Physics 224 - Spring 2010

Week 4
RECOMBINATION AND DARK MATTER

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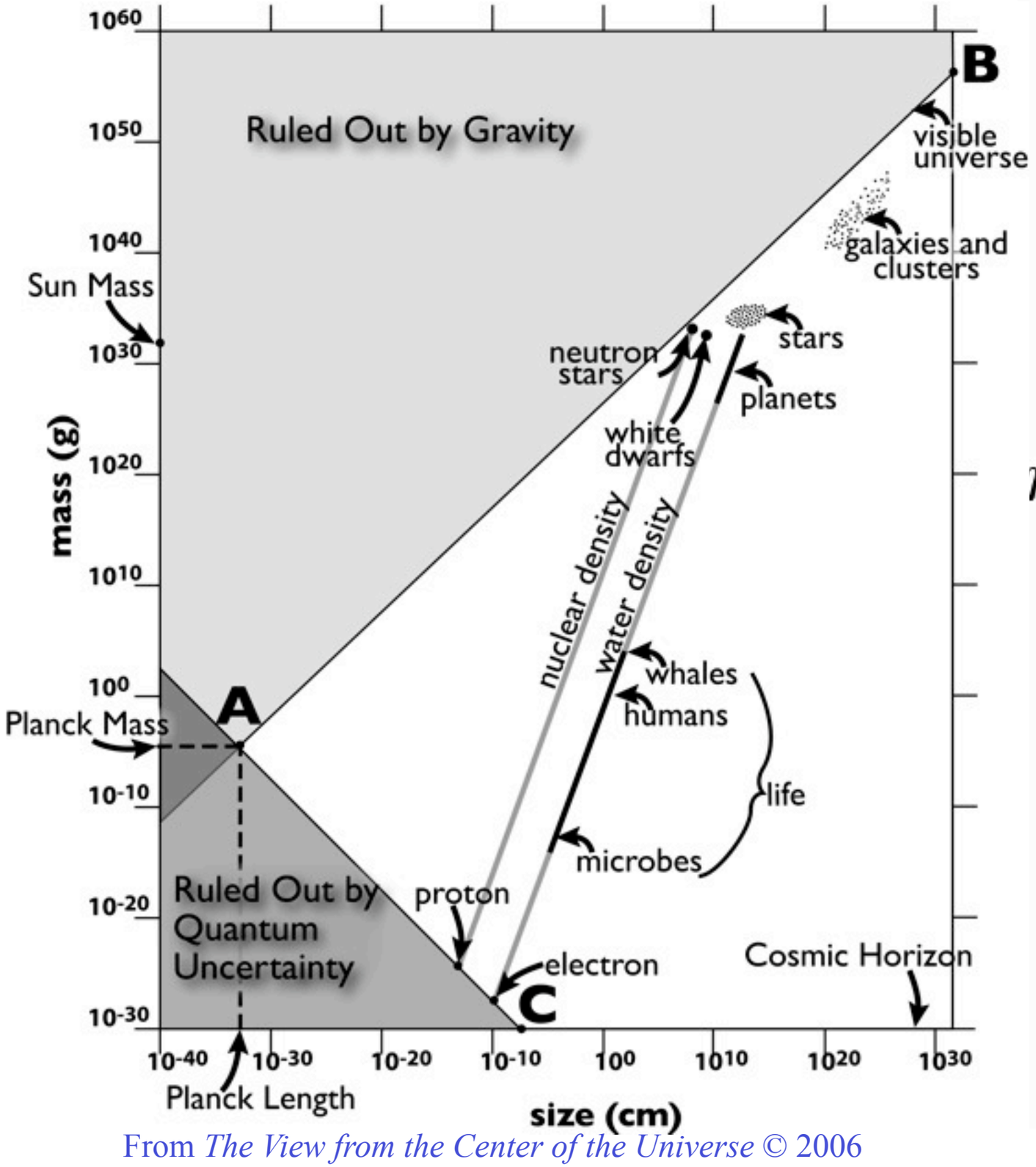
The Wedge of Material Reality



From *The View from the Center of the Universe* © 2006

The Planck Length

$$l_{Pl} = \sqrt{\frac{hG}{2\pi c^3}} = 1.6 \times 10^{-33}\ \text{cm}$$

is the smallest possible length.

Here h is Planck's constant

$$h = 6.626068 \times 10^{-34}\ \text{m}^2\ \text{kg}\ /\ \text{s}$$

The Planck Mass is

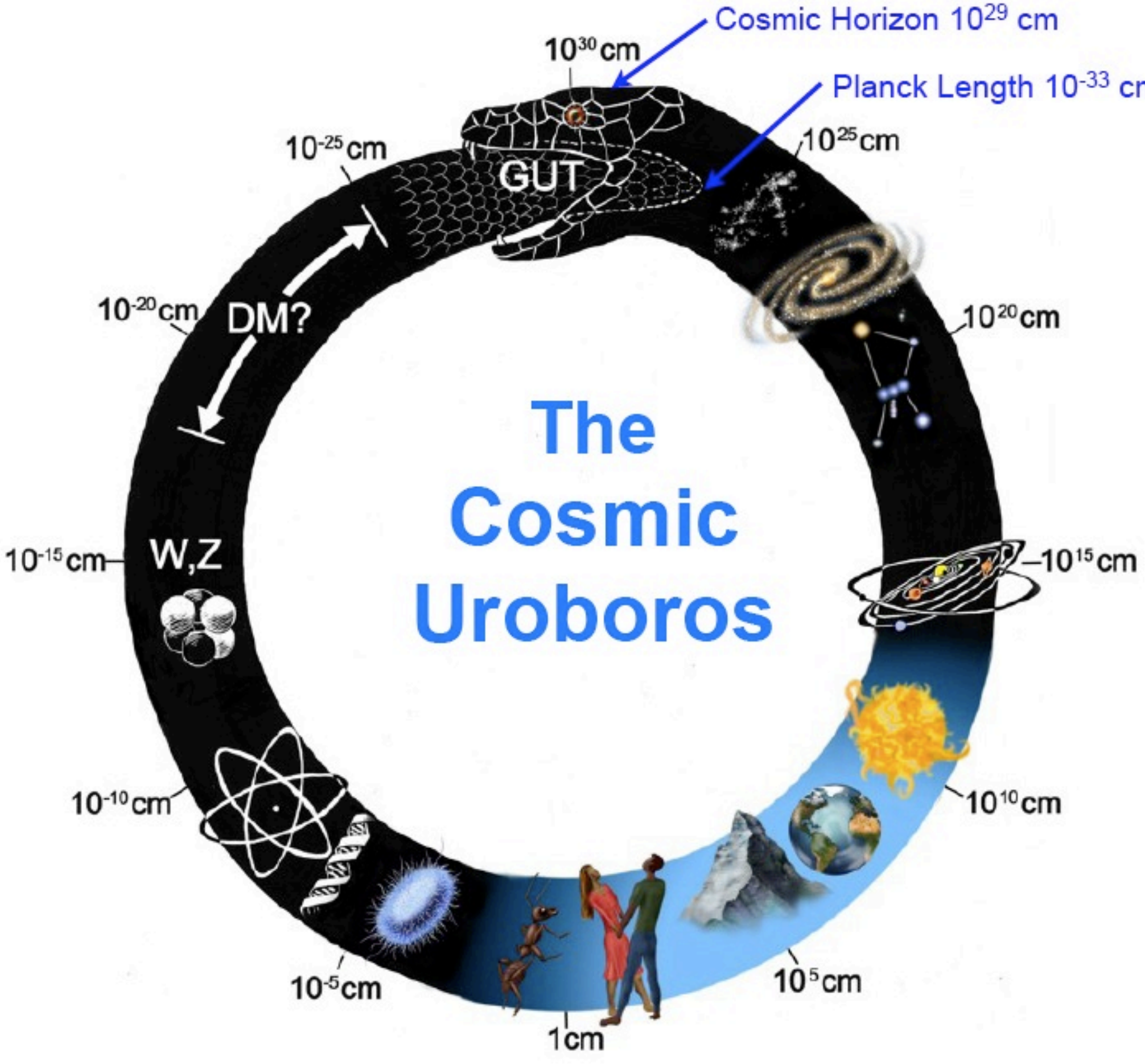
$$m_{Pl} = \sqrt{\frac{hc}{2\pi G}} = 2.2 \times 10^{-5}\ \text{g}$$

The Compton (i.e. quantum) wavelength $l_C = \frac{h}{2\pi mc}$

equals the Schwarzschild radius $l_S \approx \frac{Gm}{c^2}$

when $m = m_{Pl} = 1.2 \times 10^{19}$ GeV/c^2

The Cosmic Uroboros



Boltzmann Equation

$$a^{-3}\frac{d\left(n_1 a^3\right)}{dt} = \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4}$$

Dodelson (3.1)

$$\times\ (2\pi)^4 \delta^3(p_1 + p_2 - p_3 - p_4)\delta(E_1 + E_2 - E_3 - E_4)\left|\mathcal{M}\right|^2$$

$$\times\ \left\{f_3 f_4[1 \pm f_1][1 \pm f_2] - f_1 f_2[1 \pm f_3][1 \pm f_4]\right\}.$$

+ bosons
- fermions

In the absence of interactions (rhs=0) n_1 falls as a^{-3}

We will typically be interested in T>> E-μ (where μ is the chemical potential). In this limit, the exponential in the Fermi-Dirac or Bose-Einstein distributions is much larger than the ±1 in the denominator, so that

$$f(E) \rightarrow e^{\mu/T} e^{-E/T}$$

and the last line of the Boltzmann equation above simplifies to

$$f_3 f_4[1 \pm f_1][1 \pm f_2] - f_1 f_2[1 \pm f_3][1 \pm f_4]$$

$$\rightarrow \quad e^{-(E_1+E_2)/T}\left\{e^{(\mu_3+\mu_4)/T} - e^{(\mu_1+\mu_2)/T}\right\}.$$

The number densities are given by $n_i = g_i e^{\mu_i/T} \int \frac{d^3p}{(2\pi)^3} e^{-E_i/T}$. For our applications, i's are

Table 3.1. Reactions in This Chapter: $1 + 2 \leftrightarrow 3 + 4$

	1	2	3	4
Neutron-Proton Ratio	n	ν_e or e^+	p	e^- or $\bar{\nu}_e$
Recombination	e	p	H	γ
Dark Matter Production	X	X	l	l

The equilibrium number densities are given by

$$n_i^{(0)} \equiv g_i \int \frac{d^3p}{(2\pi)^3} e^{-E_i/T} = \begin{cases} g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T} & m_i \gg T \\ g_i \frac{T^3}{\pi^2} & m_i \ll T \end{cases} . \tag{3.6}$$

With this defintion, $e^{\mu_i/T}$ can be rewritten as $n_i/n_i^{(0)}$, so the last line of Eq. (3.1) is equal to

$$e^{-(E_1+E_2)/T} \left\{ \frac{n_3 n_4}{n_3^{(0)} n_4^{(0)}} - \frac{n_1 n_2}{n_1^{(0)} n_2^{(0)}} \right\} . \tag{3.7}$$

With these approximations the Boltzmann equation now simplifies enormously. Define the thermally averaged cross section as

$$\langle \sigma v \rangle \equiv \frac{1}{n_1^{(0)} n_2^{(0)}} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} e^{-(E_1+E_2)/T}$$

$$\times (2\pi)^4 \delta^3(p_1 + p_2 - p_3 - p_4) \delta(E_1 + E_2 - E_3 - E_4) \left|\mathcal{M}\right|^2 . \tag{3.8}$$

Then, the Boltzmann equation becomes

$$\frac{a^{-3} \frac{d\left(n_1 a^3\right)}{dt}}{n_2 \langle \sigma v \rangle} = n_1^{(0)} n_2^{(0)} \langle \sigma v \rangle \left\{ \frac{n_3 n_4}{n_3^{(0)} n_4^{(0)}} - \frac{n_1 n_2}{n_1^{(0)} n_2^{(0)}} \right\} . \tag{3.9}$$

If the reaction rate is much smaller than the expansion rate (~ H), then the {} on the rhs must vanish. This is called *chemical equilibrium* in the context of the early universe, *nuclear statistical equilibrium* (NSE) in the context of Big Bang nucleosynthesis, and the *Saha equation* when discussing recombination of electrons and protons to form neutral hydrogen.

BBN is a Prototype for Hydrogen Recombination and DM Annihilation

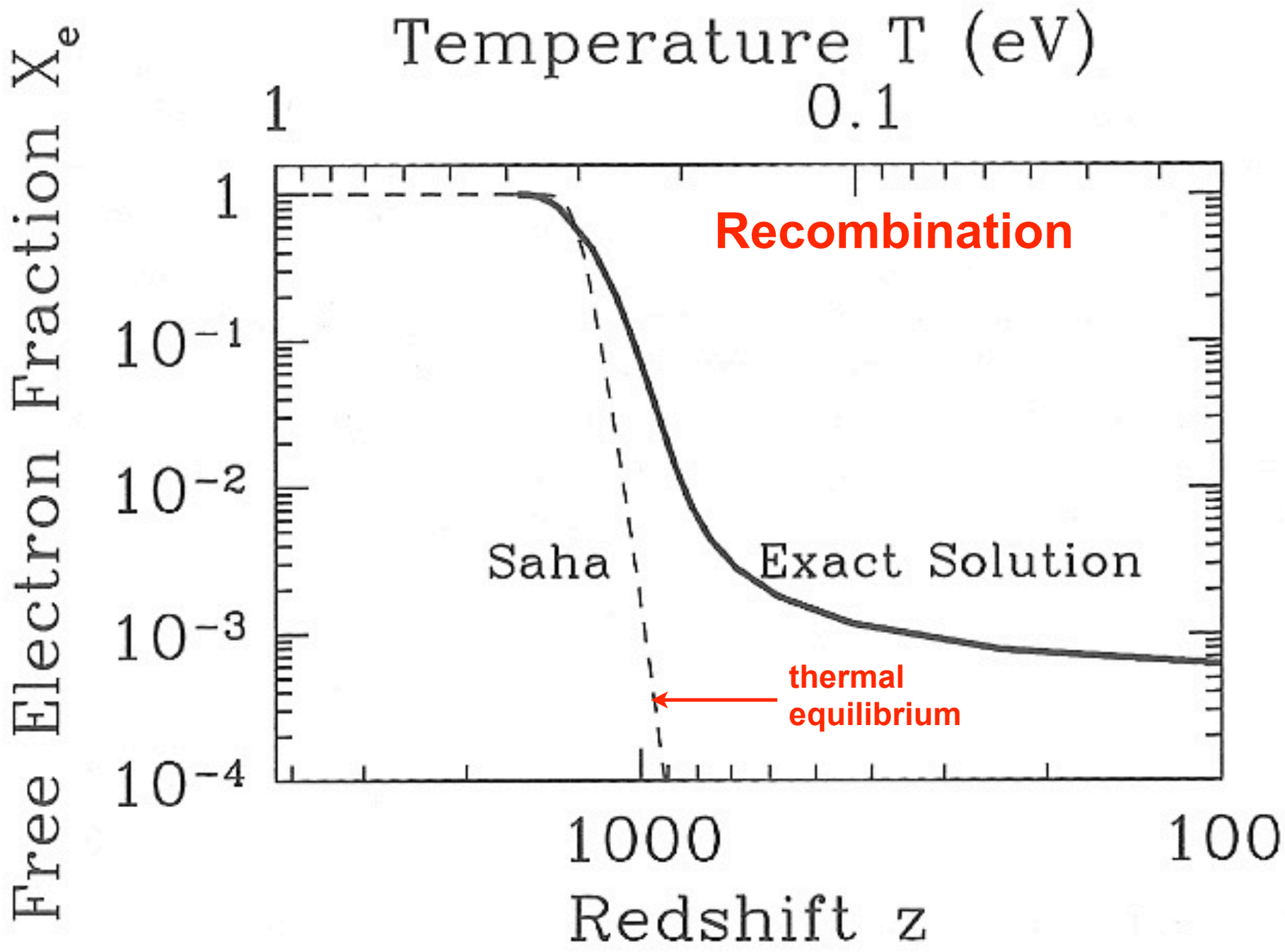


Figure 3.4. Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of X_e. Here $\Omega_b = 0.06, \Omega_m = 1, h = 0.5$.

Dodelson, *Modern Cosmology*, p. 72

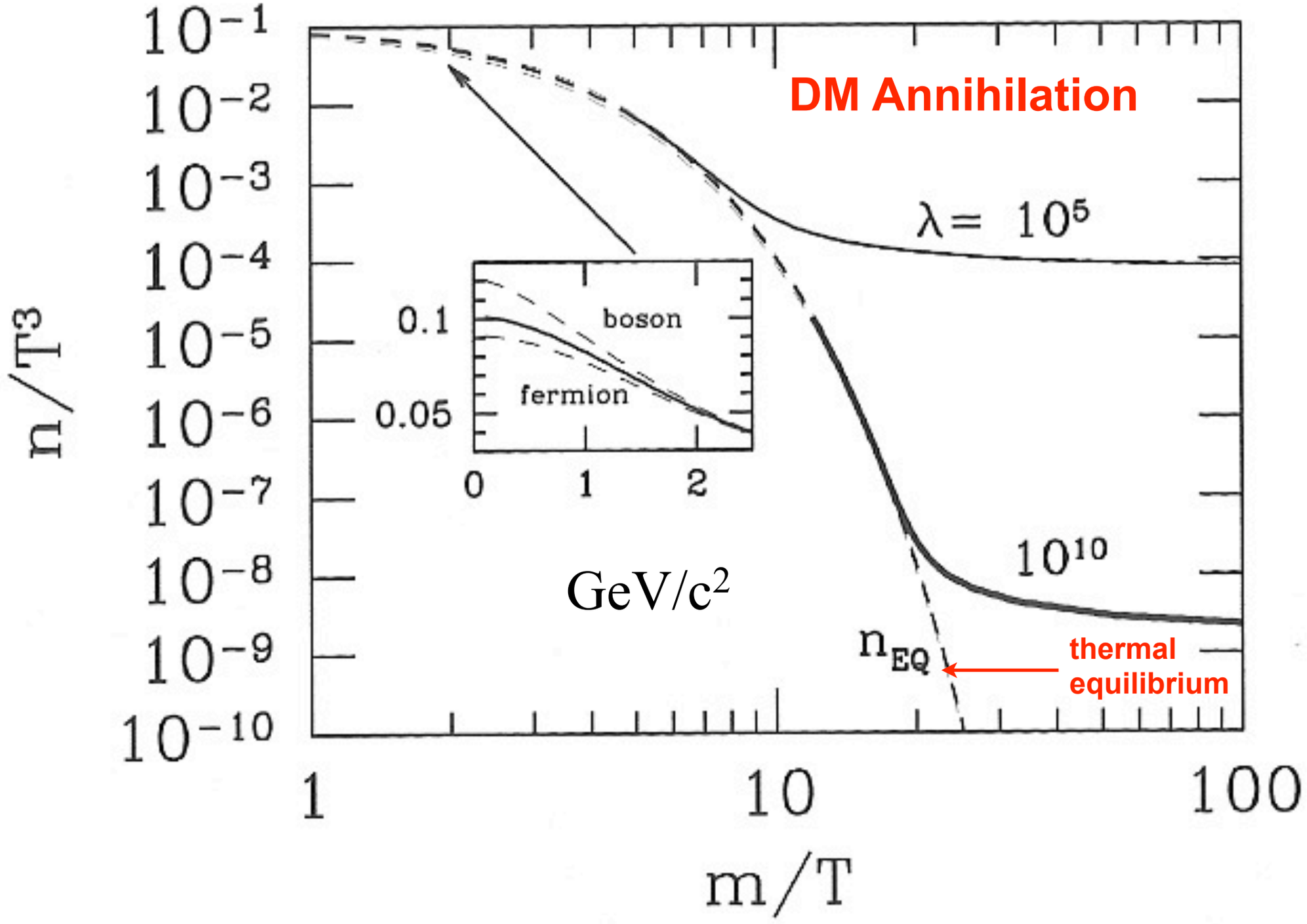


Figure 3.5. Abundance of heavy stable particle as the temperature drops beneath its mass. Dashed line is equilibrium abundance. Two different solid curves show heavy particle abundance for two different values of λ, the ratio of the annihilation rate to the Hubble rate. Inset shows that the difference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

Dodelson, *Modern Cosmology*, p. 76

In addition to the textbooks listed on the Syllabus, a good place to find up-to-date information is the Particle Data Group websites
http://pdg.lbl.gov
http://pdg.lbl.gov/2009/reviews/contents_sports.html

For example, there are 2009 Mini-Reviews of

Big Bang Nucleosynthesis including a discussion of ^{7}Li
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-bbang-nucleosynthesis.pdf

Big-Bang Cosmology
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-bbang-cosmology.pdf

Cosmological Parameters
http://pdg.lbl.govhttp://pdg.lbl.gov/2009/reviews/rpp2009-rev-cosmological-parameters.pdf

CMB
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-cosmic-microwave-background.pdf

and Dark Matter http://pdg.lbl.gov/2009/reviews/rpp2009-rev-dark-matter.pdf

(Re)combination: $e^- + p \rightarrow H$

As long as e- + p ⇔ H remains in equilibrium, the condition

$$\left\{ \frac{n_3 n_4}{n_3^{(0)} n_4^{(0)}} - \frac{n_1 n_2}{n_1^{(0)} n_2^{(0)}} \right\} = 0$$

with 1 = e^-, 2 = p, 3 = H, ensures that

$$\frac{n_e n_p}{n_H} = \frac{n_e^{(0)} n_p^{(0)}}{n_H^{(0)}}.$$

Neutrality ensures $n_p = n_e$. Defining the free electron fraction

$$X_e \equiv \frac{n_e}{n_e + n_H} = \frac{n_p}{n_p + n_H},$$

the equation above becomes

$$\frac{X_e^2}{1 - X_e} = \frac{1}{n_e + n_H} \left[\left(\frac{m_e T}{2\pi} \right)^{3/2} e^{-[m_e + m_p - m_H]/T} \right]$$

, which

$\epsilon = 13.6$ eV

is known as the *Saha equation*. When T ~ ε, the rhs ~ 10^{15}, so X_e is very close to 1 and very little recombination has yet occurred. As T drops, the free electron fraction also drops, and as it approaches 0 equilibrium cannot be maintained. To follow the freezeout of the electron fraction, it is necessary to use the Boltzmann equation

$$a^{-3} \frac{d\left(n_e a^3\right)}{dt} = n_e^{(0)} n_p^{(0)} \langle \sigma v \rangle \left\{ \frac{n_H}{n_H^{(0)}} - \frac{n_e^2}{n_e^{(0)} n_p^{(0)}} \right\}$$

$$= n_b \langle \sigma v \rangle \left\{ (1 - X_e) \left(\frac{m_e T}{2\pi} \right)^{3/2} e^{-\epsilon_0/T} - X_e^2 n_b \right\}$$

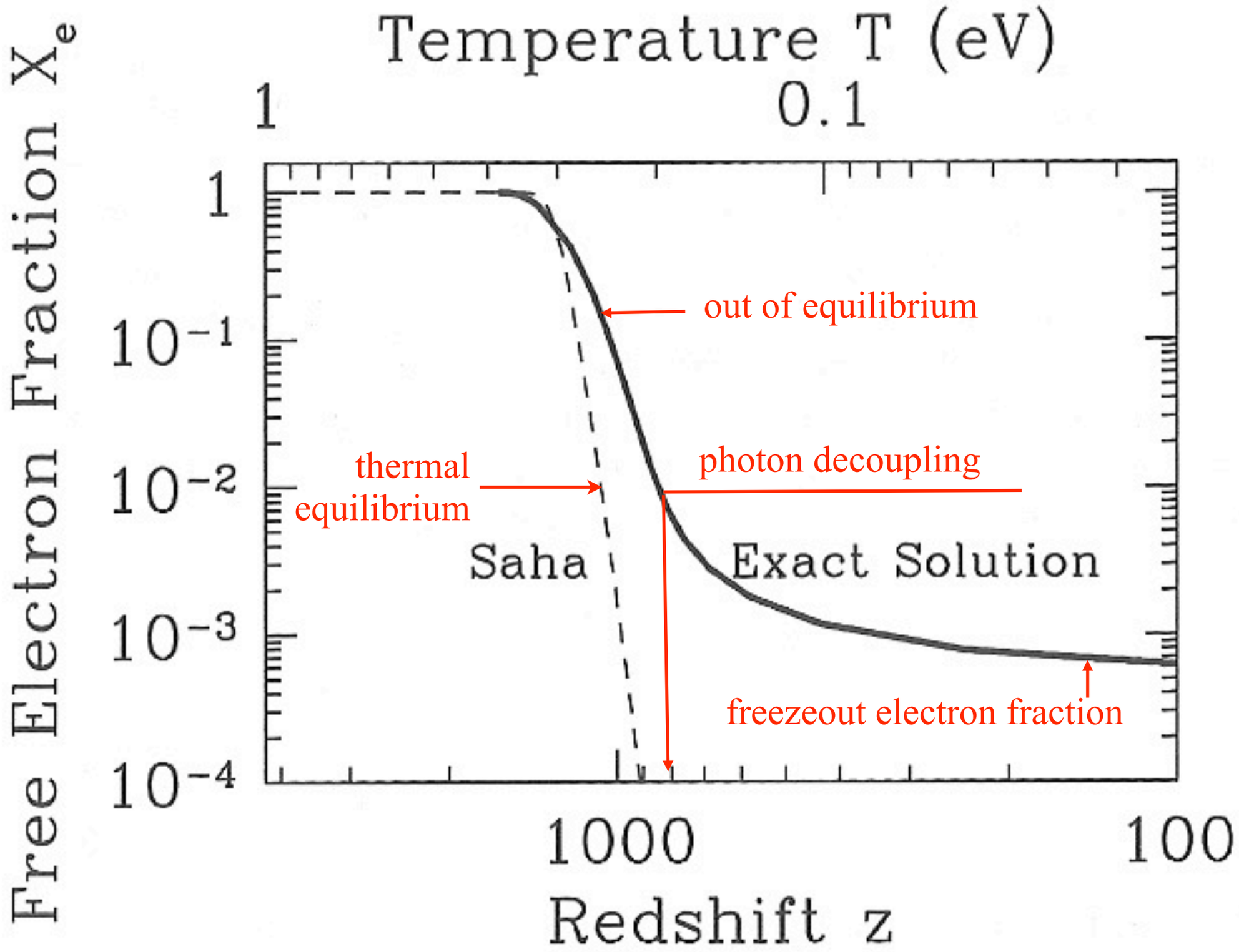
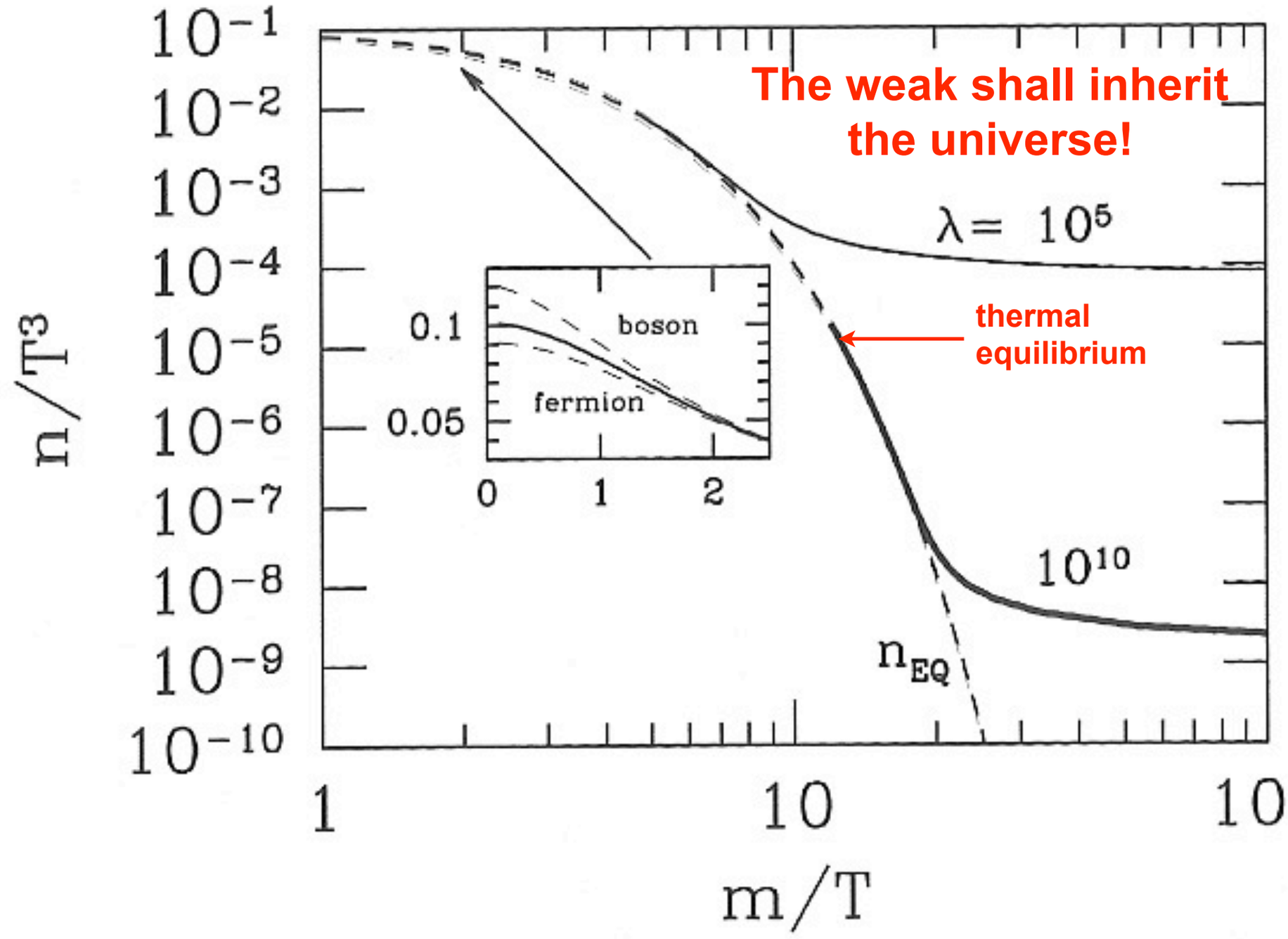


Figure 3.4. Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of X_e. Here $\Omega_b = 0.06, \Omega_m = 1, h = 0.5$.

Dodelson, *Modern Cosmology*, p. 72

Dark Matter Annihilation



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)

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

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

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

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.

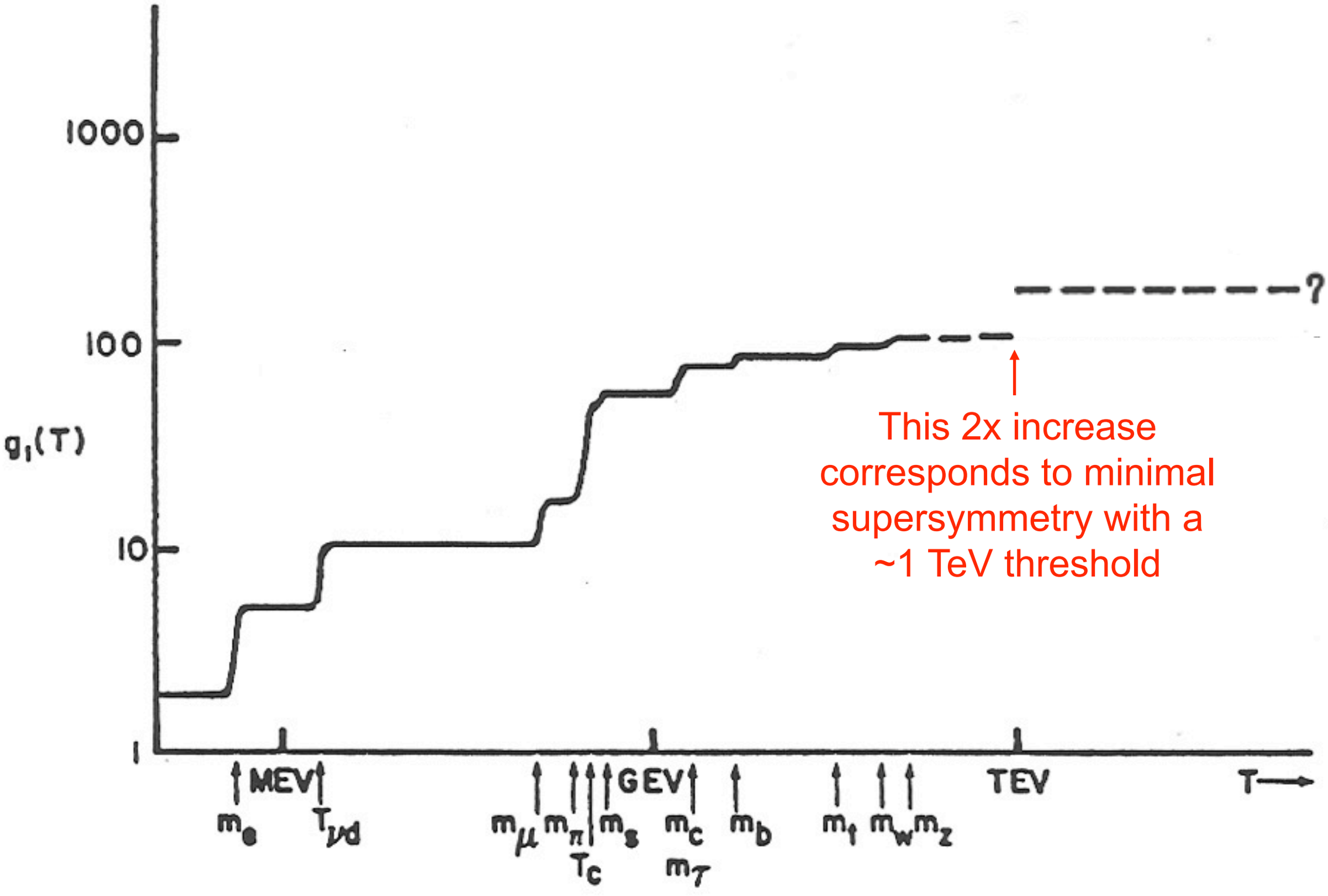


Fig. 1 The effective number of degrees of freedom of thermally interacting relativistic particles as a function of temperature.

Supersymmetry is the basis of most attempts, such as superstring theory, to go beyond the current "Standard Model" of particle physics. Heinz Pagels and Joel Primack pointed out in a 1982 paper that the lightest supersymmetric partner particle is stable because of R-parity, and is thus a good candidate for the dark matter particles – weakly interacting massive particles (**WIMP**s).

Michael Dine and others pointed out that the **axion**, a particle needed to save the strong interactions from violating CP symmetry, could also be the dark matter particle. Searches for both are underway.

Supersymmetric WIMPs

When the British physicist Paul Dirac first combined Special Relativity with quantum mechanics, he found that this predicted that for every ordinary particle like the electron, there must be another particle with the opposite electric charge – the anti-electron (positron). Similarly, corresponding to the proton there must be an anti-proton. Supersymmetry appears to be required to combine General Relativity (our modern theory of space, time, and gravity) with the other forces of nature (the electromagnetic, weak, and strong interactions). The consequence is another doubling of the number of particles, since supersymmetry predicts that for every particle that we now know, including the antiparticles, there must be another, thus far undiscovered particle with the same electric charge but with *spin* differing by half a unit.

Spin	**Matter** (fermions)	**Forces** (bosons)
2		graviton
1		photon, $W^{\pm}, Z^0$ gluons
1/2	quarks u,d,... leptons $e, \nu_e, \ldots$	
0		Higgs bosons axion

Supersymmetric WIMPs

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after doubling

Spin	**Matter** (fermions)	**Forces** (bosons)	**Hypothetical Superpartners**	**Spin**
2		graviton	gravitino	3/2
1		photon, $W^{\pm}, Z^0$ gluons	photino, winos, zino, gluinos	1/2
1/2	quarks u,d,... leptons $e, \nu_e, \ldots$		squarks $\tilde{u}, \tilde{d}, \ldots$ sleptons $\tilde{e}, \tilde{\nu}_e, \ldots$	0
0		Higgs bosons axion	Higgsinos axinos	1/2

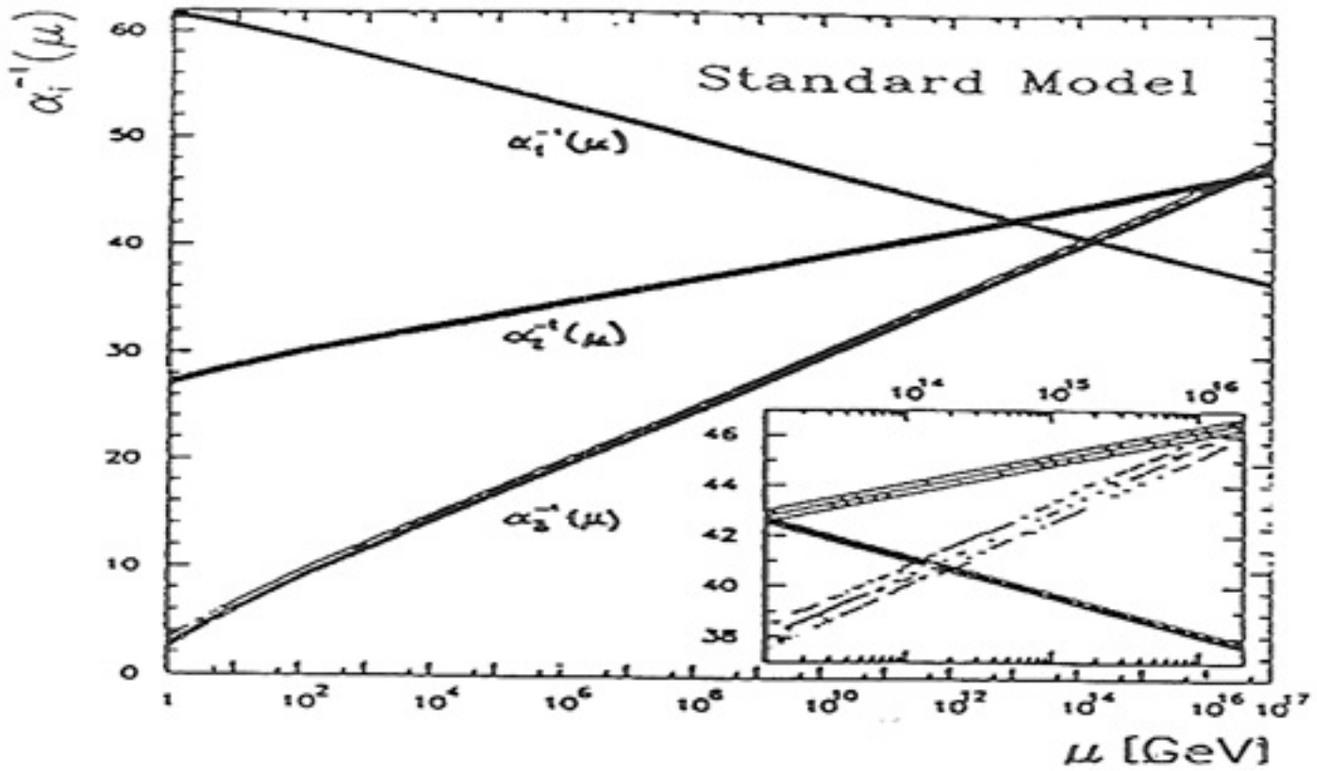
Note: Supersymmetric cold dark matter candidate particles are underlined.

Supersymmetric WIMPs, continued

Spin is a fundamental property of elementary particles. Matter particles like electrons and quarks (protons and neutrons are each made up of three quarks) have spin ½, while force particles like photons, W,Z, and gluons have spin 1. The supersymmetric partners of electrons and quarks are called selectrons and squarks, and they have spin 0. The supersymmetric partners of the force particles are called the photino, Winos, Zino, and gluinos, and they have spin ½, so they might be matter particles. The lightest of these particles might be the photino. Whichever is lightest should be stable, so it is a natural candidate to be the dark matter WIMP. Supersymmetry does not predict its mass, but it must be more than 50 times as massive as the proton since it has not yet been produced at accelerators. But it will be produced soon at the LHC, if it exists and its mass is not above ~1 TeV!

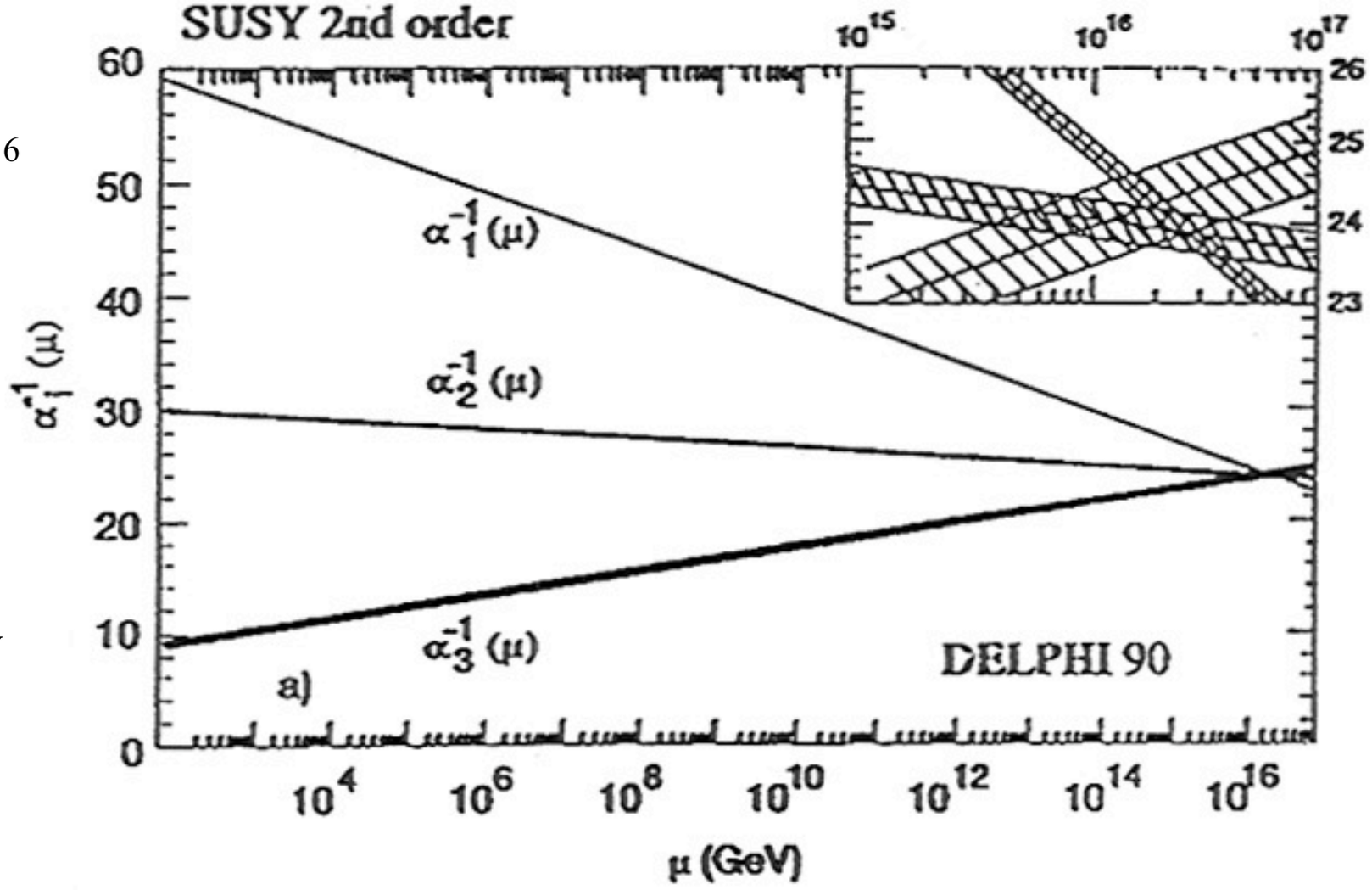
SUPERSYMMETRY

The only experimental evidence for supersymmetry is that running of coupling constants in the Standard Model does not lead to Grand Unification (of the weak, electromagnetic, and strong interactions)



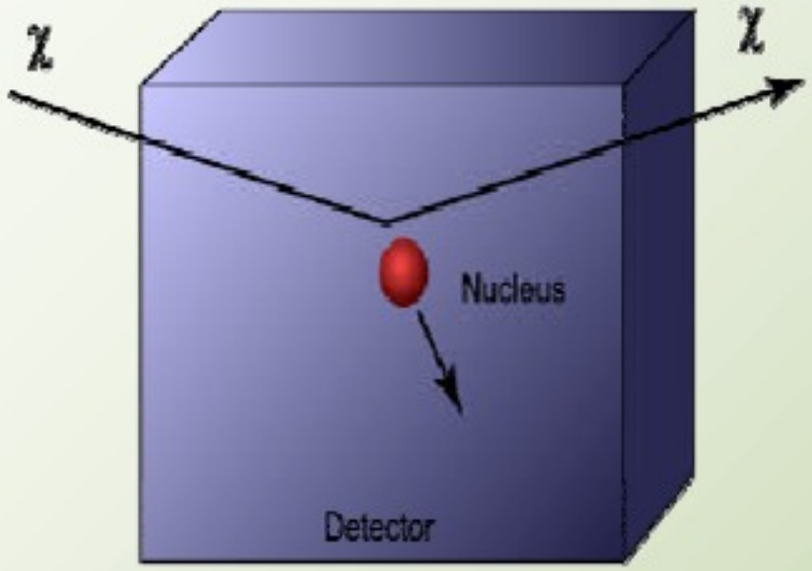
while with supersymmetry the three couplings all do come together at a scale just above 10^{16} GeV.

Other arguments for SUSY include: helps unification of gravity since it controls the vacuum energy and moderates loop divergences, solves the hierarchy problem, and naturally leads to DM with $\Omega \sim 1$.

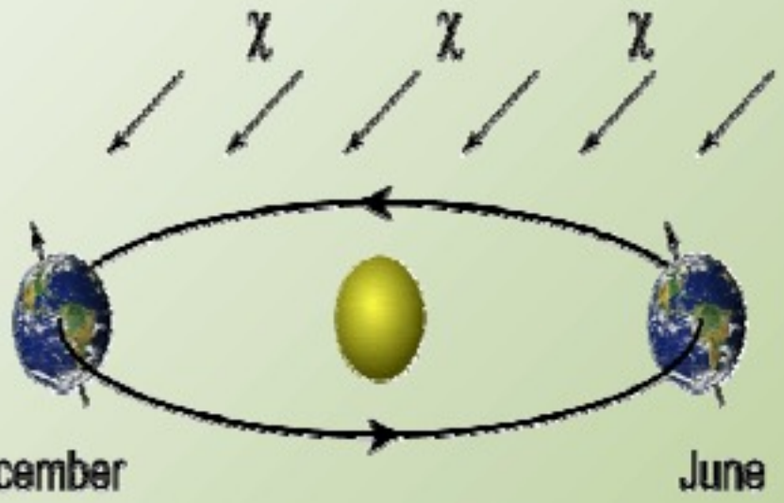


Experiments are Underway for Detection of WIMPs

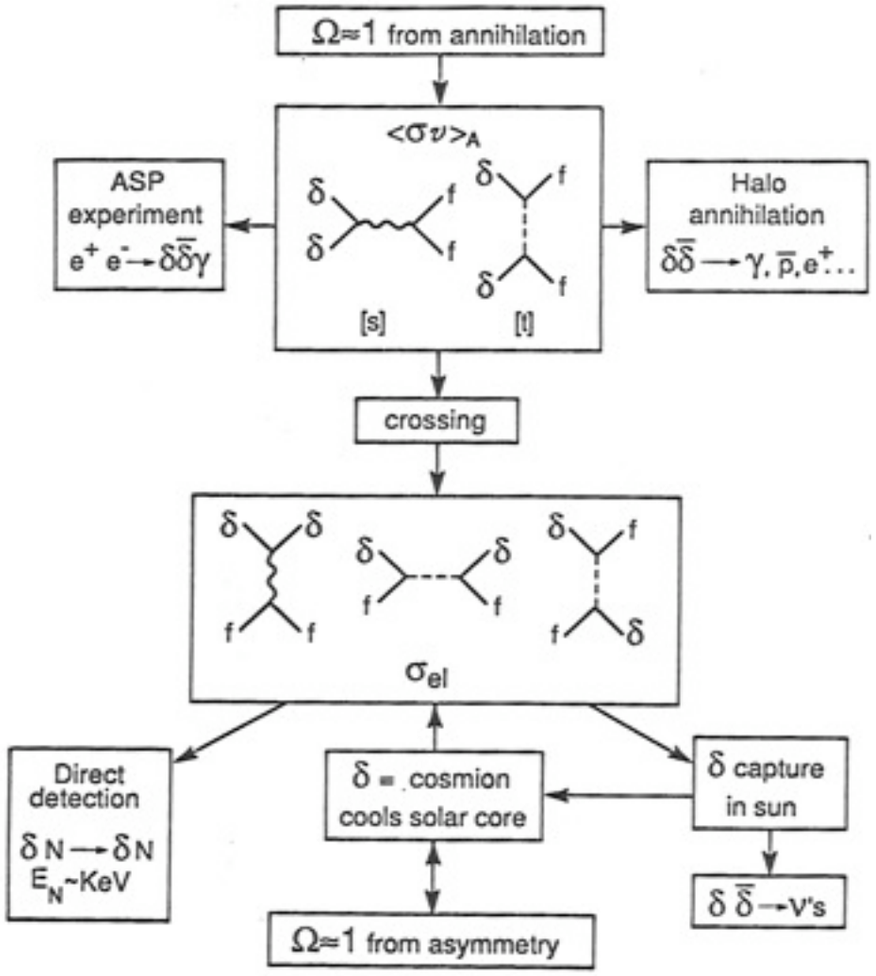
Direct detection - general principles

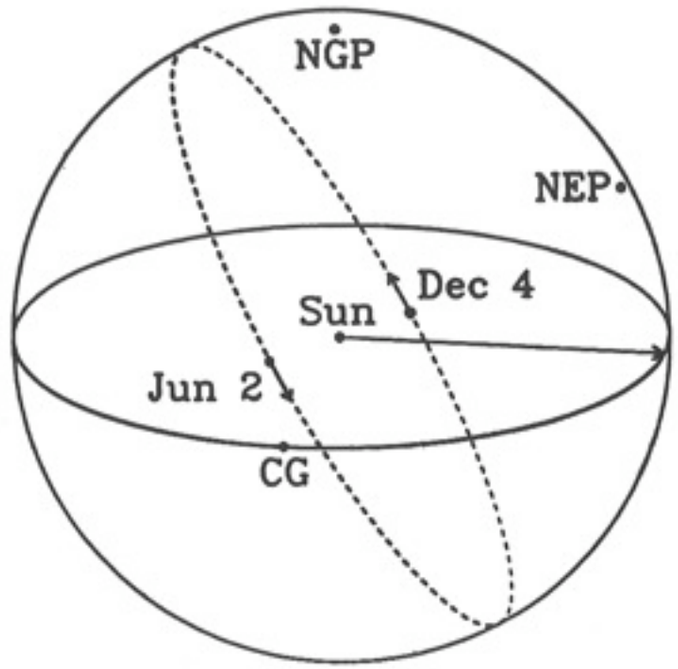


- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...



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

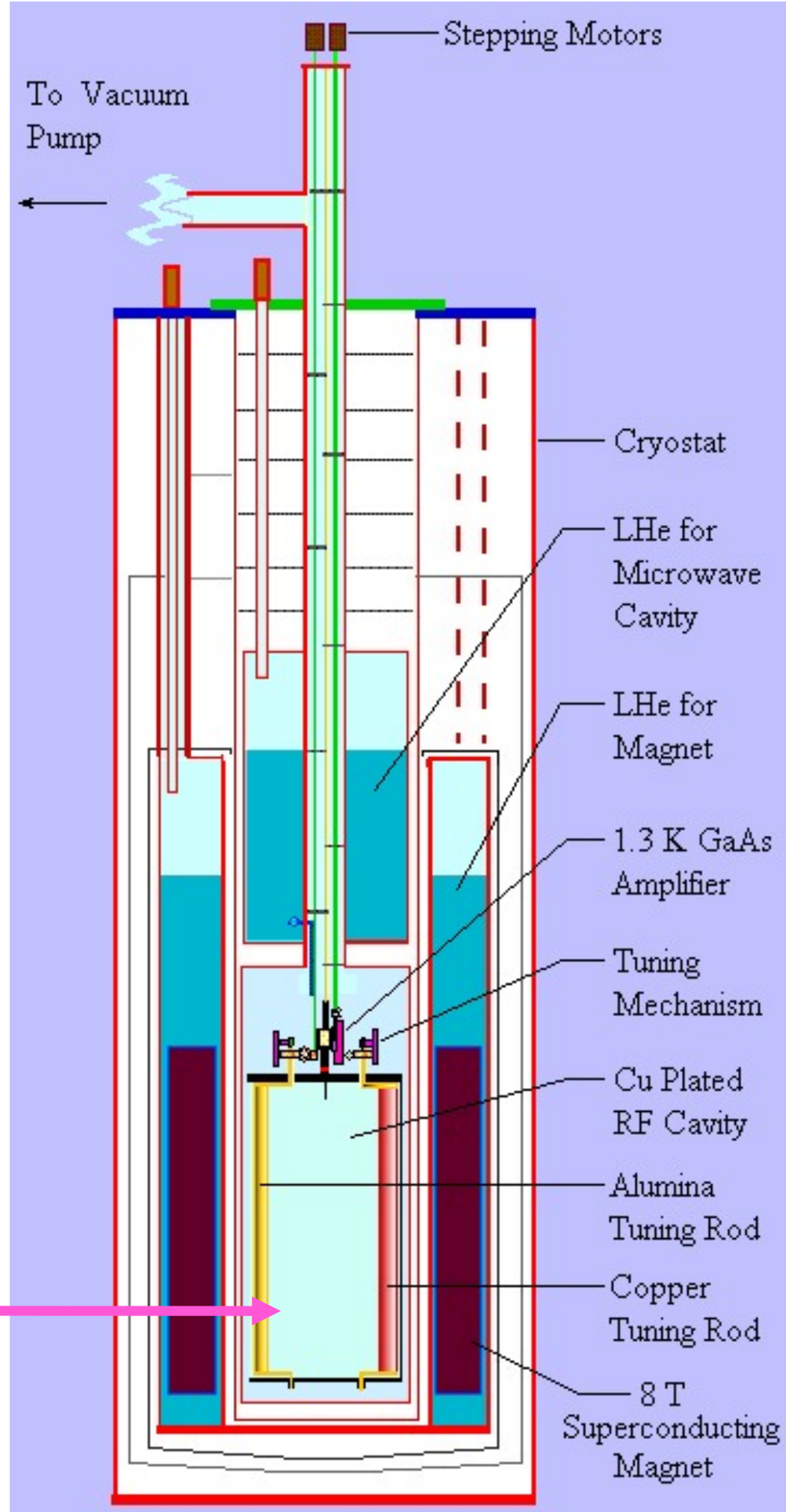




Primack, Seckel, & Sadoulet (1987)

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.



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

WHAT IS THE DARK MATTER?

Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

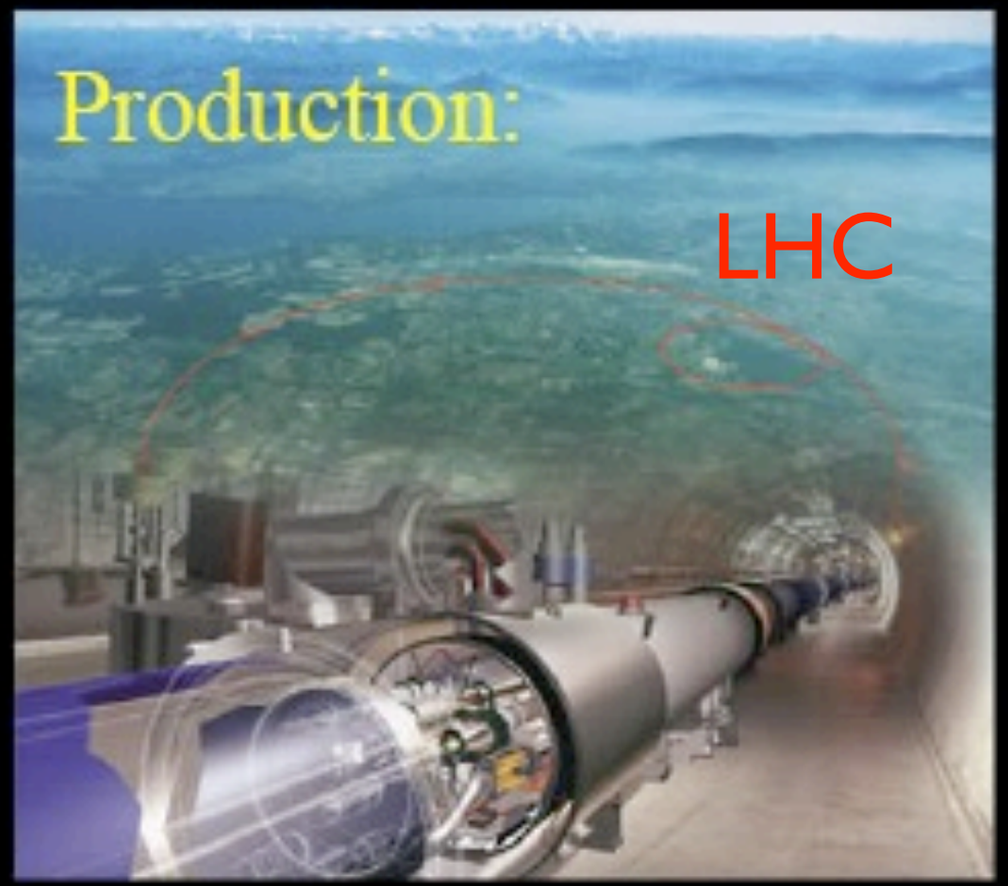
With many upcoming experiments

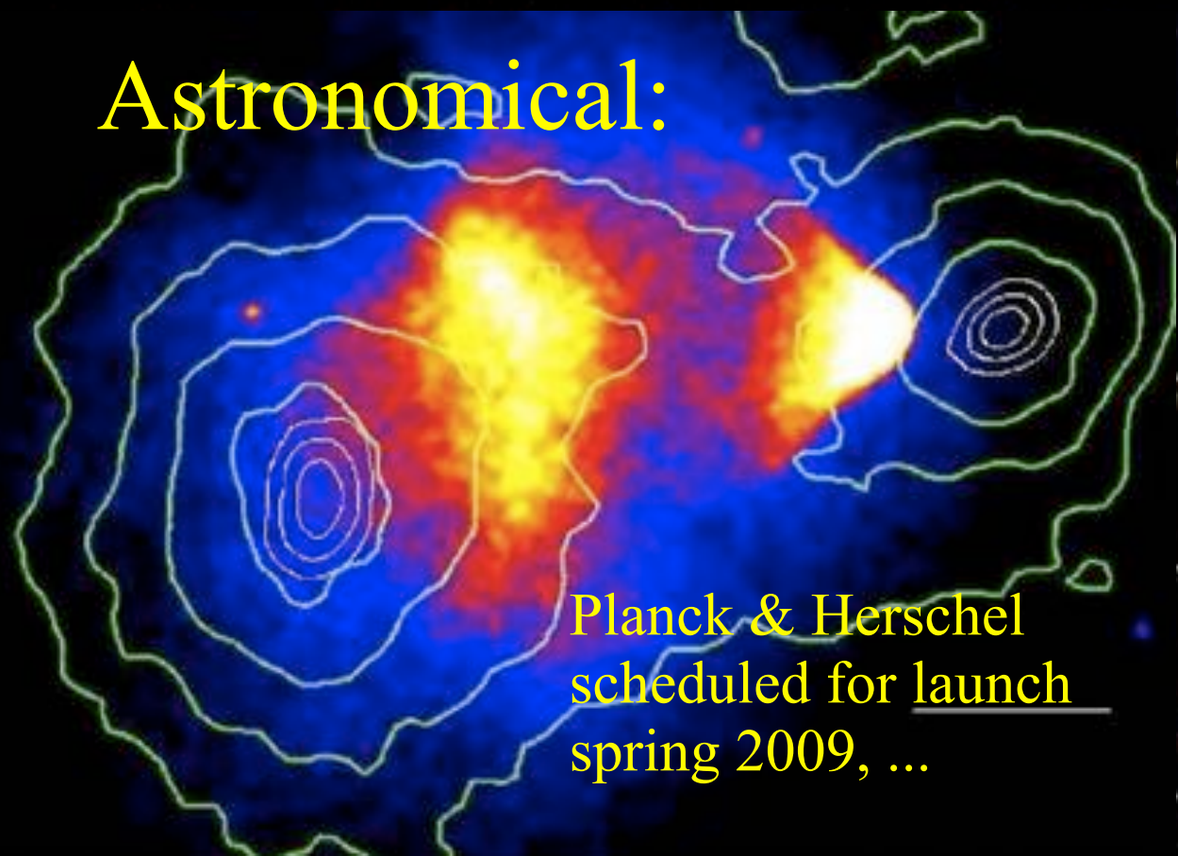
- Production at Large Hadron Collider
- Better CMB data from PLANCK
- Direct Detection
  - Spin Independent - CDMS-II, XENON50, LUX
  - Spin Dependent - COUPP, PICASSO
- Indirect detection via
  - GLAST and larger ACTs
  - PAMELA and ATIC

-- 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*

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

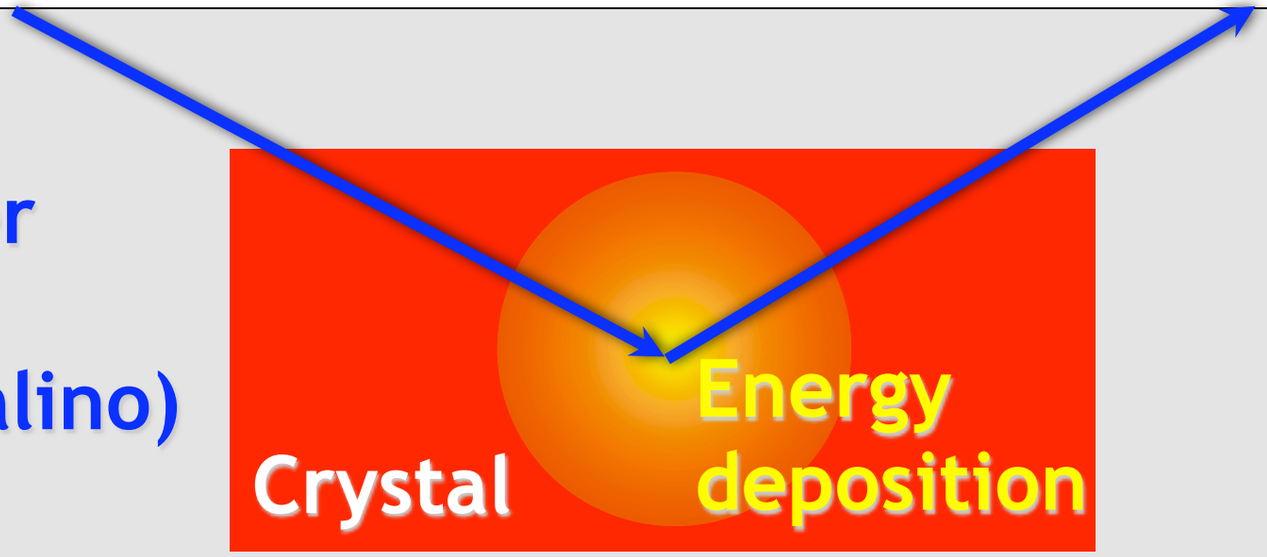




Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)

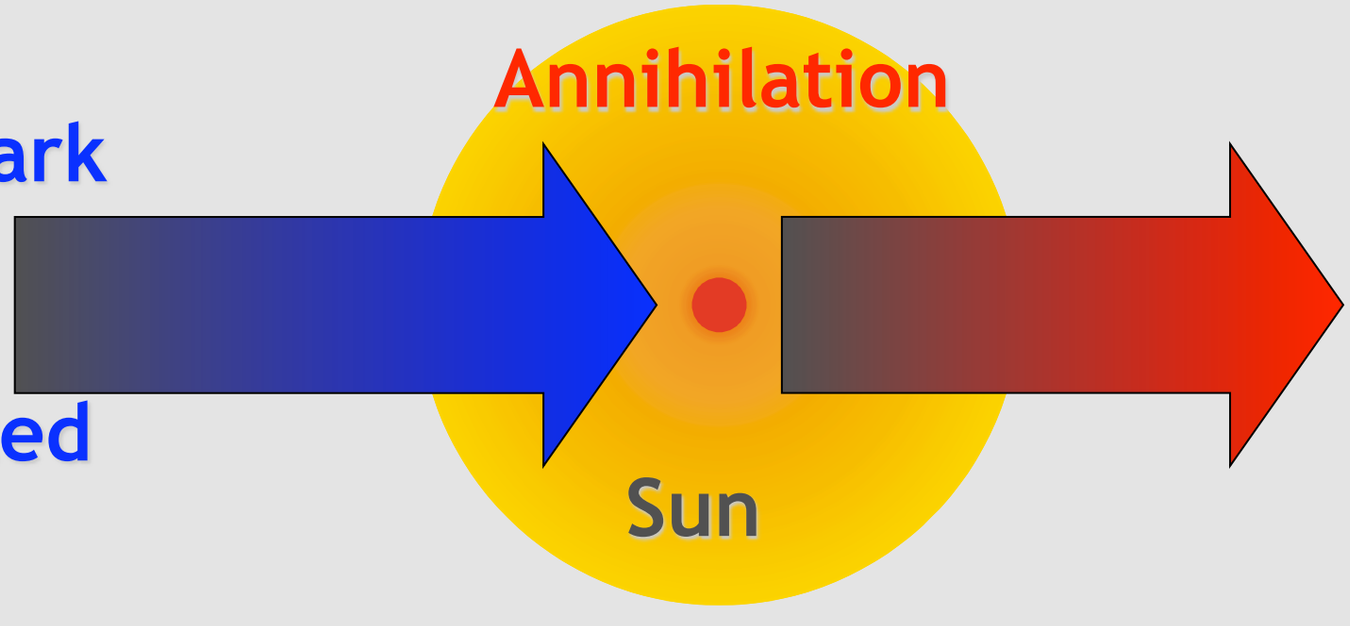


Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

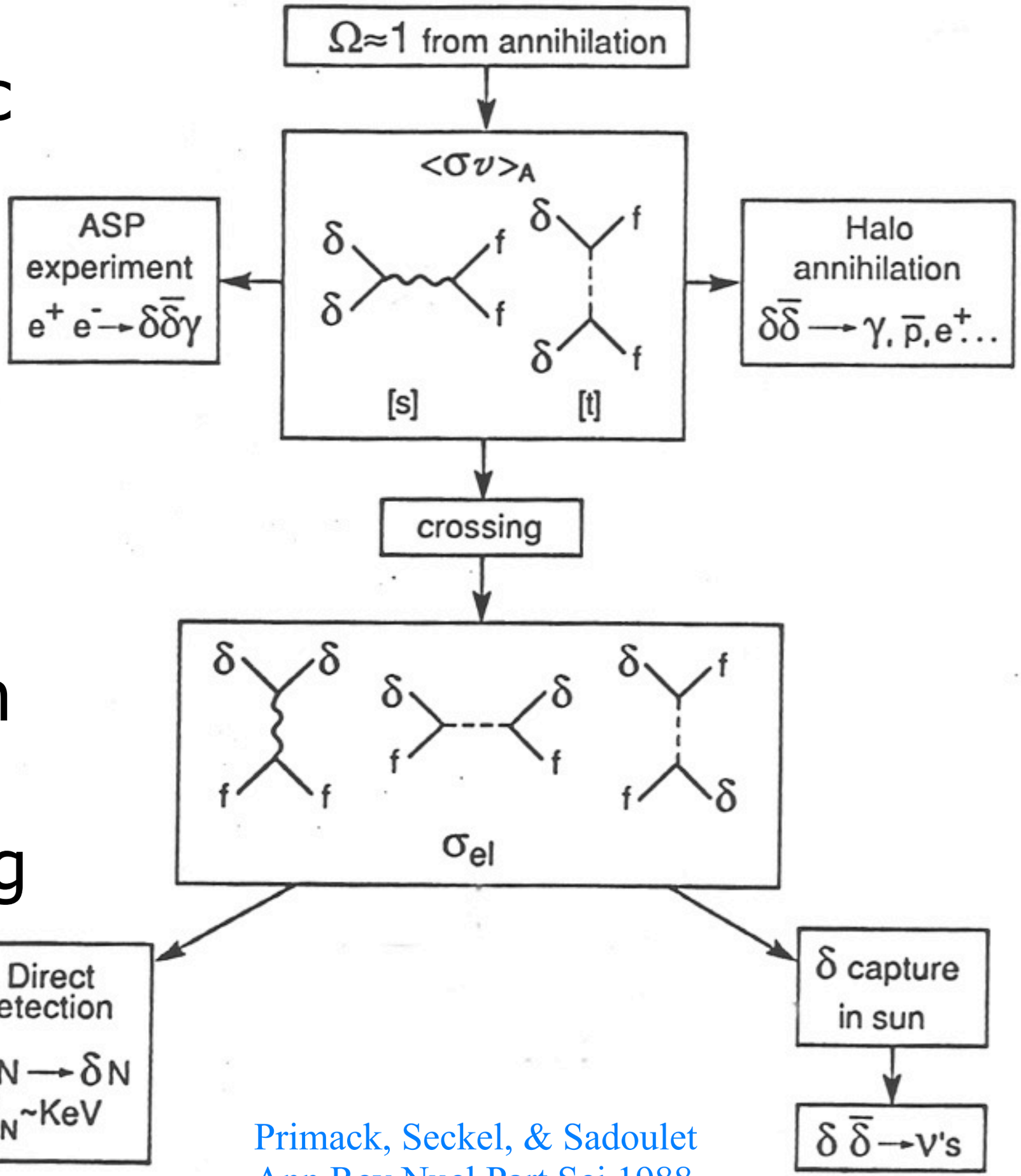
Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



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

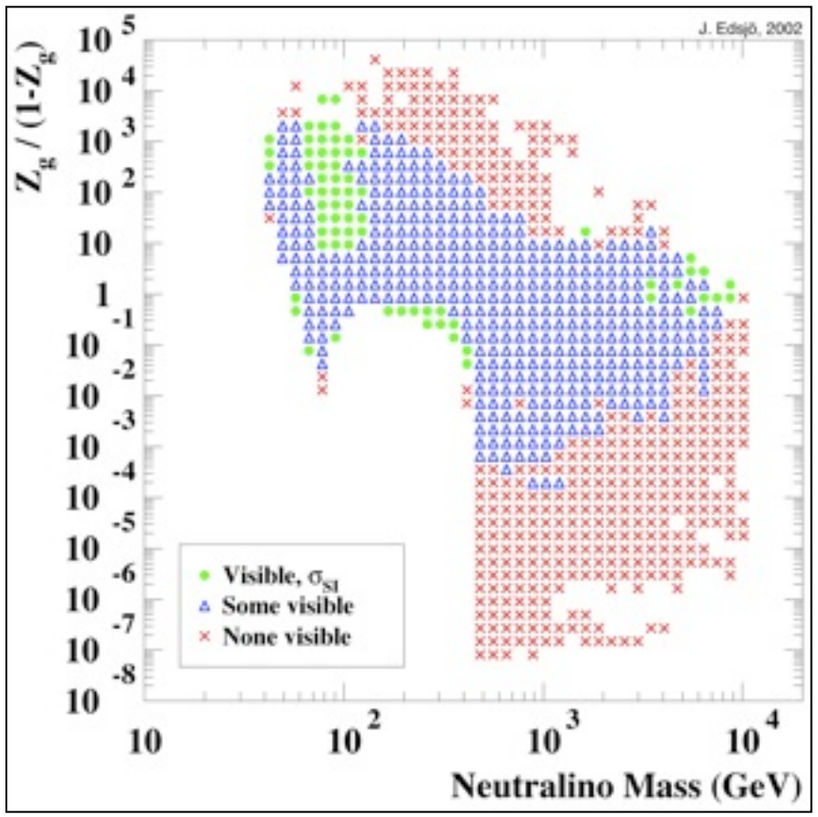
Supersymmetric WIMP (δ) annihilation is related by crossing to WIMP Direct Detection by Elastic Scattering

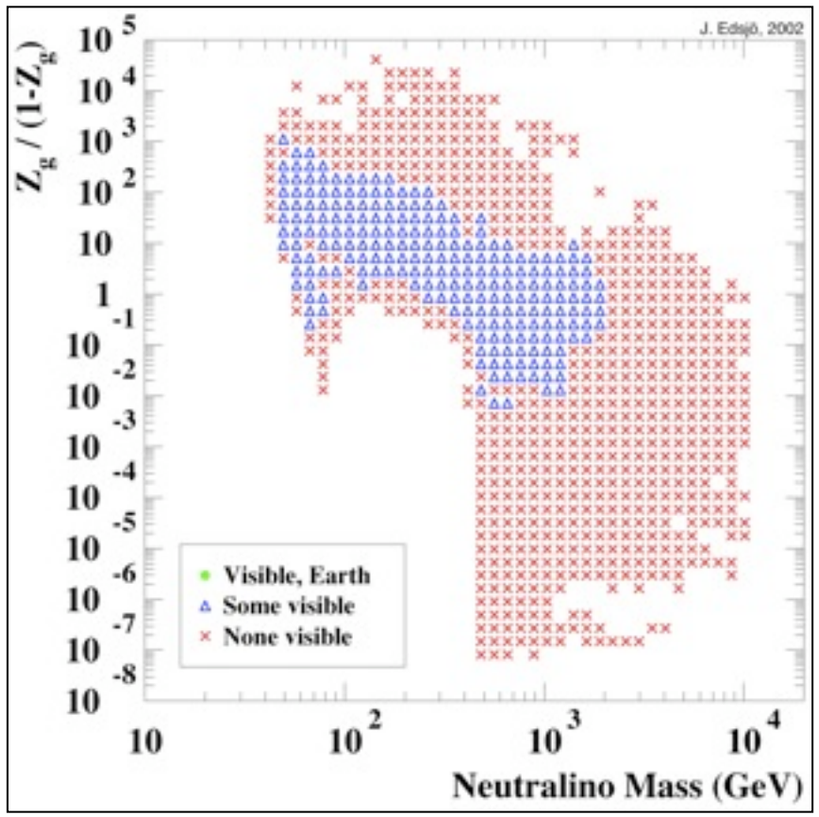


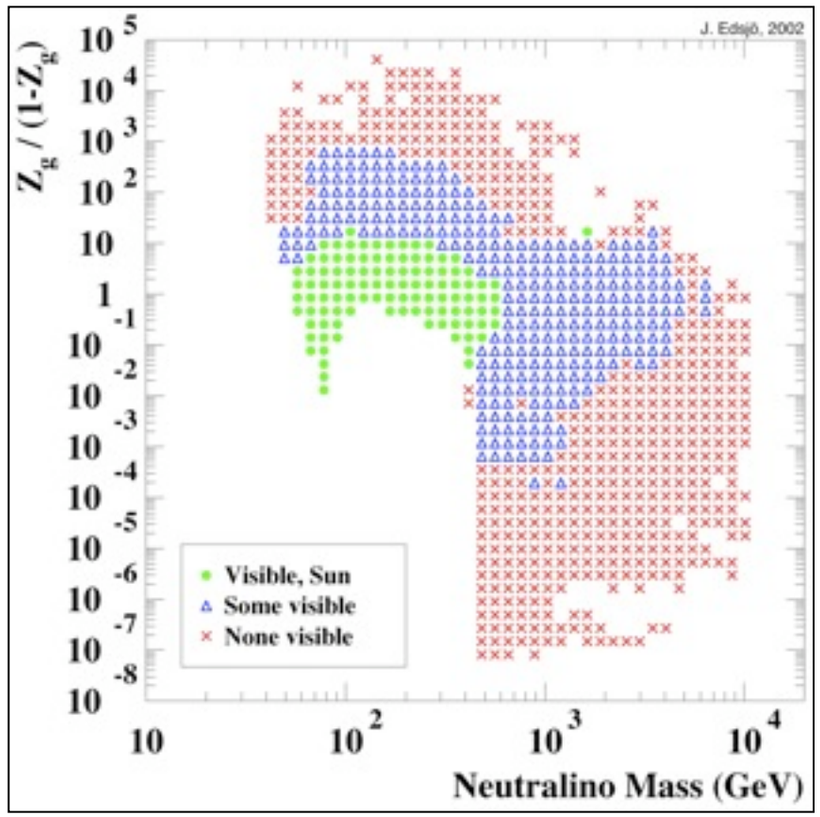
Primack, Seckel, & Sadoulet
Ann Rev Nucl Part Sci 1988

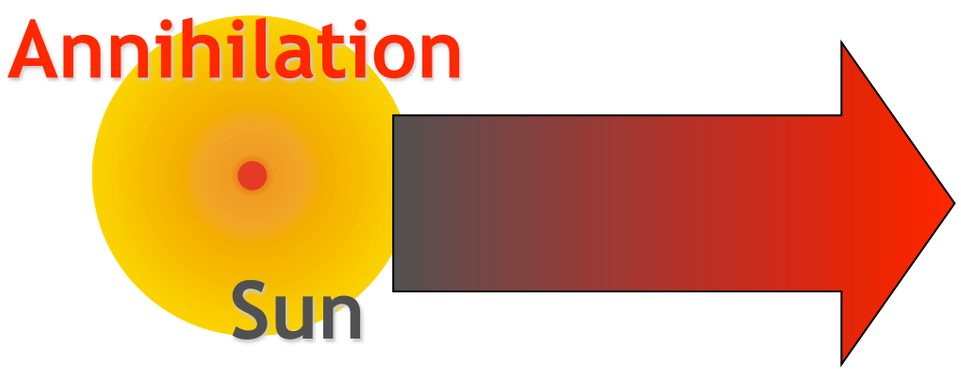
Future WIMP Sensitivities

Direct Detection	Indirect, km^3 Detector	
Genius/CRESST	Earth	Sun





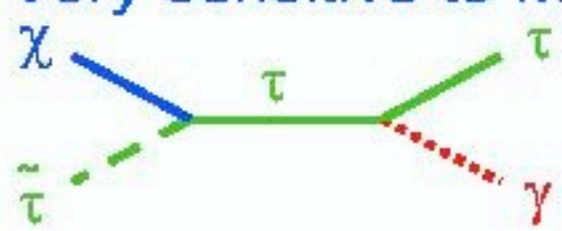




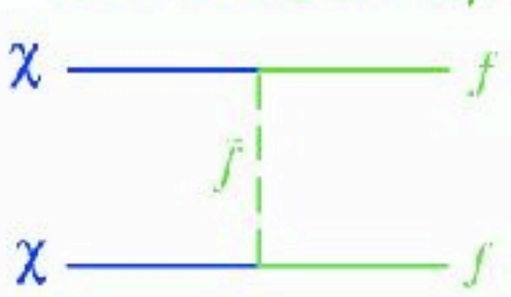
Relic Density

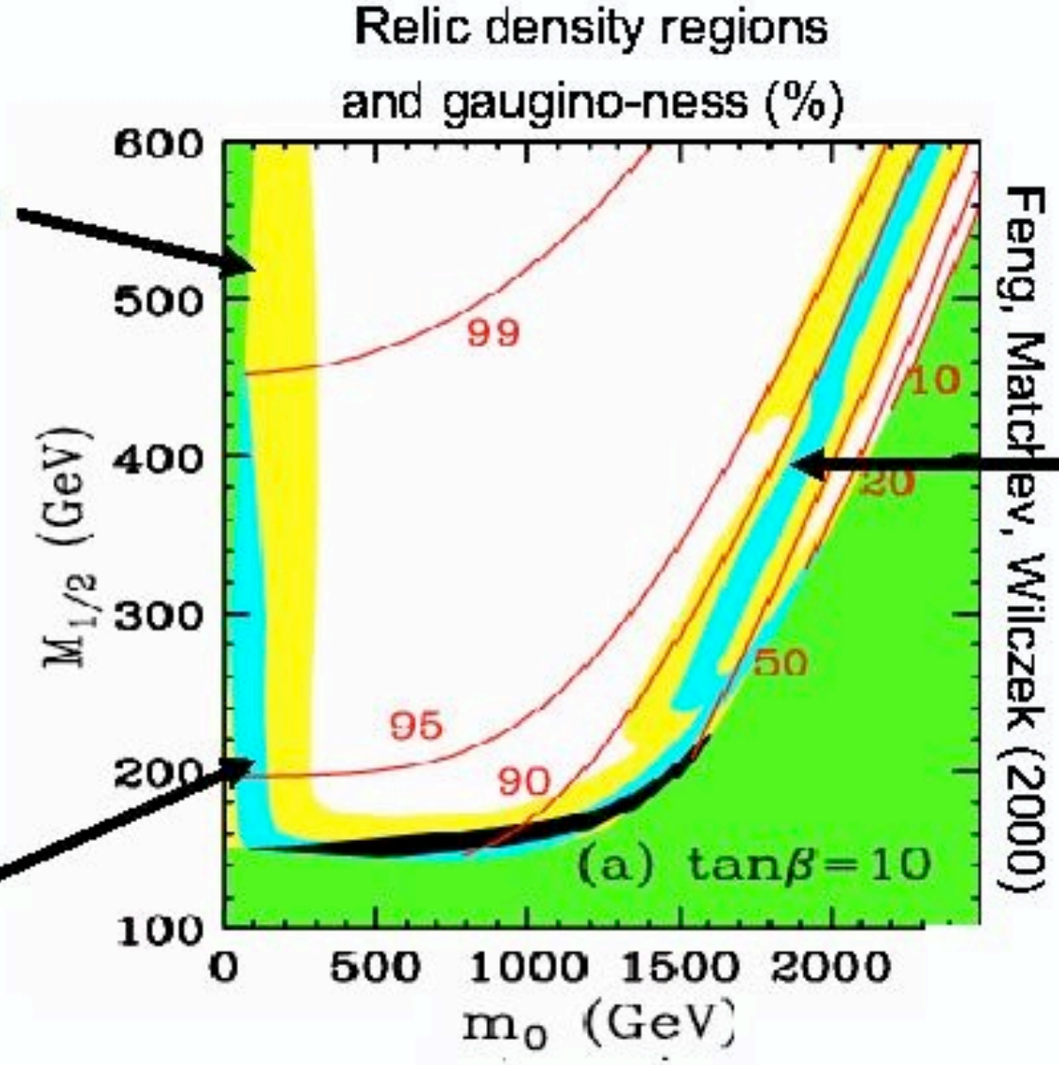
- Cosmology: $\Omega_{DM} = 0.23$

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

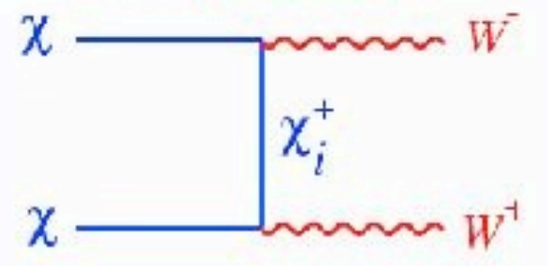


Bulk region
$\chi \approx$ pure Bino
Sensitive to $m_{\tilde{f}}$





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

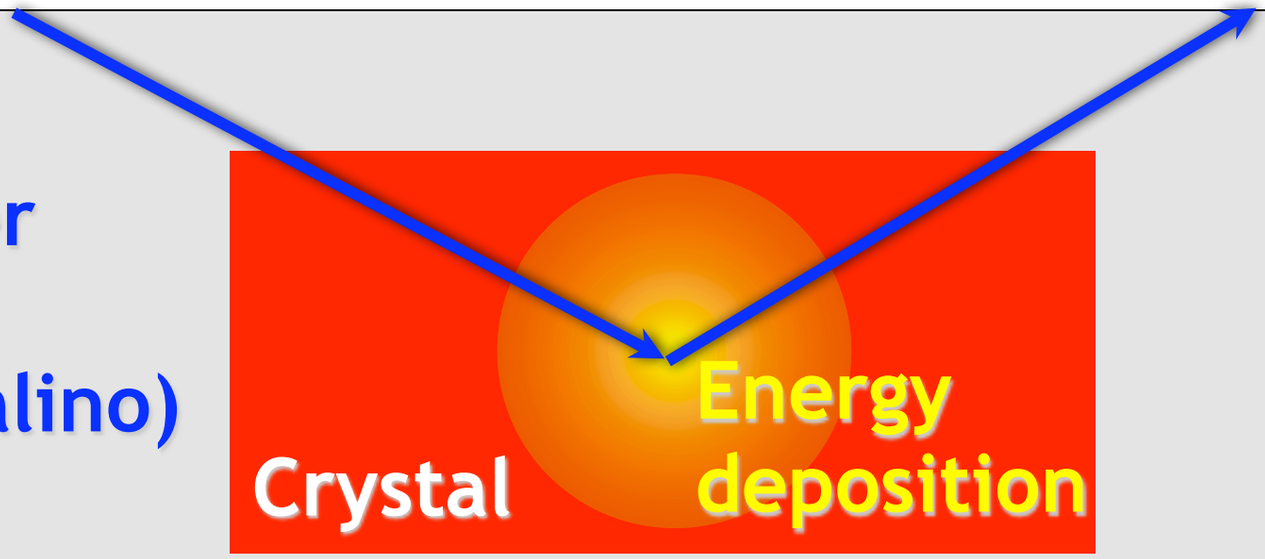


Jonathan Feng, SLAC Summer School 2003

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

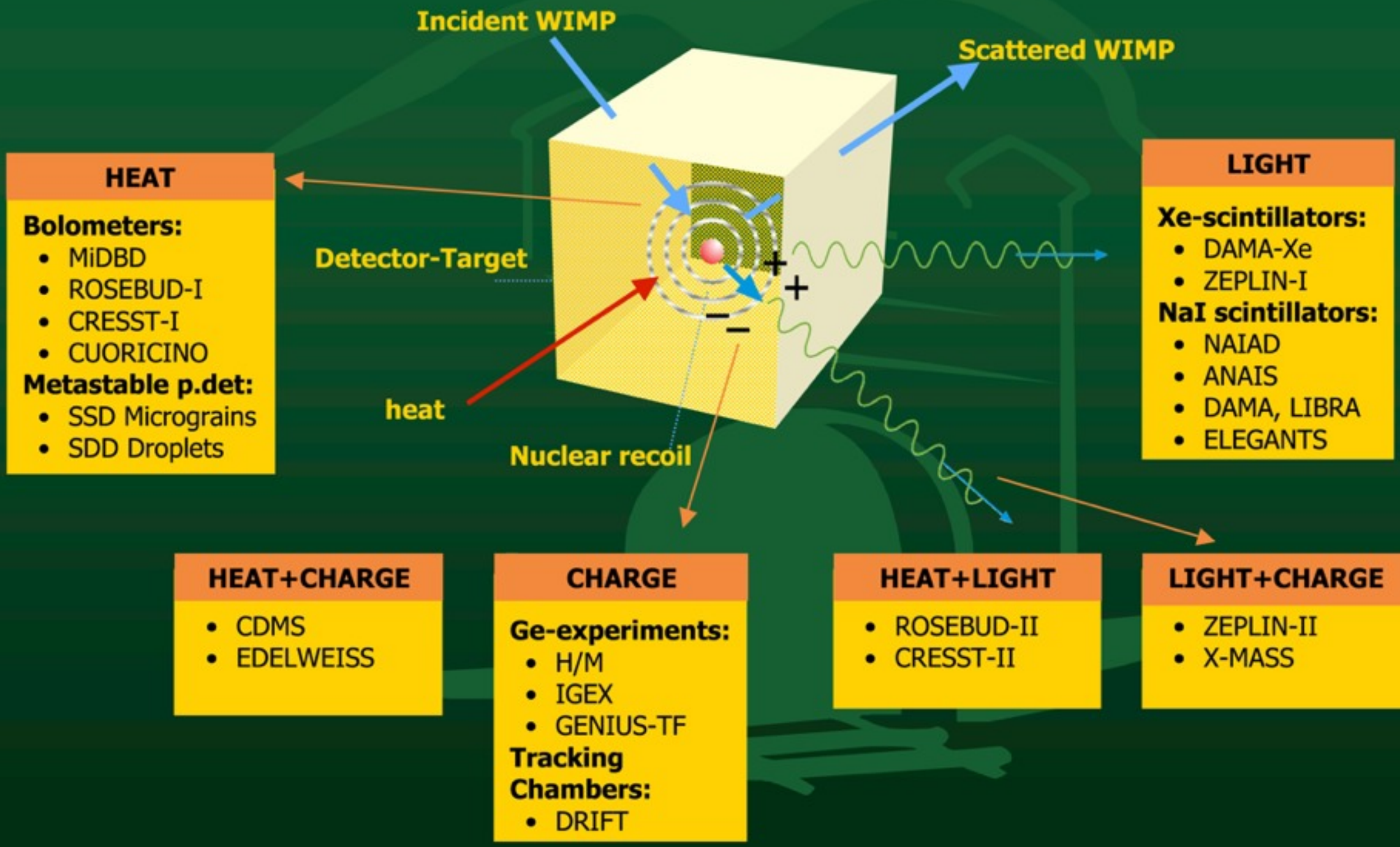
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

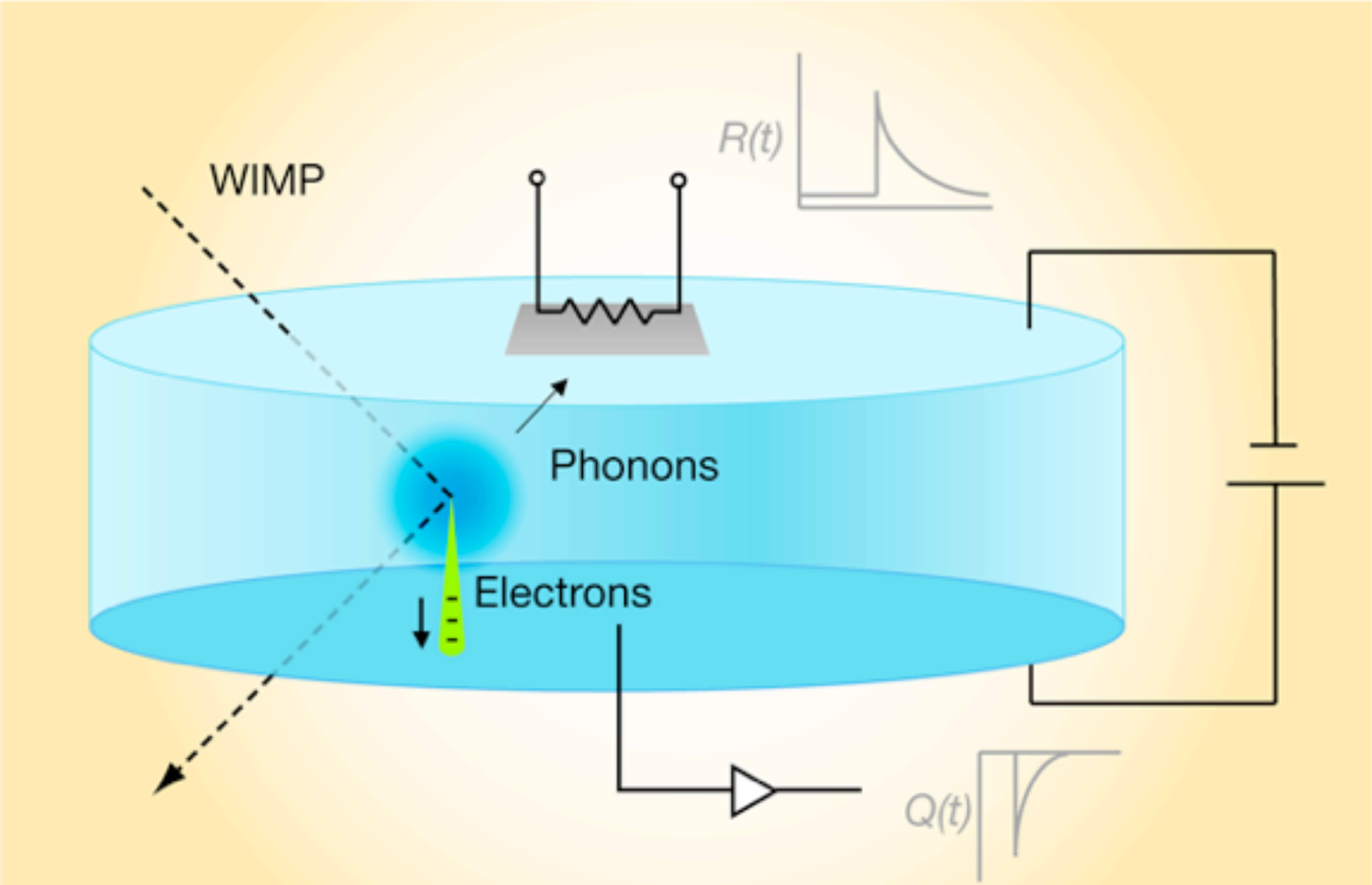
Detectability of certain dark-matter candidates

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





CDMS - Cryogenic DM Search

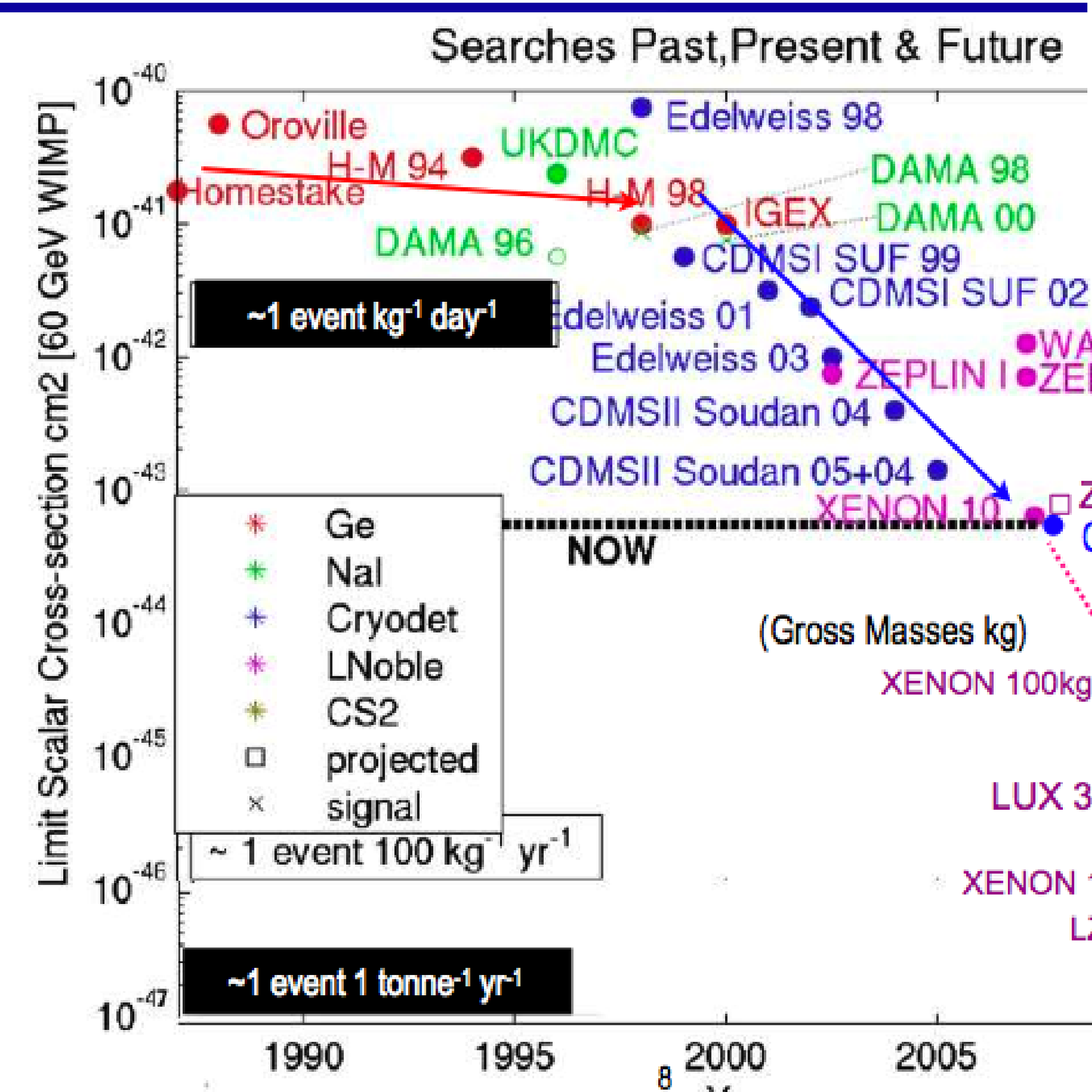
Berkeley-Stanford-led experiment has been at forefront

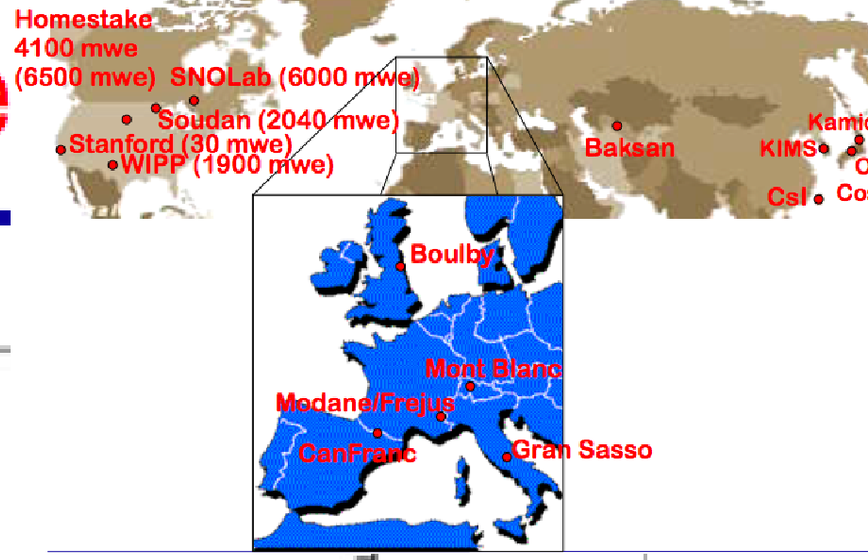
Figure from: Perspective by Karl van Bibber http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.011301 on Z. Ahmed et al. CDMS Collaboration, "Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory,"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

- [Overview of dark matter searches](#) Katherine Freese (Univ. of Michigan)

DM Direct Search Progress Over Time

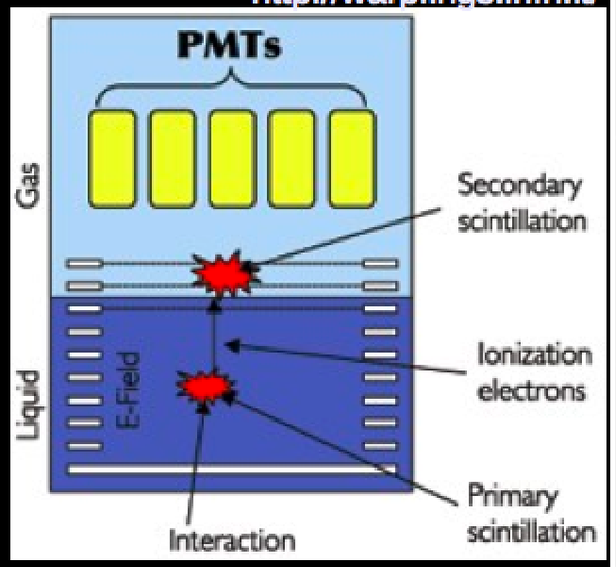




liquid noble detectors

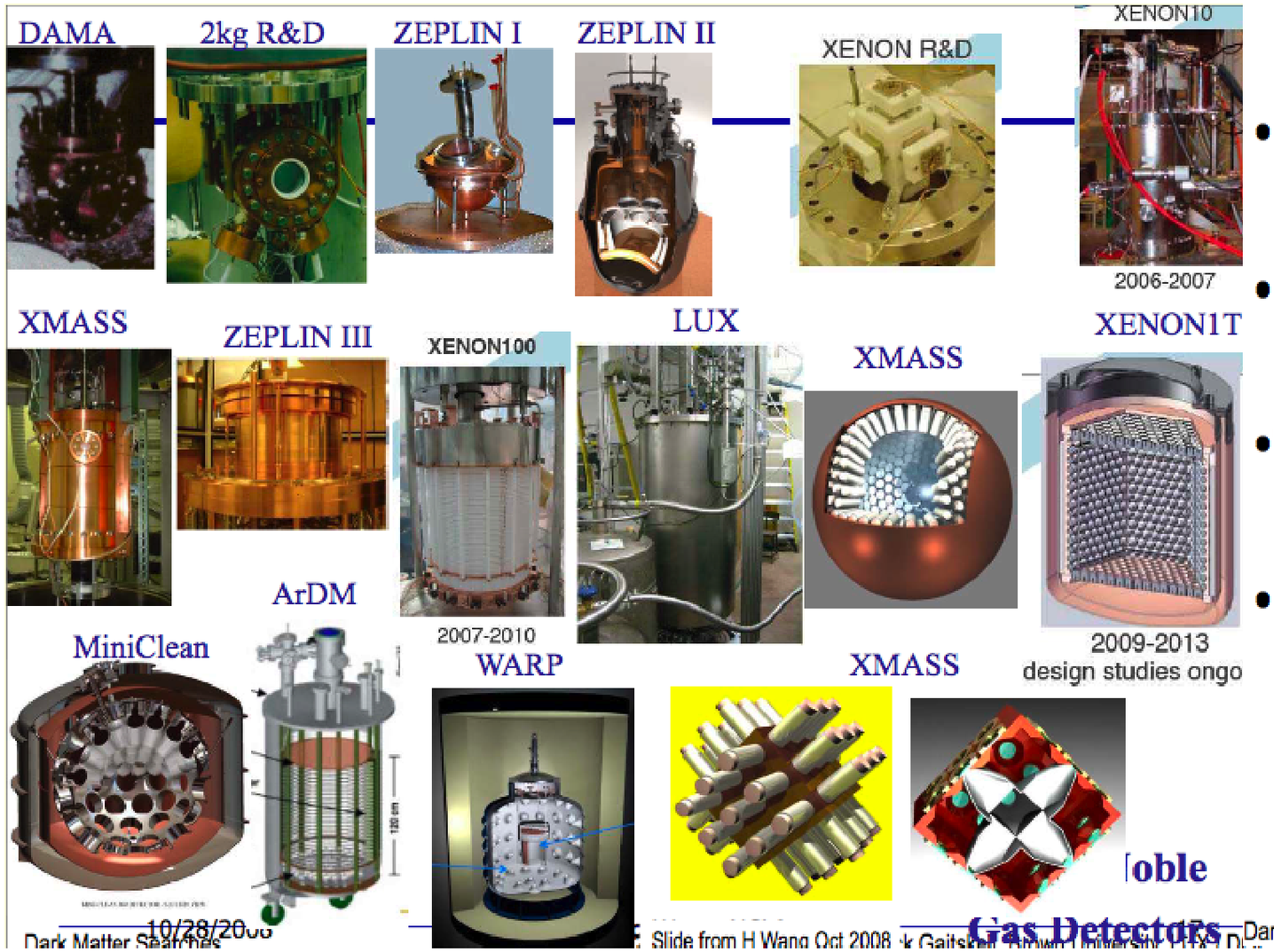
- WIMP-nucleus elastic scattering produces ionization electrons and photons.
- Photons (primary scintillation) are detected by PMTs
- Electrons are drifted (by E field) to gas region, where they are accelerated and collide with gas atoms, producing secondary scintillation
- Shape of primary and ratio 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

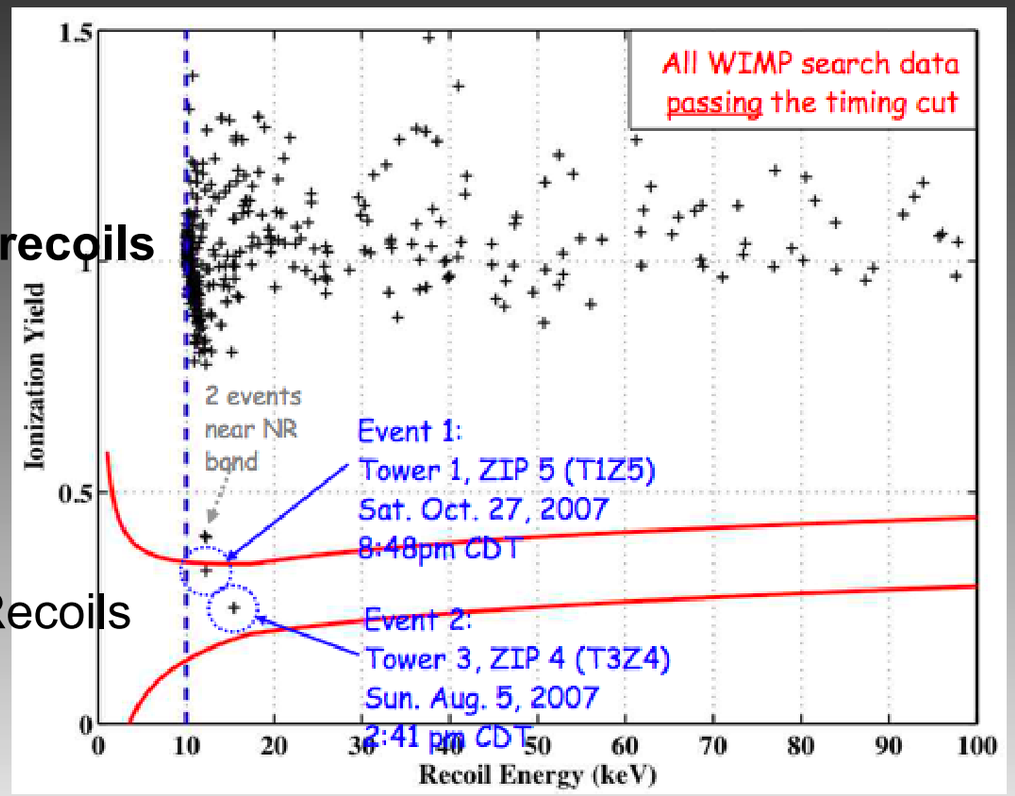


Future of Direct Detection

- 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

CDMS updates Jeter Hall (Fermilab)

Unblind Events Passing Timing Cut



Electron recoils

Nuclear Recoils

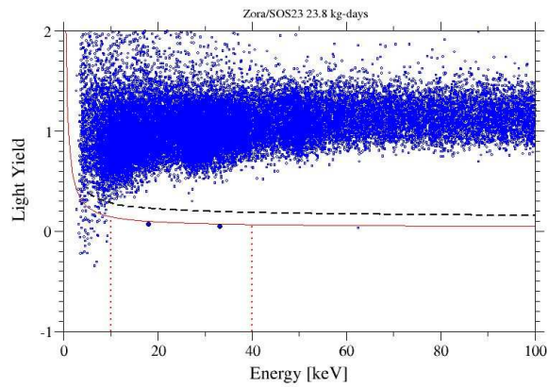
2 events in the NR band pass the timing cut!

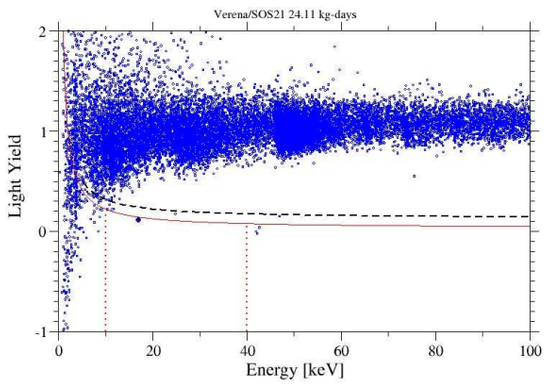
- Two events observed
  - Consistent with 0.9 ± 0.2 events expected from known backgrounds
  - Neither are golden events
    - Likelihood encourages suspicion about one event
    - Event reconstruction encourages suspicion about the other event
  - No obvious errors to exclude either event

Progress of the CRESST II experiment

Leo Stodolsky (Max Plank Institute)

CRESST had three 'unexplained events' in 'Commissioning Run'





"BRAND X" has *only* two unexplained events. Commissioning Run: G. Angloher et al., Astroparticle Phys. **31**, 270 (2009); arXiv:0809.1829

Overview of dark matter searches Katherine Freese

What will it take for us to believe DM has been found?

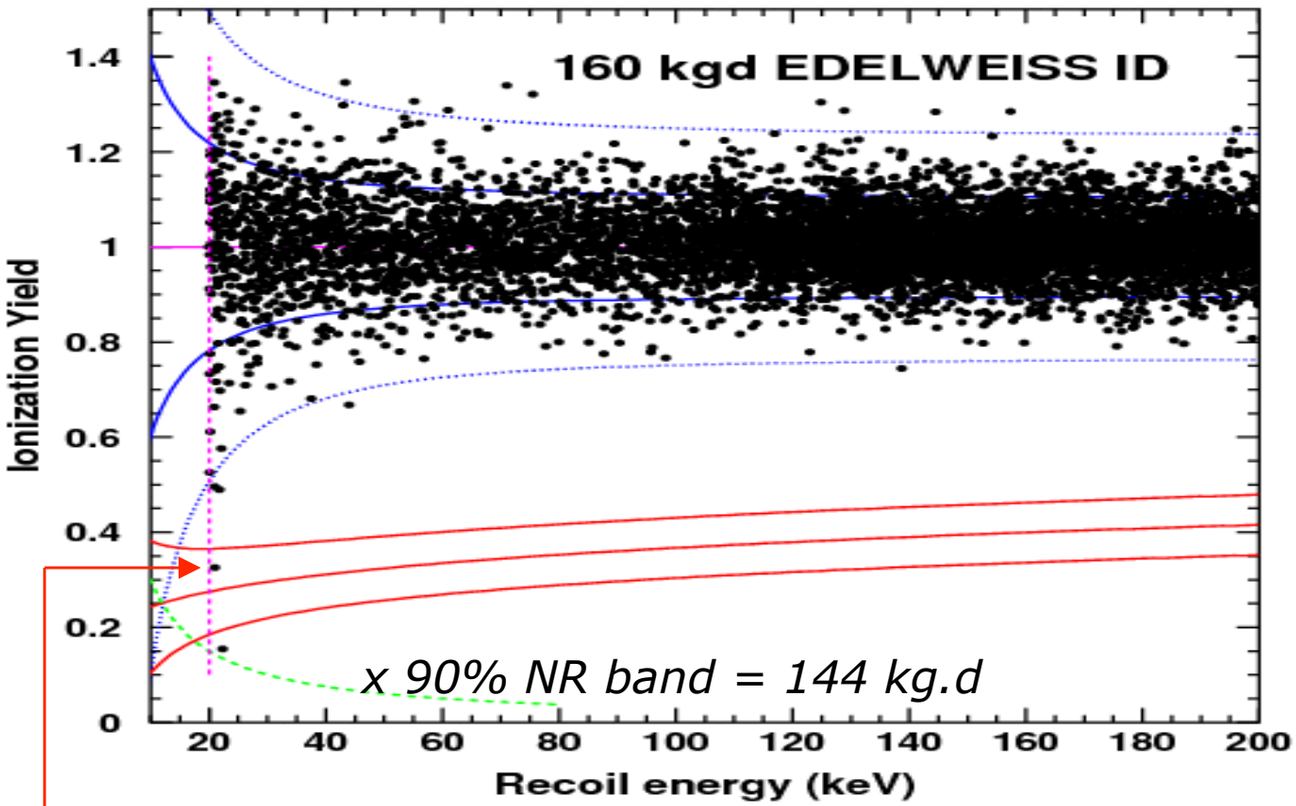
- I. Direct detection:

  compatible signals in a variety of experiments made of different detector materials, and all the parties agree
- 2. Indirect detection:

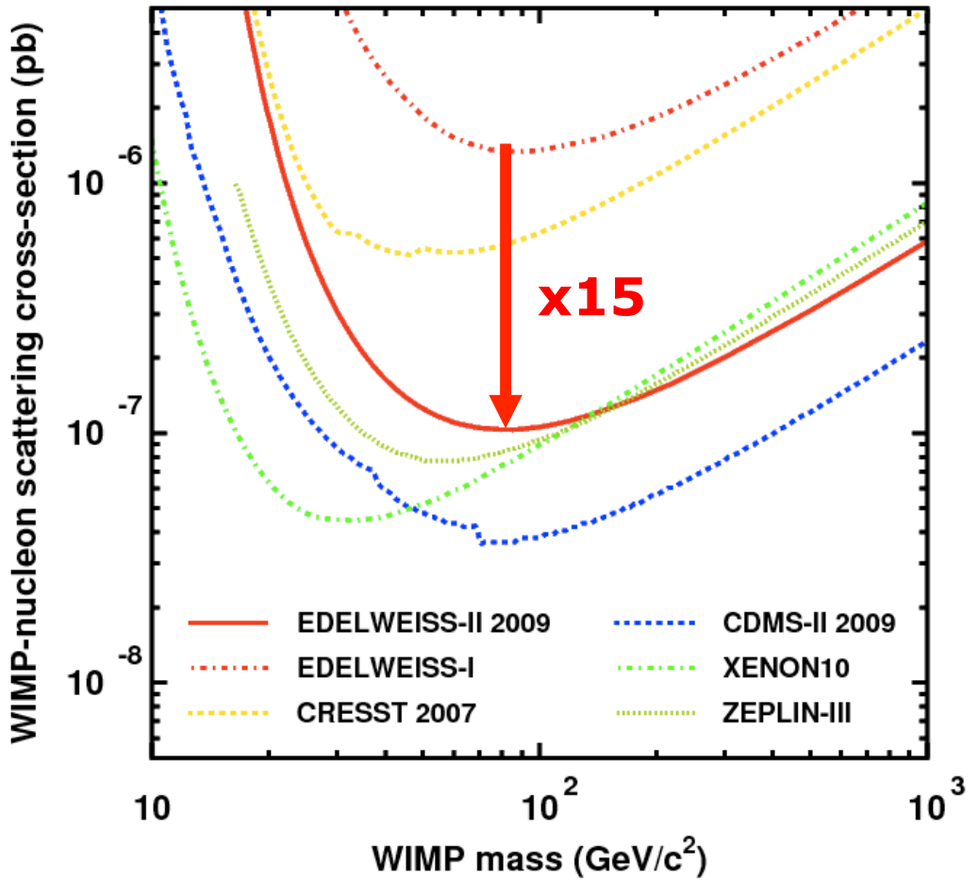
  annihilation signals in a variety of channels (neutrinos, gamma-rays, etc) all coming from the same source

EDELWEISS-II: First Results

- *Background reduced wrt EDELWEISS-I by a factor 50* **arXiv:0912.0805**



« WIMP candidate »
Er = 21 keV



End of January:
~ x1.75 exposure,
Run continues
until spring

Background estimation from previous calibrations/ simulations:
- gamma < 0.01 evt (99.99% rejection)
- beta ~ 0.06 evt (from ID201 calibration+obs. surf. evts)
- neutrons from ^{238}U in lead < 0.1 evt
- neutrons from ^{238}U+(α,n) in rock ~ 0.03 evt
- neutrons from muons < 0.04 evt

} < 0.23 evt

PICASSO New Results

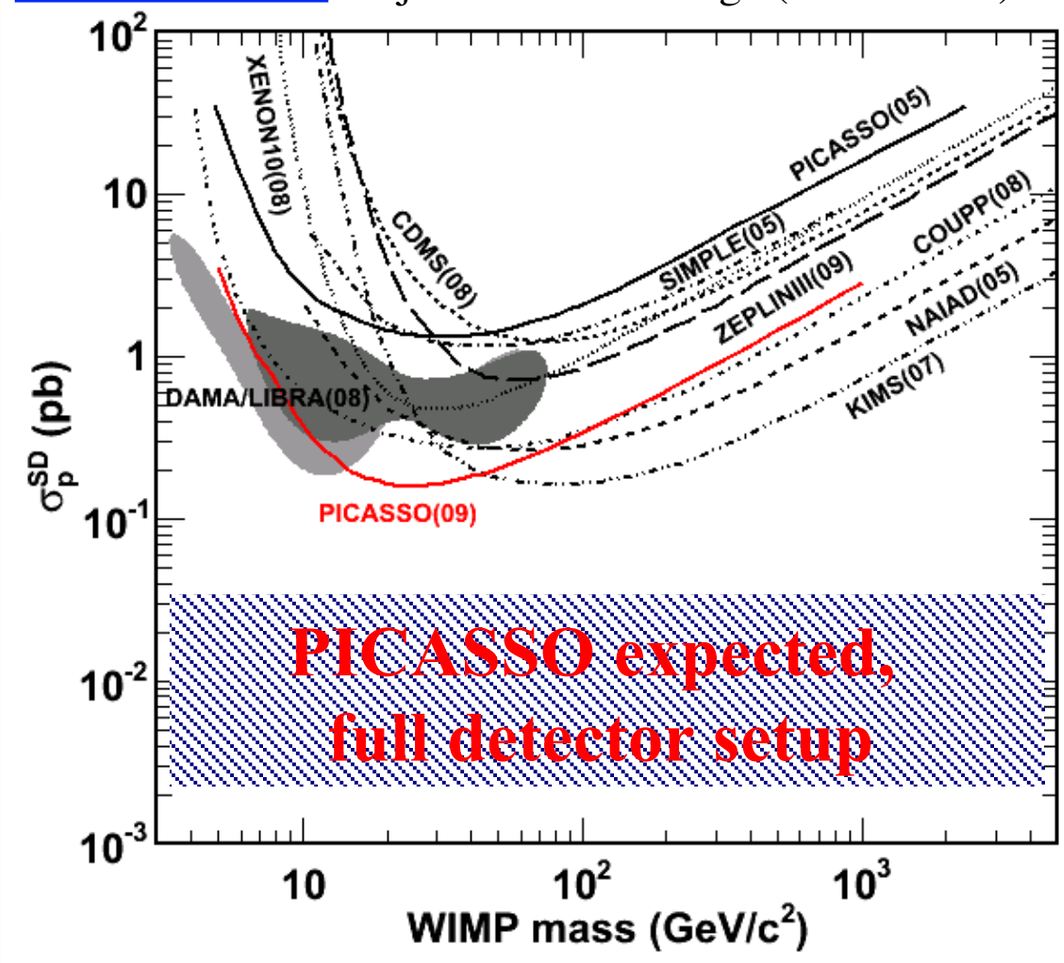
Publishing again soon this summer…

2009

σ_p = - 0.0051pb ± 0.124pb ± 0.007pb (1σ)

13.75±0.48 kg.days (134g ^{19}F)

Spin dependent limits on WIMP-proton scattering crossection from PICASSO Sujeewa Kumaratunga (U Montreal)



in progress

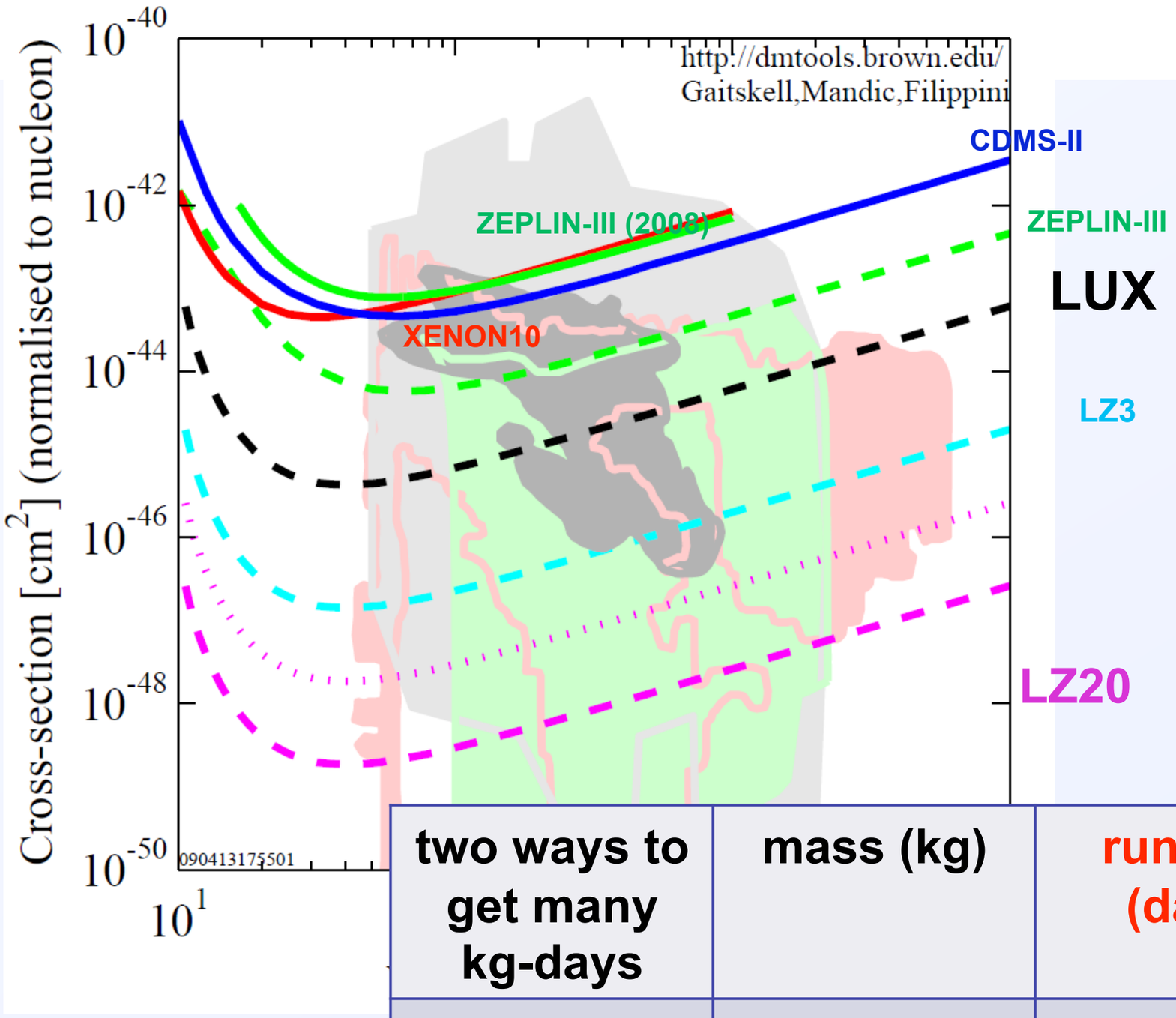
full analysis
32 detectors
2.6 kg ^{19}F, 144 kgd

limit of σ_p = 0.16 pb (90%C.L.) for a WIMP mass of 24 GeV/c2

* S. Archambault et al.; Phys. Lett B. 682 (2009) 185 (arXiv: 0907.0307)

Projected sensitivity of LUX

Large Underground Xenon (LUX) Collaboration Adam Bernstein (LLNL)



Predicted WIMP rate = 4 events in 300 day for $7 \cdot 10^{-46}$ cm^2 @ 100 GeV

Predicted background = <1 event in 300 day

PMTs dominate

two ways to get many kg-days	mass (kg)	run time (days)	kg-days of search data
LUX	100 (fiducial)	6	600
recent CDMS run	about 3	~200	612

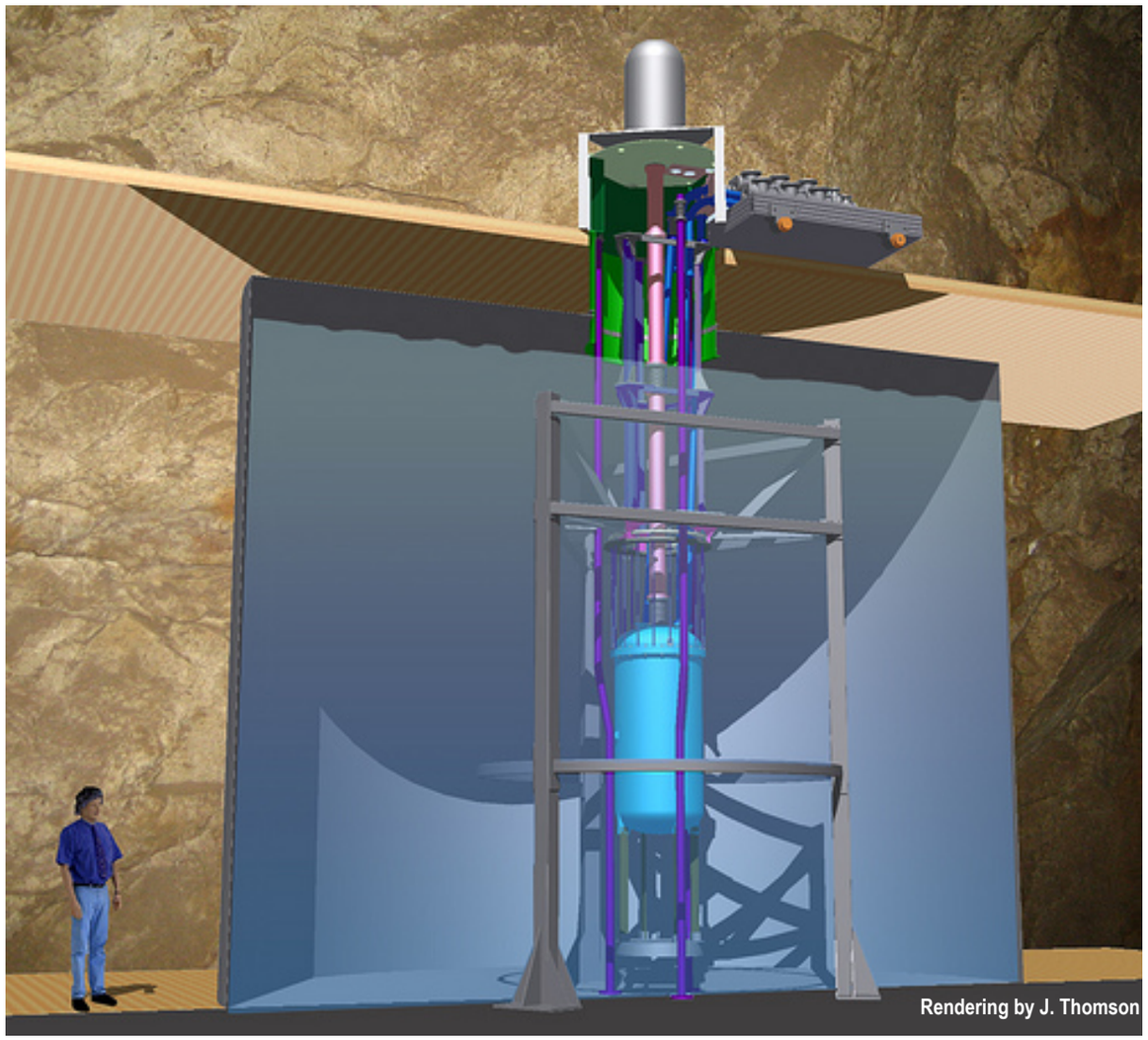
WIMP Signals in a Dual-Phase Xenon Detector

www.luxdarkmatter.org

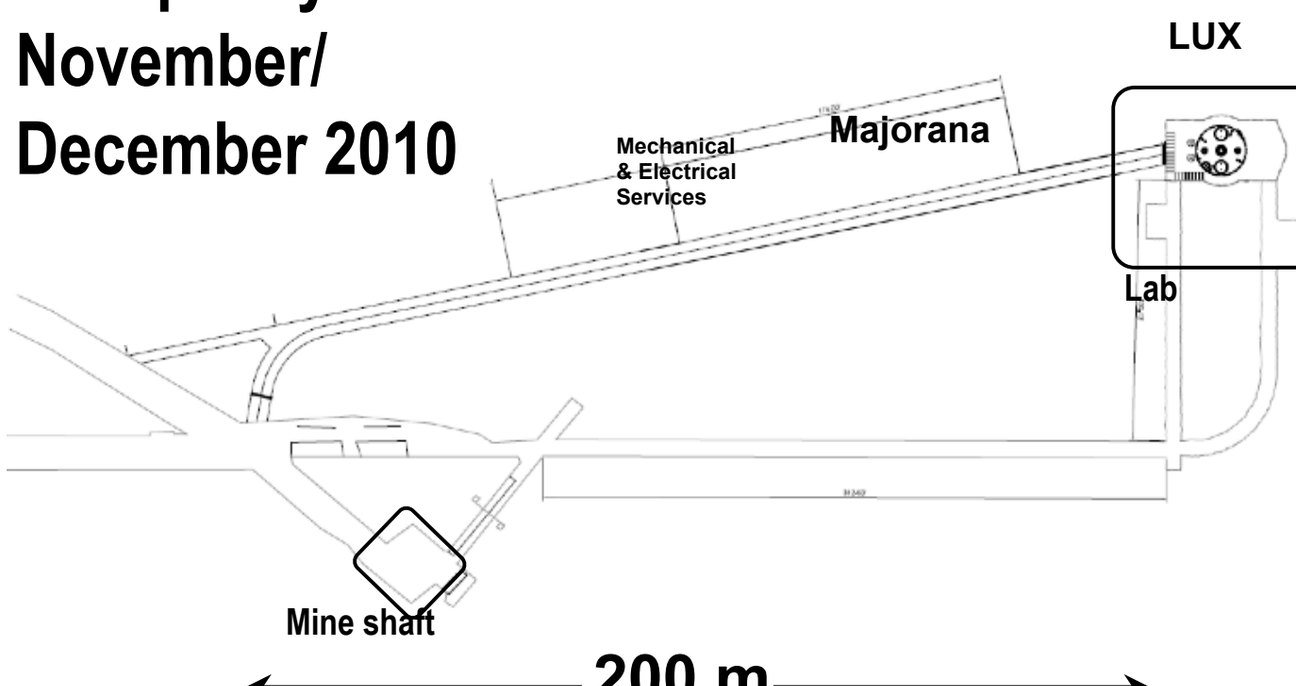
LUX in the Davis Laboratory at the Homestake Mine in South Dakota (4850

- 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



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: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

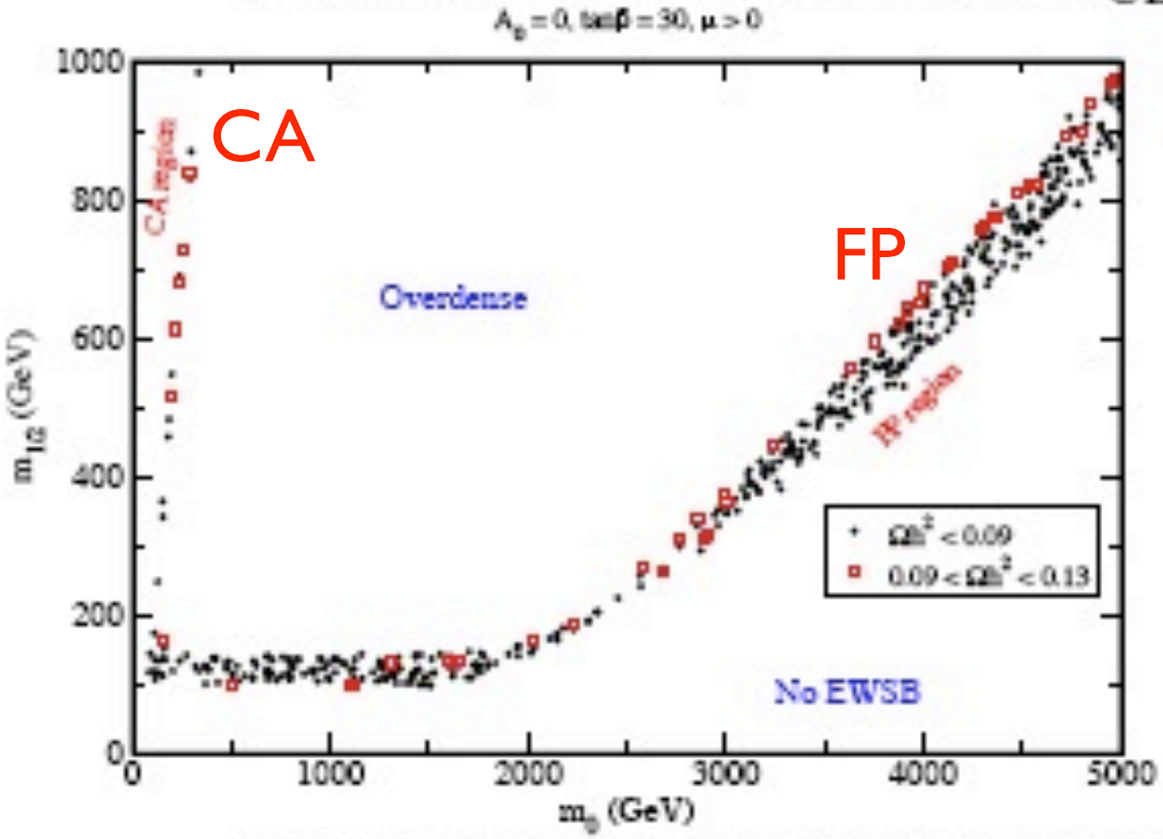
- Find well defined regions of parameter space consistent with the relic density from WMAP

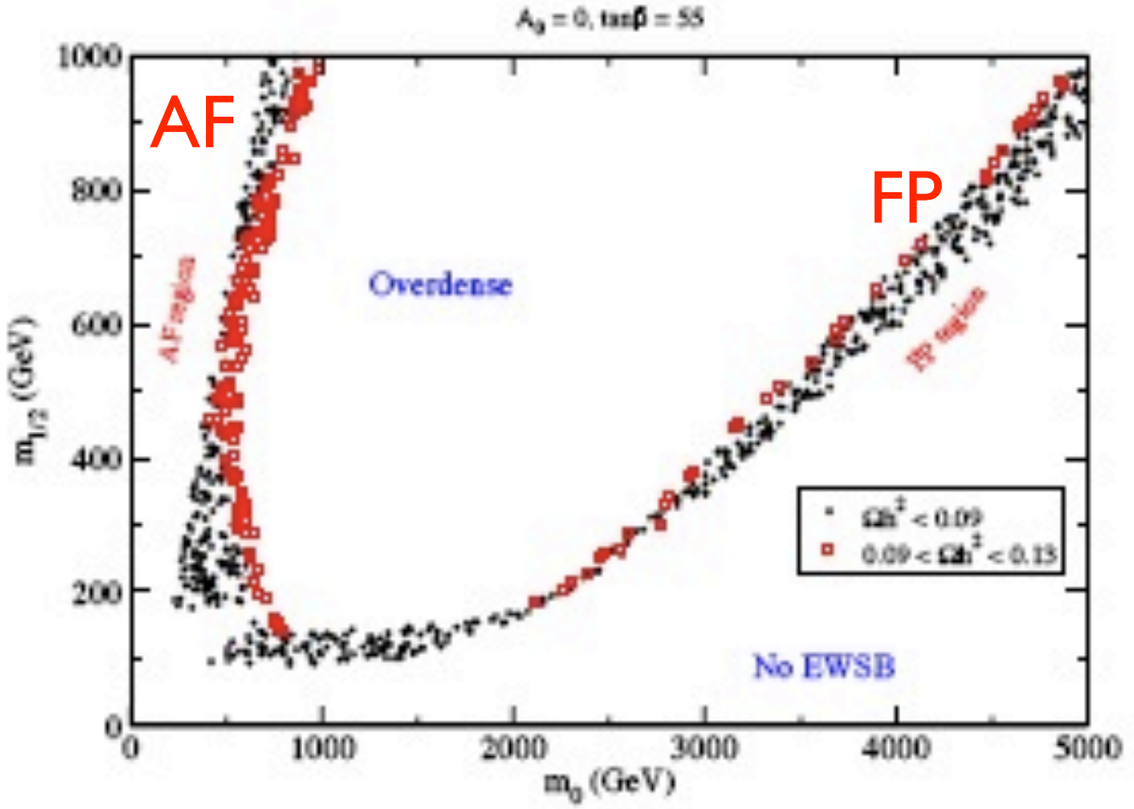
$$0.099 < \Omega_{DM} h^2 < 0.123 \ (2\sigma)$$

- 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

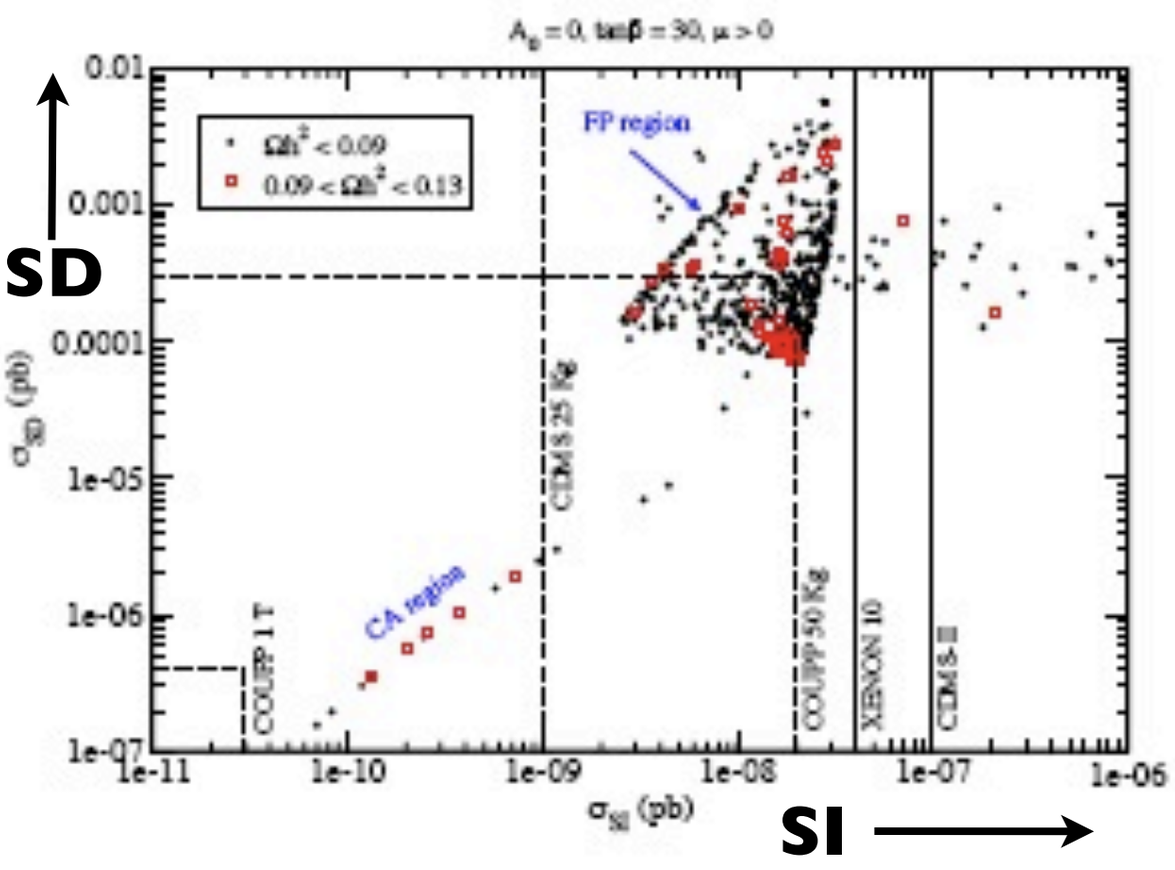
  Preferred by $b - \tau$ unification

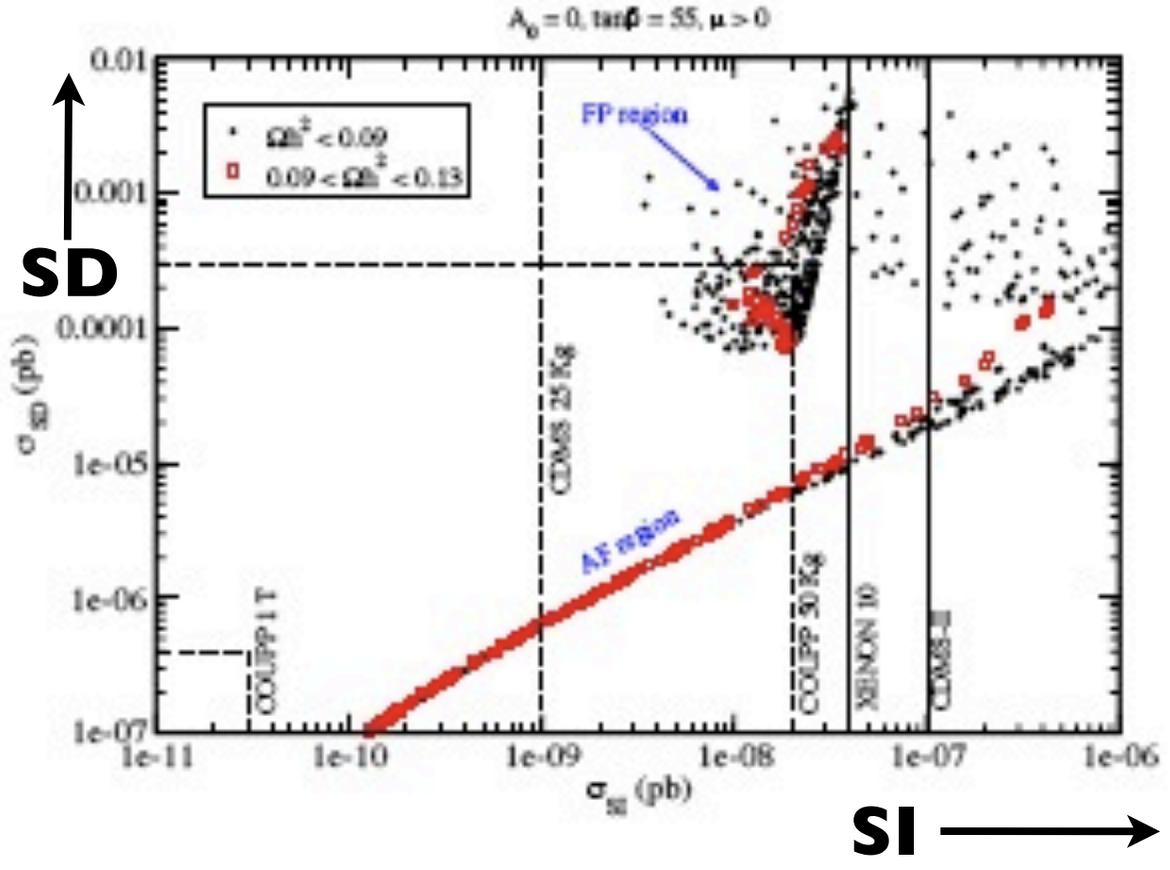
  Solves SUSY FCNC and CP-violating problems

- 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

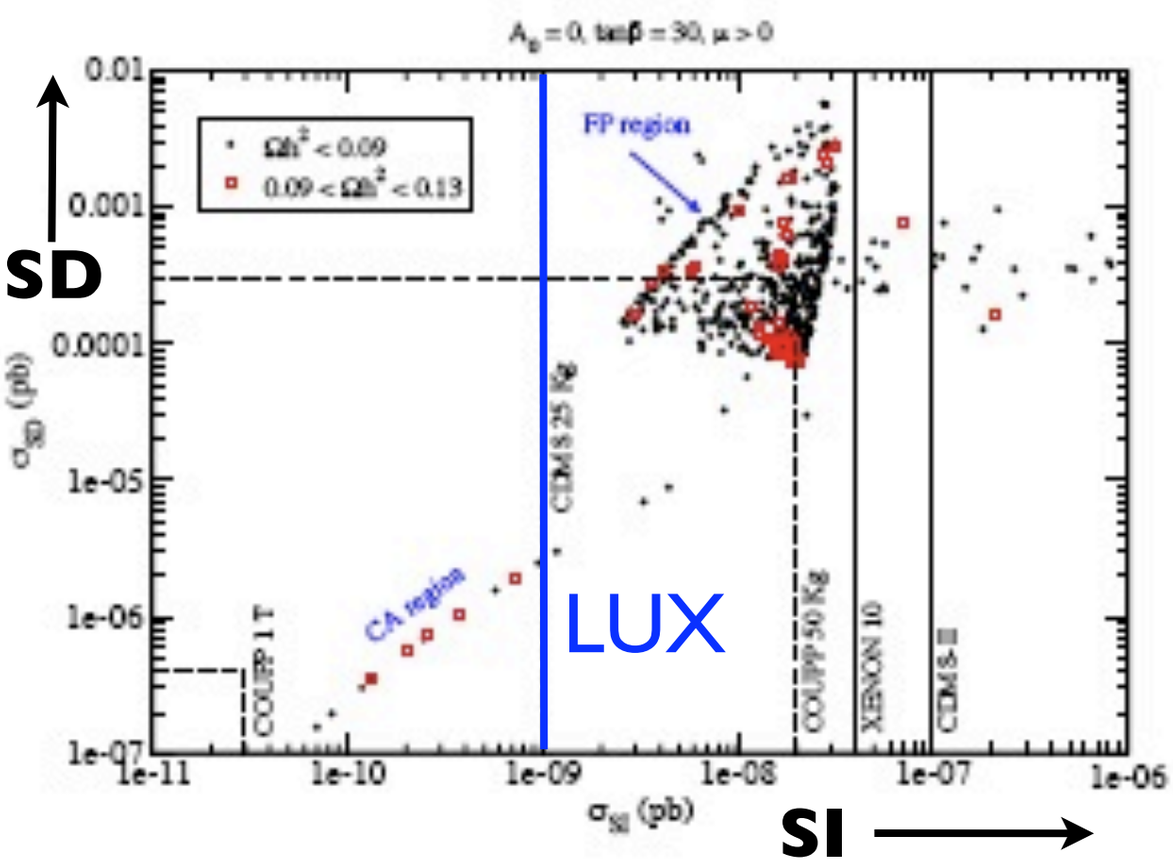


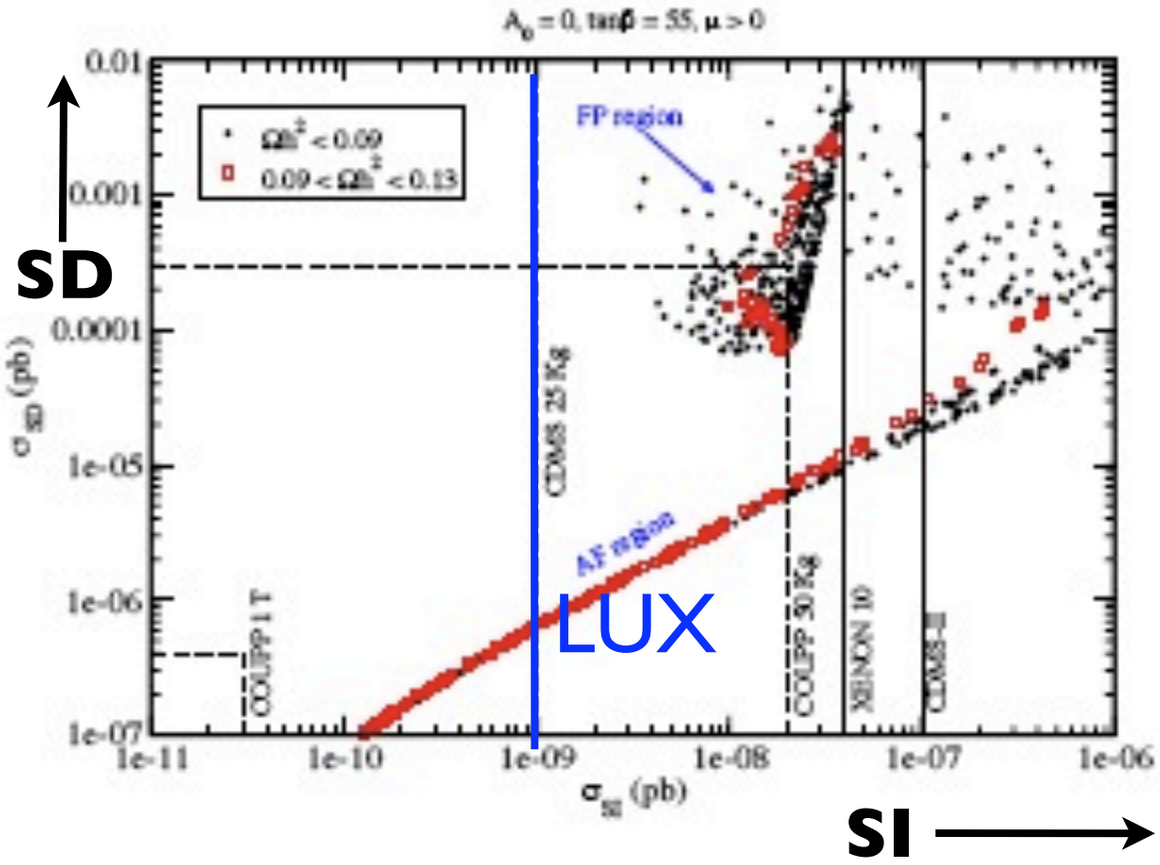


- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

Scattering rates in mSUGRA

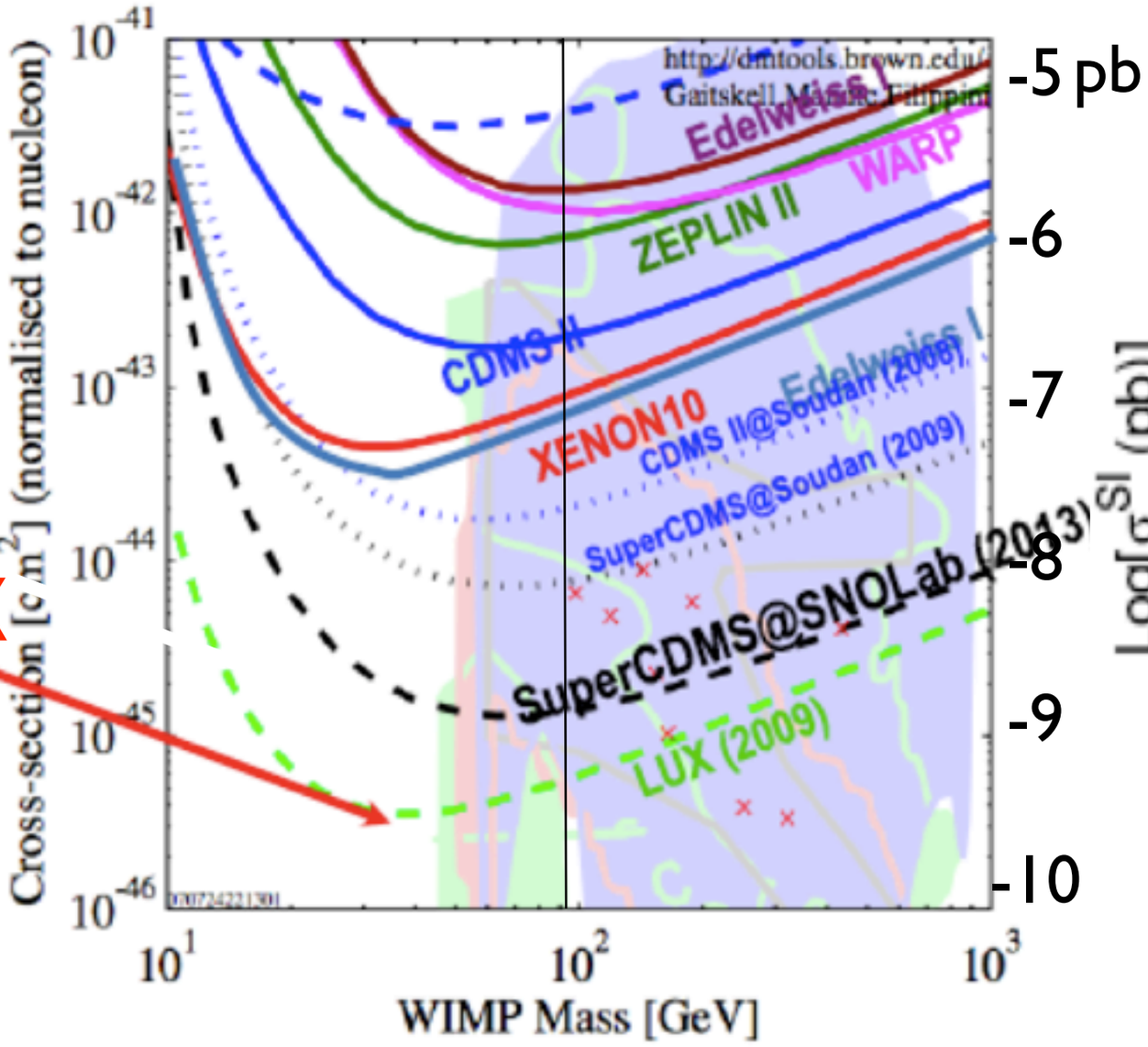
- Different solutions to DM relic density populate different regions of σ_{SD} vs. σ_{SI} Spin Dependent vs. Spin Indenepdent

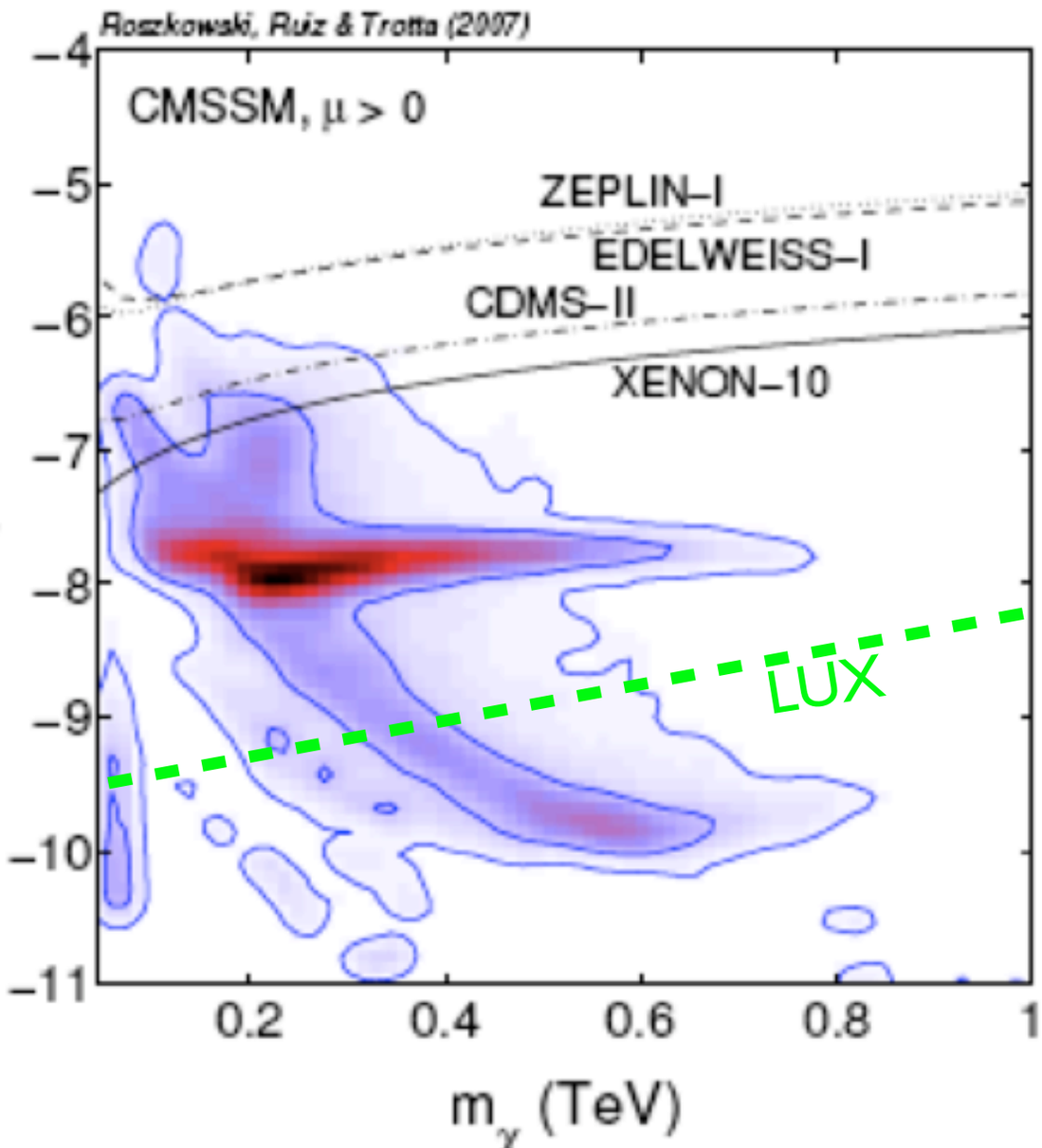




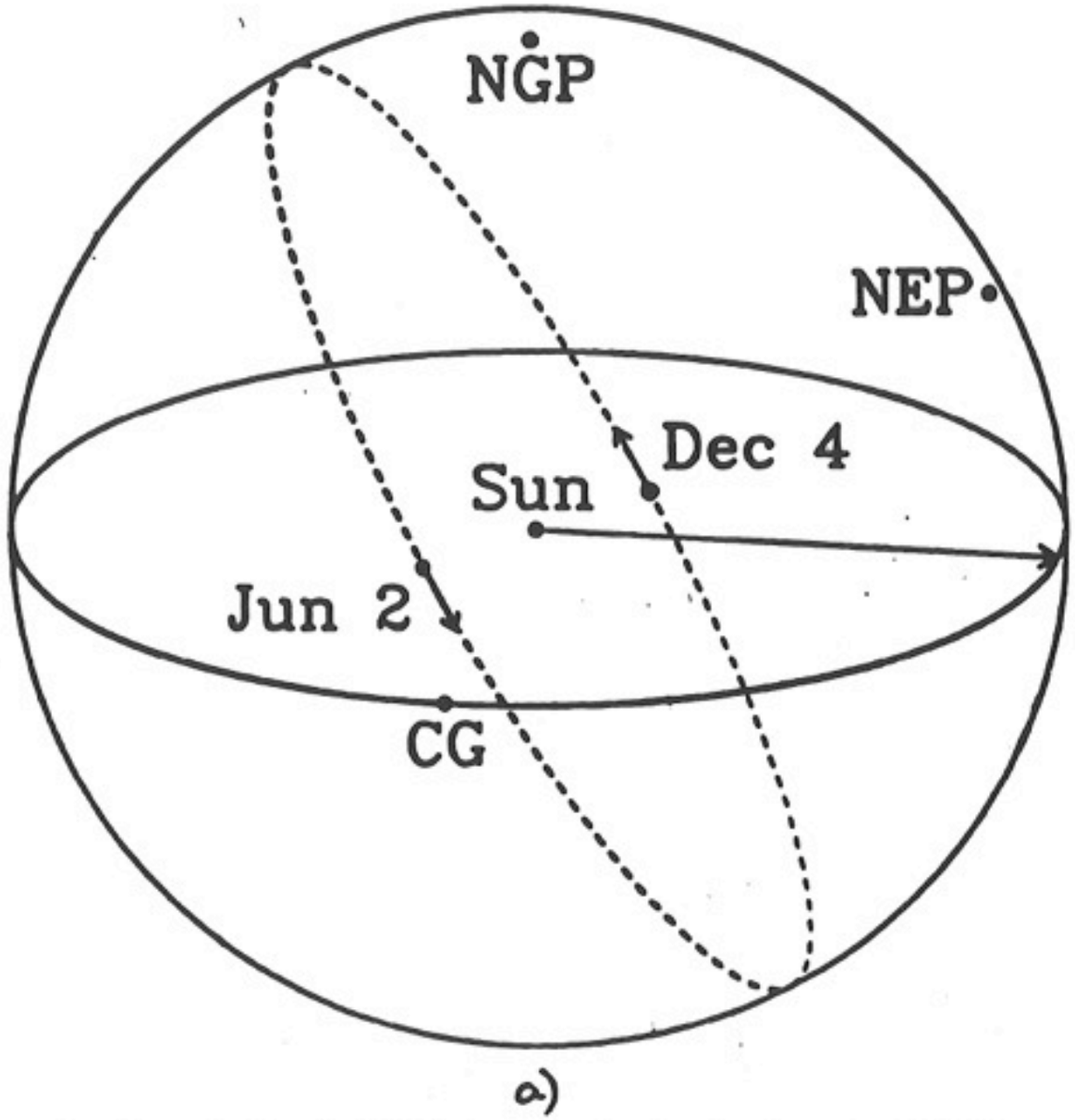
- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

By ~2010 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 2010-11.

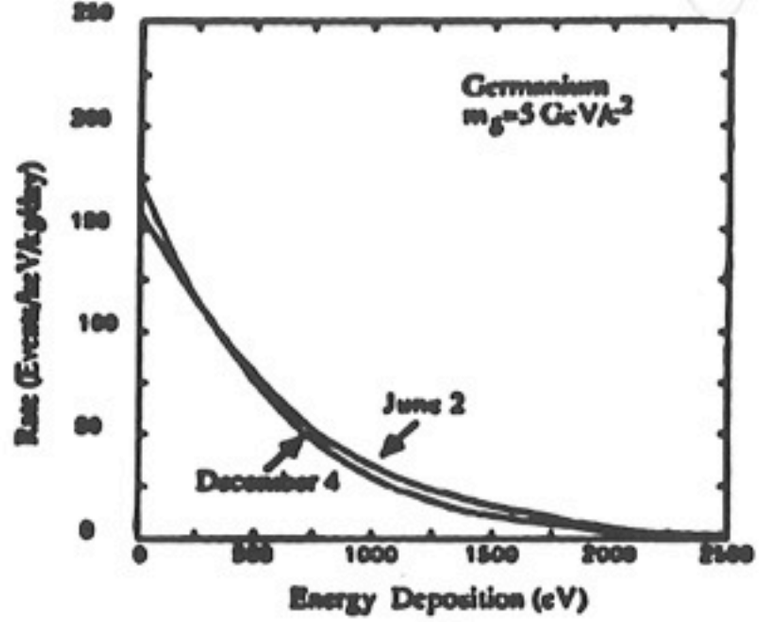




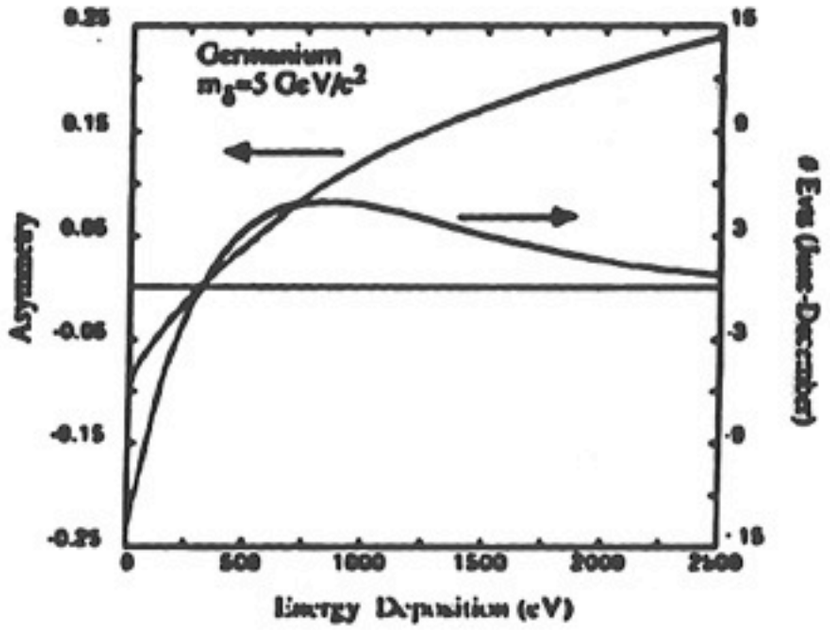
10^{-8} pb = 10^{-44} cm^2 (barn=10^{-24} cm^2, pb = 10^{-12} b = 10^{-36} cm^2)



a)



b)

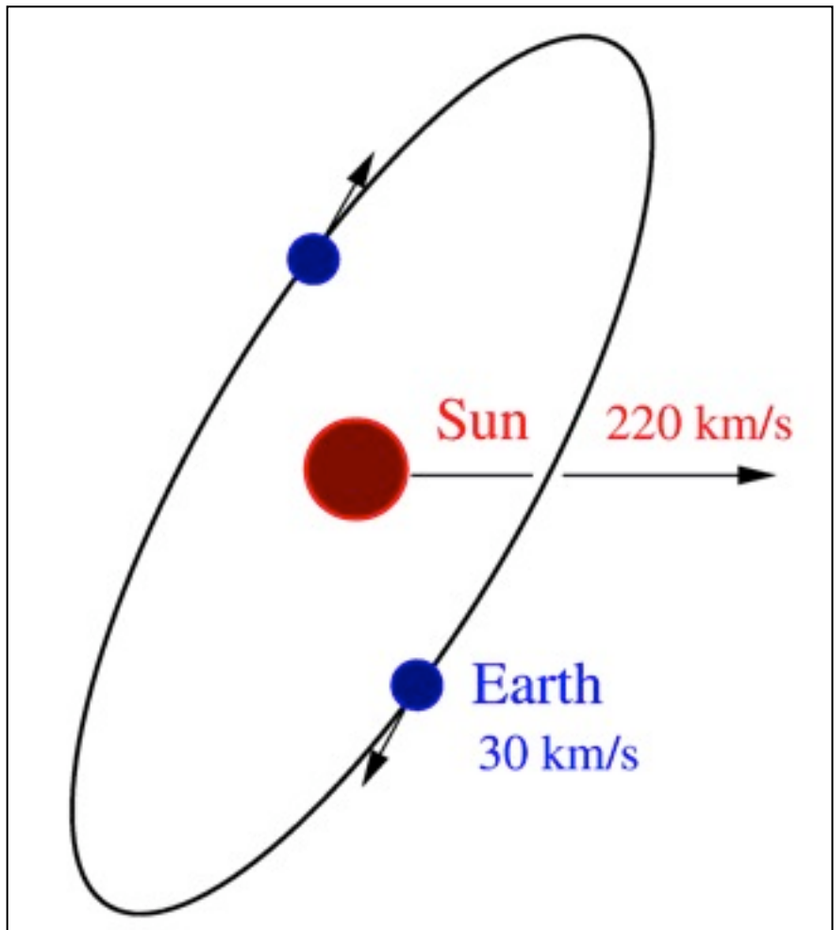


c)

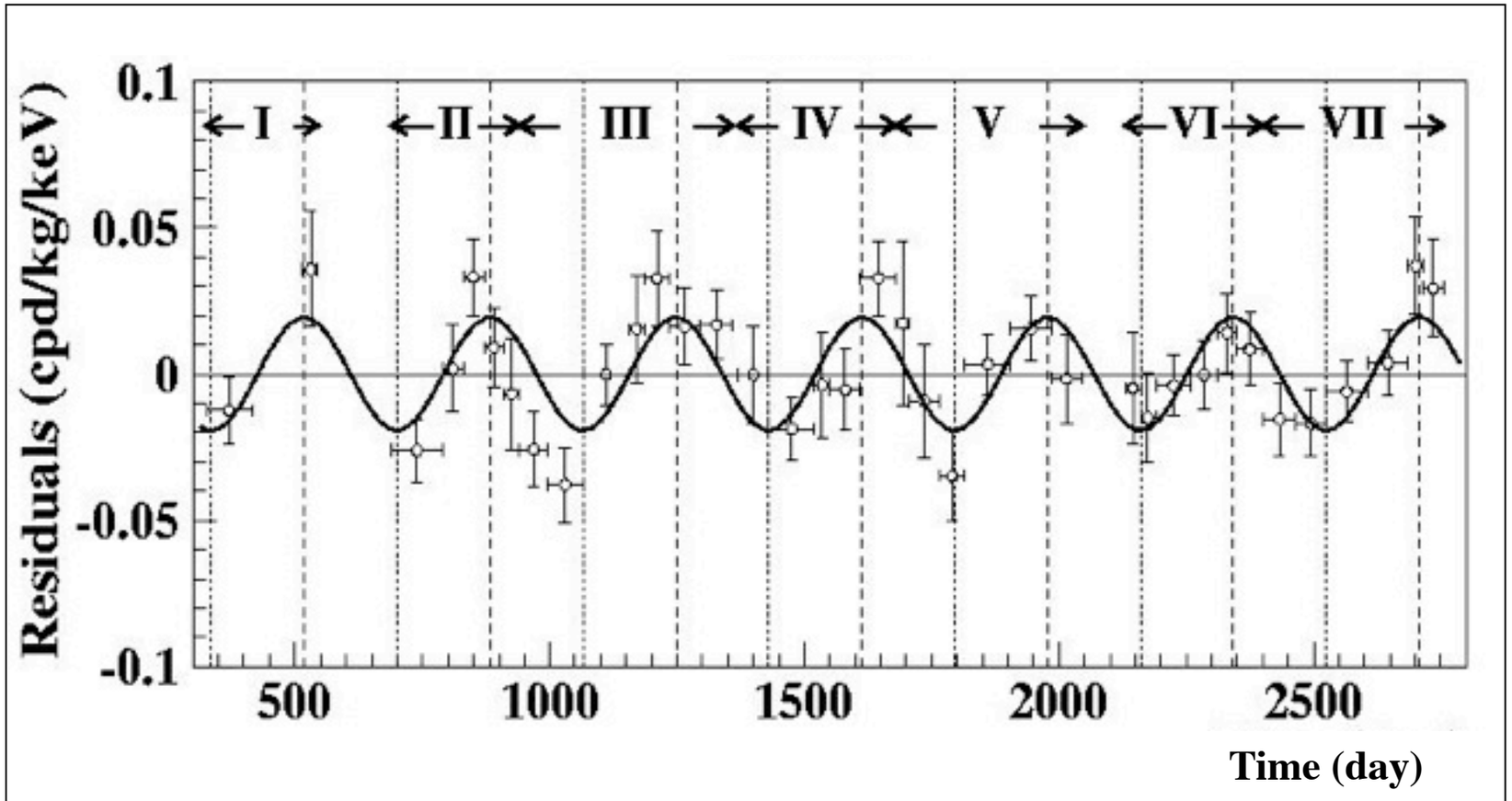
Figure 3. Annual effect in WIMP detection by elastic scattering. (a) Why expected: The solid line (darker in the front) shows the plane of the galactic disk and the Sun's orbit; the dashed circle is the orbit of the Earth (ecliptic plane). NGP and NEP are the north galactic and ecliptic poles. CG shows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



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]

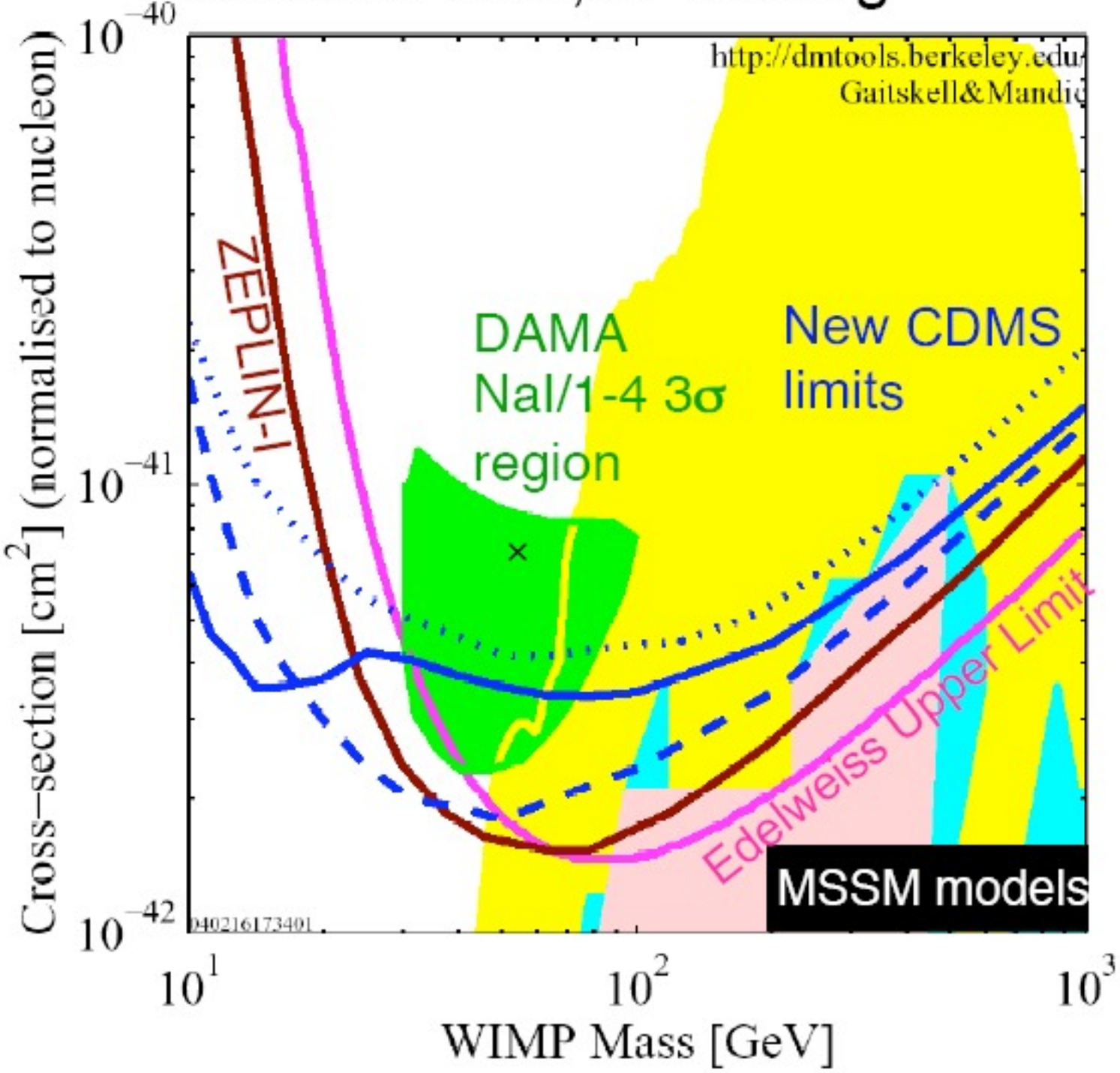


Annual modulation of WIMP signal a "smoking gun" signature

- Detector stability ?
- Background stability ?

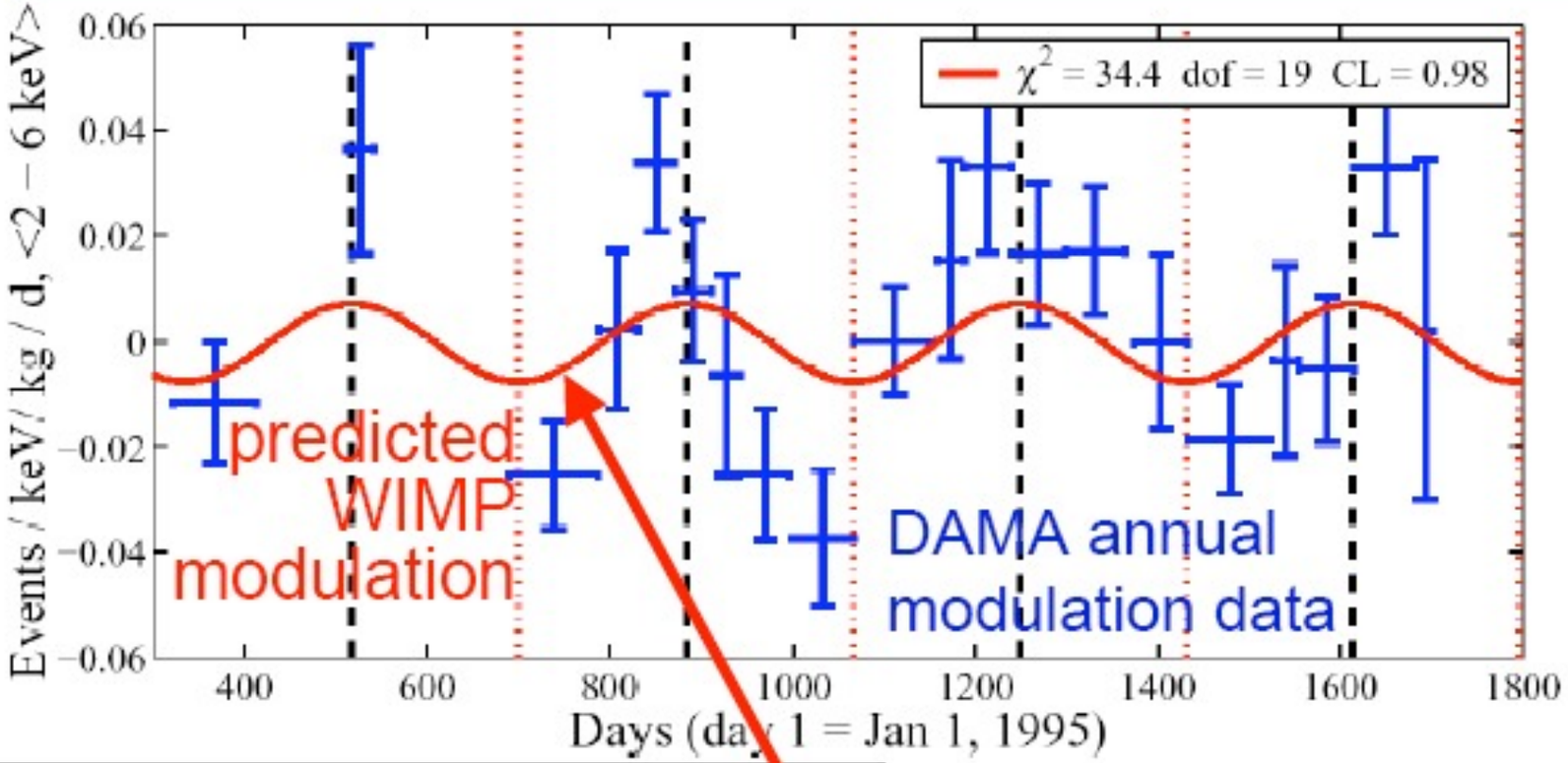
Resulting Experimental Upper Limits

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

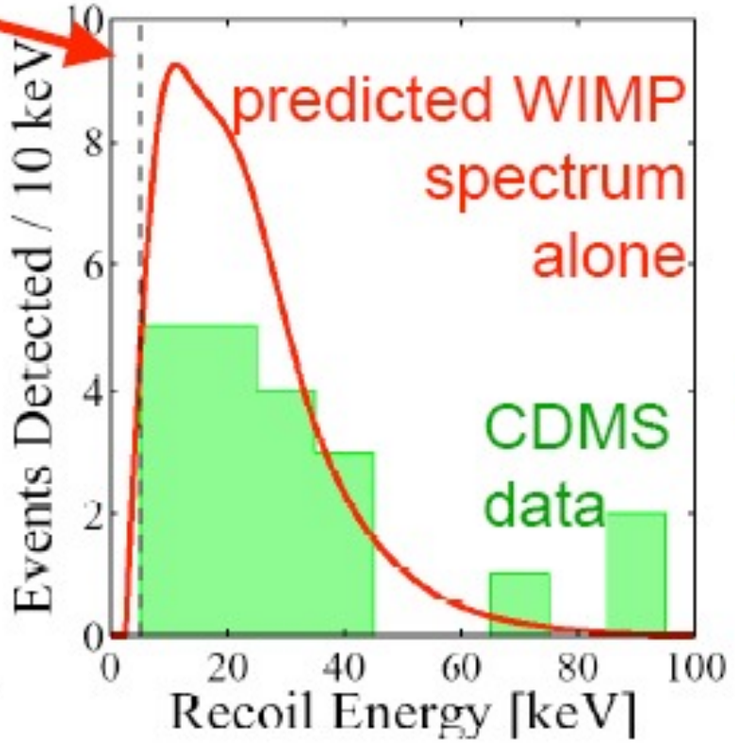


- Calculate allowed region using extension of "Feldman Cousins" method
  - Constrain neutron background based on neutron multiples, Si
- Limits slightly worse than expected sensitivity (dashes), slightly better than limits wo/ subtraction (dots)
- Exclude new parameter space for WIMP masses below 20 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)

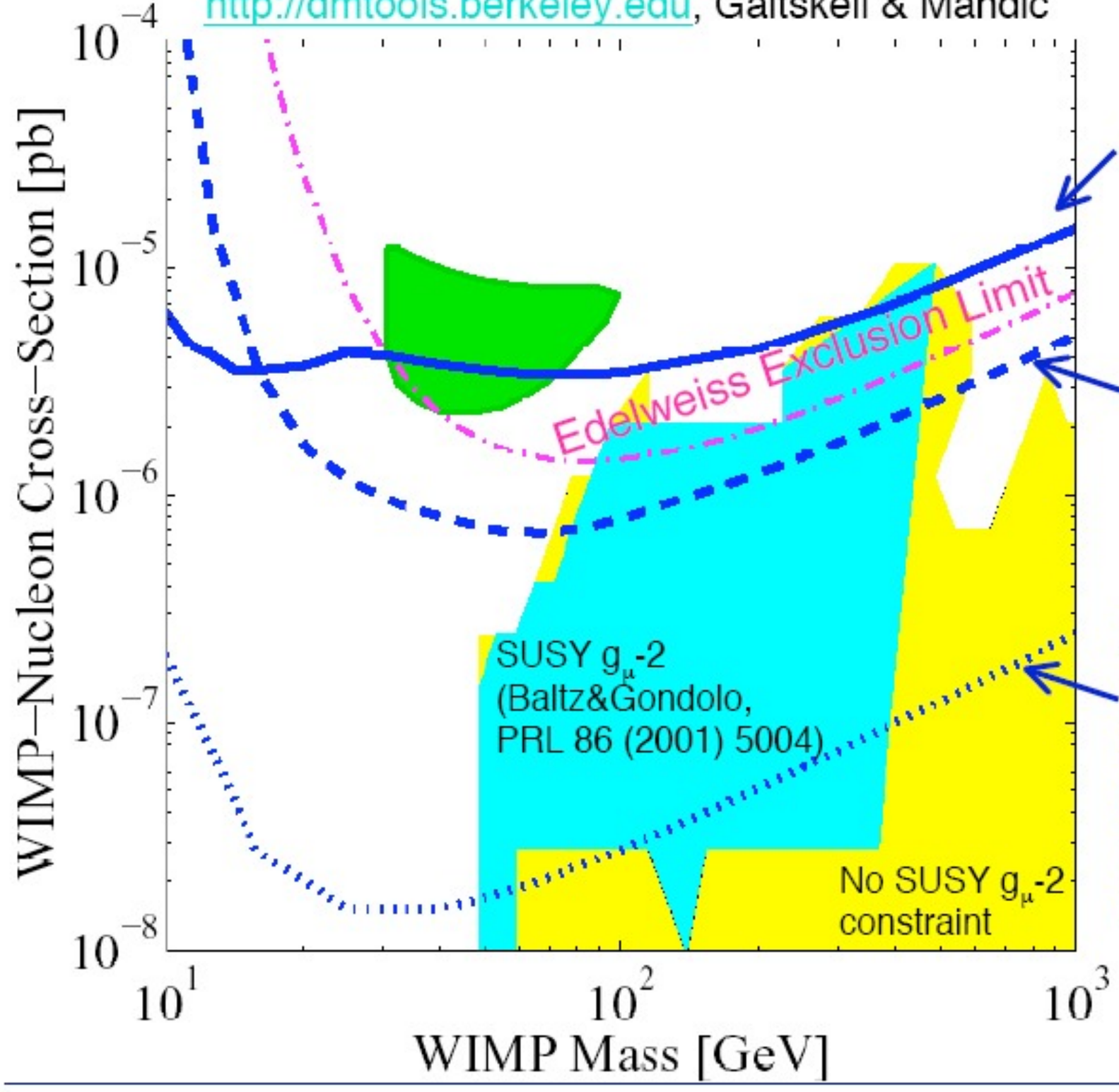


- Test under assumptions of
  - "standard" halo
  - standard WIMP interactions
- CDMS results incompatible with DAMA model-independent annual-modulation data (left) at > 99.8% CL even if all low-energy events are WIMPs

The 2009 limits are much stronger.

Current and Projected CDMS Sensitivity

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



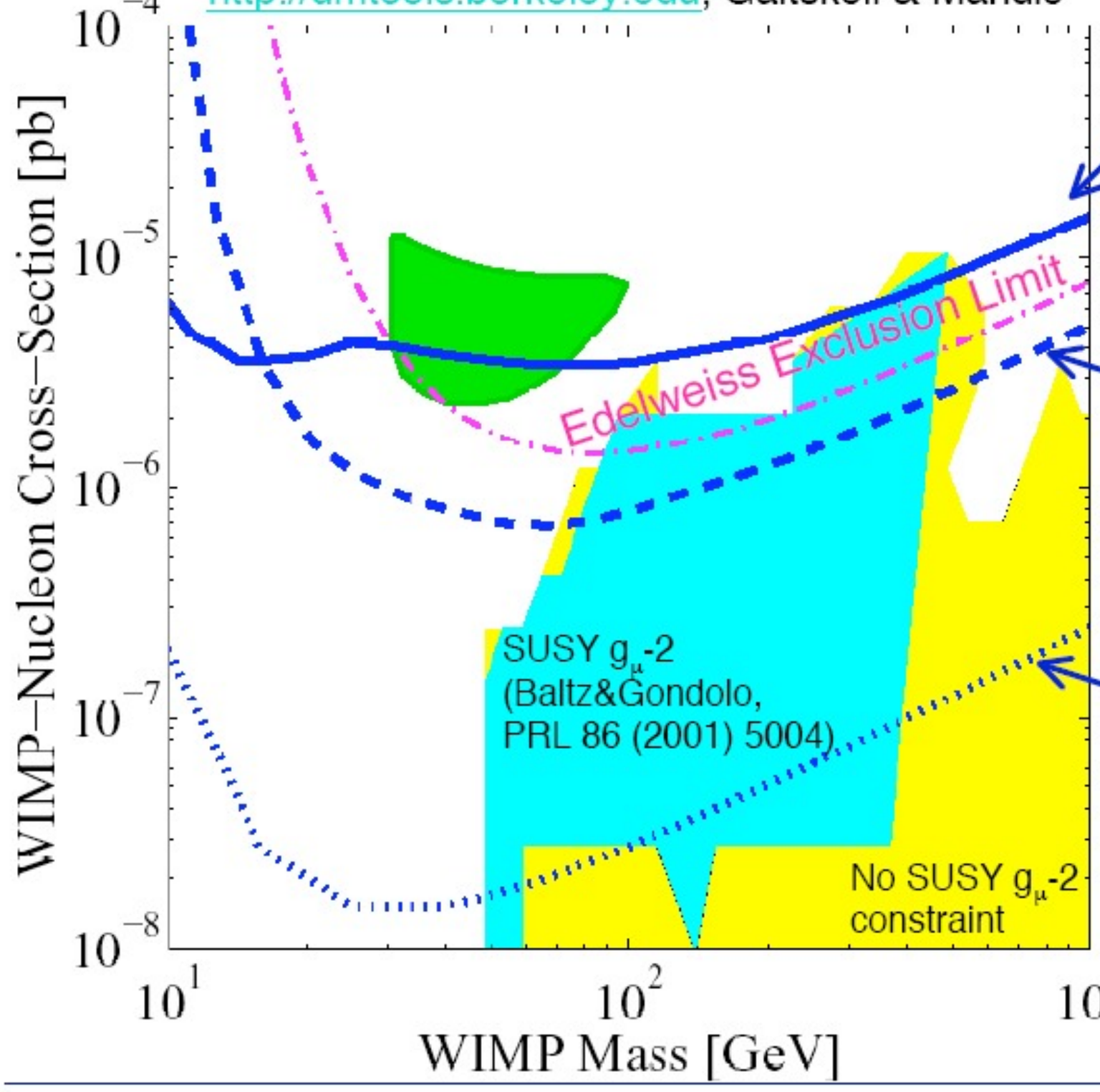
Current CDMS Limit

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!

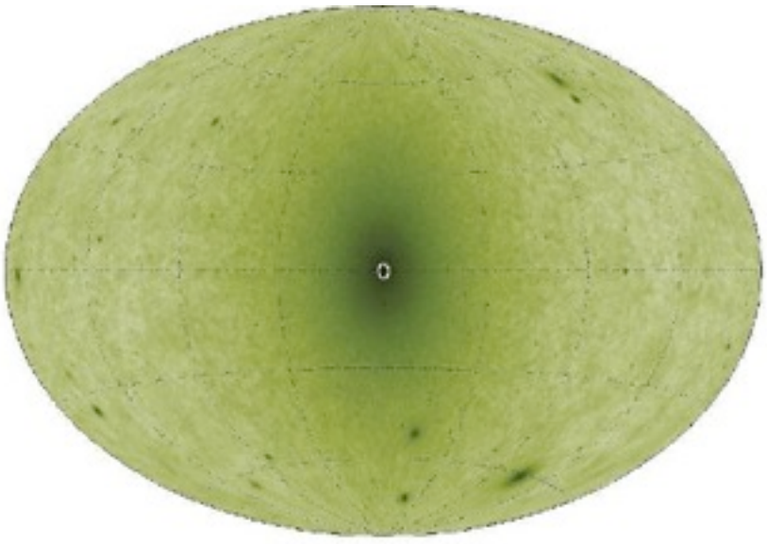
THE DARK MATTER ANNIHILATION SIGNAL FROM GALACTIC SUBSTRUCTURE: PREDICTIONS FOR GLAST

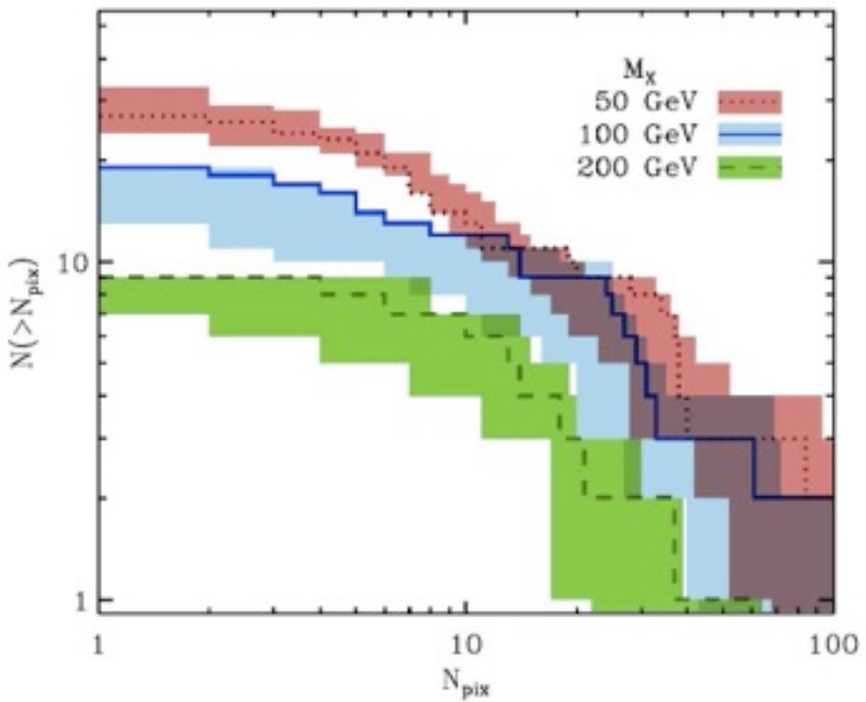
2008 ApJ 686, 262

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 $V_{\rm max}$ of 24 km s^{-1}) and therefore likely hosts of dwarf galaxies, but many subhalos with $V_{\rm max}$ 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.



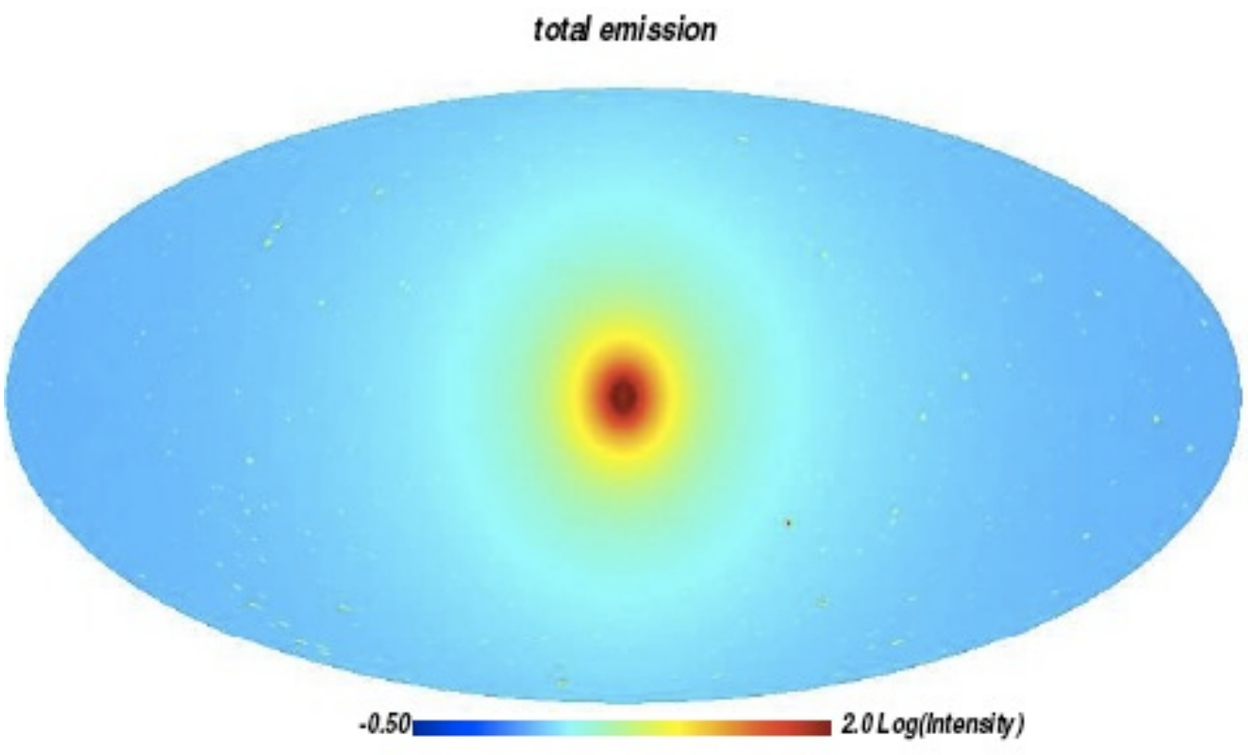


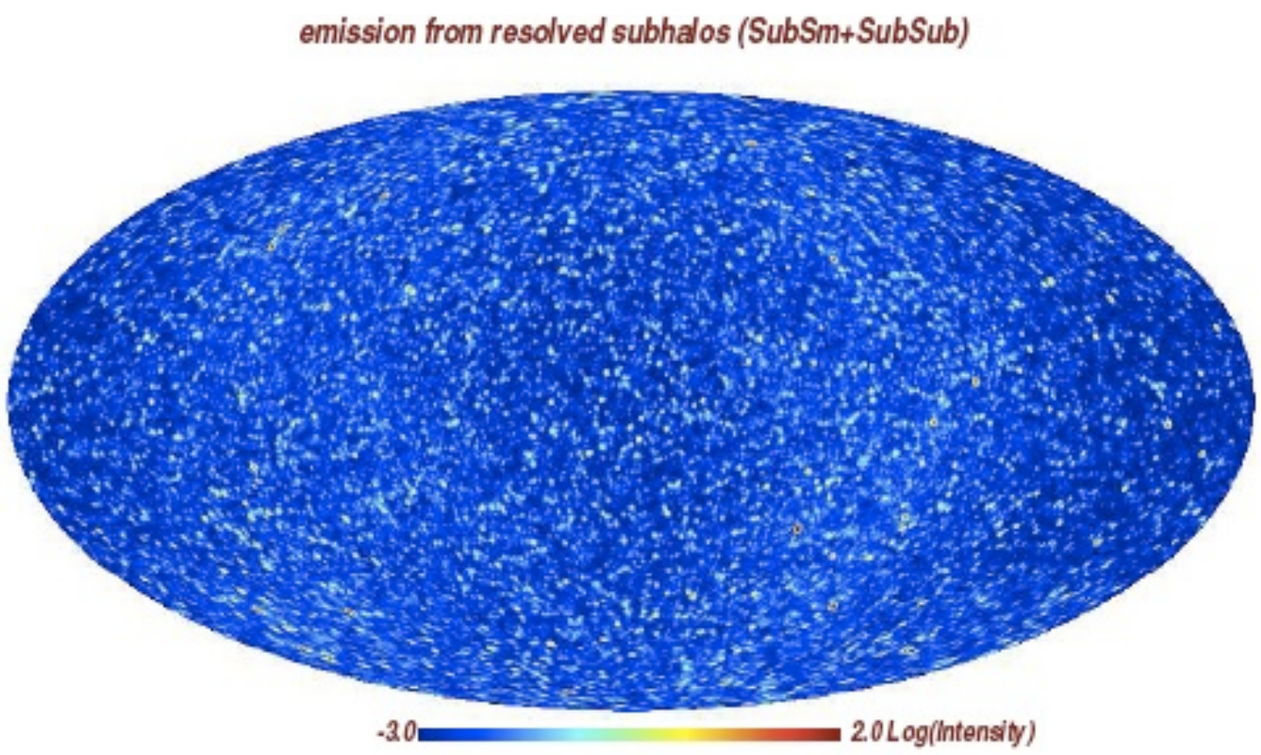
The number of detectable (S = 5) subhalos with more than N_{pix} detectable pixels versus N_{pix}, for three different choices of M(for $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3 s^{-1}). The shaded regions show the range of N(>Npix) for ten randomly chosen observer locations and the solid lines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

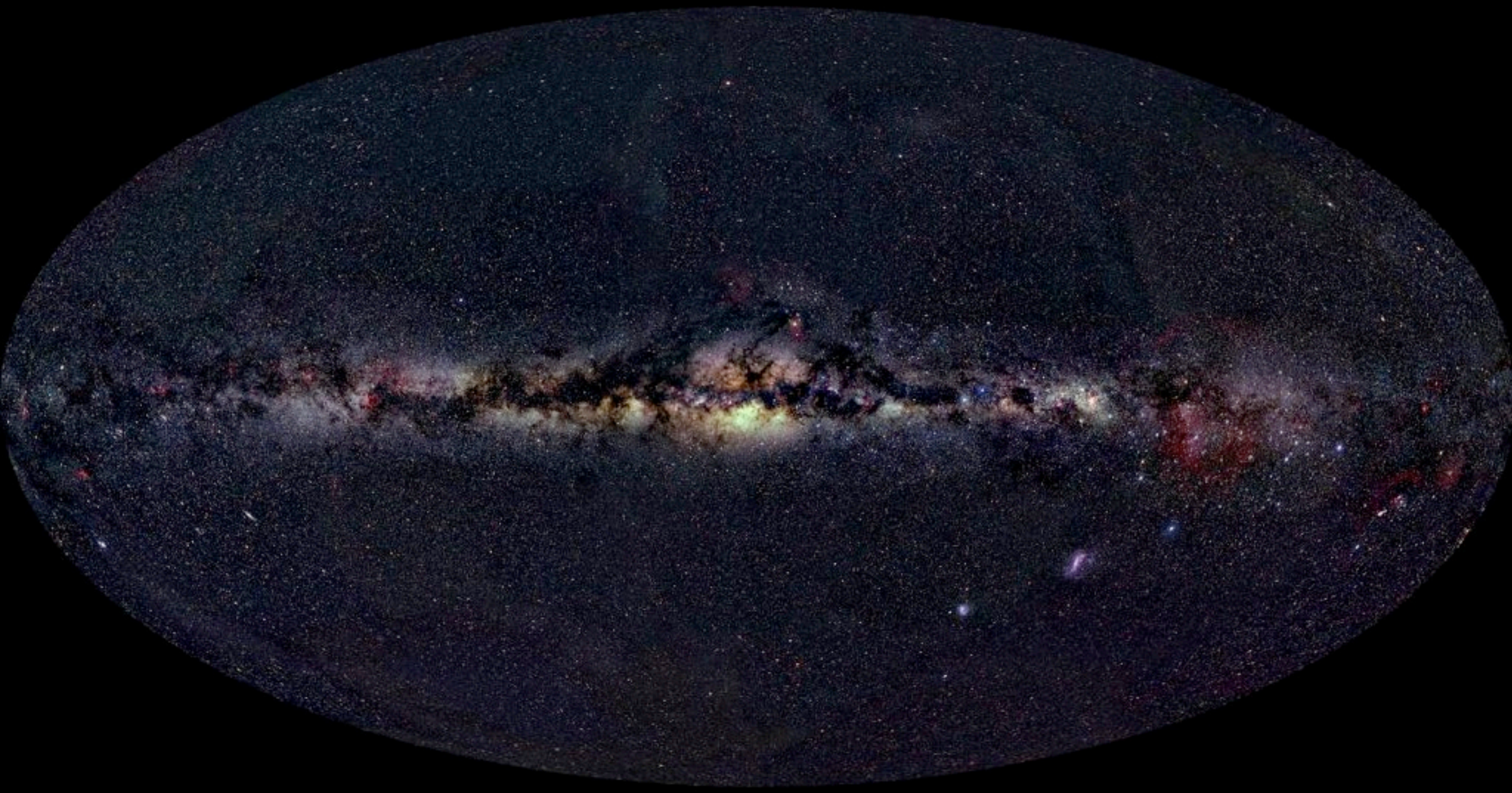
Dark matter is the dominant form of matter in the universe, but its nature is unknown. It is plausibly an elementary particle, perhaps the lightest supersymmetric partner of known particle species[1]. In this case, annihilation of dark matter in the halo of the Milky Way should produce γ-rays at a level 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.





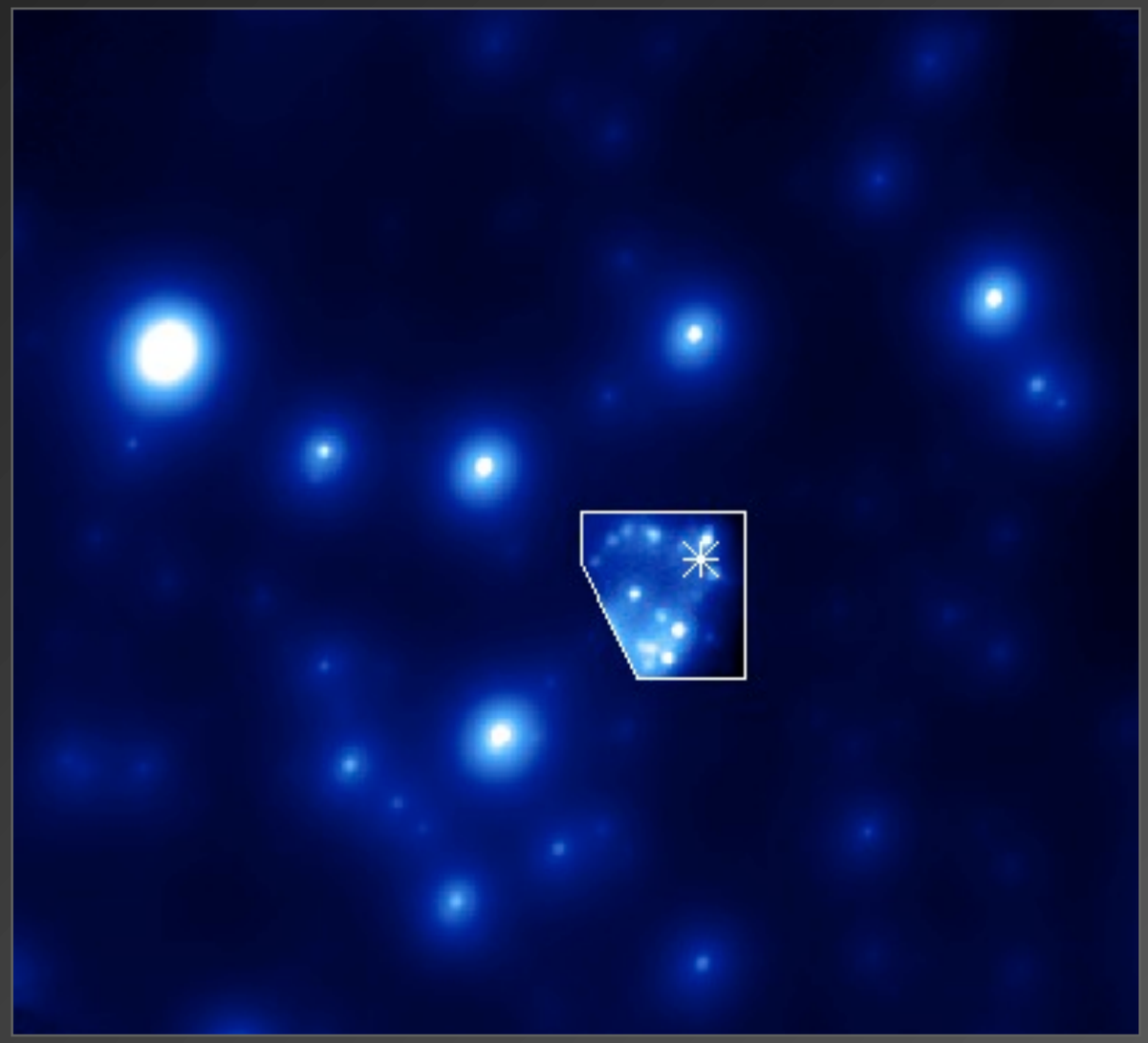
DARK MATTER ANNIHILATION AT THE GALACTIC CENTER?

The Milky Way in the Sky

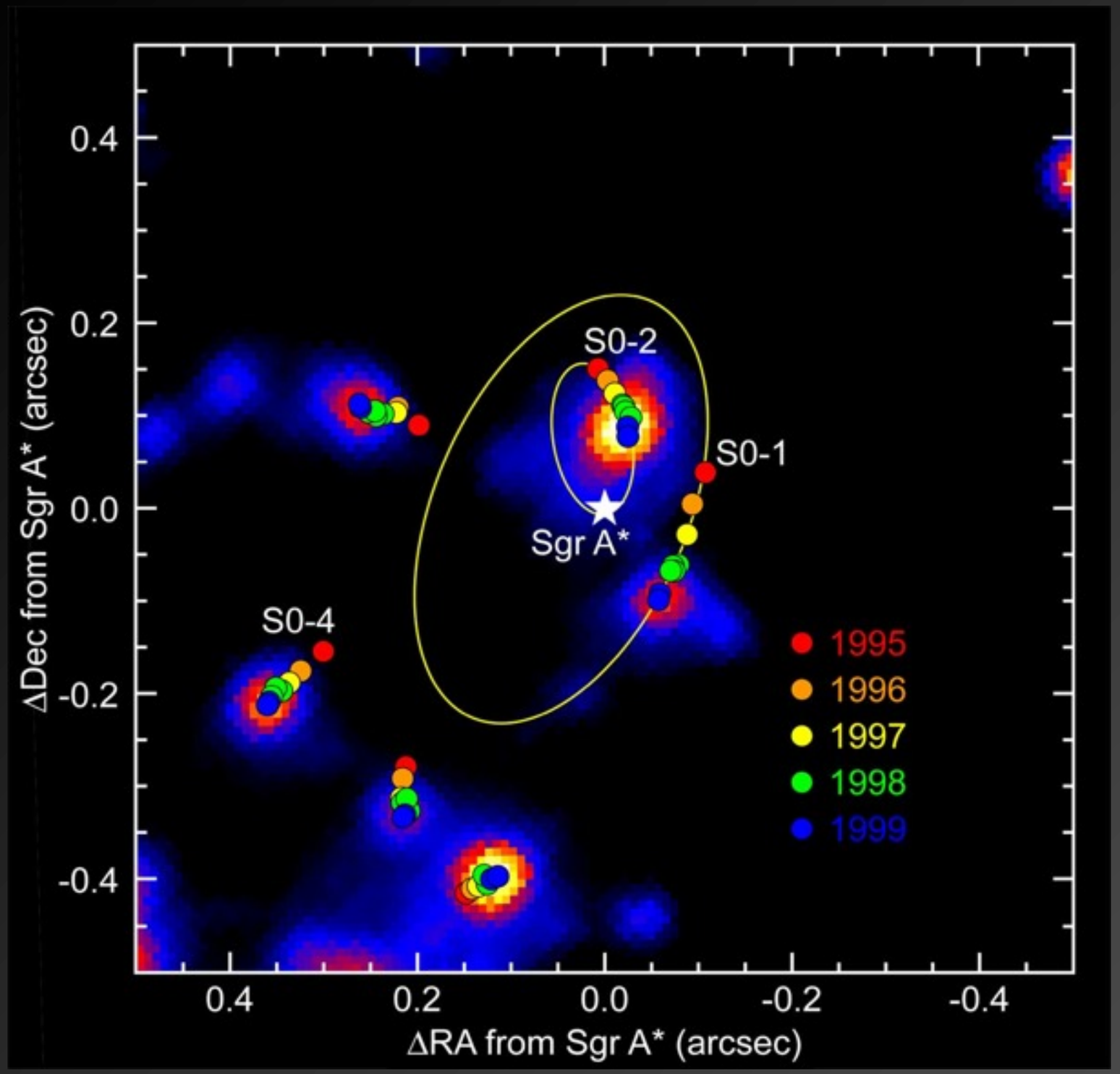


There's a supermassive black hole at the center of our galaxy…

- 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 10 years, with improving resolution…

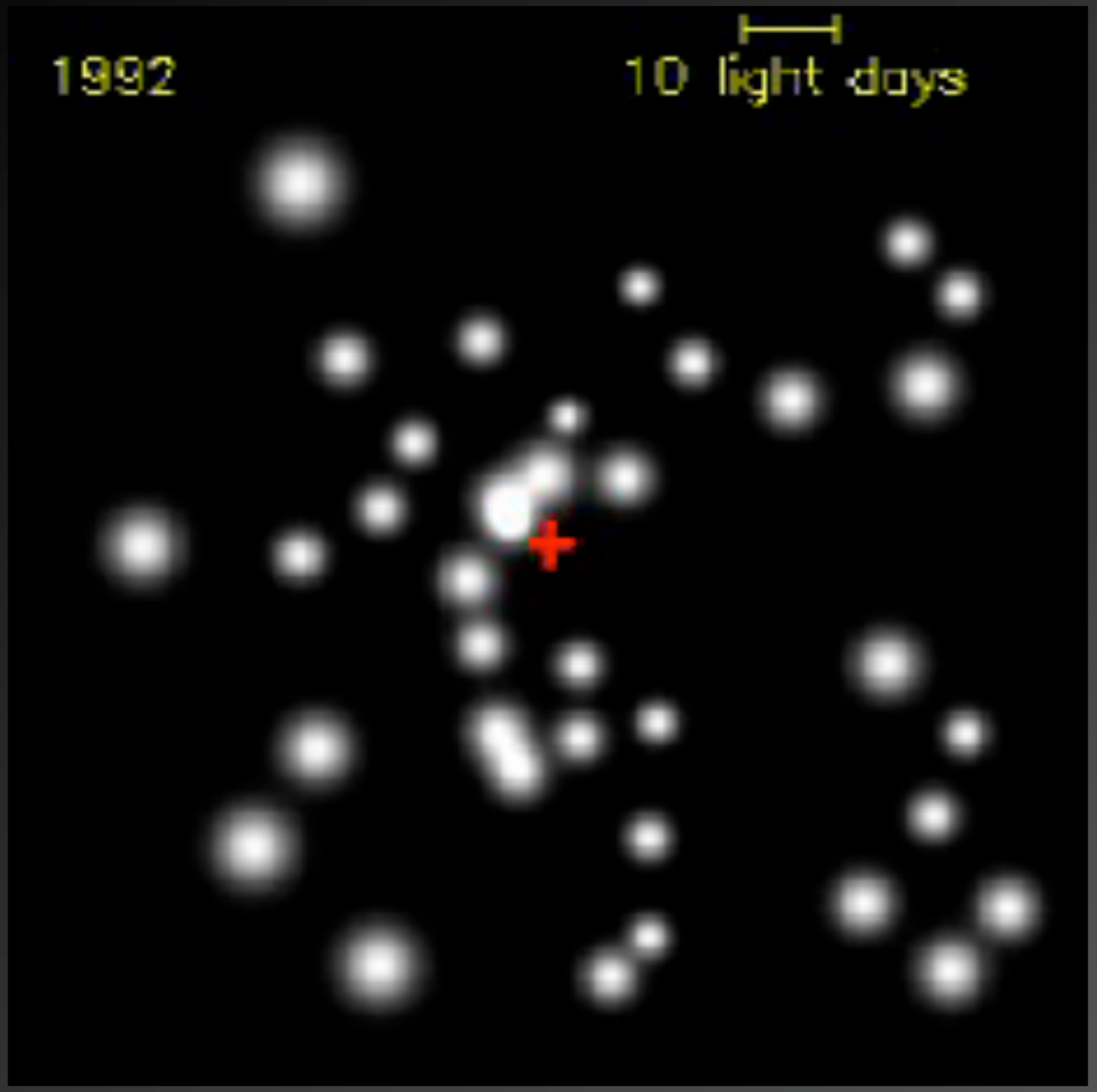


Keck, 2 μm *Ghez, et al.*

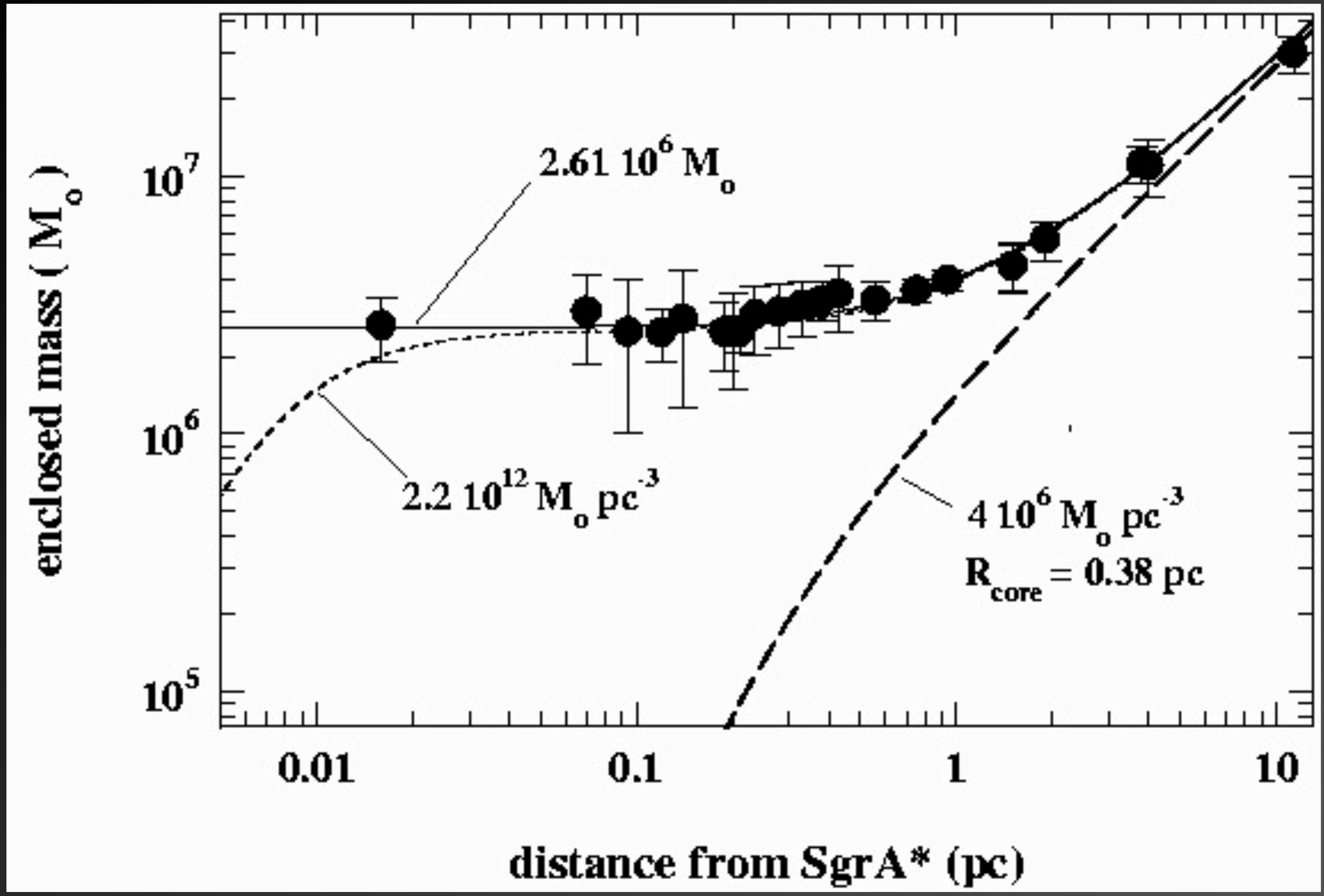


Motions of stars consistent with large, dark mass located at Sgr A...*

Ghez, et al.



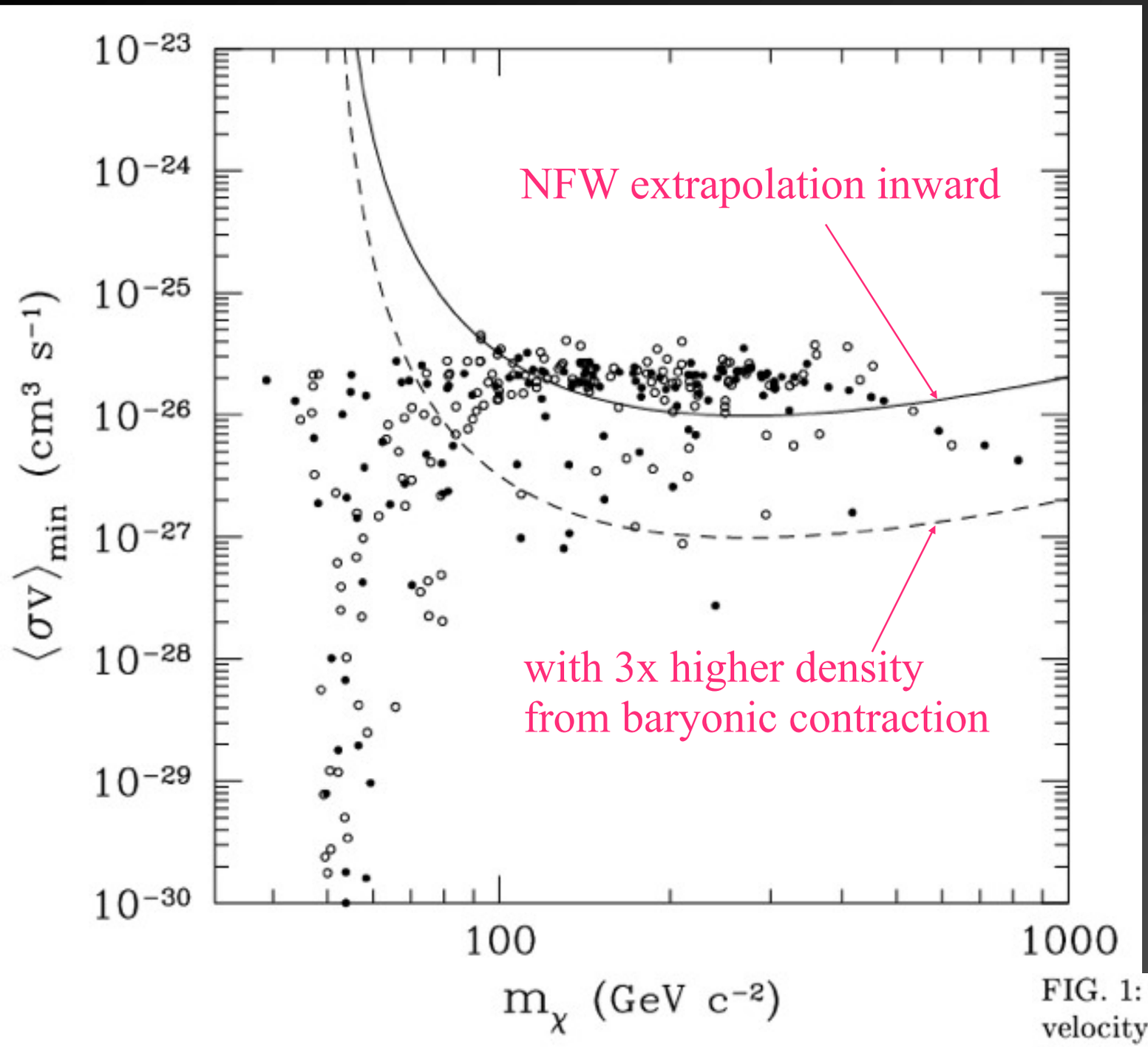
Schödel, Genzel, et al. 2004



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



Gnedin & Primack, Phys Rev Lett 2004

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 $\propto \rho^2$ 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.

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:

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

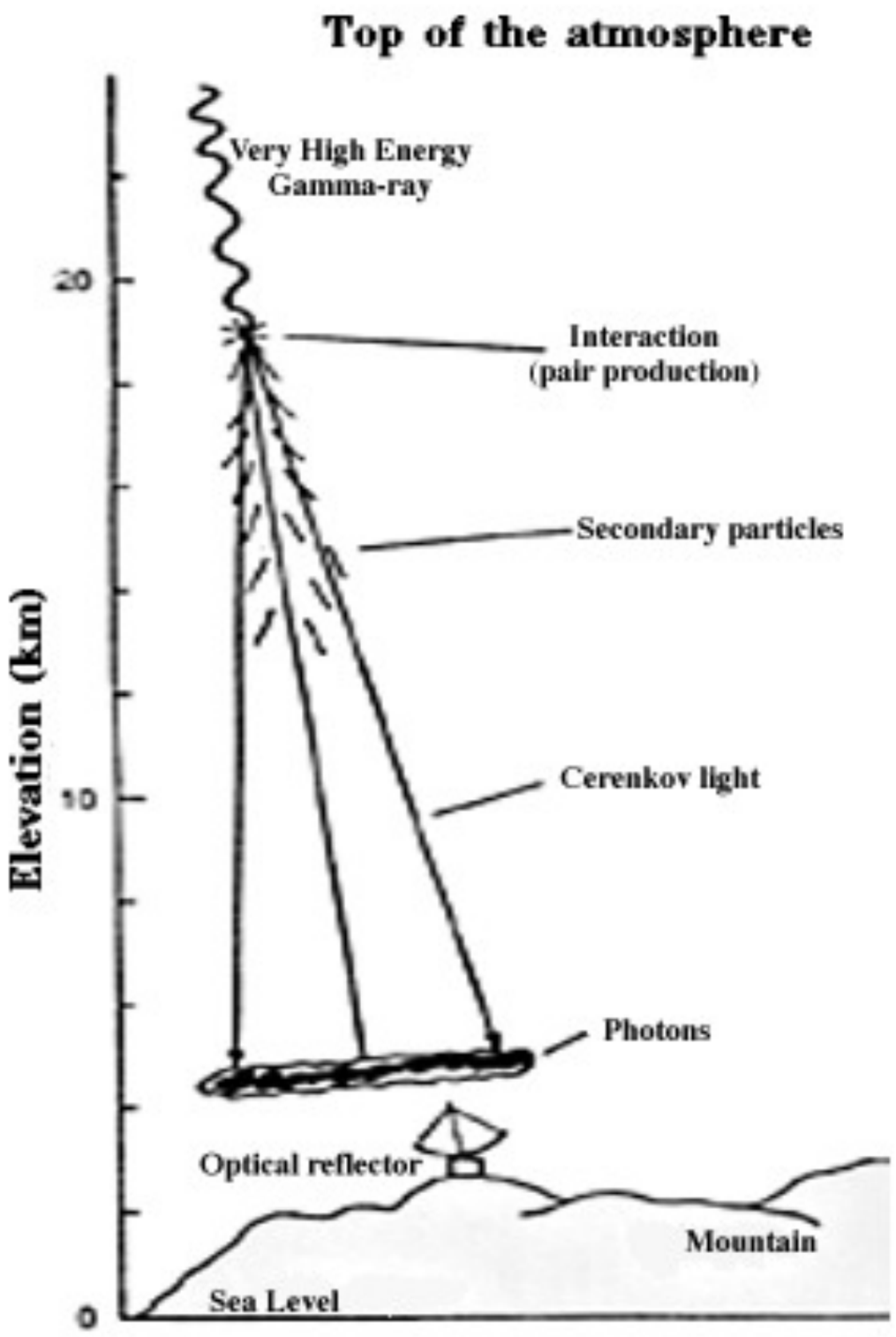
where $E = v^2/2 - GM_{\rm bh}/r$ is the energy within the sphere of influence of the black hole, $q(E) = (2^{3/2}/3)\pi^3 G^3 M_{\rm bh}^3 E^{-3/2}$, $A \equiv 16\pi^2 G^2 m_*^2 \ln\Lambda$, and $\ln\Lambda = \ln M_{\rm bh}/m_* \approx 15$ is the standard Coulomb logarithm. The equilibrium distribution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

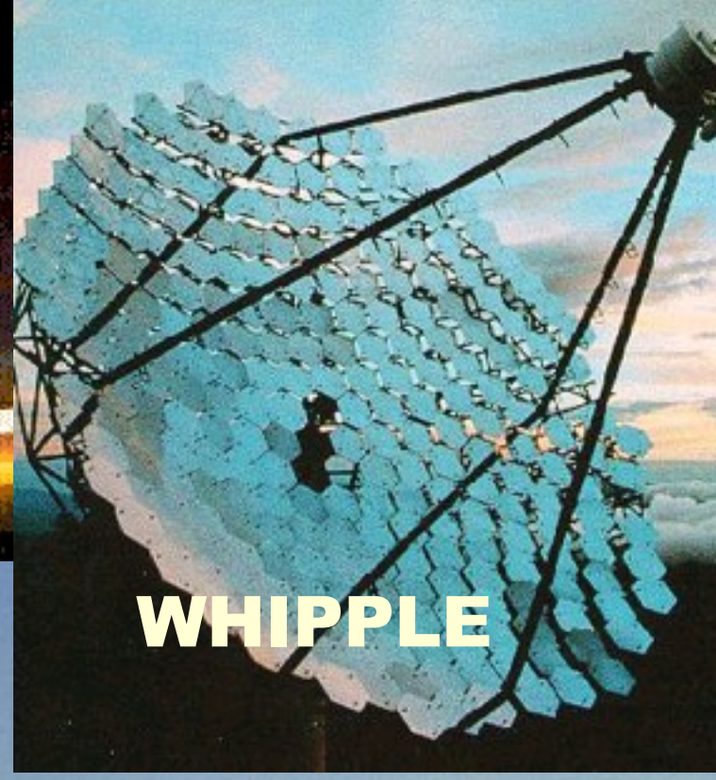
Implications for dark matter searches.— The dark matter density in the central region of the Galaxy is thus given by

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

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

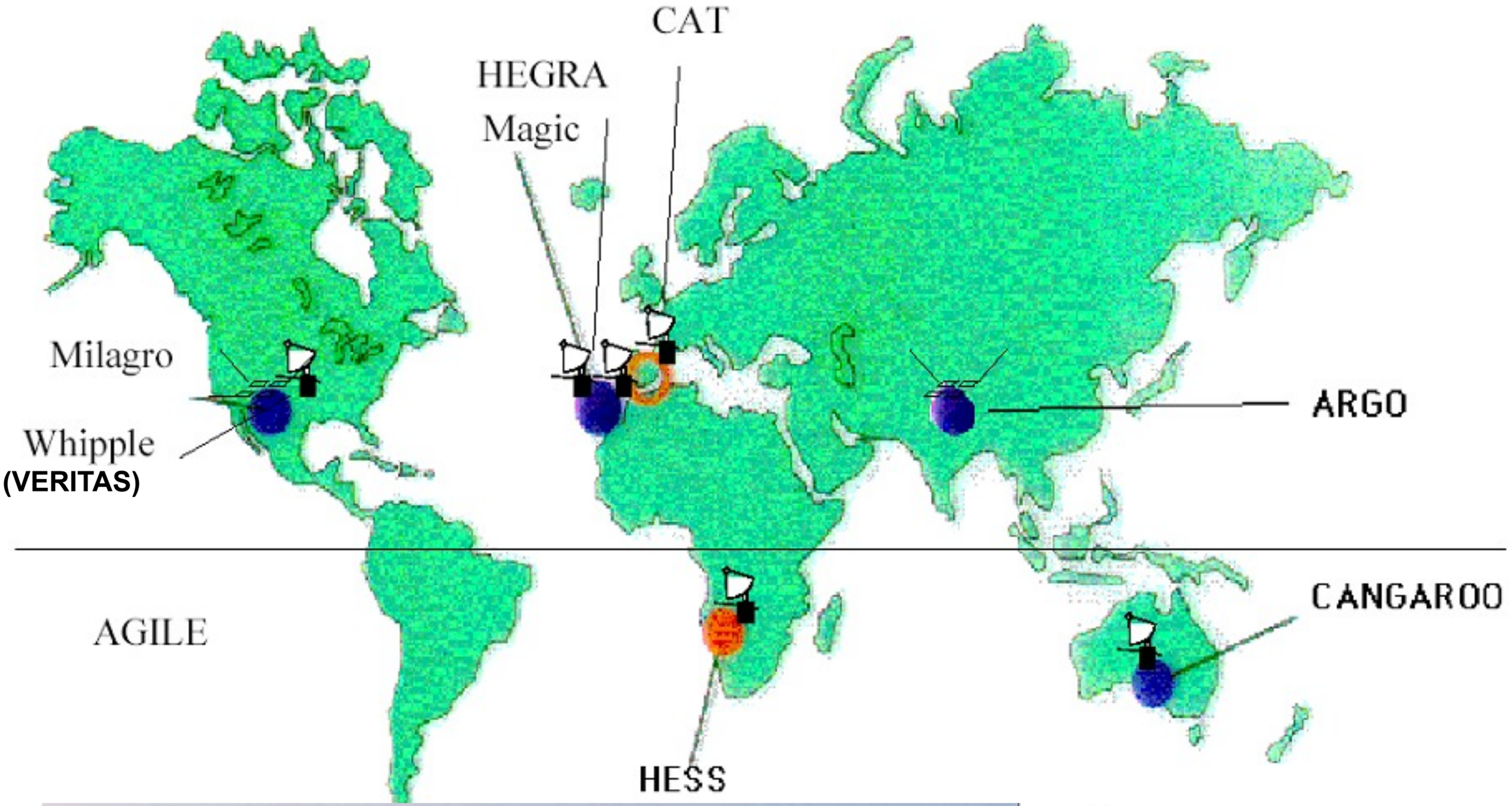
Early Atmospheric Čerenkov Telescopes





New Ground and Space Based Telescopes

Ground-based Gamma Ray Telescopes 2



Cerenkov telescope

"all sky" monitors

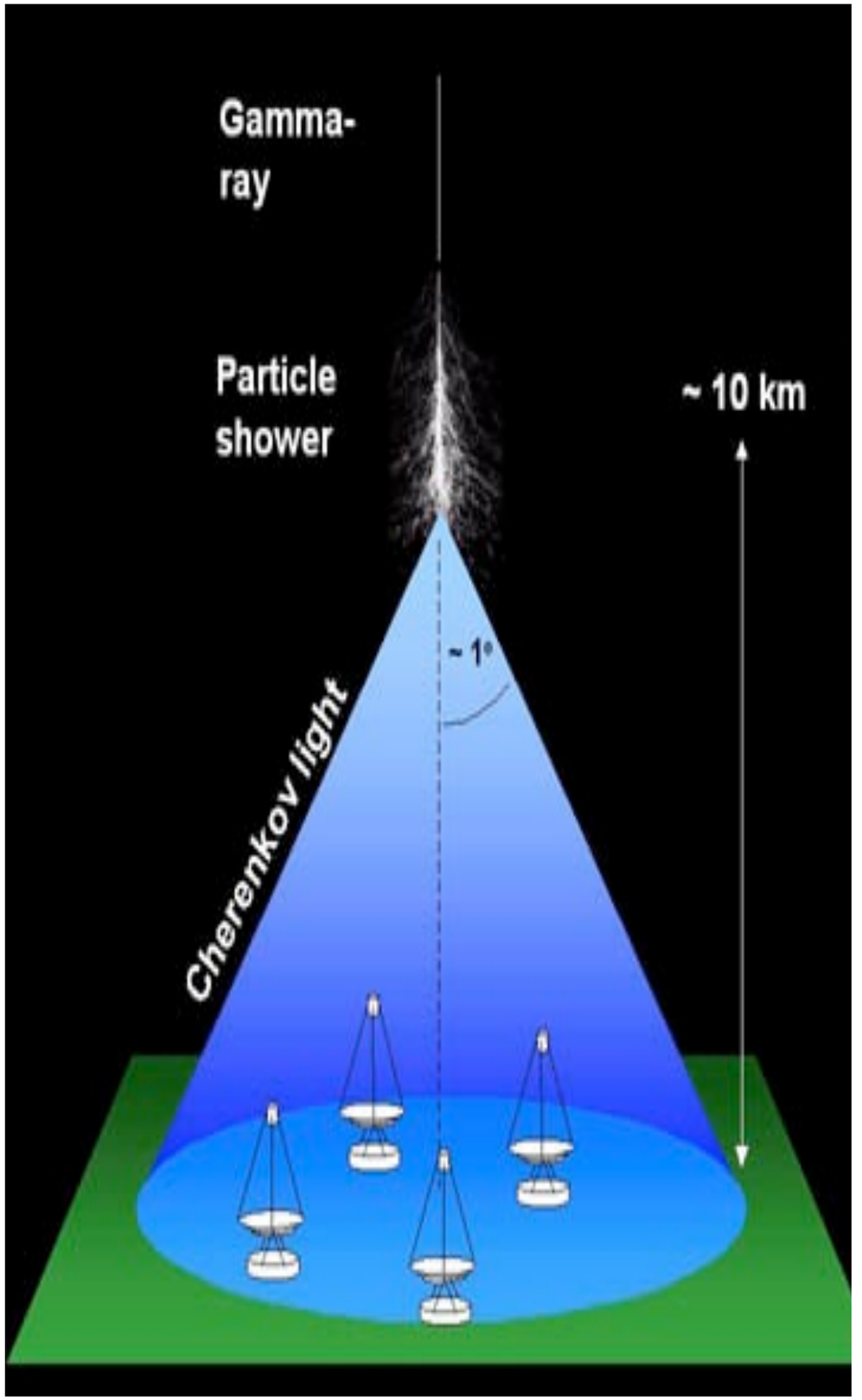
Results from H.E.S.S. on MWy Center

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

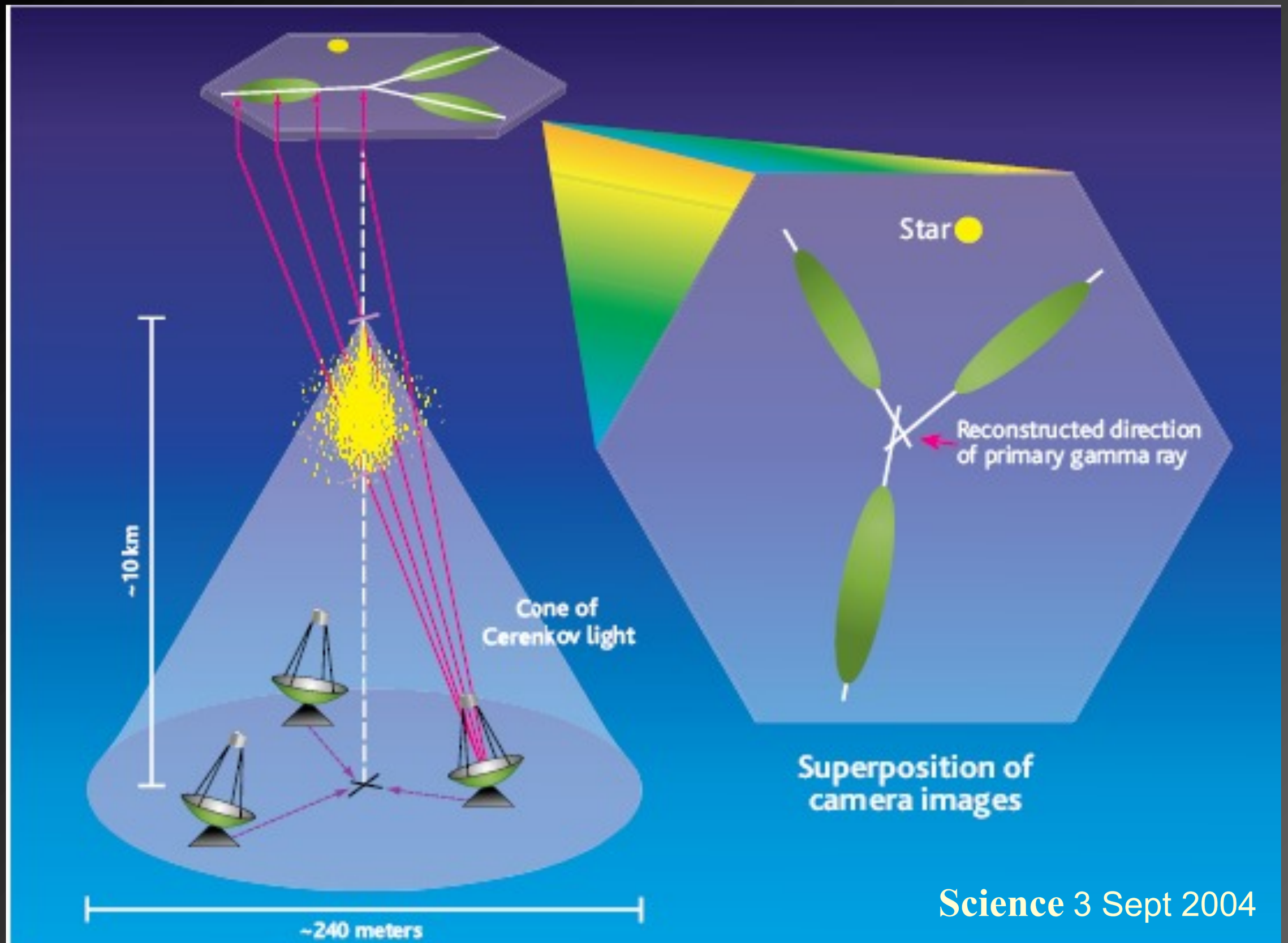
- Array 4 telescopes, diameter ~12 m
- Field of view ~5°
- Angular resolution (single photon): ~ 6 '
  (with hard cuts): ~ 4 '
- Energy resolution ~15%
- Location: Namibia, 1800 m asl
  Coord.: 23°16' S, 16°30' E

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-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

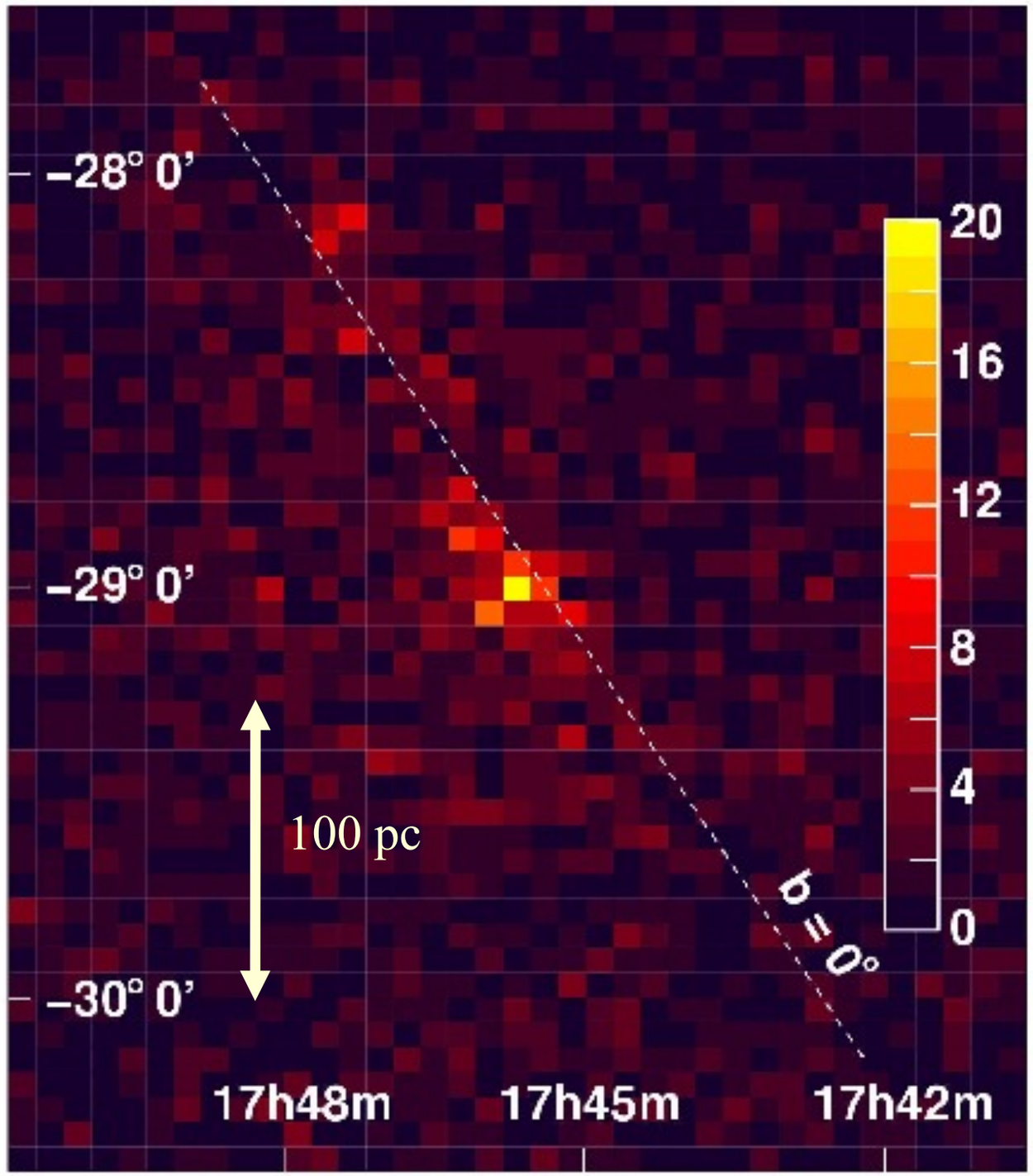


Fig. 1. Angular distribution of γ-ray candidates for a 3° field of view centred on Sgr A*. Both data sets ('June/July' and 'July/August') are combined, employing tight cuts to reduce the level of background. The significance of the feature extending along the Galactic Plane is under investigation.

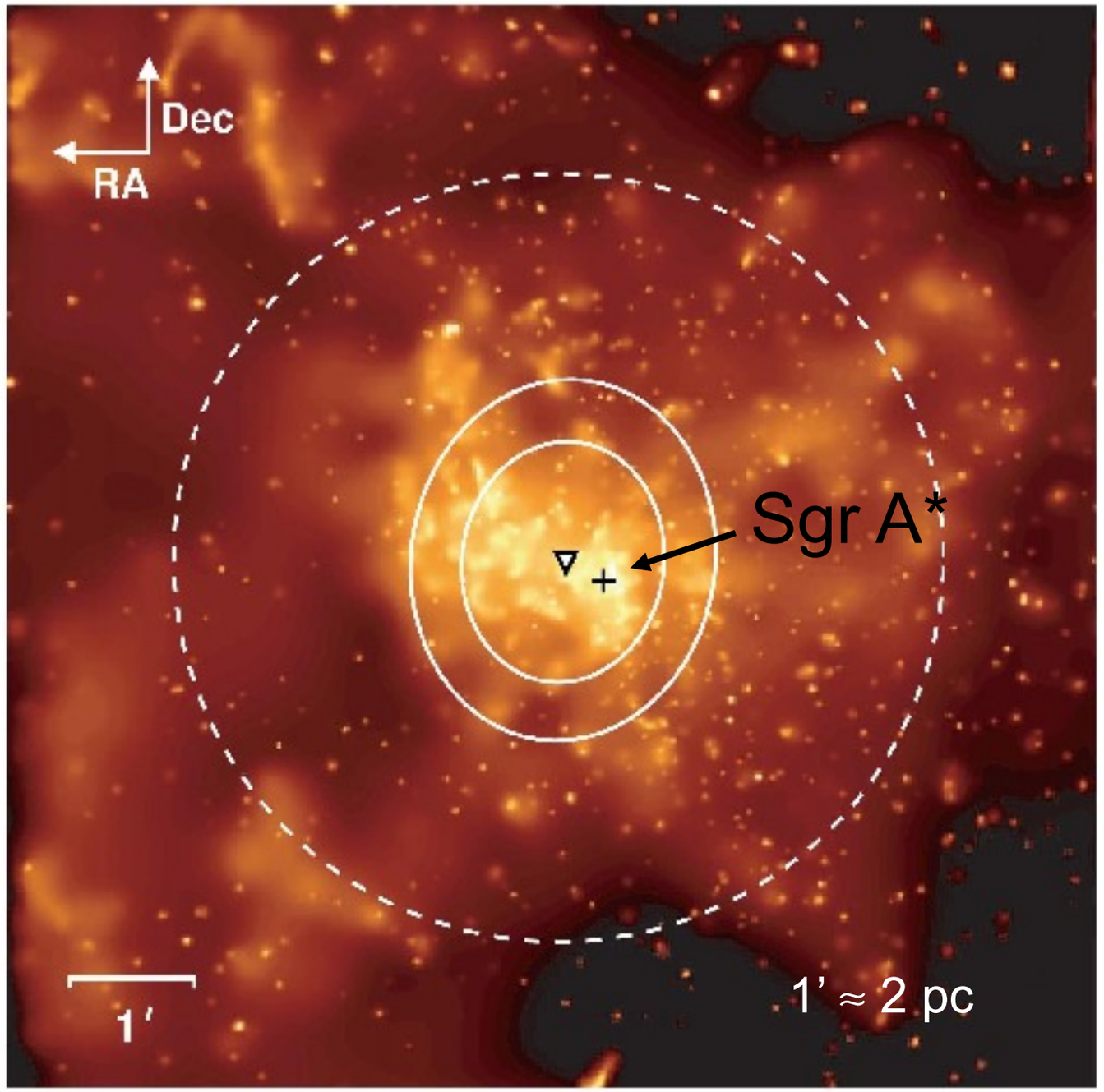
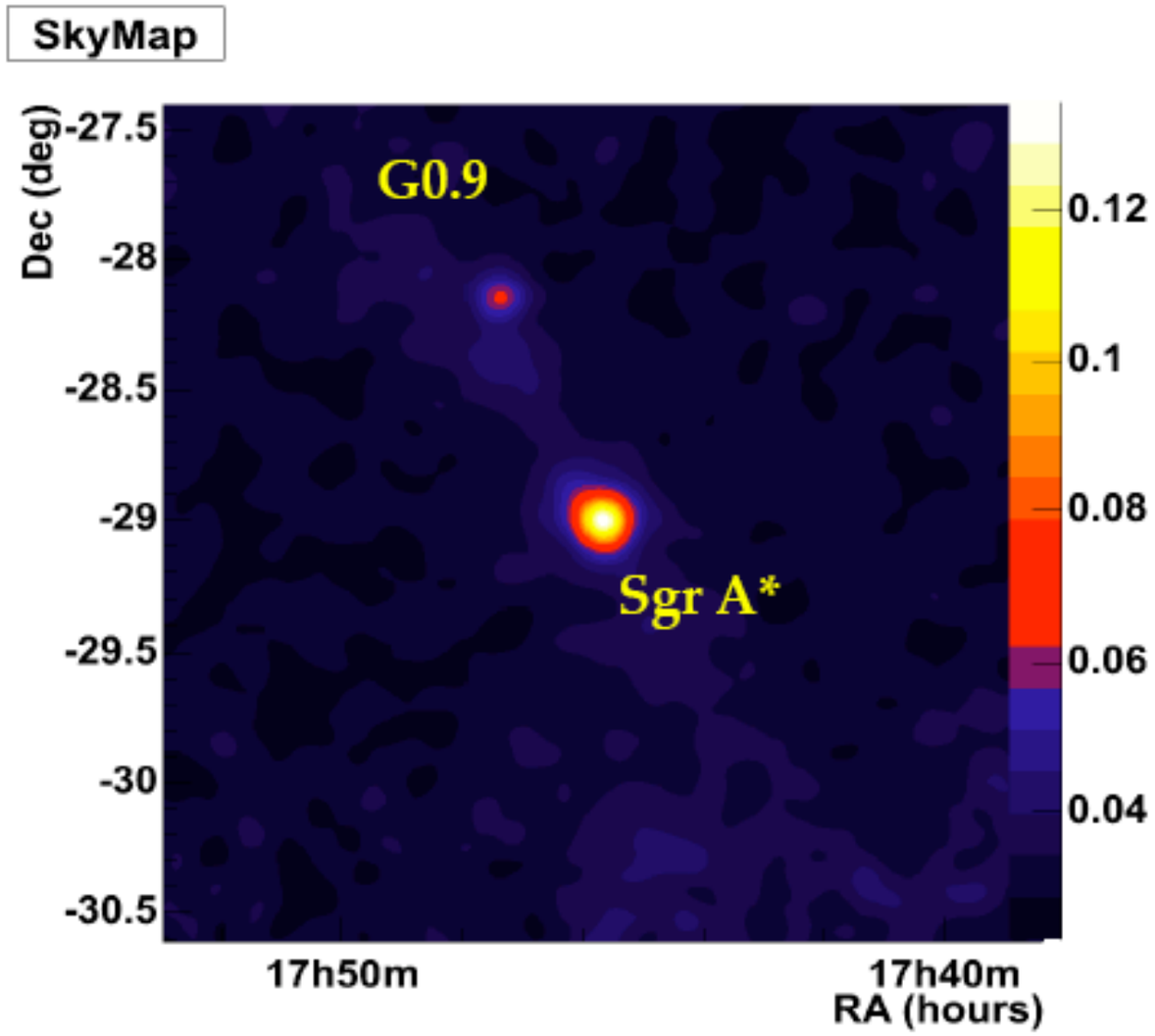
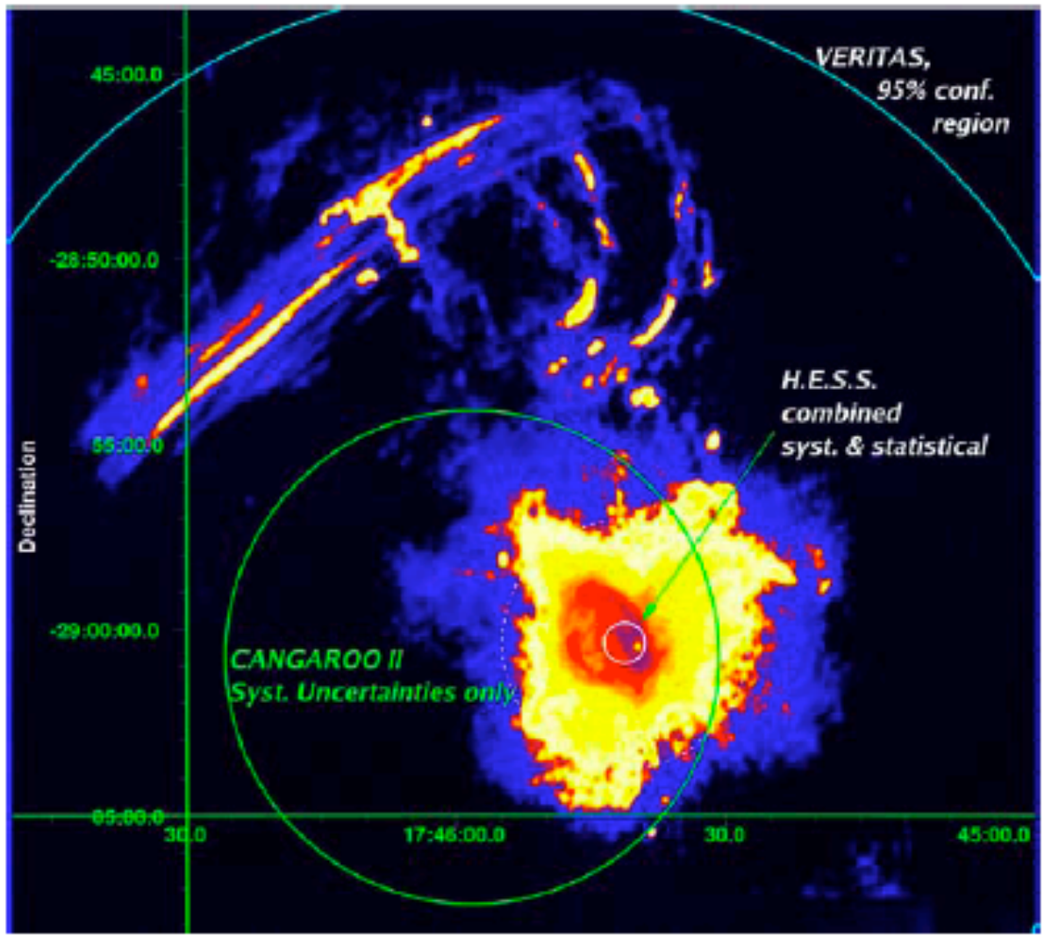


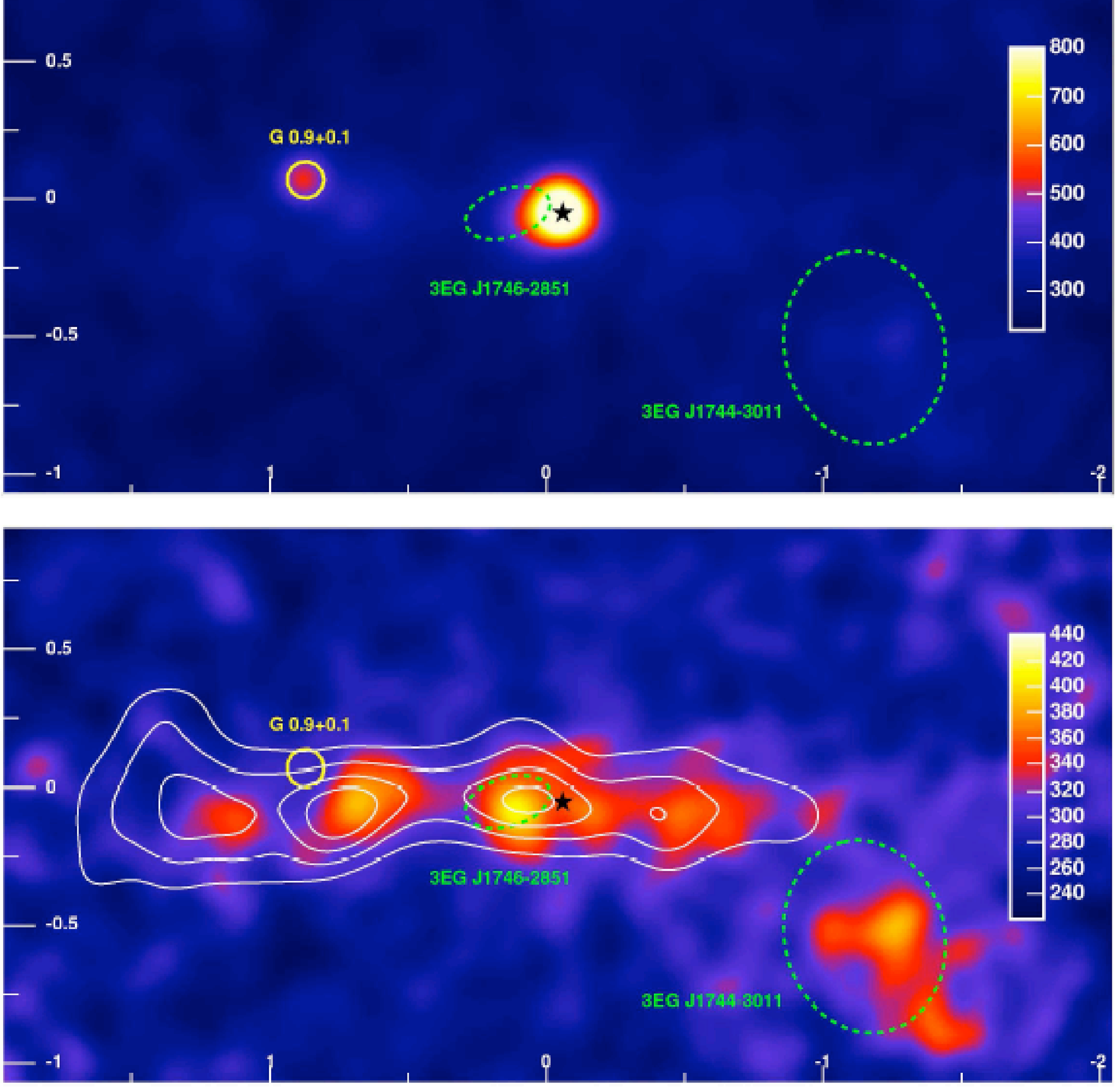
Fig. 2. Centre of gravity of the VHE signal (triangle), superimposed on a 8.5′ by 8.5′ Chandra X-ray map (Munro et al. 2003) of the GC. The location of Sgr A* is indicated by a cross. The contour lines indicate the 68% and 95% confidence regions for the source position, taking into account systematic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

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

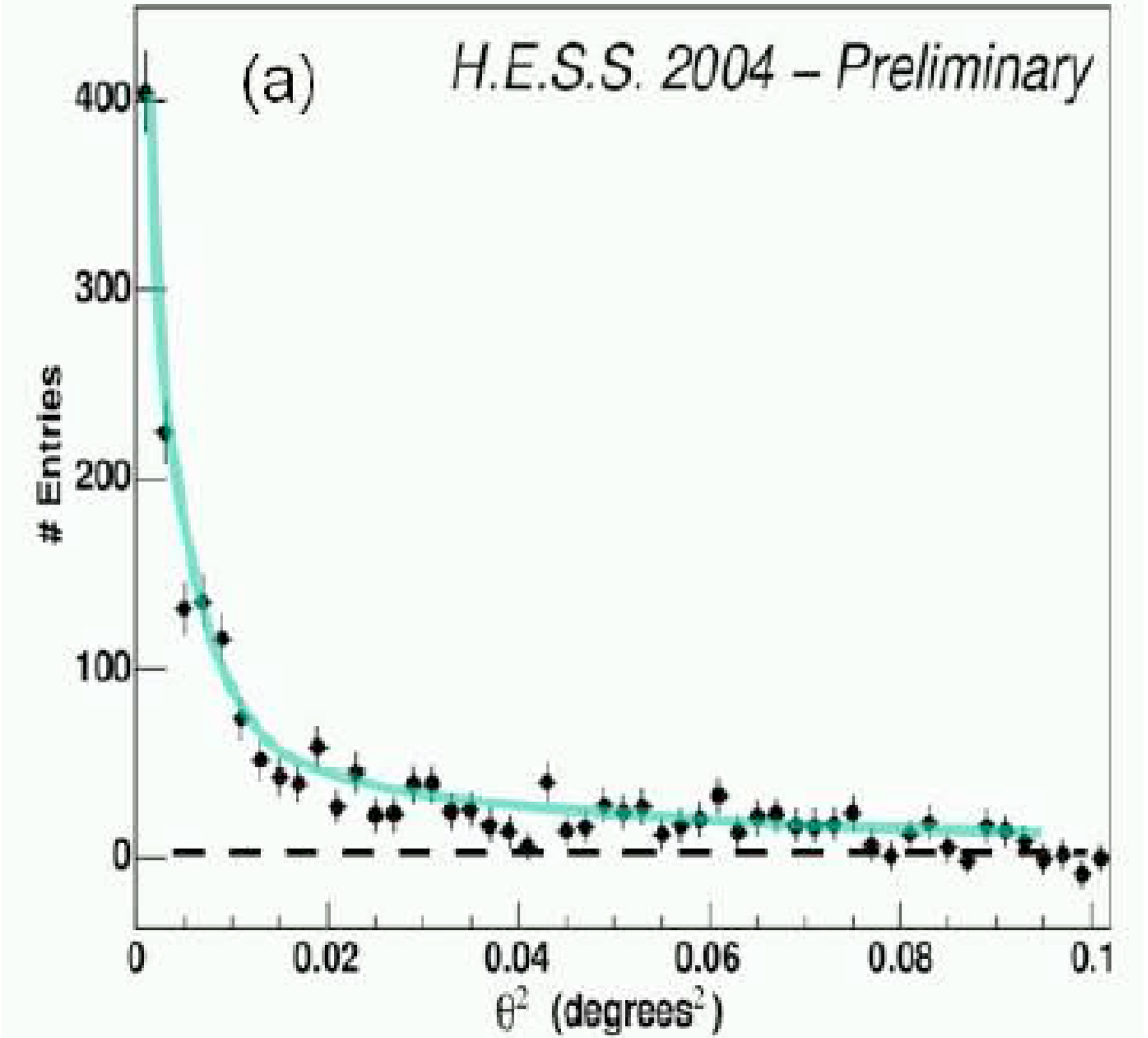
Nature

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.

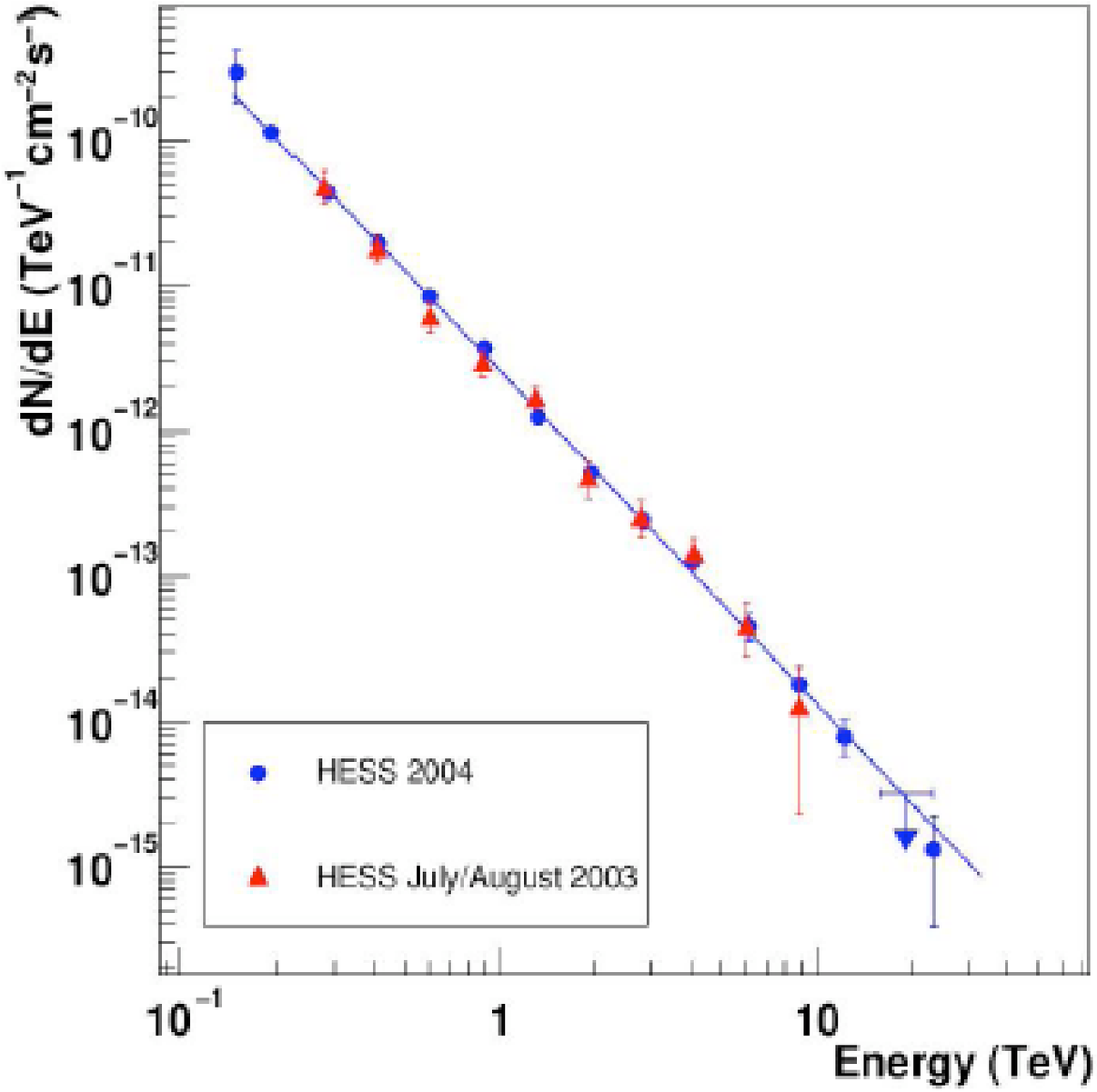
W. Hoffman plenary talk at ICRC29 2005

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

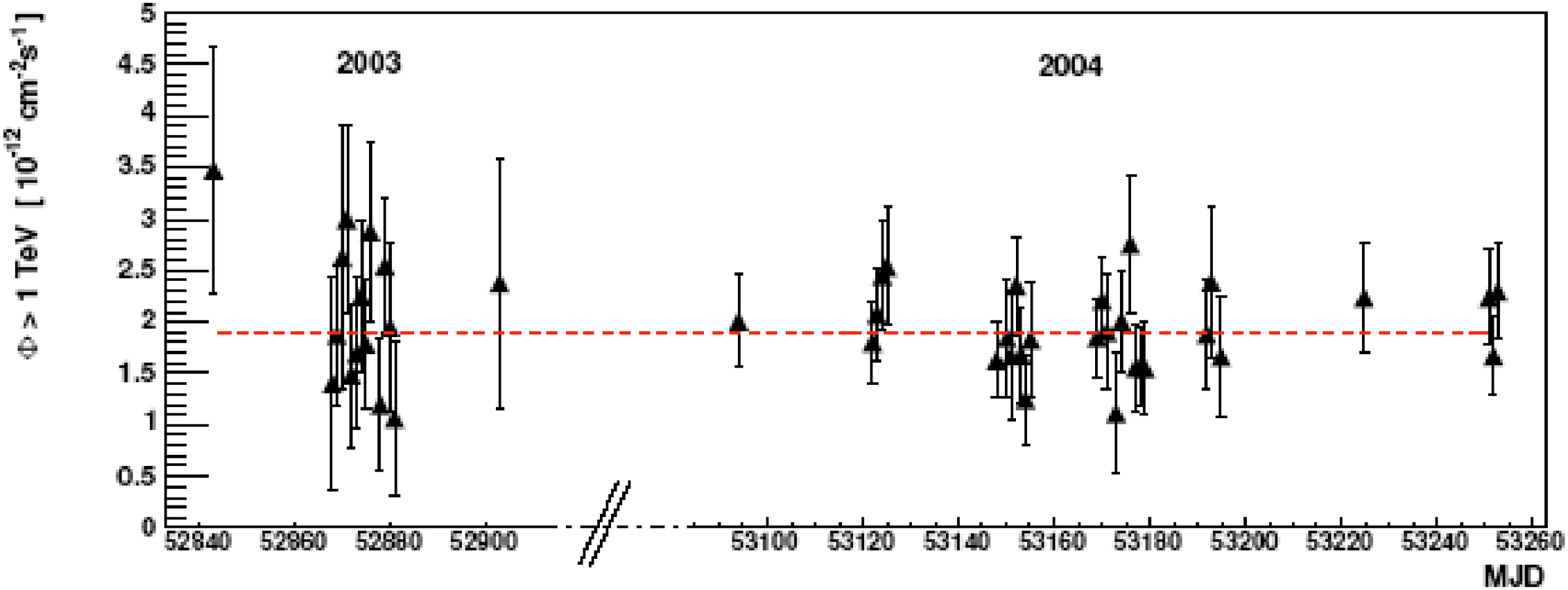
Spectrum and variability of the VHE Galactic Centre source observed with H.E.S.S.

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).

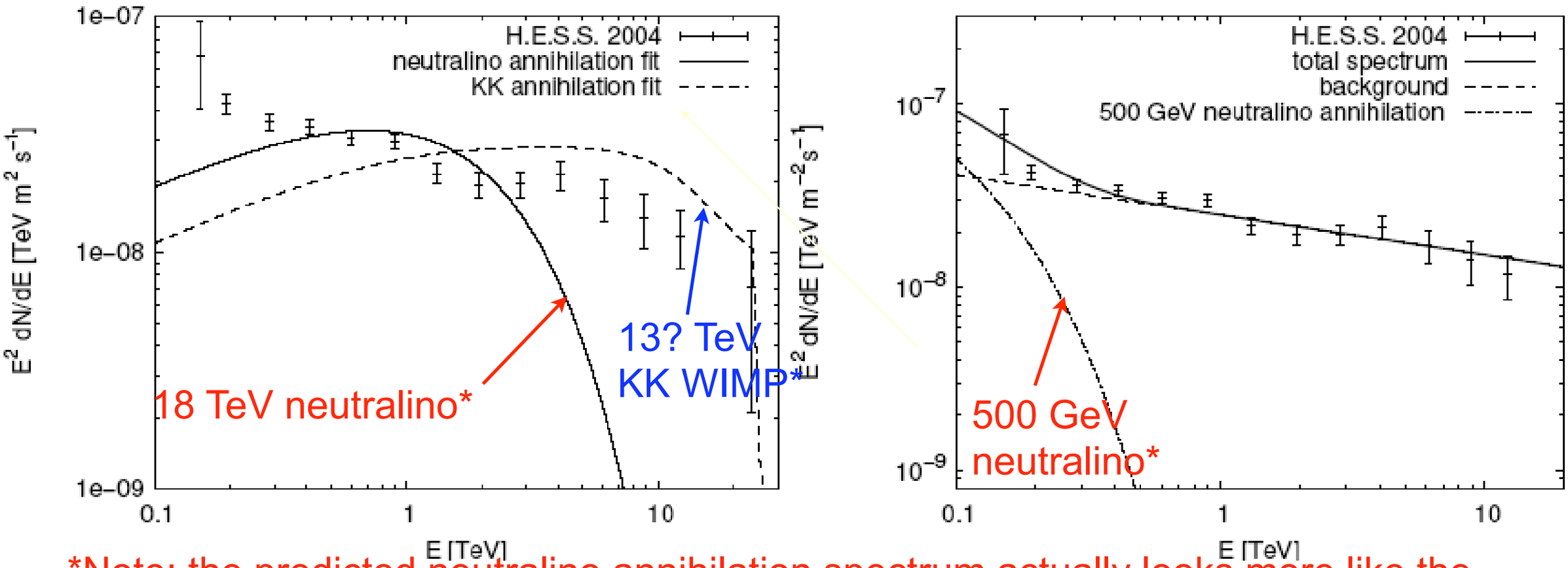


Galactic Centre source light curves. The integral nightly average flux above 1 TeV is given as function of time in modified Julian Days for both 2003 and 2004 observations. The Galactic Centre source flux is consistent with a constant flux at all probed time scales.

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



*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.

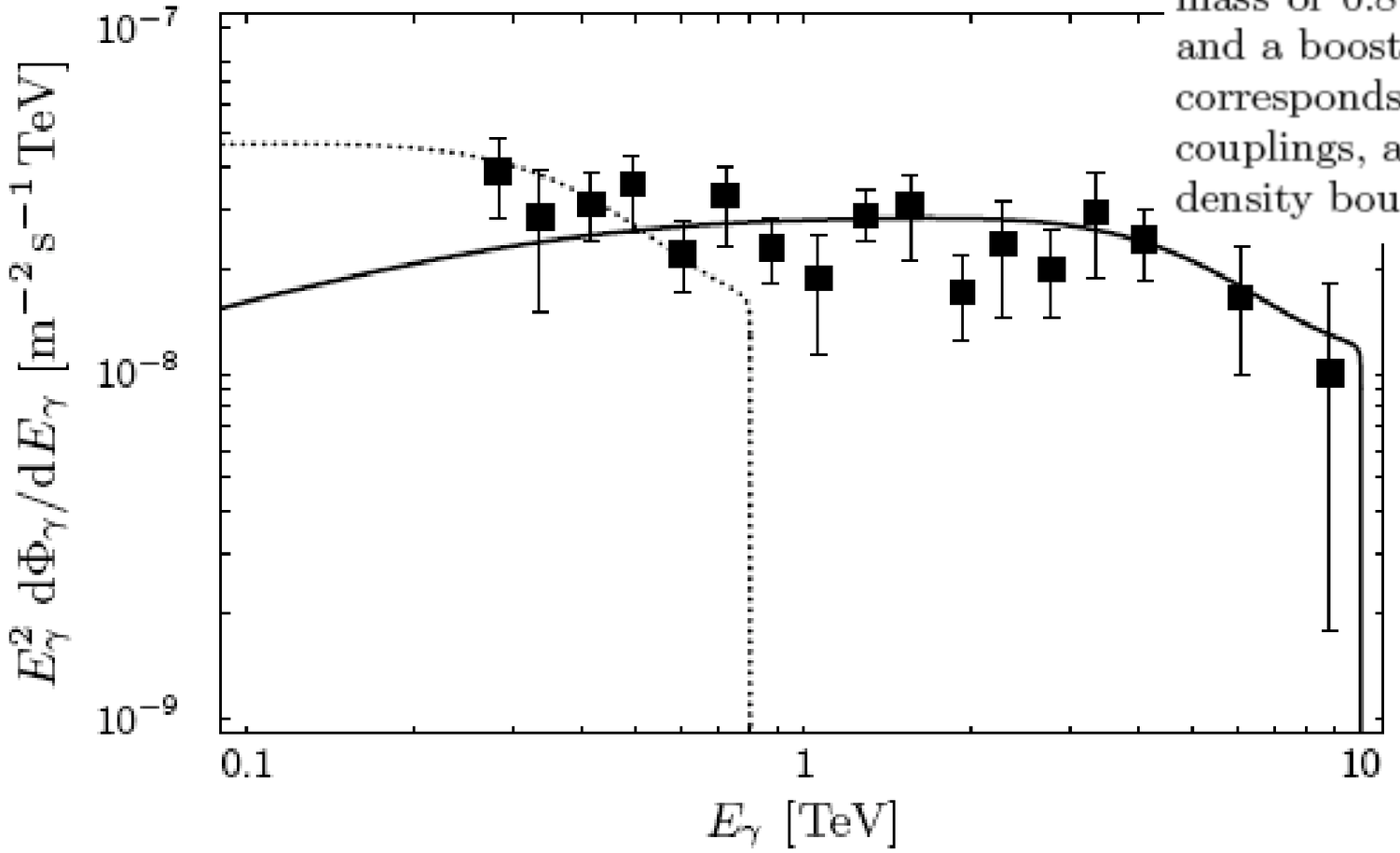


FIG. 3: The H.E.S.S. data [3] compared to the gamma-ray flux from a region of 10^{-5} sr encompassing the GC, for a $B^{(1)}$ mass of 0.8 TeV, a 5% mass splitting at the first KK level, and a boost factor b around 200 (dashed line). The solid line corresponds to a hypothetical 10 TeV WIMP with similar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

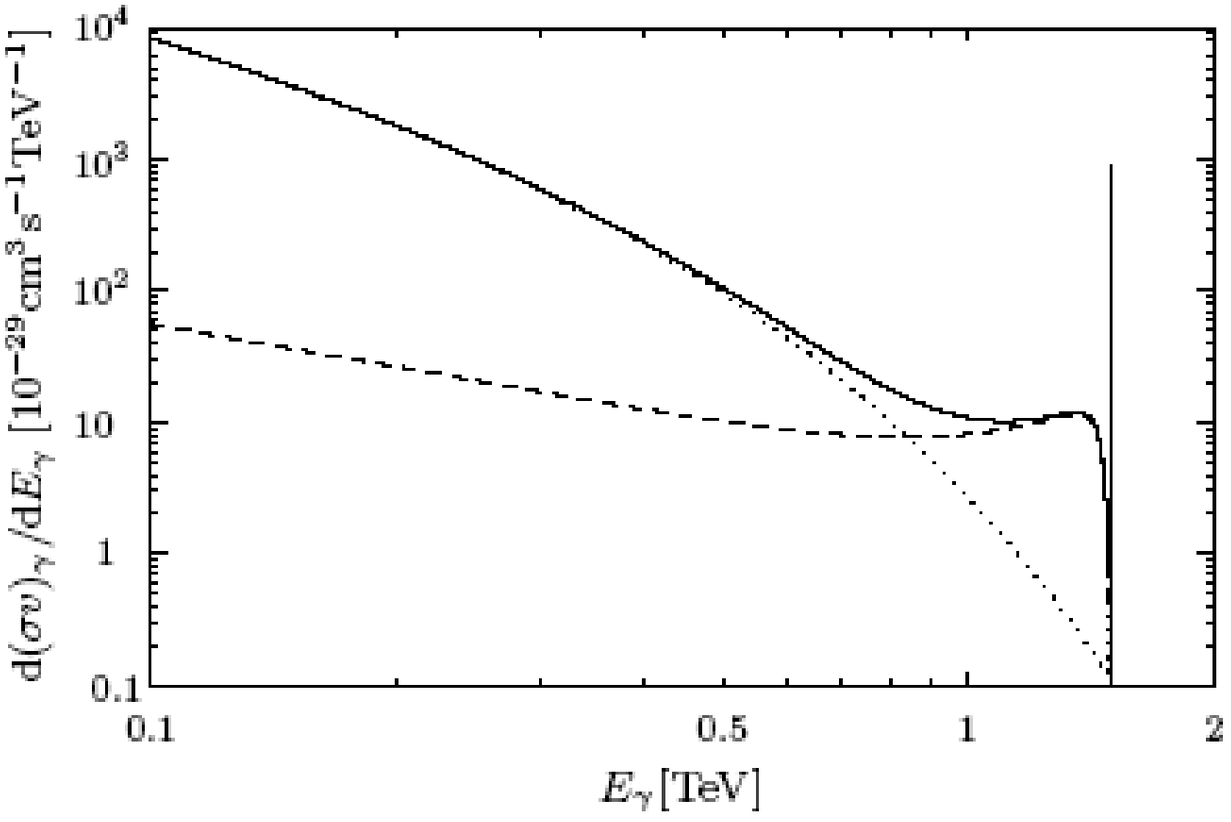


FIG. 3: The total differential photon distribution from $\chi\chi$ annihilations (solid line) for the MSSM model of Table I. Also shown separately is the contribution from radiative processes $\chi\chi \to W^+W^-\gamma$ (dashed), and the W fragmentation together with the $\chi\chi \to \gamma\gamma, Z\gamma$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

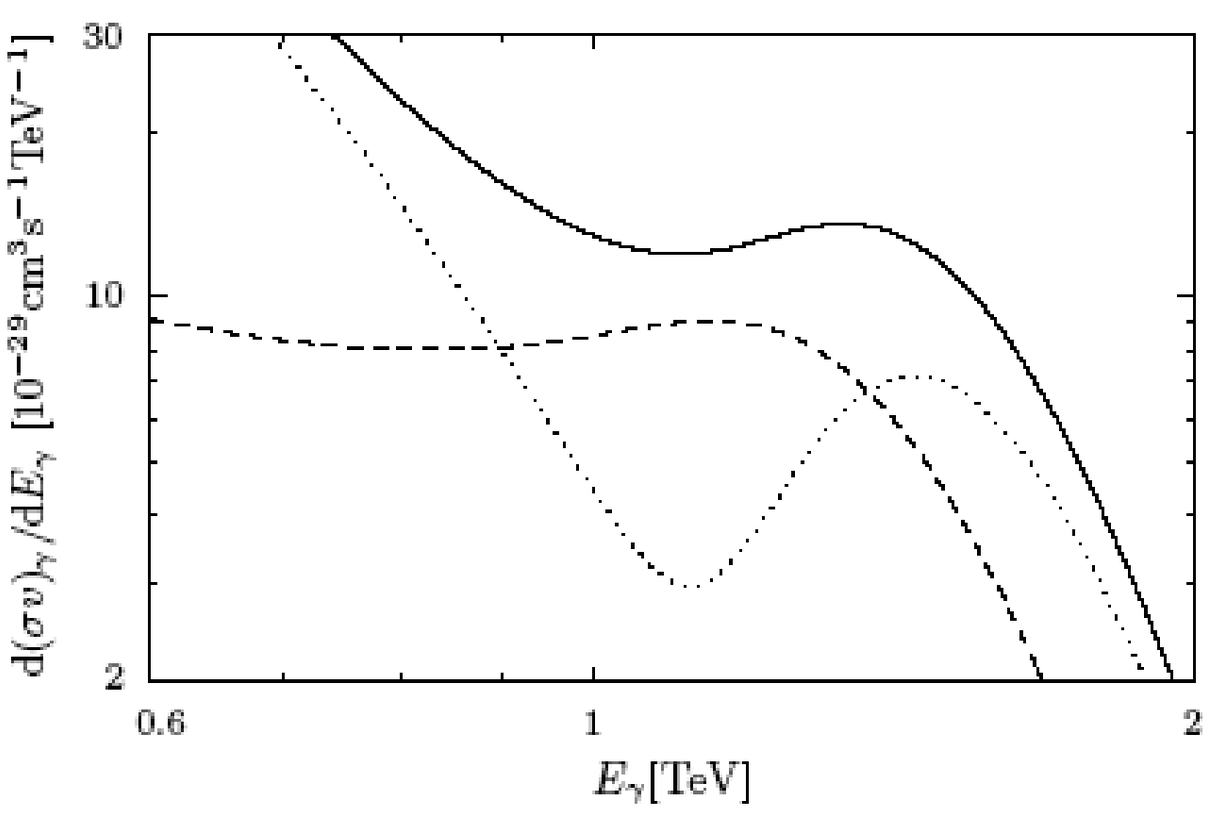


FIG. 4: The same spectra as in Fig. 3, as seen by a detector with an energy resolution of 15 percent.

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.

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

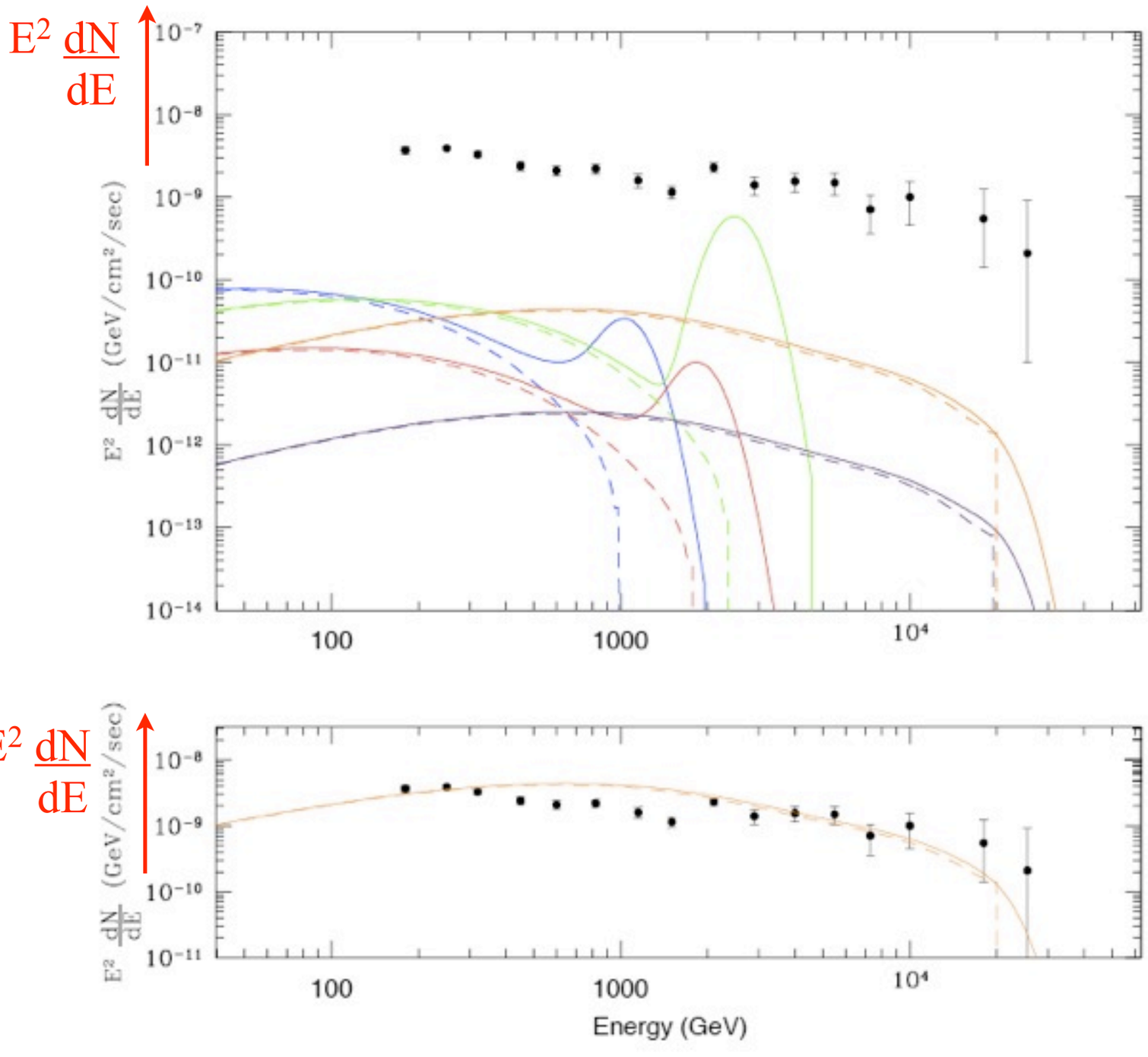
Rudy C. Gilmore, Mass Limits on Neutralino Dark Matter

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

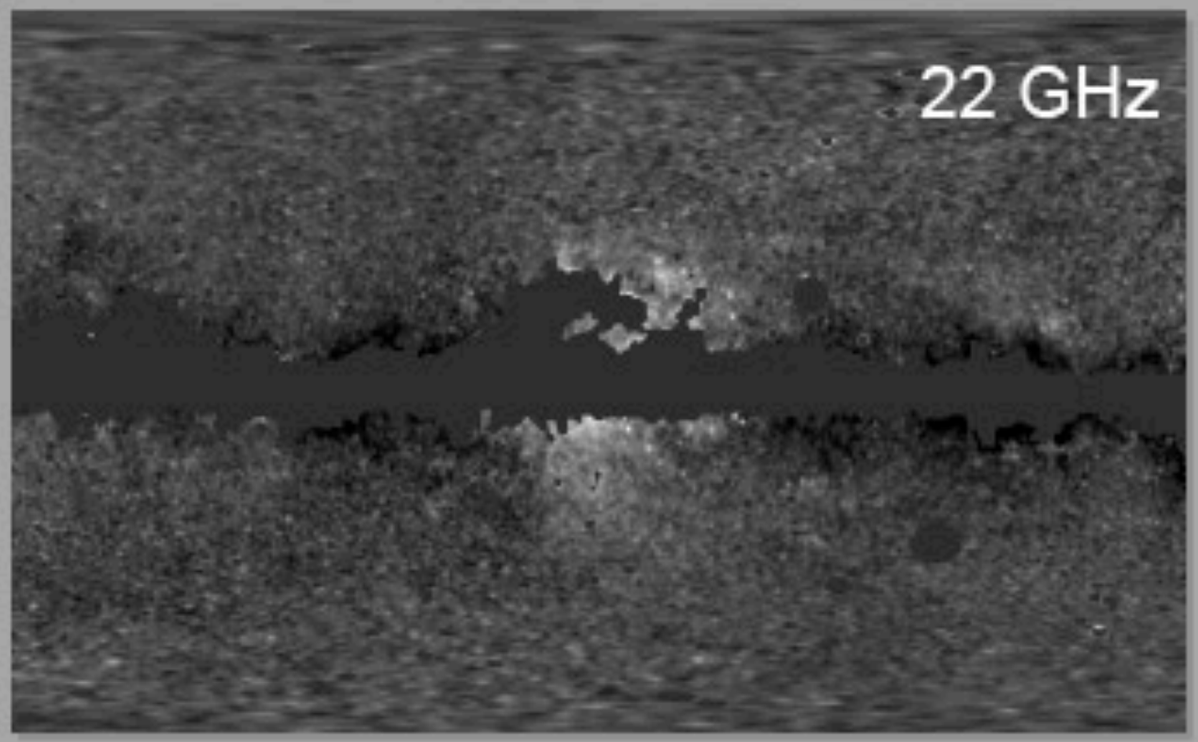
SUSY DM maximum mass is too low, spectrum shape is wrong, to account for Sag A* gamma rays



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

$\sim 1.2 \times 10^{39}$ 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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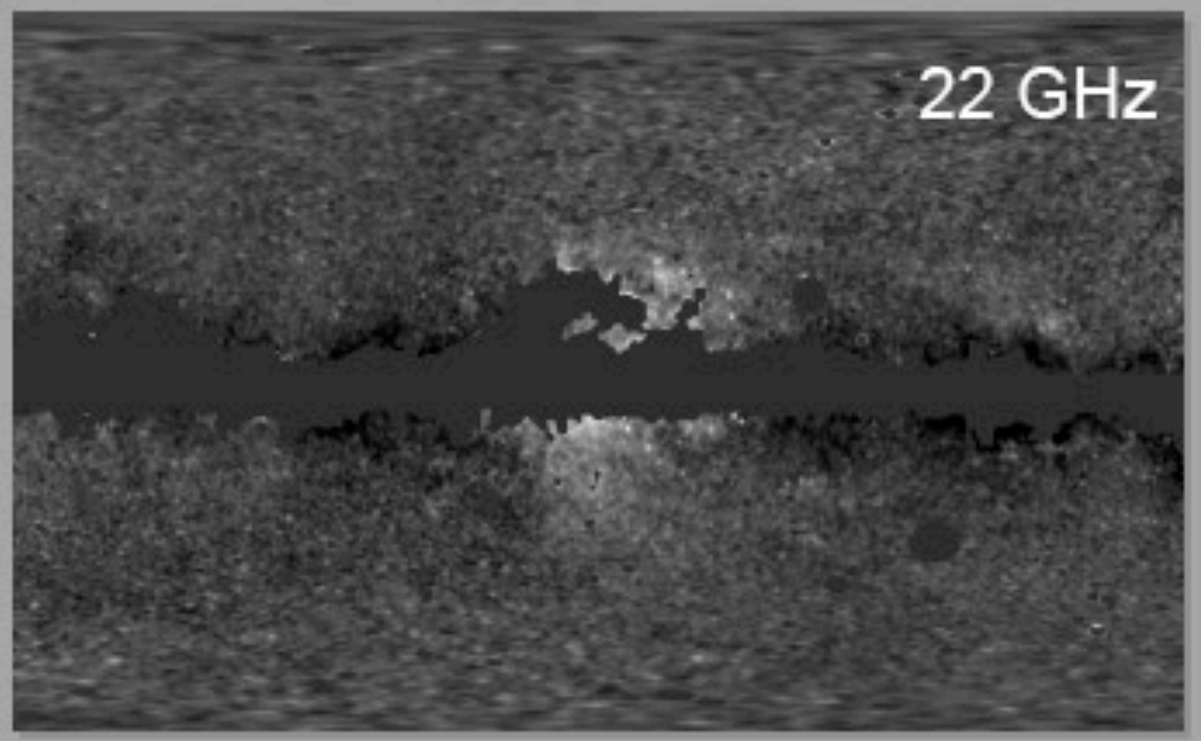


•In particular, he noted that:

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?

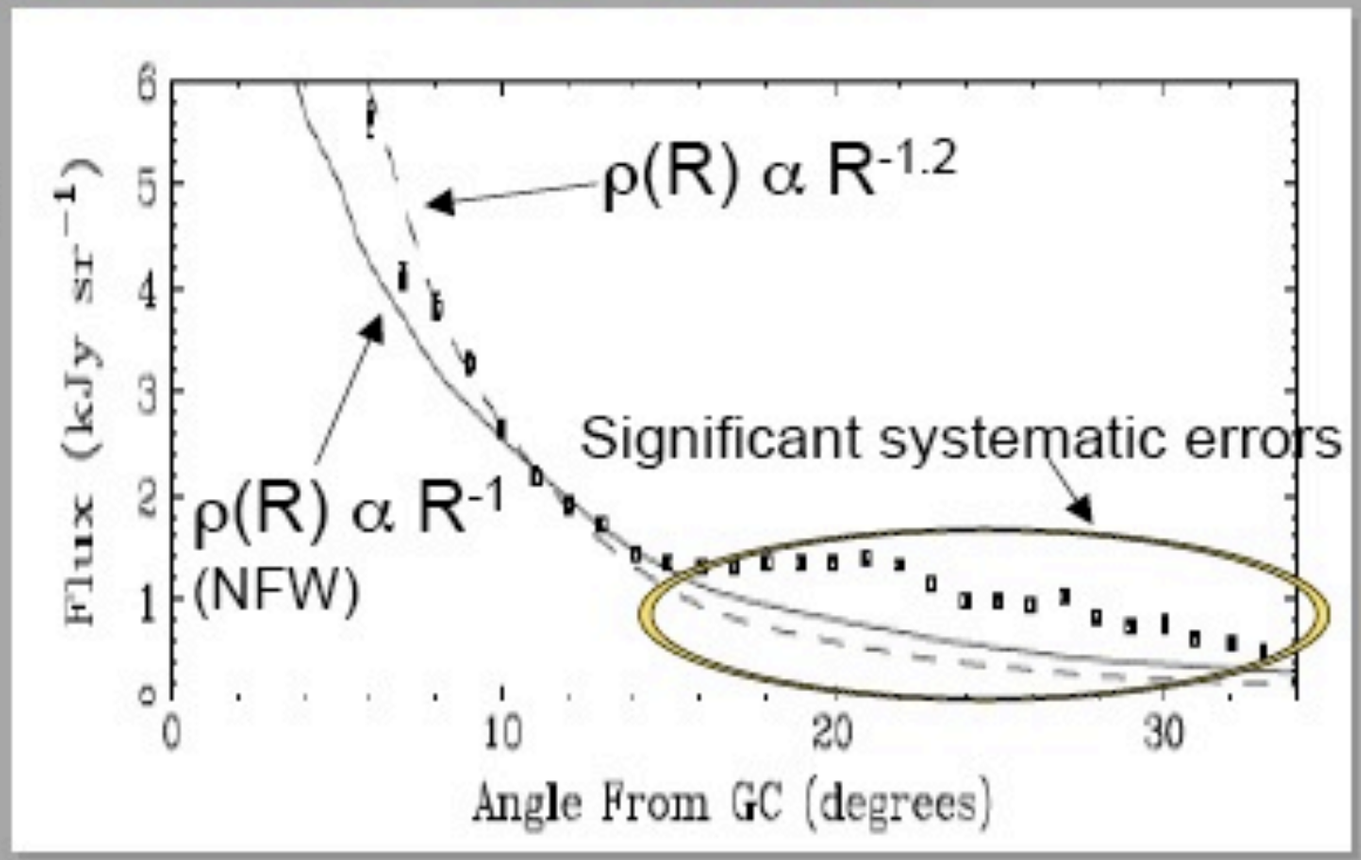
2) The total power of the WMAP Haze is between

0.7×10^{39} and 3×10^{39} GeV/sec

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

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 $\rho \propto R^{-1.2}$

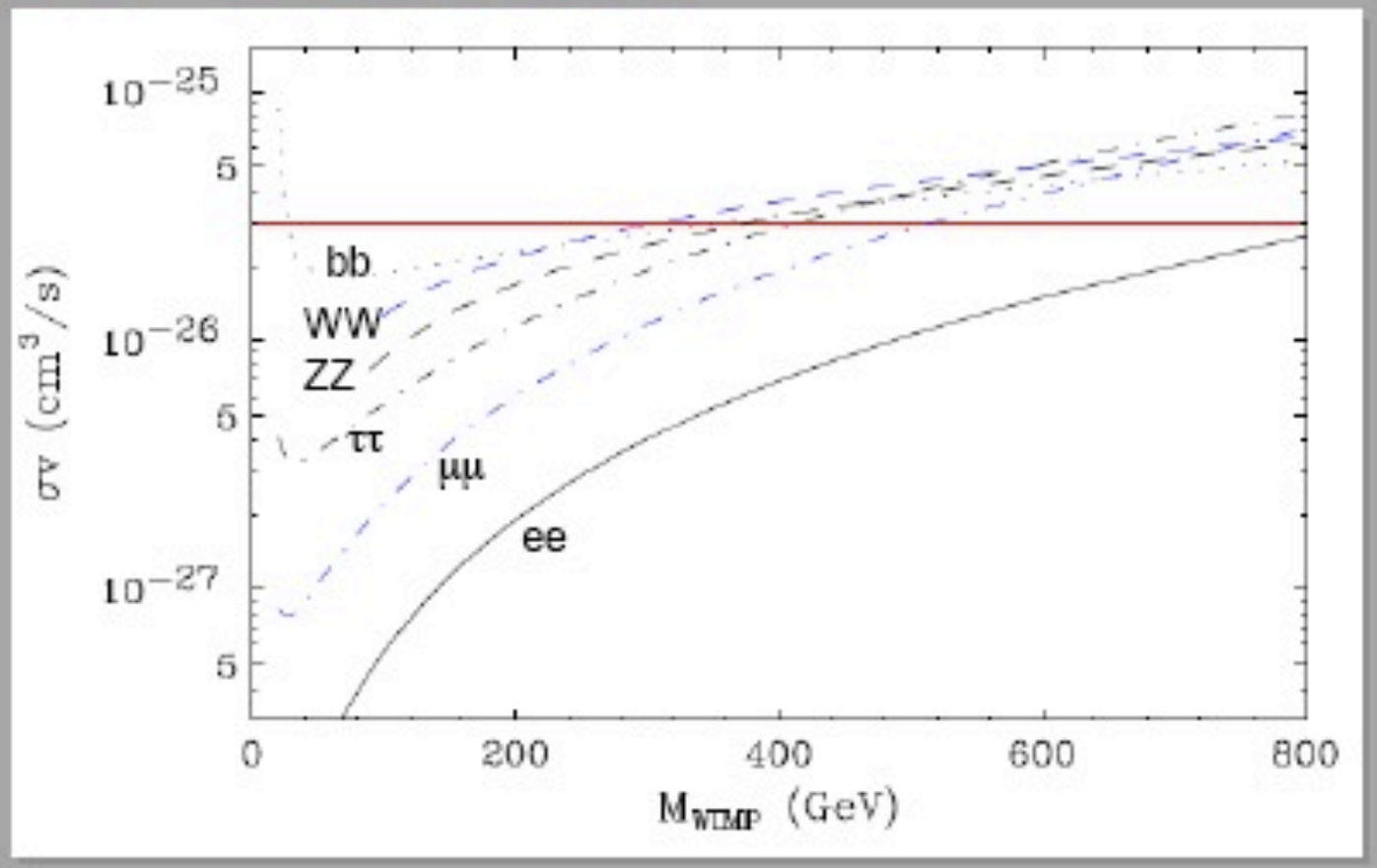


- Although the precise result of this fit depends on the diffusion parameters adopted (magnetic fields, starlight density, etc.), the approximate result (slope of -1.1 to -1.3) is fairly robust

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 (3×10^{-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 $\rho \alpha R^{-1.2}$ 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!

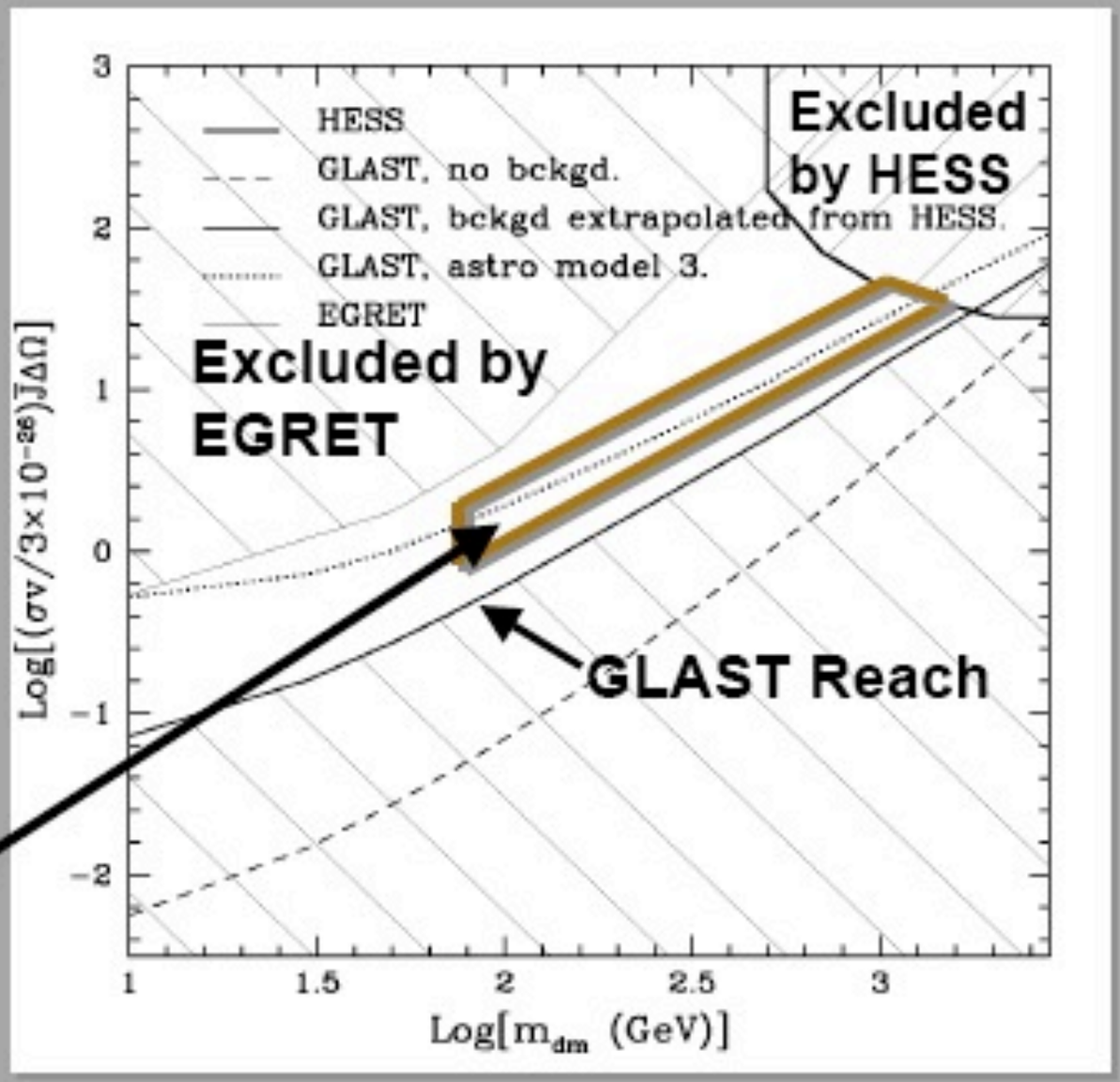
Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

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

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

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