Astroparticle Physics (2/3)

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CERN Summer Student Lectures, August 2006

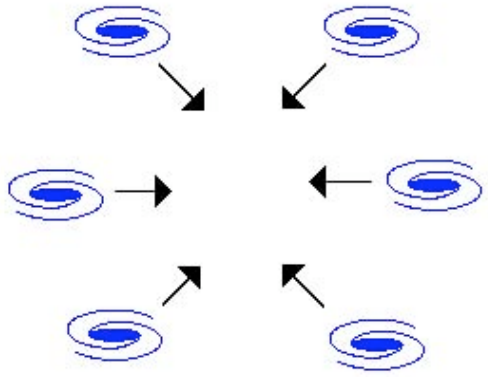
1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

2) Dark matter, dark energy
   Evidence for dark matter
   Candidates and experimental status
   Supernovae and dark energy

3) High energy astrophysics

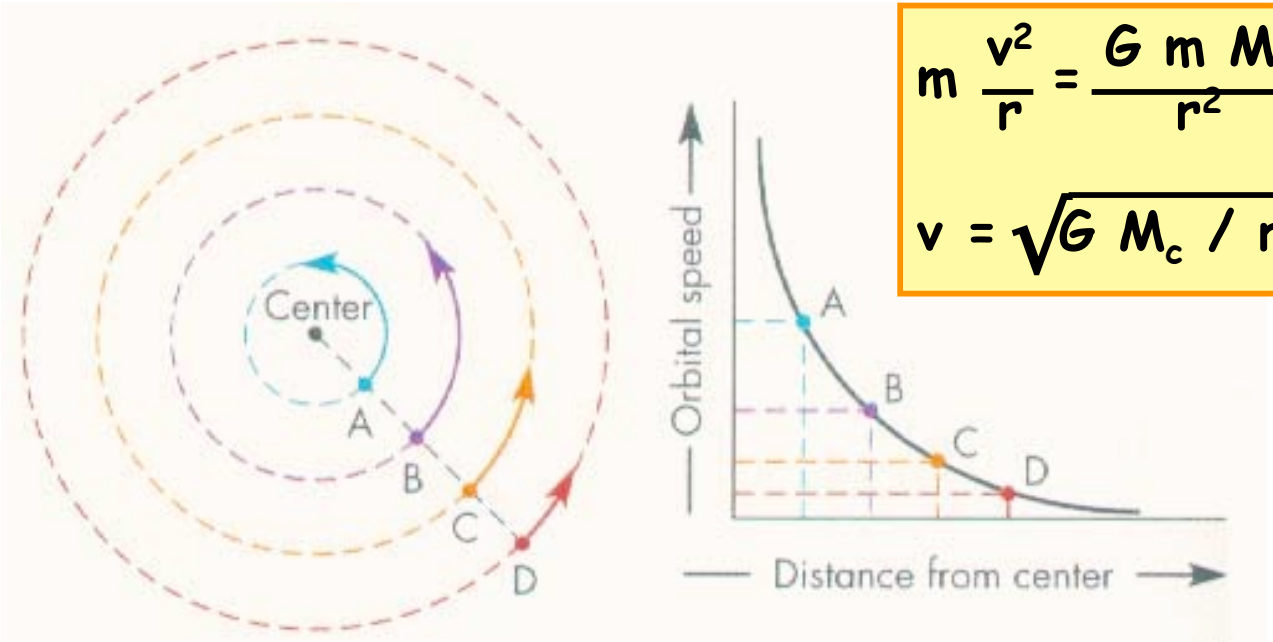
Dark matter in clusters

Zwicky, 1933



Mass of luminous matter
=
10%
Gravitational mass

Rotation curves (planets)



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

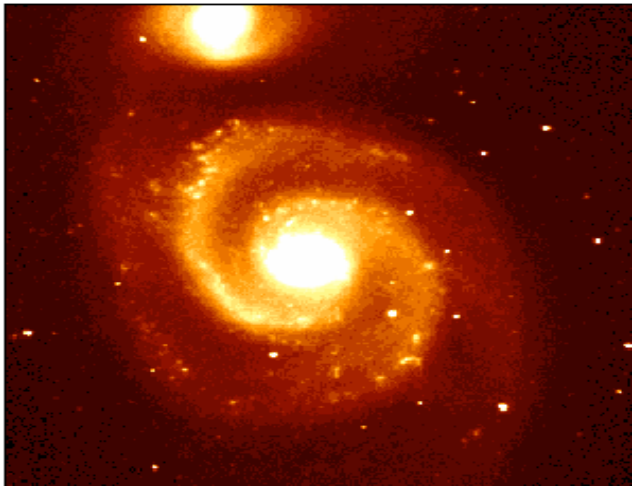
$$v = \sqrt{G\, M_c / r}$$

Rotation of planets

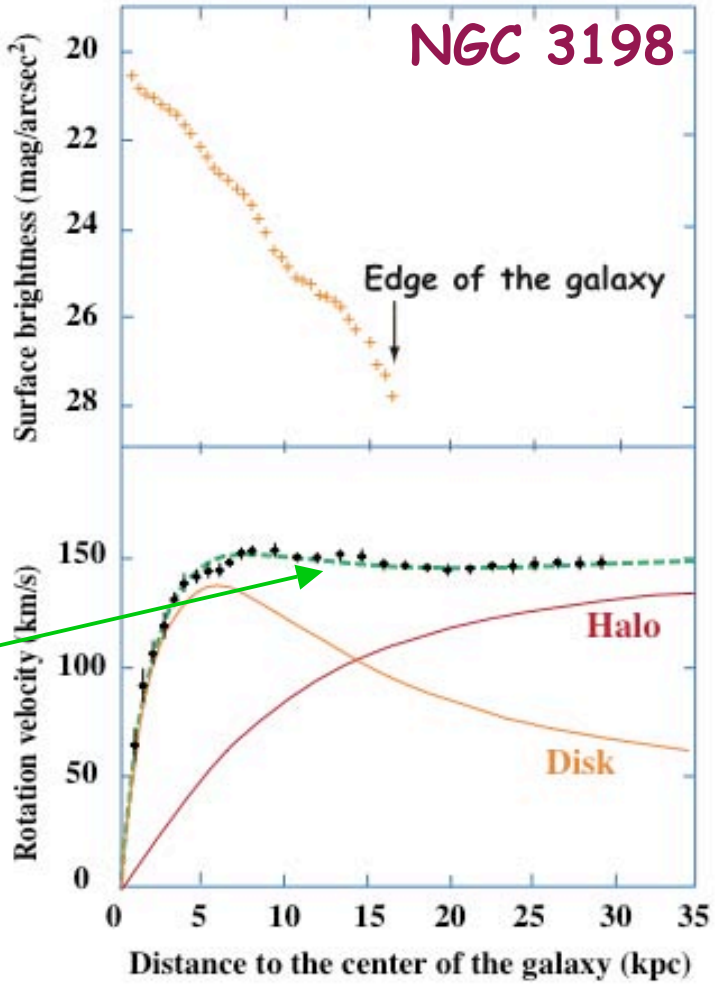
Associated rotation curve

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



Doppler shifts across galaxy
⇒ velocity distribution
⇒ Flat rotation curve !



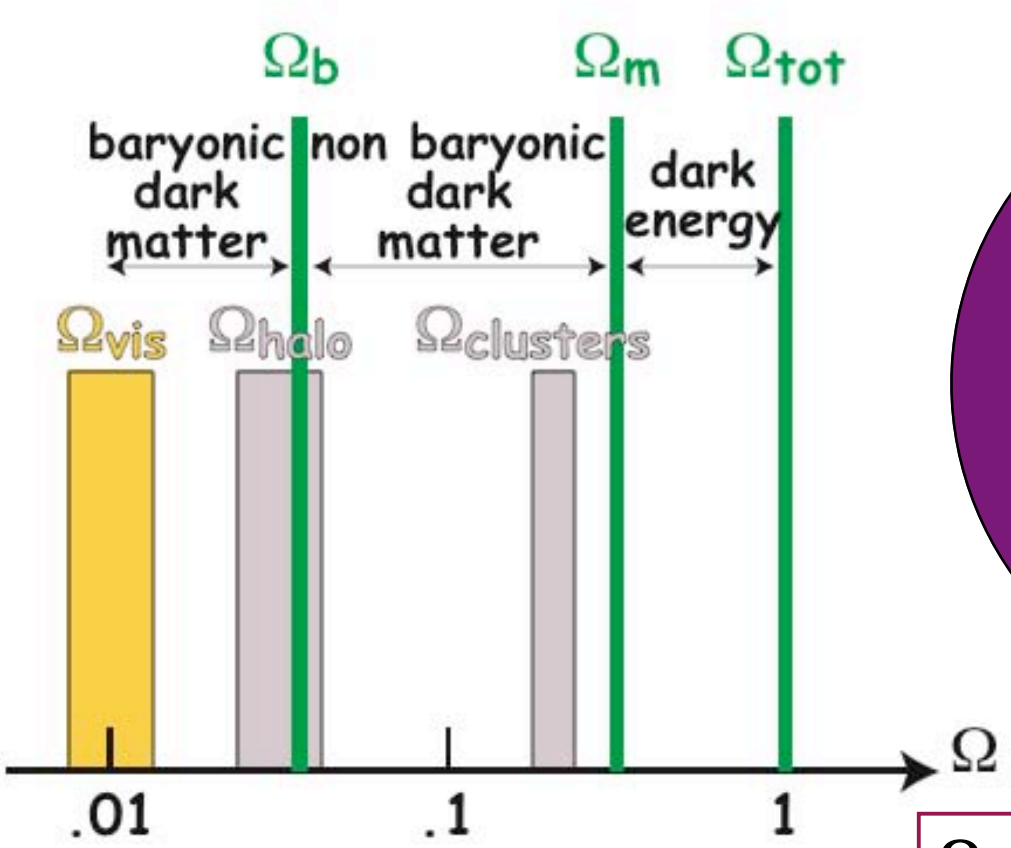
90% of gravitational mass is invisible (DARK HALOs)

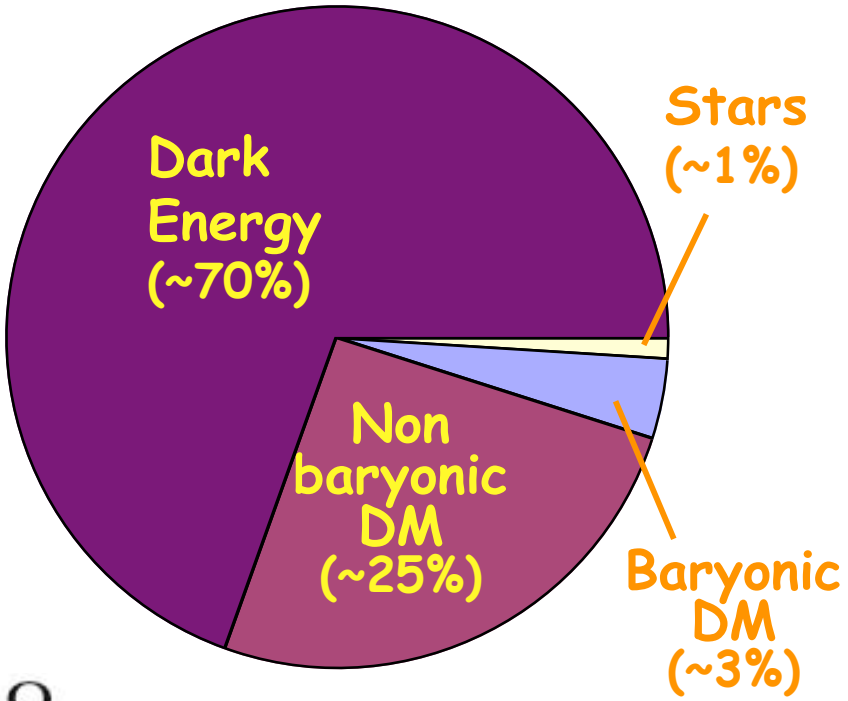
Gravitational lensing

HST

⇒ Luminous mass ~ 1% Gravitational mass

Summary of evidence





$\Omega = \rho / \rho_c$
$\Omega = 1$ for $k = 0$

Lecture outline

1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
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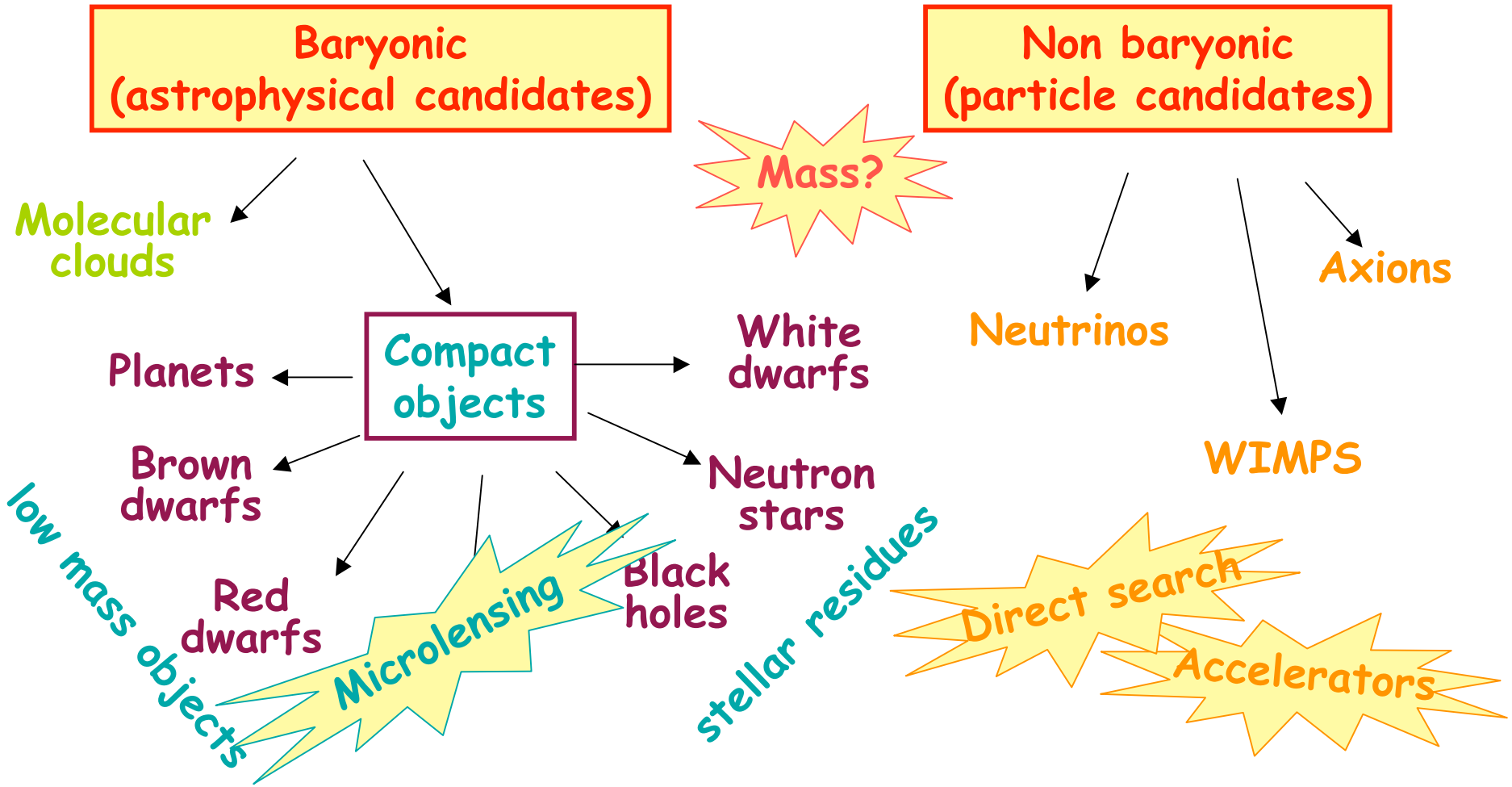
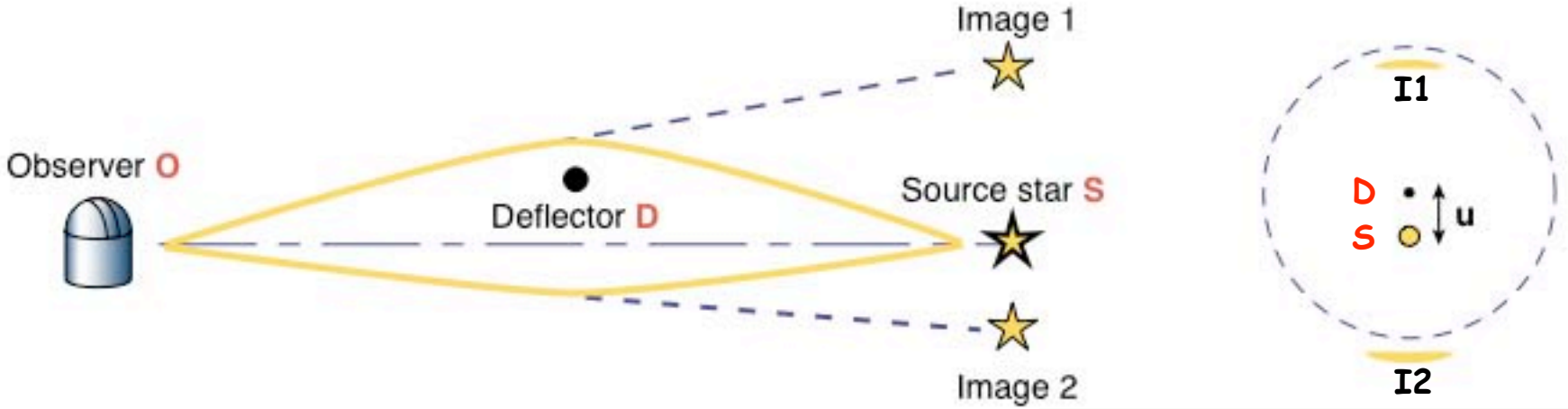
2) Dark matter, dark energy
   Evidence for dark matter
   Candidates and experimental status
      Baryonic (EROS, MACHO)
      Exotic (Edelweiss, DAMA, Antares)
   Supernovae and dark energy

3) High energy astrophysics

Dark matter candidates

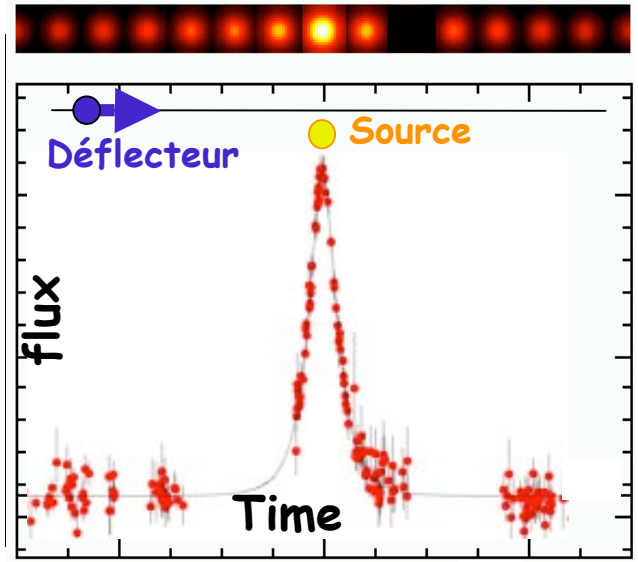


Principles of microlensing



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

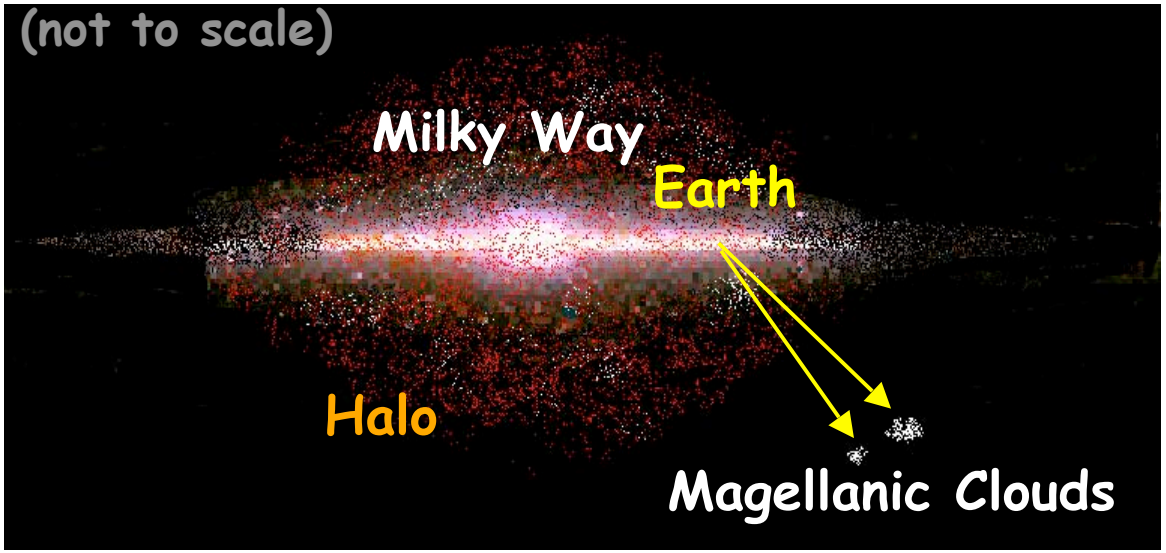
Motion of deflector (220 km/s)
⇒ Duration $t_E \sim 70 \sqrt{M/M_{sun}}$ days

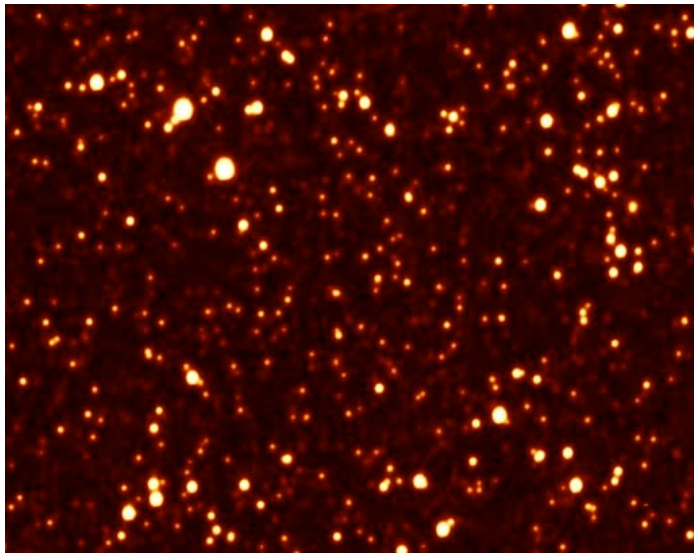


Targets (EROS, MACHO)

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)

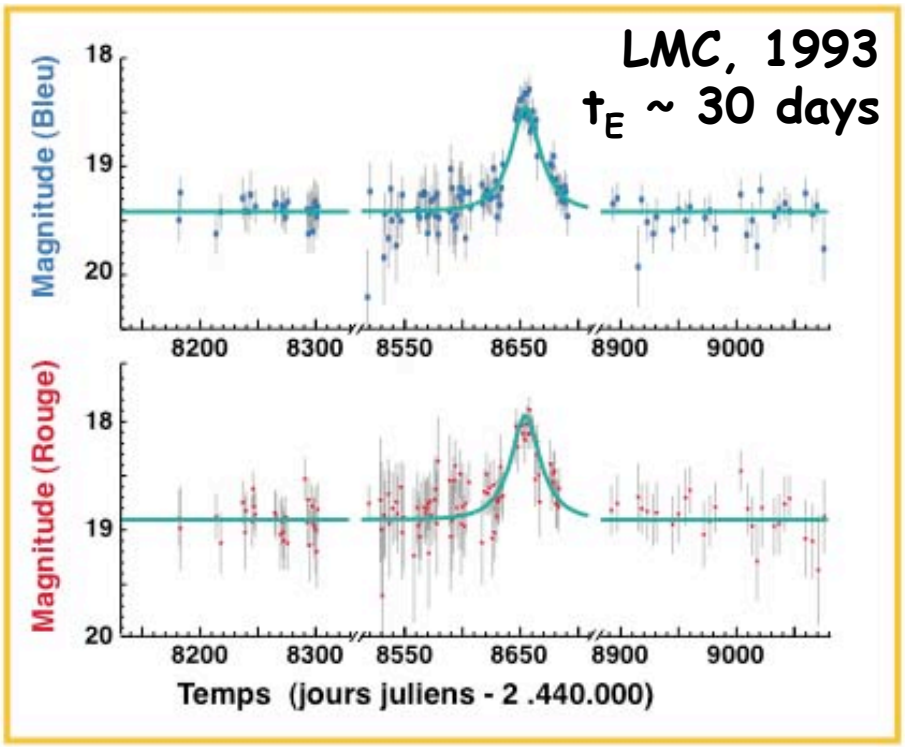


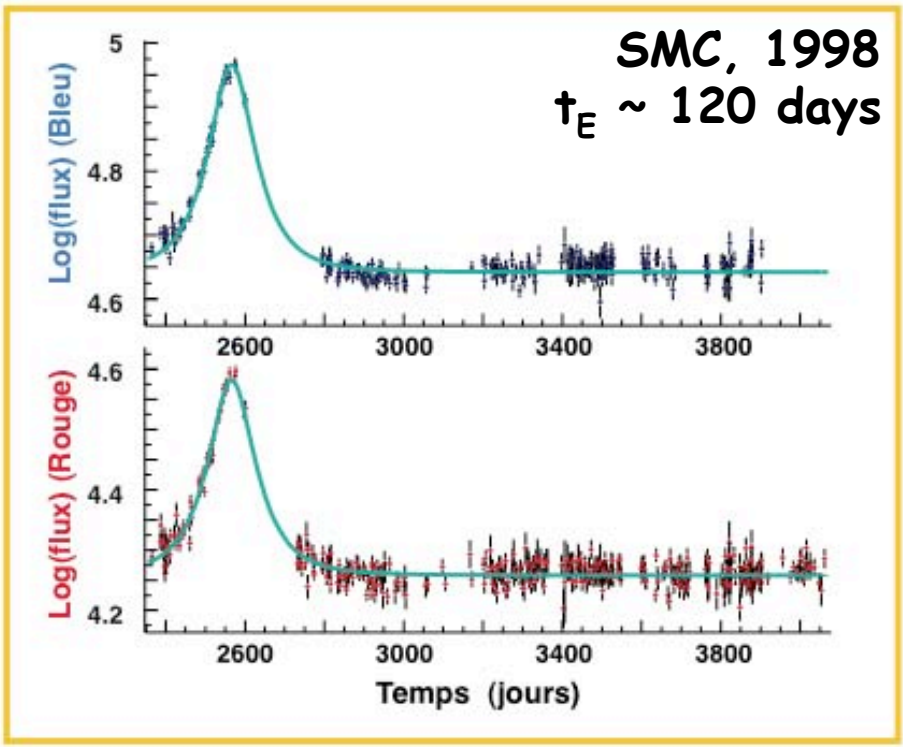


~30 million stars monitored:
- >10 000 variable stars
- >100 SN
- Microlensing events ?

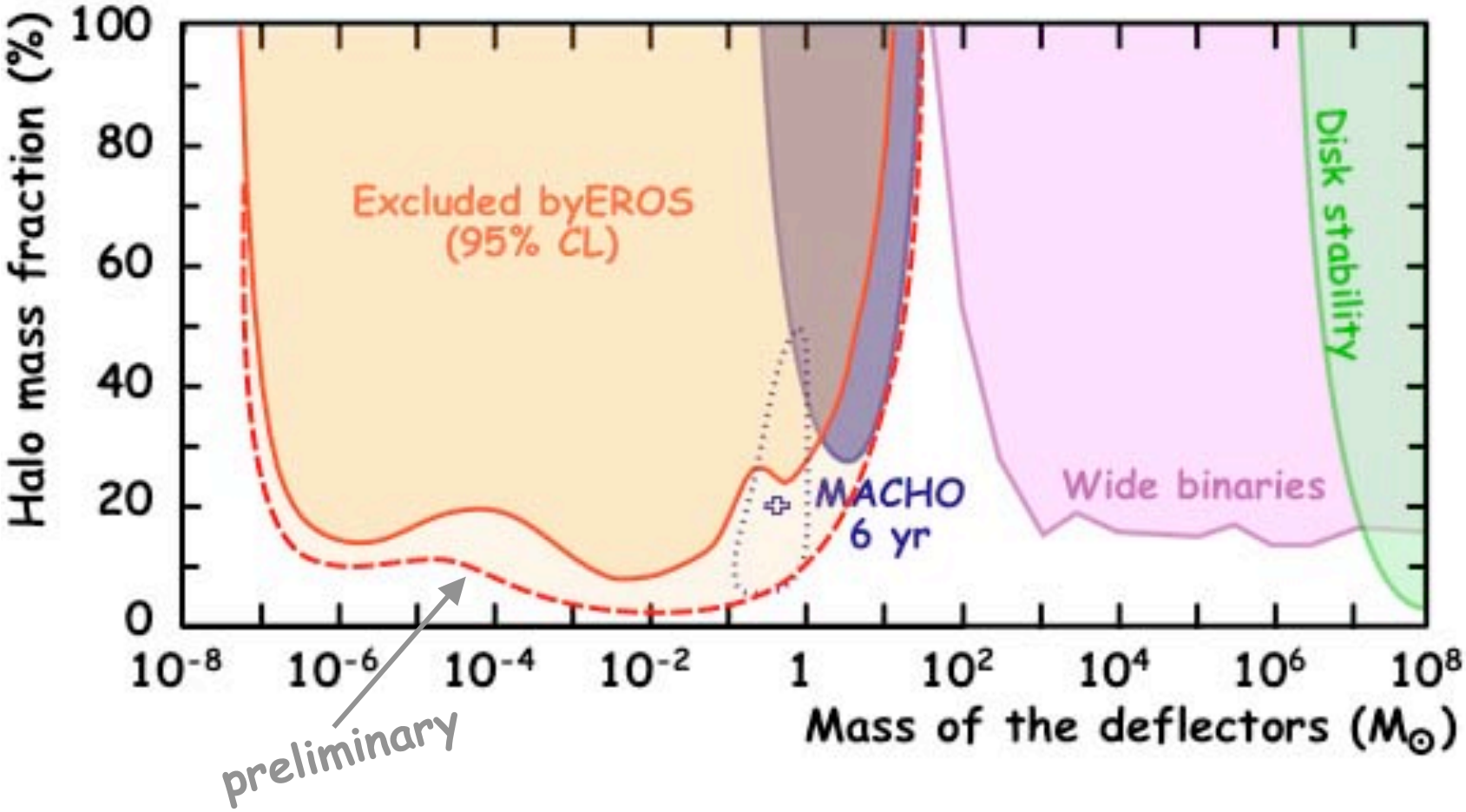
Initial results

Candidates detected (microlensing technique validated)





Final results



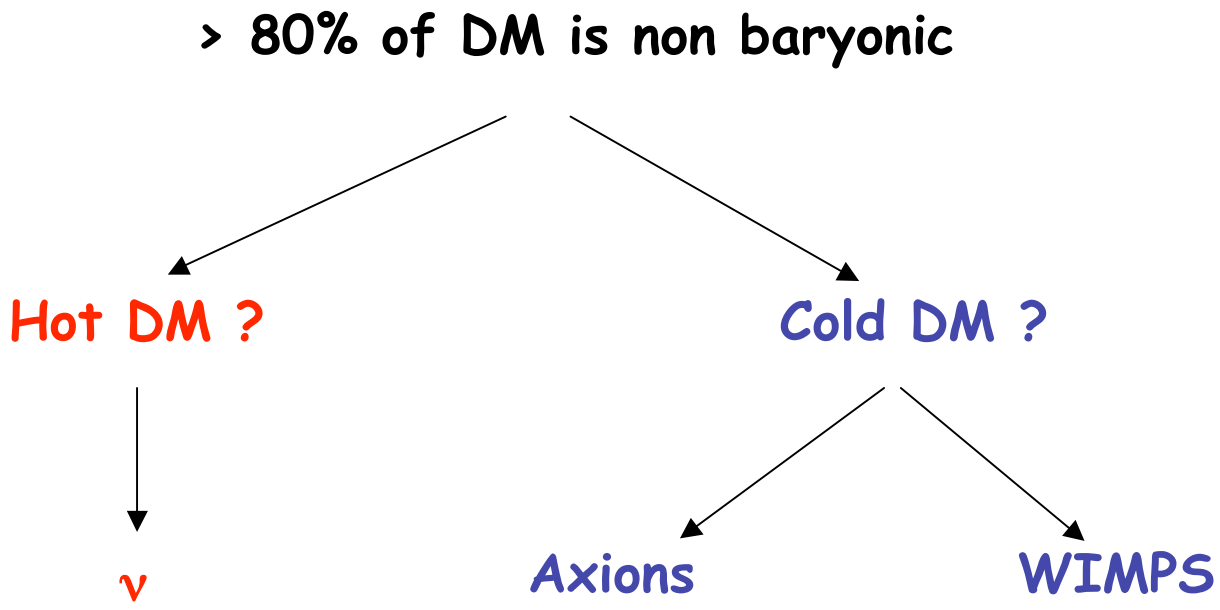
Conclusions on baryonic DM

Favored candidates (compact astrophysical objects) rejected on all mass range

(only small window remaining at ~ 10-100 M_{sun})

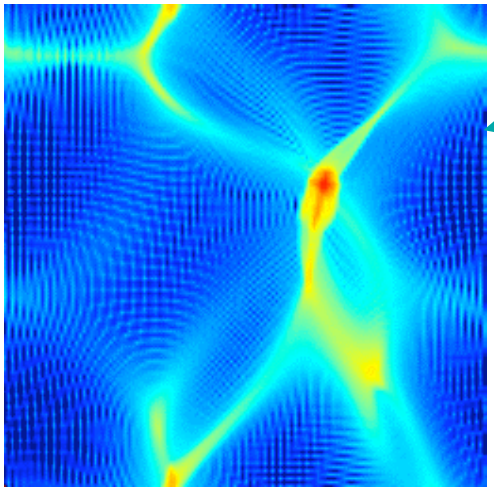
Gas
Cold molecular clouds
...

Non baryonic DM



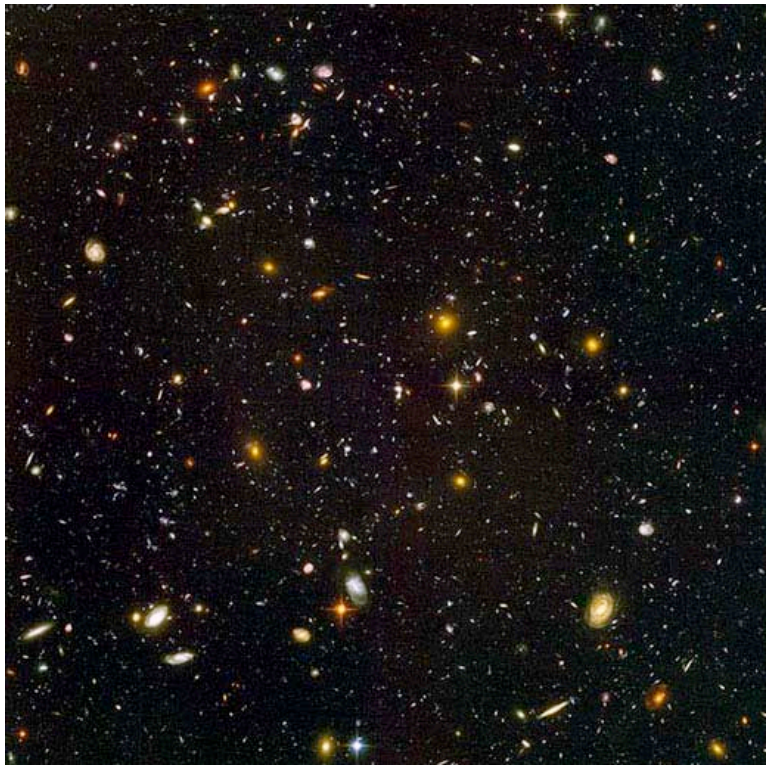
Structure formation

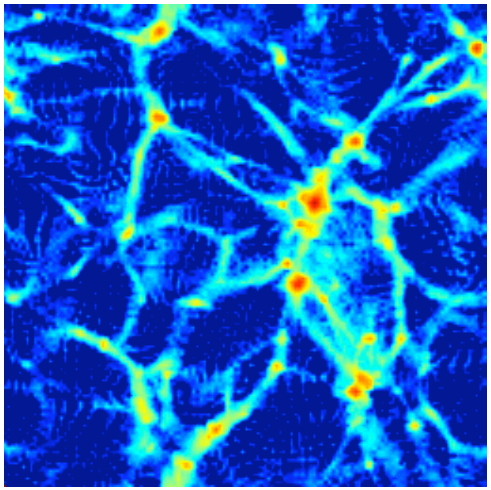
Simulations of
DM density maps



HDM wipes out
structure on
small scales

Hubble Deep Field



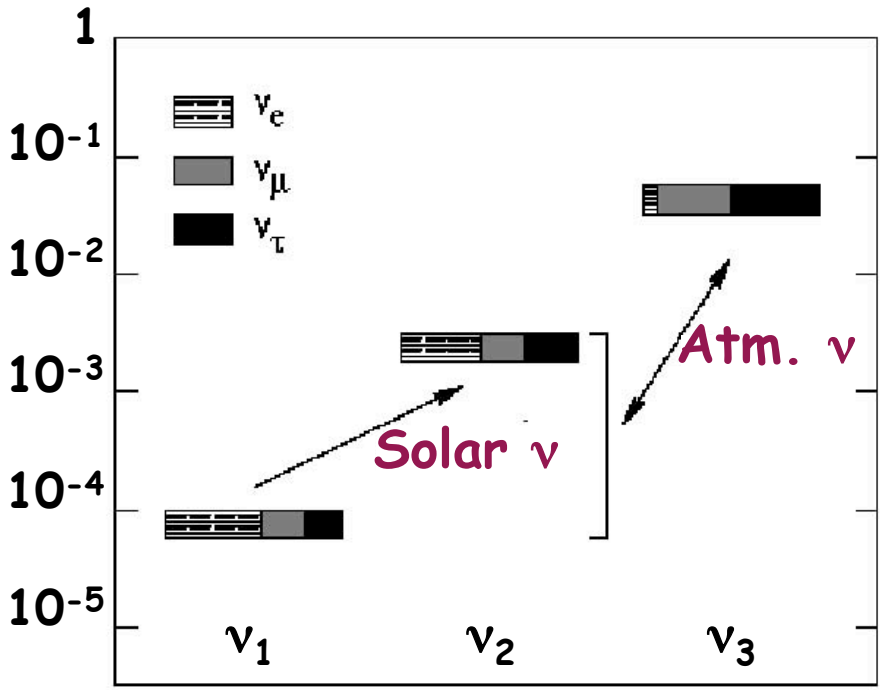


CDM creates
too many
sub-structures?

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 $\Rightarrow \Omega_\nu \sim 0.003$

Axions

Postulated to solve the strong CP problem
Interesting CDM candidates if m_a in 10^{-5} eV - 10^{-3} eV ($\Omega_a \sim 1$)
Primakoff effect: 2-photon interaction in external B field

ADMX

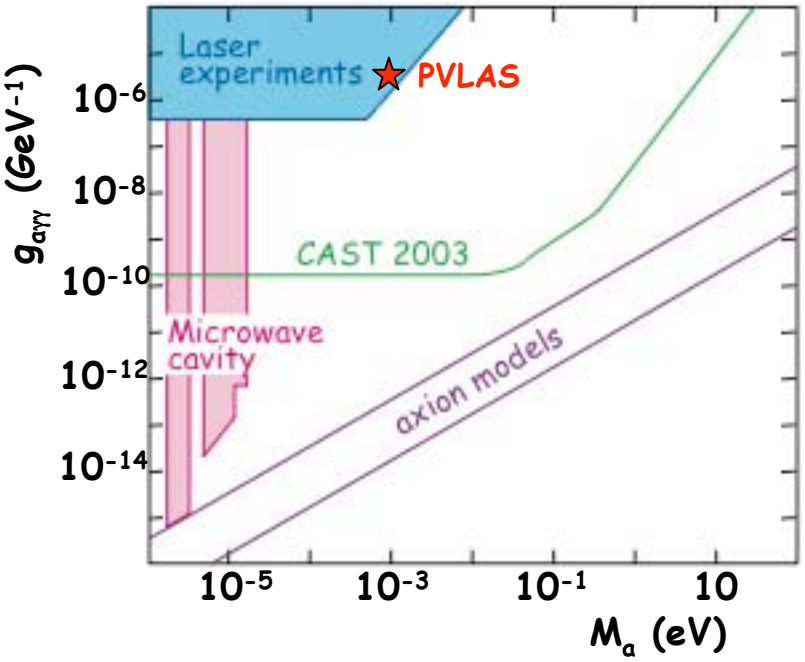
Microwave cavity

CAST

B field to convert solar axions into X-rays
→ strong upper limit

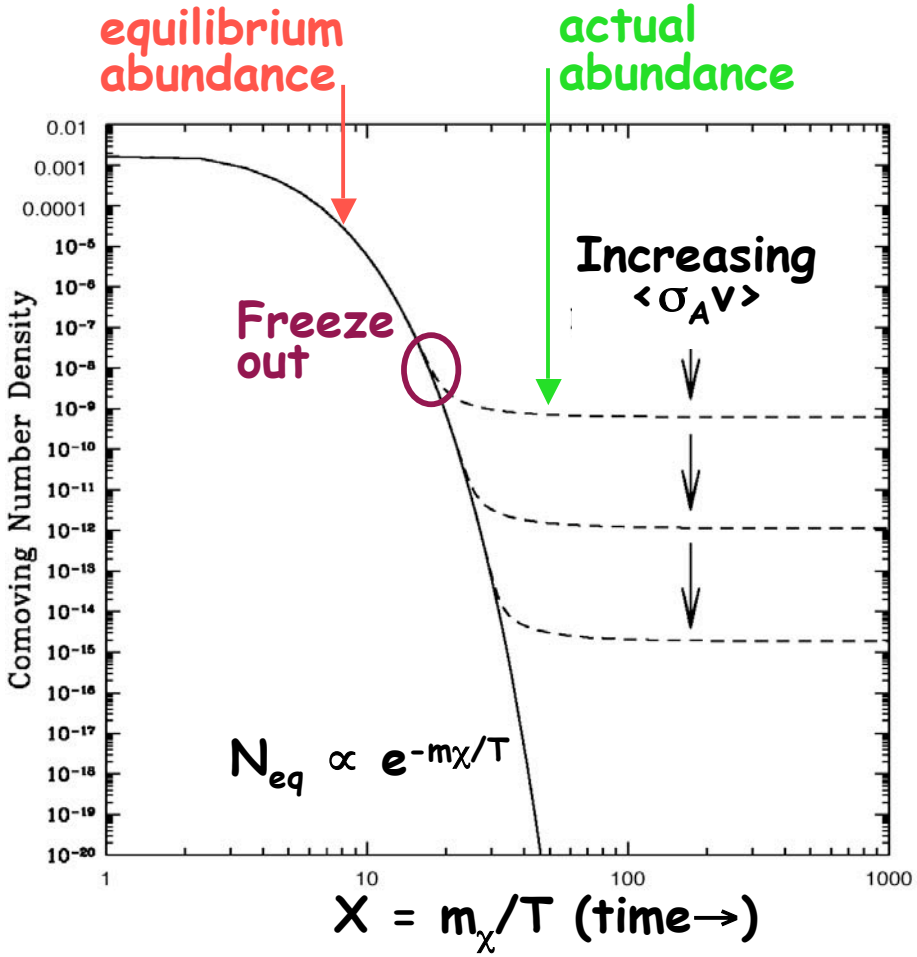
PVLAS

B field to search for ellipticity in laser polarization due to axion-induced birefringence
→ axion-like signal?



Weakly Interacting Massive Particles

If SUSY exists
- production of sparticles in early universe
- all decay except LSP (conservation of R-parity) → relic from Big Bang
- $m_\chi \sim 50$ GeV (accelerator)
- annihilate through $\chi\,\overline{\chi} \leftrightarrow X\,\overline{X}$
- relic density $\Omega_\chi \sim 0.3$ for typical weak annihilation rates



Direct detection of WIMPS

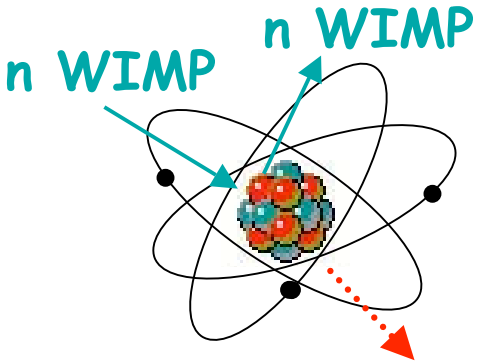
If halo DM made of WIMPS

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

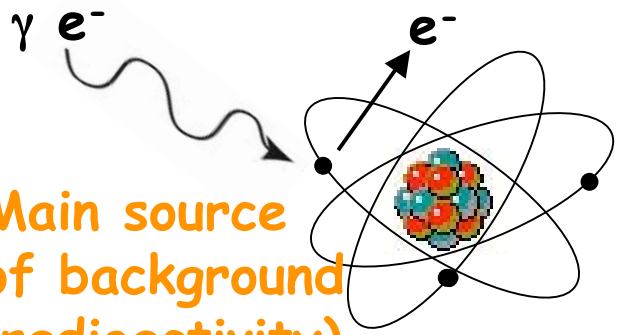
$\Rightarrow$ > 10 000 WIMPs/cm^2/s on Earth (from $-\vec{v}_{sun}$)

Experimental signature :

nuclear recoil



(vs. electronic "recoil")



Main source of background (radioactivity)

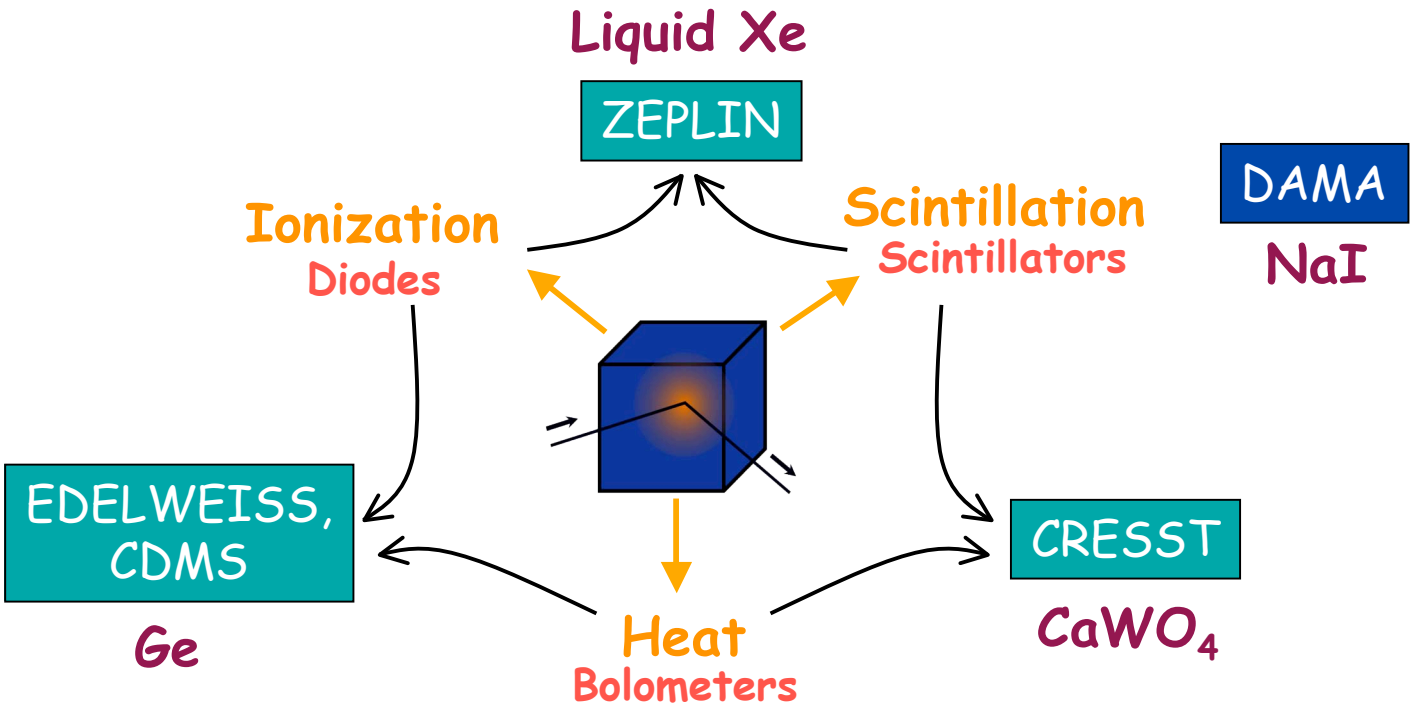
<< 1 evt / kg / day

Requirement : High mass detectors

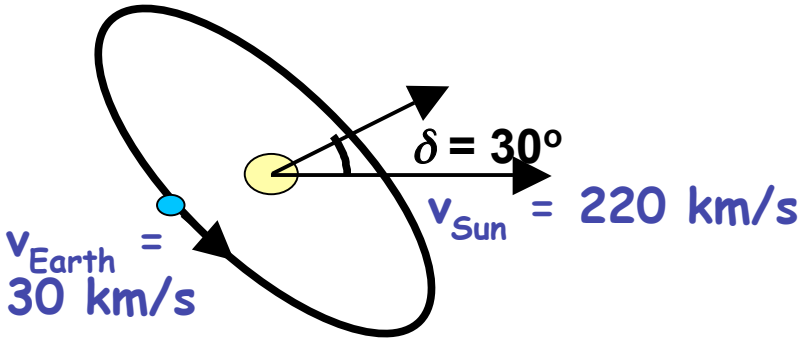
Low radioactive background (discrimination)

Background rejection

Event by event discrimination of nuclear vs. electronic recoil

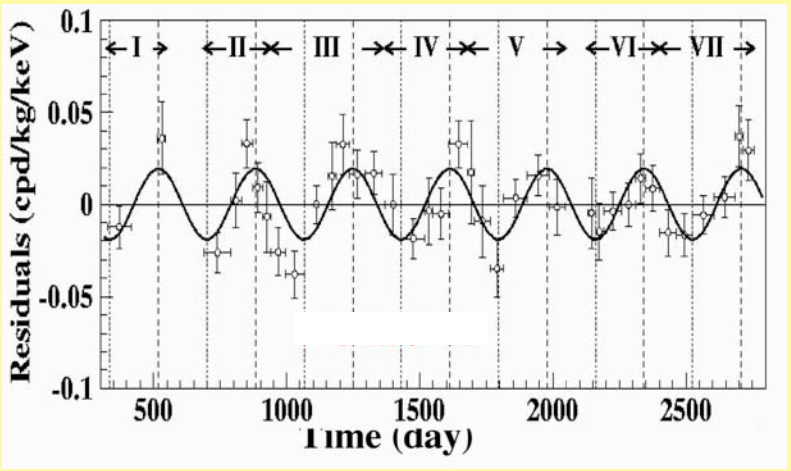


Annual modulation



Motion of Earth in the χ wind

Modulation of annual rate ± 7%
Max in June

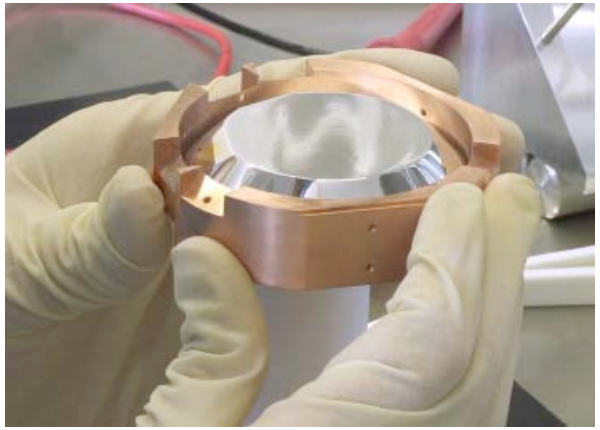


DAMA:
Annual modulation at 6.3σ
m_χ ~ 44-62 GeV

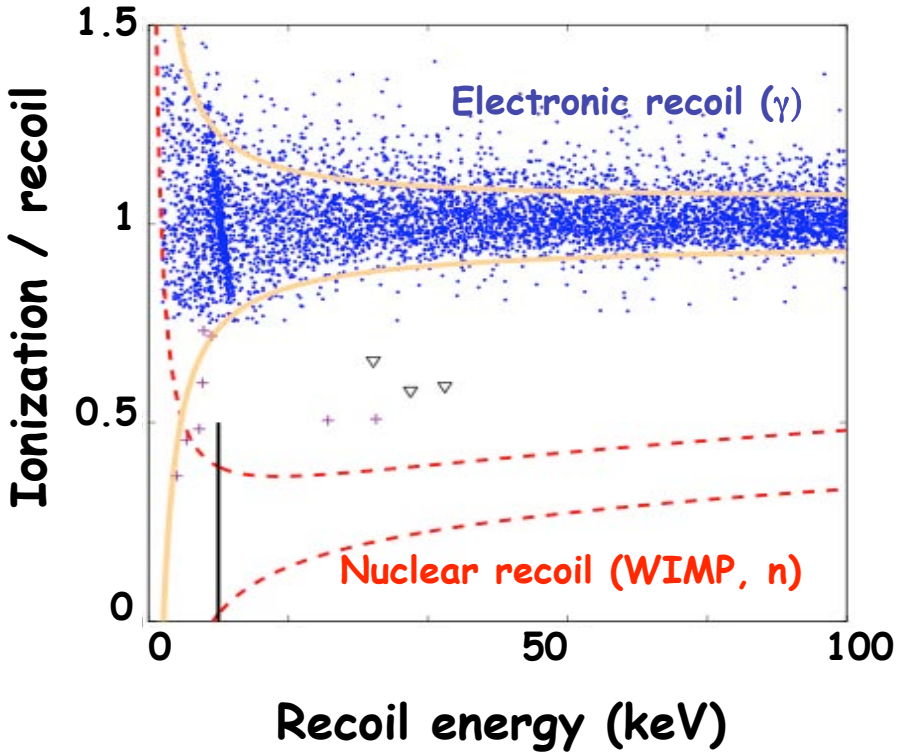
BUT
1 signature only
Result in contradiction with other expts.

2nd phase LIBRA running

Heat + ionization
Edelweiss / CDMS

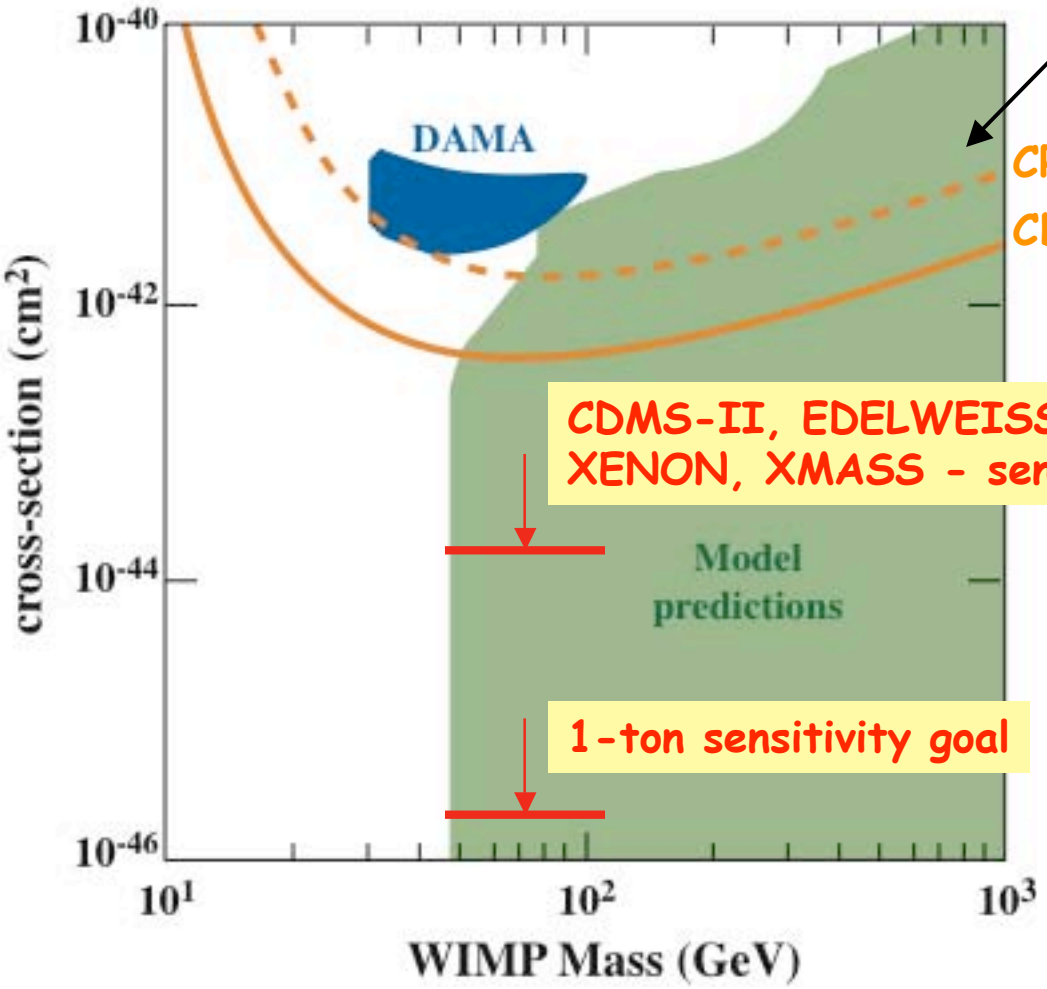


300g Ge bolometer



Background free analysis
No event in signal region

Conclusions on direct detection

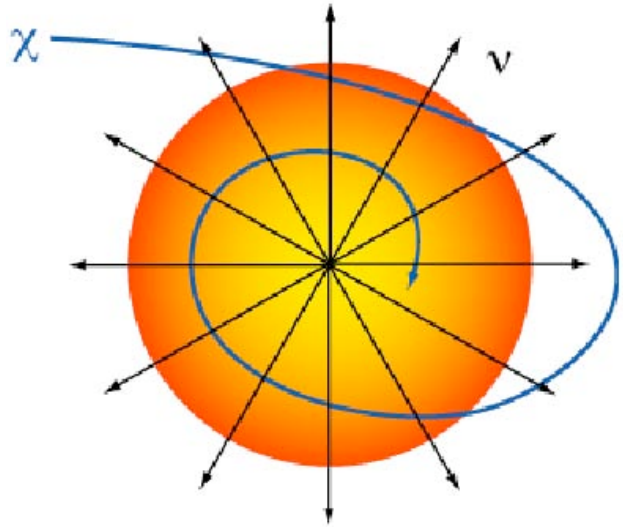


Testing most SUSY param. space (MSSM) requires 3 orders of magnitude beyond present best performances

Indirect detection of WIMPs

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

Gravitational capture + annihilation



Halo $\chi\chi \rightarrow \gamma\gamma$	High energy astronomy AMS, GLAST, VERITAS, BESS, CELESTE, CAPRICE, MILAGRO…

Earth, Sun, GC $\chi\chi \rightarrow X\nu$	ν telescopes SuperK, Baksan, IMB, MACRO AMANDA, ANTARES, Baïkal…

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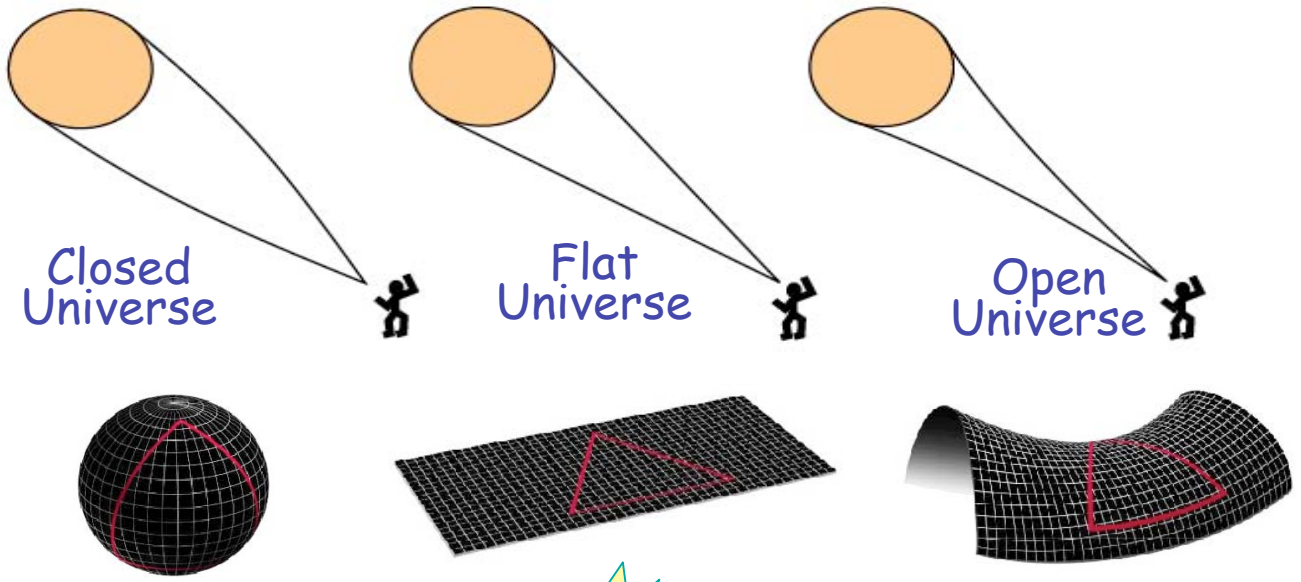
3) High energy astrophysics

Measurement of the geometry

$$1 - \Omega_k(t) = \sum\Omega_x(t) + \Omega_\Lambda(t)$$



AT A GIVEN DISTANCE

Known physical size — CMB — **angle depends on geometry**

Known luminosity — SN Ia — **flux depends on geometry**

Life of a small star (<8 M_{sun})

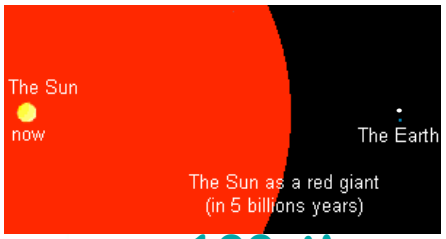
The Life of Stars Like the Sun

Forms in Dust & Gas Cloud

Burns Hydrogen for 10 Billion Years

τ_{MS} = 10 Gyr

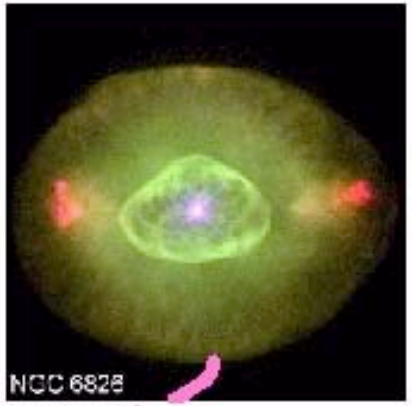
Becomes Red Giant Star burning Helium for 100 million years



τ_{RG} = 100 Myr

Ejects outer layers and is a planetary nebula for 100,000 years

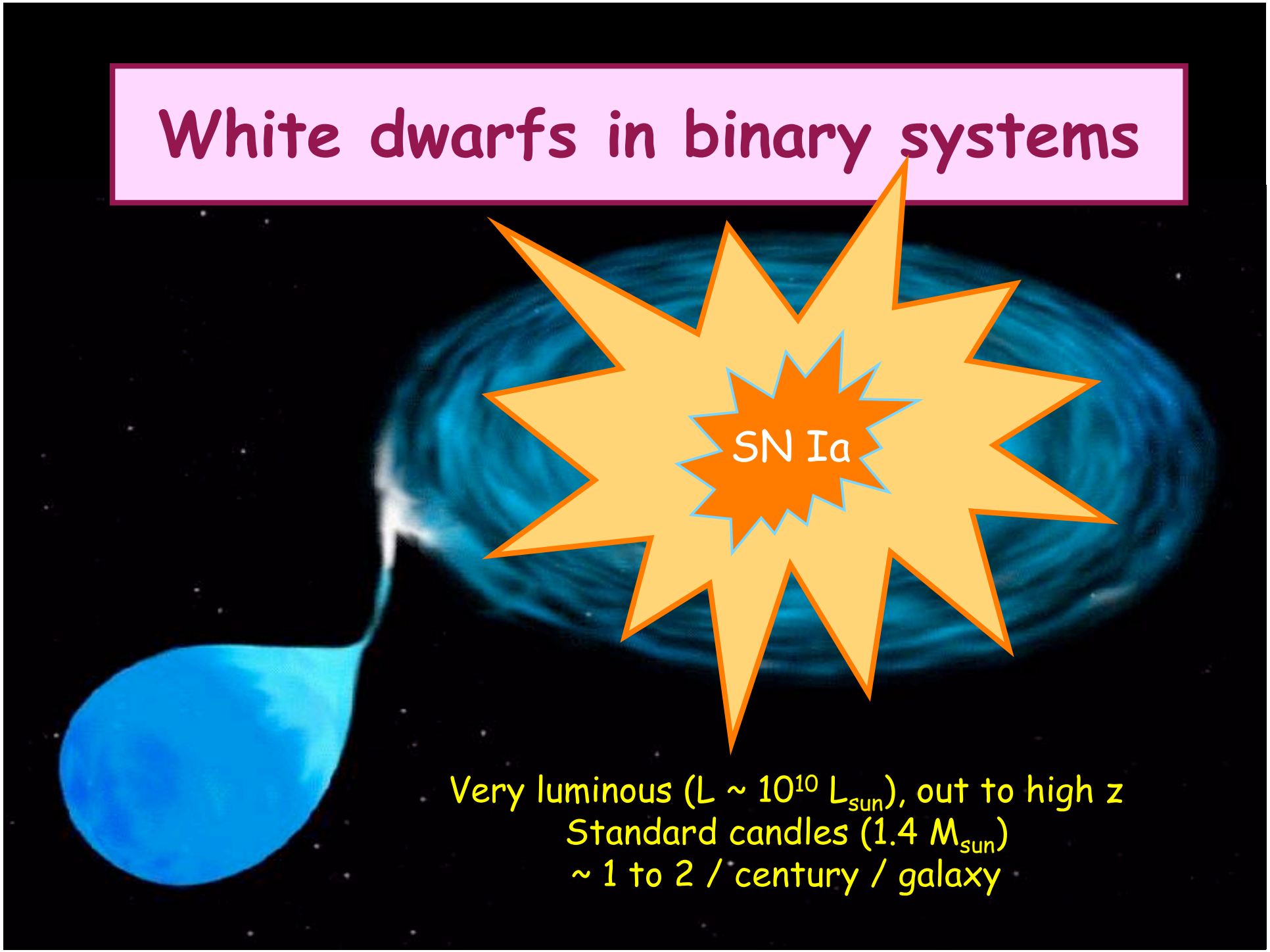
τ_{PN} = 100 kyr



Becomes White Dwarf star for Eternity

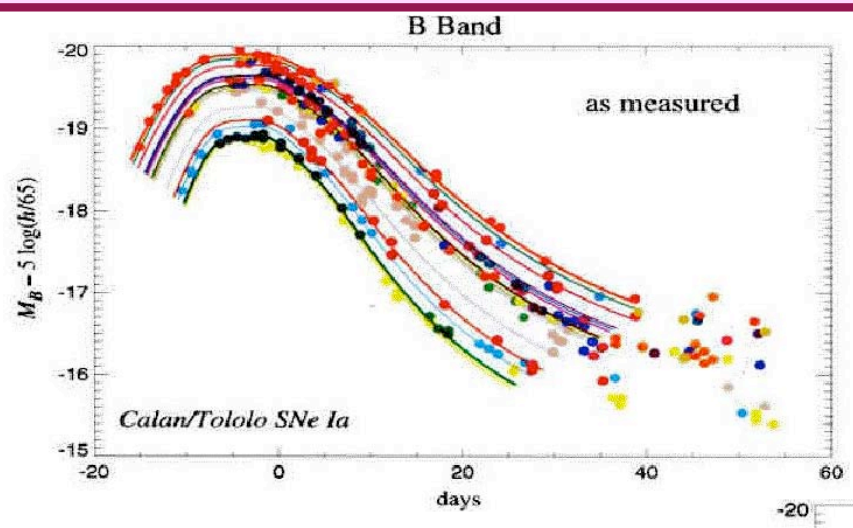
τ_{WD} = ∞

White dwarfs in binary systems

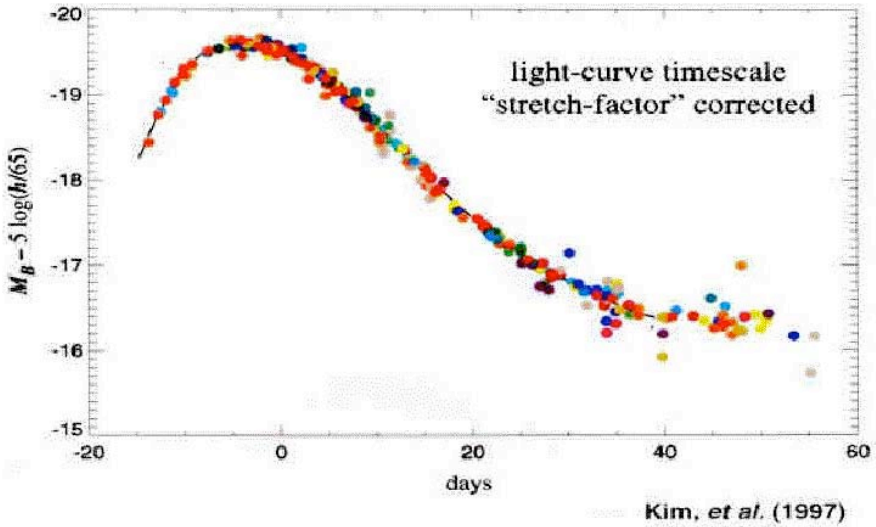


Very luminous ($L \sim 10^{10} L_{sun}$), out to high z
Standard candles ($1.4 M_{sun}$)
~ 1 to 2 / century / galaxy

Light curves

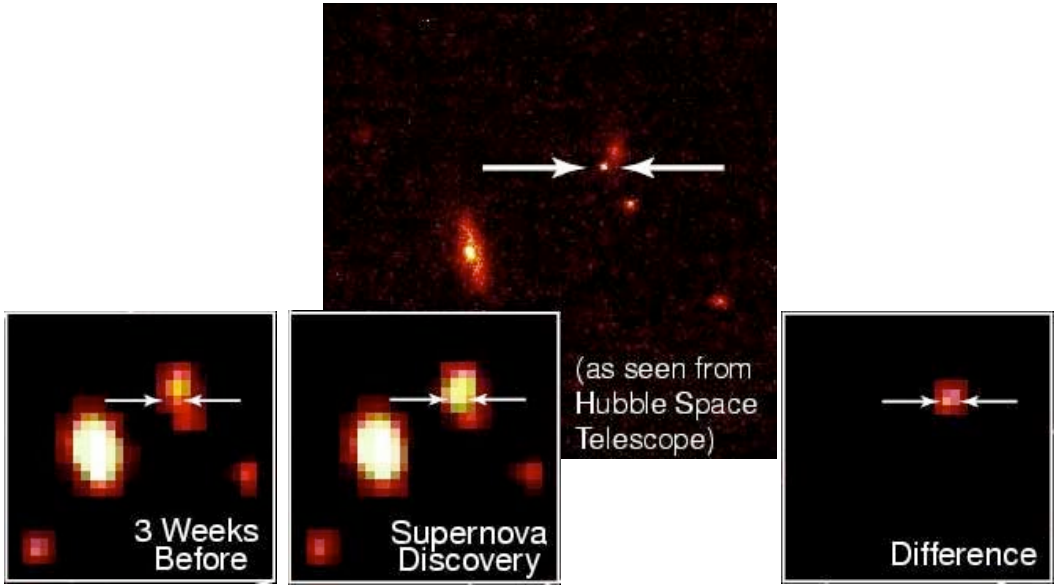


Unique parameter
(strech factor)

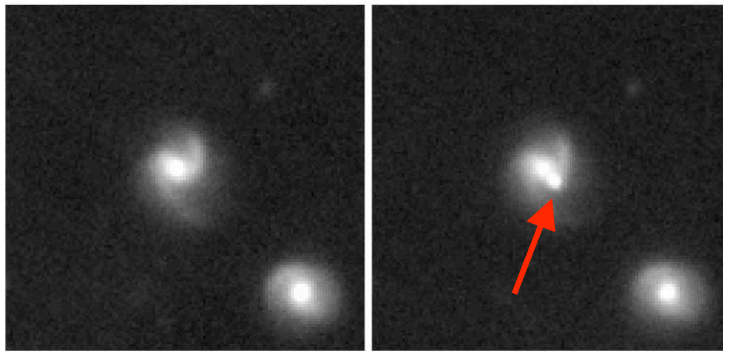


Kim, *et al.* (1997)

SuperNova Legacy Survey



3 steps
- discovery (differential photometry)
  4 deg^2 monitored from CFHT (Hawaii)
- identification (spectrum)
- photometric follow-up → light curve



CCD detectors at CFHT

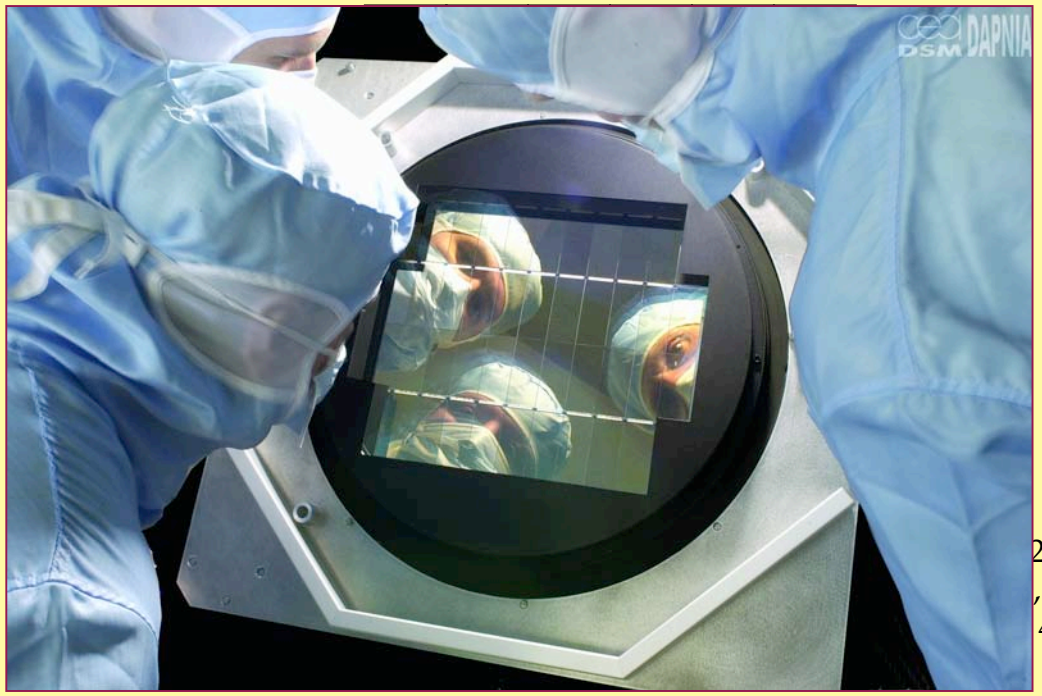
RCA1 1981-1986
1 CCD, 320 x 512
champ 2′ x 3.5′

RCA2 1986-1995
1 CCD, 640 x 1024
champ 2′ x 3.5′

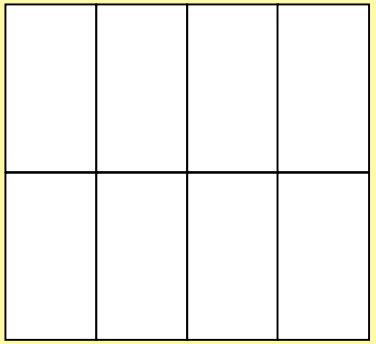
SAIC1 1990
1 CCD, 1K x 1K
champ 4.2′ x 4.2′

Lick2 1992
1 CCD, 2K x 2K
champ 7′ x 7′

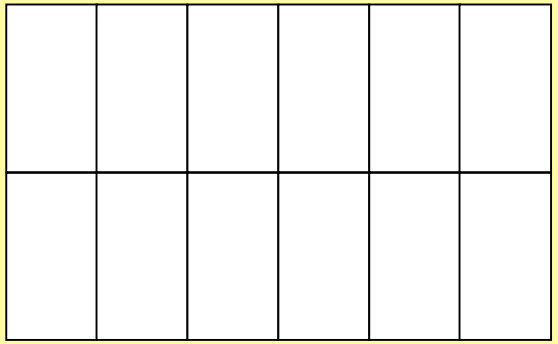
MOCAM 1994
4 CCDs, 4K x 4K
champ 14′ x 14′



MegaCam 2002
40 CCDs, 20K x 18K
champ 1° x 1°



UH8K 1996
8 CCDs, 8K x 8K
champ 28′ x 28′



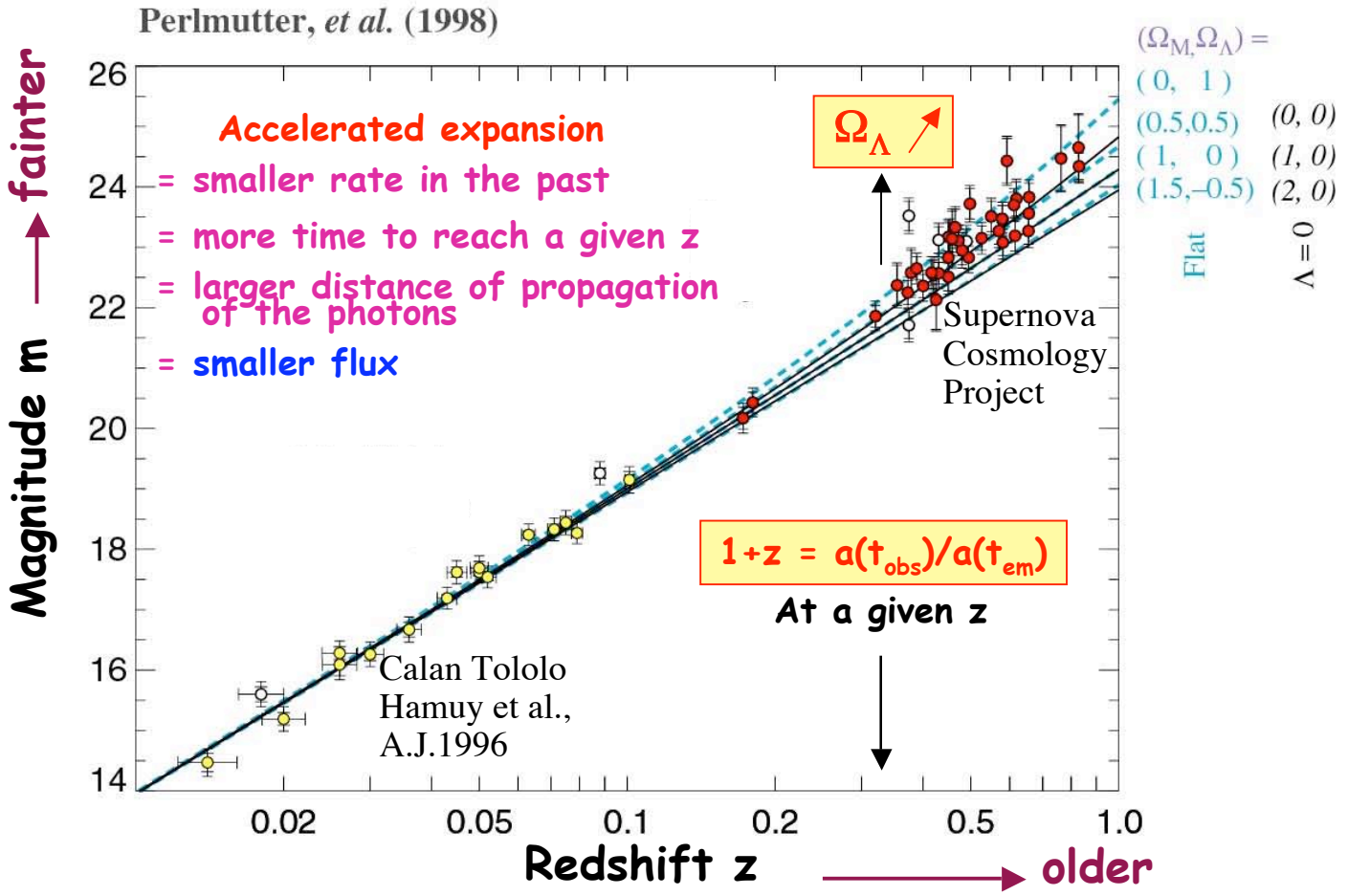
2K 1999
, 12K x 8K
42′ x 28′

Hubble diagram

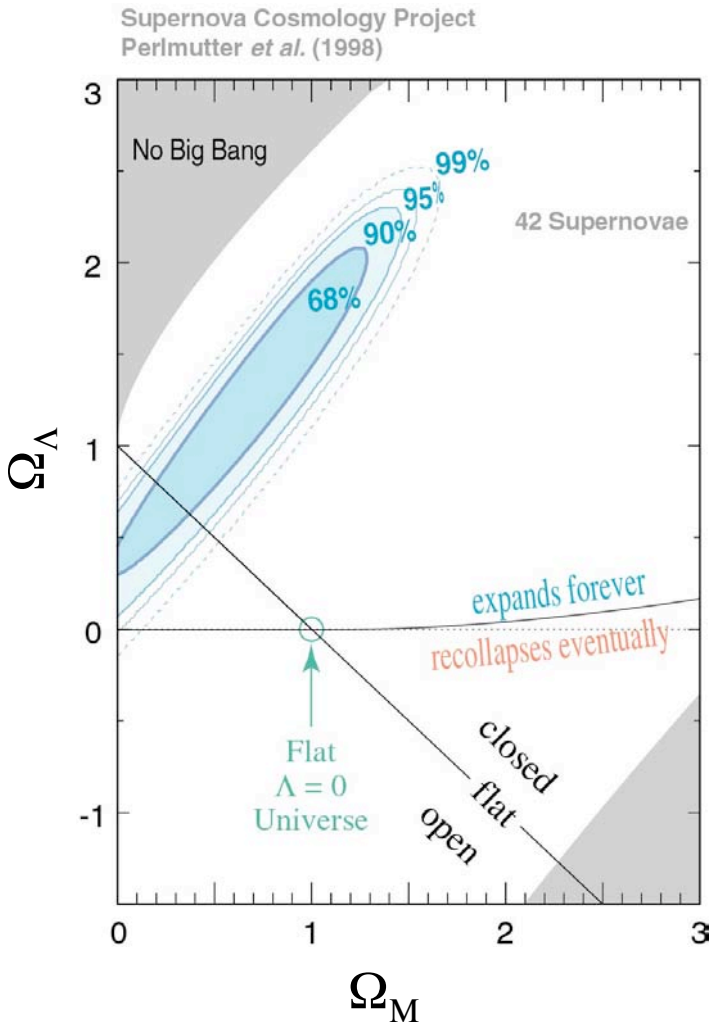
$$m = -2.5 \log F + cst = 5 \log (H_0 D_L) + M - 5 \log H_0 + 25$$

$H_0 \longrightarrow cz/D_L$ (z → 0) ⟹ mesure of H_0

Large z : mesure of Ω_m, Ω_Λ



Initial constraints (1998)



42 supernovae

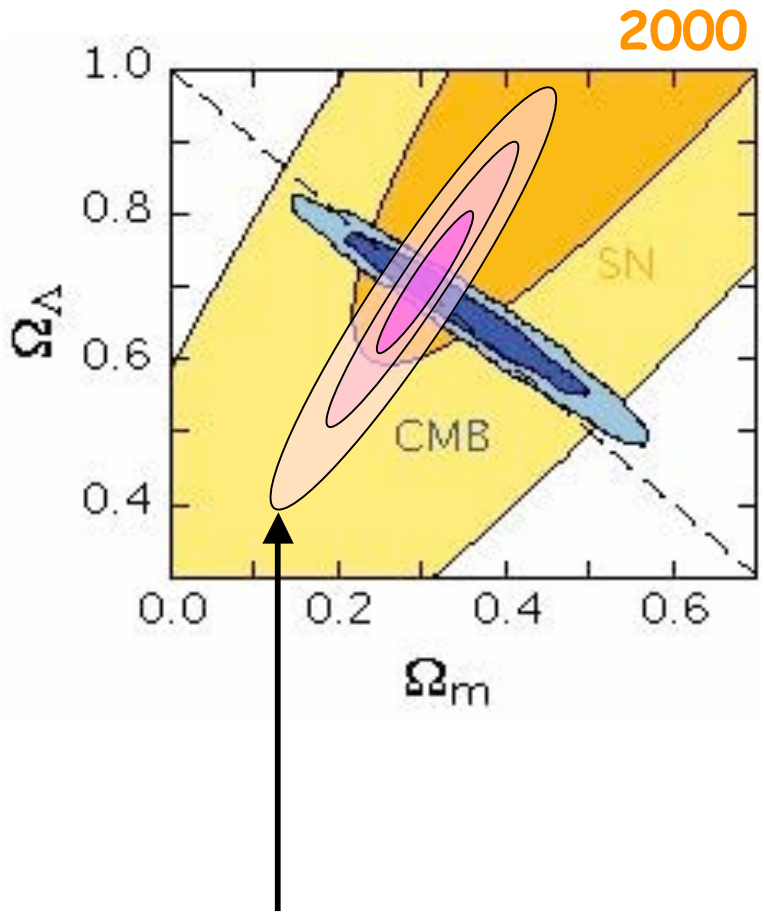
$q_0 = -\ddot{a}/(aH_0^2) = \Omega_M/2 - \Omega_\Lambda < 0$:
Accelerating Universe

If flat ($\Omega_{tot} = 1$) :

$\Omega_M = 0.28$

$\Omega_\Lambda = 0.72$

Concordance



Expected precision
with SNLS 2008

Beyond Ω_Λ...

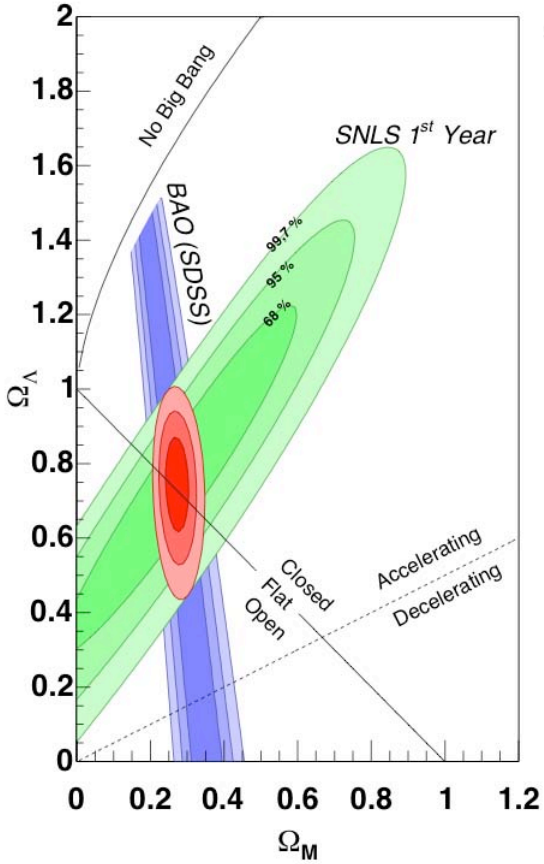
- ρ_v incompatible with a possible ρ_v from particle physics
  $\Omega_\Lambda = 0.7 \rightarrow \rho_v = \Omega_\Lambda \times \rho_c \sim 10^9$ eV m^{-3}
  ρ_v from quantum field theory : $\rho_v \sim M^4 / (hc)^3$
  $M = M_{pl} \rightarrow \rho_v \sim 10^{132}$ eV m^{-3} (would require $M \sim 10^{-3}$ eV)

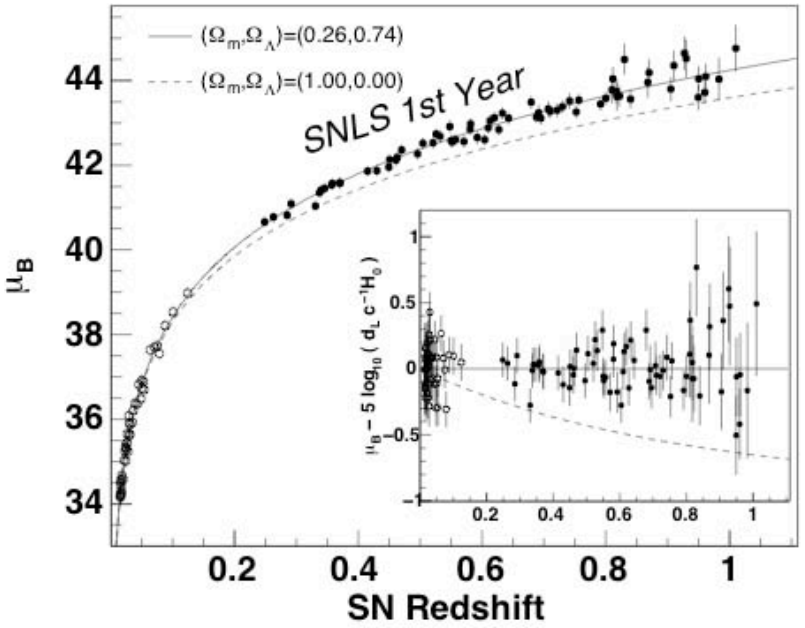
- Coïncidence problem
  $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ yet different evolution with time

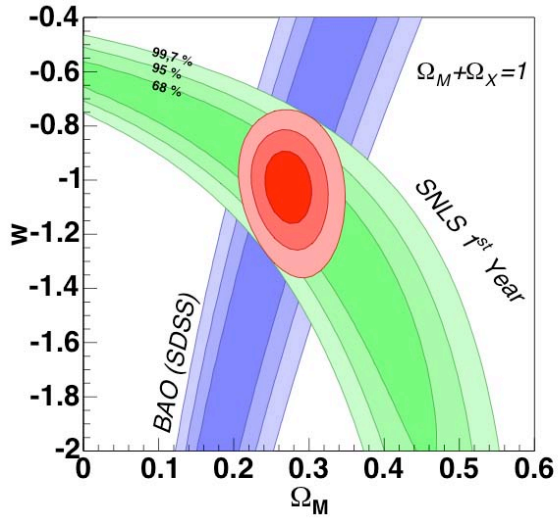
- quintessence ?

$p = w\rho$
- $w = 0$ for matter
- $w = 1/3$ for radiation
- $w = -1$ for cosmological constant
- $w > -1$ for "quintessence", dynamical dark energy

SNLS 2006







$\Omega_\Lambda = 0.7,\ \Omega_M = 0.3$

No evidence for $w \neq -1$
(and no serious theory)

Conclusions