Dark Matter

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University of Utah

Tools 2008

Summary

- We have evidence for non-baryonic dark matter that is not made of any known elementary particle
- We are in the exploratory stage to figure out its nature
- There are many particle physics and astrophysics ideas currently explored, and more will come
- Tools for dark matter should be flexible, modular, adaptable to new ideas

The current content of the Universe

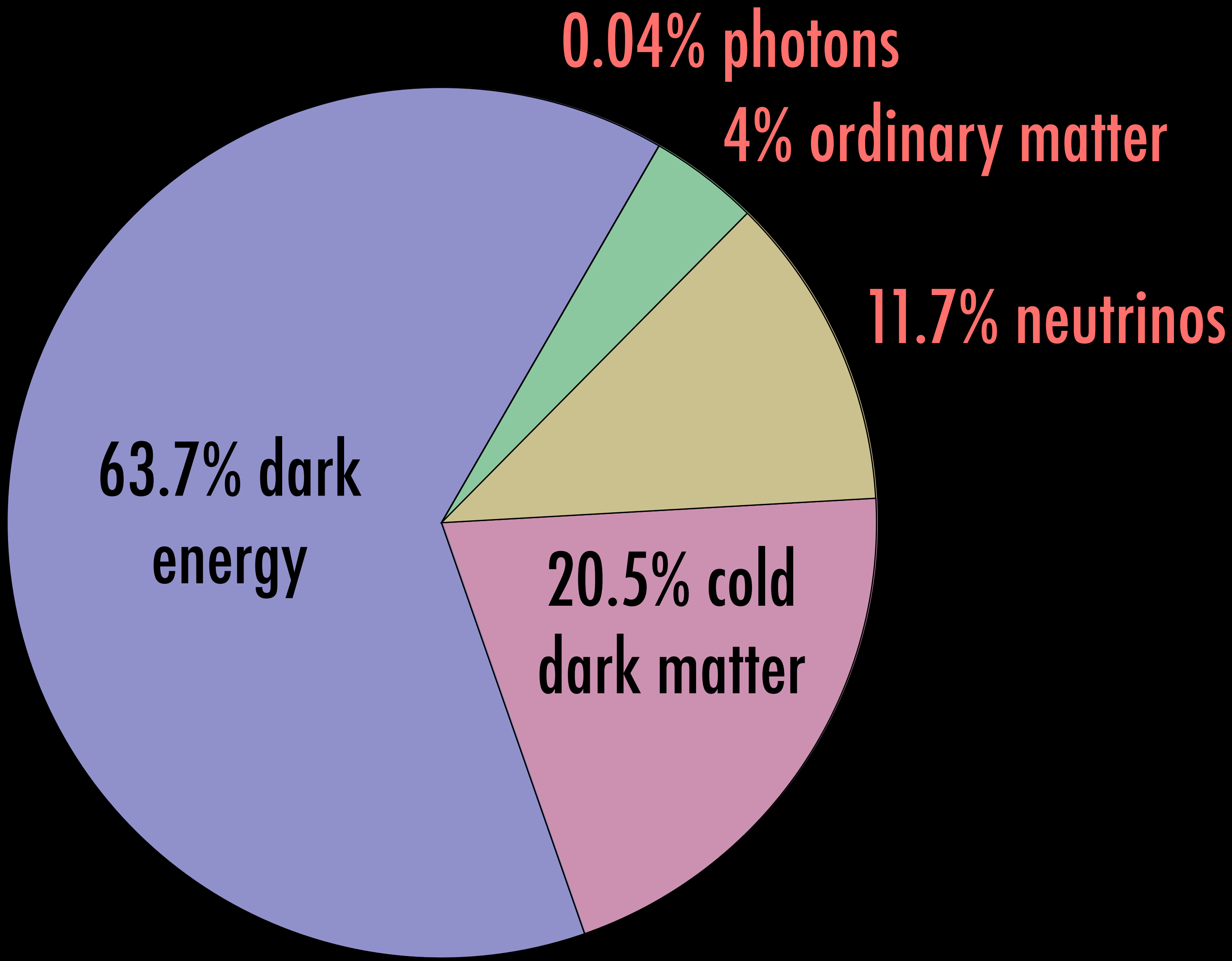
WMAP+SN+BAO (Hinshaw et al. 2008)

Cosmological constant	$\Omega_\Lambda h^2 = 0.354 \pm 0.008$
Matter ($p \approx 0$)	$\Omega_m h^2 = 0.1369 \pm 0.003$
Radiation ($p = \rho/3$)	$\Omega_r h^2 = 2.47 \times 10^{-5}$

Matter $\begin{cases} \text{ordinary matter} & \Omega_b h^2 = 0.02265 \pm 0.00059 \\ \text{neutrinos} & \Omega_\nu h^2 < 0.065 \text{ (95\% C.L.)} \\ \text{cold dark matter} & \Omega_c h^2 = 0.1143 \pm 0.0034 \end{cases}$

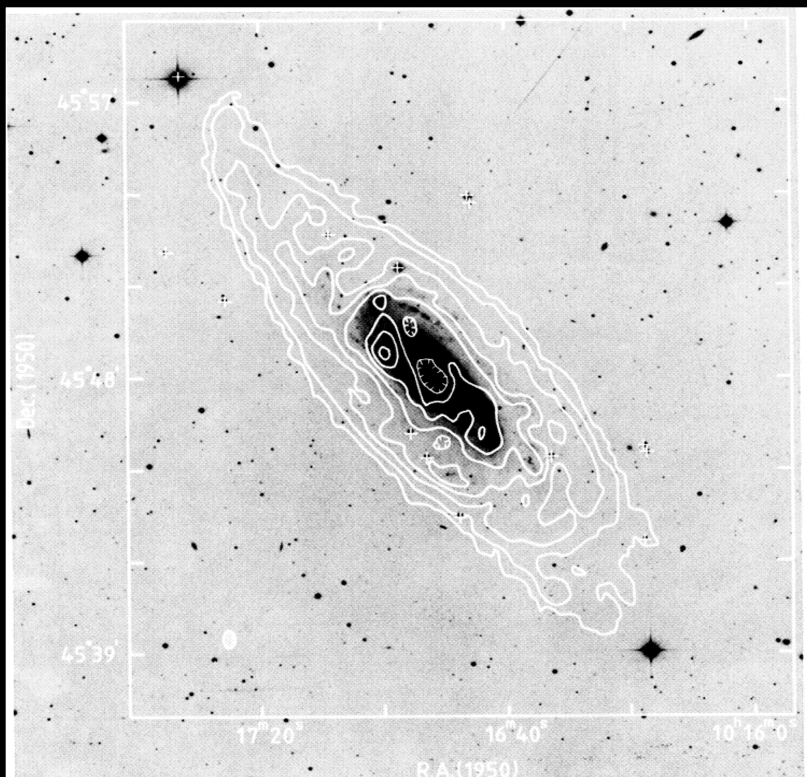
(Units are 1.879×10^{-29} g/cm^3 = 18.79 yg/m^3)

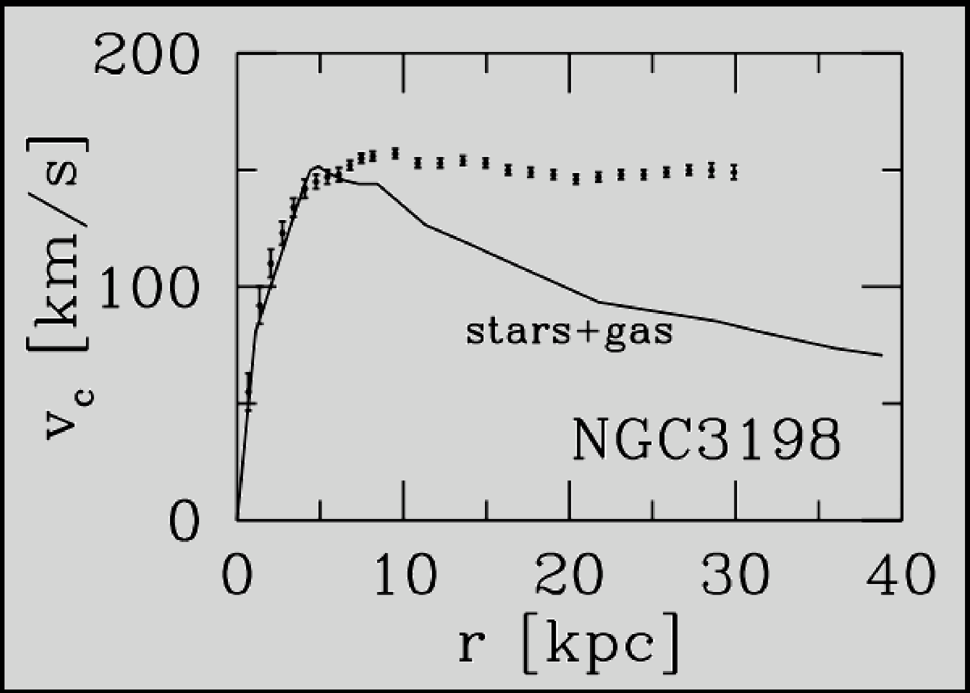
The current content of the Universe



Mass of Galaxies

Galaxies spin faster than gravity of known matter can support





$$M = 1.6 \times 10^{11} M_{\odot} (r / 30\,\mathrm{kpc})$$

$$M_{\mathrm{stars+gas}} = 0.4 \times 10^{11} M_{\odot}$$

$$\frac{M_{\mathrm{total}}}{M_{\mathrm{visible}}} > 4$$

Dark matter

1 pc = 3.08×10^{16} m

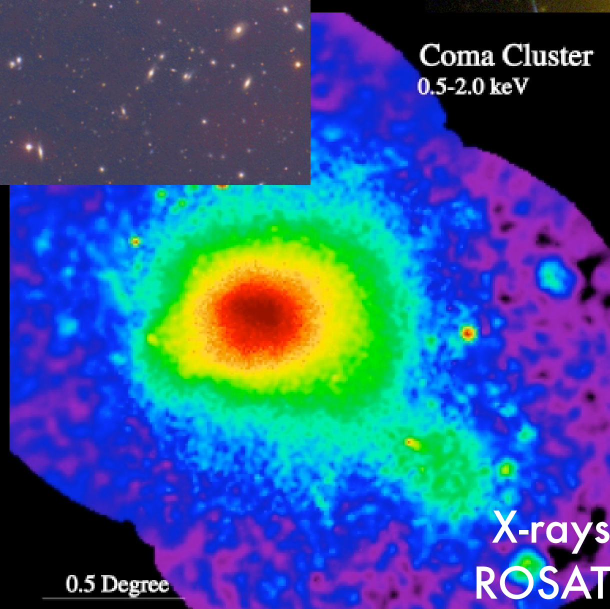
Much more than galactic rotation curves

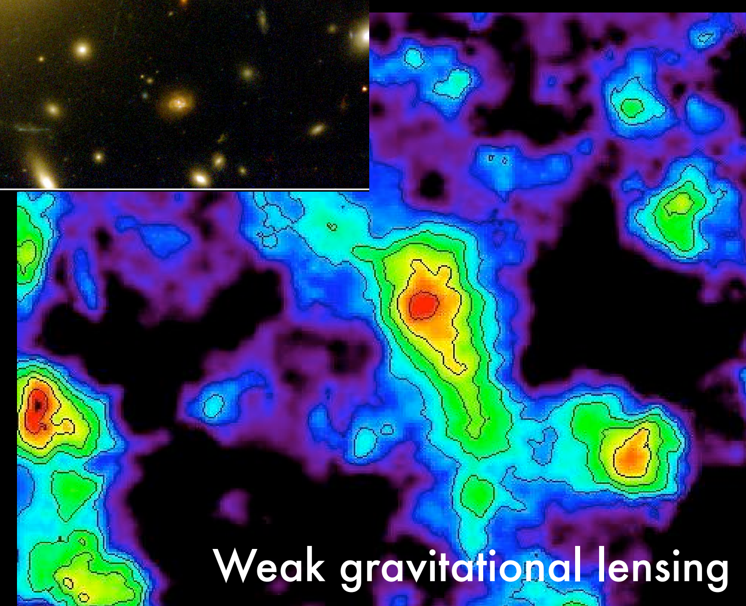
- Dynamics of galaxy clusters (motion of galaxies, gas density and temperature, gravitational lensing)
- Acoustic peaks in Cosmic Microwave Background
- Power spectrum of matter fluctuations
- Primordial nucleosynthesis
- Large Scale Structure formation

Mass of galaxy clusters

Different observations lead to same conclusion: Dark Matter

$$\frac{M_{\text{total}}}{M_{\text{visible}}} \approx 6$$

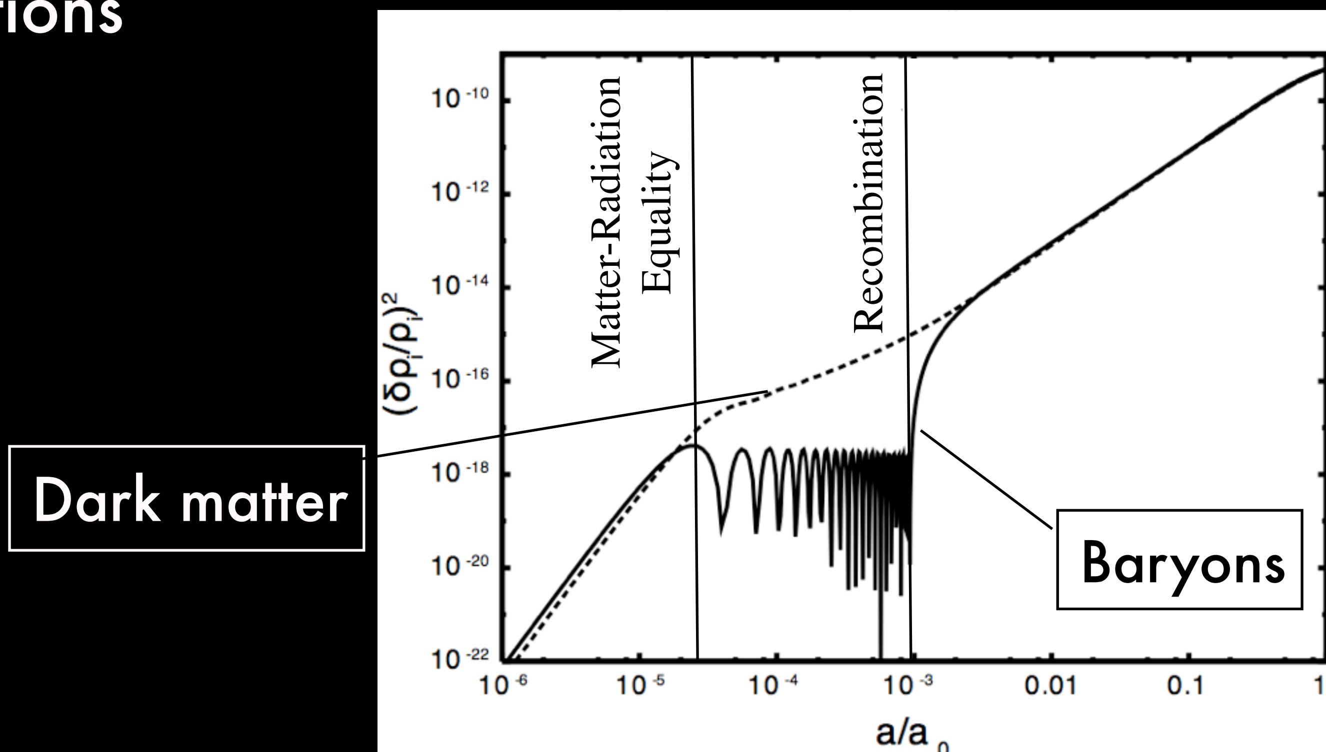




The need for dark matter

Baryon fluctuations start growing at recombination, and grow by a factor of $z_{rec} \approx 1100$ from 10^{-5} to 10^{-2}. Not enough!

Dark matter fluctuations start growing before the baryon fluctuations



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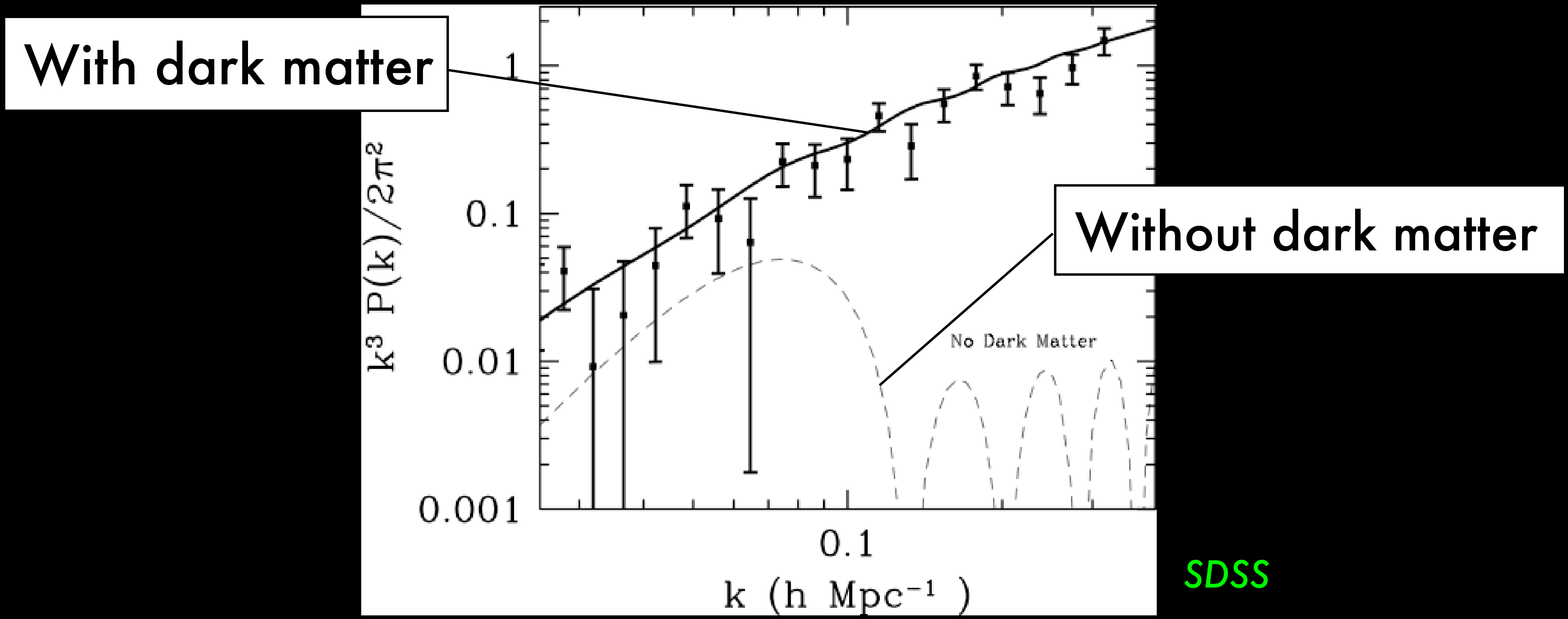
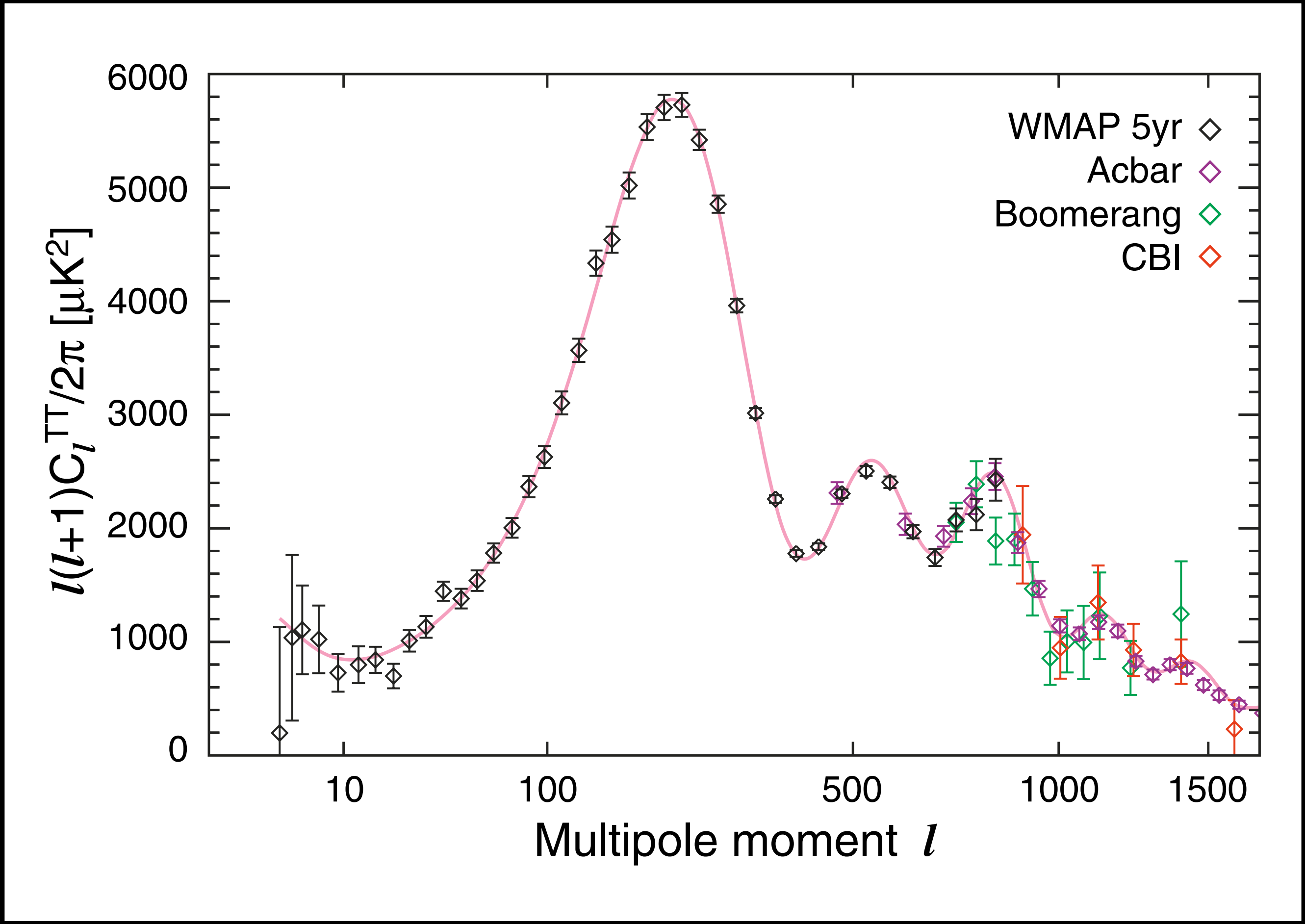


SDSS

Evidence for *non-baryonic* dark matter

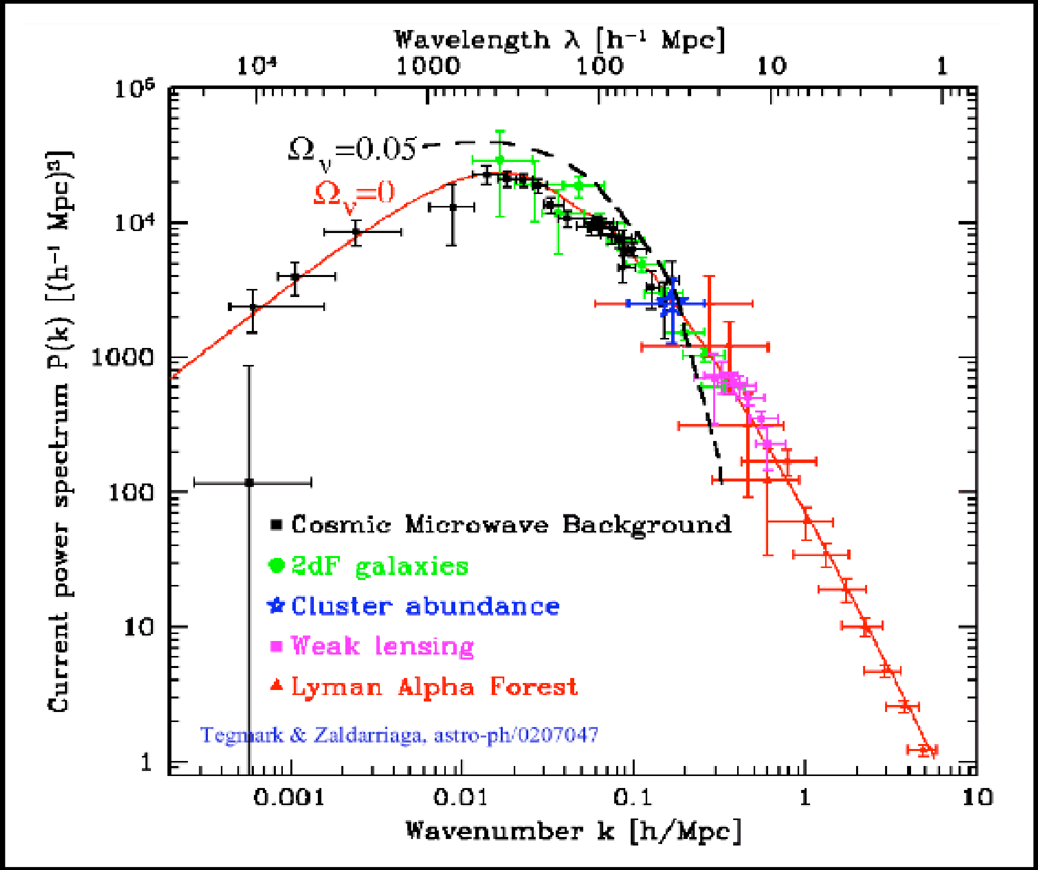
Fact number 1: height of acoustic peaks in the angular spectrum of the Cosmic Microwave Background

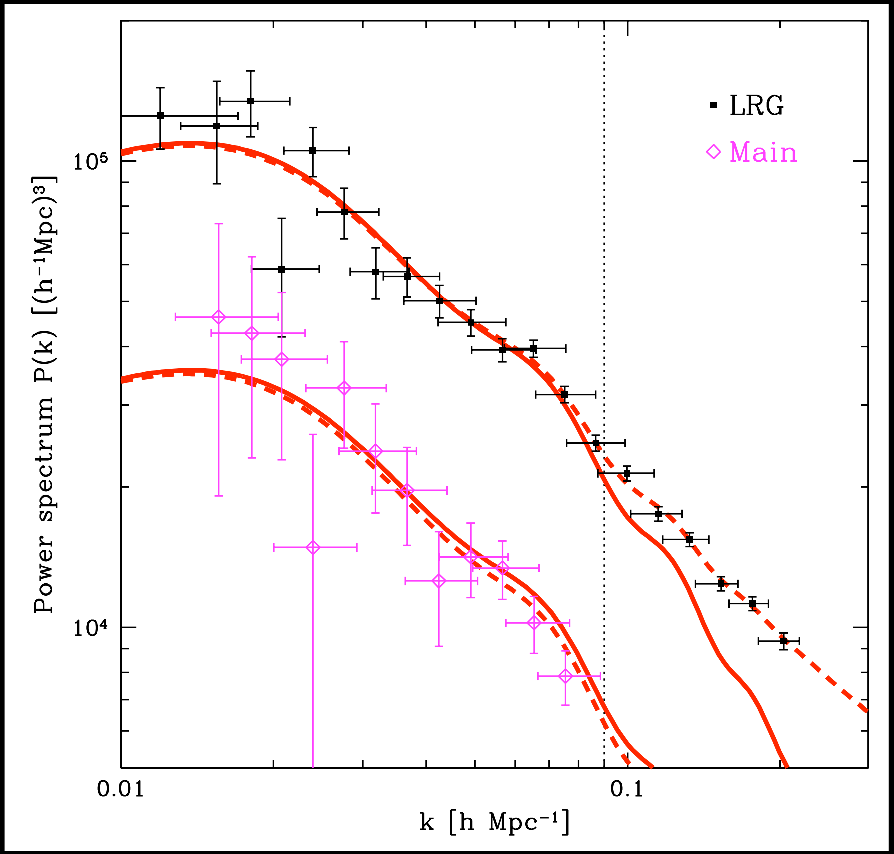


WMAP

Evidence for *non-baryonic* dark matter

Fact number 2: Change of slope in power spectrum of density fluctuations $P(k)$

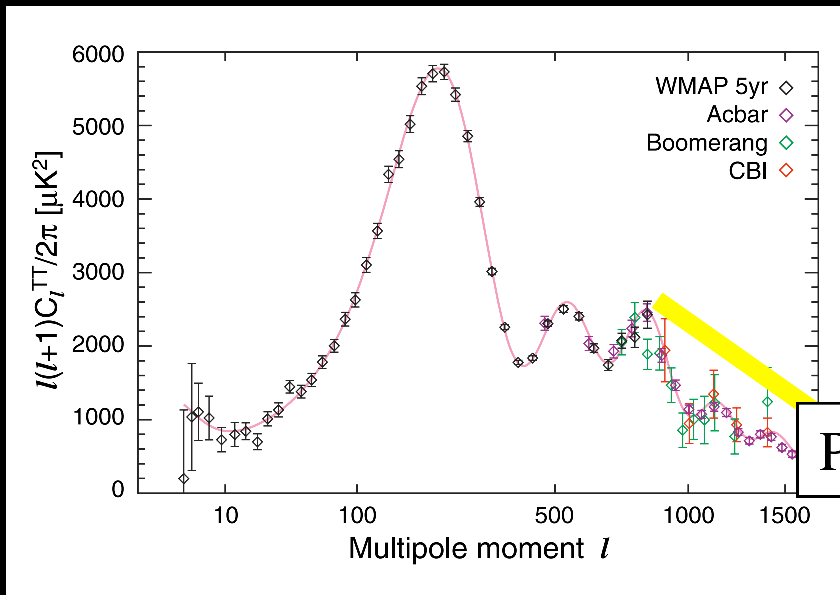


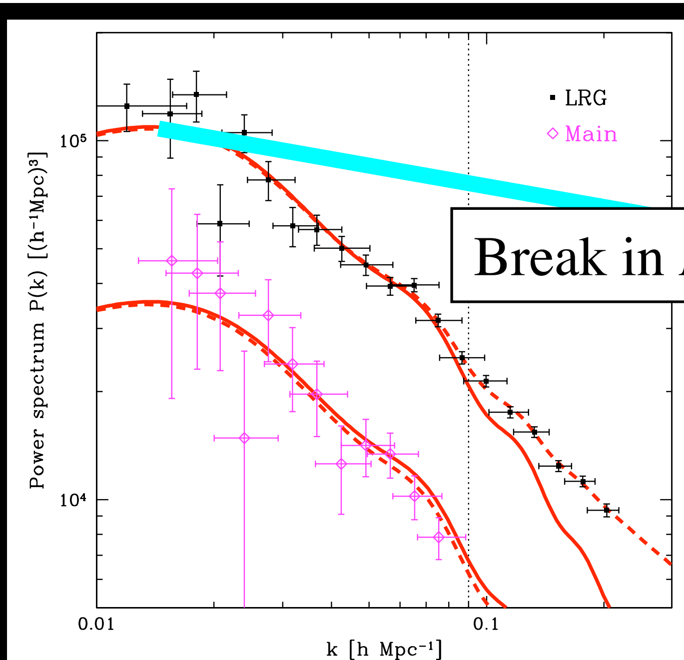


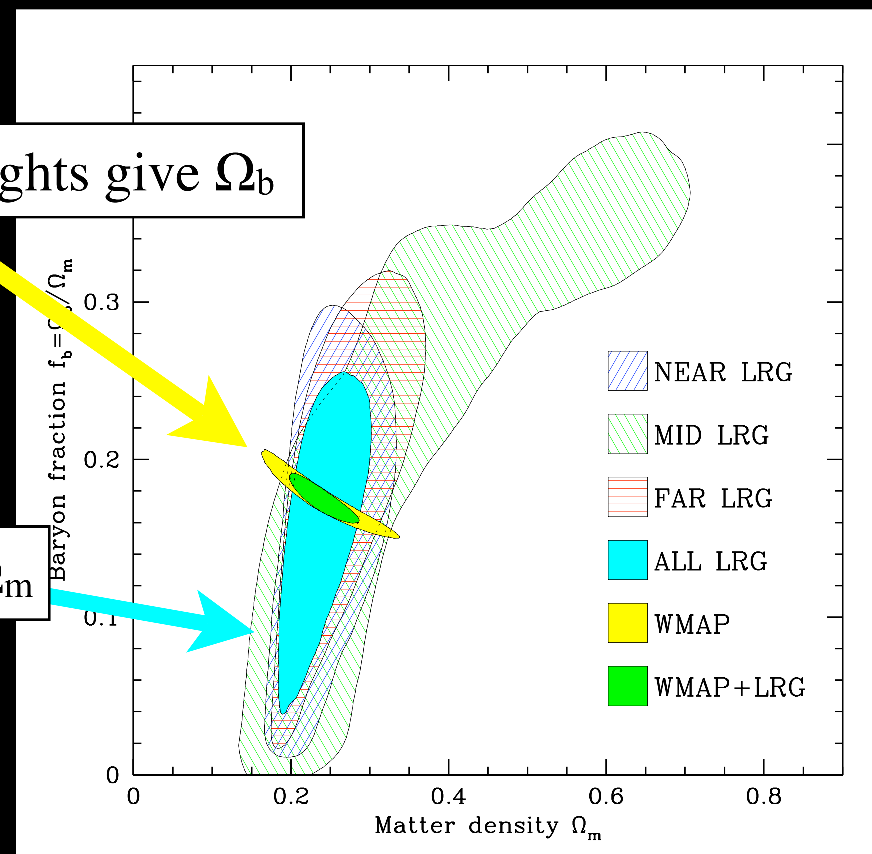
Tegmark

SDSS

Evidence for *non-baryonic* dark matter





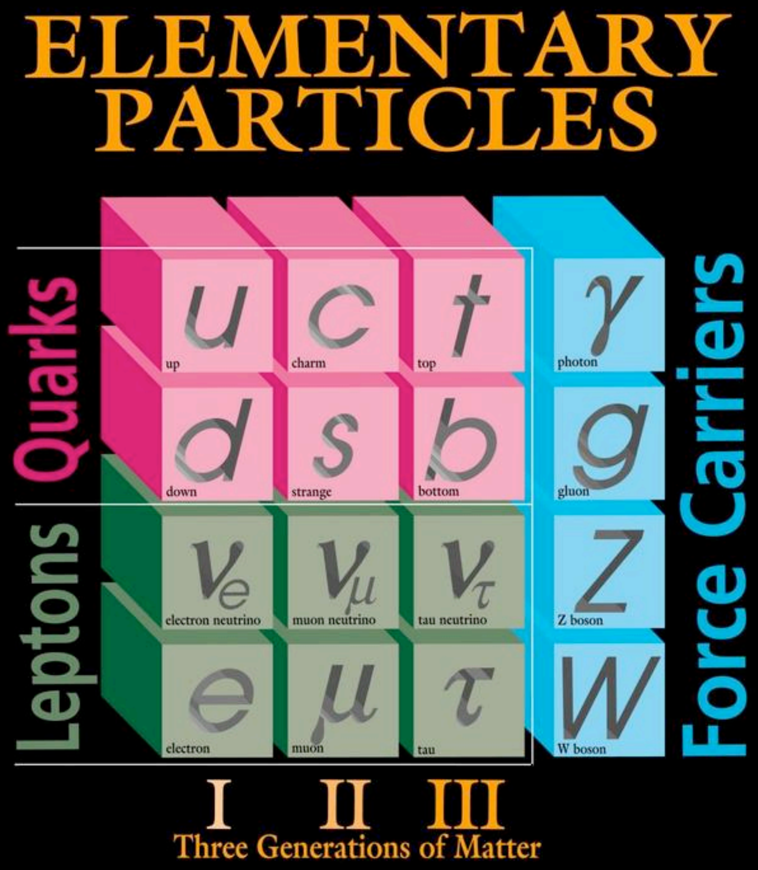


Peak heights give Ω_b

Break in $P(k)$ gives Ω_m

Tegmark et al (SDDS) 2006

No known particle can be cold dark matter



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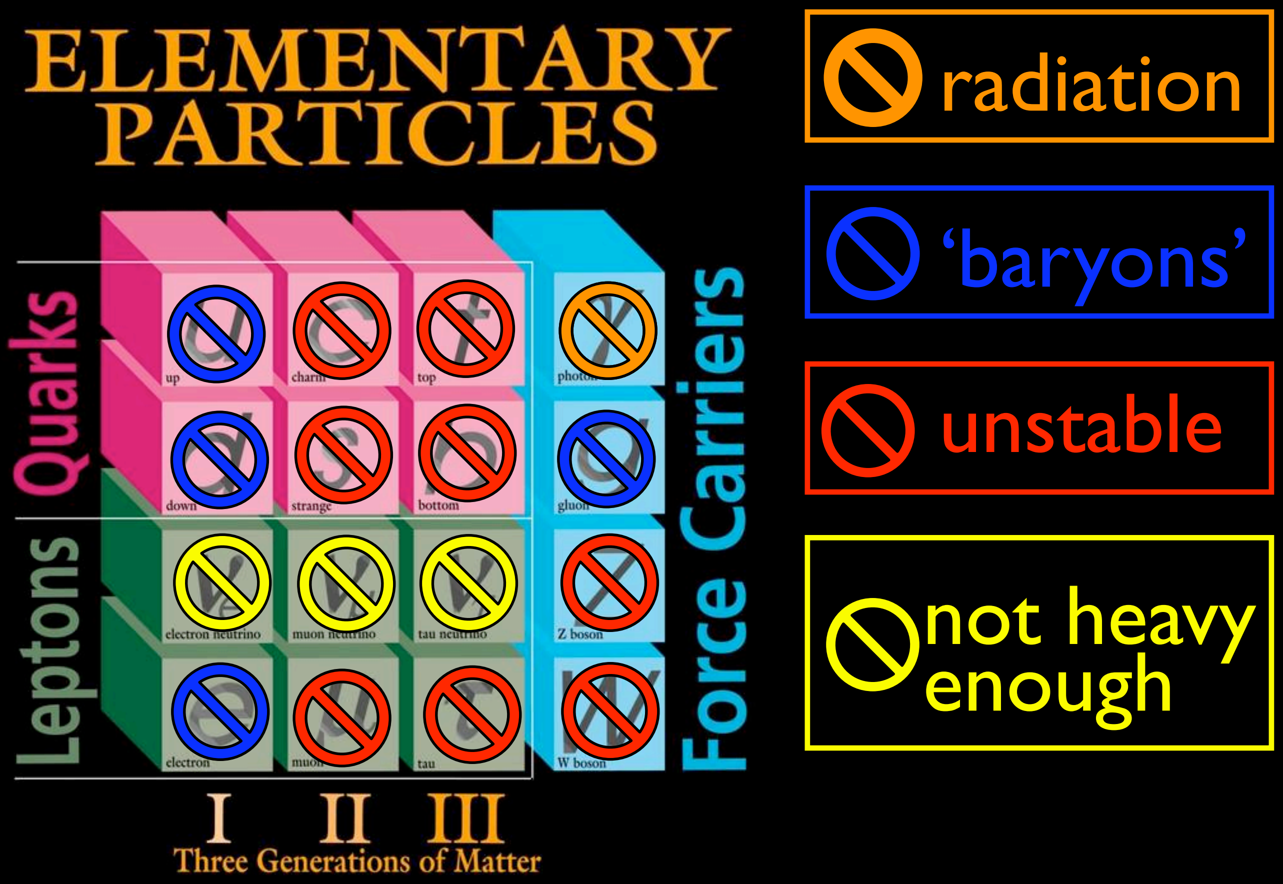

Is cold dark matter a new elementary particle?

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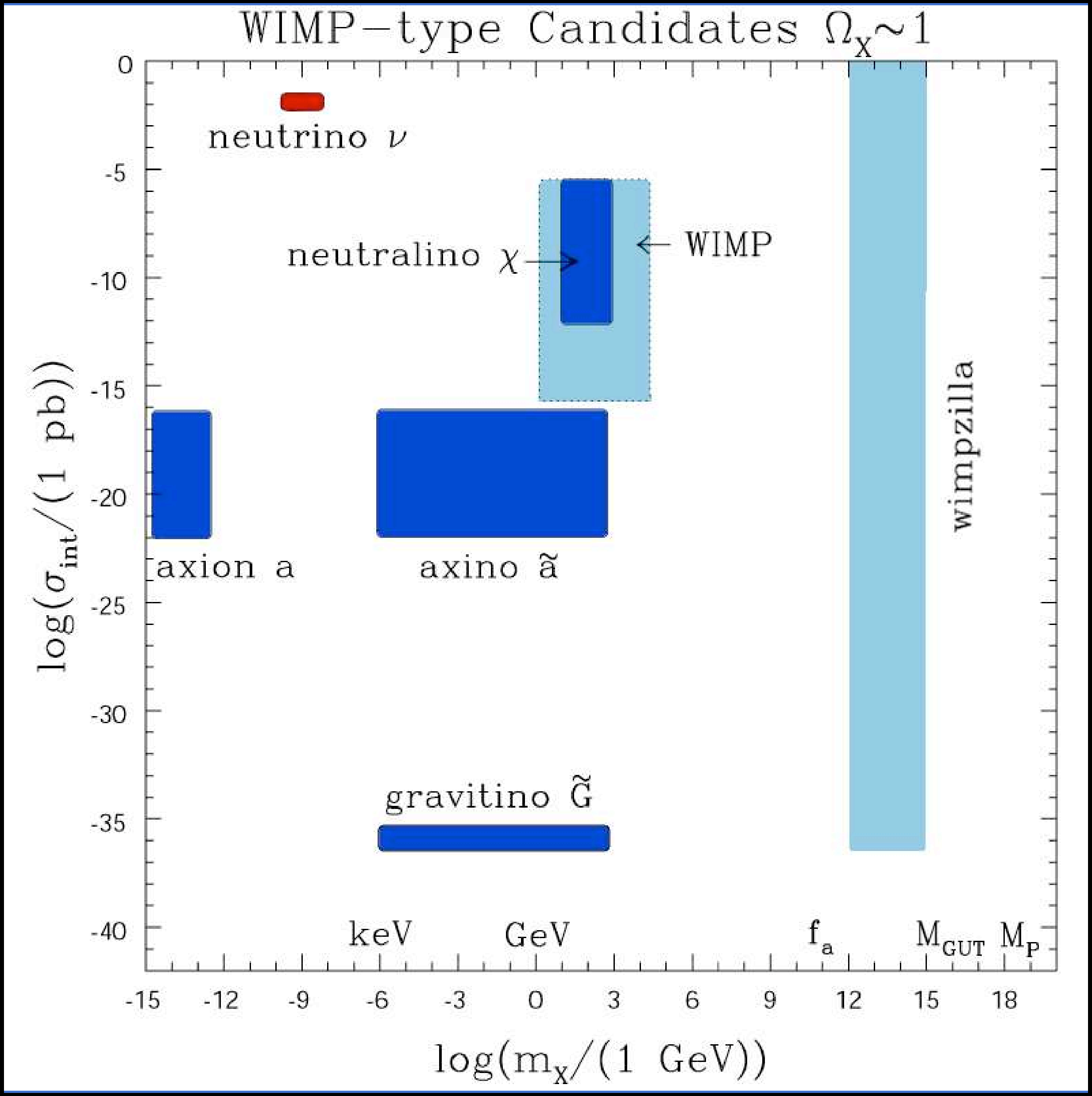
Ideas from theoretical particle physics:

- From Quantum Chromodynamics:
  - Axions
- From Grand Unified Theories & String Theories:
  - Lightest Supersymmetric Particle
- From String Theories & Extra-dimensions:
  - Kaluza-Klein Particle
- Etc., etc., etc.

Many candidates for non-baryonic dark matter



Roszkowski 2004

The wonder WIMP

Weakly Interacting Massive Particle

A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter

The wonder WIMP

Weakly Interacting Massive Particle

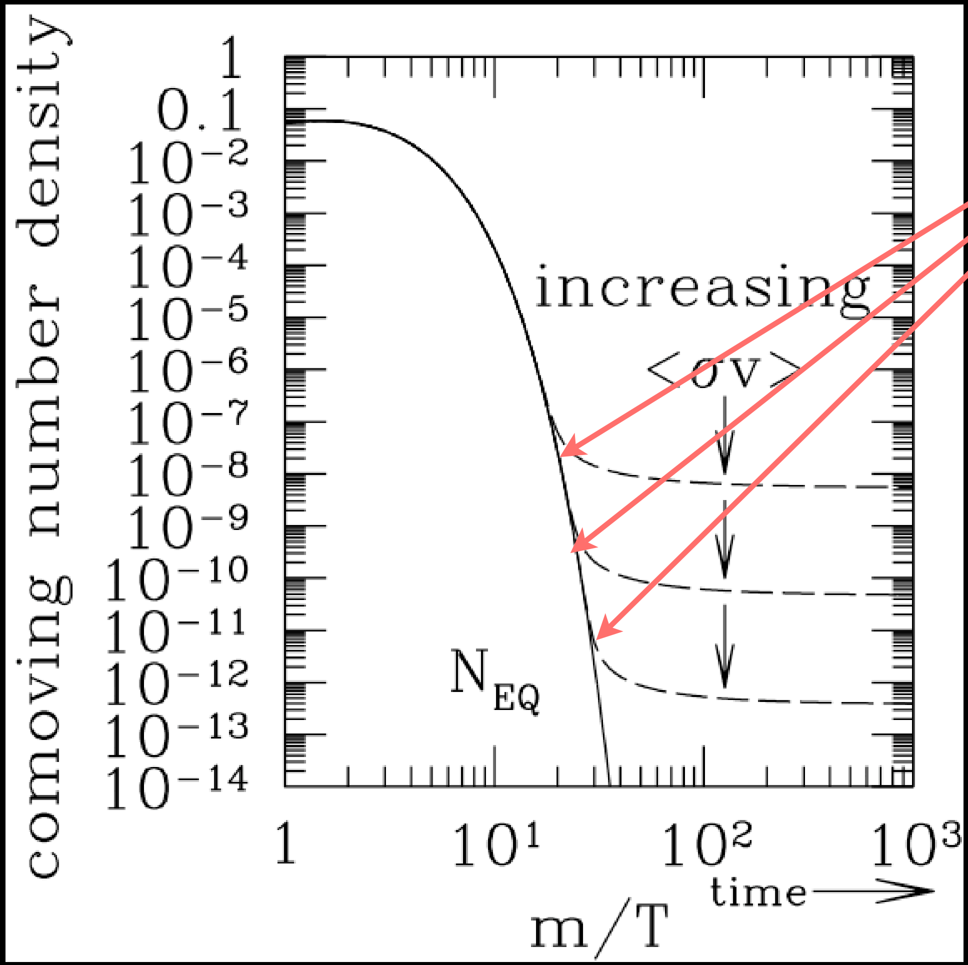
A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter

- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

$$\chi + \chi \leftrightarrow e^+ + e^-, \mu^+ + \mu^-, \mathrm{etc.}$$

- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [*freeze-out*].
- After freeze-out, the number of WIMPs per photon is constant.

The WIMP annihilation cross section determines its cosmological density



freeze-out

$$\Gamma_{\text{ann}} \equiv n\langle \sigma v \rangle \sim H$$

annihilation rate *expansion rate*

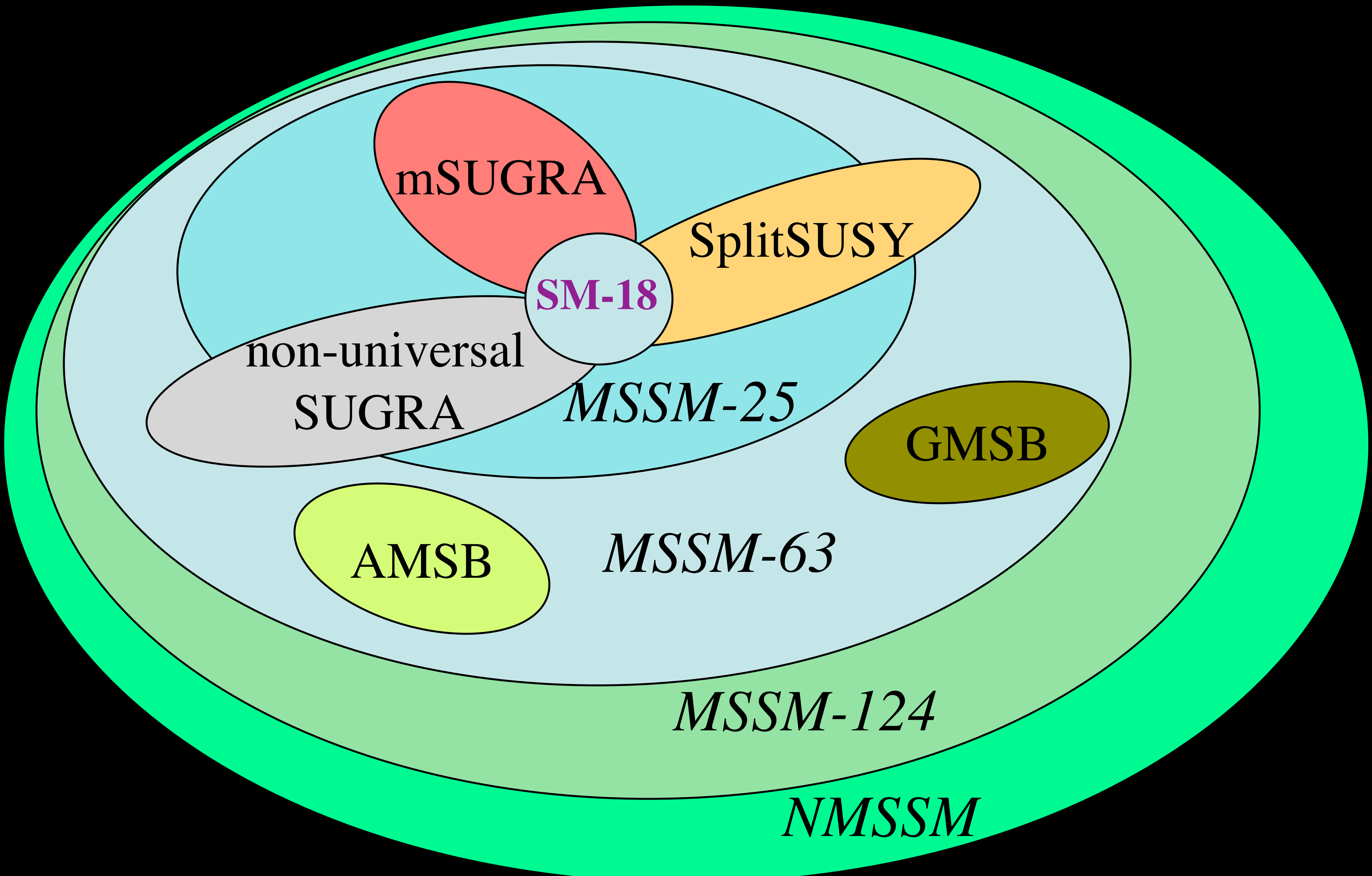
$$\boxed{\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{cm}^3/\text{s}}{\langle \sigma v \rangle_{\text{ann}}}}$$

$$\Omega_\chi h^2 = \Omega_{\text{cdm}} h^2 \simeq 0.1143$$

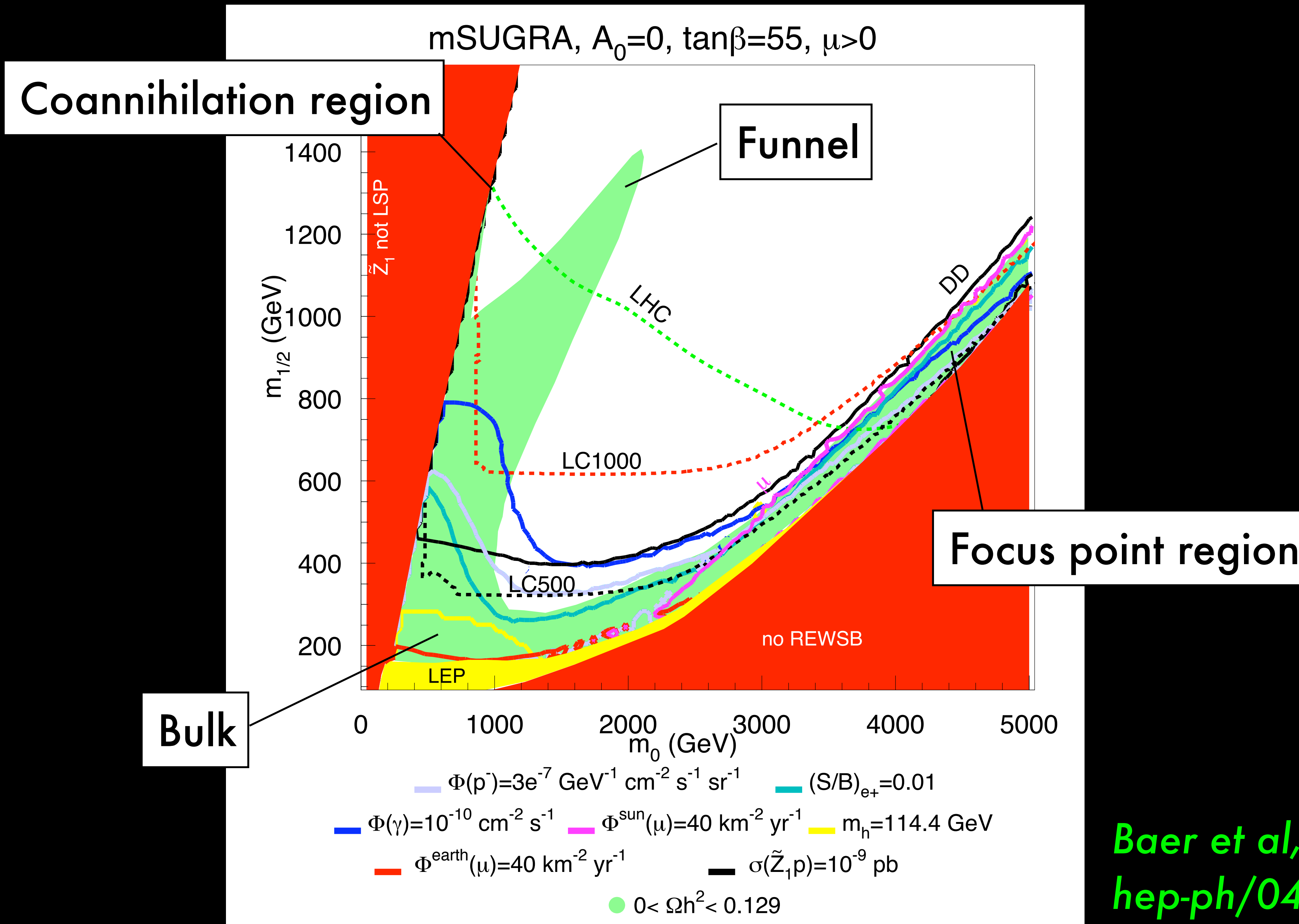
for $\langle \sigma v \rangle_{\text{ann}} \simeq 3 \times 10^{-26} \text{cm}^3/\text{s}$

Modern tools handle concomitant annihilation (co-annihilation) of many particles into many final states

The set-theory diagram of SUSY models

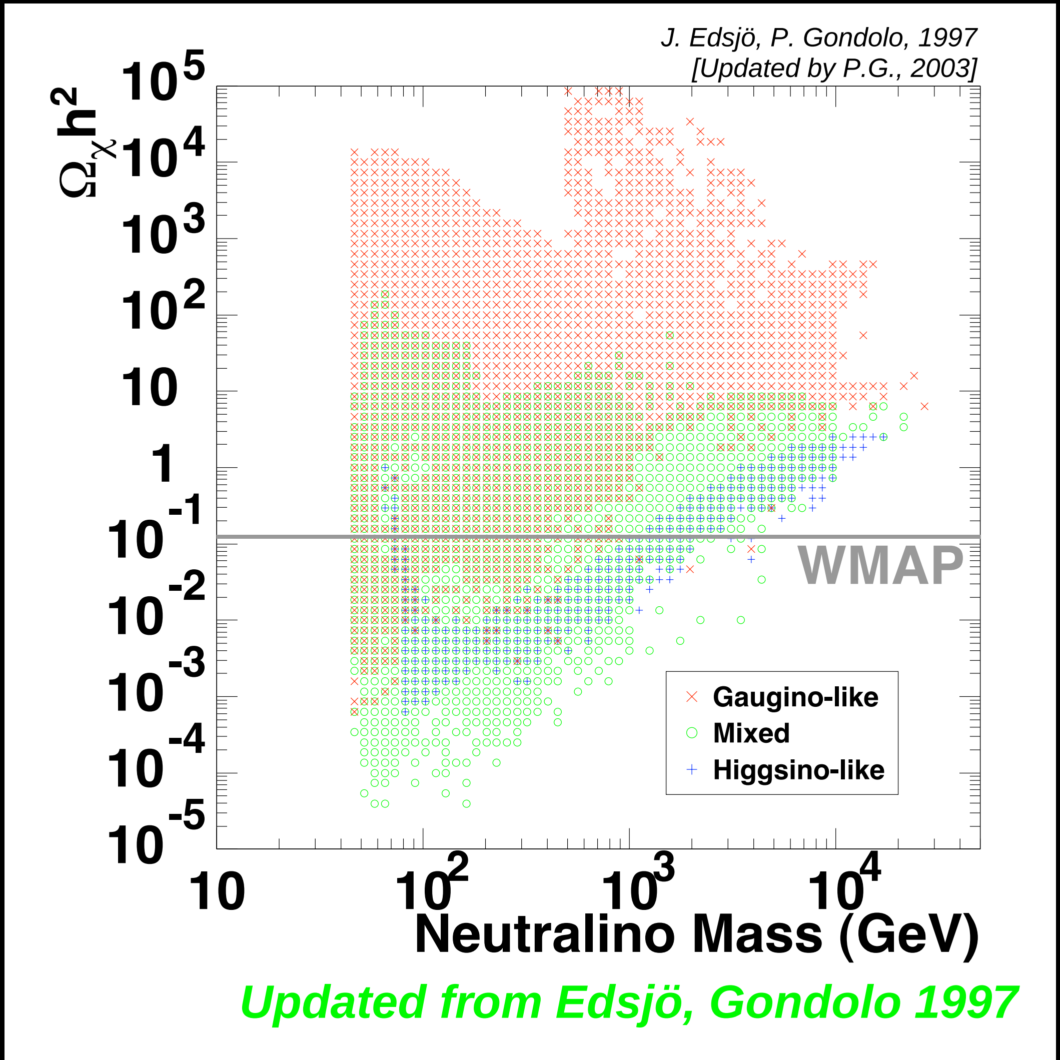


Neutralino dark matter: mSUGRA



Baer et al, hep-ph/0405210

Neutralino dark matter: MSSM-25



The density of points in parameter space

- Results of Bayesian analyses depend on priors

$$P(\theta|\text{data}) = \frac{\text{Likelihood}(\text{data}|\theta)\,\text{Prior}(\theta)\,d\theta}{\text{Evidence}(\text{data})}$$

- Priors describe our beliefs in the value of the model parameters

The density of points in parameter space

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- Example: a scan in parameter space using an anthropic prior

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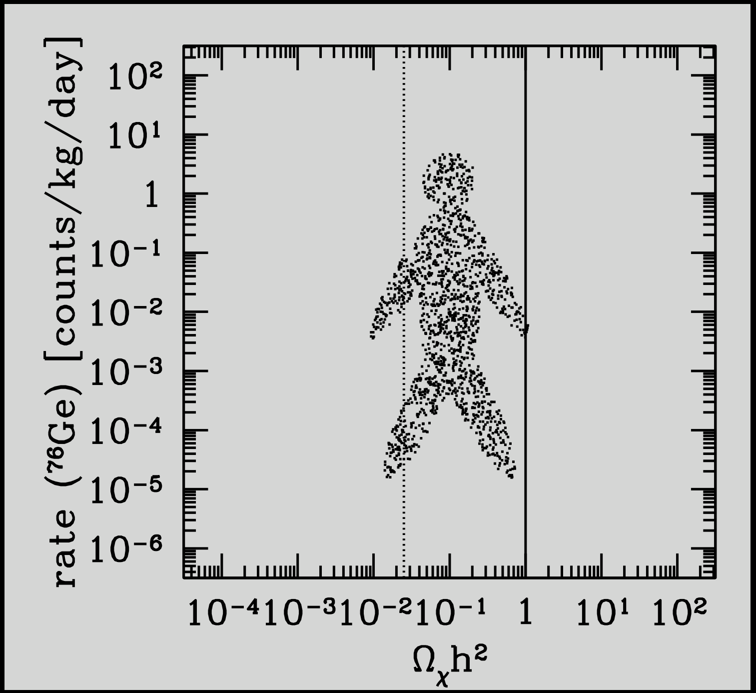

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- Priors describe our beliefs in the value of the model parameters

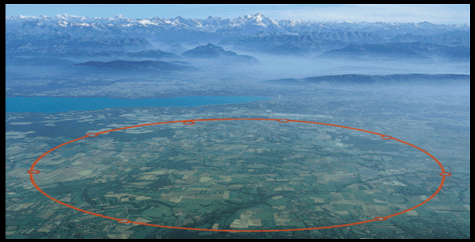
- What is a sensible prior for M_2, say?
  - Flat in M_2? Flat in $\log(M_2)$? Exponential in $\arctan(M_2)$?

More supersymmetric dark matter

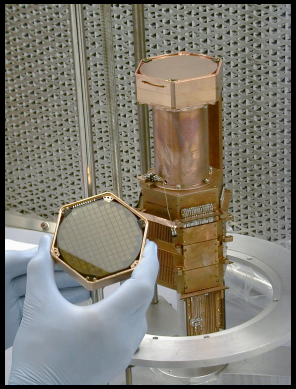
- **SuperWIMPs**
  they solve the Lithium problem in primordial nucleosynthesis
- **Sneutrinos**
  they may account for the DAMA modulation
- **Gravitinos**
  they may solve the "satellite problem" but are undetectable
- **Particles in the hidden sector**
  they might have the right properties for Cold Dark Matter
- **NMSSM (Next-to-Minimal Susy Standard Model)**
  more parameters, more possibilities
- ......

Searches for WIMP Dark Matter

- Accelerators
- Direct detection
- Indirect detection (neutrinos)
  - Sun
  - Earth
- Indirect detection (gamma-rays, positrons, antiprotons)
  - Milky Way halo
  - External galaxies
  - Galactic Center



LHC



CDMS

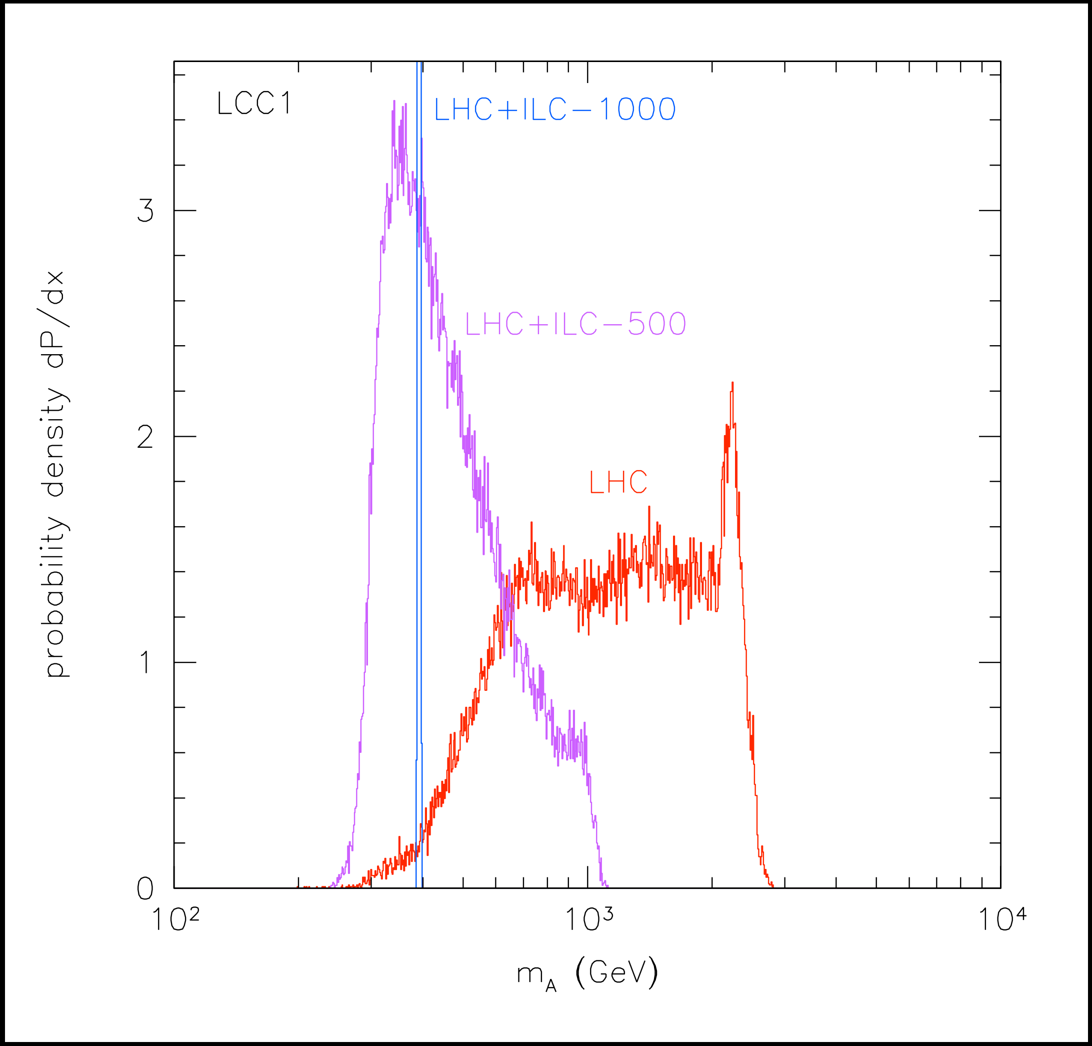
IceCube

GLAST

Dark matter in accelerators

- Existence of dark matter particle to be inferred from detection of charged/colored particles
- Theoretical model needed for interpretation
- Thus variety of possible scenarios: neutralinos, superWIMPs, Kaluza-Klein particles, etc.

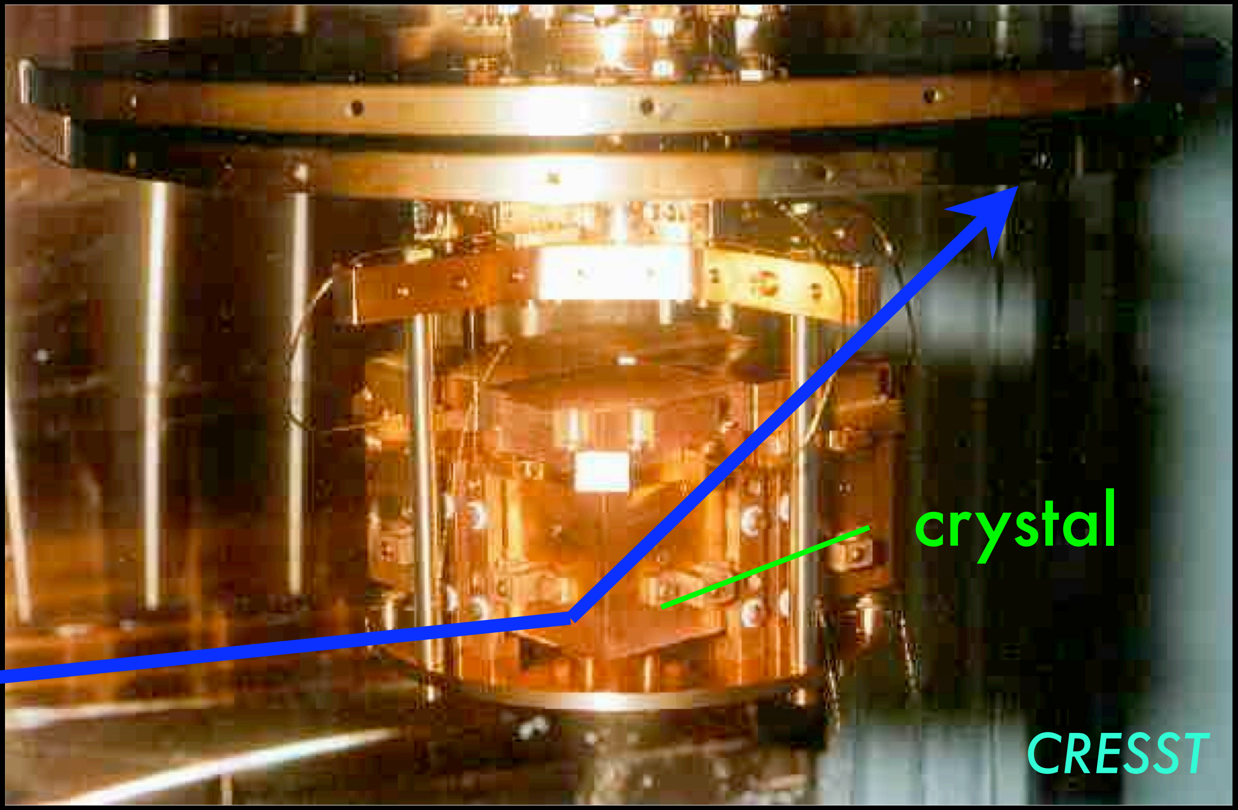
WIMP mass from the LHC



From Baltz et al. 2006

Direct detection

Dark matter particle



Low-background underground detector

CDMS
EDELWEISS
DAMA
CRESST
DRIFT
XENON
COUPP
TARP
DMTPC
TEXONO
...

WIMP mass from direct detection experiments

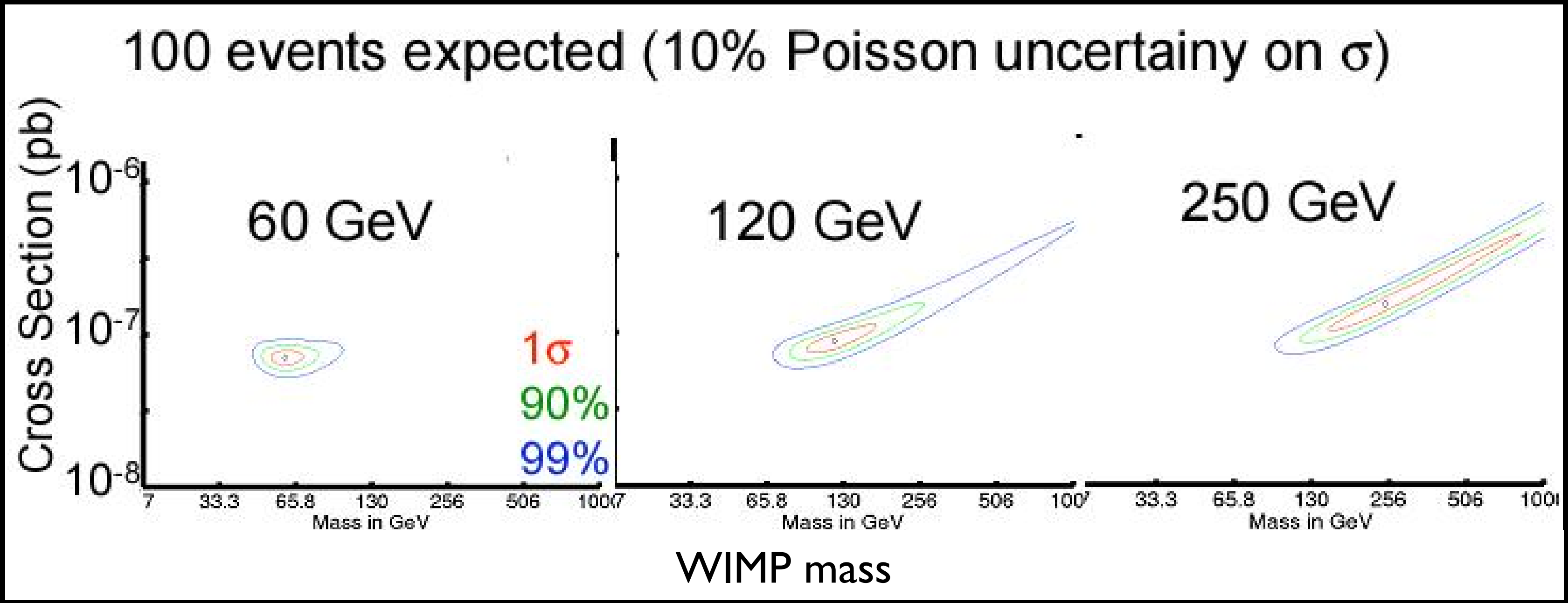
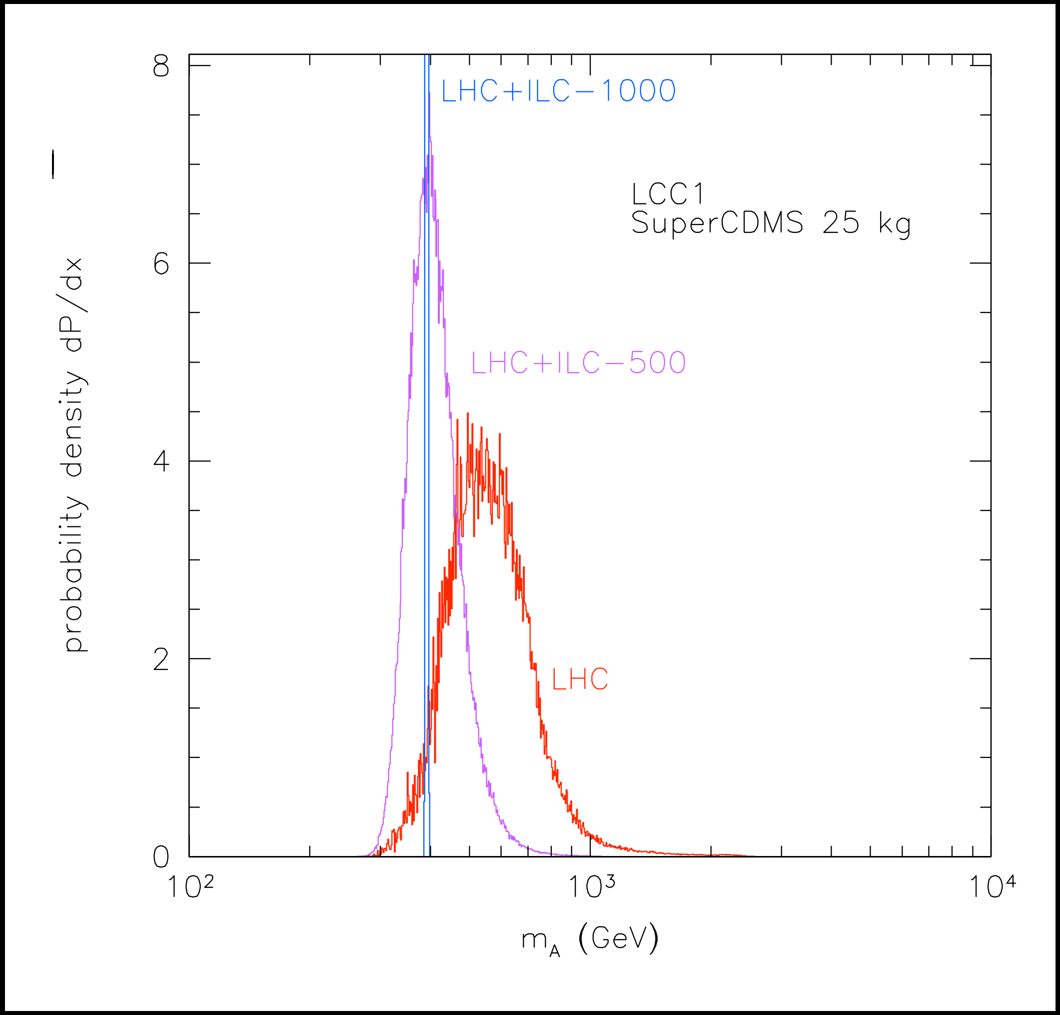


Figure from Schnee

Direct detection experiments
can measure m_{WIMP} if it is below ~100 GeV

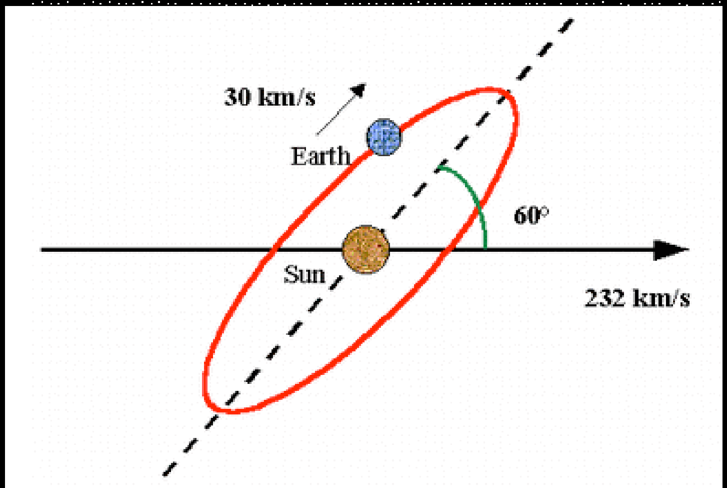
WIMP mass from the LHC + direct detection



From Baltz et al. 2006

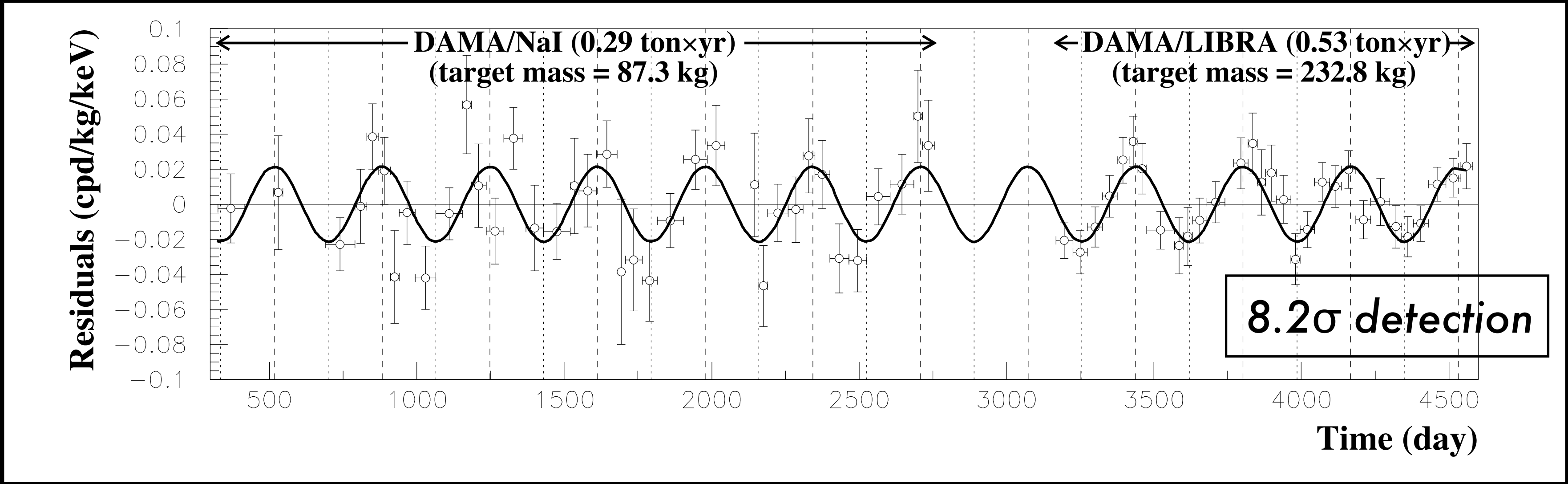
The DAMA modulation

DAMA finds a yearly modulation as expected for dark matter particles



Drukier, Freese, Spergel 1986

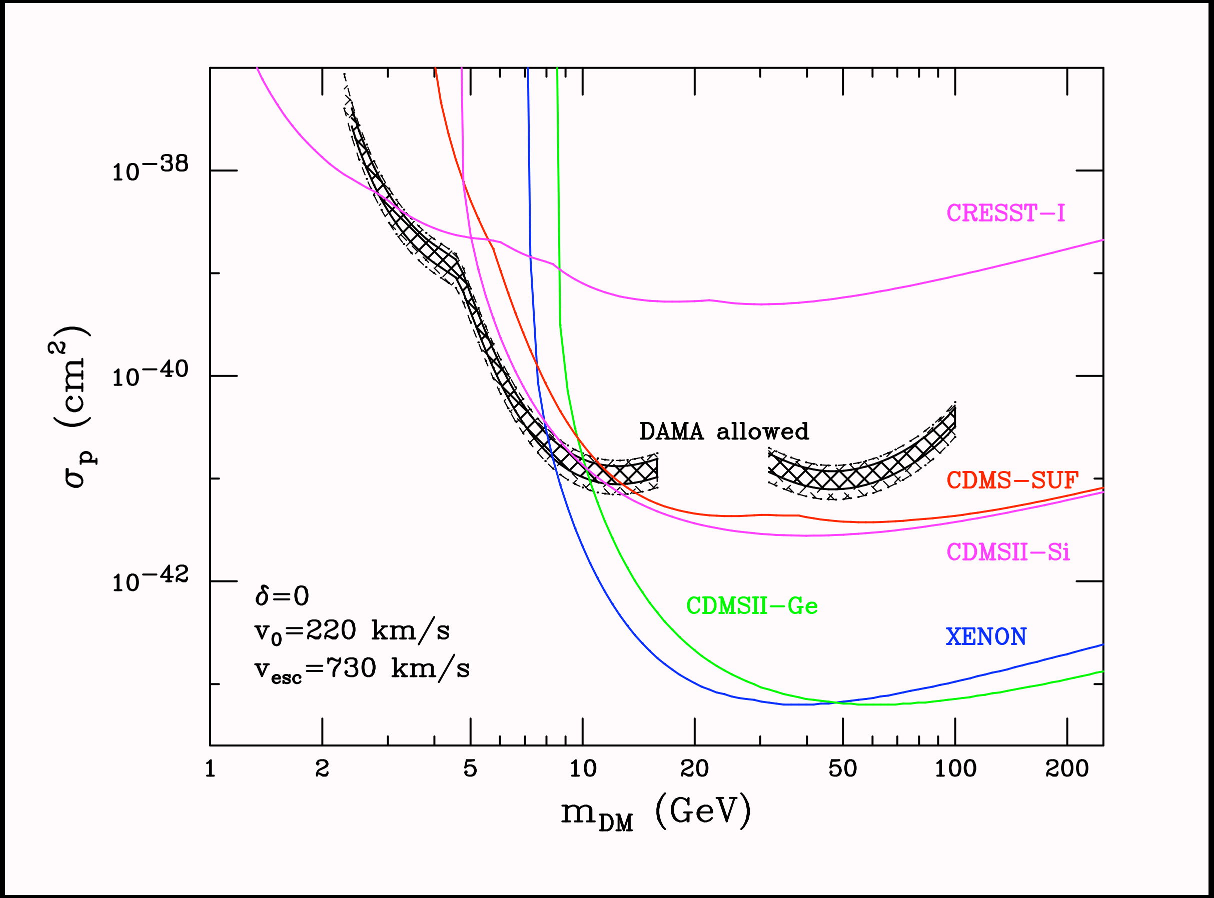
Bernabei et al 2003-2008



Interpretation of DAMA modulation

Low mass WIMPs are compatible with other experiments

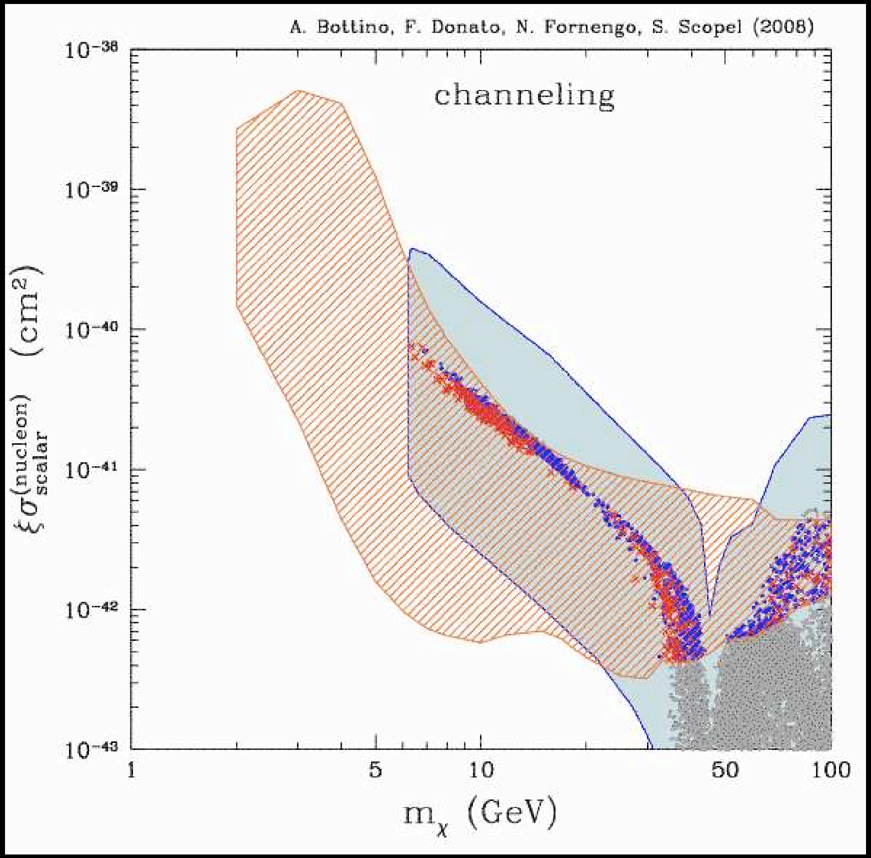
Gondolo, Gelmini 2005; Petriello, Zurek 2008

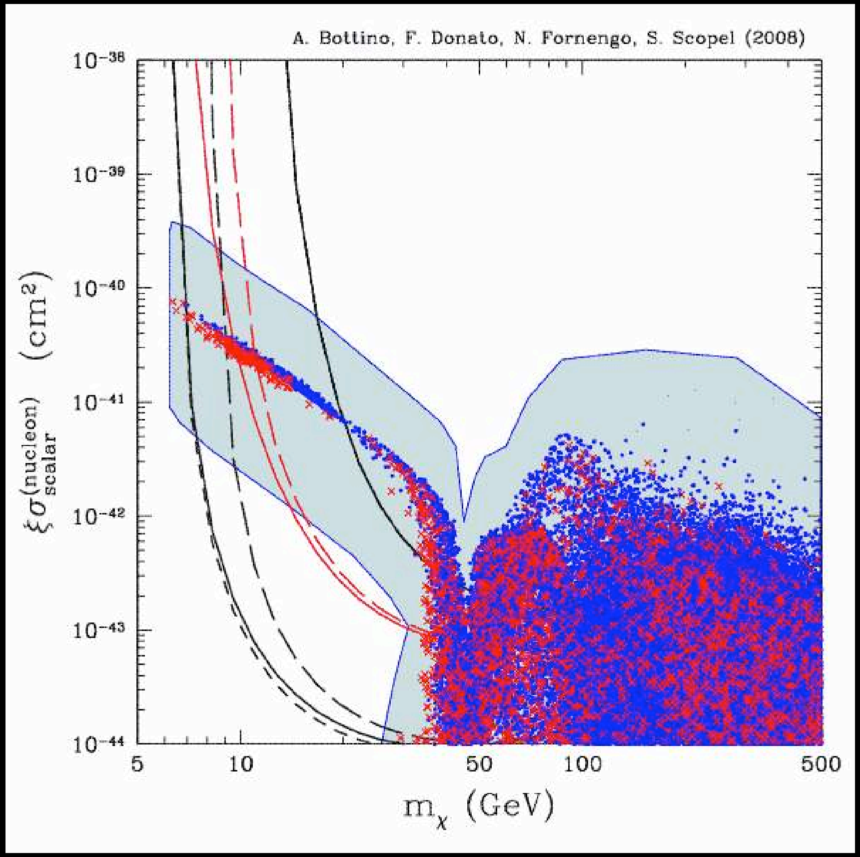


Interpretation of DAMA modulation

Neutralino with mass between ~5 GeV and ~50 GeV

Bottino, Donato, Fornengo, Scopel
2003-2008





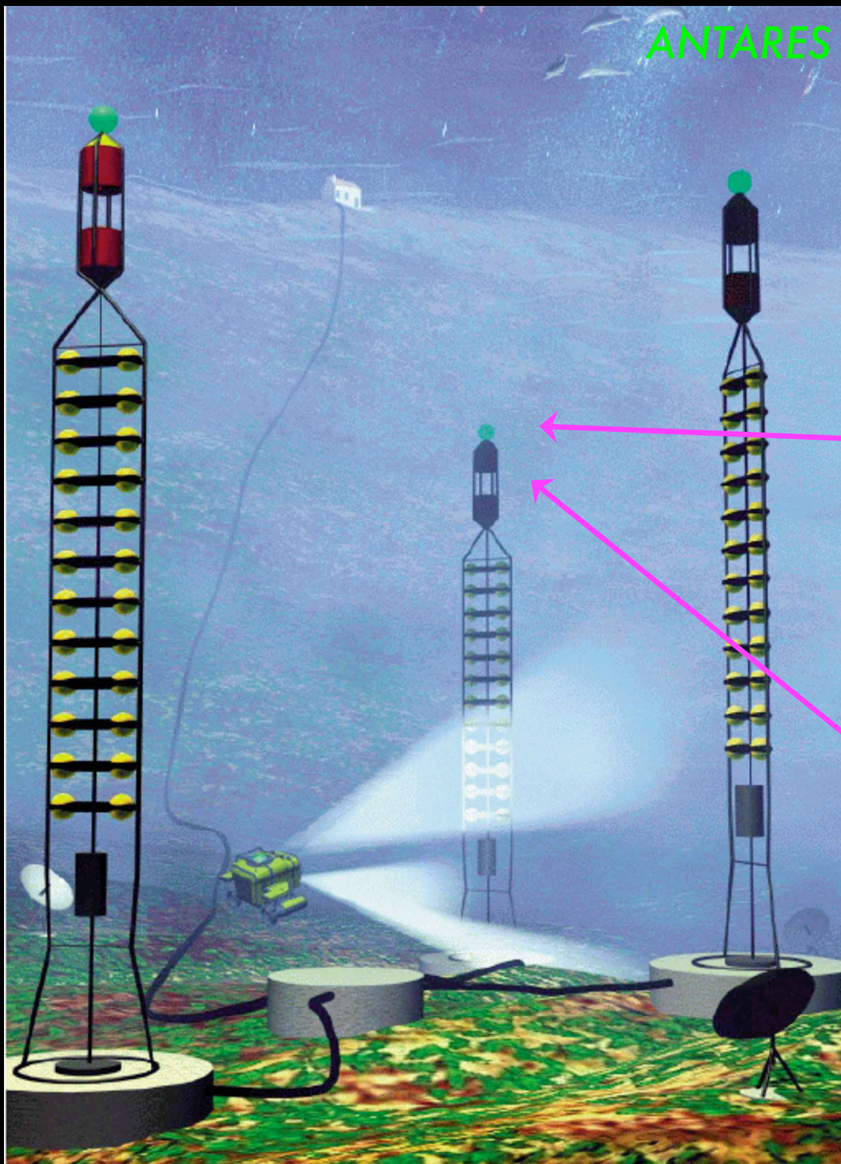
Indirect detection

The same annihilation cross section that determines the WIMP relic density fixes the rate of WIMP annihilation in indirect searches (but for kinematical factors)

Annihilation of neutralinos is important wherever dark matter density is high ($\Gamma \propto \rho^2$):

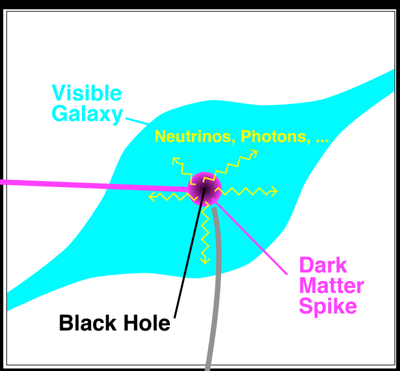
- Early universe (gives right relic density)
- Earth, Sun, Galaxy, the first stars

Indirect searches: neutrinos



Kamiokande
AMANDA
ANTARES
IceCube
...

Black Hole at
Galactic Center

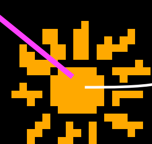


neutrino

dark
matter

neutrino

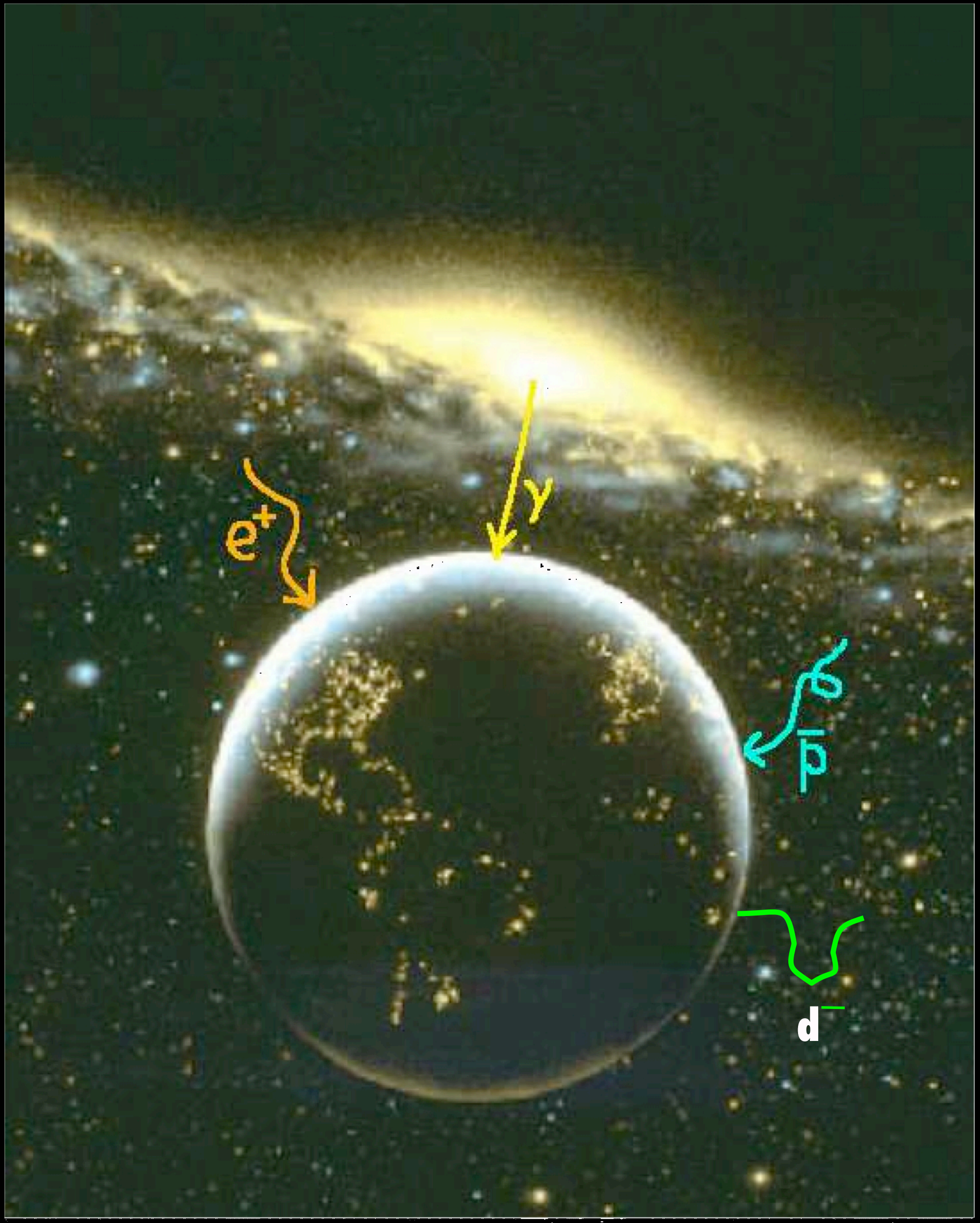
Sun



Neutrinos from Sun, Earth, and Galactic Center

- “Mature” modelling for Sun and Earth
  - Neutrino oscillations are relatively unimportant
- Still crude modelling for Galactic Center
  - “Multi-messenger” observations are beneficial (synchrotron, radio, gamma, neutrino)

Indirect searches



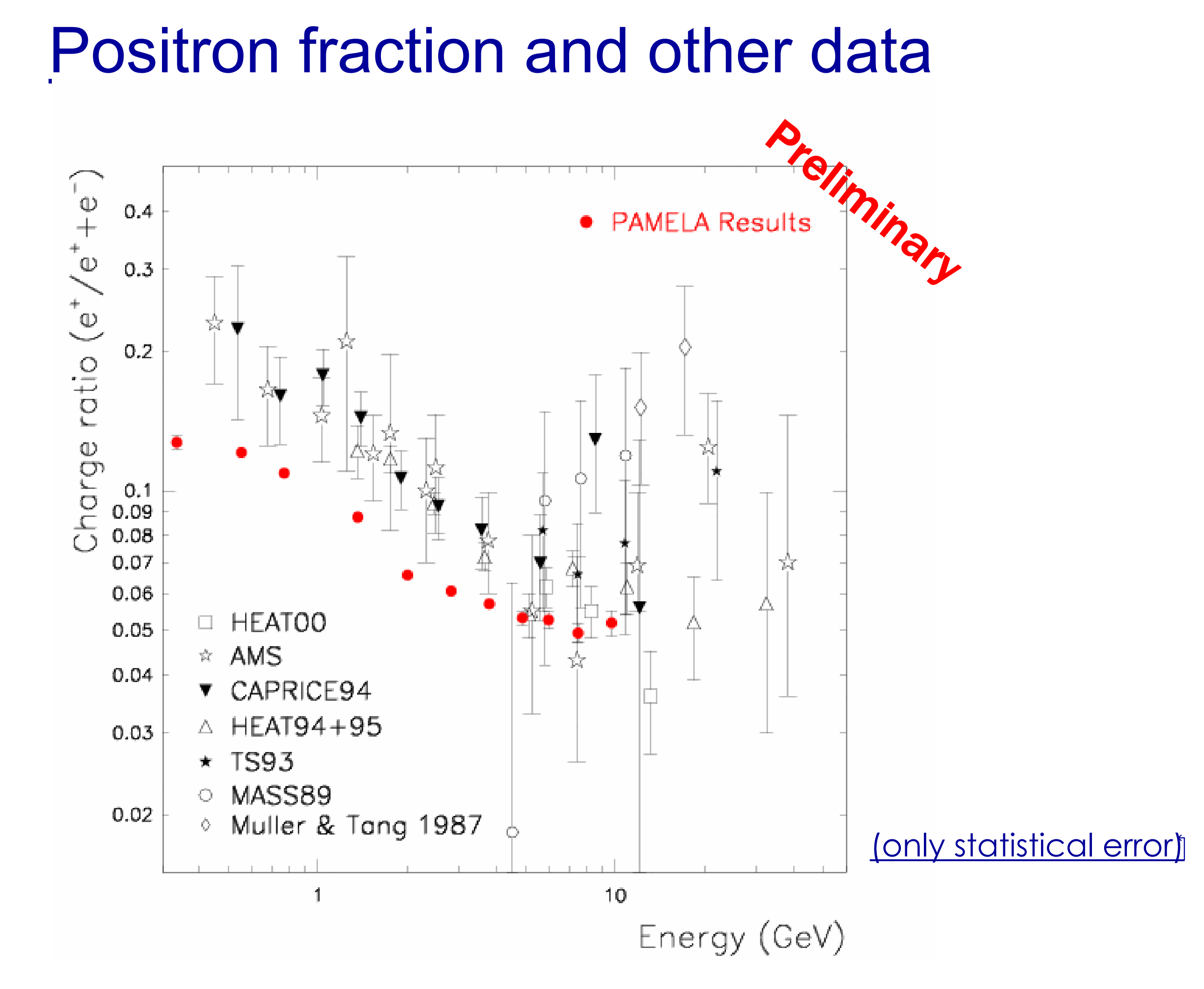
Background by J. Lomberg 1989

HEAT
BESS
PAMELA
AMS
GAPS
EGRET
HESS
MAGIC
VERITAS
GLAST
STACEE
CACTUS
...

Positrons/Antiprotons/Antideuterons

- Strong dependence on propagation model
- Still tuning the galactic cosmic ray model
  - Uncertainties in the size of diffusion region, energy dependence of diffusion constant, spatial dependence of diffusion constant, reacceleration, galactic winds, etc.

Positrons/Antiprotons/Antideuterons



PAMELA

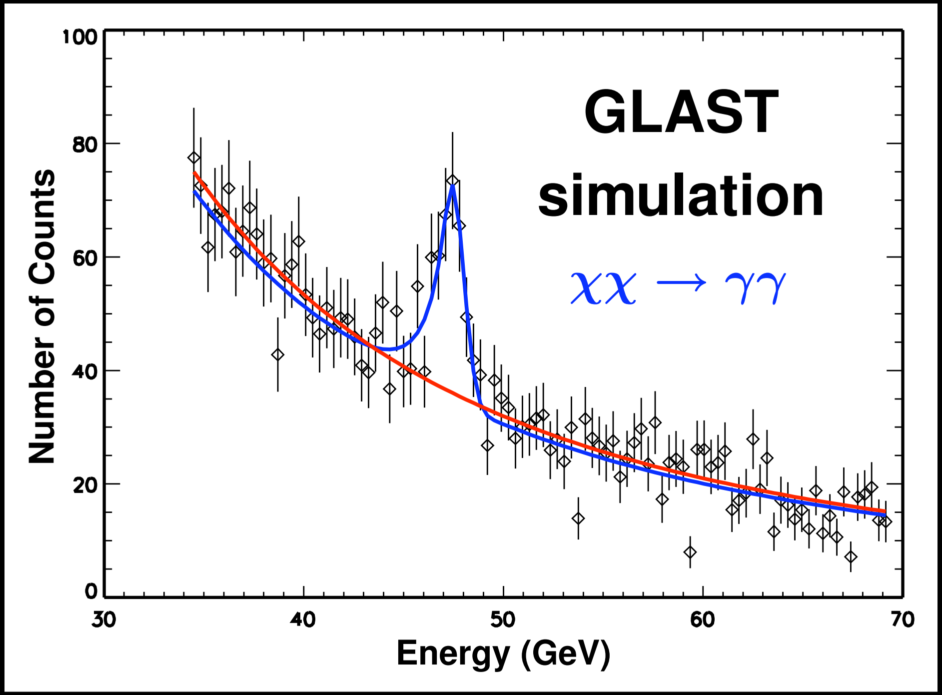
Galactic Gamma Rays

- Gamma-rays fluxes still not completely reproduced in cosmic-ray models
- Strong dependence on dark halo profile and substructure

$$\Phi_\gamma = N_\gamma \frac{\sigma v}{2m^2} \int \rho^2(\ell) d\ell$$

- But clear signature: gamma-ray lines!

Galactic gamma-rays



GLAST was successfully launched June 11, 2008 and is taking data

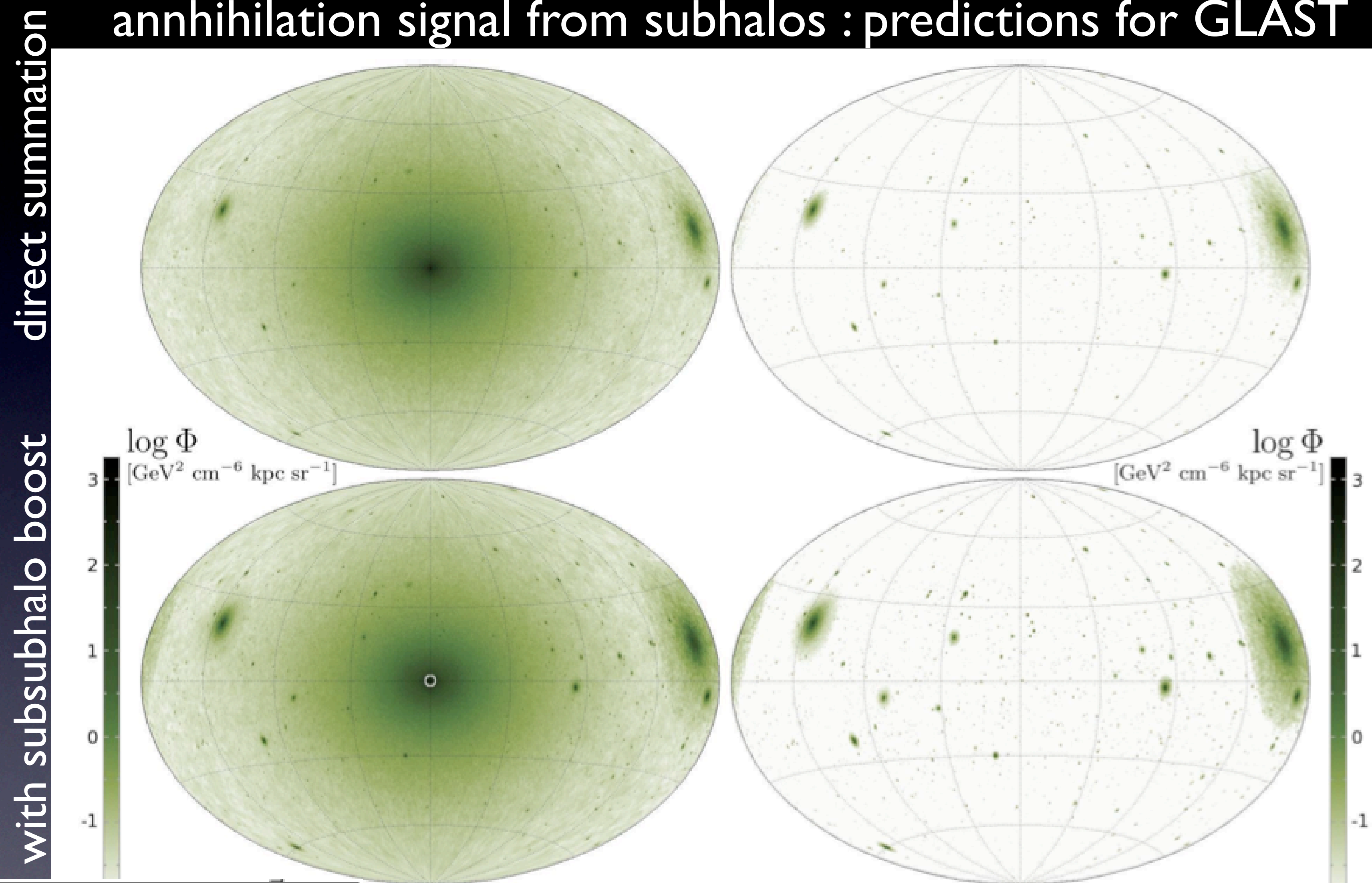
Dark halo substructure

"Via Lactea" simulation
(Diemand, Kuhlen, Madau, 2008)

Dark halo substructure

first results from via lactea II

annhihilation signal from subhalos : predictions for GLAST



$$S_i = \int_{V_i} \rho_{\mathrm{sub}}^2 dV_i = \sum_{j \epsilon \{P_i\}} \rho_j m_p$$

total DM signal subhalos only

Kuhlen, JD, Madau, submitted

Courtesy J. Diemand

Diemand’s comments on “Via Lactea”:

our approach:
collision-less (pure N-body, dark matter only) simulations

- treat all of Omega_m like dark matter
- bad approximation near and in large galaxies
  OK for dwarf galaxies and smaller scales
- simple physics: just gravity, good #CPU scaling → allows high resolution
- no free parameters (ICs known thanks to CMB + ...)

→ accurate solution of the idealized problem

complementary approach:
hydrodynamical simulations

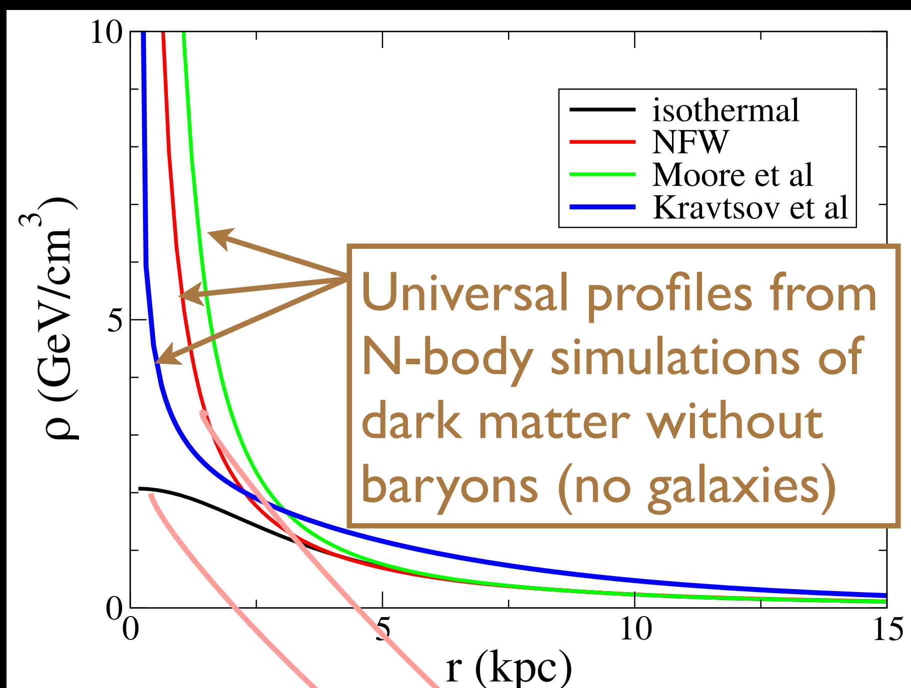
- computationally expensive, resolution relatively low
- SPH and grid disagree even in simple tests, Agertz et al 2007
- processes far below the resolved scales (star formation,SN, ... ?)
  implemented through uncertain functions and free parameters

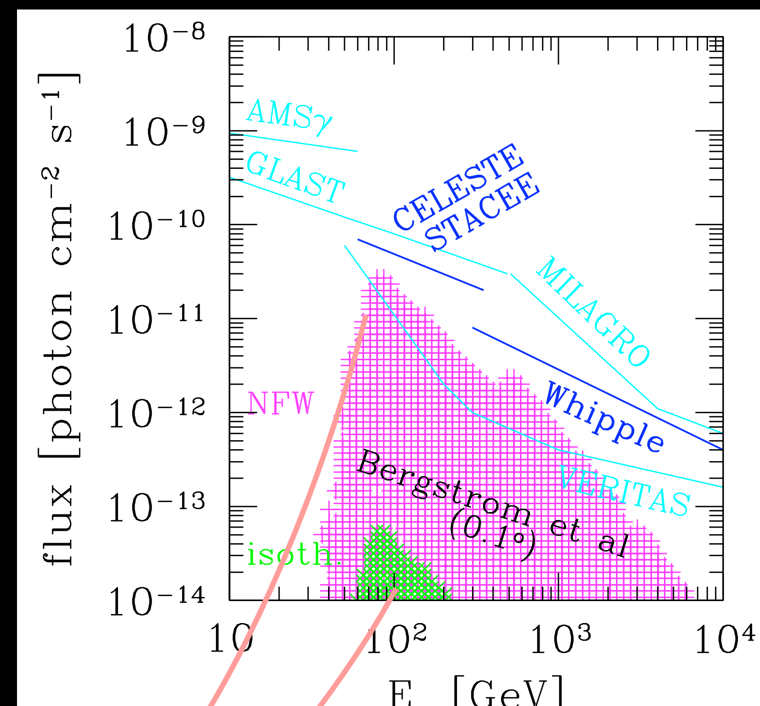
→ approximate solution to the more realistic problem

Courtesy J. Diemand

Galactic gamma-rays

Very sensitive to halo density distribution



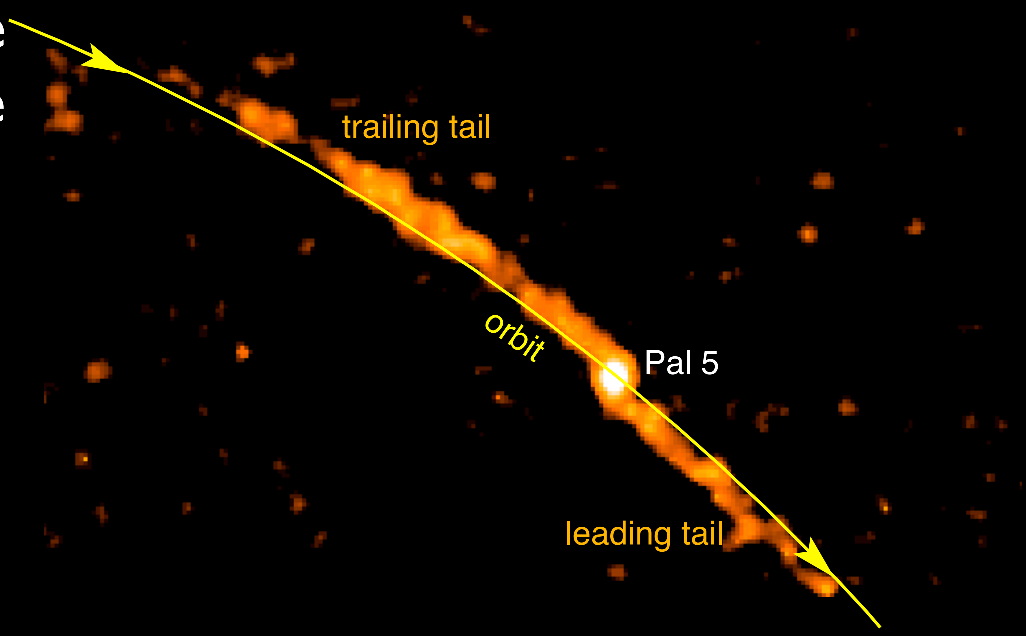


Dark halo substructure

Tidal forces can destroy subhalos and generate tidal streams

Streams of stars have been observed in the galactic halo

SDSS-1
2MASS
SEGUE
....



Odenkirchen et al 2002 (SDSS)

Extragalactic Gamma Rays

- From other galaxies
  - Milky Way satellites, like the Large Magellanic Cloud, Draco, Sagittarius, etc.
  - Intermediate Mass Black Holes
  - Cluster of galaxies (multi-messenger)

- From the whole Universe

The importance of radiative corrections

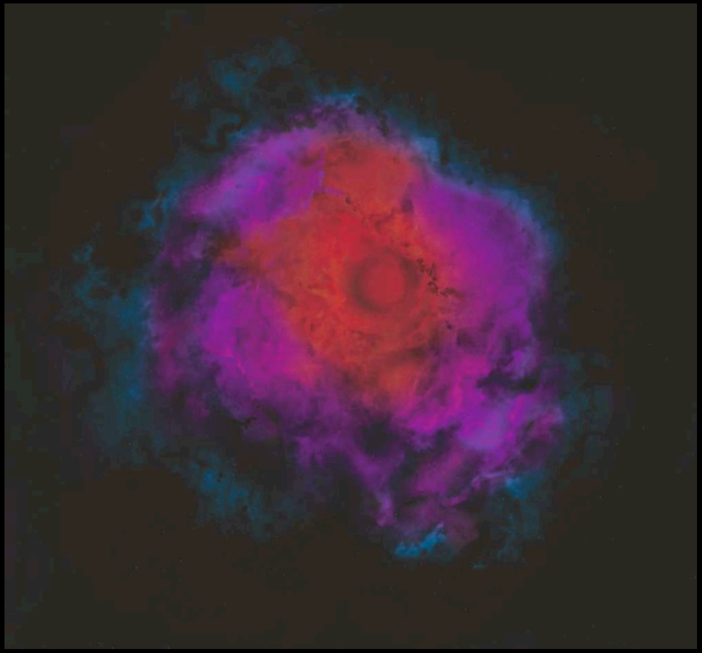
- Internal bremsstrahlung
- Annihilation and co-annihilation of heavy ($\gtrsim$TeV) neutralinos - unitarity of cross section
- Final state interactions

Dark Stars

Spolyar, Freese, Gondolo 2007

Cold Dark Matter particles can dramatically alter the formation of the first stars, leading to a new stellar phase powered by CDM annihilation instead of nuclear fusion

A Dark Star



Artist's impression

Some consequences

- Affects reionization and early stellar enrichment
- Dark stars may be precursors to the supermassive black holes that power high red-shift quasars

Summary

- We have evidence for non-baryonic dark matter that is not made of any known elementary particle
- We are in the exploratory stage to figure out its nature
- There are many particle physics and astrophysics ideas currently explored, and more will come
- Tools for dark matter should be flexible, modular, adaptable to new ideas