Astroparticle Physics (2/3)

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CERN Summer Student Lectures, August 2008

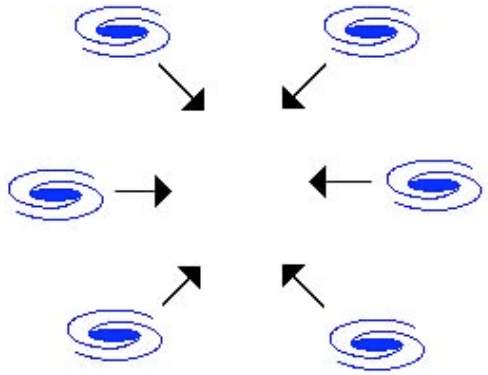
1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy

2) Dark matter
   Evidence for dark matter
   Candidates and experimental status
   Indirect searches

3) High energy astrophysics

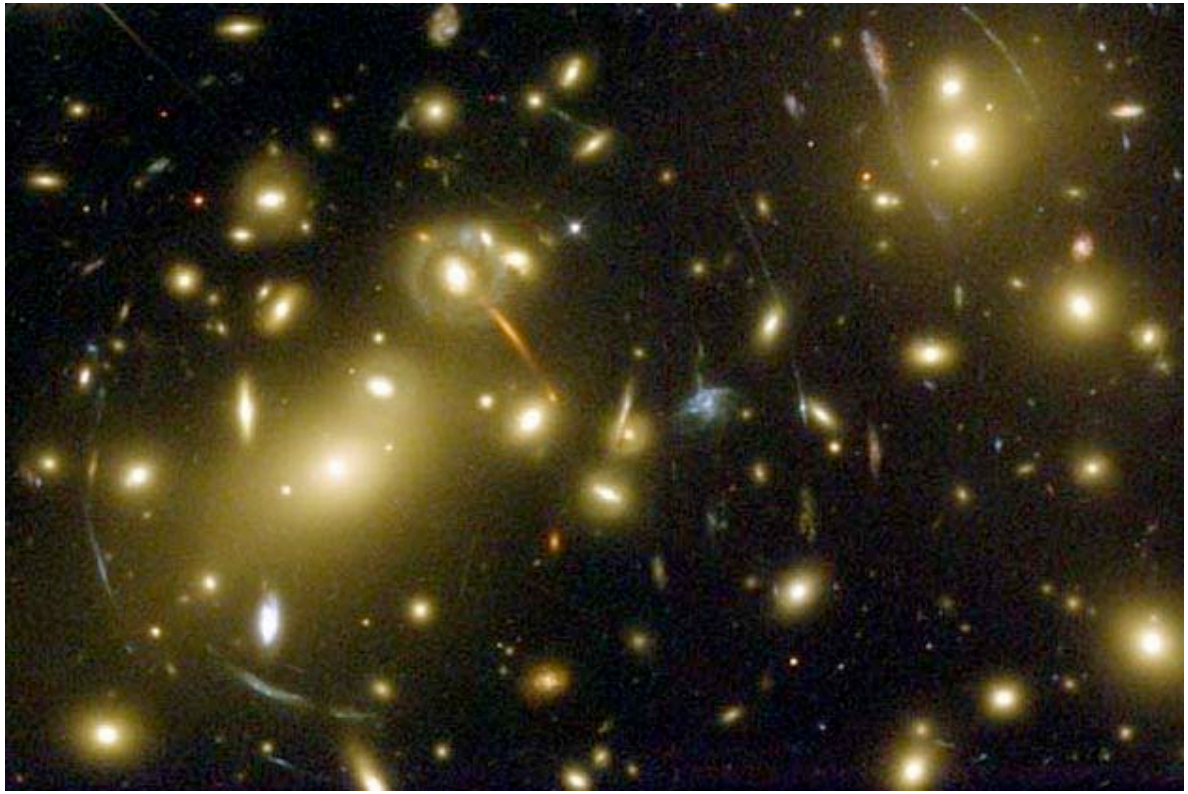
Dark matter in clusters

Zwicky, 1933



Mass of luminous matter
~ 1-10%
Gravitational mass

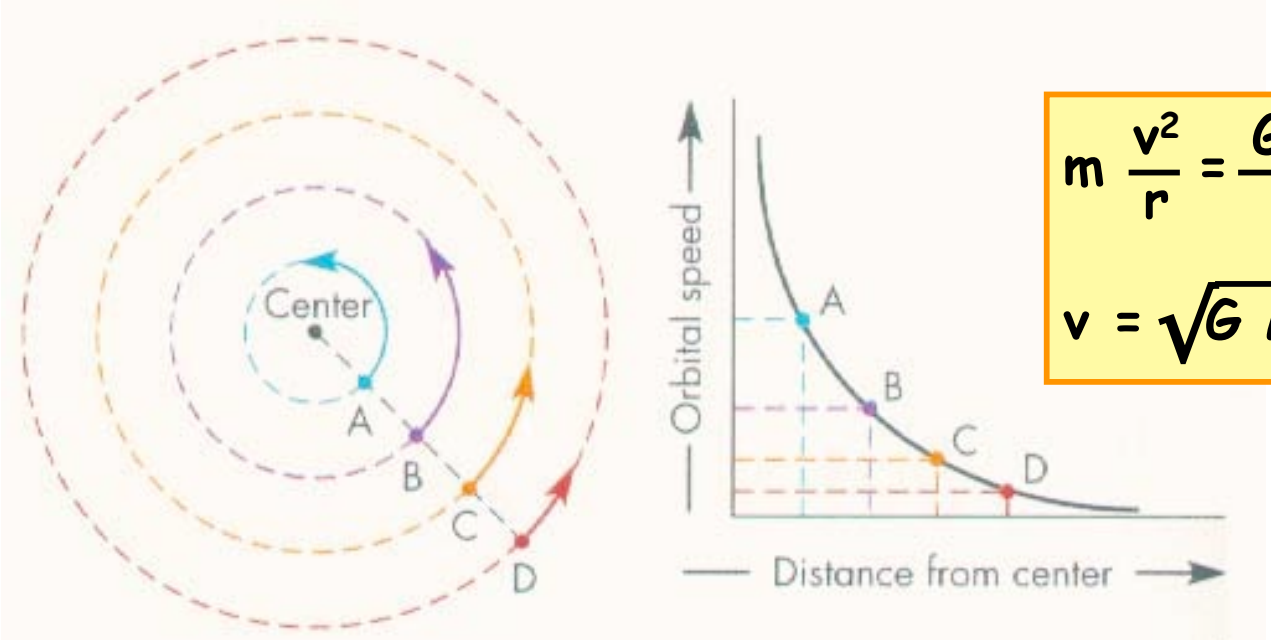
Gravitational lensing



HST

⇒ Luminous mass ~ 1% Gravitational mass

Rotation curves (planets)



$$m \frac{v^2}{r} = \frac{G\, m\, M_c}{r^2}$$

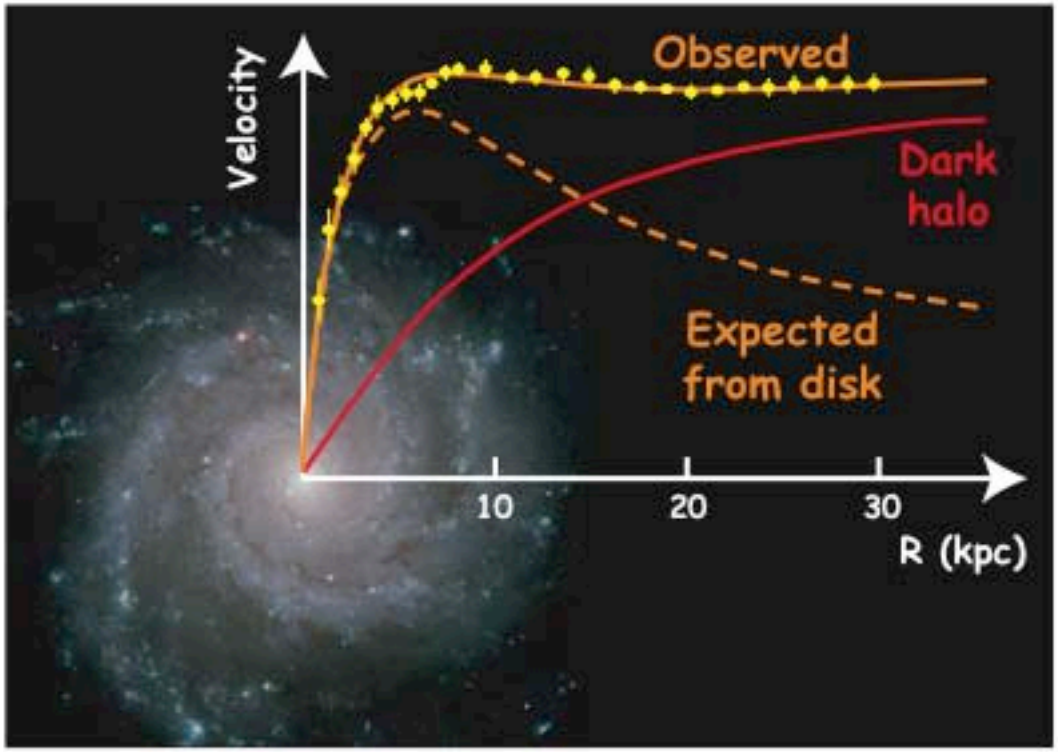
$$v = \sqrt{G\, M_c / r}$$

Rotation of planets

Associated rotation curve

Earth :	1 yr (at 150 10^6 km)	v=30 km/s
Saturn :	30 yrs (at 1,4 10^9 km)	v=10 km/s

Rotation curve of spiral galaxies



Flat rotation curves

⇓

Dark Matter

OR

MOdified Newtonian Dynamics

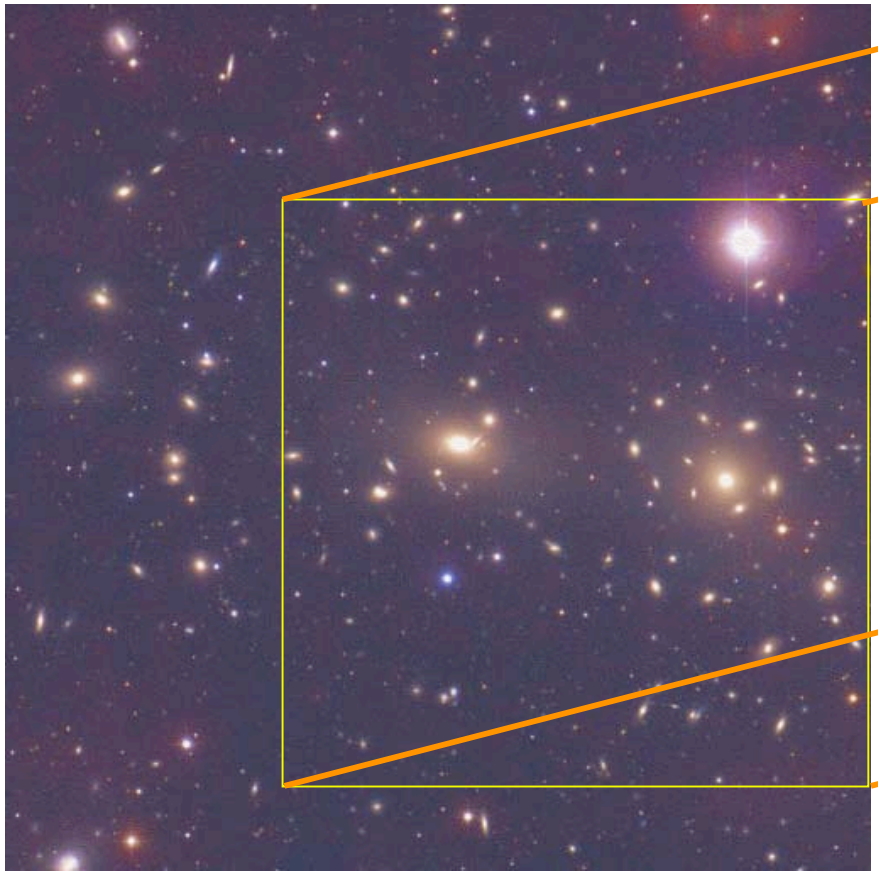
(acceleration ≠ GM/r)

Doppler shifts across galaxy
⇒ velocity distribution

90% of gravitational mass is invisible (DARK HALOs)

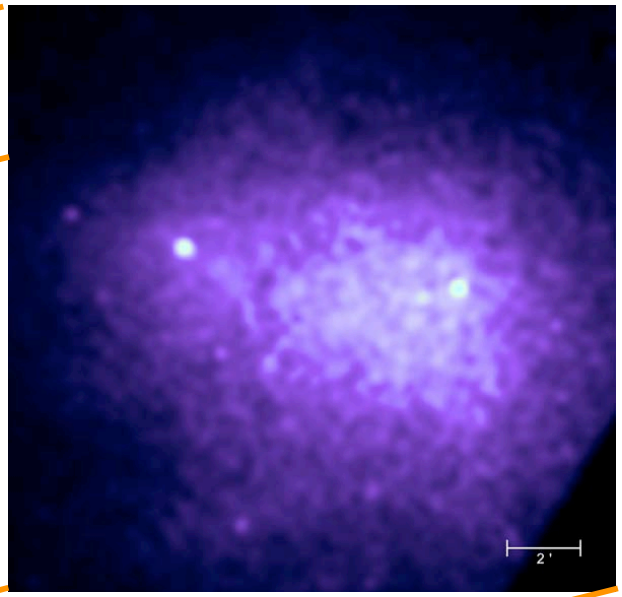
Collision between 2 clusters (1/3)

Optical image of Coma cluster



Credit: Kitt Peak

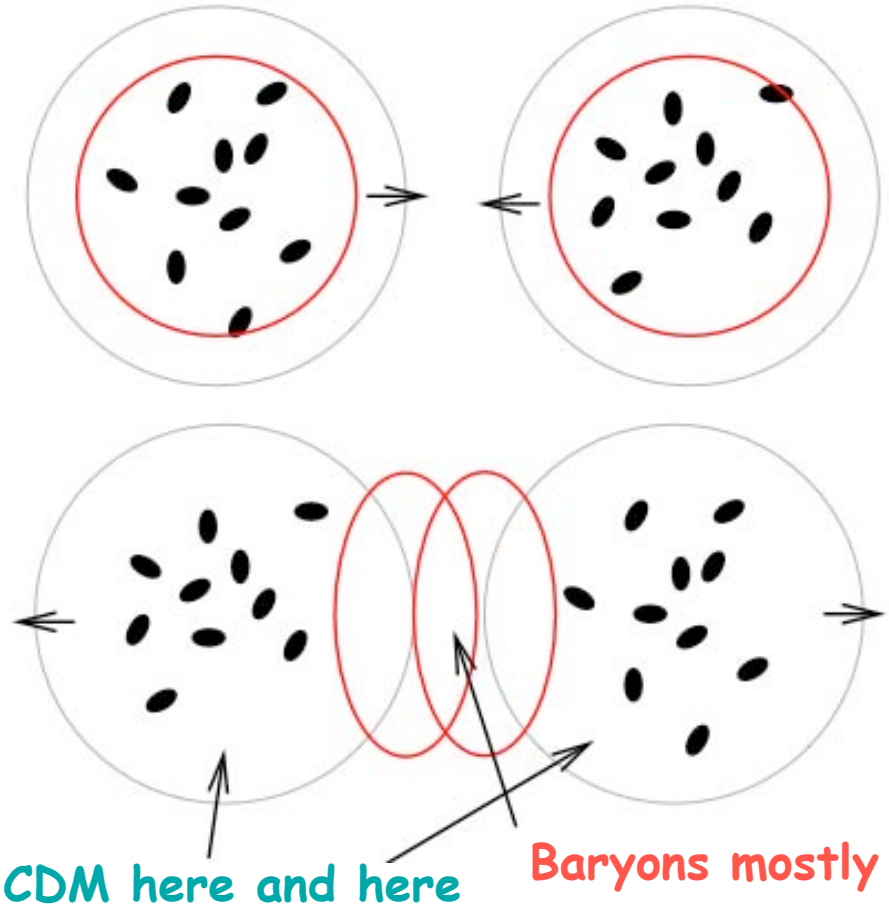
X-ray (hot intergalactic gas)



Credit: NASA / CHANDRA

10 times as much mass in gas as in galaxies

Collision between 2 clusters (2/3)



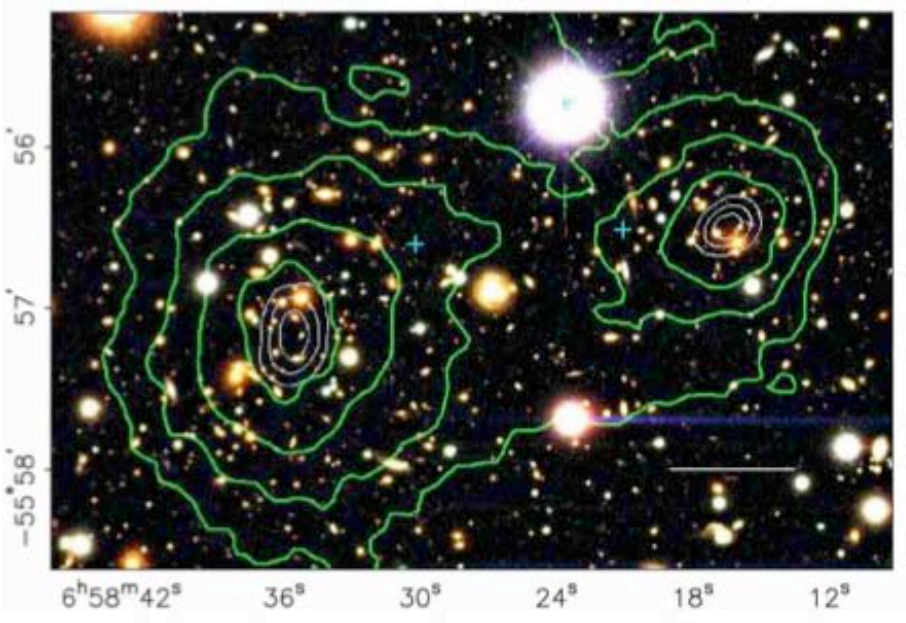
Collision between 2 clusters (3/3)

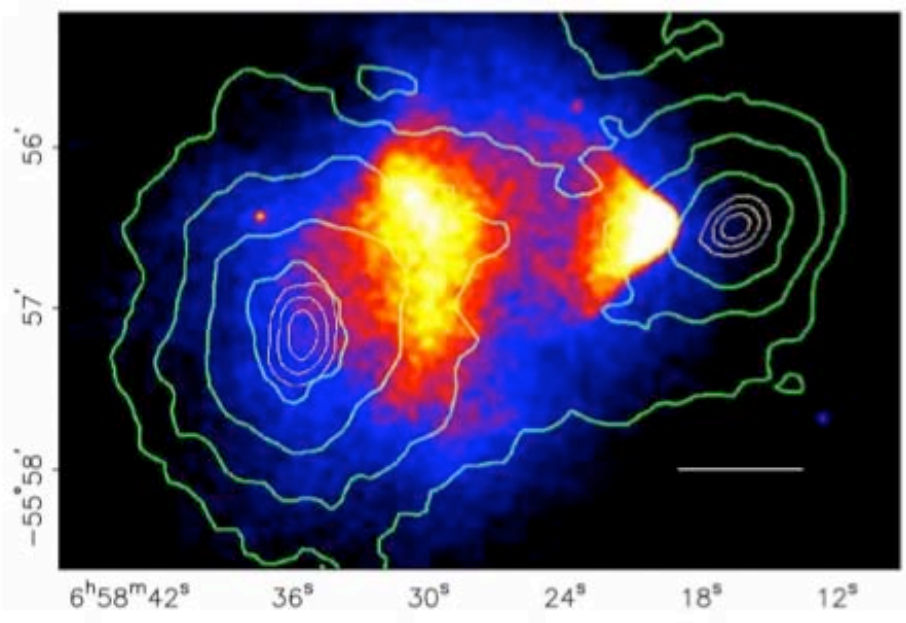
D. Clowe et al., astro-ph/0608407, AJ 648 (2006) L109-113

Collision in 1E0657-558 = bullet cluster

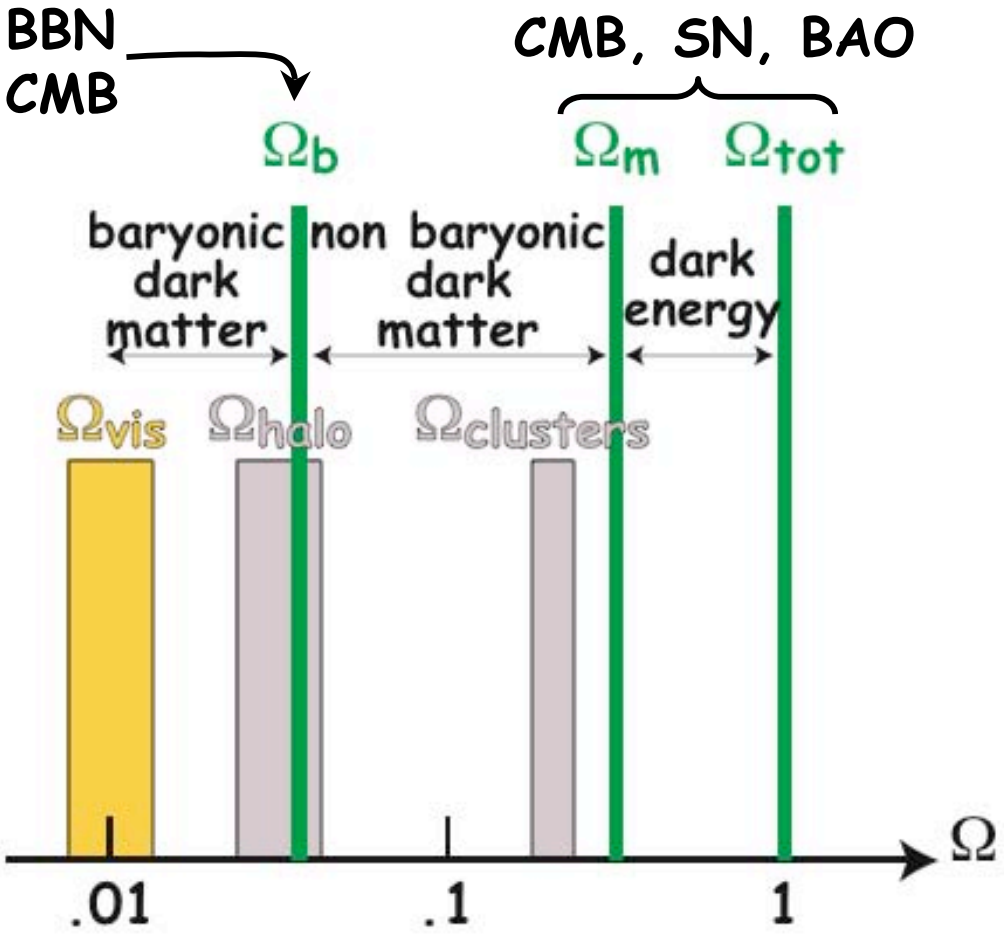
Weak lensing ⇒ **Mass not centered on gas**

⇒ **Confirmation of existence of Dark Matter**





Summary of evidence



$\Omega_i = \rho_i / \rho_c$
$\Omega_{tot} = 1$ for $\Omega_k = 0$

Lecture outline

1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy

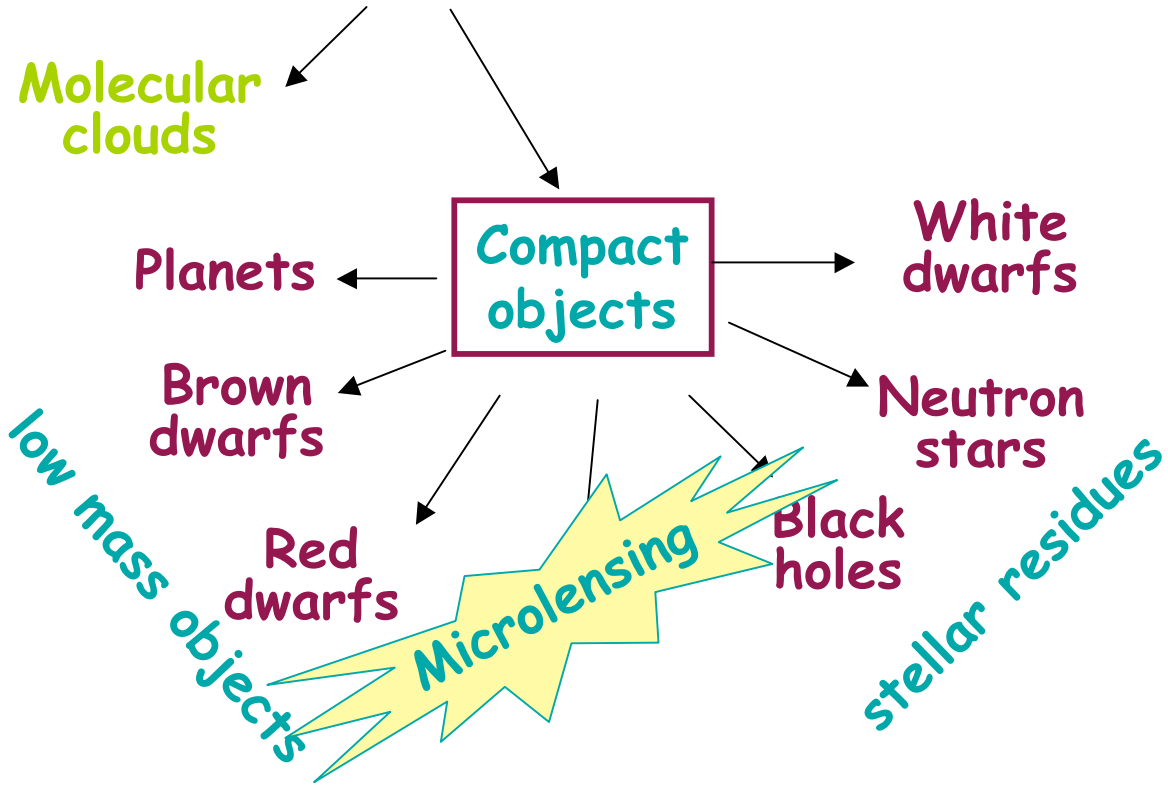
2) Dark matter
   Evidence for dark matter
   Candidates and experimental status
      Baryonic (EROS, MACHO)
      Exotic (Edelweiss, DAMA)
   Indirect searches

3) High energy astrophysics

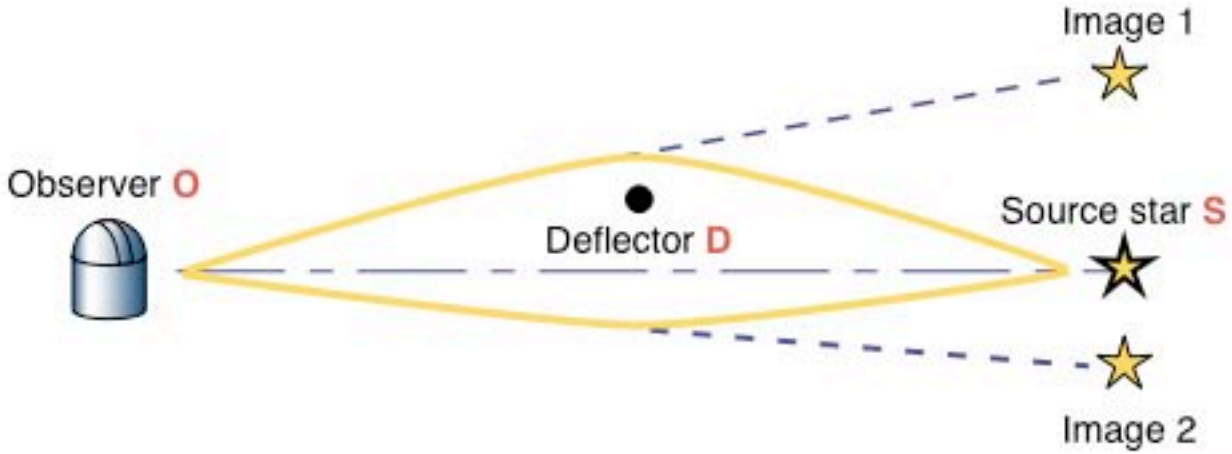
Dark matter candidates

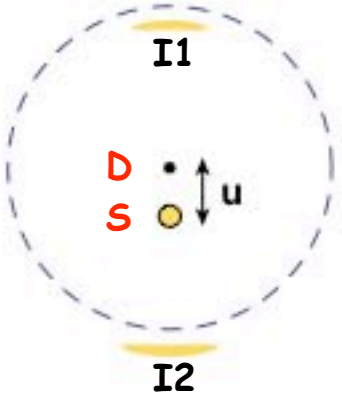
Baryonic
(astrophysical candidates)

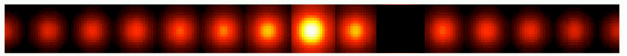
Non baryonic
(particle candidates)

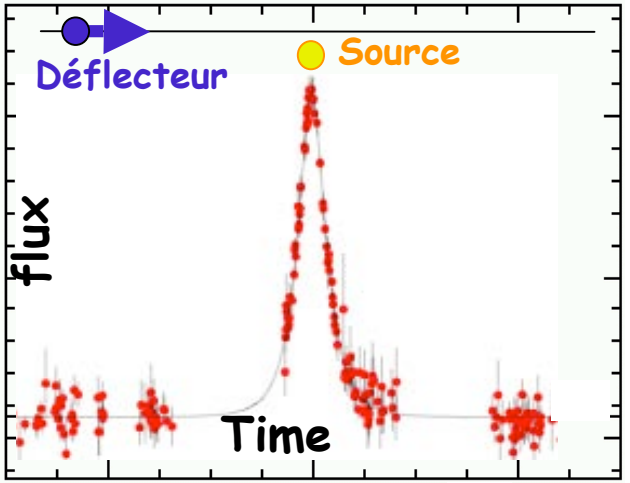


Principles of microlensing









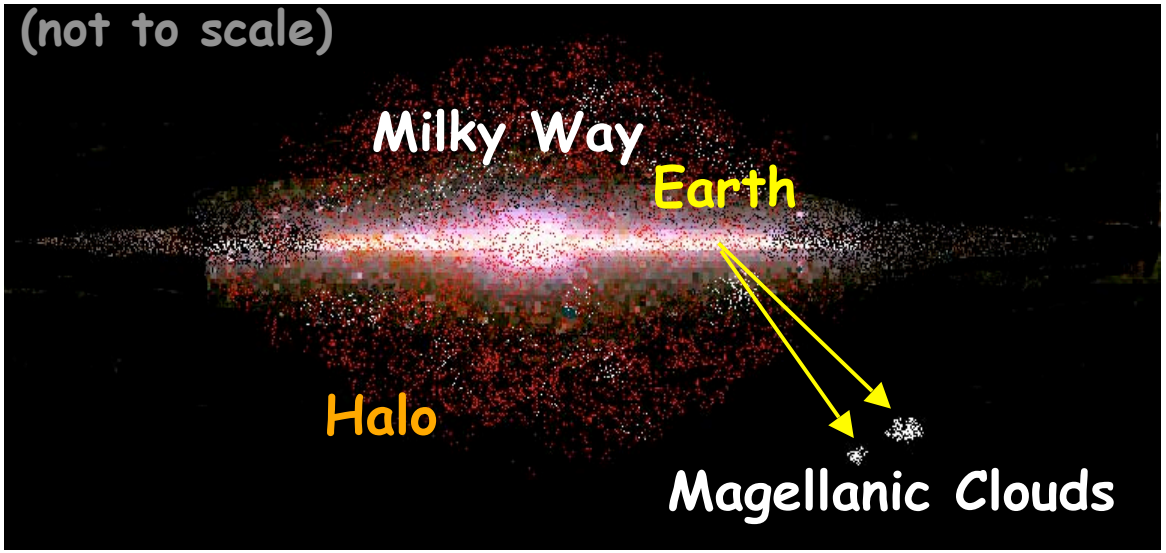
Angular separation of images ~ 10^{-3} rad
⇒ Only 1 (combined) image, amplified

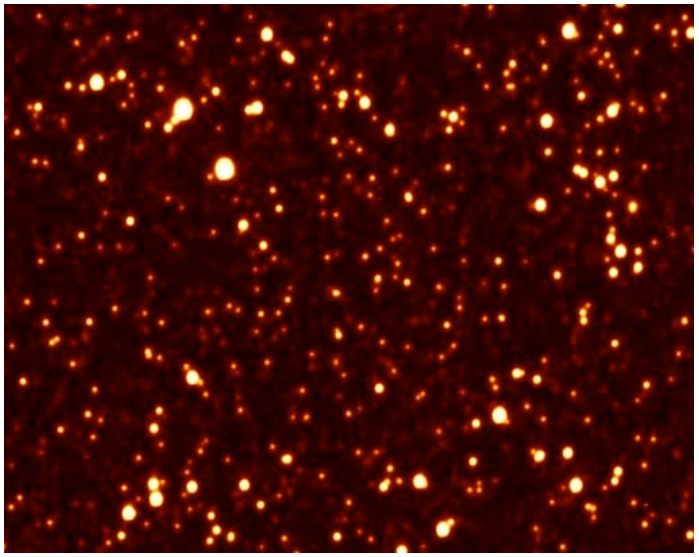
Motion of deflector (220 km/s)
⇒ Duration $t_E \sim 70 \sqrt{M/M_{sun}}$ days

Targets (EROS, MACHO)

Event rate : ~ 1 per year per 20 million stars monitored

Magellanic clouds : 200 000 ly away (edge of halo?)
(Milky Way ~ 70 000 ly in diameter)

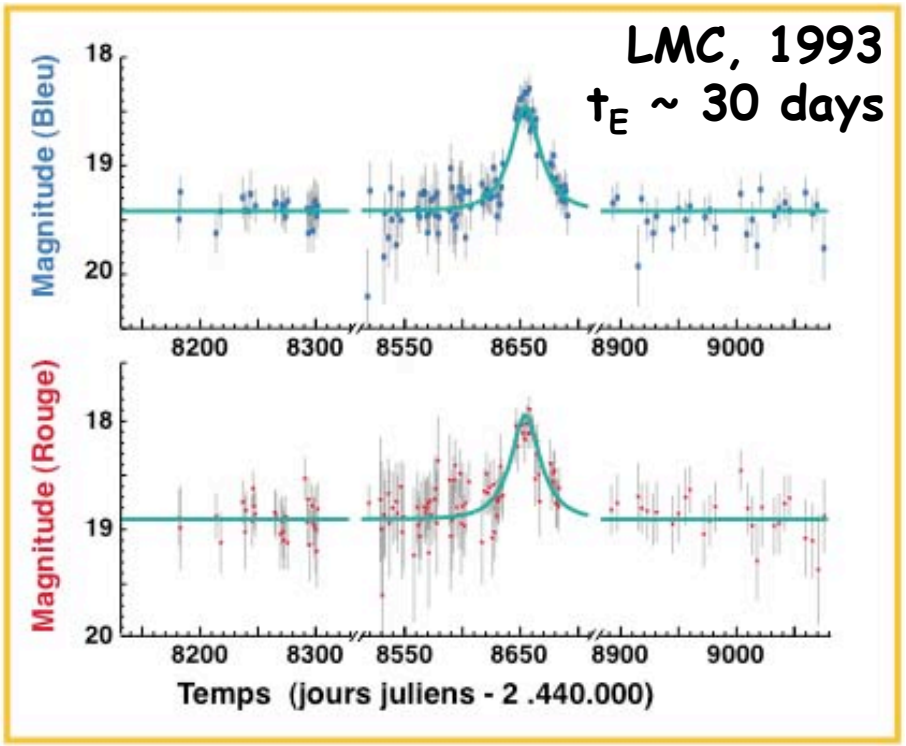


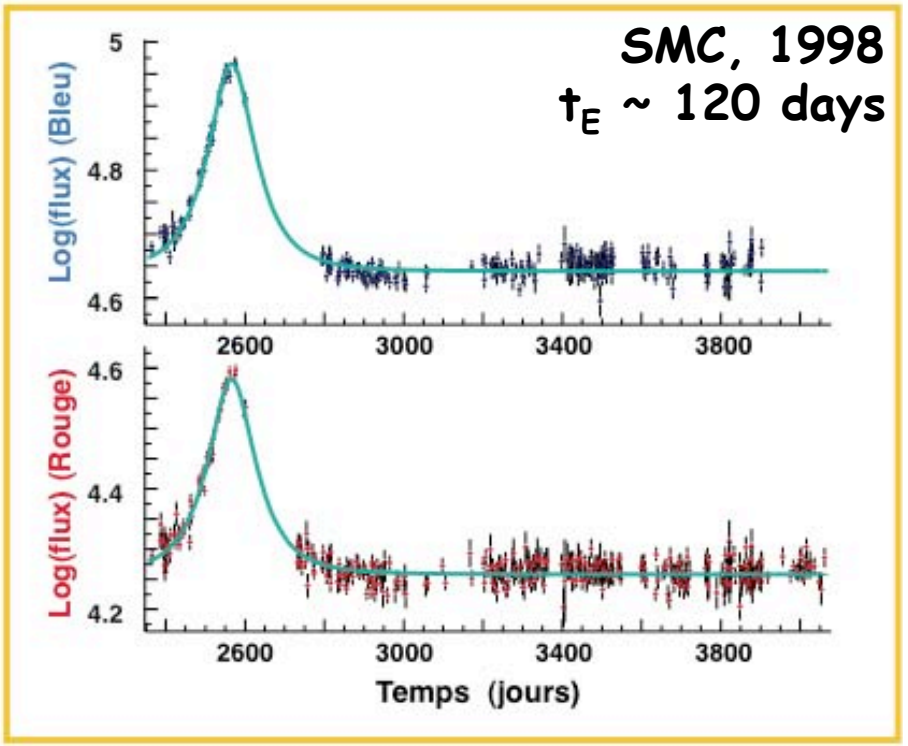


~30 million stars monitored:
- >10 000 variable stars
- >100 SN
- Microlensing events ?

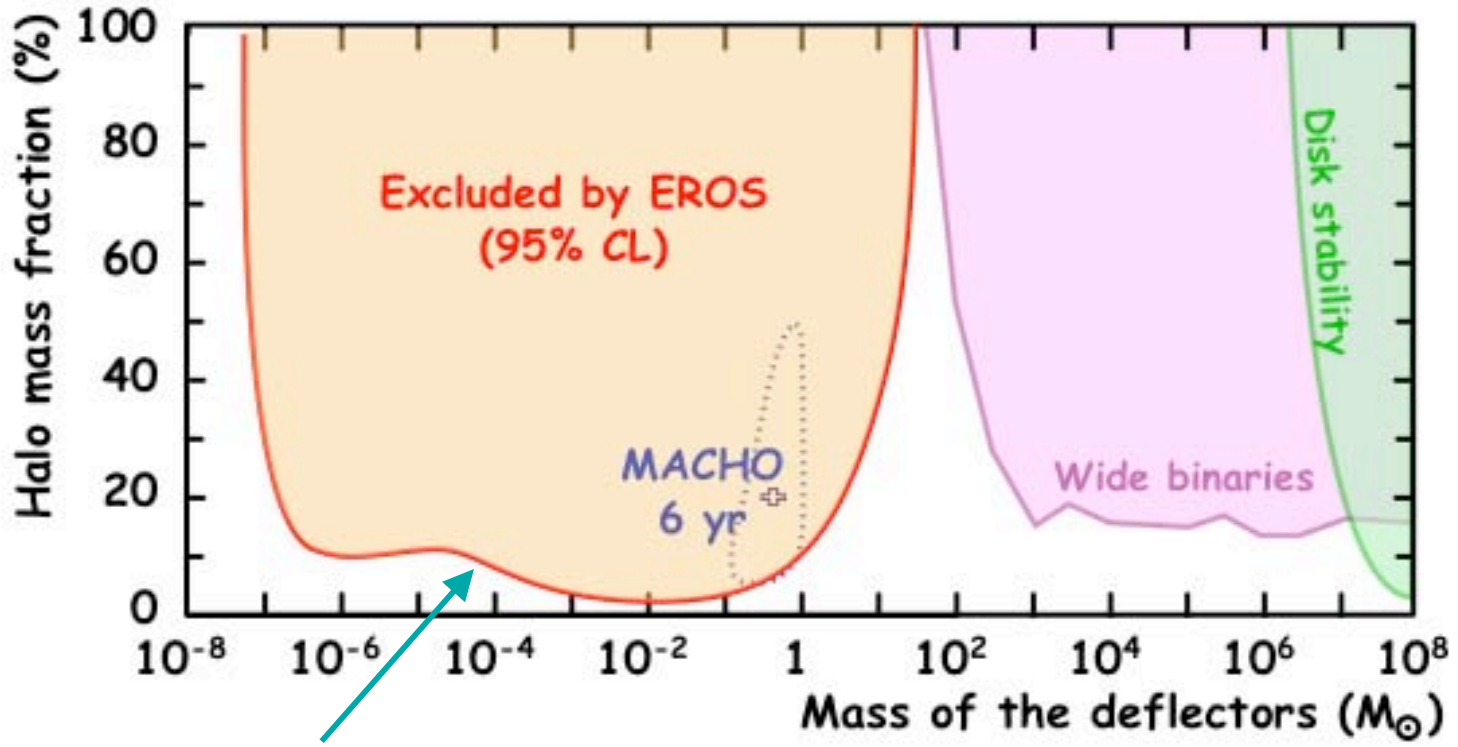
A few events

Candidates detected (microlensing technique validated)





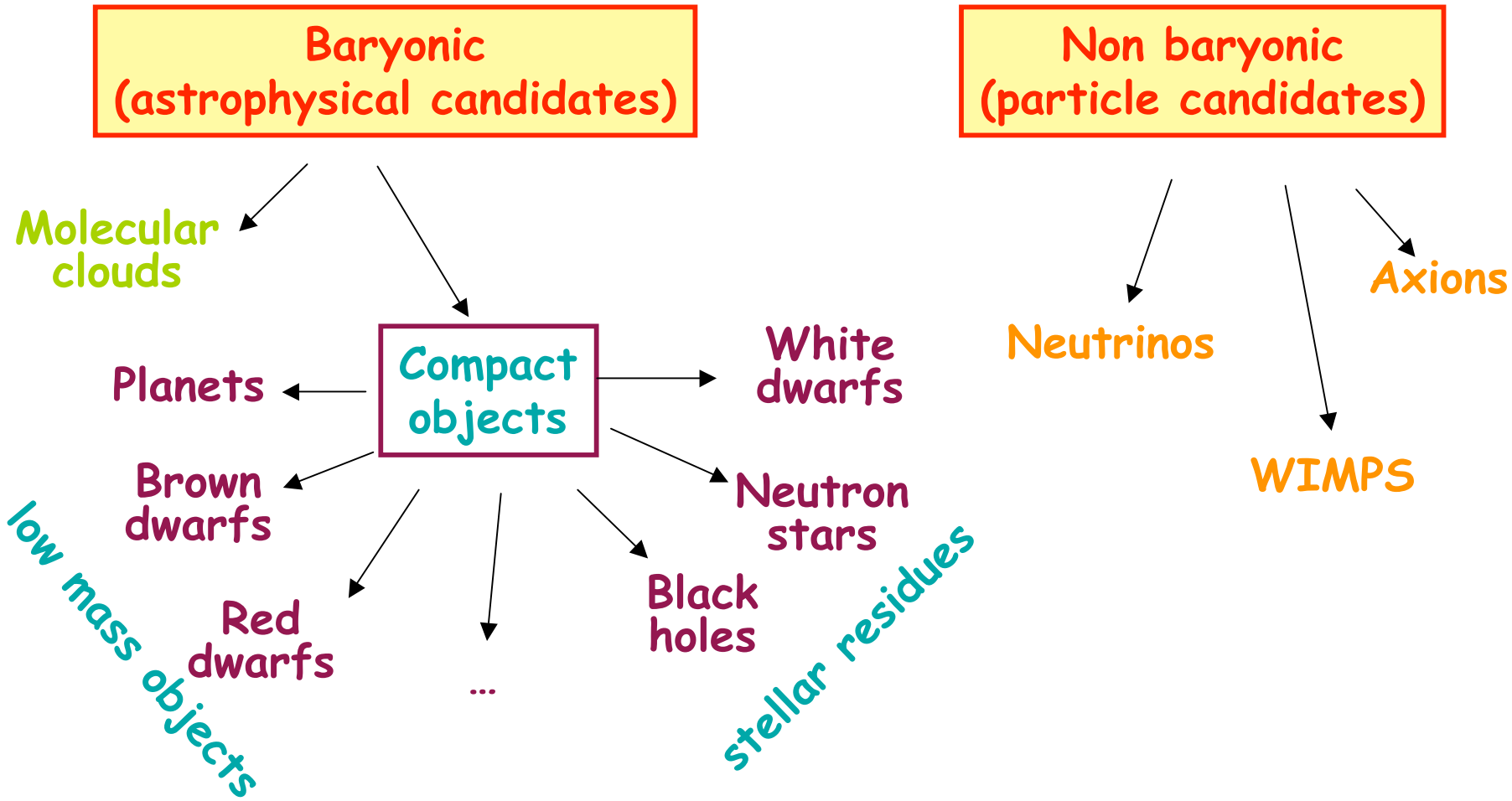
Final results



Tisserand et al.,
A&A 469 (2007) 387-404

Favored baryonic DM candidates rejected on all mass range

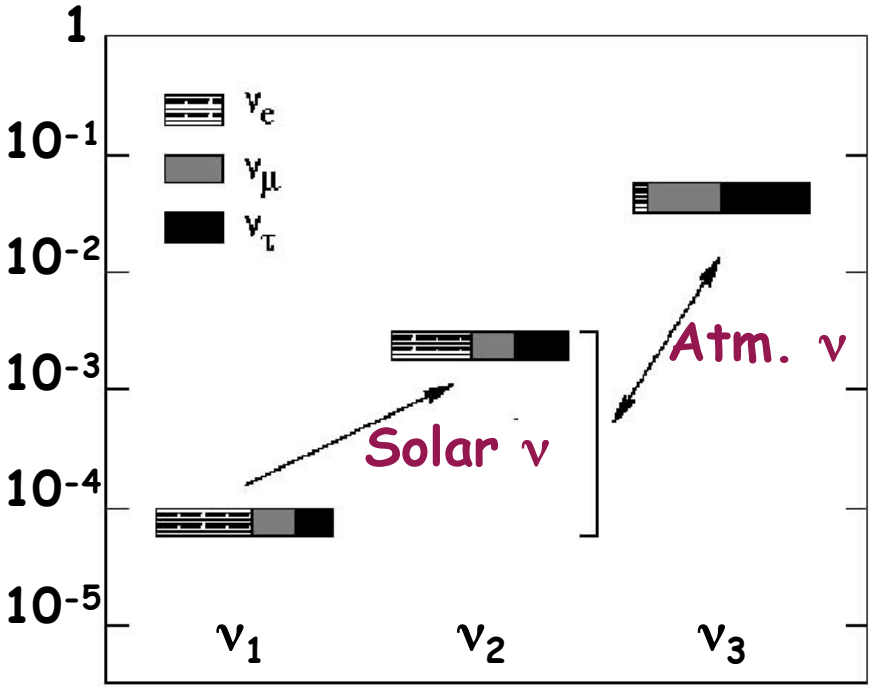
Dark matter candidates



Neutrinos as HDM

- exist as relic from Big Bang (~ 300 cm^{-3})
- (now) known to have mass: neutrino oscillations

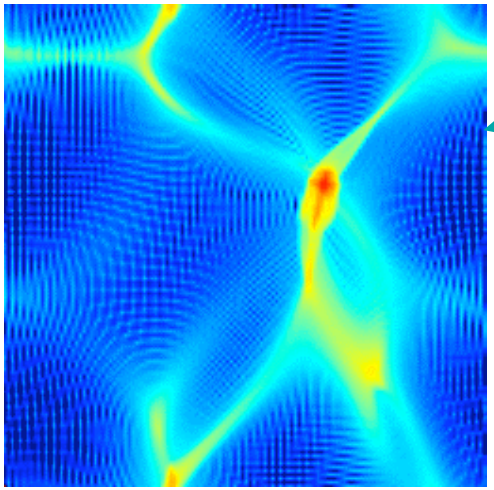
ν masses (eV) from
ν oscillations
(most likely solution)



ν contribution to matter density: $\Omega_\nu \sim m_\nu n_\nu / \rho_c$
$m \sim 0.05$ eV $\Rightarrow \Omega_\nu \sim 0.003$

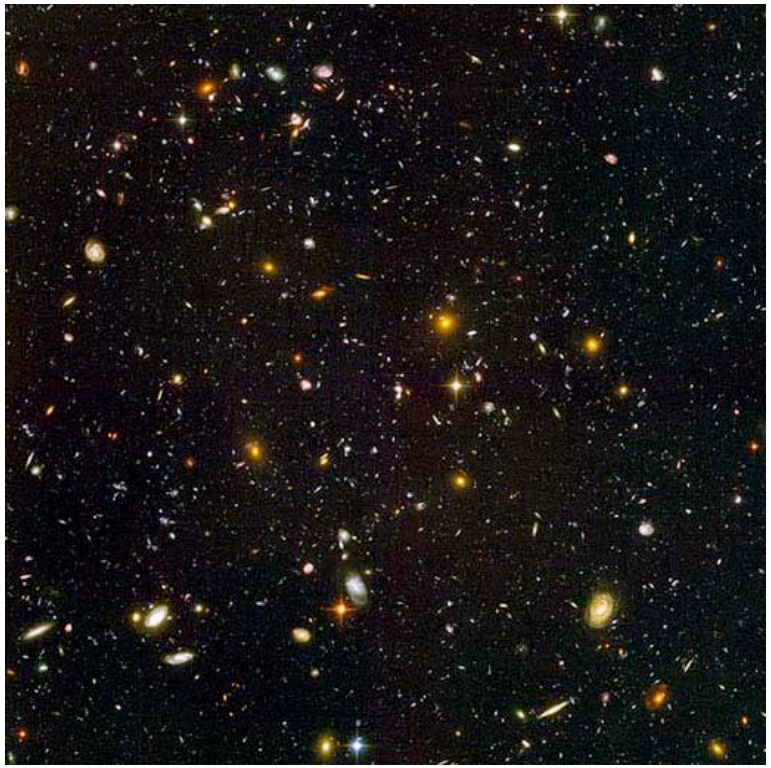
Structure formation

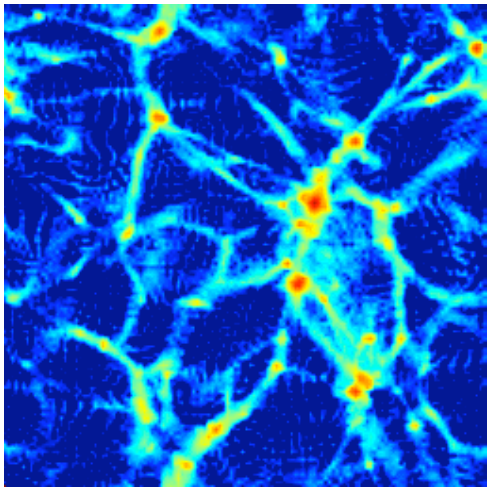
Simulations of
DM density maps



HDM wipes out
structure on
small scales

Hubble Deep Field





CDM creates
too many
sub-structures?

Weakly Interacting Massive Particles

If SUSY exists
- production of sparticles in early universe
- all decay except **LSP** (conservation of R-parity)

→ stable relic from Big Bang

Equilibrium density through

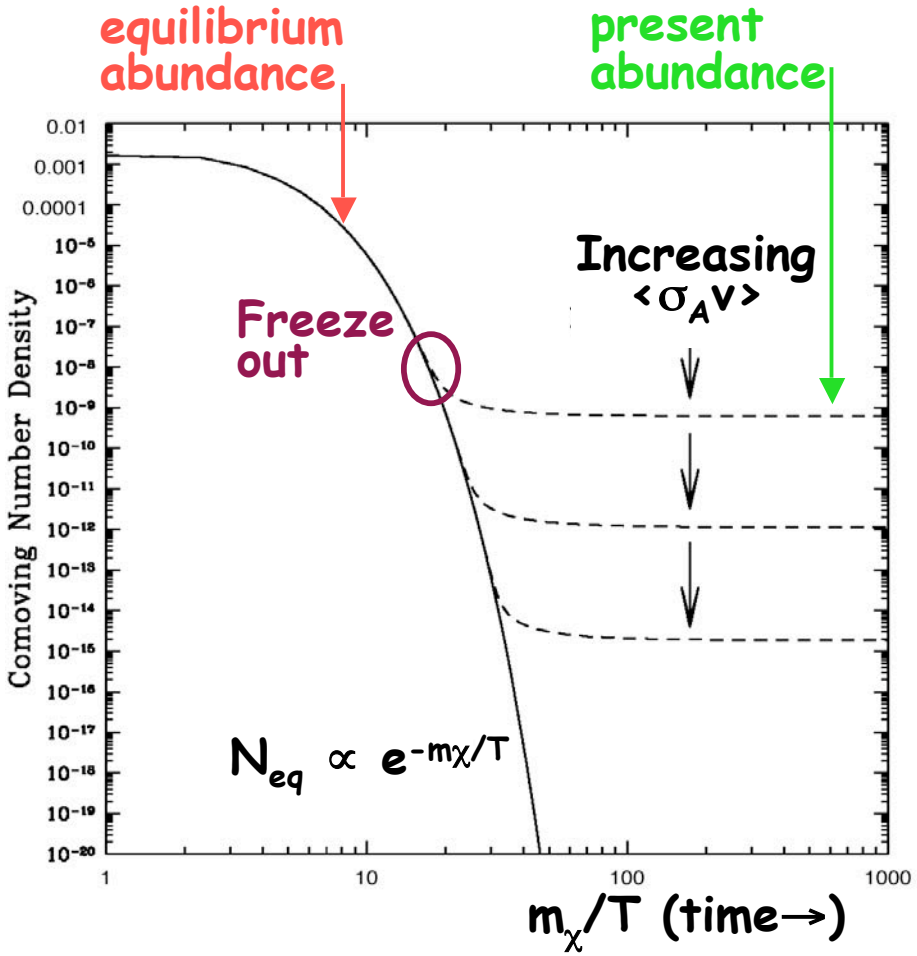
$\chi\,\overline{\chi} \leftrightarrow X\,\overline{X}$

$(N_{eq} \propto e^{-m\chi/T})$

Relic density

$\Omega_\chi \propto 1 / \langle \sigma_A\, v \rangle$

$\sigma_A \sim \sigma_{weak} \Rightarrow \Omega_\chi \sim 25\%$



Direct detection of WIMPS

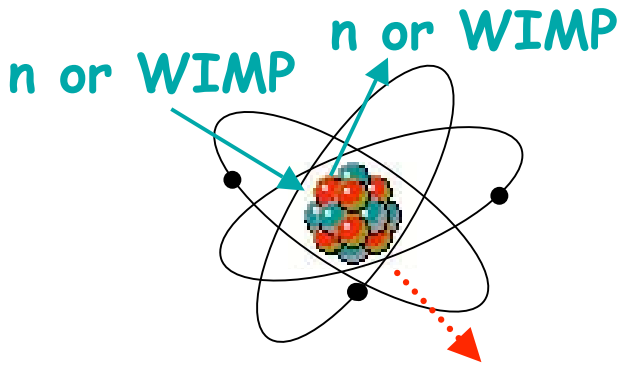
If halo DM made of WIMPS

~ 500 WIMPS/m^3 with v ~ 220 km/s

$\Rightarrow$ > 10 000 WIMPs/cm^2/s on Earth (from $-\vec{v}_{sun}$)

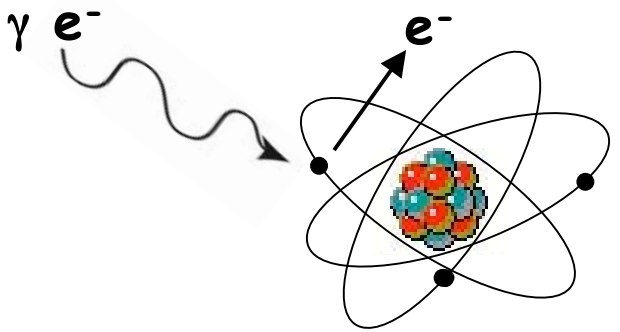
Experimental signature

nuclear recoil



Background (radioactivity)

electronic recoil



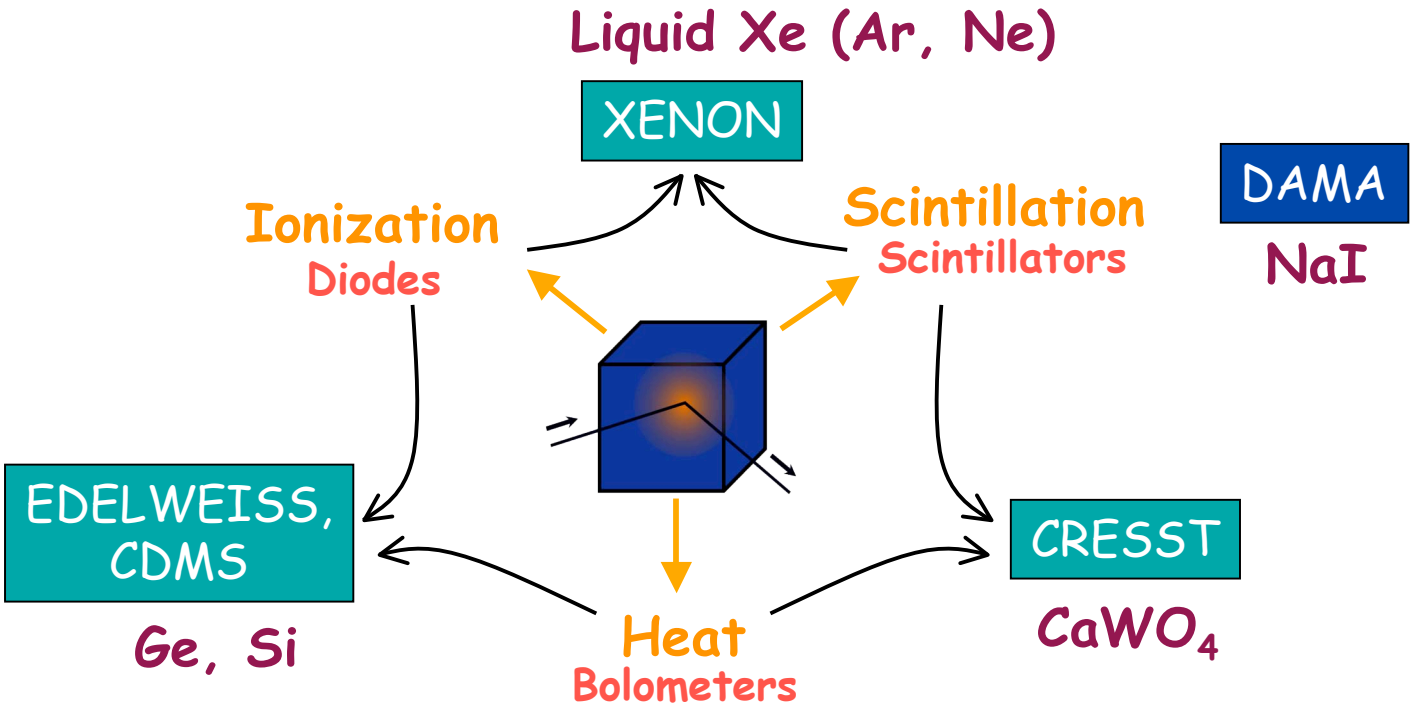
<< 1 evt / kg / day

Requirement : High mass detectors

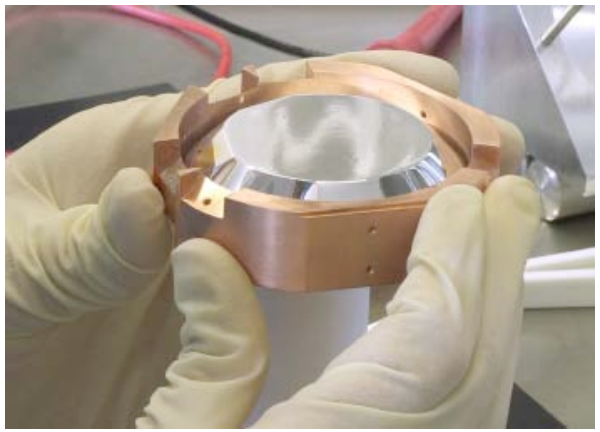
Low radioactive background (discrimination)

Background rejection

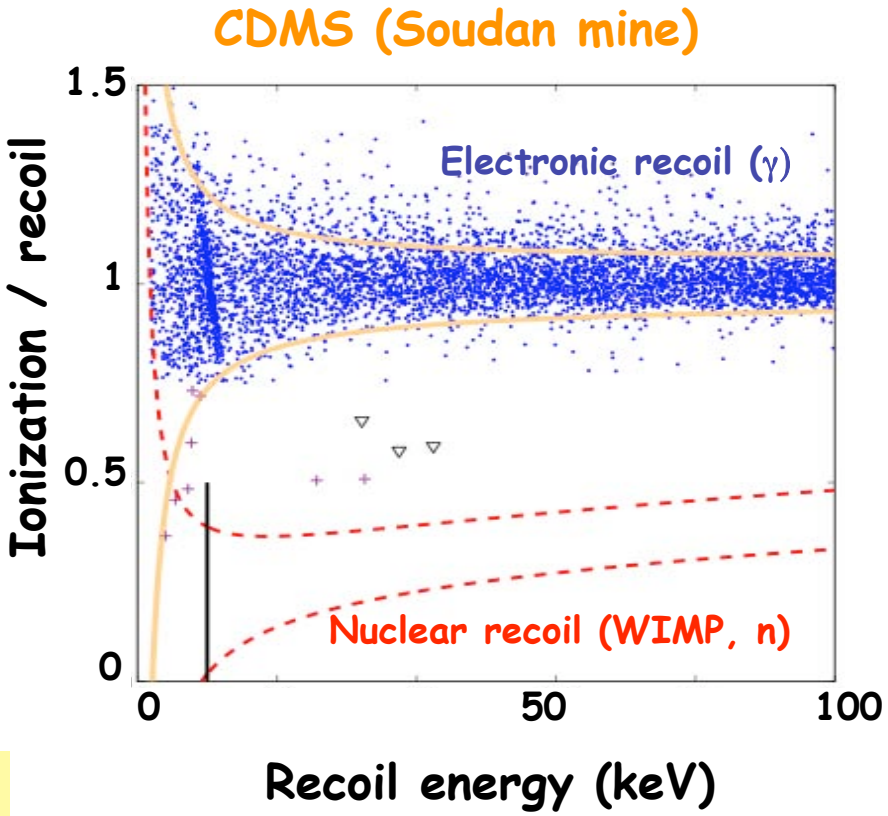
Event by event discrimination of nuclear vs. electronic recoil



Heat + ionization
Edelweiss / CDMS



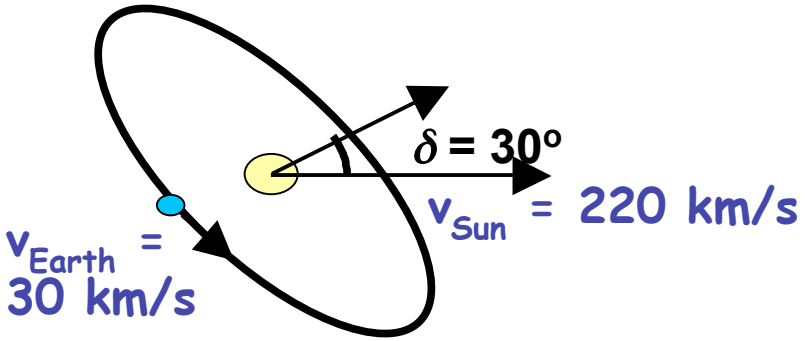
300g Ge bolometer



~ background free analysis
No event in signal region

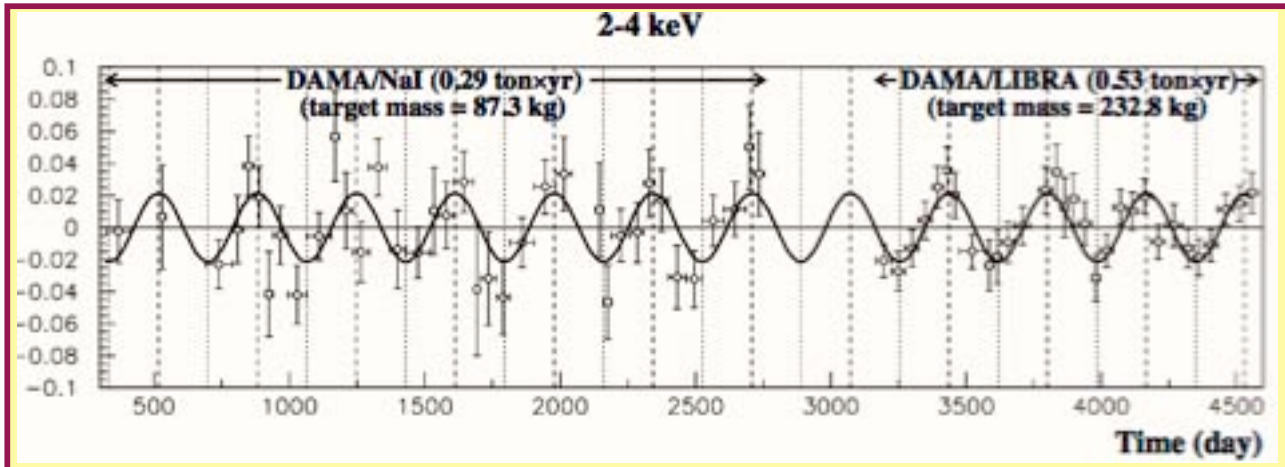
Akerib et al.,
Phys Rev D72 (2005) 052009

Annual modulation



Motion of Earth in the χ wind

Modulation of annual rate ± 7%
Max in June



DAMA/LIBRA
250kg NaI

Annual modulation
at 8.2σ
m_χ ~ 44-62 GeV

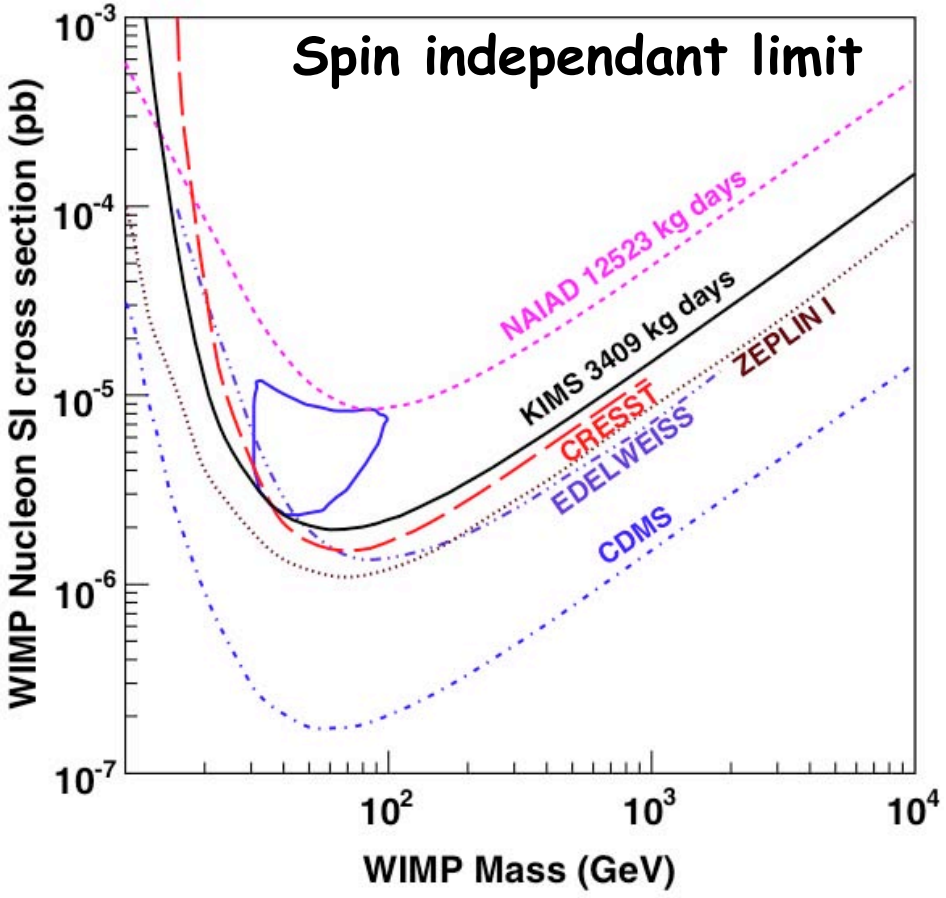
Barnabei et al., arXiv:0804.2741

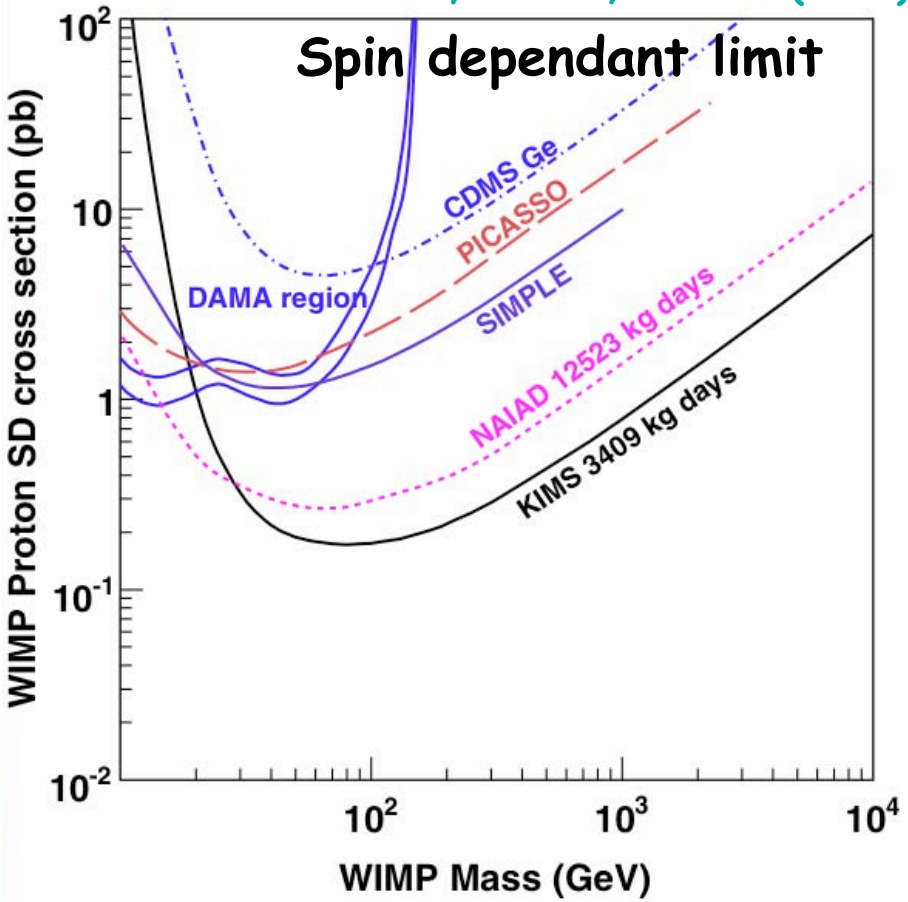
BUT 1 signature only (scintillation)
Result in contradiction with other expts.

KIMS (CsI)

Korea Invisible Mass Search

H.S. Lee et al., PRL 99, 091301 (2007)



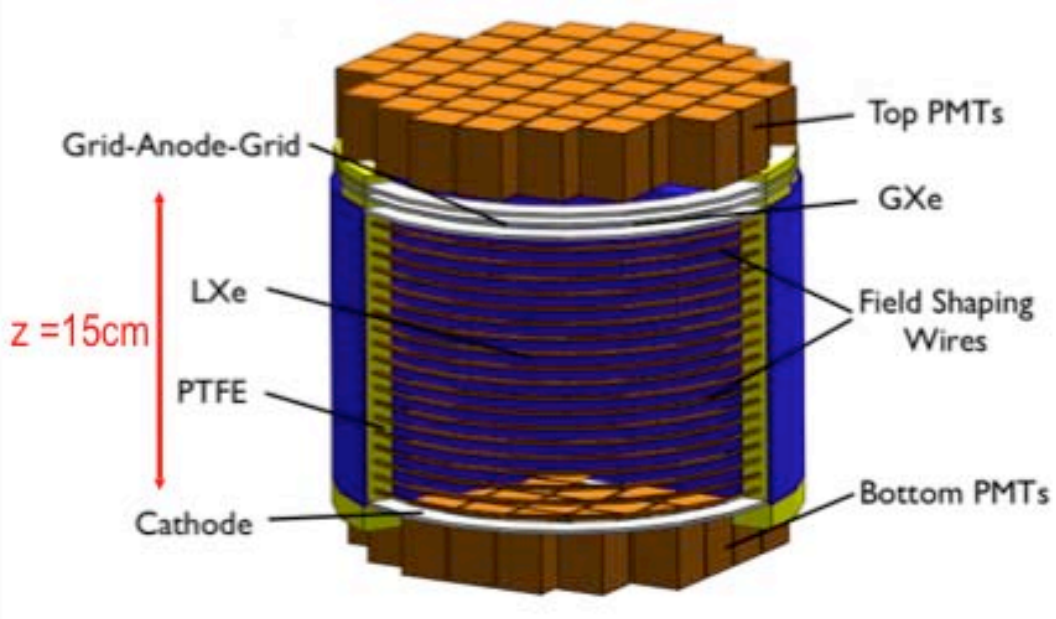


First rule-out of DAMA region by a crystal detector with ^{127}I

XENON

scintillation + ionization

Liquid detectors, easily extendable to larger masses
Good sensitivity to low-mass WIMPs
The way to go?

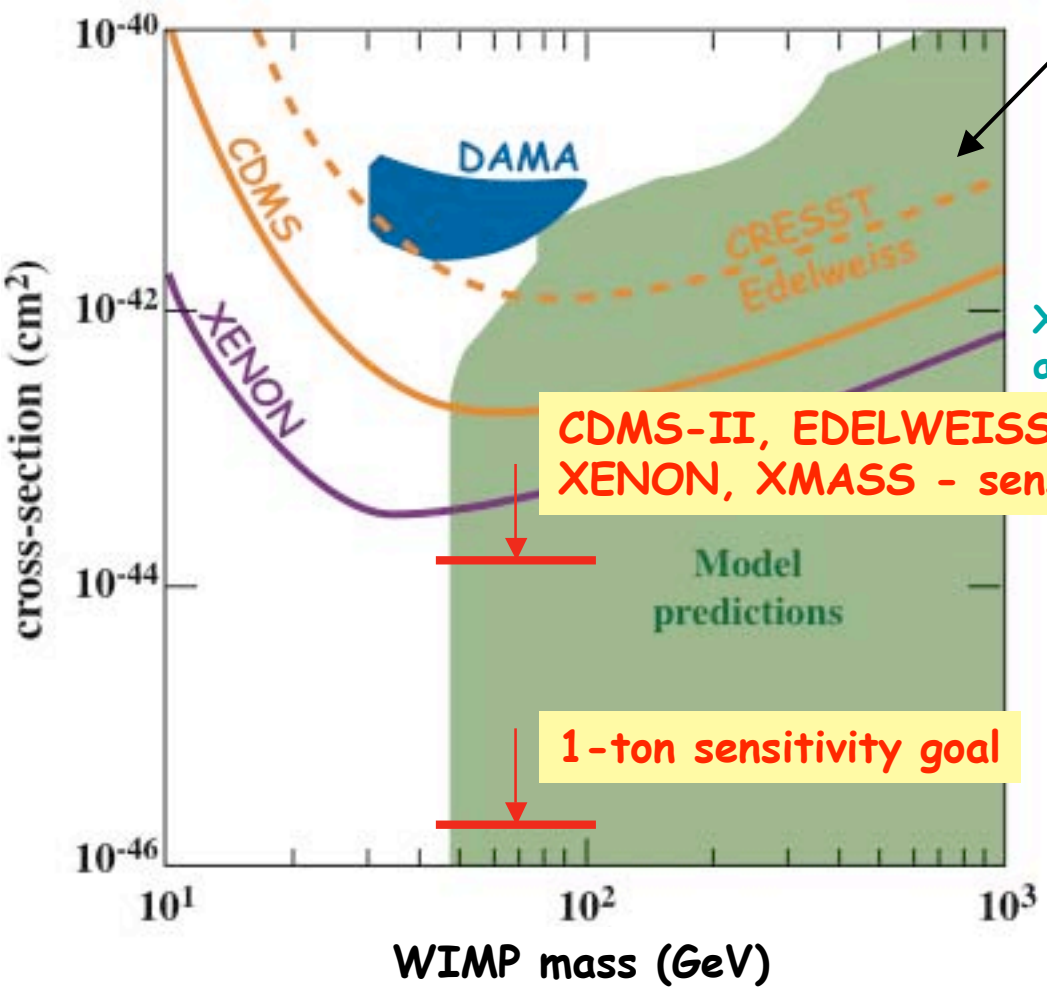


Remaining background
(despite a fiducial volume of ~ 50% of total)

S/N ∝ sqrt(time)

vs. sensitivity ∝ time
in background-free exp.

Conclusions on direct detection



Region above curves excluded by experiments

(~ 1 kg)

XENON: Angle, J. et al., astro-ph/0603449v2

CDMS-II, EDELWEISS-II, CRESST-II
XENON, XMASS - sensitivity goal

(~ 30 kg)

1-ton sensitivity goal

Testing most SUSY param. space (MSSM) requires 3 orders of magnitude beyond present best performances

Indirect detection of WIMPs

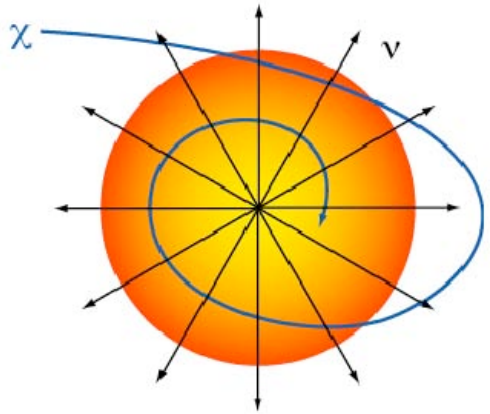
Energy loss by elastic scattering
with massive bodies
(halos, Earth, Sun, galactic center)

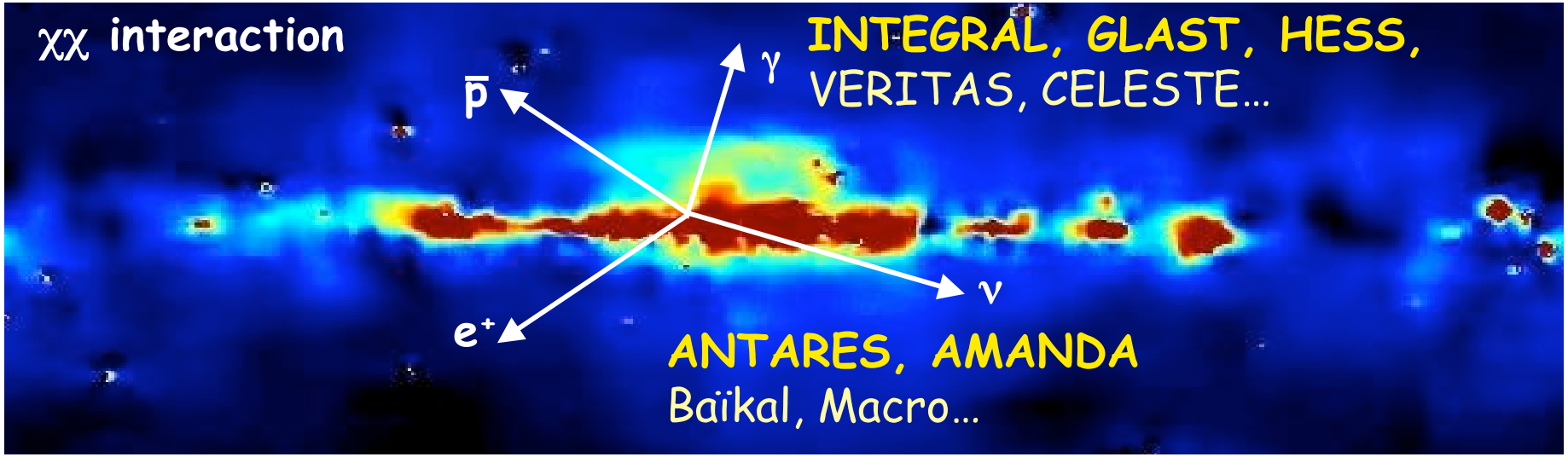
↓

Gravitational capture + annihilation

↓

DM searches in dense regions

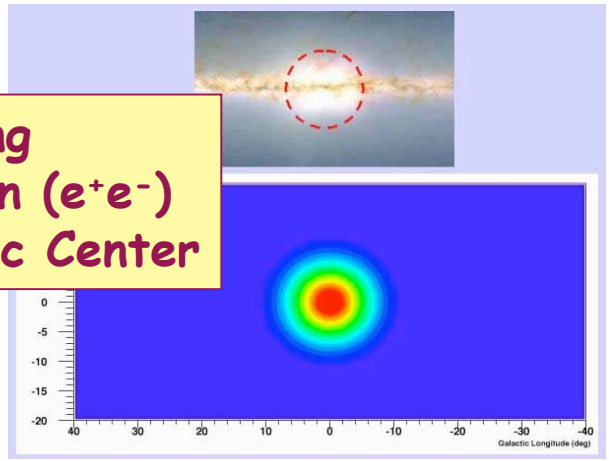




INTEGRAL (20 keV - 10 MeV)

INTErnational Gamma Ray Astrophysics Laboratory

2005

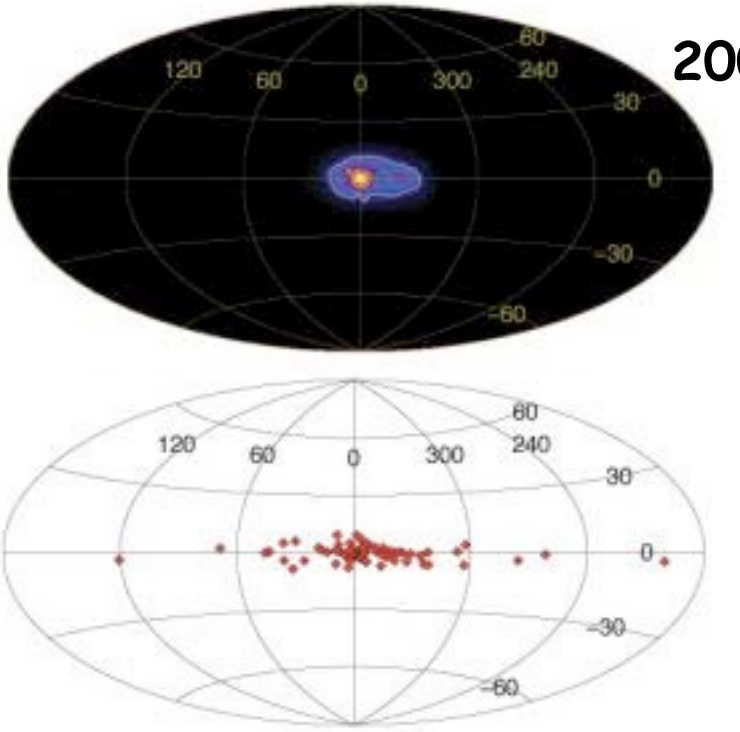


Very strong
511 keV emission (e^+e^-)
8° around Galactic Center

Dark matter?
e^+ annihilation at rest (positronium)
⇒ Alternative form of DM particle?
light DM (1-100 MeV)
(otherwise radiating e^- unseen)

Hypernovae?
needs 1 / 5000 yrs
e^+ from radioactive decay of CO^{56}

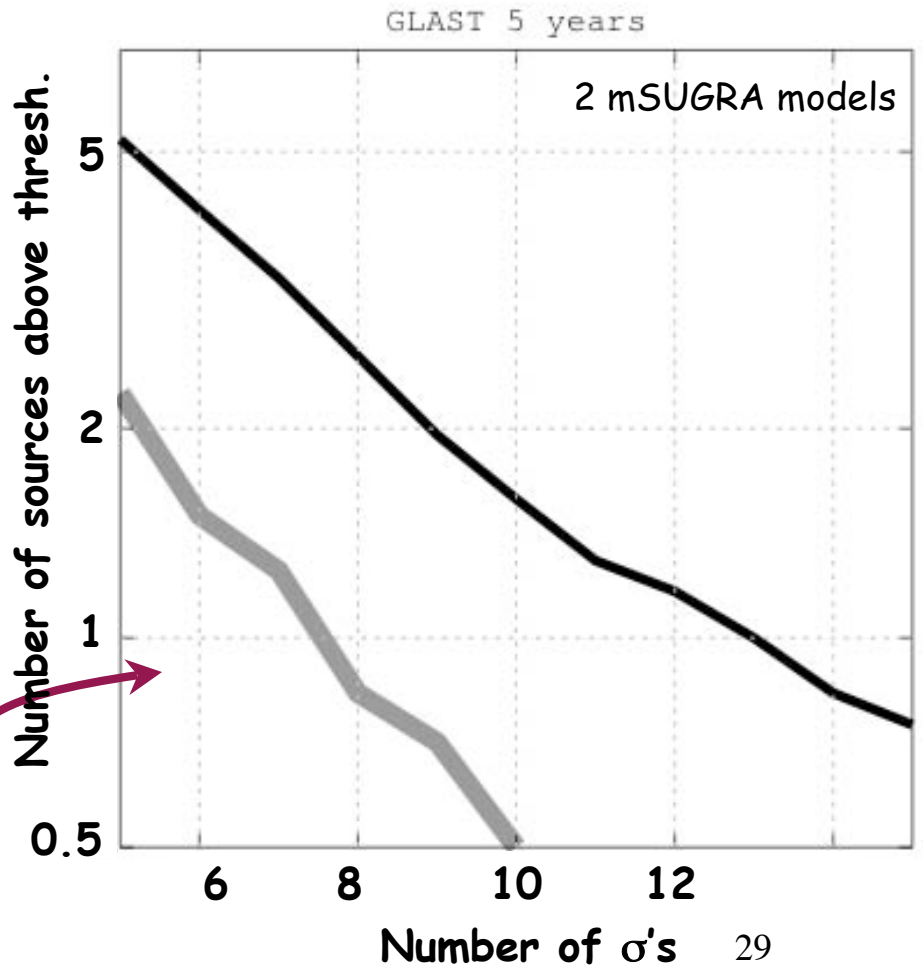
2008



Asymmetry correlated with distribution of hard LMXB (50-70% of signal)

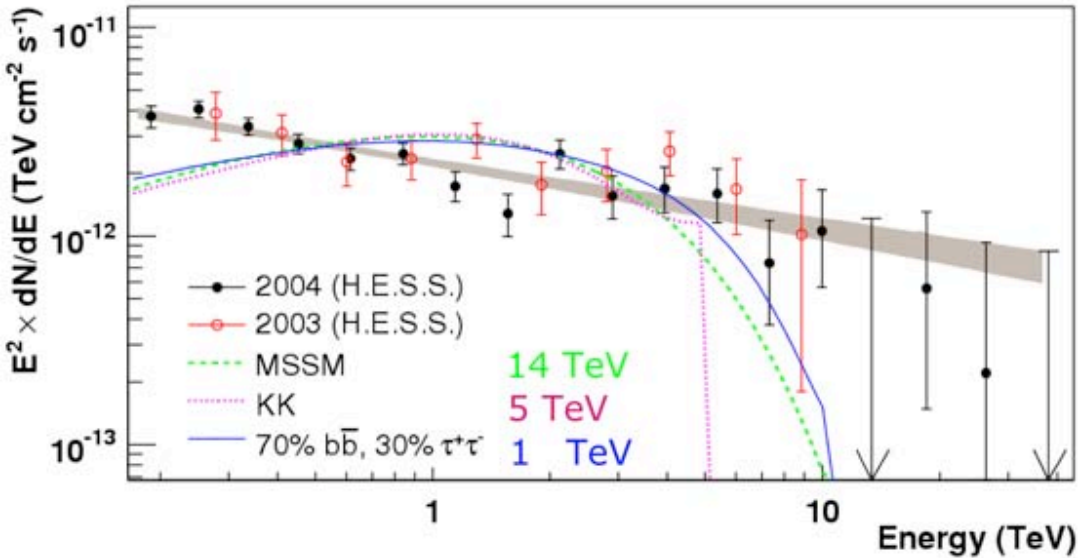
GLAST (20 MeV - 300 GeV)

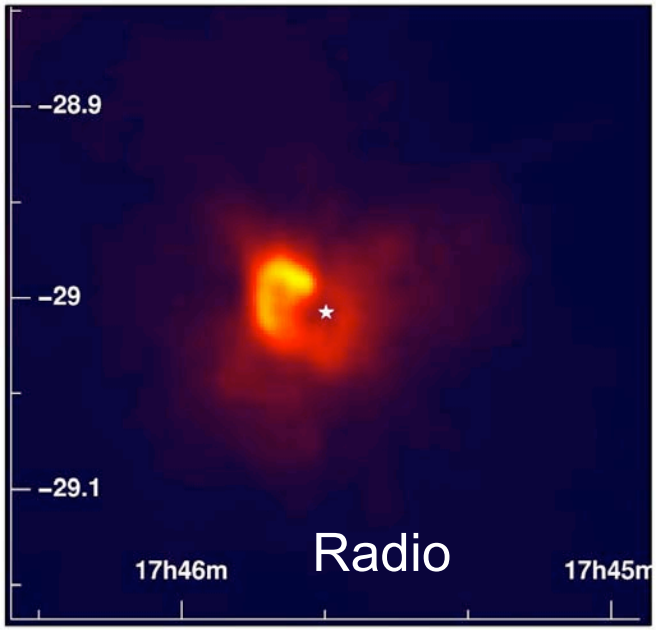
Aim:
- Galactic center
- Galactic halo
- Dwarf galaxies in halo (~10)
- CDM clumps in halo



H.E.S.S. (E > 100 GeV)

High Energy Stereoscopic System





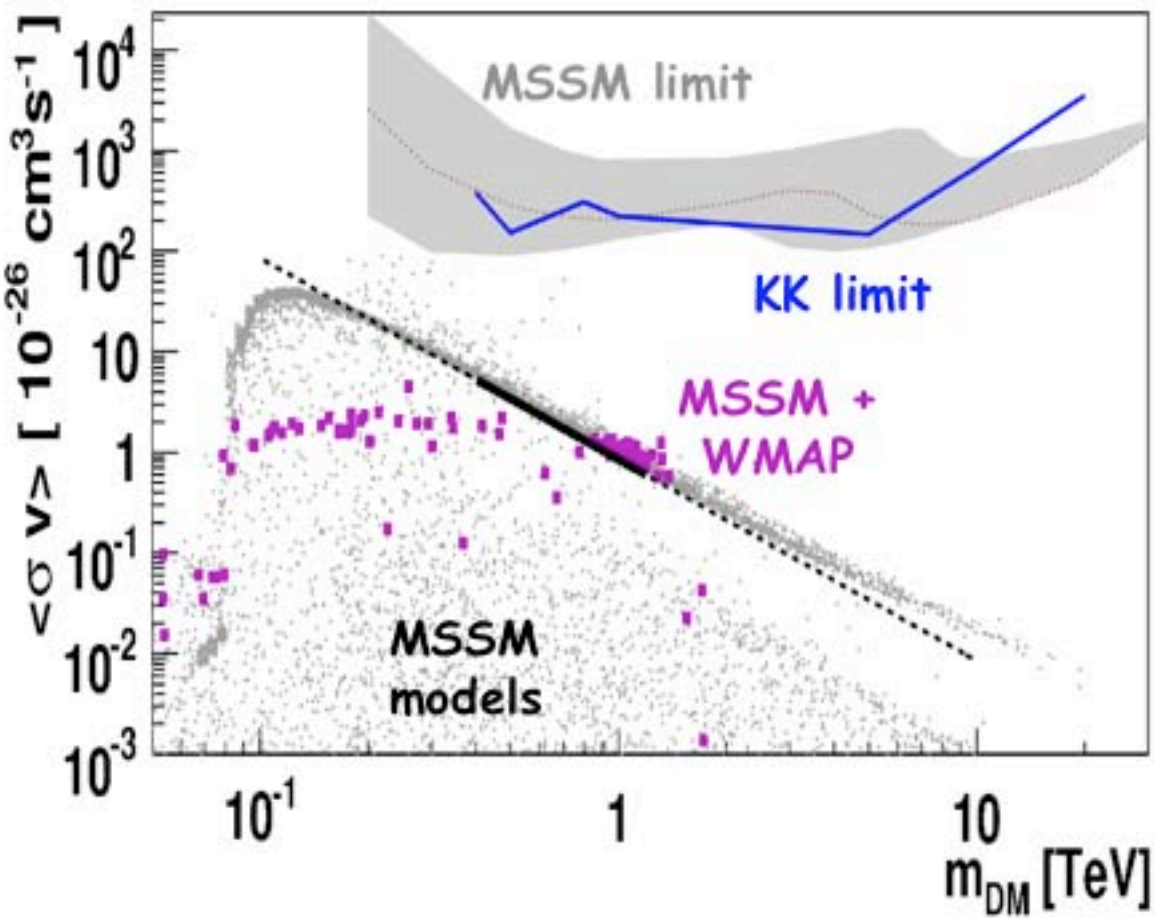
→ Unlikely pure DM

Astrophysical source candidates:
- 3x10^6 Msun black hole SgR A
- Supernova Remnant Sgr A East

Aharonian et al. PRL 97 (2006) 221102

H.E.S.S.: Dark Matter at GC?

High Energy Stereoscopic System



Assuming

DM (NFW* profile for DM halo)

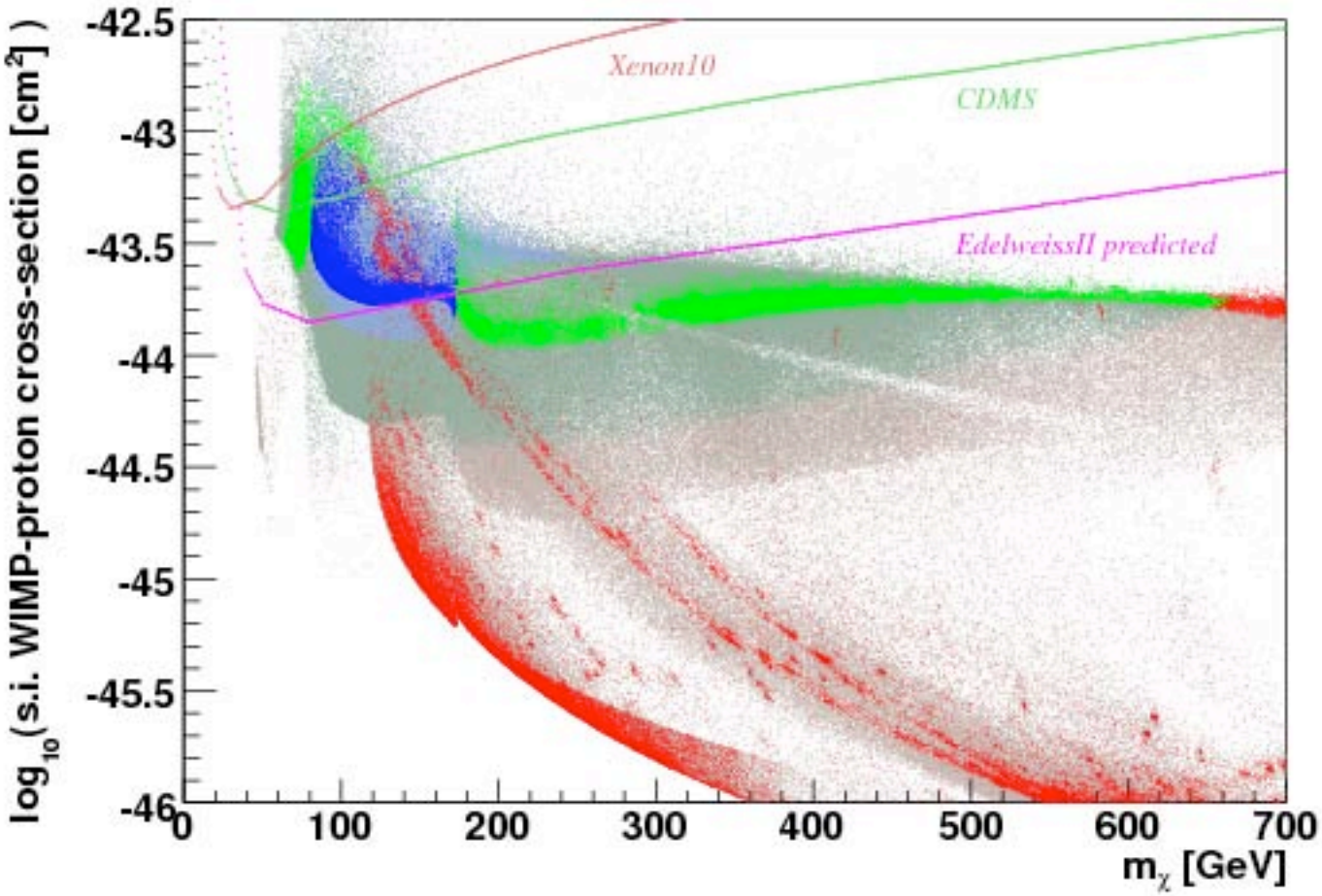
+ astrophys. source (power spectrum)

*NFW :

$\rho(r) = \rho 0\ R^2 / (r^2+R^2)$

ν telescopes

Predicted sensitivity for ANTARES, KM3net, out of reach



mSUGRA scenarii

ν oscillations included

halo with local density
ρ_{DM} = 0.3 GeV/cm^3

Conclusions

Concordance model → the unknown dominates !