Cosmology and gravitation: the grand scheme for high energy physics
Part 3

Pierre Binétruy, APC, Paris

ESHEP, 2012

Plan

A (not so) brief history of cosmology

The days where cosmology became a quantitative science:

Cosmic Microwave Background

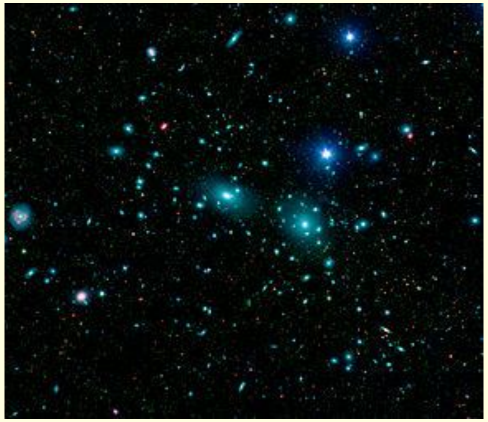
Light does not say it all (1): the violent Universe

Light does not say it all (2): dark matter

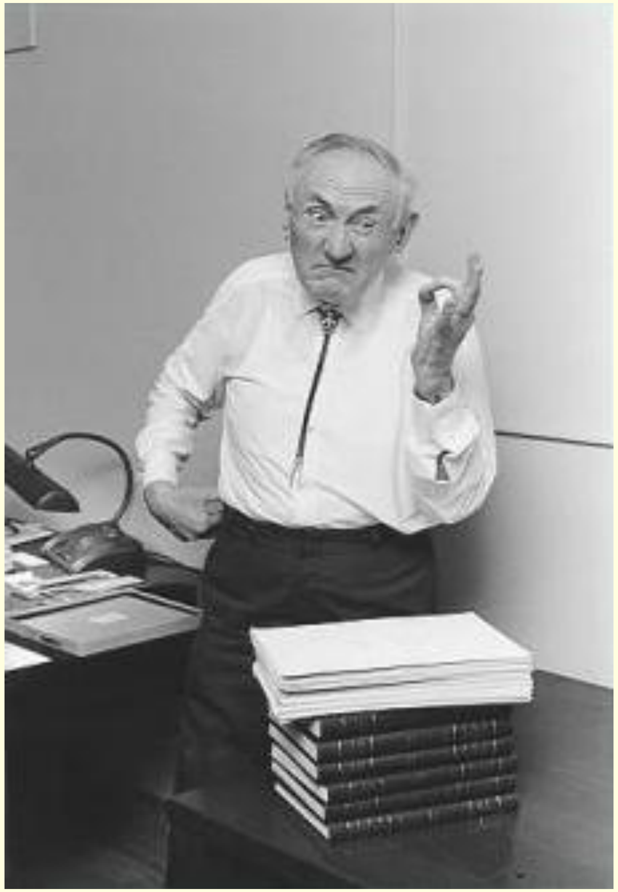
Light does not say it all (3) : dark energy

The beginning and the end

Light does not say it all (2): dark matter



Coma cluster



Fritz Zwicky

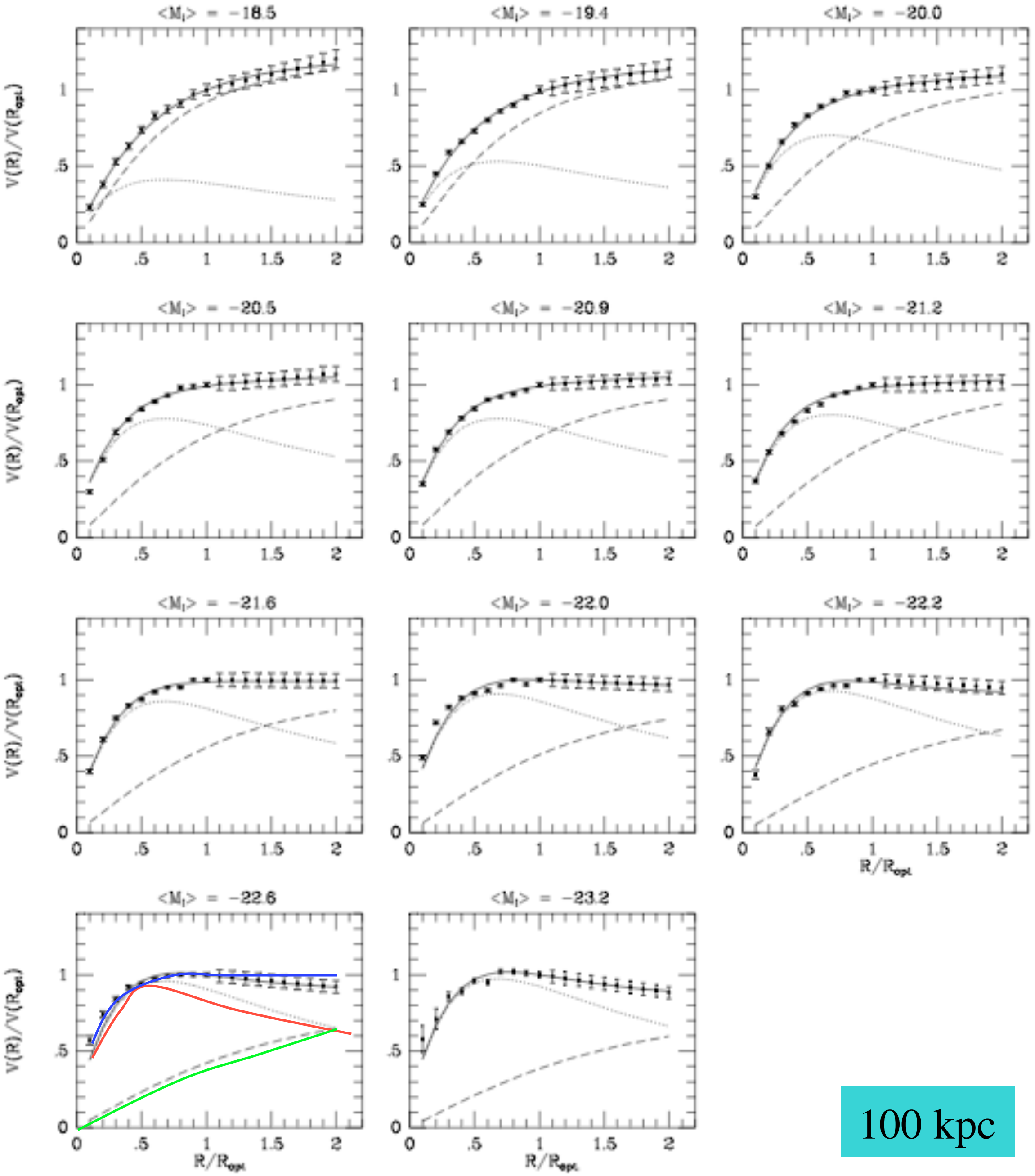
Studying the velocity distribution of Galaxies in the Coma cluster and using the virial theorem

$$2\langle E_{kin}\rangle = -\langle E_{pot}\rangle$$

time averaged

F. Zwicky shows in 1933 that there is 400 times more mass than expected from the luminosity.

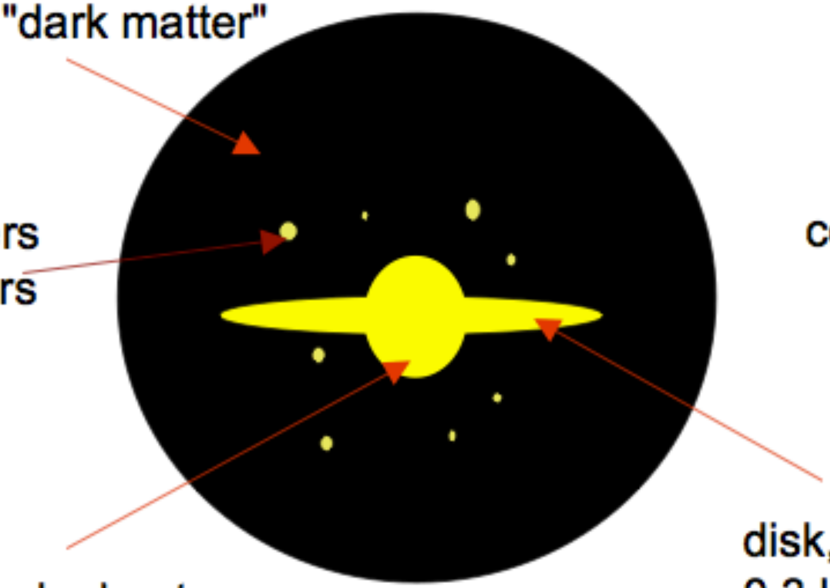
rotation curves of galaxies



100 kpc

Vera Rubin, 1975

Collections of ~10^{11}~ 10^{12} Stars



Schematic of the Milky Way

nearly spherical
halo of "dark matter"

globular clusters
of ~10^{6} old stars

contains ~10^{11} stars

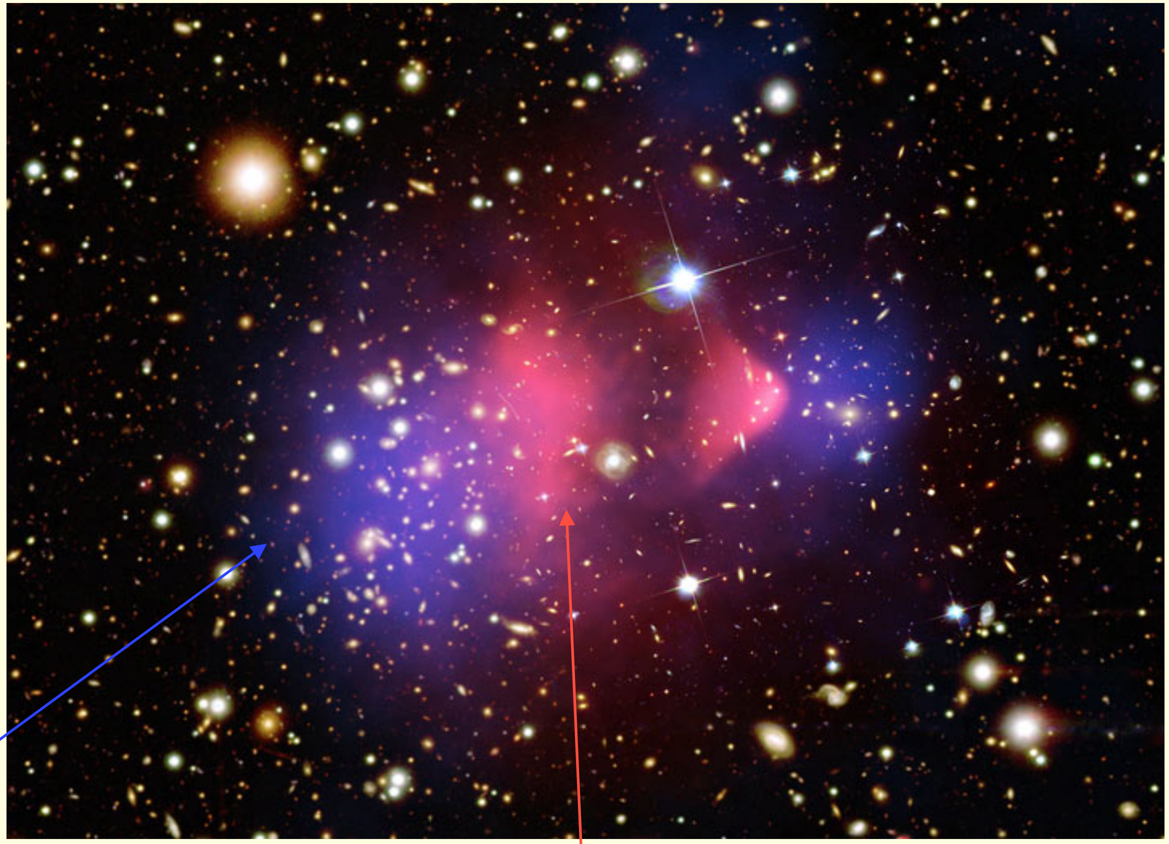
bulge
flattened, about
6 Kpc by 1 Kpc

disk, about
0.3 kpc thick
and 12.5 kpc in radius

Bullet cluster

Clowe, Randall, Markevitch

astro-ph/0611496



Dark matter
Gravitational lensing

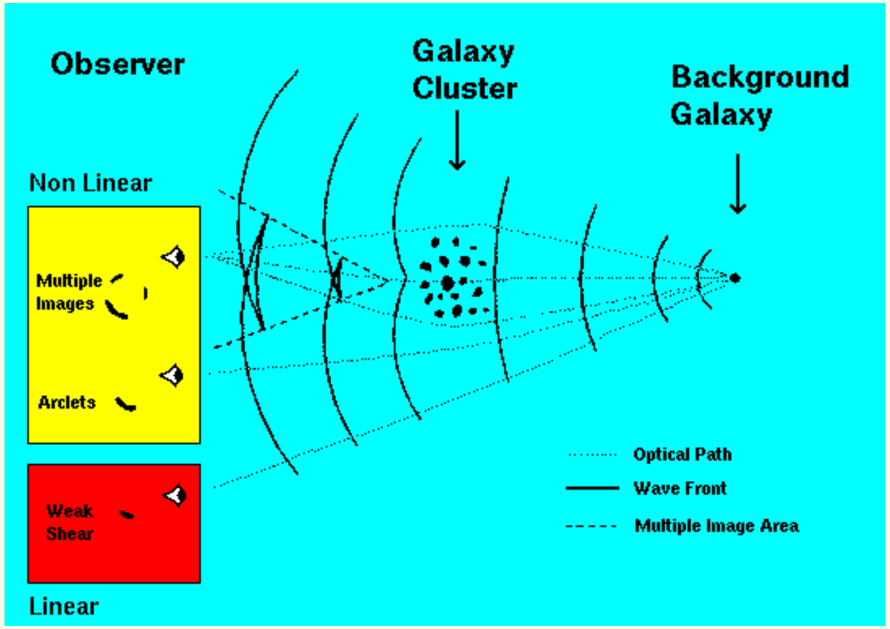
Ordinary matter
X-rays (Chandra)

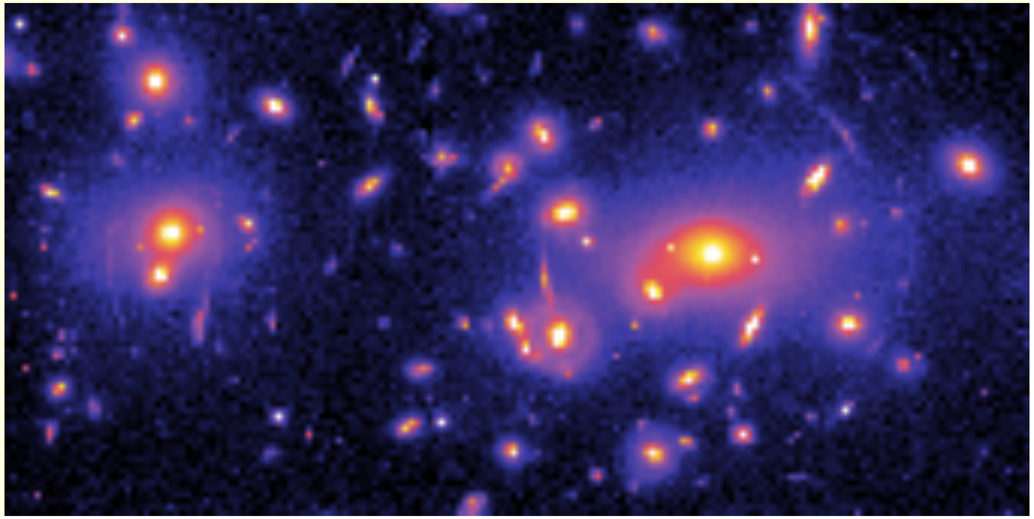
A powerful cosmological probe of Dark Matter: gravitational lensing

1 Mpc

Abell 2218: A Galaxy Cluster Lens, Andrew Fruchter et al. (HST)

Gravitational lensing





Finally, we have seen that, at the level of the whole Universe,

$\Omega_M \sim 0.3$

whereas luminous matter can only account for $\Omega_{\mathrm{luminous}} \sim 0.04$

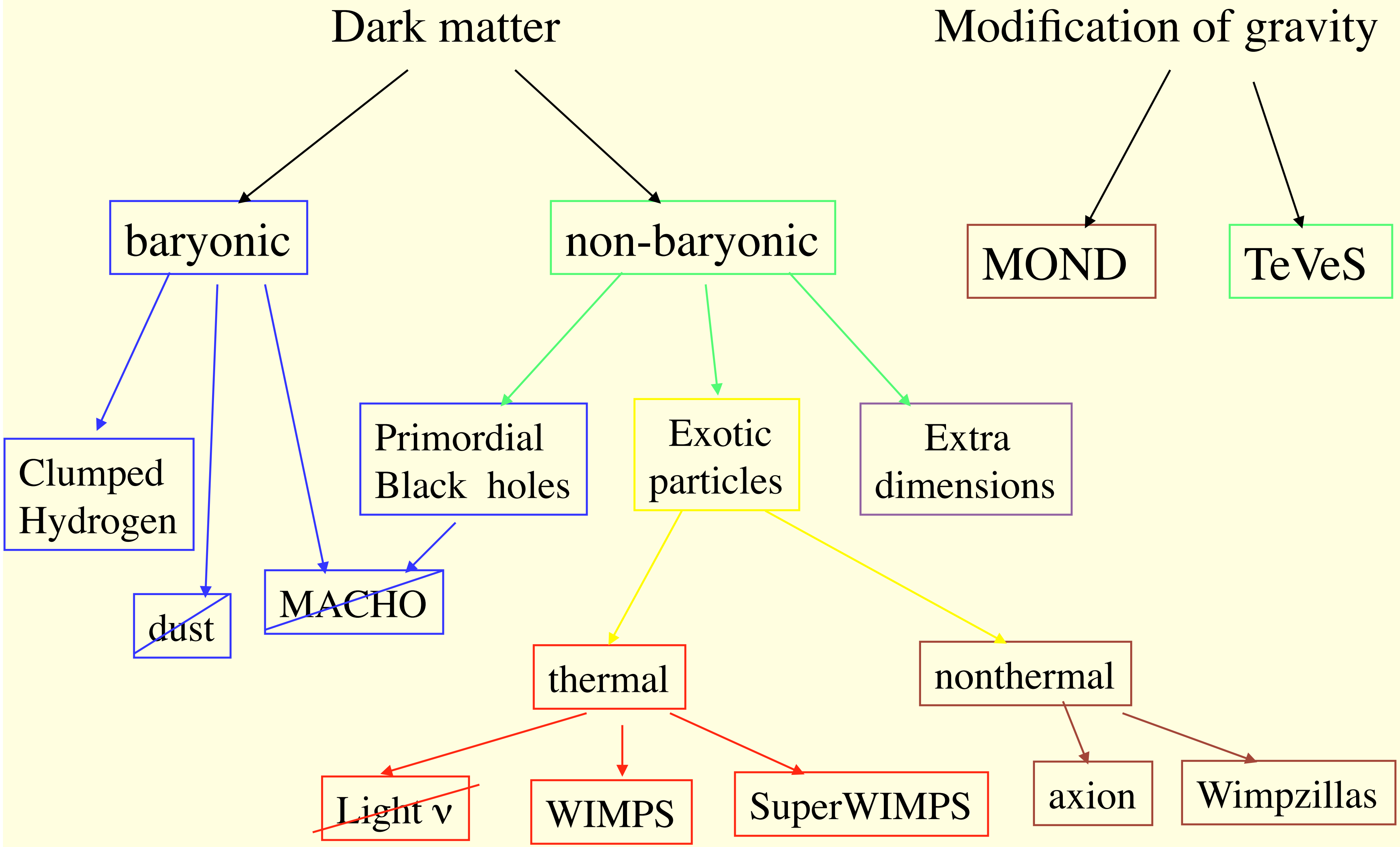
What is dark matter?

Not luminous matter

Not neutrinos because their random motions (free streaming) would wash out any density fluctuations and prevent the formation of galaxies (hot dark matter)

We need cold dark matter (i.e. particles with smaller free streaming length), most probably in the form of weakly interacting massive particles or wimps.

Models for dark matter



Dark matter

Modification of gravity

baryonic

non-baryonic

MOND

TeVeS

Clumped Hydrogen

~~dust~~

~~MACHO~~

Primordial Black holes

Exotic particles

Extra dimensions

thermal

nonthermal

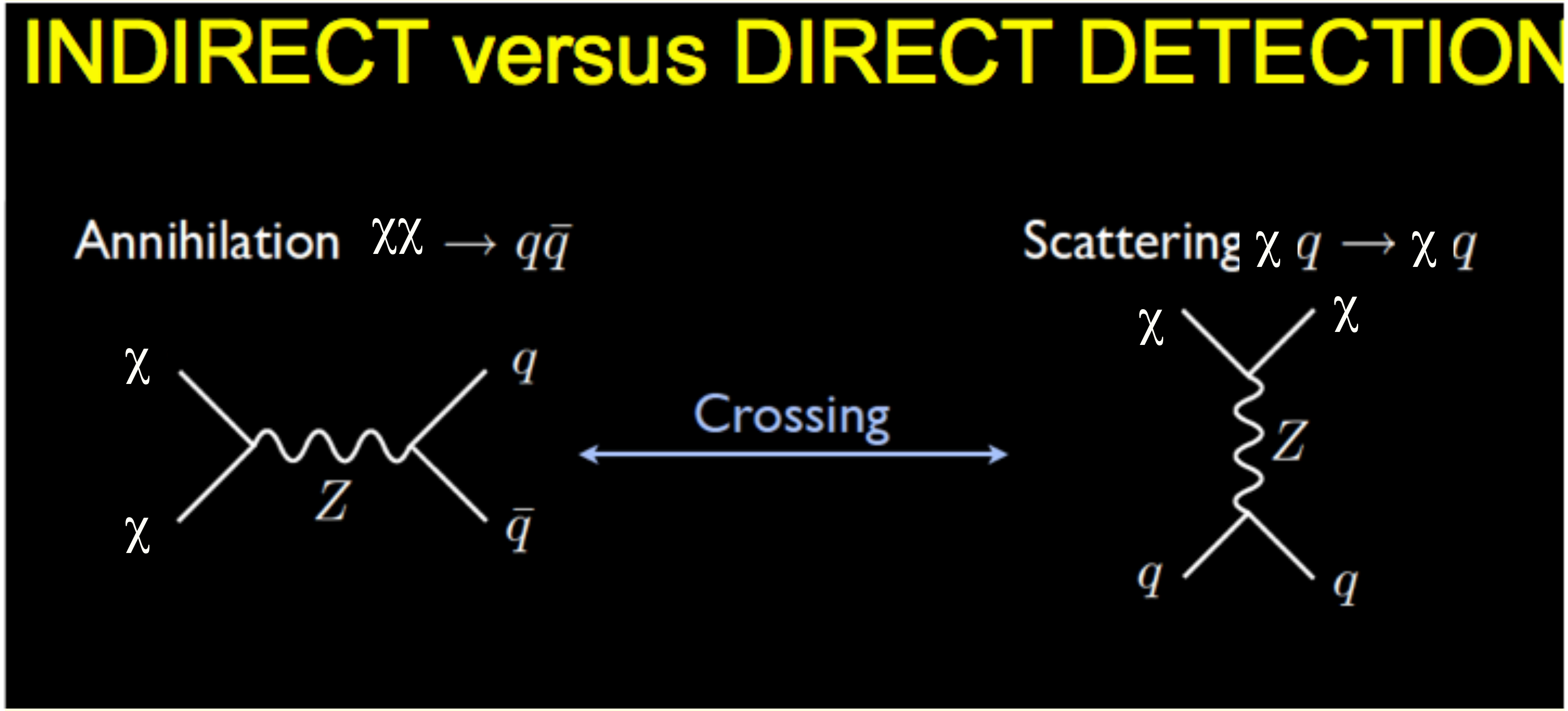
~~Light ν~~

WIMPS

SuperWIMPS

axion

Wimpzillas



INDIRECT versus DIRECT DETECTION

Annihilation $\chi\chi \longrightarrow q\bar{q}$

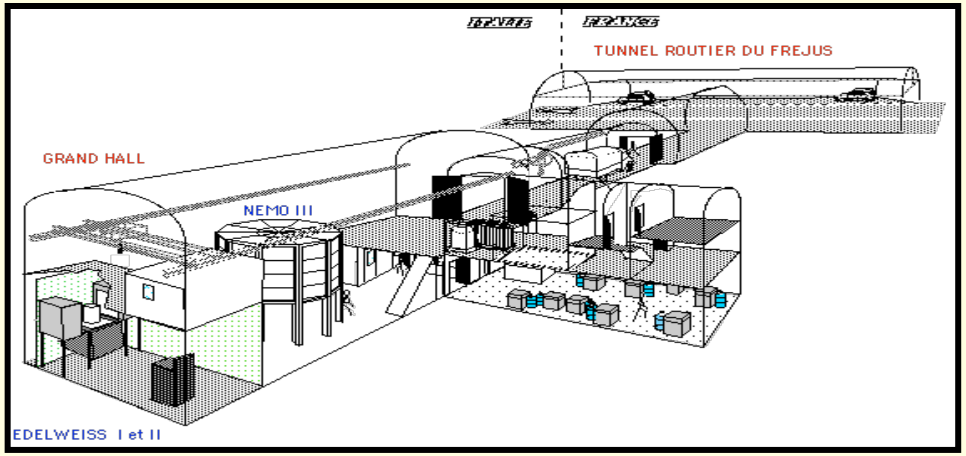
Crossing

Scattering $\chi\, q \longrightarrow \chi\, q$

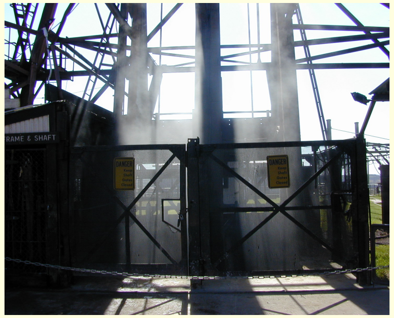
Annihilation in the heart of the Sun
or at the centre of our Galaxy

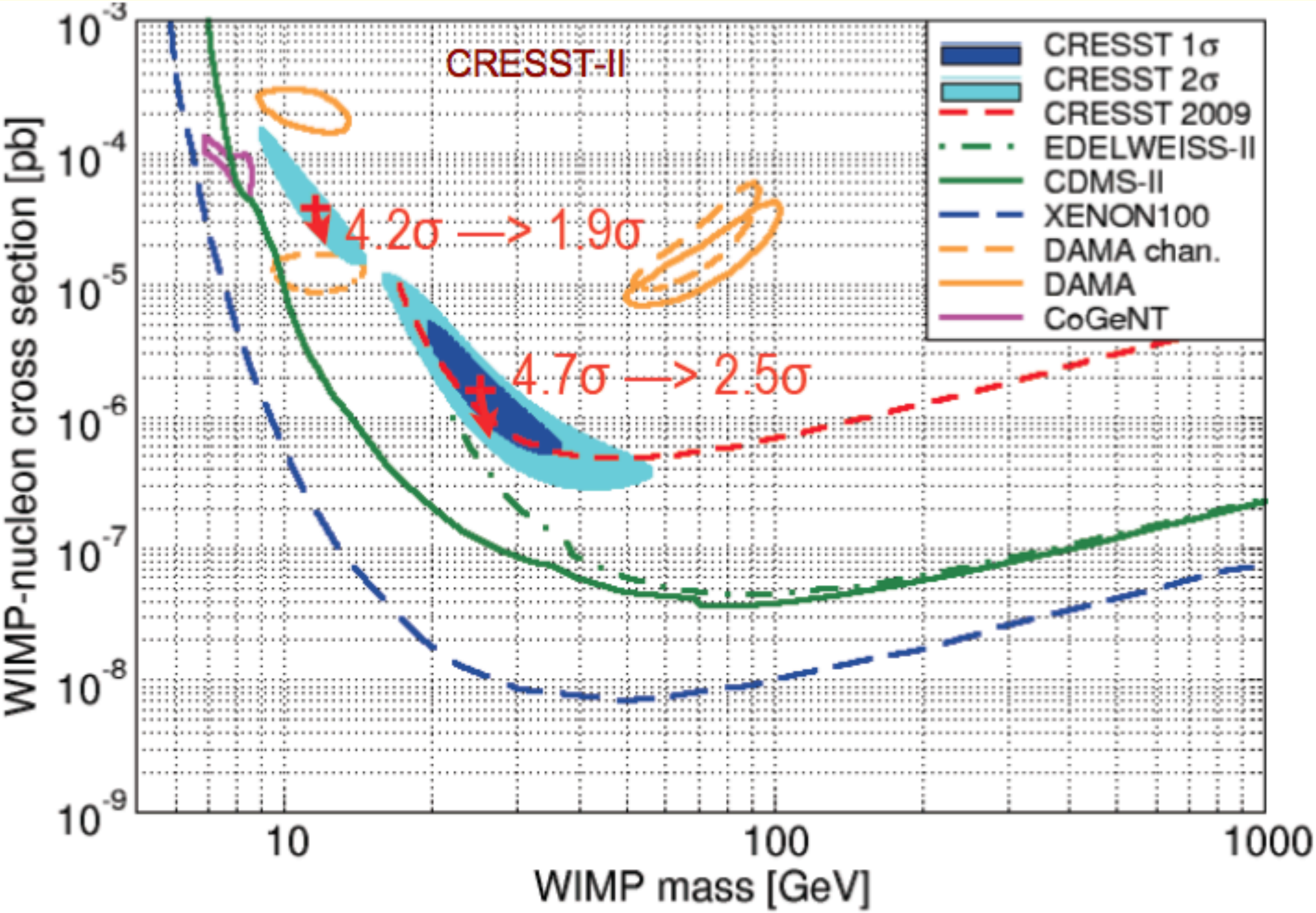
Detection in underground labs

Direct detection



Underground labs
(mines, tunnels…)

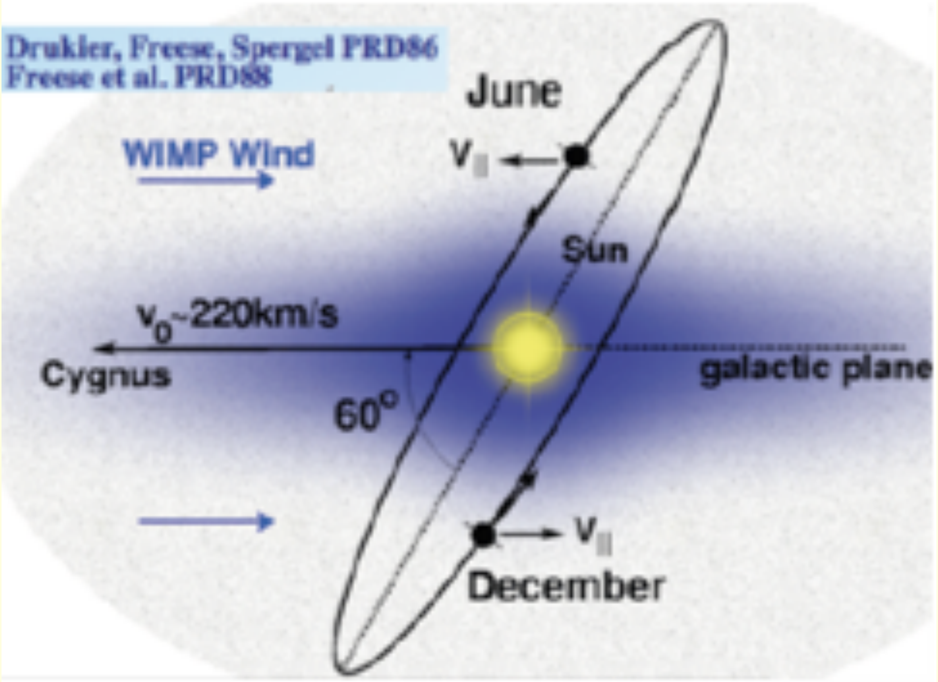


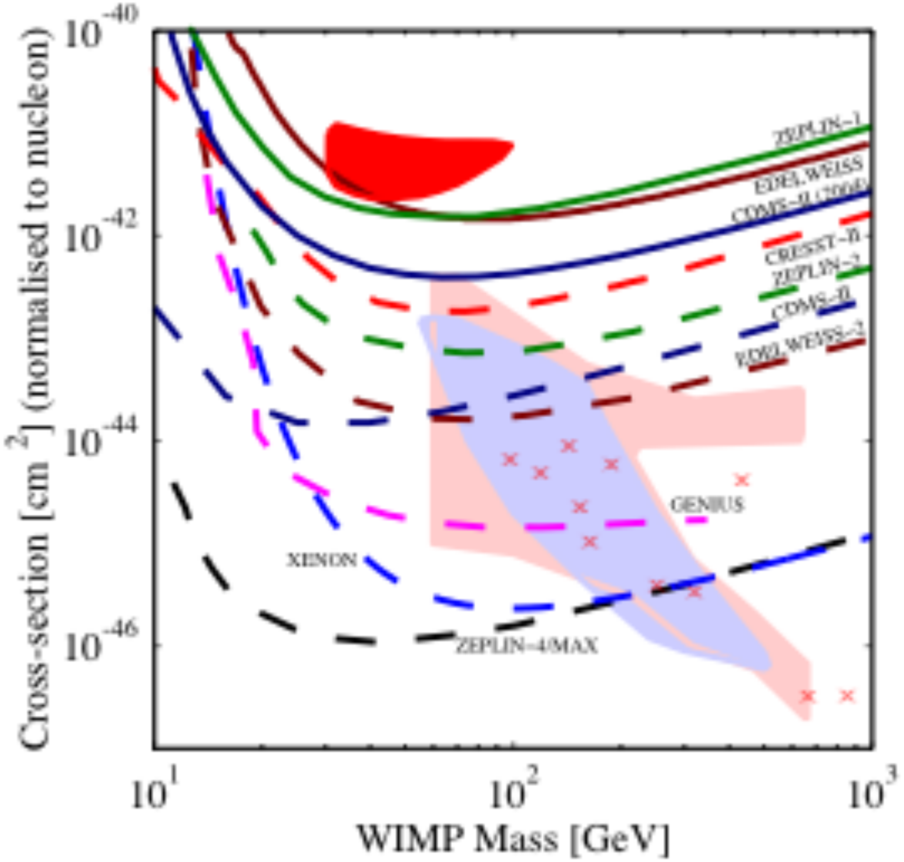


4.2σ —> 1.9σ

4.7σ —> 2.5σ

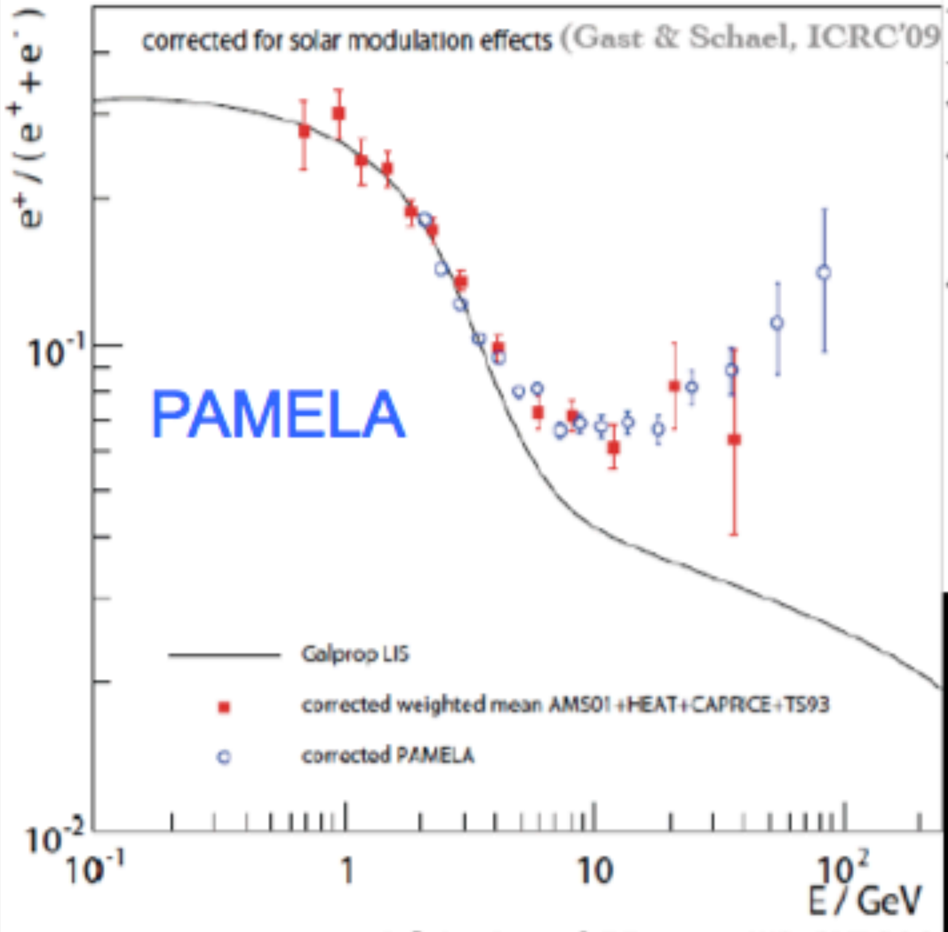
Annual modulation




ZEPLIN-1
EDELWEISS
CDMS-II (2004)
CRESST-II
ZEPLIN-2
CDMS-II
EDELWEISS-2
GENIUS
XENON
ZEPLIN-4/MAX
10^{-40}
10^{-42}
10^{-44}
10^{-46}
Cross-section [cm ^{2}] (normalised to nucleon)
10^{1}
10^{2}
10^{3}
WIMP Mass [GeV]

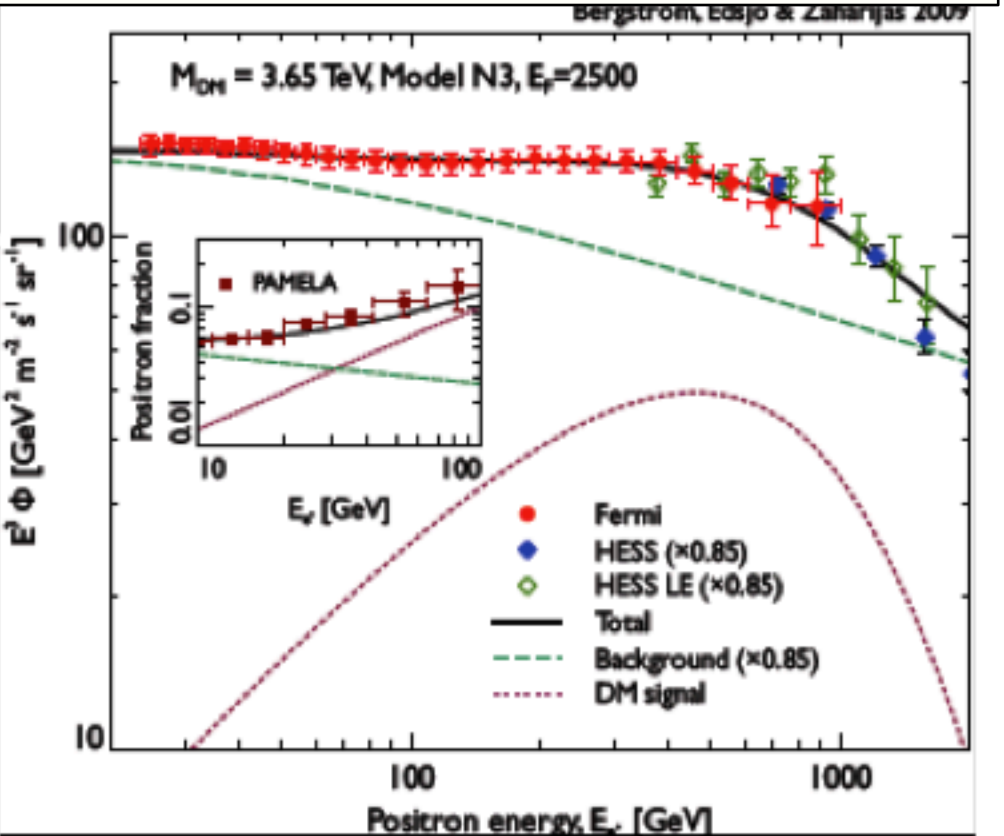
Indirect detection

positron excess



Adriani *et al*, Nature 458:607,2009

Bergstrom, Edsjo & Zaharijas 2009



Need boost ~100..... flux ~ ρ^2/m_x^2

Sommerfeld effect: $S=S_0[1+(v_{esc}/v)^2]$

due to DM light mediator

Arkani-Hamed et al 2009, Lattanzi and JS 2009, March-Russell and West 2009

Light does not say it all (3) : dark energy

Vacuum energy:

Classically, the energy of the fundamental state (vacuum) is not measurable. Only differences of energy are (e.g. Casimir effect).

Einstein equations: $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu}$

geometry energy

Hence geometry may provide a way to measure absolute energies i.e. vacuum energy:

$$R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu} + 8\pi G < T_{\mu\nu} > \qquad \text{vacuum energy}$$

similar to the cosmological term introduced by Einstein :

$$R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu} + \lambda\, g_{\mu\nu}$$

$H = \dot{a}/a$

Einstein equations → Friedmann equation

$\boxed{c = 1}$

$$H^2 = (8\,\pi G\,\rho + \lambda\,)\,/3 - k/a^2$$

$\boxed{\lambda \equiv \ell_\Lambda^{\,-2}}$

$$\rho_c = 3\,H_0^{\,2} / 8\,\pi G$$

$$\rho_\Lambda = \lambda / 8\,\pi G$$

$$\Omega_\Lambda \equiv \rho_\Lambda / \rho_c = (H_0^{-1} / \ell_\Lambda)^2 / 3 \sim 0.7 \Rightarrow \quad \ell_\Lambda \sim H_0^{-1} \sim 10^{26}\,\mathrm{m}$$

A very natural value for an astrophysicist !

Introduce $\hbar$

Planck length $\ell_P = \sqrt{8\pi G_N \hbar / c^3} = 8.1\text{x}10^{-35}\text{m}$

Planck	$\ell_P \sim 10^{-34}$ m	$m_P \sim 10^{27}$ eV
λ	$\ell_\Lambda \sim 10^{26}$ m	$m_\Lambda \sim 10^{-33}$eV

$$mc^2 \equiv \frac{\hbar c}{l} = \frac{200\ \text{MeV.fm}}{\ell}$$

$H = \dot{a}/a$

Einstein equations → Friedmann equation

$c = 1$

$$H^2 = (8 \pi G \rho + \lambda) /3 - k/a^2$$

$$\boxed{\lambda \equiv \ell_\Lambda^{-2}}$$

$$\rho_c = 3 H_0^2 / 8 \pi G$$

$$\rho_\Lambda = \lambda / 8 \pi G$$

$$\Omega_\Lambda \equiv \rho_\Lambda / \rho_c = (H_0^{-1} / l_\Lambda)^2 / 3 \sim 0.7 \Rightarrow \quad \ell_\Lambda \sim H_0^{-1} \sim 10^{26}\ \mathrm{m}$$

~~A very natural value for an astrophysicist~~ !

A very unnatural value for a Universe which presumably started in a quantum state!

$$\rho_\Lambda = \frac{1}{8\pi G \ell_\Lambda^2} = \frac{\hbar}{\ell_P^2 \ell_\Lambda^2} \equiv \frac{\hbar}{\ell_{DE}^4}$$

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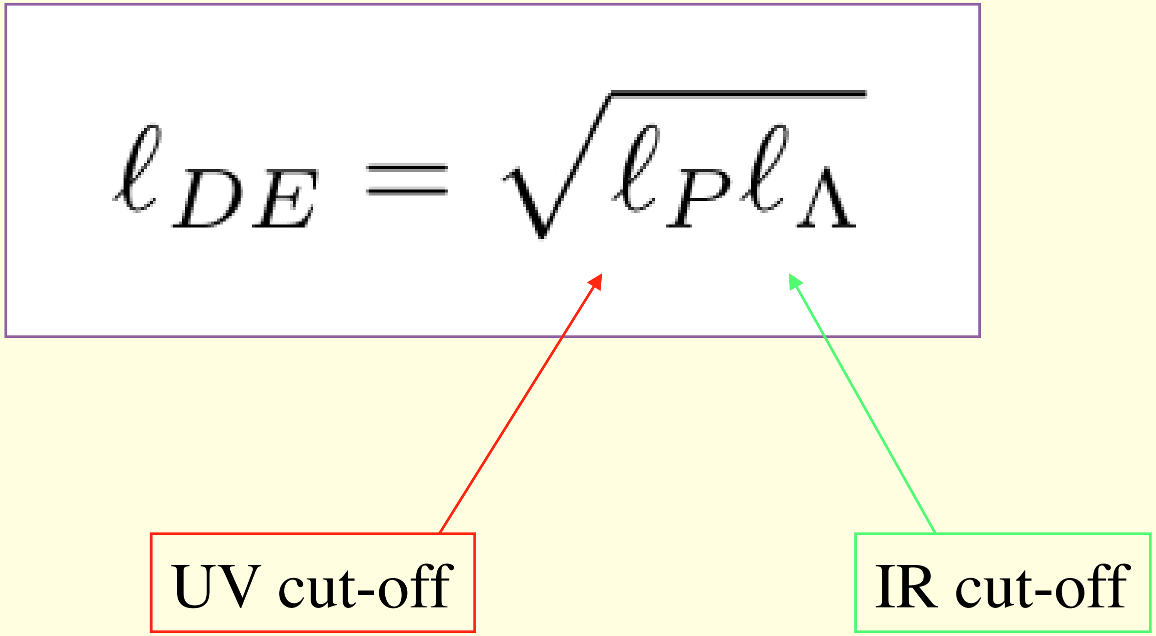


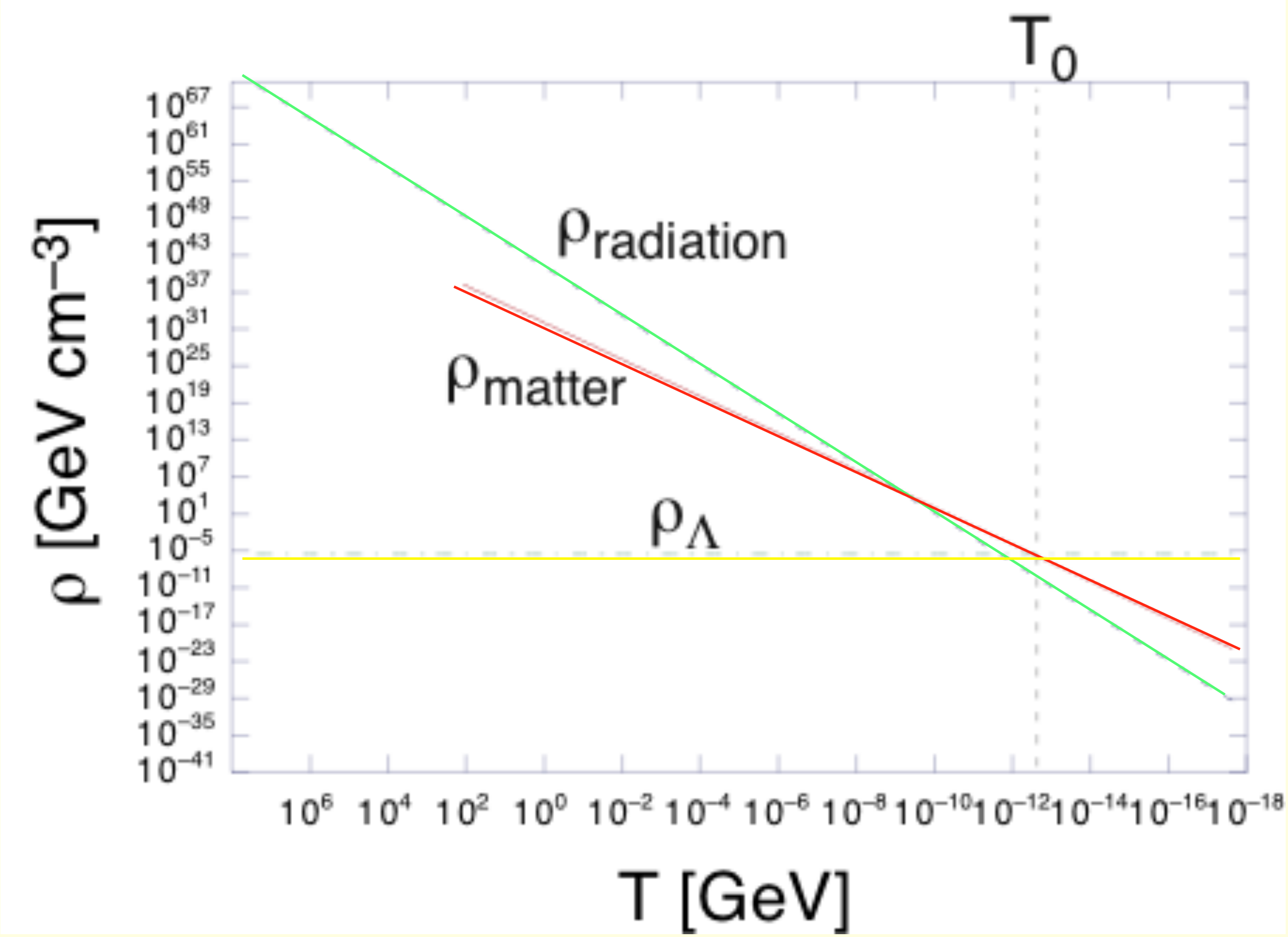
$$\boxed{\ell_{DE} = \sqrt{\ell_P \ell_\Lambda}}$$

UV cut-off

IR cut-off

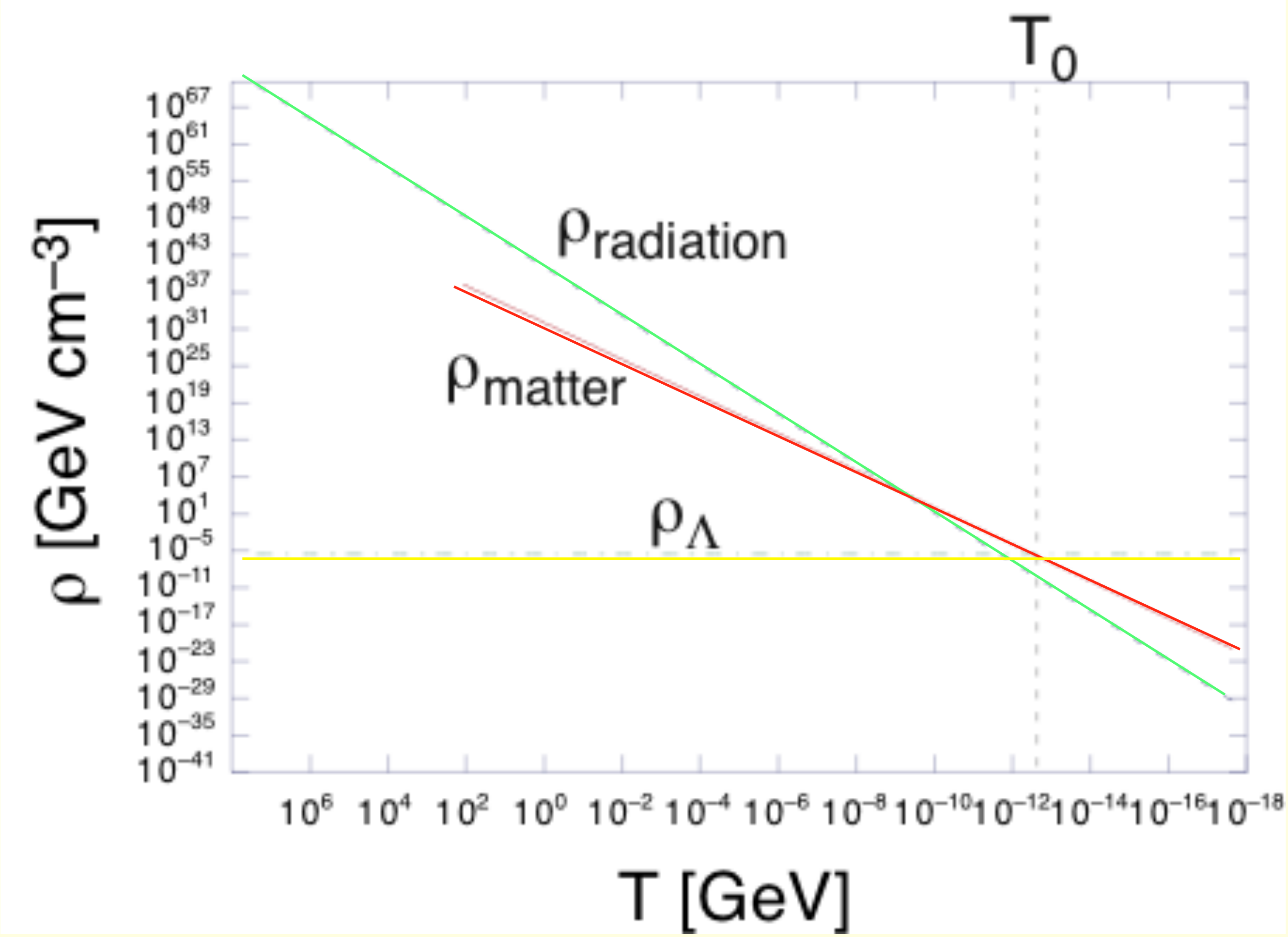
Cosmological constant problem : where the two ends meet

Central question : why now?
why is our Universe so large, so old?



Cosmic coincidence problem:

Why does the vacuum energy starts to dominate at a time t_Λ ($z_\Lambda \sim 1$) which almost coincides with the epoch t_G of galaxy formation ($z_G \sim 3$)?



Are there more general ways than a cosmological constant to account for the acceleration of the expansion?

Einstein equations: $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu}$

Dark energy

geometry matter-energy

modify gravity

add new effects or a new form of energy

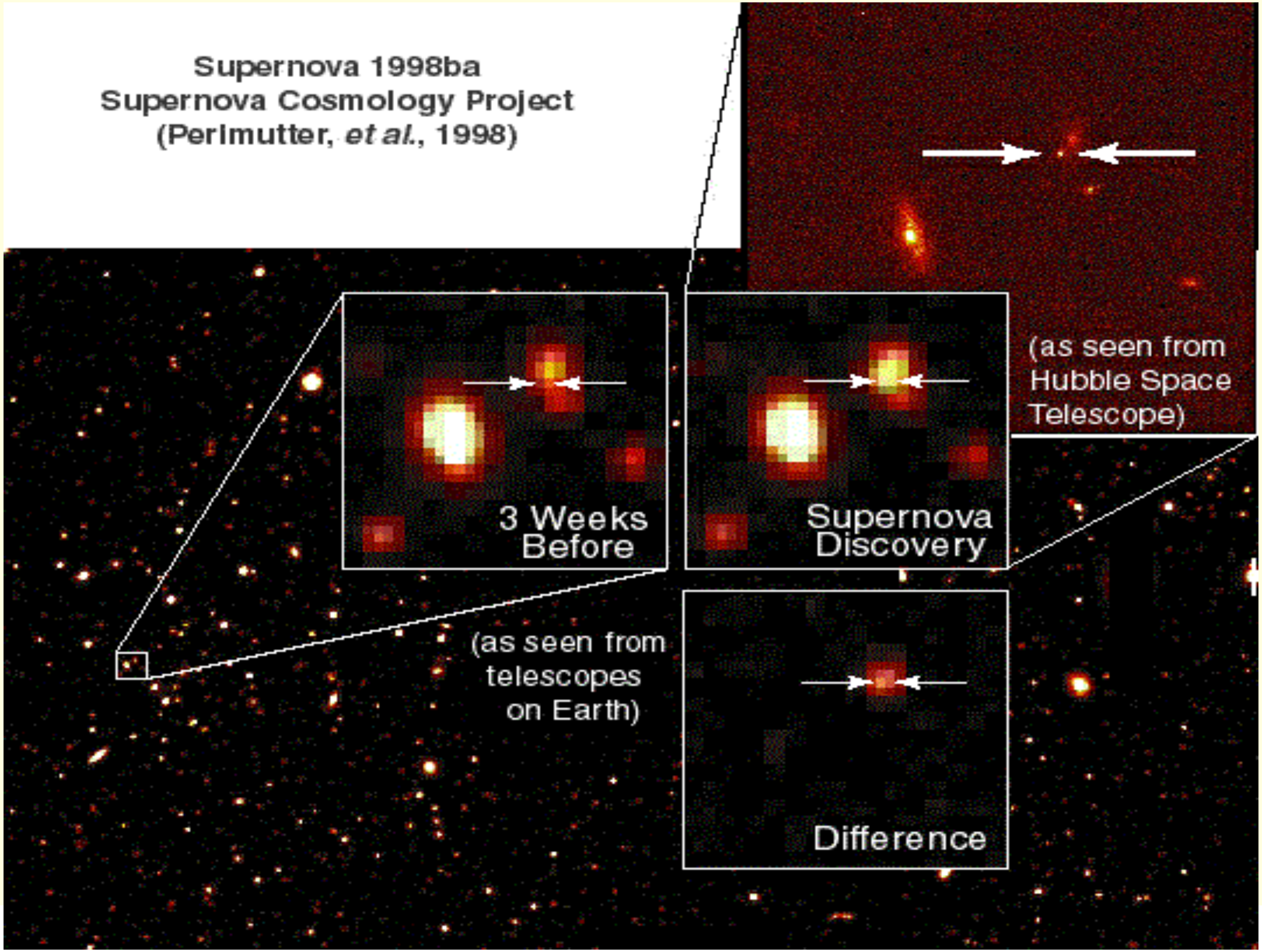
Friedmann equation : $H^2 = 8\,\pi G\,\rho\,/3 - k/a^2$

modified Friedmann equation

new contributions to the Friedmann equation

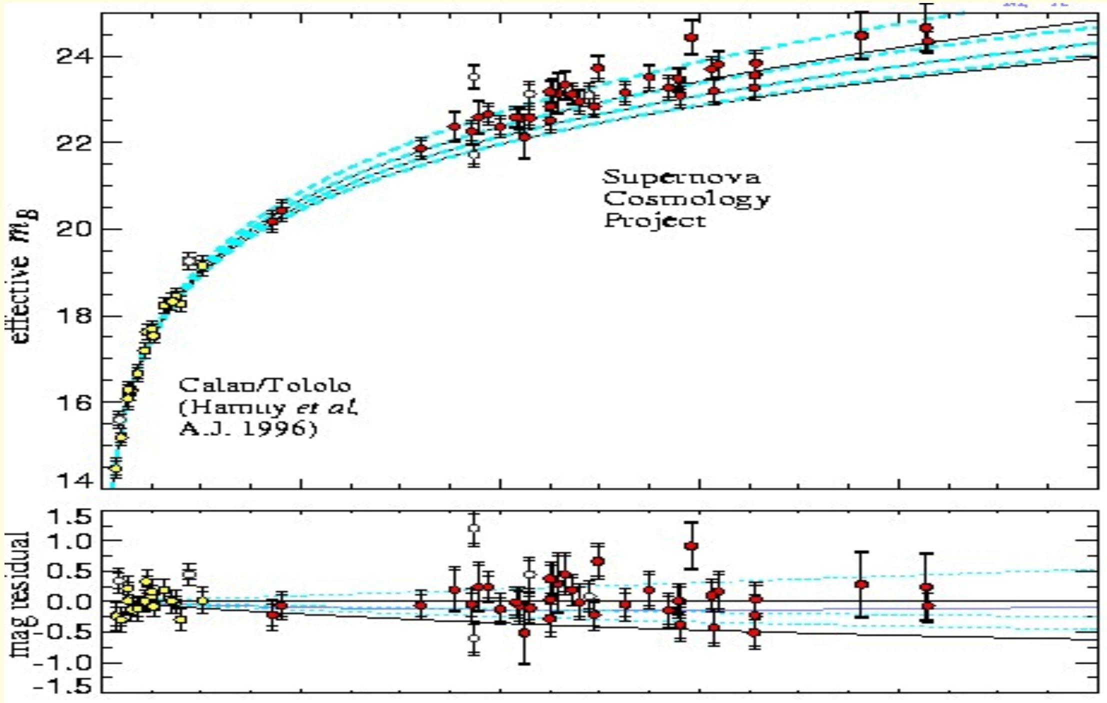
The observational case

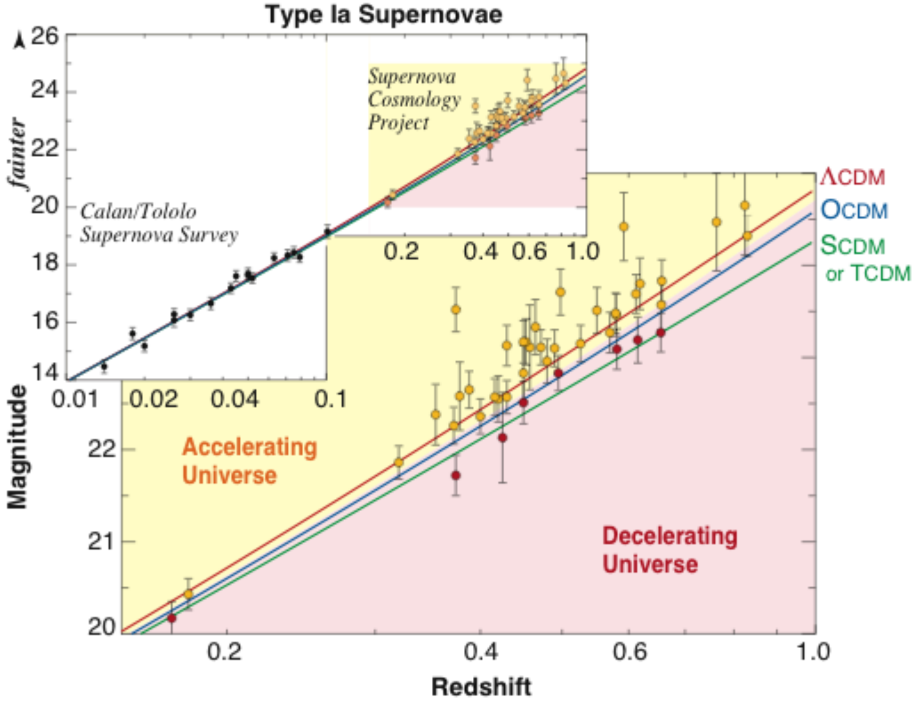
Supernovae of type Ia may be used as standard candles to test the geometry of spacetime



Distant supernovae appear less bright than in an expanding universe

➔ accelerated expansion



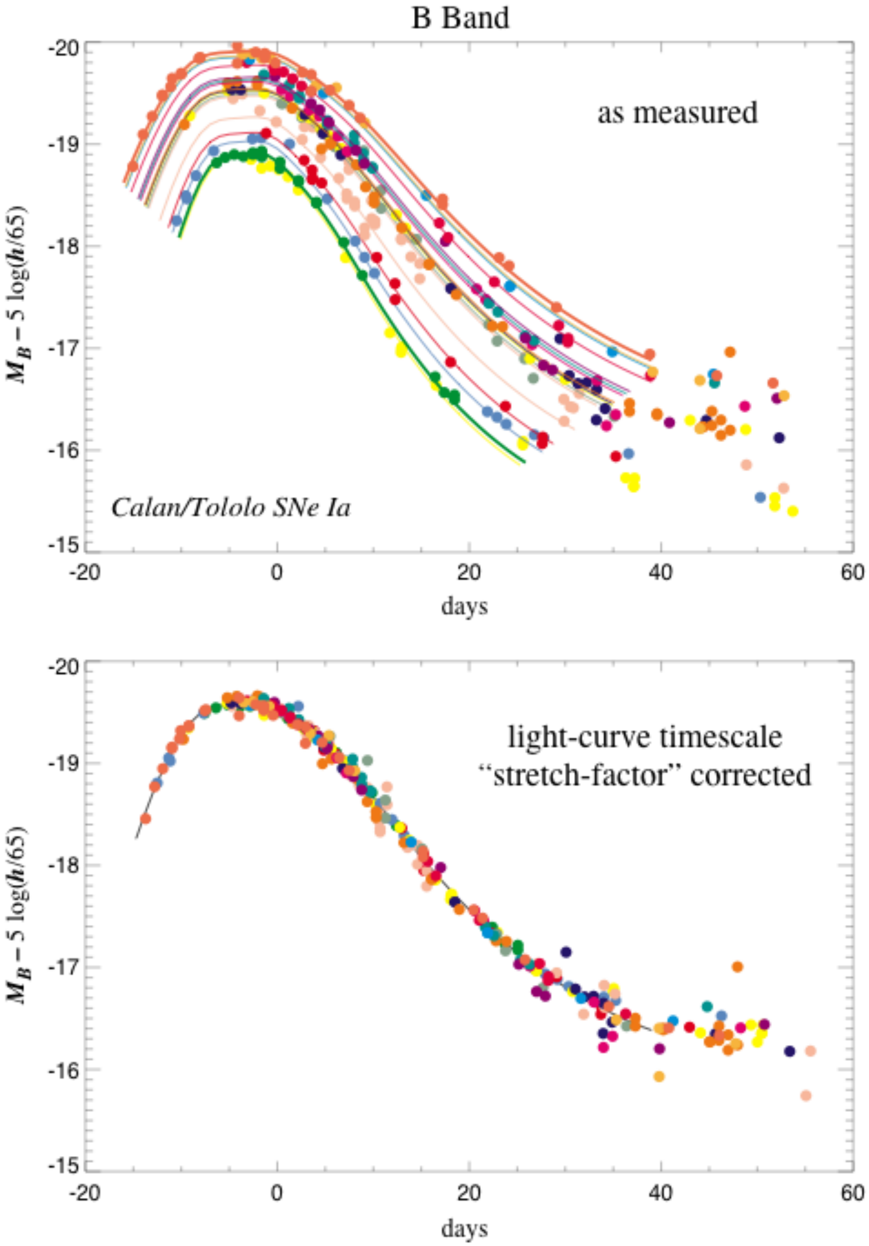


$$\boxed{m_B = 5 \log(H_0 d_L) + M - 5 \log H_0 + 25}$$

luminosity distance $d_L = l_{H0}\, z \left(1 + \frac{1-q_0}{2}\, z + \ldots \right)$

q_0 deceleration parameter

$$\boxed{q_0 = - a\, \ddot{a} / \dot{a}^2}$$



Kim, *et al.* (1997)

Could this be explained by a cosmological constant ?

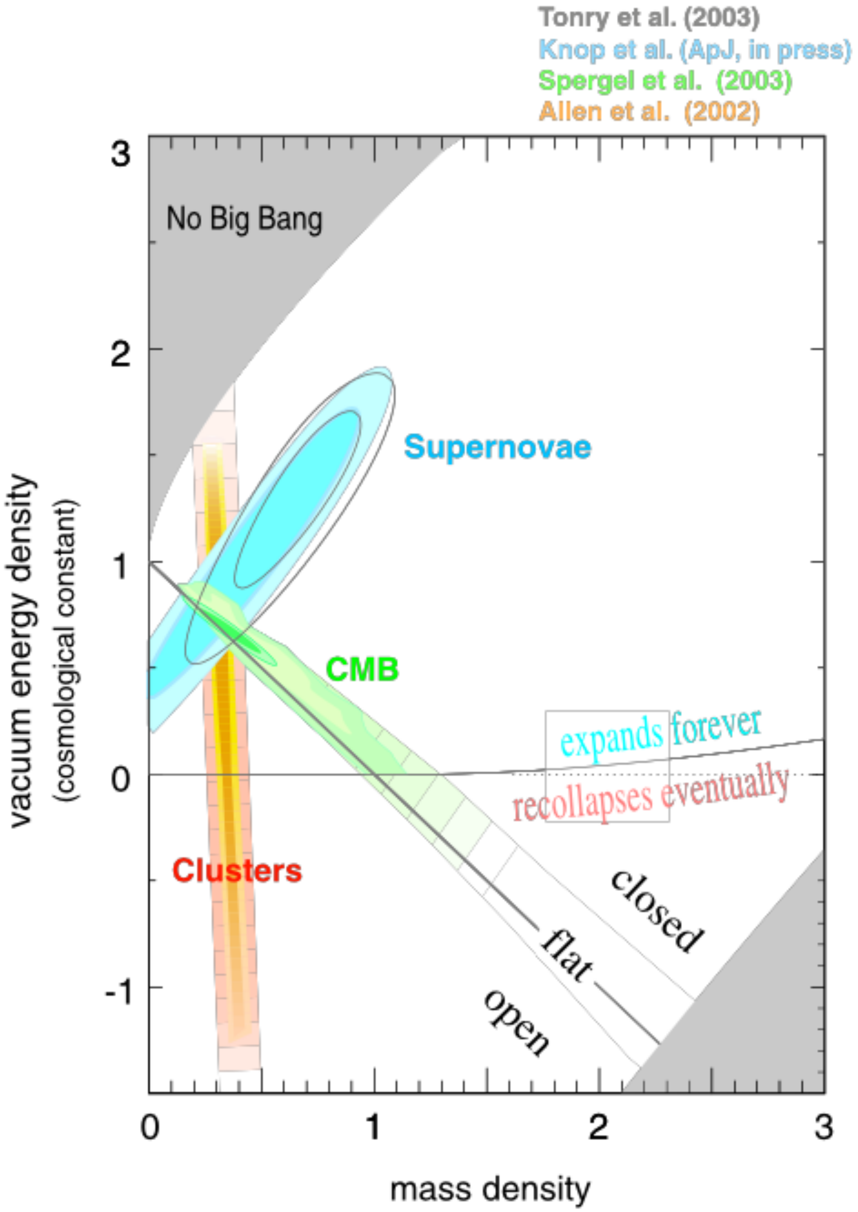
Plot $(\Omega_\Lambda , \Omega_M)$:

$$\Omega_\Lambda = \rho_\Lambda/\rho_c \, , \, \Omega_M = \rho_M/\rho_c$$

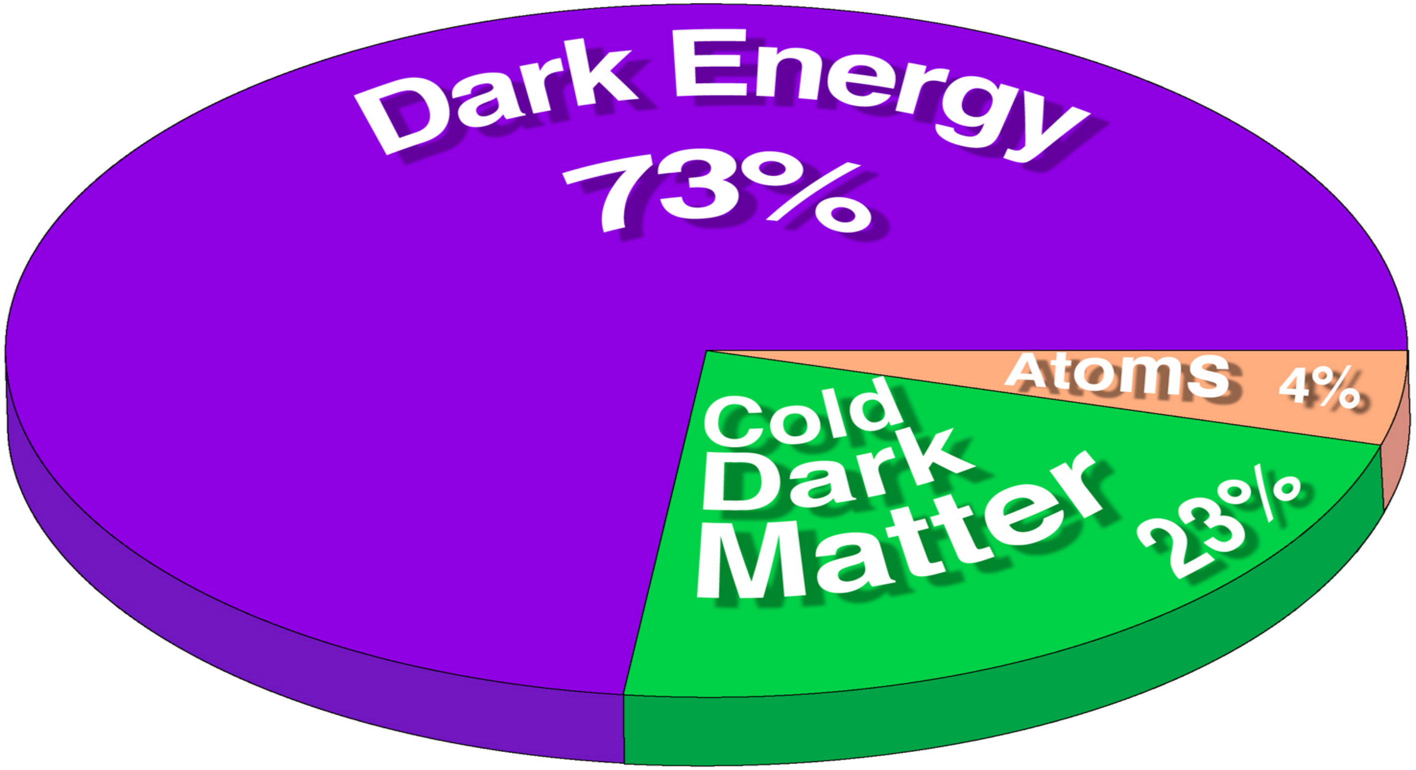
Concordance model

Note: if this is so, the vacuum energy takes the value expected in the context of gravity. Associated energy scale :

$\Lambda \sim 10^{-3}$ eV



The energetic budget of the Universe



Dark energy

Assume the existence of a new component assmilated to a perfect fluid with pressure p and energy density ρ :

equation of state $p = w\rho$

Note: vacuum energy has w=-1

Friedmann equation at late epochs :

$$\boxed{H^2 = H_0^2 [\, \Omega_m (1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}}$$

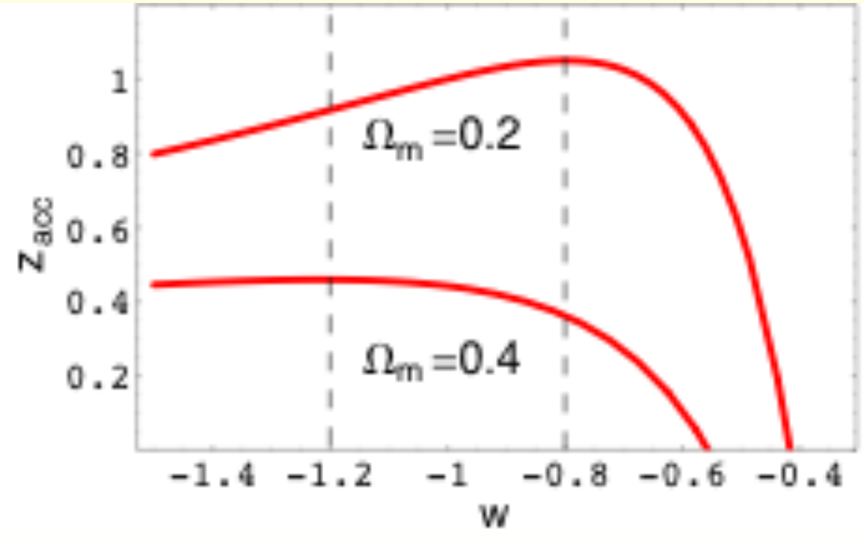
$$\Omega_{DE} \sim 1 - \Omega_m$$

In the case of z dependent w, w in previous formula is some averaged value

Acceleration of the expansion : $3\,\ddot{a} / a = -\,4\pi G\,(\rho+3p)\,/3$

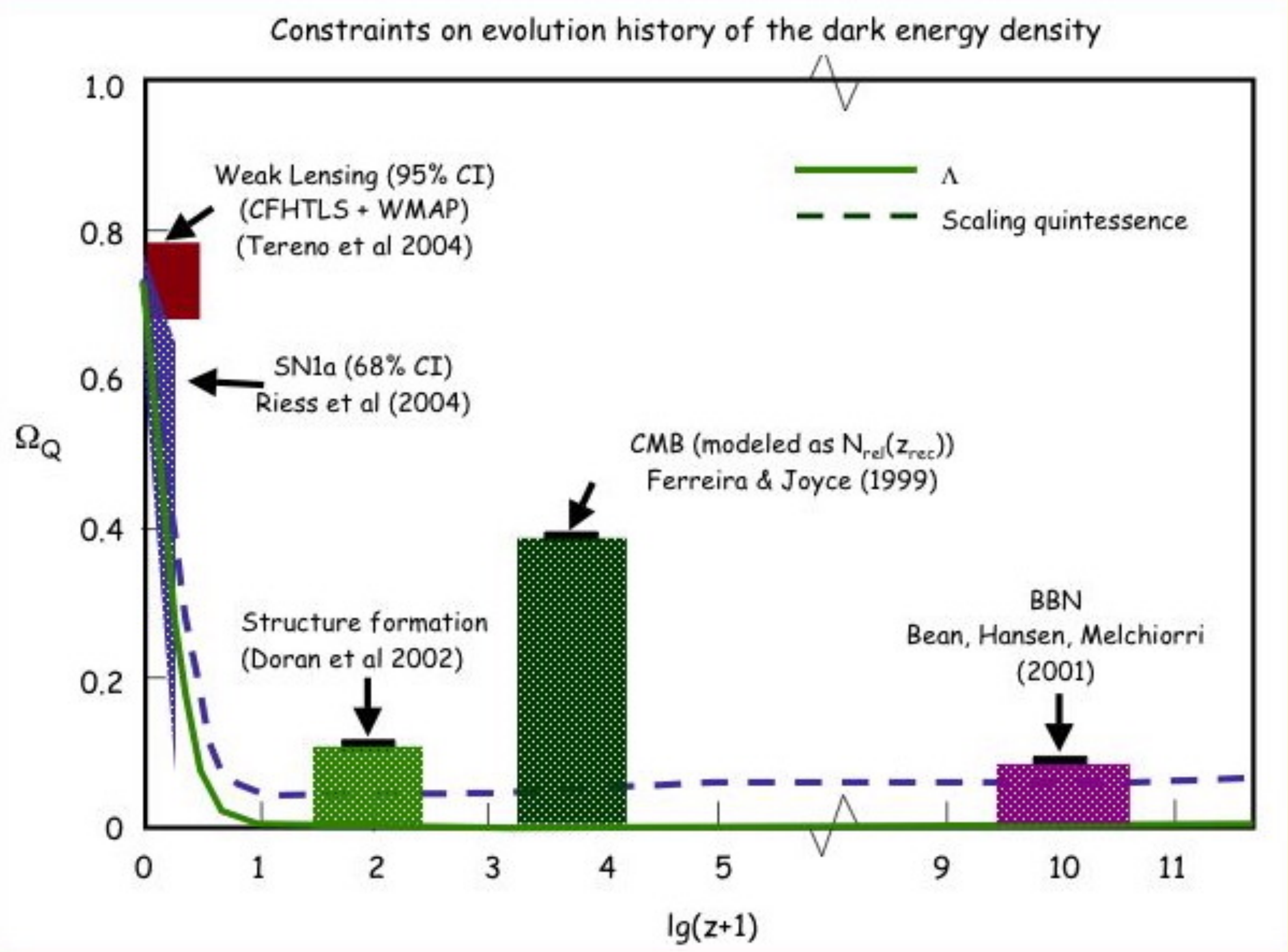
Then redshift at beginning of acceleration :

$$\boxed{1 + z_{acc} = [(3\,w(z_{acc}) + 1)(\Omega_m - 1)/\,\Omega_m]^{-1/3w}}$$



astro-ph/0610574

$\Omega_{DE}(z)$

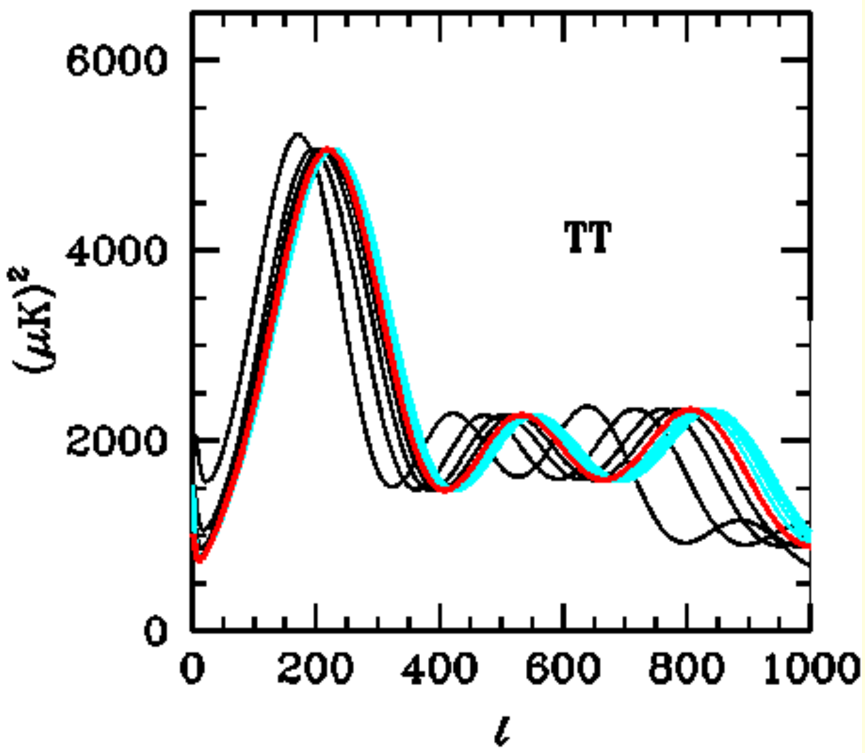

Constraints on evolution history of the dark energy density
1.0
0.8
0.6
0.4
0.2
0
Ω_Q
Weak Lensing (95% CI)
(CFHTLS + WMAP)
(Tereno et al 2004)
SN1a (68% CI)
Riess et al (2004)
CMB (modeled as $N_{rel}(z_{rec})$)
Ferreira & Joyce (1999)
Structure formation
(Doran et al 2002)
BBN
Bean, Hansen, Melchiorri
(2001)
Λ
Scaling quintessence
0
1
2
3
4
5
9
10
11
lg(z+1)

Angular diameter distance

CMB

w = -1.8,..,-0.2

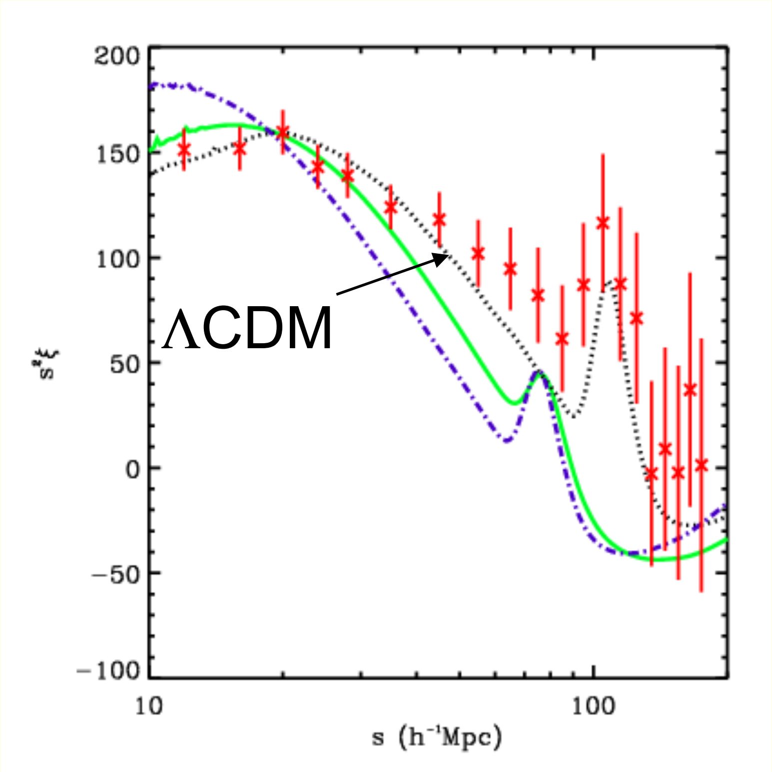
When combined with measurement of matter density constrains data to a line in Ω_M-w space

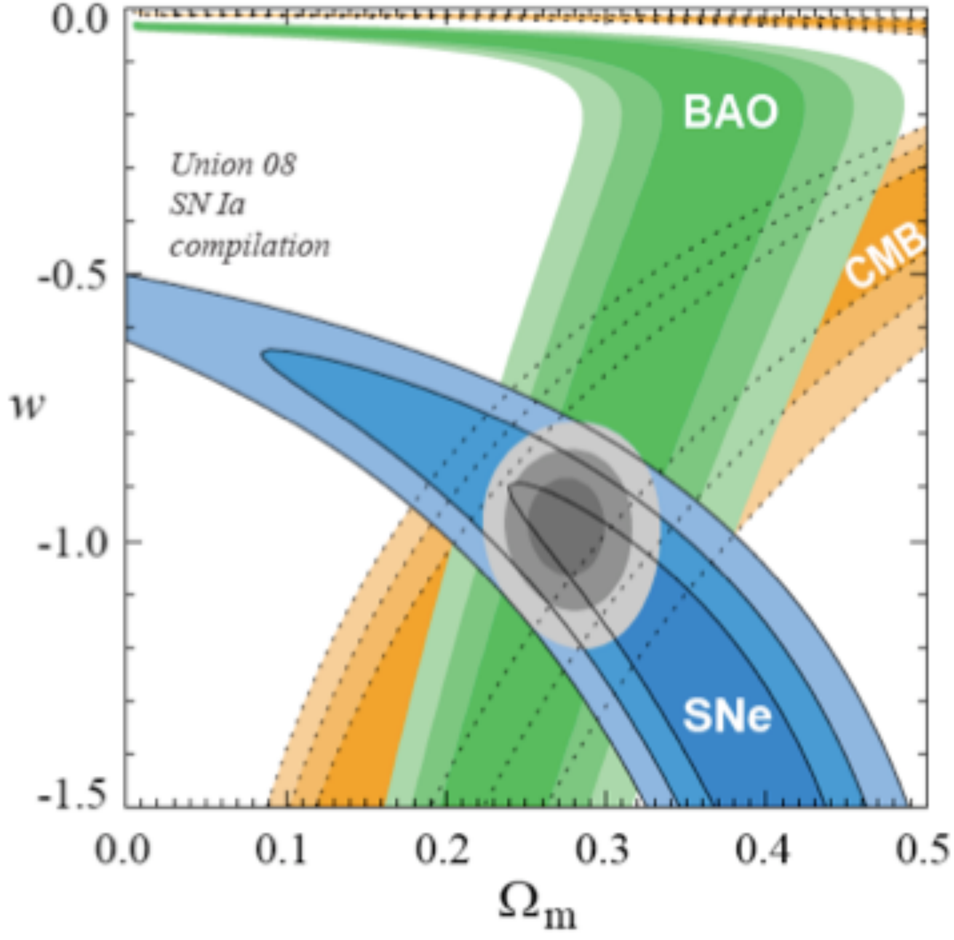


Baryon oscillations are really discriminating for dark energy

Acoustic oscillations are seen in the CMB .

Look for the the same waves in the galaxy correlations.

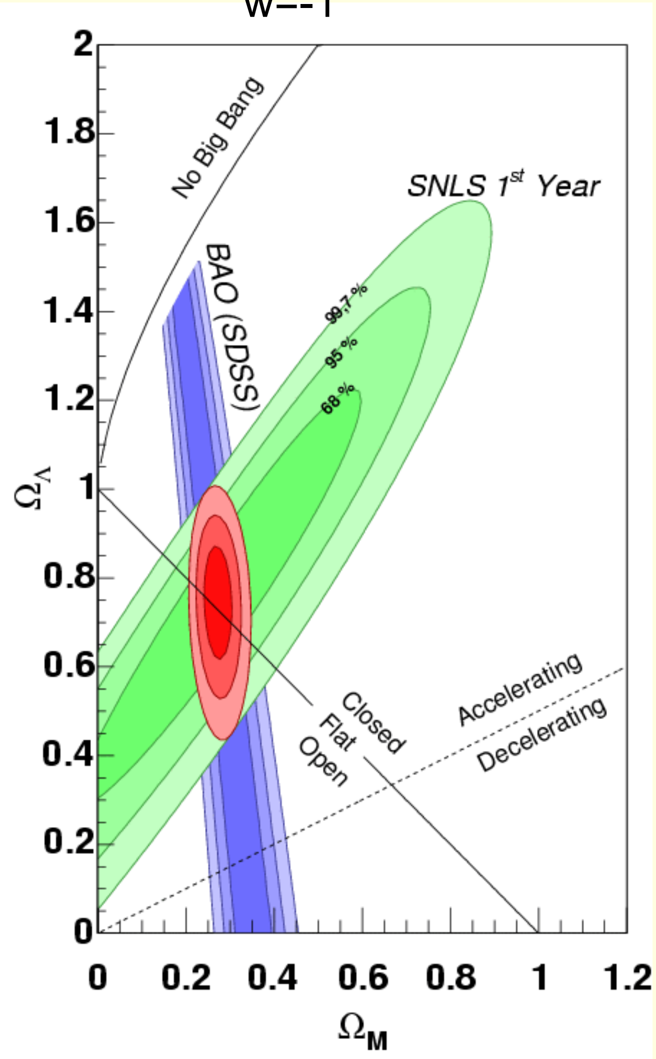




Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)

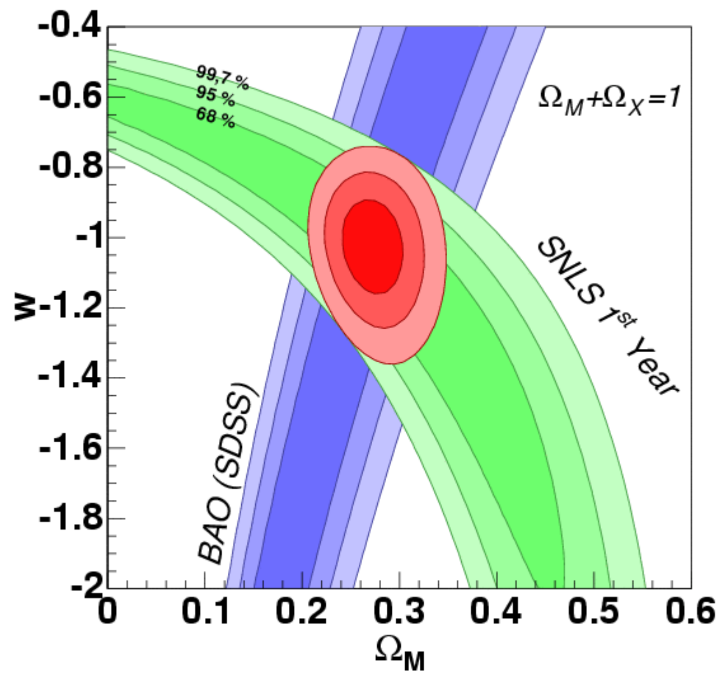
Confidence Contours

w=-1



68.3, 95.5 et 99.7% CL

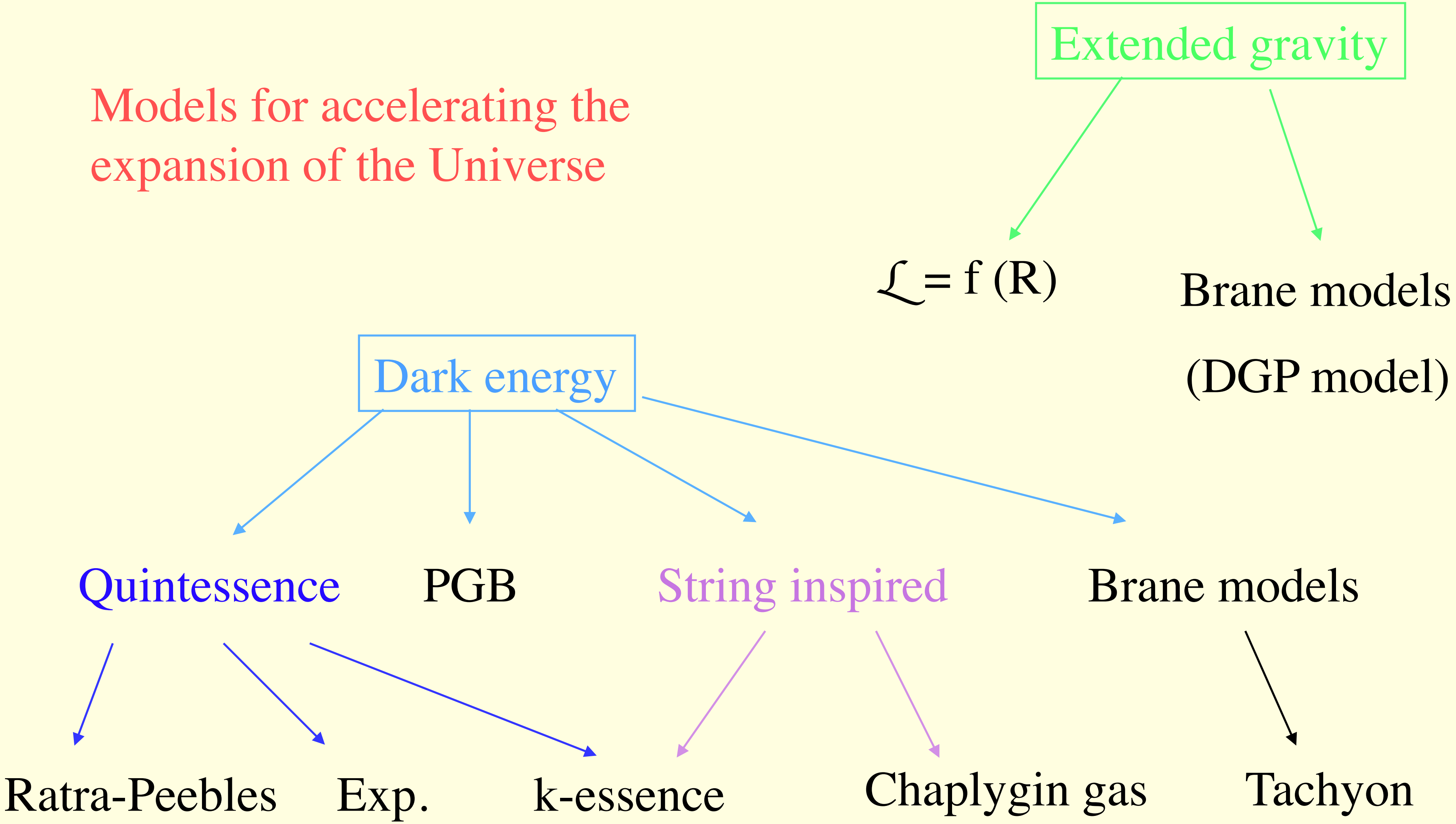
Ω_{Tot}=1



BAO: Baryon Acoustic Oscillations (Eisenstein et al 2005, SDSS)

fit	parameters (stat only)
$(\Omega_M, \Omega_\Lambda)$	$(0.31 \pm 0.21, 0.80 \pm 0.31)$
$(\Omega_M - \Omega_\Lambda, \Omega_M + \Omega_\Lambda)$	$(-0.49 \pm 0.12, 1.11 \pm 0.52)$
$(\Omega_M, \Omega_\Lambda)$ flat	$\Omega_M = 0.263 \pm 0.037$
$(\Omega_M, \Omega_\Lambda)$ + BAO	$(0.271 \pm 0.020, 0.751 \pm 0.082)$
(Ω_M, w)+BAO	$(0.271 \pm 0.021, -1.023 \pm 0.087)$

Models for accelerating the expansion of the Universe



Extended gravity

$\mathcal{L} = f\,(R)$

Brane models

(DGP model)

Dark energy

Quintessence

PGB

String inspired

Brane models

Ratra-Peebles

Exp.

k-essence

Chaplygin gas

Tachyon

Why scalar fields to model dark energy?

Scalar fields easily provide a diffuse background

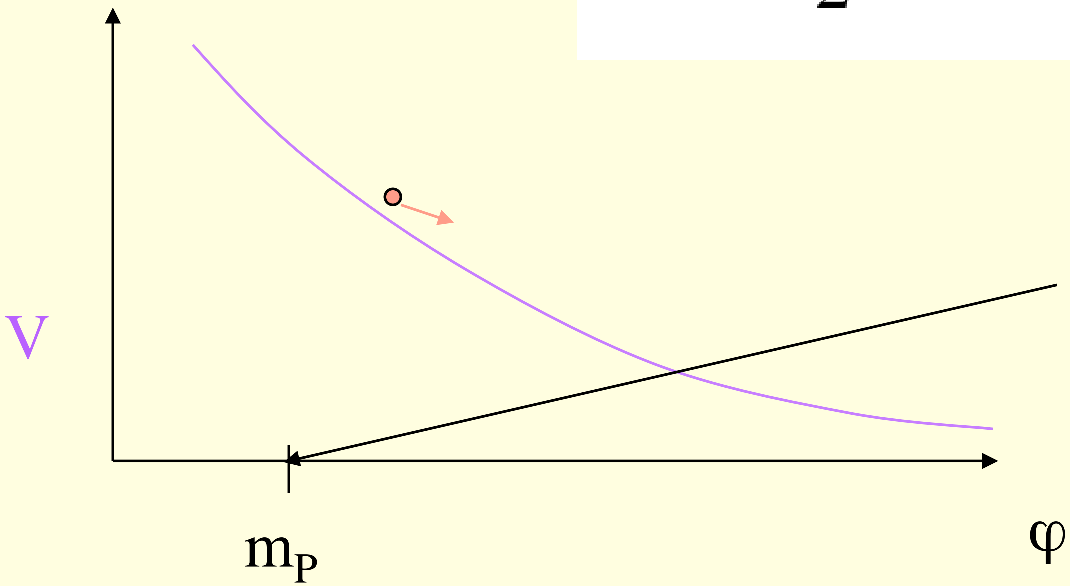
Speed of sound $c_s^2 = (\delta p \,/\, \delta\rho)_{\text{adiabatic}}$

In most models, $c_s^2 \sim 1$, i.e. the pressure of the scalar field resists gravitational clustering :

scalar field dark energy does not cluster

Example (quintessence)

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - V(\phi)$$



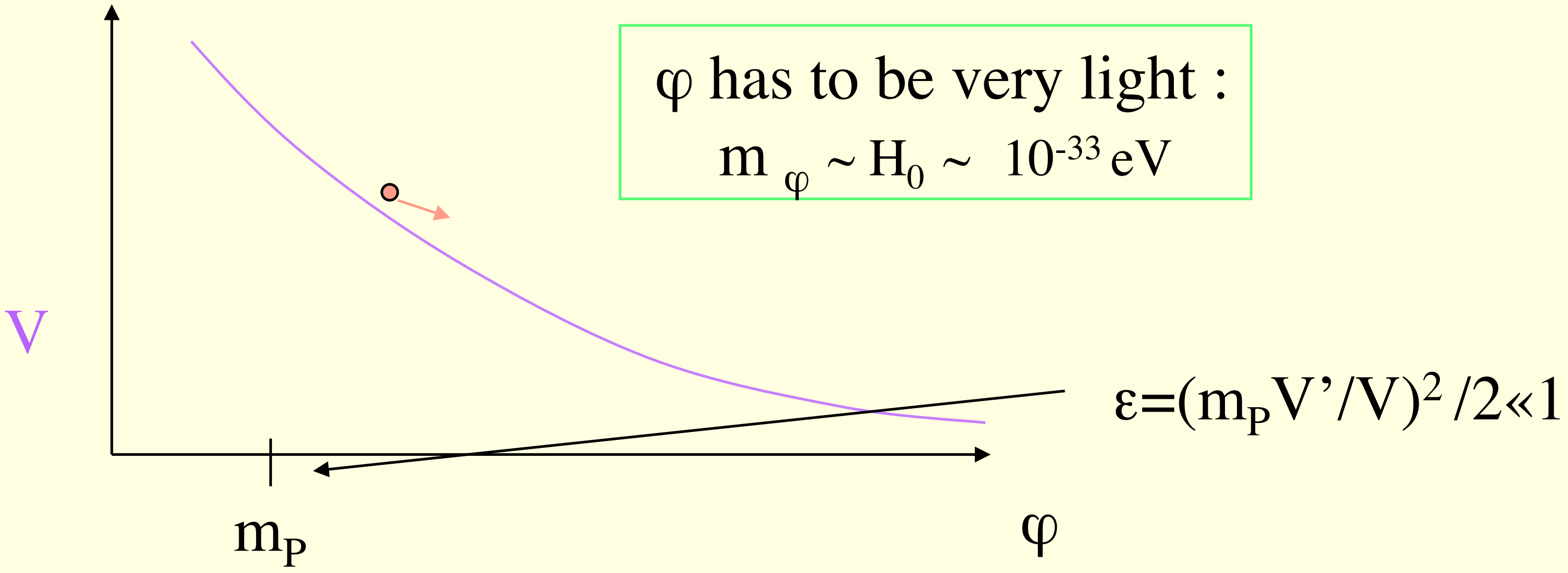
$\varepsilon = (m_P V'/V)^2/2 \ll 1$

$$w = p_\varphi/\rho_\varphi = \frac{\dot{\varphi}^2/2 - V(\varphi)}{\dot{\varphi}^2/2 + V(\varphi)} > -1$$

The problems of scalar field models of dark energy

Example of quintessence :

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)$$



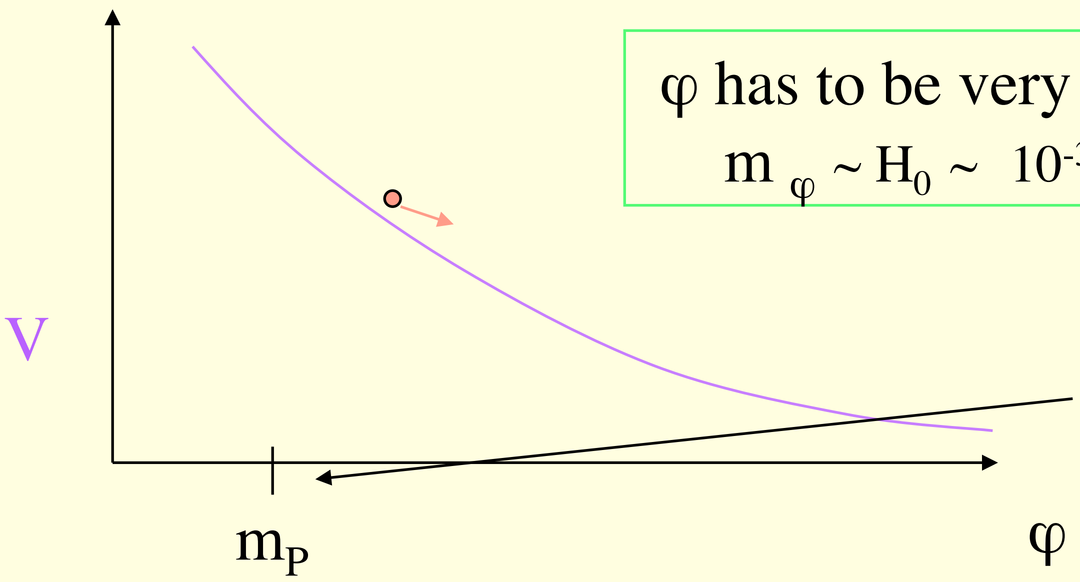
φ has to be very light :
$m_\varphi \sim H_0 \sim 10^{-33}$ eV

$\varepsilon = (m_P V'/V)^2/2 \ll 1$

The problems of scalar field models of dark energy

Example of quintessence :

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)$$

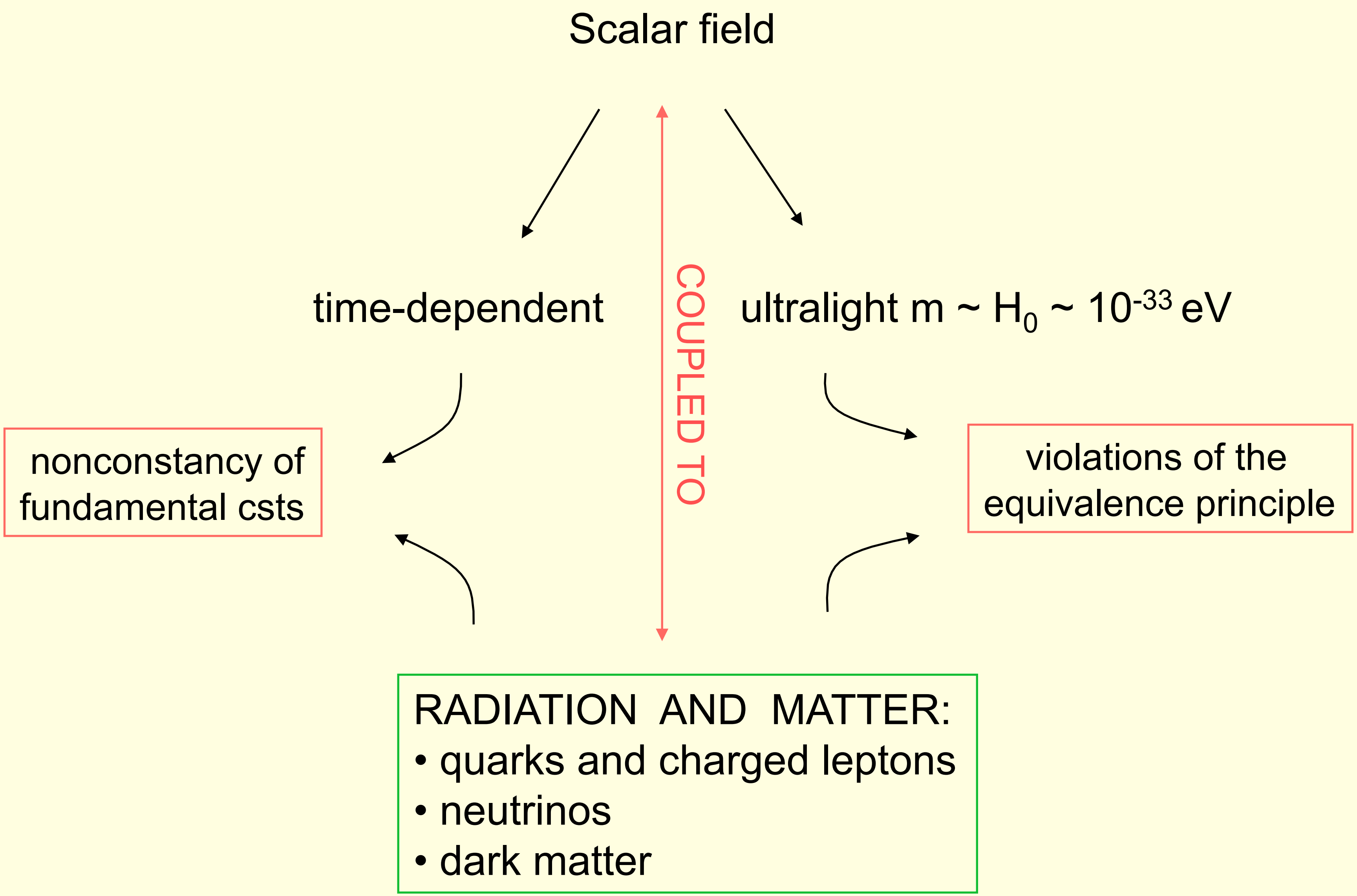


$\varepsilon=(m_P V'/V)^2/2 \ll 1$

φ has to be very light :

$m_\varphi \sim H_0 \sim 10^{-33}$ eV

φ exchange would provide a long range force :
φ has to be extremely weakly coupled to ordinary matter
(more weakly than gravity!)



Scalar field

time-dependent

COUPLED TO

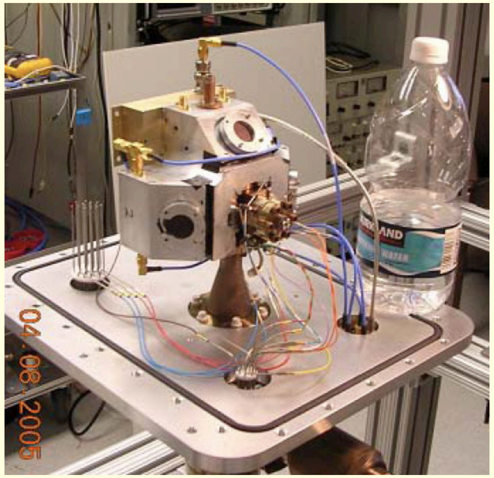
ultralight $m \sim H_0 \sim 10^{-33}$ eV

nonconstancy of fundamental csts

violations of the equivalence principle

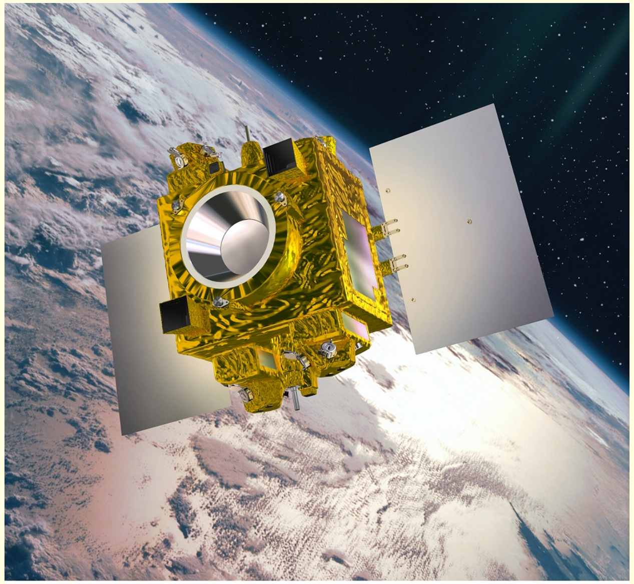
RADIATION AND MATTER:
- quarks and charged leptons
- neutrinos
- dark matter

A rich experimental program will allow to test the models of dark energy through tests of the theory of gravity



Atomic clocks…

MICROSCOPE



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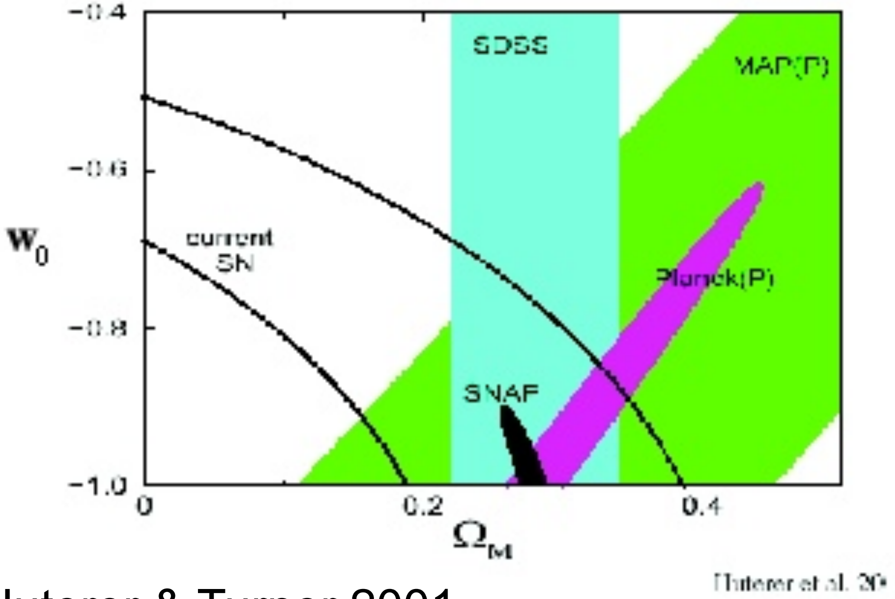
Space missions

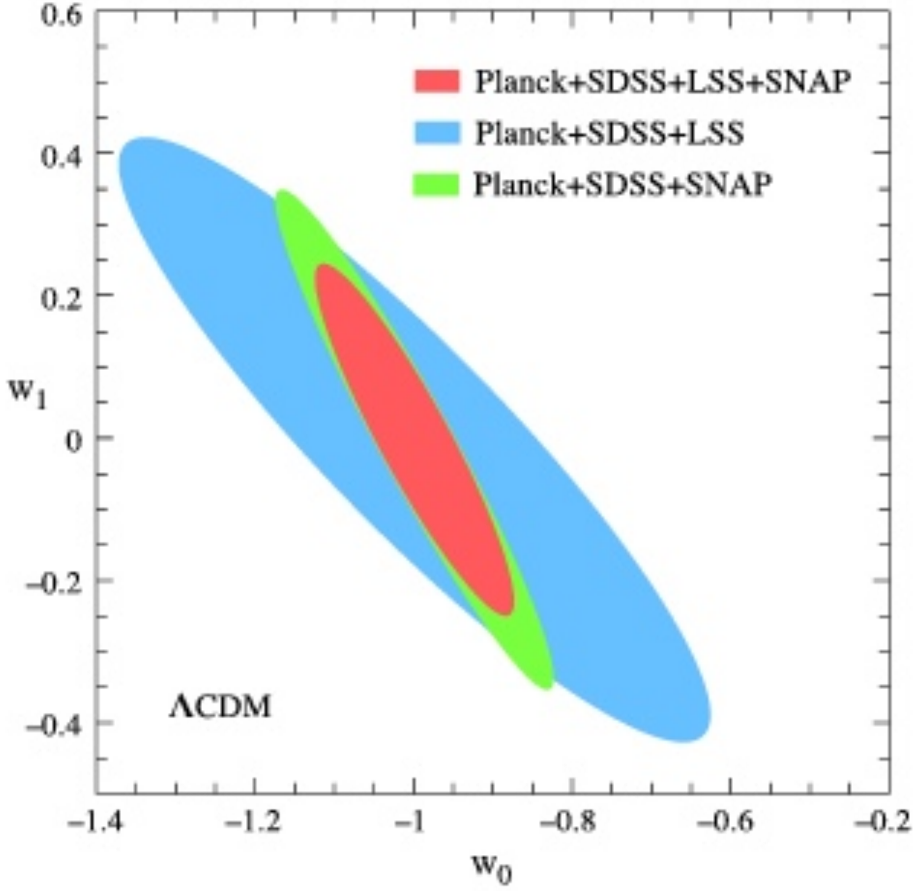
Expected Planck performance on dark energy equation of state

$$w = w_0 + w_1 z$$

Seo & Eisenstein 2003

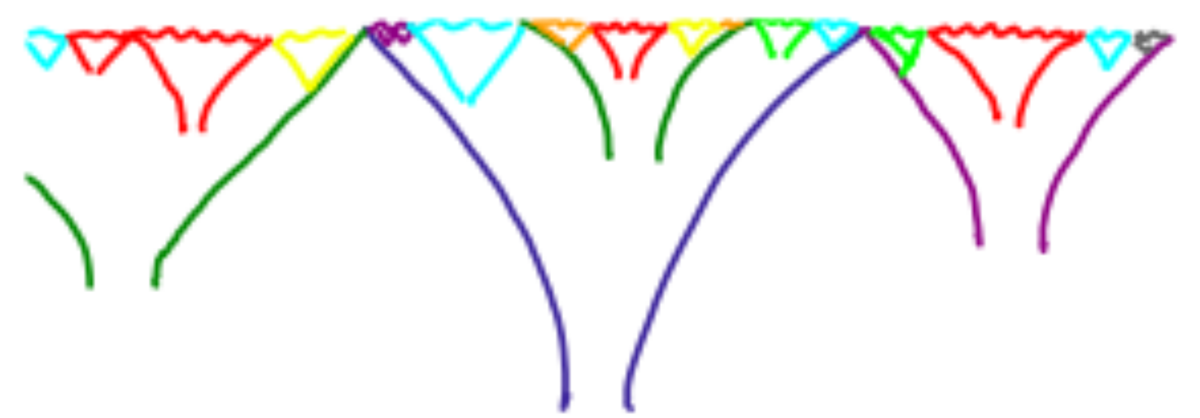


Huterer & Turner 2001



Back to the cosmological constant

A multitude of universes?



Eternal inflation

String theory

Anthropic approach

Vilenkin, Weinberg,Linde,string theorists

Consider regions (universes) with different values of t_G and t_Λ :

- when ρ_Λ starts to dominate (at t_Λ), the Universe enters a de Sitter phase of exponential expansion
- galaxy formation (at t_G) must precede this phase (otherwise no observer available)

Hence $t_G \leq t_\Lambda$

- Regions with $t_\Lambda \gg t_G$ have not undergone yet any de Sitter phase of reacceleration and are thus phase space suppressed compared with regions with $t_\Lambda \sim t_G$:

Hence $t_\Lambda \gtrsim t_G$

$\rho_\Lambda \sim \rho_M$

But

- the precise prediction for λ is larger than what is observed
- the argument does not involve $\hbar$

Conclusion

+	--
A rich array of proposed models	Not so many are complete (problem of interactions of dark energy with the rest of matter)
A rich program of observations and experiments	A lot of interests invested
The issue of dark energy will contribute to the development of large and deep surveys: expect progress for cosmology at large	*The identification of dark energy does not solve the problem of the vacuum energy*

THE END

Other possibility: our observations are prejudiced because we leave in a local inhomogenity

We may live in a « void » of size of a few Gpc

Geometry described locally by a Lemaître-Tolman-Bondi Universe which is isotropic but non-homogeneous

Leads to a dimming of the distant supernovae

We must be close to the centre of the void.