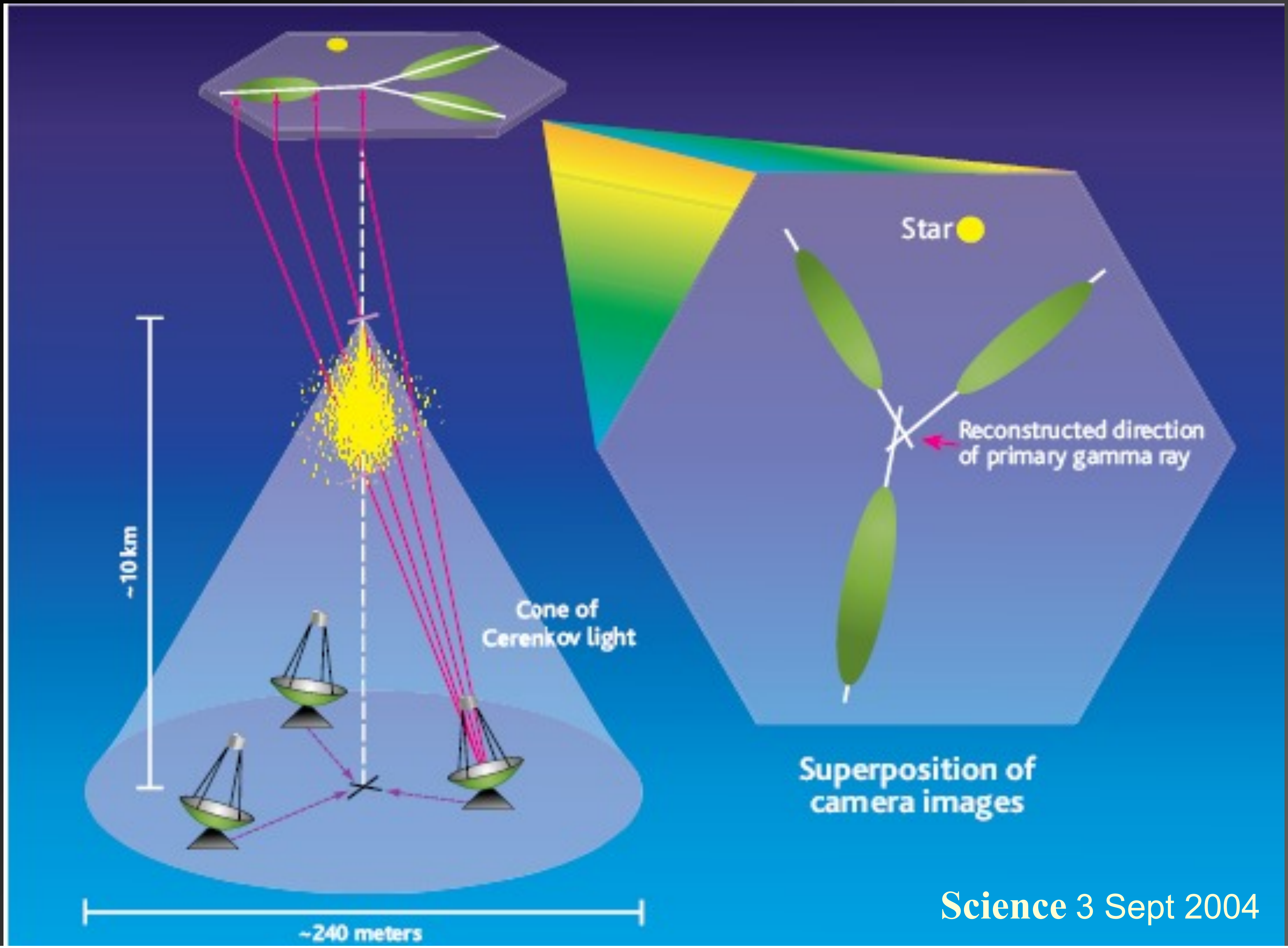
Energy Threshold (pre - post cuts):

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



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-Ataï[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

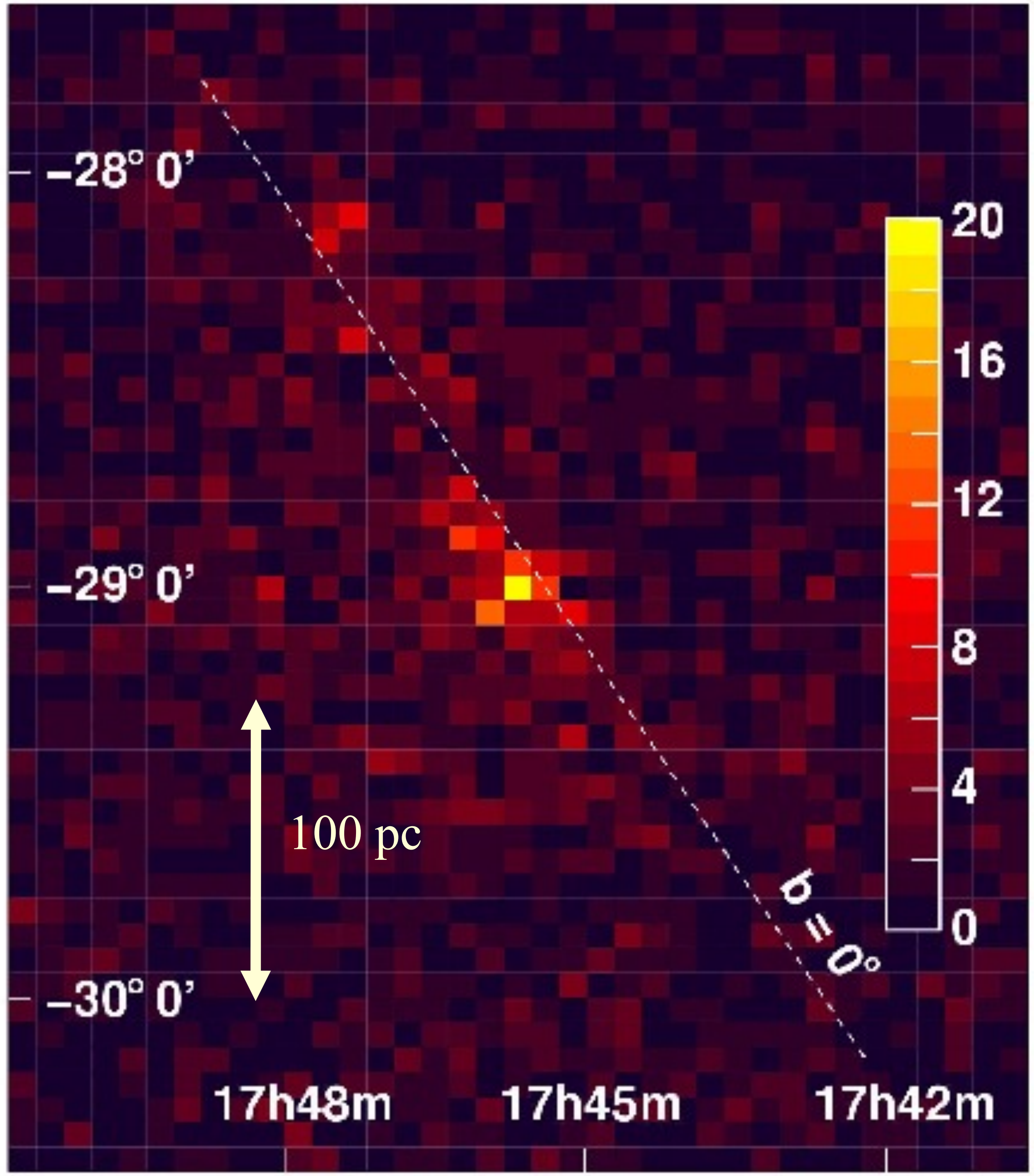


Fig. 1. Angular distribution of γ-ray candidates for a 3° field of view centred on Sgr A*. Both data sets ('June/July' and 'July/August') are combined, employing tight cuts to reduce the level of background. The significance of the feature extending along the Galactic Plane is under investigation.

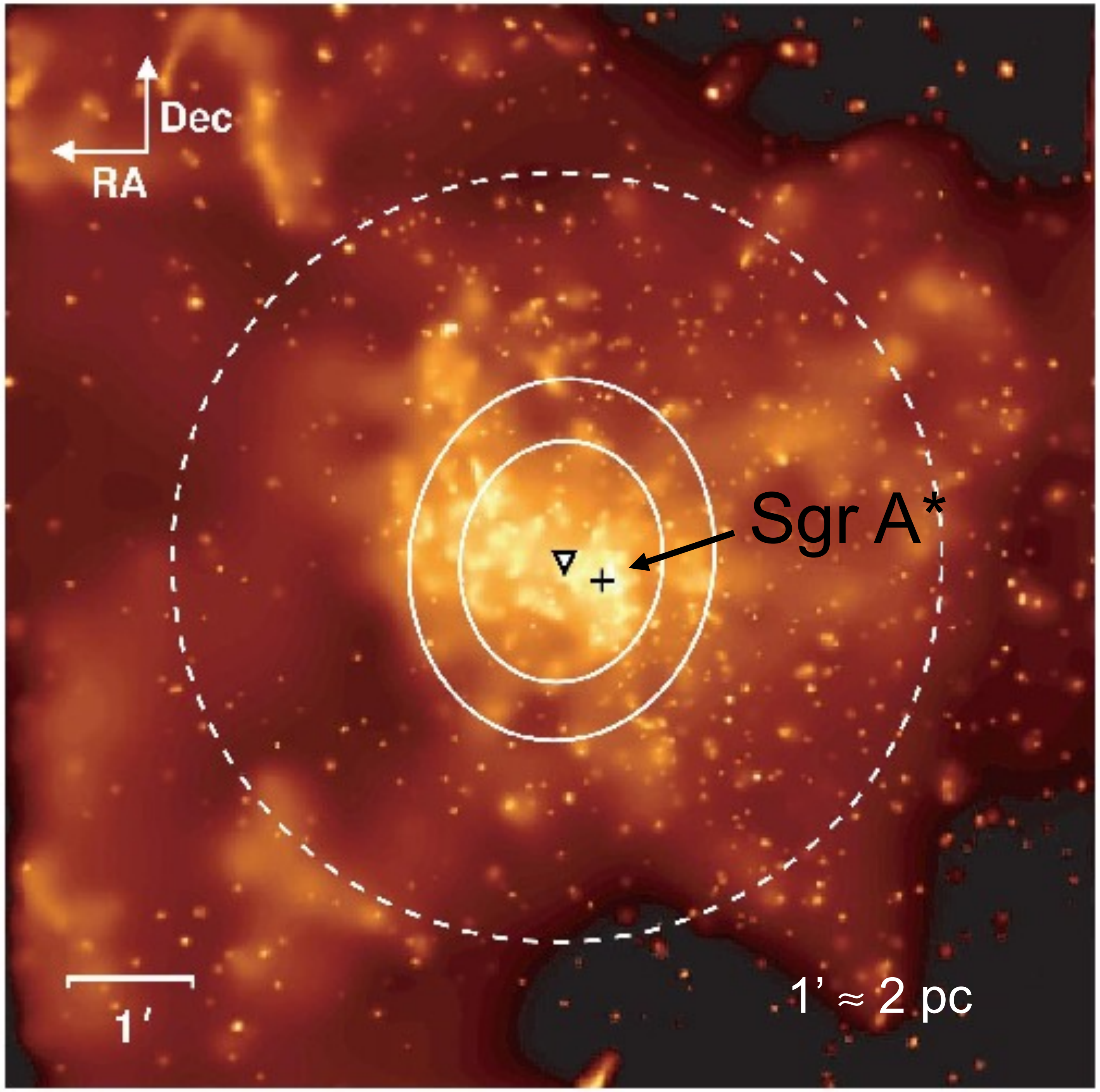
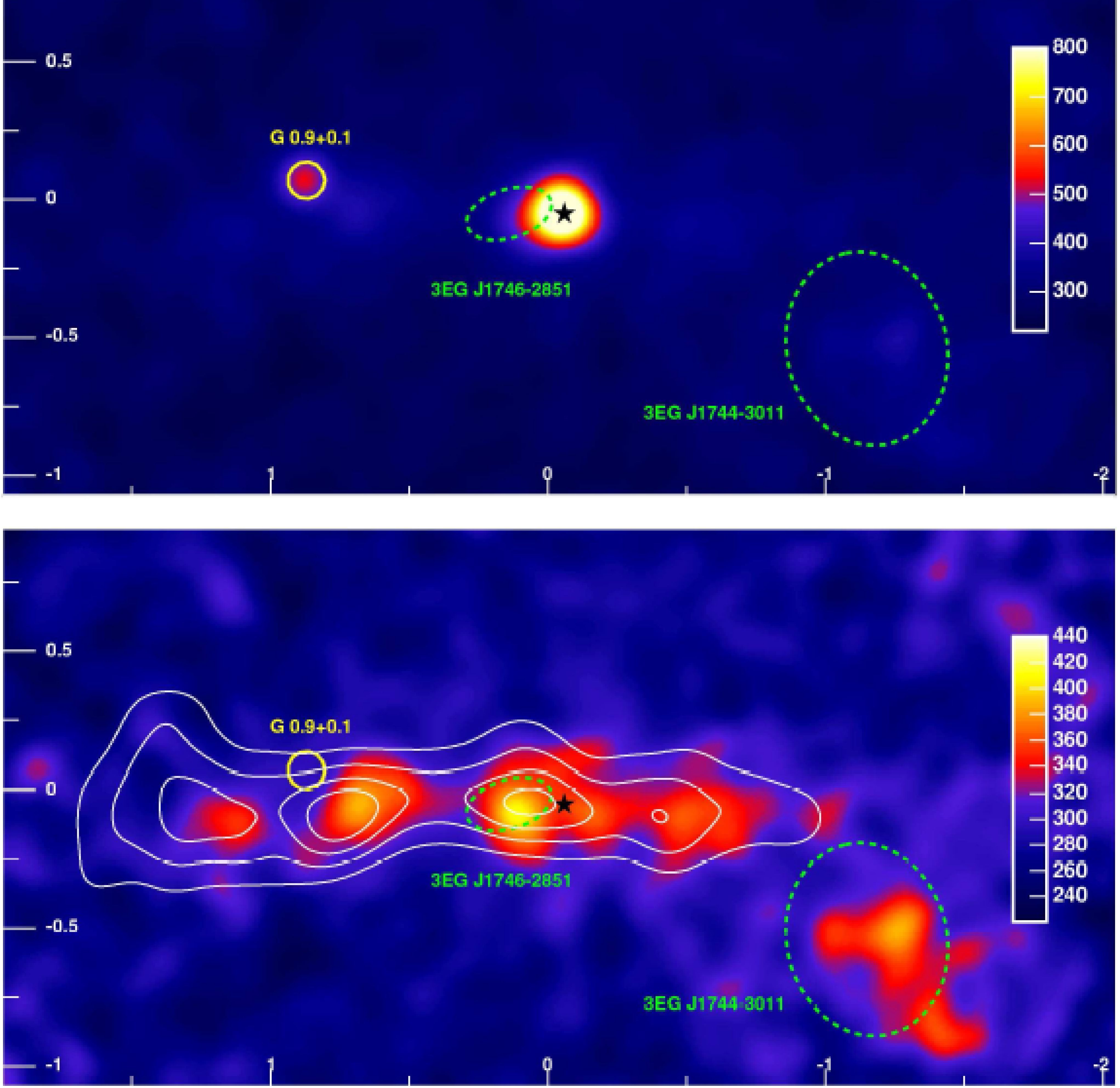
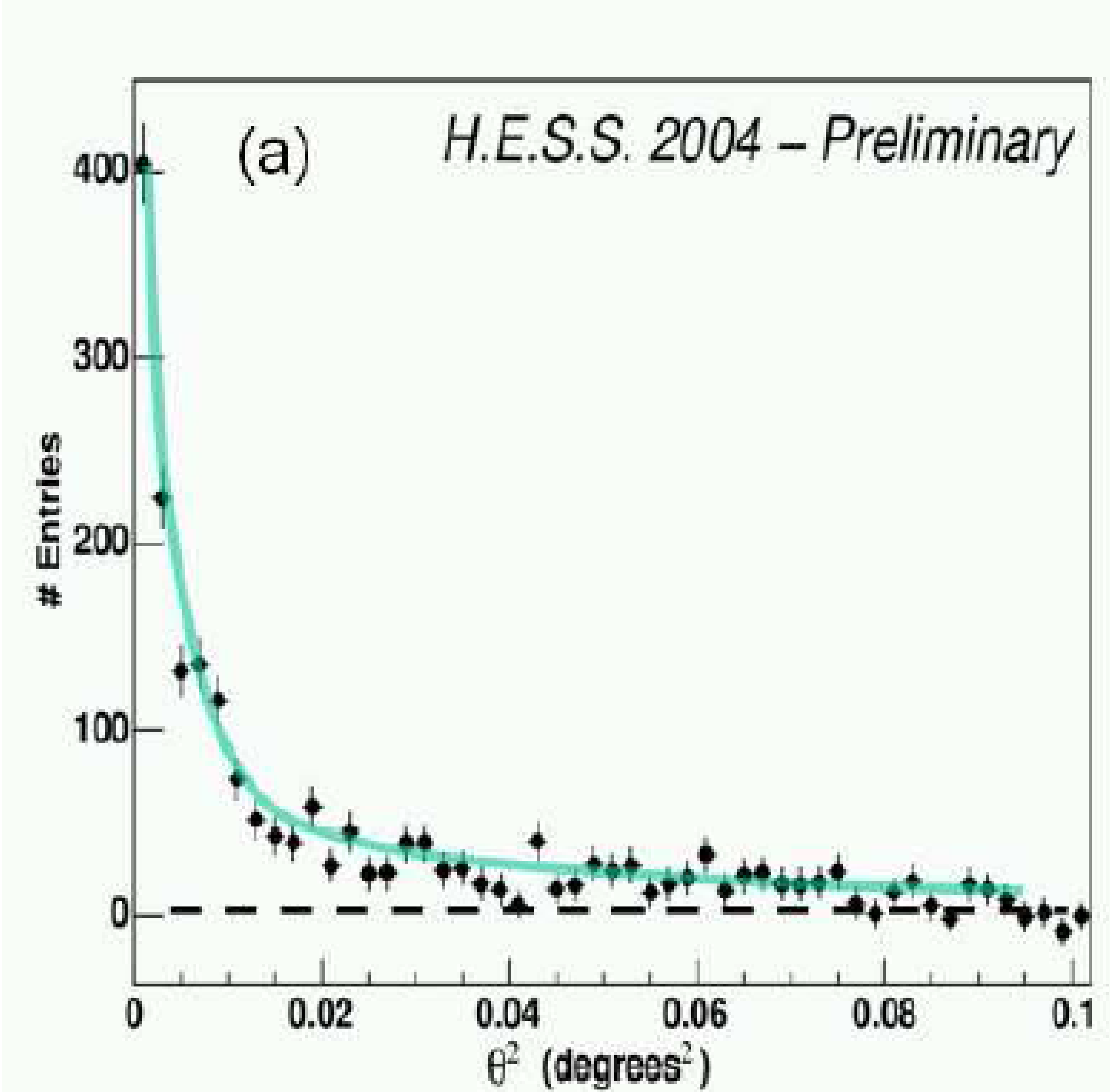


Fig. 2. Centre of gravity of the VHE signal (triangle), superimposed on a 8.5′ by 8.5′ Chandra X-ray map (Munro et al. 2003) of the GC. The location of Sgr A* is indicated by a cross. The contour lines indicate the 68% and 95% confidence regions for the source position, taking into account systematic 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).



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



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

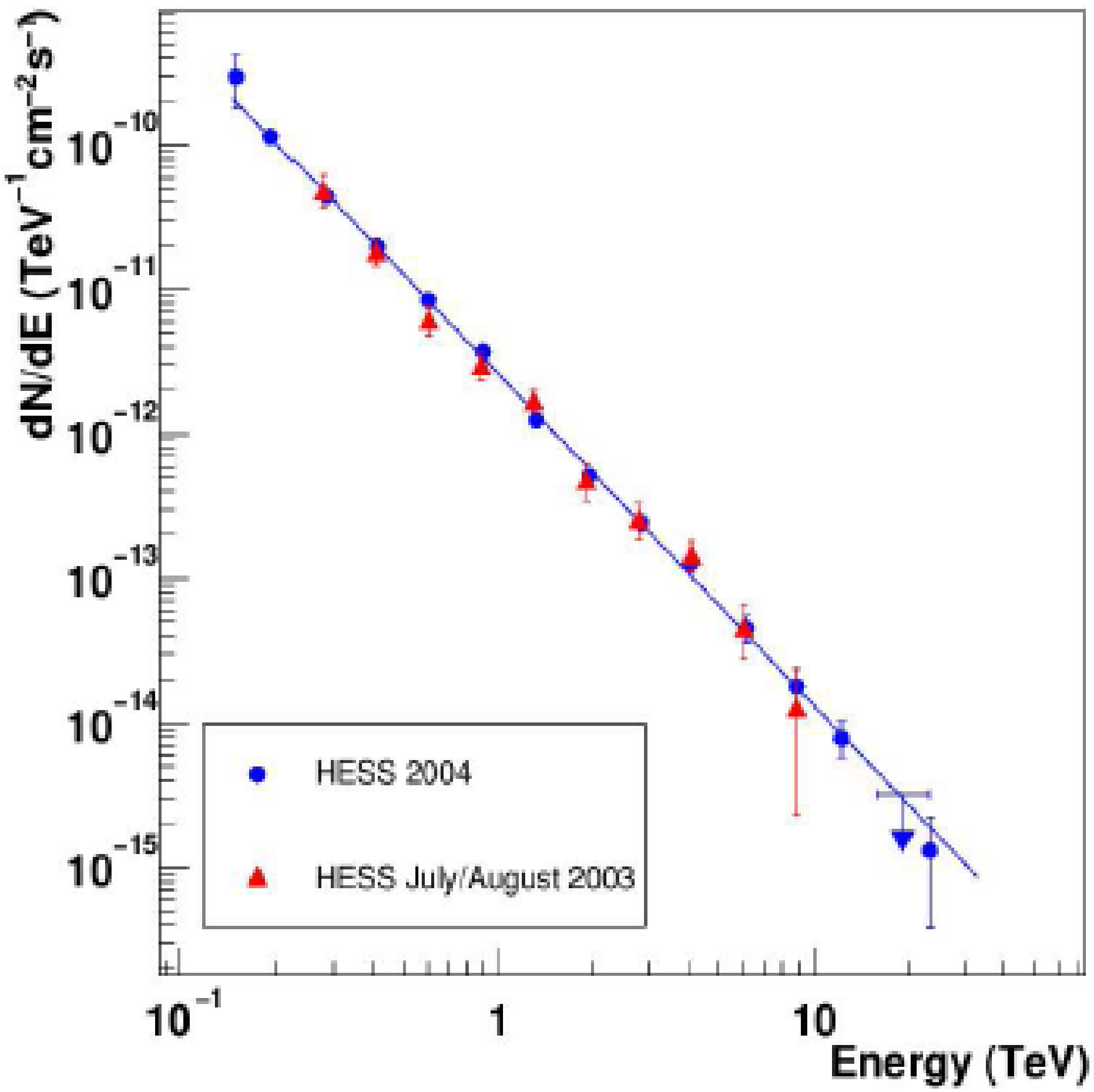
W. Hoffman plenary talk at ICRC29 2005

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

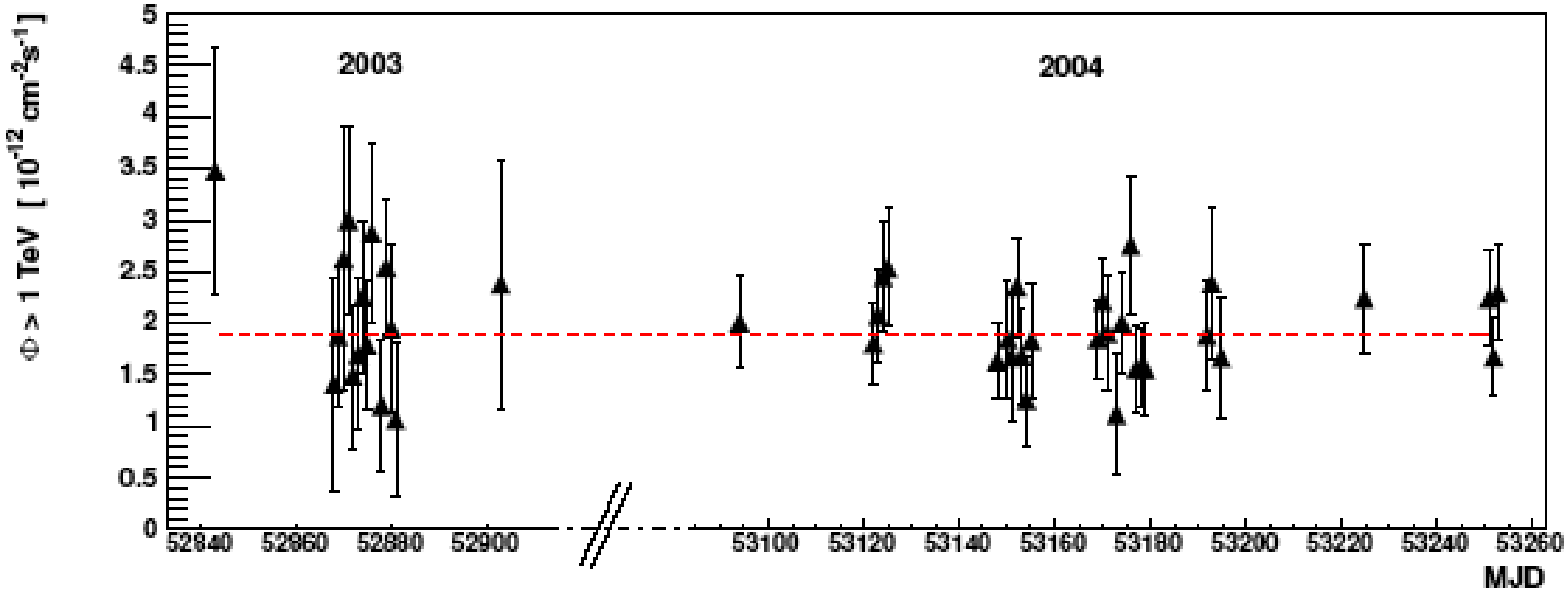
Spectrum and variability of the VHE Galactic Centre source observed with H.E.S.S.

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).

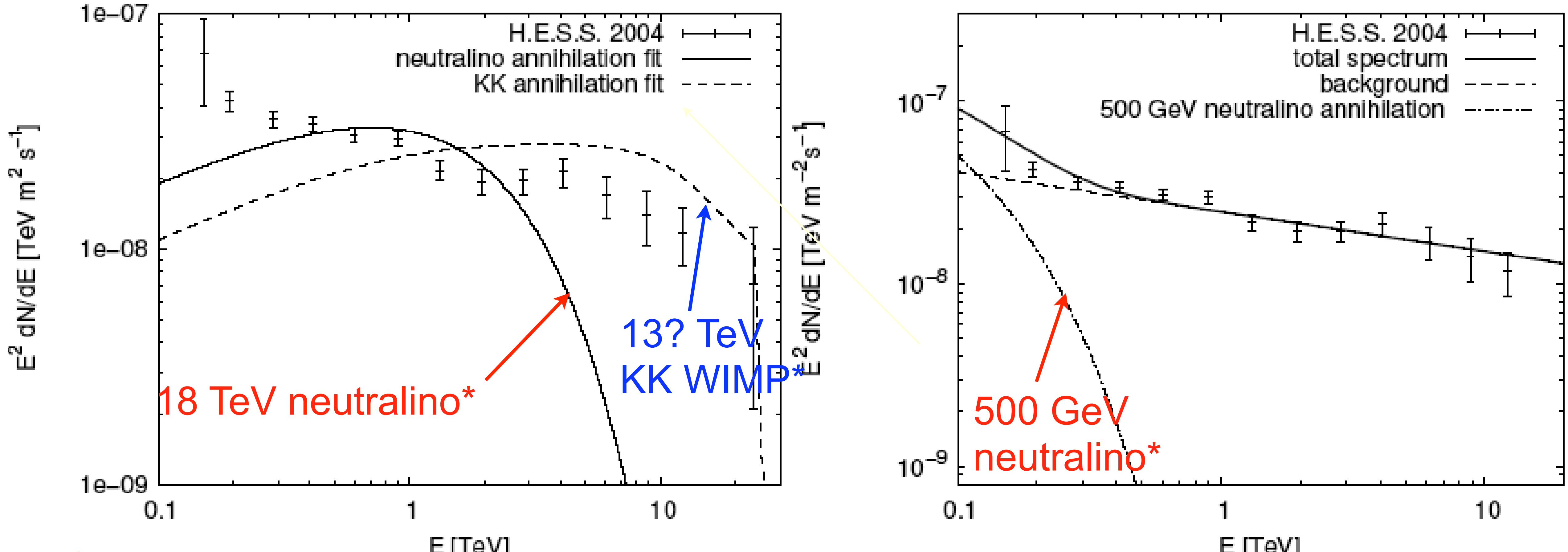


Galactic Centre source light curves. The integral nightly average flux above 1 TeV is given as function of time in modified Julian Days for both 2003 and 2004 observations. The Galactic Centre source flux is consistent with a constant flux at all probed time scales.

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



*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.

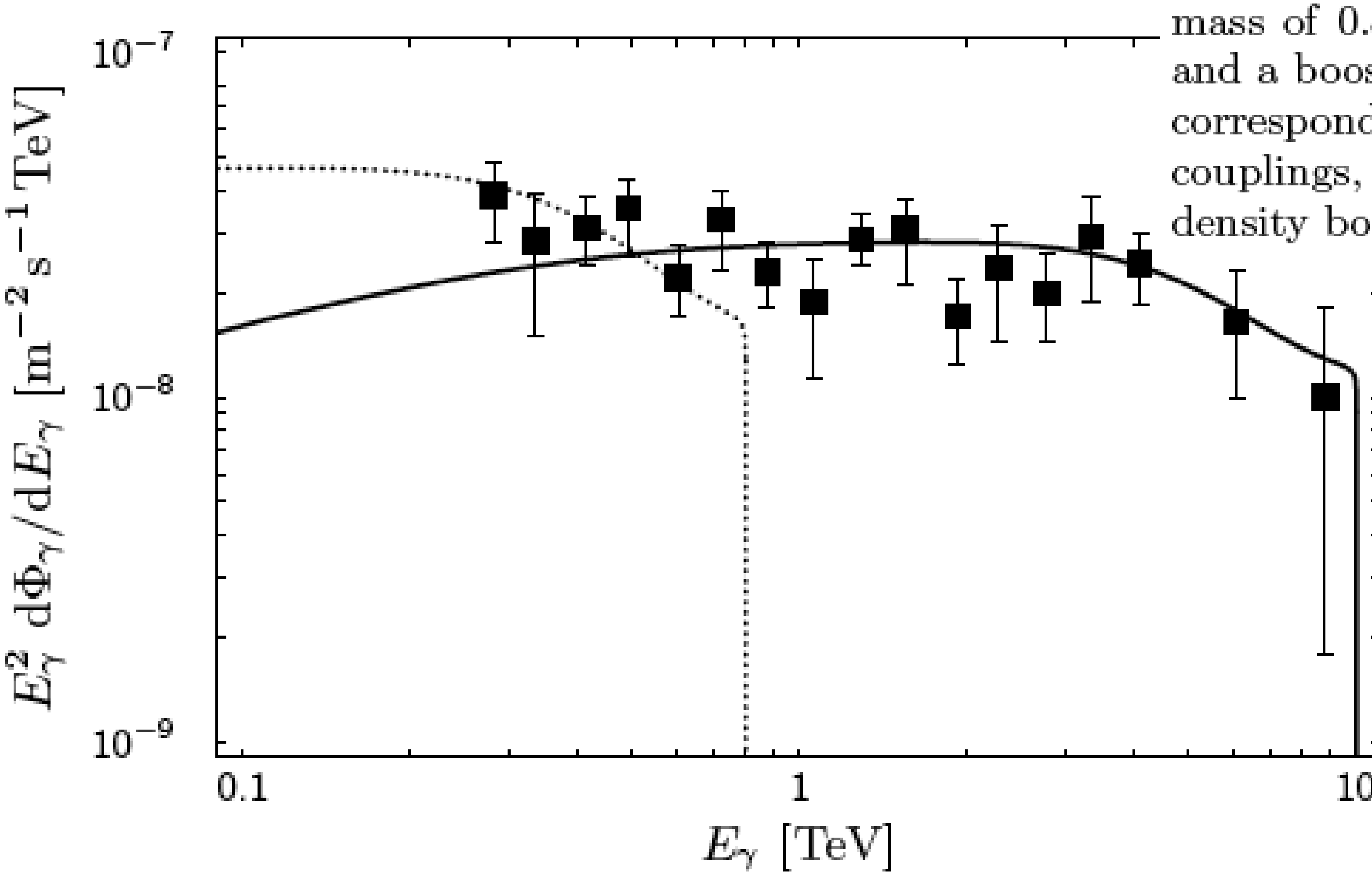


FIG. 3: The H.E.S.S. data [3] compared to the gamma-ray flux from a region of 10^{-5} sr encompassing the GC, for a $B^{(1)}$ mass of 0.8 TeV, a 5% mass splitting at the first KK level, and a boost factor b around 200 (dashed line). The solid line corresponds to a hypothetical 10 TeV WIMP with similar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

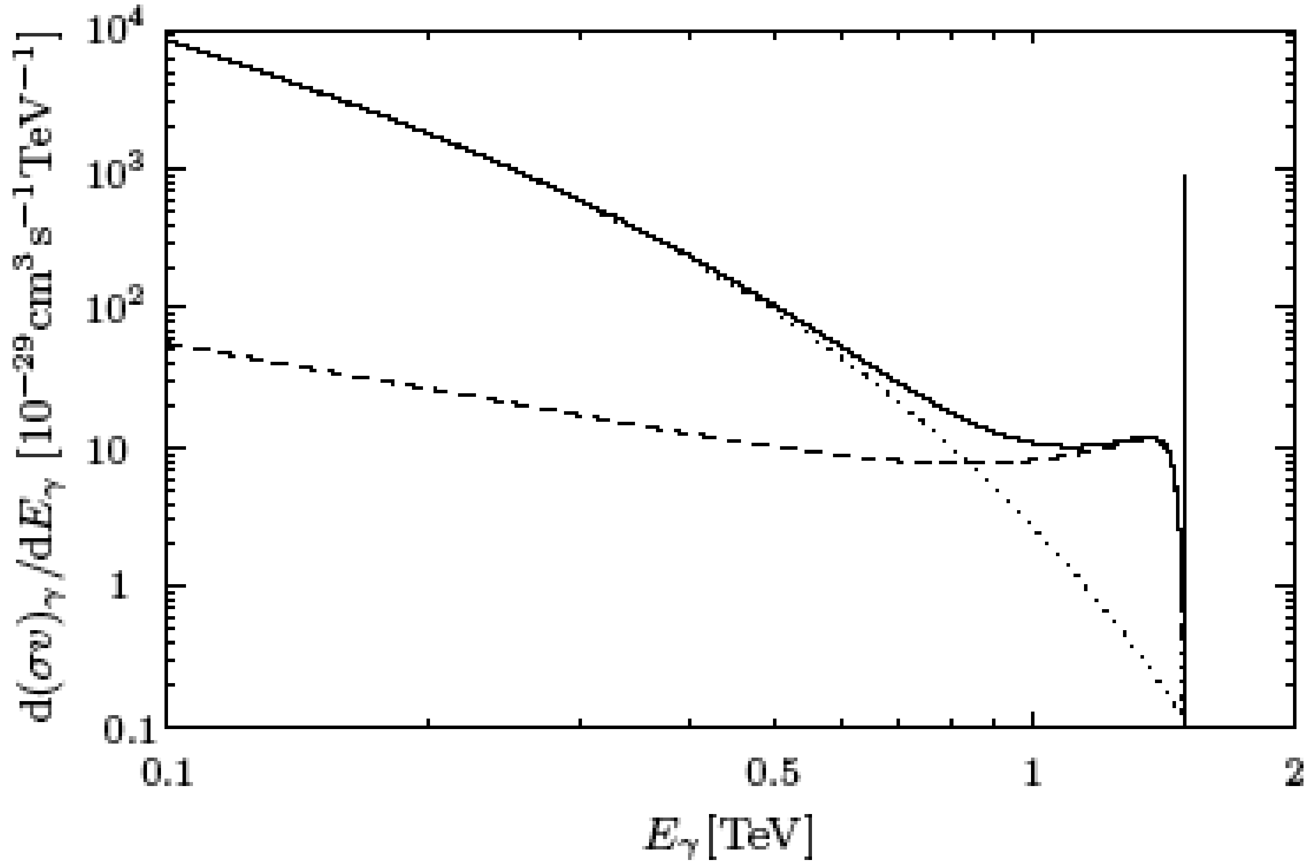


FIG. 3: The total differential photon distribution from $\chi\chi$ annihilations (solid line) for the MSSM model of Table I. Also shown separately is the contribution from radiative processes $\chi\chi \to W^+W^-\gamma$ (dashed), and the W fragmentation together with the $\chi\chi \to \gamma\gamma$,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

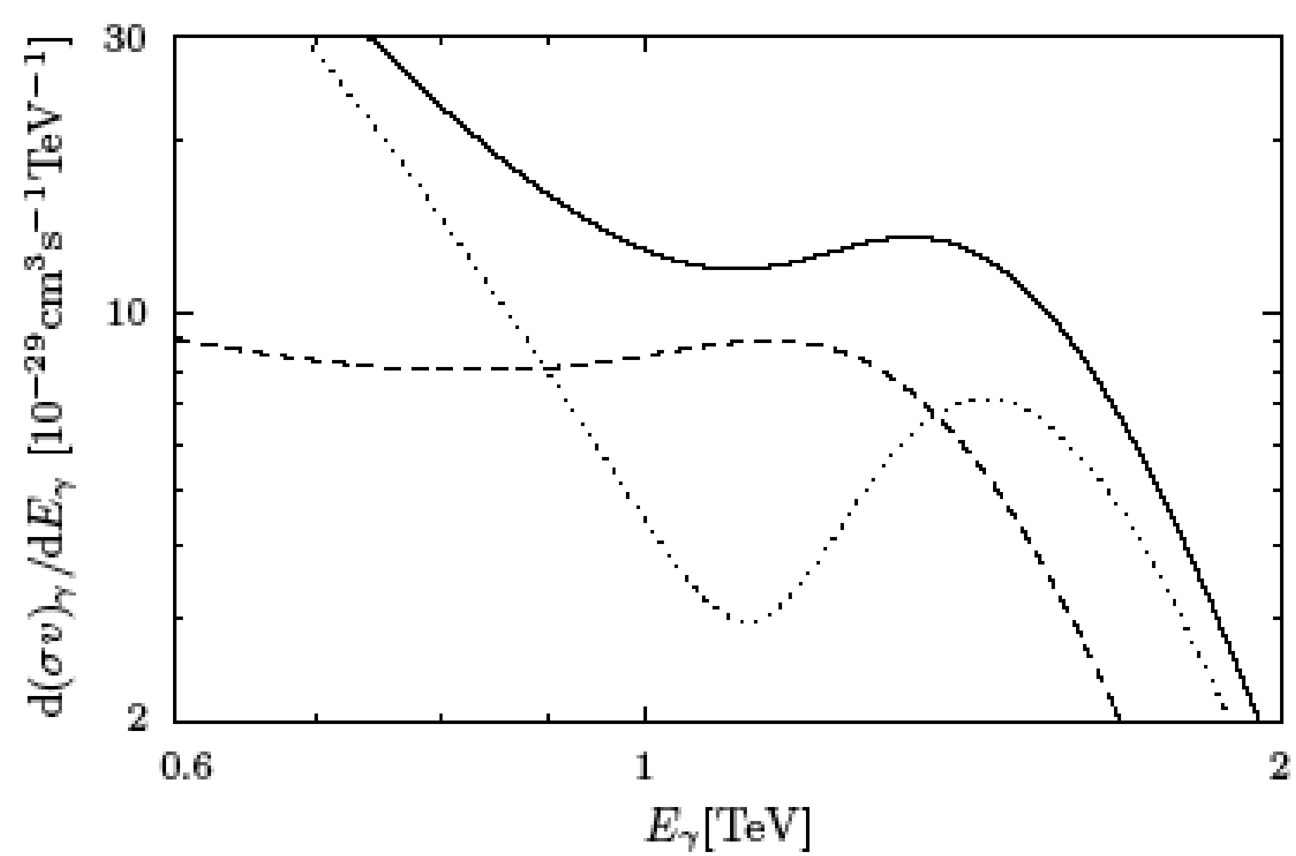


FIG. 4: The same spectra as in Fig. 3, as seen by a detector with an energy resolution of 15 percent.

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.

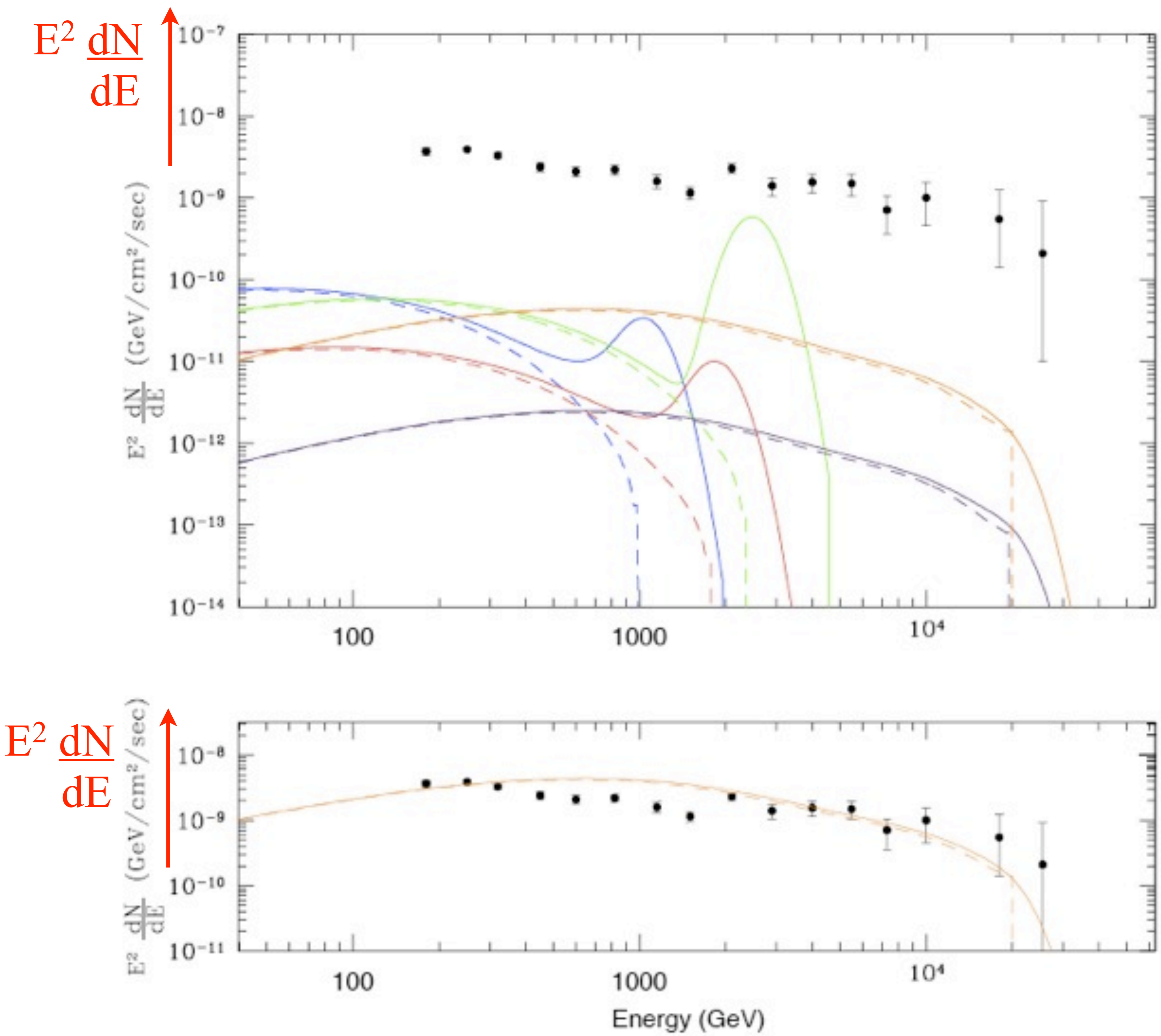
Rudy C. Gilmore, Mass Limits on Neutralino Dark Matter

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.

The Inner Region of the Milky Way Galaxy in High Energy Gamma Rays

Simona Murgia, SLAC-KIPAC
for the Fermi LAT Collaboration

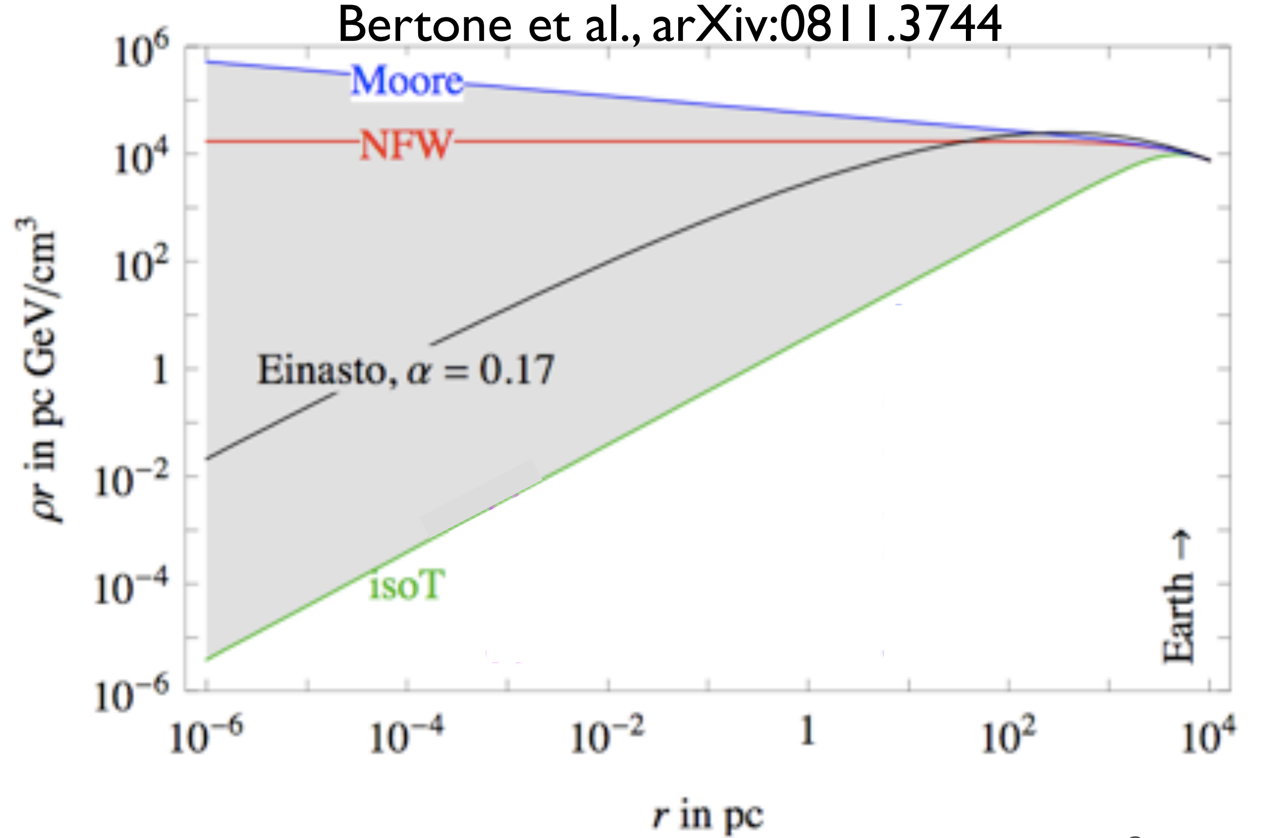
Dark Matter 2012 Conference

https://hepconf.physics.ucla.edu/dm12/agenda.html

Dark Matter Distribution

- The dark matter annihilation (or decay) signal strongly depends on the dark matter distribution.
- Cuspier profiles and clumpiness of the dark matter halo can provide large boost factors

Bertone et al., arXiv:0811.3744



NFW profile

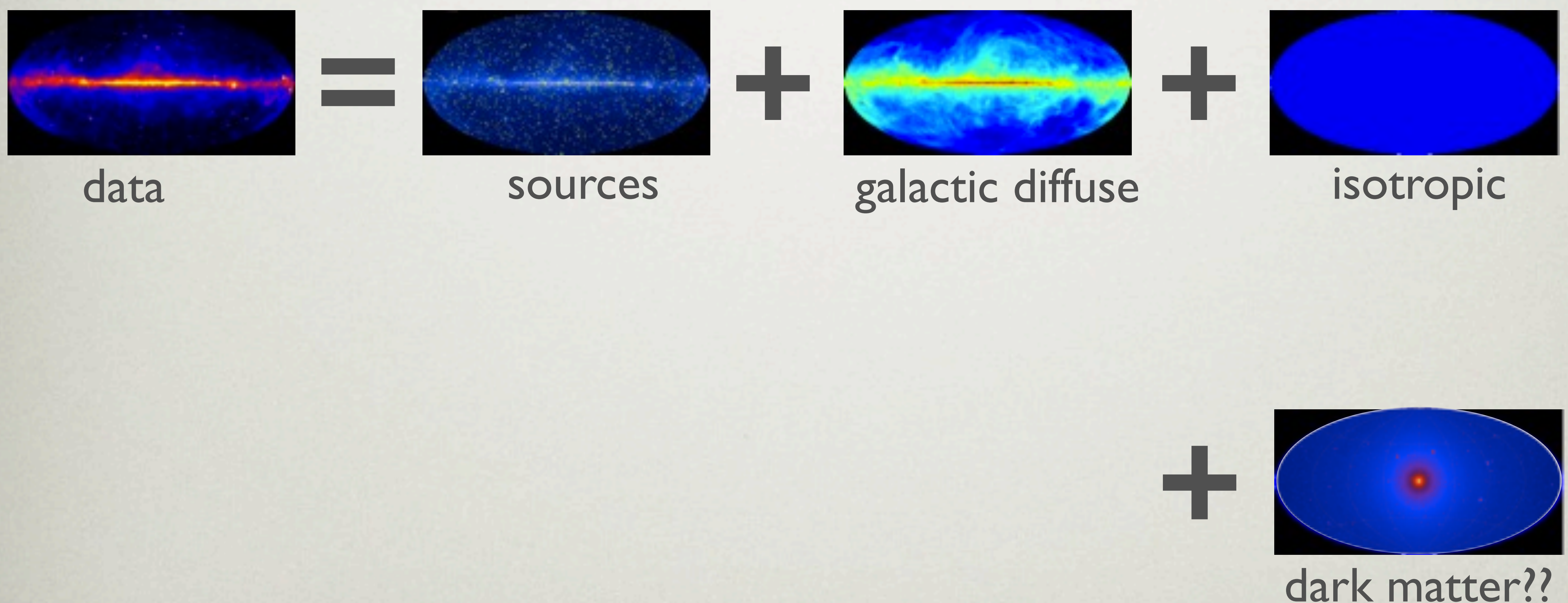
Navarro, Frenk, and White 1997

$$\rho(r) = \rho_0 \frac{r_0}{r} \frac{(1 + r_0/a_0)^2}{(1 + r/a_0)^2}$$

$$\rho_0 = 0.3 \text{ GeV/cm}^3$$
$$a_0 = 20 \text{ kpc}, \; r_0 = 8.5 \text{ kpc}$$

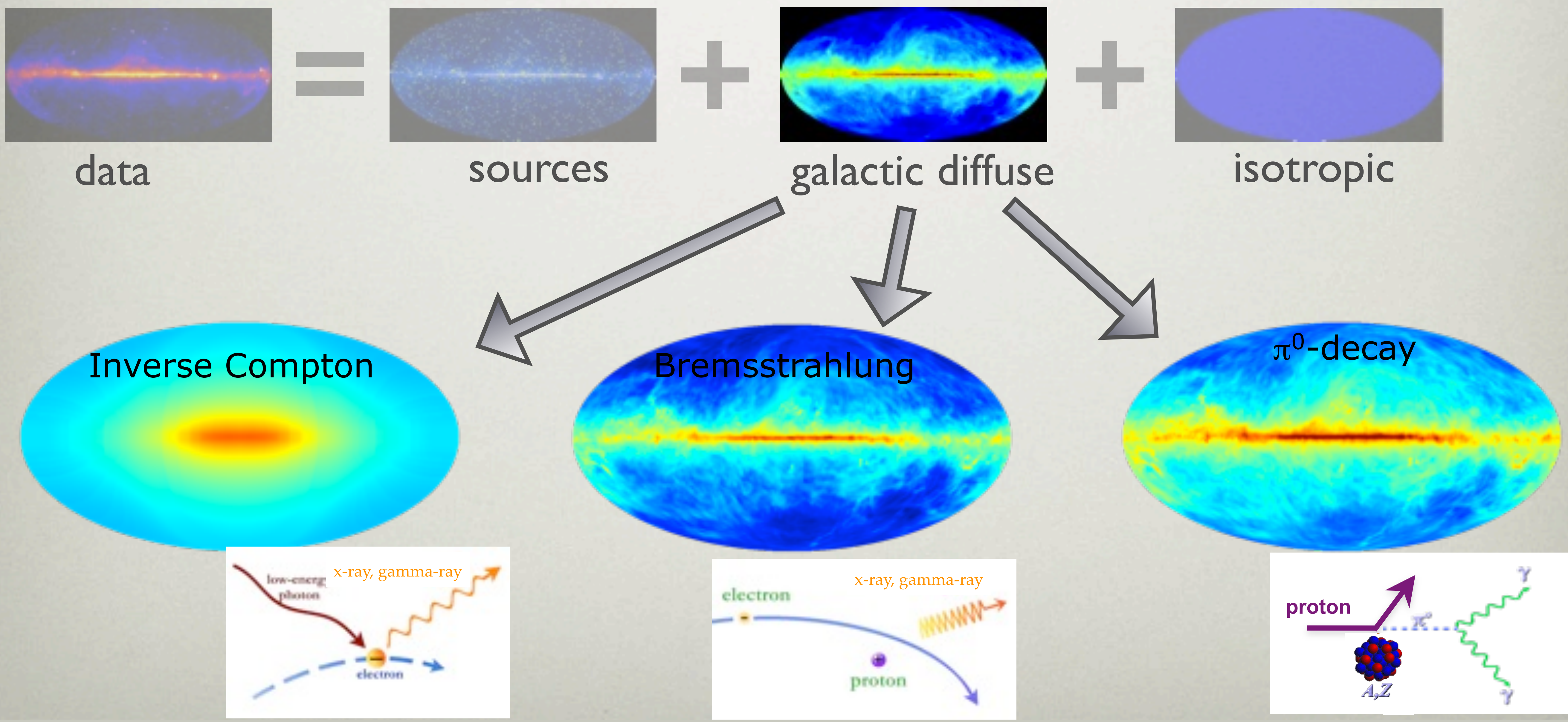
- ✓ Via Lactea II (Diemand et al 2008) predicts a cuspier profile, $\rho(r) \propto r^{-1.2}$
- ✓ Aquarius (Springel et al 2008) predicts a shallower than r^{-1} innermost profile

Understanding the Gamma-ray Sky



Galactic Diffuse Emission

- The diffuse gamma-ray emission from the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field and carries important information on the acceleration, distribution, and propagation of cosmic rays.



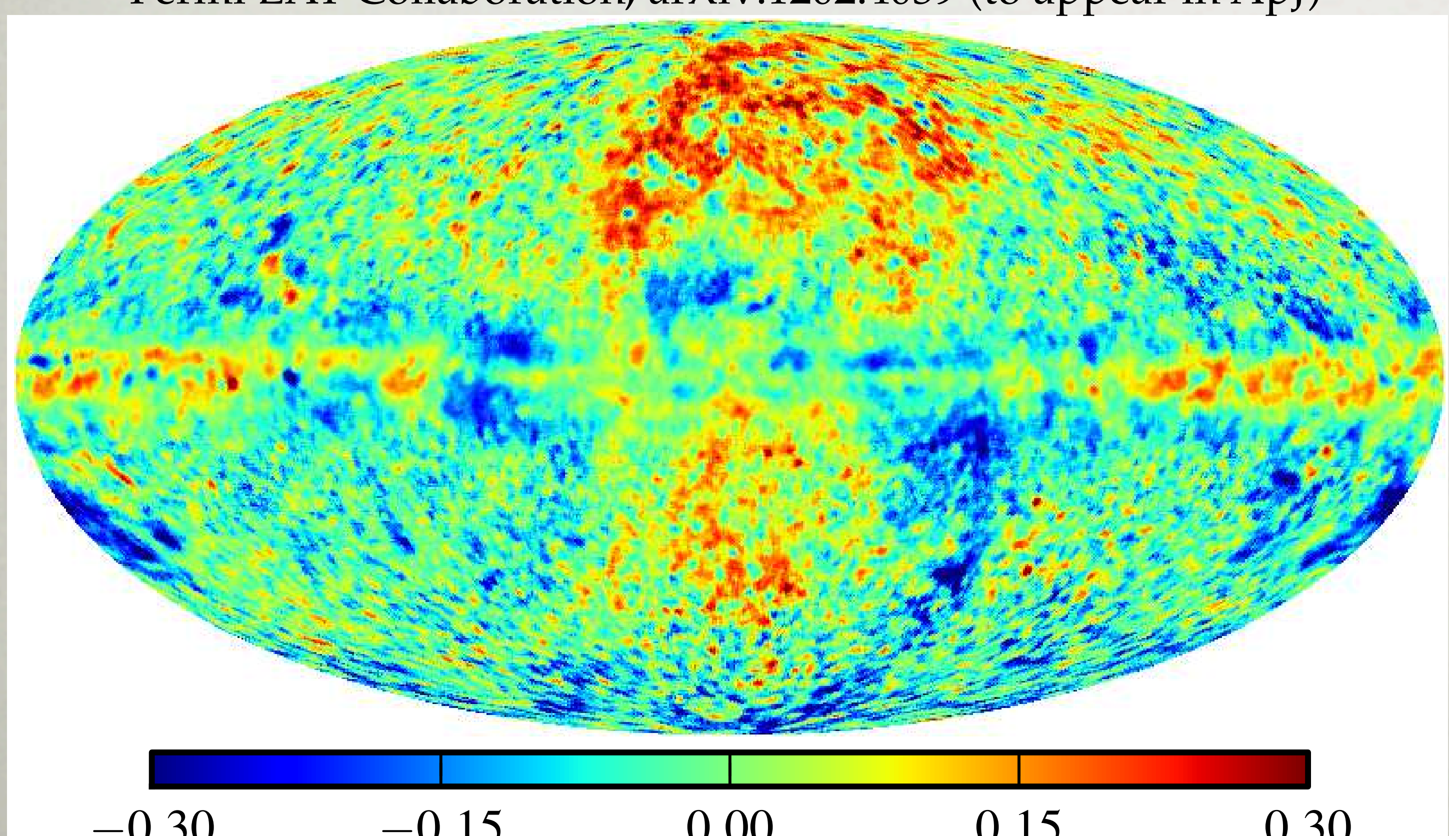
All Sky Modeling

- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions.
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare with Fermi LAT data (21 months, 200 MeV to 100 GeV, P6 DATACLEAN)

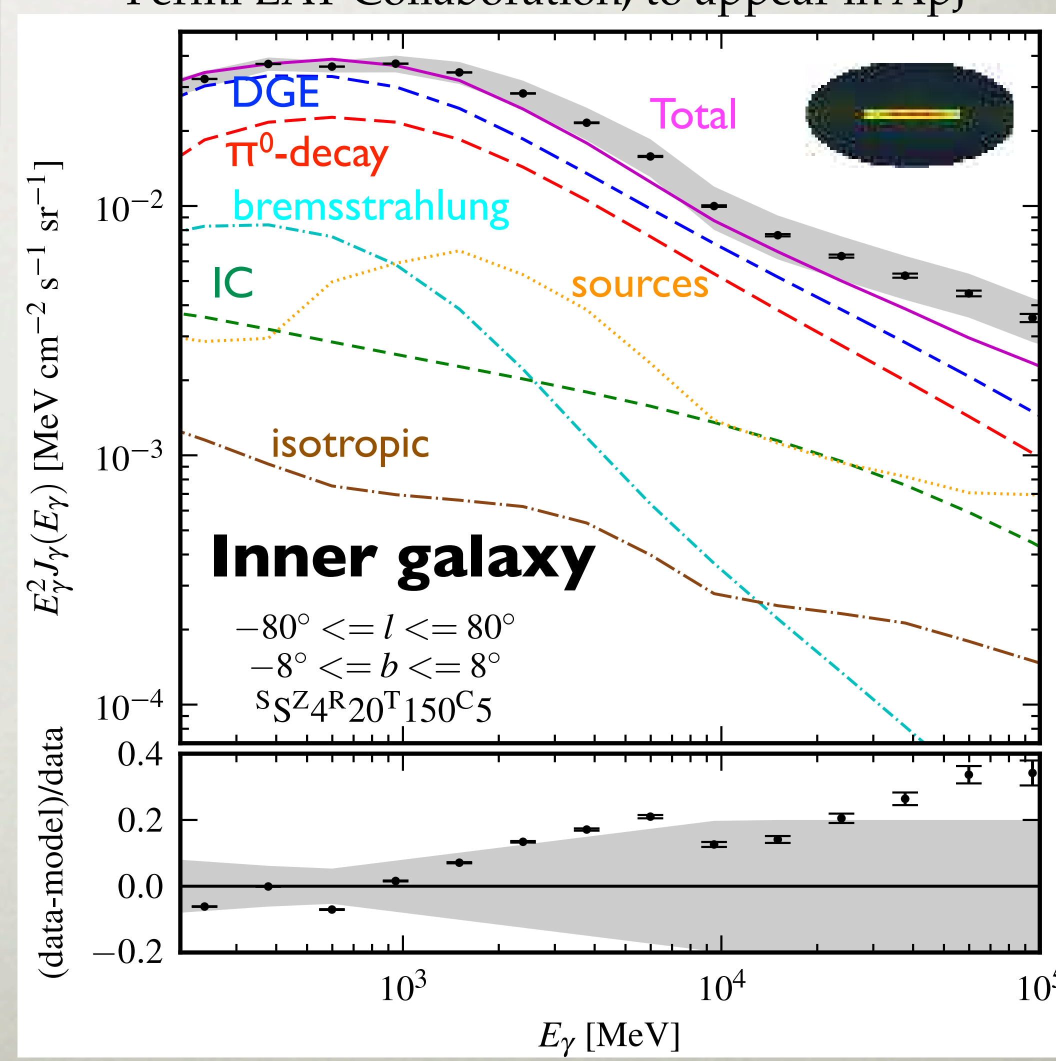
On a large scale the agreement between data and prediction is overall good, however some extended excesses stand out.

(data - prediction)/prediction) for example model

Fermi LAT Collaboration, arXiv:1202.4039 (to appear in ApJ)



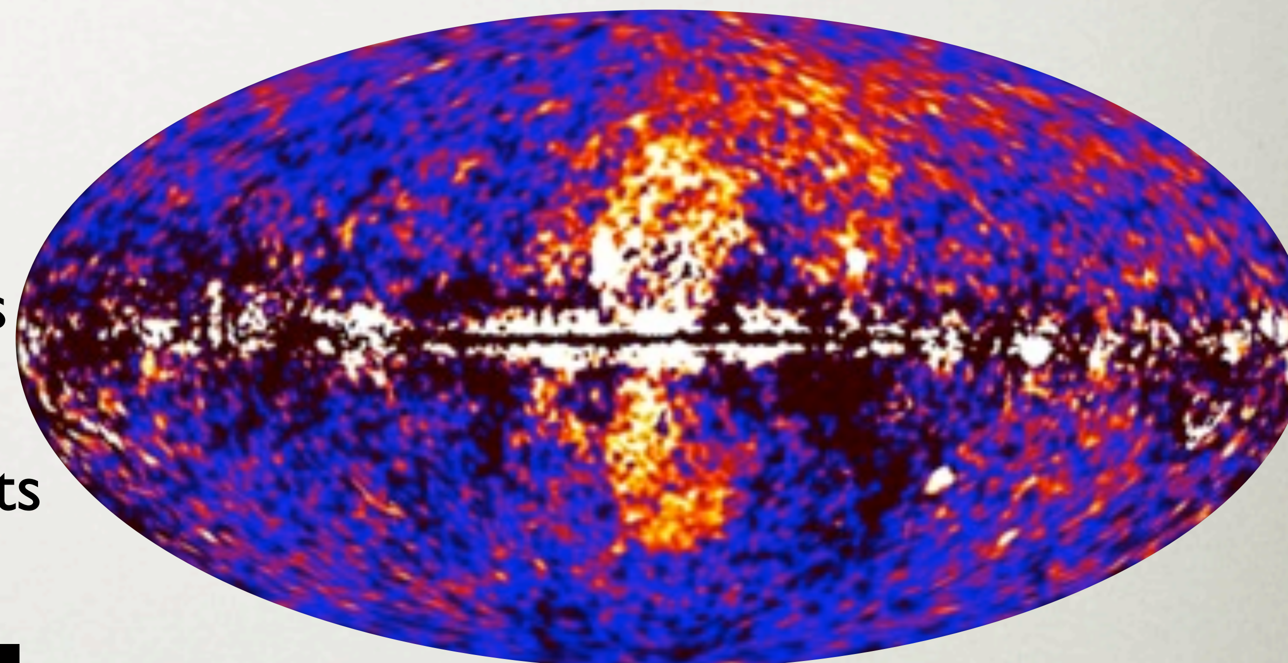
Fermi LAT Collaboration, to appear in ApJ

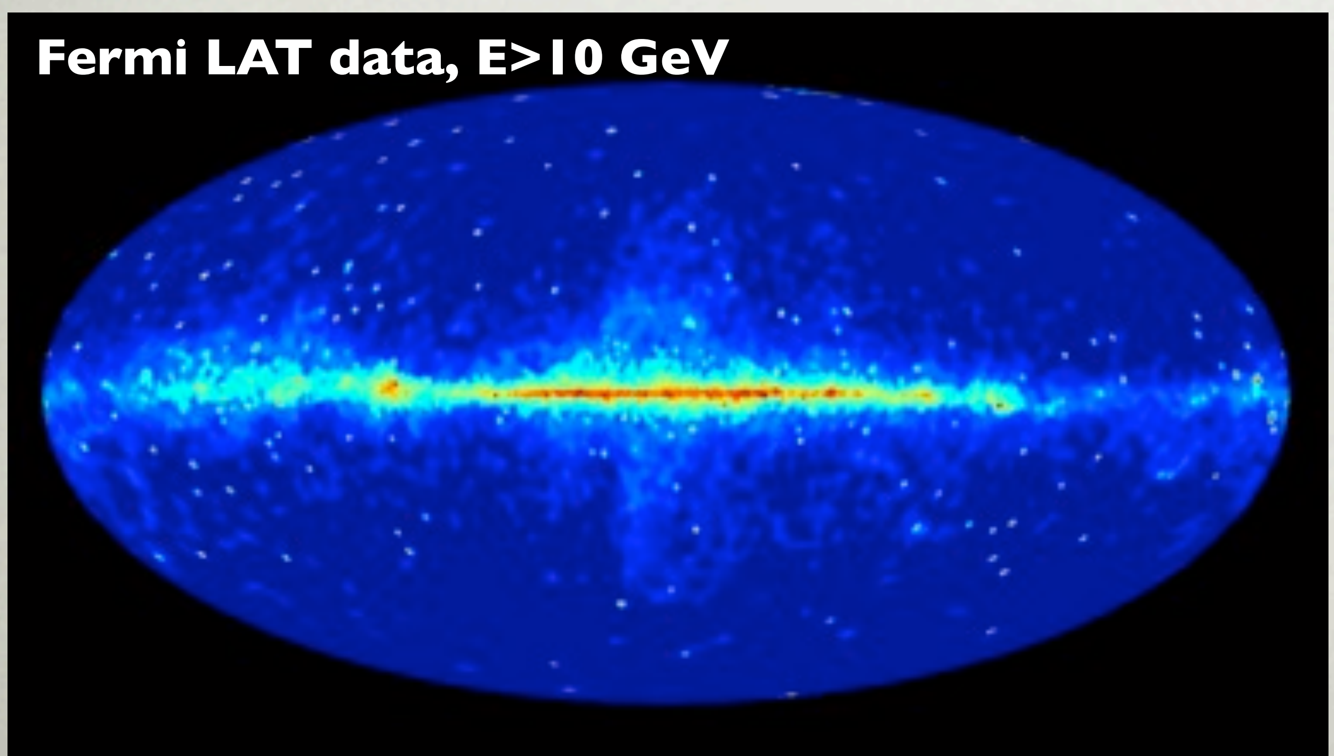


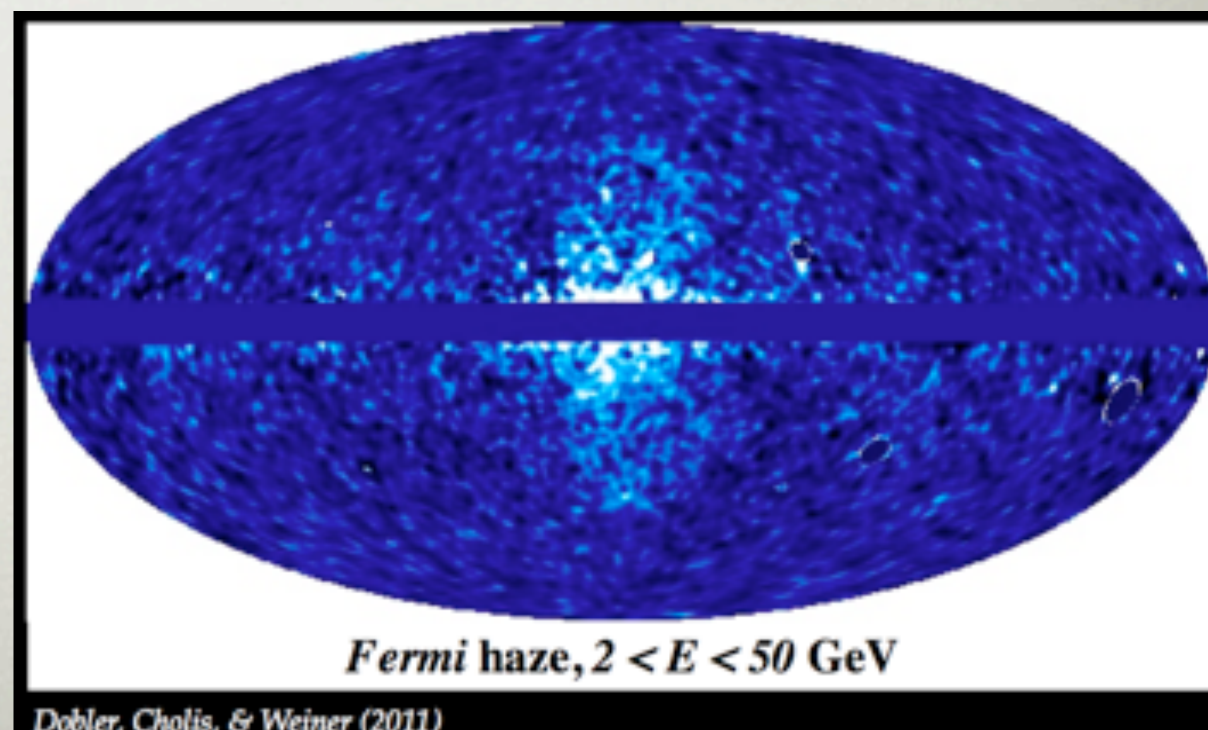
Extended Lobe-like Features in the Fermi Sky

- Gamma-ray bubbles (Su et al 2010):
  - very extended (~ 50° from plane)
  - hard spectrum (~E^{-2}, 1-100 GeV)
  - sharp edges
  - possible counterparts in other wavelengths (ROSAT, WMAP, and Planck)
- Outflow from the center of the Milky Way: jets from the supermassive black hole? starburst?

"Gamma-ray Bubbles"
Su, Slatyer, and Finkbeiner (2010)







Galactic Center Region

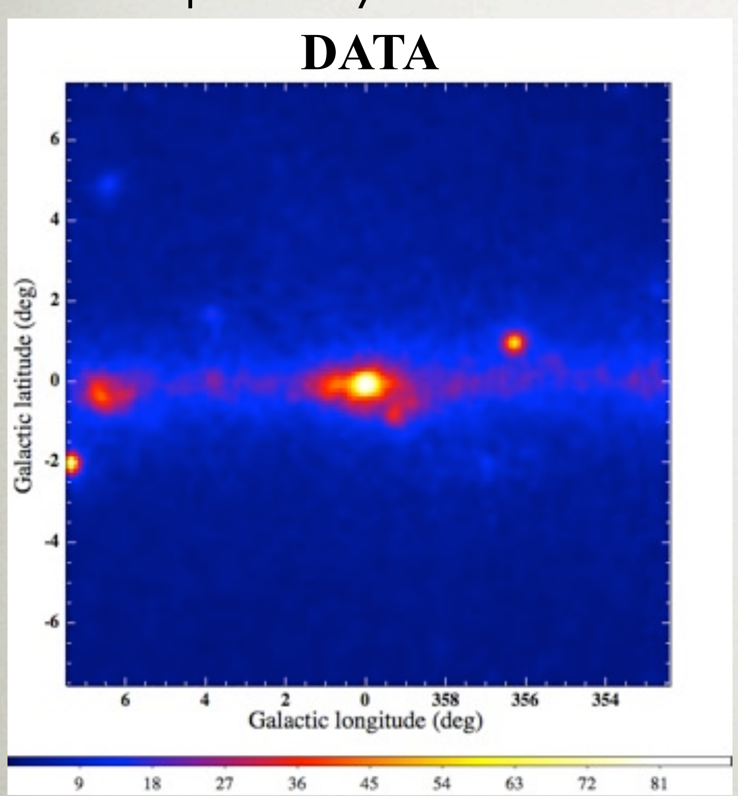
☺ Steep DM profiles predicted by CDM ⇒ Large DM annihilation/decay signal from GC!

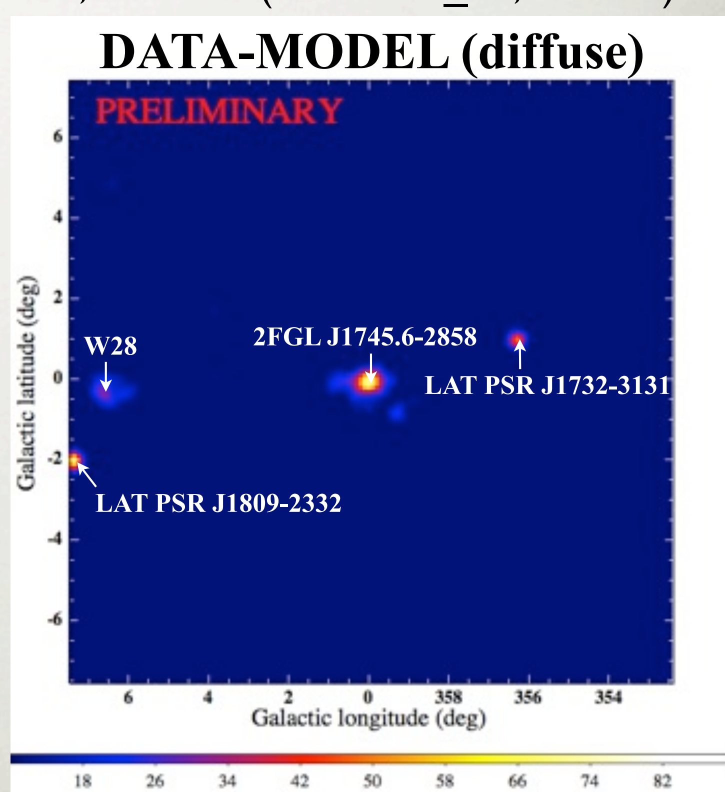
☹ Good understanding of the conventional astrophysical background is crucial to extract a potential DM signal from this complex region of the sky:

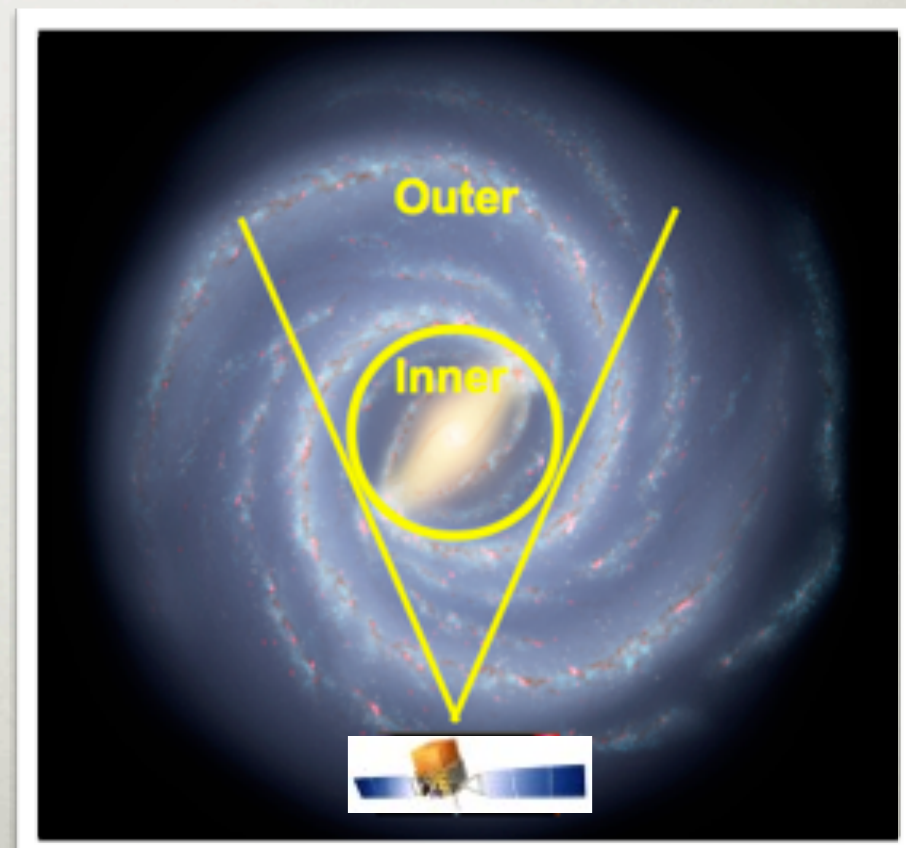
- source confusion: many energetic sources near to or in the line of sight of the GC
- diffuse emission modeling: large uncertainties due to the overlap of structures along the line of sight, difficult to model

Fermi's View of the Inner Galaxy (15°x15° region)

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):





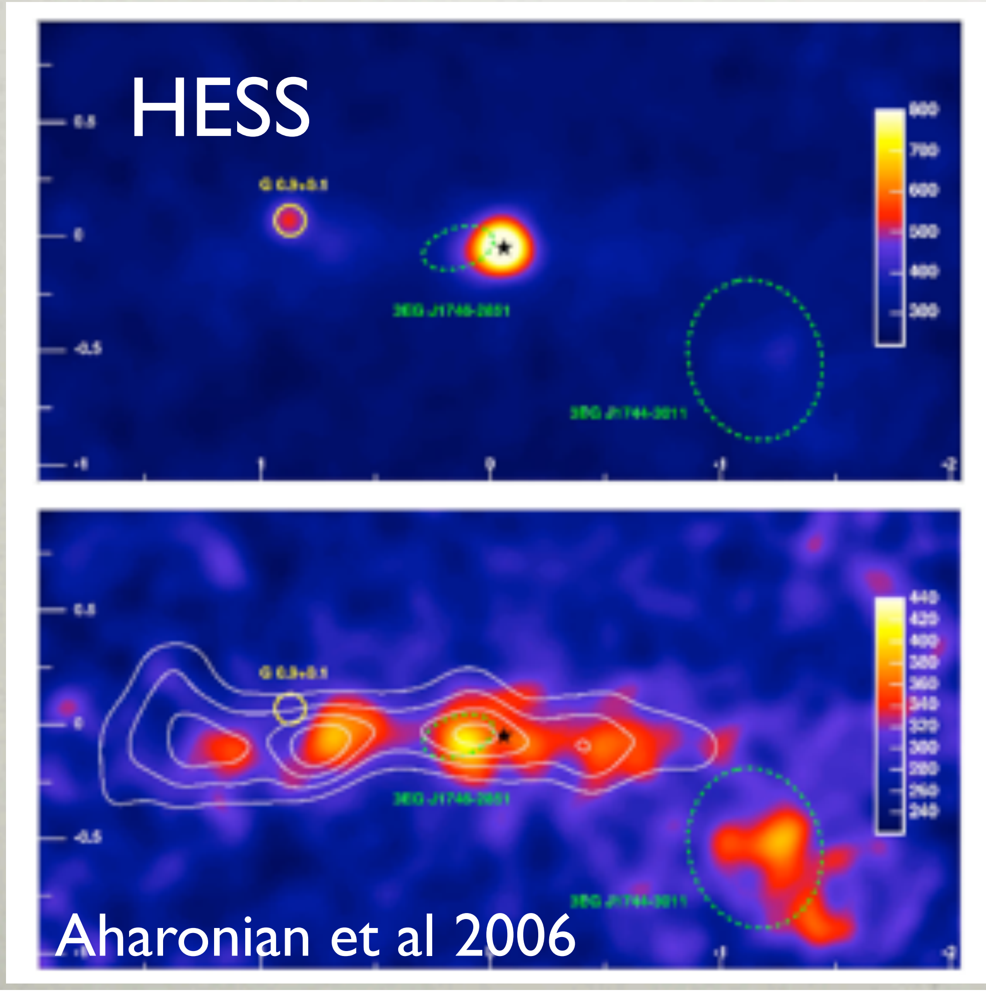


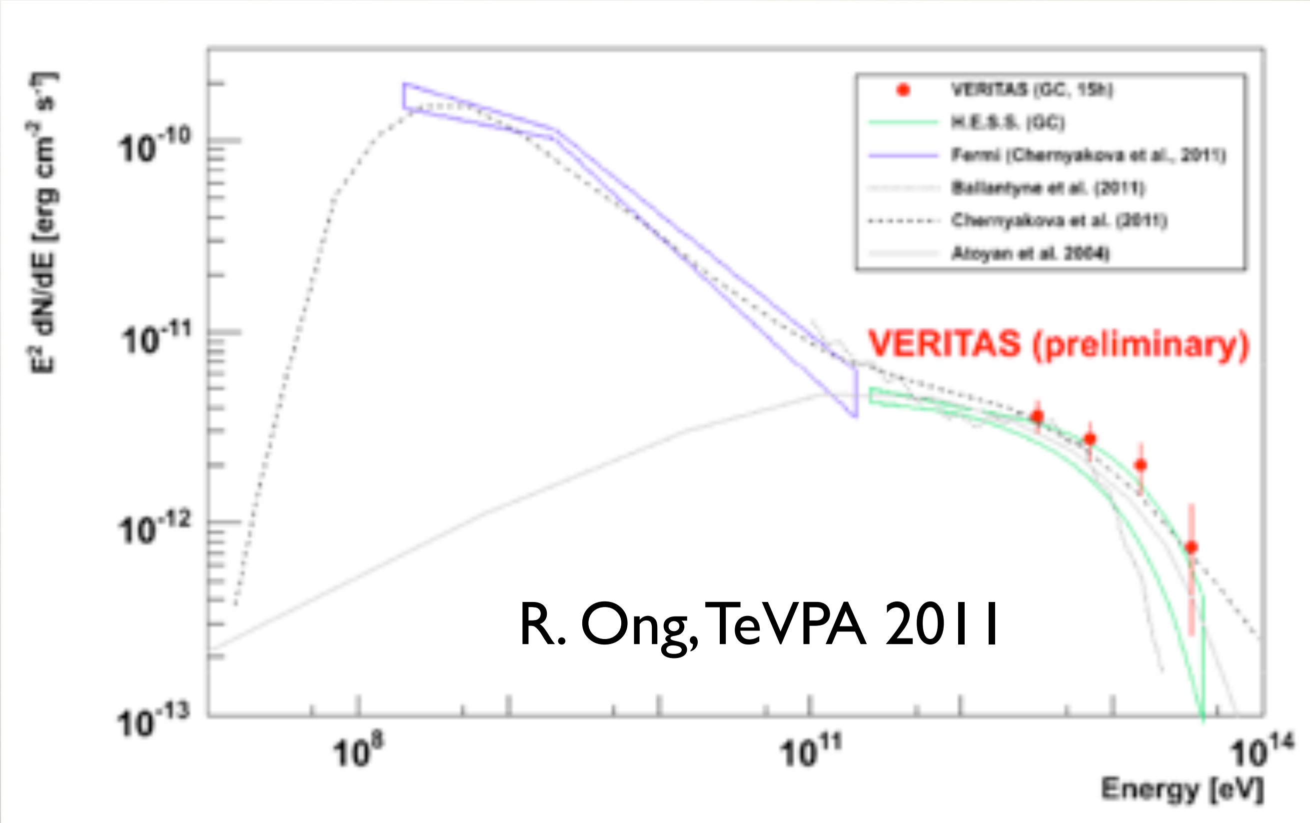
- Galactic diffuse emission model: all sky GALPROP model tuned to the inner galaxy

➡ Bright excesses after subtracting diffuse emission model are consistent with known sources.

Galactic Center Source: GeV/TeV

- GeV/TeV spectrum compatible with gamma-ray production from protons accelerated in Sgr A* and diffusing in the interstellar medium
- No time variability





Conclusions

- Preliminary results from Fermi LAT show that most of the emission from a 15°x15° region around the direction of the Galactic center can be modeled in terms of diffuse emission and sources. Papers are forthcoming and will include dark matter results
- Interesting constraints on the nature of dark matter have been determined by HESS with very high energy gamma rays
- Our knowledge of the conventional astrophysical background is uncertain. This is currently a big limitation for the search of dark matter in the Galactic center with gamma rays, which otherwise has huge potential for discovery or for setting constraints.
- In addition, better understanding of the dark matter density distribution in the Galactic center is essential in interpreting observations.

Dan Hooper's talk at Dark Matter 2012 conference

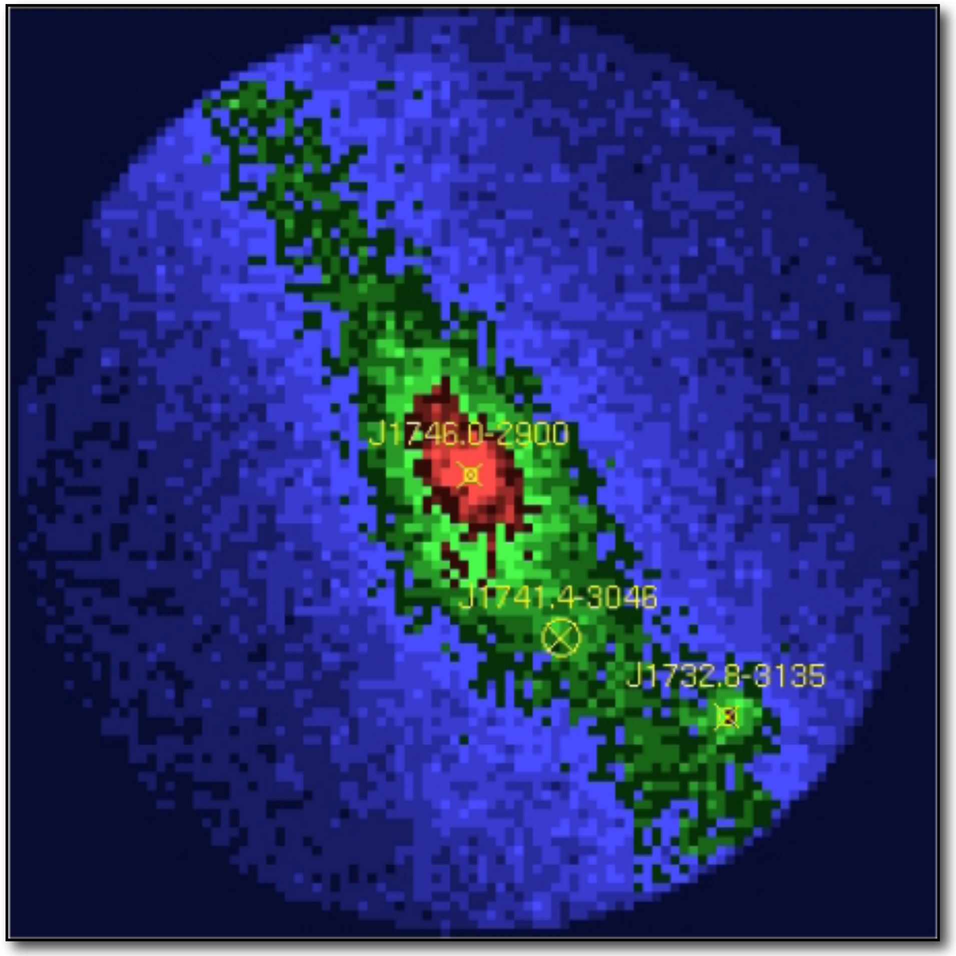
Dark Matter In The Galactic Center Region With Fermi

- The region surrounding the Galactic Center is complex; backgrounds present are not necessarily well understood

- This does not, however, necessarily make searches for dark matter in this region intractable

- The signal from dark matter annihilation is large in most benchmark models (for a typical 10 GeV WIMP, comparable to total flux observed in inner 1°)

- To separate dark matter annihilation products from backgrounds, we must focus on the distinct observational features of these components



The characteristics of a signal from dark matter annihilations:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_X^2} \int_{\rm los} \rho^2(r) dl$$

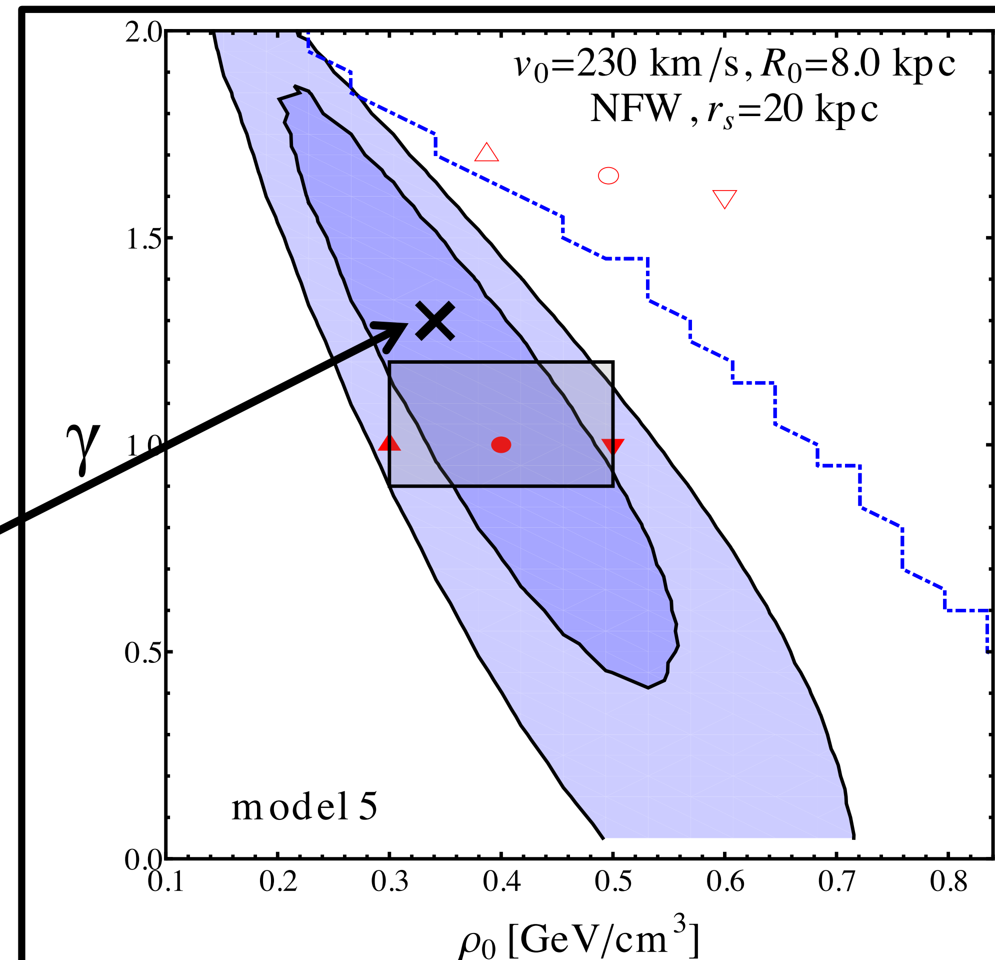
The Distribution of Dark Matter in the Inner Milky Way

- Dark matter only simulations (Via Lactea, etc.) yield halos which possess inner profiles of $\rho \propto r^{-\gamma}$ where γ=1.0 to 1.2

- The inner volume (~10 kpc) of the Milky Way is dominated by baryons, not dark matter – significant departures from dark matter only results should be expected

- For years, an active debate has taken place in the literature over the question of how the baryons alter the profiles of dark matter halos

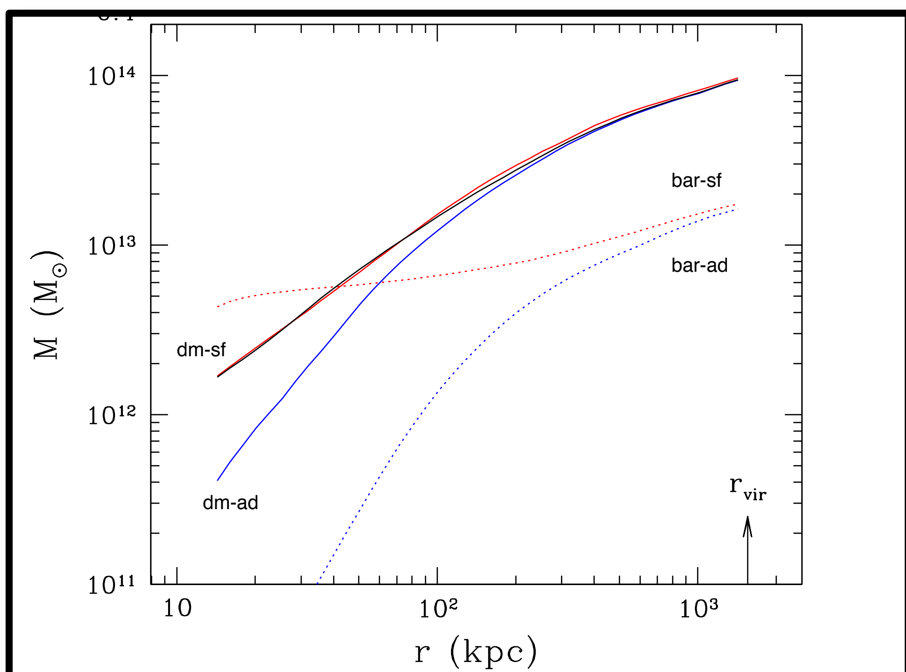
- Existing microlensing and dynamical data are not capable of determining the inner slope, although γ~1.3 provides the best fit



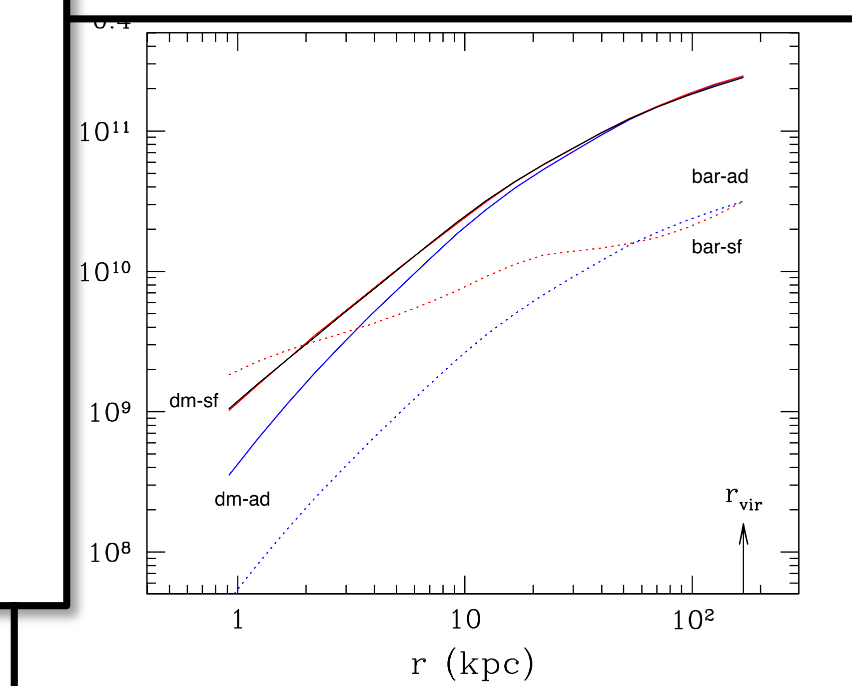
Iocco, Pato, Bertone, Jetzer, arXiv:1107.5810

The Distribution of Dark Matter in the Inner Milky Way

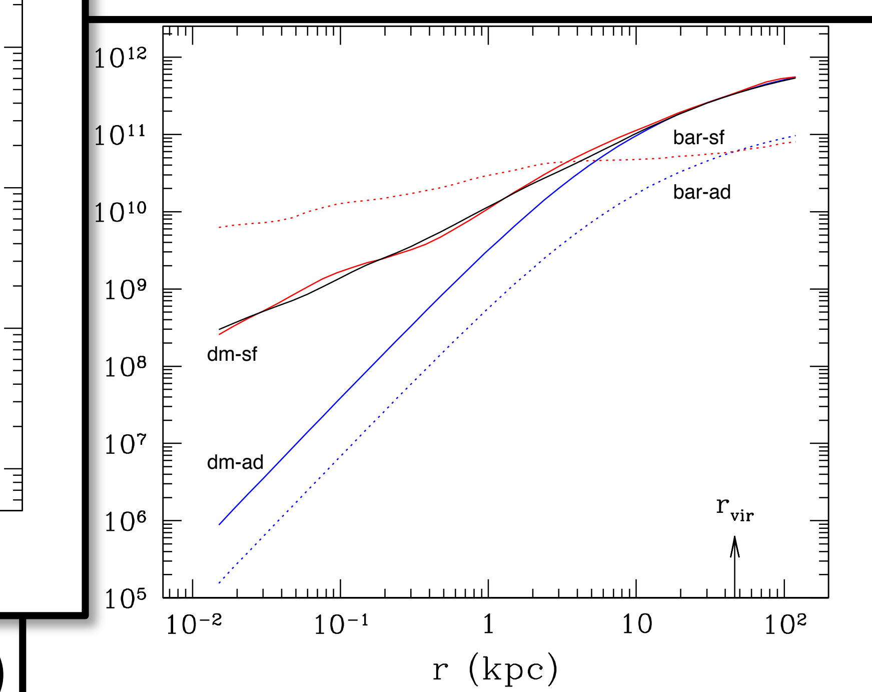
- Recently, state-of-the-art hydrodynamical simulations carried out by several different groups, running different codes, have begun to converge in favor of a moderate degree of contraction in Milky Way-like halos, typically steepening the inner slope γ from ~1.0 to ~1.2-1.5
- Such simulations include rapid supernova winds, cold accretion, galactic bars, inspiraling of dense baryonic clumps by dynamical friction, etc., but consistently find that baryonic contraction dominates over these effects



D. Nagai (2006)



Gottloeber et al. (2010)

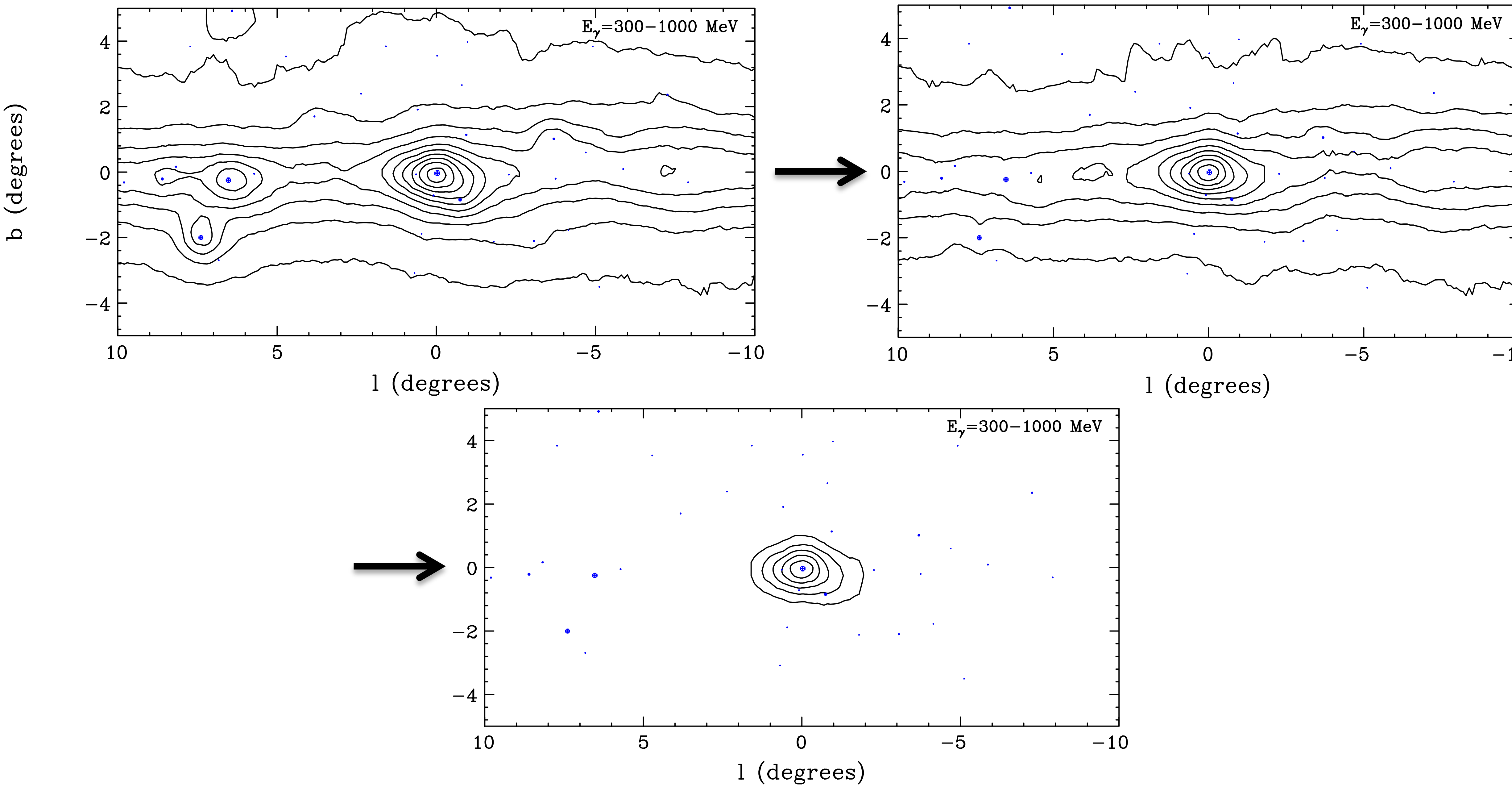


Levine et al. (2008)

(Gnedin, et al. arXiv:1108.5736)

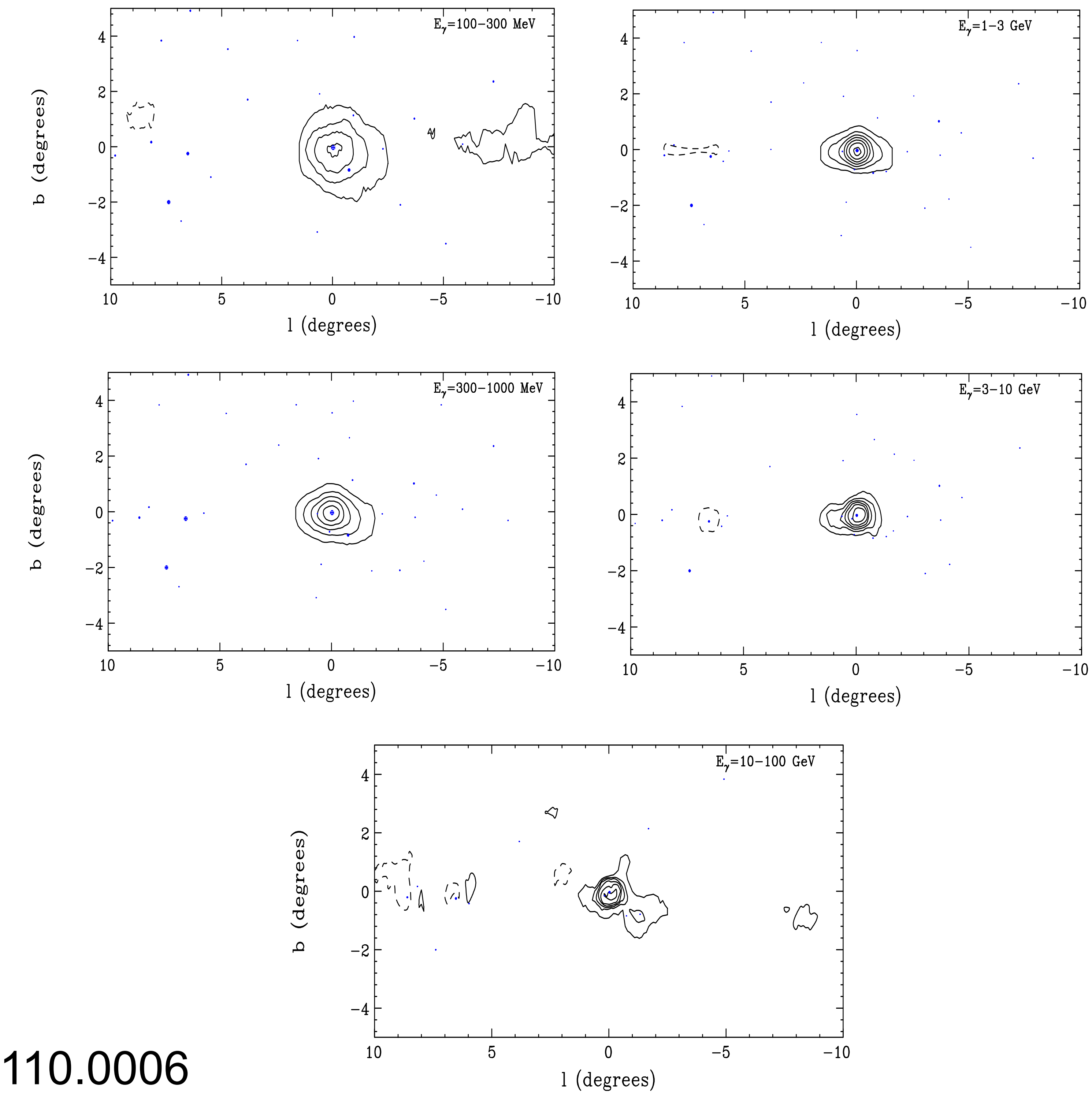
A Simple (but effective) Approach To The Galactic Center

1) Start with raw map (smeared over 0.5° circles)
2) Subtract known point sources (Fermi 2nd point source catalog)
3) Subtract line-of-sight gas density template (empirical, good match to 21 cm)



A Simple (but effective) Approach To The Galactic Center

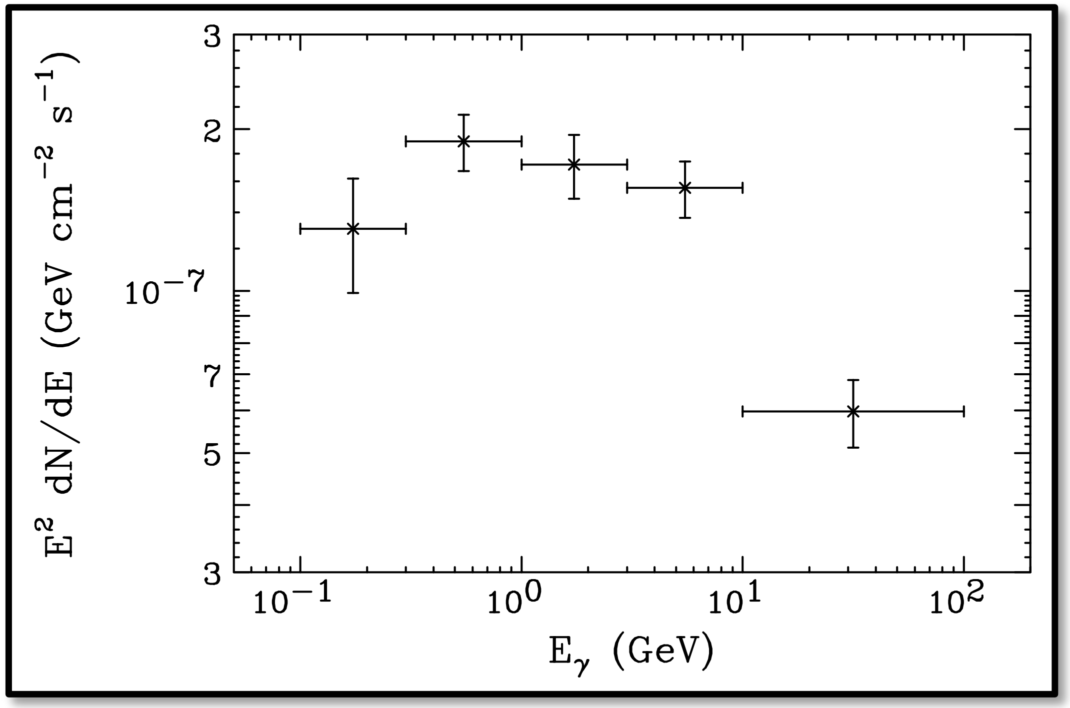
- This method removes ~90% of emission in the inner galaxy (outside of the innermost few degrees)
- Typical residuals are ~5% or less as bright as the inner residual – spatial variations in backgrounds are of only modest importance
- Clearly isolates the emission associated with the inner source or sources (supermassive black hole? dark matter?), along with a subdominant component of “ridge” emission



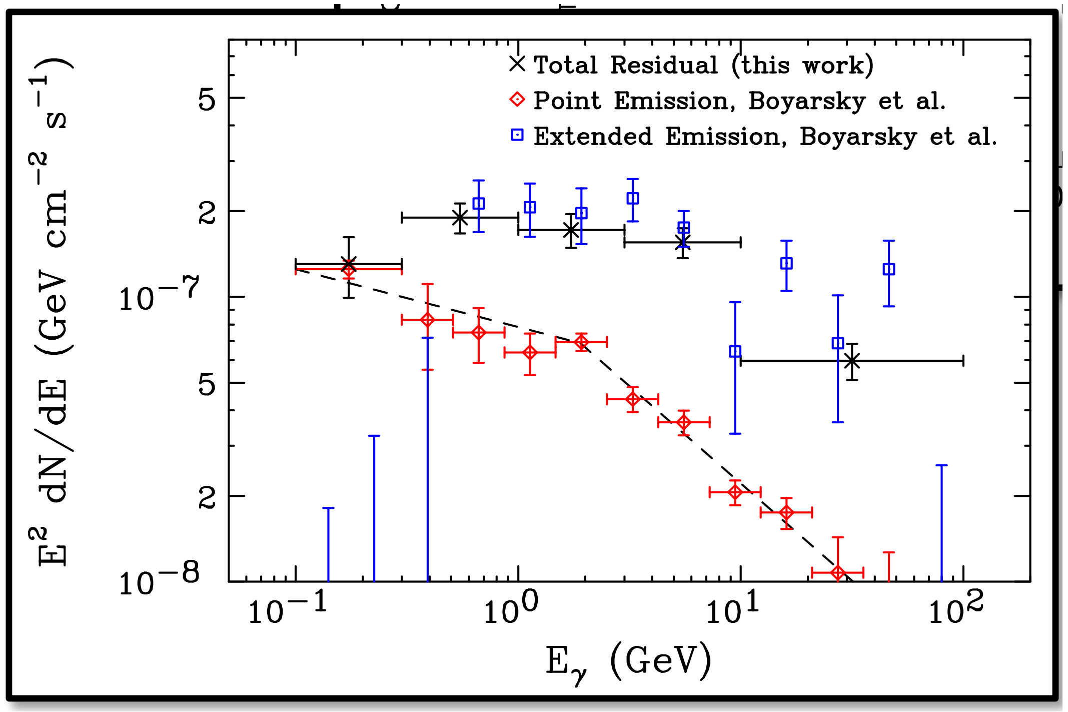
Hooper and Linden, PRD, arXiv:1110.0006

Characteristics of the Observed Gamma ray Residual

1) The spectrum peaks between ~300 MeV and ~10 GeV

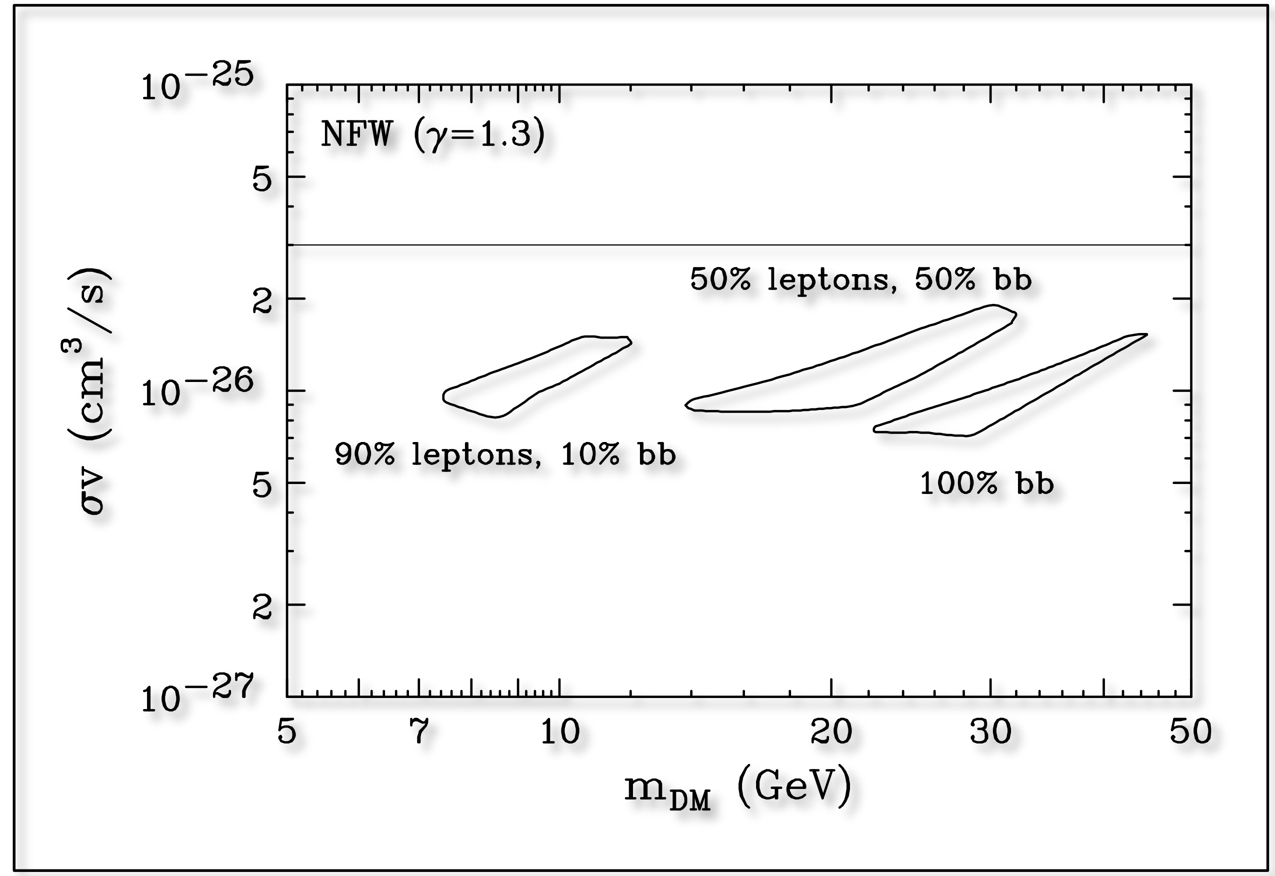


2) Clear spatial extension - only a small fraction of the emission above ~300 MeV is point-like



The Dark Matter Interpretation

- The spectral shape of the excess can be well fit by a dark matter particle with a mass in the range of 7 to 12 GeV (*similar to that required by CoGeNT, DAMA, and CRESST*), annihilating primarily to $\tau^+\tau^-$ (possibly among other leptons)



- The angular distribution of the signal is well fit by a halo profile with $\rho(r) \sim r^{-\gamma}$, with $\gamma \sim 1.25$ to 1.4 (in good agreement with expectations from simulations)

- The normalization of the signal requires the dark matter to have an annihilation cross section within a factor of a few of the value predicted for a simple thermal relic ($\sigma v \sim 3\times10^{-26}$ cm^3/s)

Hooper and Linden, PRD, arXiv:1110.0006

Astrophysical Interpretations?

Unresolved Point Sources?

Perhaps a population of several/many unresolved points sources distributed throughout the inner tens of parsecs of the Milky Way could produce the observed signal - millisecond pulsars, for example

-Much has been made of the qualitative similarity with the spectra of gamma ray pulsars, but in actuality very few of the pulsars observed by Fermi are compatible (the average spectrum is clearly incompatible); perhaps a somewhat different population or class of pulsars could be responsible?

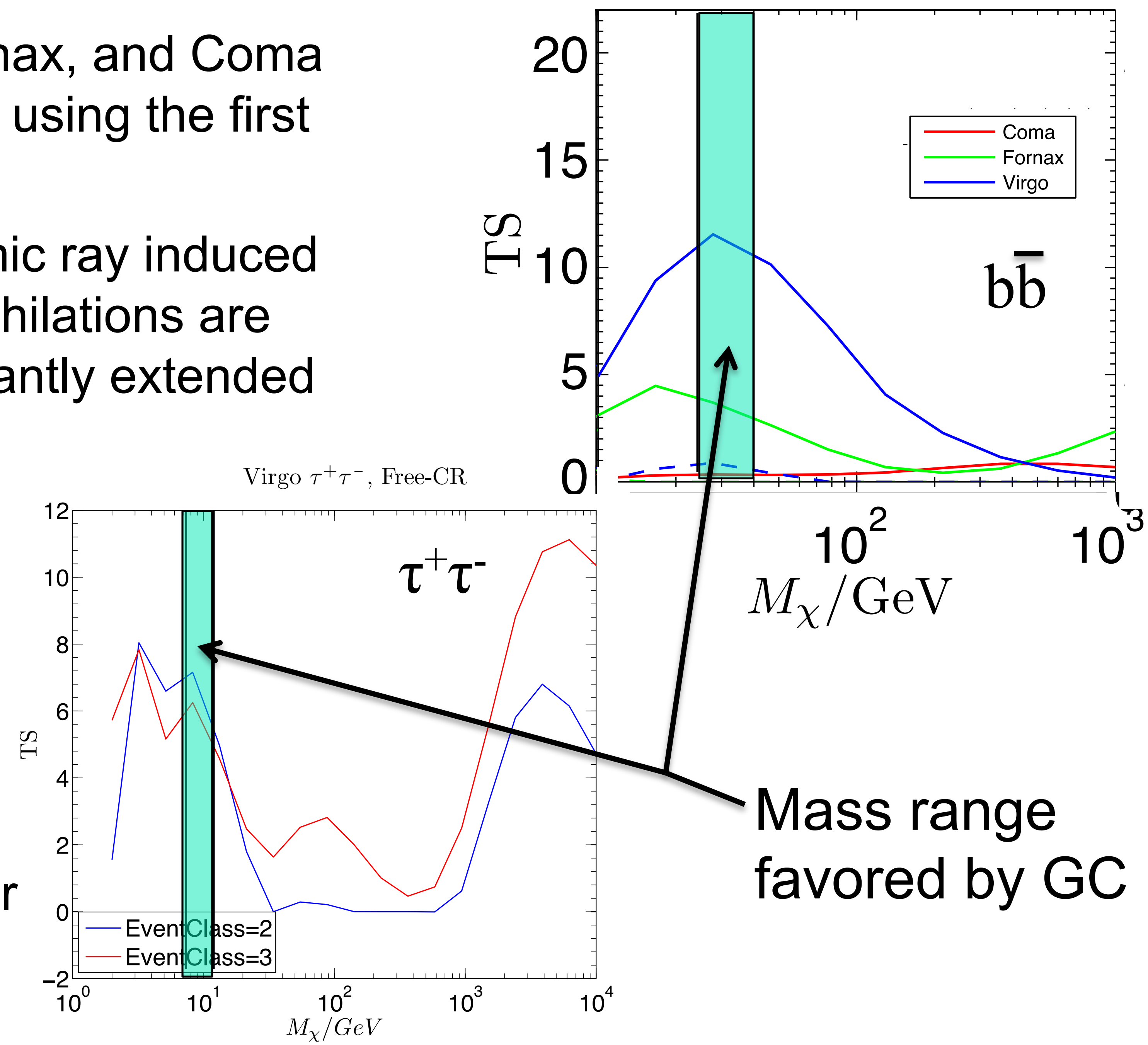
-Why is the signal so concentrated (why so many in the inner 20 pc, and so few at 100 pc?); the signal ($F \alpha r^{-2.5}$) is much more steeply cusped than the observed stellar distribution ($n_{star} \alpha r^{-1.25}$)

-With typical pulsar kicks of 250-500 km/s, millisecond pulsars should escape the inner region of the galaxy, and be distributed no more steeply than r^{-2} (assuming that *none* are created outside of the inner tens of parsecs)

Abazajian, JCAP, arXiv:1011.4275,
Hooper, Goodenough PLB 2010,
Hooper, Linden PRD 2011

Extended Gamma Ray Emission From Galaxy Clusters

- The regions of the Virgo, Fornax, and Coma clusters were recently studied, using the first three years of Fermi data
- In contrast to (hadronic) cosmic ray induced backgrounds, dark matter annihilations are predicted to produce a significantly extended pattern of emission
- Highest significance signal is found from Virgo (4.4σ); 2.3 and 2.1σ for others
- Can be fit by dark matter annihilations with same mass, channels, and cross section required by the Galactic Center
- Preferred over vanilla cosmic ray interpretation at ~3σ



Han, Frenk, Eke, Gao, White, arXiv:1201.1003

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!

$\Omega_m > 1$ — SN87A — RED GIANTS — ACCEL. EXPTS

$m_a < 10^{-6}$ eV — 10^{-2} eV — 100 keV

window

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

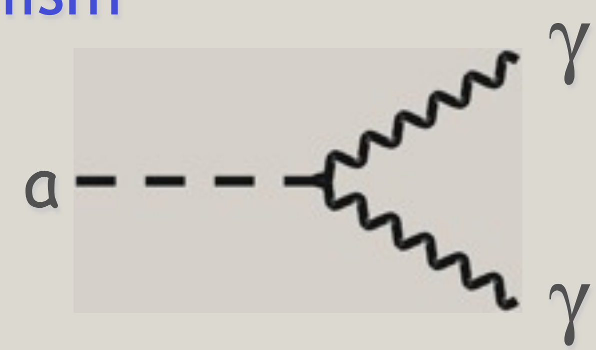
When the temperature T drops to $T \sim f_a$, the axion field gets a vacuum expectation value $f_a e^{i\theta}$, and then when T drops to $\Lambda_{QCD} \sim 100$ MeV QCD causes the axion to get mass m_a and density $\rho_a \propto 1/m_a$.

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

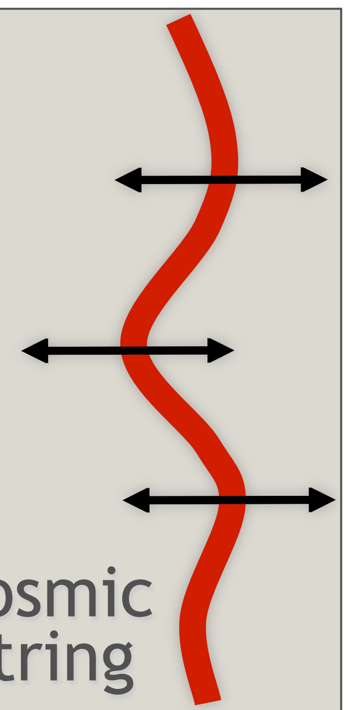
- Search for solar axions (CAST)

Cosmology

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

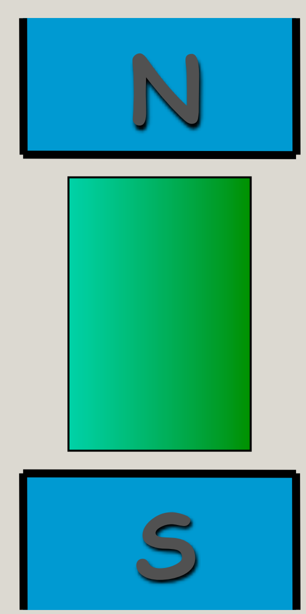
→ "Cold dark matter" candidate

$m_a \sim 1\text{-}1000\ \mu\text{eV}$

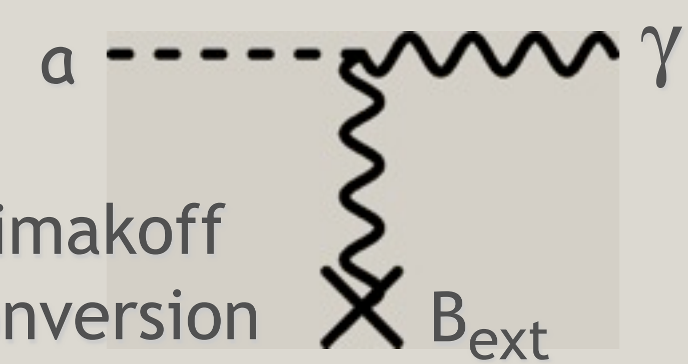


Cosmic String

Search for Axion Dark Matter



Microwave resonator
(1 GHz = 4 μeV)



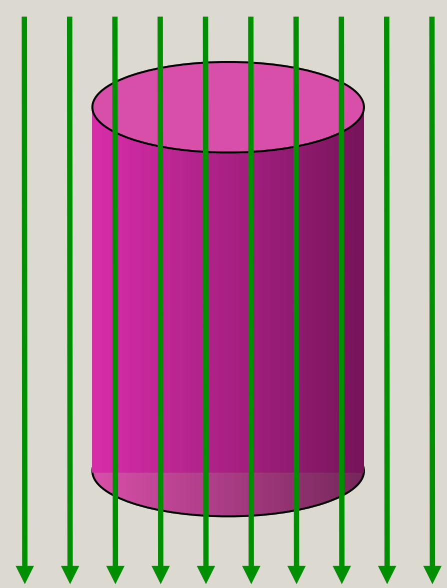
Primakoff conversion

Experimental Search for Axions

DM axions $m_a = 10\text{-}3000\ \mu eV$
Velocities in galaxy $v_a \approx 10^{-3}\ c$
Energies therefore $E_a \approx (1 \pm 10^{-6})\ m_a$

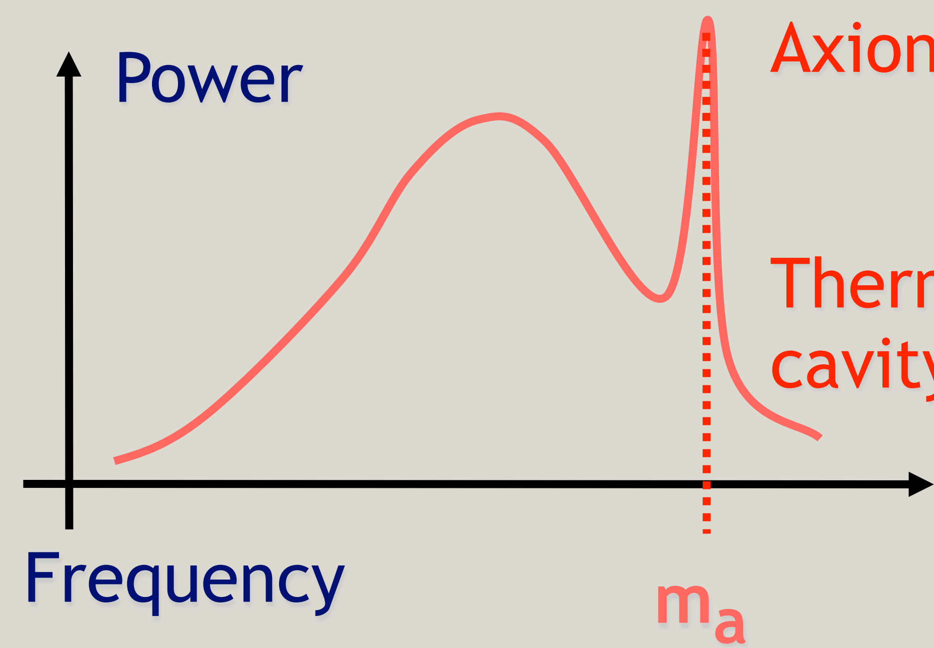
Microwave Energies
(1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)



$B_{ext} \approx 8$ Tesla

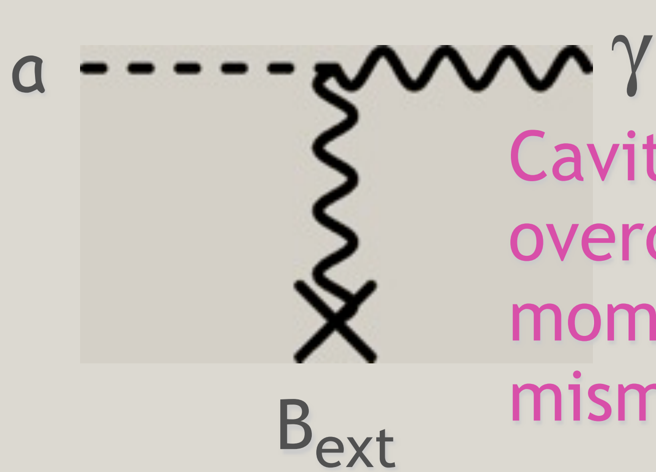
Microwave Resonator
$Q \approx 10^5$



Axion Signal

Thermal noise of cavity & detector

Primakoff Conversion



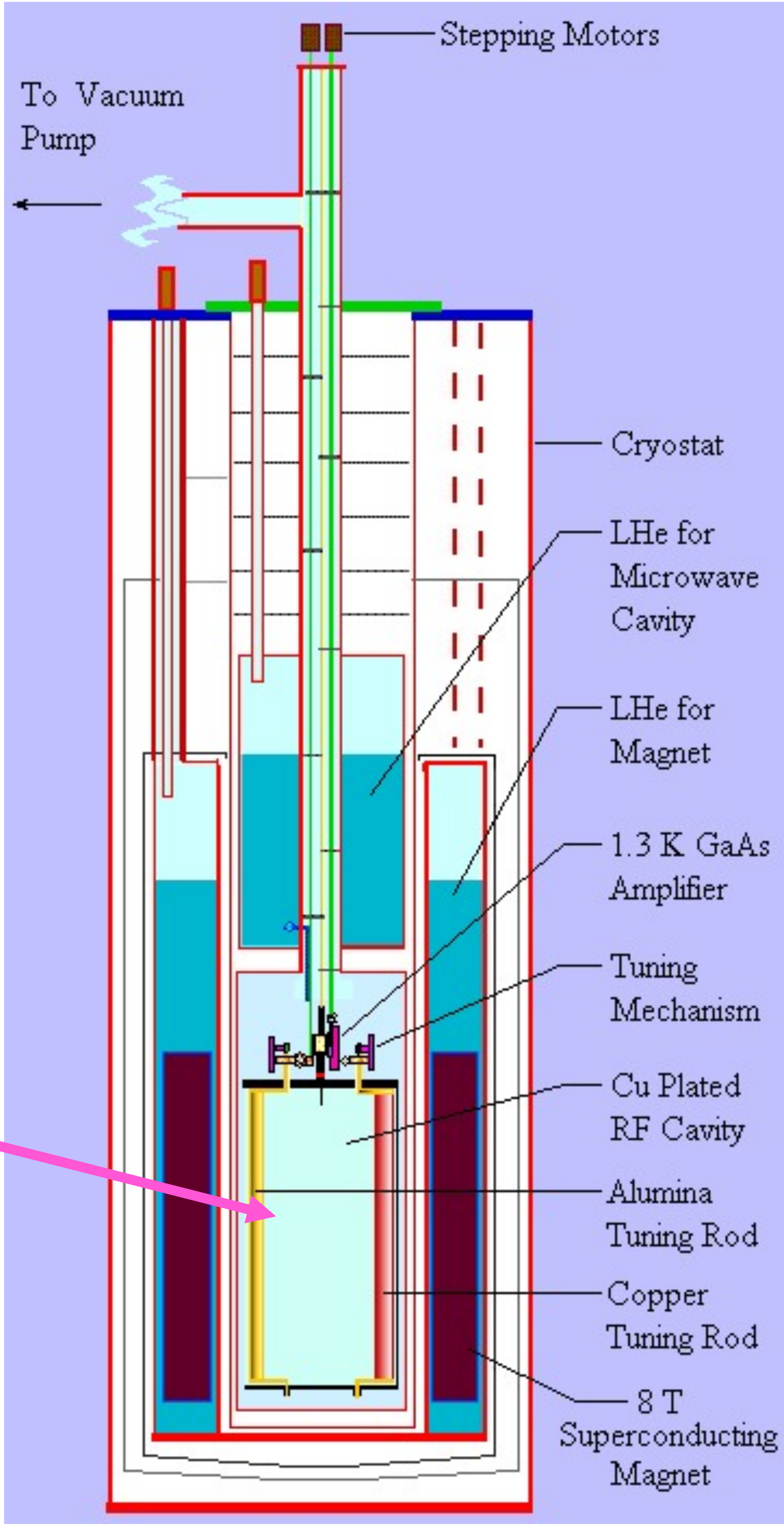
Cavity overcomes momentum mismatch

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.



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.