Astroparticle Physics (2/3)

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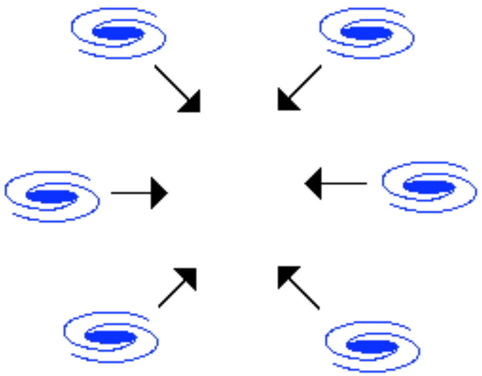
Dark matter in clusters

Zwicky, 1933



Mass of luminous matter

=

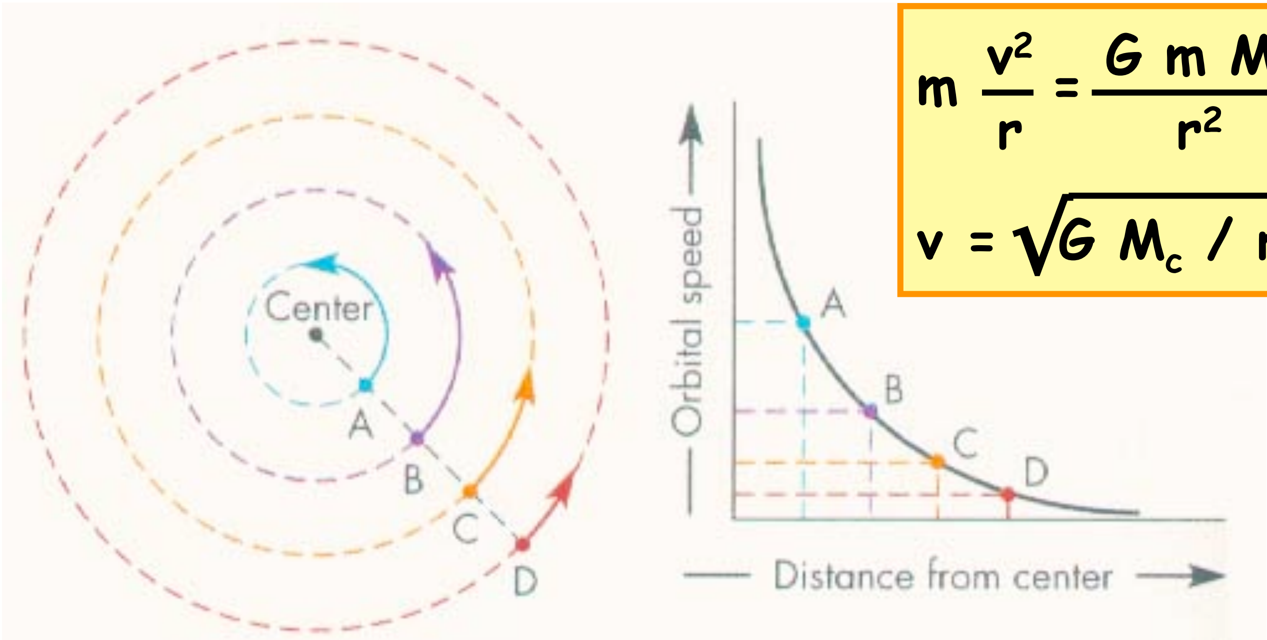
10%

Gravitational mass

Rotation curves (planets)

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

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

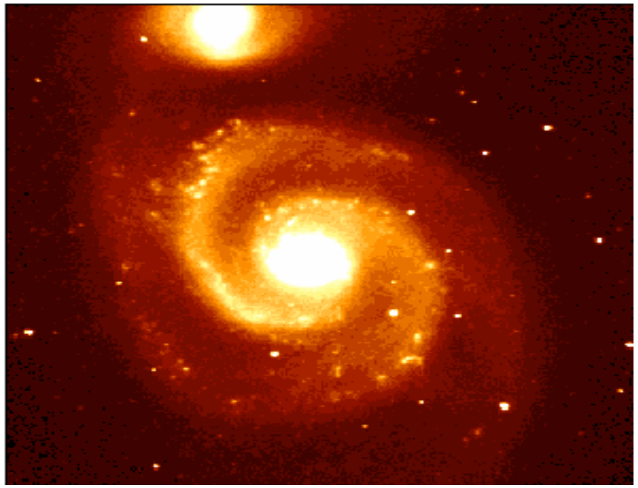


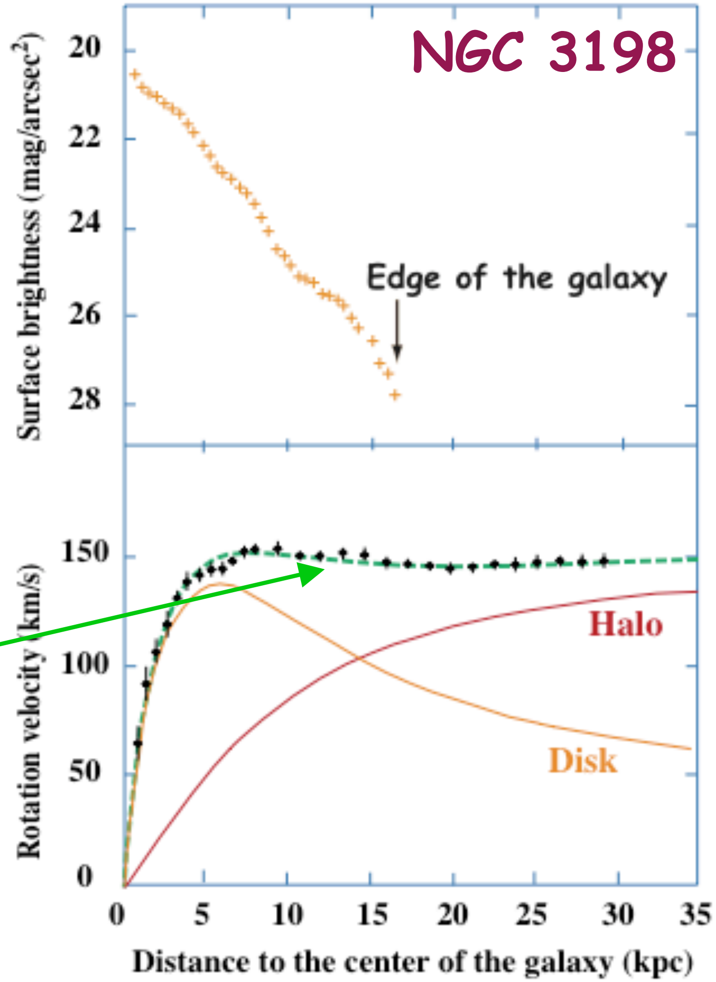
Rotation of planets

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 !

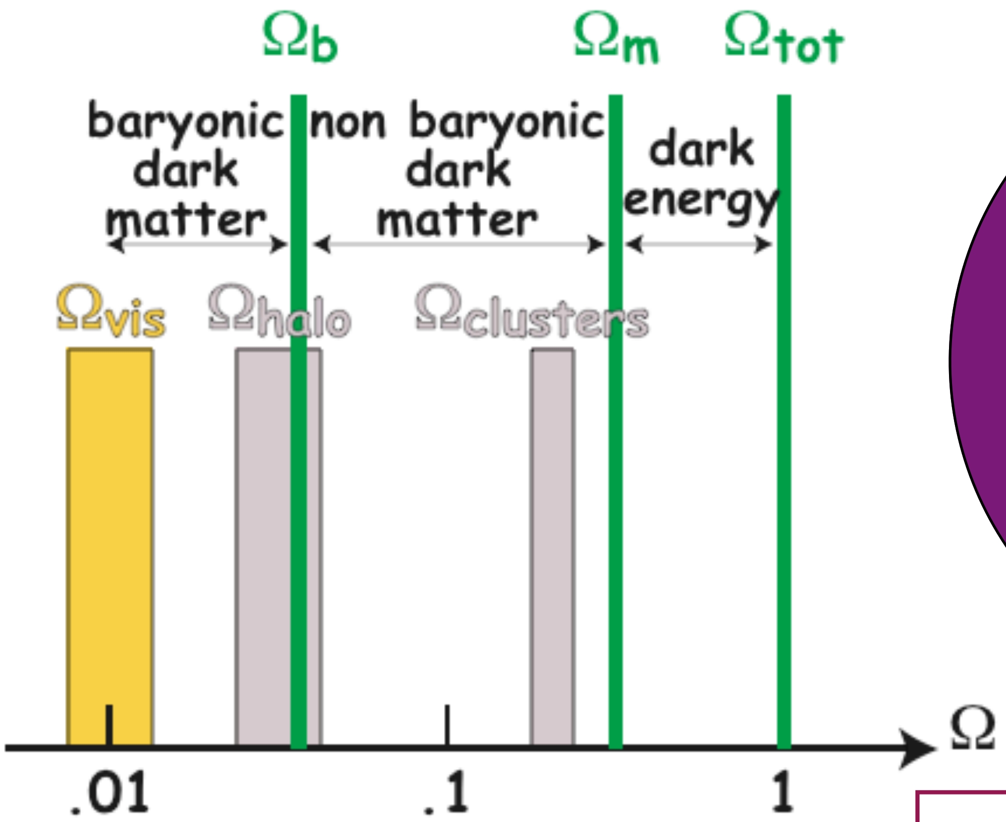
90% of gravitational mass is invisible (DARK HALOs)

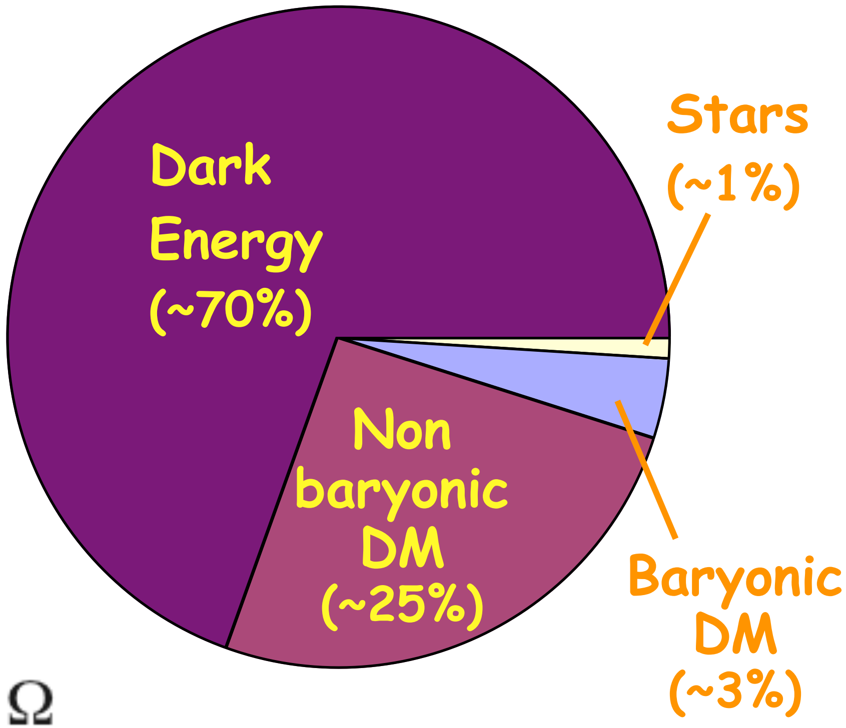
Gravitational lensing

HST

⇒ **Luminous mass ~ 1% Gravitational mass**

Summary of evidence





$\Omega = \rho / \rho_c$

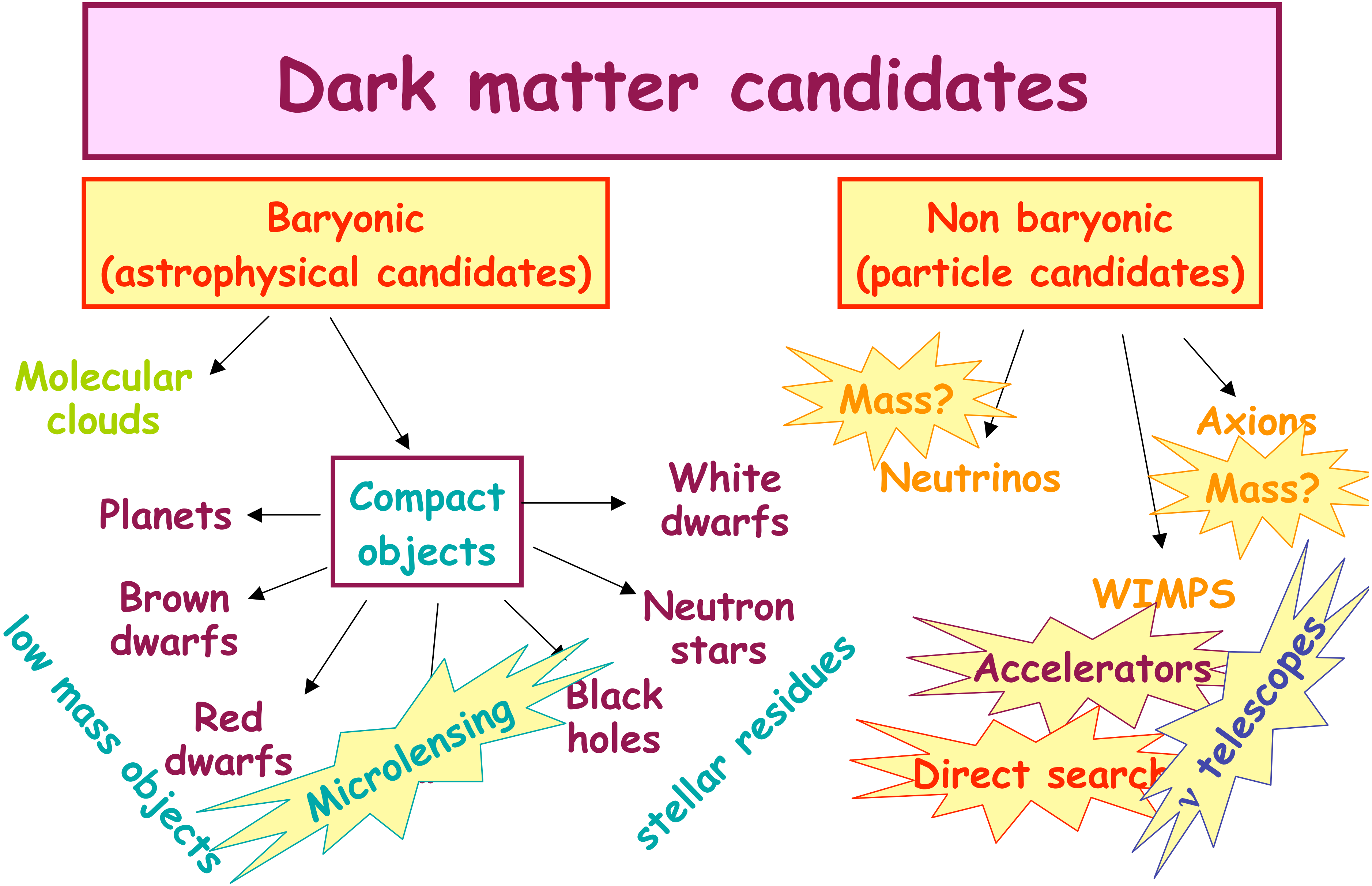
$\Omega = 1$ for $k = 0$

Lecture outline

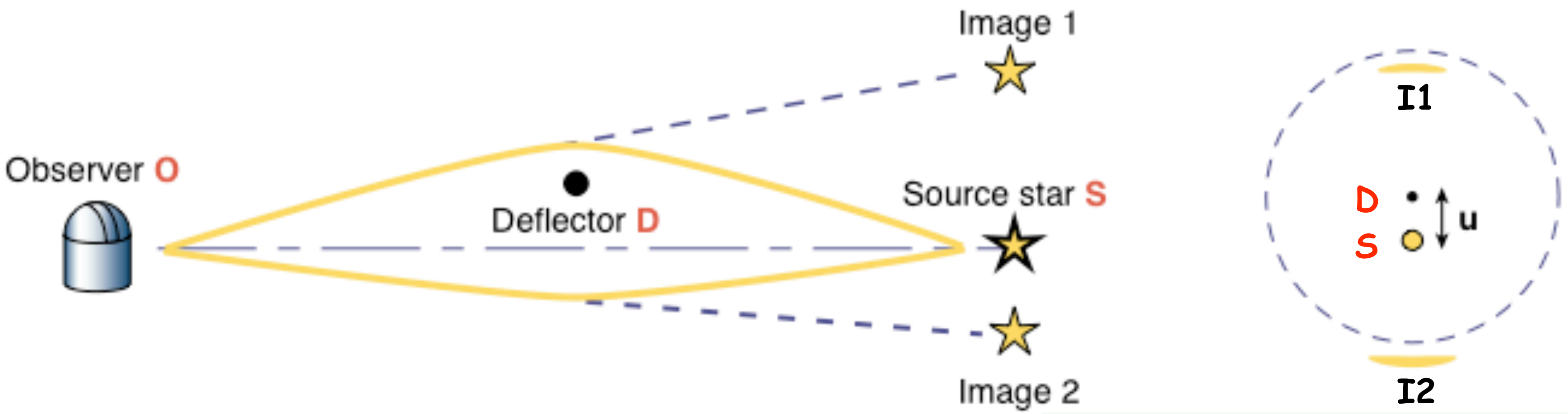
1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

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
Baryonic
(astrophysical candidates)
Non baryonic
(particle candidates)
Molecular
clouds
Compact
objects
Planets
Brown
dwarfs
Red
dwarfs
White
dwarfs
Neutron
stars
Black
holes
low mass objects
stellar residues
Microlensing
Mass?
Neutrinos
Axions
Mass?
WIMPS
Accelerators
Direct search
ν telescopes

Principles of microlensing

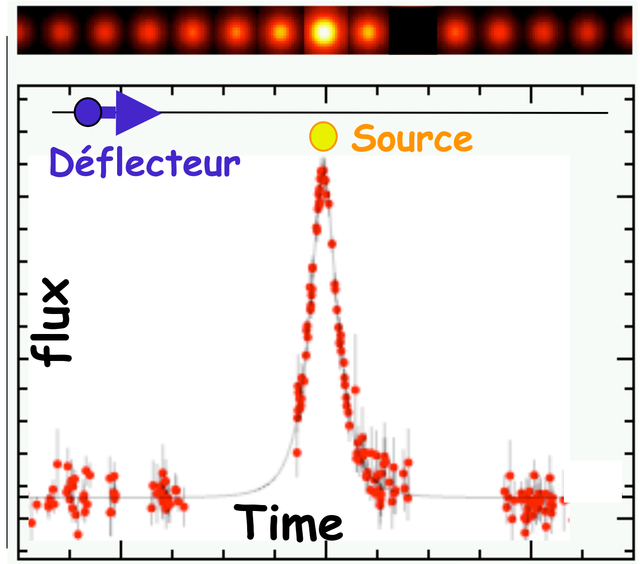


Angular separation of images ~ 10^{-3} rad

⇒ Only 1 (combined) image, amplified

Motion of deflector (220 km/s)

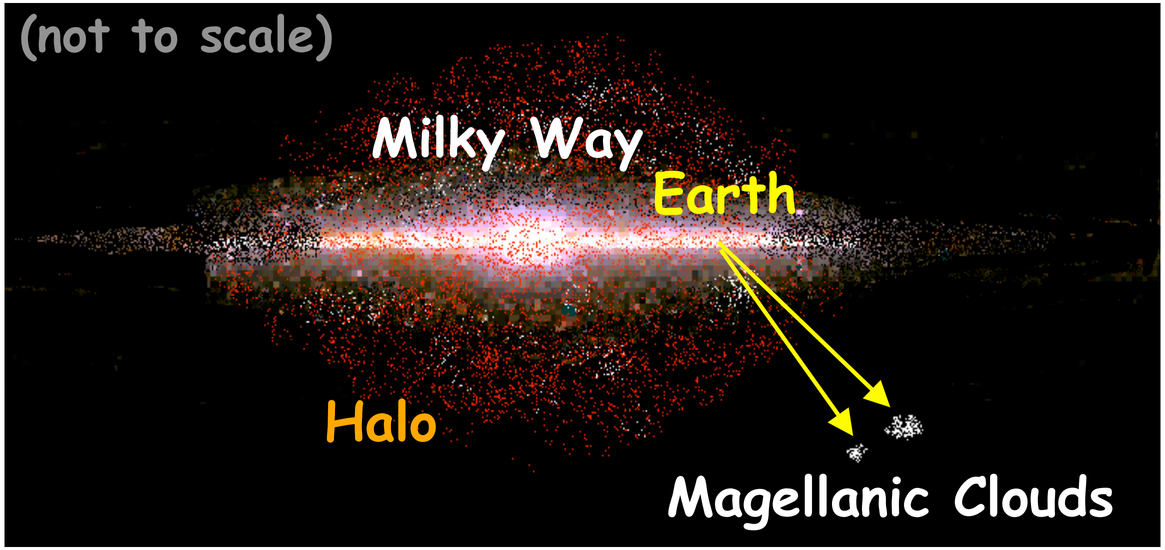
⇒ Duration $t_E \sim 70 \sqrt{M/M_{sun}}$ days

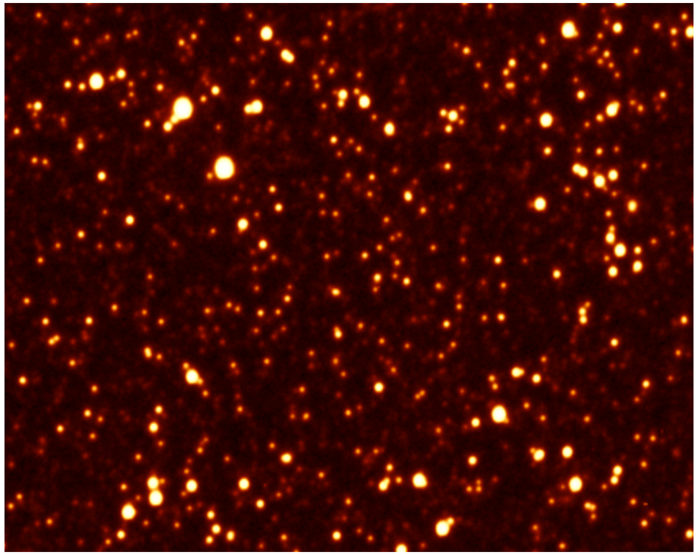


Targets (EROS, MACHO)

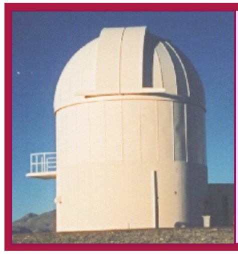
Event rate : ~ 1 per year per 20 million stars monitored

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



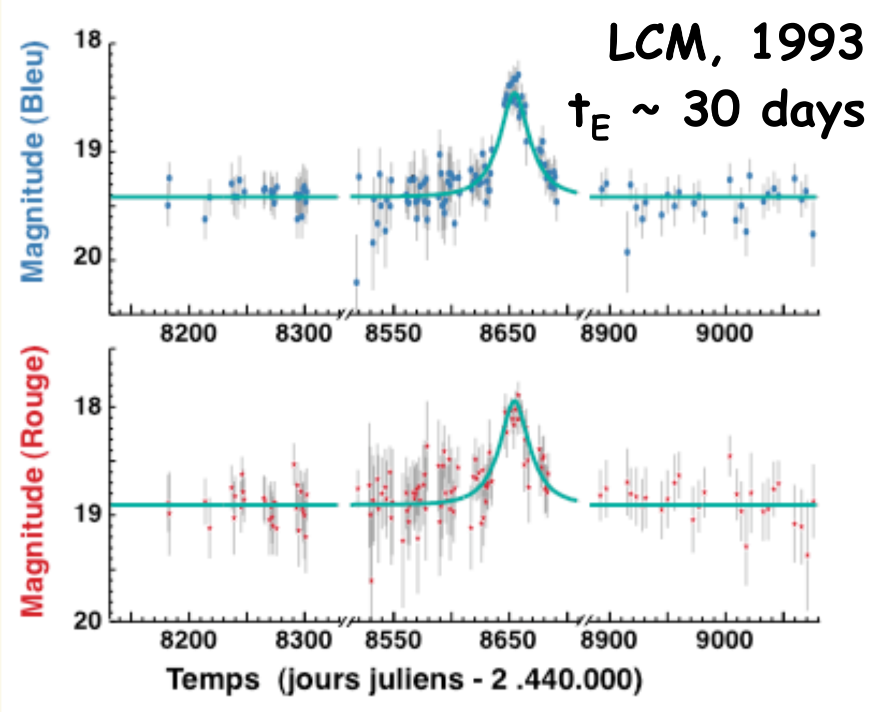


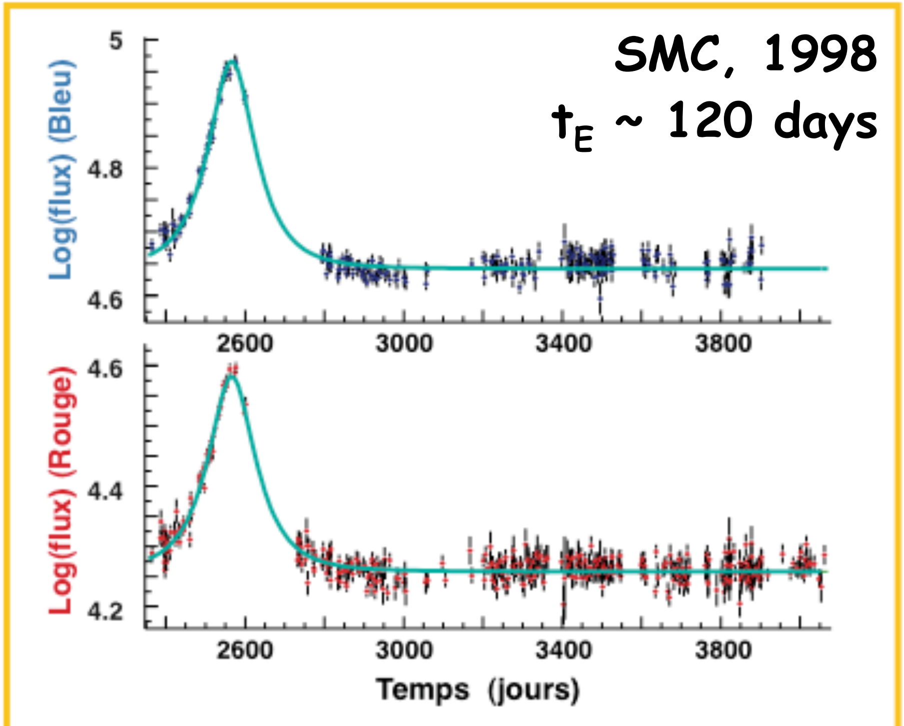
~30 million stars monitored:
- >10 000 variable stars
- >100 SN
- Microlensing events ?

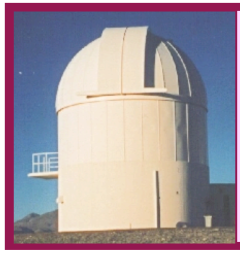


Initial results

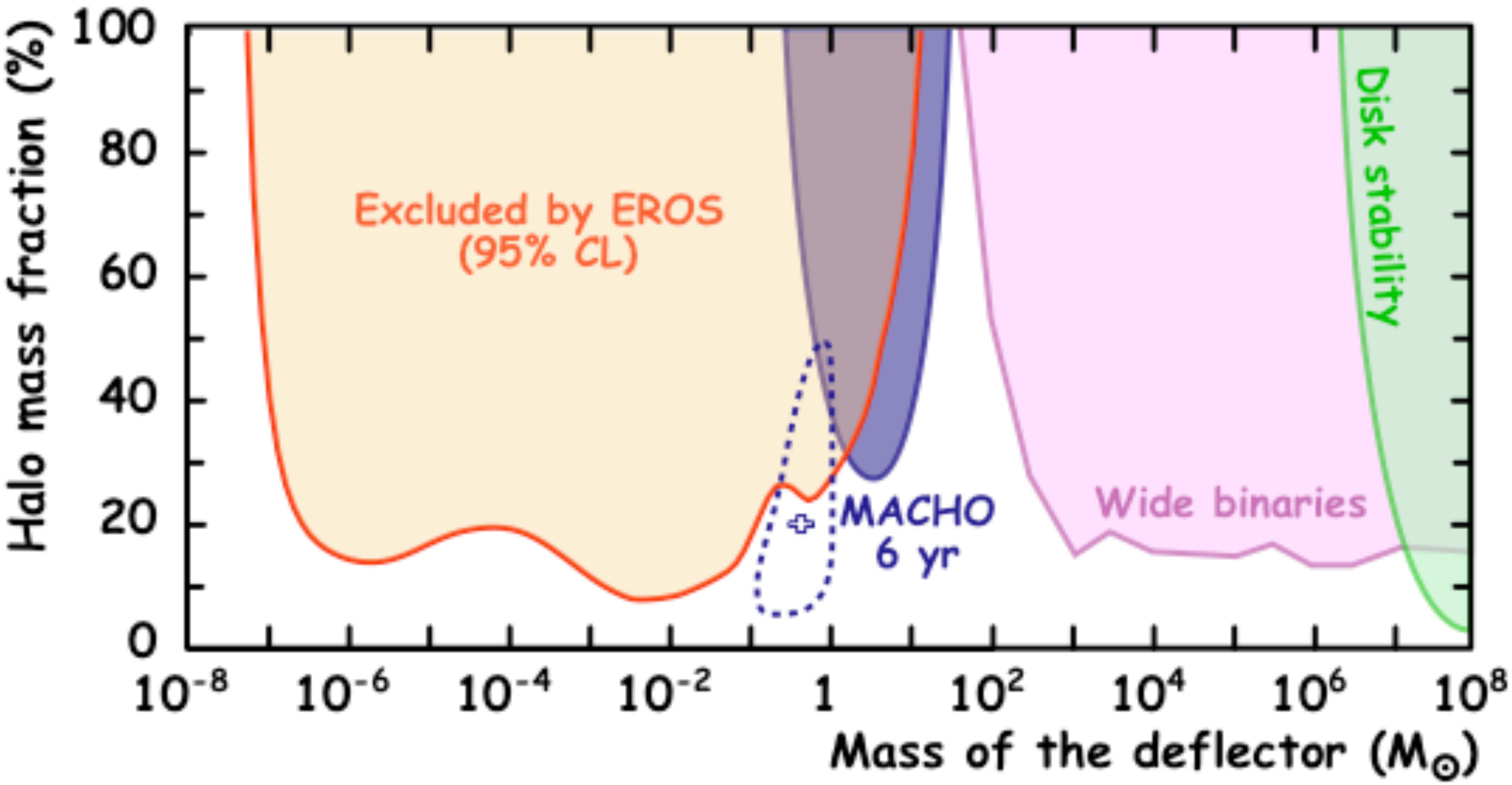
Candidates (microlensing technique validated), t_E ~ 30 days
Over half of the dark halo in the form of
dark objects of ~ 0.3 solar mass !



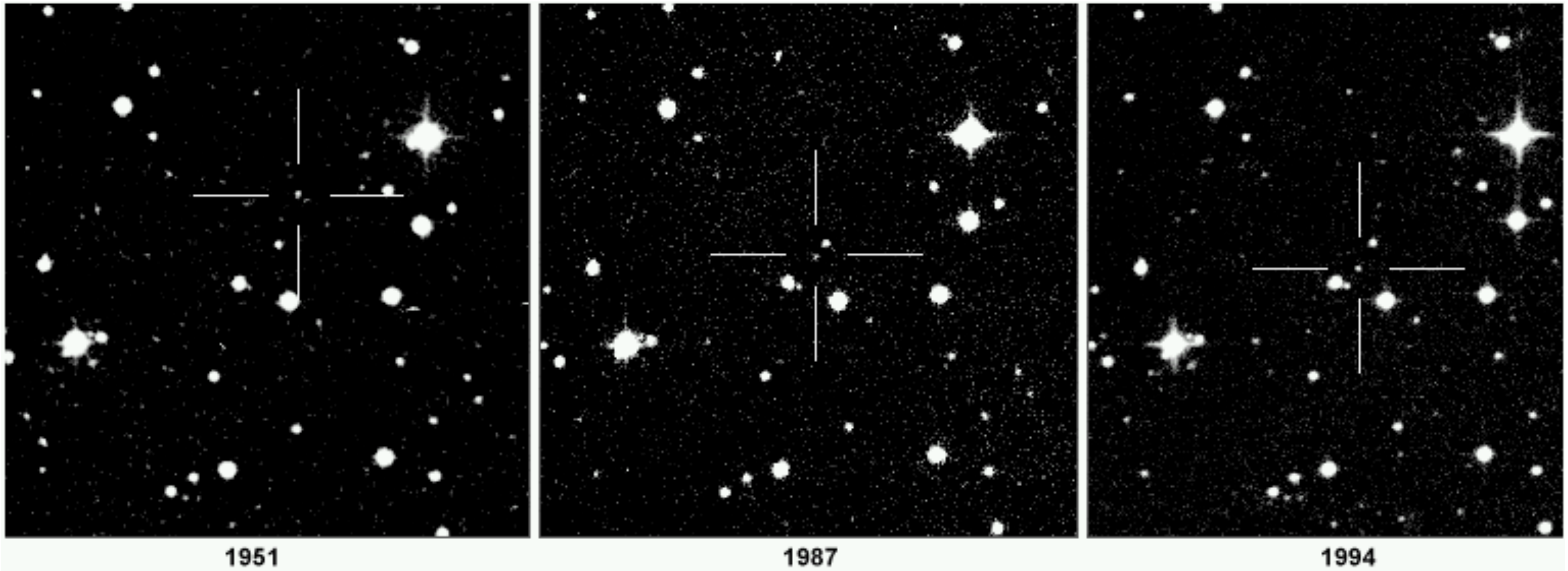




Final results



White dwarfs



White dwarf = final state of low mass star

38 white dwarfs found in old plates

- moving fast ⇒ belongs to halo (vs. disk)
- old (i.e. cold) ⇒ 1st population of stars in our Galaxy

White dwarfs (~1 M_{sun}) may compose 3 to 35% of the halo

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

…

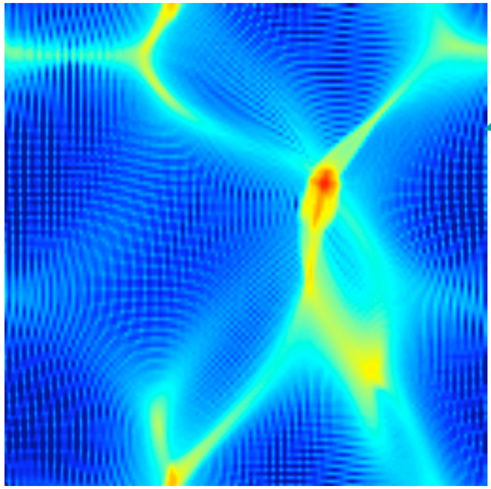
Non baryonic DM

> 80% of DM is non baryonic

- Hot DM ?
  - ν
- Cold DM ?
  - Axions
  - WIMPS

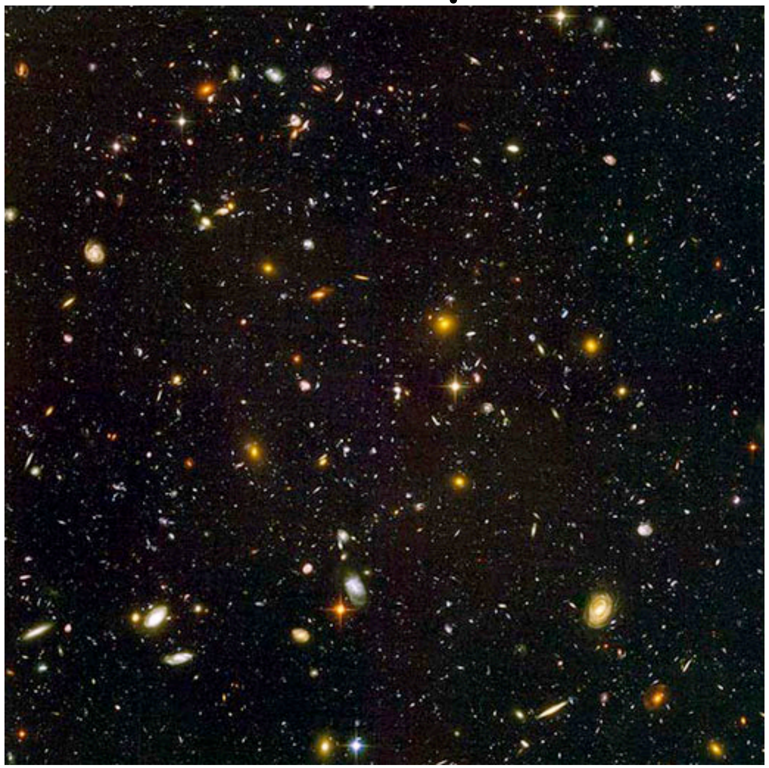
Structure formation

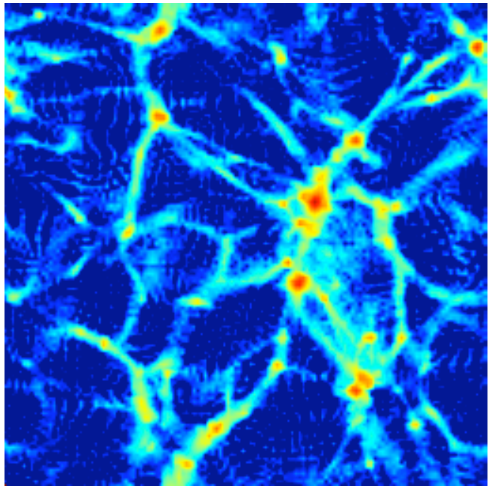
Simulations of
DM density maps



HDM wipes out
structure on
small scales

Hubble Deep Field



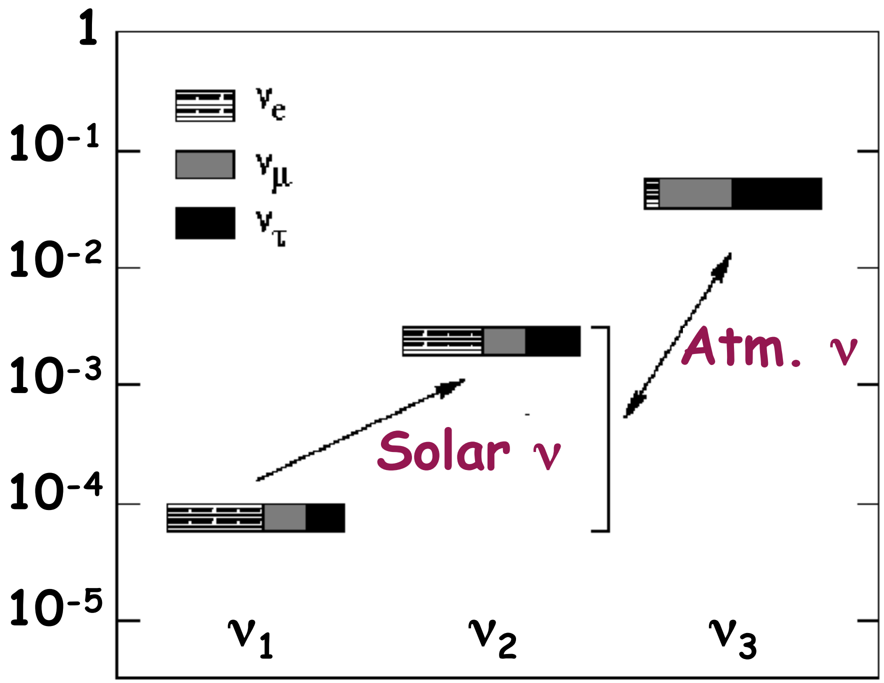


CDM creates
too many
sub-structures?

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)

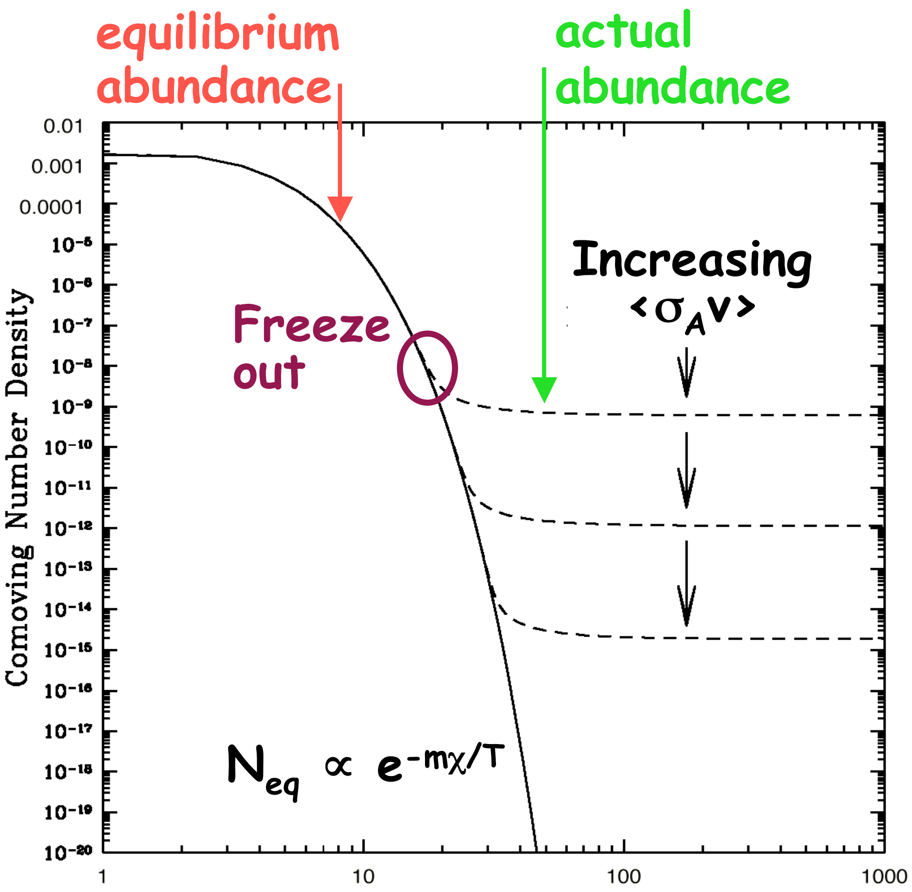


ν contribution to matter density: $\Omega_\nu \sim m_\nu n_\nu / \rho_c$

$m \sim 0.05$ eV $\Rightarrow \Omega_\nu \sim 0.003$

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_χ ~ 50 GeV (accelerator)
- annihilate through $\chi\bar{\chi} \leftrightarrow X\bar{X}$
- relic density Ω_χ ~ 0.3 for typical weak annihilation rates



$X = m_\chi/T$ (time→)

Direct detection of WIMPS

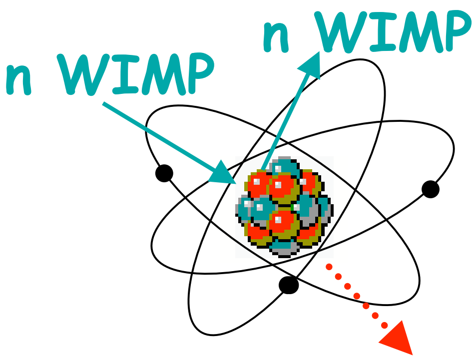
If halo DM made of WIMPS

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

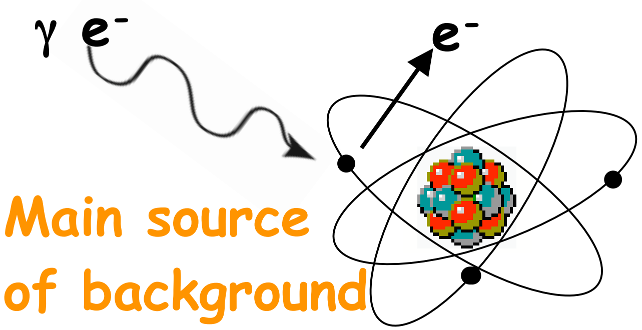
⇒ > 10 000 WIMPs/cm^2/s on Earth (from $-\vec{v}_{sun}$)

Experimental signature :

nuclear recoil



(vs. electronic "recoil")



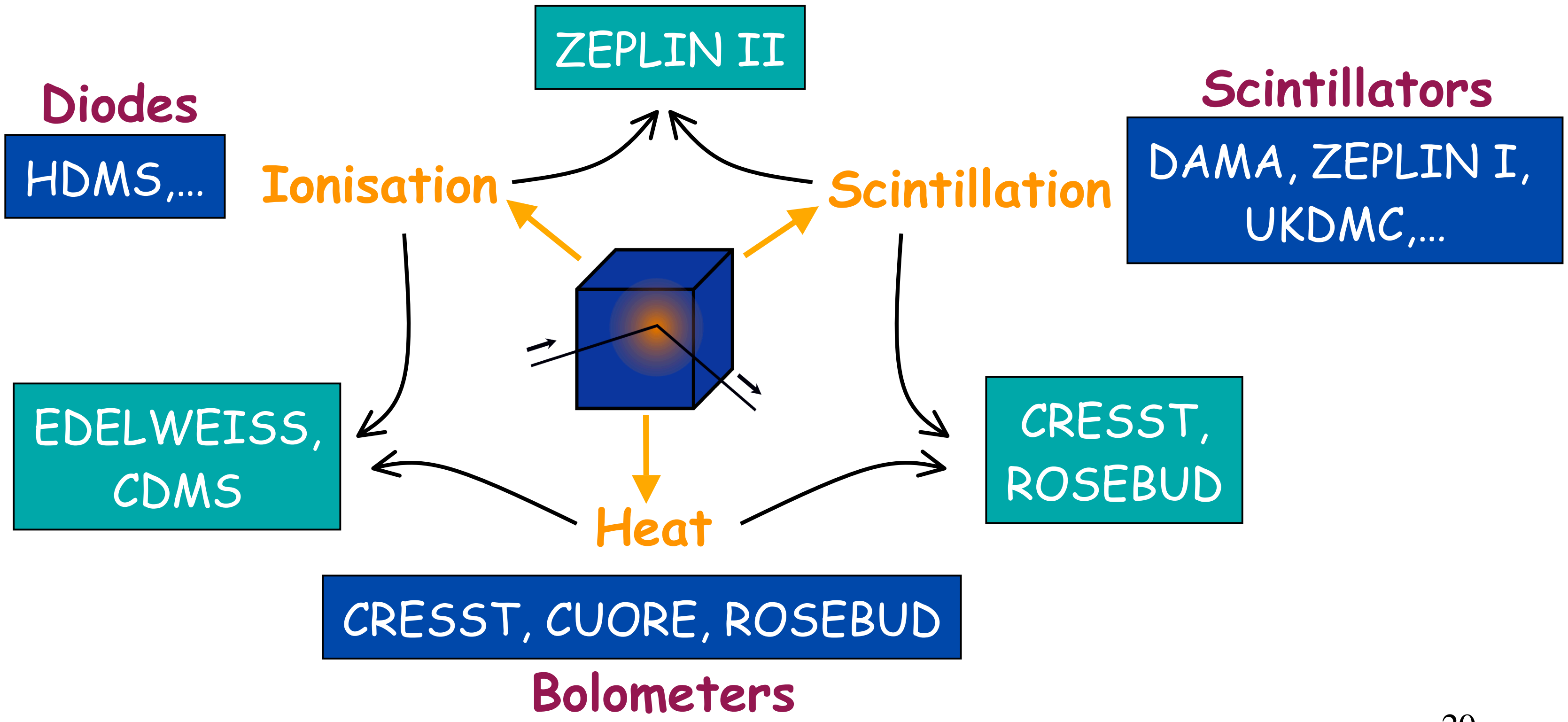
Main source of background (radioactivity)

Requirement : High mass detectors

Low radioactive background (discrimination)

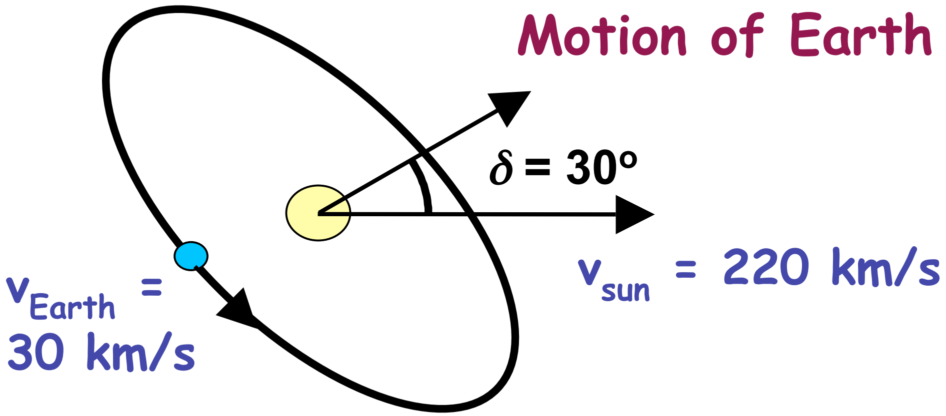
Background rejection

- Deep underground
- Event by event discrimination of nuclear vs. electronic recoil



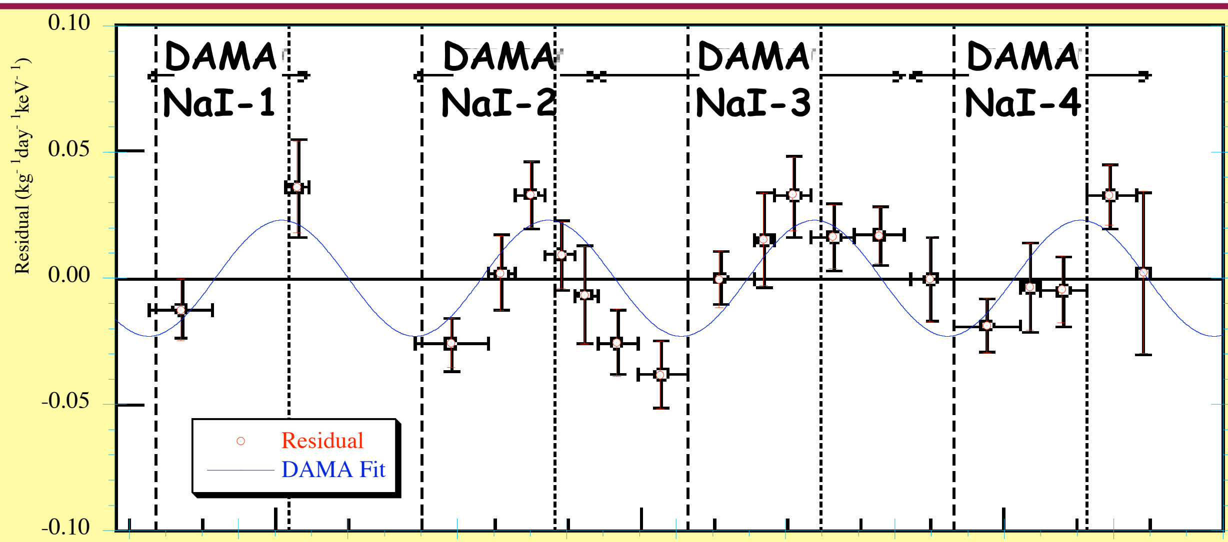
Annual modulation

Motion of Earth in the χ wind



Modulation of annual rate ± 7%
Max in June

Seen by DAMA?

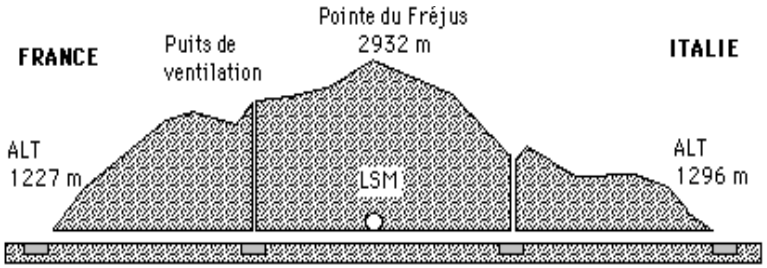


m_{χ} ~ 44-62 GeV

BUT
1 signature only
Not confirmed independantly

Edelweiss: detector

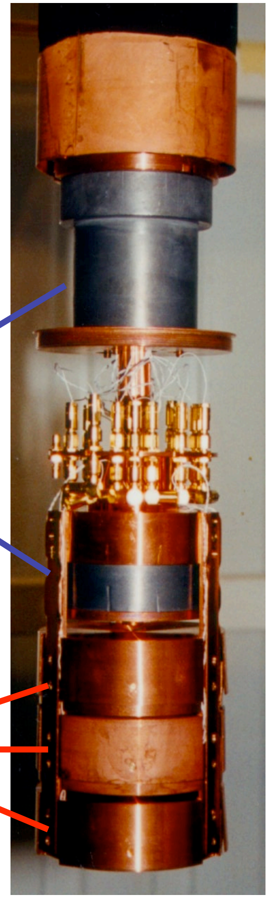
In Modane underground laboratory



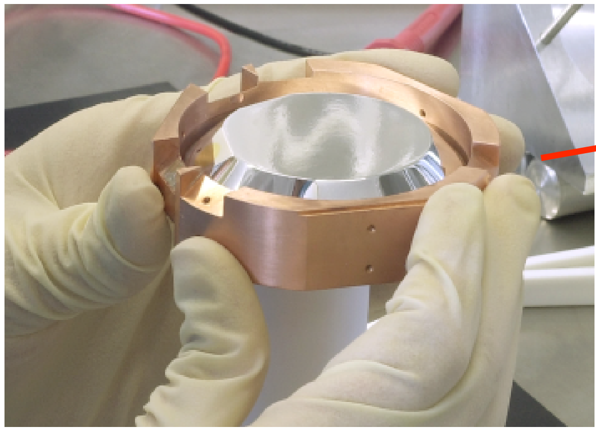
Negligible neutron background
(~ 0,01 evt/kg/day)

Dilution cryostat
low background
(temperature ~15mK)

Archeological lead shielding



Detectors
3 x 320g
bolometers

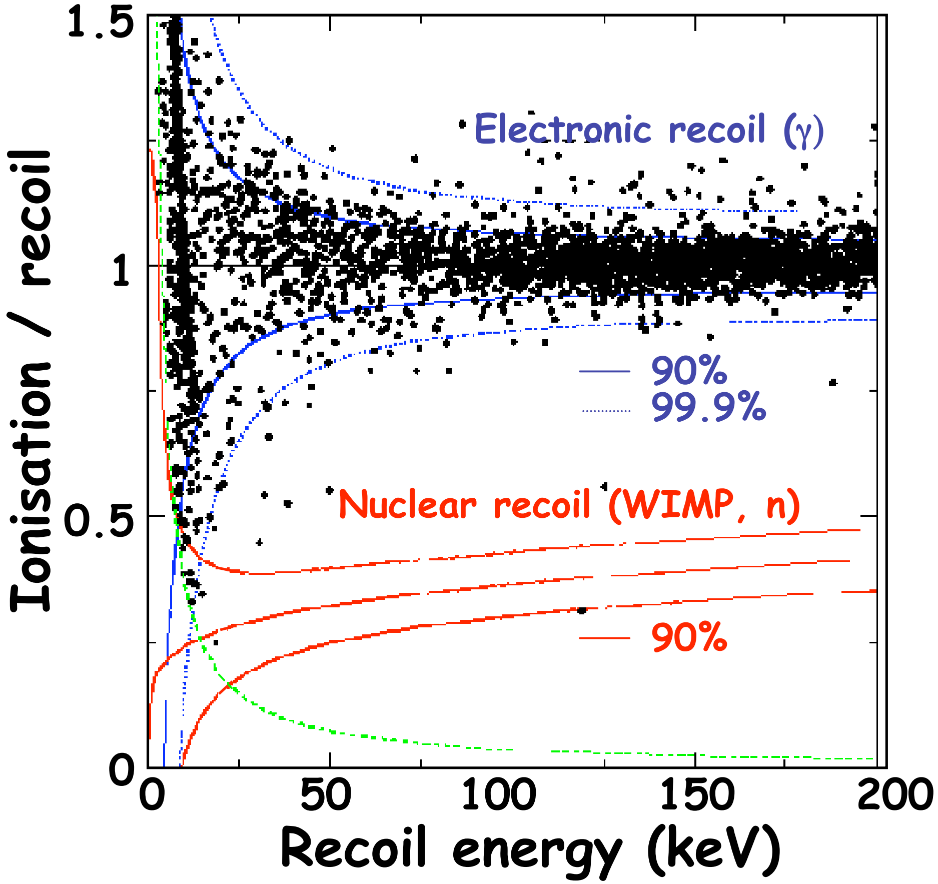


Edelweiss: analysis

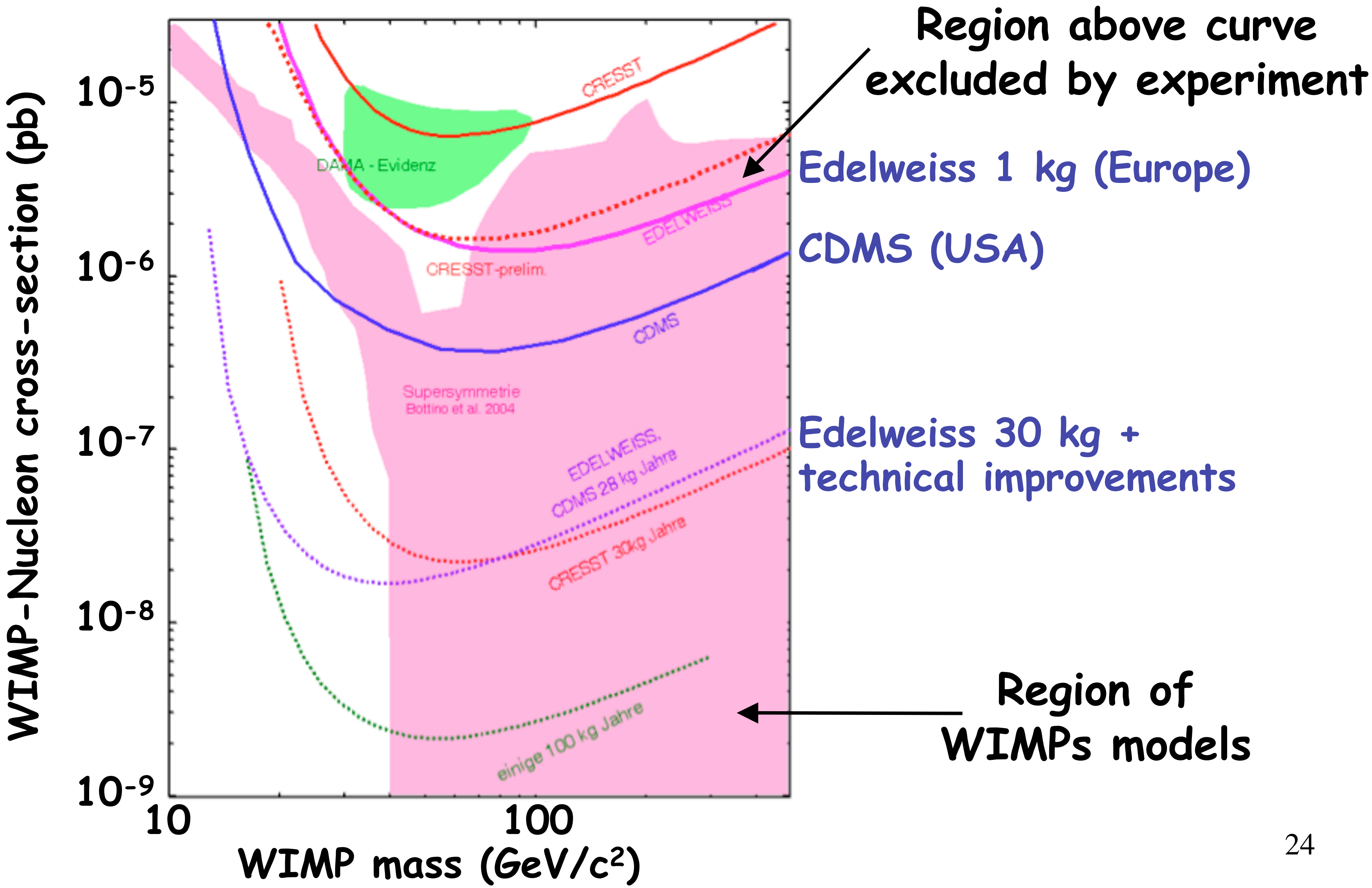
Heat + Ionisation

Background free analysis

No event in signal region



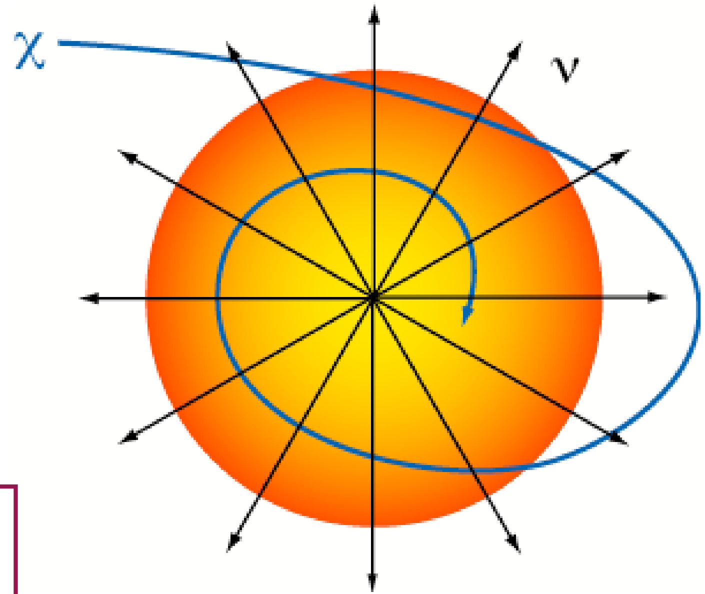
Conclusions on direct detection



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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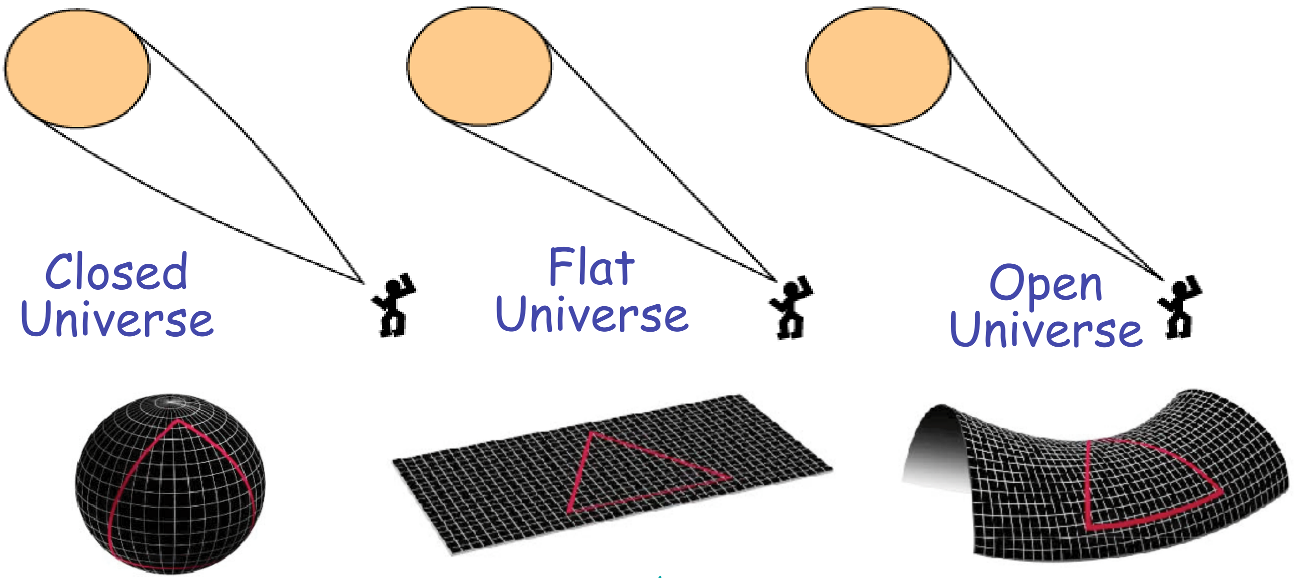
3) High energy astrophysics

Measurement of the geometry

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

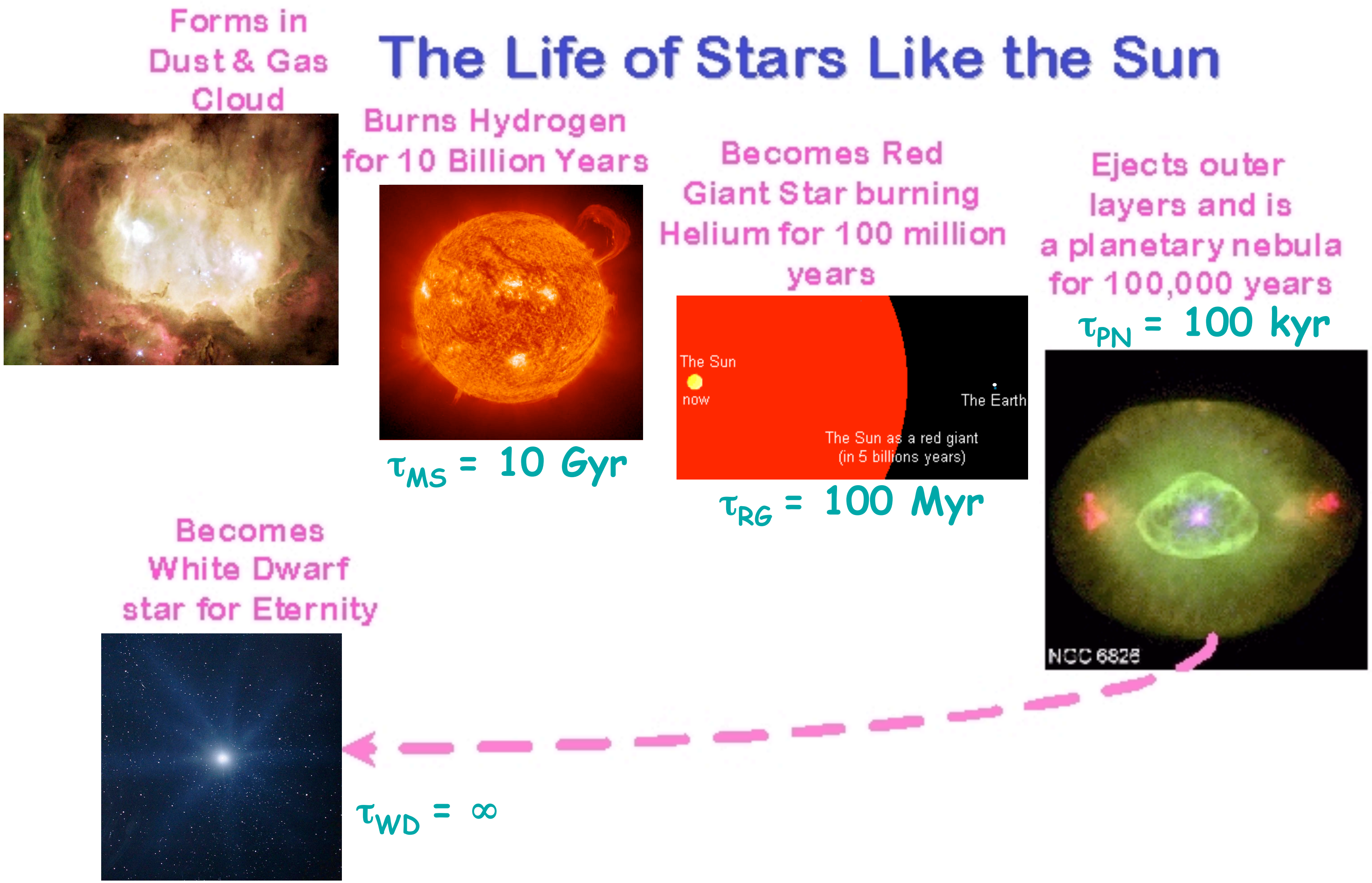


AT A GIVEN DISTANCE

Known physical size → (CMB) → angle depends on geometry

Known luminosity → (SN Ia) → flux depends on geometry

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



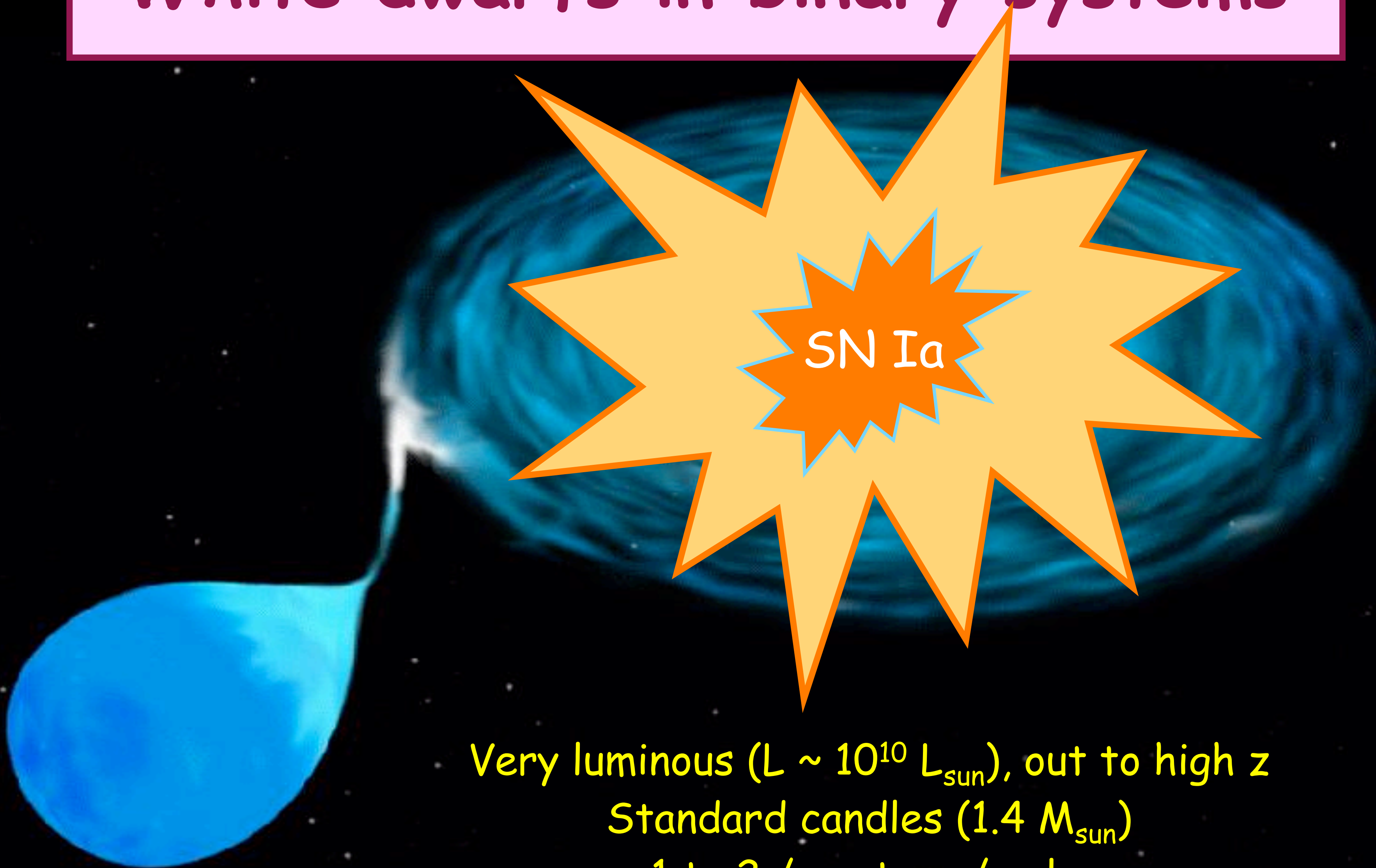
τ_{MS} = 10 Gyr

τ_{RG} = 100 Myr

τ_{PN} = 100 kyr

$\tau_{WD} = \infty$

White dwarfs in binary systems

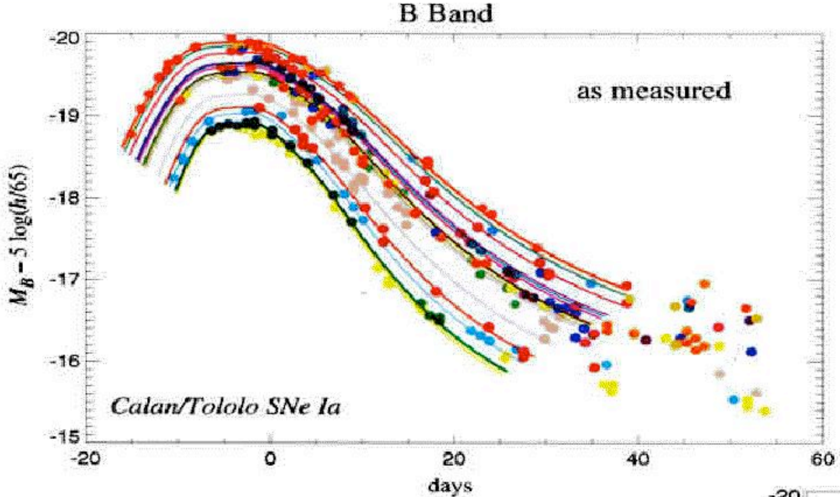


Very luminous ($L \sim 10^{10}\ L_{sun}$), out to high z

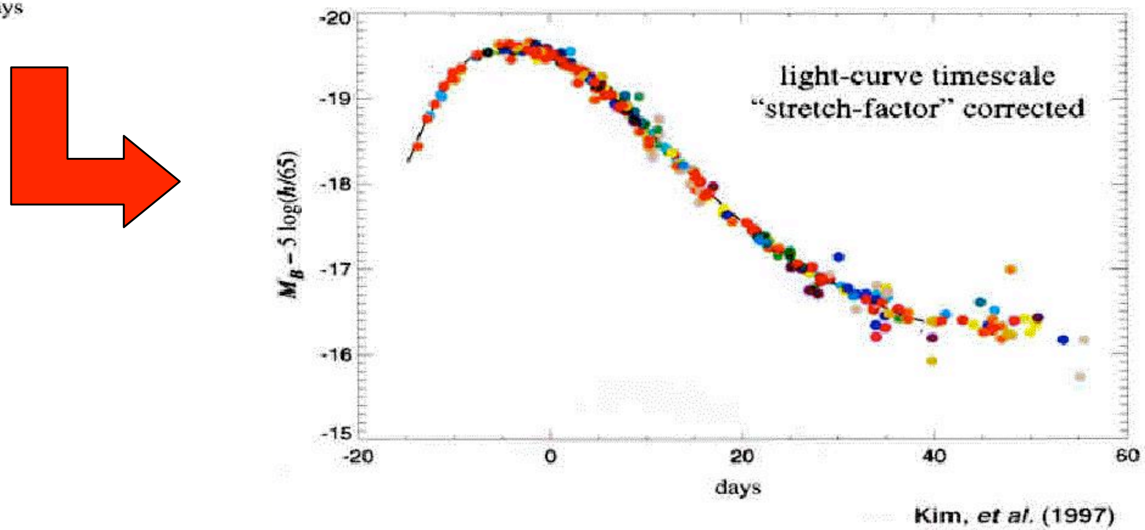
Standard candles ($1.4\ M_{sun}$)

~ 1 to 2 / century / galaxy

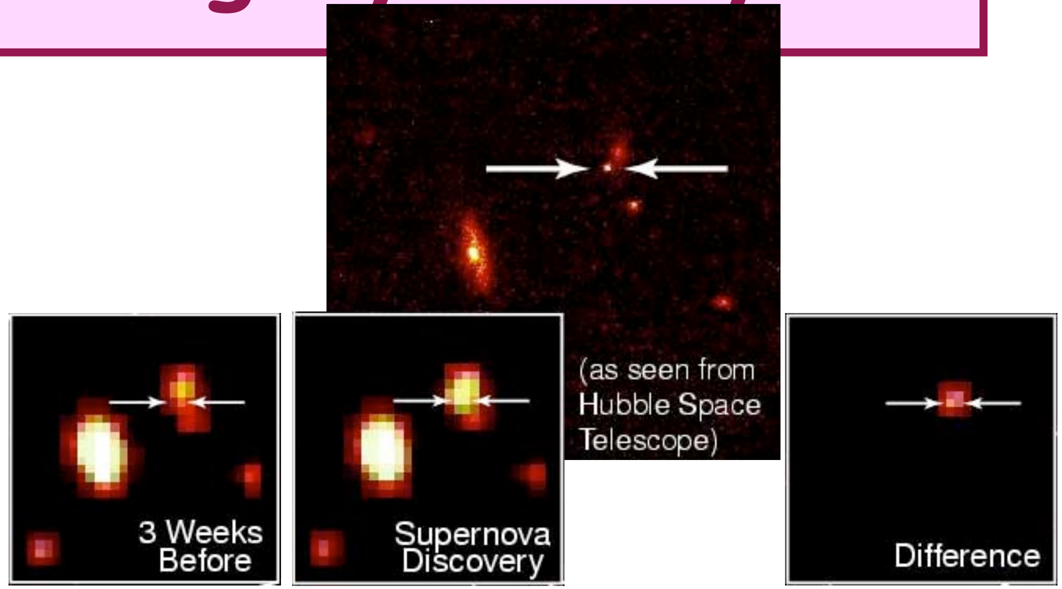
Light curves



Unique parameter
(strech factor)

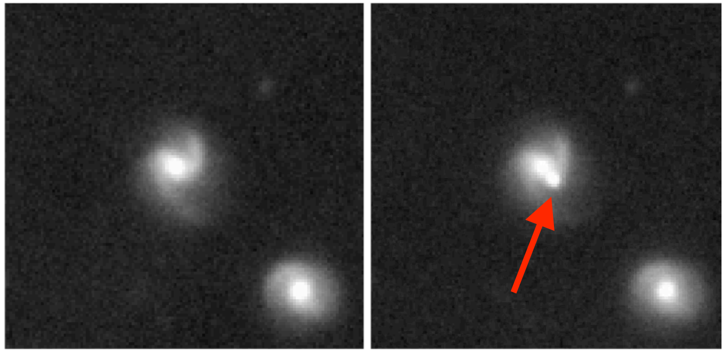


SuperNova Legacy Survey



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′

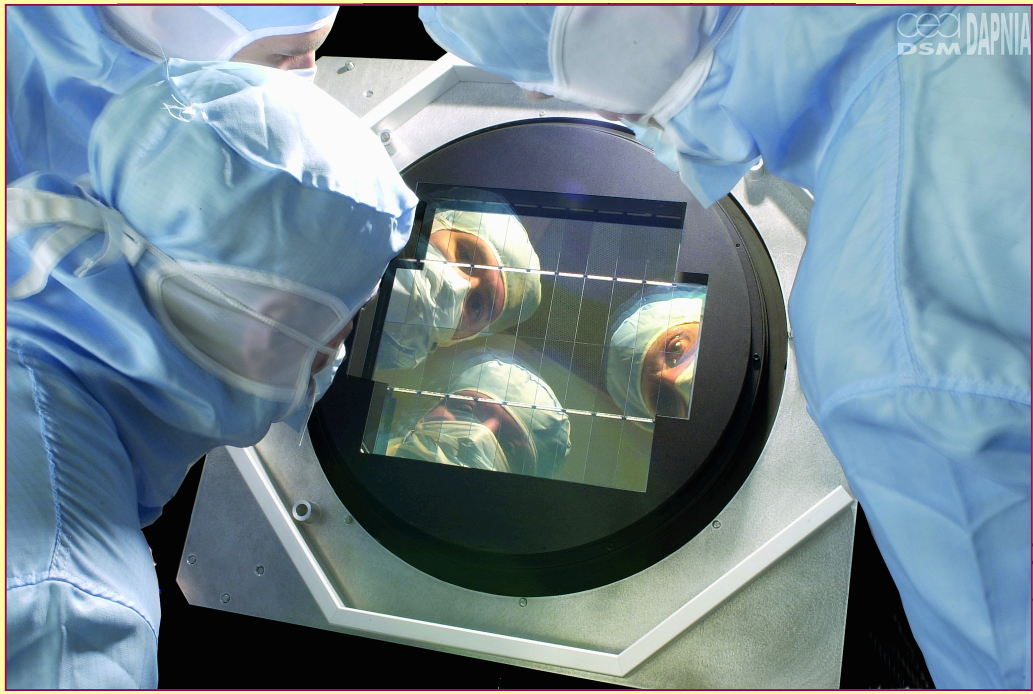
RCA2 1986-1995
1 CCD, 640 x 1024
champ 2′ x 3.5′

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′

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



2K 1999
, 12K x 8K
42′ x 28′

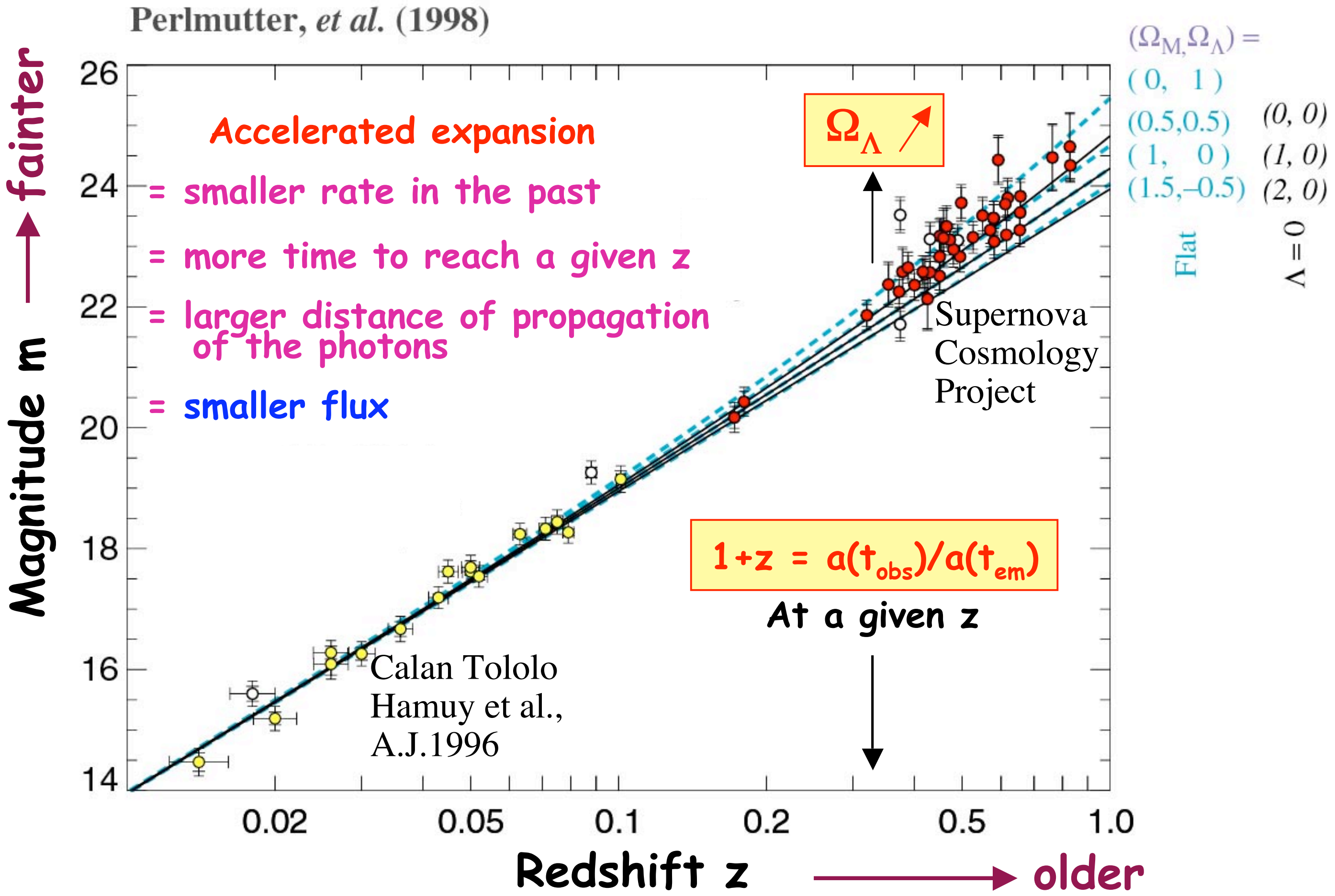
MegaCam 2002
40 CCDs, 20K x 18K
champ 1° x 1°

Hubble diagram

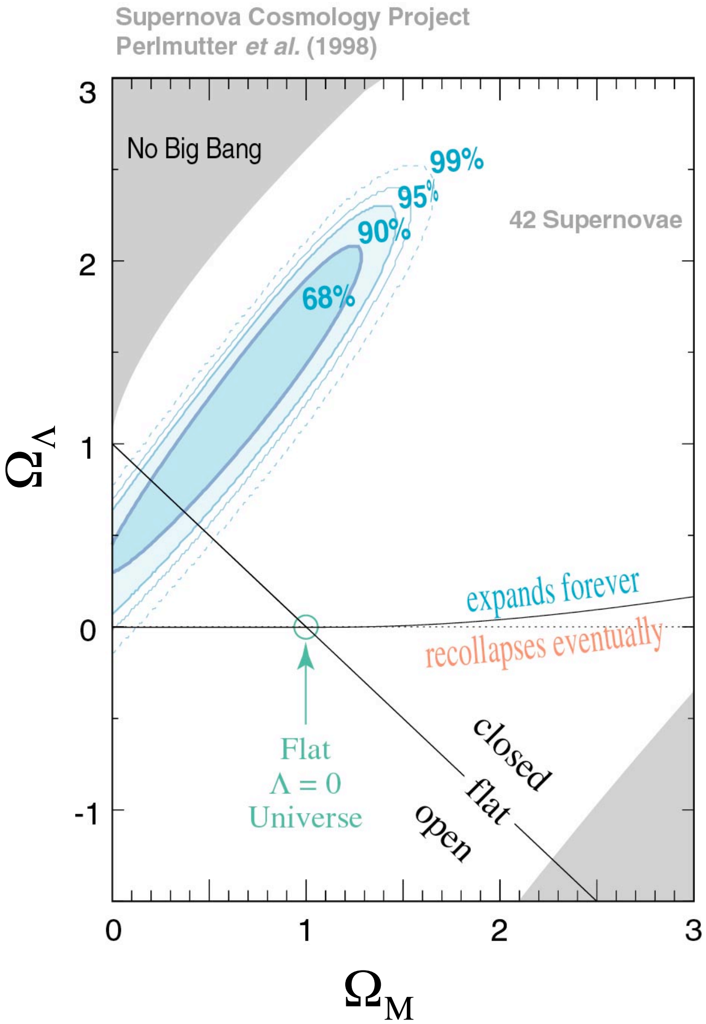
$$m = -2.5 \log F + cst = 5 \log (H_0 D_L) + M - 5 \log H_0 + 25$$

$H_0 \longrightarrow cz/D_L$, $z \longrightarrow 0$ ⇨ mesure of H_0

Large z : mesure of Ω_m, Ω_Λ



Initial constraints (1998)



42 supernovae

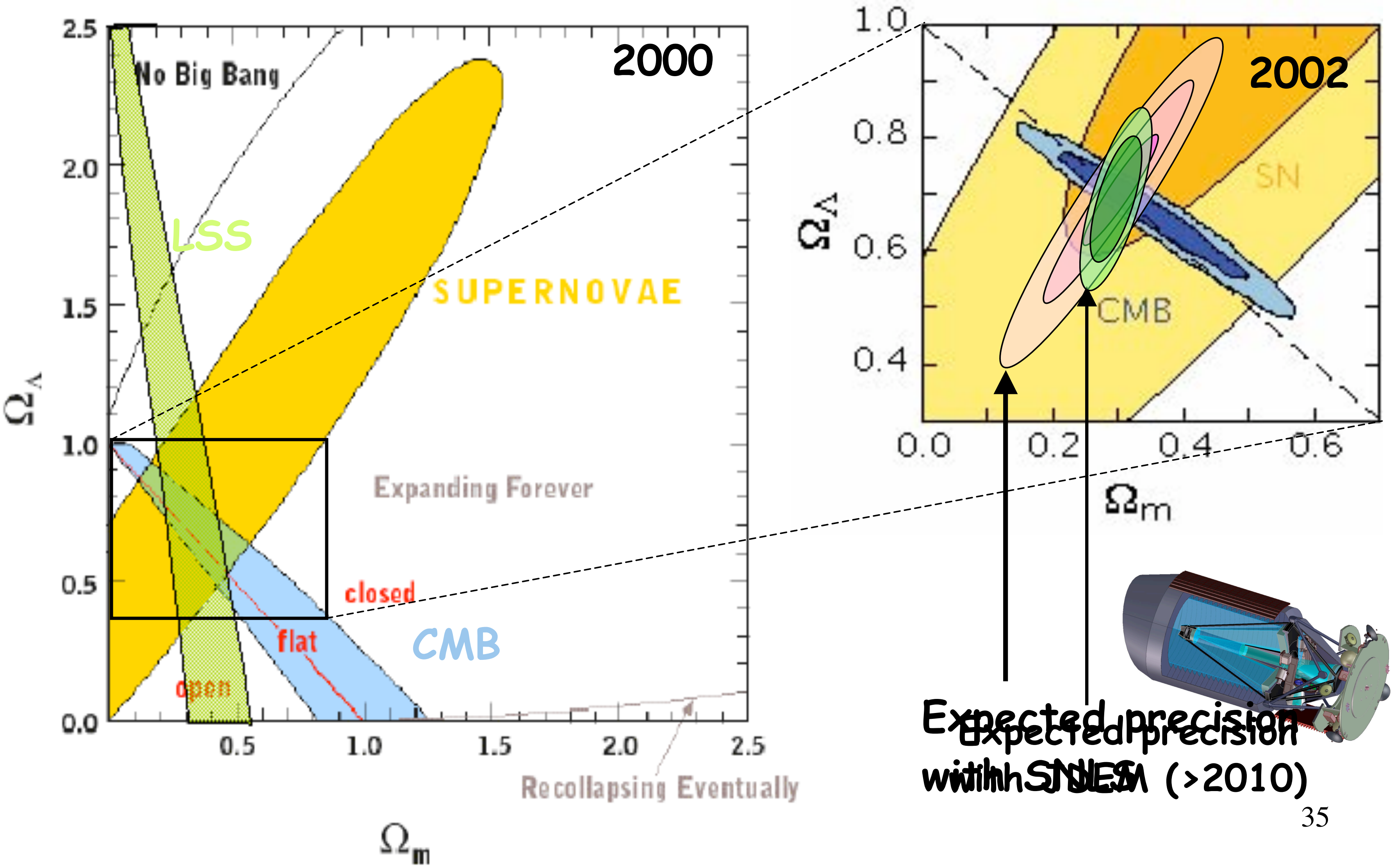
$q_0 = -\ddot{a}/(aH_0^2) = \Omega_M/2 - \Omega_\Lambda < 0$:
Accelerating Universe

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

$\Omega_M = 0.28$

$\Omega_\Lambda = 0.72$

Concordance



Going 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 ?

$$p = w\rho \quad \begin{cases} w = 0 \text{ for matter} \\ w = 1/3 \text{ for radiation} \\ w = -1 \text{ for cosmological constant} \\ w > -1 \text{ for ``quintessence'', dynamical dark energy} \end{cases}$$

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

Conclusions