Astronomy 233 Spring 2011

# Physical Cosmology

## Week 4

## *Recombination and Dark Matter*

Joel Primack

University of California, Santa Cruz

# 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 | $n$ | $\nu_e$ or $e^+$ | $p$ | $e^-$ or $\bar{\nu}_e$ |
| Recombination | $e$ | $p$ | $H$ | $\gamma$ |
| 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

$$\langle \sigma v \rangle \equiv \frac{1}{n_1^{(0)} n_2^{(0)}} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} e^{-(E_1+E_2)/T}$$
$$\times (2\pi)^4 \delta^3(p_1 + p_2 - p_3 - p_4)\delta(E_1 + E_2 - E_3 - E_4) |\mathcal{M}|^2 . \tag{3.8}$$

Then, the Boltzmann equation becomes

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

If the reaction rate $n_2\langle\sigma v\rangle$ 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

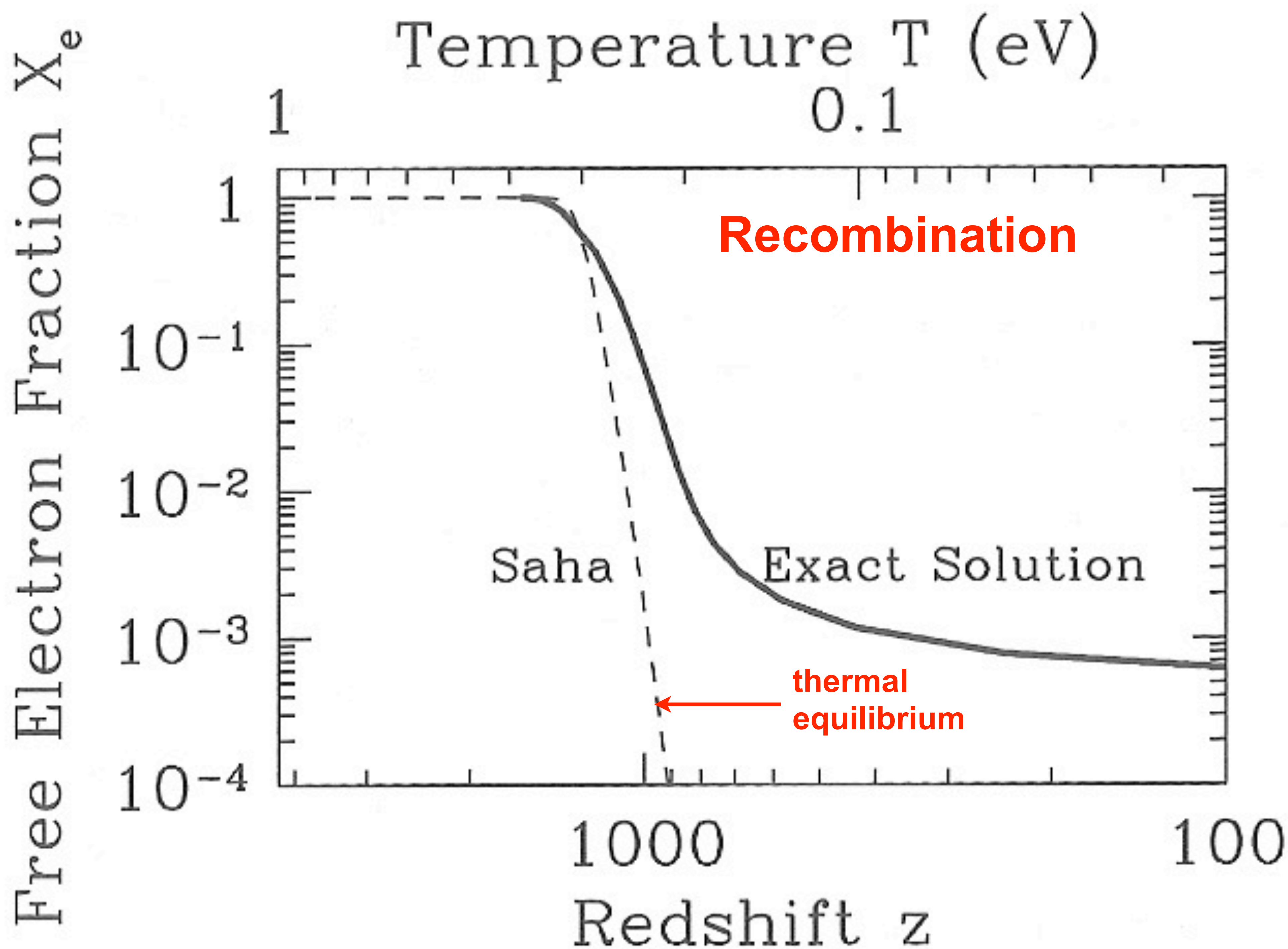



**Figure 3.4.** Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of $X_e$.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

Dodelson, *Modern Cosmology*, p. 72

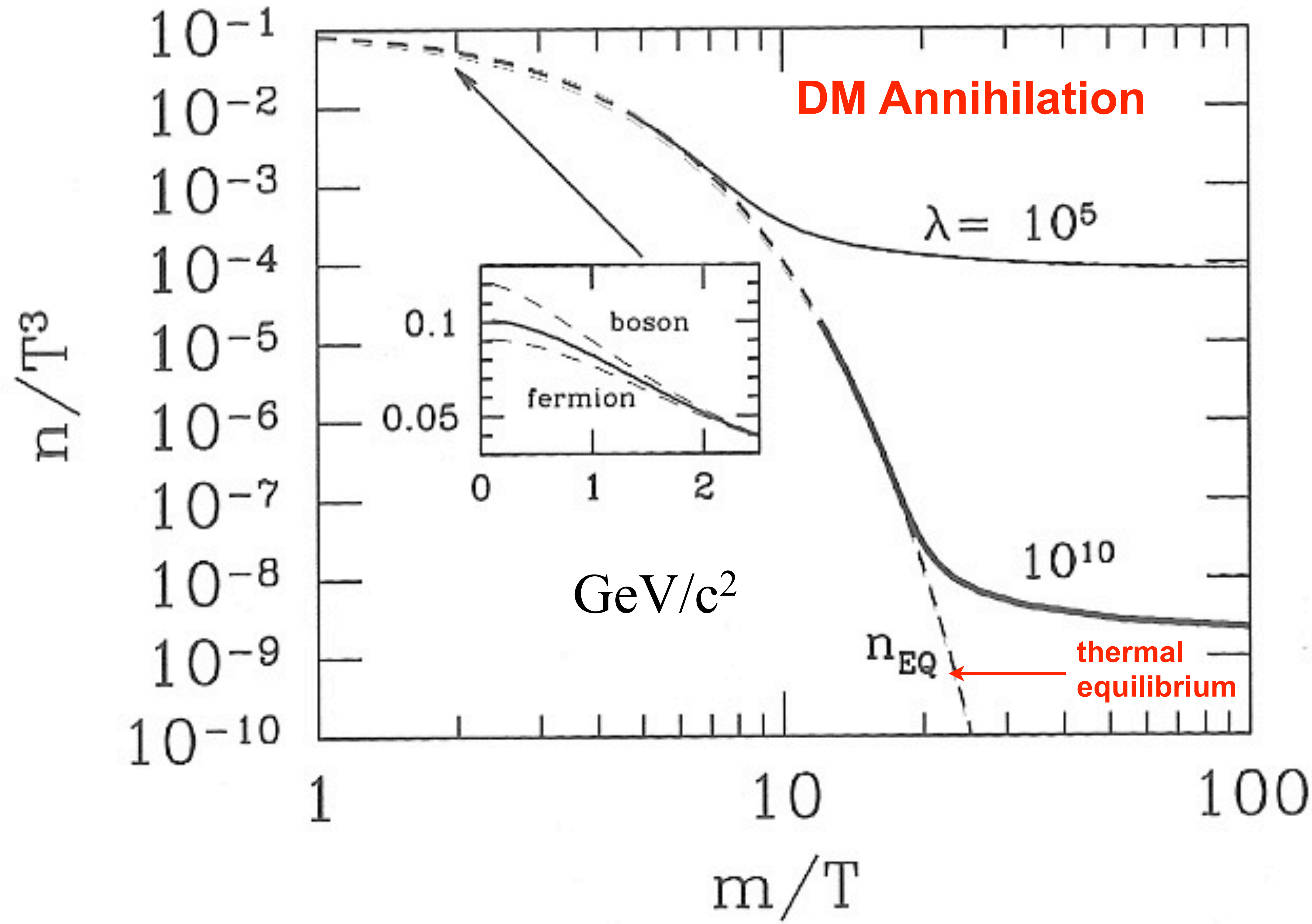



**Figure 3.5.** Abundance of heavy stable particle as the temperature drops beneath its mass. Dashed line is equilibrium abundance. Two different solid curves show heavy particle abundance for two different values of $\lambda$, the ratio of the annihilation rate to the Hubble rate. Inset shows that the 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/2010/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

$\varepsilon$ = 13.6 eV

is known as the *Saha equation*. When T ~ $\varepsilon$, 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

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

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

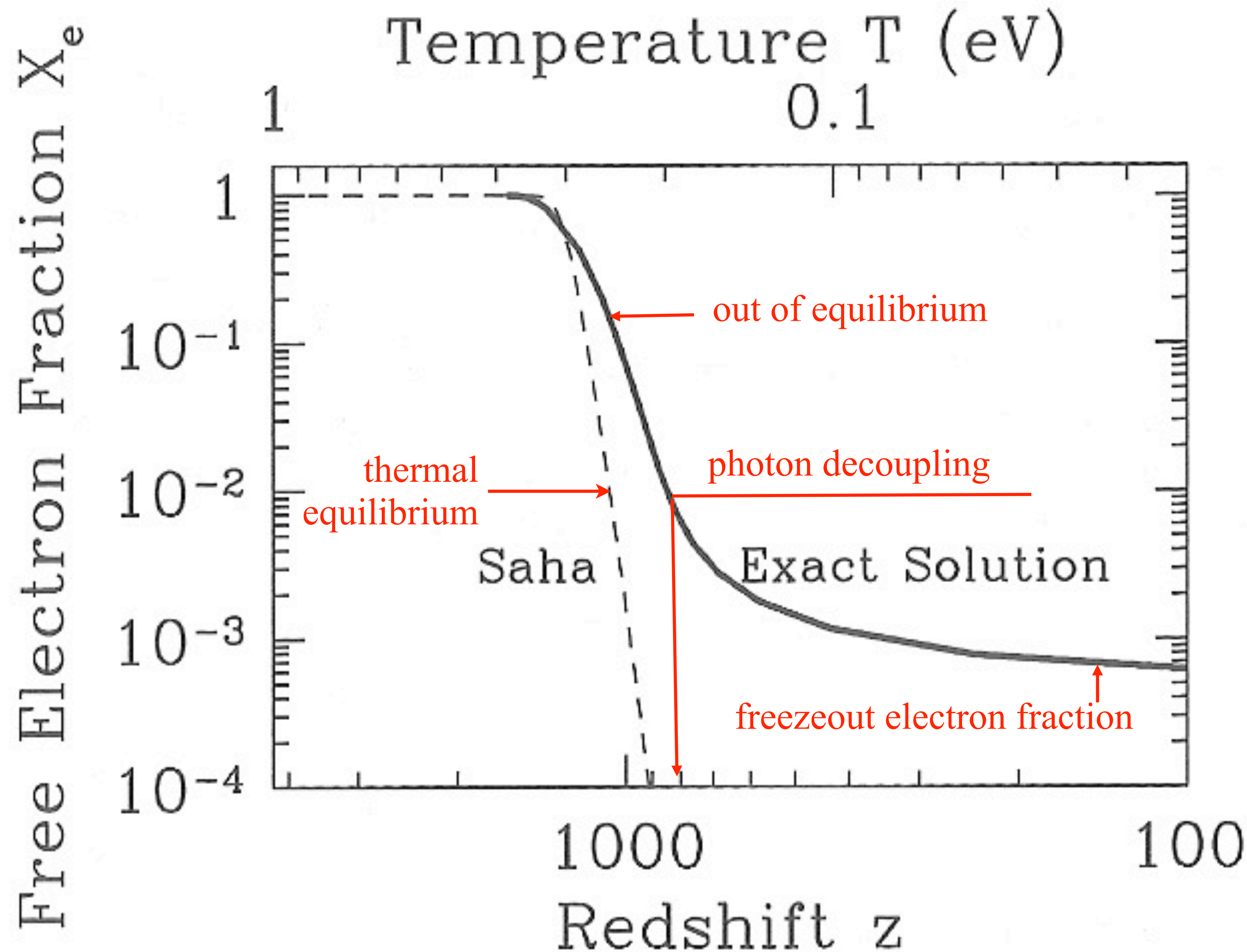
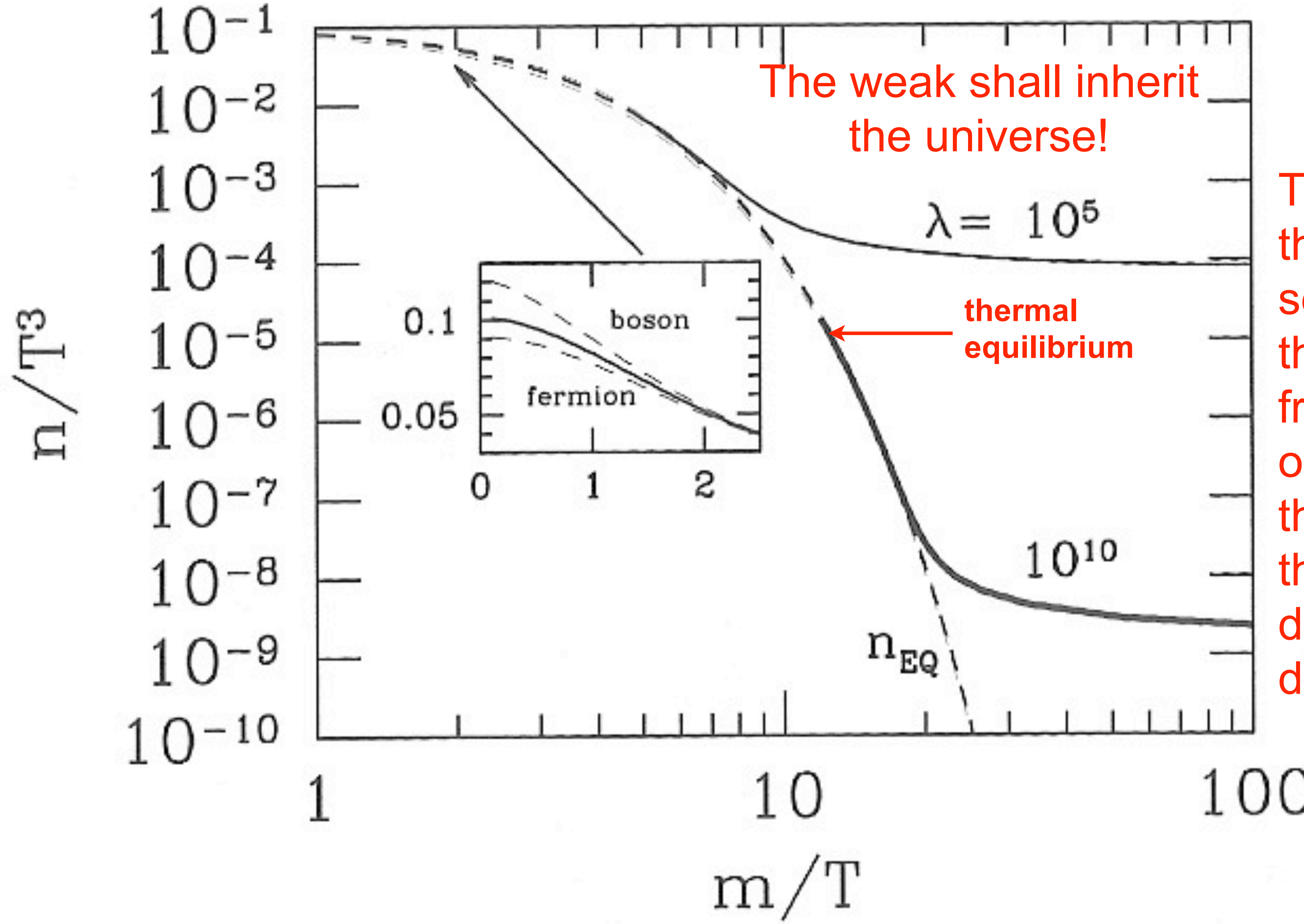



**Figure 3.4.** Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of $X_e$. 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 $\lambda$, the ratio of the annihilation rate to the Hubble rate. Inset shows that the difference between quantum statistics and Boltzmann statistics is important only at temperatures larger than the mass.

Dodelson, *Modern Cosmology*, p. 76

# Dark Matter Annihilation

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

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

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

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

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 $\sigma$. For Susy WIMPs the natural values are $\sigma \sim 10^{-39}$ cm$^2$, so $\Omega_X \approx 1$ naturally.

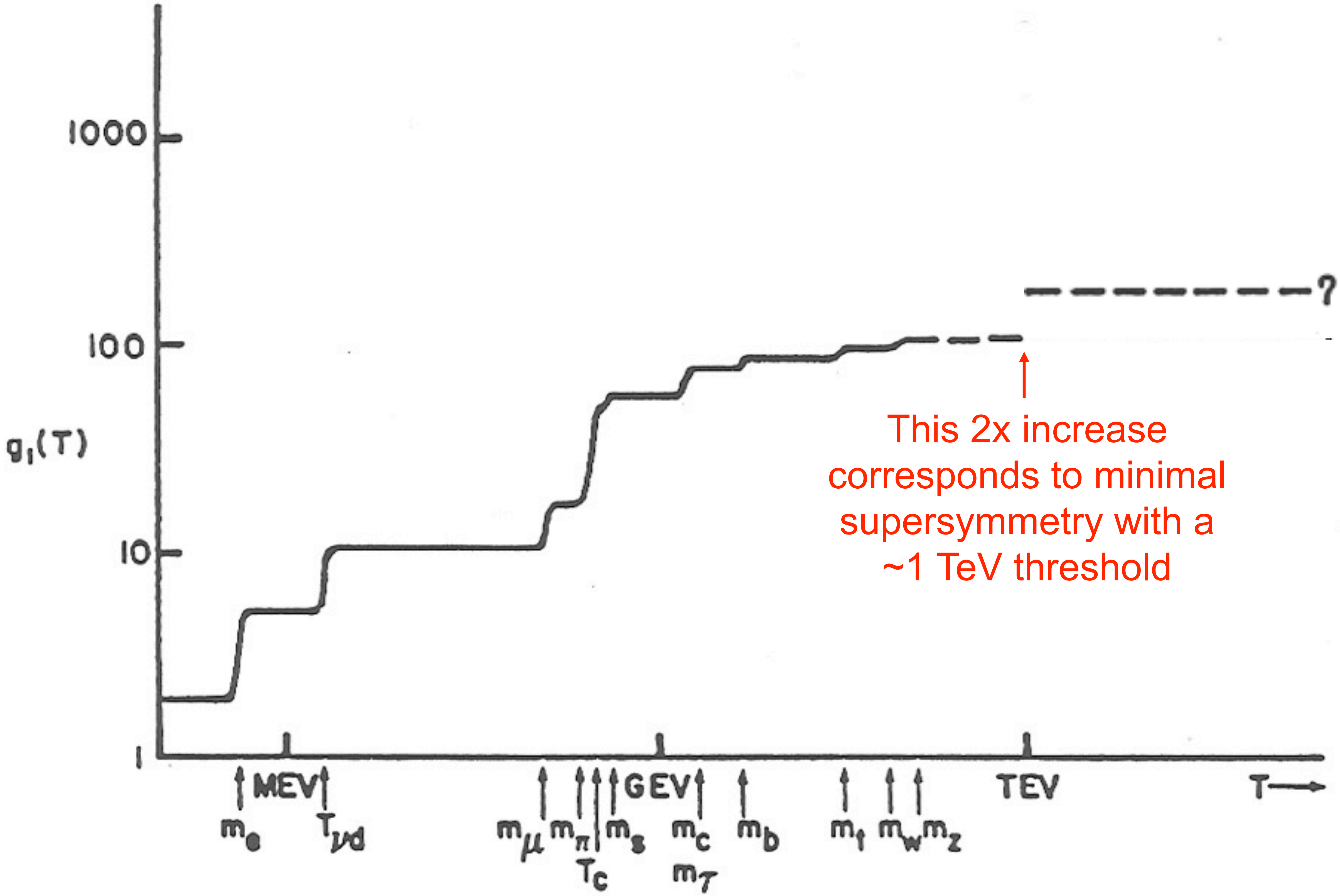



Fig. 1 The effective number of degrees of freedom of thermally interacting relativistic particles as a function of temperature.

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 | <u>photino</u>, winos, <u>zino</u>, 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 | <u>Higgsinos</u> <u>axinos</u> | 1/2 |

Note: Supersymmetric cold dark matter candidate particles are underlined.

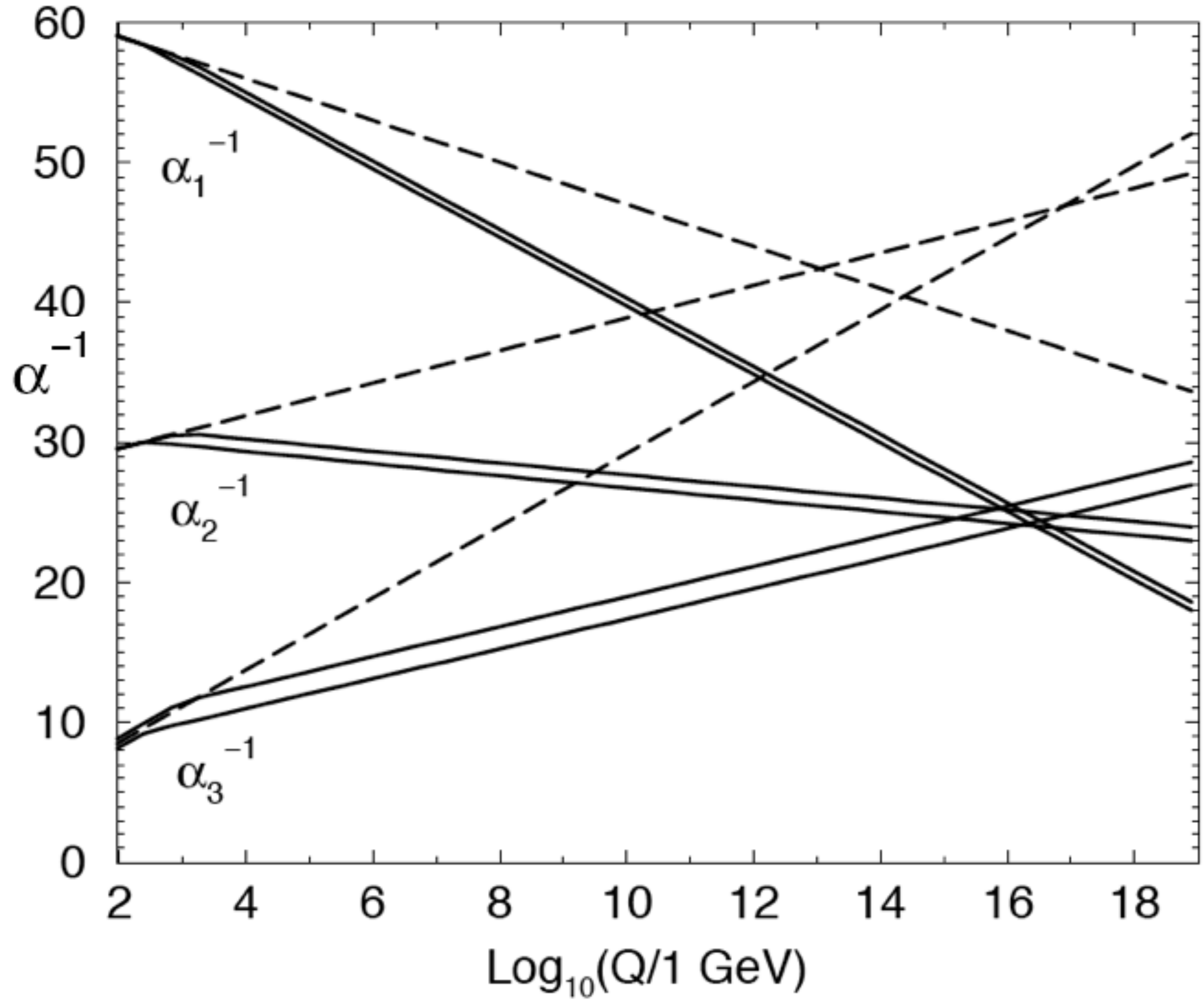
# Supersymmetric WIMPs, continued

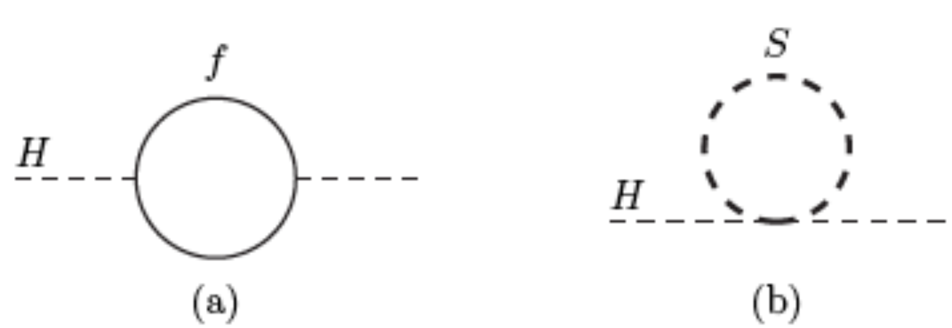
Spin is a fundamental property of elementary particles. Matter particles like electrons and quarks (protons and neutrons are each made up of three quarks) have spin ½, while force particles like photons, W,Z, and gluons have spin 1. The supersymmetric partners of electrons and quarks are called selectrons 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 (dashed lines in firgure) 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. The figure assumes the Minimal Supersymmetric Standard Model (MSSM) with sparticle masses between 250 GeV and 1 TeV.

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

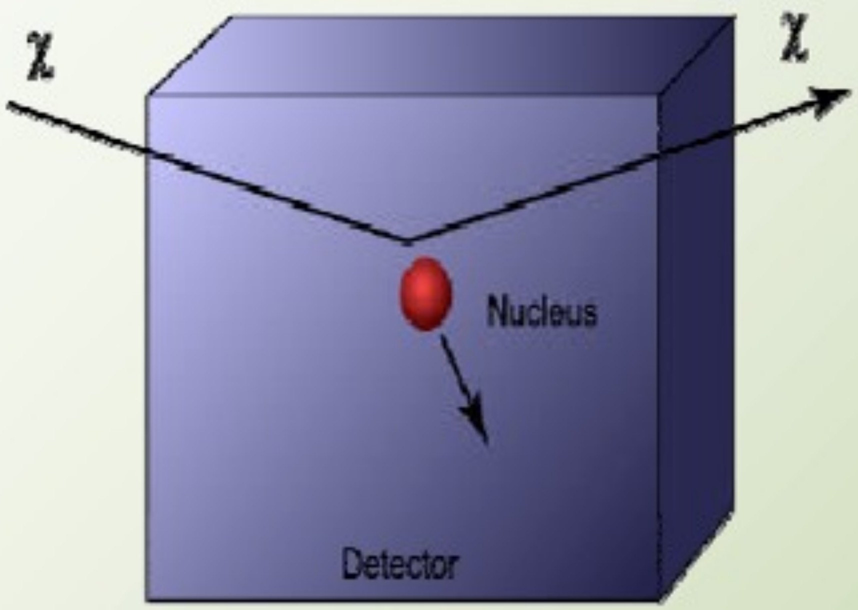


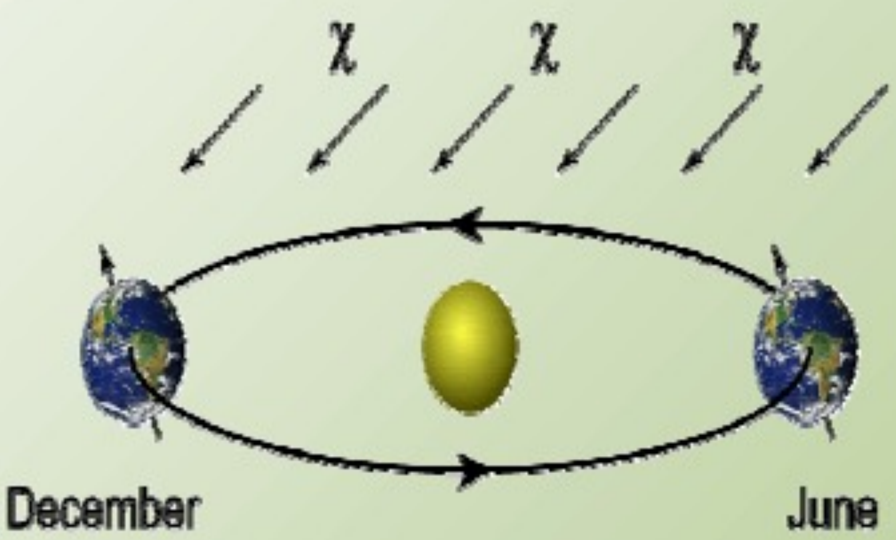

figs from S. P. Martin, A Supersymmetry Primer, arXiv:hep-ph/9709356v5

# Experiments are Underway for Detection of WIMPs

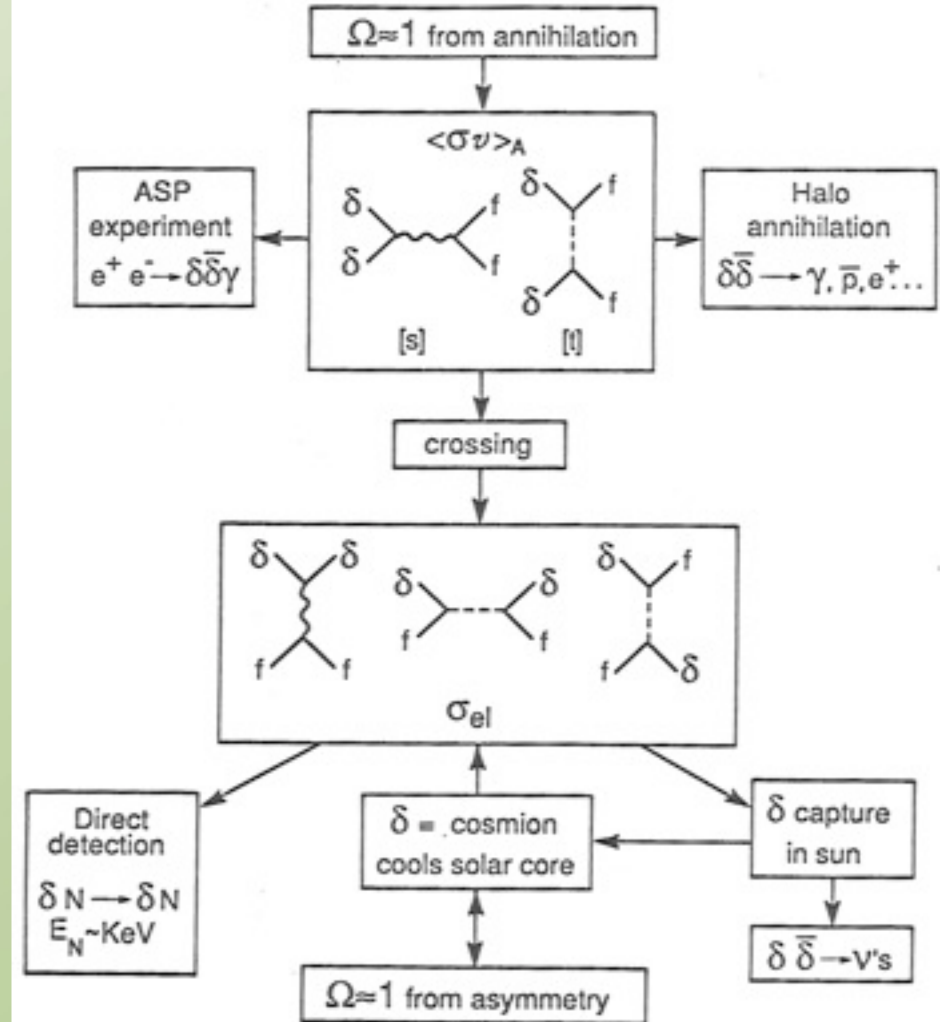
## Direct detection - general principles

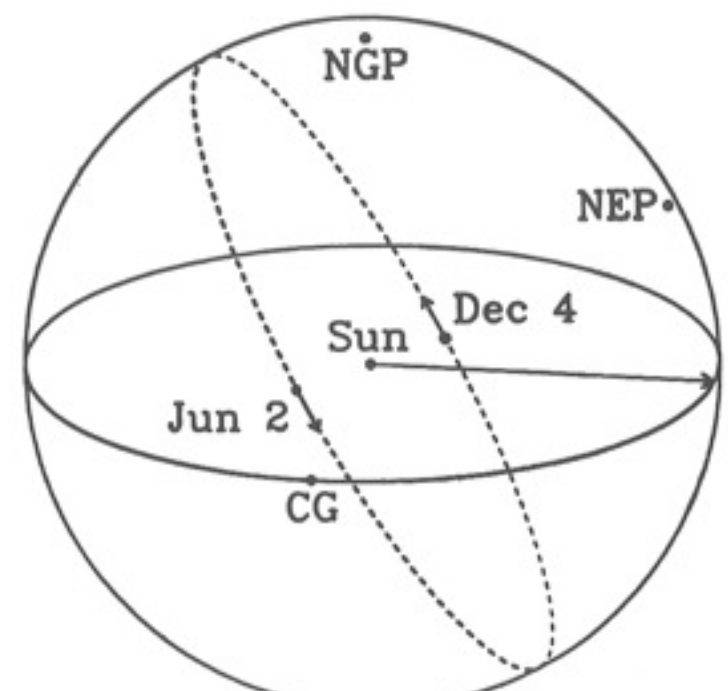



- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...




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

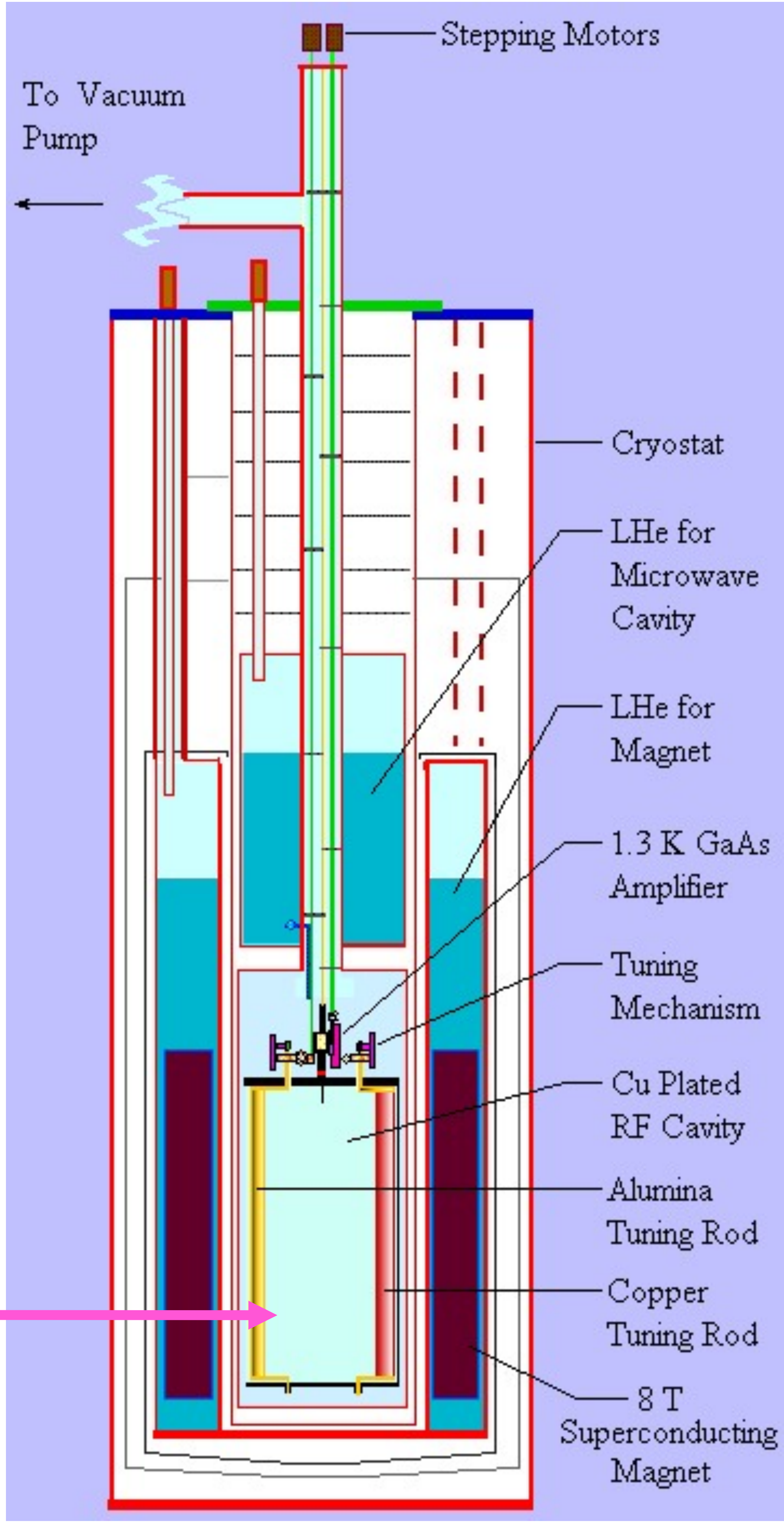



Primack, Seckel, & Sadoulet (1987)

# 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

$\Omega_i$ 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

$\Omega_m$ represents the fraction of the critical density in all types of matter.
$\Omega_\Lambda$ 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?

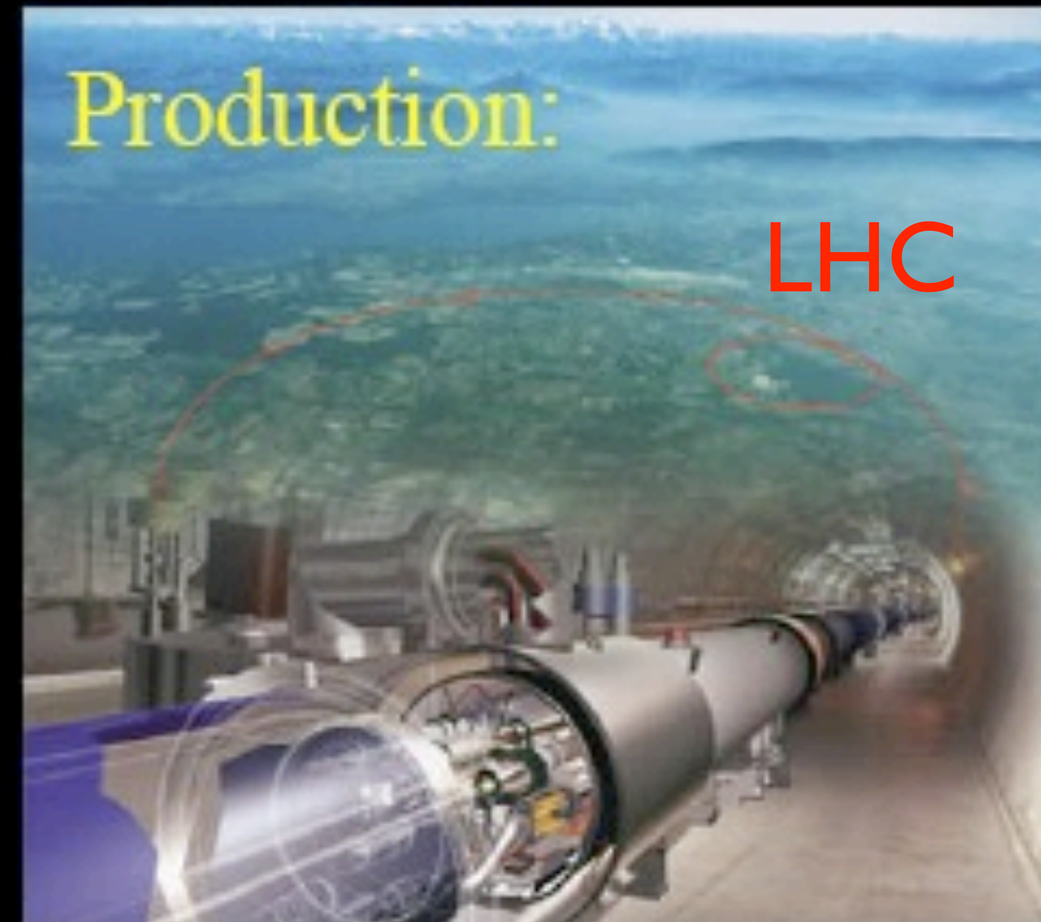
Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many upcoming experiments

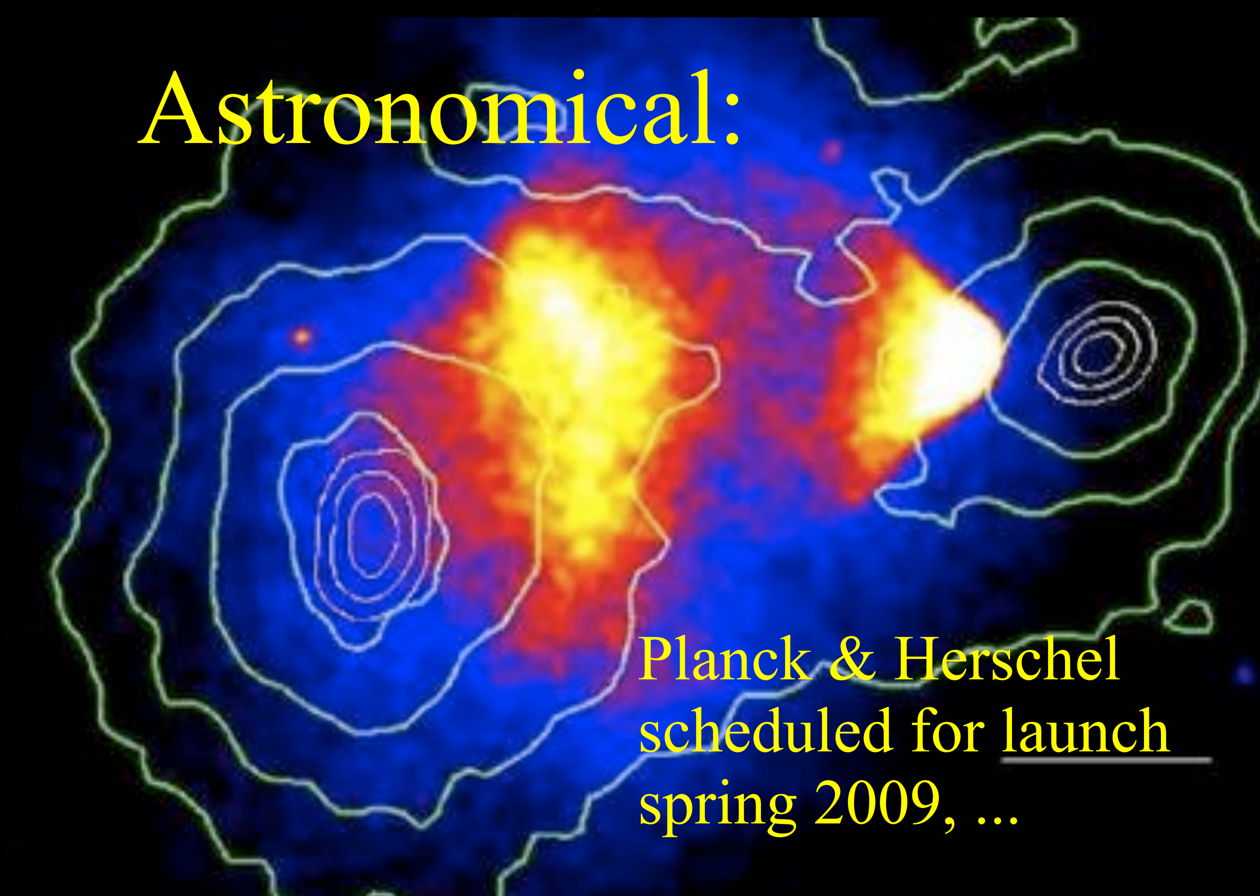
- Production at Large Hadron Collider
- Better CMB data from PLANCK
- Direct Detection
  - Spin Independent - CDMS-II, XENON50, LUX
  - Spin Dependent - COUPP, PICASSO
- Indirect detection via
  - GLAST and larger ACTs
  - PAMELA and ATIC

-- 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*

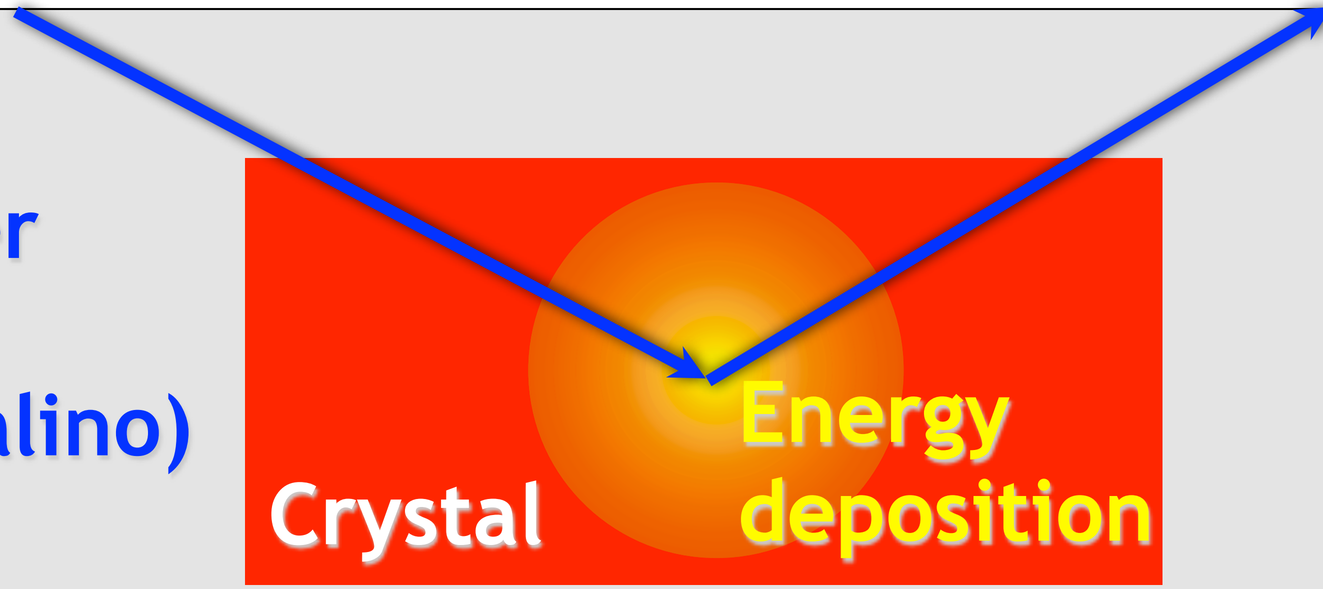

With all these upcoming experiments, the next few years will be very exciting!

# Search for Neutralino Dark Matter

## Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)

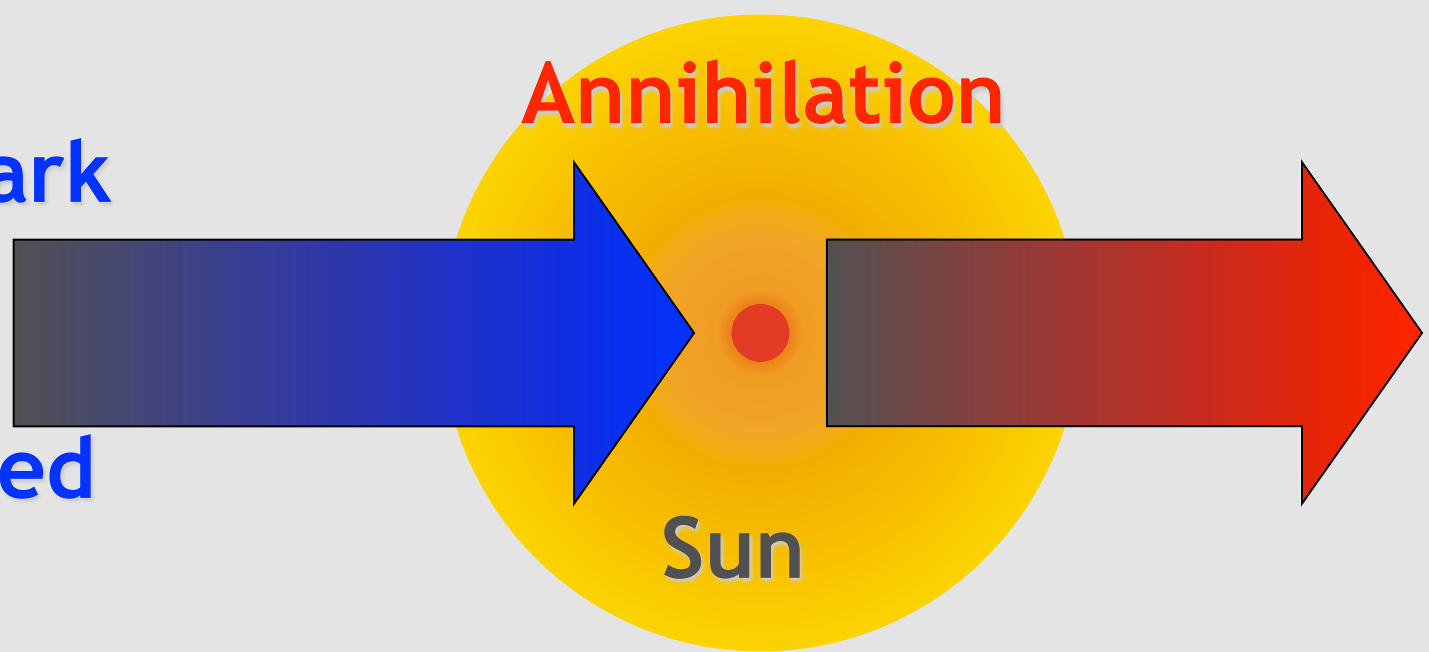



Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

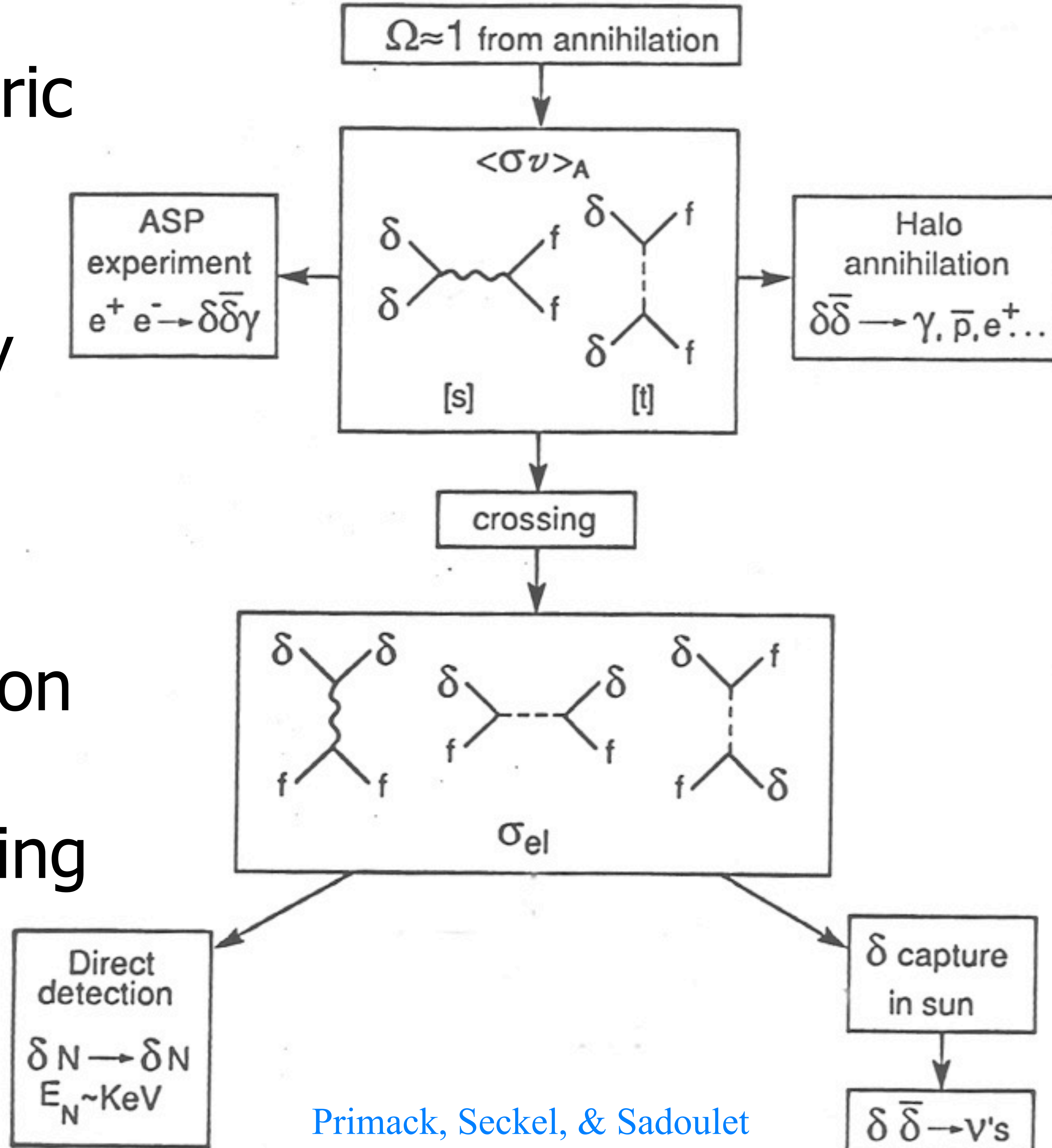
## Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted




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

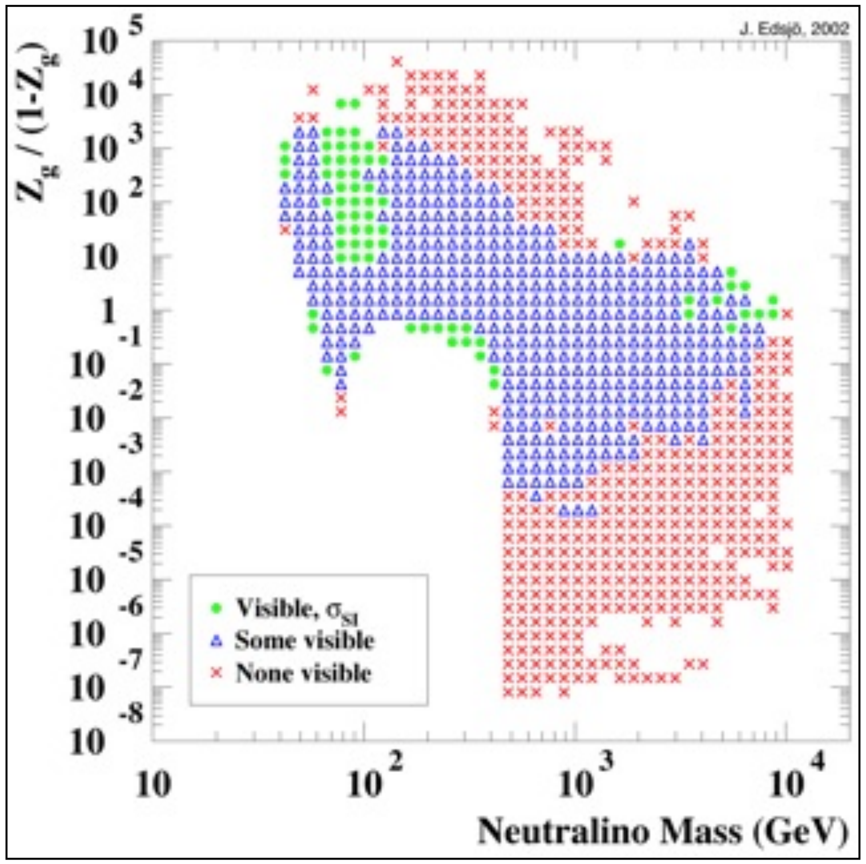
# Supersymmetric WIMP (δ) annihilation is related by crossing to WIMP Direct Detection by Elastic Scattering

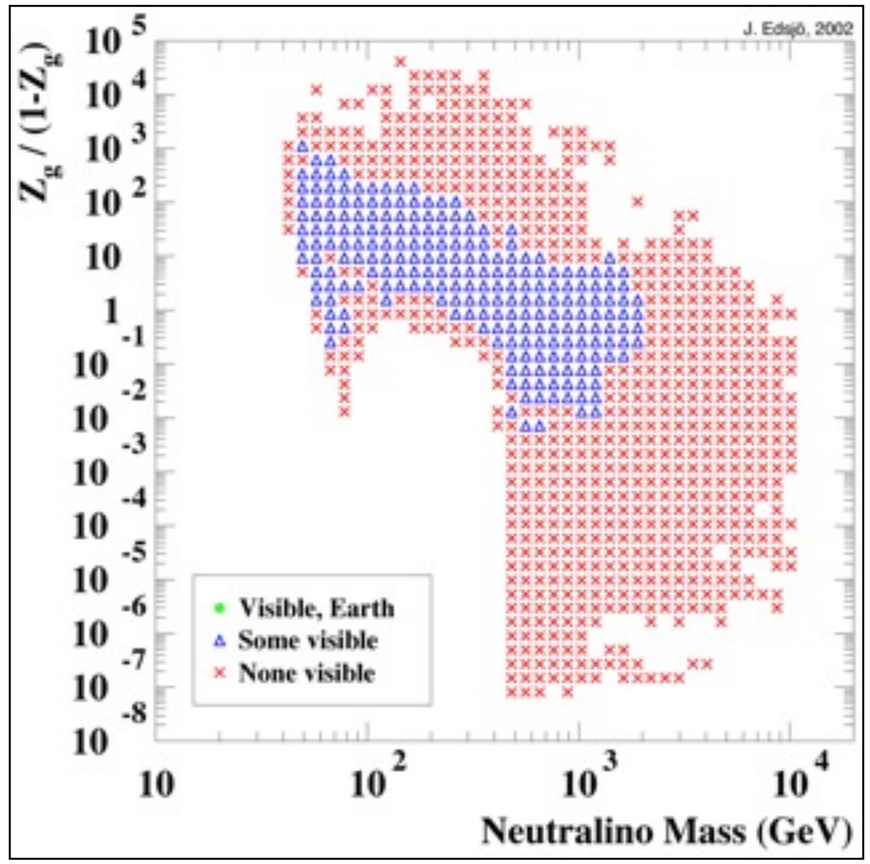


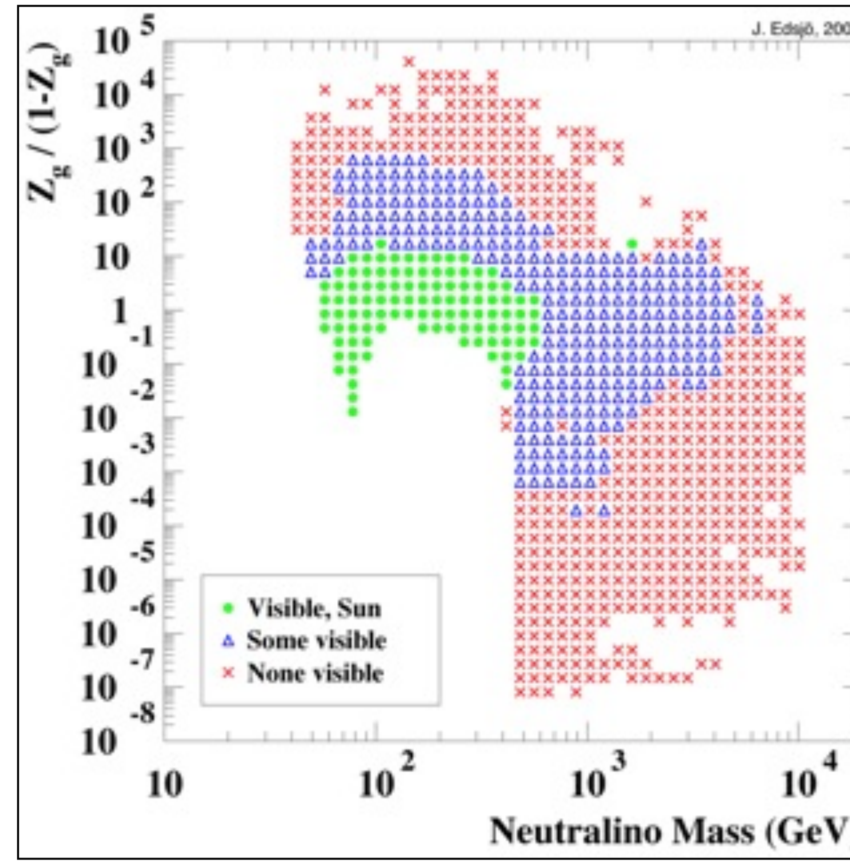

Primack, Seckel, & Sadoulet
Ann Rev Nucl Part Sci 1988

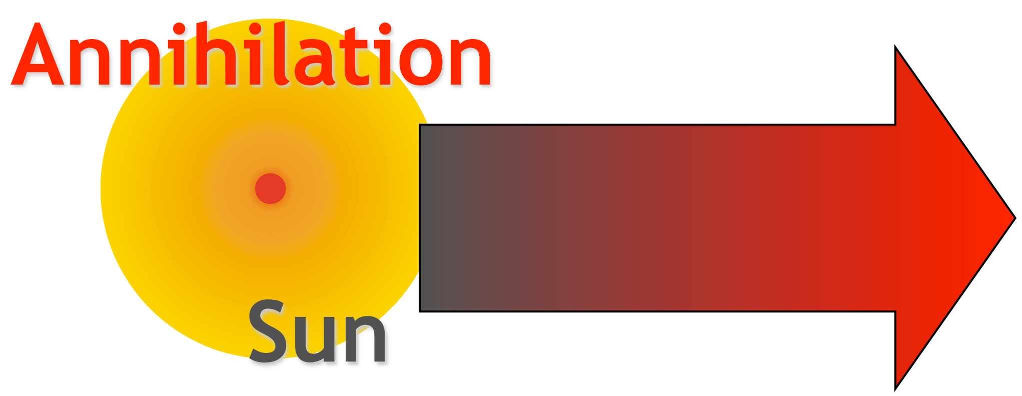
# Future WIMP Sensitivities

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



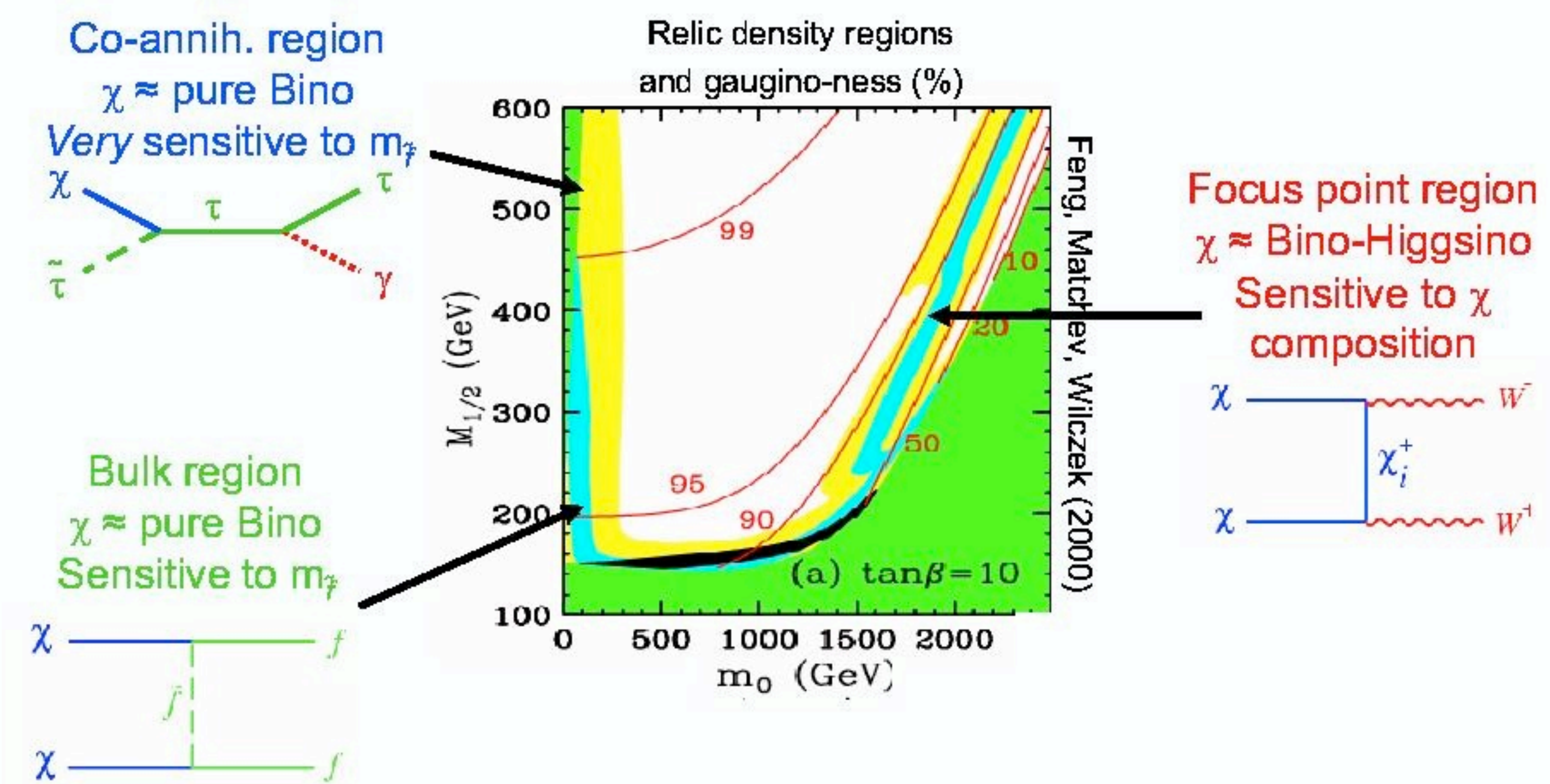




High-energy neutrinos (GeV-TeV) can be measured

# Relic Density

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

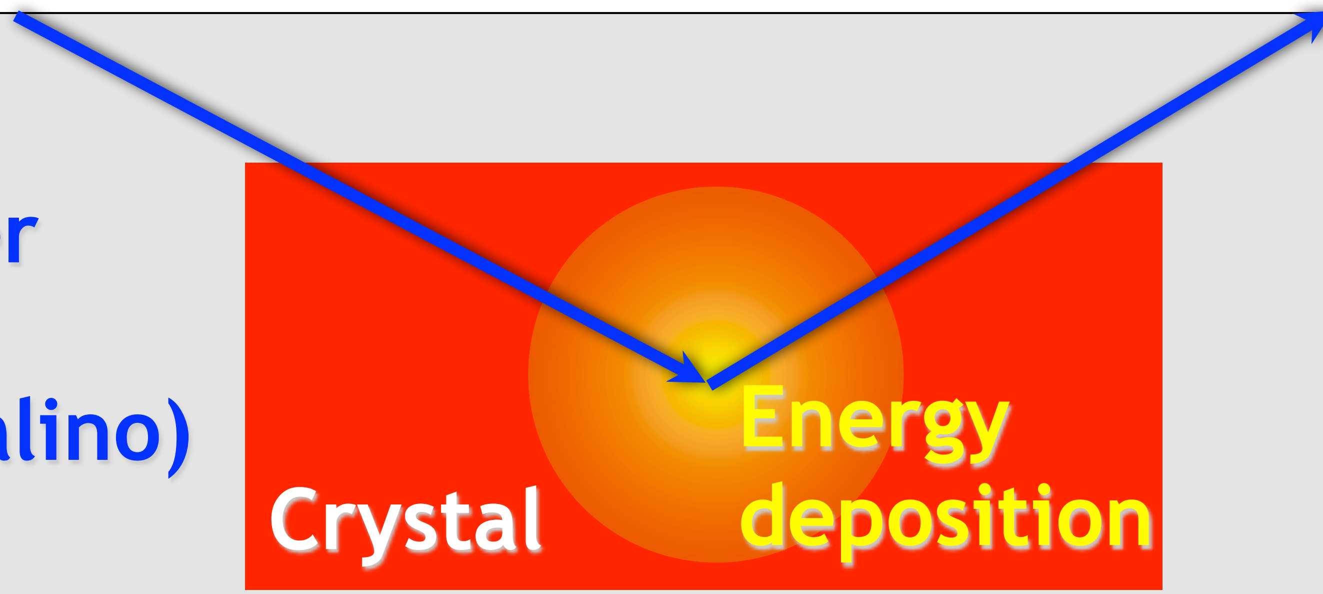



Jonathan Feng, SLAC Summer School 2003

# Search for Neutralino Dark Matter

## Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)




Recoil energy (few keV) is measured by
- Ionisation
- Scintillation
- Cryogenic

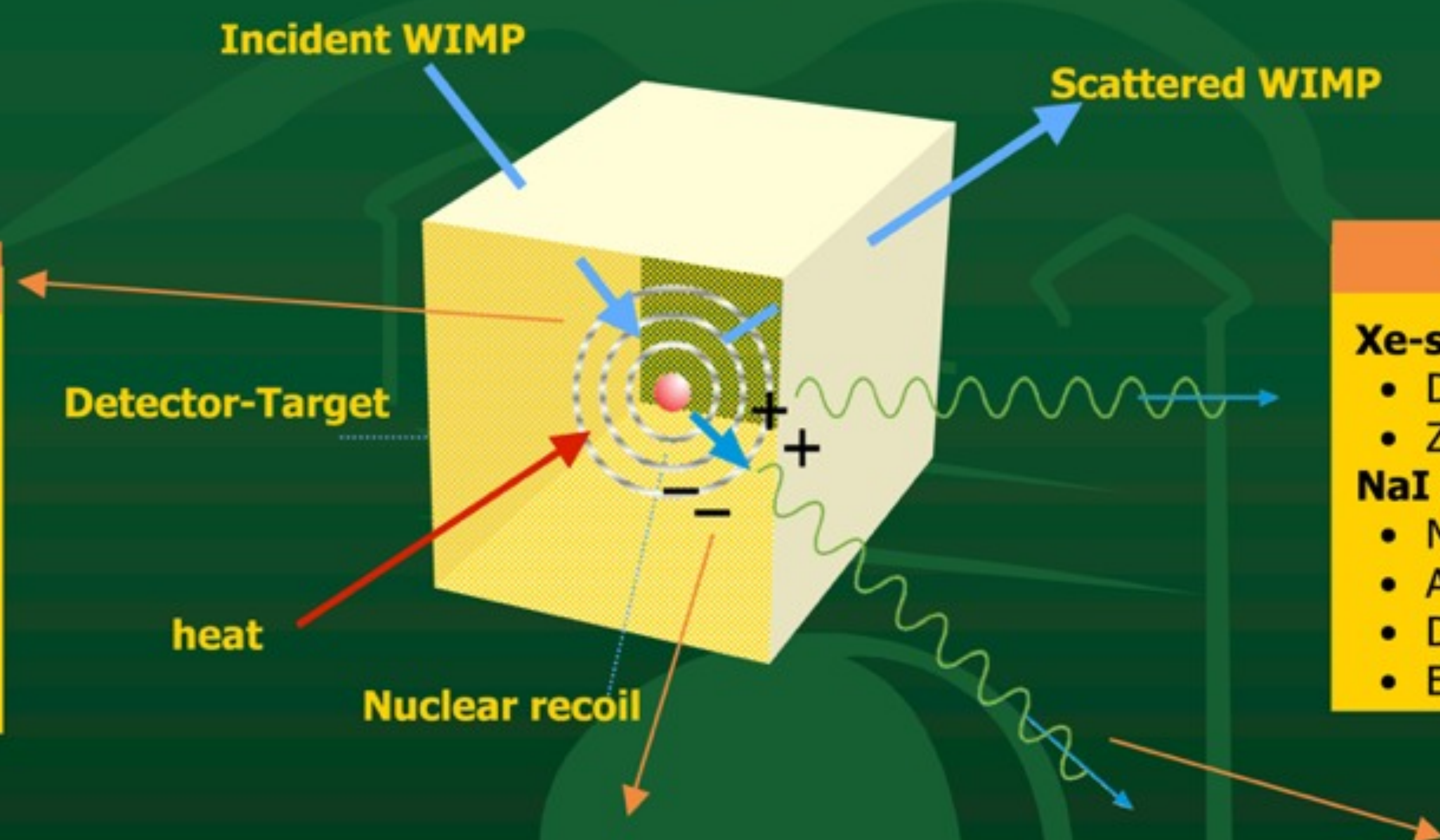
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

### Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

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

# Direct Detection Methods




**HEAT**

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

**Metastable p.det:**
- SSD Micrograins
- SDD Droplets

**LIGHT**

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

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

**HEAT+CHARGE**
- CDMS
- EDELWEISS

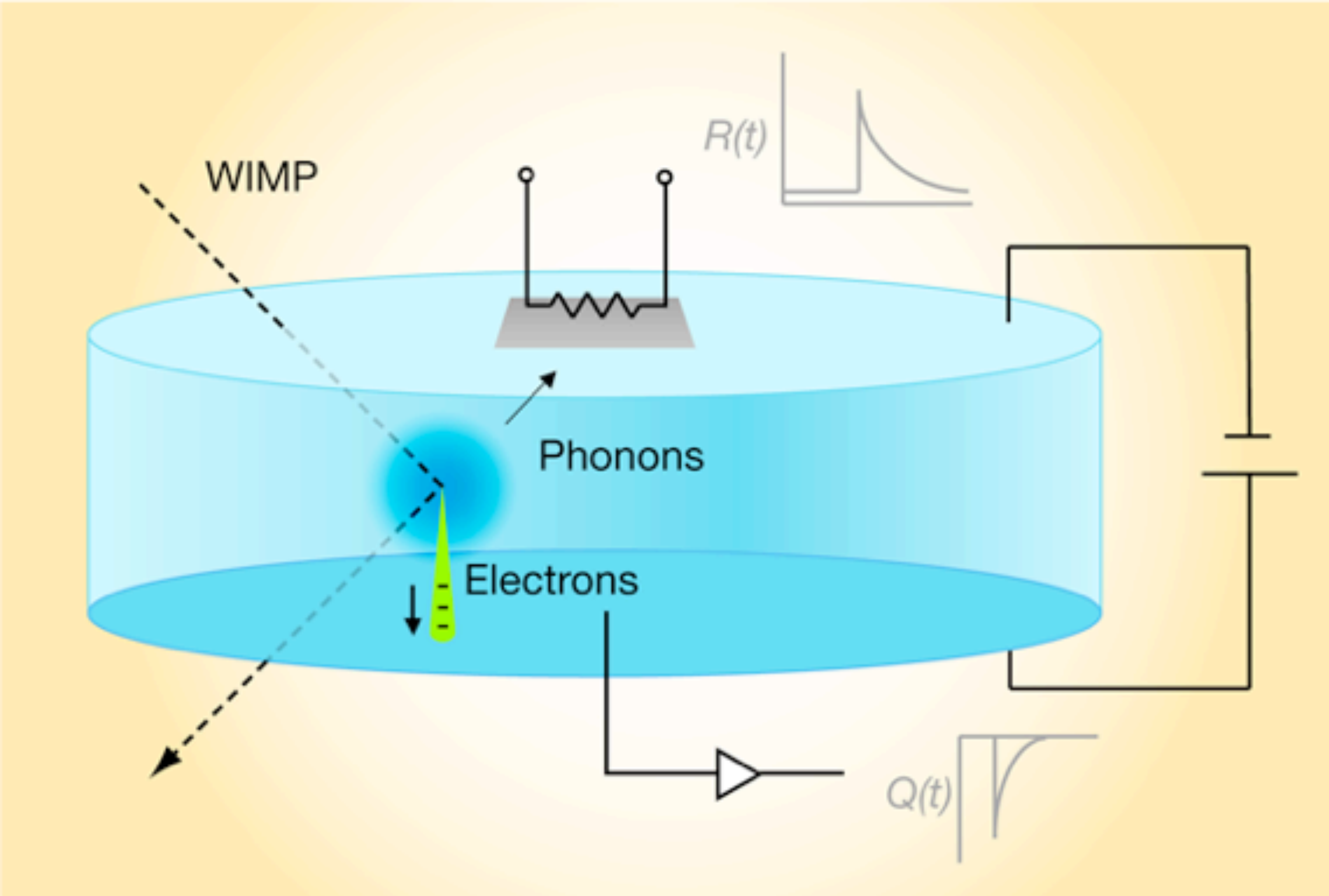
**CHARGE**

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

**Tracking Chambers:**
- DRIFT

**HEAT+LIGHT**
- ROSEBUD-II
- CRESST-II

**LIGHT+CHARGE**
- ZEPLIN-II
- X-MASS




# CDMS - Cryogenic DM Search

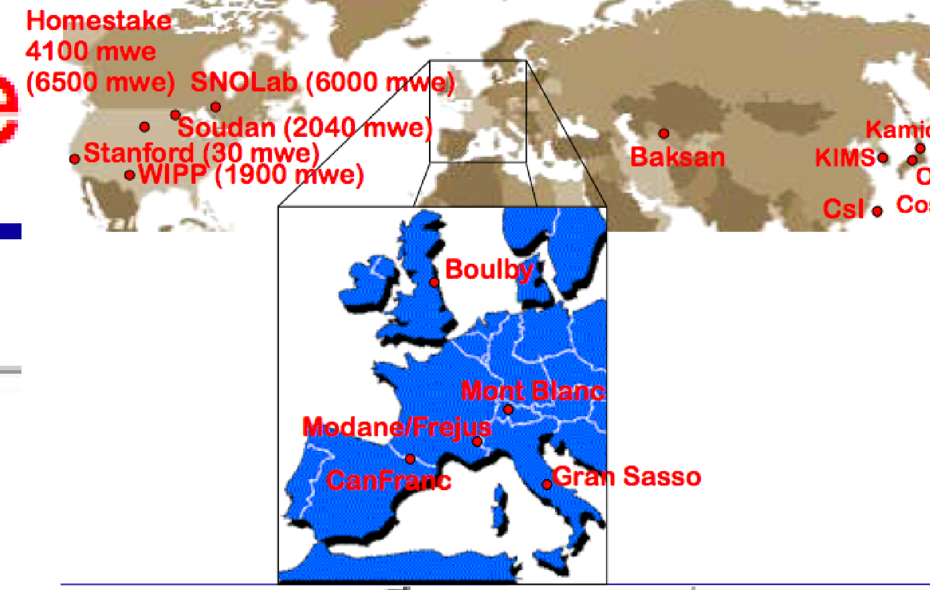
## Berkeley-Stanford-led experiment has been at forefront

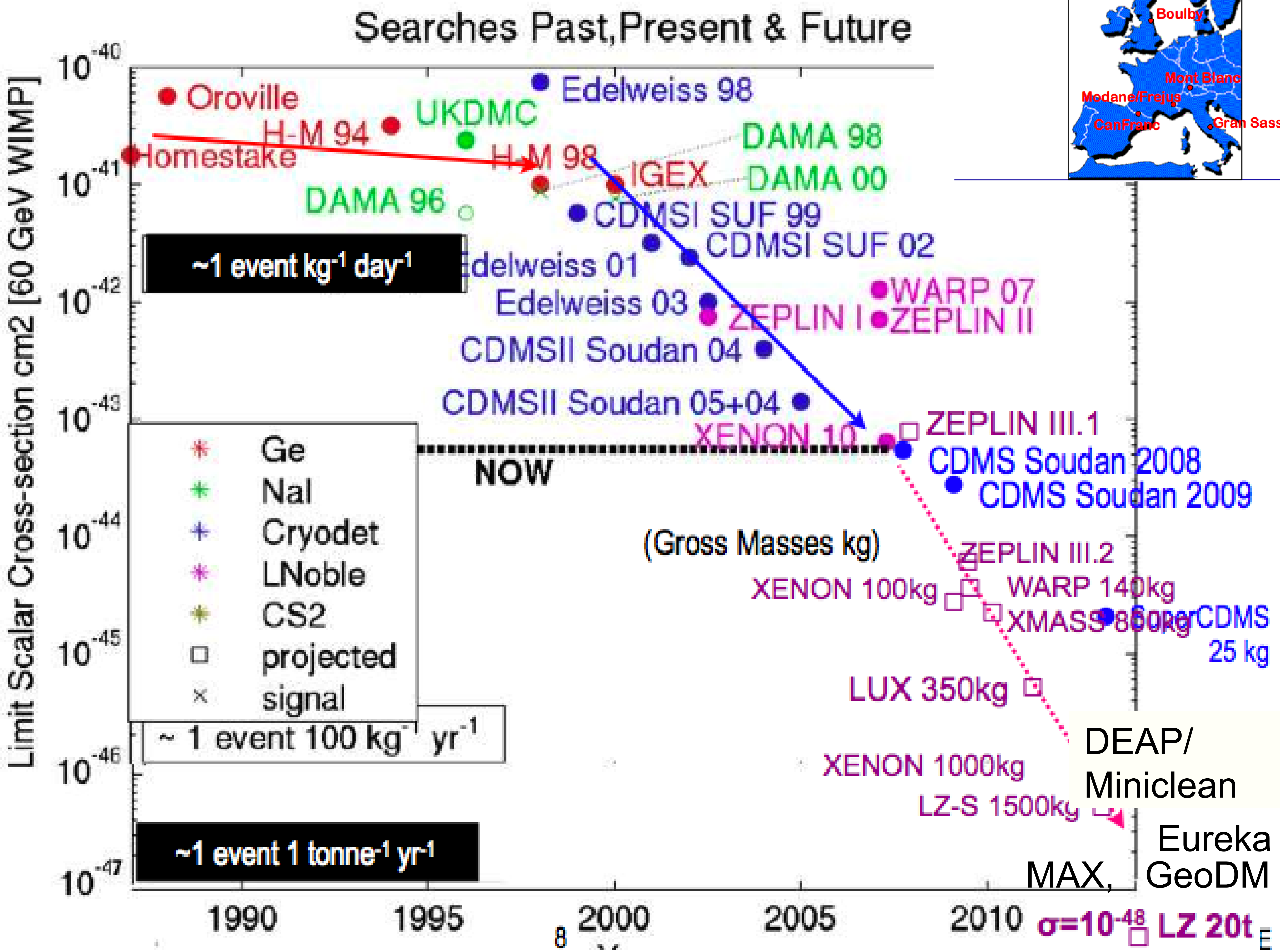
Figure from: Perspective by Karl van Bibber http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.011301 on Z. Ahmed et al. CDMS Collaboration, “Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory,”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

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

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

# DM Direct Search Progress Over Time



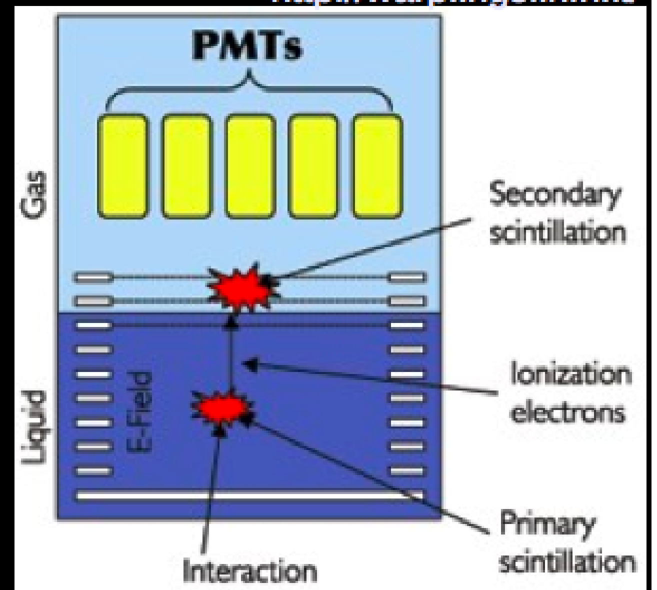



Tuesday, April 19, 2011

# 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)<br>$60/kg<br>100% even-even nucleus | 85 nm<br>Requires wavelength Shifter | Low BP (20K) - all impurities frozen out<br>No radioactive isotopes | Scalar Coupling:<br>Eth>50 keVr, 0.02x<br>Axial Coupling: 0 (no odd isotope) |
| Ar (A=40)<br>$2/kg<br>(isotope separation >$1000/kg)<br>~100% even-even | 125 nm<br>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:<br>Eth>50 keVr, 0.10x<br>Axial Coupling: 0 (no odd isotope) |
| Xe (A=131)<br>$1000/kg<br>50% odd isotope | 175 nm<br>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$^2$.<br>85Kr can be removed by charcoal or distillation separation. | Scalar Coupling:<br>Eth>5 keVr, 1.30x<br>Axial Coupling: ~5x (model dep)<br>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 $(\alpha,n)$ & 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: $7\times10^{-46}$ cm$^2$ in 10 months

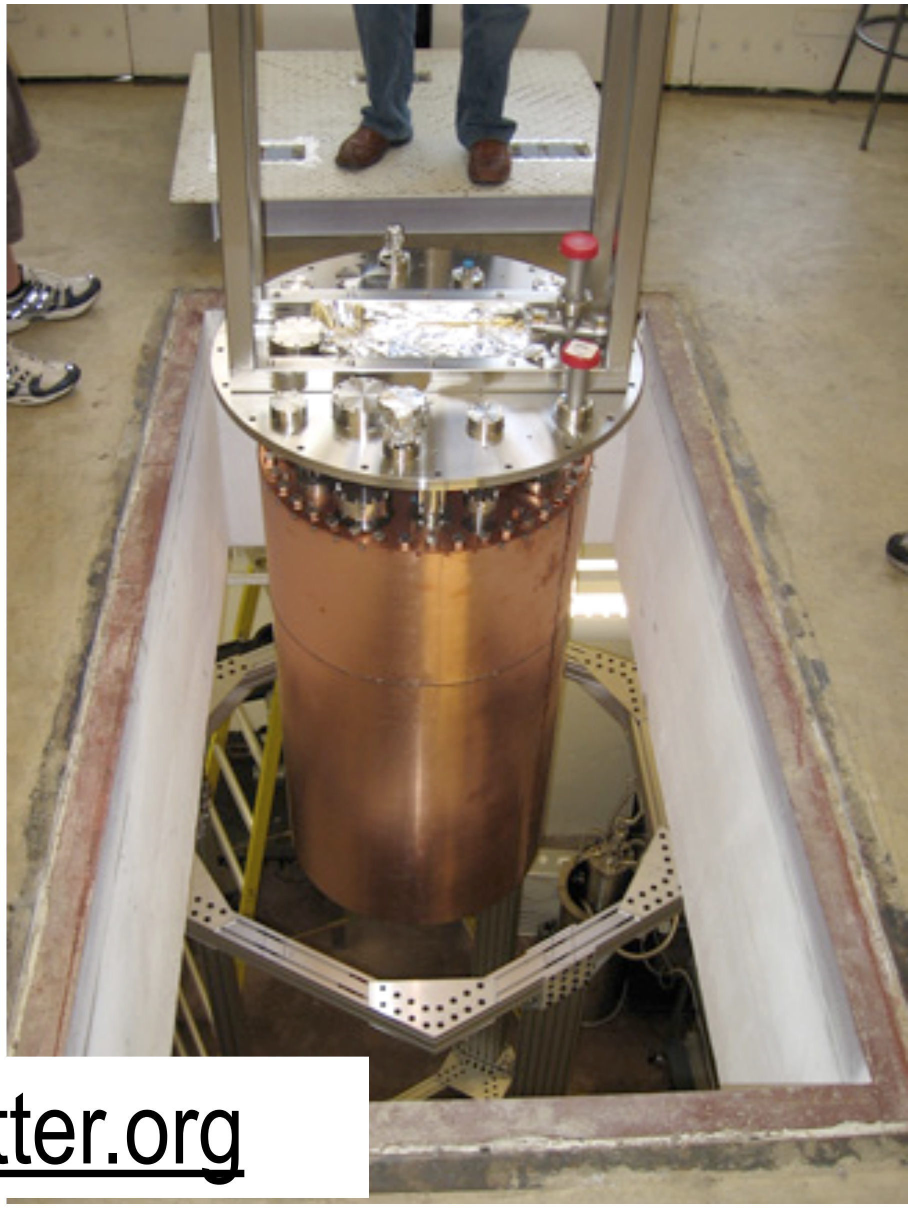
In DUSEL

(Deep Underground Science and Engineering Laboratory)

Homestake Mine

Lead, South Dakota, USA

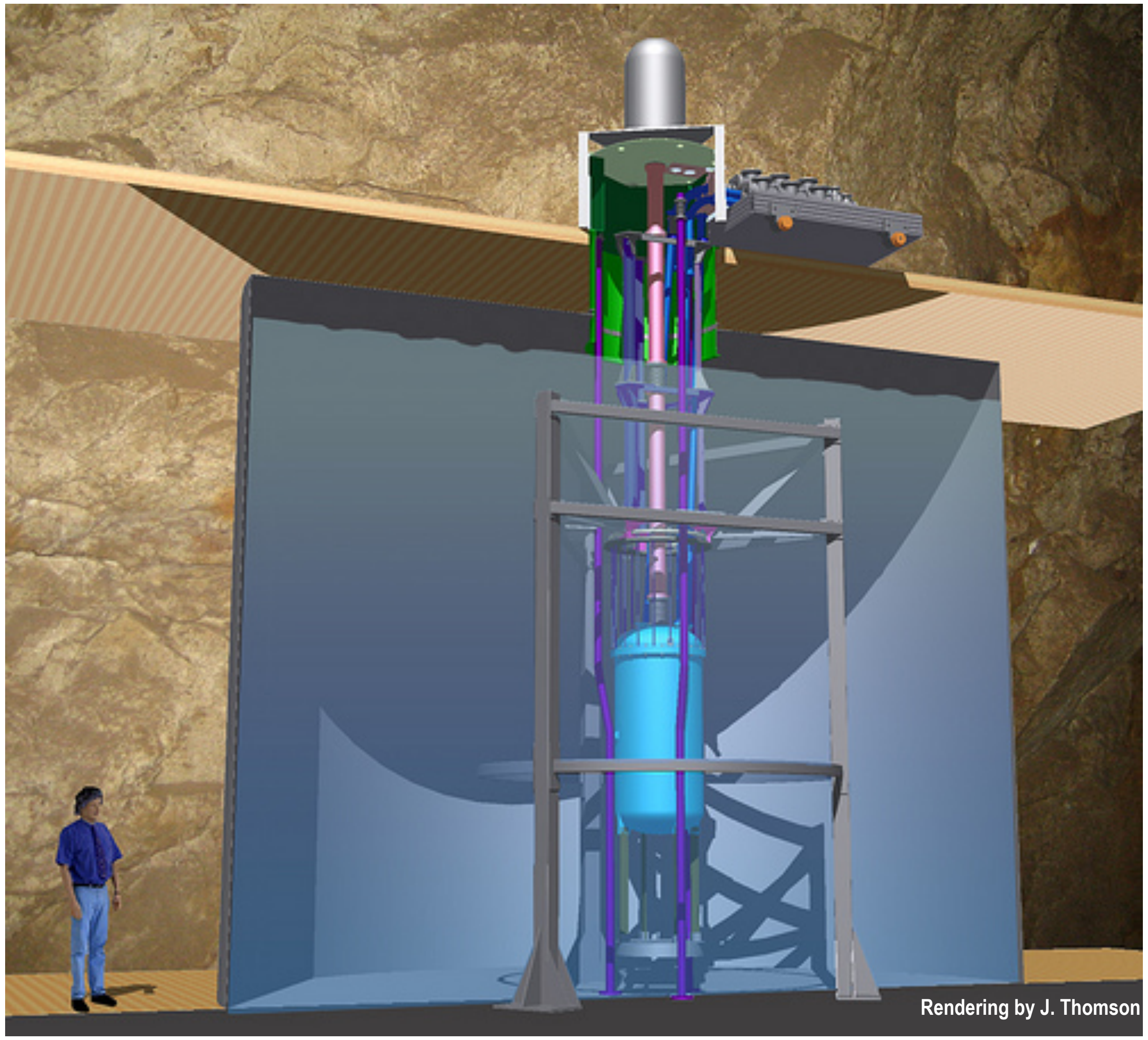
2012?



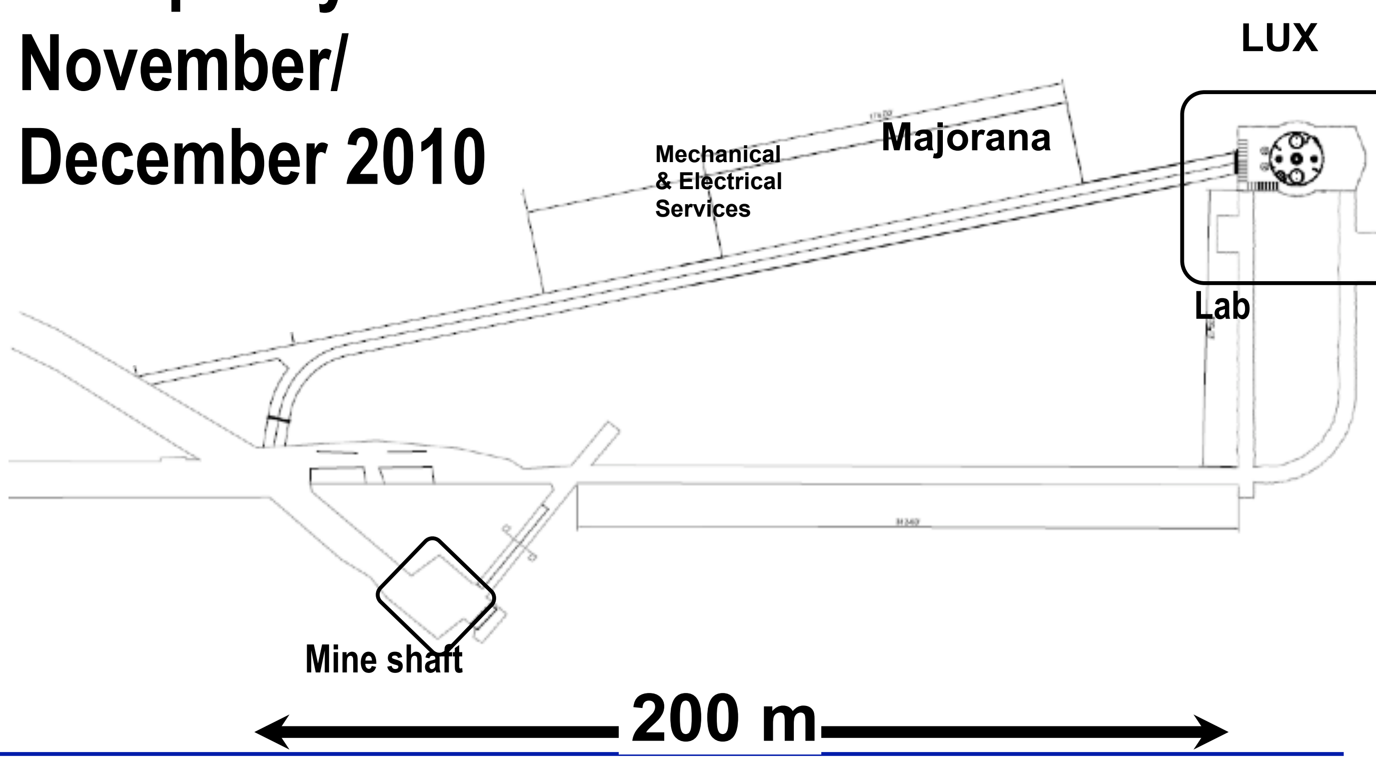
www.luxdarkmatter.org

# 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



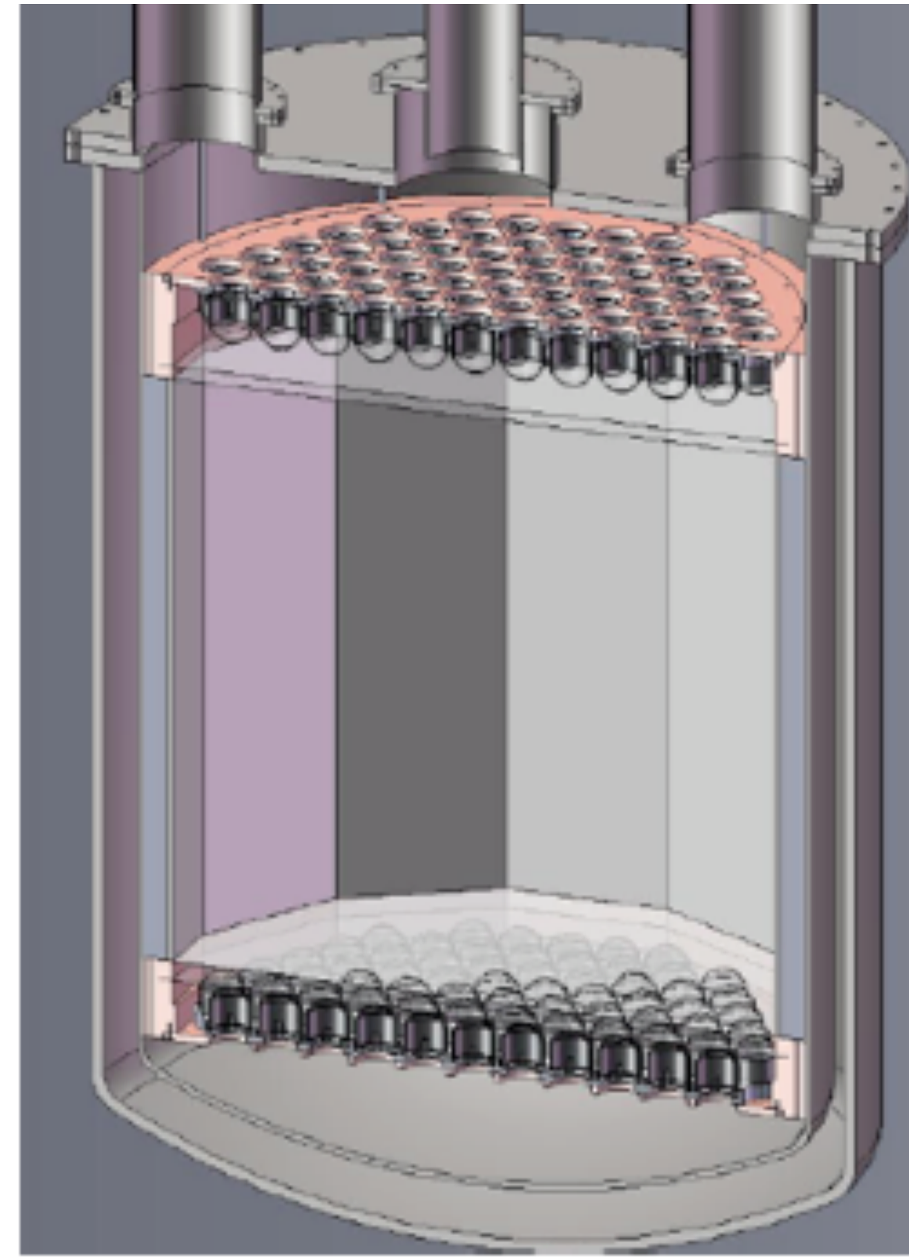

- Beneficial occupancy: November/ December 2010



WIMP Signals in a Dual-Phase Xenon Detector


www.luxdarkmatter.org

| 2005-2007 | 2008-2011 | 2011-2012 |
|---|---|---|



**XENON10** **XENON100** **XENON1T**

*Achieved (2007)* $\sigma_{SI}$=8.8 x$10^{-44}$ $cm^2$ *Projected (2010)* $\sigma_{SI}$~2x$10^{-45}$ cm *Goal:* $\sigma_{SI}$ <$10^{-46}$ $cm^2$

*Phys. Rev. Lett.* **100**, 021303 (2008)
*Phys. Rev. Lett.* **101**, 091301 (2008

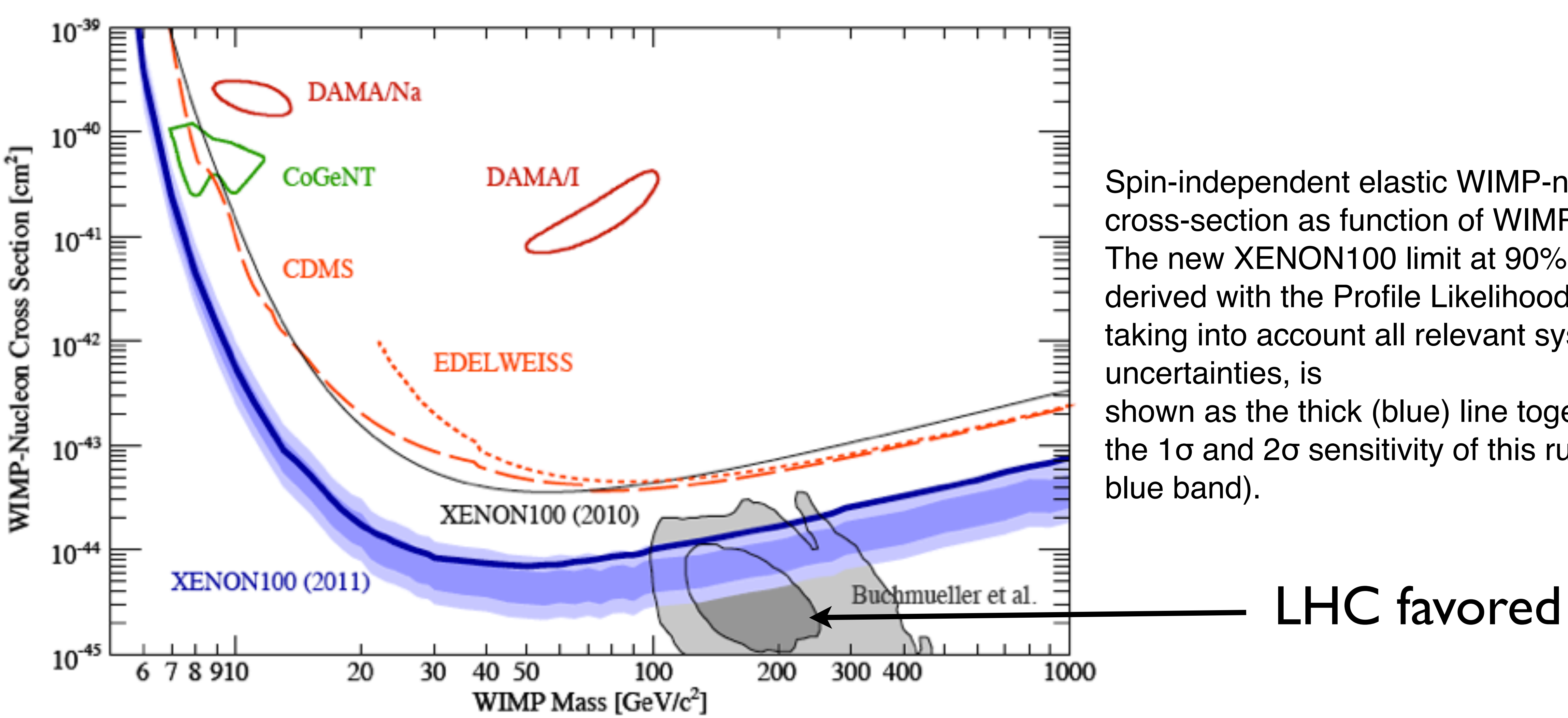
XENON100 is a collaboration of Columbia and Rice universities, University of Zurich, University of Coimbra and Gran Sasso National Laboratory. UCLA joined the XENON100 effort in April 2008.

arXiv:1104.2549v1

# 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 $(1.8 \pm 0.6)$ events. This leads to the most stringent limit on dark matter interactions today, excluding spin-independent elastic WIMP-nucleon scattering cross-sections above $7.0 \times 10^{-45}$ 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).

## Implications on Inelastic Dark Matter from 100 Live Days of XENON100 Data

E. Aprile et al. 4/15/11

The XENON100 experiment has recently completed a dark matter run with 100.9 live-days of data, taken from January to June 2010. Events in a 48kg fiducial volume in the energy range between 8.4 and 44.6 $keV_{nr}$ have been analyzed. A total of three events have been found in the predefined signal region, compatible with the background prediction of $(1.8 \pm 0.6)$ events. Based on this analysis we present limits on the WIMP-nucleon cross section for inelastic dark matter. With the present data we are able to rule out the explanation for the observed DAMA/LIBRA modulation as being due to inelastic dark matter scattering off iodine at a 90% confidence level.

## A search for light dark matter in XENON10 data

E. Aprile et al. 4/15/11

We report results of a search for light ($\lesssim$ 10 GeV) particle dark matter with the XENON10 detector. The event trigger was sensitive to a single electron, with the analysis threshold of 5 electrons corresponding to 1.4 keV nuclear recoil energy. Considering spin-independent dark matter-nucleon scattering, we exclude cross sections $\sigma_n > 3.5 \times 10^{-42}$ cm$^2$, for a dark matter particle mass $m_\chi = 8$ GeV. We find that our data strongly constrain recent elastic dark matter interpretations of excess low-energy events observed by CoGeNT and CRESST-II, as well as the DAMA annual modulation signal.

# Dark Matter and Terascale Physics

V. Barger

# The Gold Standard: mSUGRA

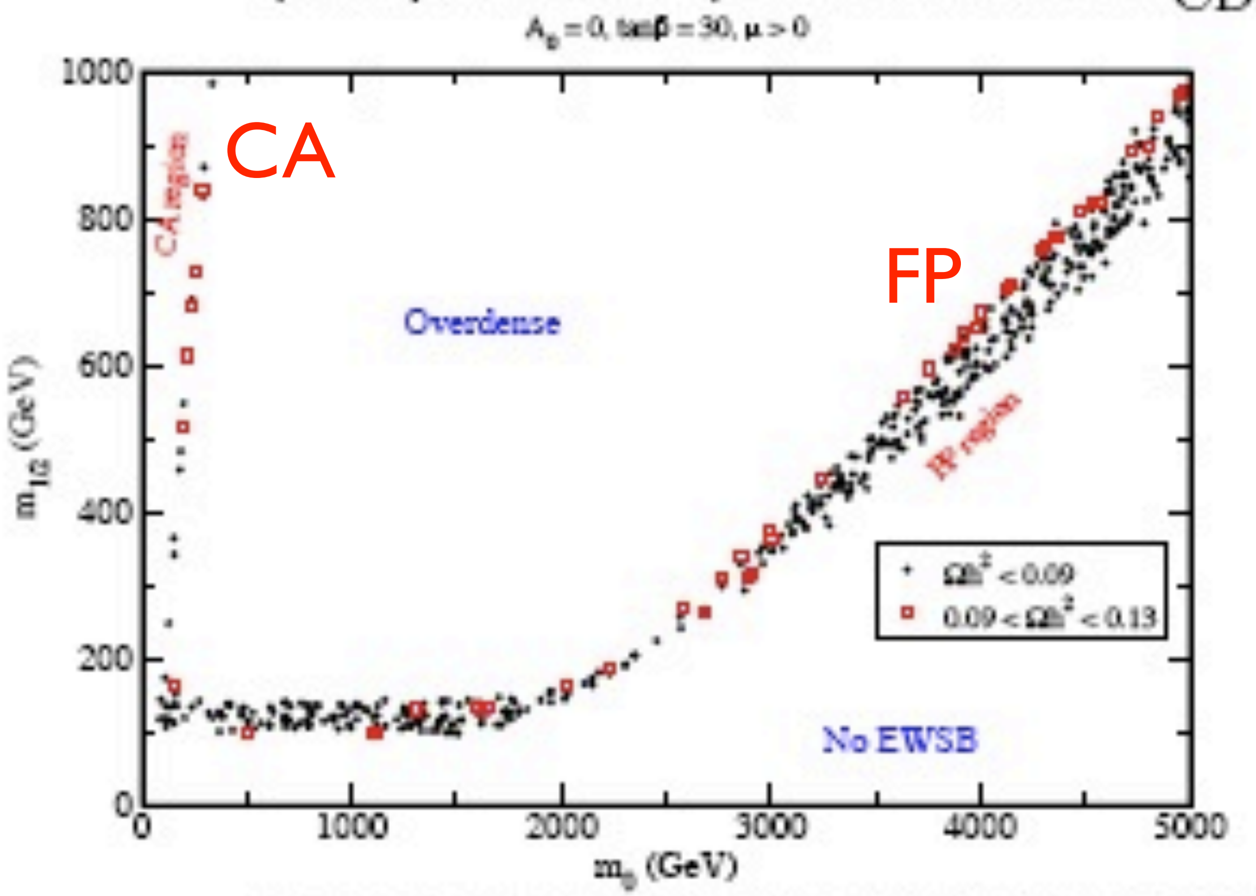
- SUSY stabilizes radiative corrections to the Higgs mass and realizes GUT unification of electroweak and strong couplings
- Weird quantum numbers of particles explained by 16 representation of SO(10)
- mSUGRA: SUSY broken by gravity
  - predictive--small number of parameters: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$
- Find well defined regions of parameter space consistent with the relic density from WMAP

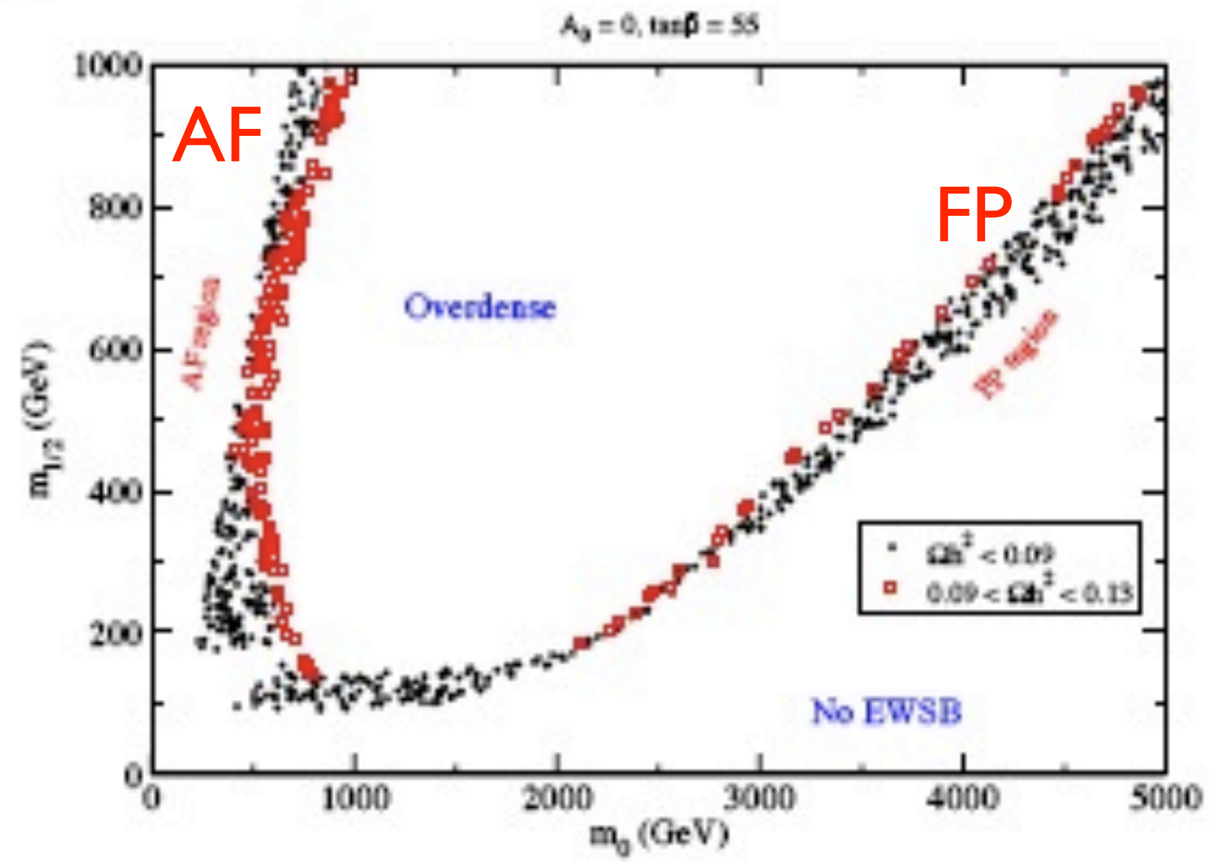
$$0.099 < \Omega_{DM} h^2 < 0.123 \ (2\sigma)$$

- 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 $\Omega_{CDM}$)

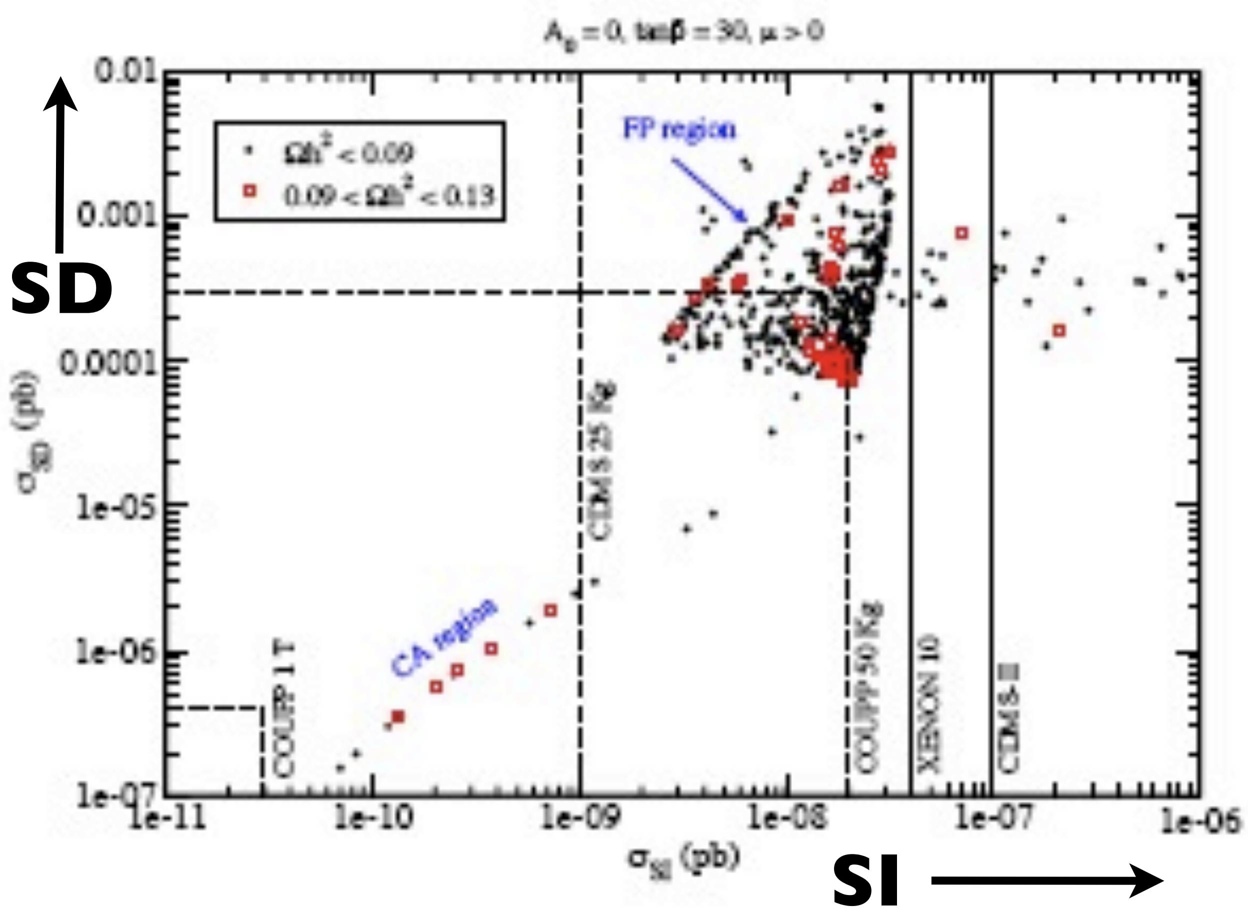


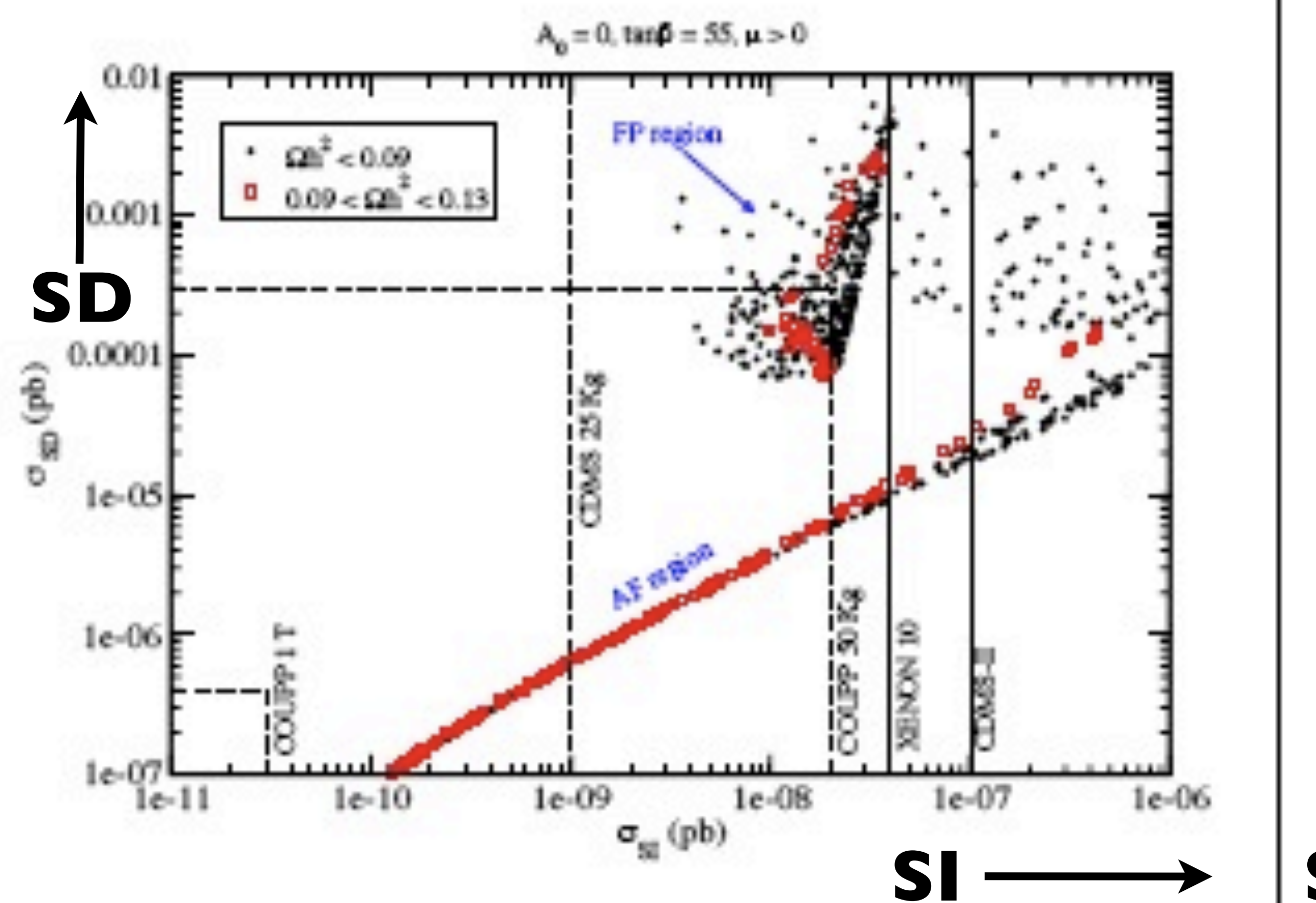




- Focus Point (FP) region: high mass scalar fermions
  - Preferred by $b - \tau$ unification
  - Solves SUSY FCNC and CP-violating problems
- A-funnel (AF) region: annihilation through CP-odd Higgs (A)
- $\tilde{\tau} - \chi_1^0$ coannihilation (CA) region
- Bulk region (BR) at low $m_0, m_{1/2}$ nearly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

# Scattering rates in mSUGRA

- Different solutions to DM relic density populate different regions of $\sigma_{SD}$ vs. $\sigma_{SI}$   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)

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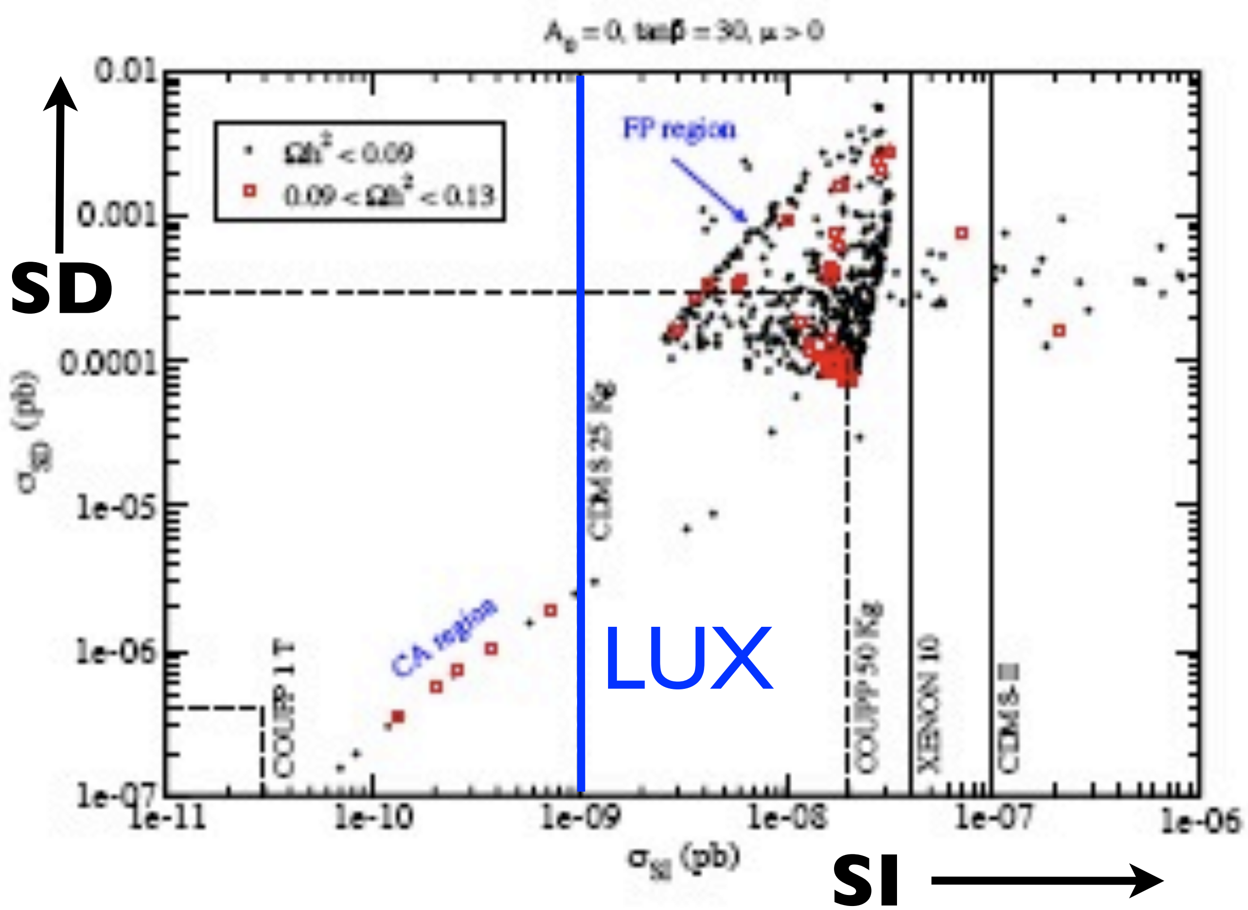
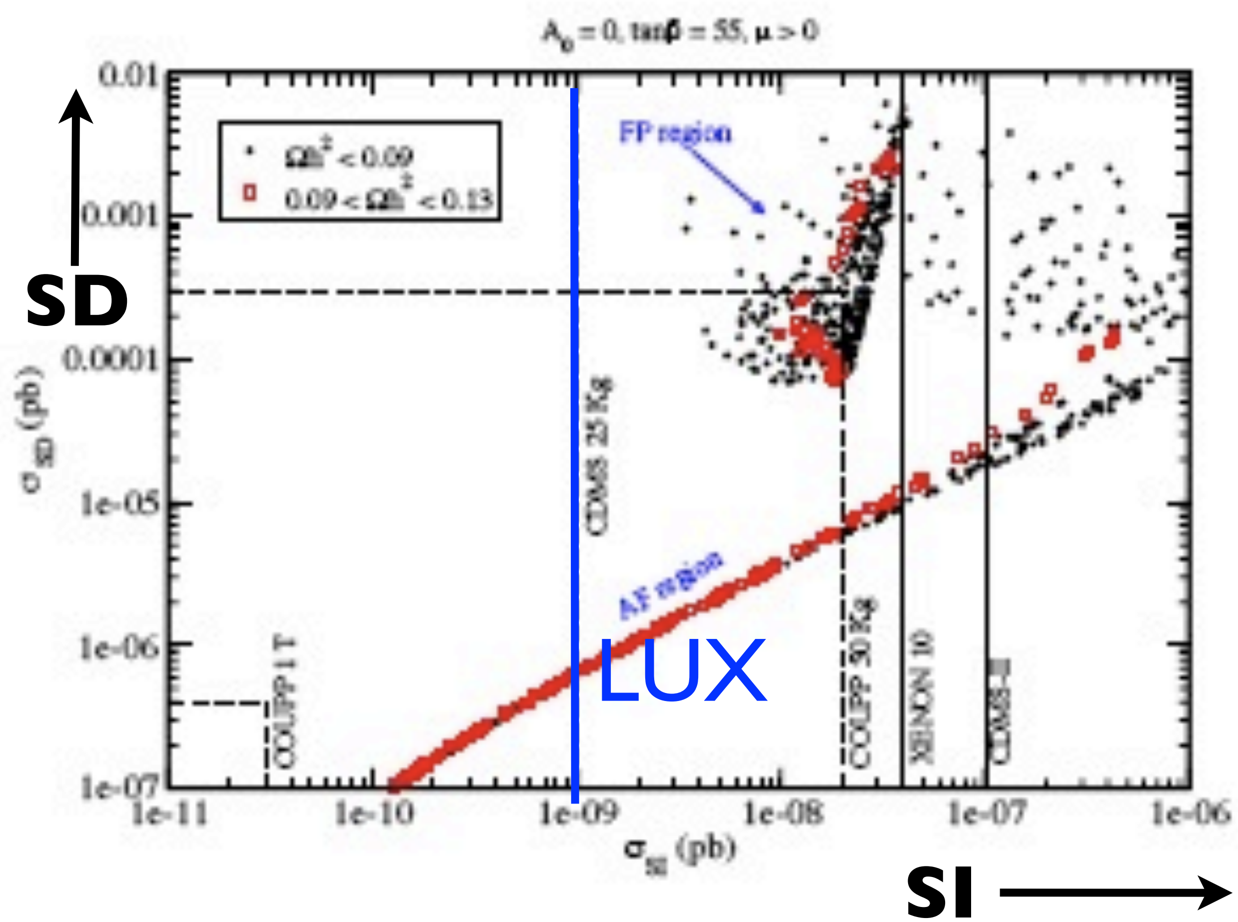
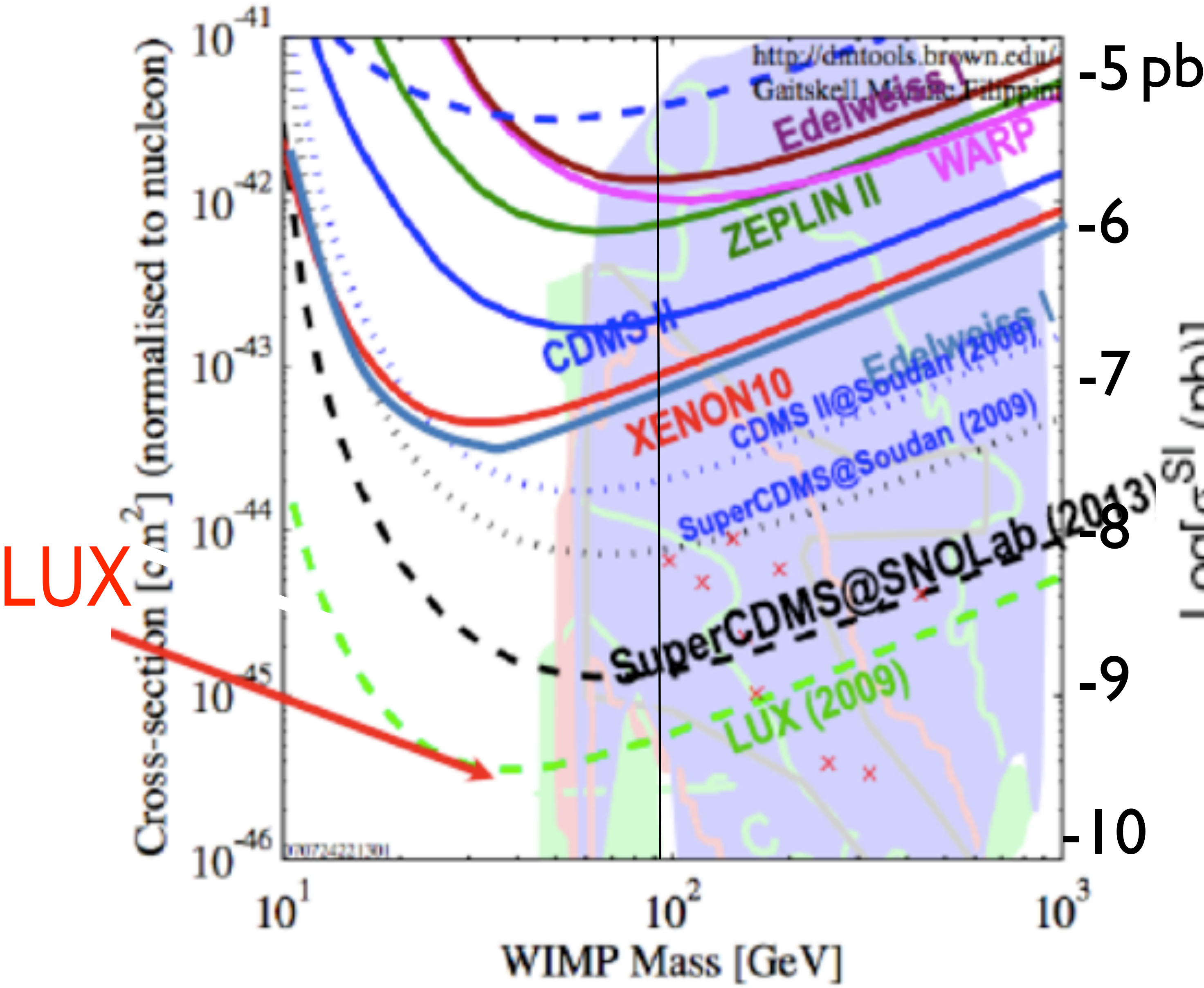
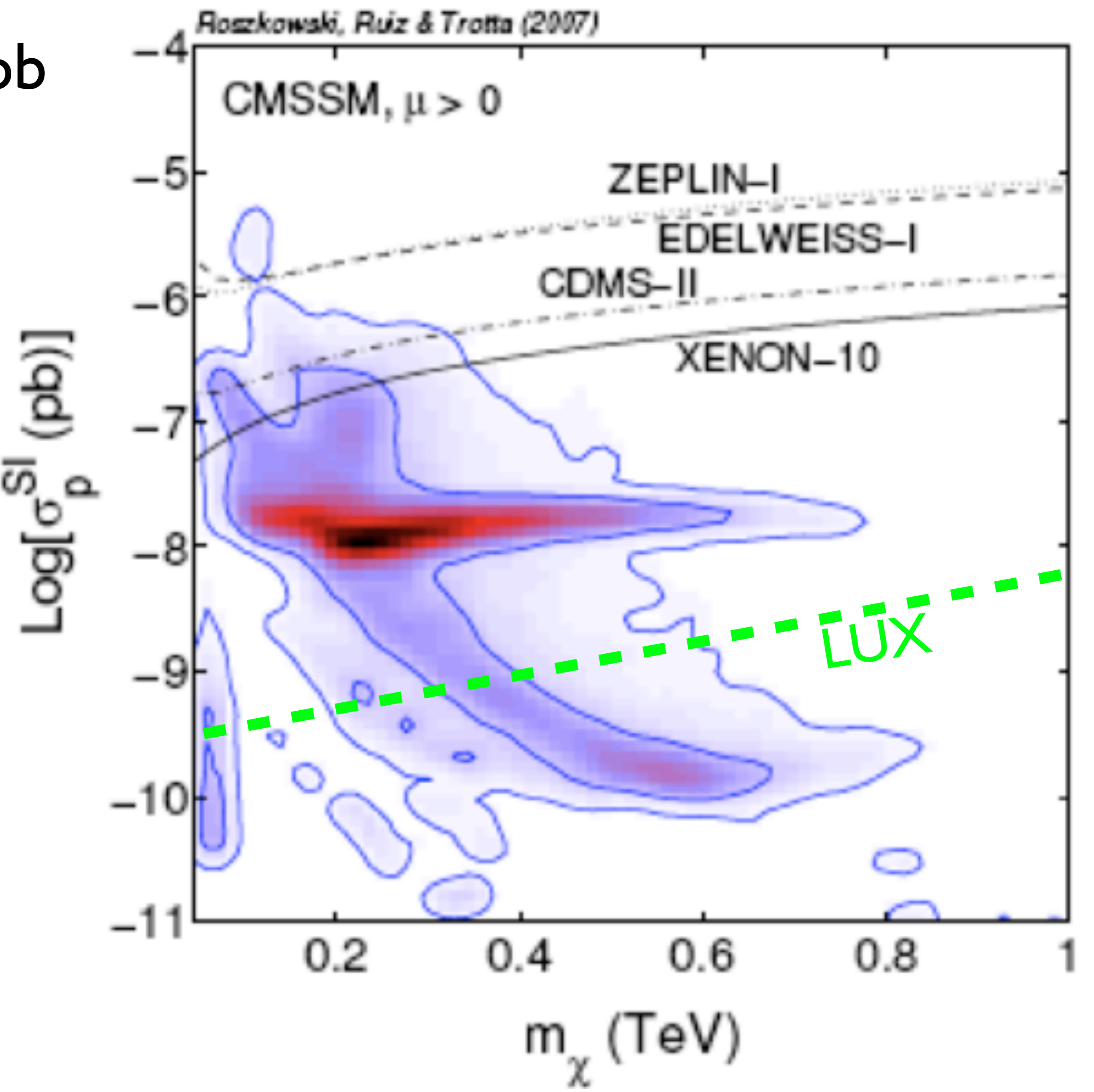



- FP region can be verified or disproved by both SD and SI measurements
- Detection in FP region would be of major significance for colliders (high mass scalars)

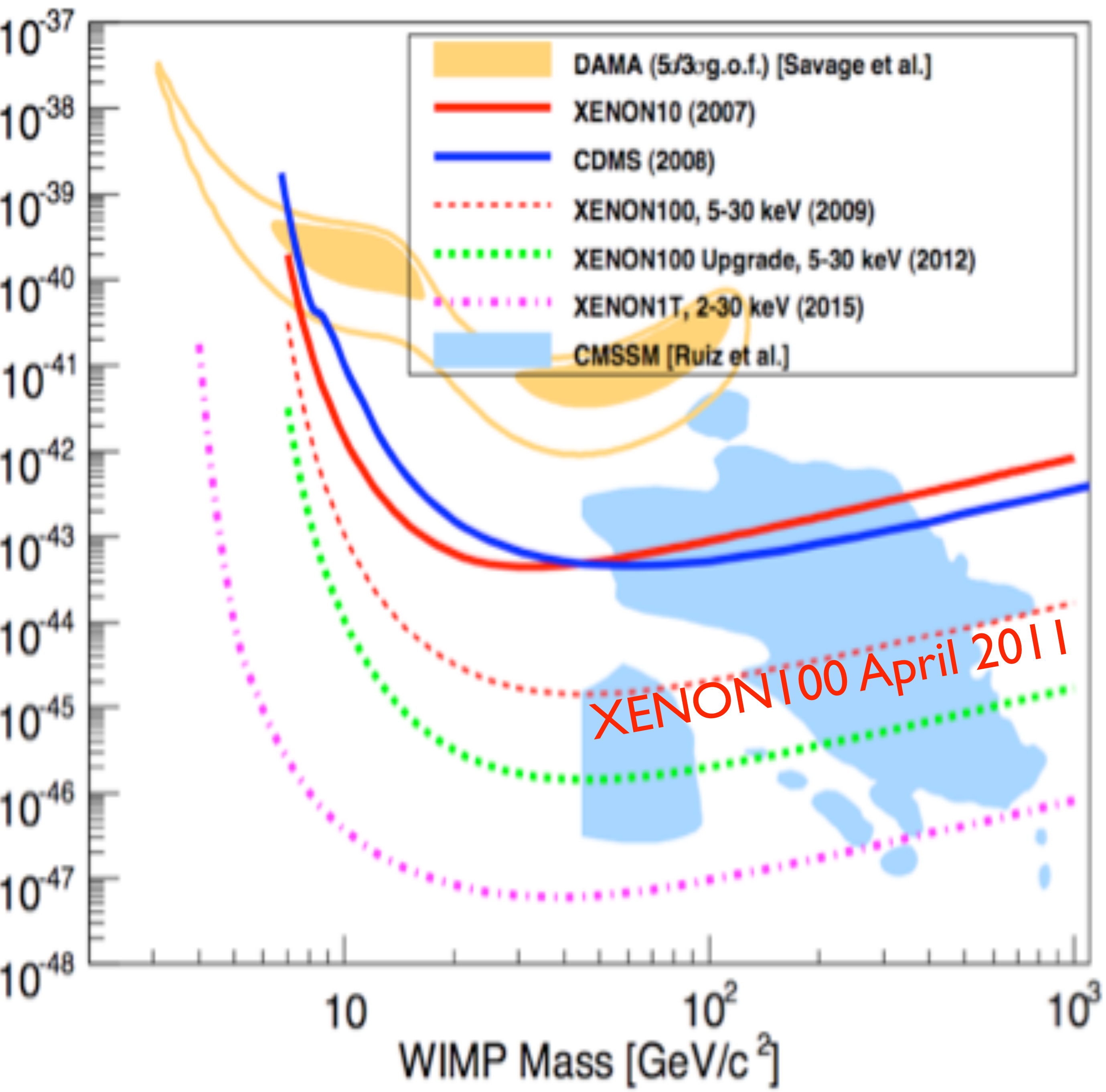
By ~2012 Direct Detection could probe most of the CMSSM (constrained minimal supersymmetric standard model) and mSUGRA (minimal supergravity) WIMP parameter space! If LUX and other large noble gas detectors succeed, they will leapfrog over CDMS and have great discovery potential during 2010-11.

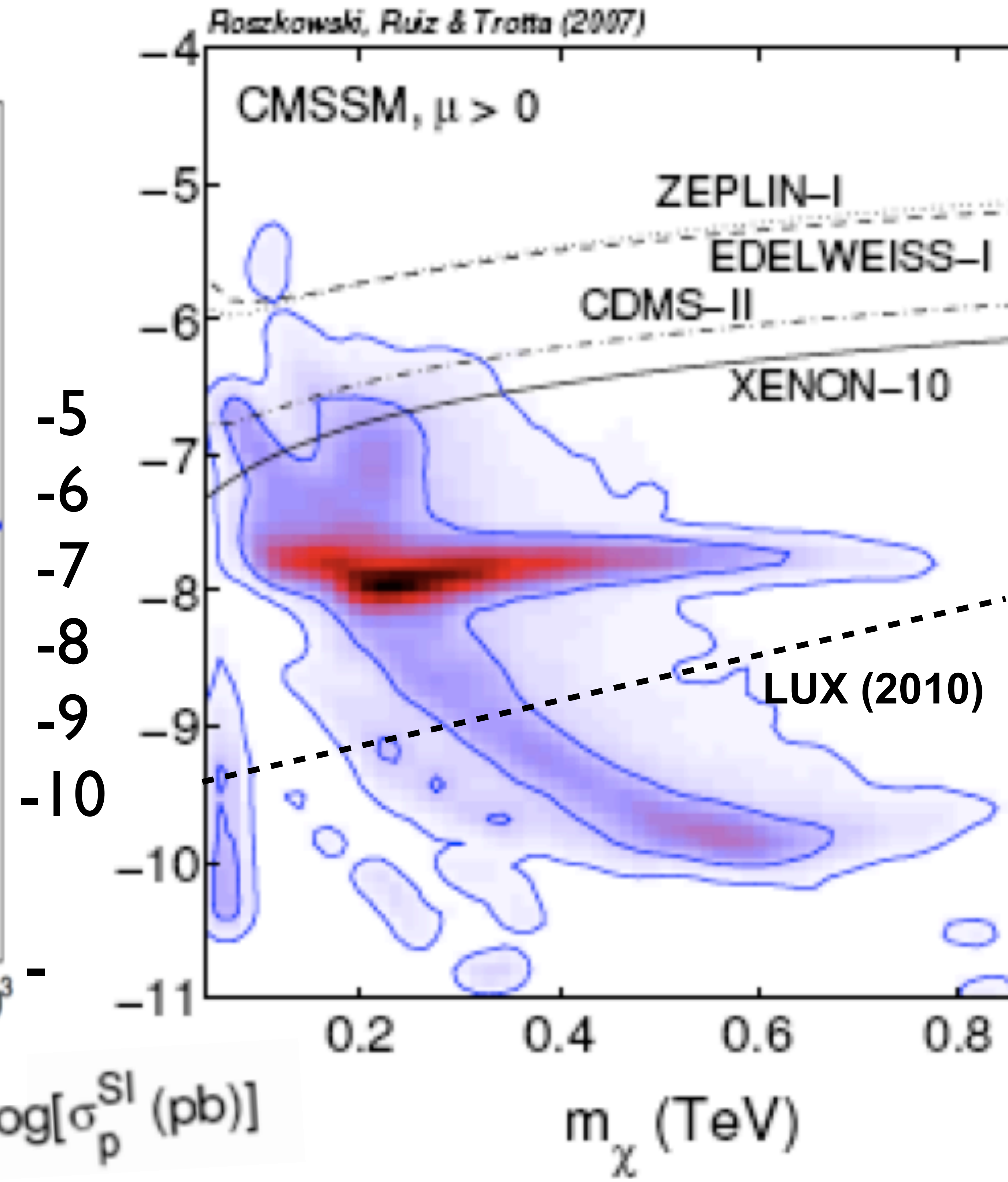



$10^{-8}$ pb = $10^{-44}$ cm$^2$ (barn=$10^{-24}$ cm$^2$, pb = $10^{-12}$ b = $10^{-36}$ cm$^2$)

# By ~2012 Direct Detection could probe most of the CMSSM (constrained minimal supersymmetric standard model) and mSUGRA (minimal supergravity) WIMP parameter space!



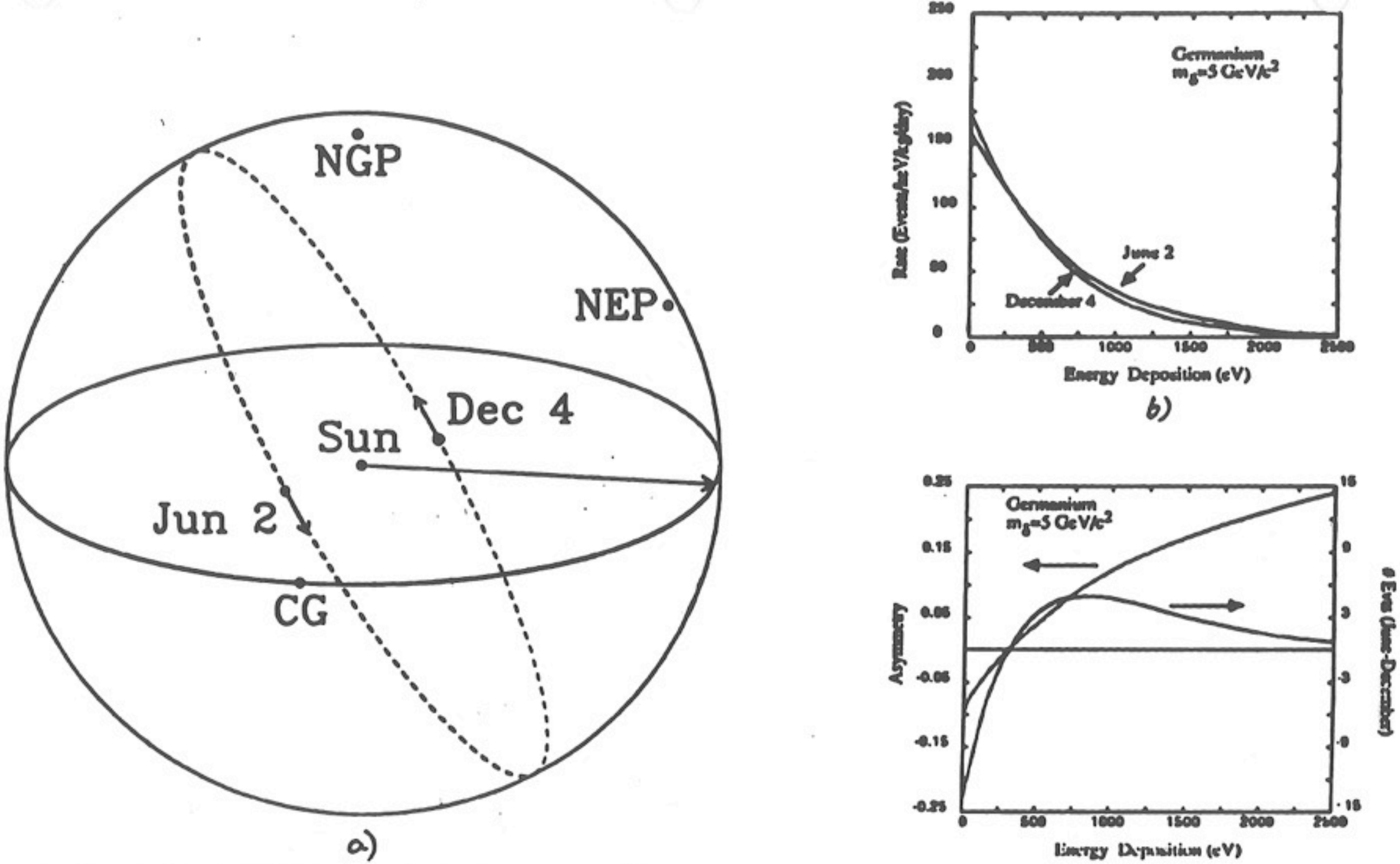
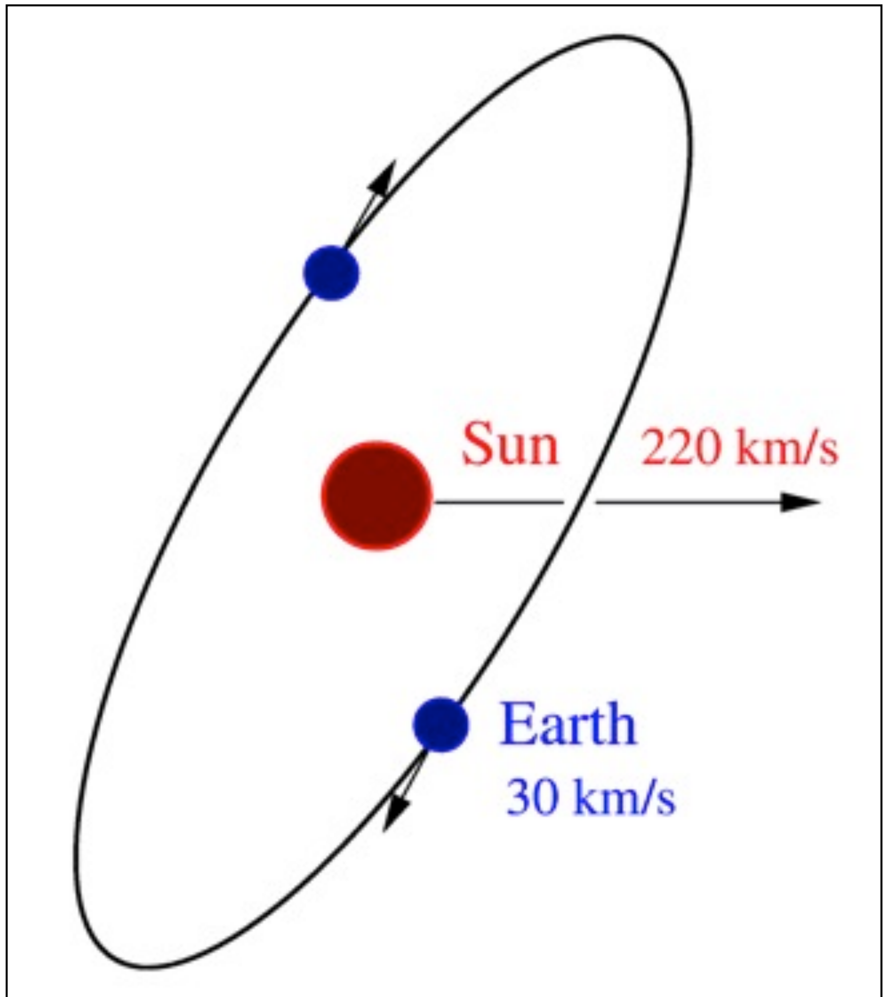



Figure 3. Annual effect in WIMP detection by elastic scattering. (a) Why expected: The solid line (darker in the front) shows the plane of the galactic disk and the Sun's orbit; the dashed circle is the orbit of the Earth (ecliptic plane). NGP and NEP are the north galactic and ecliptic poles. CG shows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

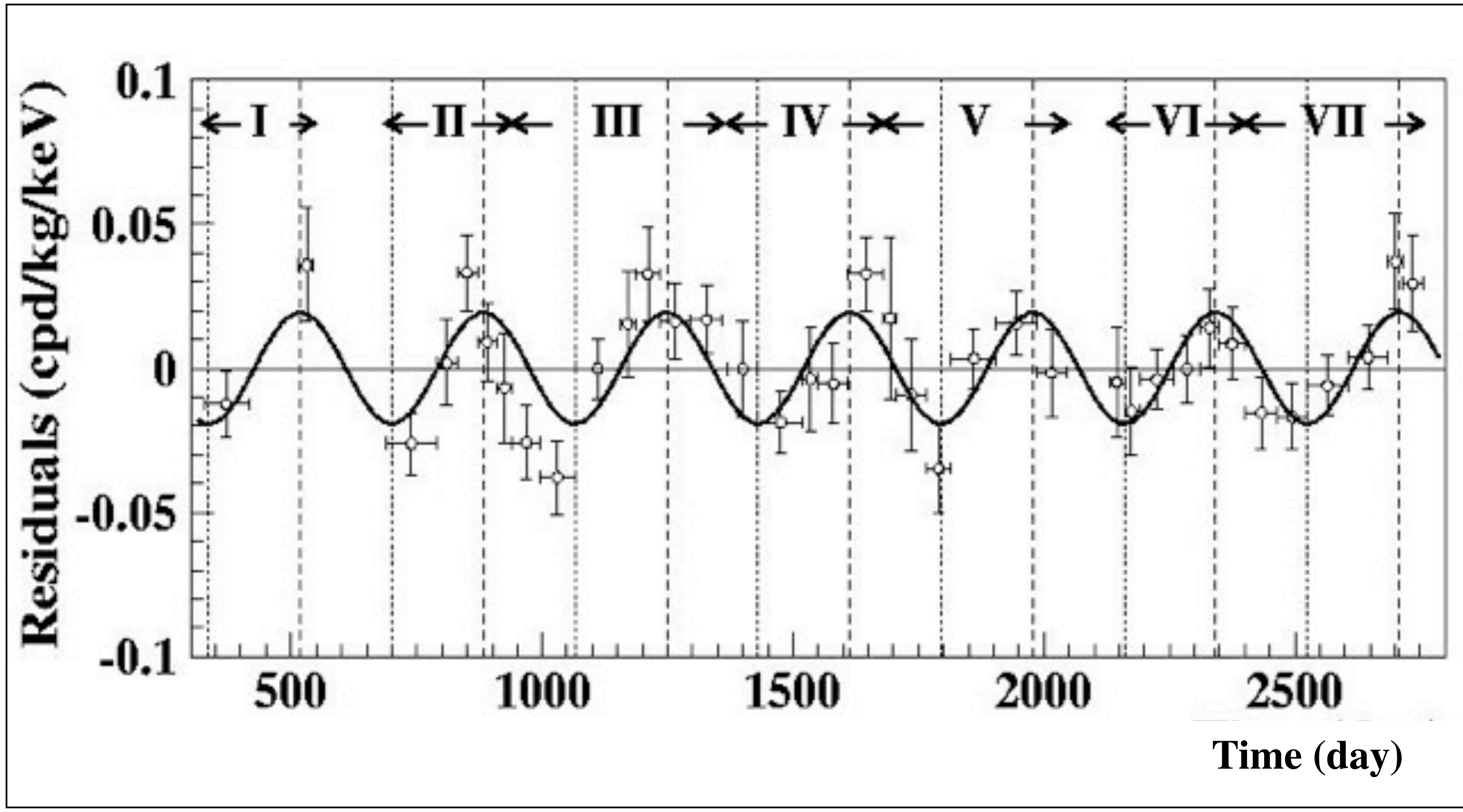
Primack, Seckel, & Sadoulet, Ann Rev Nucl Part Sci 1988

# DAMA Evidence for WIMP detection




Annual modulation of WIMP signal a "smoking gun" signature

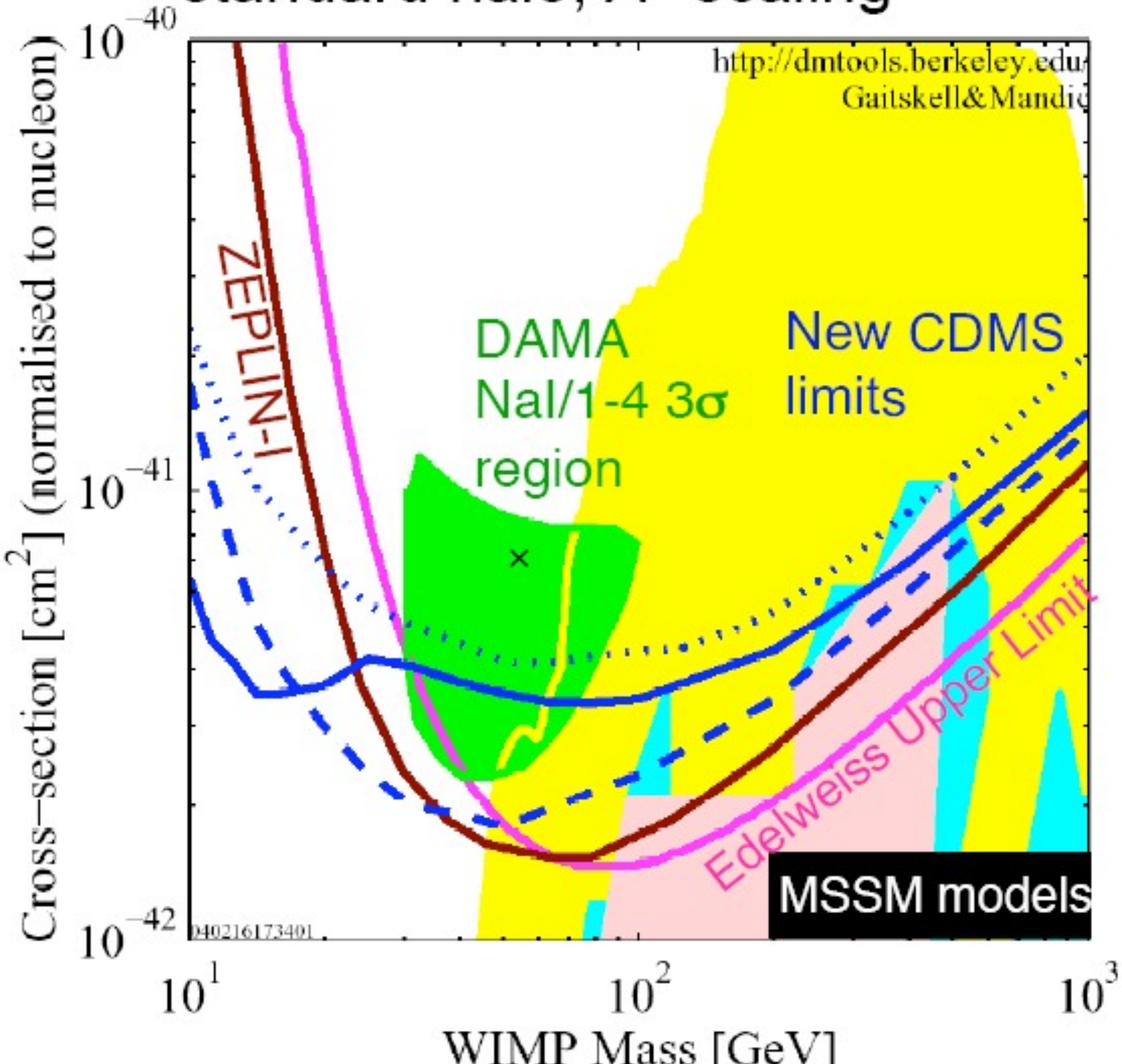
DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]




- Detector stability ?
- Background stability ?

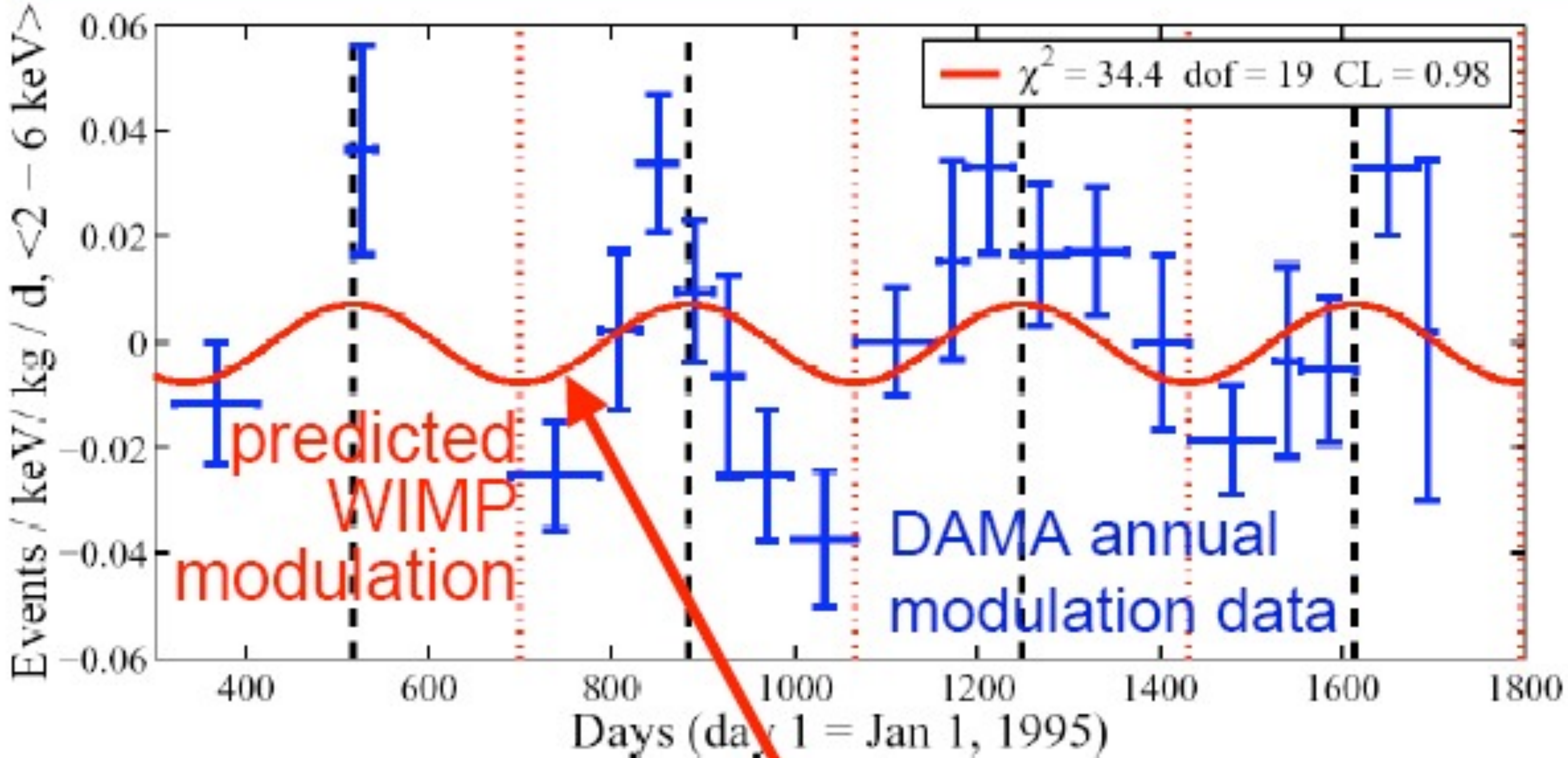
# CDMS Resulting Experimental Upper Limits

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

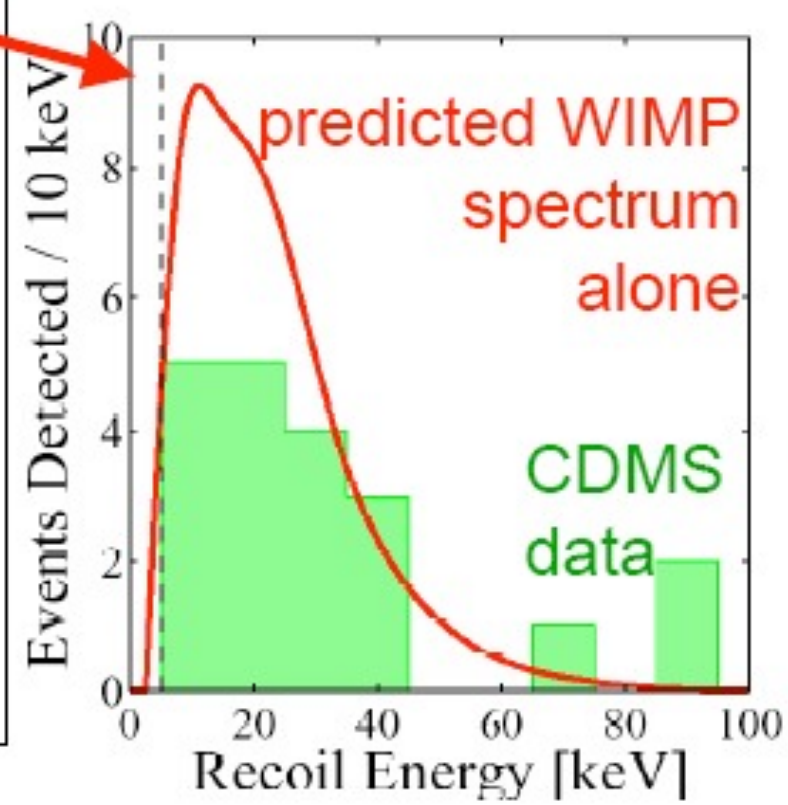



- Calculate allowed region using extension of "Feldman Cousins" method
    - Constrain neutron background based on neutron multiples, Si
- Limits slightly worse than expected sensitivity (dashes), slightly better than limits wo/ subtraction (dots)
- Exclude new parameter space for WIMP masses below 20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

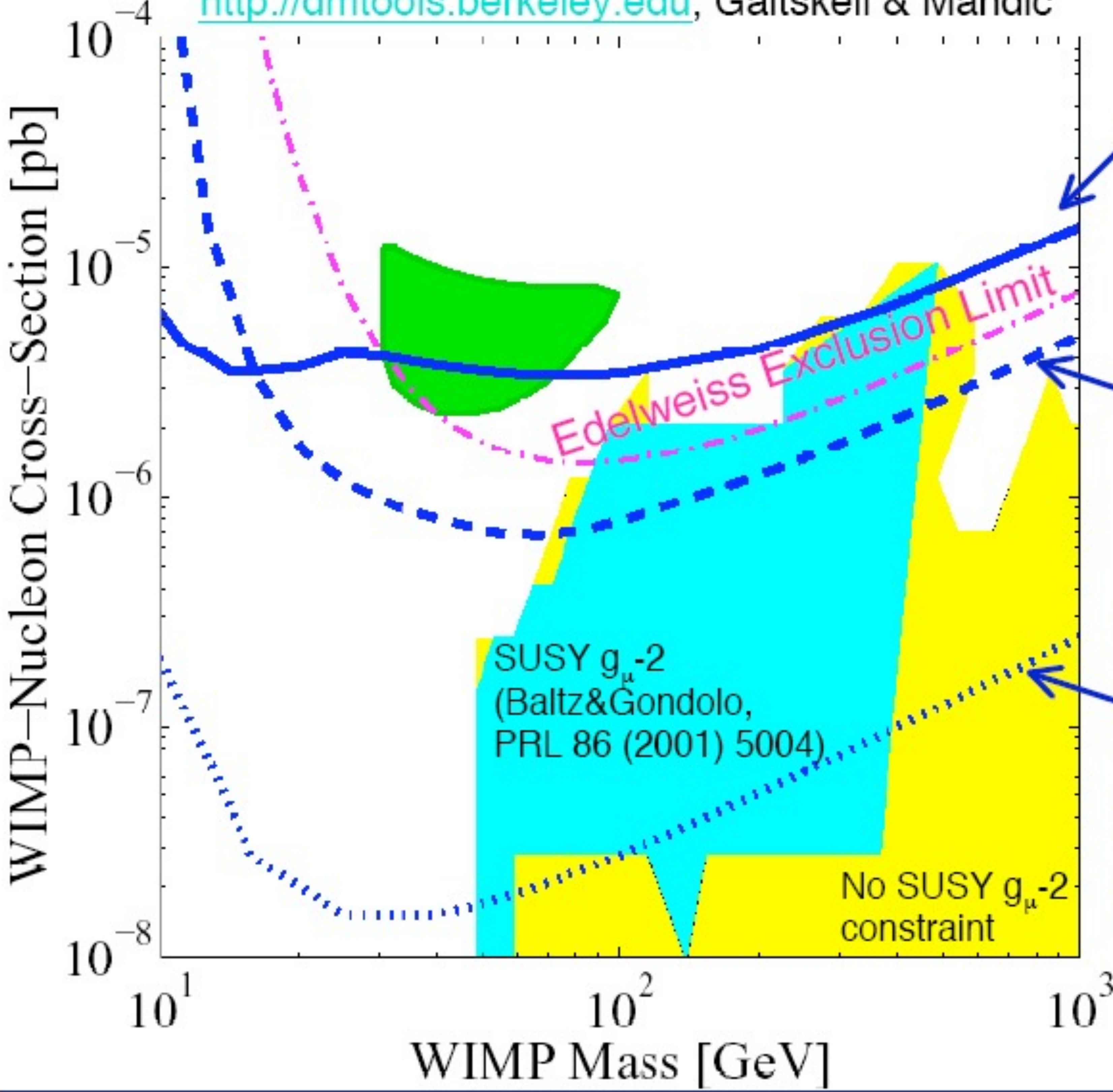



- Test under assumptions of
  - "standard" halo
  - standard WIMP interactions
- CDMS results incompatible with DAMA model-independent annual-modulation data (left) at > 99.8% CL even if all low-energy events are WIMPs

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).

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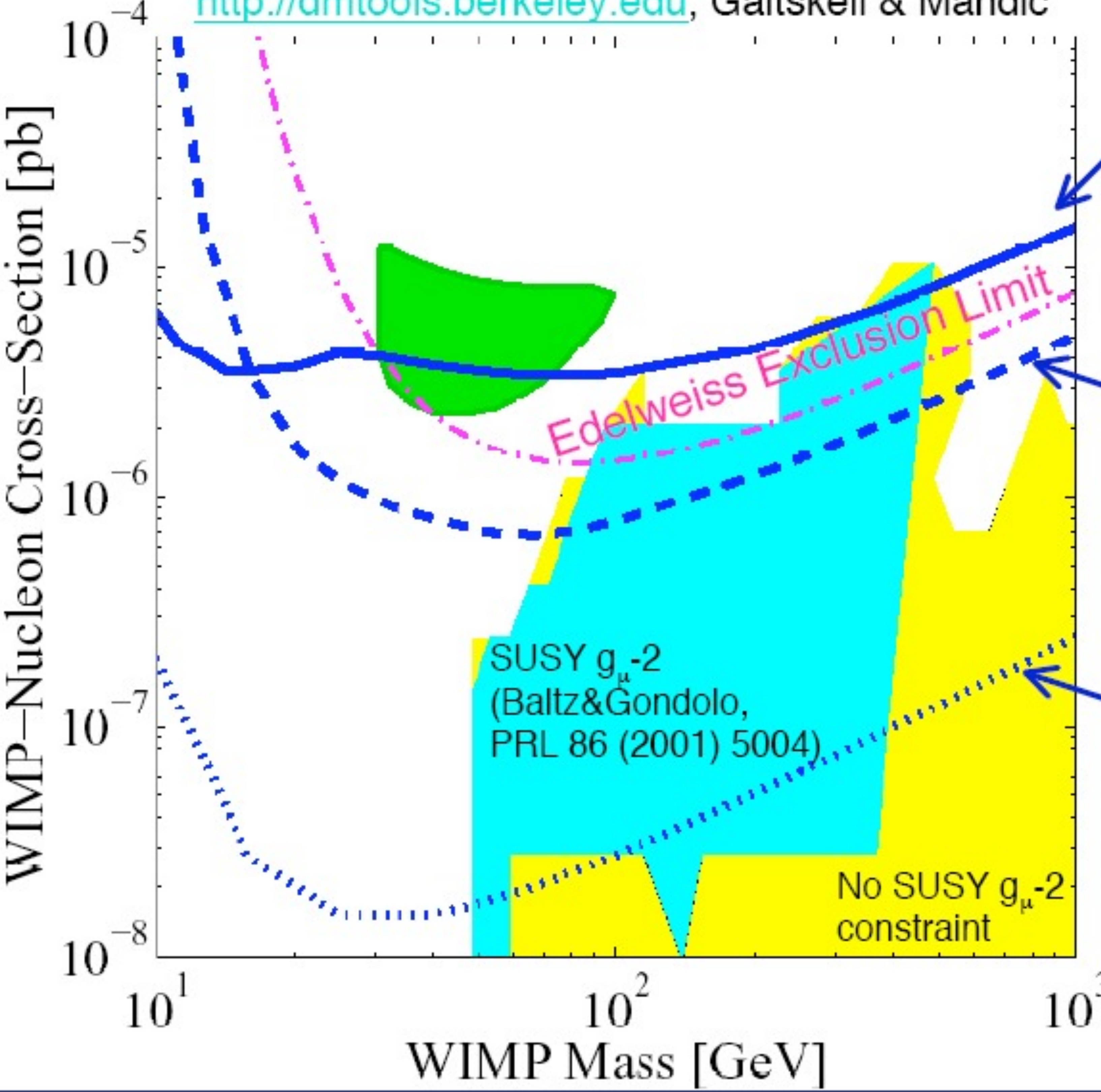



Current CDMS Limit 2003

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!

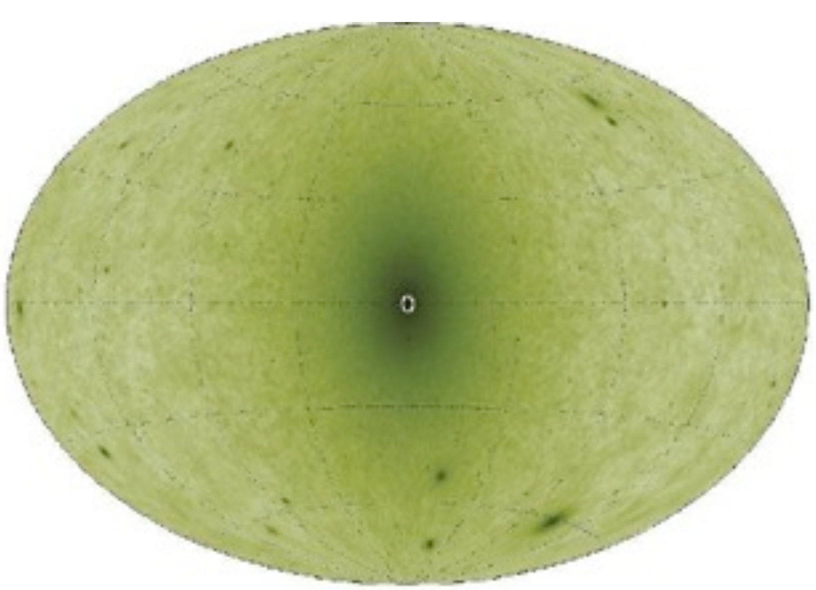
# THE DARK MATTER ANNIHILATION SIGNAL FROM GALACTIC SUBSTRUCTURE: PREDICTIONS FOR GLAST

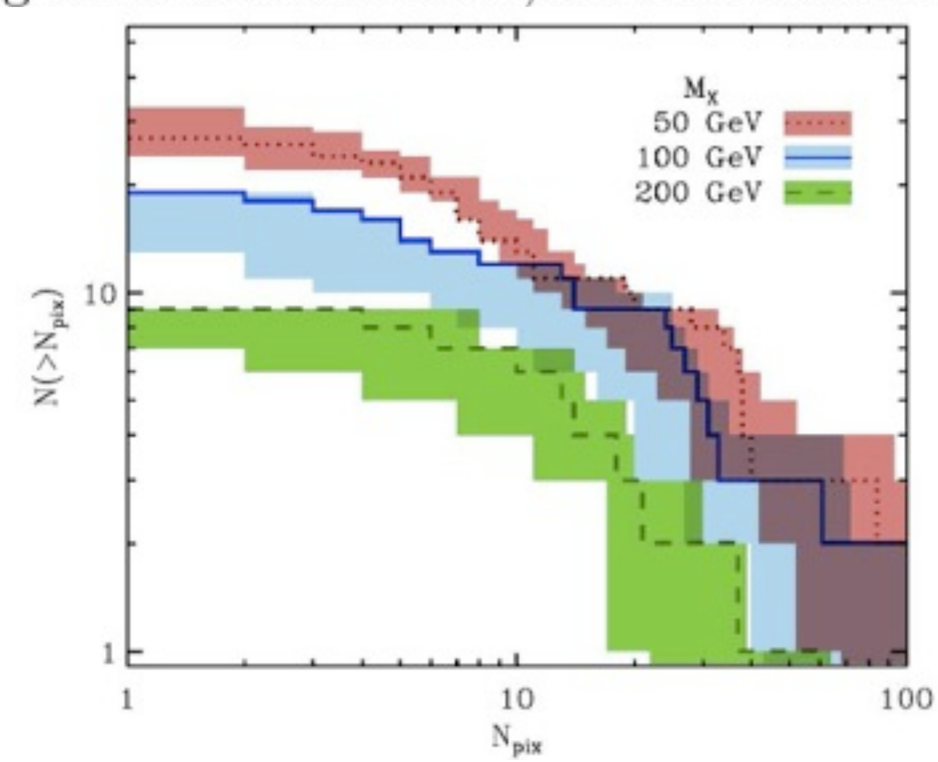
2008 ApJ 686, 262

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 $\sigma$ significance, and some at more than 20 $\sigma$. 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.



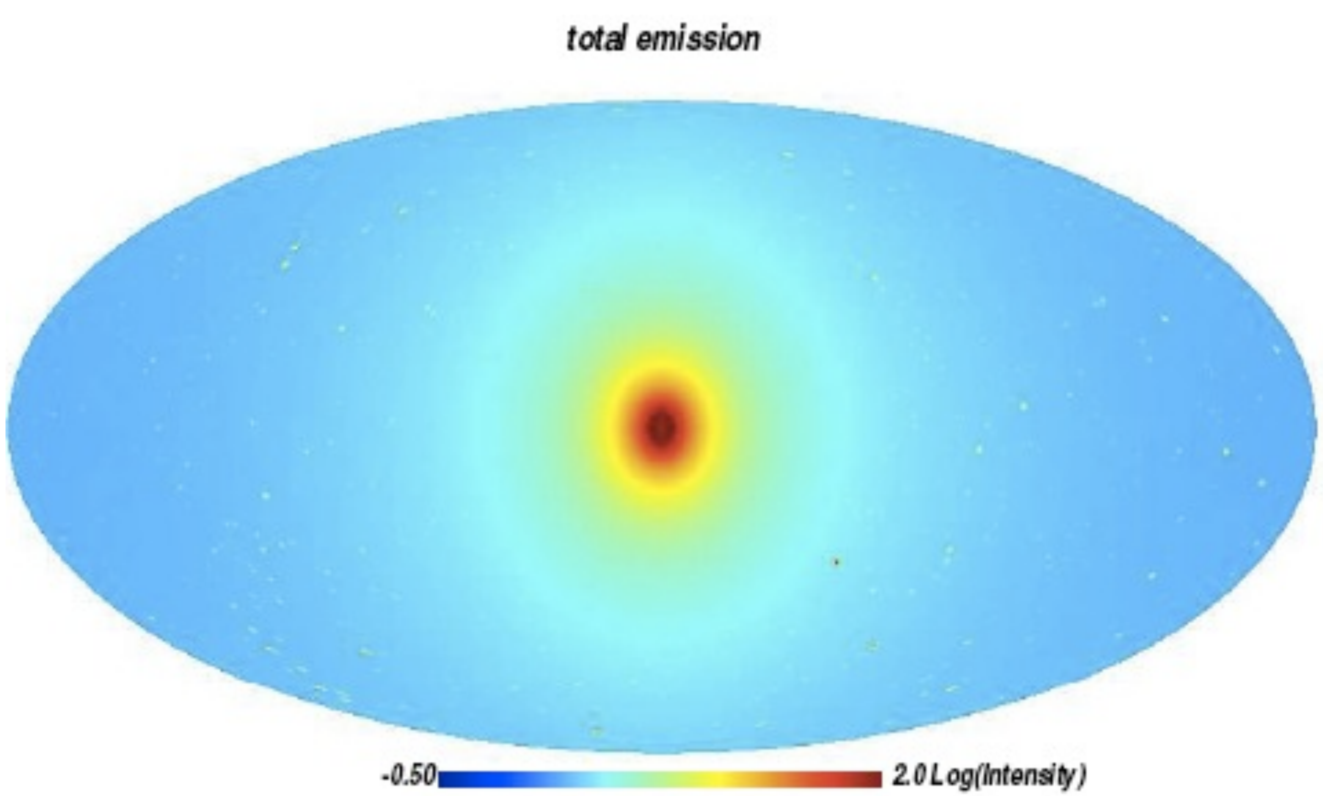


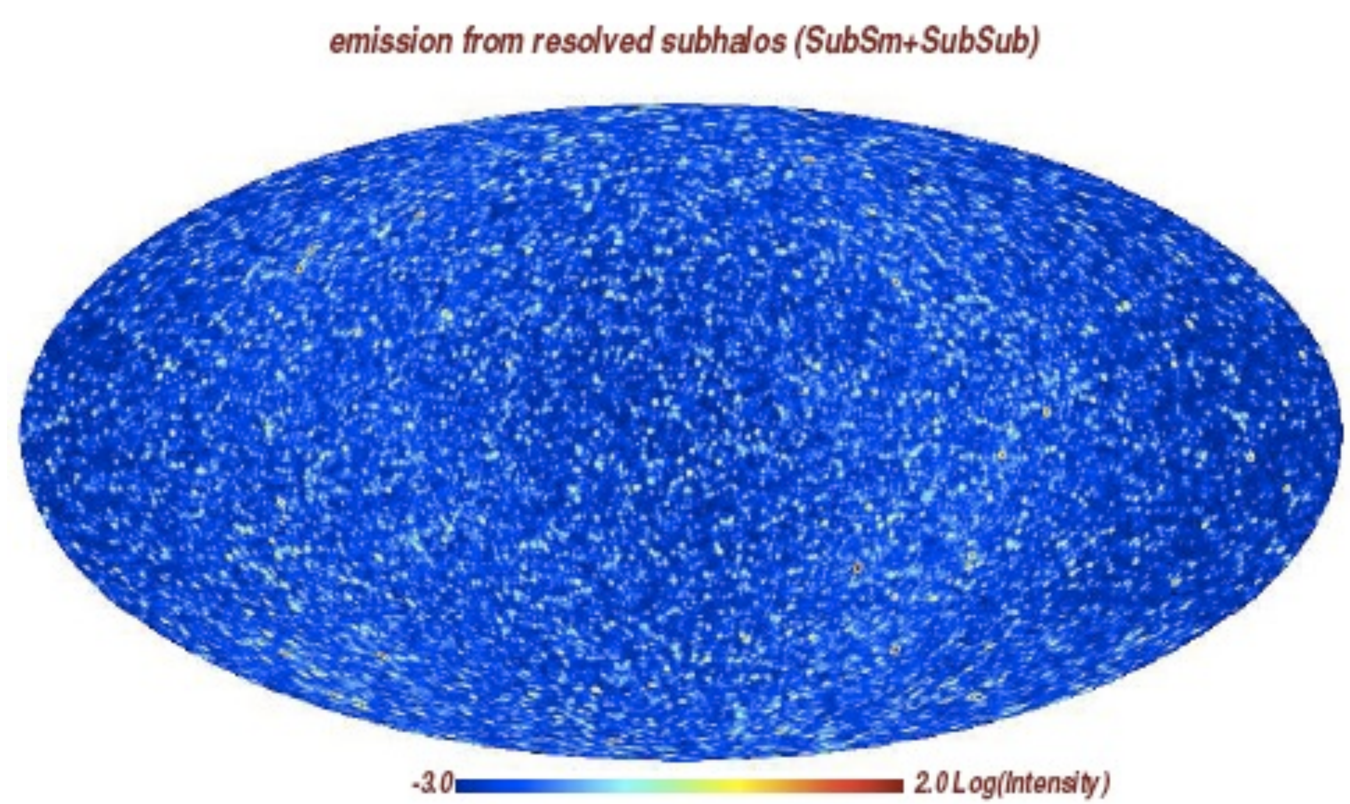

The number of detectable (S = 5) subhalos with more than $N_{pix}$ detectable pixels versus $N_{pix}$, for three different choices of M(for <σv> = $3\times10^{-26}$ cm$^3$ s$^{-1}$). The shaded regions show the range of N(>Npix) for ten randomly chosen observer locations and the solid lines refer to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

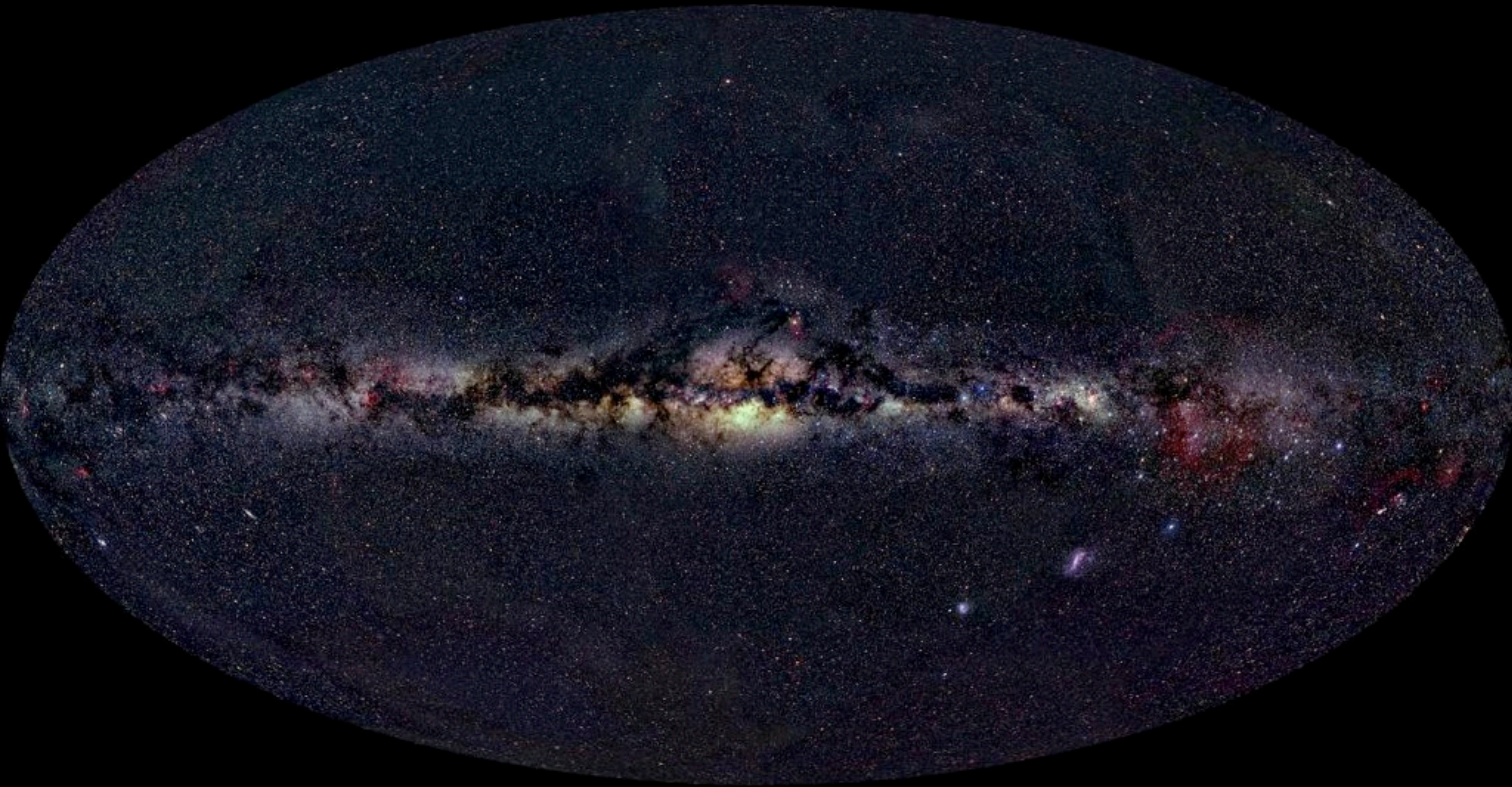
Dark matter is the dominant form of matter in the universe, but its nature is unknown. It is plausibly an elementary particle, perhaps the lightest supersymmetric partner of known particle species[1]. In this case, annihilation of dark matter in the halo of the Milky Way should produce g -rays at a level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




DARK MATTER ANNIHILATION AT THE GALACTIC CENTER?

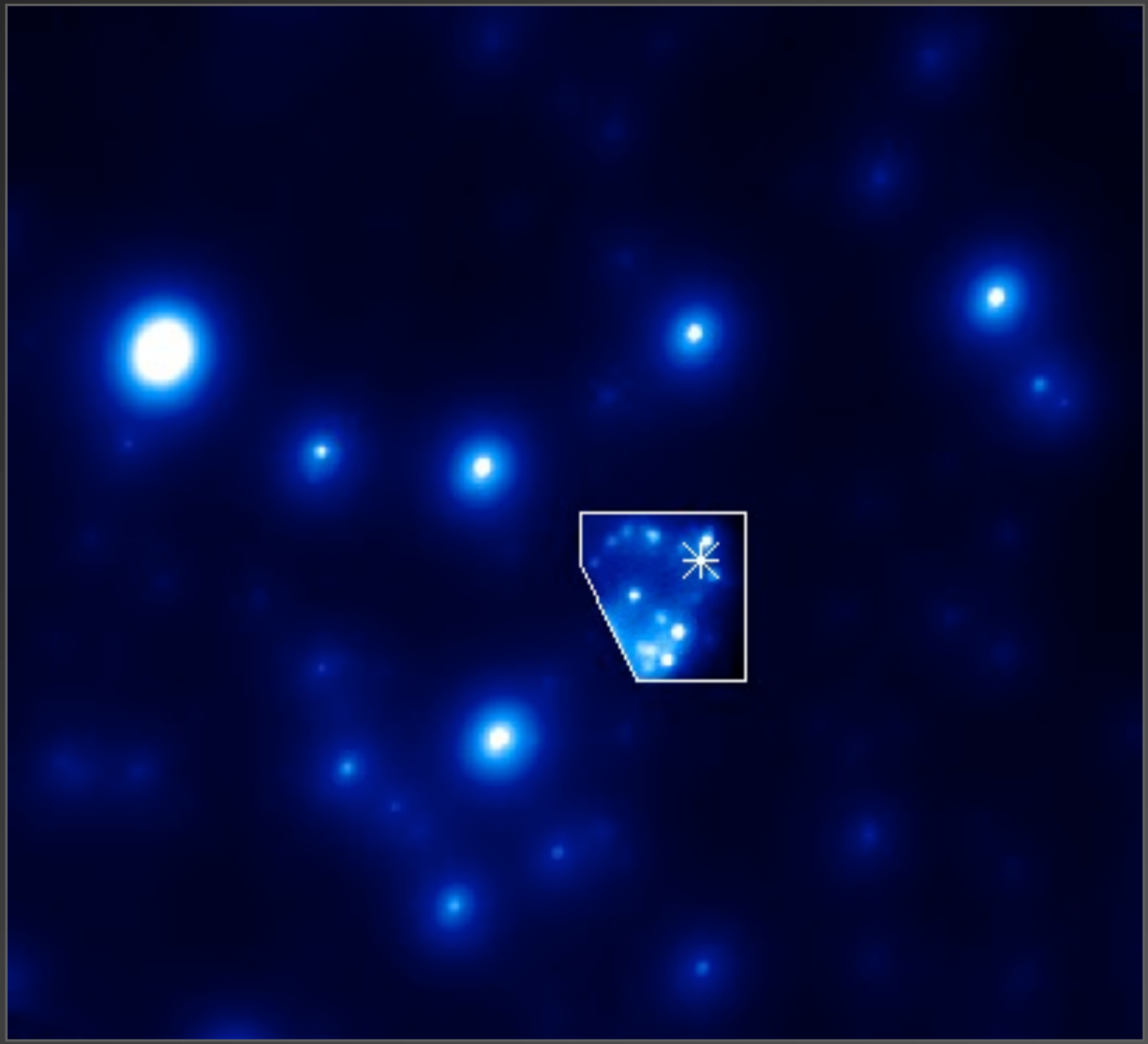
# The Milky Way in the Sky



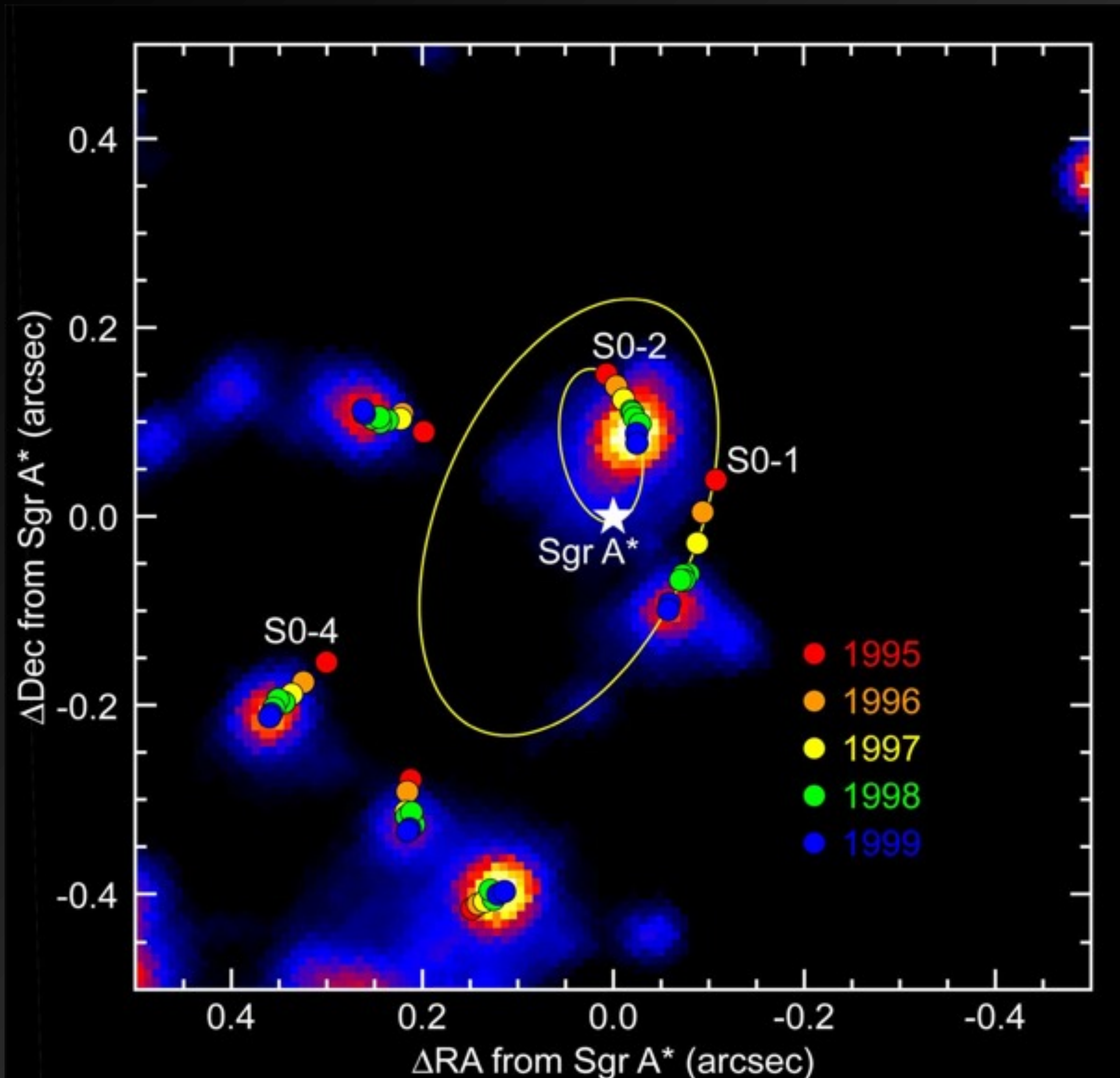
© 2000. Axel Mellinger

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

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

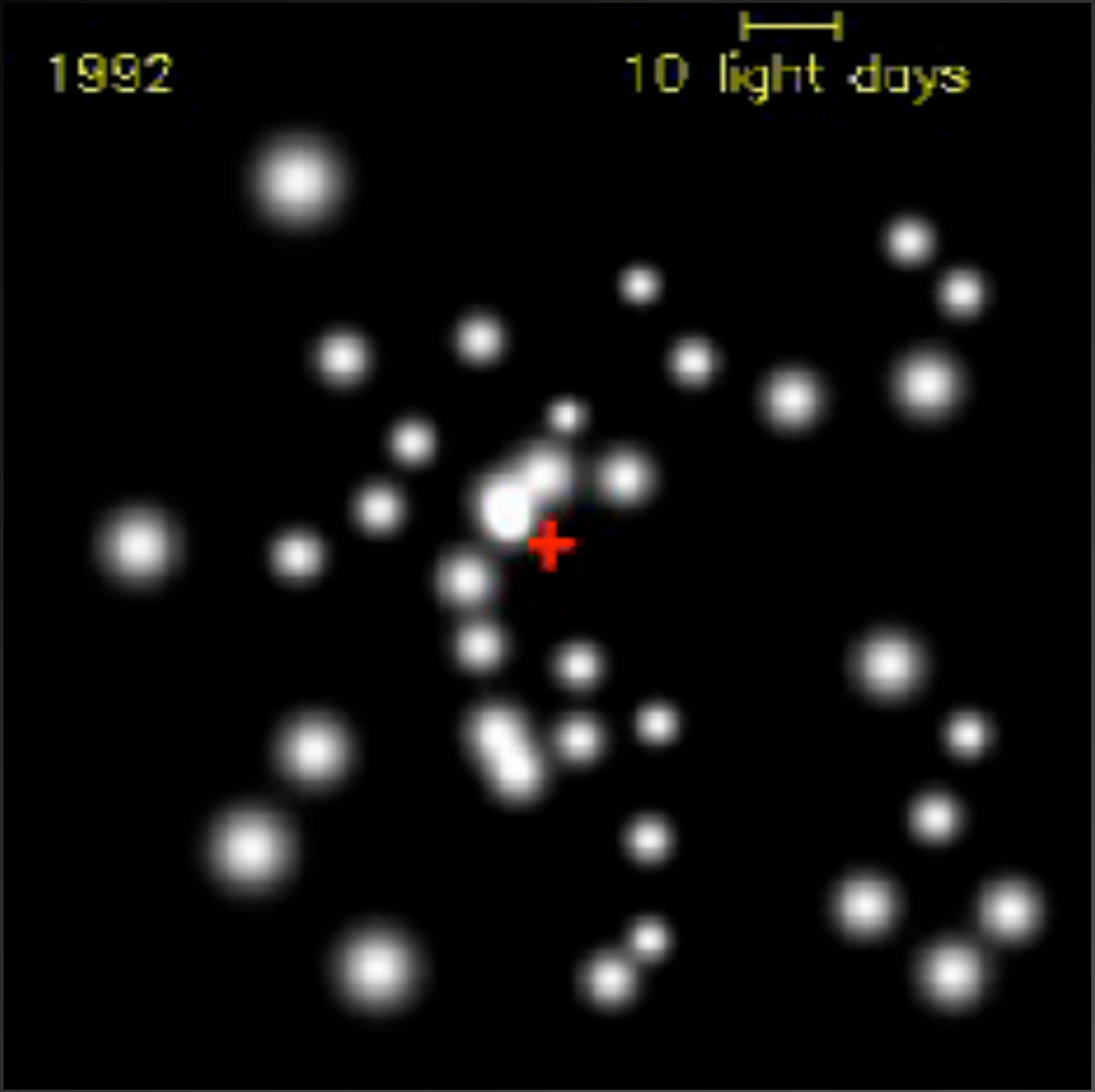


**_Keck, 2 μm_** *Ghez, et al.*

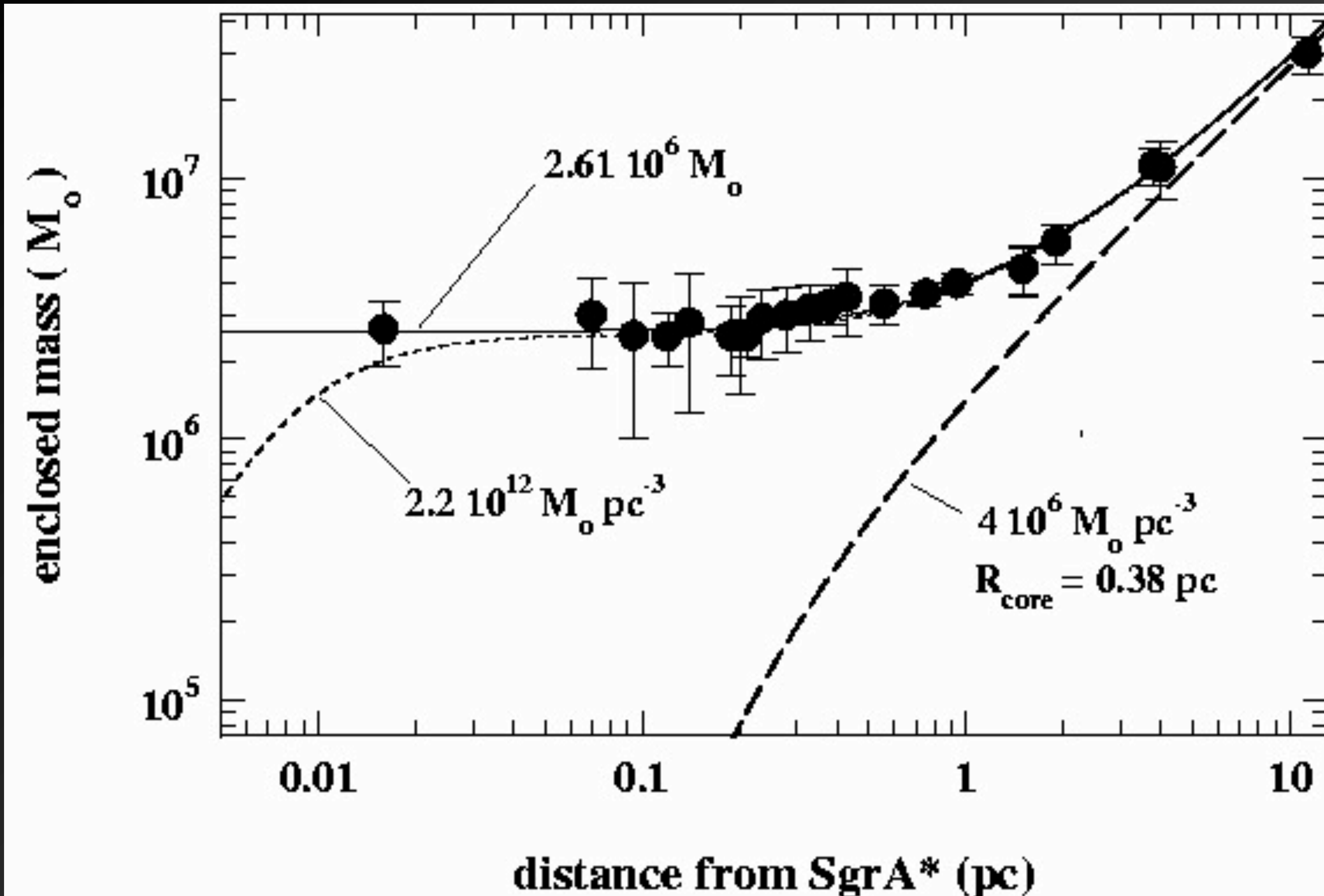



*Motions of stars consistent with large, dark mass located at Sgr A*…*

*Ghez, et al.*




*Schödel, Genzel, et al. 2004*




*Schödel et al. 2003*

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

# γ rays from WIMP annihilation at the Galactic Center

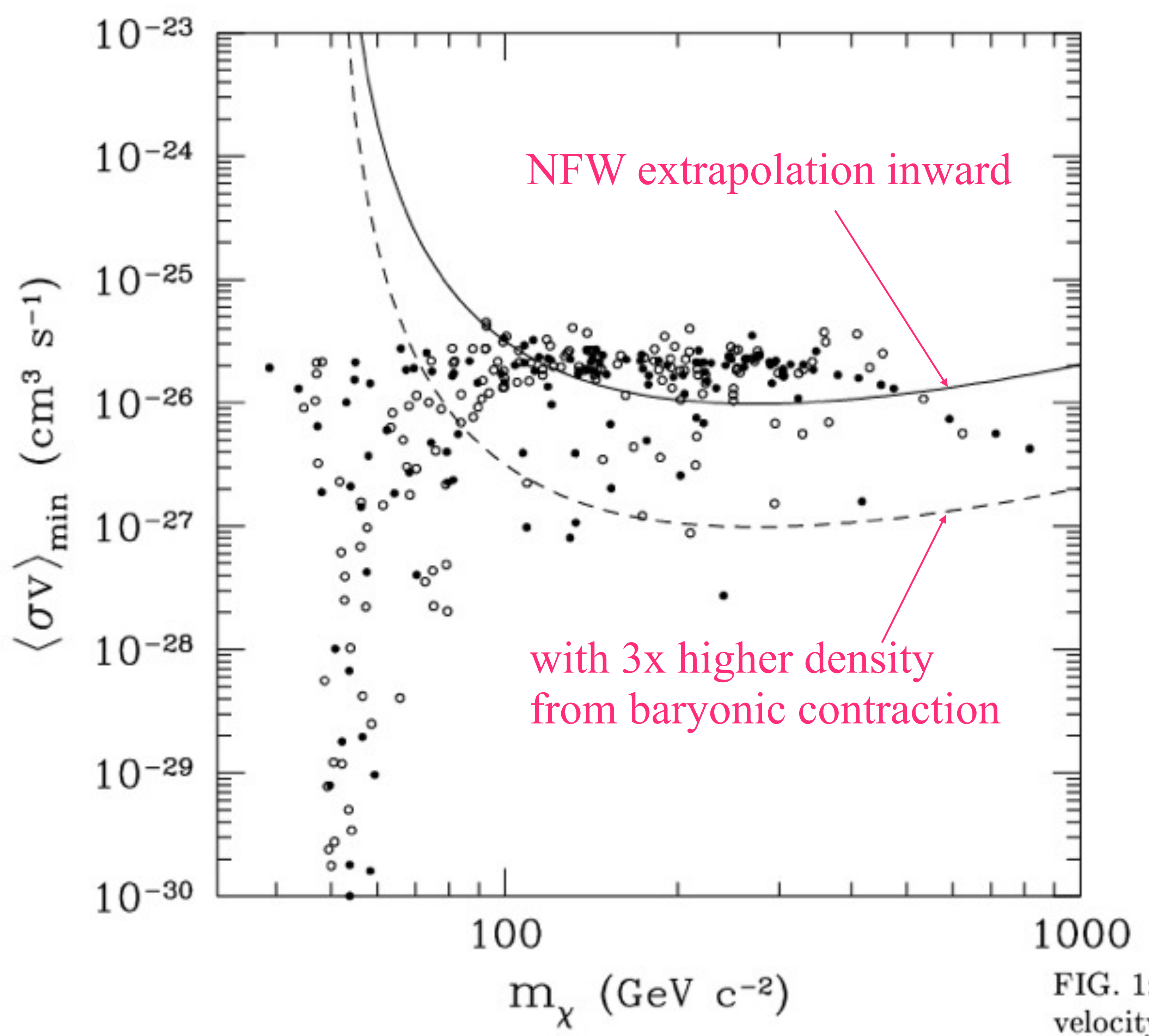



FIG. 1: Minimum detectable annihilation cross section times velocity as a function of WIMP mass. The filled circles correspond to SUSY model WIMPs with $\Omega_\chi h^2 = 0.11 \pm 0.01$ [32] and the open circles correspond to SUSY models with $\Omega_\chi h^2$ between $1\sigma$ and $2\sigma$ away from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

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.

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 $m_\chi$ and stars of mass $m_*$ can be described by a collisional equation in the Fokker-Planck form:

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

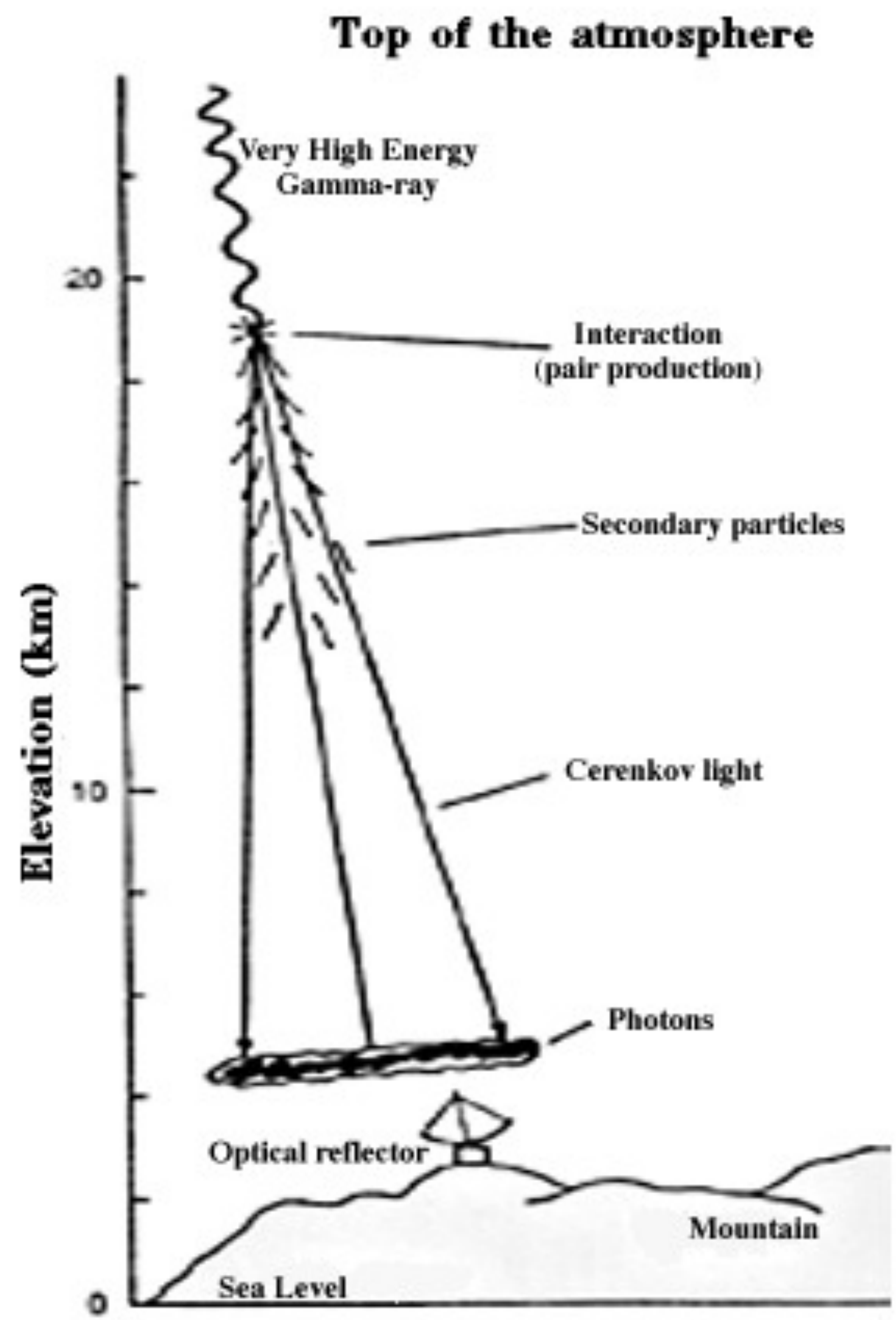
where $E = v^2/2 - GM_{\rm bh}/r$ is the energy within the sphere of influence of the black hole, $q(E) = (2^{3/2}/3)\pi^3 G^3 M_{\rm bh}^3 E^{-3/2}$, $A \equiv 16\pi^2 G^2 m_*^2 \ln\Lambda$, and $\ln\Lambda = \ln M_{\rm bh}/m_* \approx 15$ is the standard Coulomb logarithm. The equilibrium distribution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

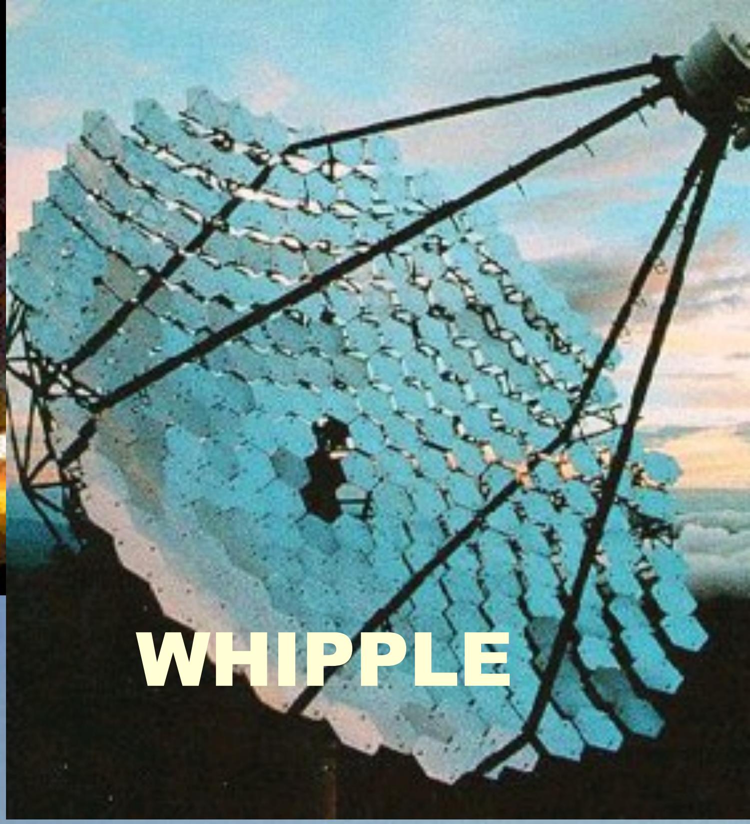
$$\rho_{\rm dm}(r) = \begin{cases} \rho_0\,(r/r_{\rm bh})^{-3/2} & L < r \le r_{\rm bh}\ , \\ \rho_0\,(r/r_{\rm bh})^{-\alpha} & r_{\rm bh} \le r\ , \end{cases}$$

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

# Early Atmospheric Čerenkov Telescopes







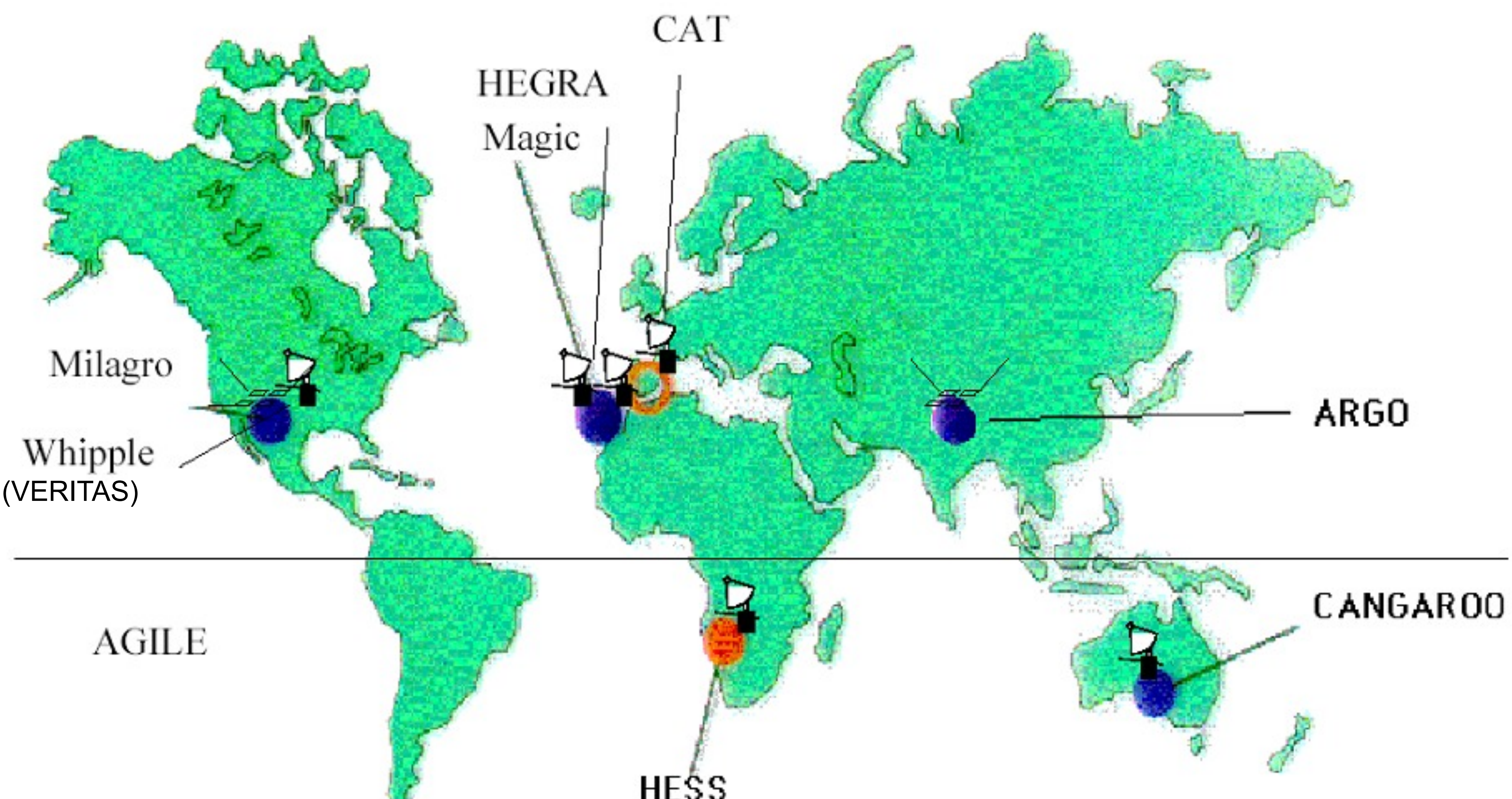


# New Ground and Space Based Telescopes





# Ground-based Gamma Ray Telescopes 2



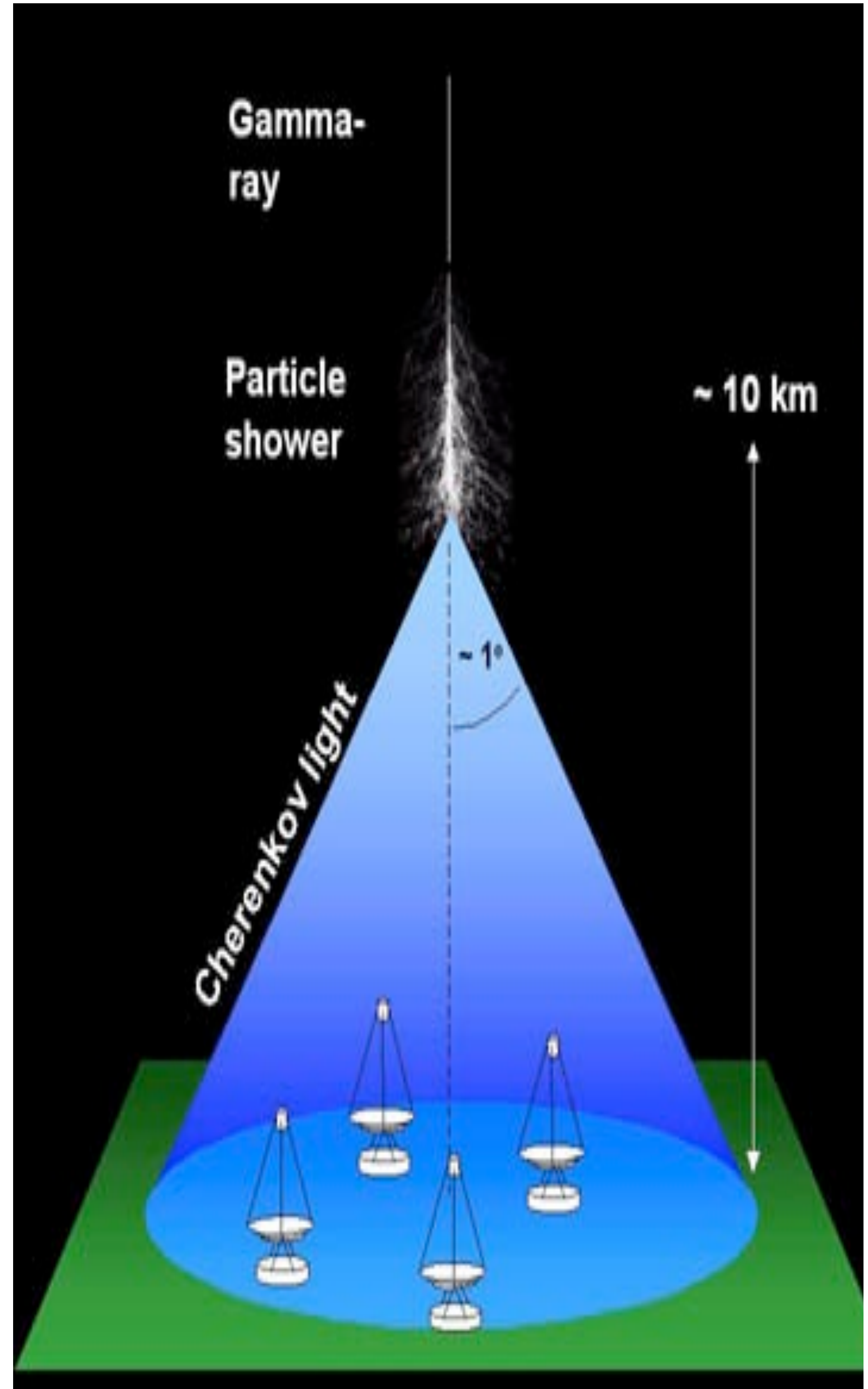

# Results from H.E.S.S. on MWy Center

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

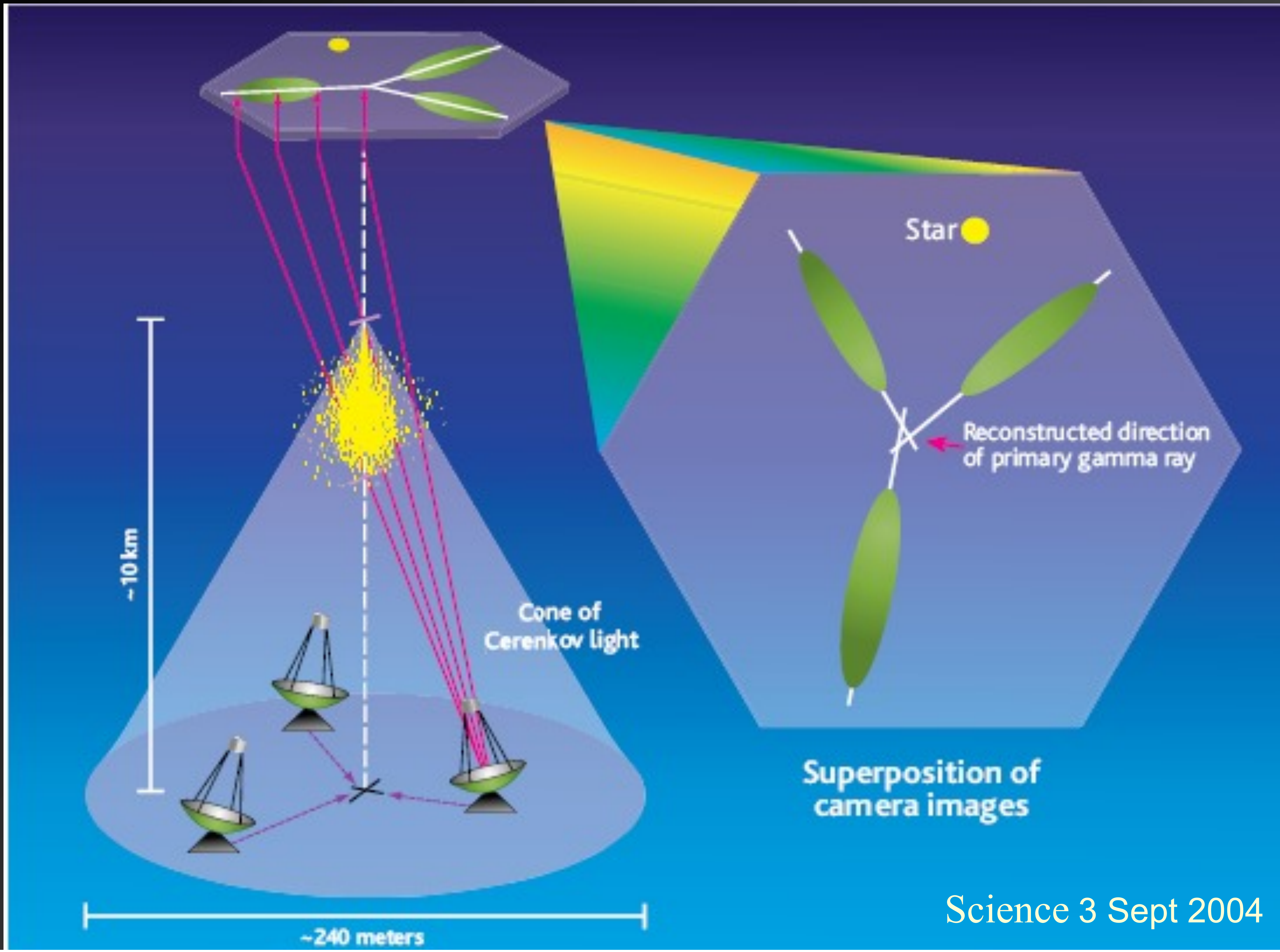
- Array 4 telescopes, diameter ~12 m
- Field of view ~5°
- Angular resolution (single photon): ~ 6 '
  (with hard cuts): ~ 4 '
- Energy resolution ~15%
- Location: Namibia, 1800 m asl
  Coord.: 23°16' S, 16°30' E

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) $\gamma$-rays coincident within $1'$ of Sgr A$^*$, obtained with the H.E.S.S. array of Cherenkov telescopes. The $\gamma$-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

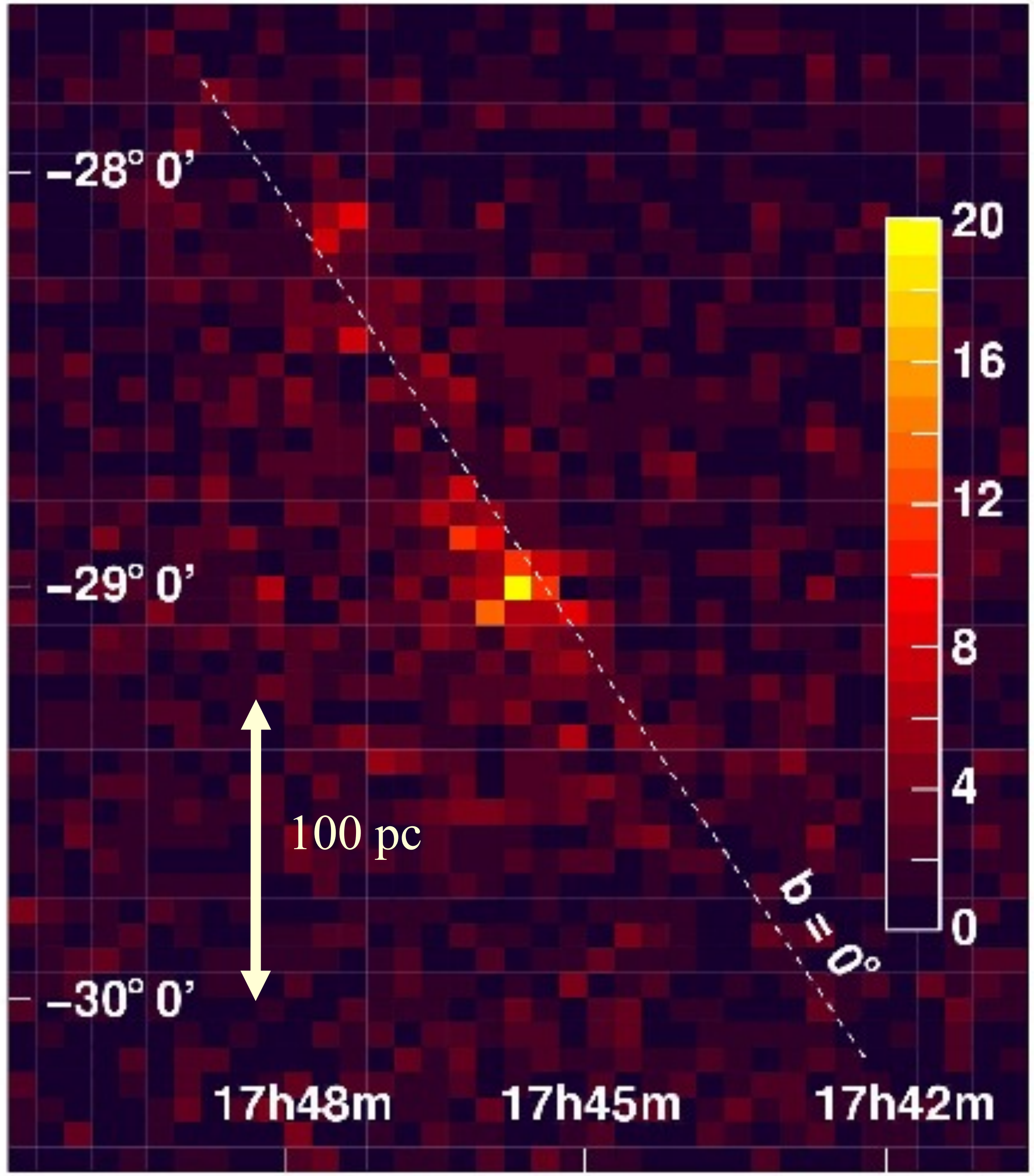



**Fig. 1.** Angular distribution of $\gamma$-ray candidates for a 3° field of view centred on Sgr A*. Both data sets ('June/July' and 'July/August') are combined, employing tight cuts to reduce the level of background. The significance of the feature extending along the Galactic Plane is under investigation.

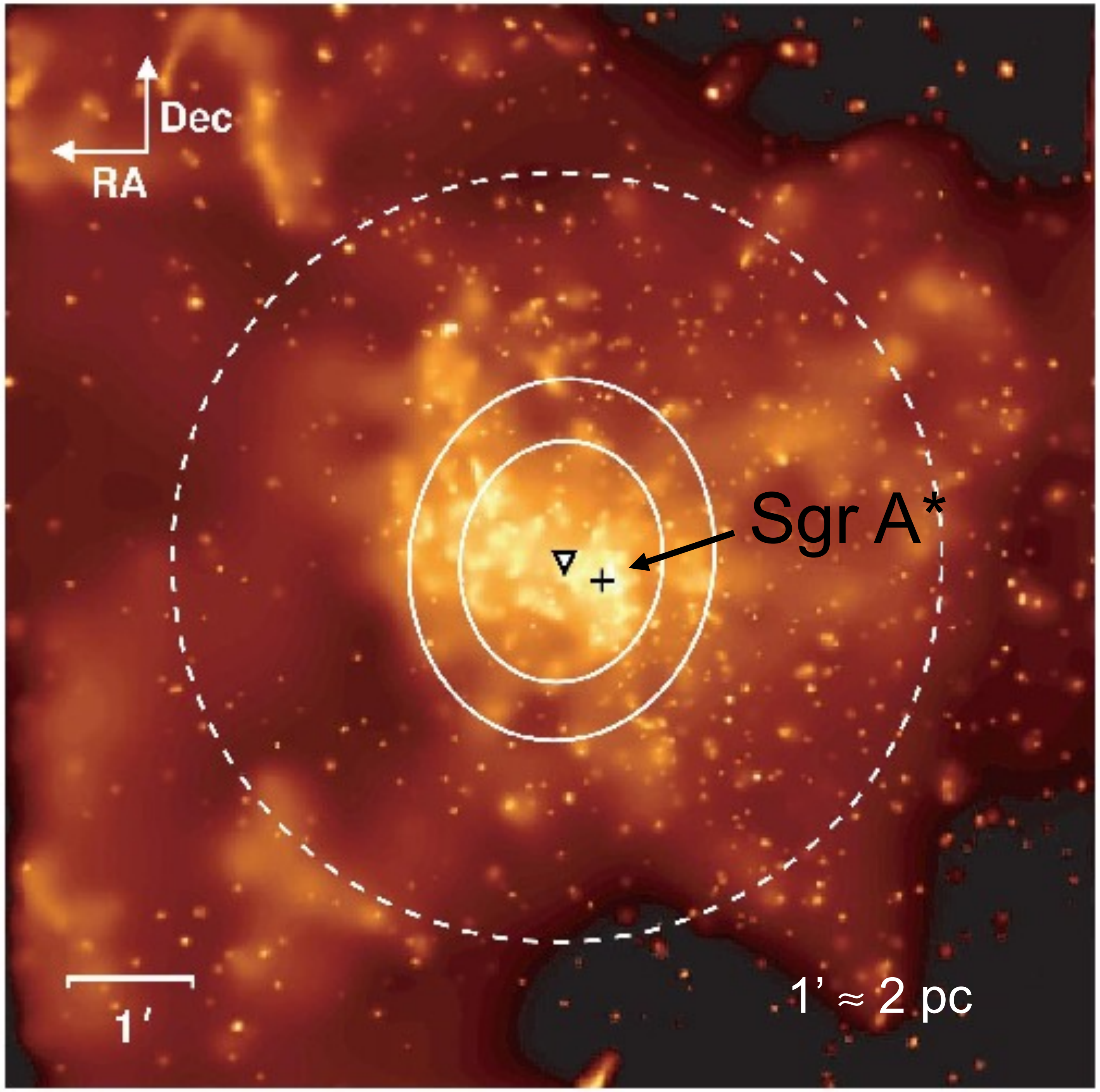
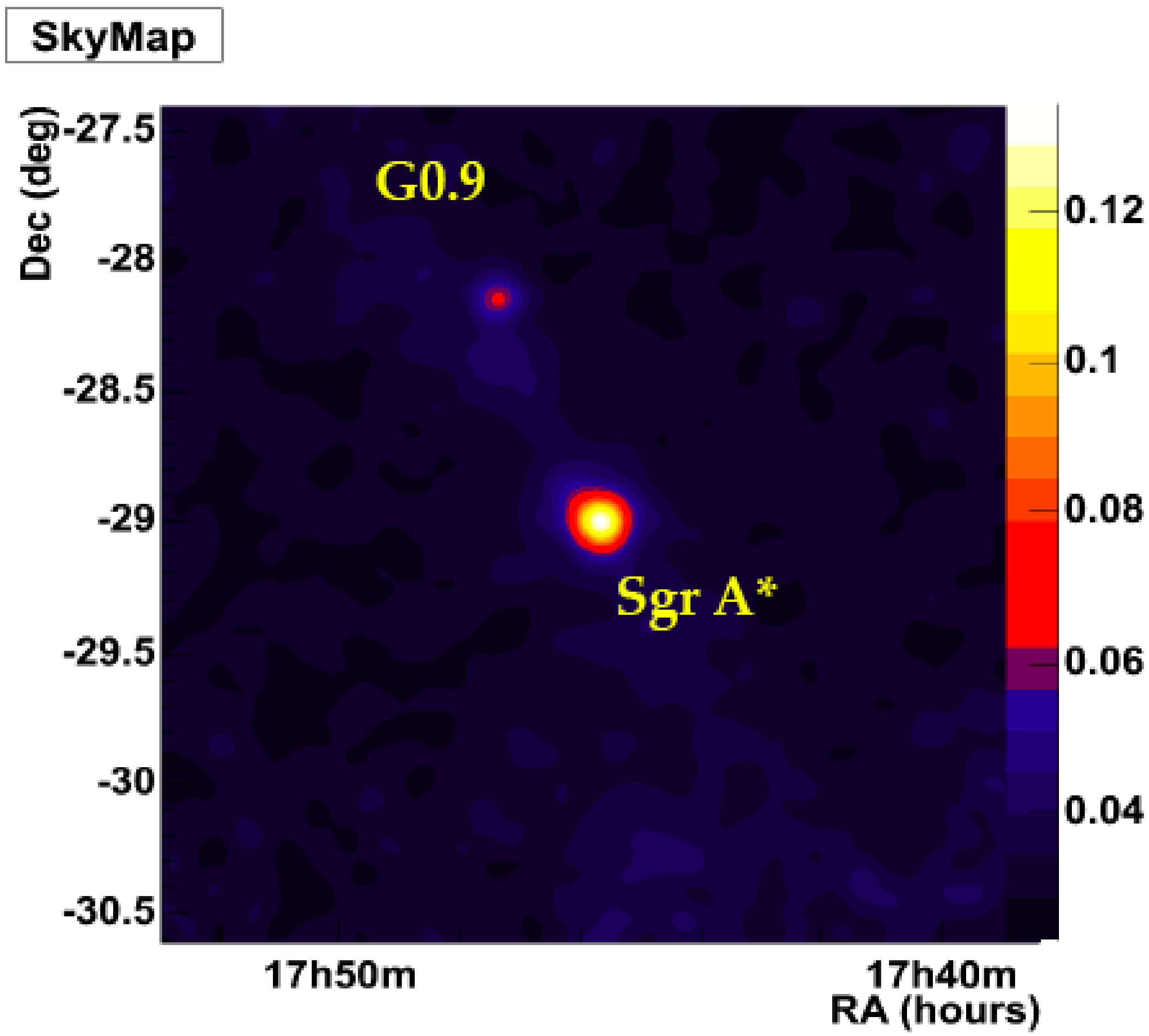
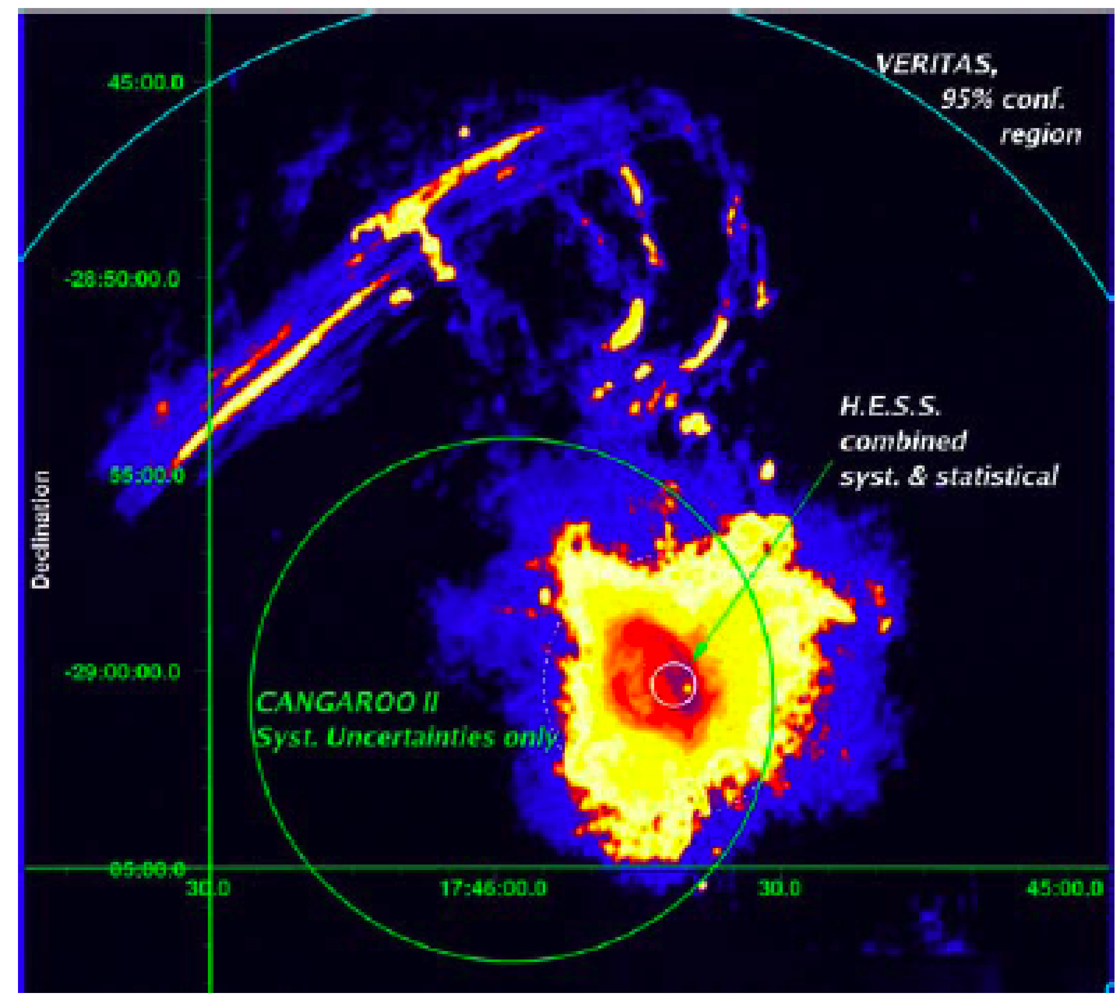


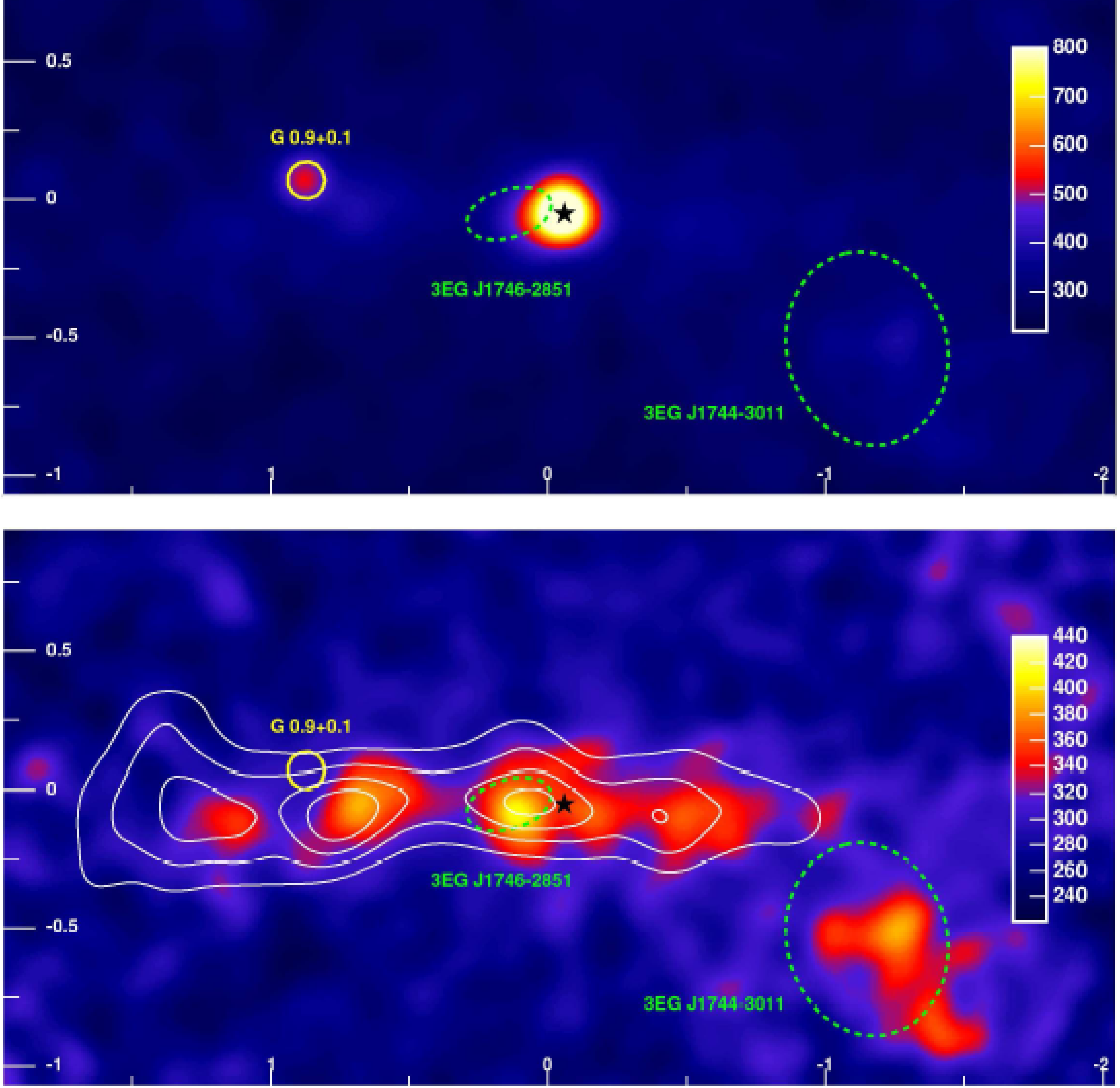

**Fig. 2.** Centre of gravity of the VHE signal (triangle), superimposed on a 8.5′ by 8.5′ Chandra X-ray map (Munro et al. 2003) of the GC. The location of Sgr A* is indicated by a cross. The contour lines indicate the 68% and 95% confidence regions for the source position, taking into account systematic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

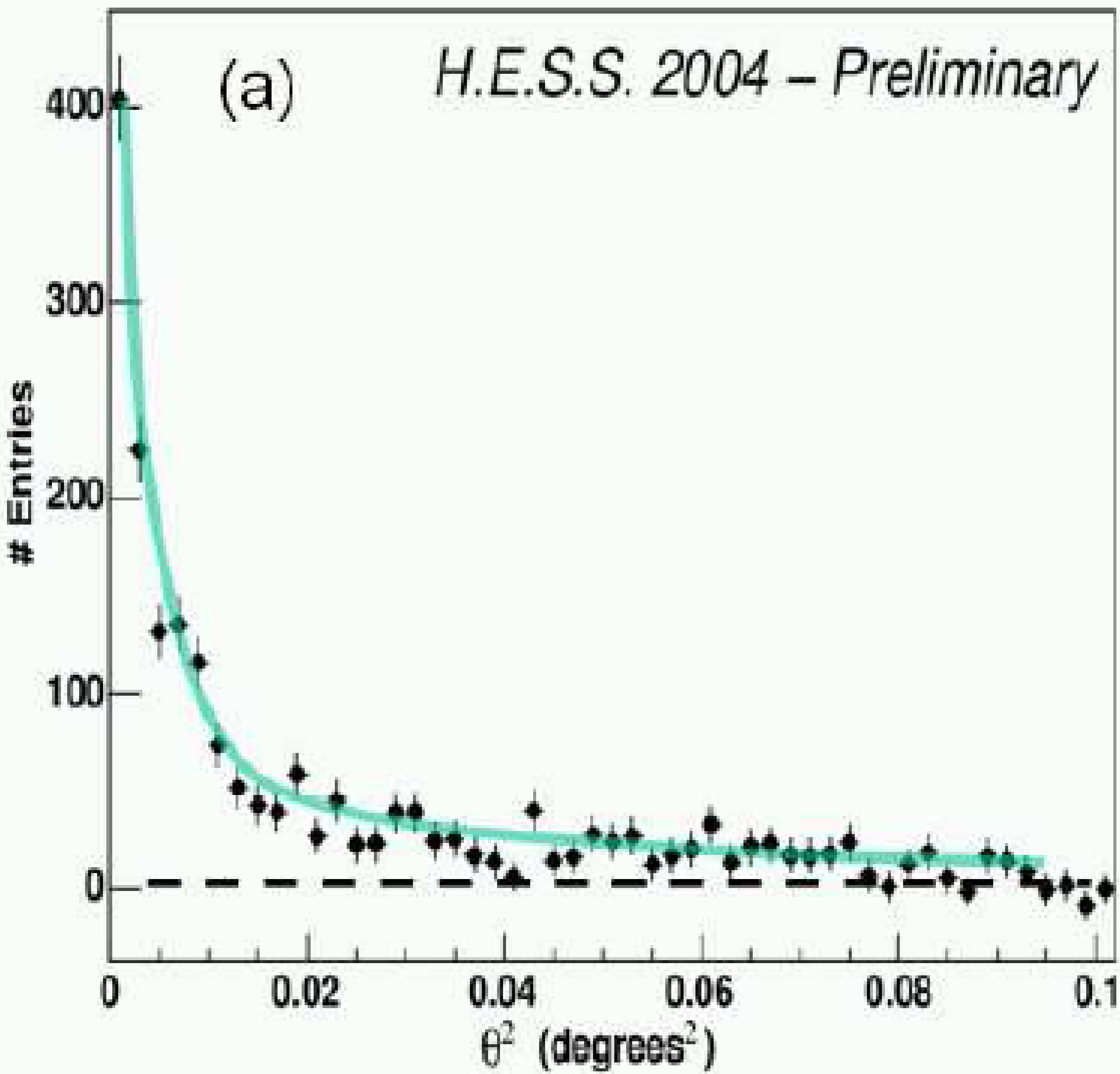



Discovery of Very-High-Energy Gamma-Rays from the Galactic Centre Ridge
Authors: The H.E.S.S. Collaboration: F. A. Aharonian, et al
Nature
Journal-ref: Nature 439 (2006) 695

# 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.

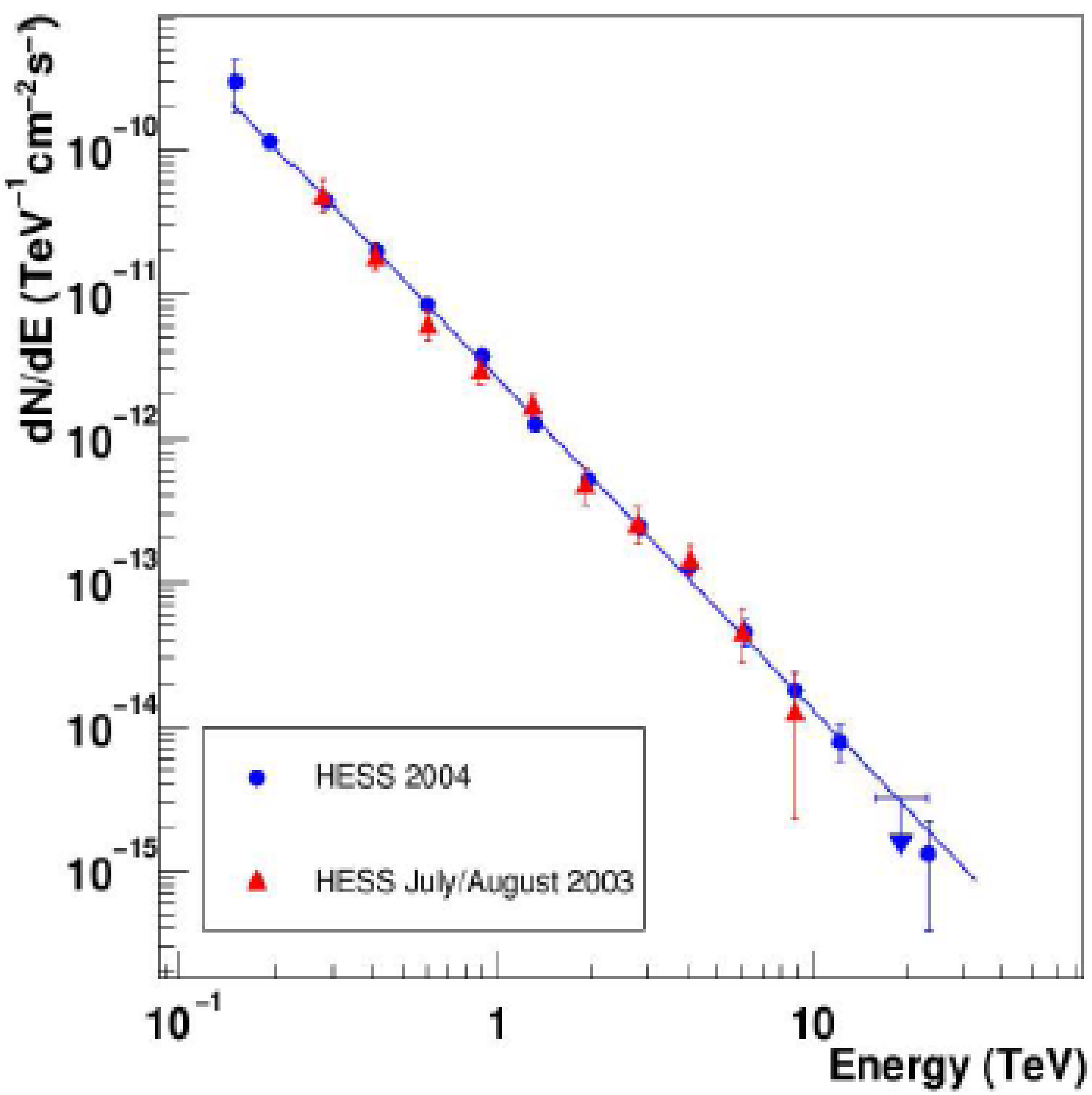
W. Hoffman plenary talk at ICRC29 2005

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

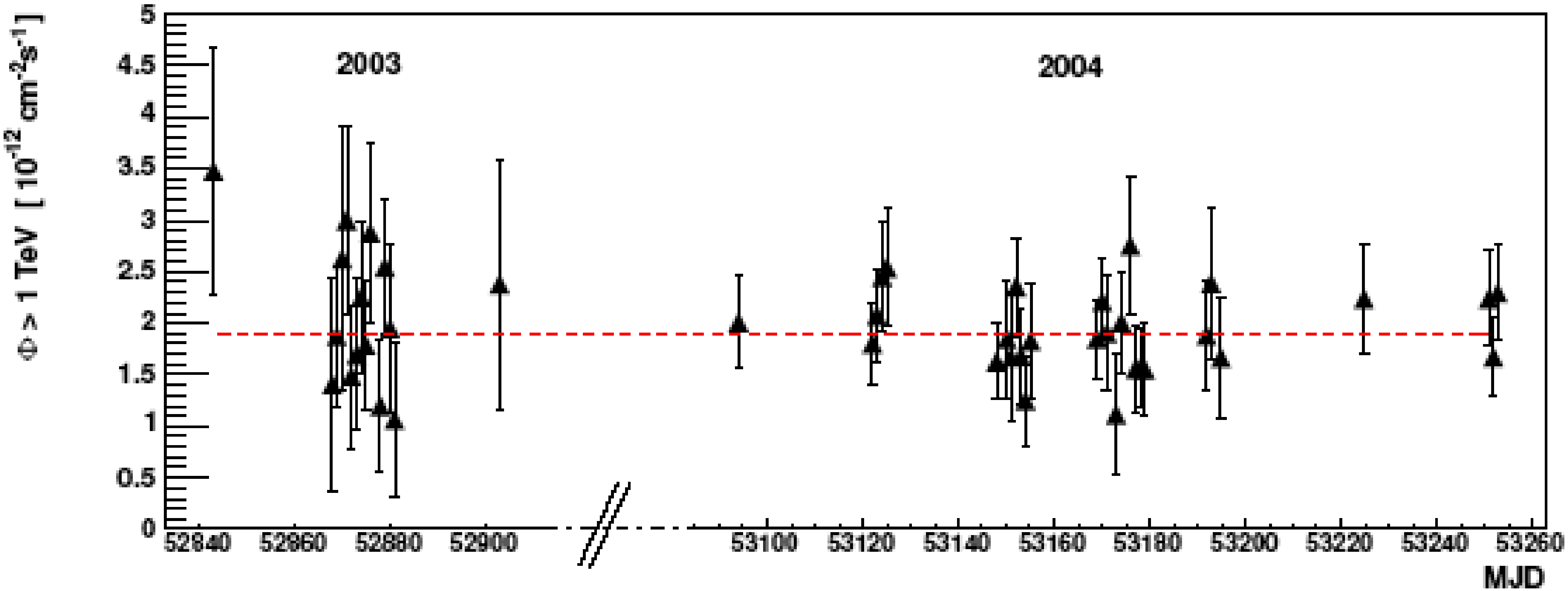
# Spectrum and variability of the VHE Galactic Centre source observed with H.E.S.S.

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 $\gamma$-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).

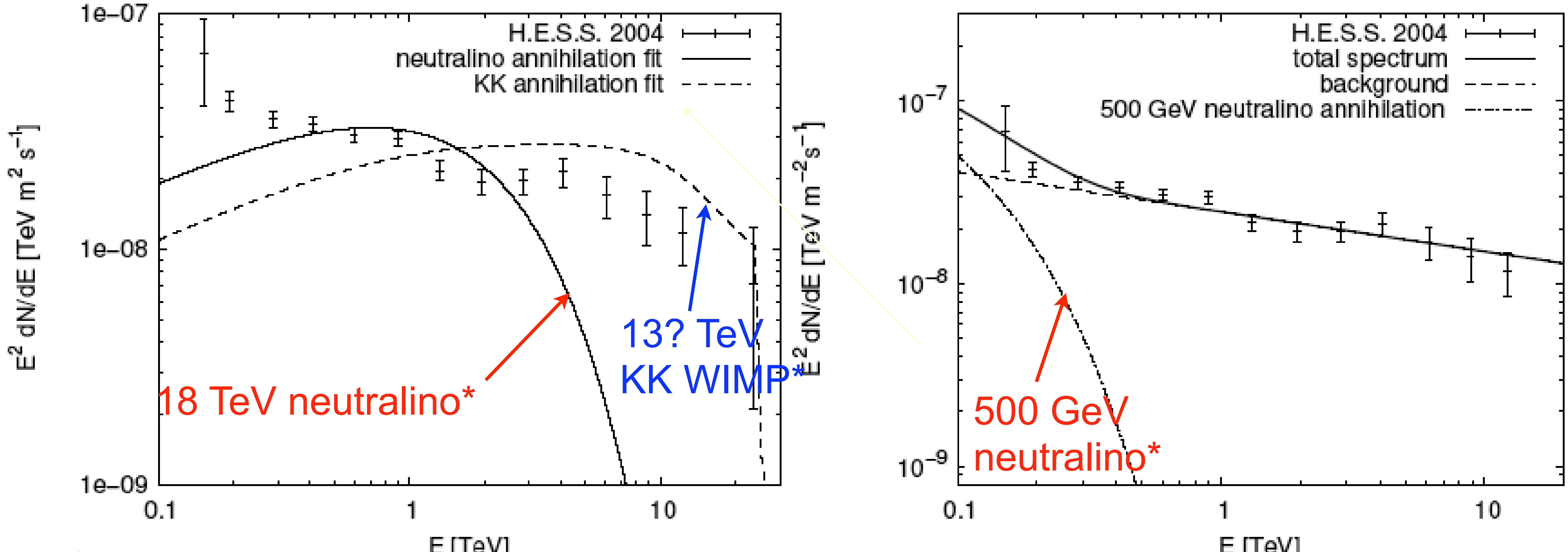



Galactic Centre source light curves. The integral nightly average flux above 1 TeV is given as function of time in modified Julian Days for both 2003 and 2004 observations. The Galactic Centre source flux is consistent with a constant flux at all probed time scales.

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

# Dark matter annihilation as possible origin of the very high energy $\gamma$-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 $\gamma$-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 $\tau$ 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.

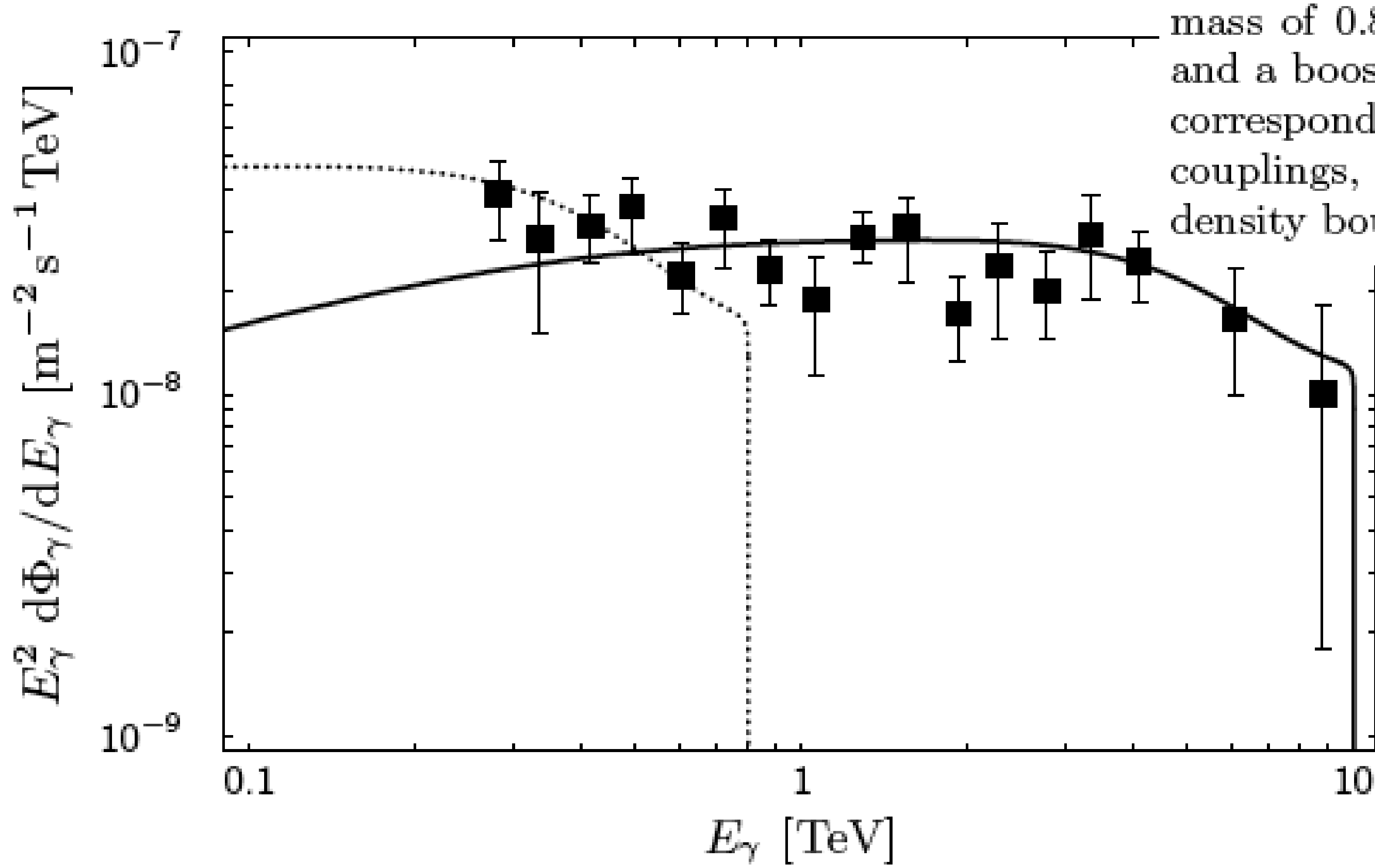



FIG. 3: The H.E.S.S. data [3] compared to the gamma-ray flux from a region of $10^{-5}$ sr encompassing the GC, for a $B^{(1)}$ mass of 0.8 TeV, a 5% mass splitting at the first KK level, and a boost factor $b$ around 200 (dashed line). The solid line corresponds to a hypothetical 10 TeV WIMP with similar 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 $\gamma Z$ line signals which are known to give large rates for heavy neutralinos. Observational prospects thus seem promising.

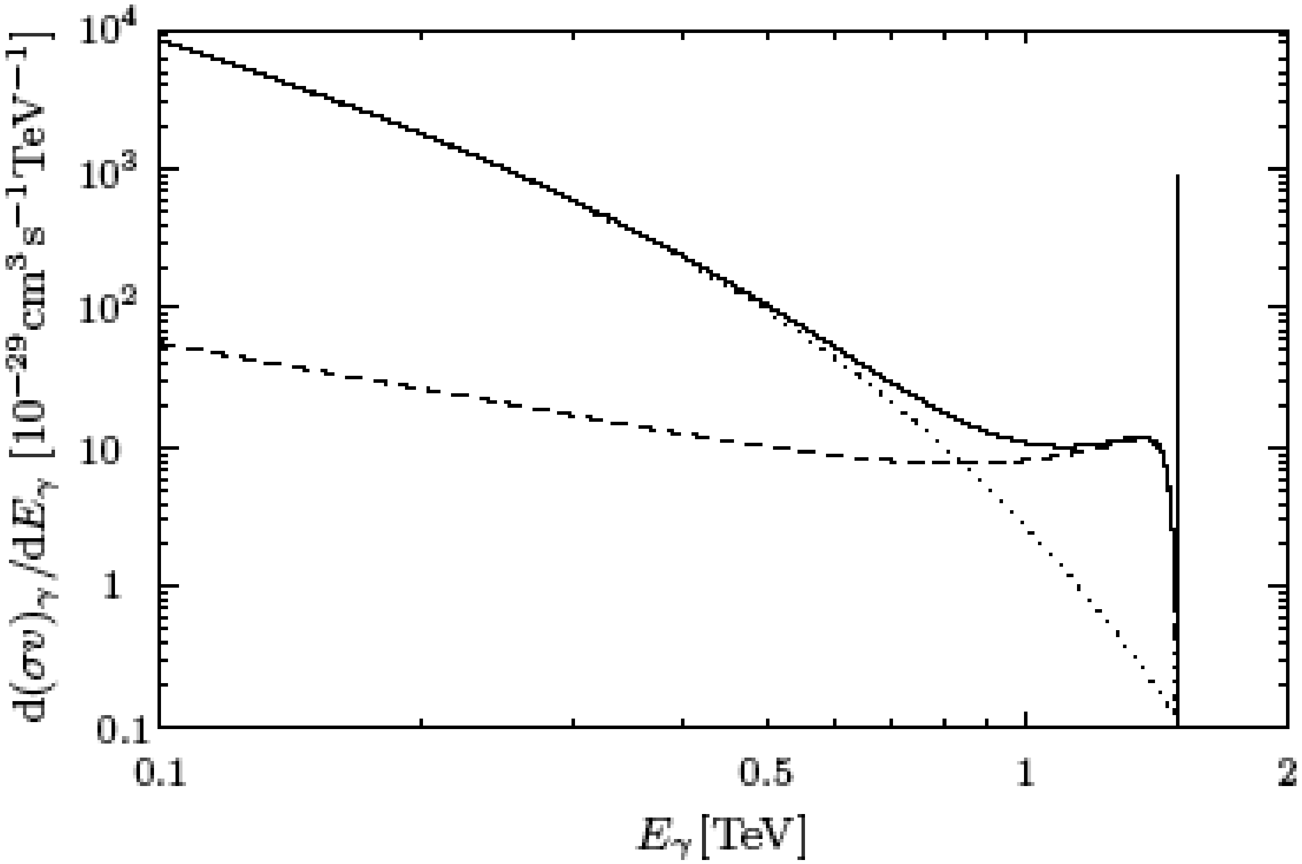



FIG. 3: The total differential photon distribution from $\chi\chi$ annihilations (solid line) for the MSSM model of Table I. Also shown separately is the contribution from radiative processes $\chi\chi \to W^+W^-\gamma$ (dashed), and the $W$ fragmentation together with the $\chi\chi \to \gamma\gamma,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

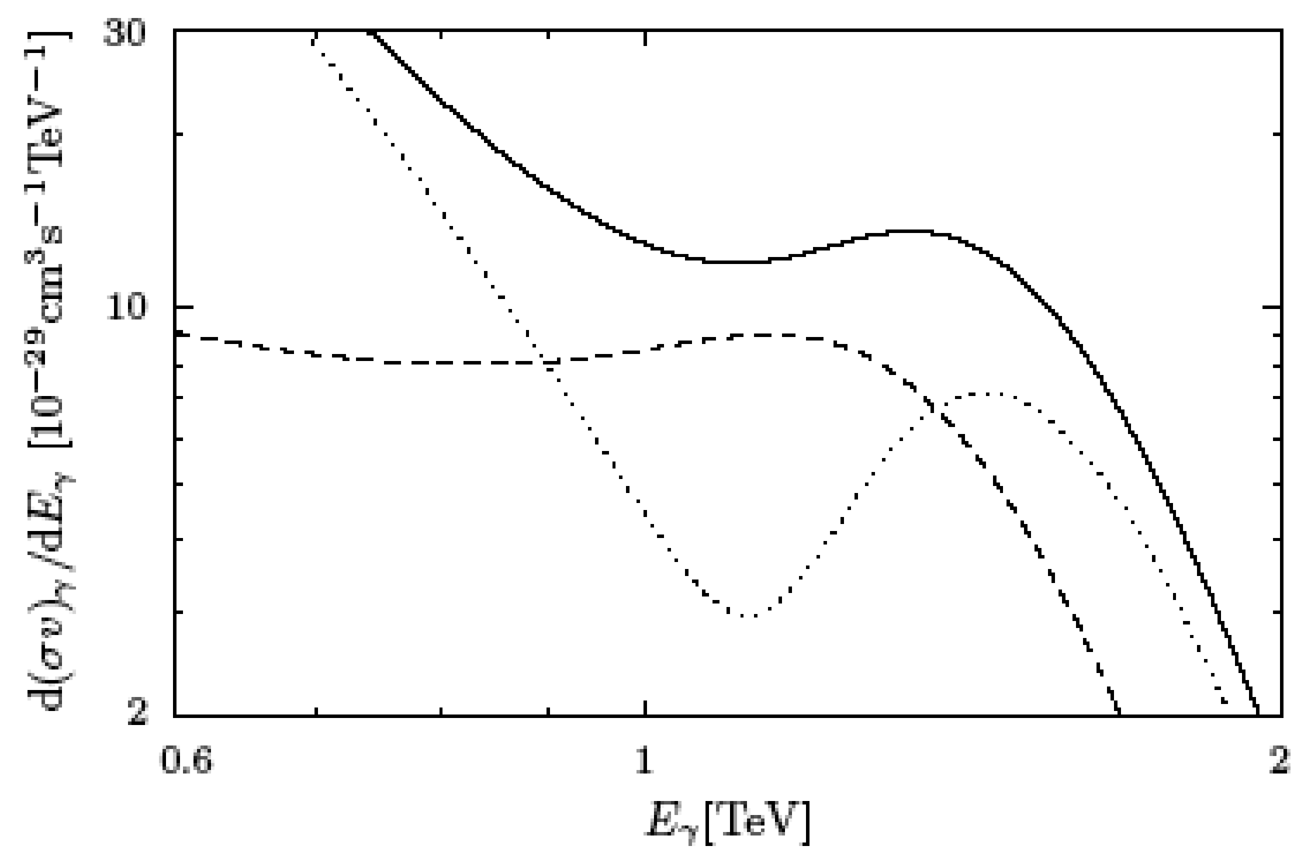



FIG. 4: The same spectra as in Fig. 3, as seen by a detector with an energy resolution of 15 percent.

# 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

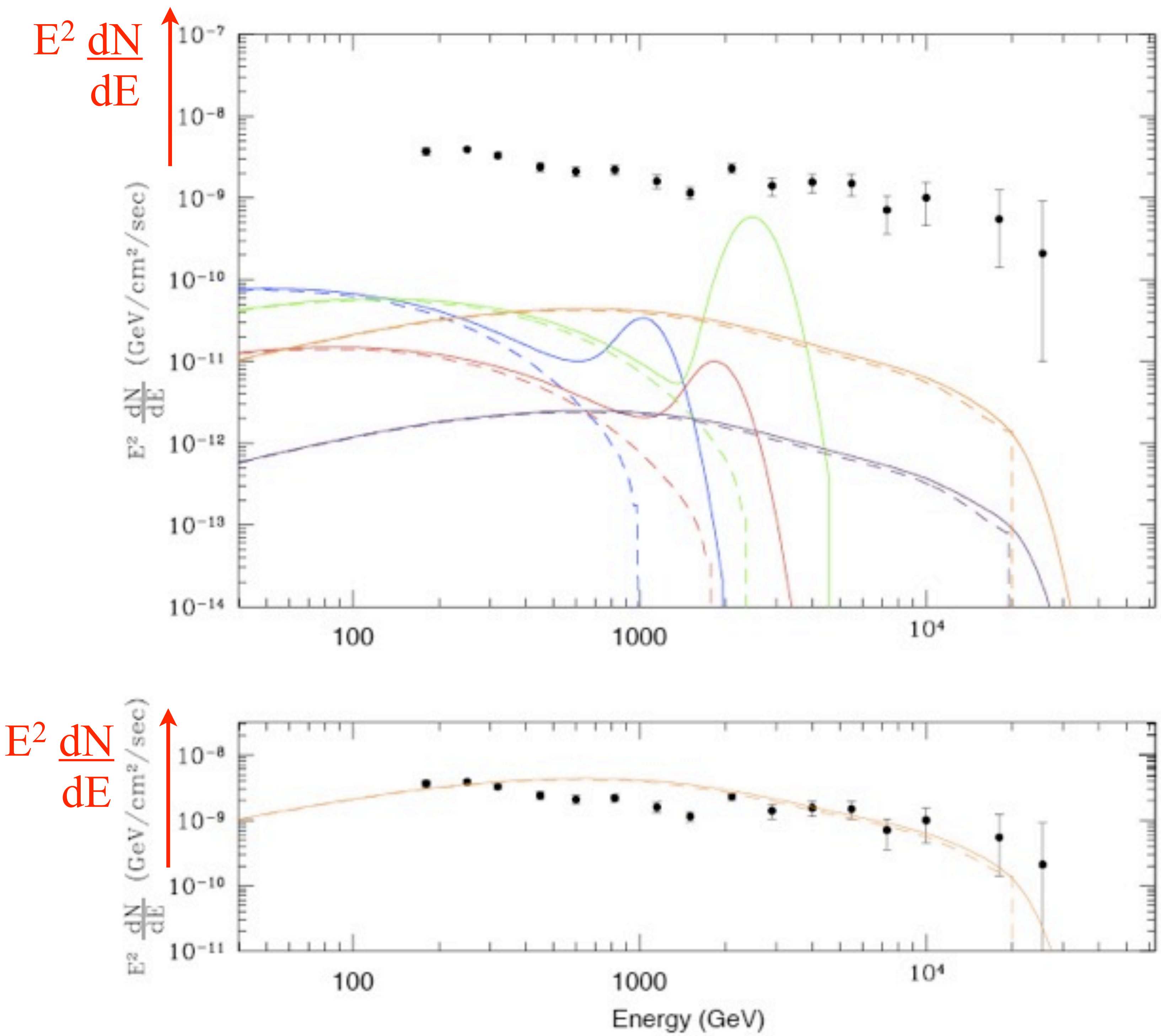
# Rudy C. Gilmore, Mass Limits on Neutralino Dark Matter

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.

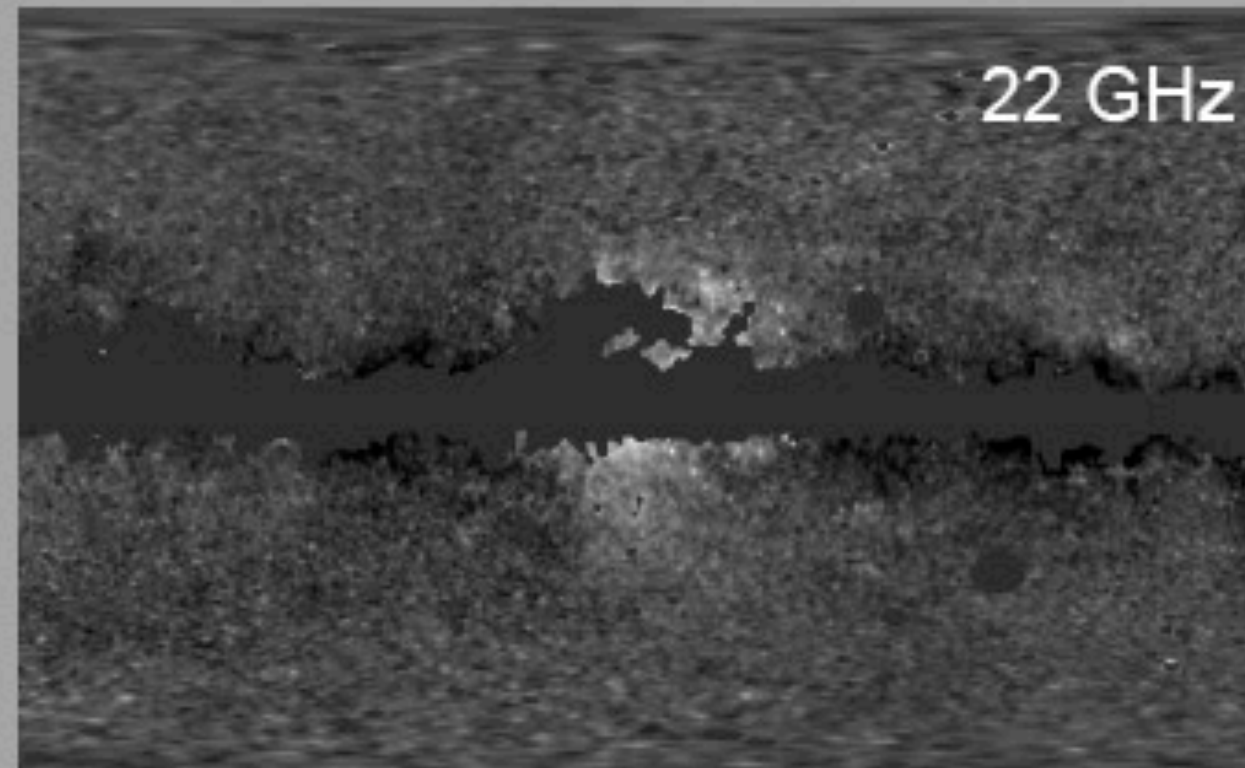
## Rudy C. Gilmore, Mass Limits on Neutralino Dark Matter

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 $3 \times 10^{-26}$ 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

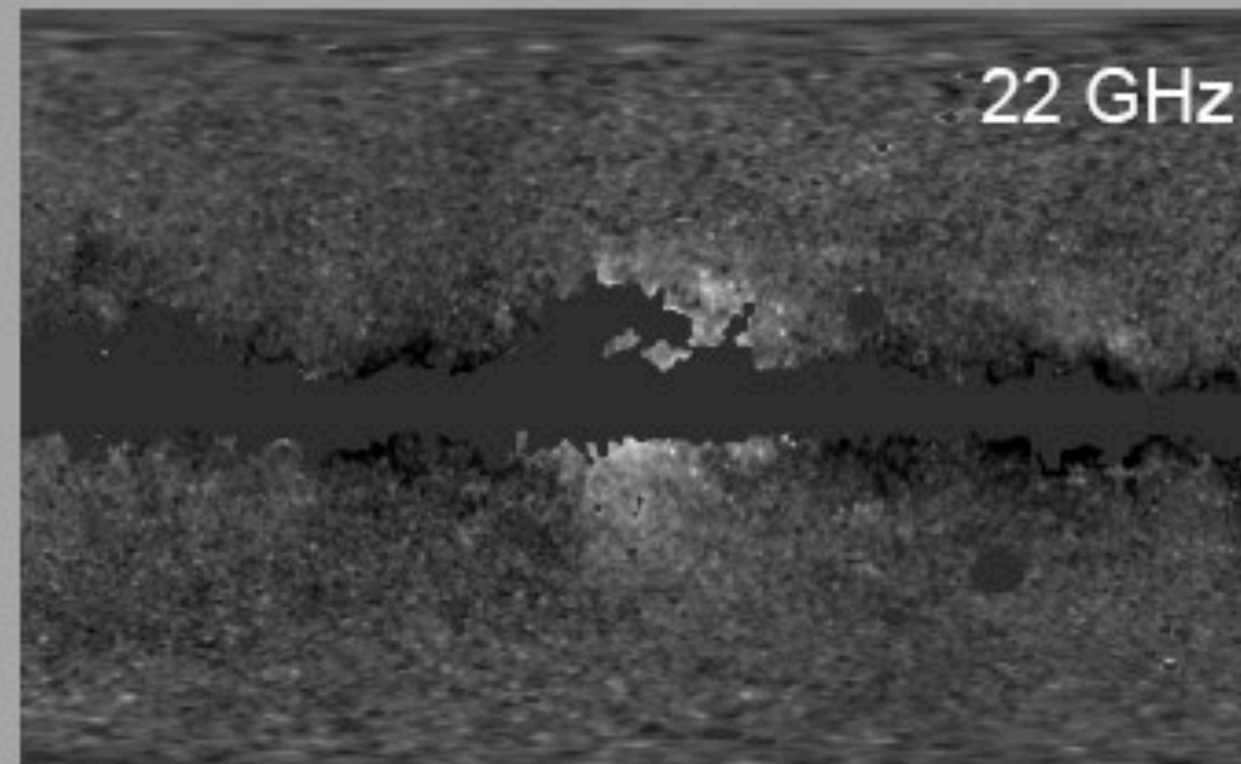
$0.7 \times 10^{39}$ and $3 \times 10^{39}$ GeV/sec

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

DM2008

# 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 $3x10^{-26}$ $cm^3/s$, the total power in dark matter annihilations in the inner 2 kpc of the Milky Way is

$\sim 1.2x10^{39}$ GeV/sec

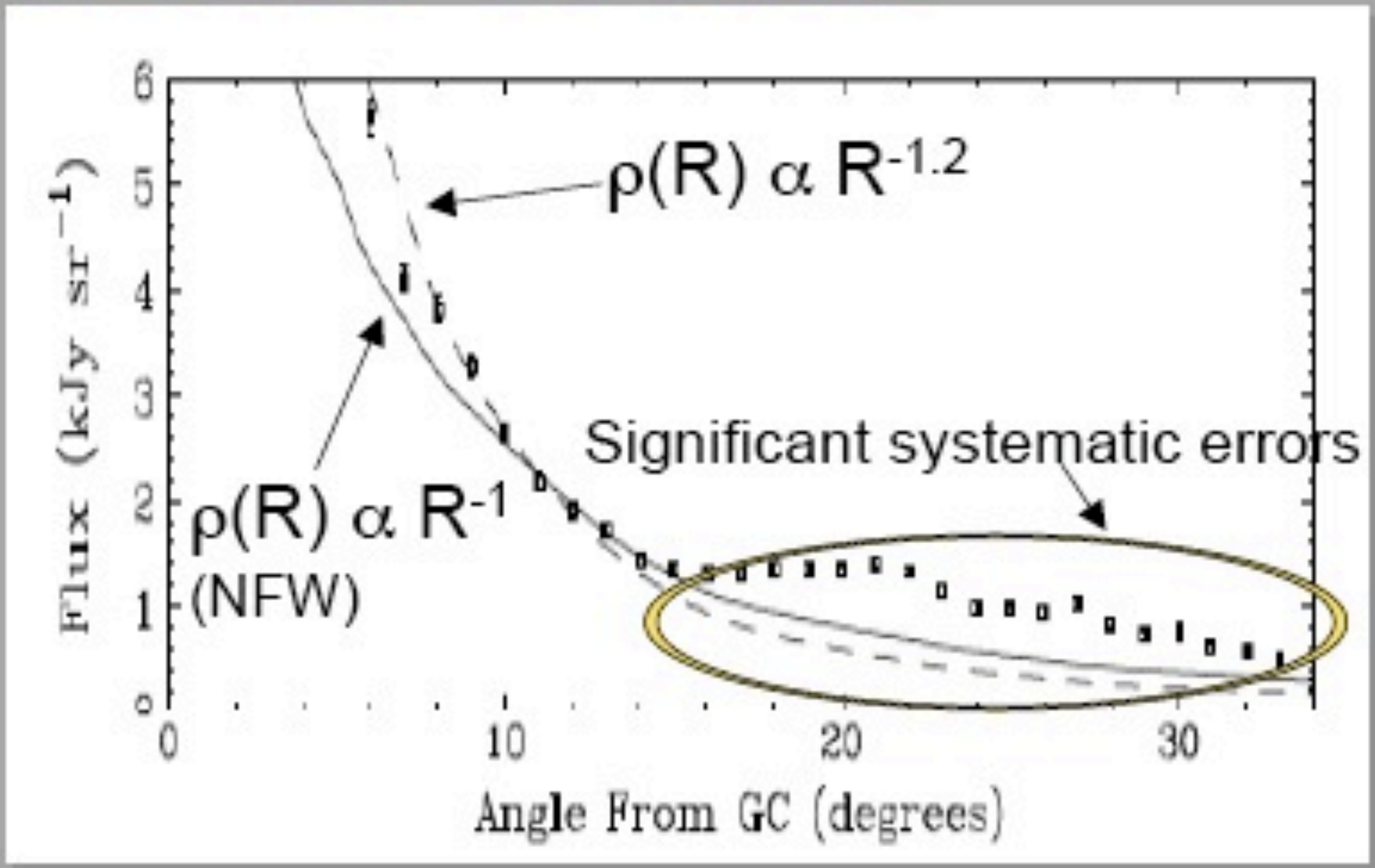
**Coincidence?**

2) The total power of the WMAP Haze is between

$0.7x10^{39}$ and $3x10^{39}$ 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 ($\rho\ \alpha\ R^{-1}$) under produces the WMAP haze at small angles

- Angular distribution of the haze matches that found for a profile, with $\rho\ \alpha\ R^{-1.2}$

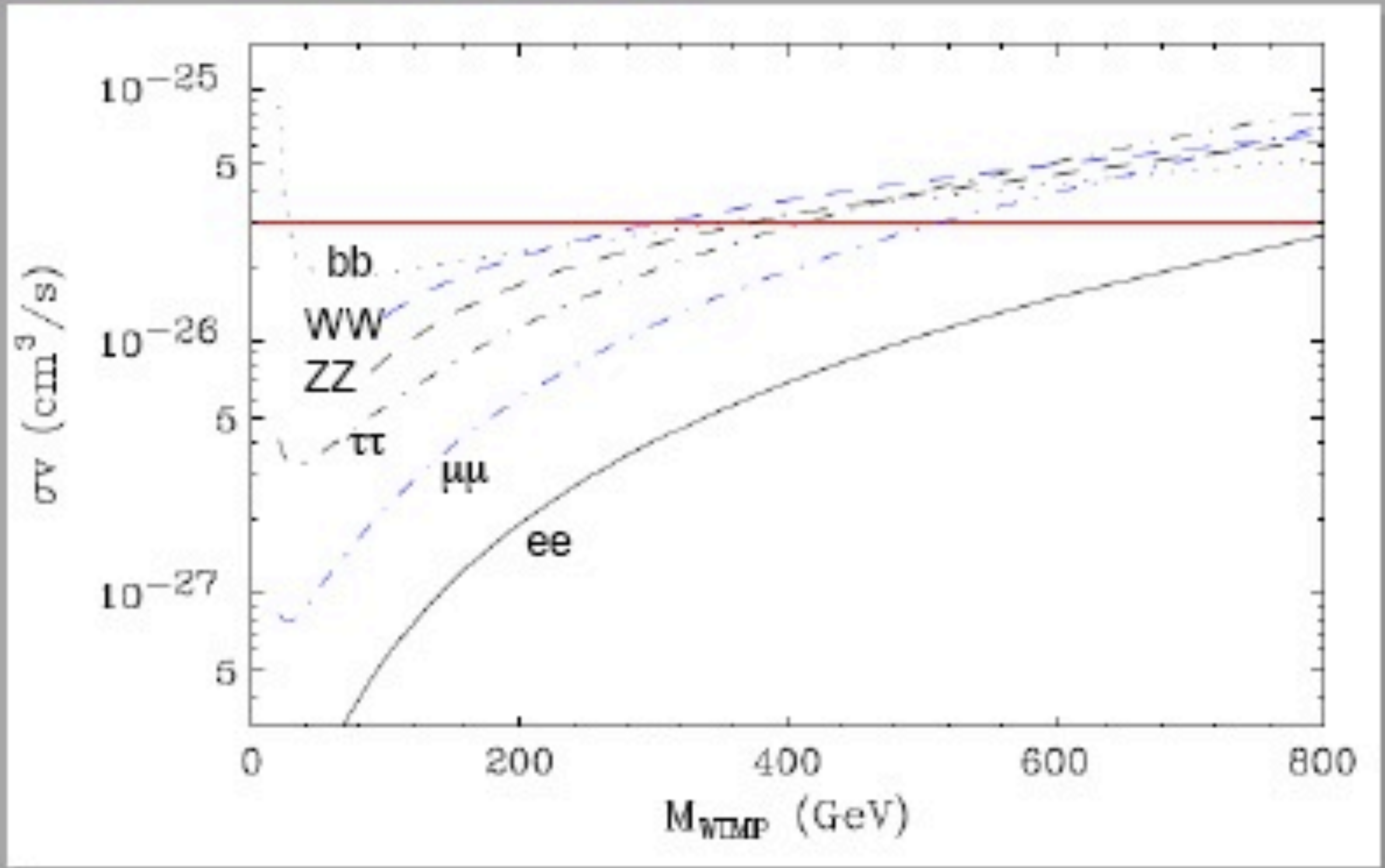
- Although the precise result of this fit depends on the diffusion parameters adopted (magnetic fields, starlight density, etc.), the approximate result (slope of -1.1 to -1.3) is fairly robust



**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 ($3 \times 10^{-26}$ cm$^3$/s)

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

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

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

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

1. A dark matter distribution with $\rho \propto R^{-1.2}$ in the inner kiloparsecs of our galaxy
2. A dark matter particle with a ~100 GeV to several TeV mass, and that annihilates to typical channels (heavy fermions, gauge bosons, etc.)
3. An annihilation cross section within a factor of a few of $3\times10^{-26}$ $cm^3/s$ (the value required of a thermal relic)

## *A completely vanilla dark matter scenario!*

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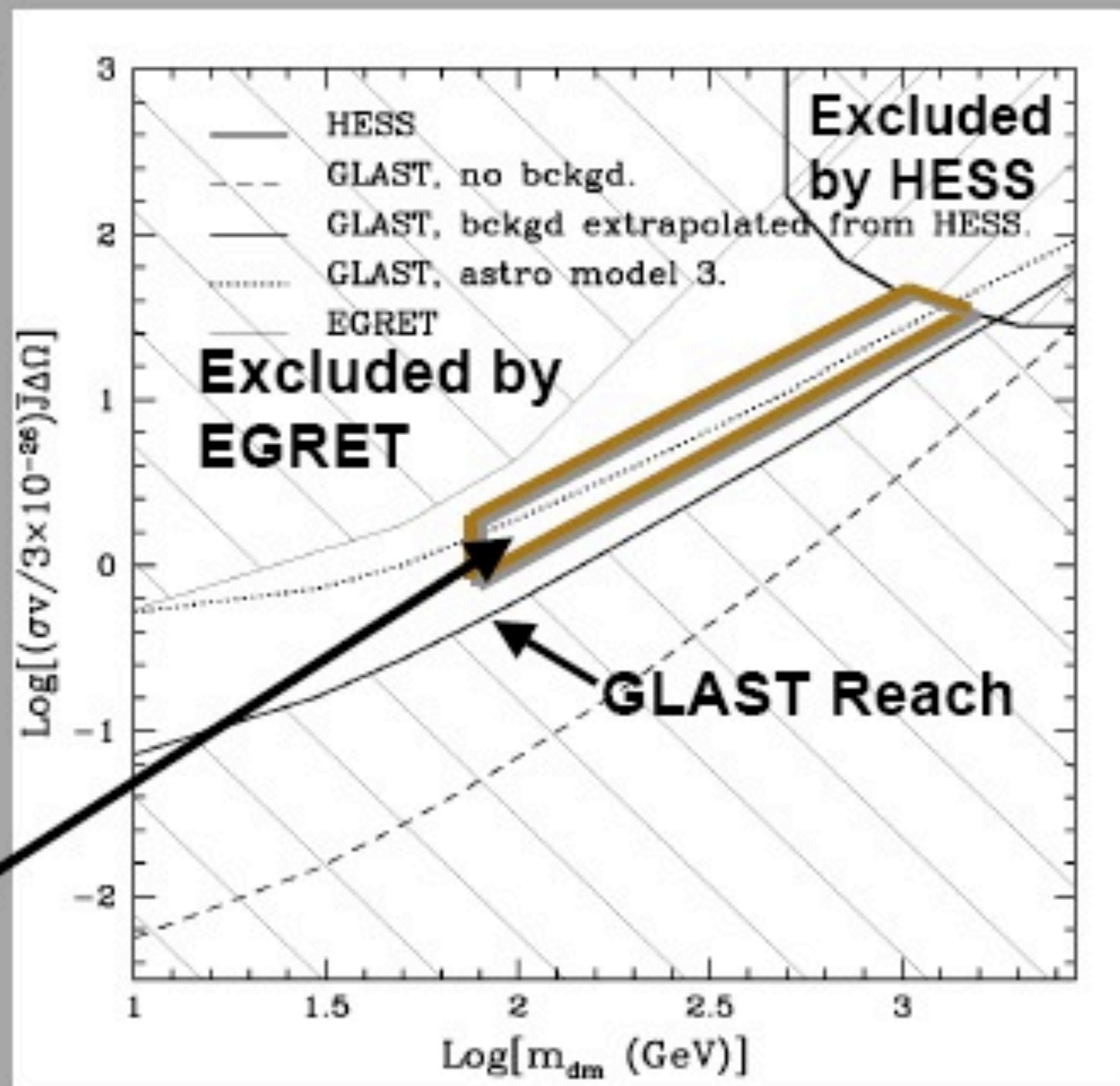
**Hooper, G. Dobler and D. Finkbeiner, PRD, arXiv:0705.3655**

# Gamma-Rays From The Galactic Center

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

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

**Range Predicted By the WMAP Haze**




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

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