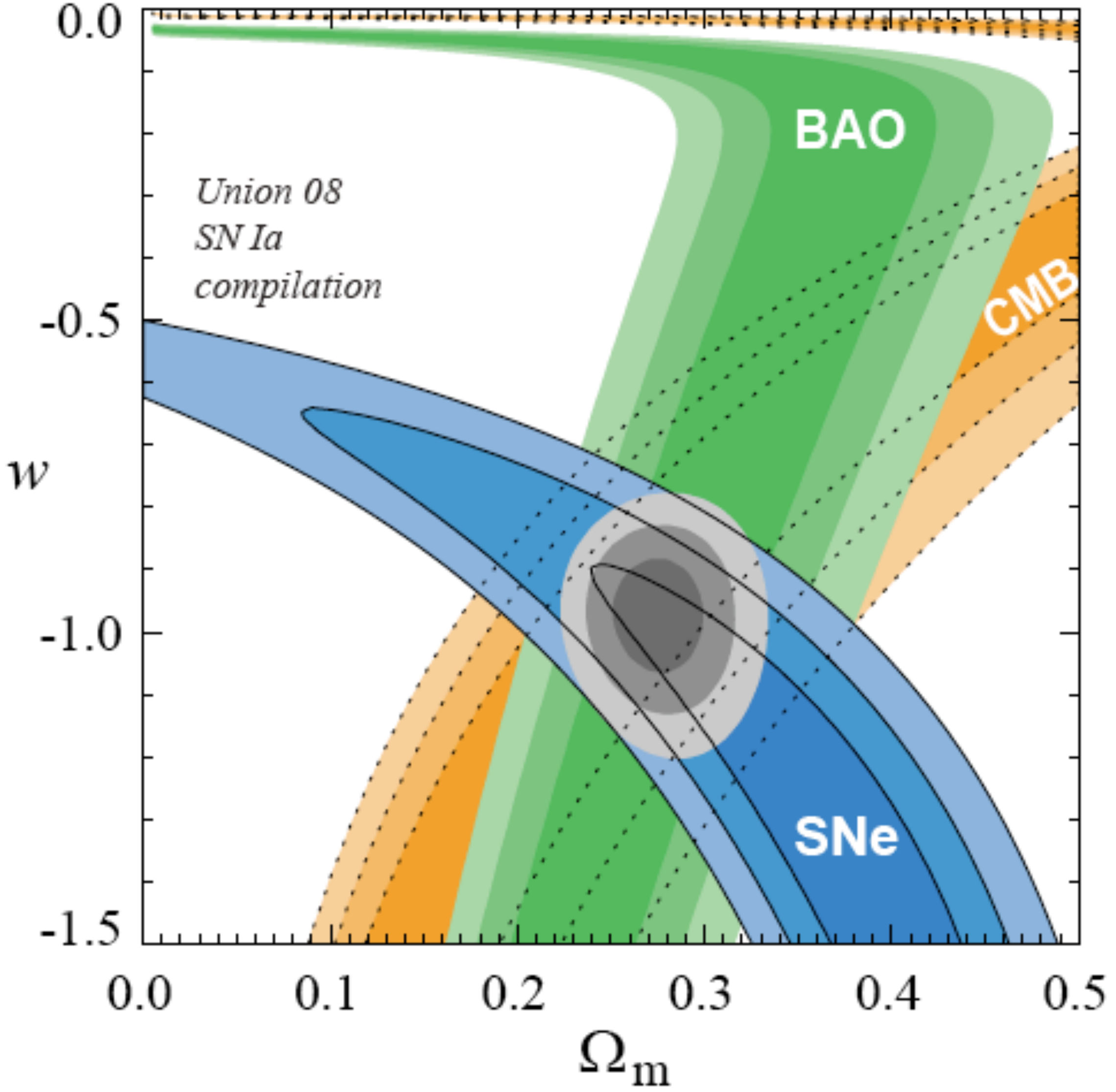
Lecture three:
the Dark Puzzles

The dark side of the Universe

70% of the energy density of the Universe
is in the form of dark energy

Dark Energy



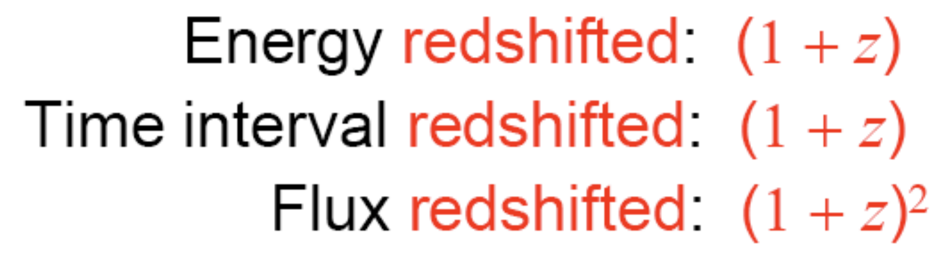
Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)

Distance-Redshift Relation

$$F = \frac{L}{4\pi d_L^2}$$ defines luminosity distance, know L, measure F

$4\pi d_L^2$ area of ${}^2S$ centered on source at time of detection

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right] \Rightarrow \text{area} = 4\pi a_0^2 r^2$$



Energy redshifted: $(1+z)$

Time interval redshifted: $(1+z)$

Flux redshifted: $(1+z)^2$

$$\boxed{d_L^2 = a_0^2 r^2 (1+z)^2}$$

Distance-Redshift Relation

Light travels on geodesics

$$ds^2 = 0 \Rightarrow \int \frac{dr}{\sqrt{1-kr^2}} = \int \frac{dt}{a(t)} = \int \frac{da}{H(a)a^2}$$

$$\int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^z \frac{a^{-1}(t_0)H_0^{-1} \quad dz'}{\sqrt{(1-\Omega_0)(1+z')^2 + \Omega_M(1+z')^3 + \Omega_w(1+z')^{3(1+w)} + \ldots}}$$

Program:

- measure d_L (via $d_L{}^2 = L/4\pi F$) and z
- input a model cosmology (Ω_i) and calculate $a_0\,r$
- compare to data
- need bright “standard candle”

Monastic Chronicles re: Supernova 1006:

> “in 1006 there was a very great famine and a comet appeared for a long time ….”

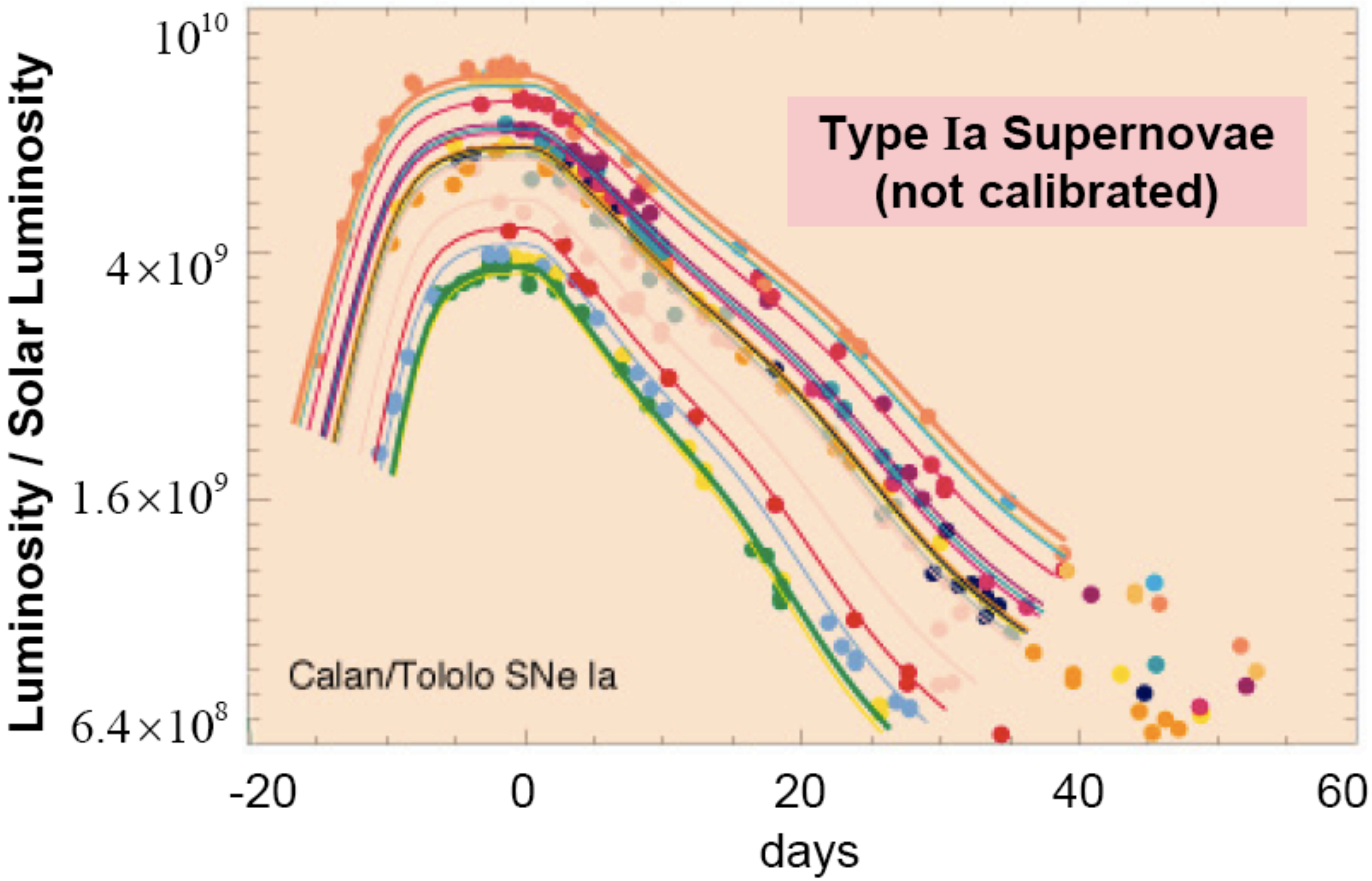
> “at the same time a comet, which always announces human shame, appeared in the southern regions, which was followed by a great pestilence…”

> “three years after the king was raised to the throne, a comet with a horrible appearance was seen in the southern part of the sky, emitting flames this way and that…”

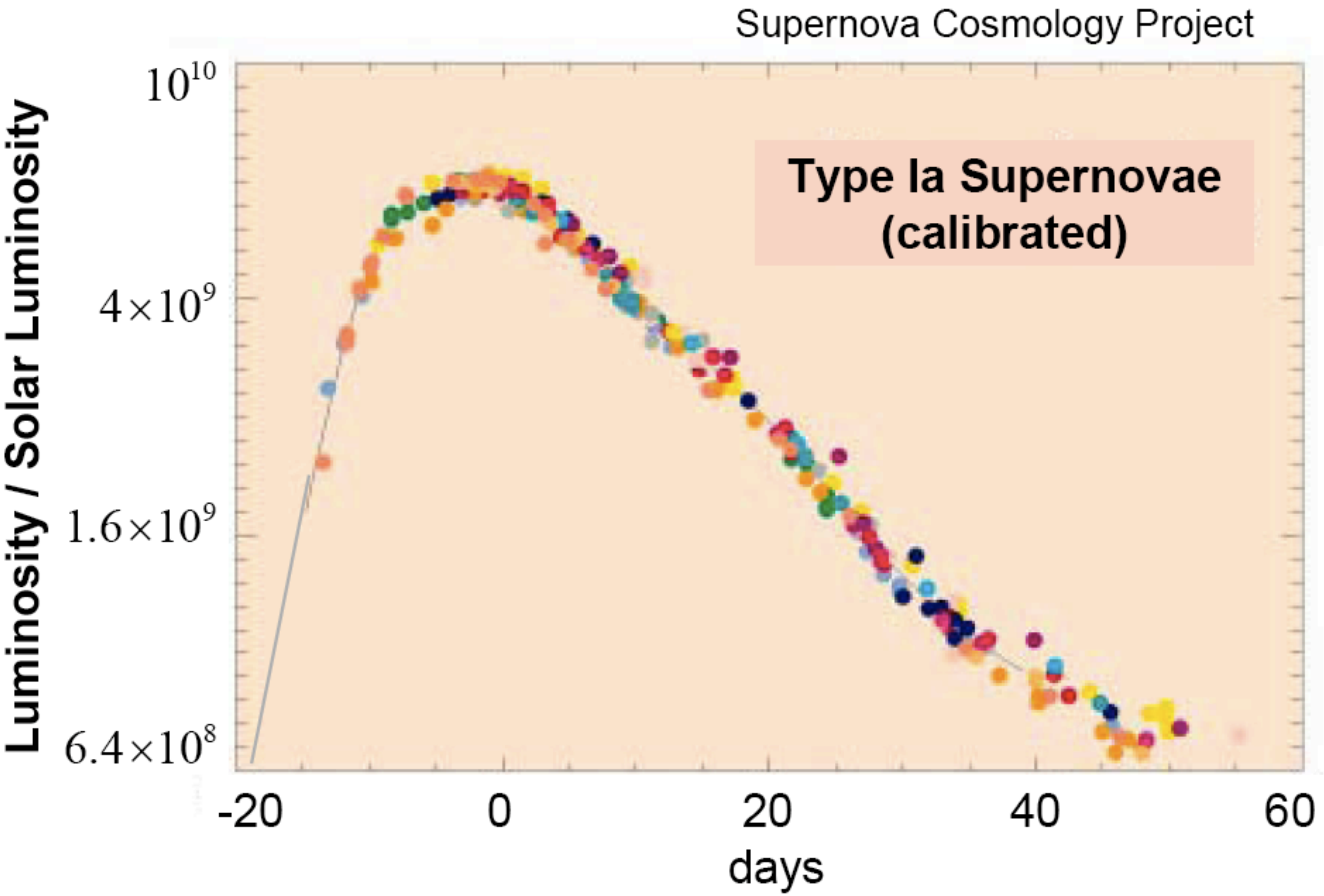
Georg Busch (German painter) in 1572:

> “It is a sign that we will be visited by all sorts of calamities such as inclement weather, pestilence, and Frenchmen.”

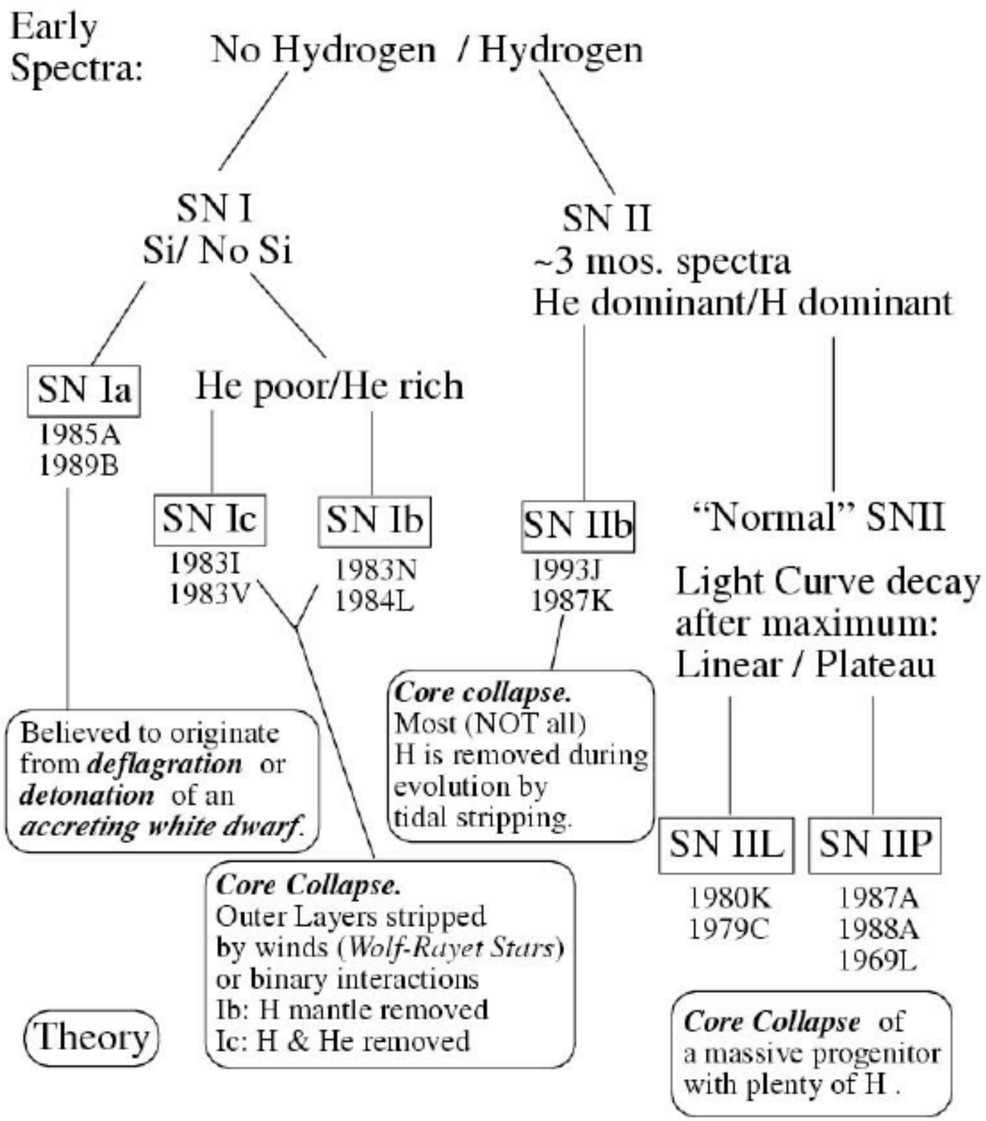
Supernova Cosmology Project



Type Ia Supernovae (not calibrated)


Supernova Cosmology Project
Type Ia Supernovae
(calibrated)
Luminosity / Solar Luminosity
10^{10}
4×10^{9}
1.6×10^{9}
6.4×10^{8}
-20
0
20
40
60
days

Supernova Taxonomy



Early Spectra: No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

"Normal" SNII

Light Curve decay after maximum:
Linear / Plateau

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf***.

Core collapse. Most (NOT all) H is removed during evolution by tidal stripping.

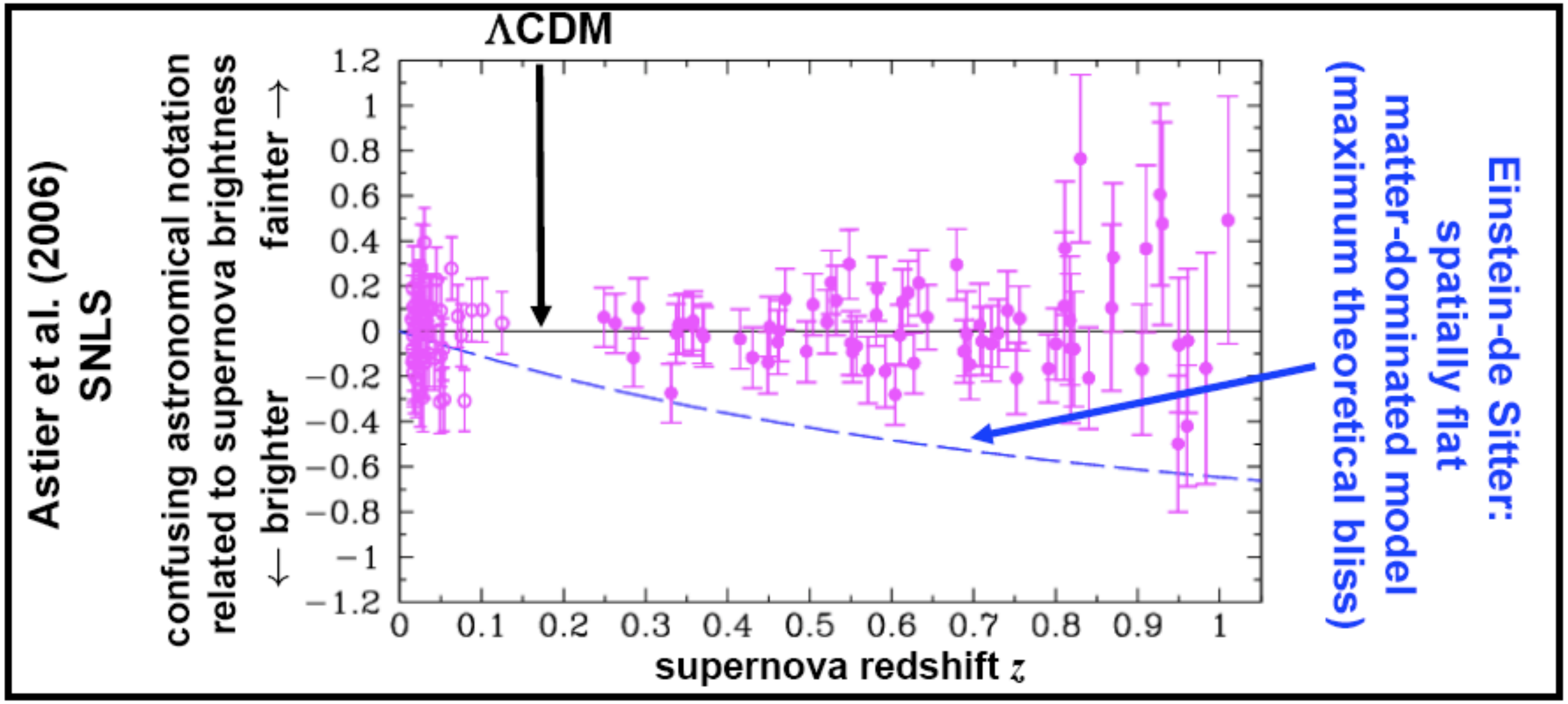
Core Collapse. Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

Core Collapse of a massive progenitor with plenty of H .

Theory

Evidence for Dark Energy

$$
\begin{aligned}
d_L(z) &= \frac{1}{H_0}\left[z + (1-q_0)\frac{z^2}{2} + \left(-j_0 + 3q_0^2 - 1 - \frac{k}{a_0^2 H_0^2}\right)\frac{z^3}{6} + \mathcal{O}(z^4)\right. \\
q &\equiv -(\ddot{a}/a)/H^2, \text{ jerk } j \equiv (\dddot{a}/a)/H^3
\end{aligned}
$$

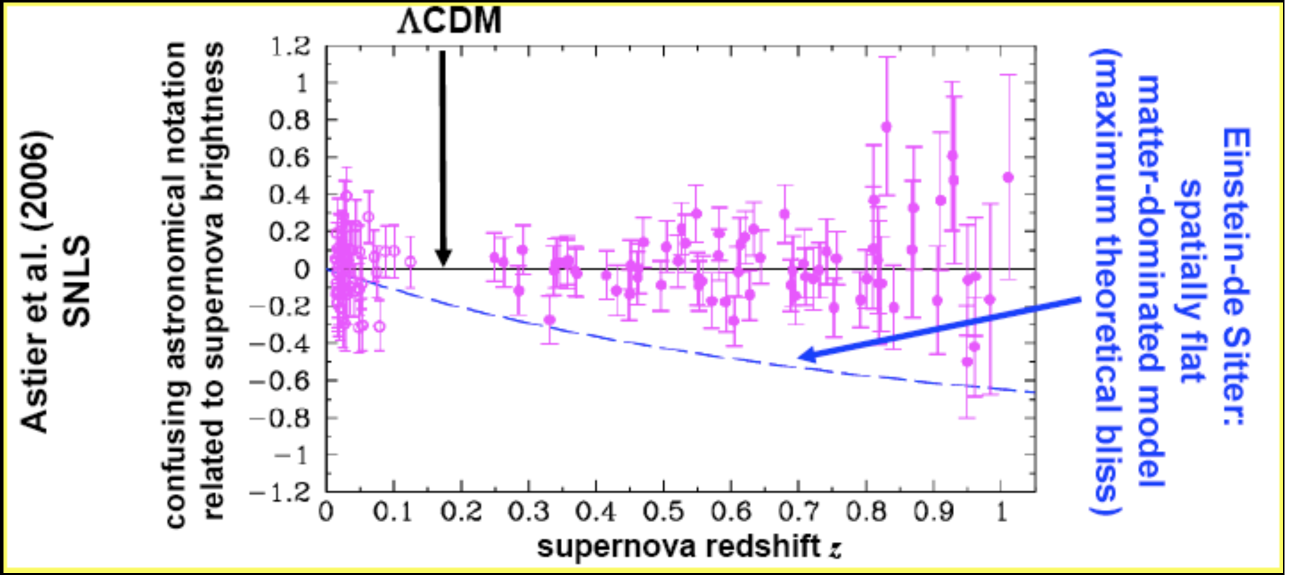


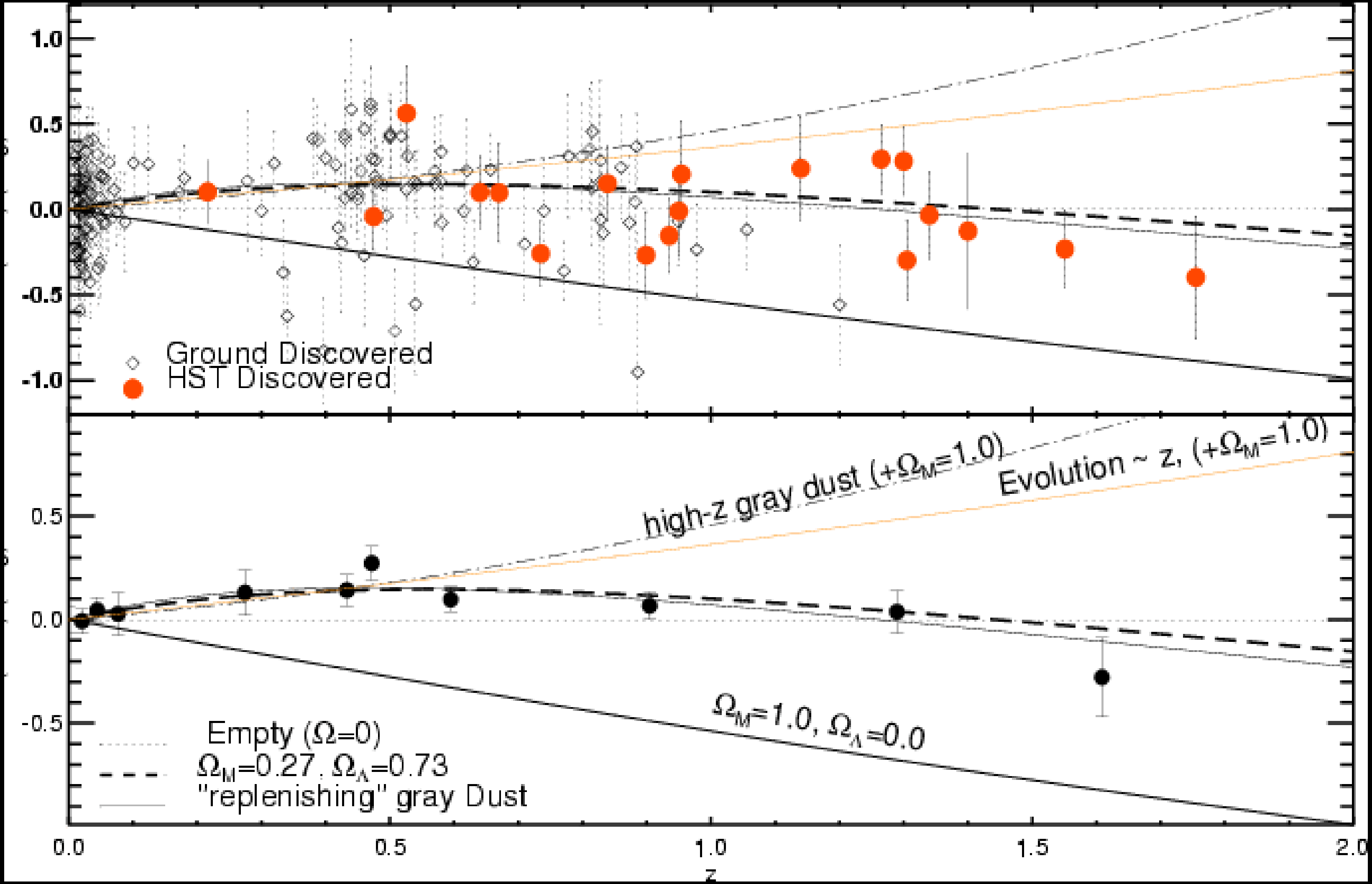
How do we know DE exists?

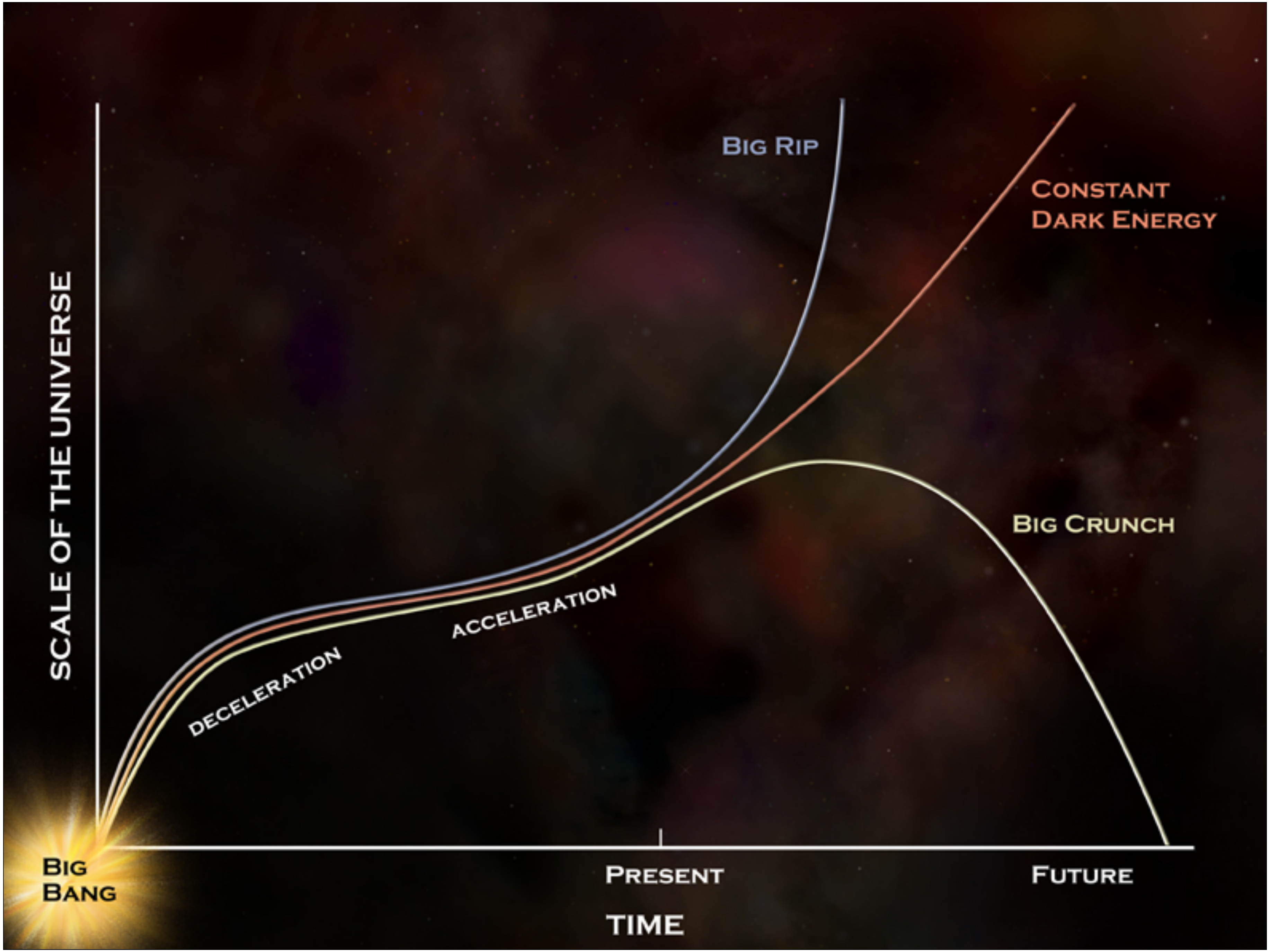
- Assume FRW model of cosmology: $H^2 = 8\pi G\rho/3 - k/a^2$
- Assume energy and pressure content: $\rho = \rho_M + \rho_\gamma + \rho_\Lambda + \cdots$
- Input cosmological parameters
- Compute observables: $d_L(z),\ d_A(z),\ H(z)$
- Model cosmology fits with ρ_Λ, but not without ρ_Λ
- All evidence for DE is INDIRECT : the observed Hubble rate is not the one predicted through all the previous steps

Evidence for Dark Energy

- Hubble Diagram (SNe)
- Baryon acoustic oscillations
- Weak lensing
- Galaxy clusters
- Age of the Universe
- Structure formation




1.0
0.5
0.0
-0.5
-1.0
Ground Discovered
HST Discovered
high-z gray dust (+Ω_M=1.0)
Evolution ~ z, (+Ω_M=1.0)
0.5
0.0
-0.5
Empty (Ω=0)
Ω_M=0.27, Ω_Λ=0.73
"replenishing" gray Dust
Ω_M=1.0, Ω_Λ=0.0
0.0
0.5
1.0
1.5
2.0
z


SCALE OF THE UNIVERSE
BIG RIP
CONSTANT
DARK ENERGY
BIG CRUNCH
DECELERATION
ACCELERATION
BIG
BANG
PRESENT
FUTURE
TIME

Taking sides:

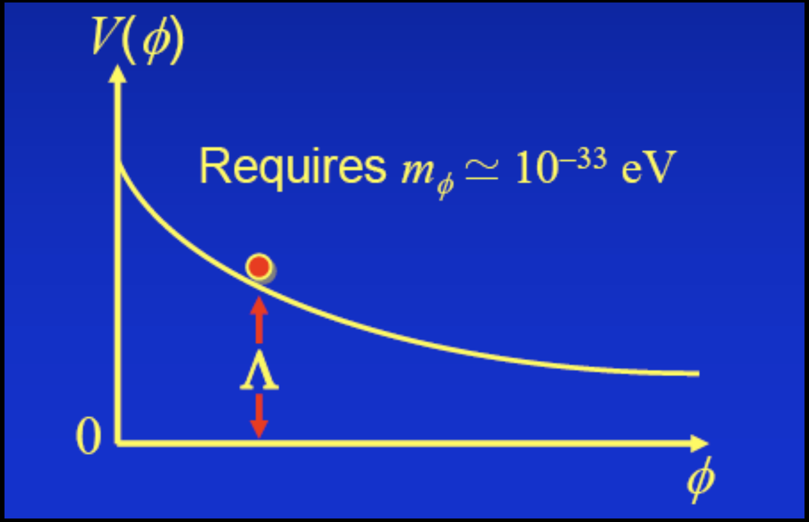
$$\boxed{G_{00}(\mathrm{FRW}) = 8\pi\, G\, T_{00}}$$

1) Modify the RHS of Einstein equations
   - a) Cosmological constant
   - b) Not constant (scalar field)

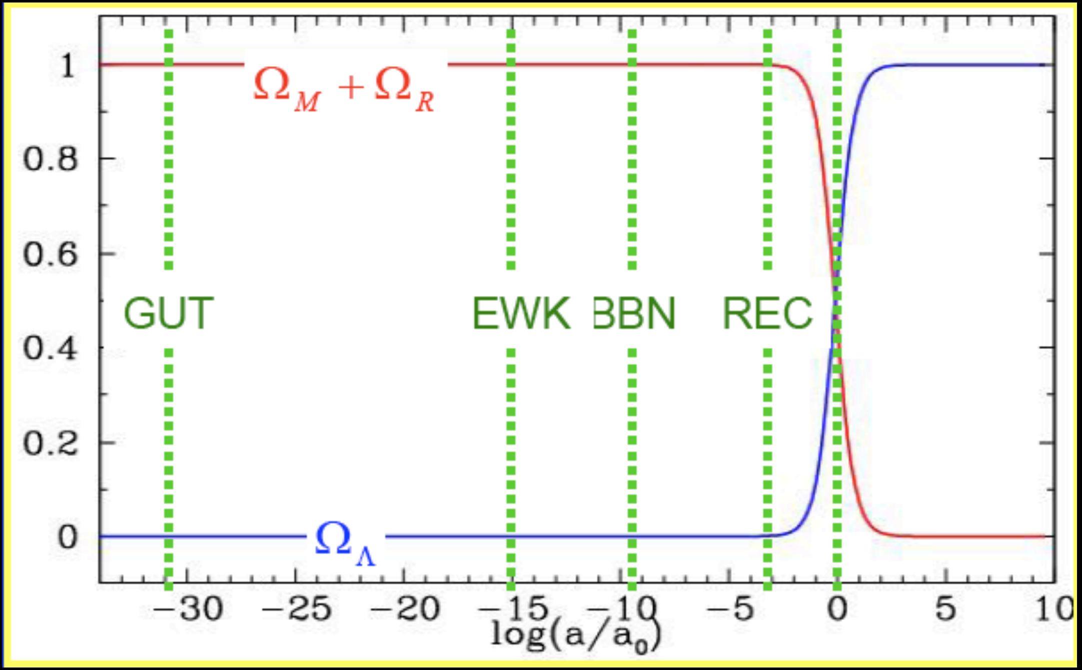
2) Modify the LHS of Einstein equations
   - a) Beyond Einstein (mod. of gravity)
   - b) Just Einstein (BR of inhomog.)

Modify the RHS: CC/Quintessence

- Many possible contributions?
- Why then is the total so small?
- Perhaps some unknown dynamics sets the total CC to zero, but we are not there yet



Why now?


$\Omega_M + \Omega_R$
Ω_Λ
GUT
EWK
BBN
REC
1
0.8
0.6
0.4
0.2
0
−30
−25
−20
−15
−10
−5
0
5
10
$\log(a/a_0)$

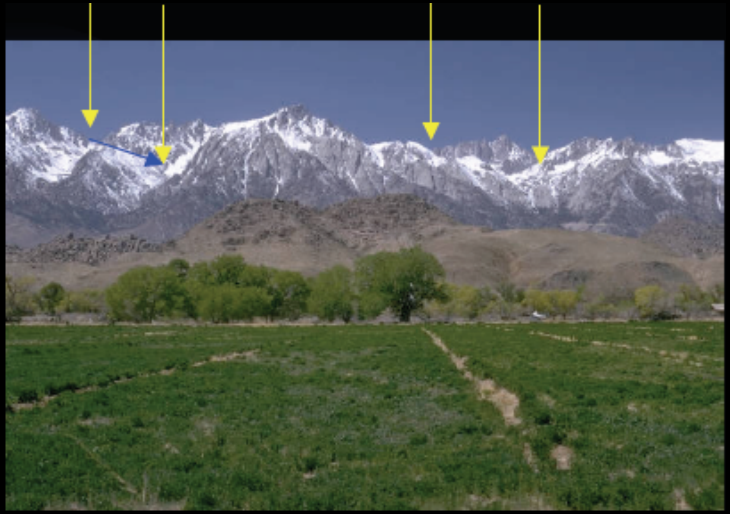
Anthropic/Landscape

- Many sources of vacuum energy
- String Theory has many vacua $> 10^{500}$
- Some of them correspond to a cancellation leading to the observed small cosmological constant

Galaxies require (Weinberg)

$$\Lambda < 10^{-118}\, M_{\rm Pl}^4$$

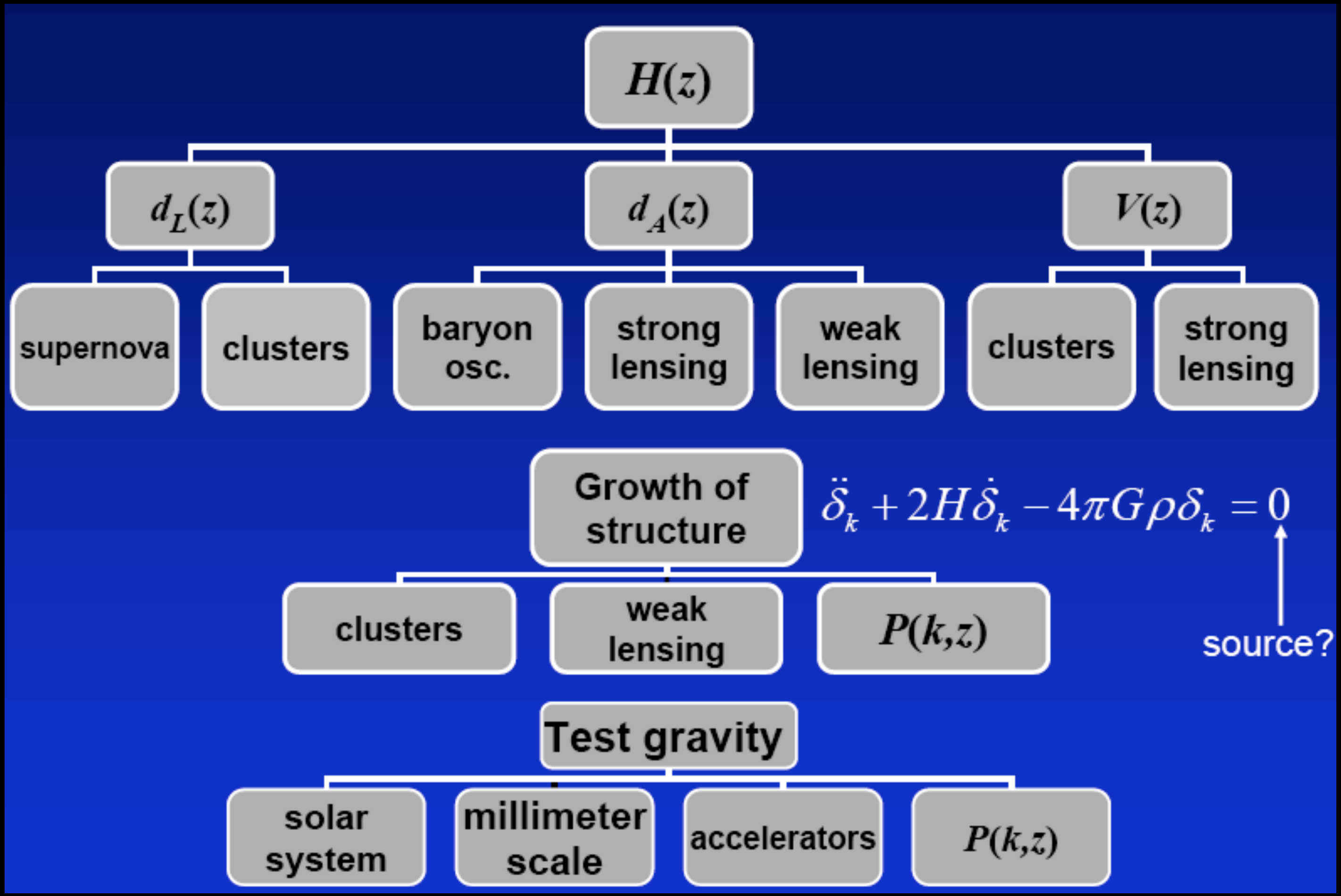
- Although the are exponentially uncommon, they are preferred because...
- More common values of the CC results in an inhospitable Universe



Modify the LHS:
non-standard gravity

$$
\begin{aligned}
F_g &= G_N \frac{m_1 m_2}{r^2} \text{ per } r < r_c \\
F_g &= G_N \frac{m_1 m_2}{r^3} \text{ per } r > r_c
\end{aligned}
$$

Observational strategy



$H(z)$

$d_L(z)$

supernova

clusters

$d_A(z)$

baryon osc.

strong lensing

weak lensing

$V(z)$

clusters

strong lensing

Growth of structure

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho\delta_k = 0$$

source?

clusters

weak lensing

$P(k,z)$

Test gravity

solar system

millimeter scale

accelerators

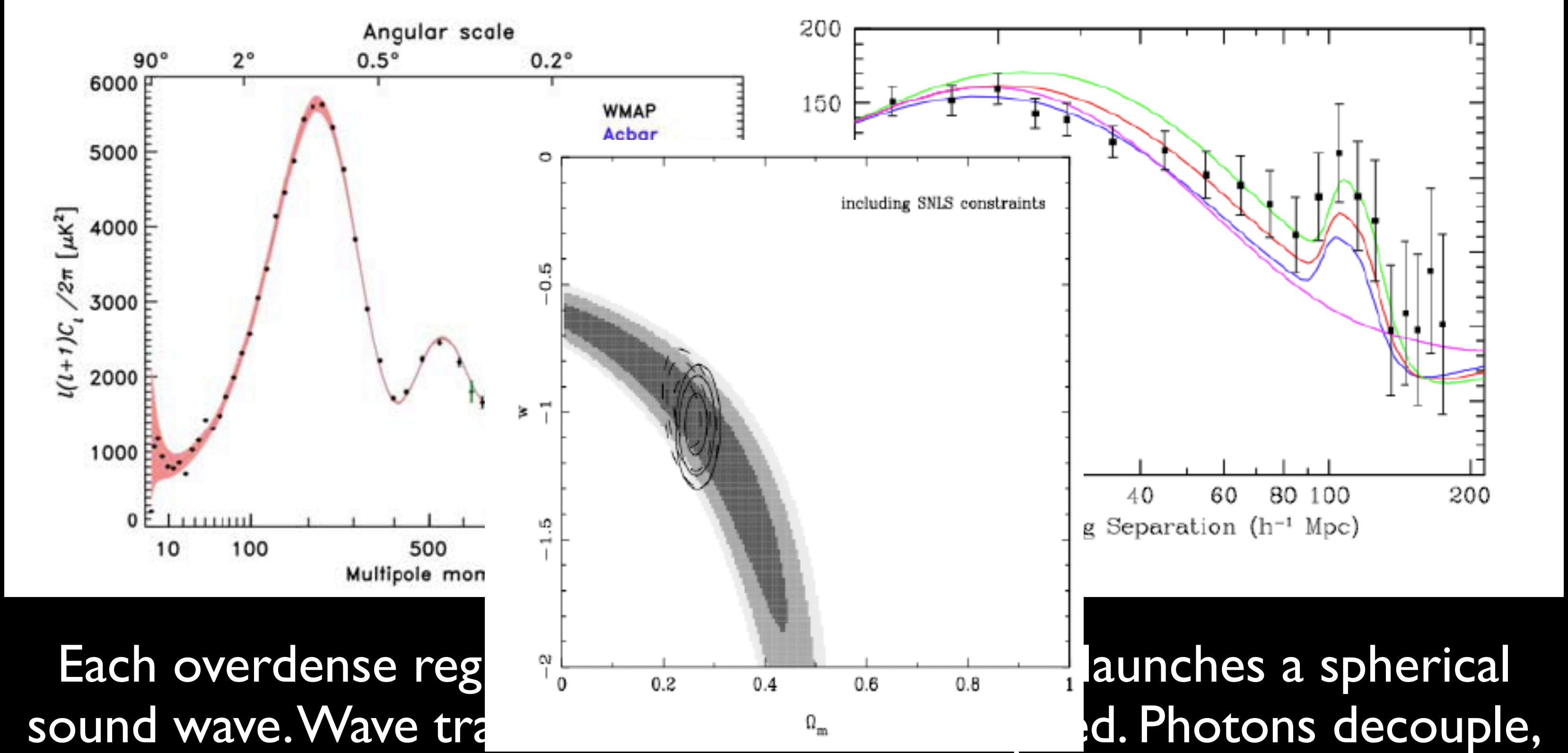
$P(k,z)$

Cosmological Perturbations are sensitive to energy content

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = \frac{3}{2}H^2\delta_m, \;\; \delta_m = \delta\rho_m/\rho_m}$$

Perturbations can be probed at different epochs:
1) CMB, z ~ 1100
2) 21 cm, z ~ 10-20
3) Ly-alpha forest, z ~ 2-4
4) Weak lensing, z ~ 0.3-2
5) Galaxy clustering, z ~ 0-2

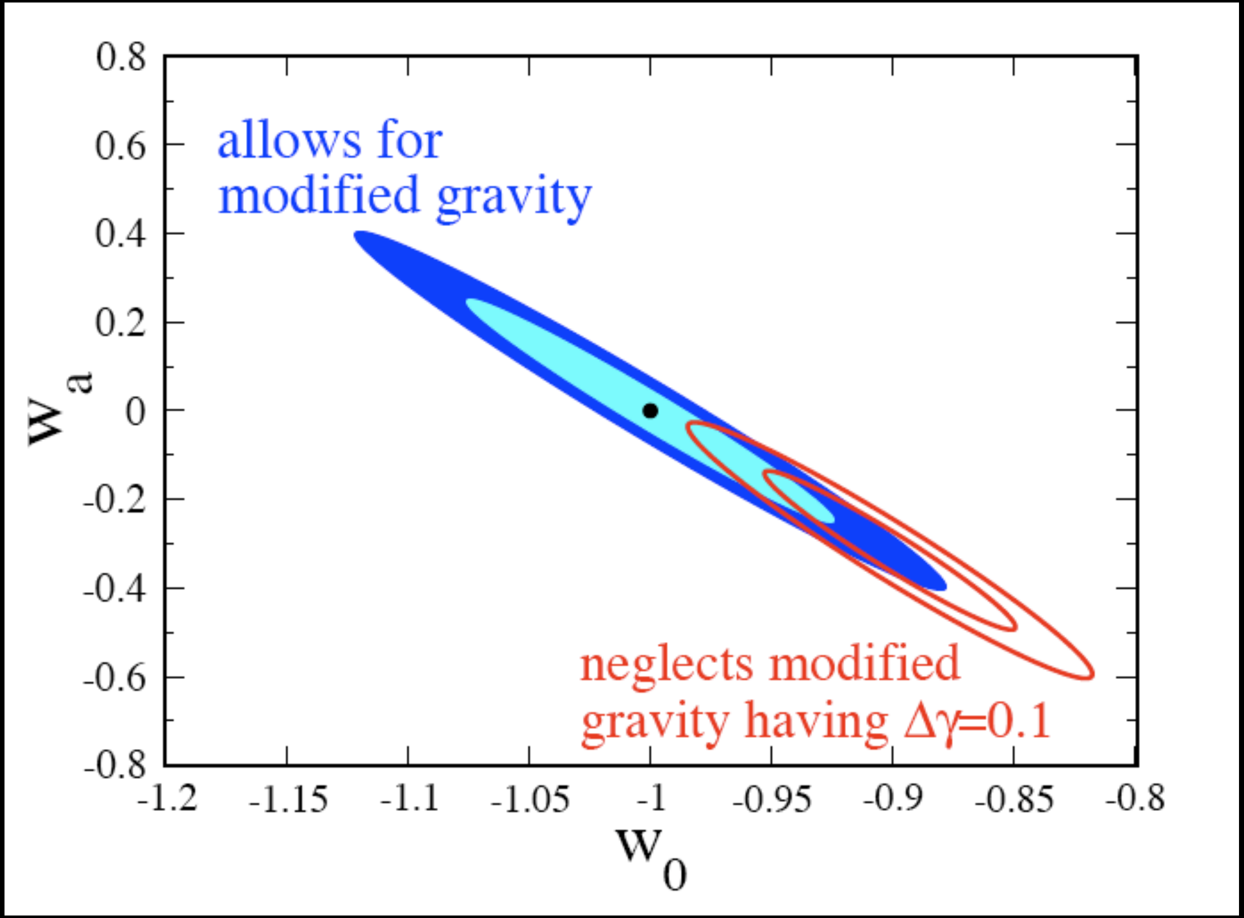
Acustic Baryonic Oscillations



Each overdense reg launches a spherical sound wave. Wave tra ed. Photons decouple, travel to us and are observable as CMB acoustic peaks. For matter, sound speed plummets, wave stalls, total distance travelled 150 Mpc imprinted on power spectrum.

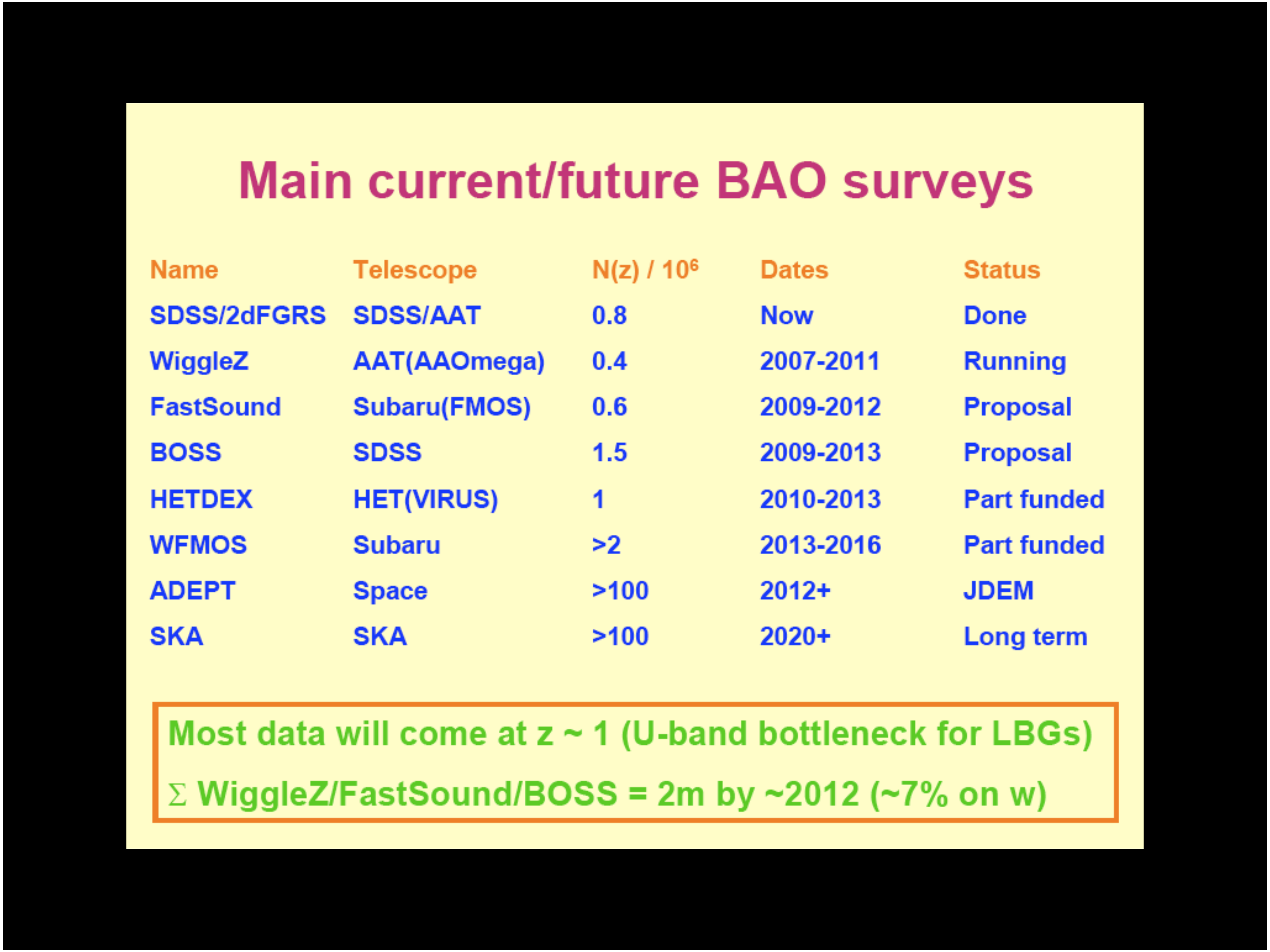
DE enters in the determination of the angular distance

$$w(a) = w_0 + (1 - a)w_a$$



$$g(a) \equiv \delta_m/a = e^{\int_0^a d\ln a' \left[\Omega_M^\gamma(a') - 1\right]}$$

D. Huterer, E. Linder, 2005



Main current/future BAO surveys

Name	Telescope	$N(z) / 10^6$	Dates	Status
SDSS/2dFGRS	SDSS/AAT	0.8	Now	Done
WiggleZ	AAT(AAOmega)	0.4	2007-2011	Running
FastSound	Subaru(FMOS)	0.6	2009-2012	Proposal
BOSS	SDSS	1.5	2009-2013	Proposal
HETDEX	HET(VIRUS)	1	2010-2013	Part funded
WFMOS	Subaru	>2	2013-2016	Part funded
ADEPT	Space	>100	2012+	JDEM
SKA	SKA	>100	2020+	Long term

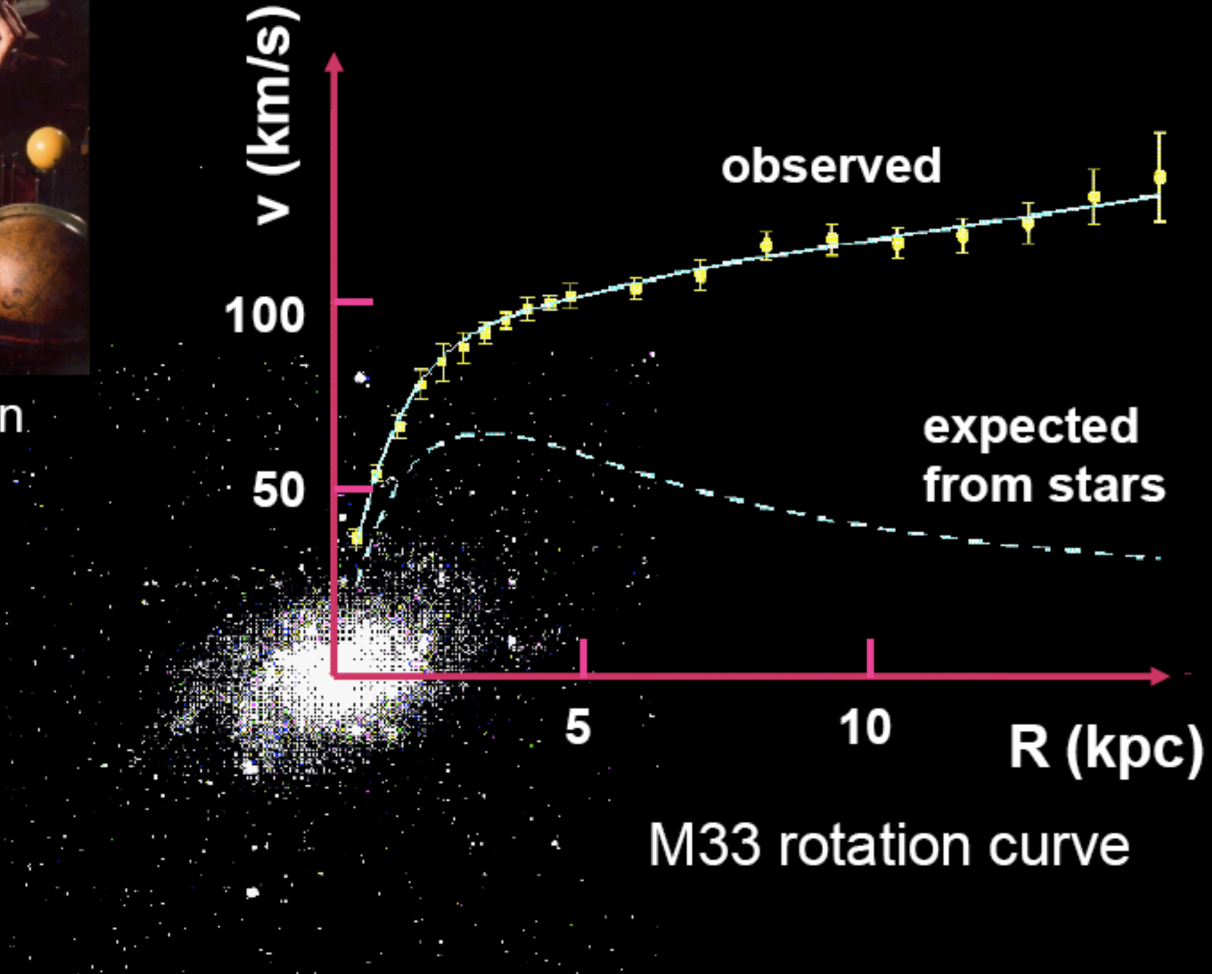
Most data will come at $z \sim 1$ (U-band bottleneck for LBGs)

Σ WiggleZ/FastSound/BOSS = 2m by ~2012 (~7% on w)

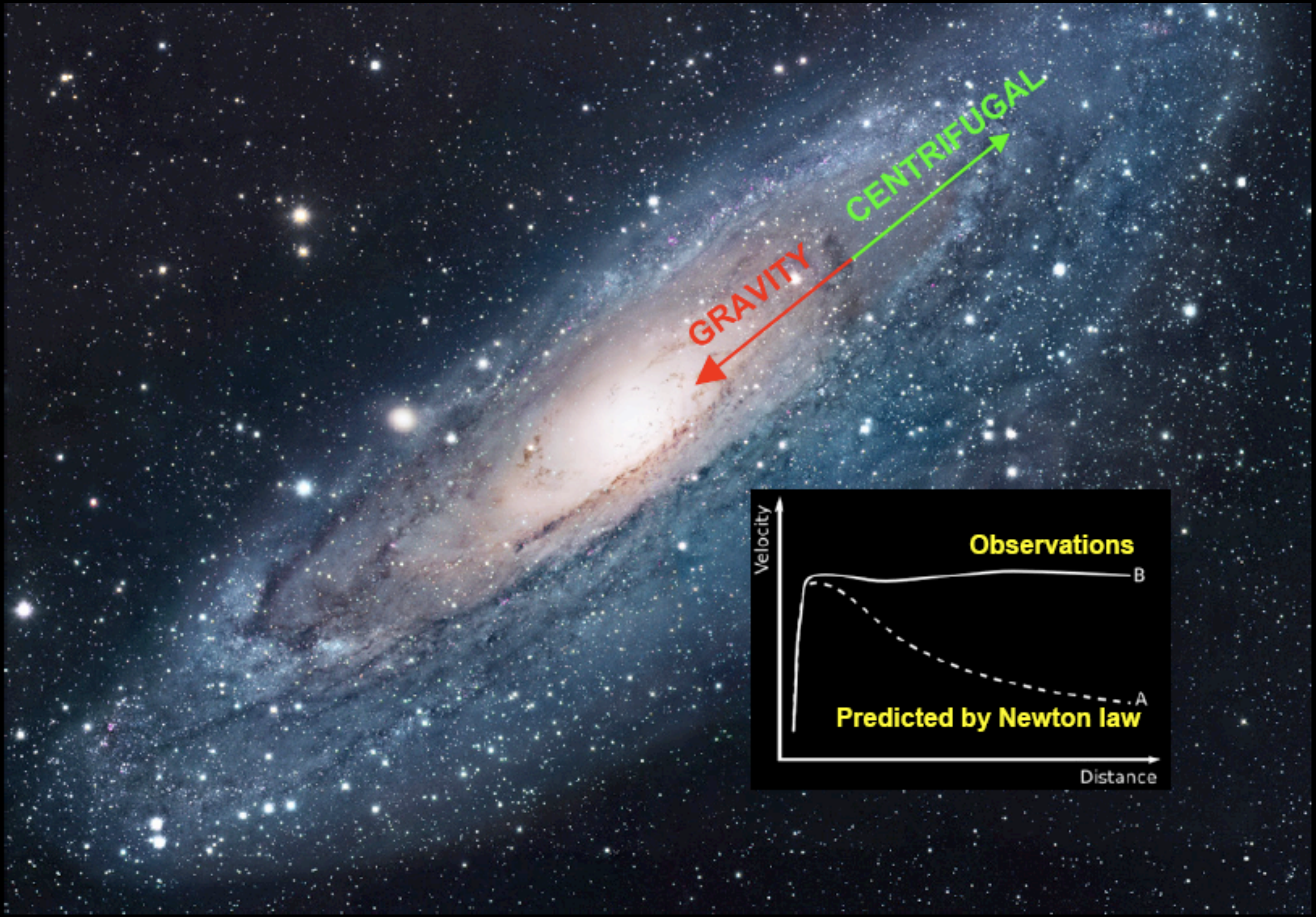
Dark Matter

The Dark Universe

Vera Rubin

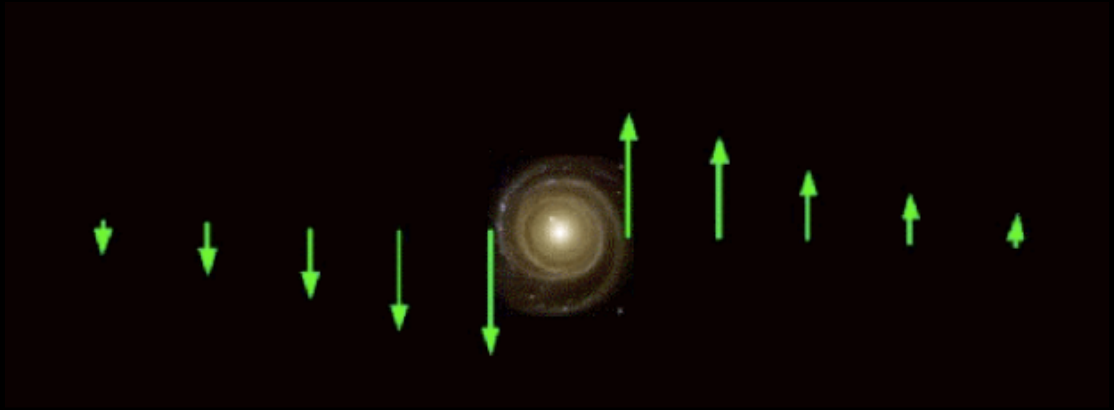


M33 rotation curve

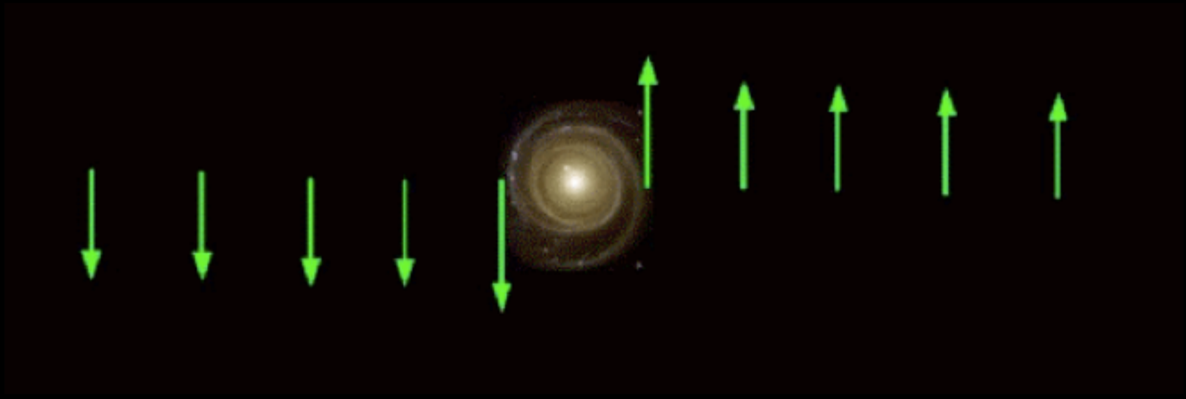


The Andromeda Galaxy (M31)

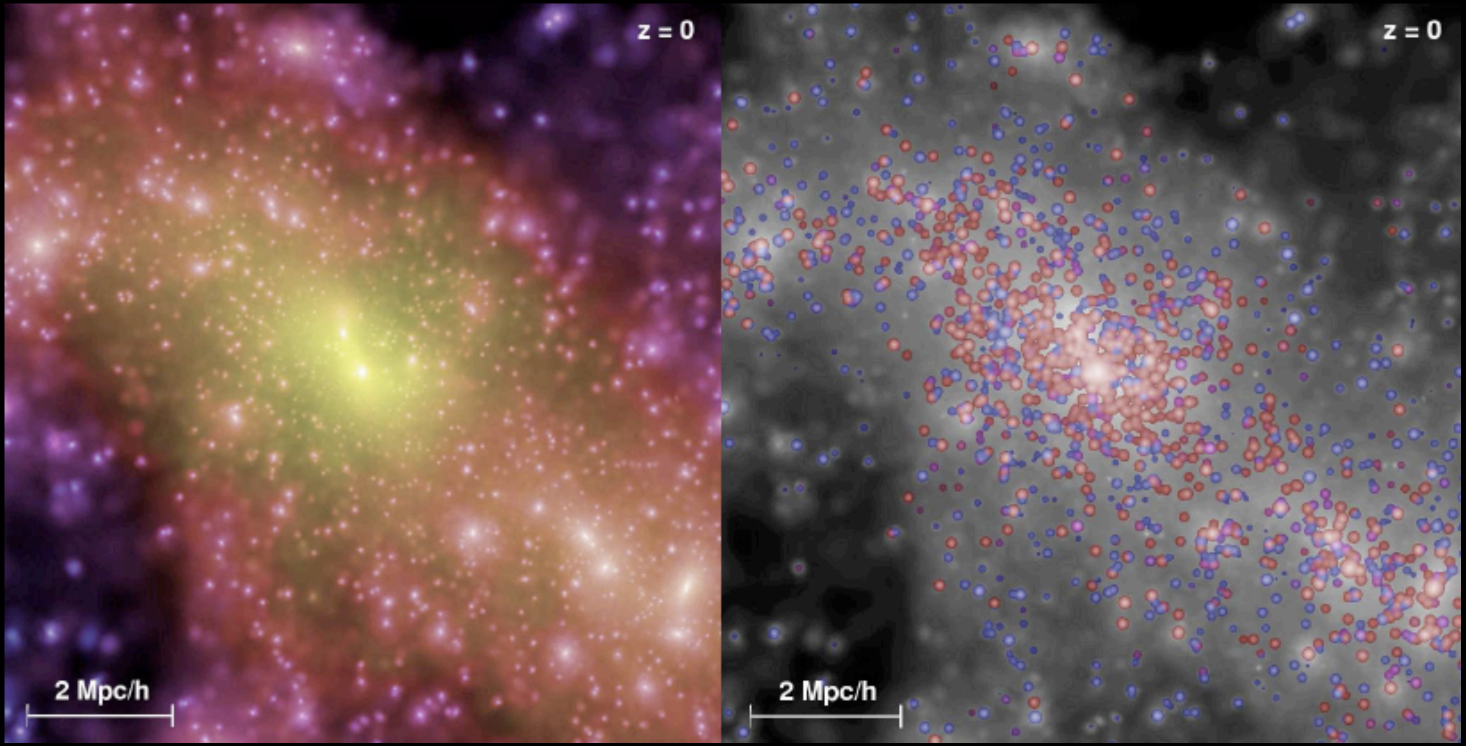
What we should see



What we do see



Dark Matter halo: $10^{14} M_\odot$

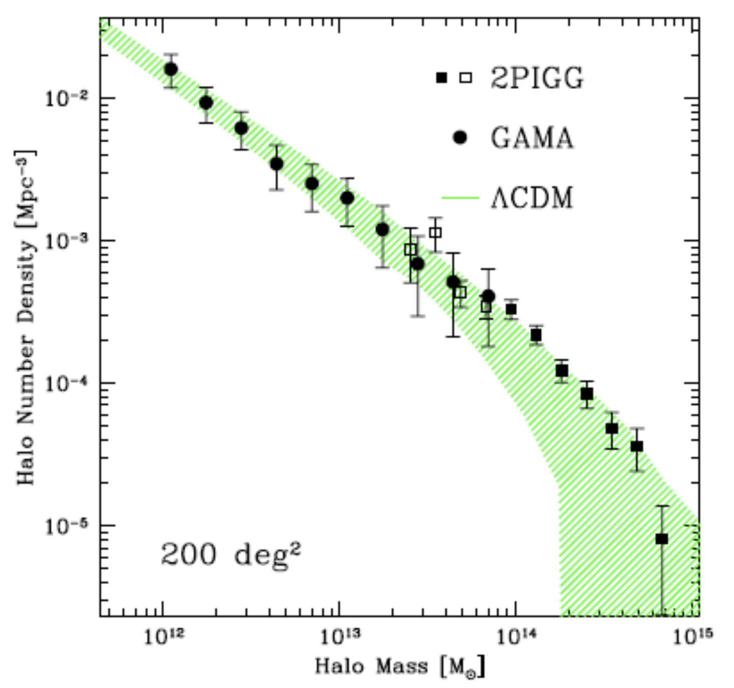


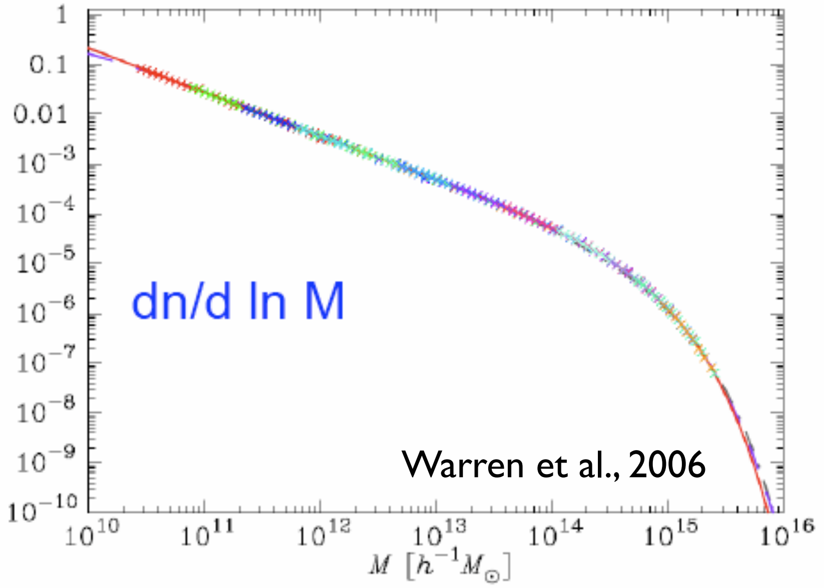
Dark Matter

Galaxies

The Millenium Simulation Project:

How dark matter mass is distributed



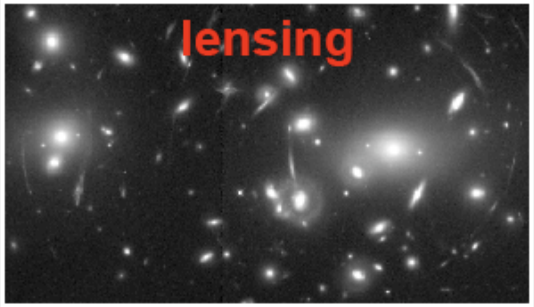


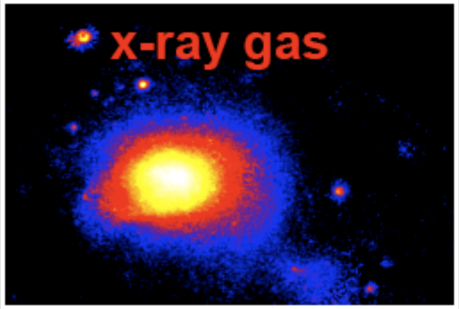
Warren et al., 2006

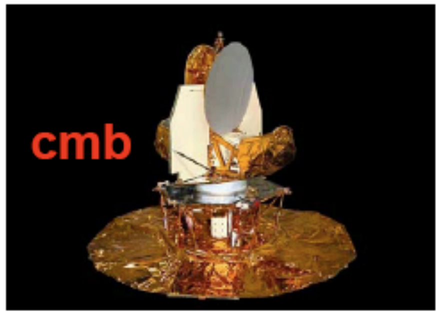
At present the knowledge of the halo mass function comes mainly from N-body simulations

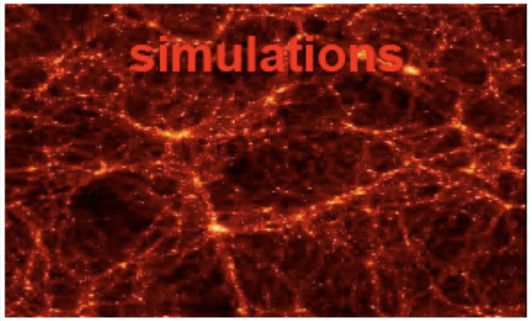
$\Omega_M \sim 0.3$

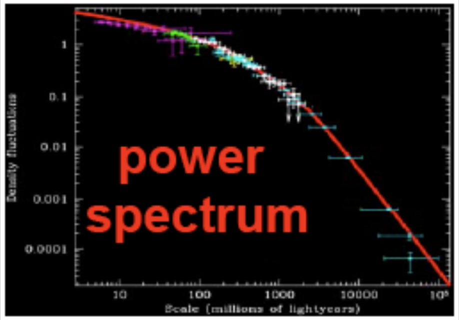

dynamics


lensing

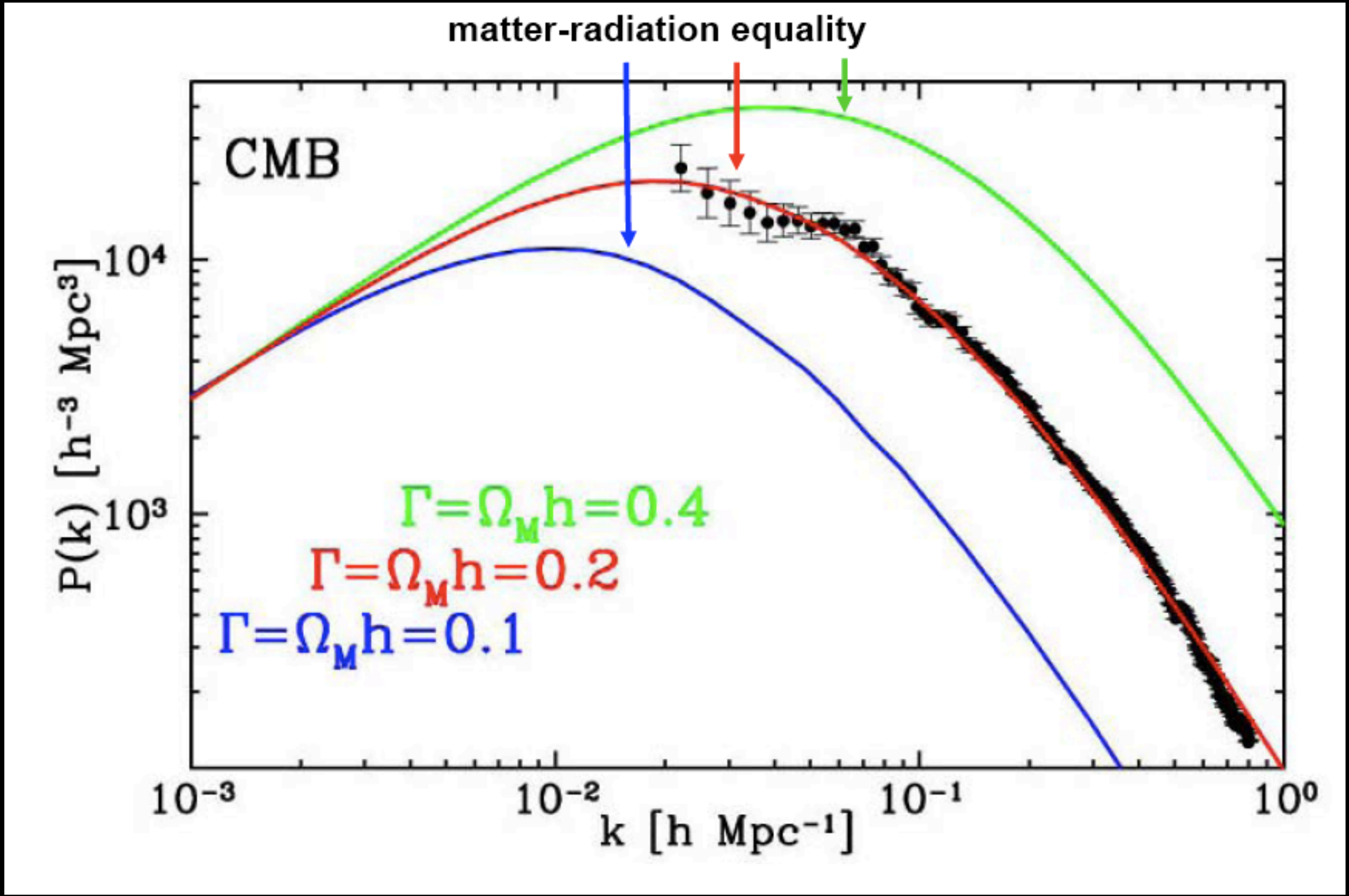

x-ray gas


cmb


simulations

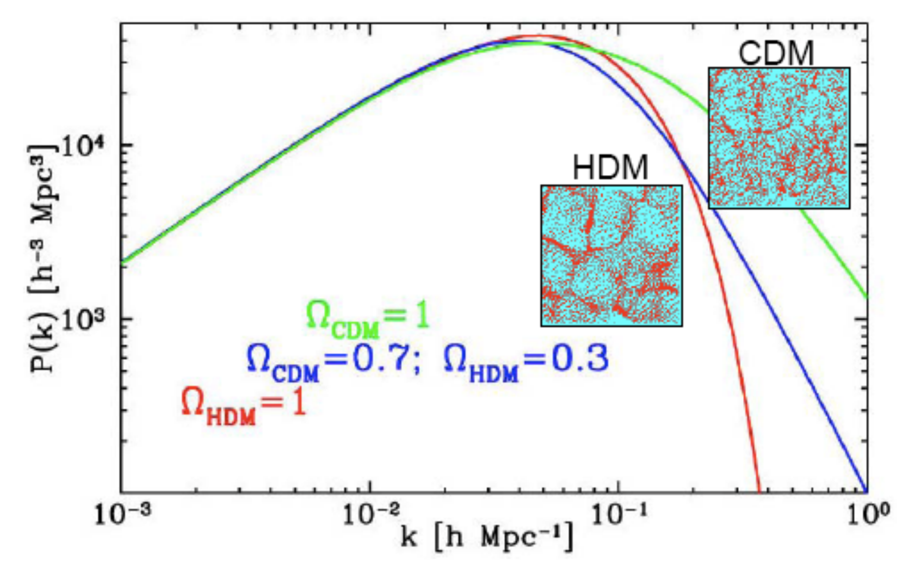

power spectrum

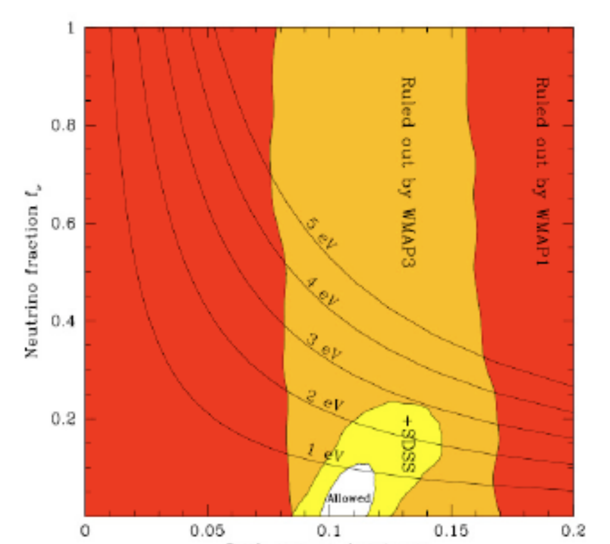
Power spectrum for CDM



Particle Dark Matter

DM is not in the form of ligh massive neutrinos



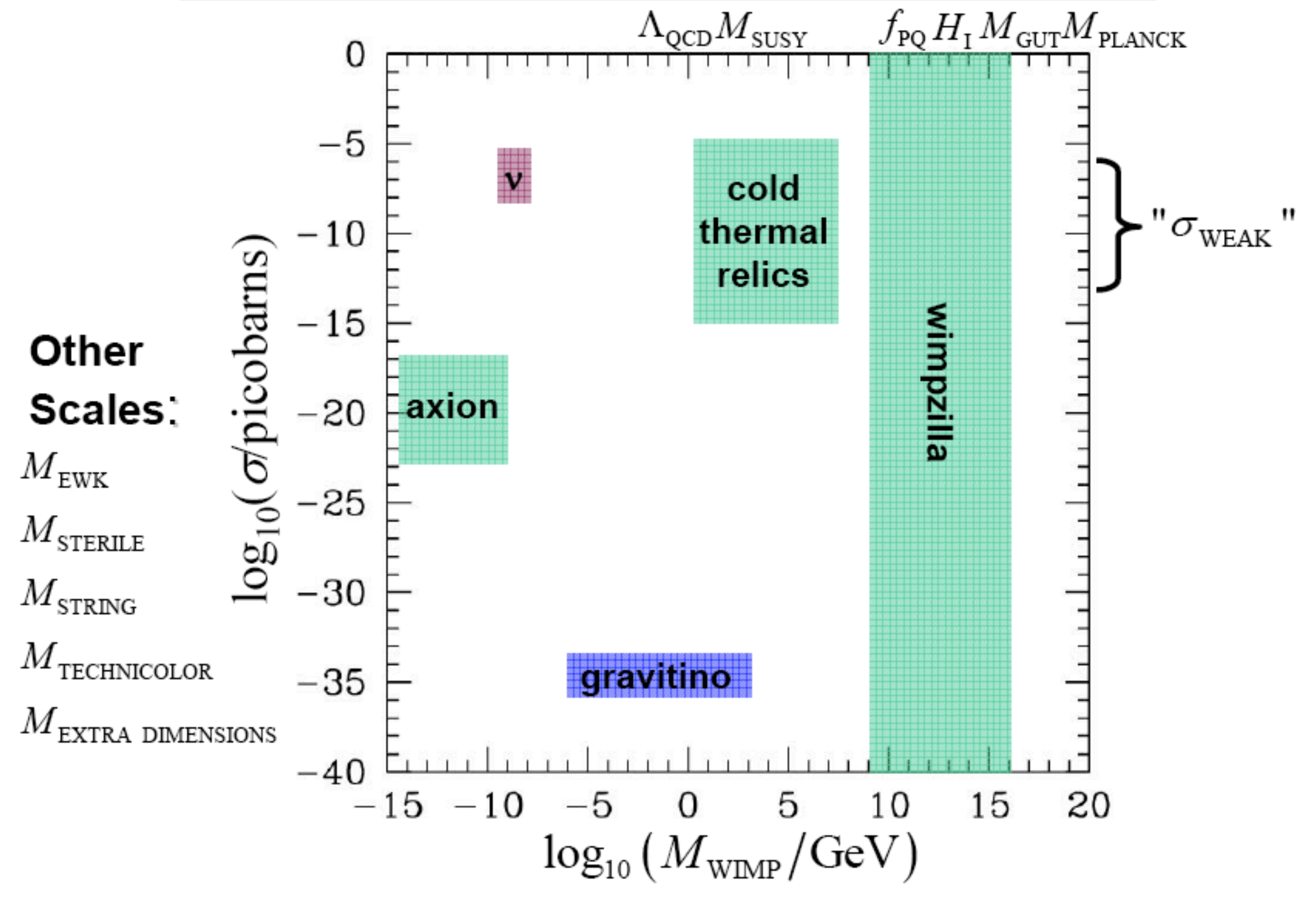


Tegmark et al., SDSS

Known facts

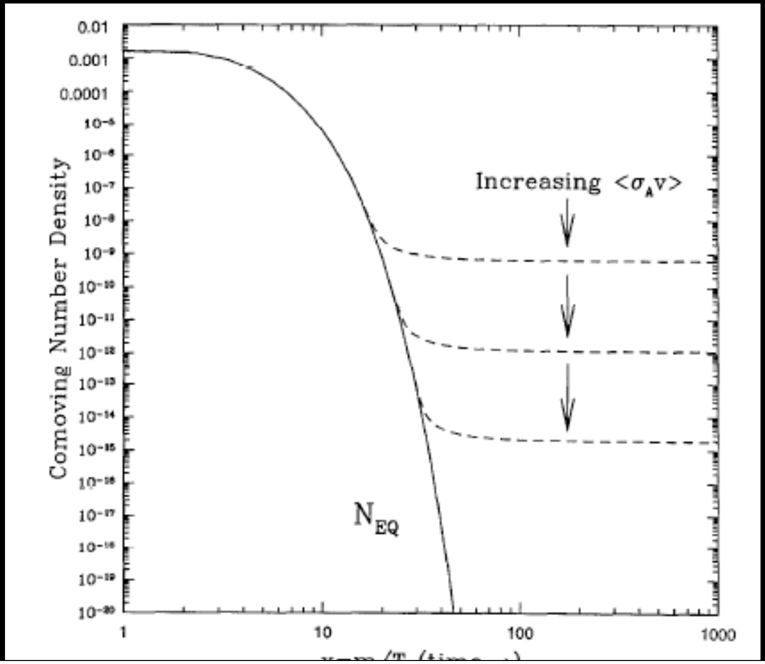
- Must be cold: by the time of matter-radiation equality and until now, DM must be nonrelativistic and clump together by gravitational attraction
- must be neutral
- WIMP paradigm

Particle DM candidates



Thermal relic

- Thermal equilibrium when T>m
- Once T<m, no more WIMPs created
- If stable, the only way to lose them is by annihilation
- Universe expands: at some point comoving number of WIMPs freeze out



Order of magnitude estimate

$$\begin{aligned} H &\sim g_*^{1/2}\frac{T^2}{M_p} \\ \Gamma_{\rm ann} &\simeq \langle\sigma_{\rm ann}v\rangle n \\ H(T_f) &\simeq \Gamma_{\rm ann} \\ n &\simeq g_*^{1/2}\frac{T_f^2}{M_p\langle\sigma_{\rm ann}v\rangle} \\ Y &= \frac{n}{s}\simeq g_*^{-1/2}\frac{1}{M_P T_f\langle\sigma_{\rm ann}v\rangle} \end{aligned}$$

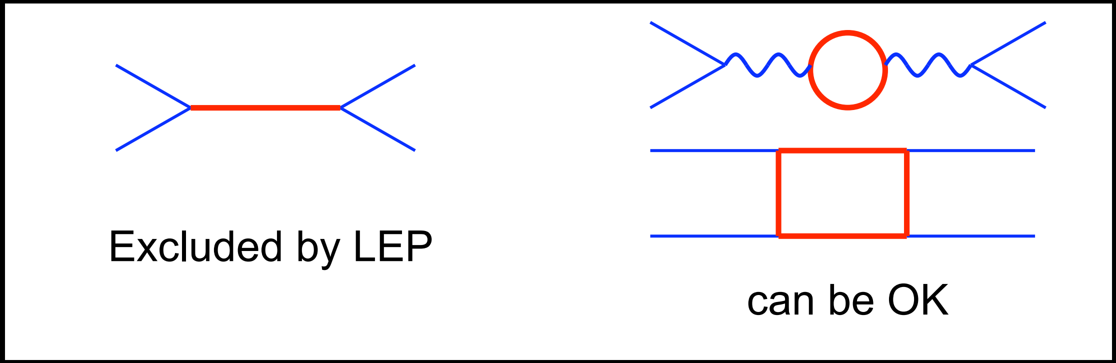
$$\boxed{\Omega\sim(0.2-0.3)\Rightarrow\langle\sigma_{\rm ann}v\rangle\simeq 10^{-9}\,{\rm GeV}^{-2}\simeq\frac{\pi\alpha^2}{m^2}\ \text{for}\ m\simeq 300\ {\rm GeV}}$$

Coincidence or evidence for new physics at TeV scale?
Impossible to overestimate the discovery of DM at LHC

Lot of uncertainties

- Thermal history of the Universe above nucleosynthesis unknown
- DM may be non-thermal
- Hubble rate at freeze-out may depend on DE
- Astrophysical uncertainties affect indirect searches

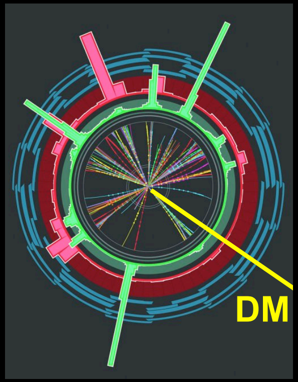
Most viable new theories at EW scale have a DM candidate



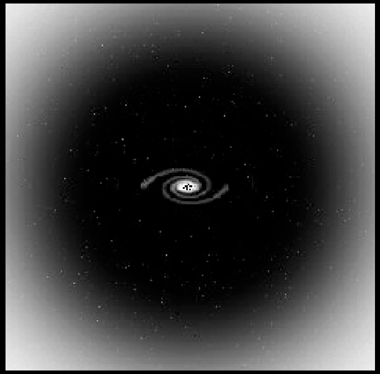
Discrete symmetry (R,T,KK) makes the lightest particle stable

Supersymmetry, Little Higgs, extra-dimensions have a DM candidate

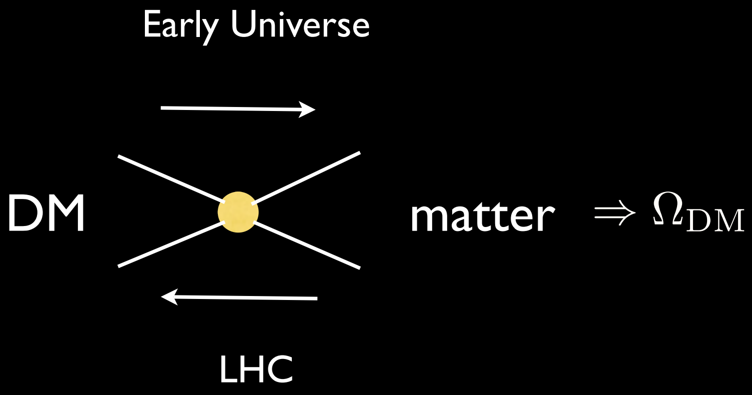
How can LHC establish that a new discovery is theDM of the Universe?



1) Excess of missing energy



2) Reconstructing DM abundance



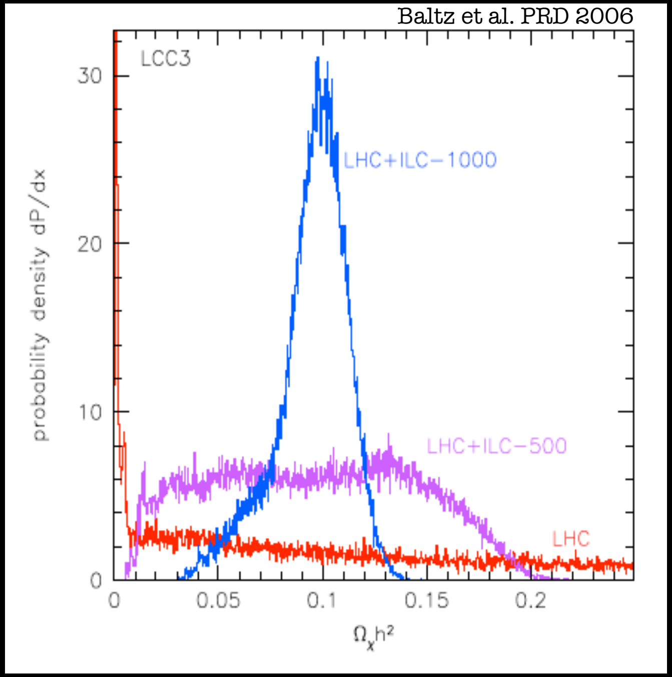
Early Universe

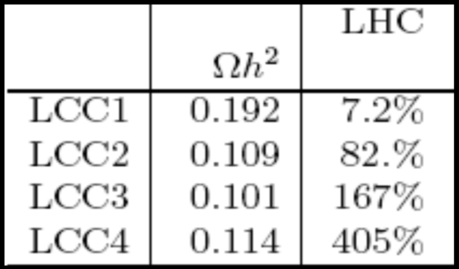
DM matter $\Rightarrow \Omega_{\rm DM}$

LHC

Warning:
LHC will not provide all the answers
&
will explore DM candidates in a limited energy range

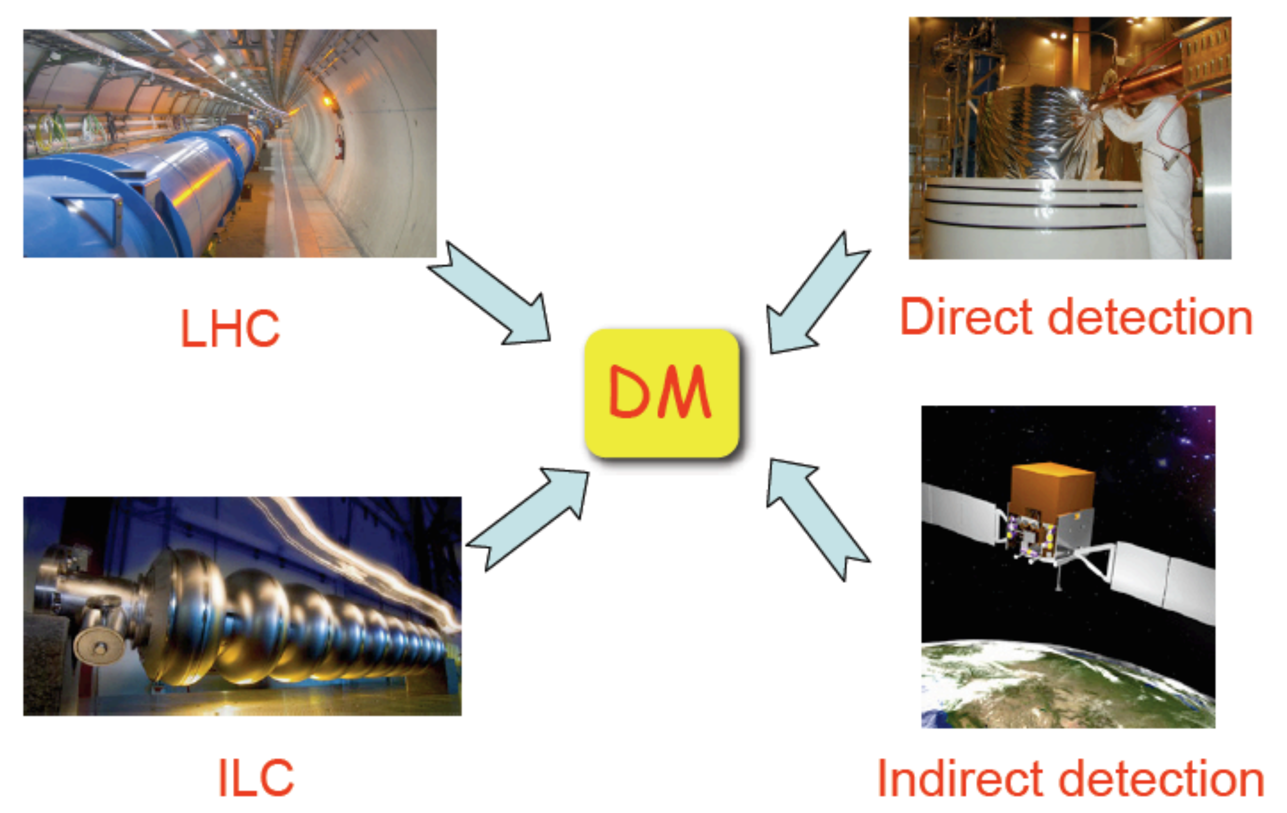
- Even if SUSY particles are discovered, it will be challenging to reconstruct the abundance


Baltz et al. PRD 2006



	Ωh^2	LHC
LCC1	0.192	7.2%
LCC2	0.109	82.%
LCC3	0.101	167%
LCC4	0.114	405%

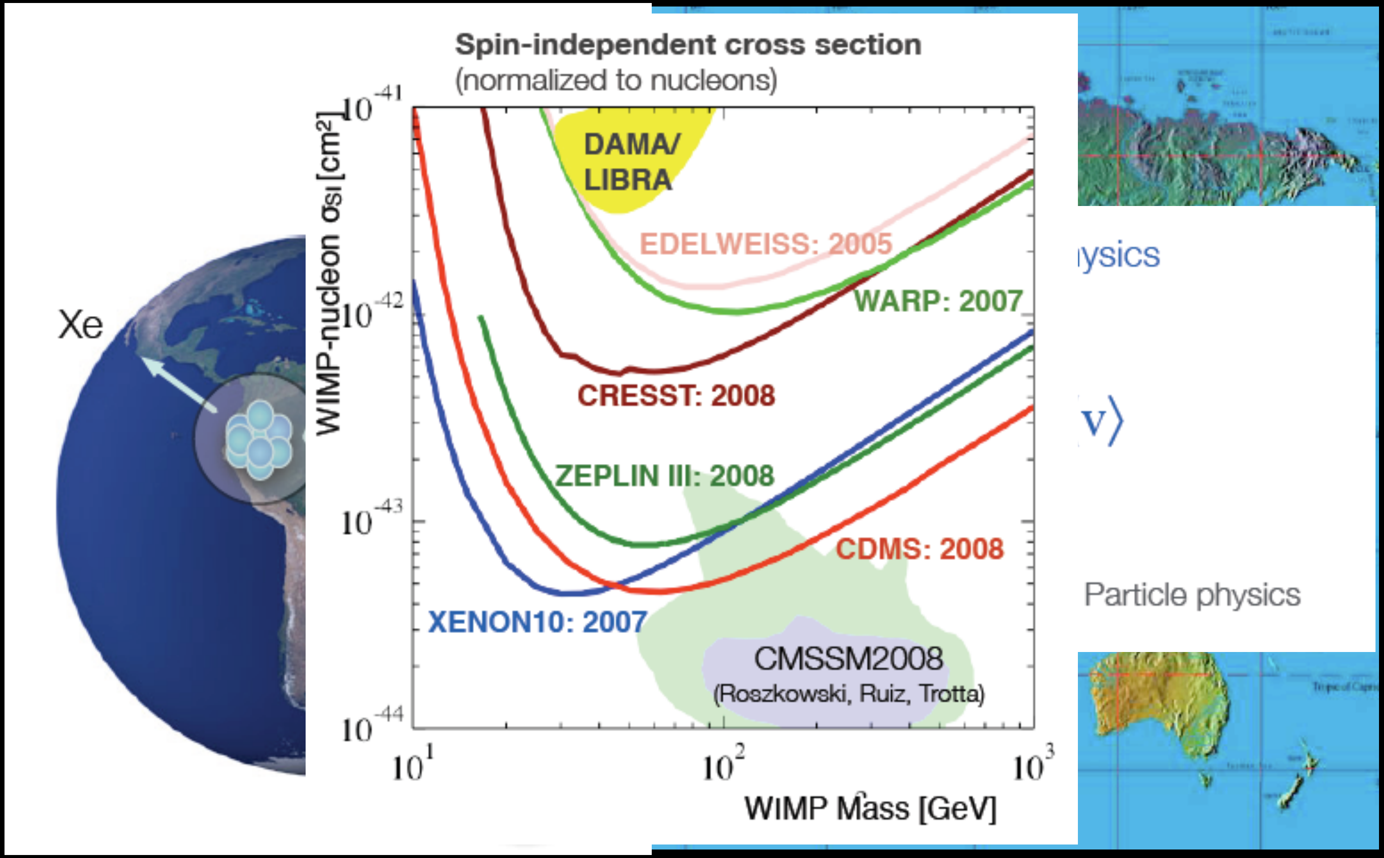
Combining collider with DM searches



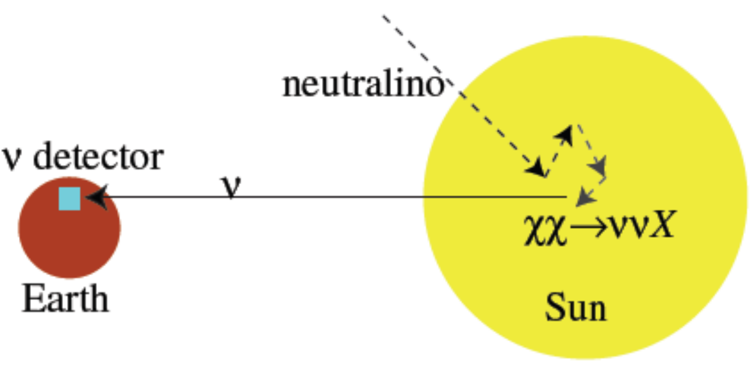
Collider: precise test of DM mass and particle physics parameters, but no information on stability, halo density, etc.

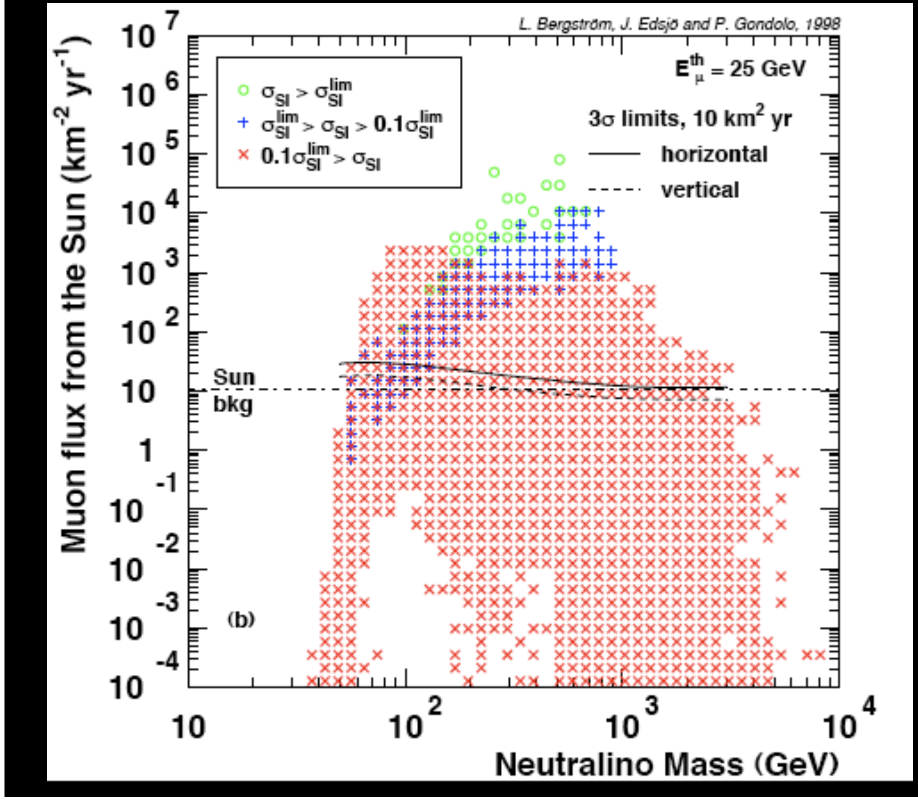
Only detection by different methods may conclusively identify the nature of DM

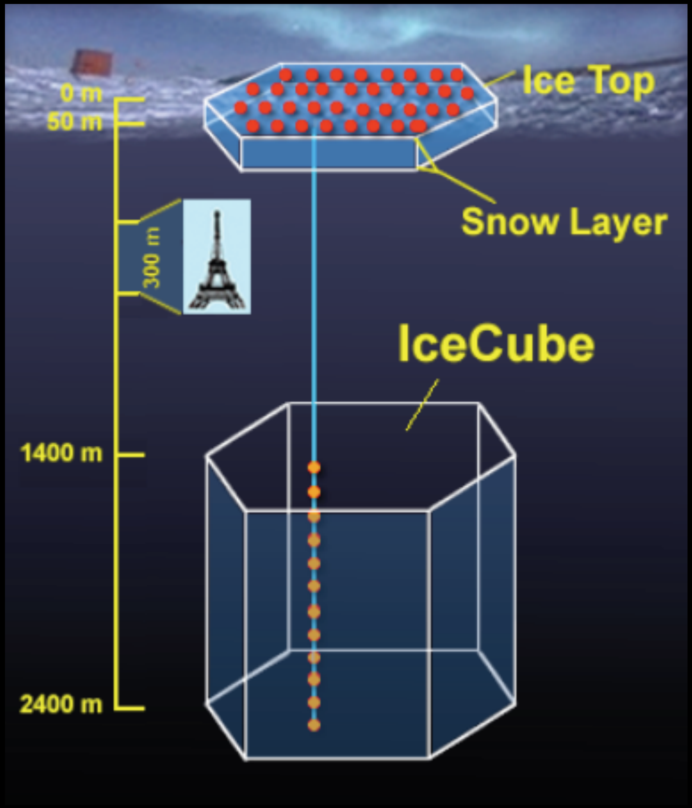
Finding DM: Direct Method



Finding DM: Indirect method







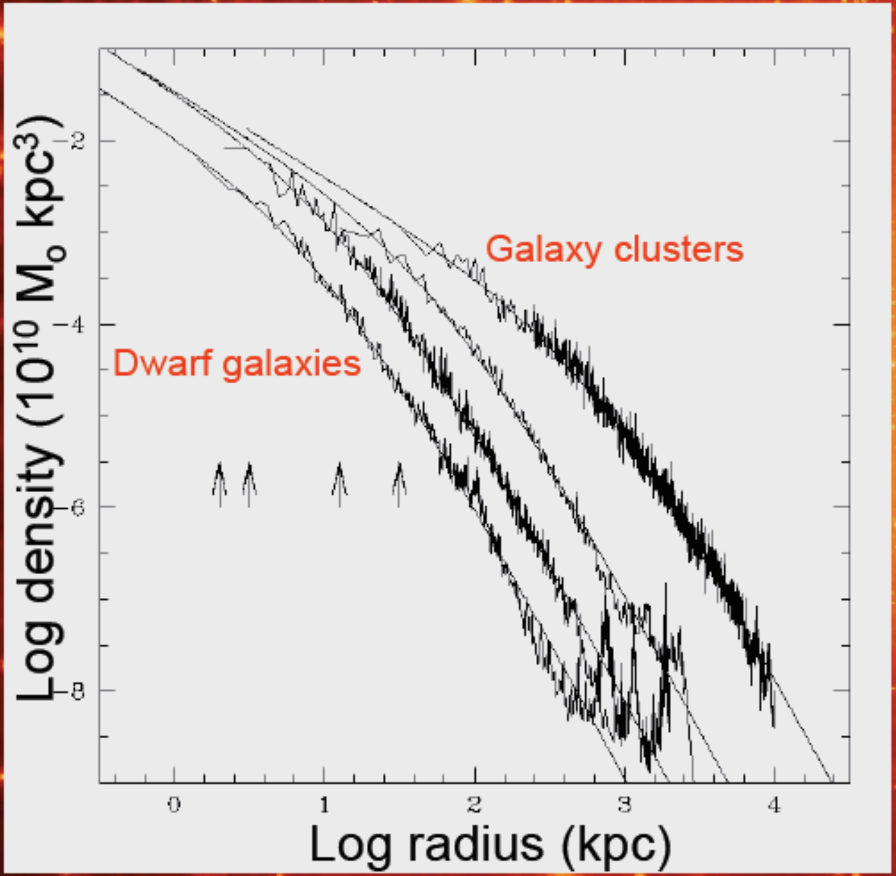
Look for signals from the sky

Fermi/GLAST launched on June 11, 2008

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Very sensitive to halo profiles near the galactic center

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

More massive halos and halos that form earlier have higher densities (bigger δ)

C. Frenk, ENTAap DM meeting, CERN, Feb. 2009

Electrons & Positrons in Cosmic Rays

- Electrons from SN
- Positrons / electrons from Secondary Production (p-ISM $\rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$)

- $e^\pm$ lose energy rapidly ($dE/dt \propto E^2$)
  - IC scattering on interstellar photons
  - synchrotron radiation (interstellar B field ~ few μG)
  - → high energy electrons (and positrons) are "local."

- $e^\pm$ produced in pairs (in ISM).
- $e^+/(e^+ + e^-)$ fraction is small (≈10%)
  → substantial primary e^- component.

Cosmic Ray Electrons

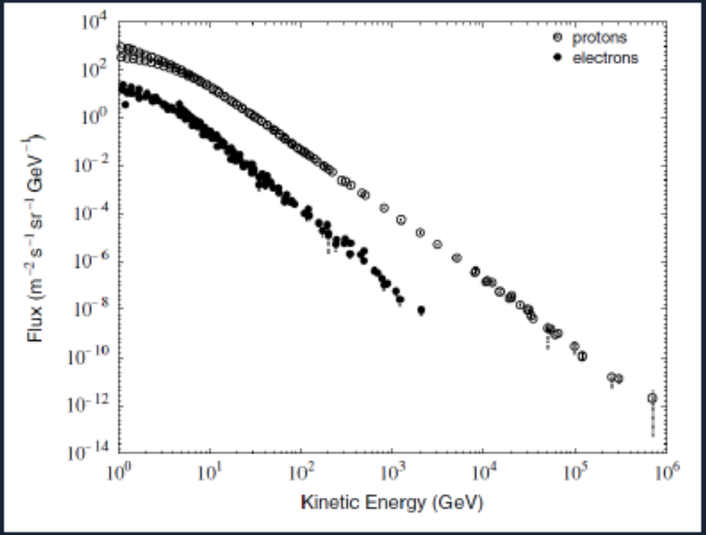
- Electron intensity ~ 1% Proton intensity (at 10 GeV)

- Power-law energy spectrum for CR protons and CR electrons

  At GeV-TeV energies:

  Protons: $I(E) \sim E^{-2.7}$

  Electrons: $I(E) \sim E^{-3.4}$

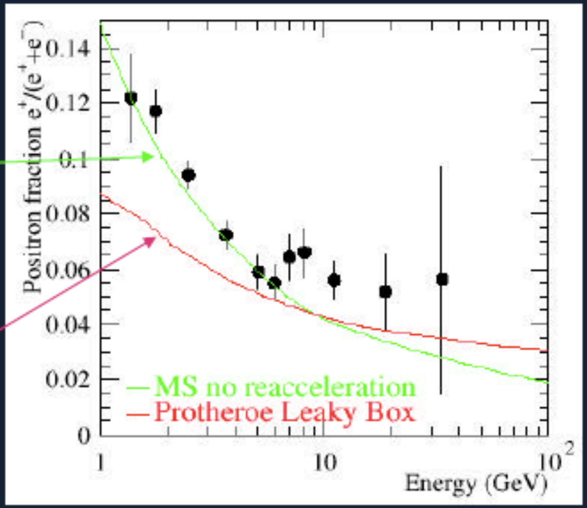


Why do we care?

Structure in the CR Positron fraction
- as first observed by HEAT instrument –
could be DM signature* (or nearby pulsars or...?**)

Galactic diffusion model (no re-acceleration)
[Moskalenko & Strong, ApJ 493, 694 (1998)]

leaky-box propagation
[Protheroe, ApJ 254, 391 (1982)]



* M. Kamionkowski and M. Turner, Phys. Rev. D 43, 1774 (1991)
** S. Coutu *et al.*, Astropart. Phys. 11, 429 (1999).

CR Positron measurements are challenging

- Flux of CR protons in the energy range 1 – 50 GeV exceeds that of positrons by a factor of ~ $5\text{x}10^4$
- Proton rejection of 10^6 is required for a positron sample with less than 1% proton contamination.

Remember: The single largest challenge in measuring CR positrons is the discrimination against the vast proton background!

Particle ID

Positron flux measurements require

- excellent particle identification for background discrimination
- sufficient MDR to separate positive and negative charged particles at high energy.

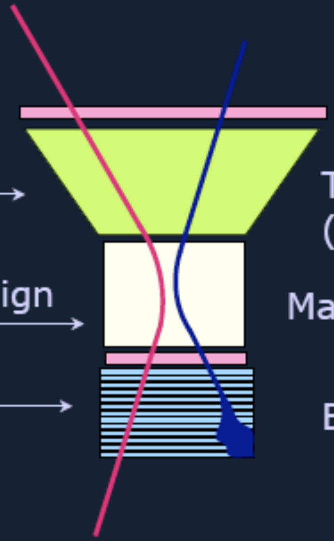
Primary sources of background for positrons:

protons and positively charged muons and pions produced in the atmosphere and material above the detector.

e^+ and e^- Instruments

Need magnet spectrometer for e^+ and e^- separation

Typical Instrument:



direction & charge → Time of Flight (ToF)

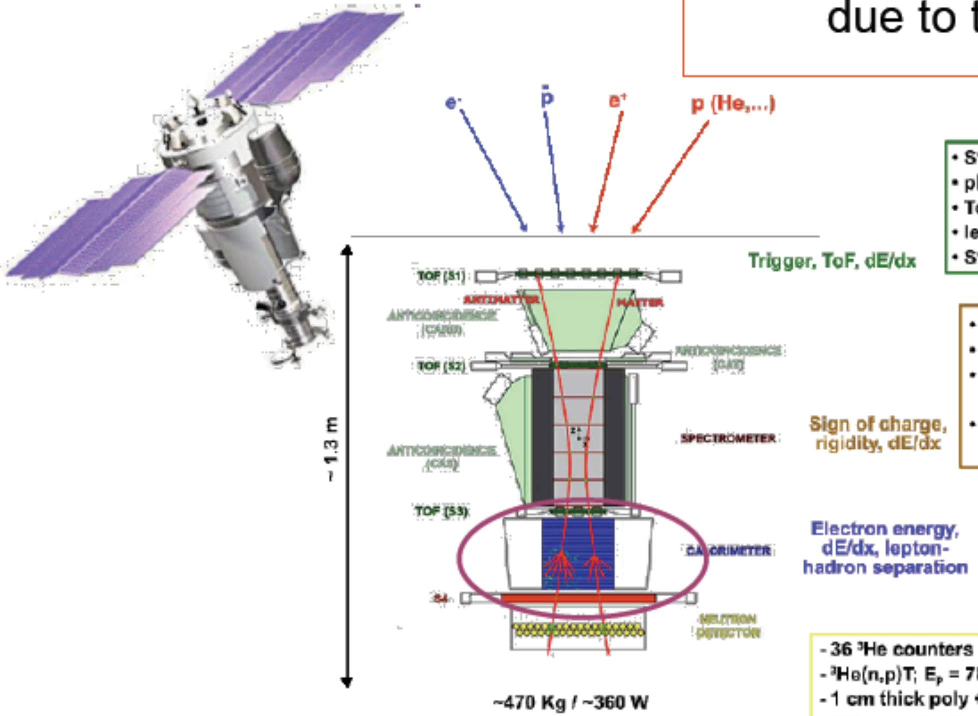
e / hadron discrimination → Transition Radiation Detector (TRD) or Gas Cherenkov

rigidity / charge sign → Magnet Spectrometer

energy & shower shape → EM Calorimeter

PAMELA

☹ Originally PAMELA had a TRD but had to drop it due to technical issues.



- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

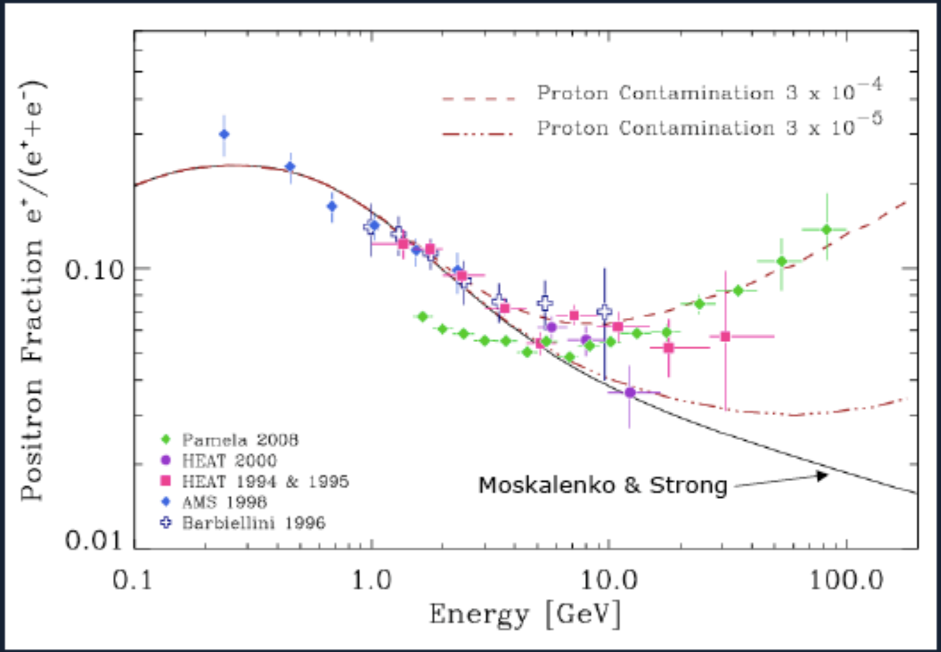
- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm² sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

Caution: Particle ID solely dependent on calorimetry.
No in-flight verification of proton rejection.

What a *little* dash of protons can do!



PAMELA claims p rejection of $^{10-5}$. CAUTION! This is not verified using independent technique in flight.

Galactic and local pulsars

D. Hooper, P. Blasi & P. D. Serpico, **arXiv:0810.1527** S. Profumo, **arXiv:0812.4457**

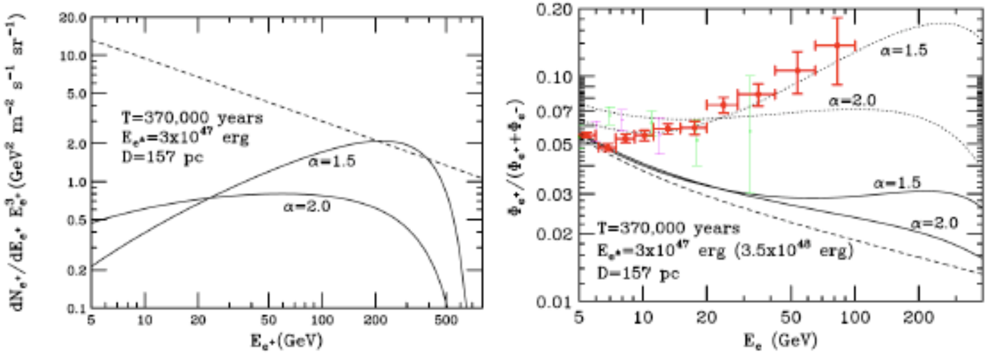


FIG. 2: The spectrum of positrons (left) and ratio of positrons to electrons plus positrons (right) from the pulsar Geminga, with the dashed lines as in Fig. 1. In the right frames, the measurements of HEAT [3] (light green and magenta) and measurements of PAMELA [2] (dark red) are also shown. Here we have used an injected spectrum such that $dN_e/dE_e \propto E^{-\alpha}\ \exp(-E_e/600\,\mathrm{GeV})$, with $\alpha = 1.5$ and 2.2. The solid lines correspond to an energy in pairs given by 3.5×10^{47} erg, while the dotted lines require an output of 3×10^{48} erg.

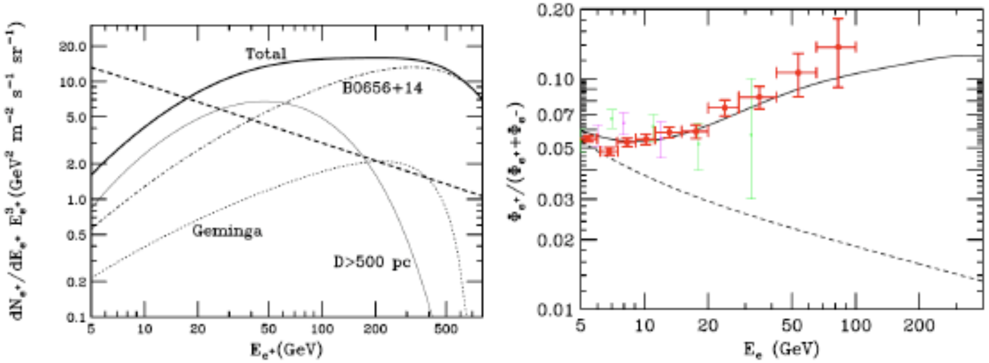
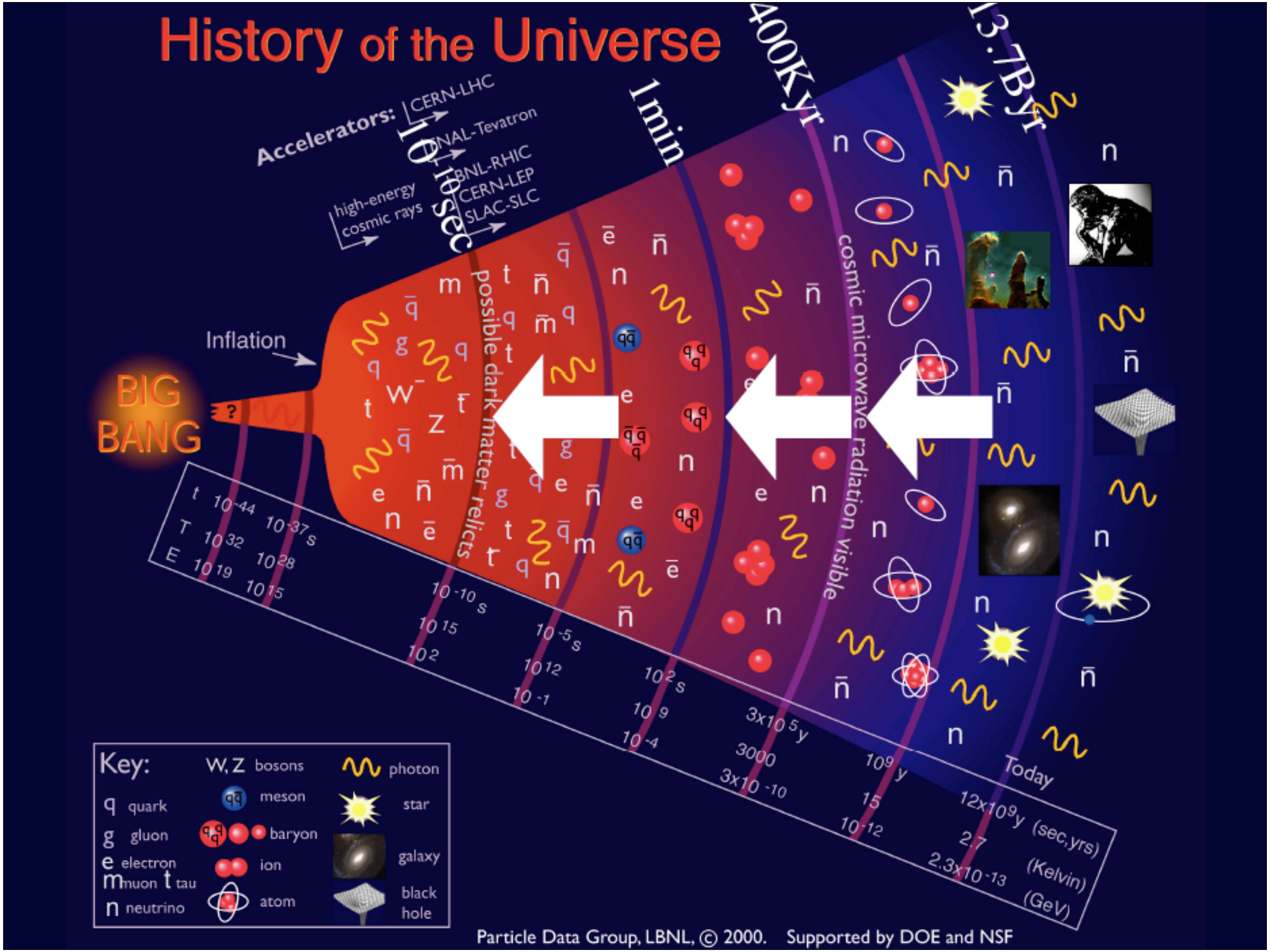


FIG. 4: The positron spectrum and positron fraction from the sum of contributions from B0656+14, Geminga, and all pulsars farther than 500 parsecs from the Solar System.



History of the Universe

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Despite the Dark Puzzles, the future is brighter