In Quest of Dark Matter

Paolo Gondolo

Outline

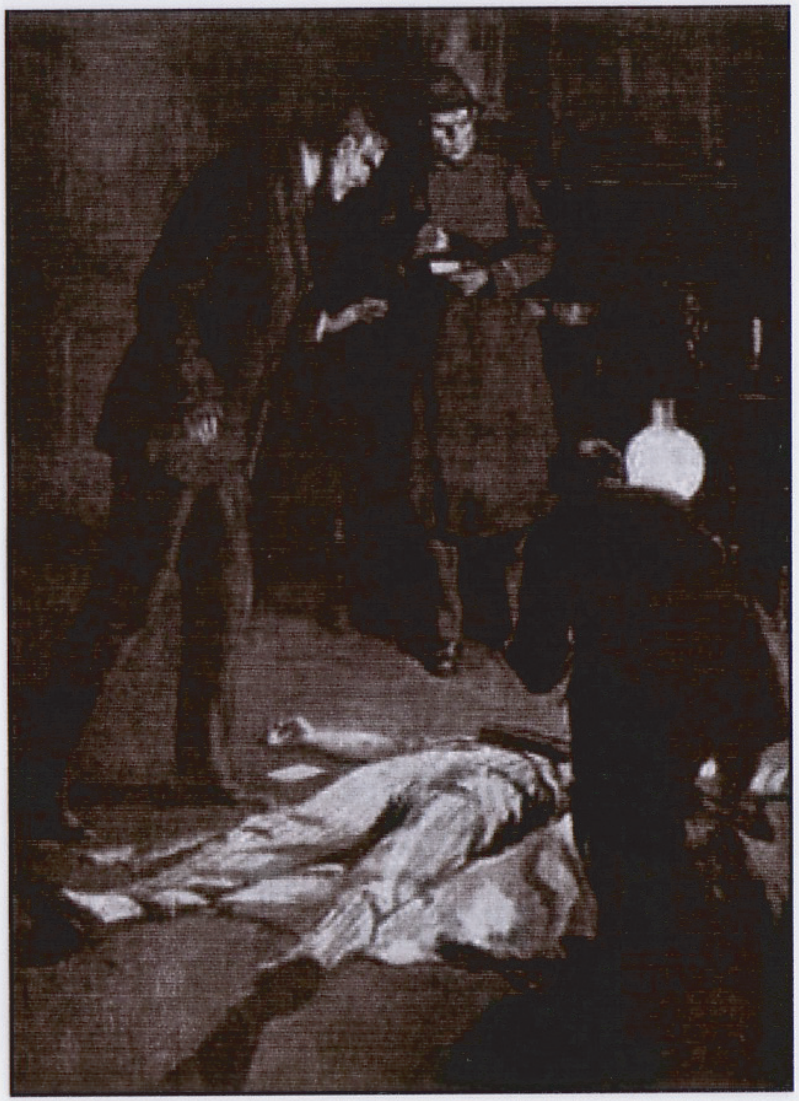
Baryonic and non-baryonic dark matter

In search of the missing baryons

In search of non-baryonic dark matter

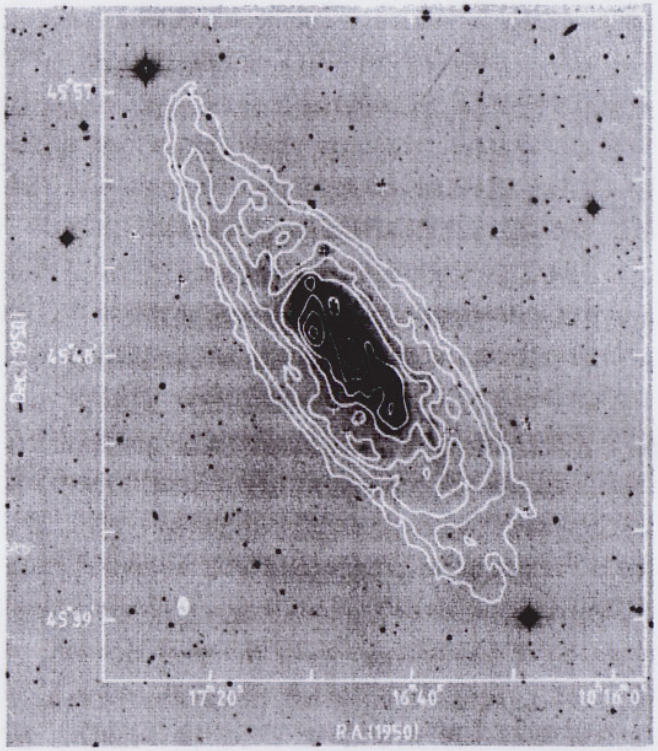
Speculations on dark energy

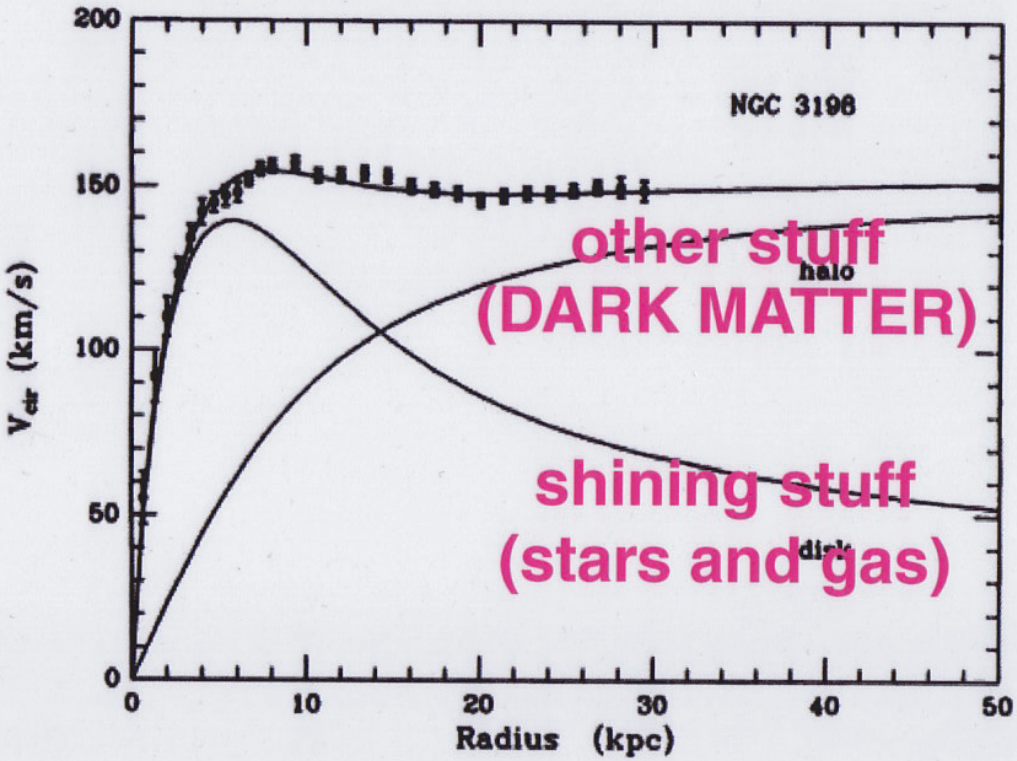
The Case



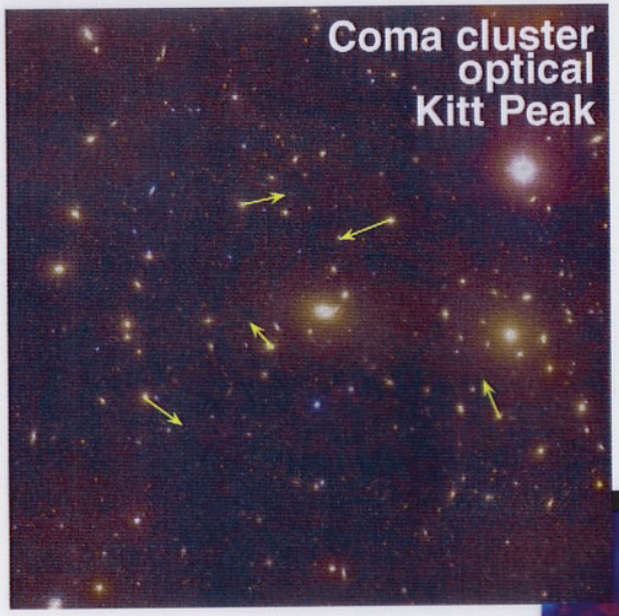
Dark matter in galaxies

Rotation curve

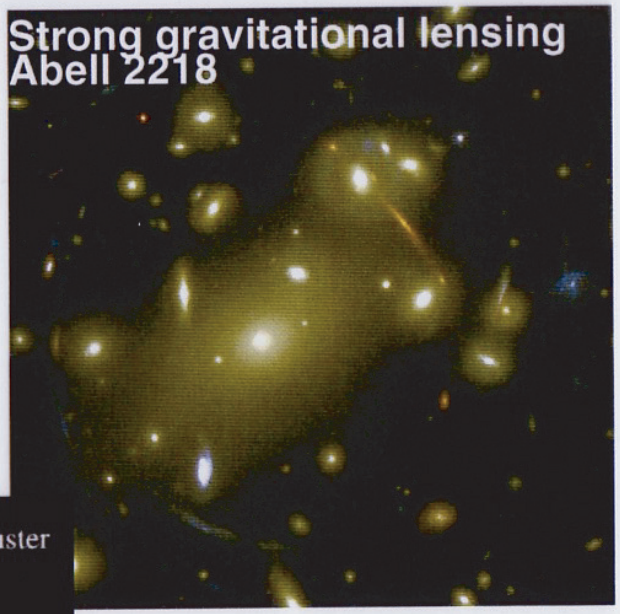


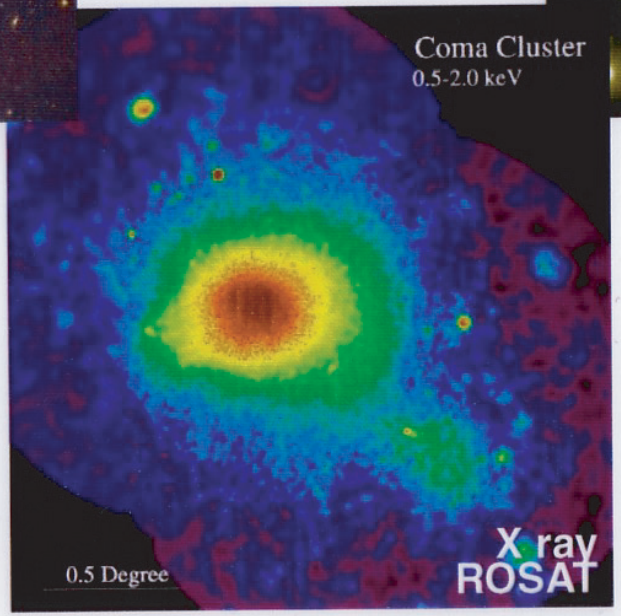


Dark matter in galaxy clusters

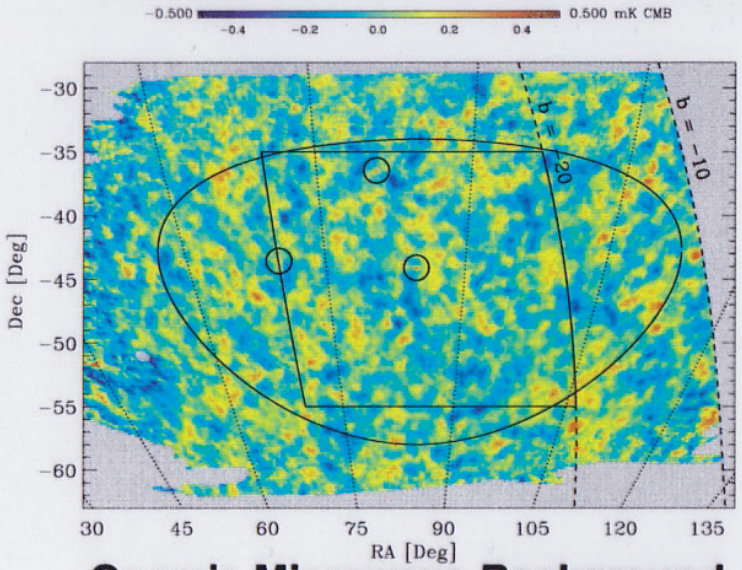


$$\Omega_m \approx 0.2$$



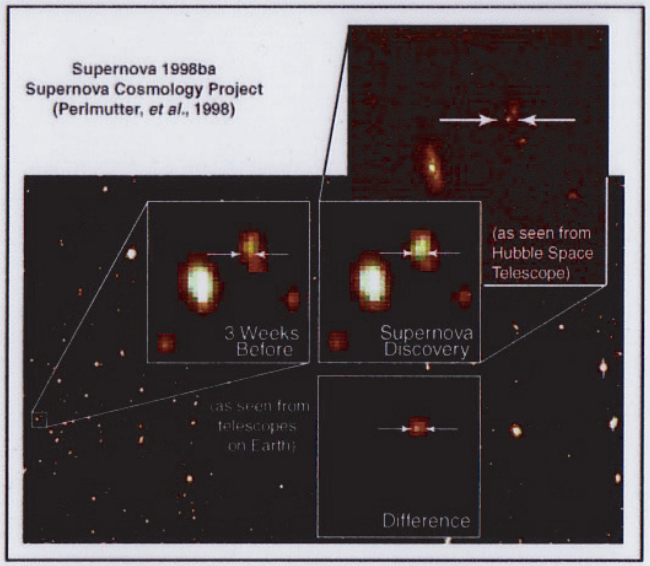


Dark matter on large scales



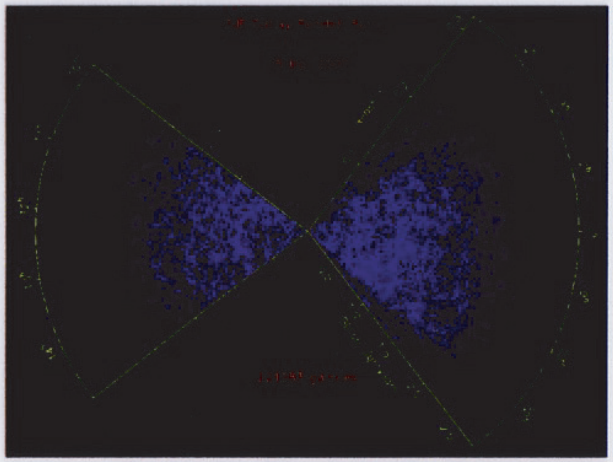
Cosmic Microwave Background

Boomerang



Supernovae Ia

SCP (Perlmutter et al)



Galaxy Redshift Surveys

2dF

The "best" matter density

WMAP (Bennett et al., 2003)

$$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$$

of which

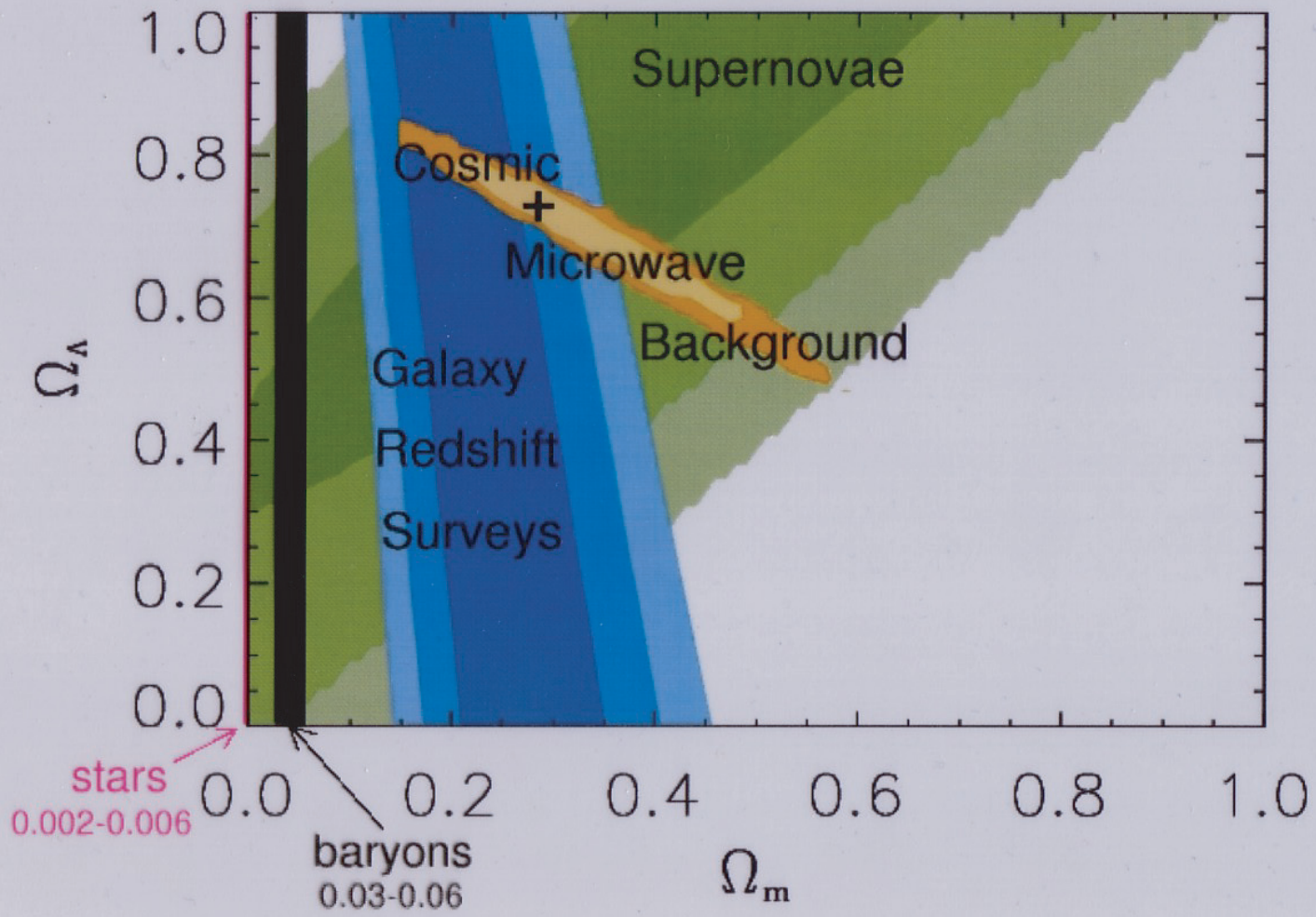
$$\Omega_\nu h^2 < 0.0076 \ (95\%\mathrm{CL})$$

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

$$\Omega_{\mathrm{CDM}} h^2 = 0.113^{+0.008}_{-0.009}$$

(Units are $1.879 \times 10^{-29}\ \mathrm{g/cm^3}$**)**

The concordance cosmology



Adapted from L. Verde

The dark matter problems

- **Missing baryons at low redshift**
- **Non-baryonic dark matter**

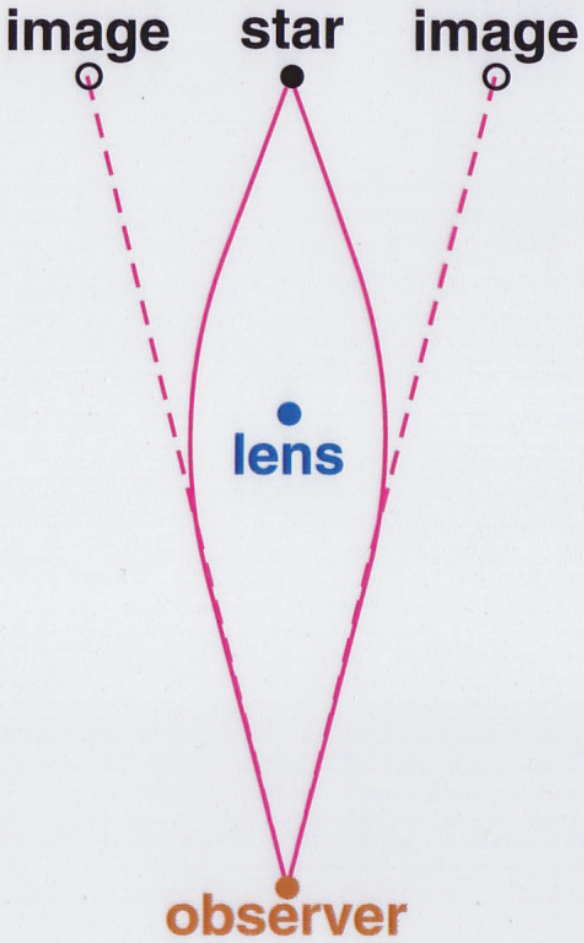
Suspects

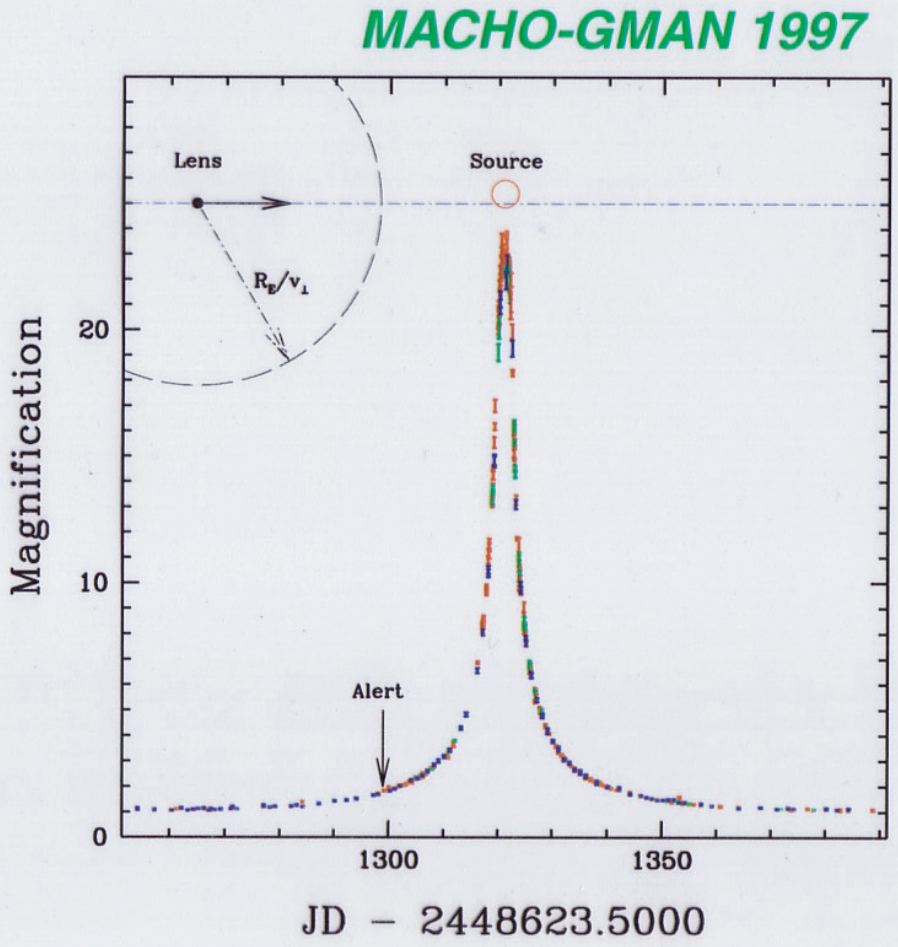
Suspect #1: MACHOs

Massive Compact Halo Objects

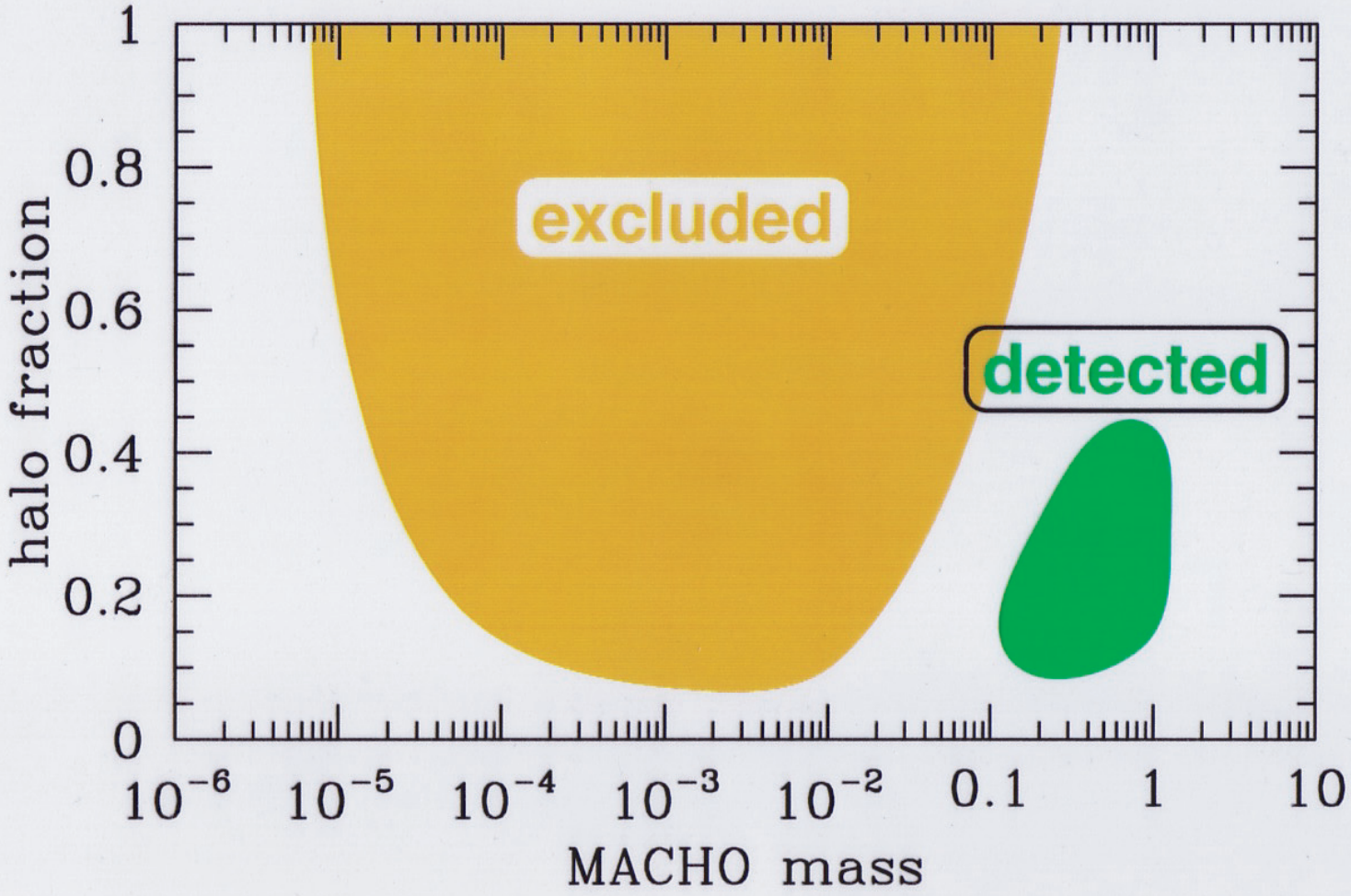
How to find MACHOs

Gravitational microlensing



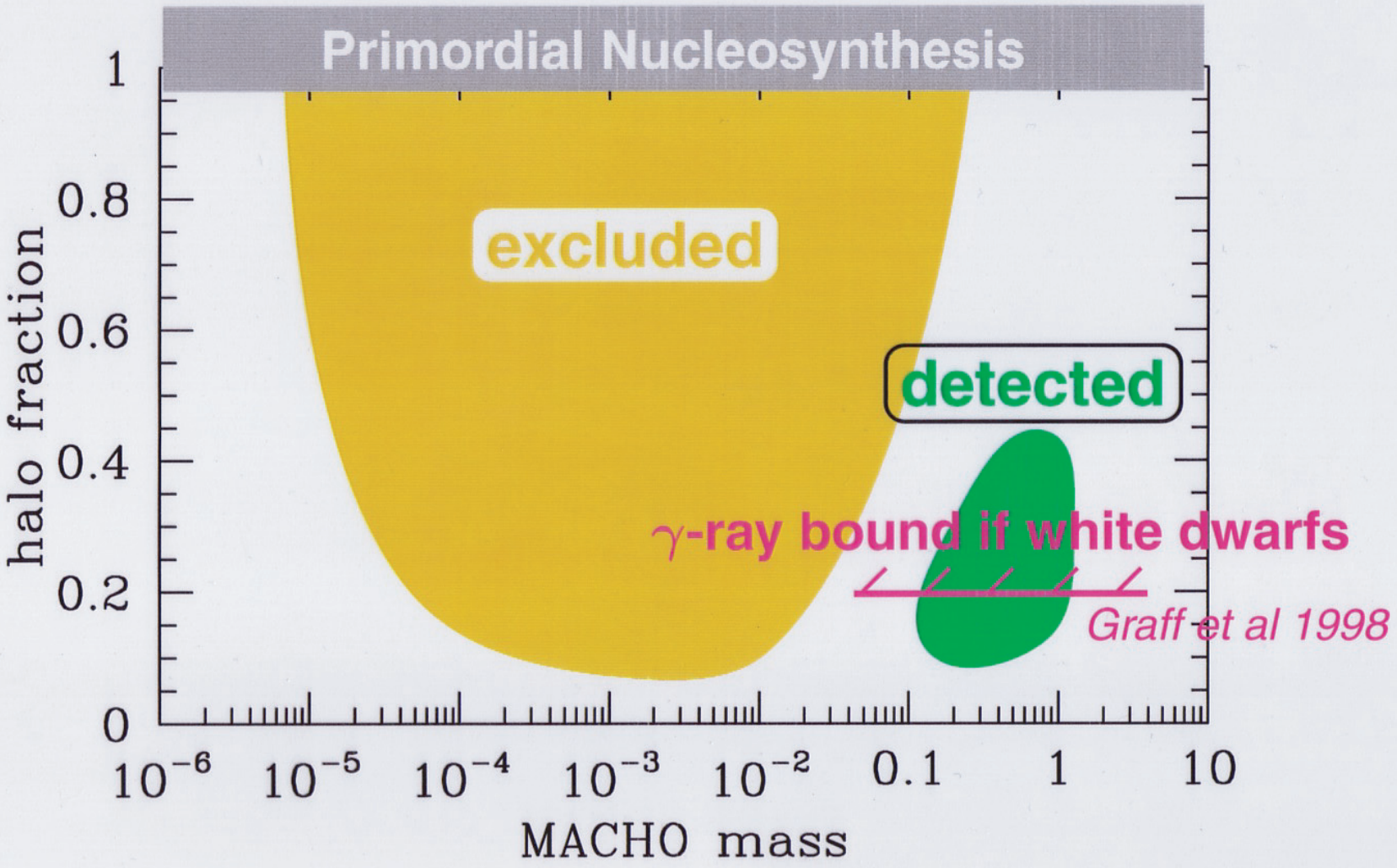


MACHOs!



MACHO & EROS 1996-2000

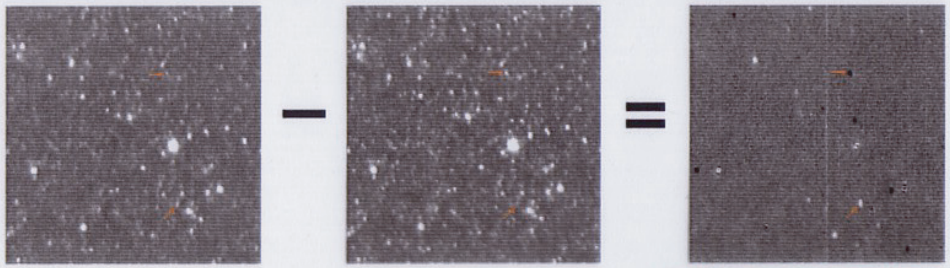
MACHOs!



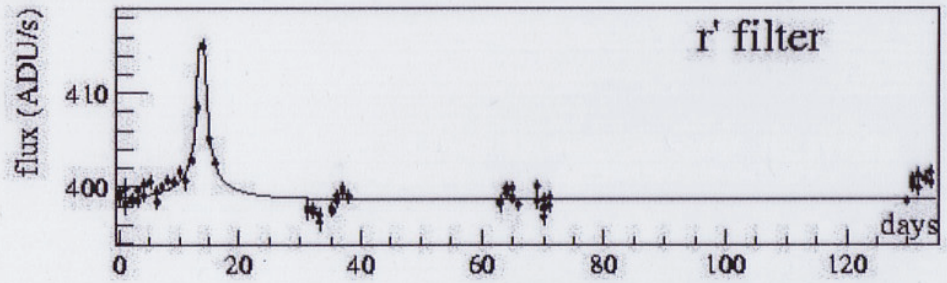
MACHO & EROS 1996-2000

"Pixel" microlensing

monitor unresolved stars in M31, M87, . . .



MEGA 2001

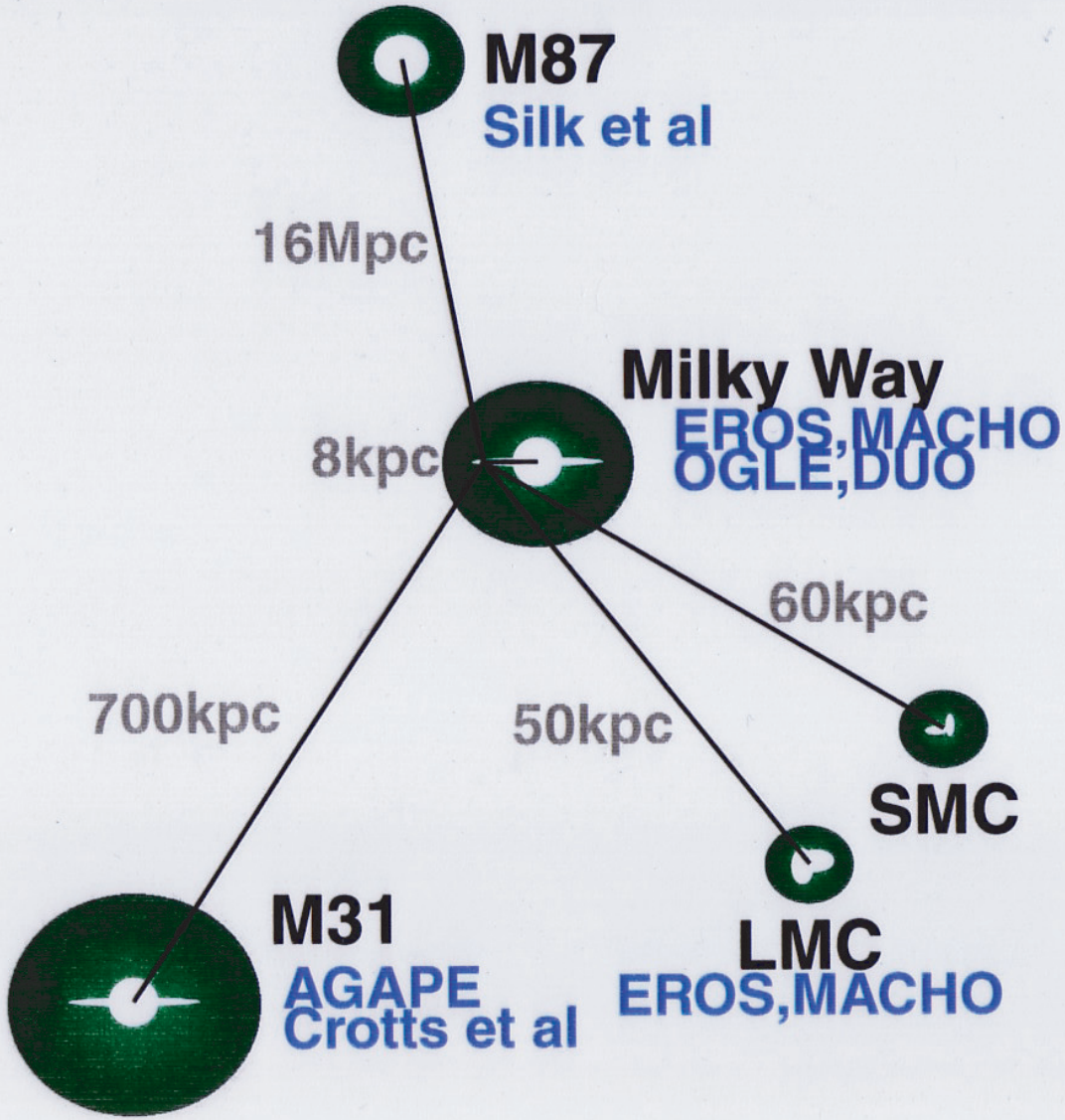


POINT-AGAPE 2001

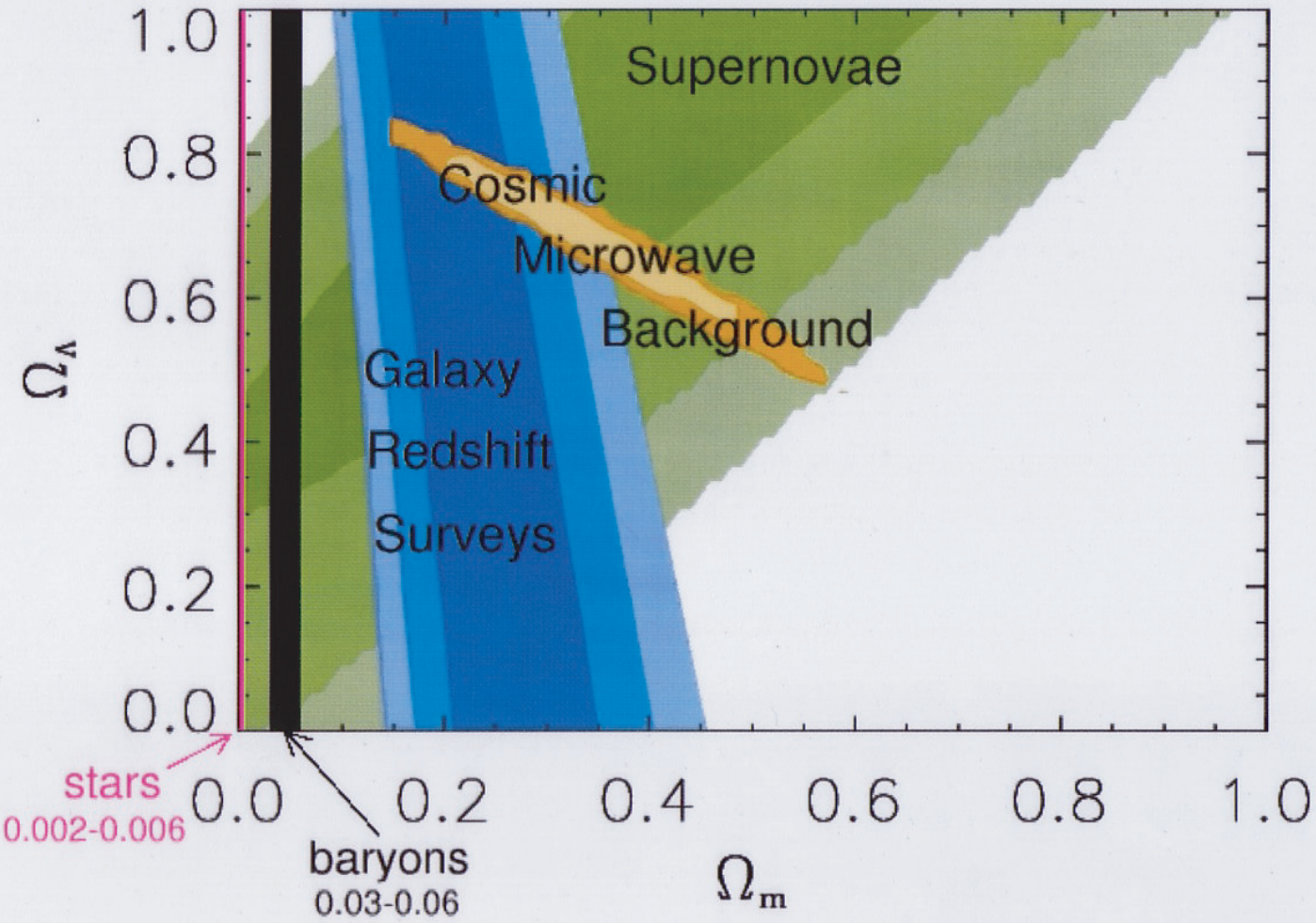
M87

Baltz,Gondolo,Lauer,
Silk,et al, in prep

Microlensing surveys



The concordance cosmology



Adapted from L. Verde

Suspect #2: neutrinos

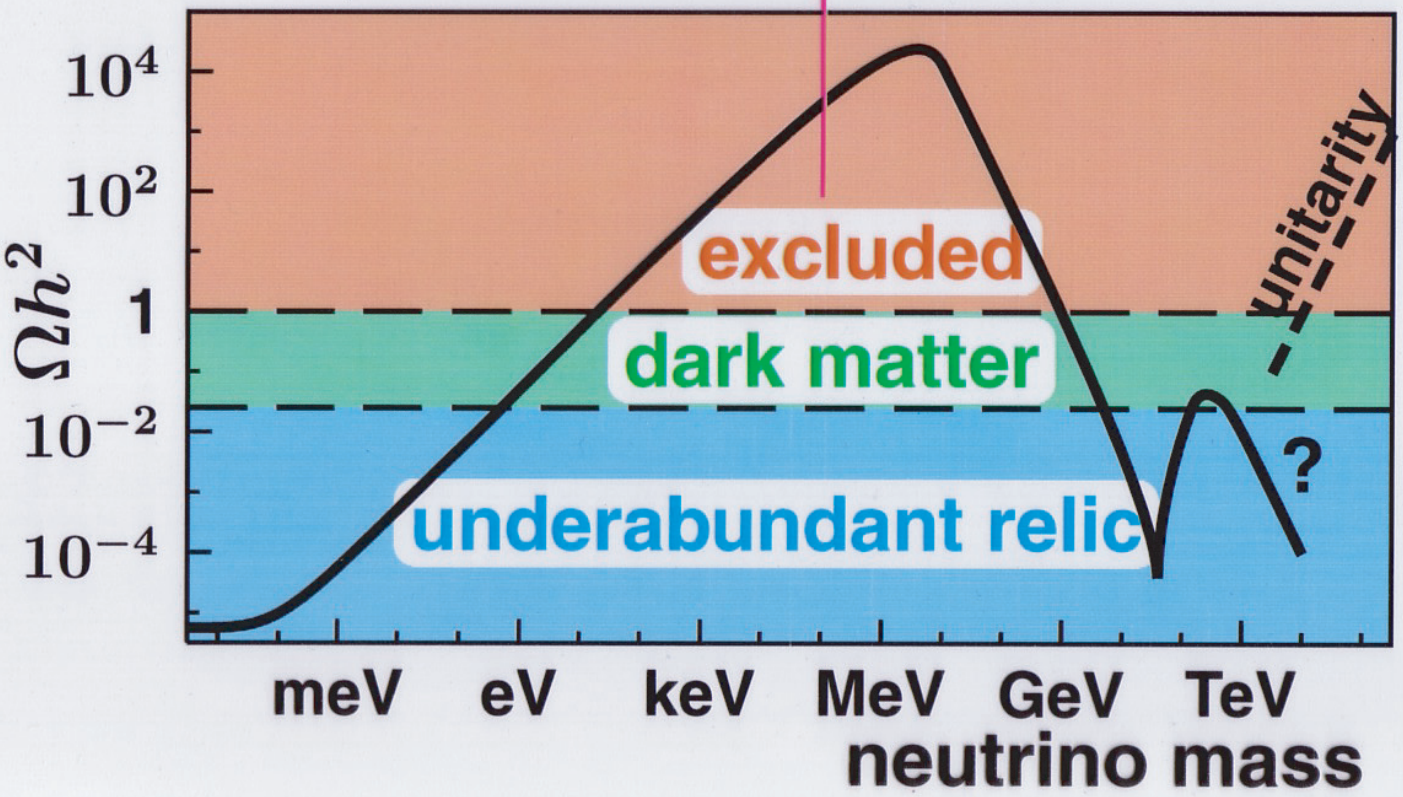
Neutrinos as dark matter

Hot Dark Matter

$$\Omega h^2 \simeq \frac{m}{45\,\mathrm{eV}}$$

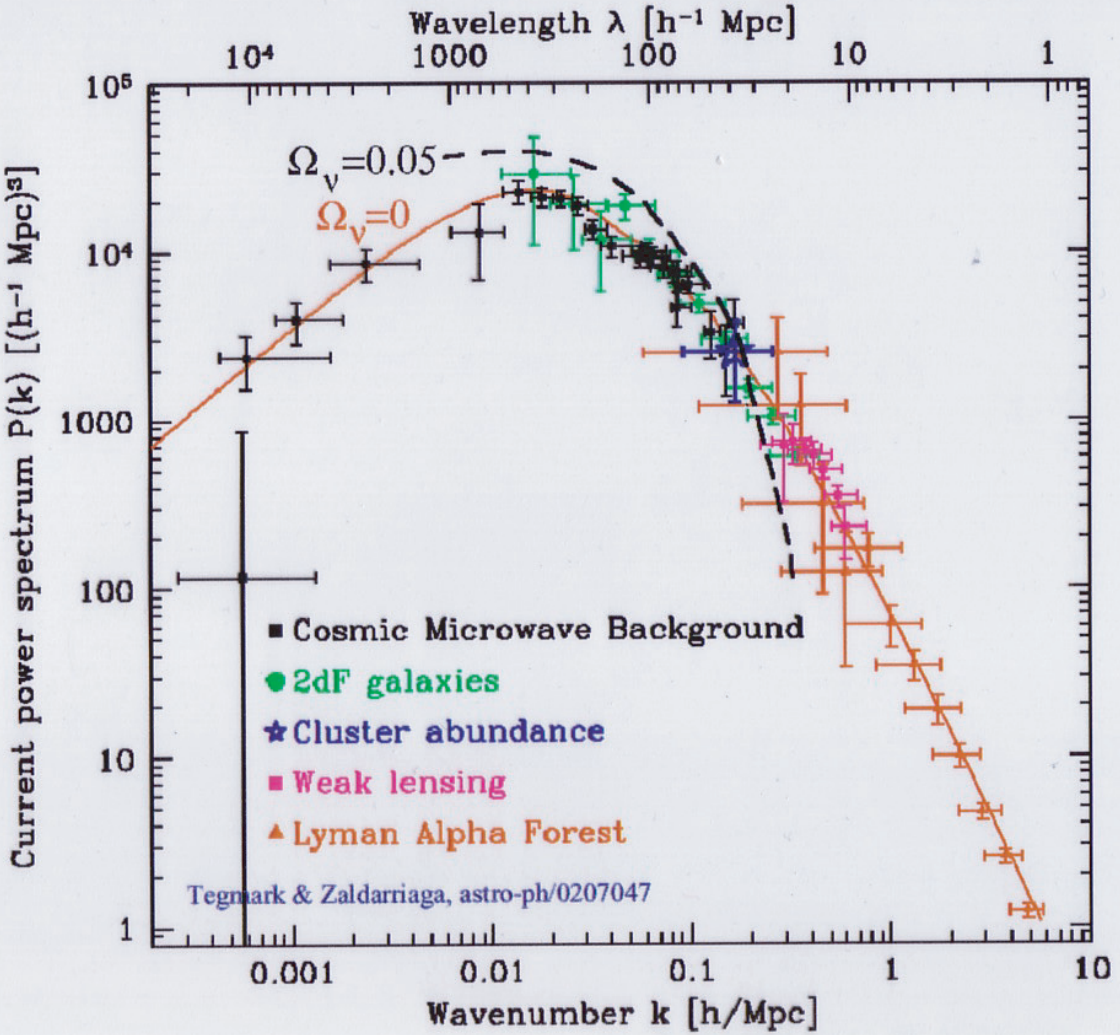
Cold Dark Matter

$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$



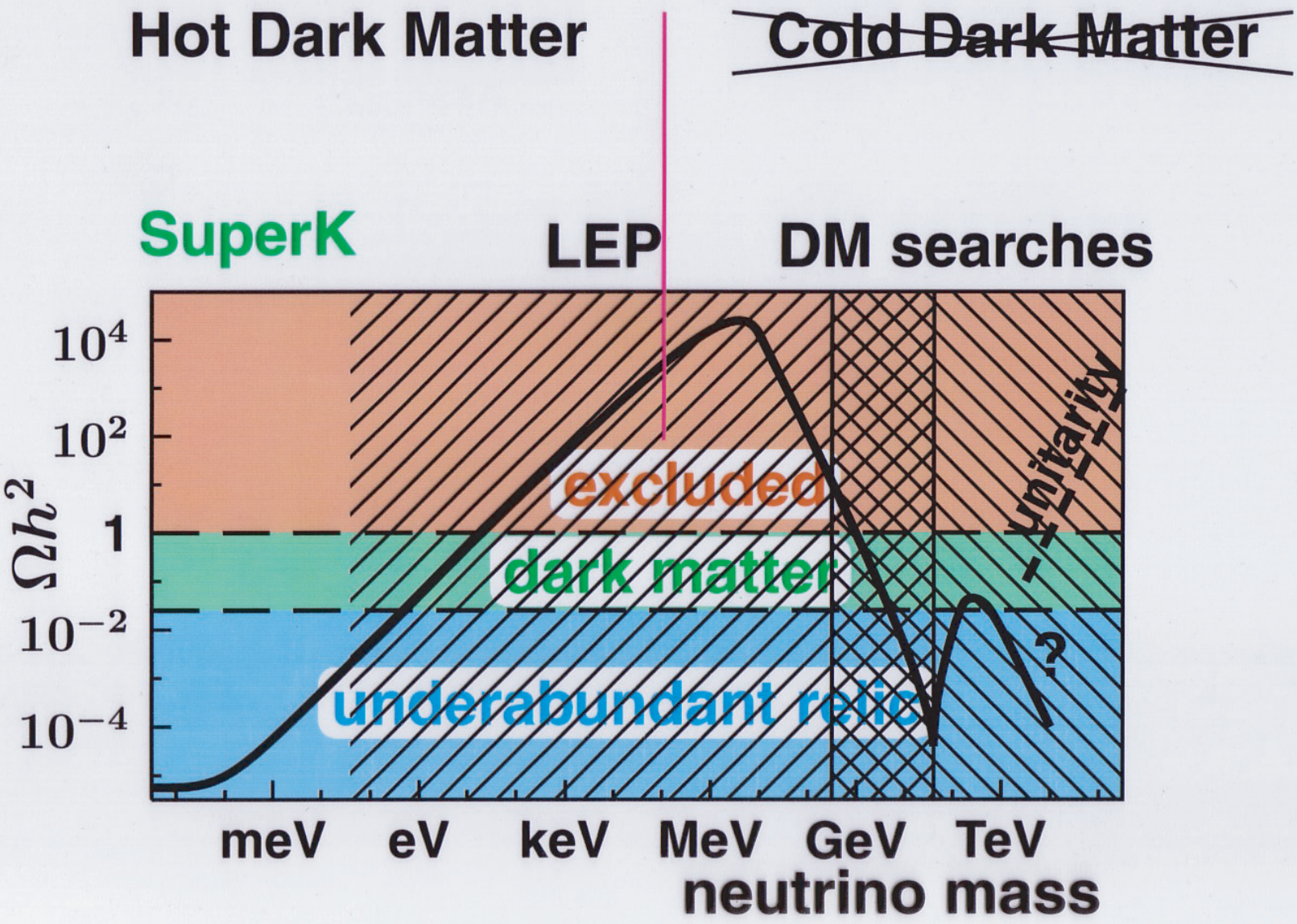
Cosmic neutrino density

Constraints from cosmic large scale structure

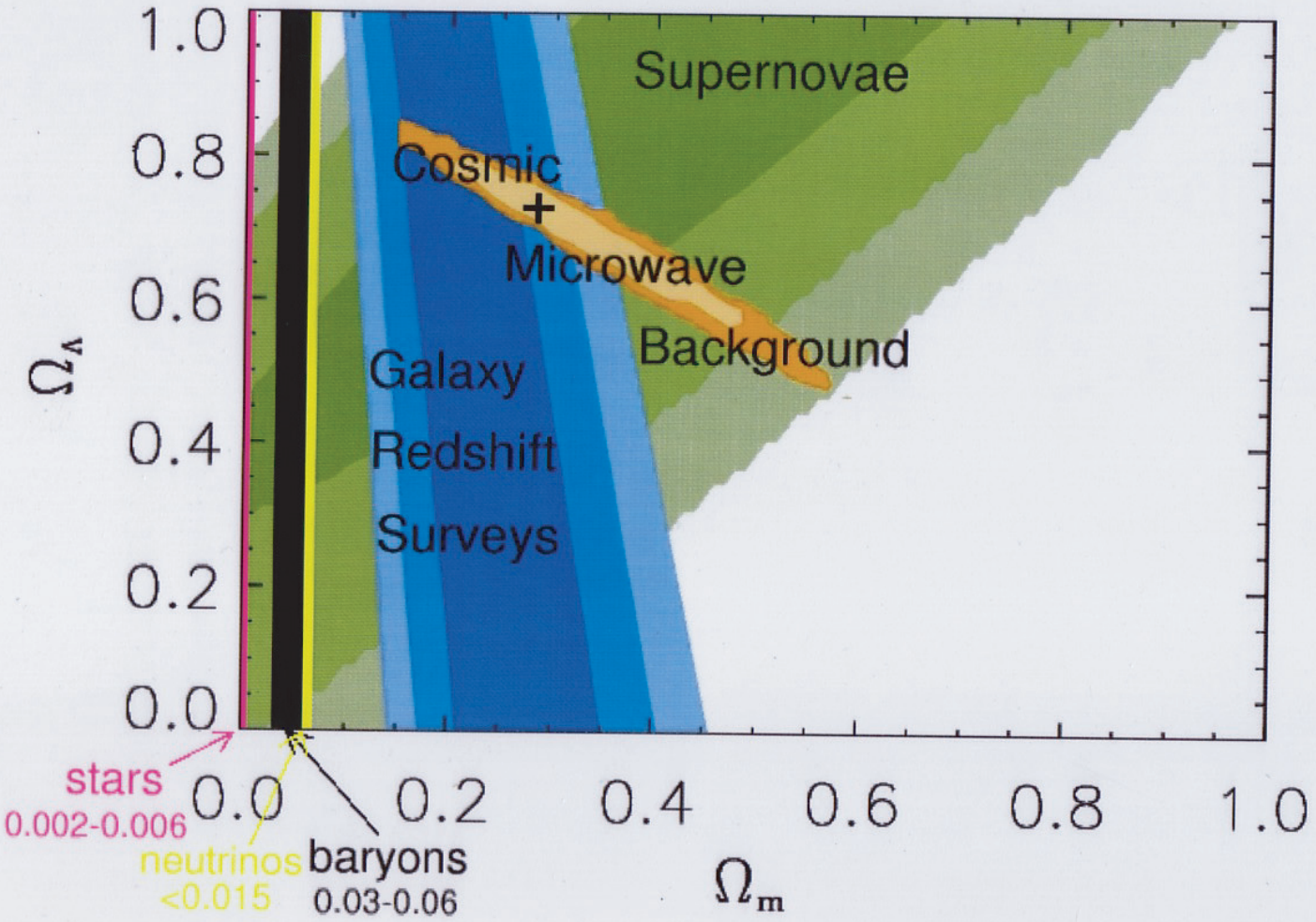


Adapted from M. Tegmark

Neutrinos as dark matter



The concordance cosmology



Adapted from L. Verde

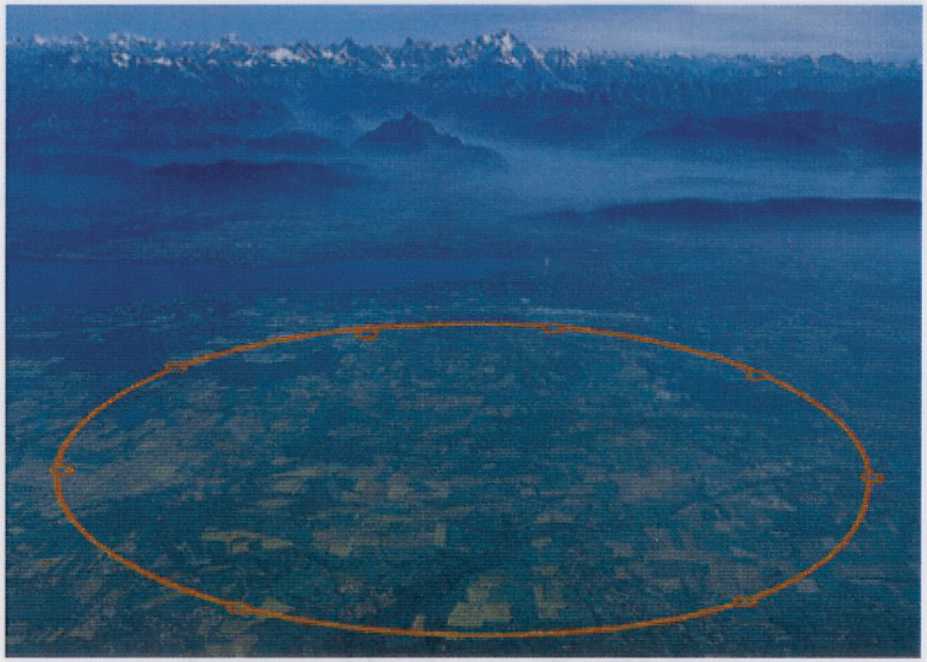
Suspect #3: WIMPs

Weakly Interacting Massive Particles

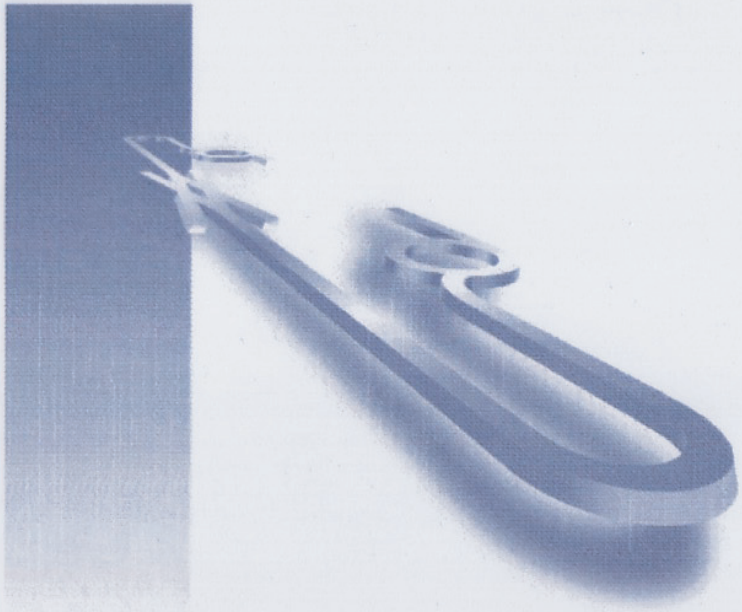
Supersymmetry

- **Unification of fundamental forces**
- **Stabilization of scalar masses**

slepton	↔	lepton
squark	↔	quark
gaugino	↔	gauge boson
higgsino	↔	Higgs boson



Large Hadron Collider



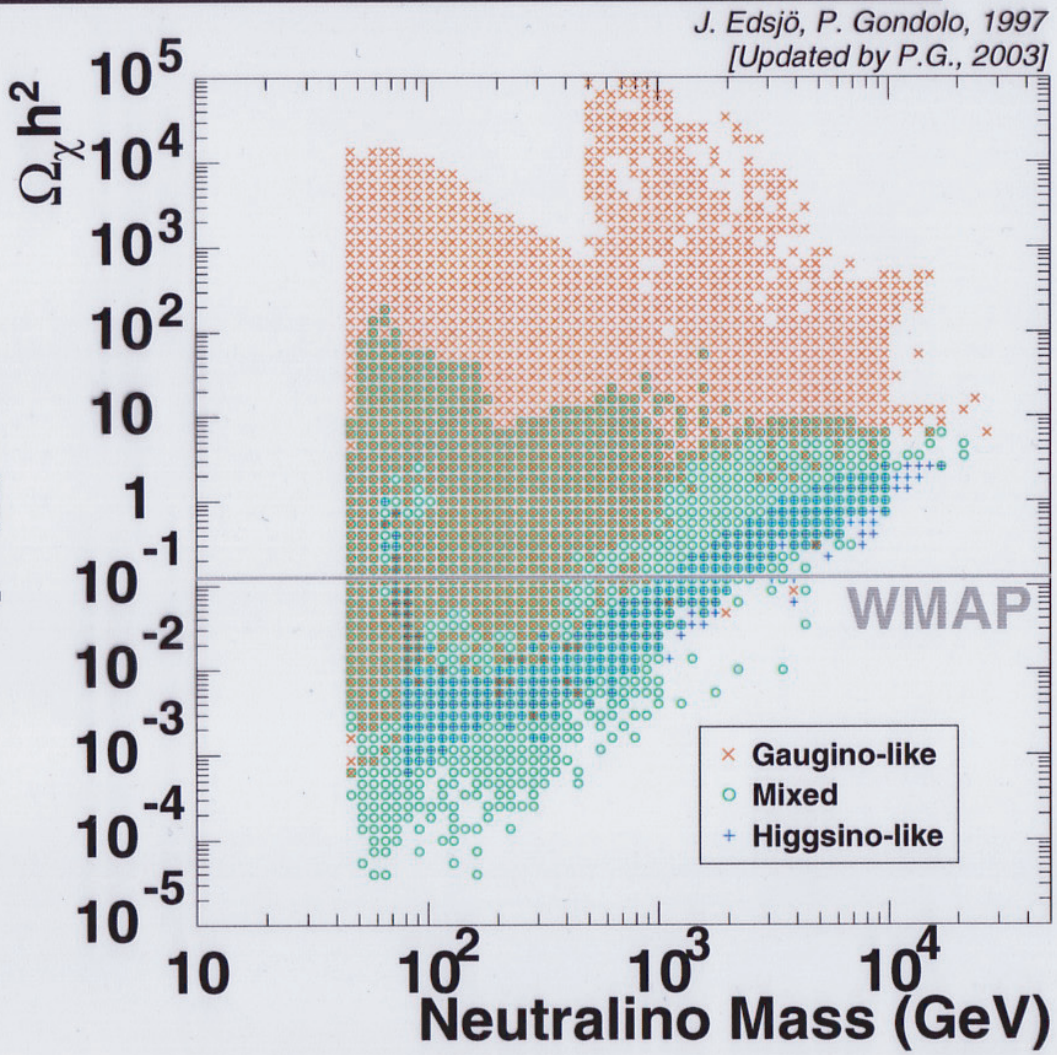
Next Linear Collider

The (Lightest) Neutralino

- $\tilde{\chi} = a\,\tilde{\gamma} + b\,\tilde{Z} + c\,\tilde{H}_1 + d\,\tilde{H}_2$
- **Lightest Supersymmetry Particle [often]**
- **Stable [R-parity conservation]**
- **Weakly interacting**
- **Massive [$\gtrsim 30\,\mathrm{GeV}$]**

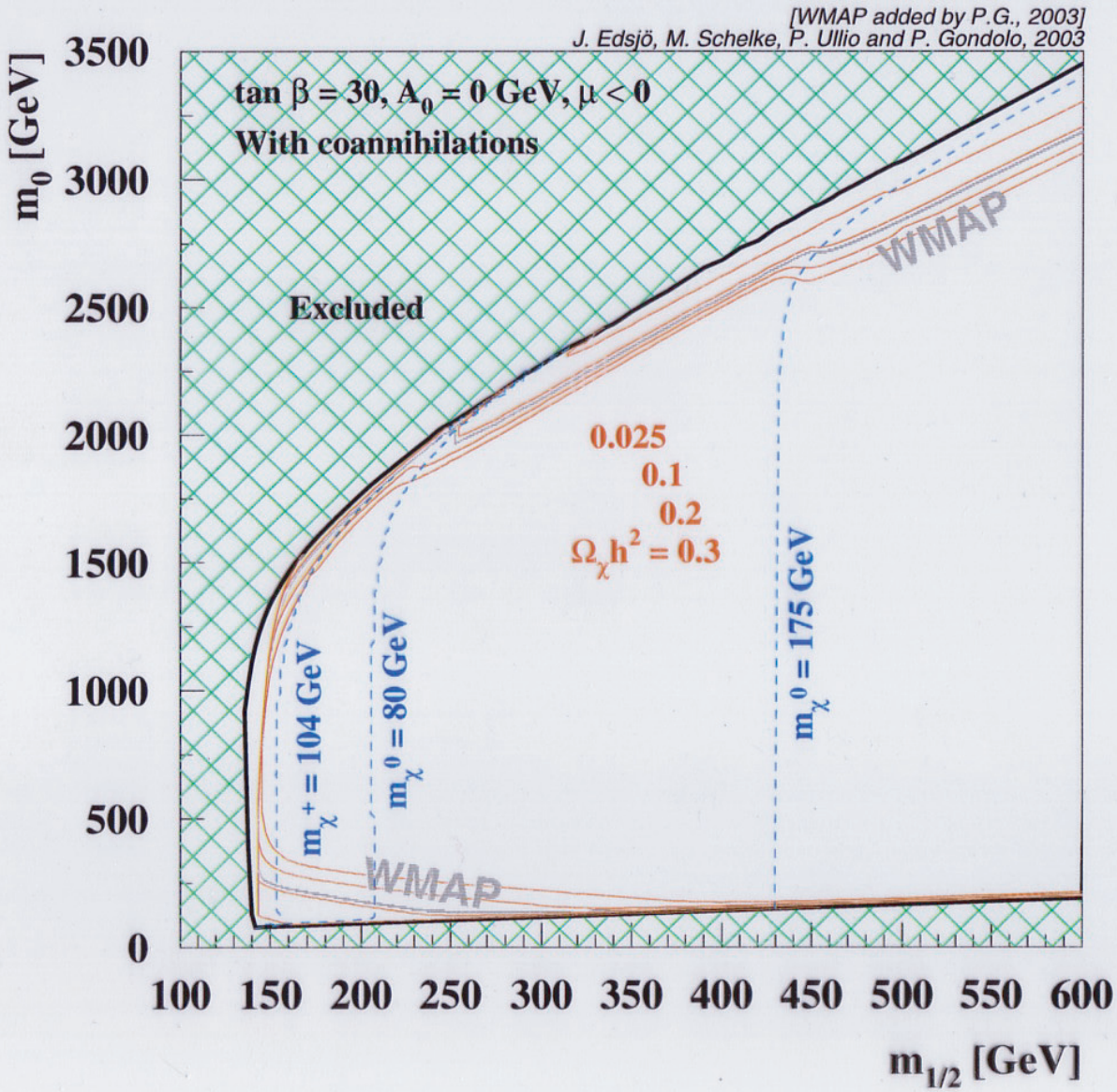
Supersymmetric dark matter

The lightest supersymmetric particle is a good dark matter candidate



Updated from Edsjö, Gondolo 1997

Some results in mSUGRA



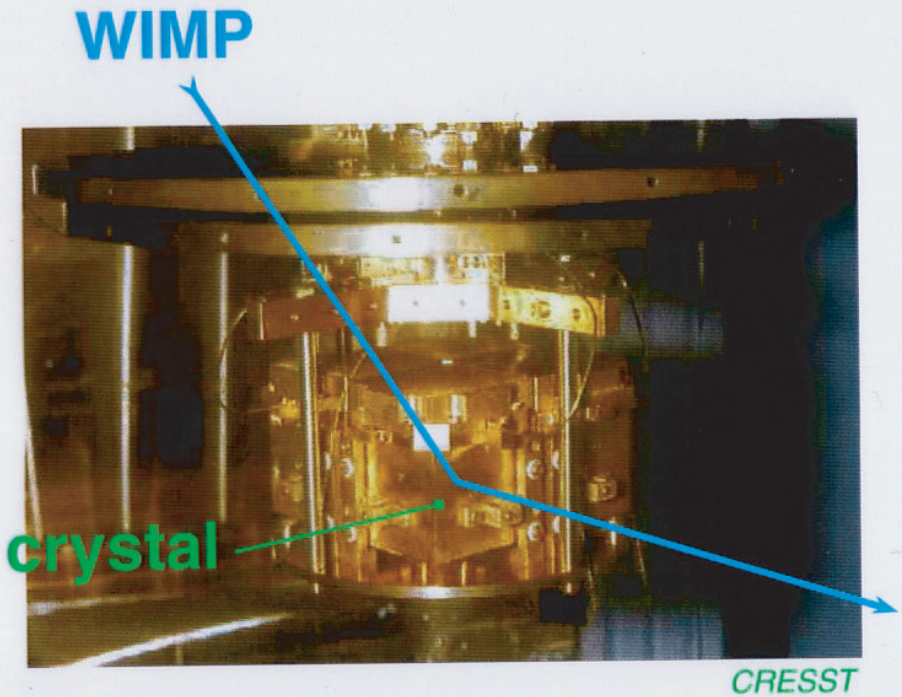
Cosmology and mSUGRA

- **Cosmological data on $\Omega_\chi h^2$:** **7%**
  WMAP first year data: $\Omega_{\rm CDM} h^2 = 0.113^{+0.008}_{-0.009}$
- **Neutralino annihilation chain:** **1%**
  Edsjö, Schelke, Ullio, Gondolo, 2003
- **Masses from GUT parameters:** **50%**
  See Allanach, Kraml, Porod, 2003

Searching for dark WIMPs

- direct detection
- neutrinos from Sun/Earth
- anomalous cosmic rays from galactic halo
- neutrinos, gamma-rays, radio waves from galactic center

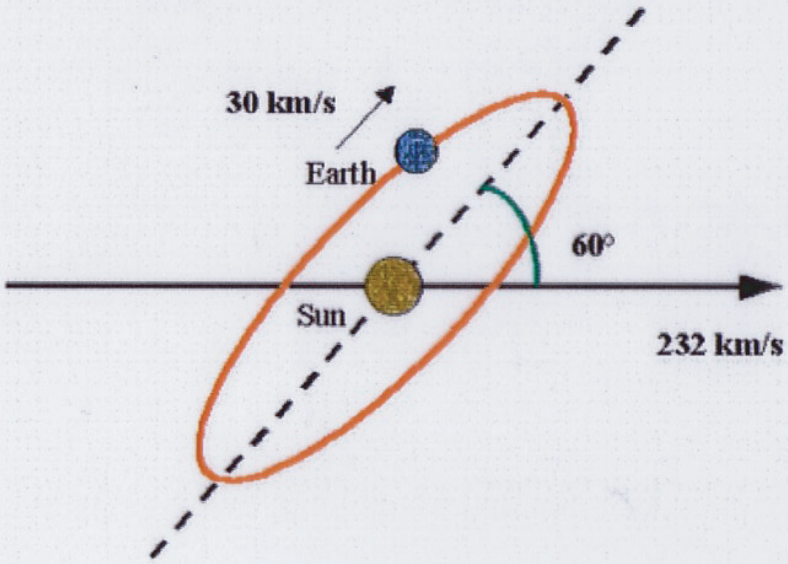
WIMP direct searches

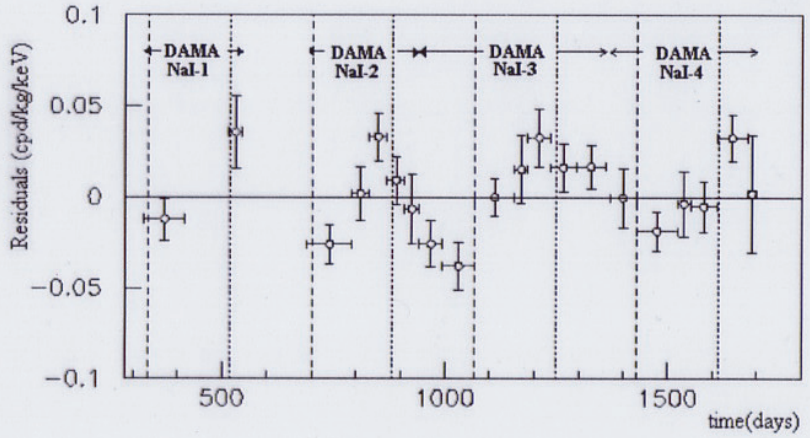


CDMS-II, DAMA, CRESST-II, DRIFT, GENIUS, . . .

Have WIMPs been detected?

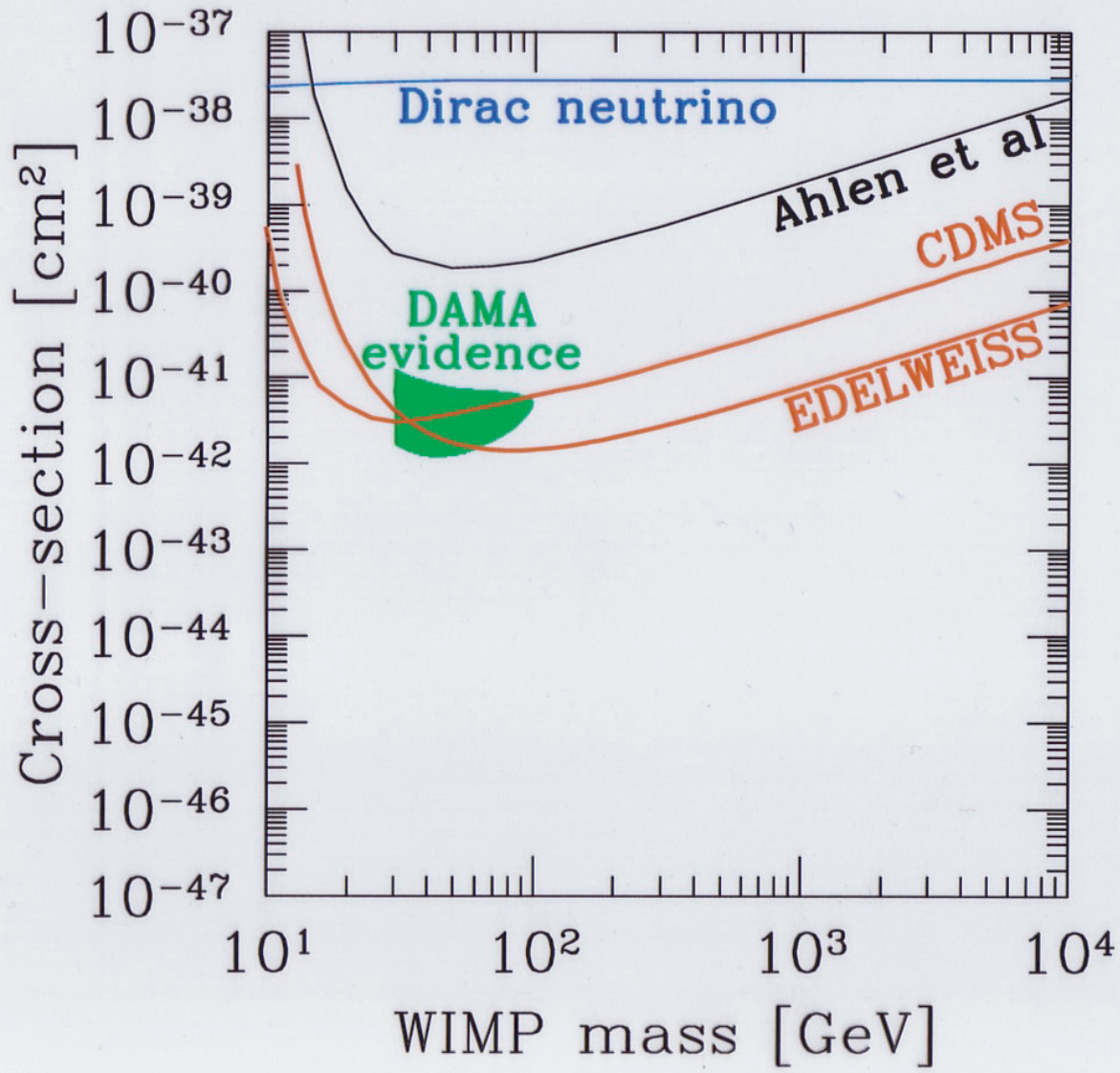
Annual modulation in DAMA data



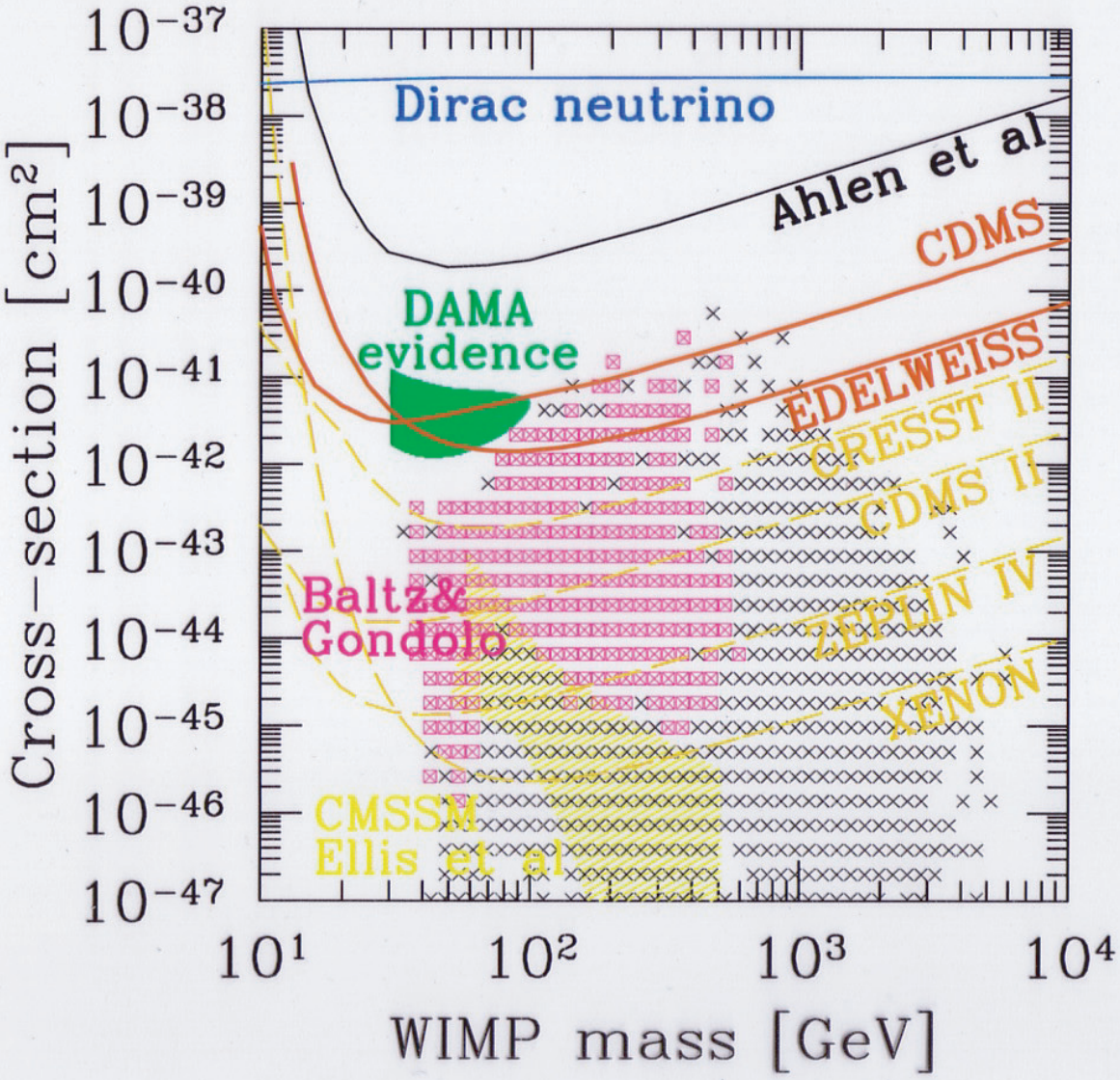


Bernabei et al 2001

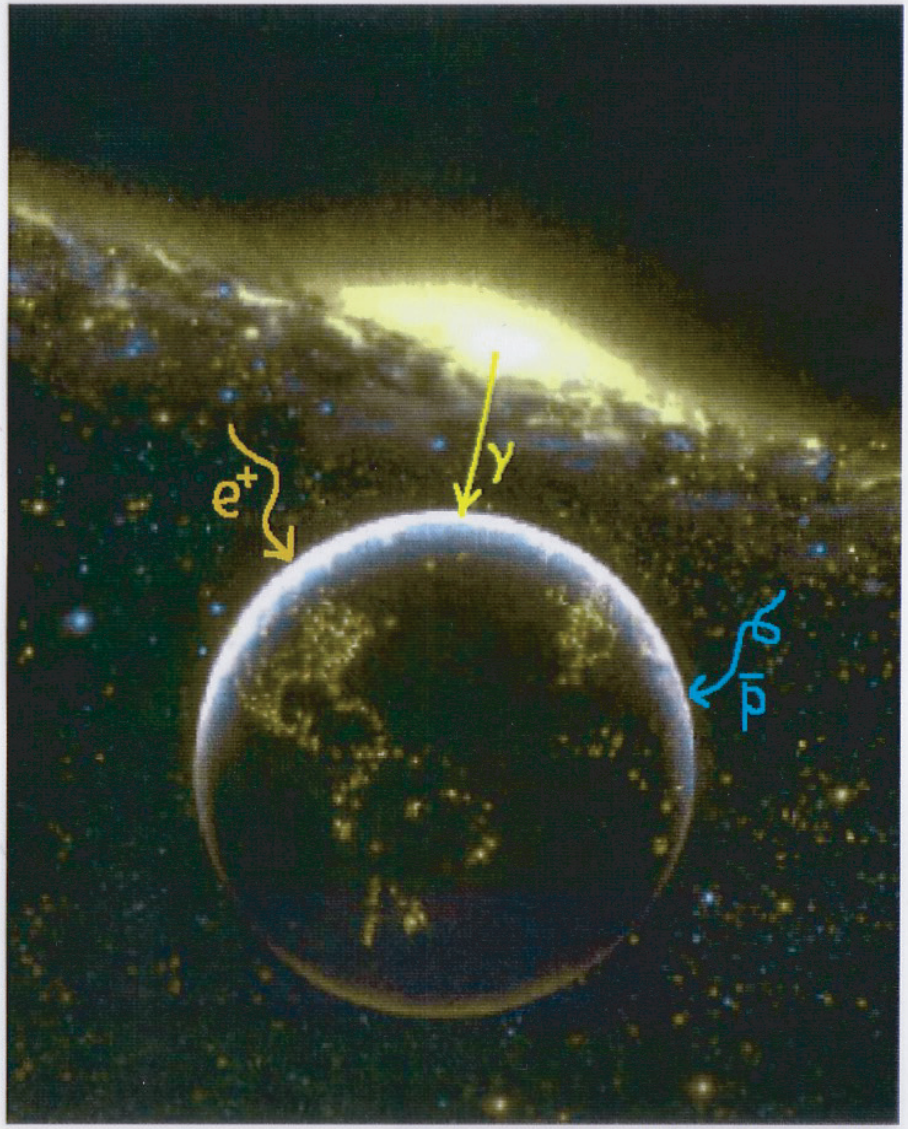
WIMP direct searches



WIMP direct searches



Cosmic rays from dark matter

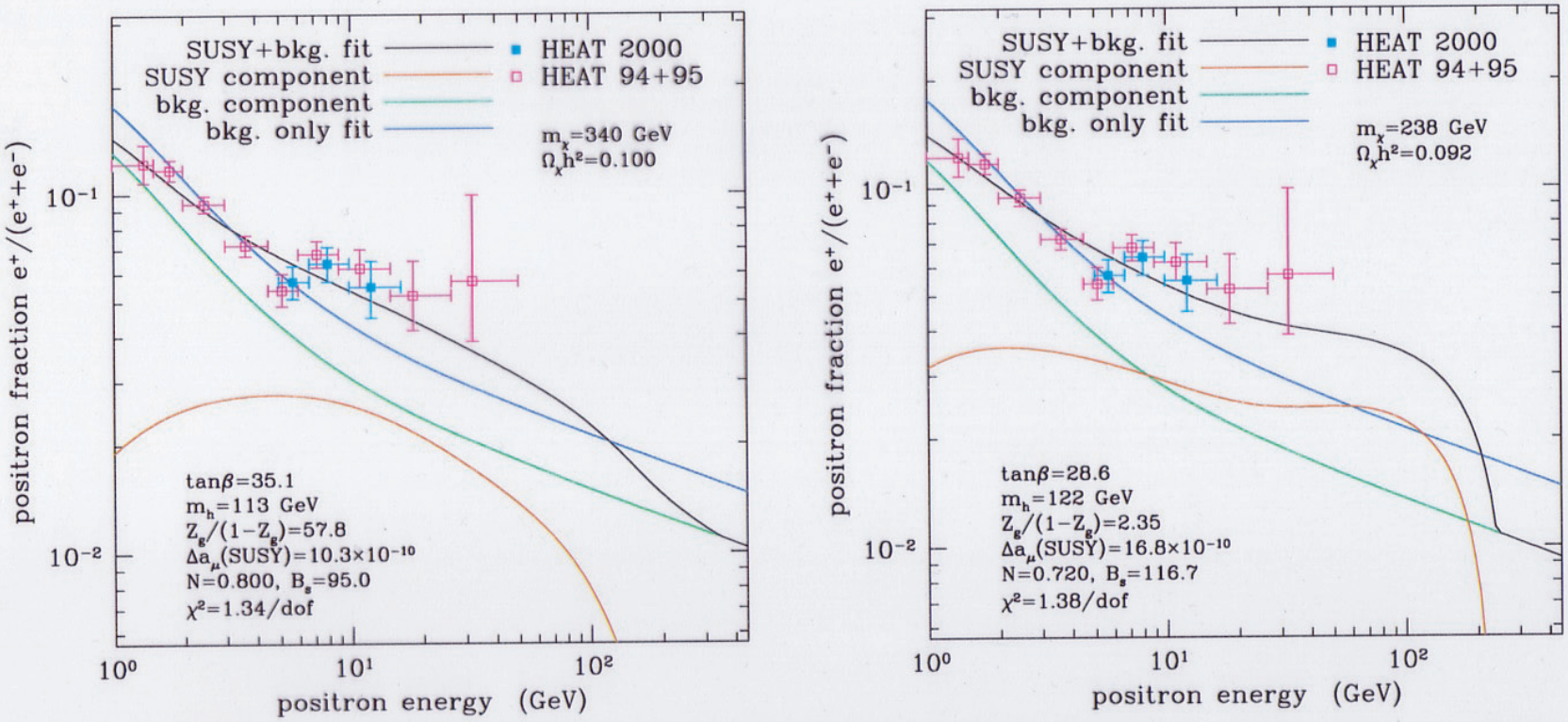


Background by J. Lomberg 1989

Positron excess

HEAT balloon finds anomaly in cosmic ray flux

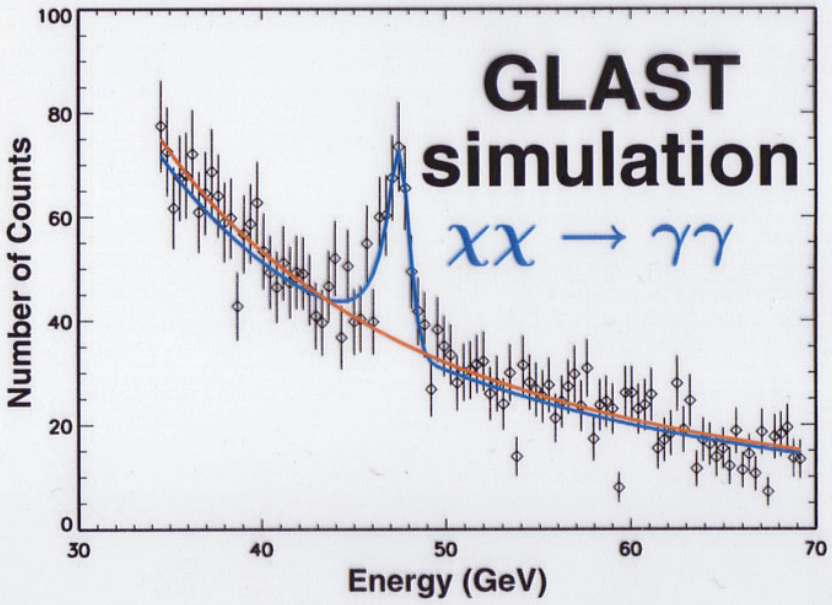
Possible explanation: supersymmetry in the galaxy

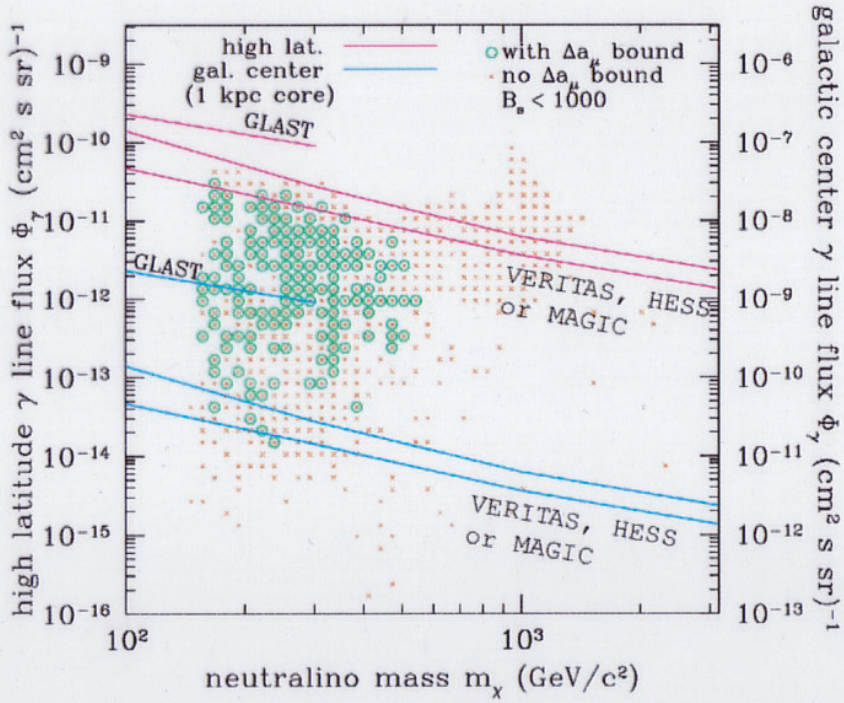


Baltz, Edsjö, Freese, Gondolo 2001

Positron excess

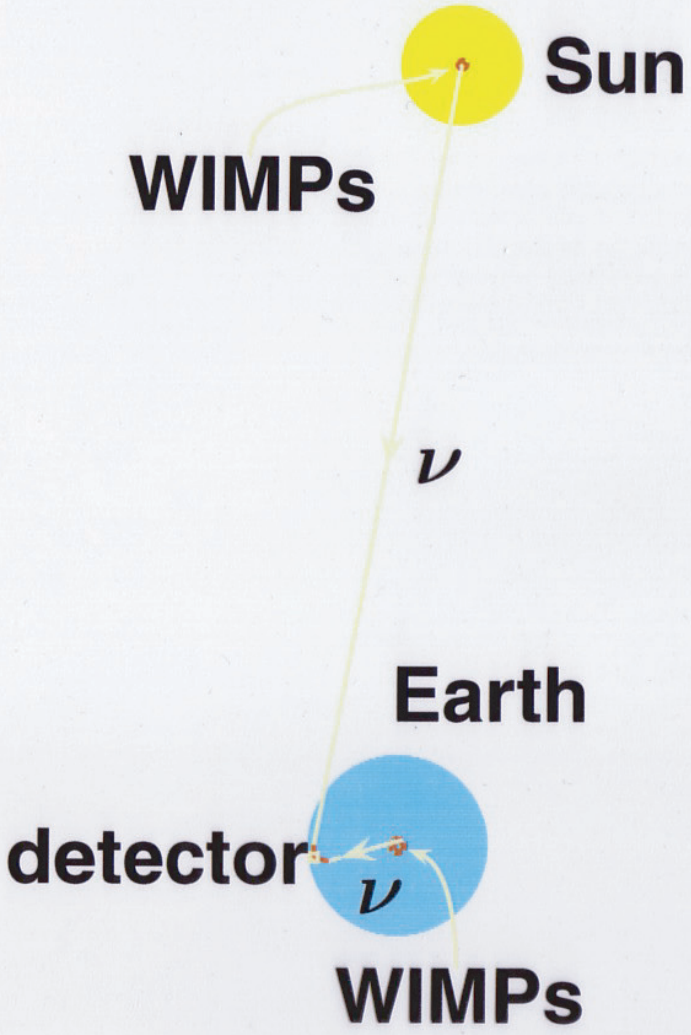
Future test of WIMP explanation: Gamma-rays from galactic halo

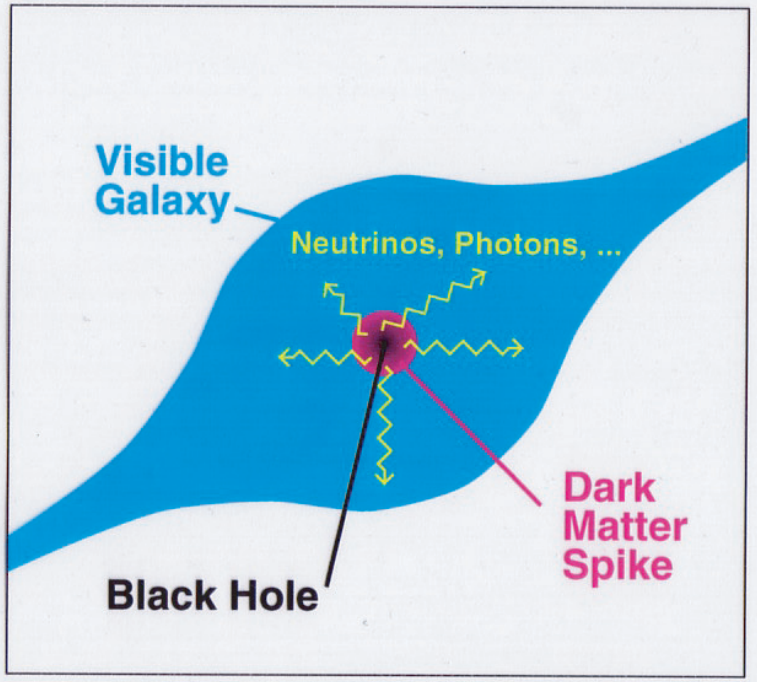




Baltz, Edsjö, Freese, Gondolo 2001

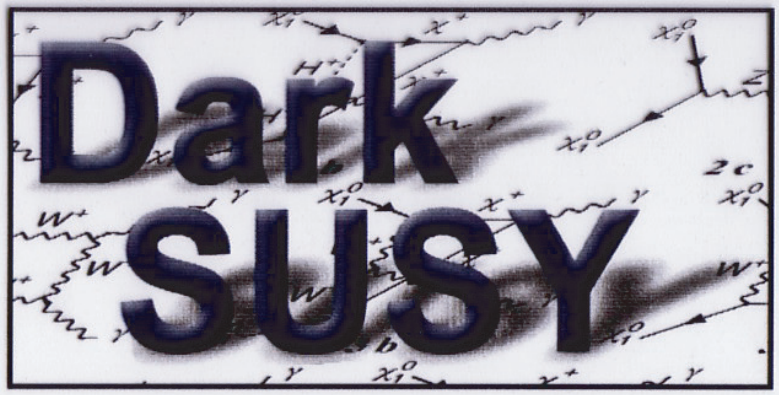
Neutrinos from dark matter





Gondolo,Silk 1999, Gondolo 2000

SuperK, AMANDA, Antares, IceCube, . . .



- Accelerator bounds
- Relic density
- Scattering off nucleons
- Signals in neutrino telescopes
- Gamma-ray signals
- Cosmic-ray positrons
- Cosmic-ray antiprotons
- Signals from galactic center

Other suspects:

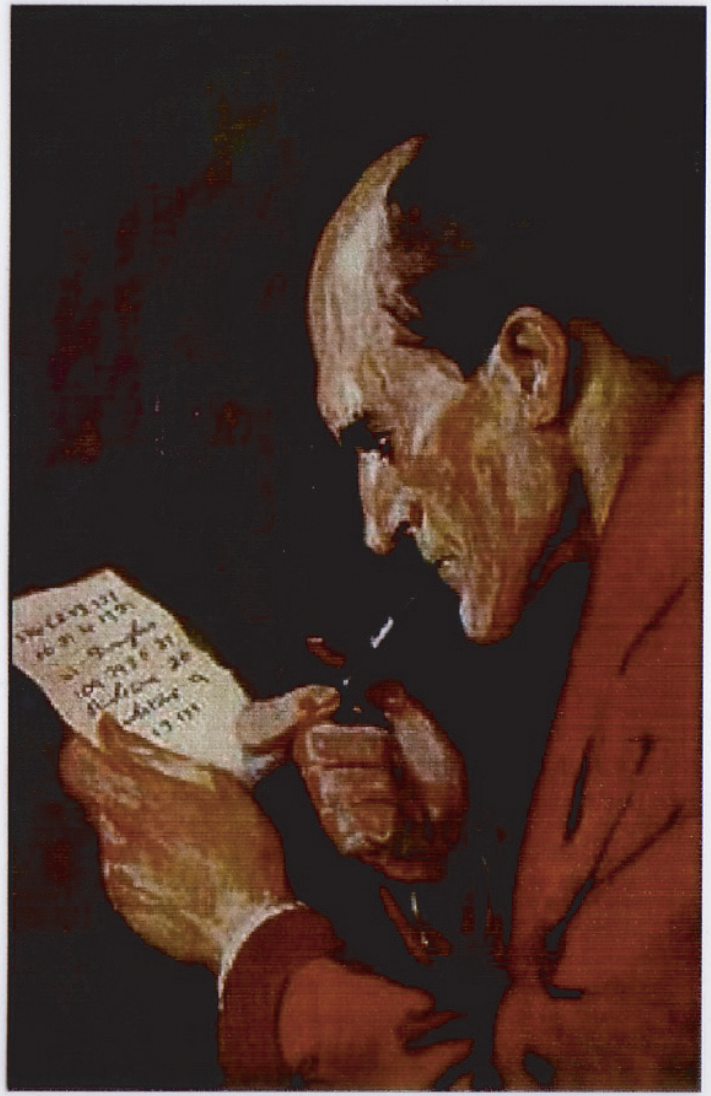
Missing baryons:

- **black holes,**
- **cold-warm gas,**
- **…**

Non-baryonic:

- **axions,**
- **WIMPZILLAs,**
- **Kaluza-Klein particles,**
- **…**

Speculations



Dark energy

- cosmological constant Λ
- quintessence
- network of cosmic defects
- transplanckian physics
- leaking gravity
- modified Friedmann equation
- Chaplygin gas
- ...

Dark energy from dark matter confinement

Gondolo,Freese 2002

- "Quanta" of confining force $F \propto r^{\alpha-1}$ have equation of state $p = -\frac{\alpha}{3}\rho$
- Dark matter subject to confining force can have negative pressure on large scales
- Compatible with SNIa data

  (Wang, Freese, Gondolo, Lewis 2003)
- Working on concrete relativistic model

Summary

Baryonic and non-baryonic dark matter

- evidence from diverse observations

In search of the missing baryons

- there are MACHOs, but what are they?

In search of non-baryonic dark matter

- neutrinos are hot dark matter
- still seeking WIMPs (neutralinos)

Speculations on dark energy

- Dark energy from interacting dark matter with negative pressure

Dark Matter Mystery Solved