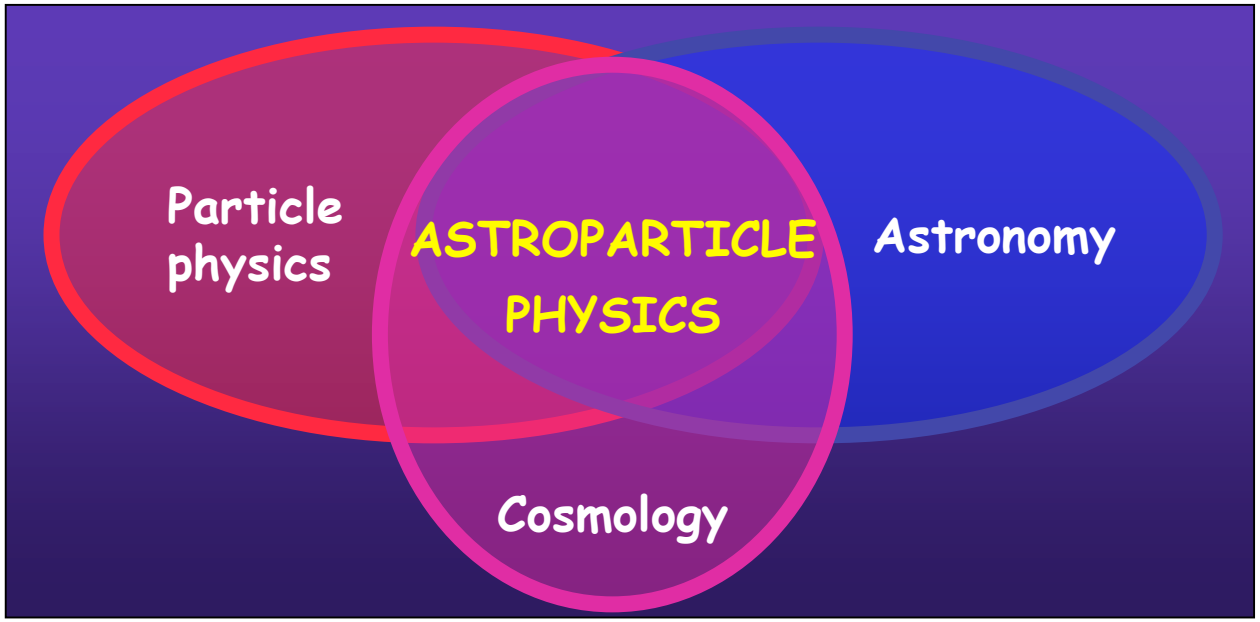
Overview of astroparticle physics and cosmology

Nathalie Palanque-Delabrouille
(and Jim Rich)

CEA-Saclay

Astroparticle physics



Composition and evolution of the Universe?

Dark matter

Dark energy

Most extreme phenomena?

Cosmic rays

Gamma rays

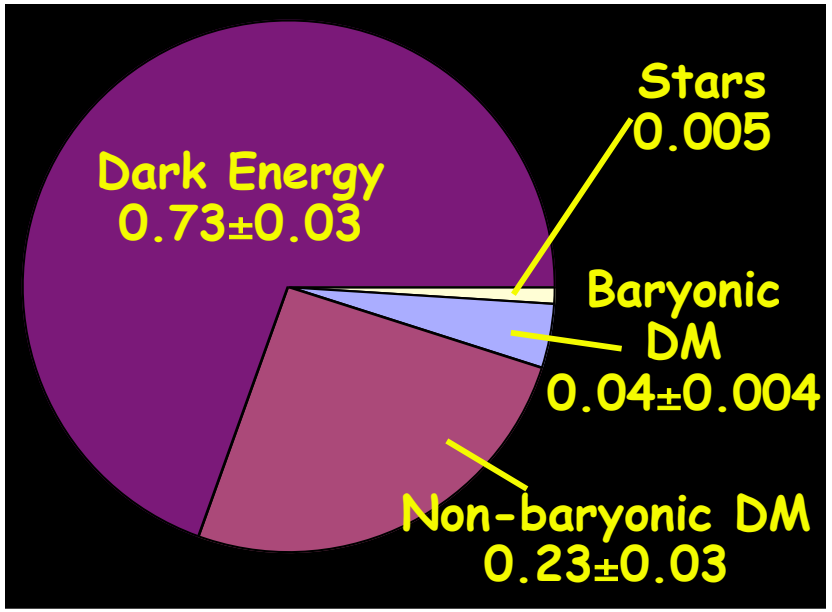
ν astrophysics

Concordance cosmology (2006)

Evidence from

- Microwave background anisotropies (WMAP)
- Type Ia Supernovae (SNLS) cf. Vanina Rulhmann in 1h
- Large scale structures (SDSS, 2DegF)

imply that the Universe behaves as though it consists of

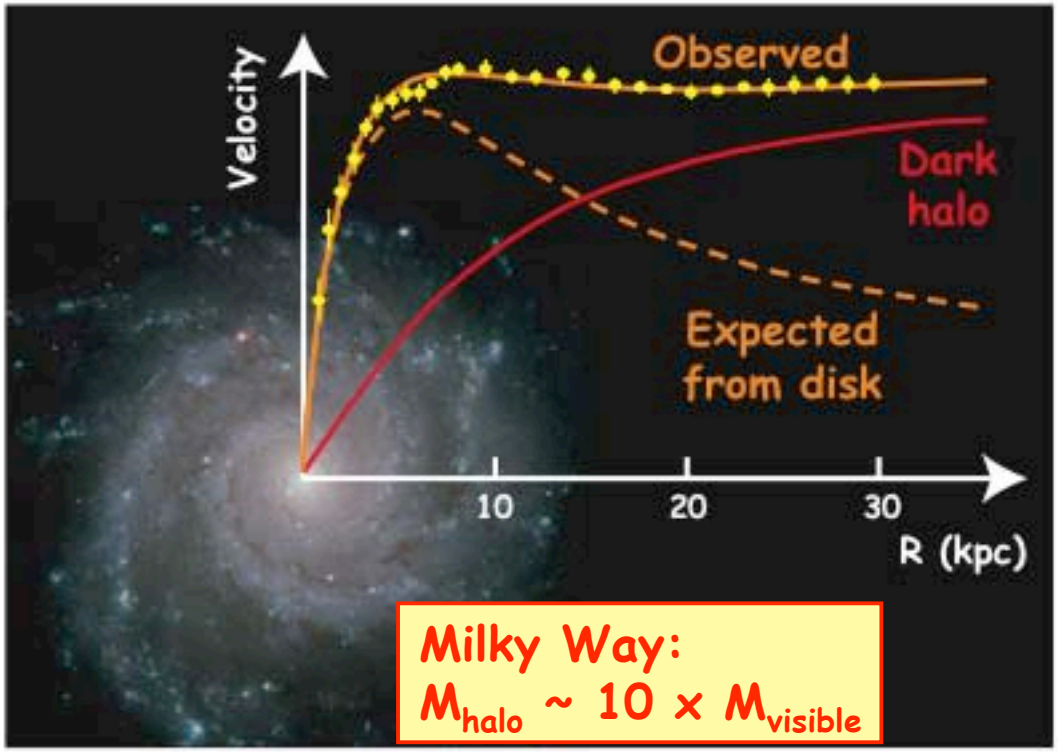


and is flat (Ω_T = 1.01 ± 0.01)

4 interesting questions

- Does dark matter really exist?
  (approaching la fin du MOND?)
- If yes, what is it?
  (MACHOs?, WIMPS?)
- Does dark energy really exist?
  (BAO : a new standard ruler)
- If yes, what is it?
  (just a number?)

Evidence for dark matter



Rotation curves

⇓

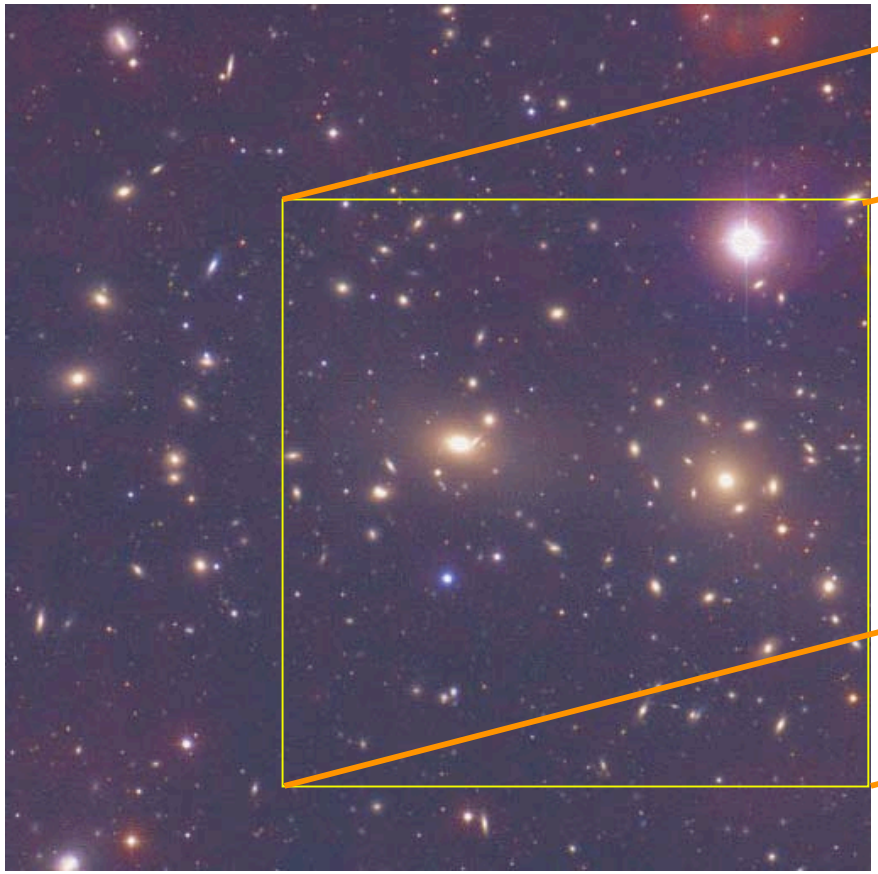
Dark Matter

OR

MOdified Newtonian Dynamics
(acceleration ≠ GM/r)

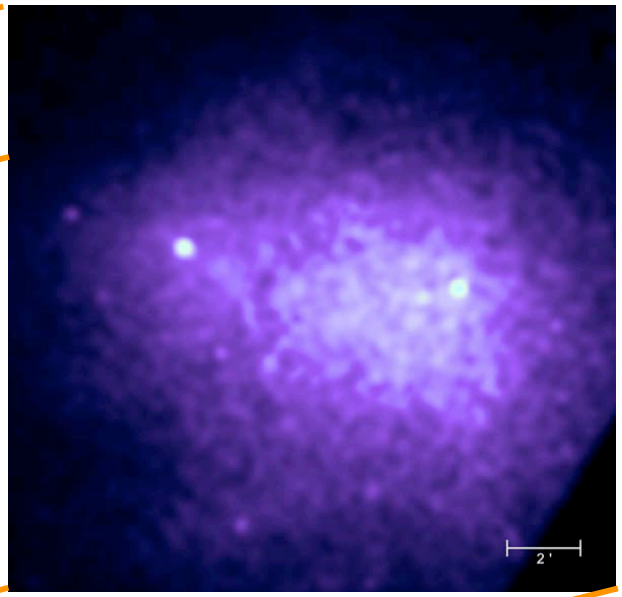
Collision between 2 clusters (1/3)

Optical image of Coma cluster



Credit: Kitt Peak

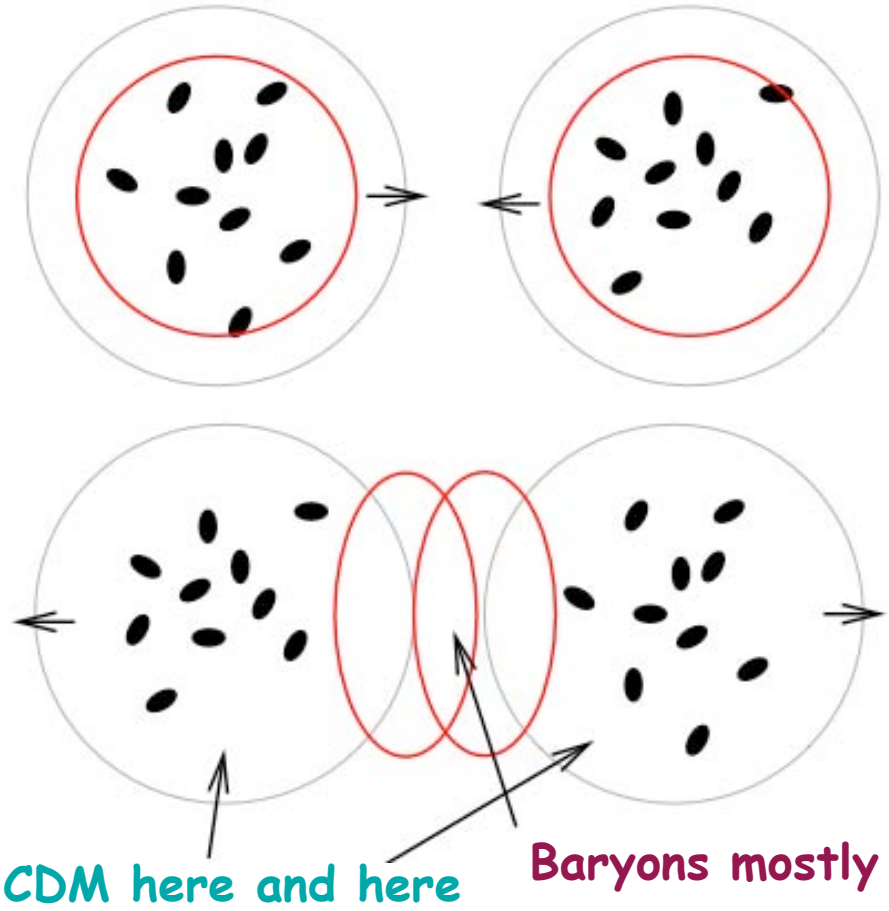
X-ray (hot intergalactic gas)



Credit: NASA / CHANDRA

Total mass of galaxies = 10% mass of gas

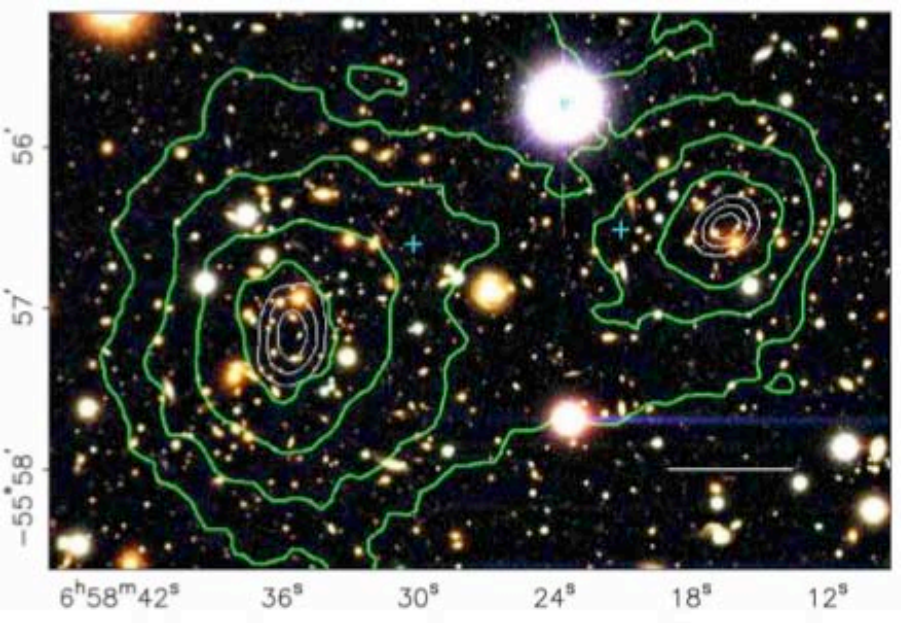
Collision between 2 clusters (2/3)

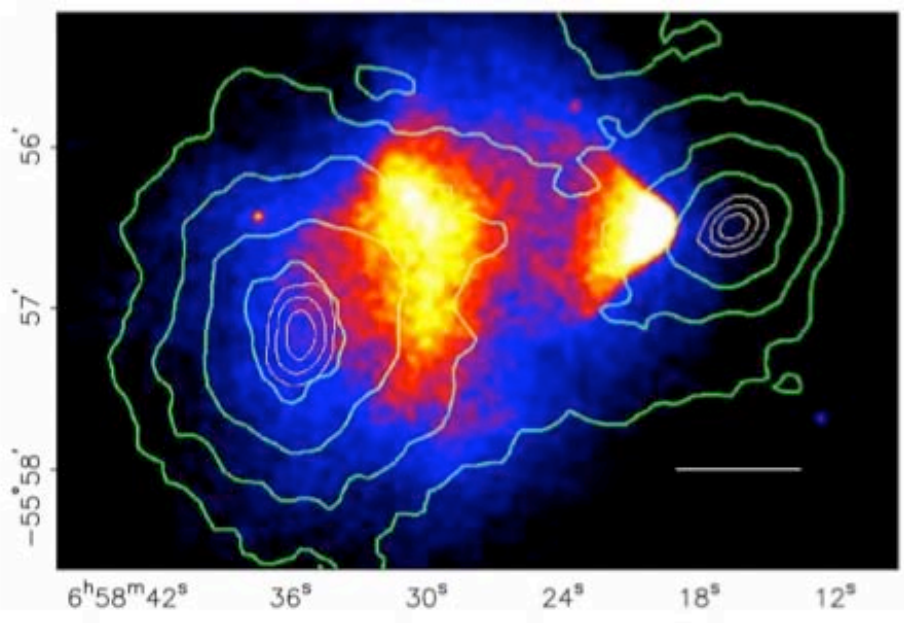


Collision between 2 clusters (3/3)

D. Clowe et al., astro-ph/0608407
Collision in 1E0657-558 = bullet cluster

Weak lensing ⇒ Mass not centered on gas
⇒ Dark Matter exists





Dark matter candidates

MAssive Compact Halo objects

e.g. brown dwarfs (M ~ 0.07 Msun)
Primordial black holes (M ?)

axions

no conclusive evidence yet

WIMPS

LSP (neutralino) natural candidate in SUSY theories

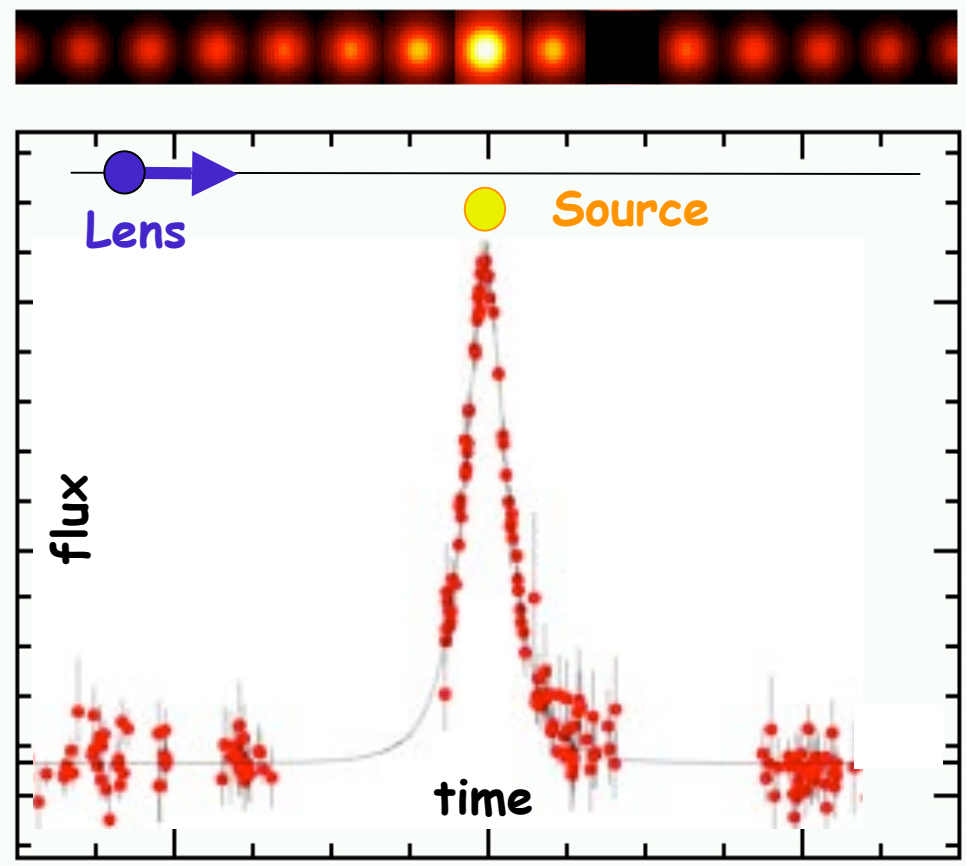
Stable relic from big bang :

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

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

Compact objects in halo?

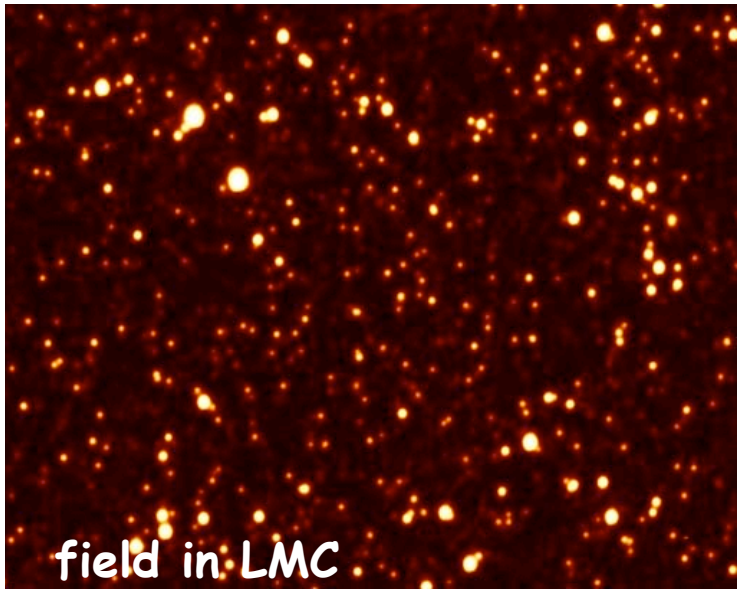
Microlensing searches (EROS, MACHO)



Microlensing (Paczynski, 1985)

$$t_E = \frac{1}{v_t}\sqrt{\frac{4GM}{c^2}\frac{D_l(D_s - D_l)}{D_s}}$$

$$t_E \propto \sqrt{M} \times f(D_l, D_s, v_t)$$



Compact objects in halo?
Microlensing searches (EROS, MACHO)

Projects

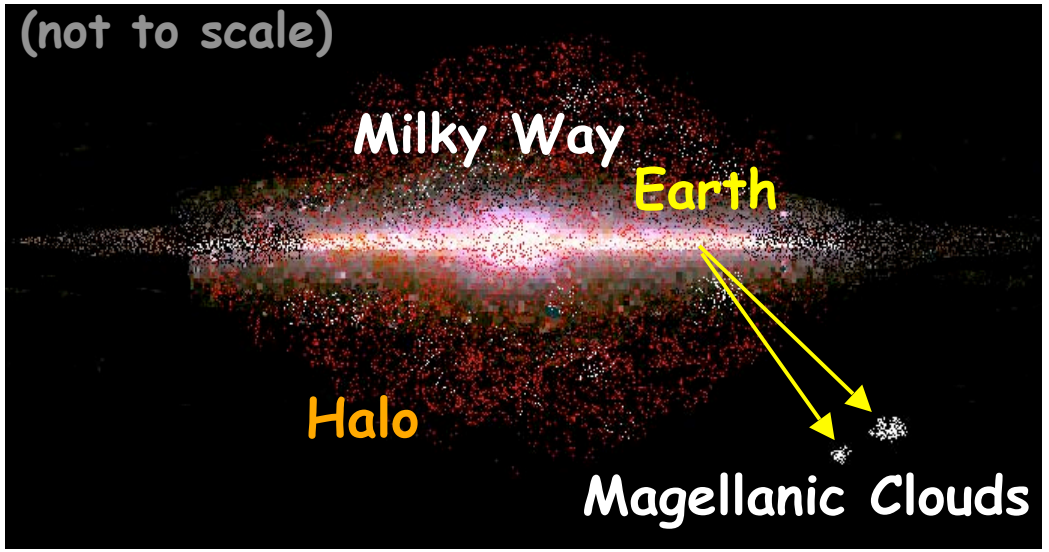
EROS: 1990-2002

MACHO: 1992-2000
10% to 50% of halo
is made of machos

OGLE: 1992-

MOA: 1998-

Supermacho: 2001-



Compact objects in halo?
Microlensing searches (EROS, MACHO)

Projects

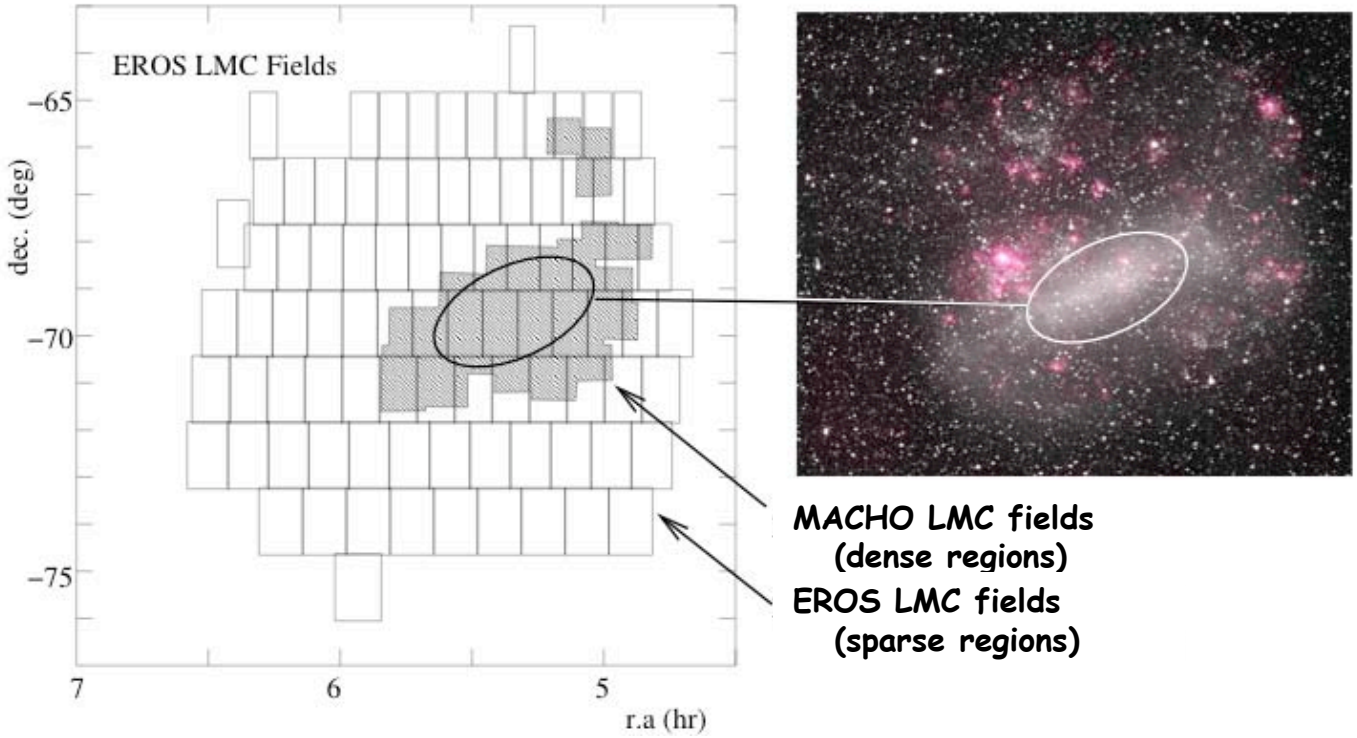
EROS: 1990-2002

MACHO: 1992-2000
10% to 50% of halo is made of machos

OGLE: 1992-

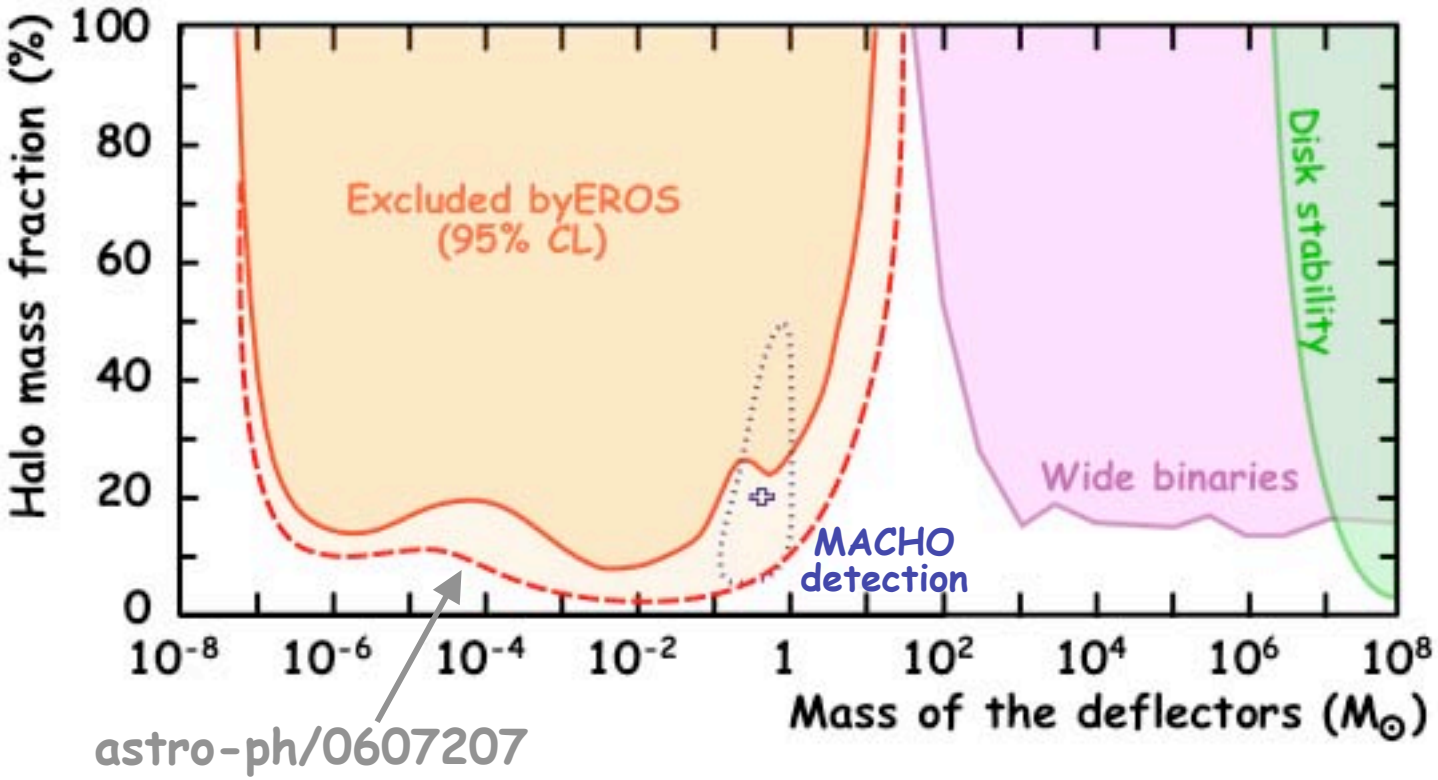
MOA: 1998-

Supermacho: 2001-



Compact objects in halo?

Microlensing searches (EROS, MACHO)

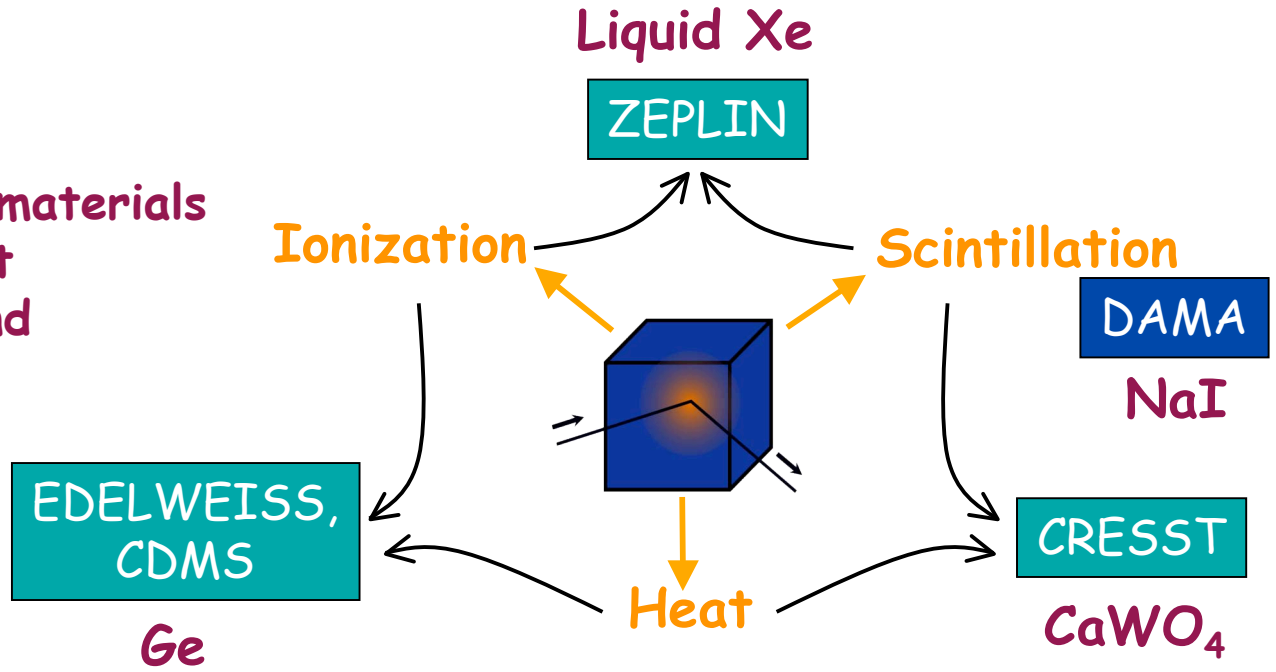


No significant contribution of dark compact baryons to halo
⇒ a non-baryonic dark halo?

WIMP searches (direct)

WIMP: elastic scattering on detector nucleus

<< 1evt / kg / day ⇒
- Deep underground
- Low radioactivity of materials
- Discrimination against radioactive background



Nuclear (vs. electronic) recoil discrimination

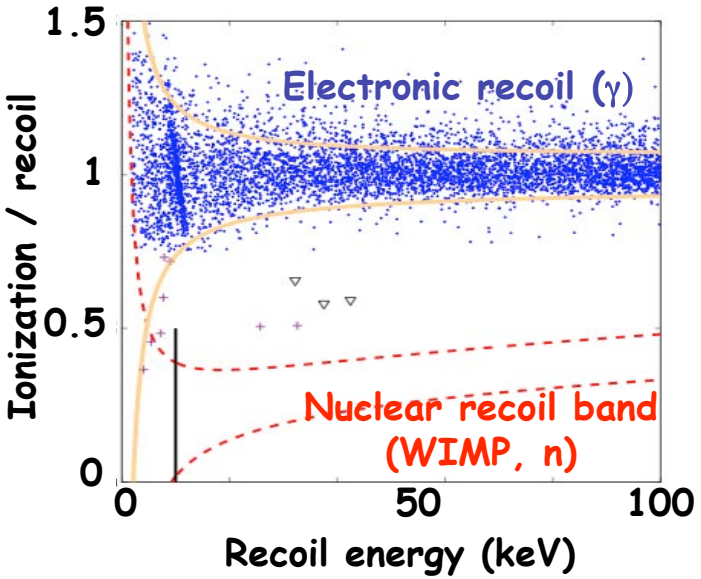
WIMP signal

Radioactive background

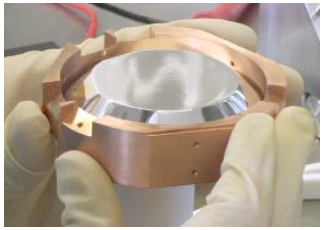
Event by event discrimination

Edelweiss / CDMS : heat + ionization

CDMS (Soudan mine)



No (few) events in signal region

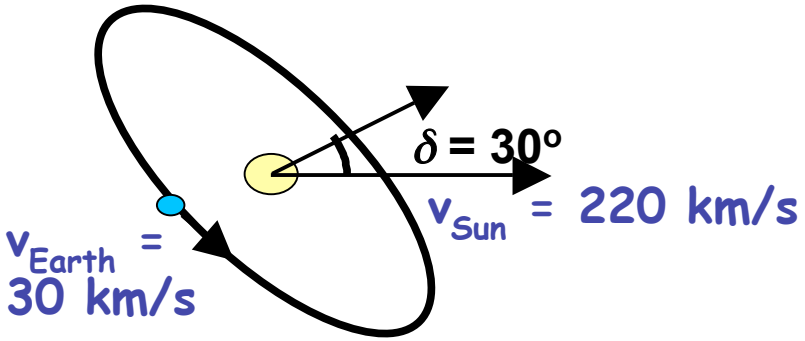


Edelweiss:
9 kg Ge (up to 36 kg)

CDMS:
250g Ge or 100g Si crystal

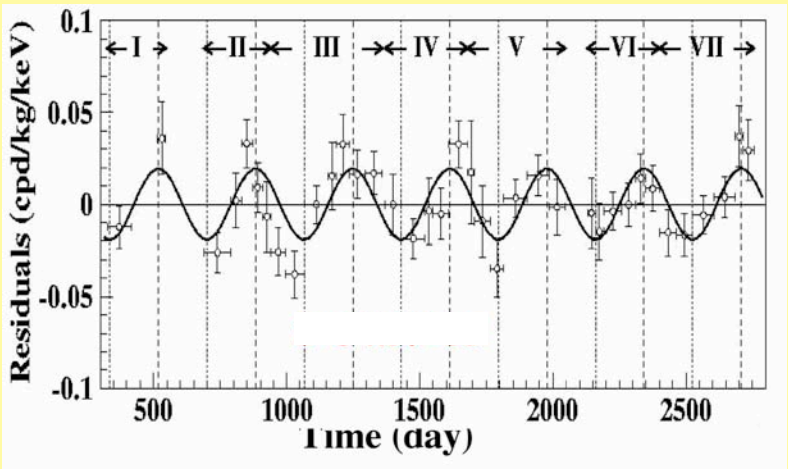
Annual modulation

a possible WIMP signature



Motion of Earth in the χ wind

Modulation of annual rate ± 7%
Max in June

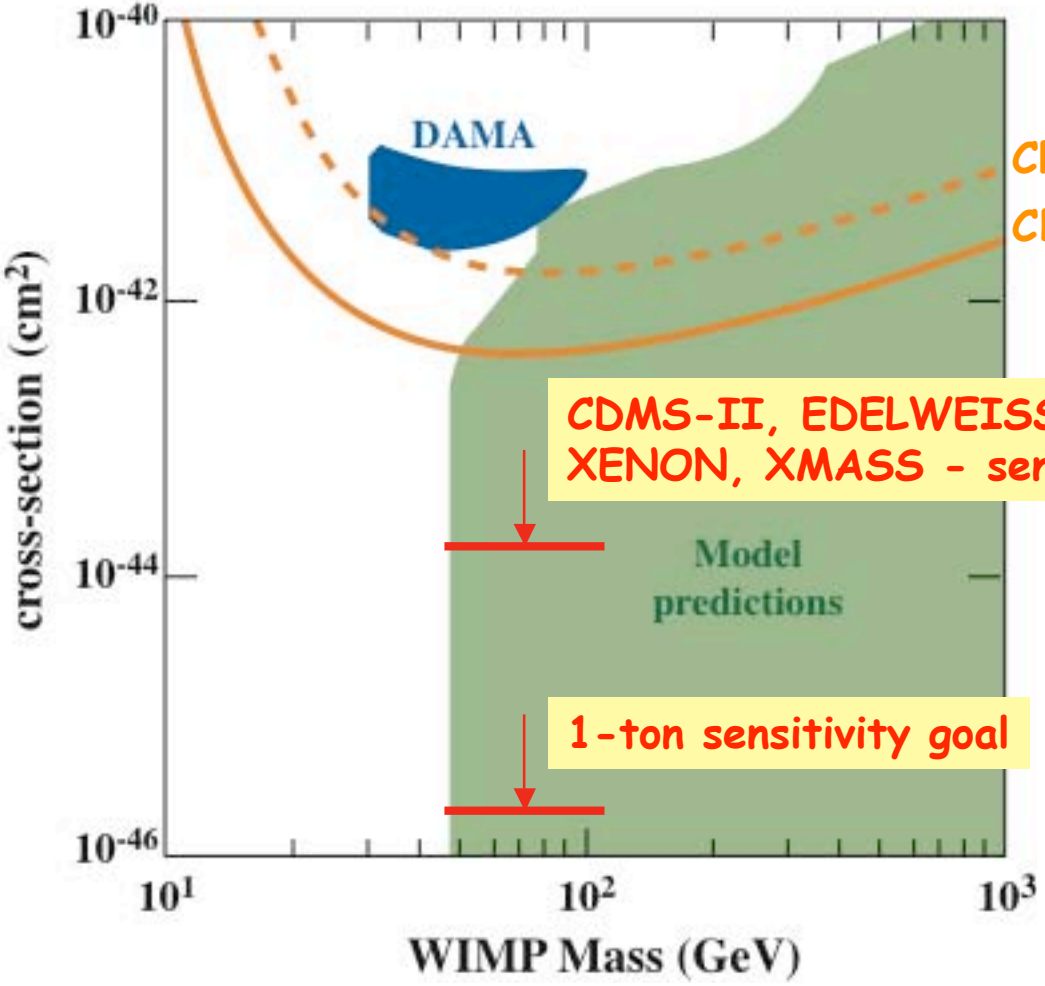


DAMA:
Total exposure of 295 kg.yr
Annual modulation at 6.3σ
m_χ ~ 44-62 GeV

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

2nd phase 250 kg (NaI) LIBRA running

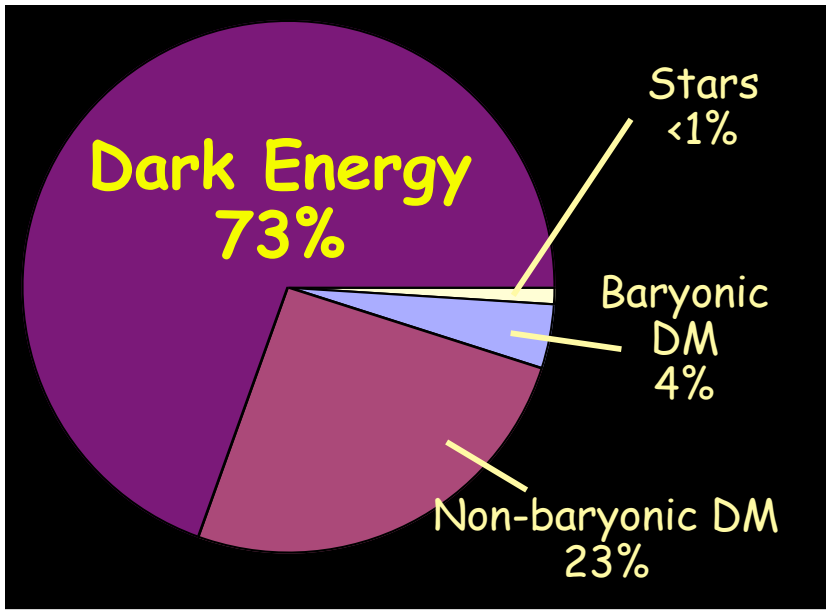
Current limits on WIMP



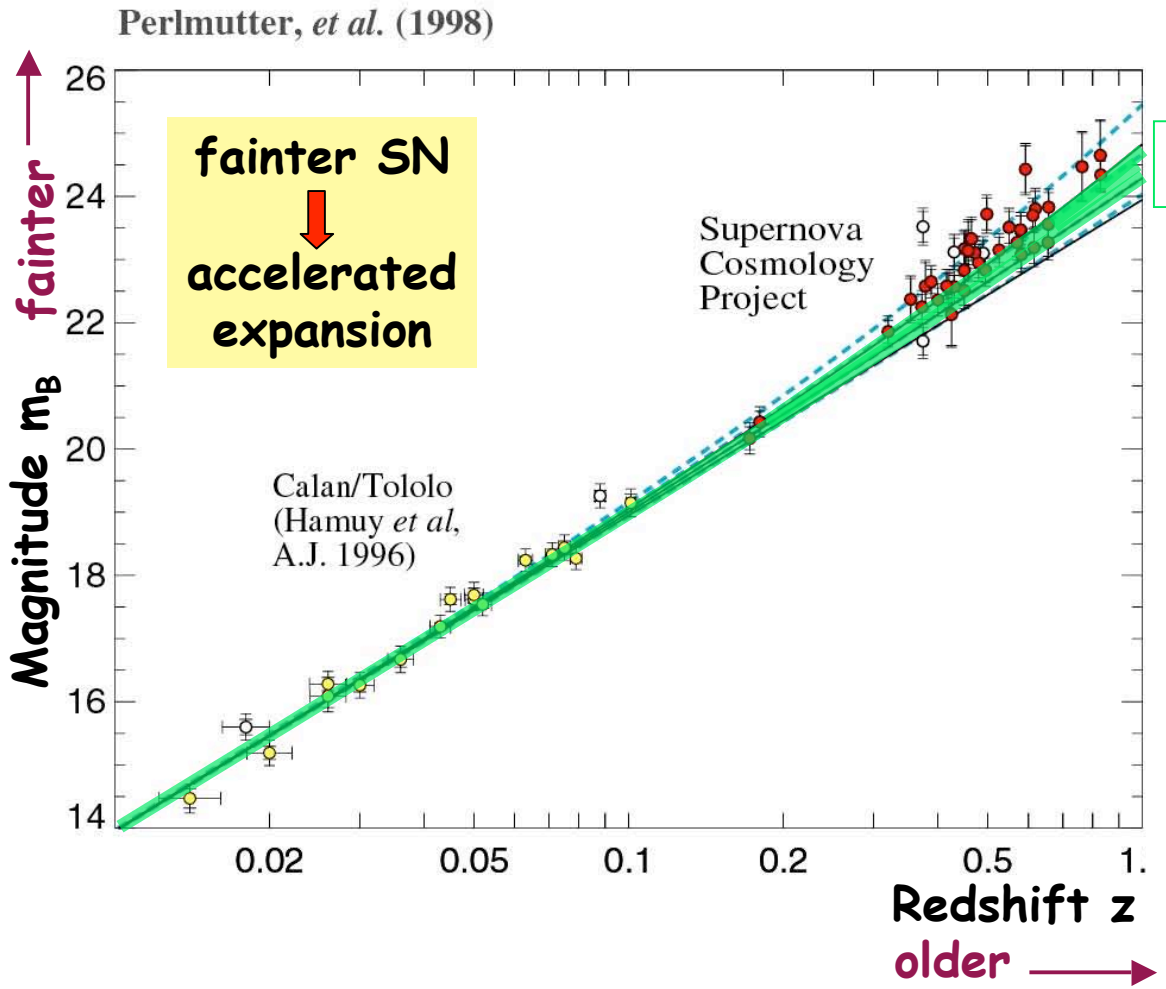
Testing most SUSY param. space (MSSM) requires 3 orders of magnitude beyond present best performances

Future : +LHC !

Dark energy



Dark energy : evidence



$\Omega_{TOT} \sim \Omega_M$ entre 0 et 1

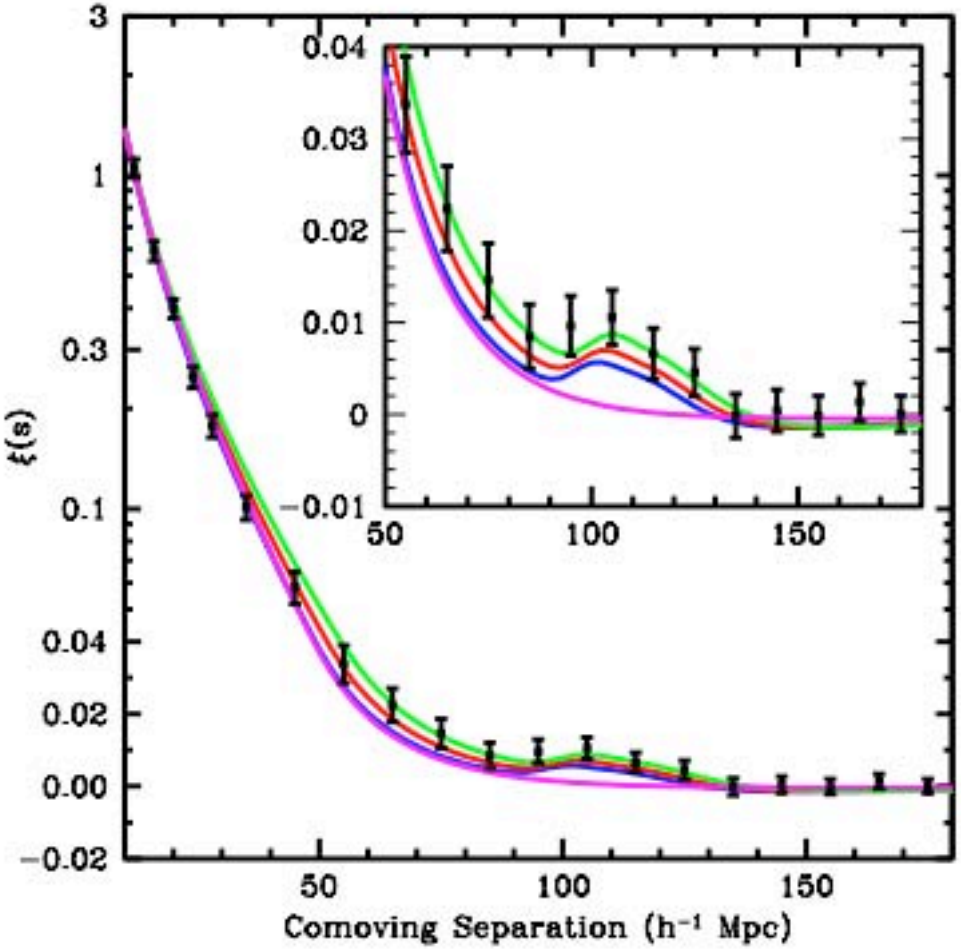
Criticisms:

- Ancient supernovae may have been fainter
- Photons from distant SN may be absorbed

Standard rulers (angular size vs. redshift) avoid these two criticisms

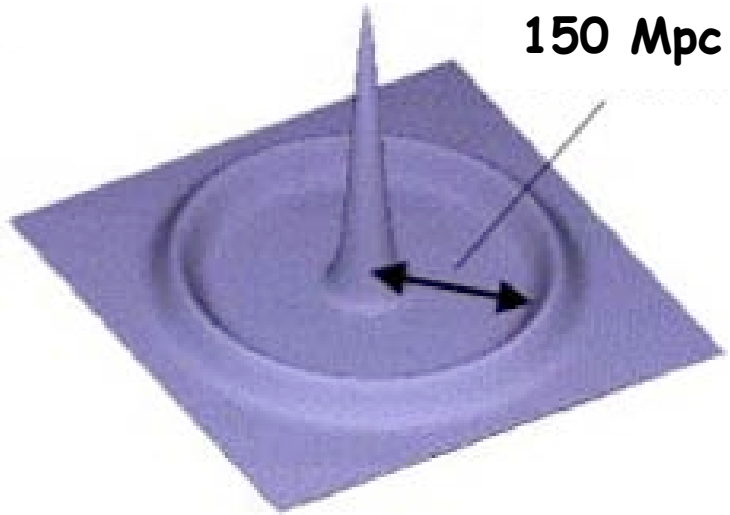
Sloan Digital Sky Survey

Galaxies like to be separated by
105 h^{-1} Mpc = 150 Mpc



Matter (galaxy) distribution

Spherical baryon-photon sound wave propagation until recombination



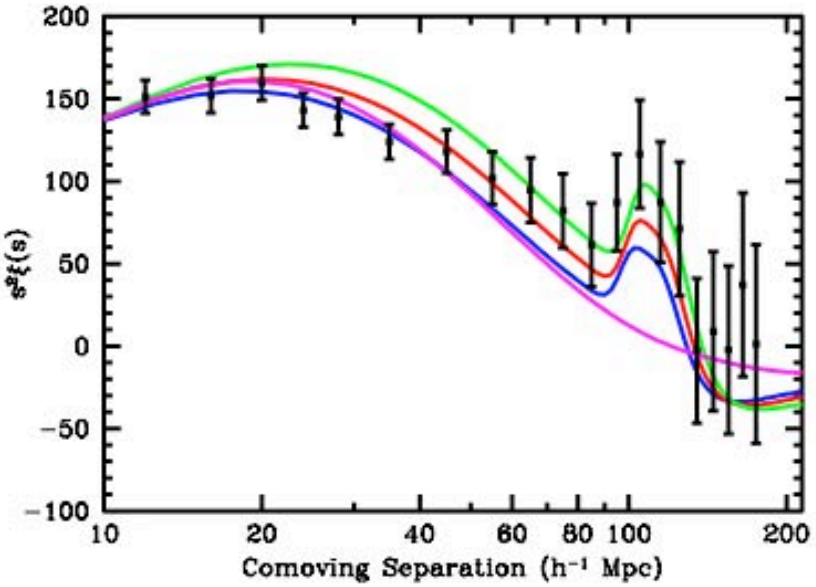
Initial overdensity of CDM, baryons (ionized gas) & photons

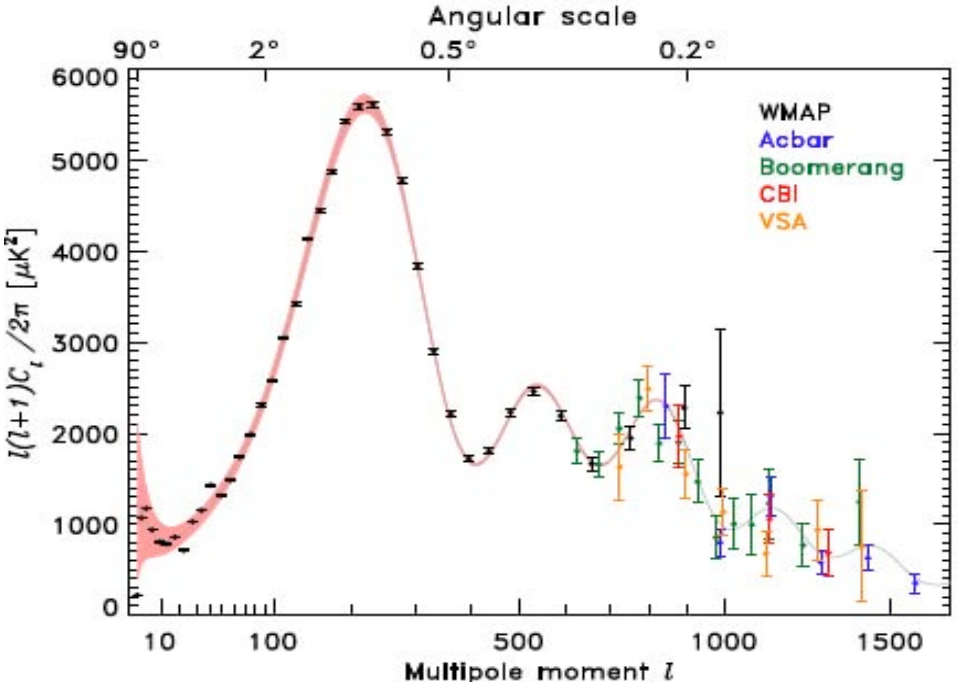
- Immobile
- Expansion of the baryon + photon plasma until recombination (t = 380 000 ans)

→ Matter accretion in these 2 overdensities

→ galaxies

SDSS acoustic peak and WMAP





SDSS (z ~ 0.3)

Eisenstein et al, Ap.J. 633 (2005) 560

⇓

$\Omega_{cdm} + \Omega_b = 0.273 \pm 0.025 + 0.123(1+w) + 0.137(1-\Omega_T)$

WMAP (z ~ 1100)

Bennett et al, Ap.J. Suppl. 148 (2003) 97

⇓

$\Omega_T = 1.010 \pm 0.009$

Time evolution of Dark Energy?

Today, $\rho_{de} = 0.7 \times 10^{-26}$ kg.m^{-3}

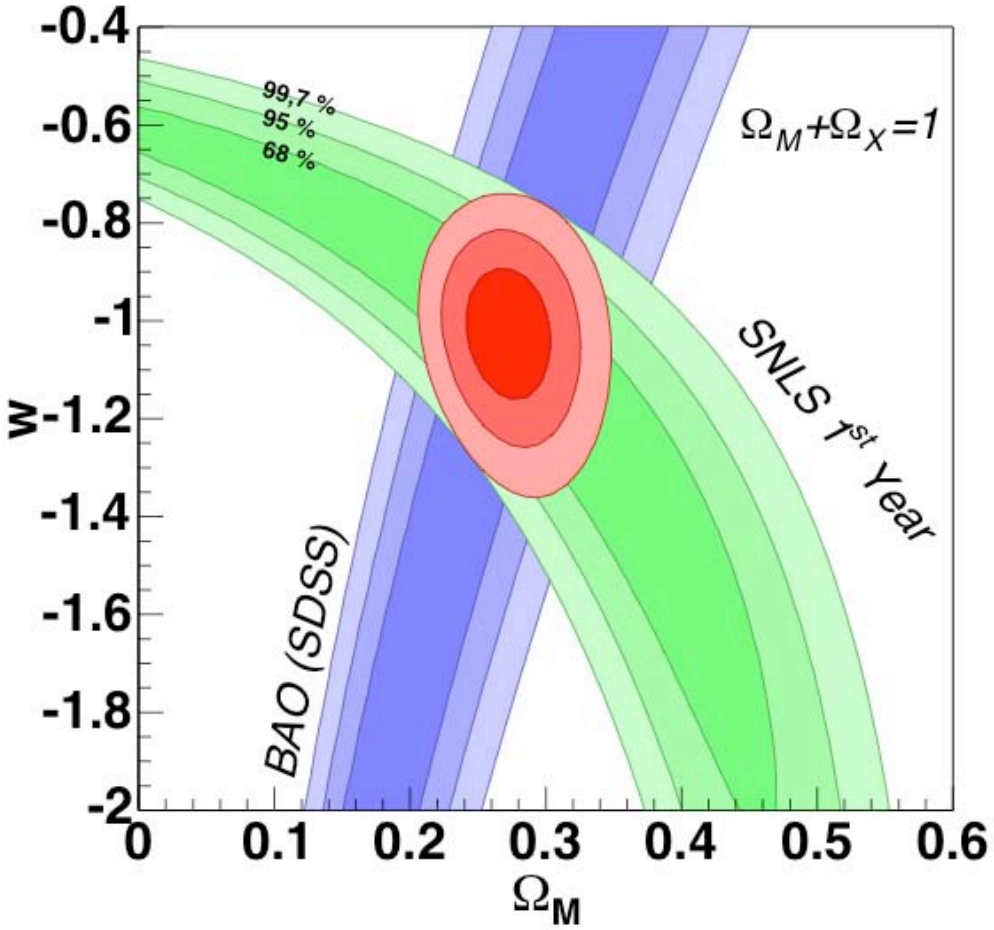
Time evolution of dark energy density ρ_{de} determined by w

$$w = \frac{p_{de}}{\rho_{de}} \qquad \frac{1}{\rho_{de}} \frac{d\rho_{de}}{dt} = -3H(1+w)$$

w = -1	for vacuum energy / cosmological constant
w = 0	for matter
w = 1/3	for relativistic matter or radiation

Present experiments : trying to constrain w

SNLS and SDSS constraints on w

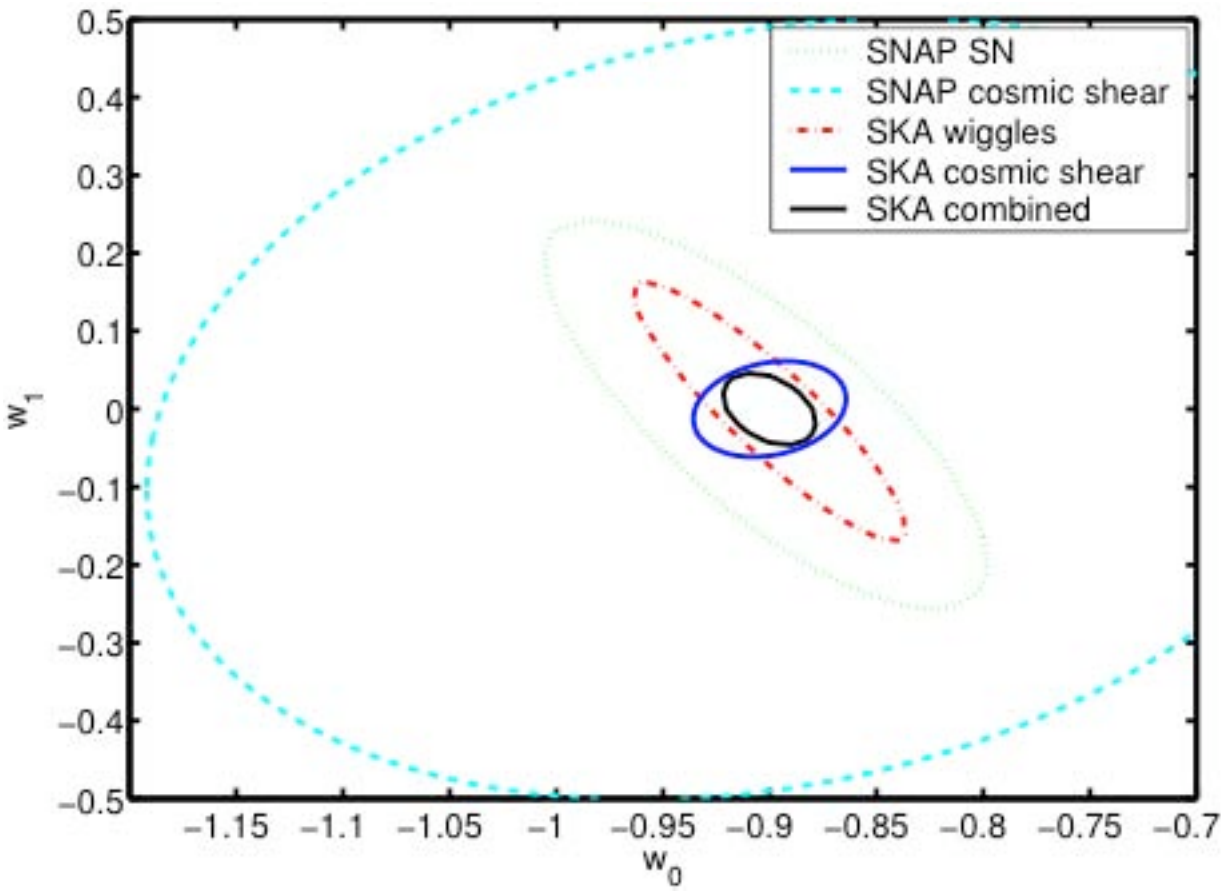


(Astier et al., A&A 447 (2006) 31A

w = -1.023 ± 0.09 ± 0.054

(BAO = Baryon Acoustic Oscillations)

Future limits on (w,w') from SKA



SKA = Square Kilometer Array (2018)

21cm (atomic H) survey to z = 3

acoustic peak +weak lensing

Dark Energy Open questions

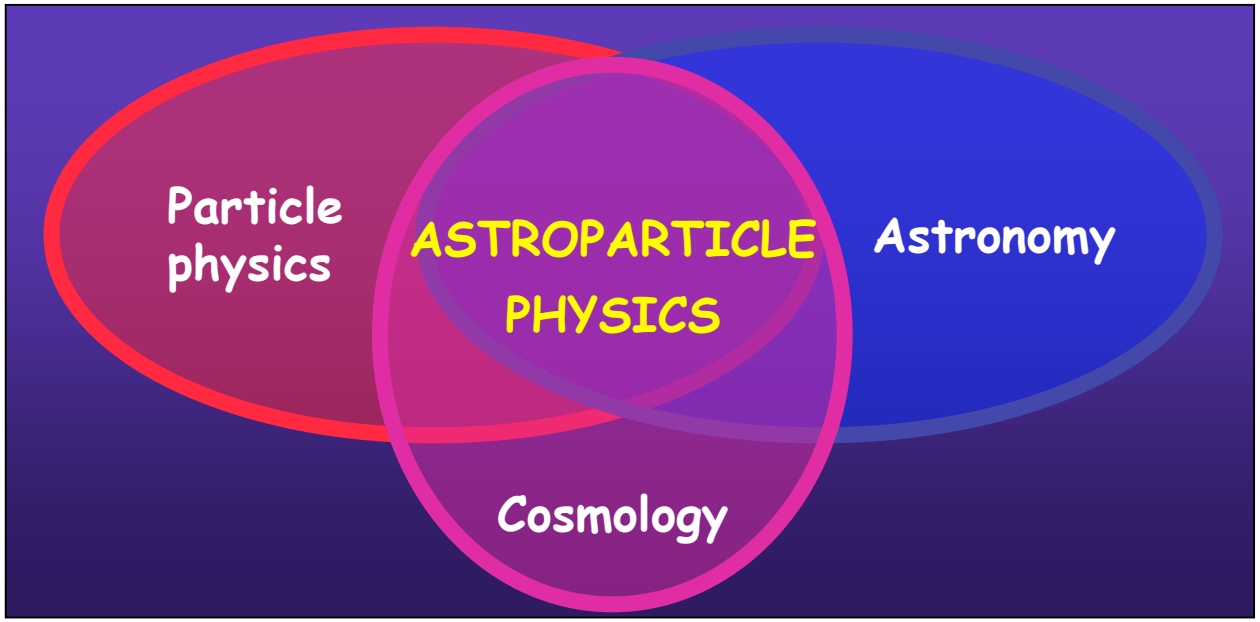
- Is ρ_Λ time independent (w'=0)

- What is its status in fundamental theory?
  (is Ω_Λ = 0.7 a law or an accident?)

- Why does $\rho_\Lambda \sim \rho_M$ now?

- Could the apparent acceleration be due to a breakdown of general relativity at large scale?

Overview of astroparticle physics



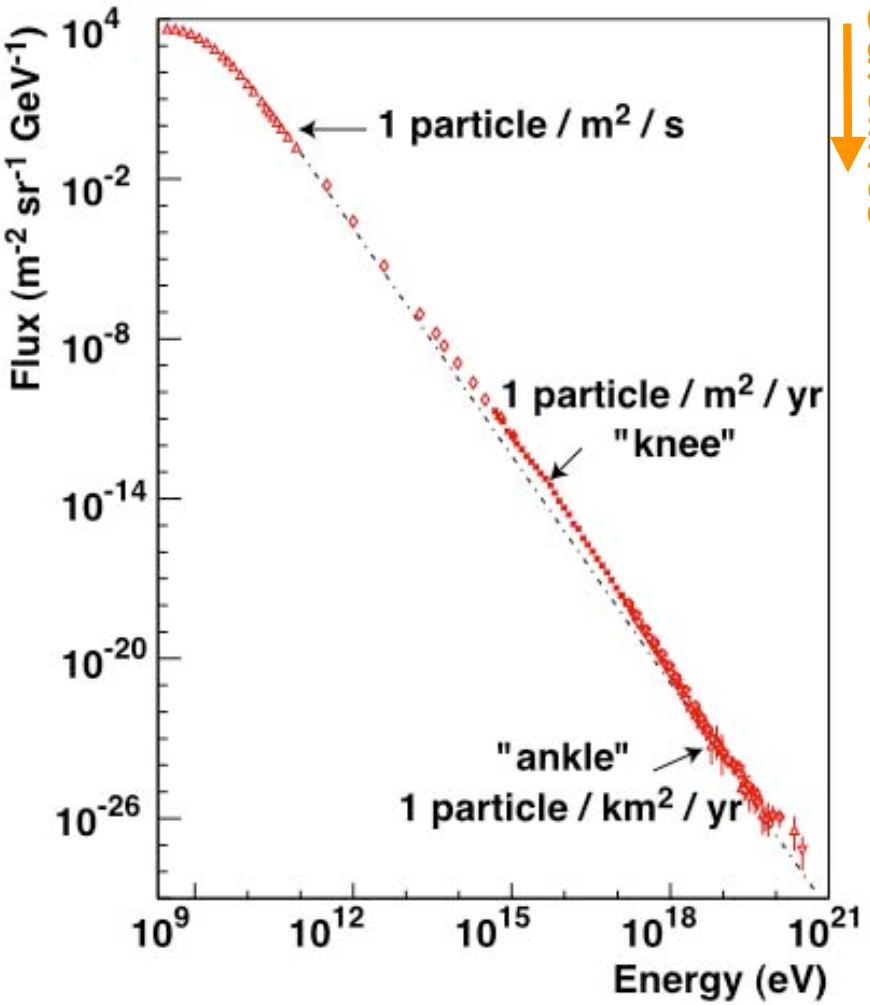
Composition and evolution of the Universe?

- Dark matter
- Dark energy

Most extreme phenomena?

- Cosmic rays
- Gamma rays
- ν astrophysics

Cosmic Ray Energy Spectrum



Satellites

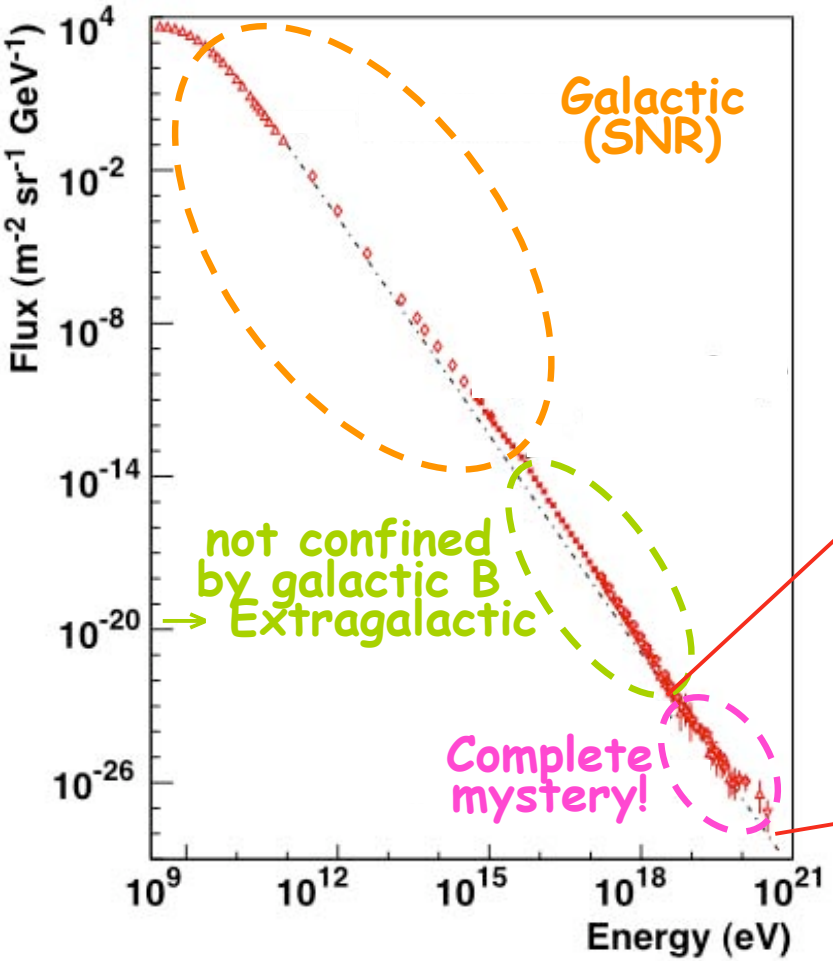
Balloons

Ground detectors

$E<10^{14}$ eV
High flux : detection of primary particle
(V. Hess, 1912)

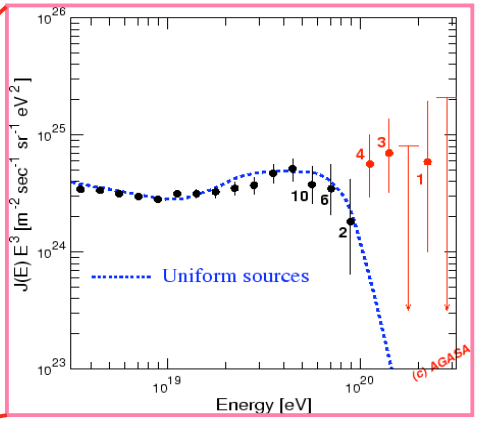
$E>10^{14}$ eV
Atmosphere → extensive air showers
(P. Auger, 1938)

Structure in CR spectrum



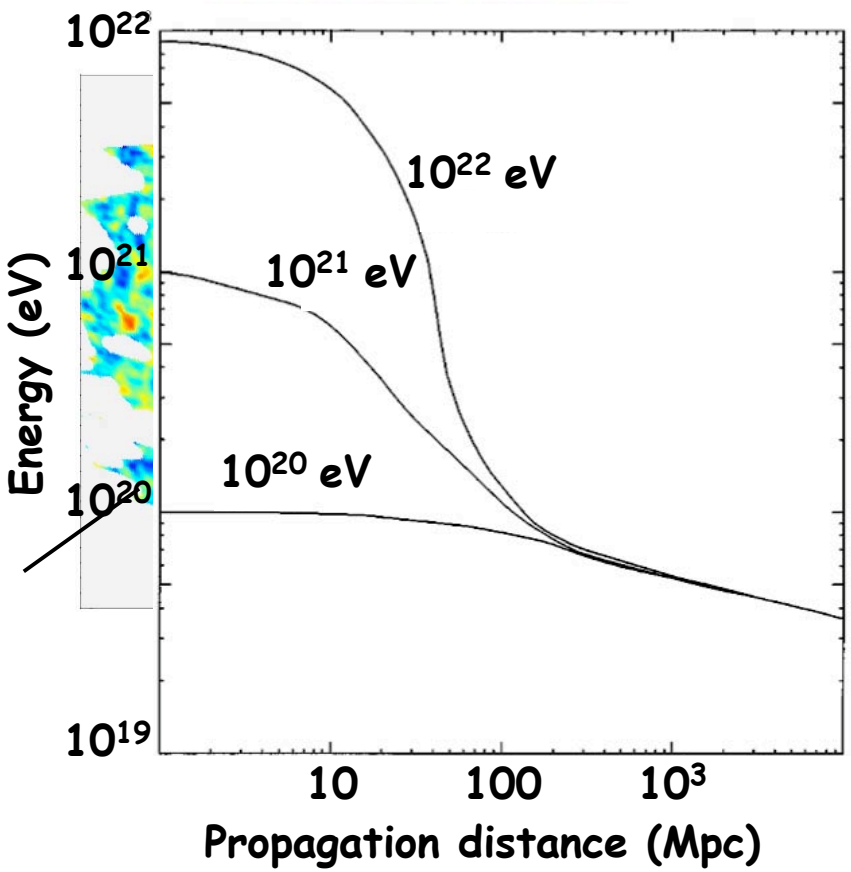
AGASA: 17 events above 6×10^{19} eV
HiRes : 2 events (~ 20 expected)

cross calibration needed



E_{max} = 3.2 10^{20} eV = 50 J !

GZK (Greisen Zatsepin Kuzmin) cut-off



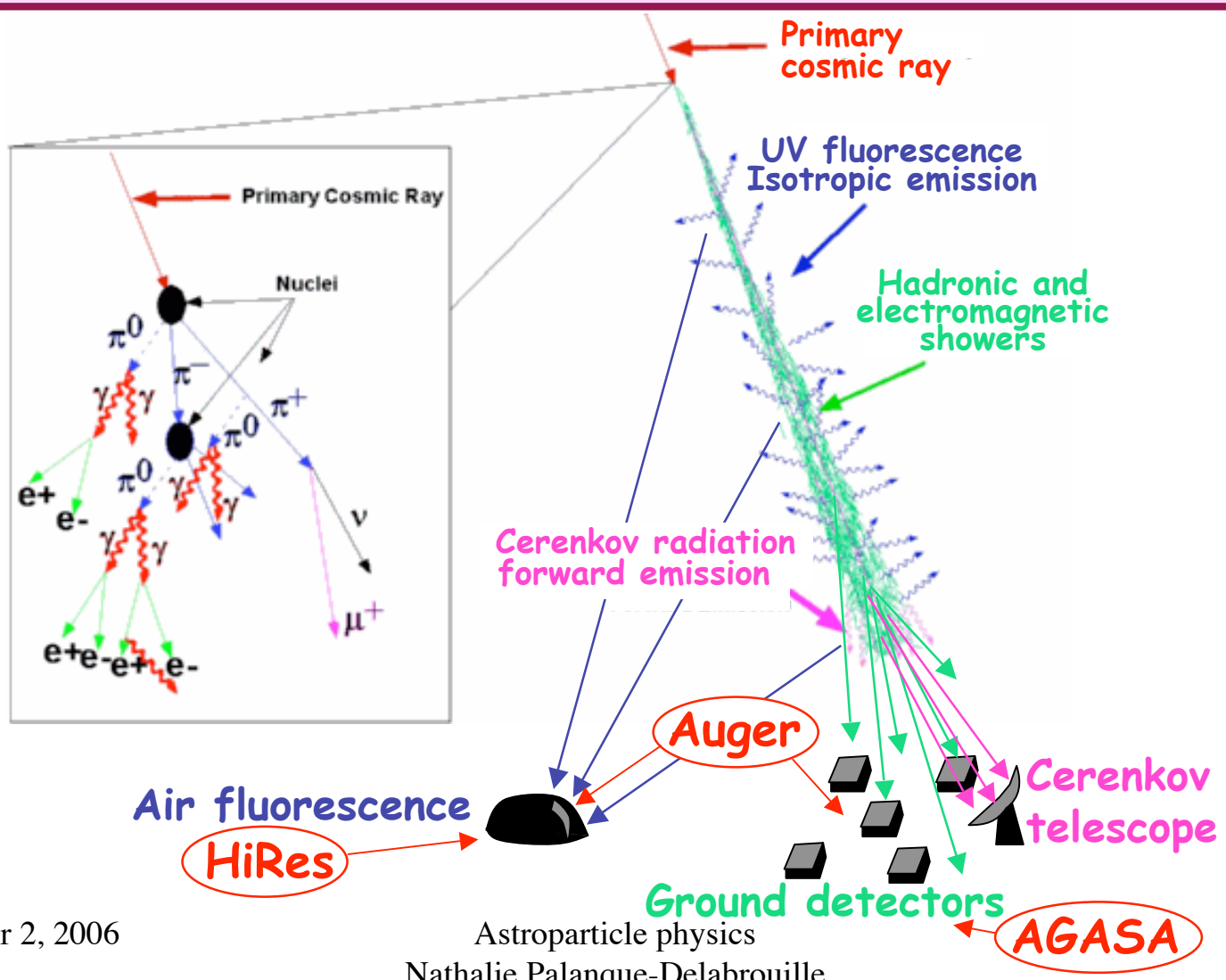
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

When process energetically allowed (>5×10^{19} eV), space becomes opaque to CR

Sources with $E > E_{GZK}$ must be at d<100 Mpc (local cluster)

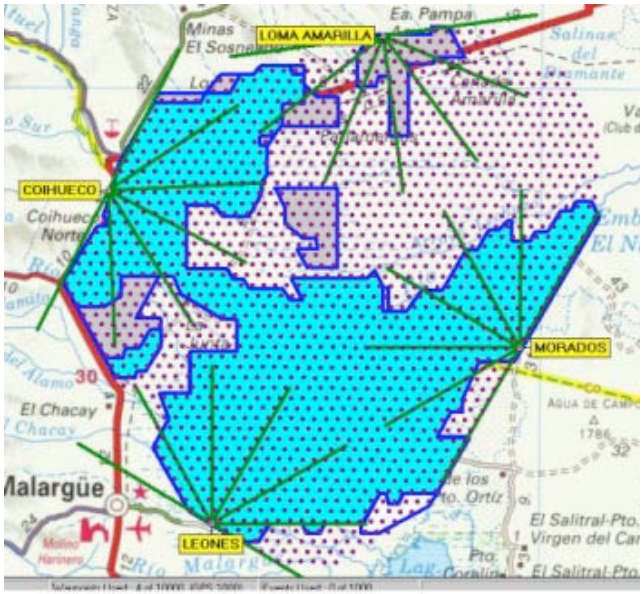
(no known acceleration sites…)

Detection techniques for UHECR



AUGER

Air fluorescence + ground arrays
2 sites (Argentina, USA):
1600 detectors + 4 telescopes, 3000 km²



Auger South
- 3 fluorescence stations (out of 4)
- 60% of ground detectors

Auger North?
- improved statistics (local supercluster)
- test of isotropy

cf. talk on Saturday by D. Zavrtanik for results from Auger

Gamma ray astronomy

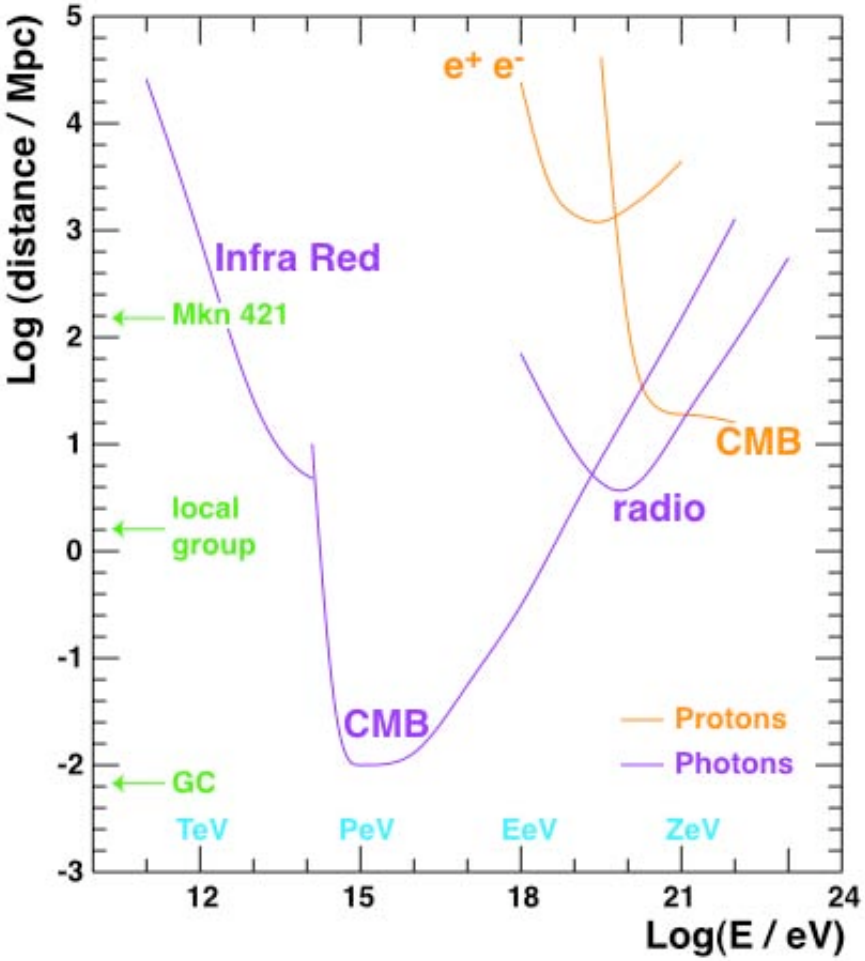
Photon = traditional astronomy

Straight propagation
⇒ allows study of sources

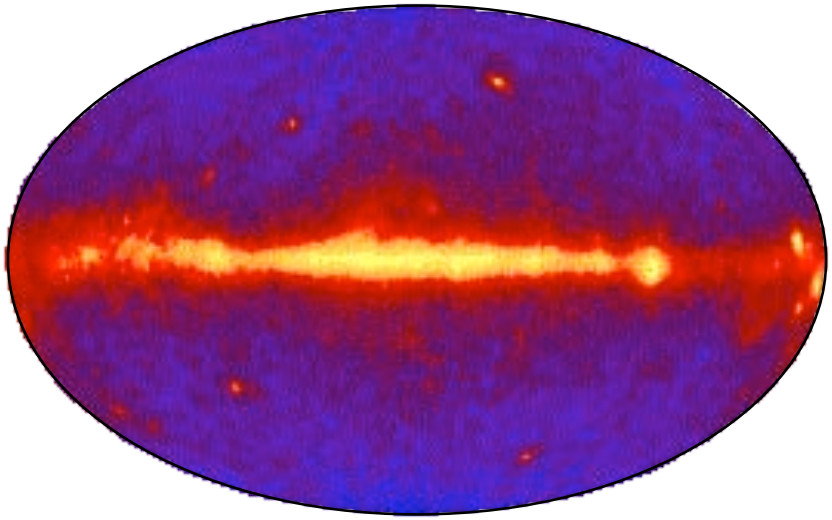
Interacts with CMB… backgrounds
⇒ existence of a gamma horizon
⇒ MeV to TeV

Gamma ray "telescopes"

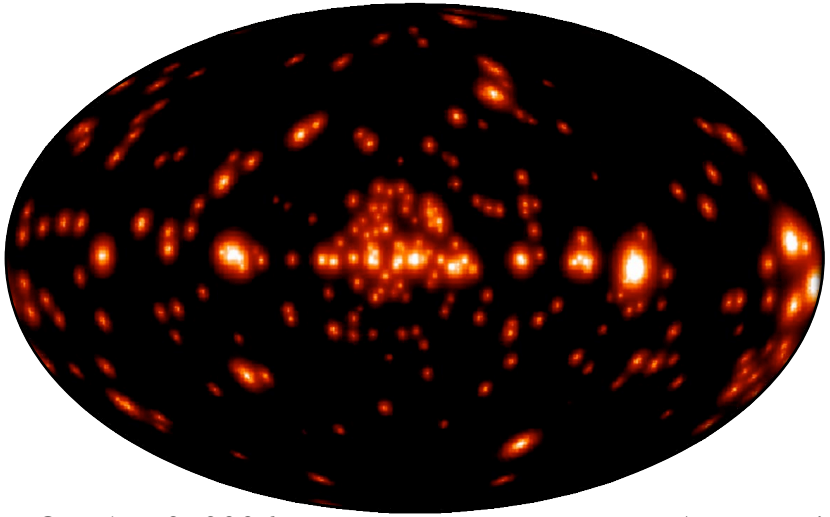
keV — GeV : satellites
(INTEGRAL)
GeV — TeV : ground-based (IACTs)
(HESS)



Compton Gamma Ray Observatory



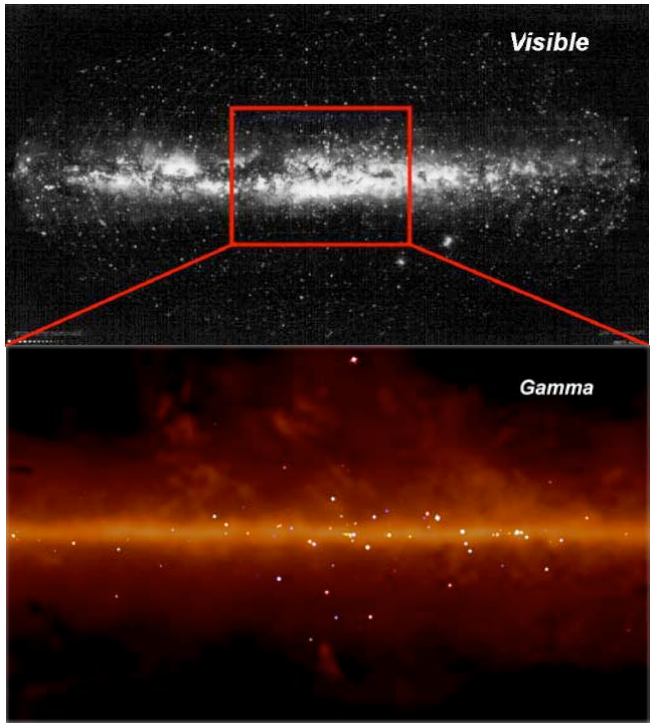
Galactic diffuse interstellar emission from interaction with cosmic rays
Excess at E<200 keV



EGRET Point sources
- Jets from active galactic nuclei
- Galactic sources (pulsars, binaries, supernova remnants …)
- Unidentified sources (170/270)

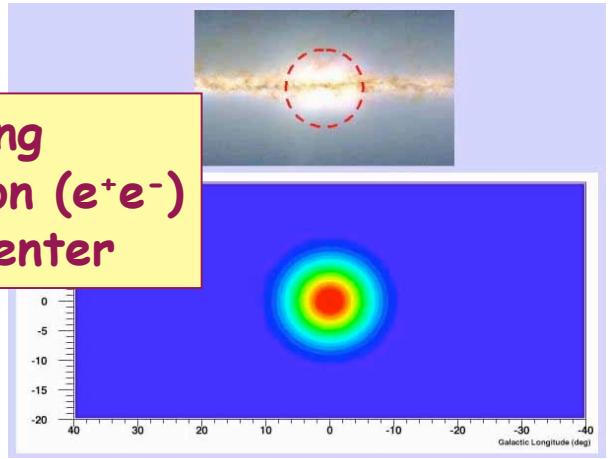
INTEGRAL (20 keV - 10 MeV)

INTErnational Gamma Ray Astrophysics Laboratory



90% of gamma diffuse emission
= 91 sources
(47 binary stars, 3 pulsars, …
37 new sources)

Very strong
511 keV emission (e^+e^-)
in Galactic Center

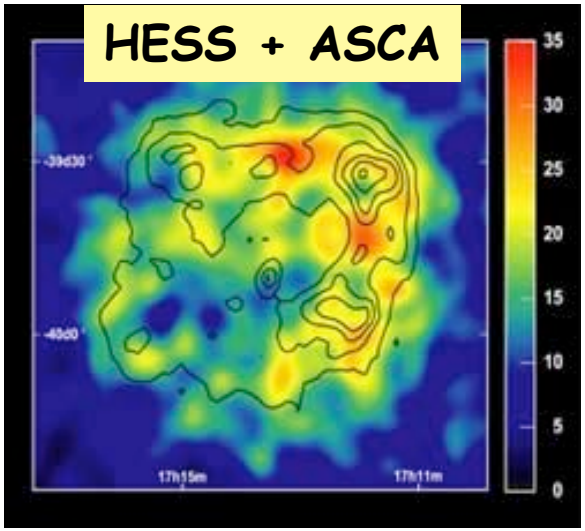


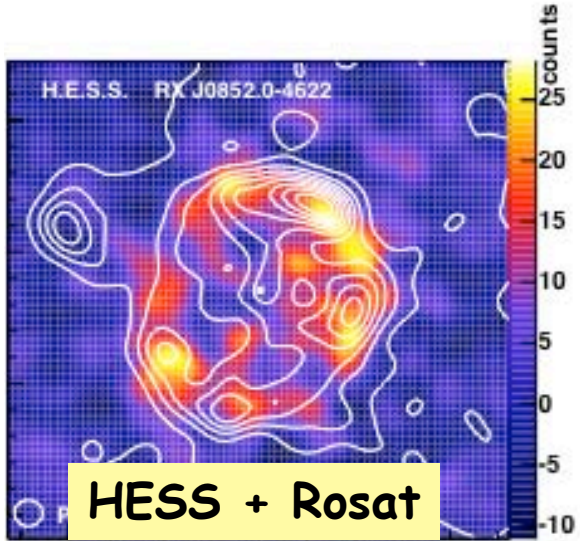
Dark matter?
e^+ annihilation at rest (positronium)
⇒ New form of DM particle?
(light DM : 1-100 MeV)

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

H.E.S.S.: the CR connection

High Energy Stereoscopic System





HESS :
color map
(E > 100 GeV)

ASCA :
X-ray contours
(E ~ 1 keV)

ROSAT :
X-ray contours

X and γ from same source

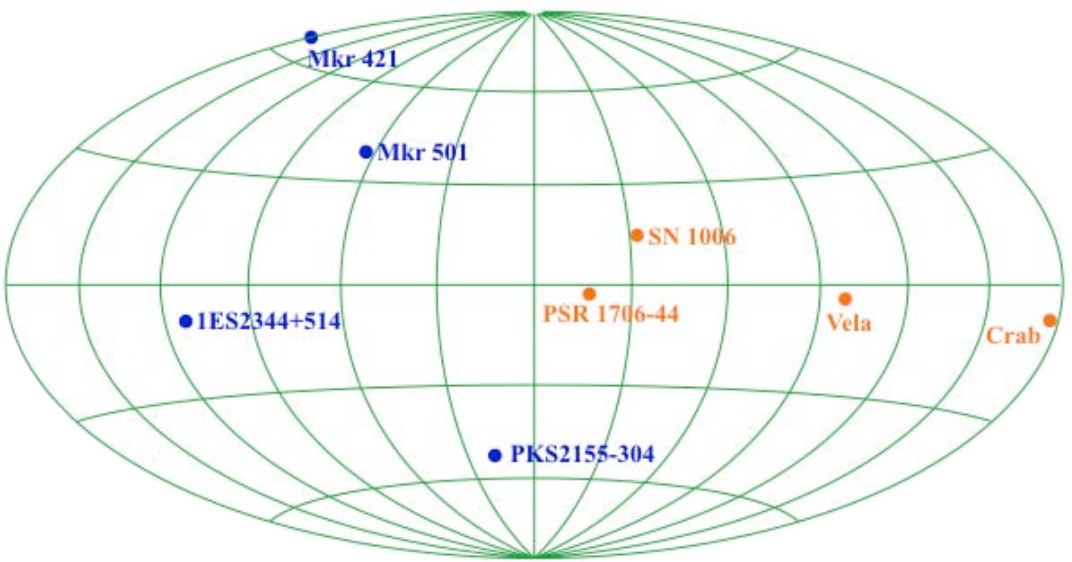
⇓

first confirmation of SNRs as particle accelerators up to 10^{14} eV (~knee of CR spectrum)

Are they protons/nuclei or e^-?

H.E.S.S. : TeV sky

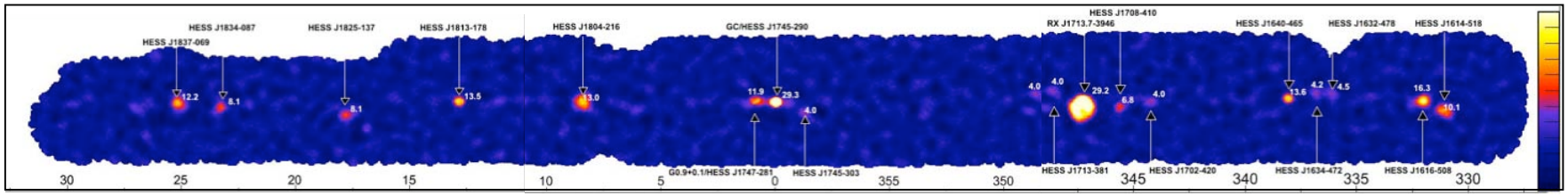
2003



2005

HESS:
Survey of galactic plane

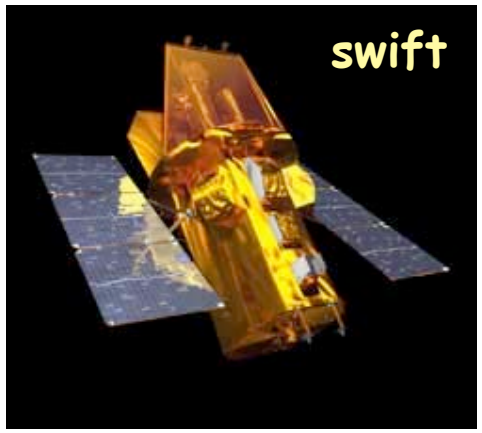
14 new sources (+ 3 already known ones):
- SNRs, X-ray binaries, pulsars
- 3 with no counterpart at any λ

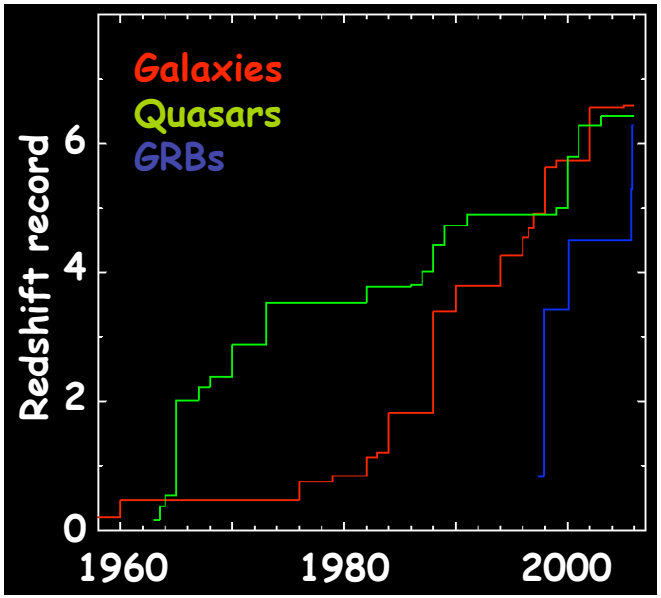


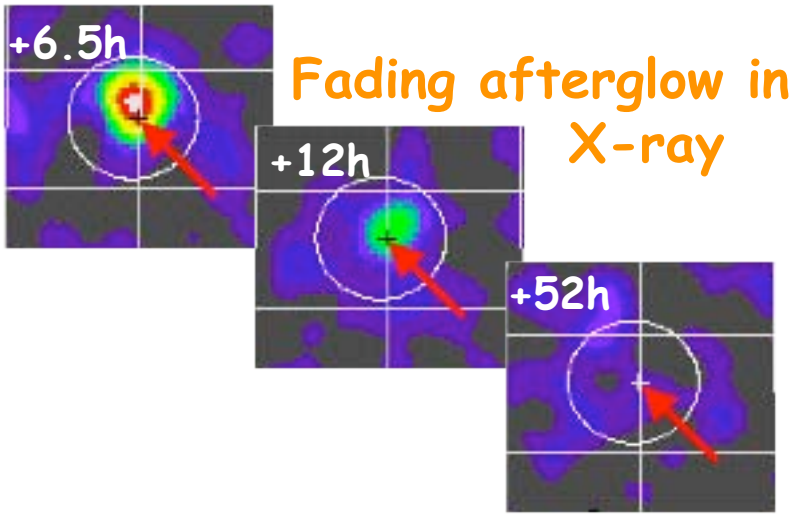
Gamma Ray Bursts

Optical counterparts

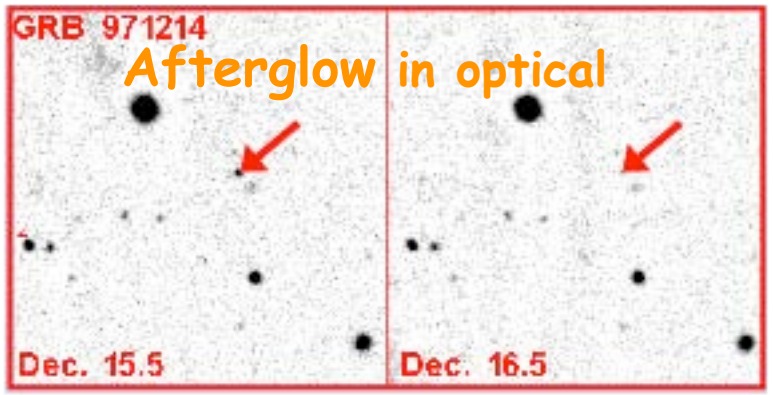
Cosmological phenomena!
out to z = 6.3 (Sept. 2005)







Fading afterglow in X-ray



Neutrinos in astronomy

Photons: absorbed (GZK)

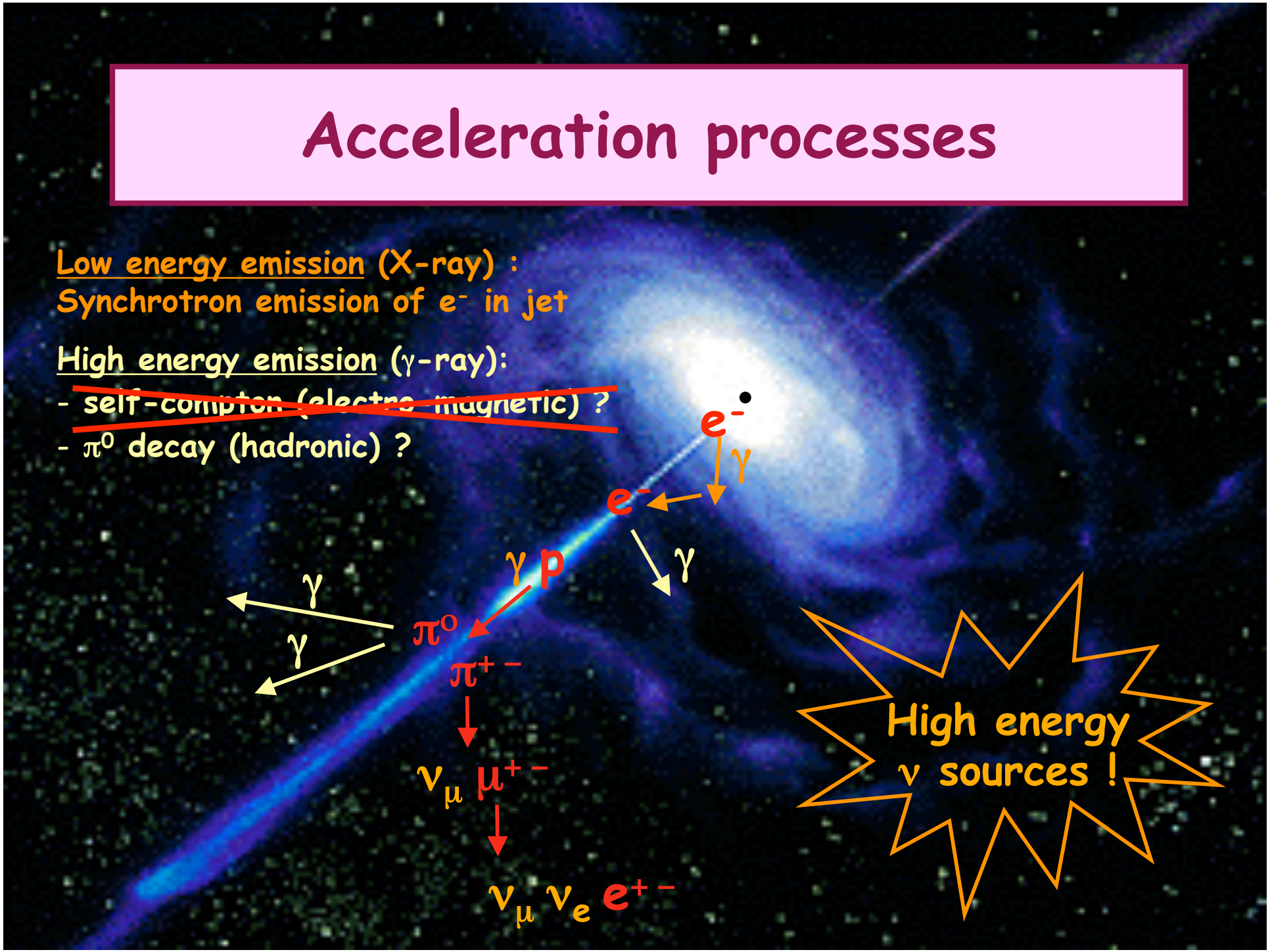
Neutrons: t ~ 15 mn
d_{max}=10 kpc (E=10^{18} eV)

Protons: absorbed (GZK)
& deviated (E<10^{18} eV)

Neutrinos: no charge,
"no" interaction
with matter nor radiation

Ideal probes of:
dense regions,
sources on cosmological scales,
acceleration processes

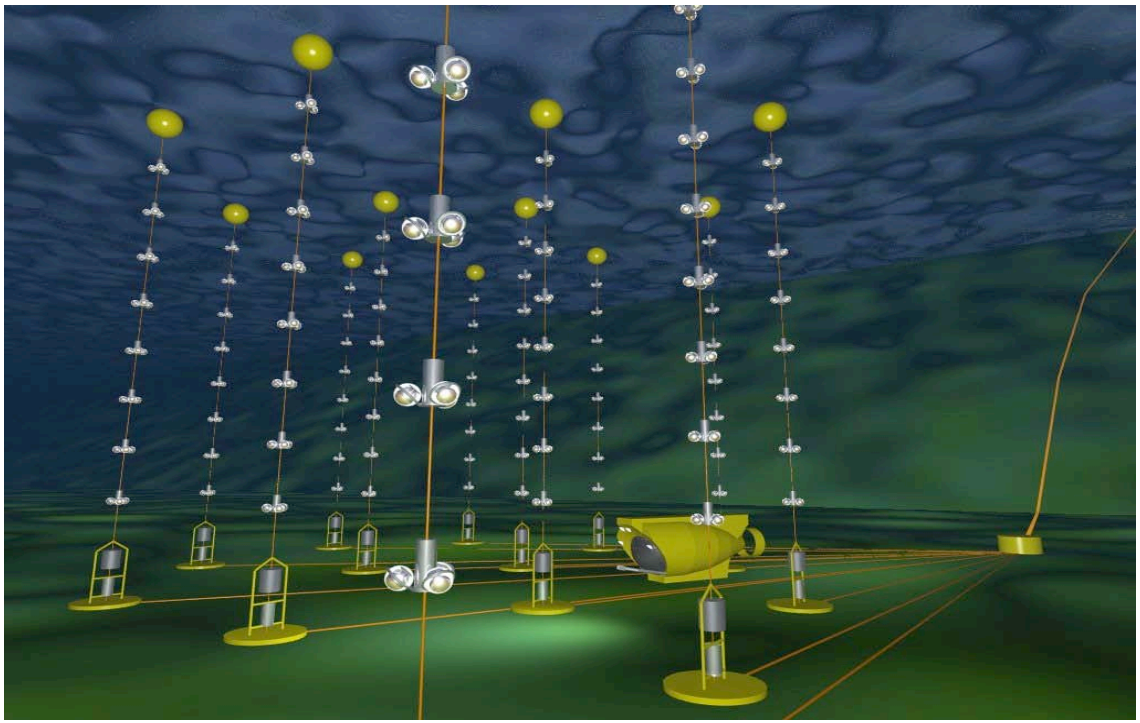
Acceleration processes

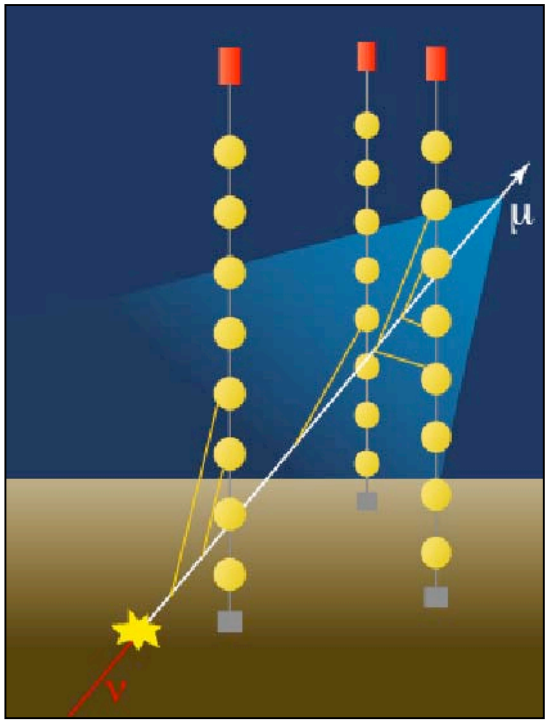


Neutrino telescopes

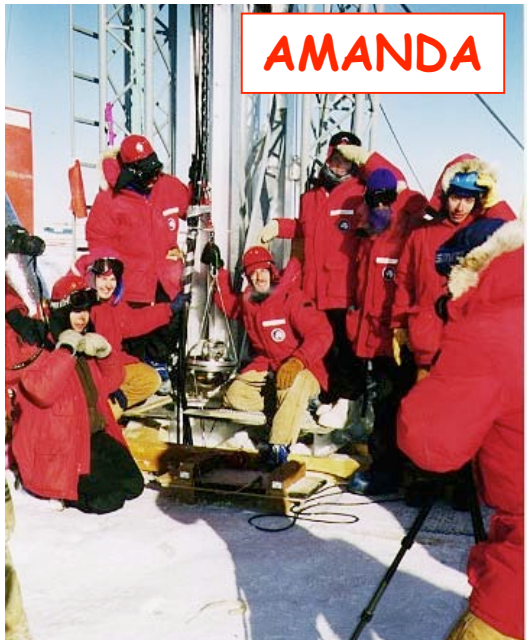
Low fluxes @ high E
Low cross-sections
→ Large volume (lake, sea, polar ice)

High background (atmospheric μ)
→ Good shielding (> 1000m water eq.)





ANTARES / AMANDA

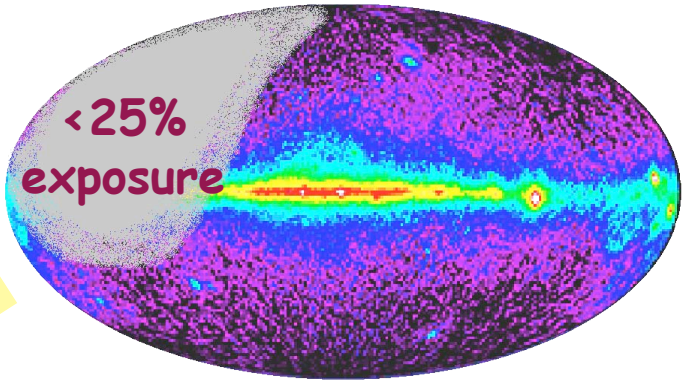


Better angular resolution (~0.2°)

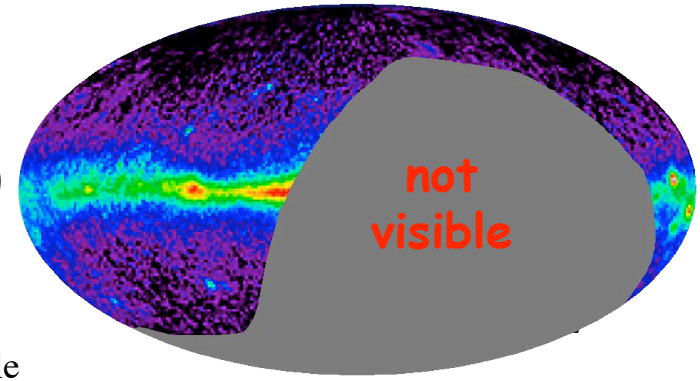
ANTARES/AMANDA 0.6π sr overlap

Better sensitivity (less absorption)

ANTARES (43° North) deployment by end 2007

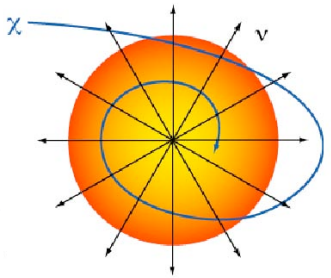


AMANDA (South pole) taking data

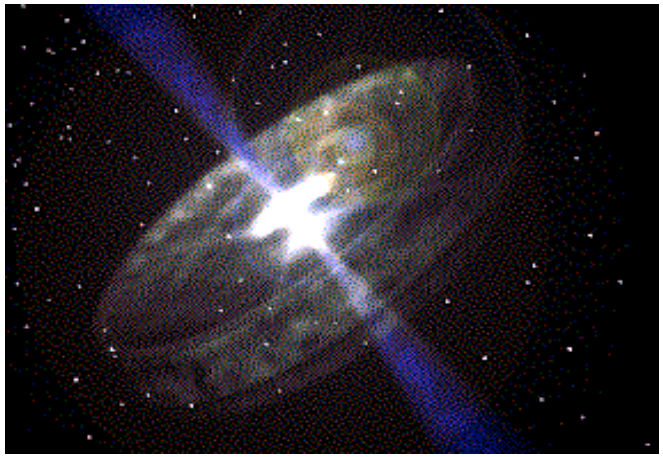


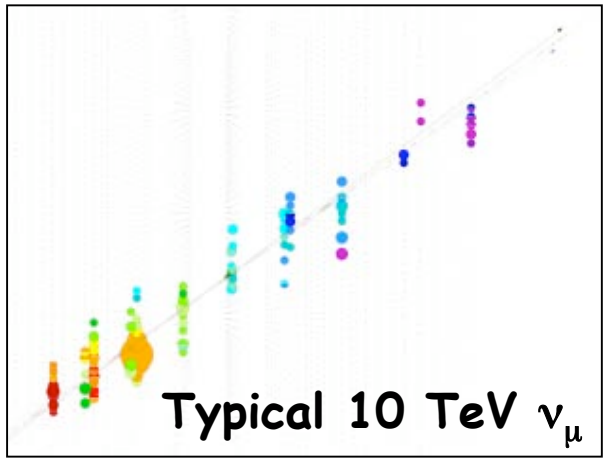
Science reach

Medium Energy (10 GeV - 1 TeV):
- Dark matter searches from dense regions
  (neutralino concentration & annihilation)
  AMANDA: reaching the level of direct searches
- ν from supernovae



High Energy (> 1 TeV): ν astronomy
ν from (extra-)galactic sources (cf. gamma rays)





cf C. Racca on Saturday

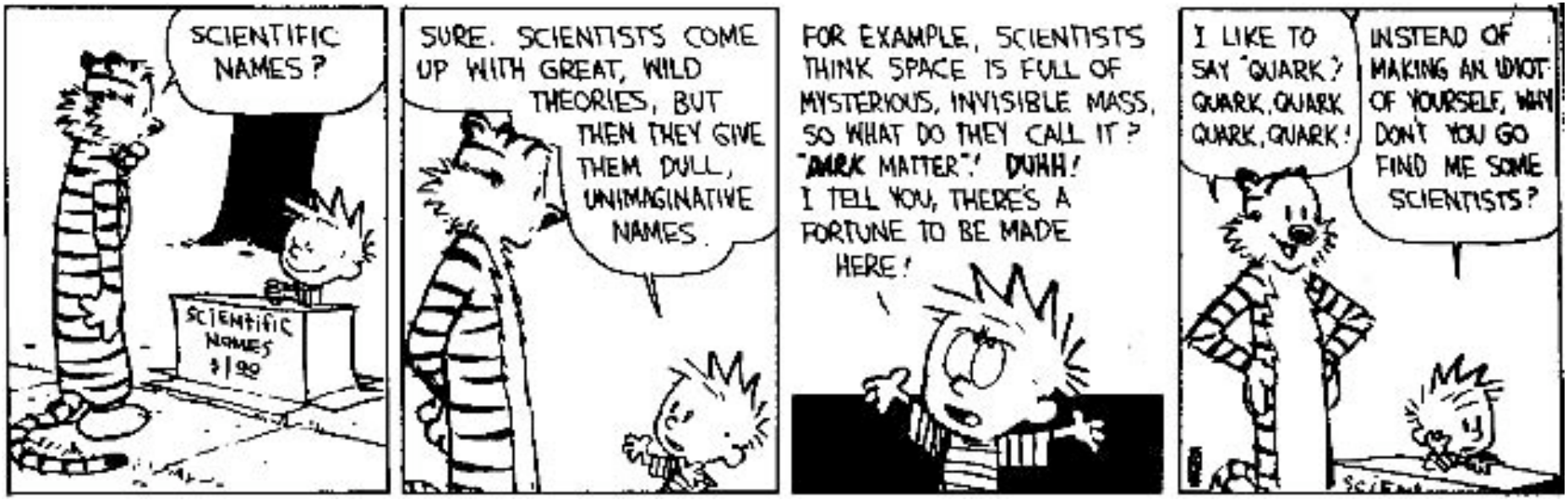
Conclusions

Of the complementarity of messengers

Cosmic rays	Charged (⇒ do not point except at UHE) Highest energies observed
Gamma rays	Traditional messenger yet unexplained phenomena (GRBs, unidentified sources…)
Neutrinos	The most challenging to detect, but no GZK

or of particle physics, cosmology, astrophysics

Dark matter	Still trying to detect it …
Dark energy	What is it???


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.99
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS. SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
I LIKE TO SAY "QUARK." QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?