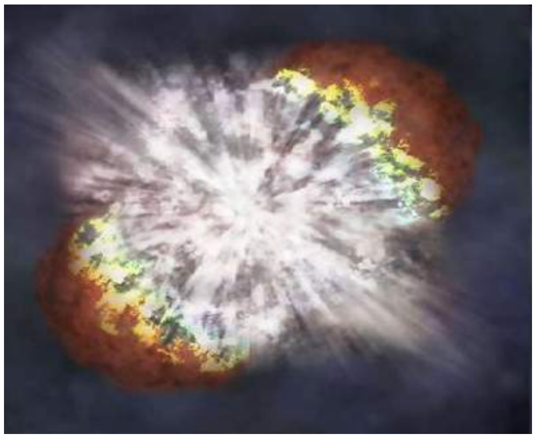
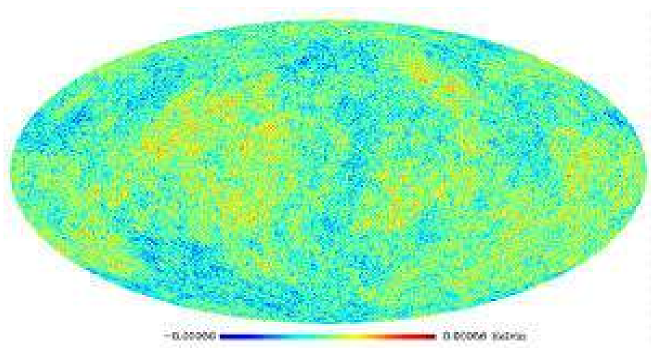
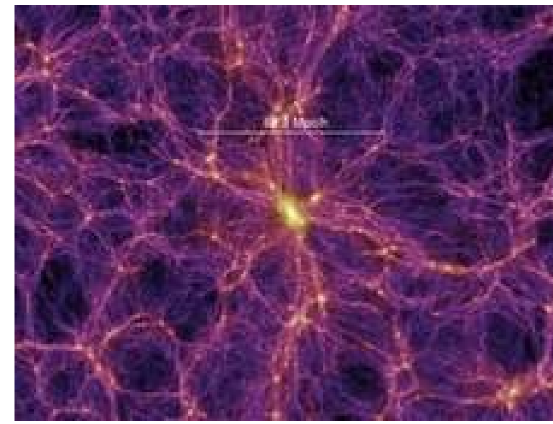
A phenomenological approach to the properties of dark matter







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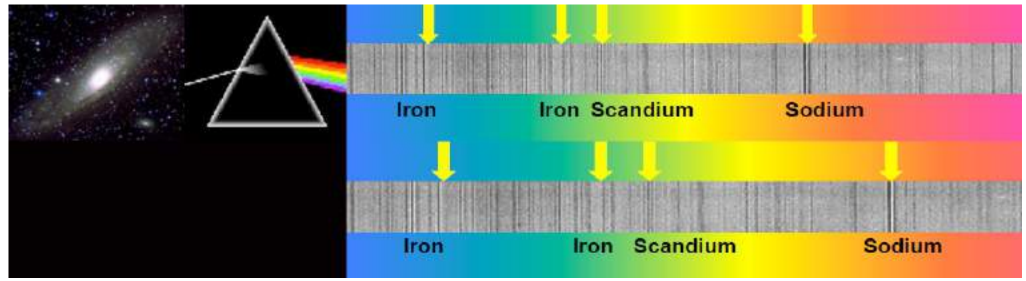
M. Kunz, S.N., I. Sawicki, arXiv: 1507.01486 & 1602.xxxxx

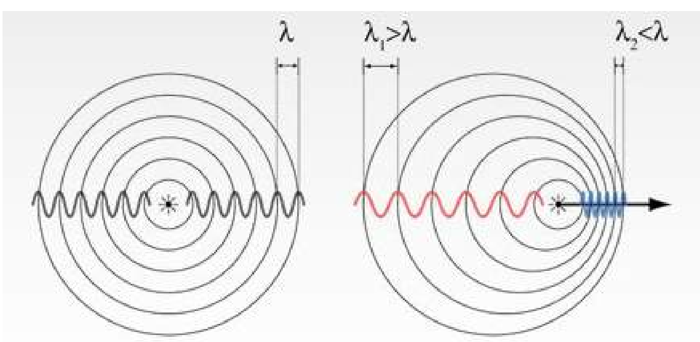
Main points of the talk

- Brief introduction to the standard cosmological model
- The observational data (SnIa, CMB, WL, BAO)
- Dark Matter (DM) perturbations and their sound speed cs2, a phenomenological approach
- Constraints on other DM properties (w,cvis...)
- Conclusions

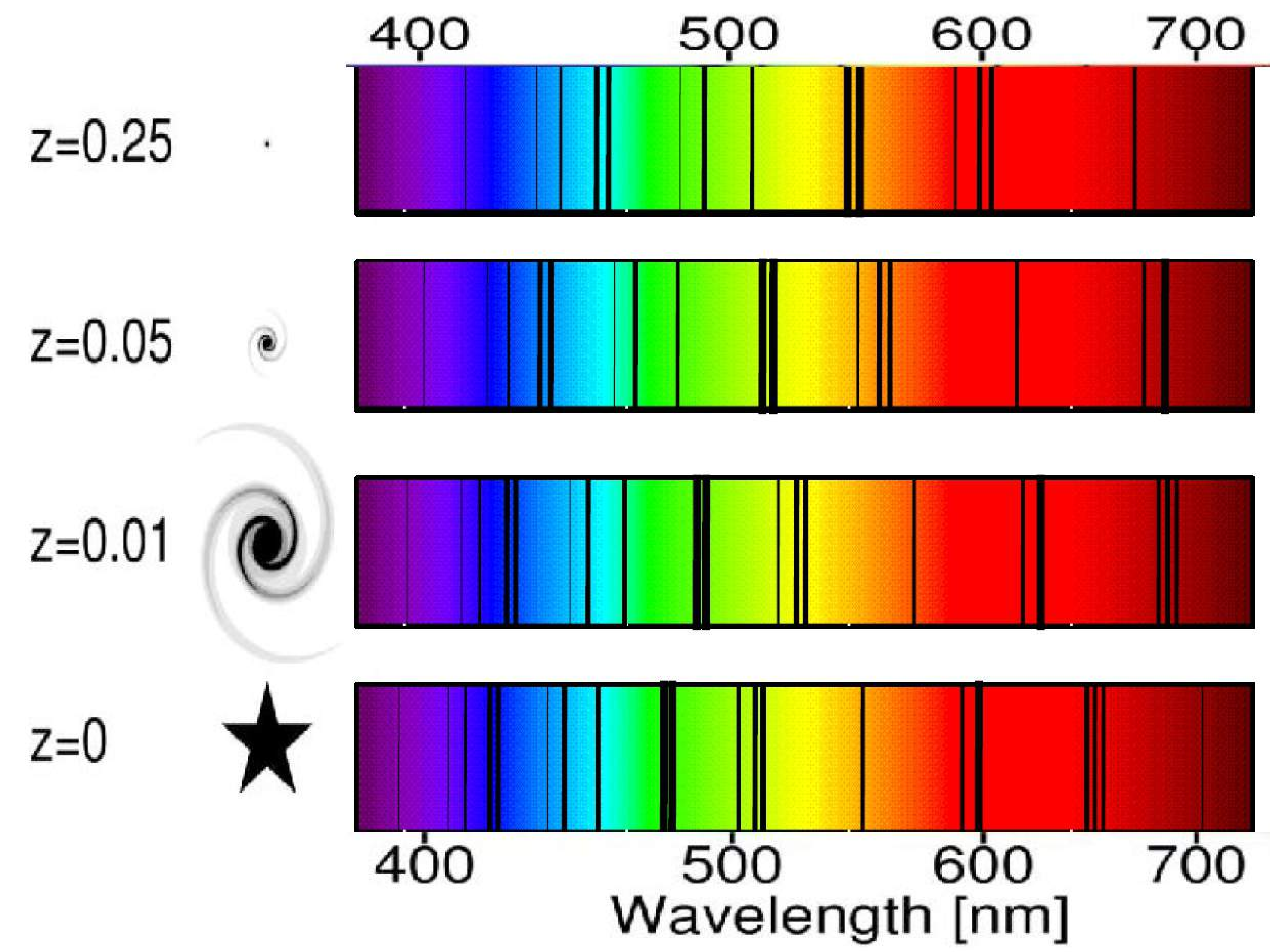
Cosmological spectra and the redshift



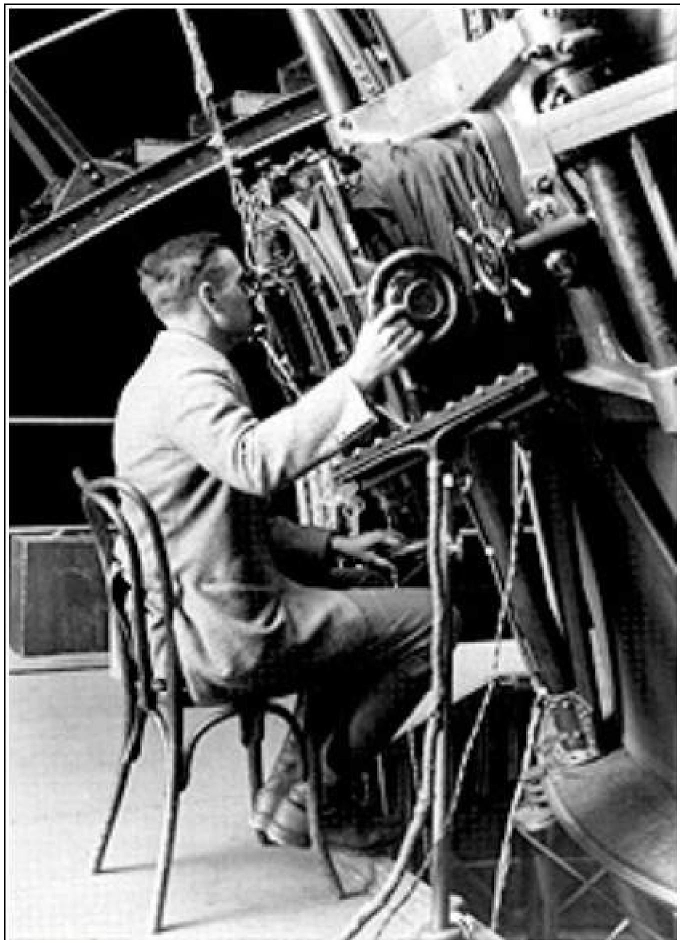
During the period 1912-16 Vesto Slipher observed the spectra of nearby galaxies (he was the first to do so!) and found that almost all the spectra were redshifted and hence, are moving away from us!



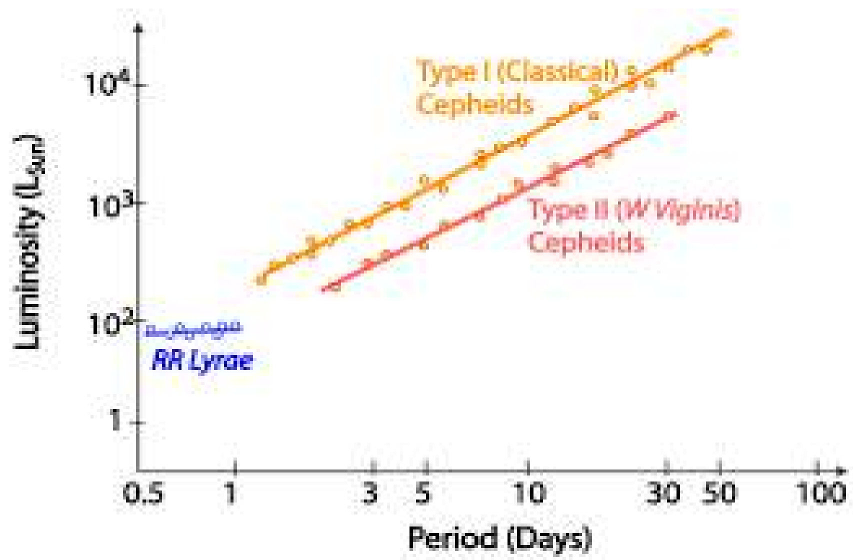
Redshift $$z \equiv \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$


400
500
600
700
z=0.25
z=0.05
z=0.01
z=0
400
500
600
700
Wavelength [nm]

Hubble's observations during 1929



Hubble used a group of variable stars (Cepheids) to measure the distances to nearby galaxies.



Hubble's observations during 1929

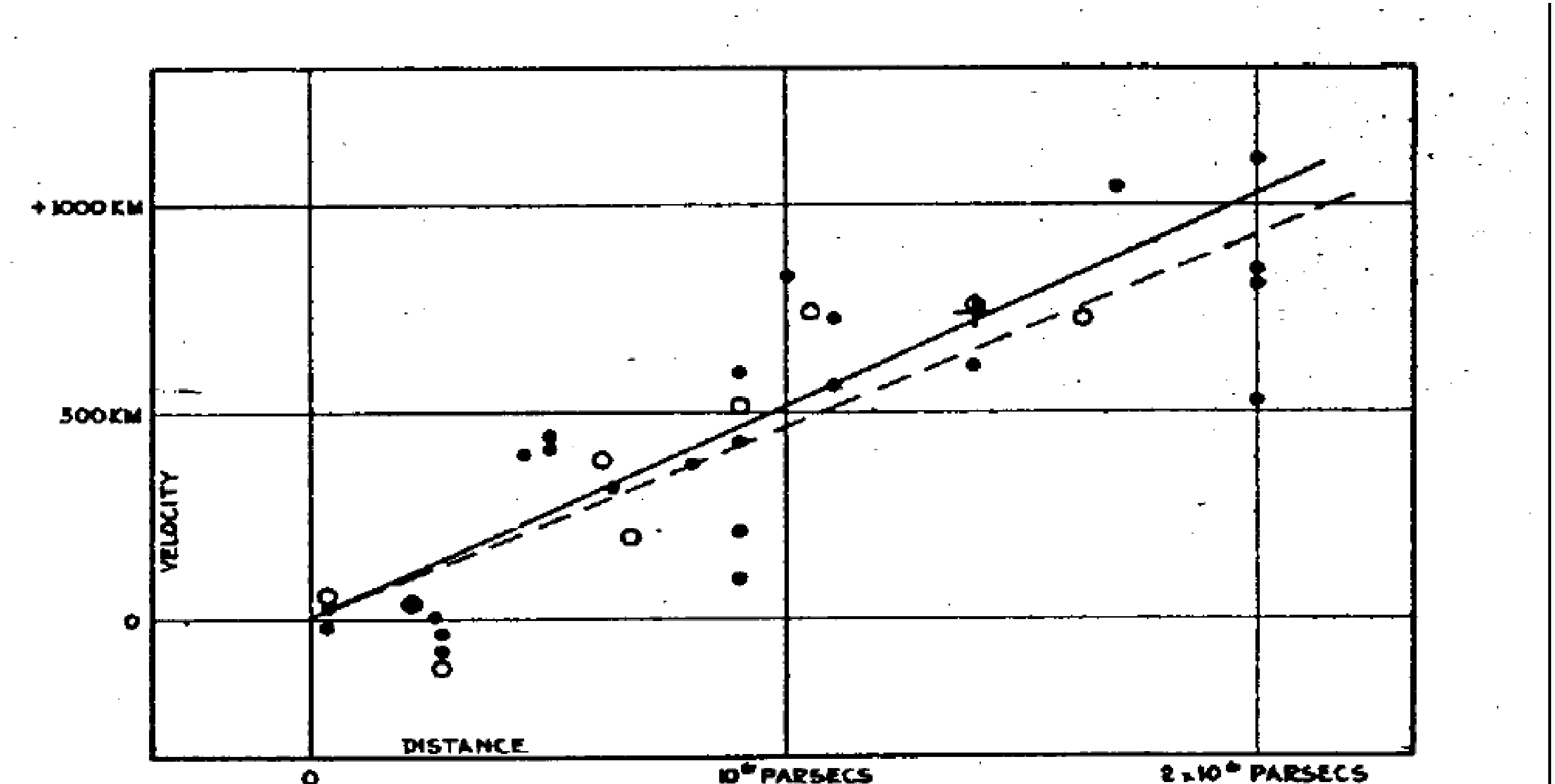


FIGURE 1

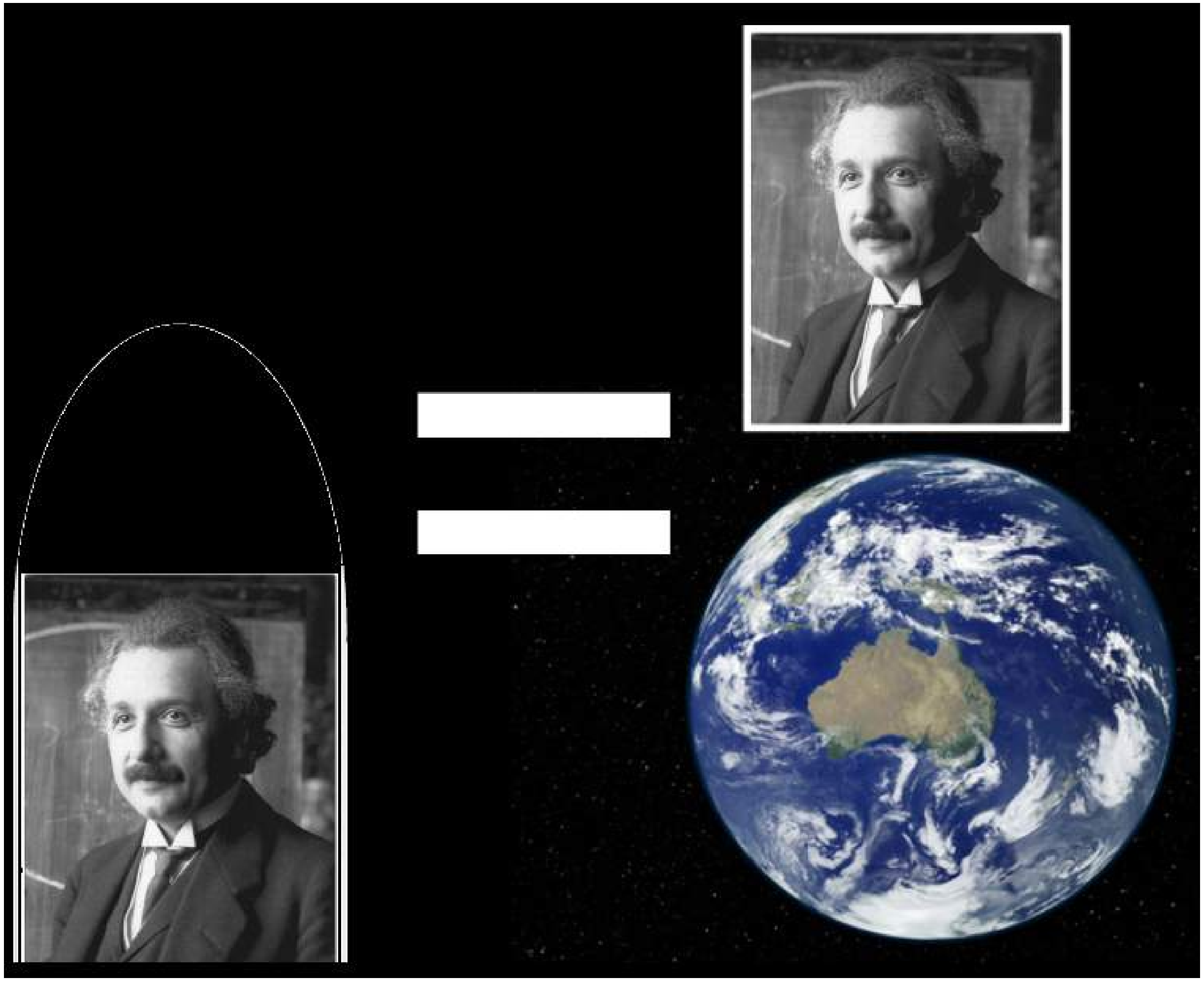
He found that the faster the galaxy moves the dimmer it is, so it's further away

v=H0*D, H0~ 500 km/s/Mpc! Today we know that H0~67.80±0.77 km/s/Mpc.

Einstein's theory of General Relativity

In 1907 Einstein realized that we cannot discriminate acceleration from gravity in sufficient small scales.

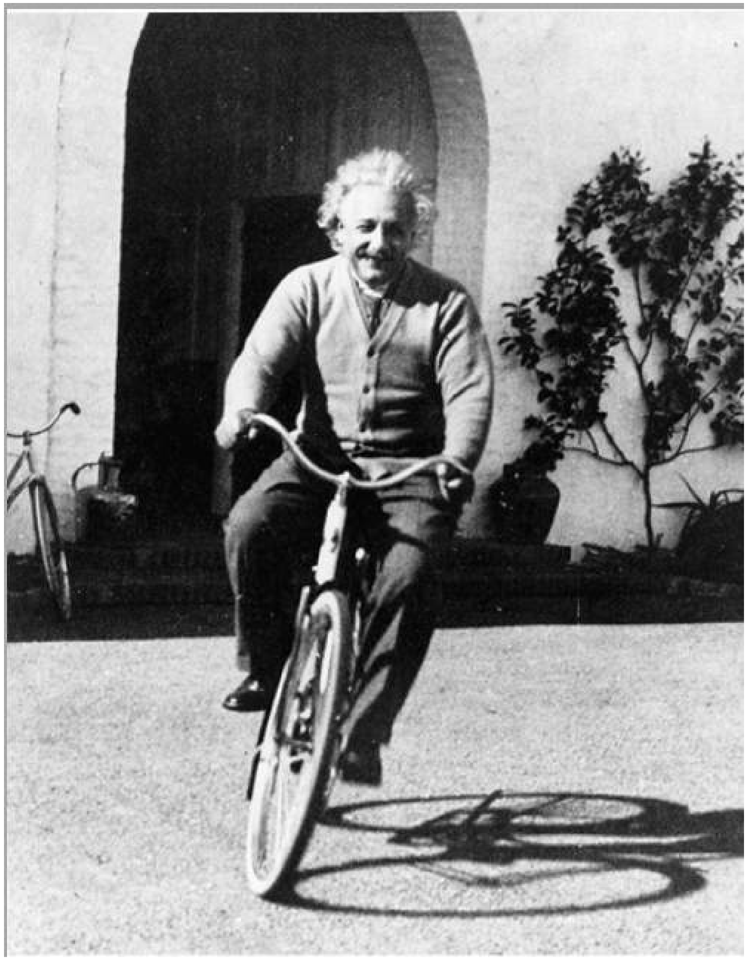
During the period 1915-16 he published the theory of General Relativity.



Einstein's theory of General Relativity and the cosmological constant Λ

The cosmological constant Λ was initially proposed by Einstein (1917) in order to counteract the gravitational pull of the universe, as it has a repelling effect instead of attractive.

However, later he withdrew it and referred to it as “my greater blunder”.



The Standard Cosmological model

Einstein equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$G_{\mu\nu}$

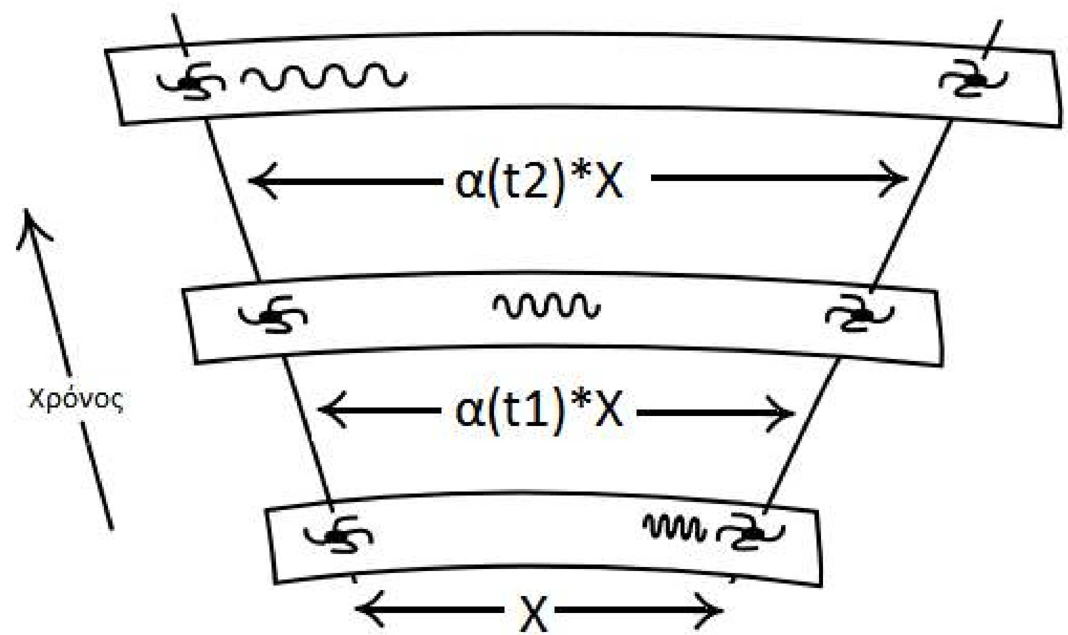
Cosmological Constant

$$T^{\mu}_{\nu} = P g^{\mu}_{\nu} + (\rho + P) U^{\mu} U_{\nu}$$

Friedmann-Lemaitre-Robertson-Walker (FLRW) metric:

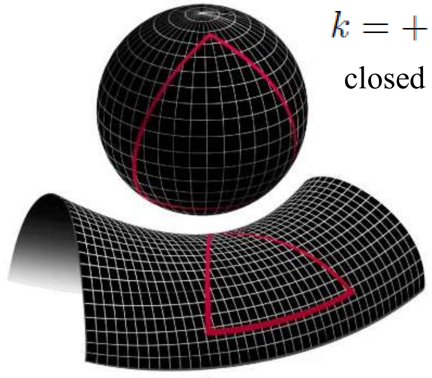
$$ds^2 = c^2 dt^2 - \alpha(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + sin(\theta)^2 d\phi^2) \right)$$

Scale factor α(t):



The Standard Cosmological model

The curvature:



Friedmann equations (1924):

$$H^2(\alpha) = \left(\frac{\dot{\alpha}}{\alpha}\right)^2 = \frac{8\pi G}{3}\rho(\alpha) - \frac{k}{\alpha^2}$$

$$\frac{\ddot{\alpha}}{\alpha} = -\frac{4\pi G}{3}\left(\rho(\alpha) + P(\alpha)\right)$$

Continuity equations:

(via Bianchi identities)

$$\nabla_\nu T^{\mu\nu} = 0 \quad \Longrightarrow \quad \dot{\rho} + 3H(\rho + P) = 0$$

The Standard Cosmological model

Hubble (1929): The Universe is expanding

Redshift of distant galaxies

Riess et al. (1998): ...and it's also accelerating!

Type Ia supernovae

2^{nd} Friedmann equation: $\frac{\ddot{\alpha}}{\alpha} = -\frac{4\pi G}{3}\left(\rho(\alpha) + 3P(\alpha)\right)$ ⇒ $P < -\frac{\rho}{3}$

Equation of state

$P = w\,\rho$

- $w = 0$ Non-relativistic matter $P << \rho$
- $w = \frac{1}{3}$ Relativistic matter (photons etc) $P = \frac{1}{3}\rho$

$P < -\frac{\rho}{3}$ ⇒ $w < -\frac{1}{3}$

The known forms of matter cannot explain the accelerated expansion of the Universe!

The Standard Cosmological model

Fractional density parameters:

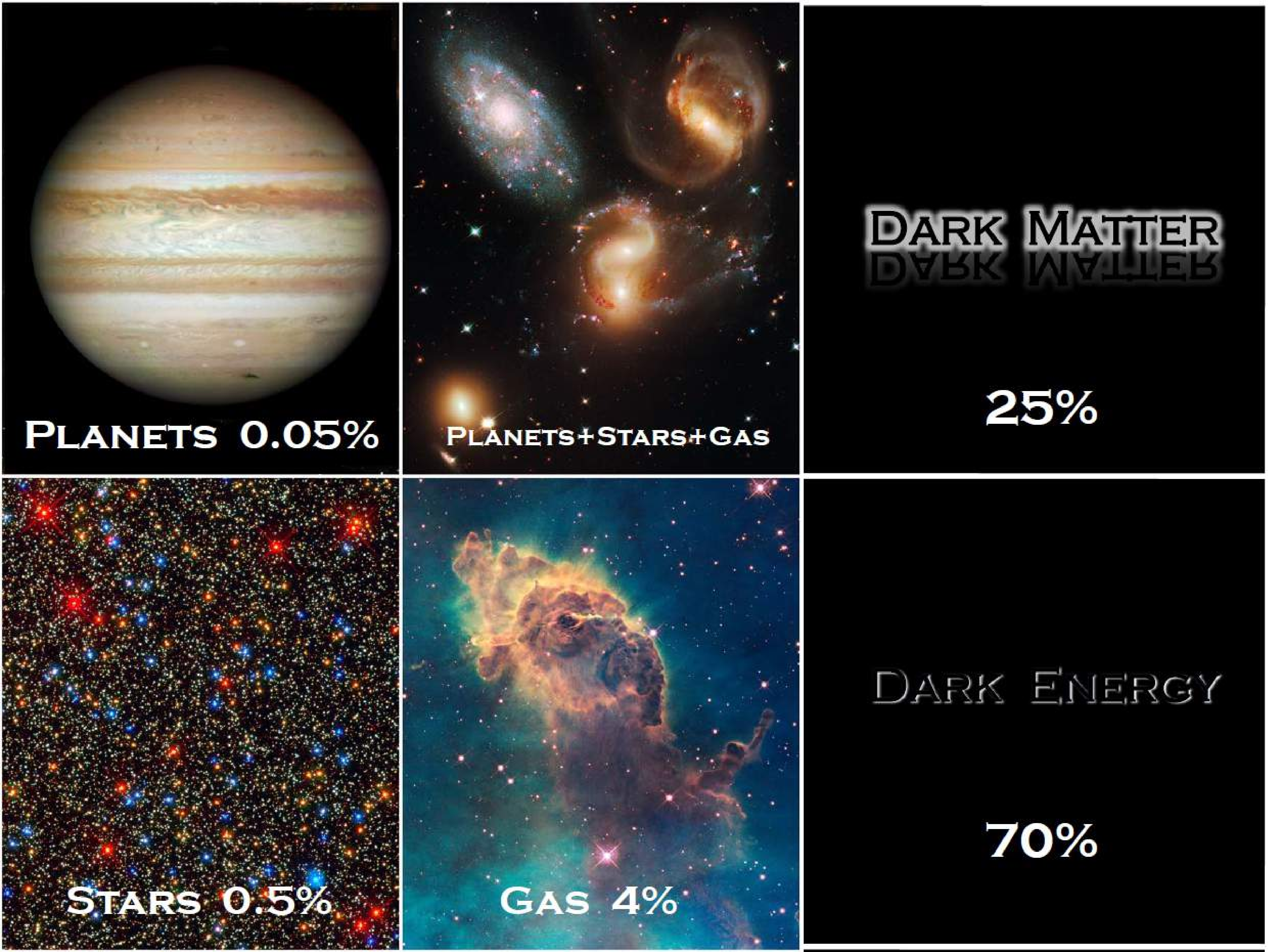
$$\rho_c(t) = \frac{3H^2}{8\pi G}$$

$$\Omega(t) \equiv \frac{\rho}{\rho_c}$$

$$\Omega_{K,0} = -\frac{k}{H_0^2 a_0^2}$$

1st Friedmann equation:

$$H(\alpha)^2 = H_0^2 \left(\Omega_{b,0}\alpha^{-3} + \Omega_{c,0}\alpha^{-3} + \Omega_{r,0}\alpha^{-4} + \Omega_{K,0}\alpha^{-2} + \Omega_{DE,0}\alpha^{-3(1+w)}\right)$$


Planets 0.05%
Planets+Stars+Gas
Dark Matter
25%
Stars 0.5%
Gas 4%
Dark Energy
70%

Main points of the talk

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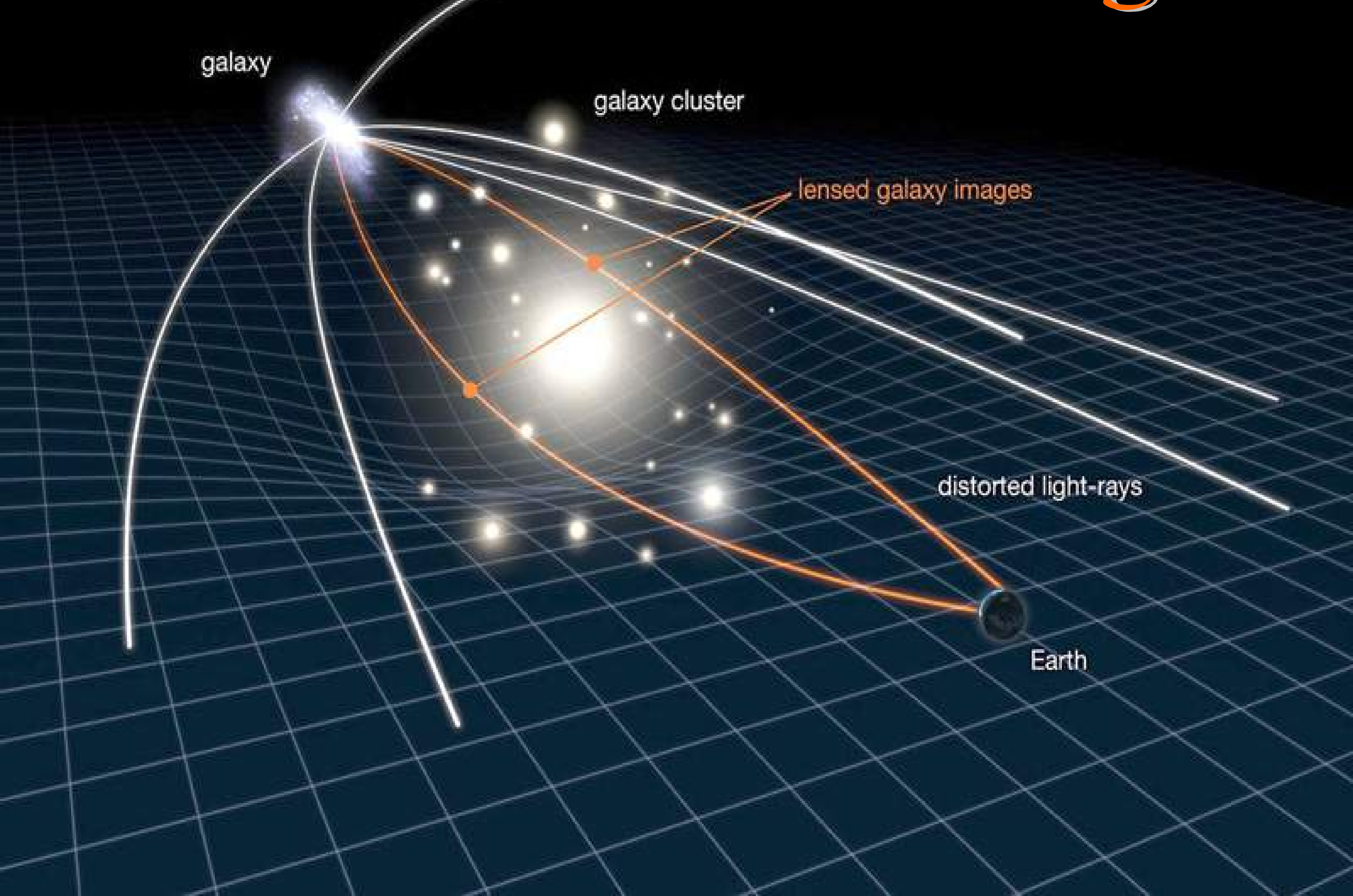
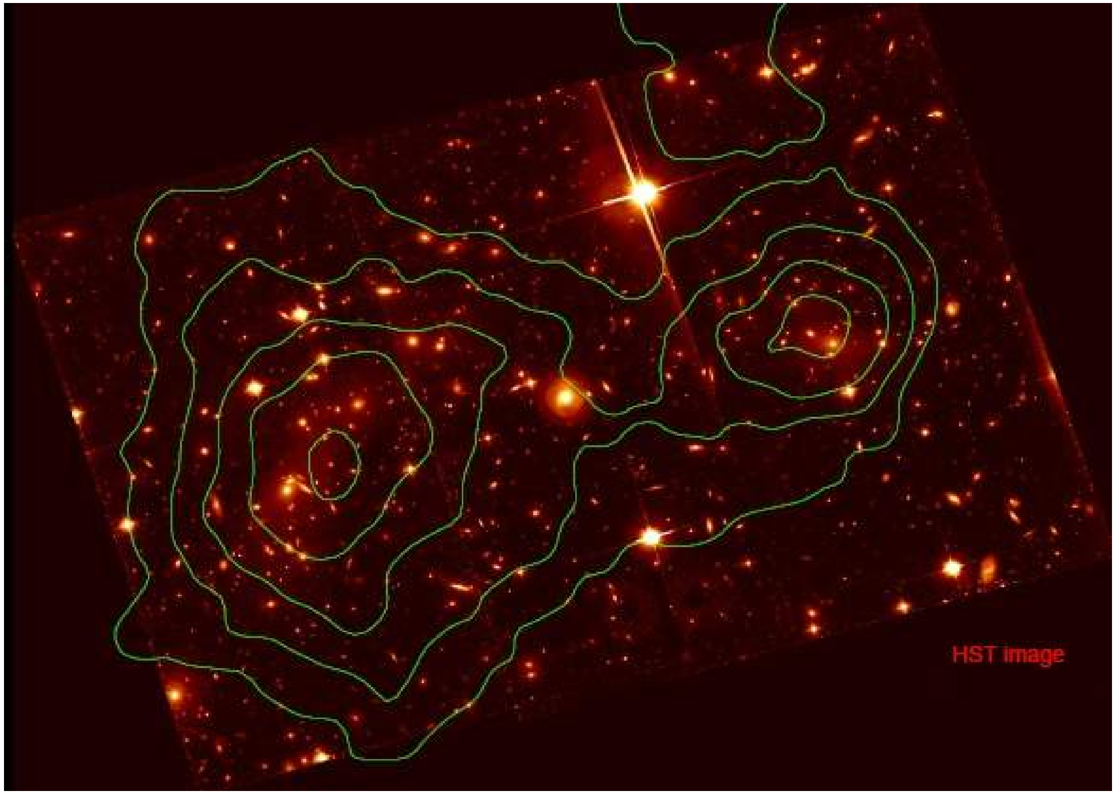
Gravitational lensing

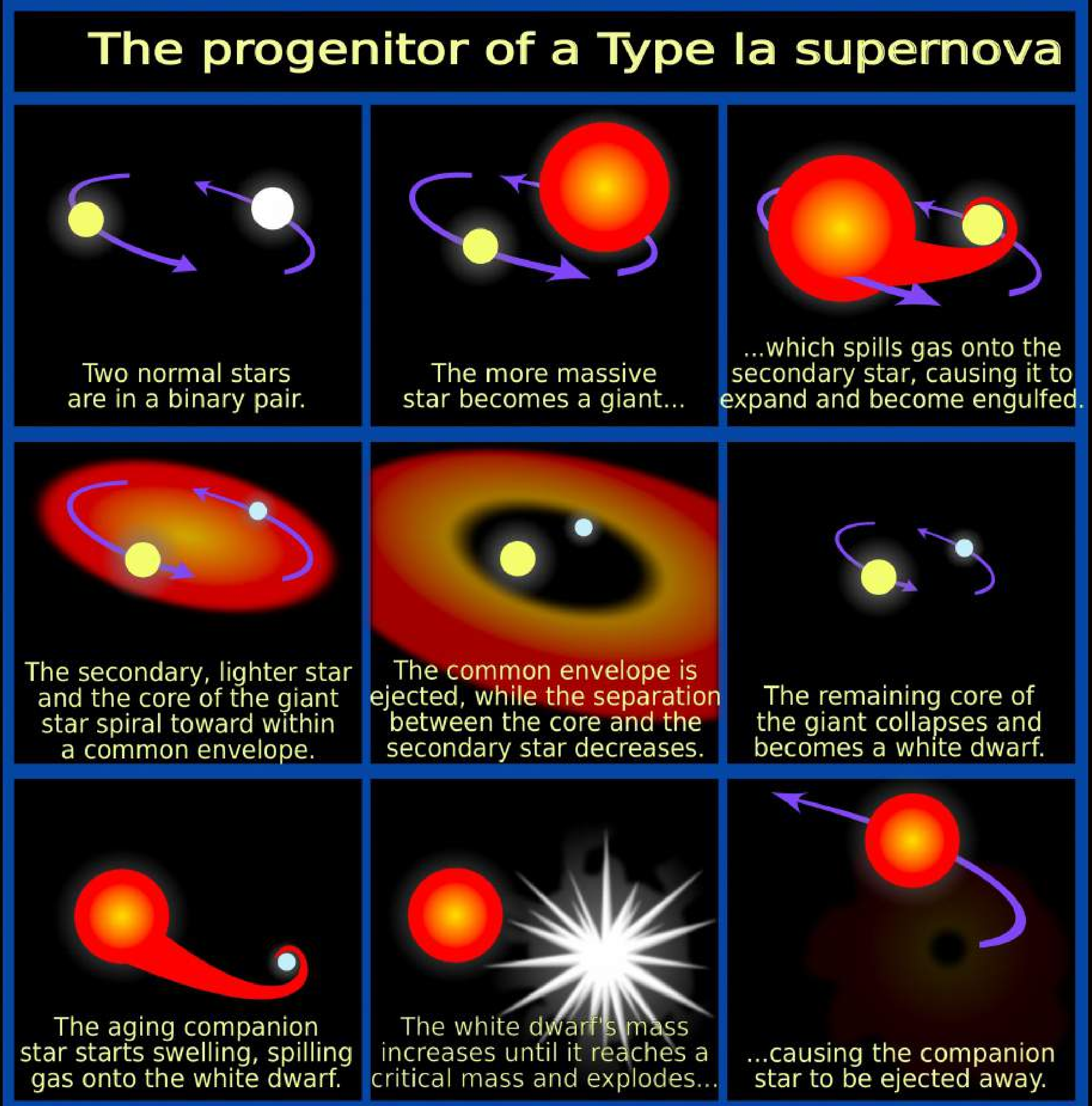


Gravitational lensing

Weak lensing can measure the masses of the clusters and the dark matter distribution

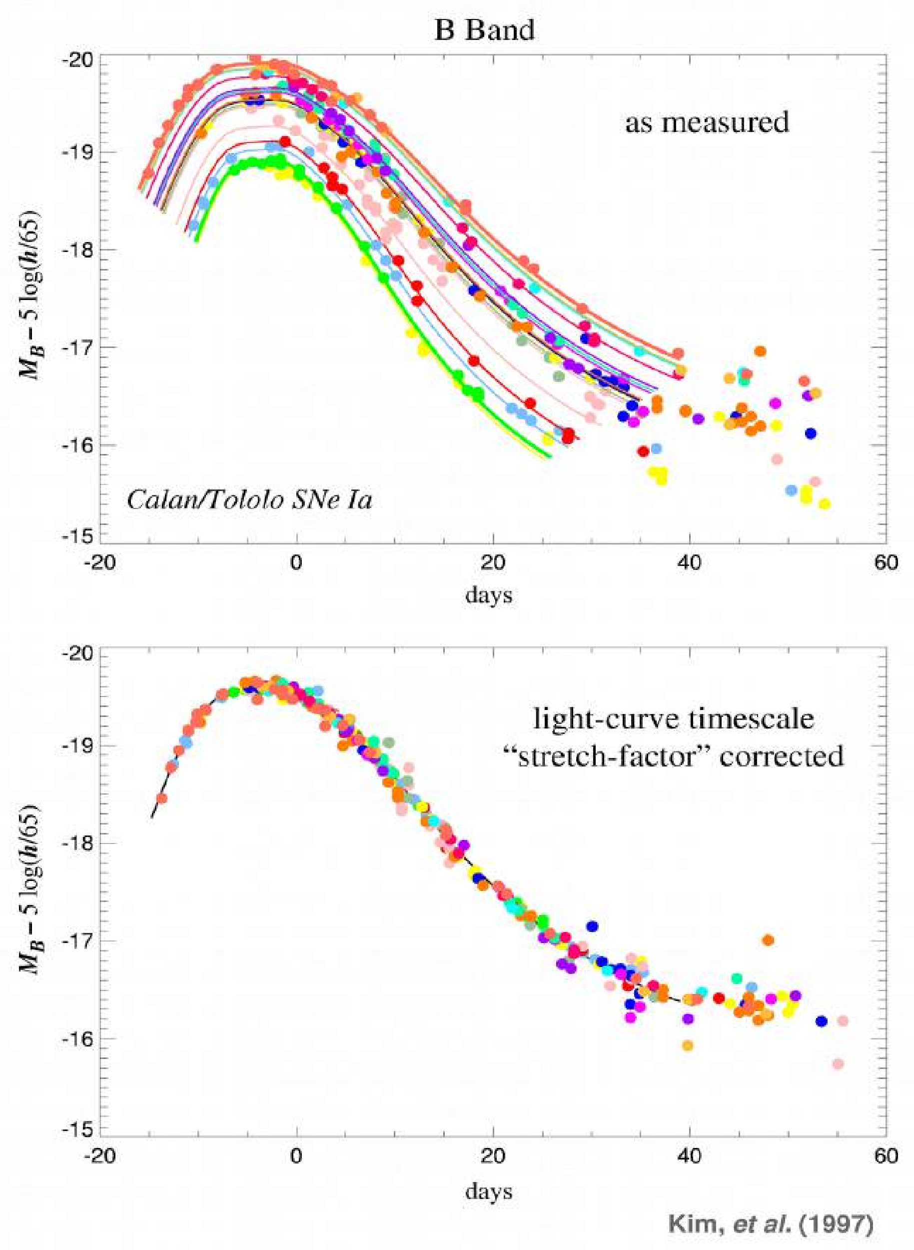


The Bullet Cluster with the total mass contours


The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away.

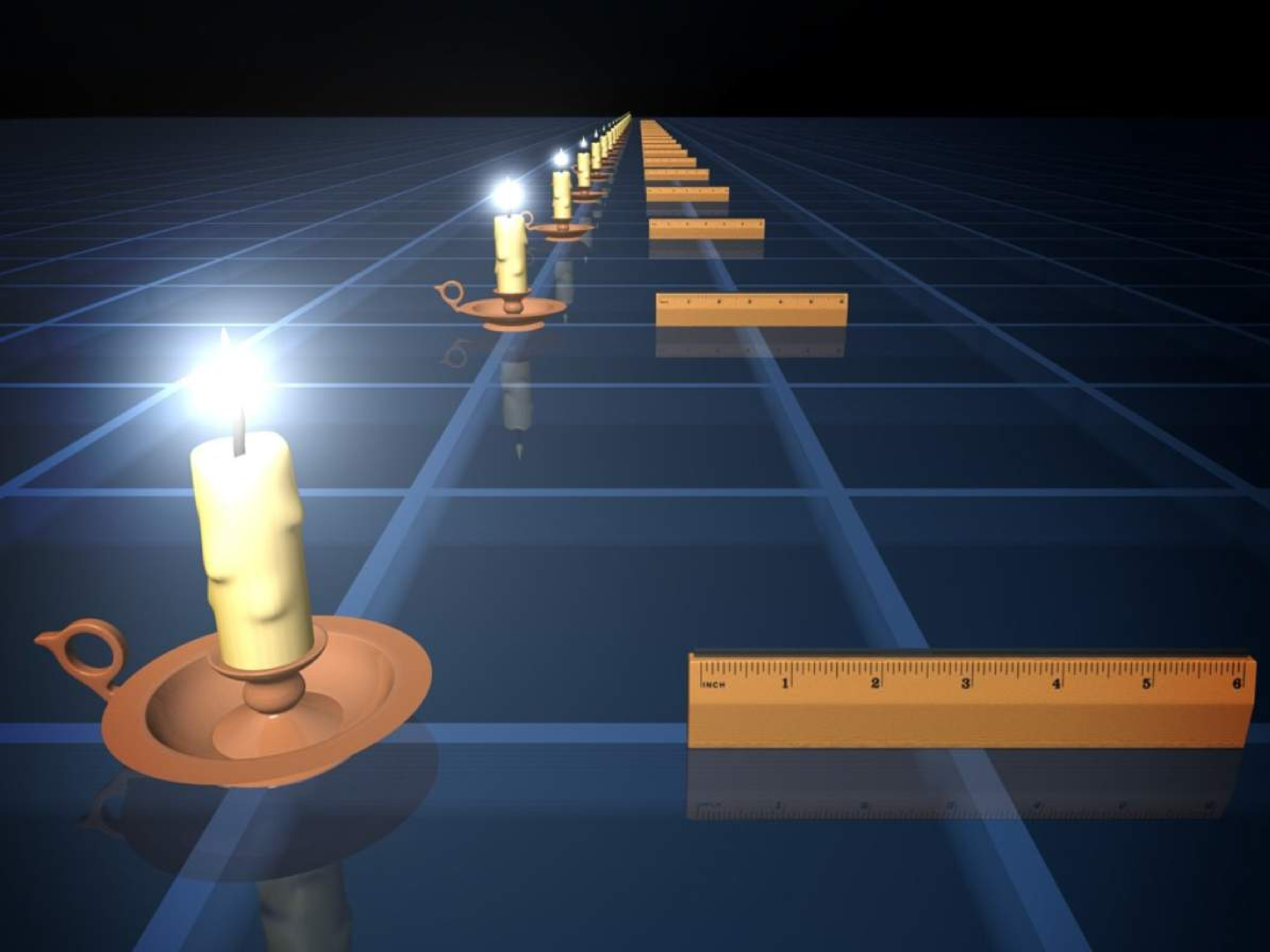
NASA.gov

Type Ia Supernovae as standard candles



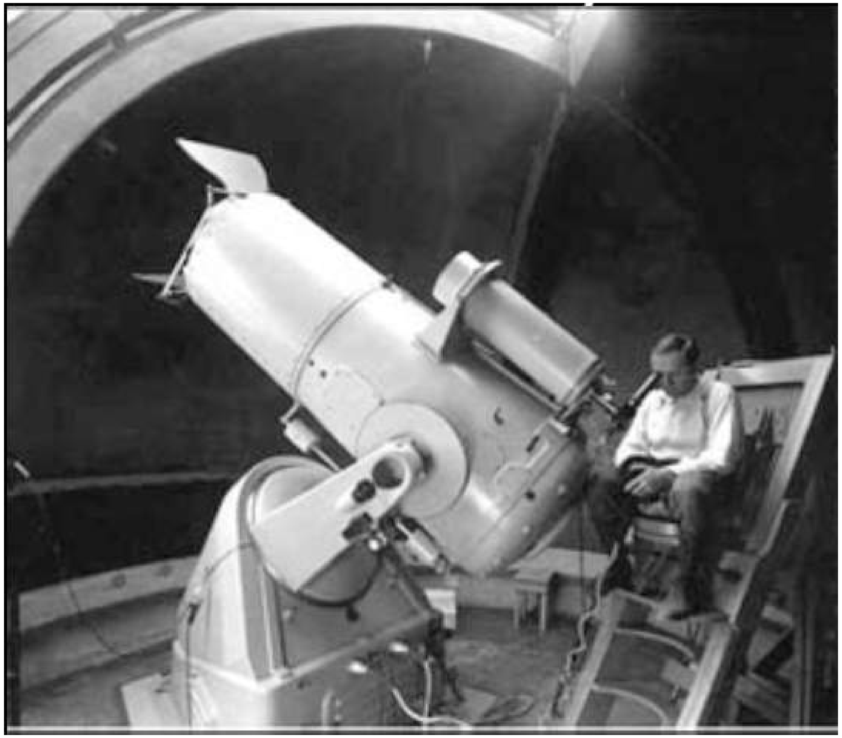
The lightcurves before...

And after the corrections...


INCH 1 2 3 4 5 6

Type Ia Supernovae as standard candles

Fritz Zwicky (1934-35):



Charles Kowal (1968)

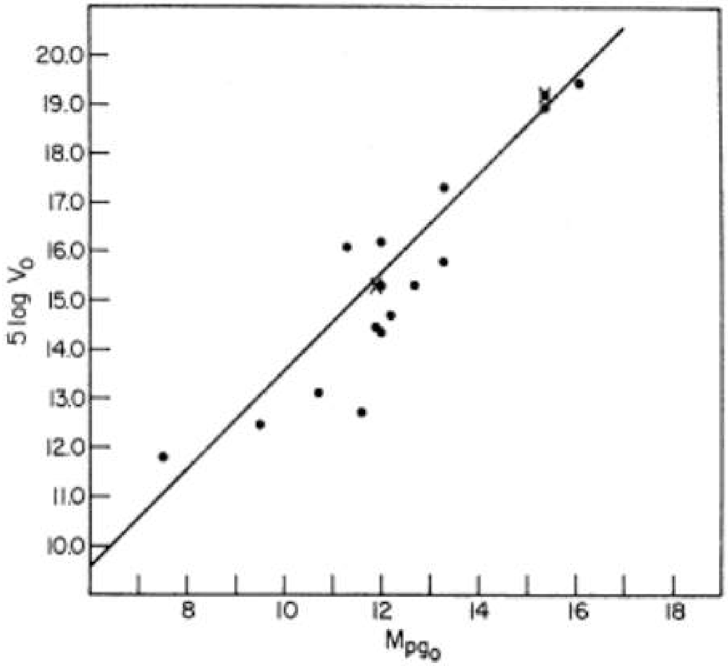


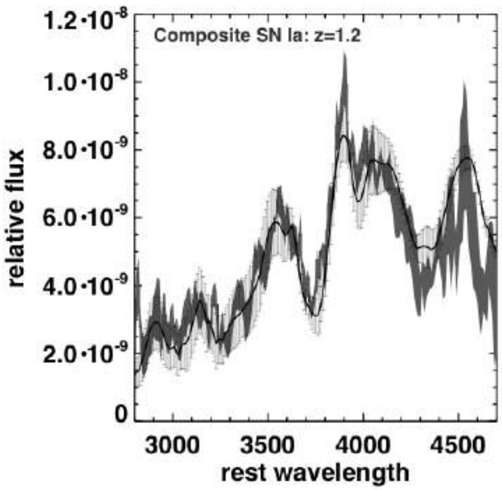
FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

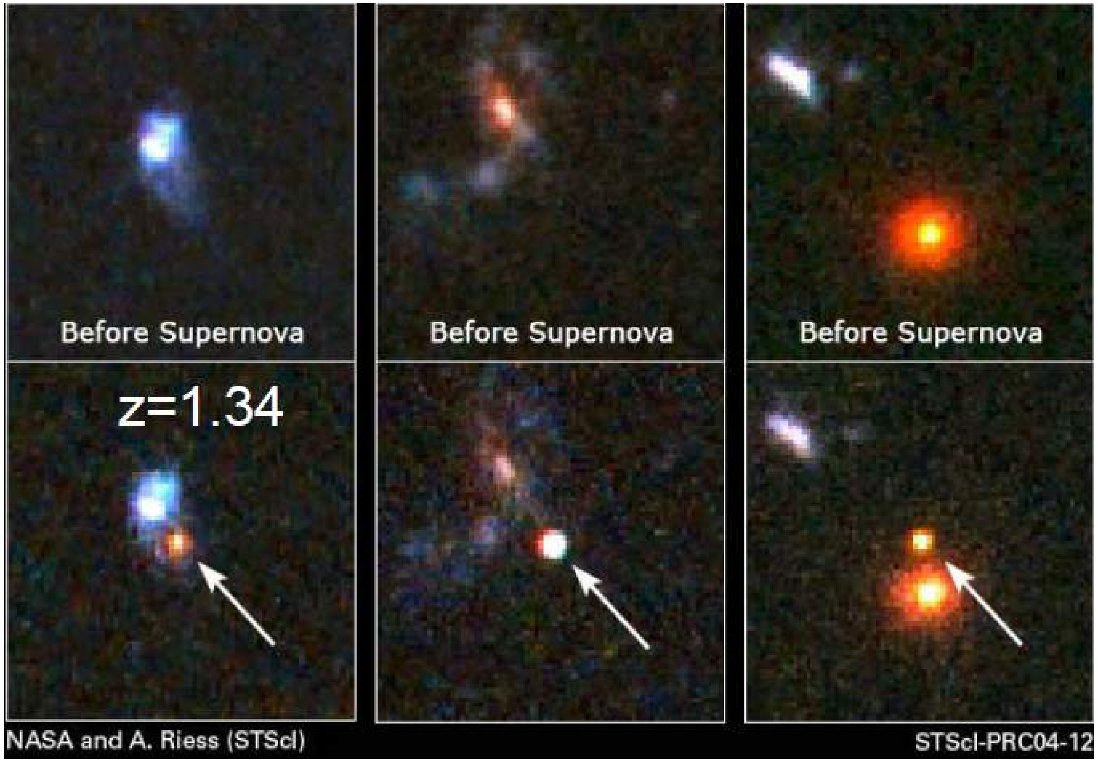
The first use of supernovae for measuring distances!

Type Ia Supernovae as standard candles

Hubble telescope:

2002-07, 23 new SnIa at z>1, eg





First measurements at z>1!

Some mathematical details about the SnIa

- The SnIa data are given in term of the dist. modulus:

$$\mu_{obs}(z_i) \equiv m_{obs}(z_i) - M$$

- Dark Energy can be described via w(z)

$w(z) \equiv \frac{P}{\rho}$

$$w(z) = -1 + \frac{1}{3}(1+z)\frac{d\ln(\delta H(z)^2)}{d\ln z}$$

$$\delta H(z)^2 = H(z)^2/H_0^2 - \Omega_{0m}(1+z)^3$$

- Theoretical prediction

(flat universe)

$$D_L(z) = (1+z)\int_0^z dz' \frac{H_0}{H(z';\Omega_{0m},w_0,w_1)}$$

$$\mu_{th}(z_i) \equiv m_{th}(z_i) - M = 5log_{10}(D_L(z)) + \mu_0$$

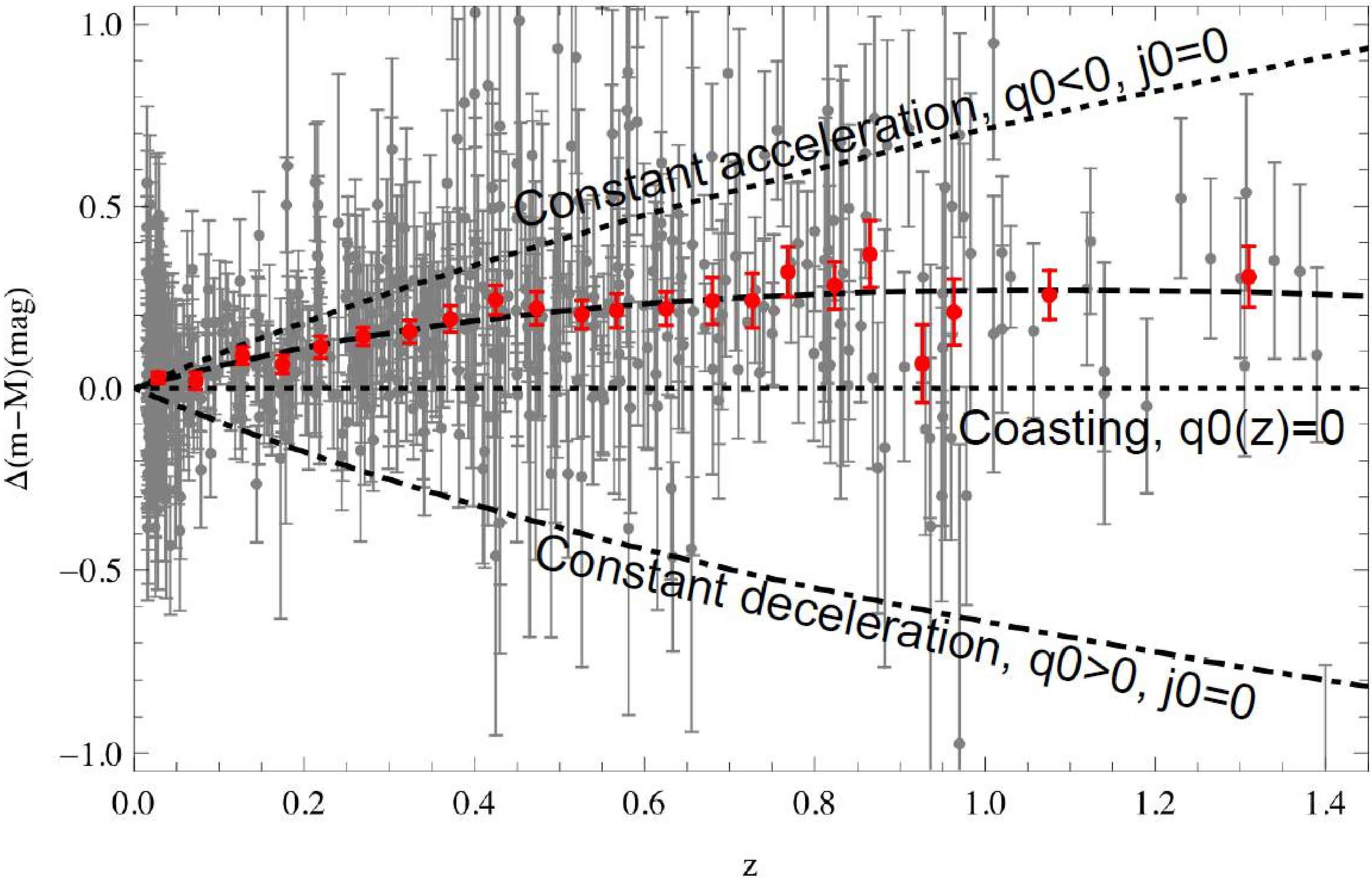
$$\mu_0 = 42.38 - 5log_{10}h$$

- Minimization:

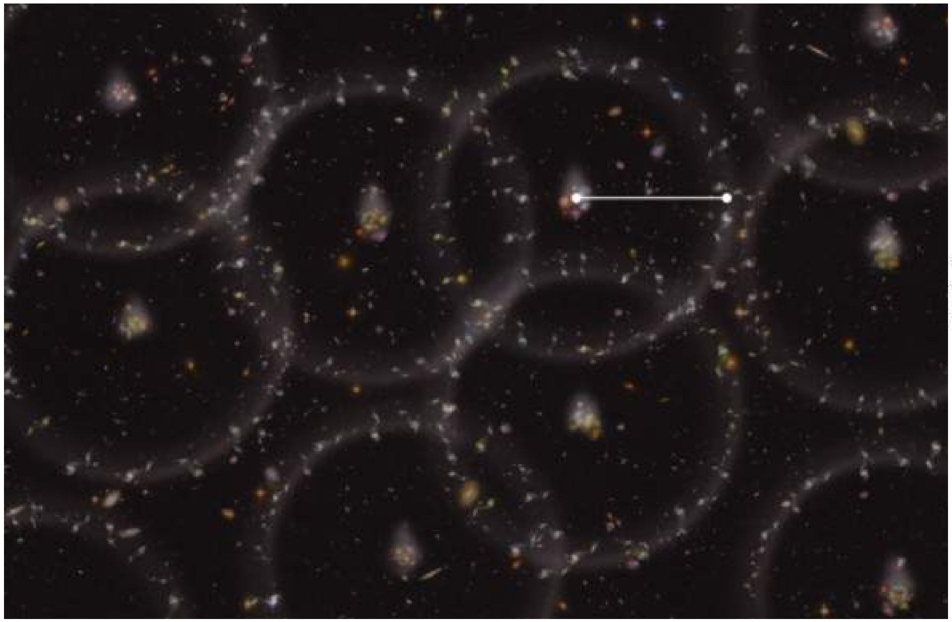
$$\chi^2_{SnIa}(\Omega_{0m},w_0,w_1) = \sum_{i=1}^{N}\frac{(\mu_{obs}(z_i) - \mu_{th}(z_i))^2}{\sigma^2_{\mu\ i}}$$

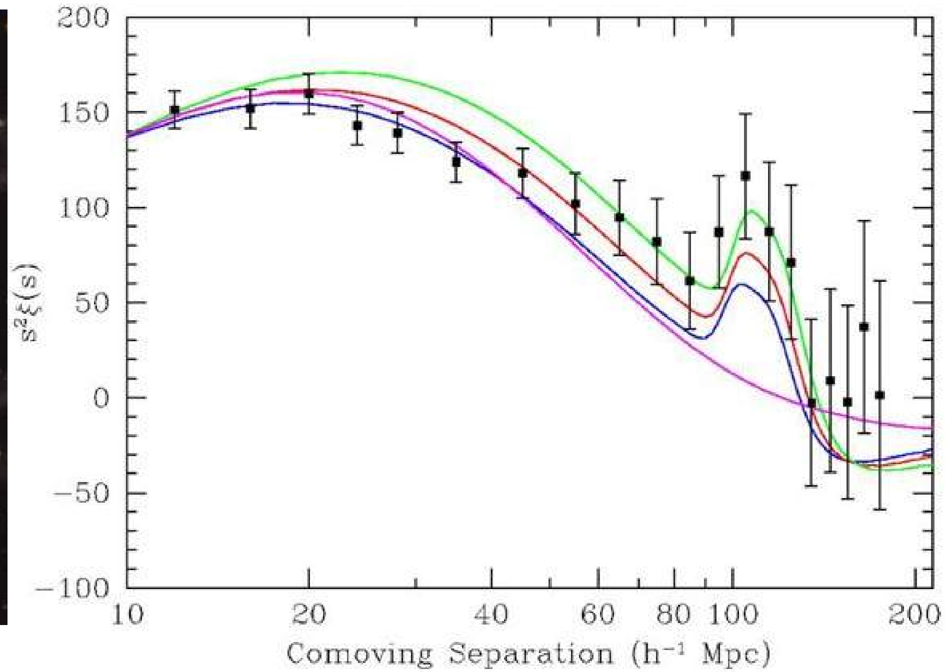
Union-2 SNe

Amanullah et al. (2010)



The Baryon Acoustic Oscillations (BAO)





1) Created by the baryons falling in and out of the potential wells (due to the photons' pressure).
2) They happen at scales where galaxies are correlated.
3) These scales are known and can be used to measure the expansion history of the Universe.

Some mathematical details about the BAO...

Probability to find two galaxies in positions 1 and 2 if they are uniformly distributed:

$$\Delta P_{\text{uniform}} = \frac{\Delta V_1}{V} \times \frac{\Delta V_2}{V}$$

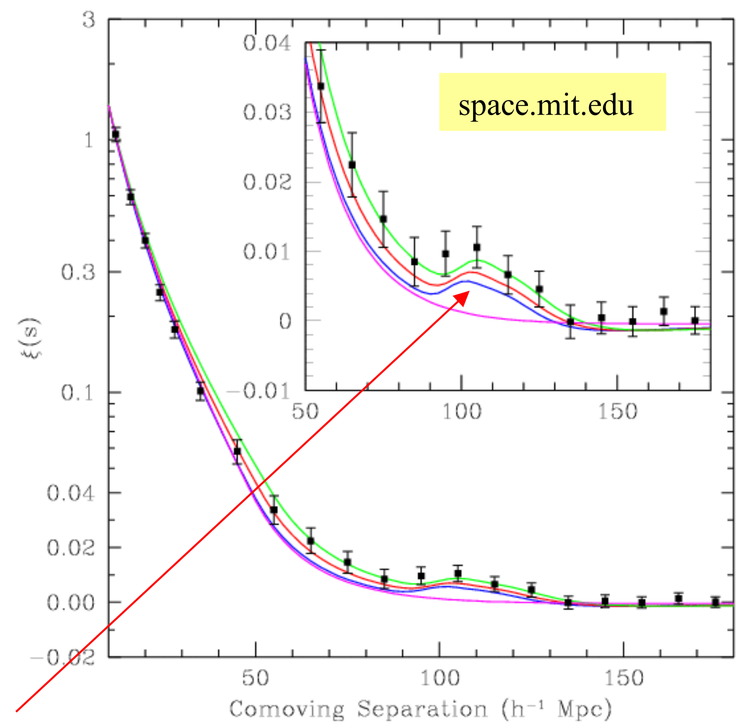
And if they are clustering:

$$\Delta P = [1 + \xi_g(r)] \frac{\Delta V_1}{V} \frac{\Delta V_2}{V}$$

$$\xi(\vec{r}) \equiv \langle \delta(\vec{x}) \delta(\vec{x} + \vec{r}) \rangle \qquad \delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \langle \rho \rangle}{\langle \rho \rangle}$$

$$\xi(r) = \frac{1}{(2\pi)^3} \int P(k) \frac{\sin(kr)}{kr} \, 4\pi k^2 dk$$

$$P(k) \equiv \langle |\delta_k|^2 \rangle$$



BAO!

Correlation function:

Related to the probability to find a galaxy at r.

Some mathematical details about the BAO...

Matter power spectrum P(k)

$$P(k) \equiv \langle |\delta_k|^2 \rangle$$

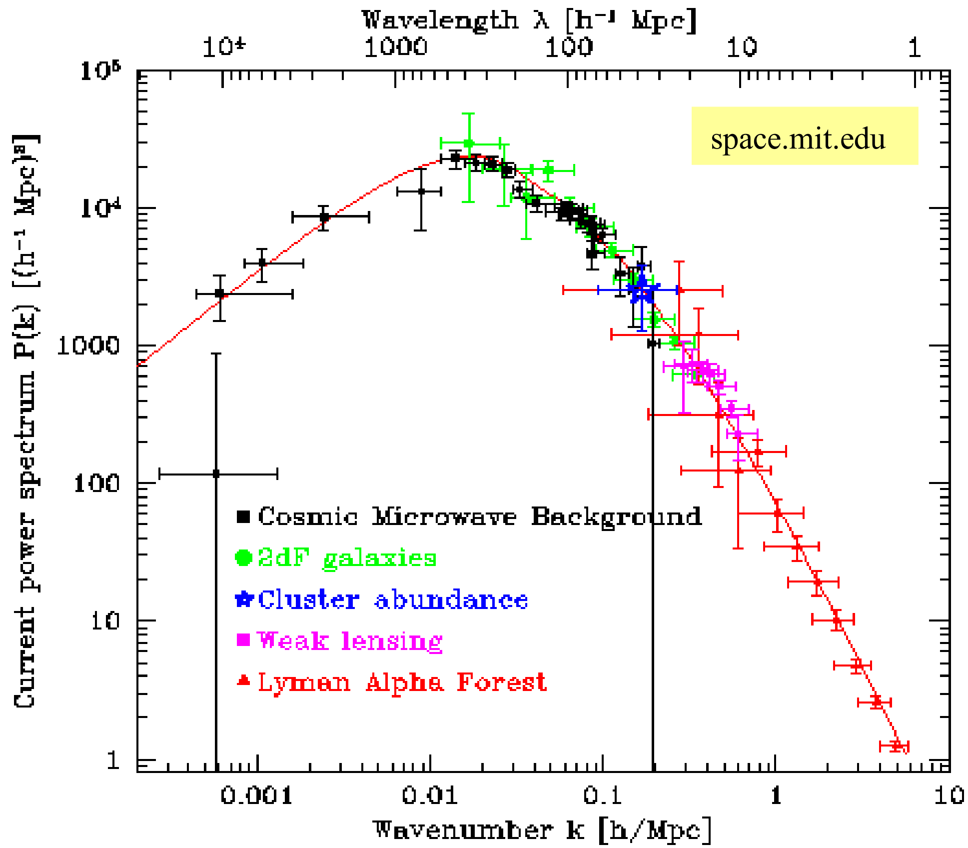
CAMB

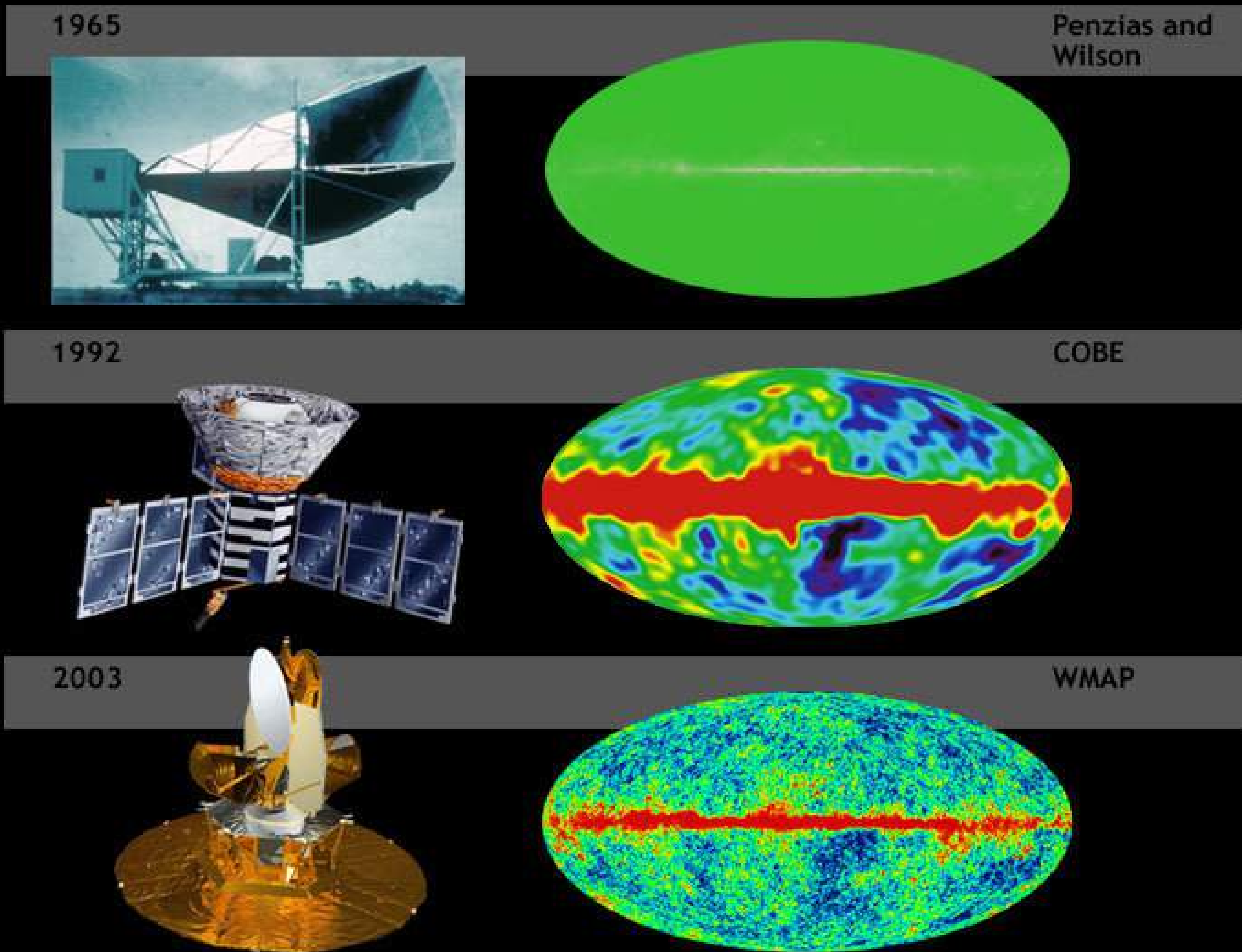
If:

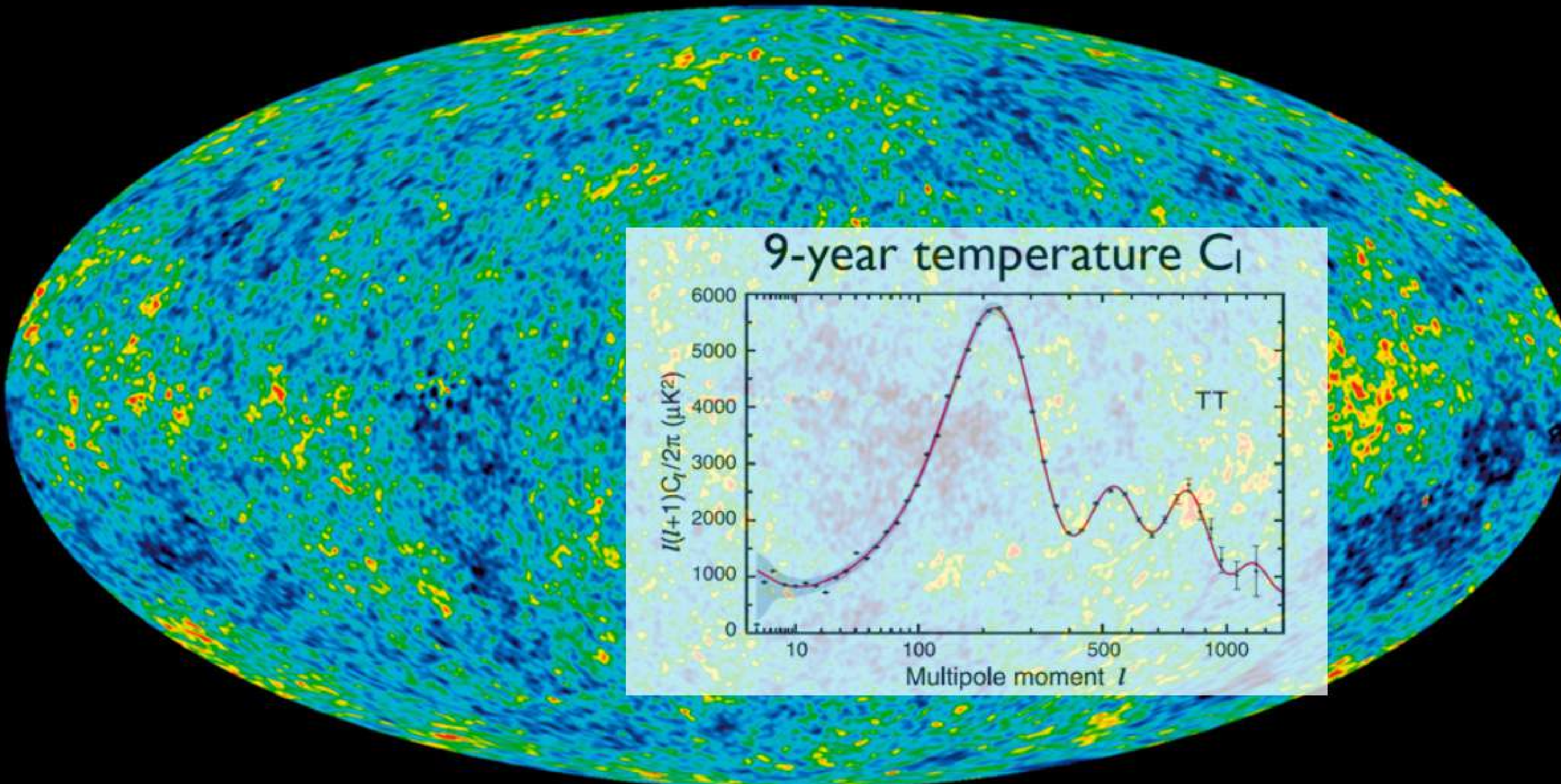
$$\xi_g(r) = \left(\frac{r}{r_0}\right)^{-(3+n)}$$

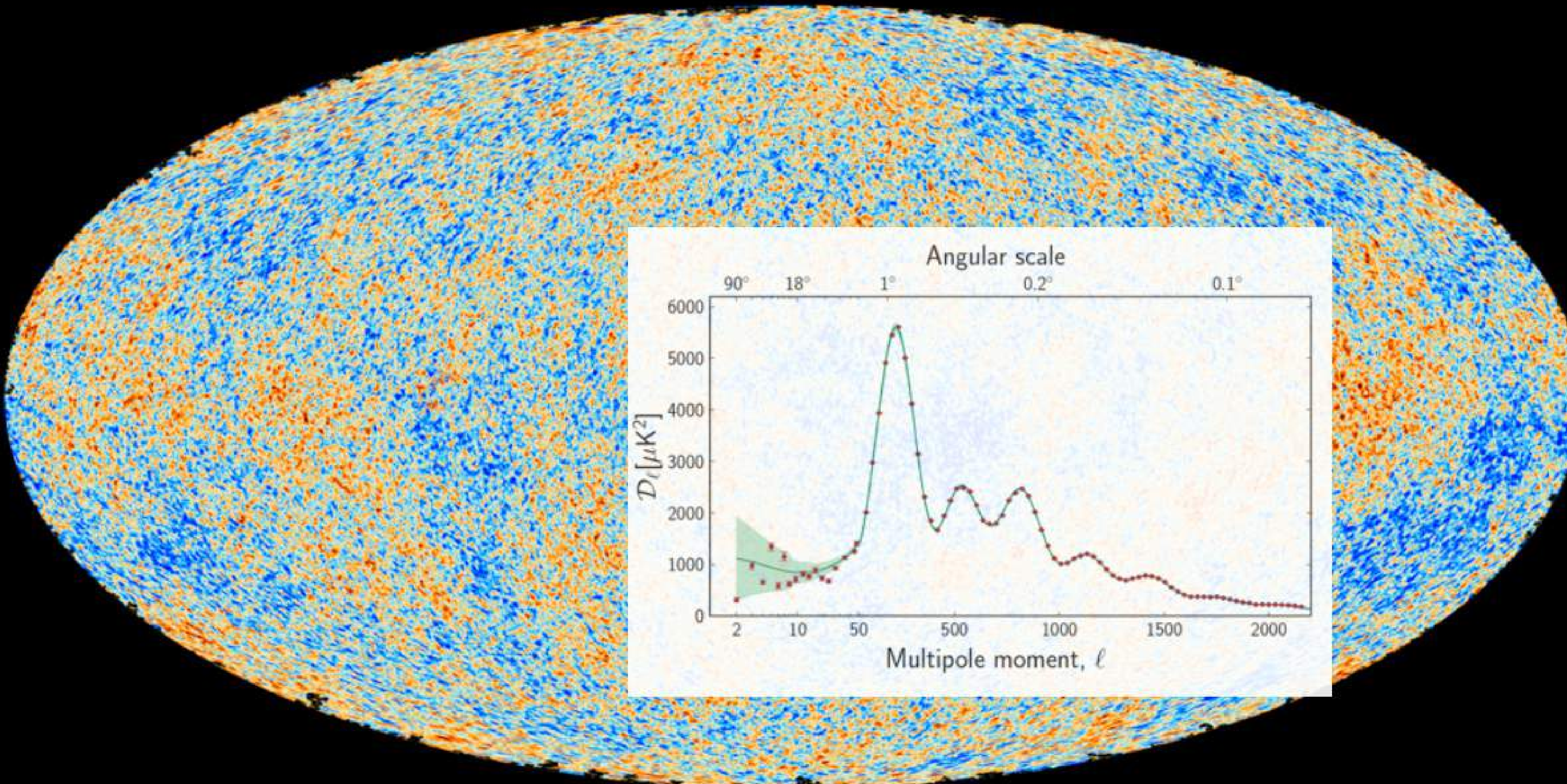
Then:

$$P_g(k) \propto k^n$$




1965
Penzias and Wilson
1992
COBE
2003
WMAP

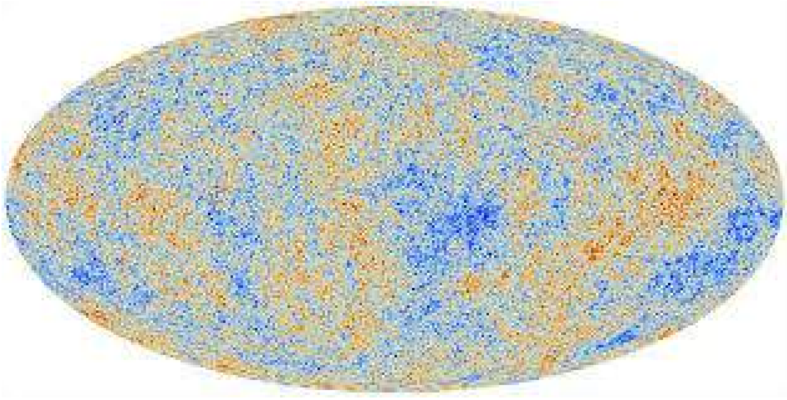

9-year temperature Cl
TT
l(l+1)Cl/2π (μK²)
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l

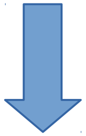

Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
Multipole moment, ℓ

Some mathematical details about the CMB...

A CMB map:

$$T(\vec{x},\hat{p},\eta) = T(\eta)\,[1+\Theta(\vec{x},\hat{p},\eta)]$$



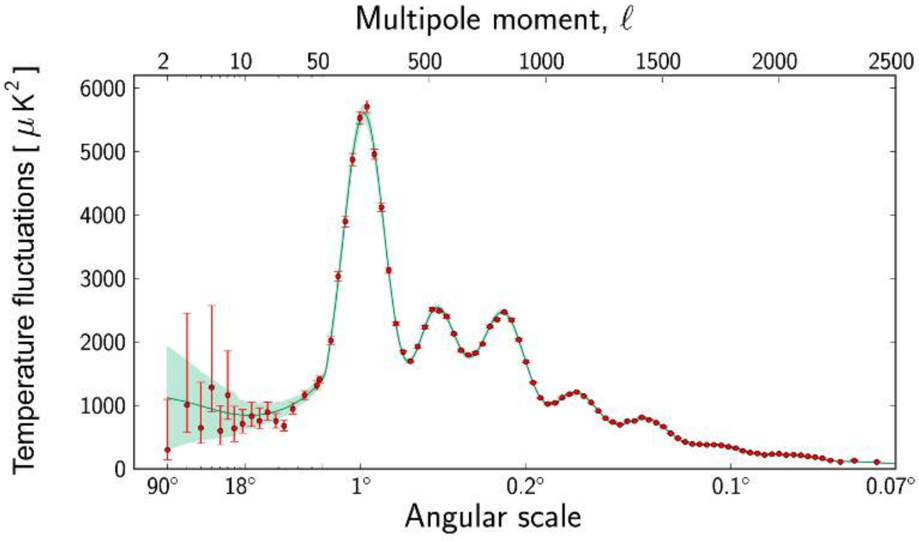


Healpix

Expand in spherical harmonics:

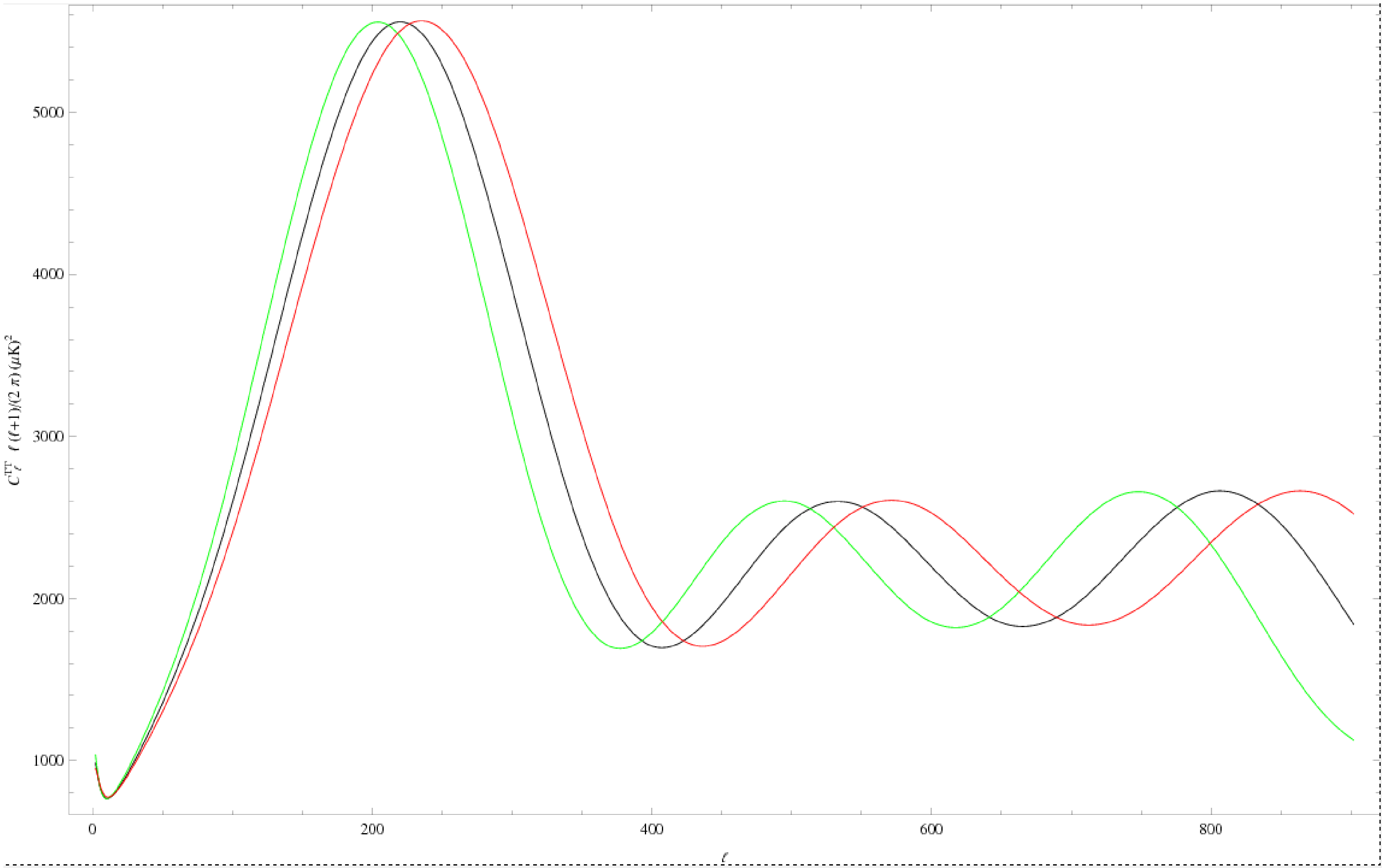
$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}\rangle = 0 \quad ; \quad \langle a_{lm}a^{*}_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_l$$



The physics of the CMB and the cosmological parameters

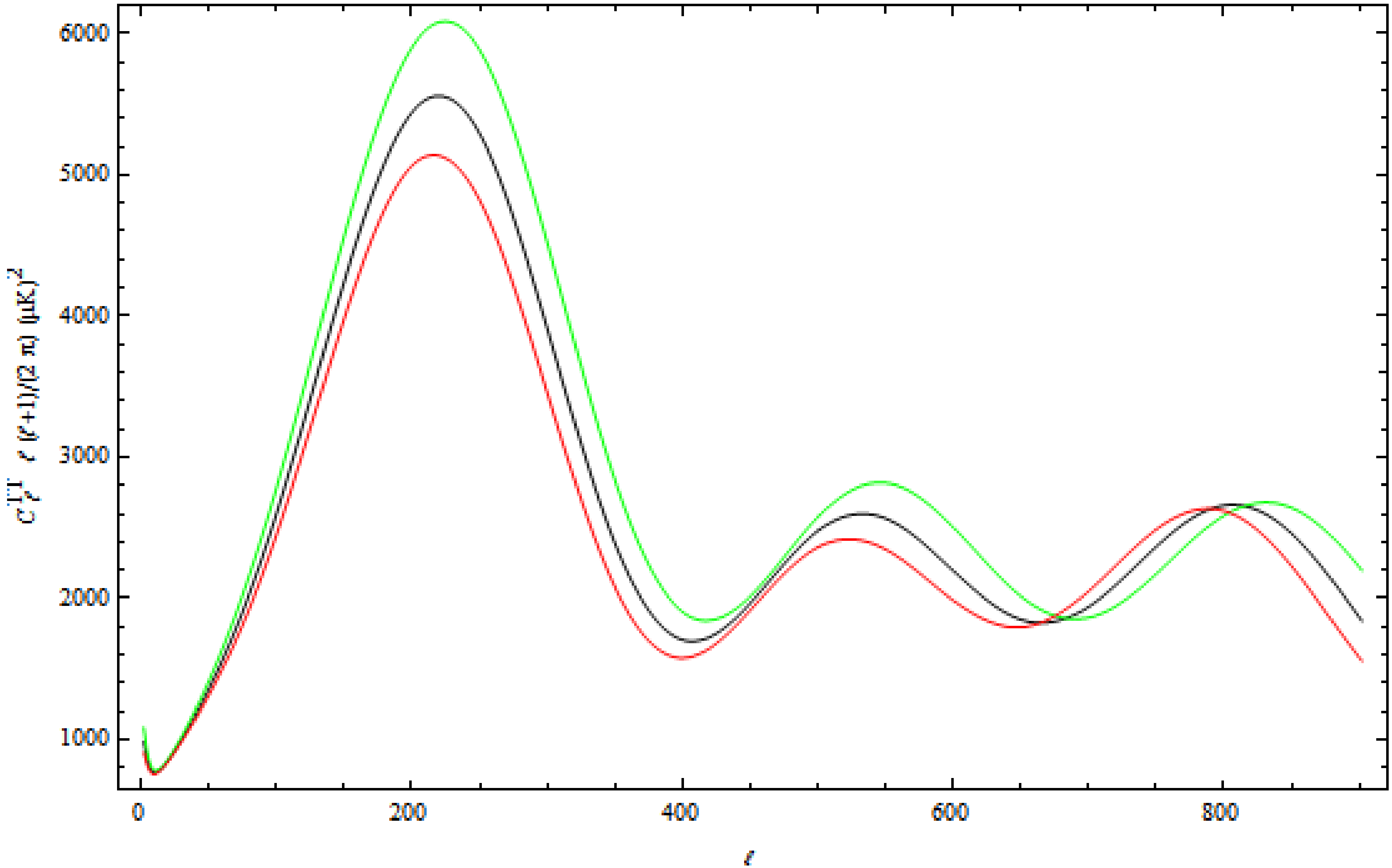
Ωk=[-0.05, 0, 0.05]



The physics of the CMB and the cosmological parameters

Ωm=[0.2038, 0.2538, 0.3038] and H0=70

Ωmh^2=[0.099862, 0.124362, 0.148862]



A phenomenological approach to Dark Matter's properties

- What is the nature of Dark Matter (DM) and what are its properties?

- What is the behaviour of the DM perturbations?

- How can we use the aforementioned data?

- How compatible is the Standard Cosmological Model with the data?

The Dark Matter perturbations and their "sound speed"

M. Kunz, S.N., I. Sawicki, arXiv: 1507.01486

Energy-momentum tensor for perfect fluid:

$$T^{\mu}_{\nu} = P g^{\mu}_{\nu} + (\rho + P) U^{\mu} U_{\nu}$$

Equation of state w

$$P = w\,\rho$$

- $w = 0$ Non-relativistic matter
- $w = \frac{1}{3}$ Radiation

Sound of perturbations cs^2:

$$\delta P = c_s^2 \delta\rho$$

- $c_s^2 = 1$ Quintessence
- $c_s^2 = 0$ "Usual" Dark Matter

The Dark Matter perturbations and their "sound speed"

M. Kunz, S.N., I. Sawicki, arXiv: 1507.01486

If $0 < c_s^2 \leq 1$ for DM, then this affects large structure in the Universe!

Reason: There's a sound horizon at scales:

$$k_J(z) \equiv \frac{H(z)}{(1+z)c_s}$$

Two cases:

- Outside the horizon => cs^2 is irrelevant.
  $k \ll k_J$
- Inside the horizon => cs^2 "behave like pressure" and try to erase the structures.
  $k \gg k_J$

The Dark Matter perturbations and their "sound speed"

M. Kunz, S.N., I. Sawicki, arXiv: 1507.01486

Methodology:

Split DM in two parts

- $c_s^2 = 0$ — Usual DM
- $0 < c_s^2 \leq 1$ — DM with a cs^2

But keep the background fixed to ΛCDM

(dark degeneracy)

$$\Omega_X(a) + \Omega_c(a) = \Omega_\Lambda(a) + \Omega_c^{\rm Planck}(a)$$

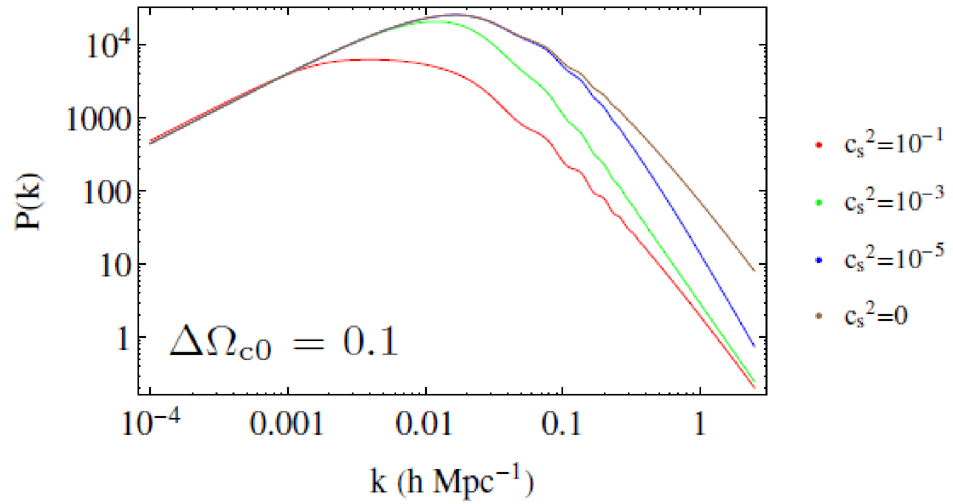
$$1 + w_X(a) = \frac{\Delta\Omega_{c0}}{\Delta\Omega_{c0} + \Omega_{\Lambda 0} a^3}$$

$$\Delta\Omega_c \equiv \Omega_c^{\rm Planck} - \Omega_c$$

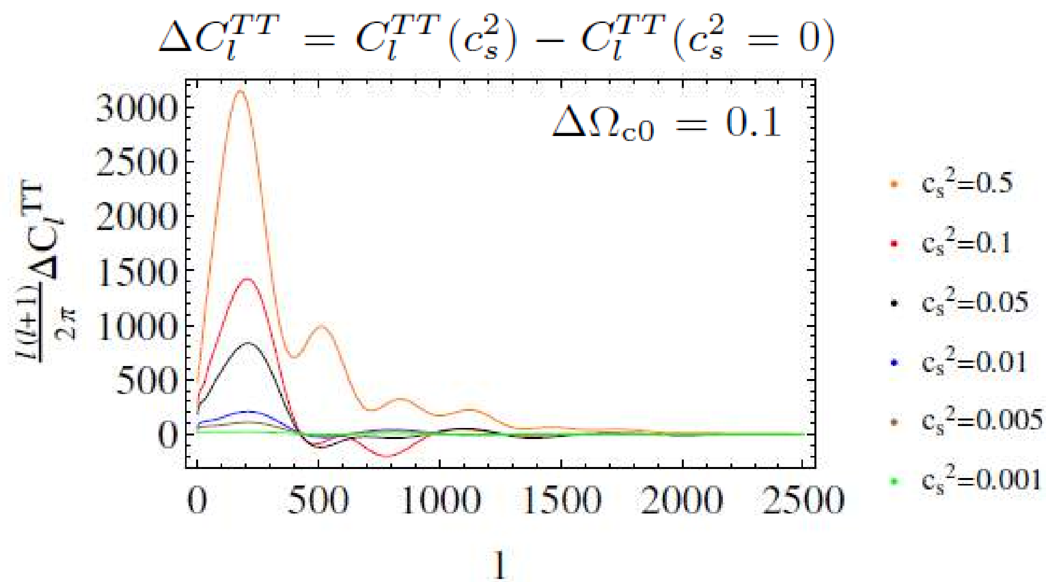
The Dark Matter perturbations and their "sound speed"

M. Kunz, S.N., I. Sawicki, arXiv: 1507.01486

It affects the power spectrum P(k):

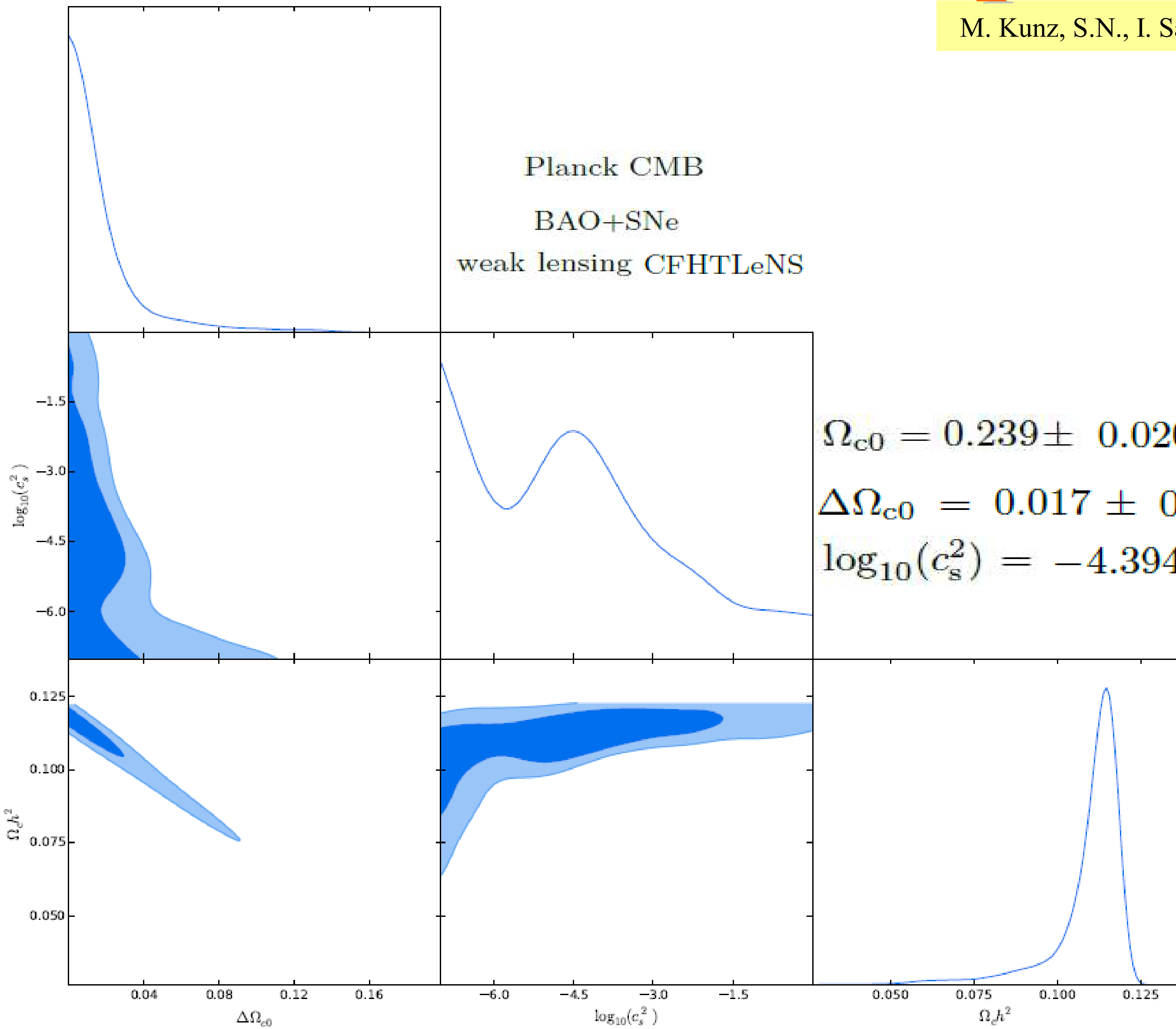


It also affects the CMB:



The Dark Matter perturbations and their "sound speed"

M. Kunz, S.N., I. Sawicki, arXiv: 1507.01486



$$\Omega_{c0} = 0.239 \pm 0.020$$

$$\Delta\Omega_{c0} = 0.017 \pm 0.019$$

$$\log_{10}(c_s^2) = -4.394 \pm 1.779$$

The Dark Matter equation of state w

M. Kunz, S.N., I. Sawicki, arXiv: 1602.xxxxx

Now, replace the usual DM with the new one, which now also has an EoS w

w = constant

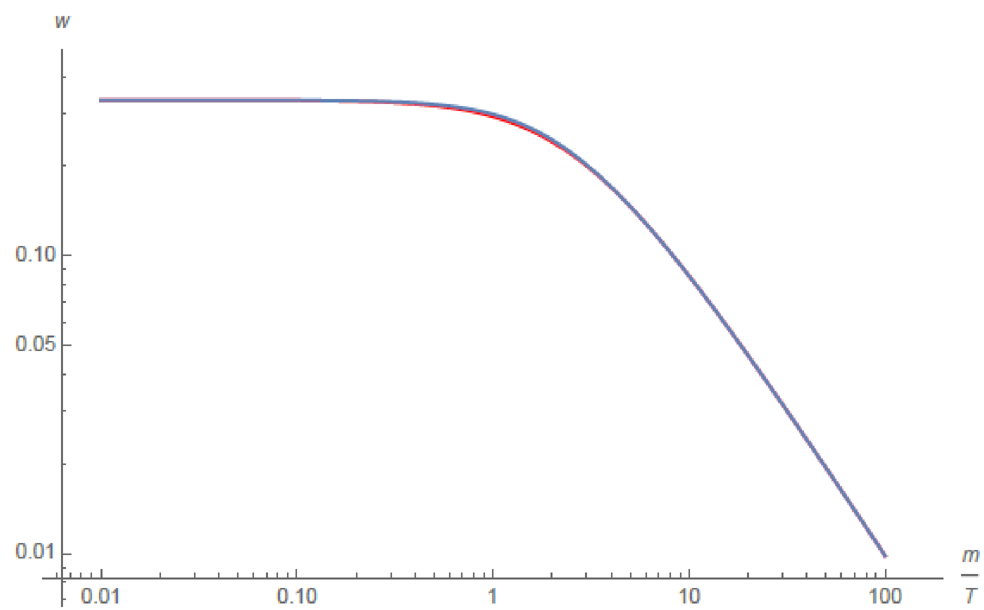
Can be small and constant (CDM)

$$w(a) = \frac{1/3}{\sqrt{1+(a/(3w_1))^2}}$$

$$T_0/m = w_1\sqrt{9/8.828}$$

DM can be relativistic (w~1/3) at early times (a<<1, z>>1)

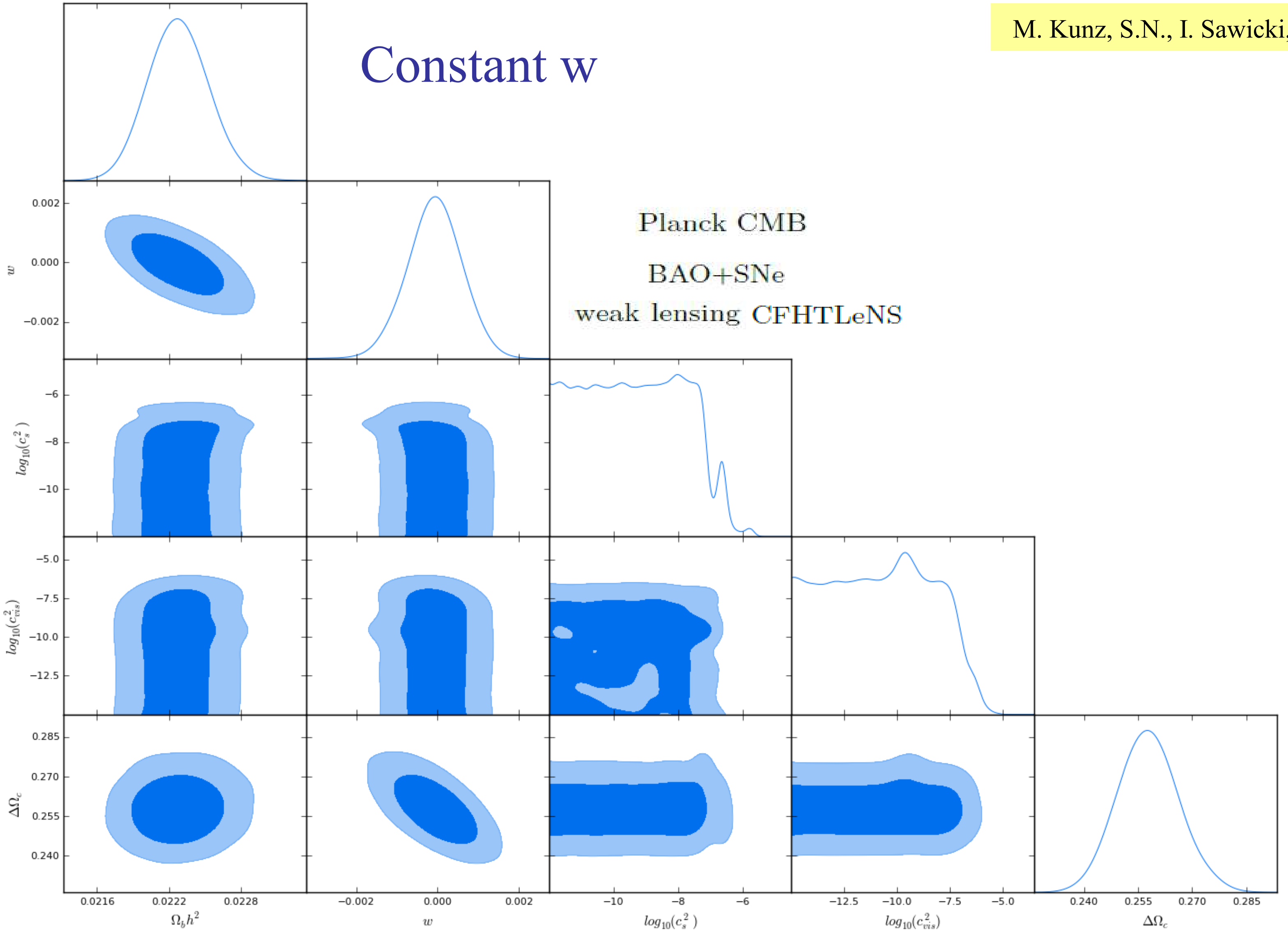
For m<<T we have w = 1/3, while for m>>T we have w~1/a.



The Dark Matter equation of state w

M. Kunz, S.N., I. Sawicki, arXiv: 1602.xxxxx

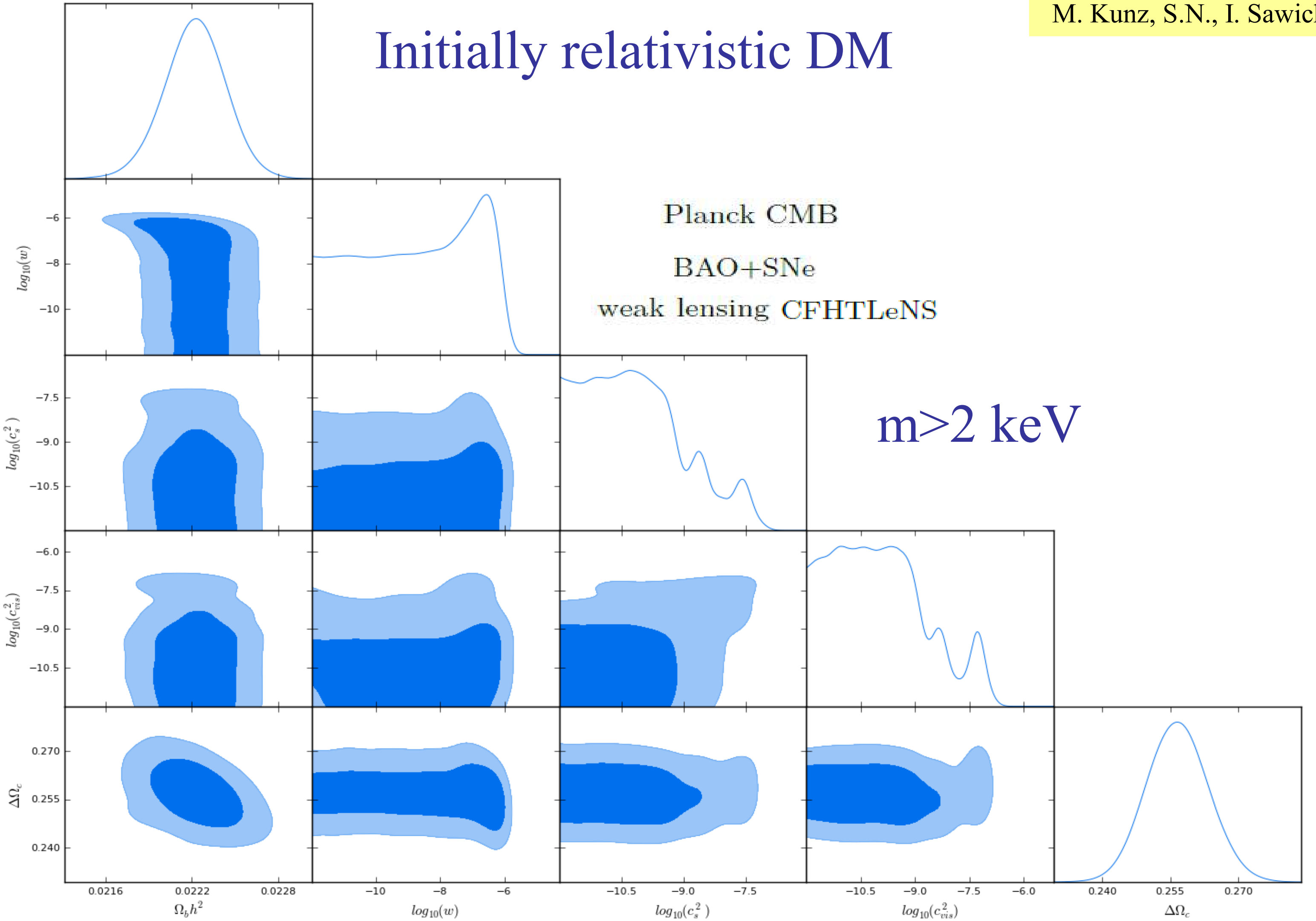
Constant w



The Dark Matter equation of state w

M. Kunz, S.N., I. Sawicki, arXiv: 1602.xxxxx

Initially relativistic DM



m>2 keV

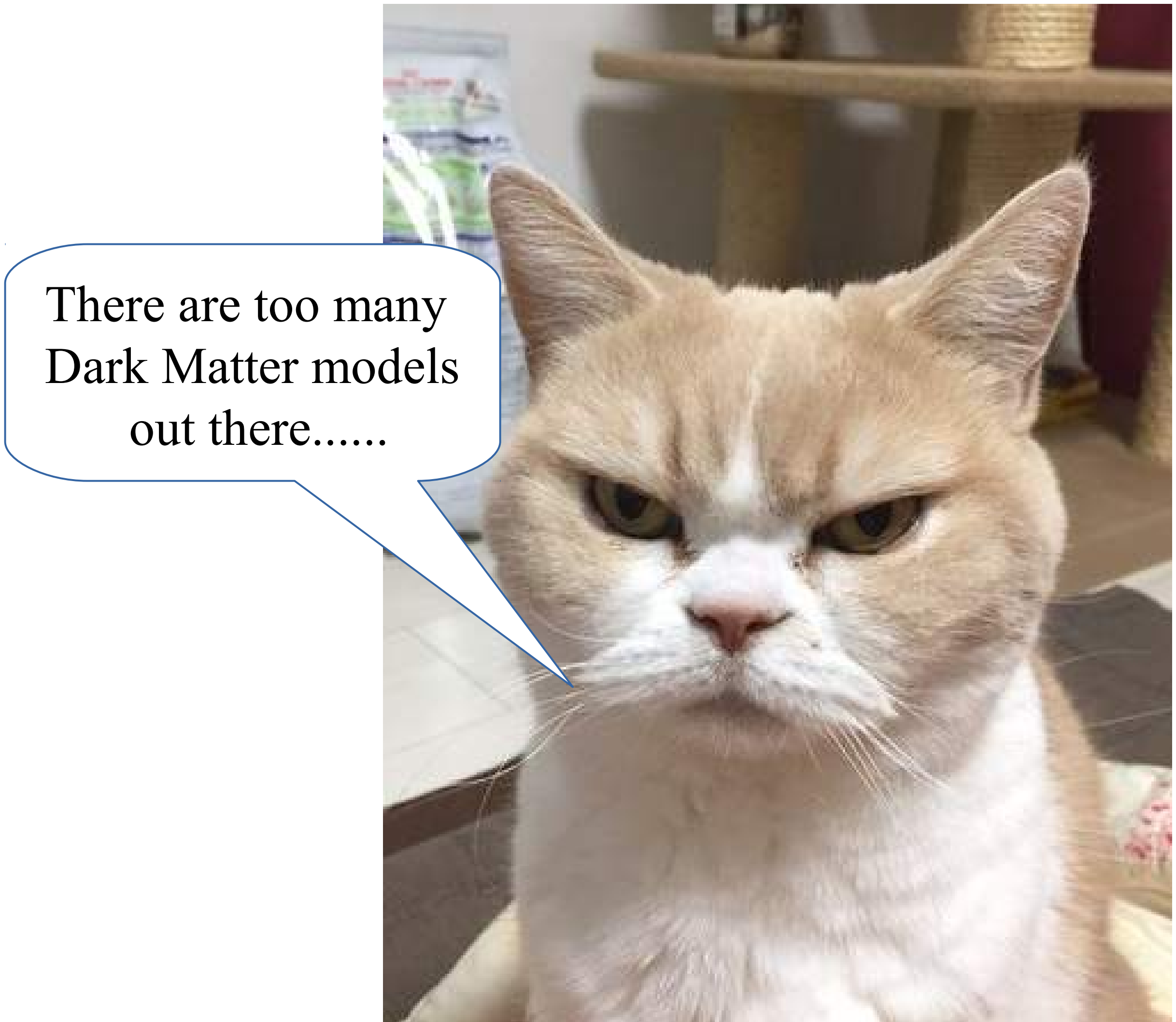
Conclusions

- Brief intro and discussion of the data (SnIa, CMB, WL, BAO).
- Discussion of DM perturbations and their effects on large scale structure.
- Constraints on the sound speed of DM: $\Delta\Omega c \sim 0.017$ (6.6% of total DM) with $cs^2 \sim 10^{-4.4}$
- Constraints on DM EoS w(z):

  Constant w: $w \sim 0$, $cs^2 < 10^{-6}$

  Initially relativistic (WDM): $m > 2$keV, $cs^2 < 10^{-7.5}$

Conclusions



The contributions of de Sitter and Lemaitre

Willem de Sitter (1917):

1) A static and isotropic Universe with a cosmological constant,

2) An empty expanding Universe with the cosmological constant, (de Sitter model).

Lemaitre (1927):

1) He introduced the theory (known today as the "Big Bang") for the creation of the Universe.

2) Pioneer in the use of General Relativity in cosmology.

3) Independently found the Friedmann

Einstein, Ehrenfest, De Sitter, Eddington & Lorentz
Leiden (1923)