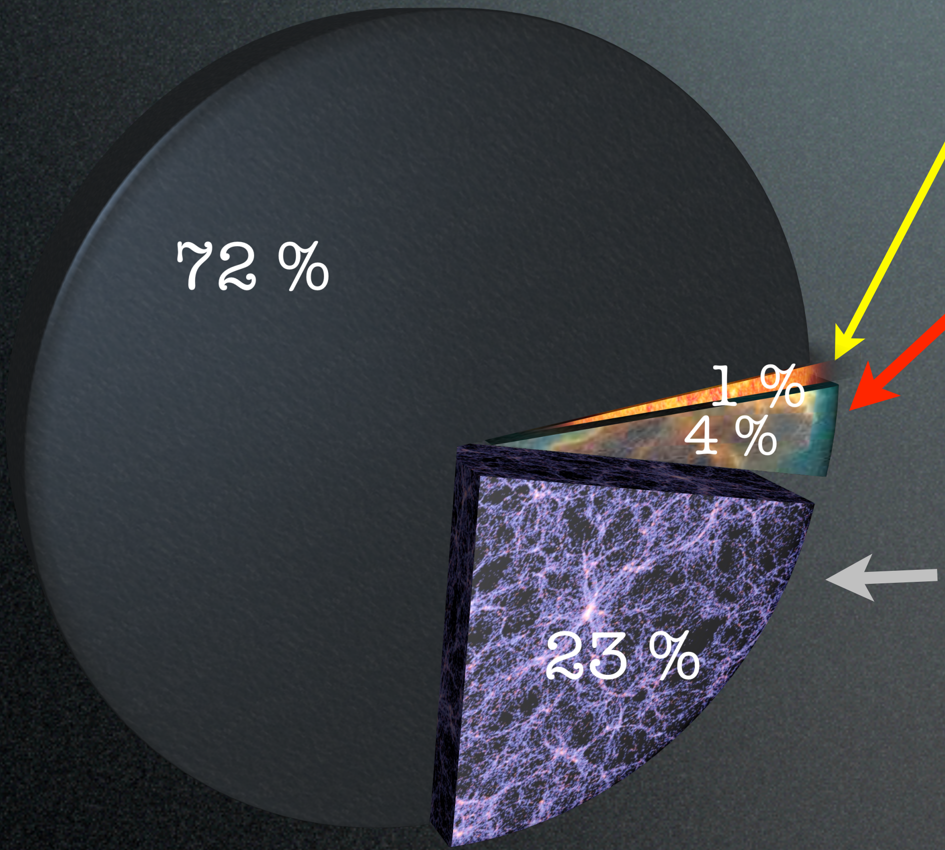
Energia Oscura

(Dark Energy)

How do we know that Dark Energy is out there?

The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

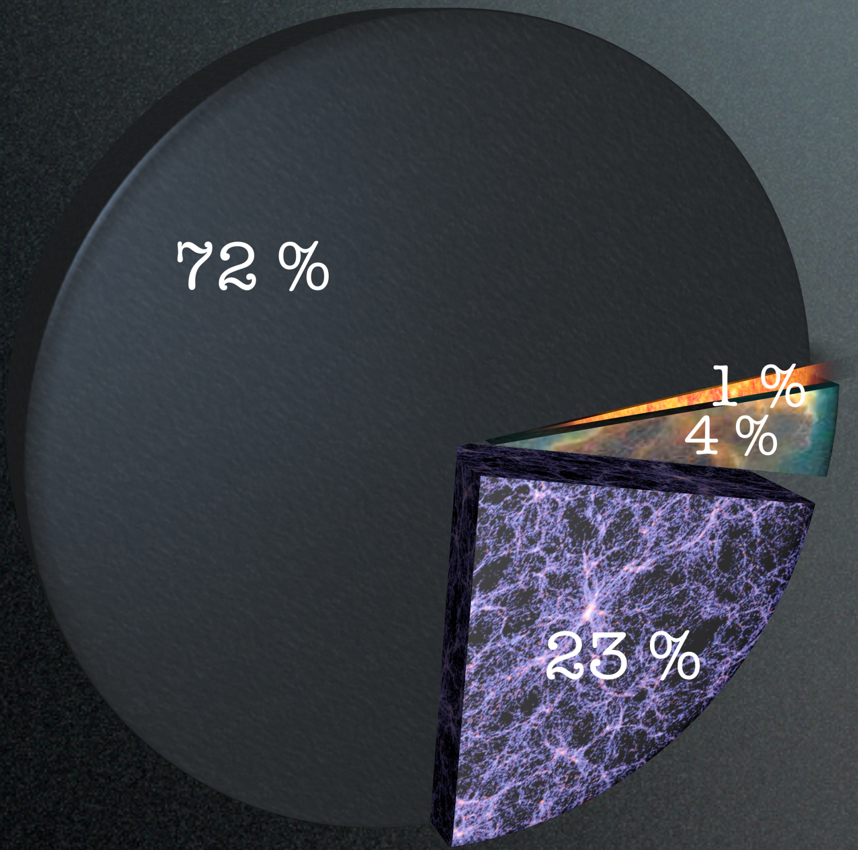
$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

$\Omega_{\rm DM} \sim 0.23$

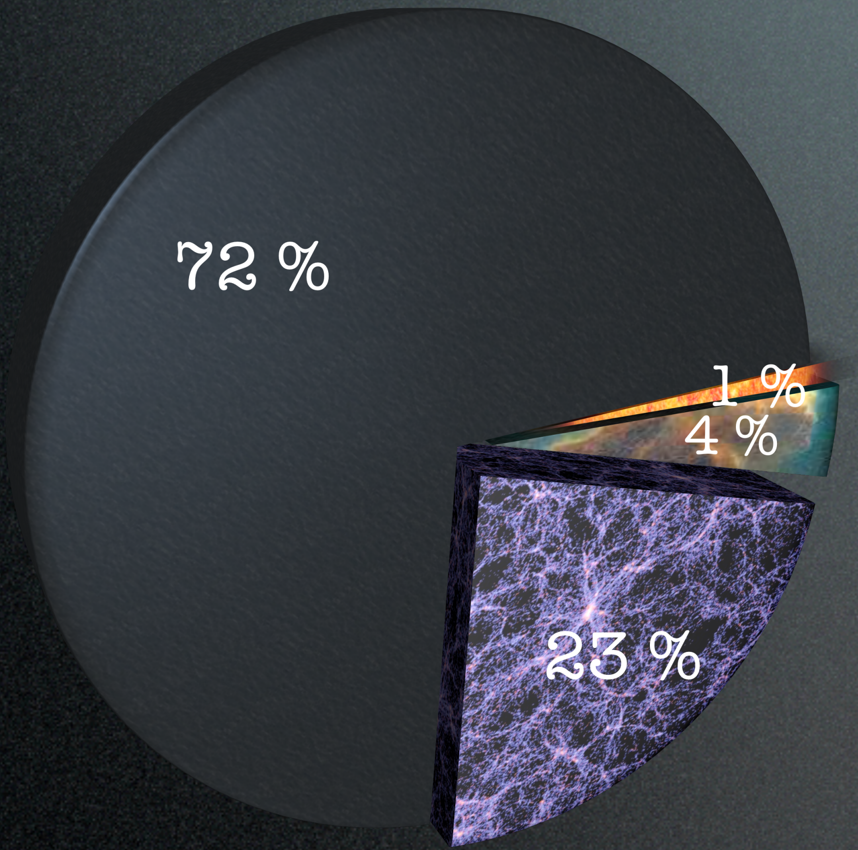
$\Omega_{\rm de} \sim 0.72$

The cosmic inventory

‘Definition’ of Dark Energy:



The cosmic inventory



'Definition' of Dark Energy:

Einstein equations

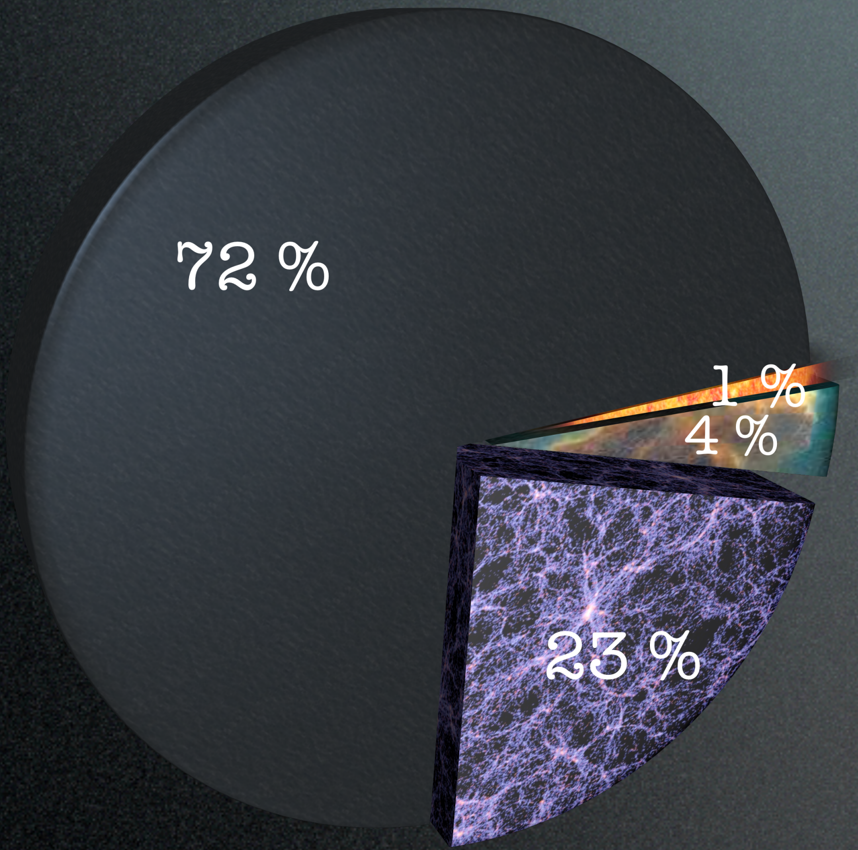
pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

density

the 'size'
of the Universe

The cosmic inventory



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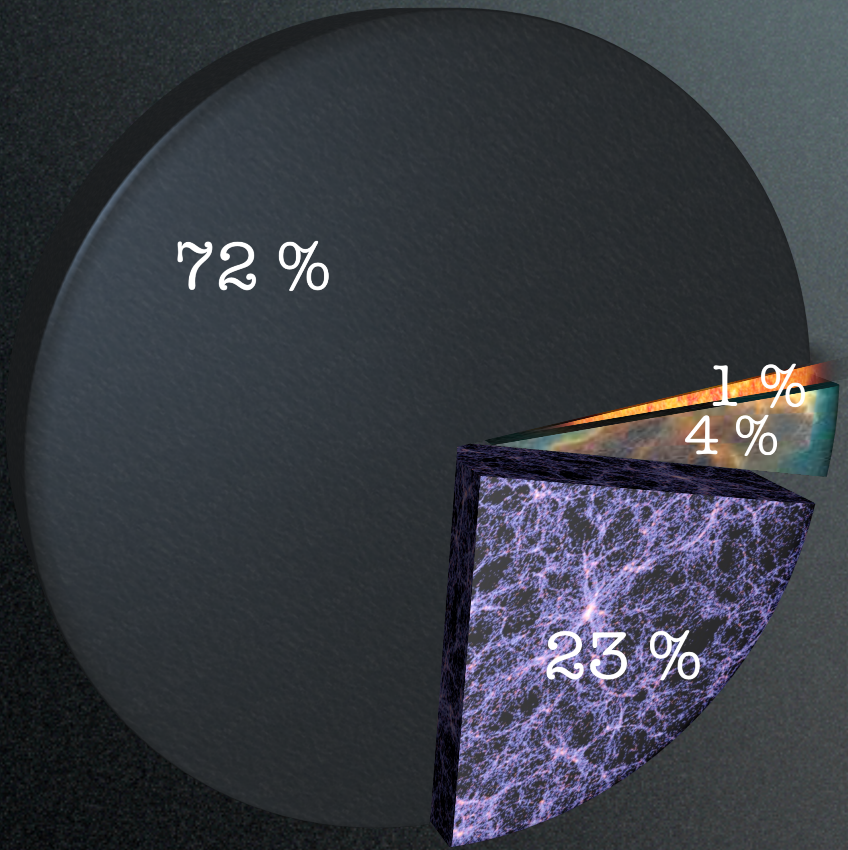
if $\rho < -p/3$ i.e. $w := \frac{\rho}{p} < -\frac{1}{3}$

⇨ acceleration!

The cosmic inventory



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$\Rightarrow$ acceleration!

special case:

$\rho = -p$ i.e. $w = -1$

cosmological constant Λ

(constant as $\rho_i \propto (1+z)^{3(1+w_i)} \rightsquigarrow \mathrm{const}$)

The Evidence for DE

1) Supernovae type Ia:

‘standard candles’

$$\mathcal{L} = 4\pi F\, d_{\rm L}^2$$

Luminosity (‘known’)

Flux (‘measured’)

Luminosity distance (‘unknown’)

The Evidence for DE

1) Supernovae type Ia:

‘standard candles’

$(1+z)$ due to redshift
$(1+z)$ due to expansion

$$\mathcal{L} = 4\pi F\, d_{\mathrm{L}}^2 = 4\pi F\, \chi^2 (1+z)^2$$

Luminosity
(‘known’)

comoving distance
(‘unknown’)

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'standard candles'

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Luminosity

comoving distance

$$\chi(z) = \int_0^z \frac{dz'}{H(z)} = \int_0^z \frac{dz'}{H_0 \sqrt{\Omega_{\mathrm{M}}(1+z')^3 + \Omega_\Lambda}}$$

so $\mathcal{L}$ as fnct of z and $\Omega_{\mathrm{M}}, \Omega_\Lambda$

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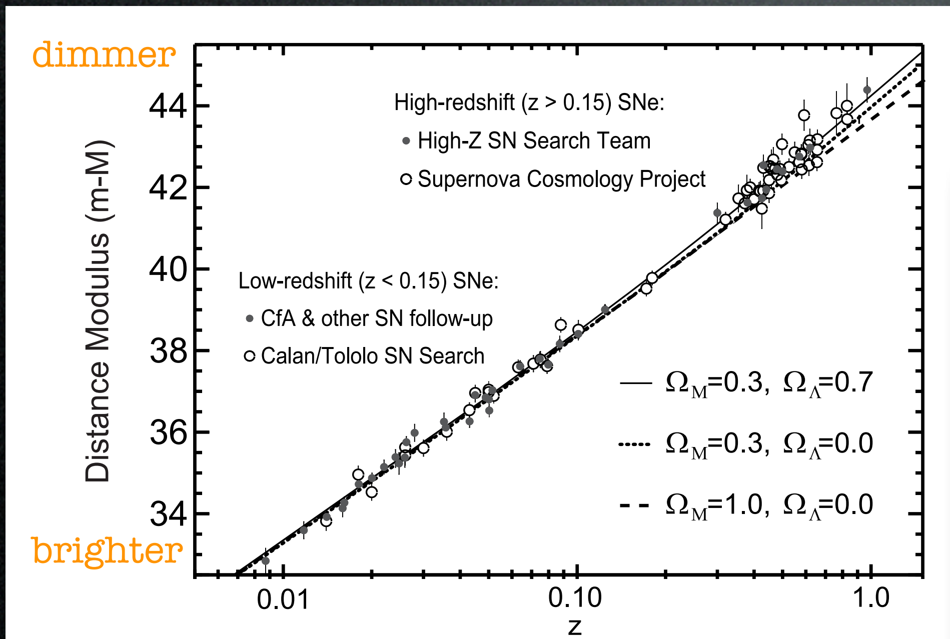
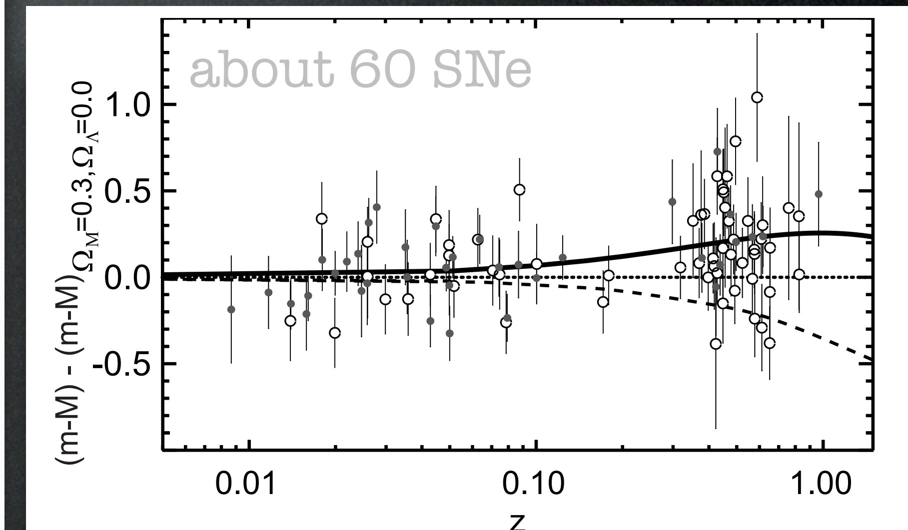


Perlmutter et al., 1999, Astrophys. J. 517
Riess et al., 1998, Astron. J. 116



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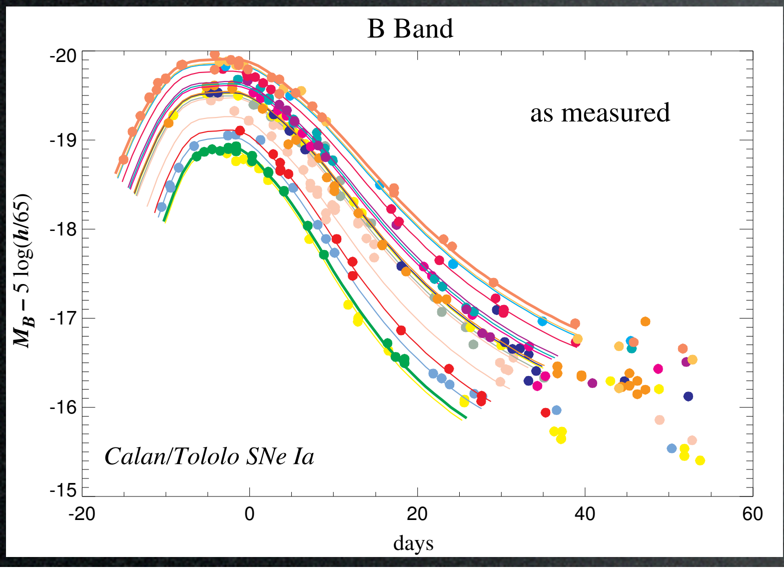
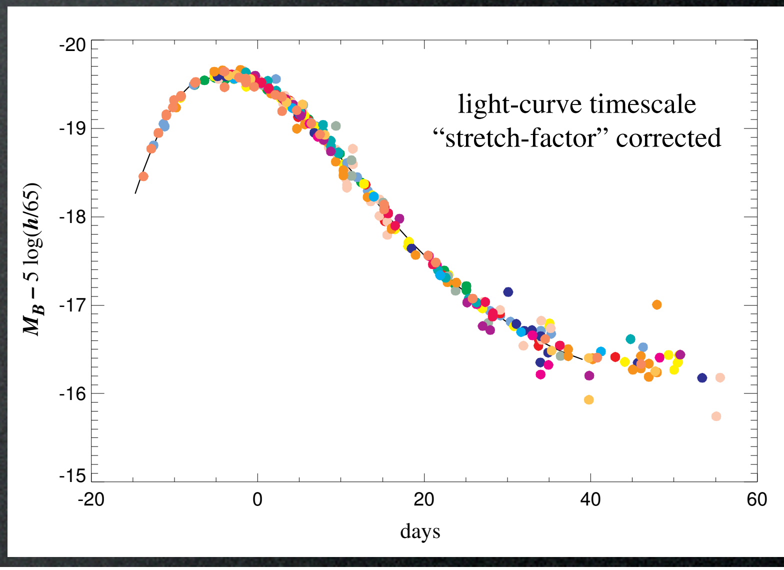
Well, they are not really standard, let’s standardize them



peak $\propto$ duration of lightcurve



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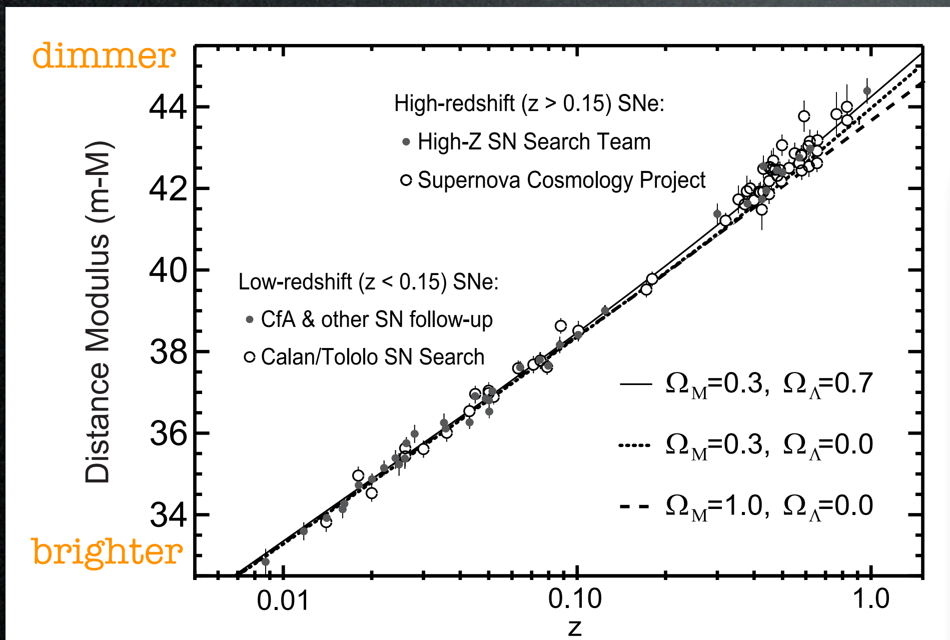

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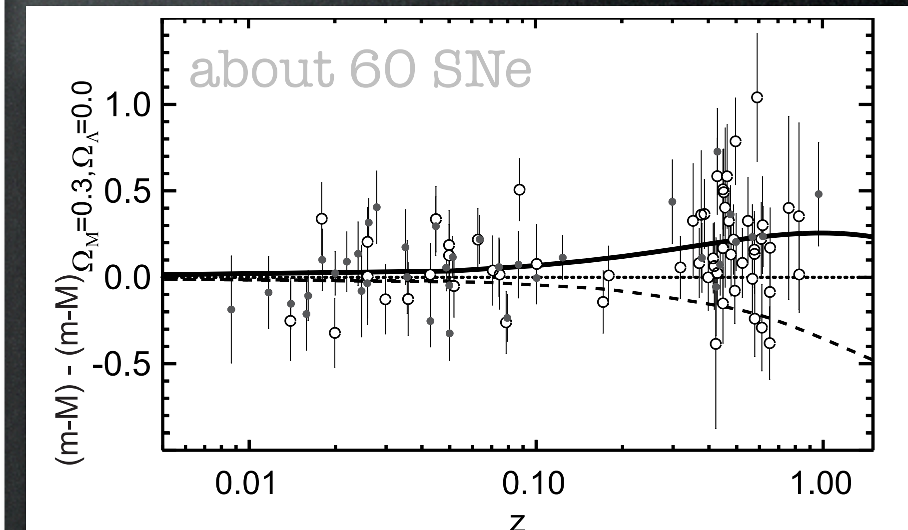

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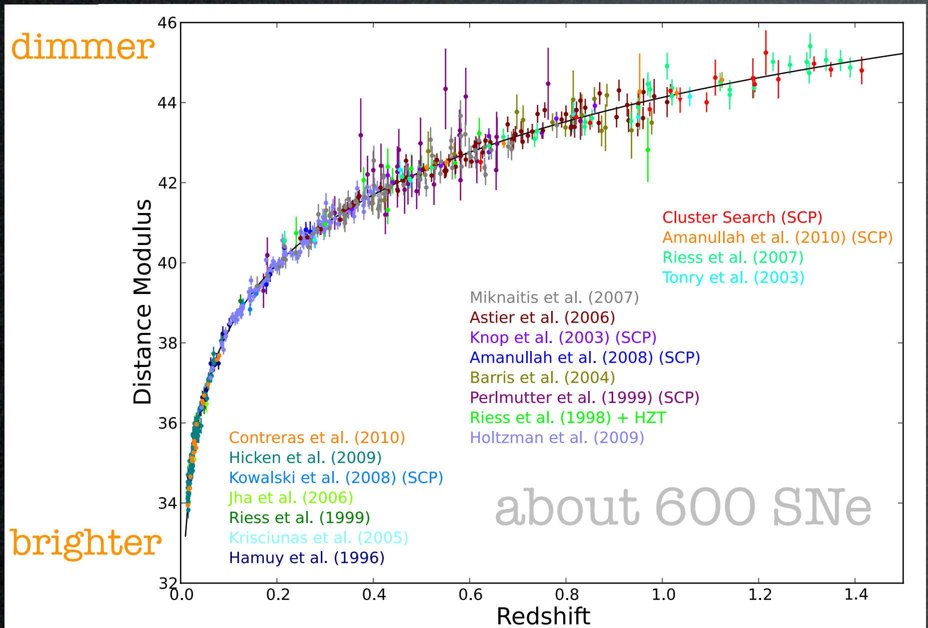


Suzuki et al., 1105.3470

Bottom line:

distant SNe appear dimmer than predicted in a Universe without DE,

the Universe has accelerated in the past 5 Gyr

The Evidence for DE

2) Baryon Acoustic Oscillations:

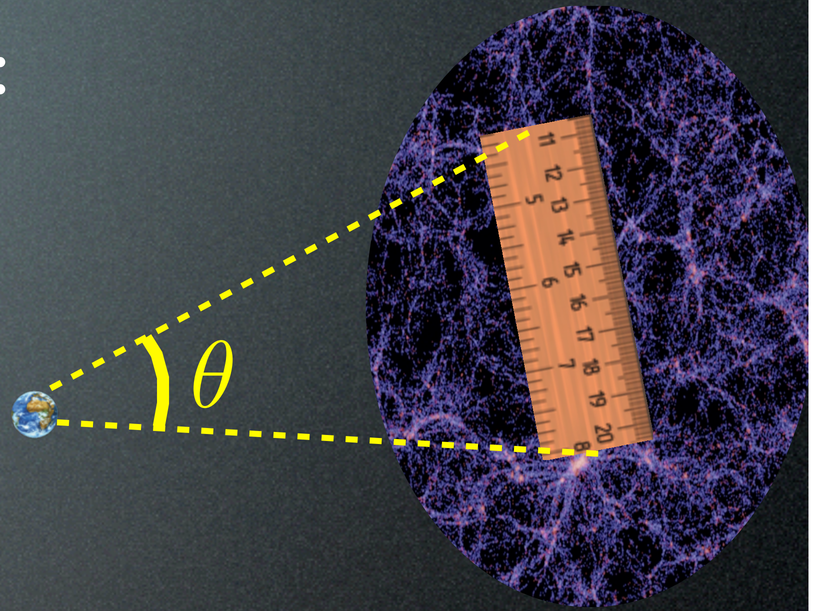
'standard ruler'

$$L = \theta \, d_{\mathrm{A}}$$

Length ('known')

Angle ('measured')

Angular distance ('unknown')



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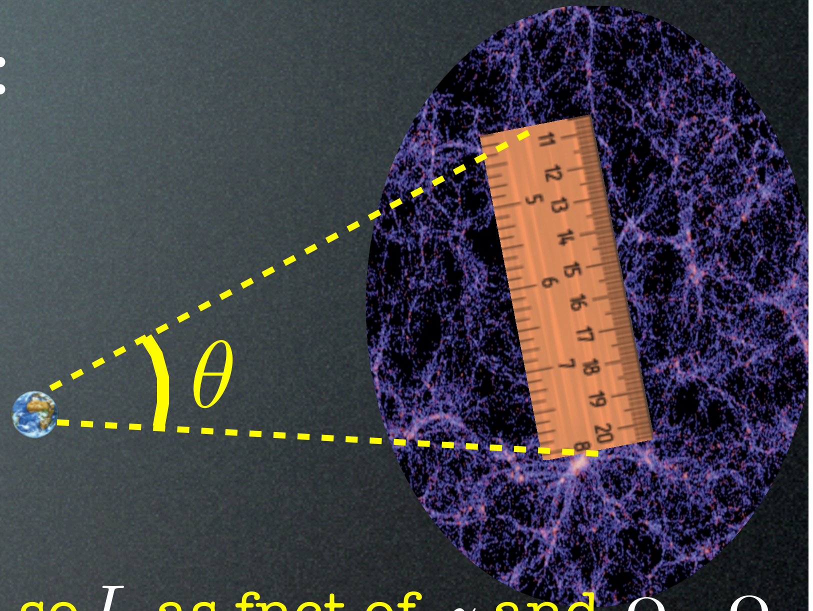

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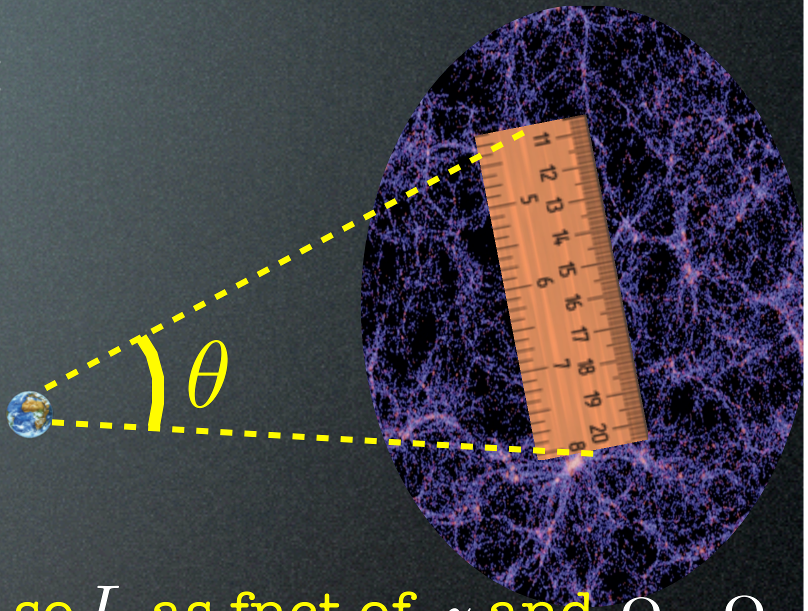

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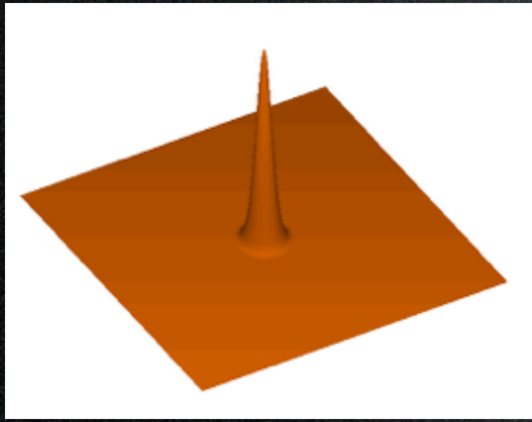

D.Eisenstein, cmb.as.arizona.edu/~eisenste/acousticpeak/

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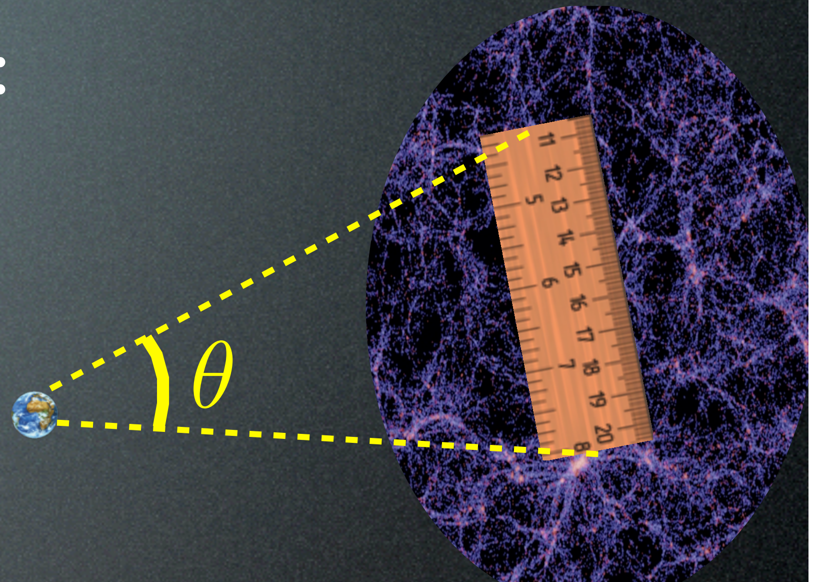

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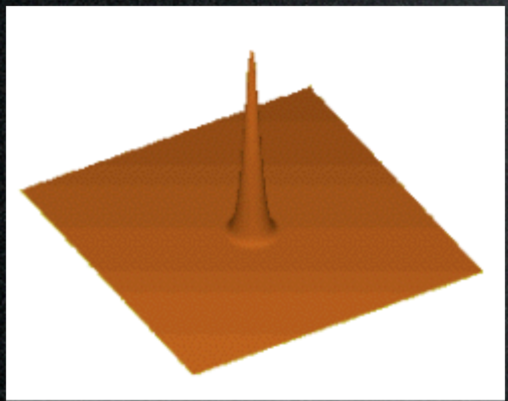

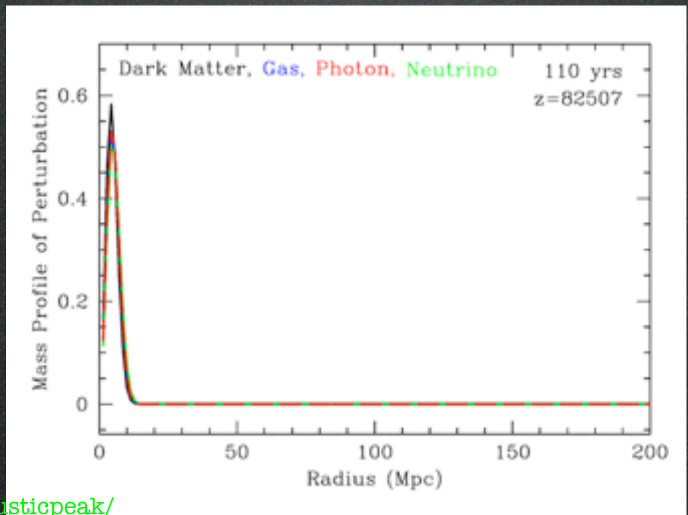

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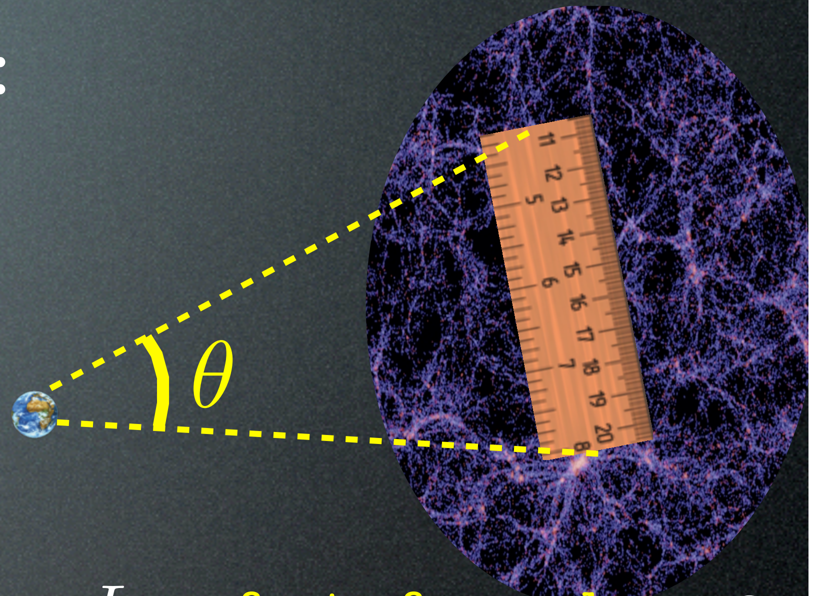

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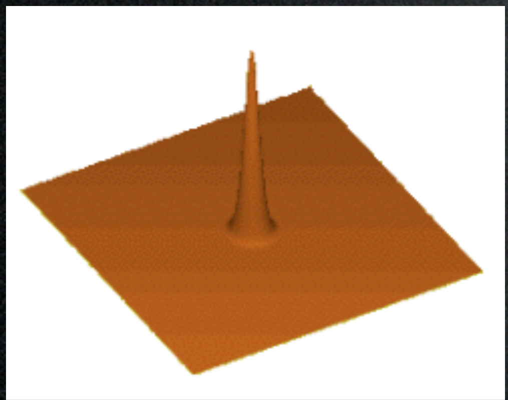

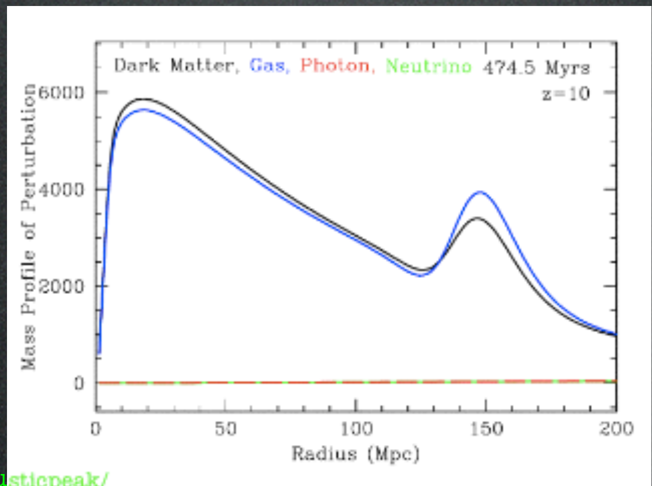

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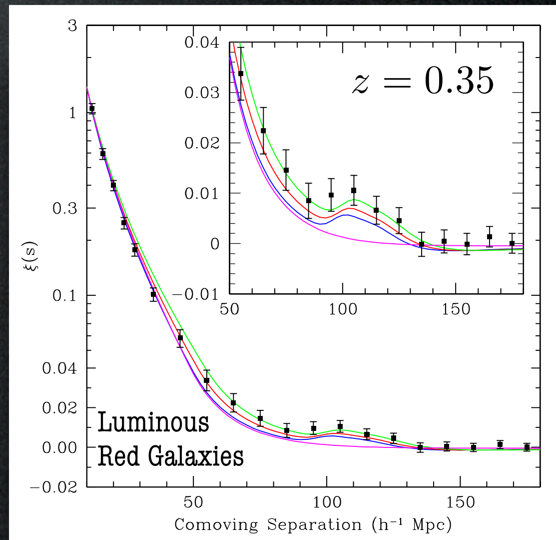

Eisenstein et al., astro-ph/0501171

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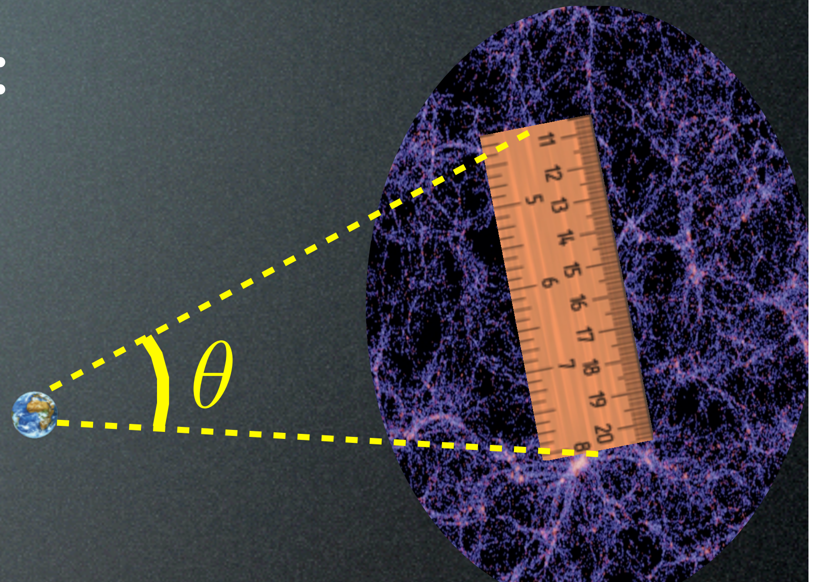

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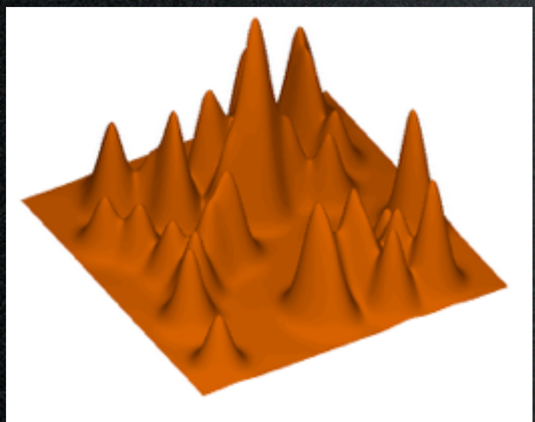
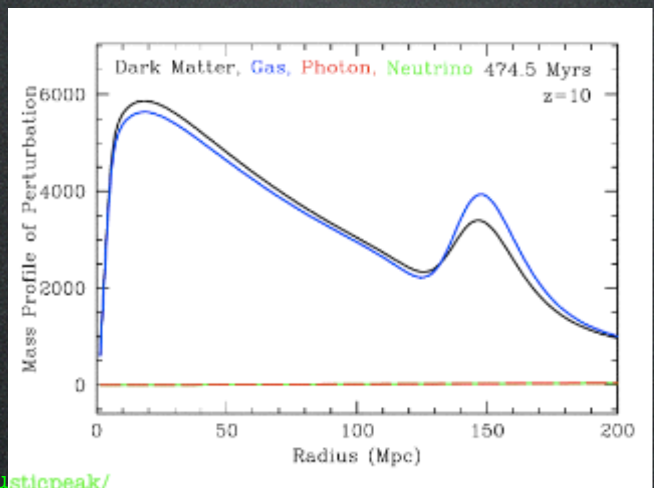
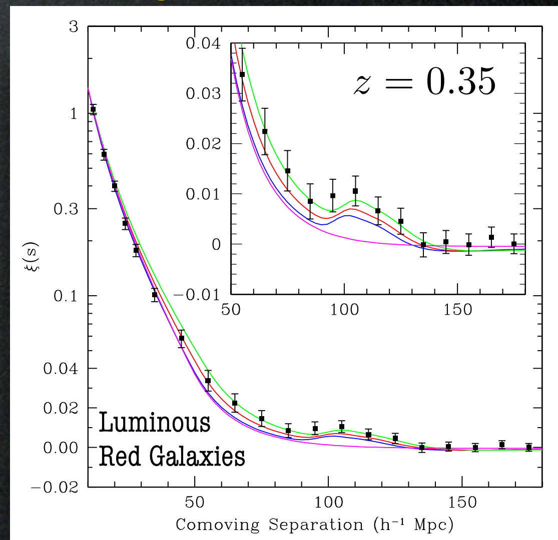
What is the ‘ruler’? A pinch in the galaxy distribution







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NB: can actually do the same in z direction

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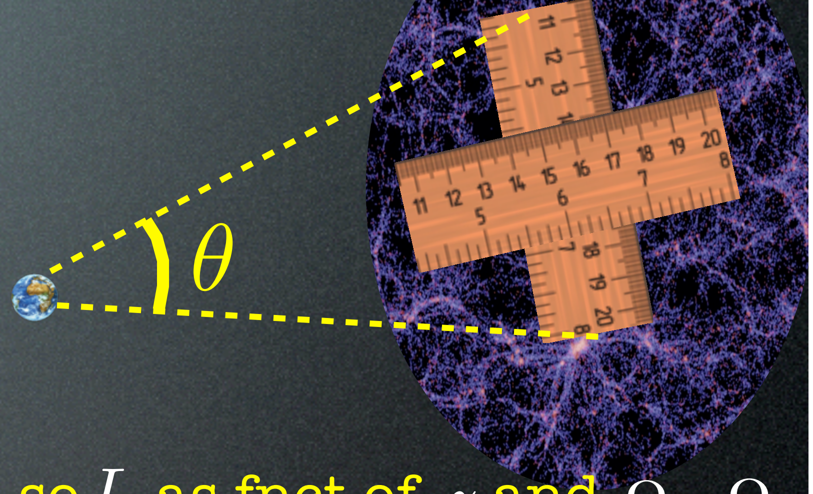

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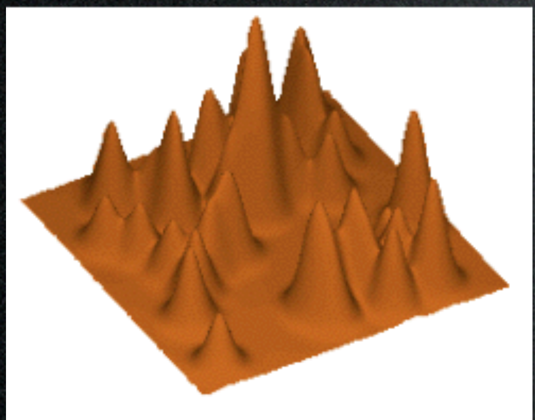

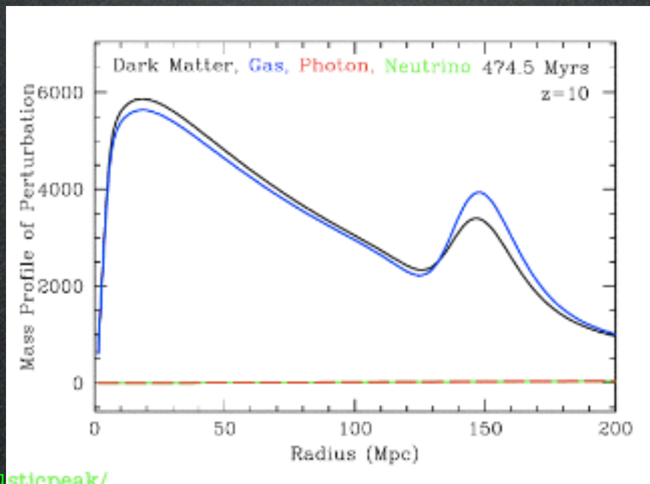

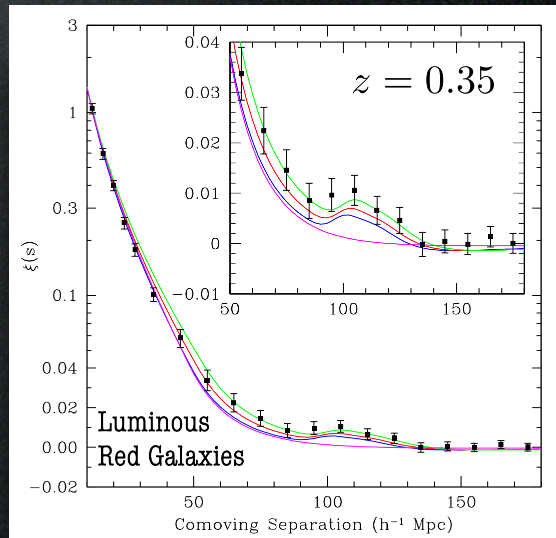

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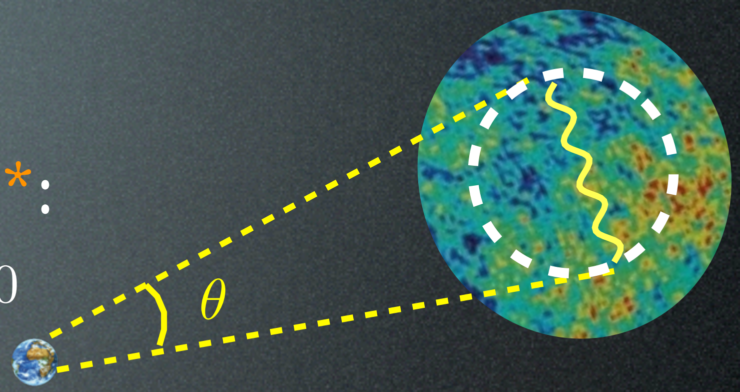
The Evidence for DE

3) CMB:

In principle: another 'standard ruler' *:

the size of the sound horizon at $z \simeq 1100$



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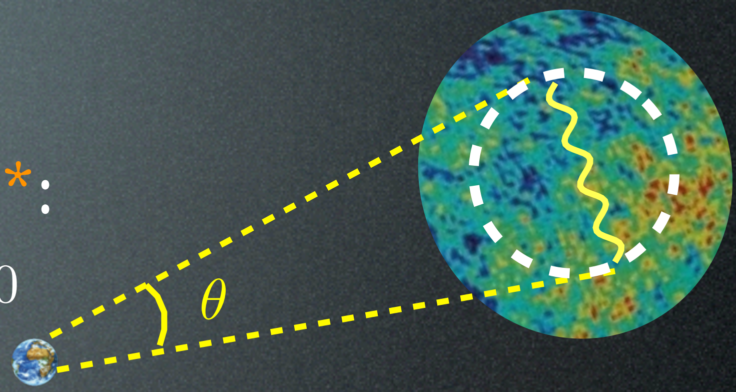

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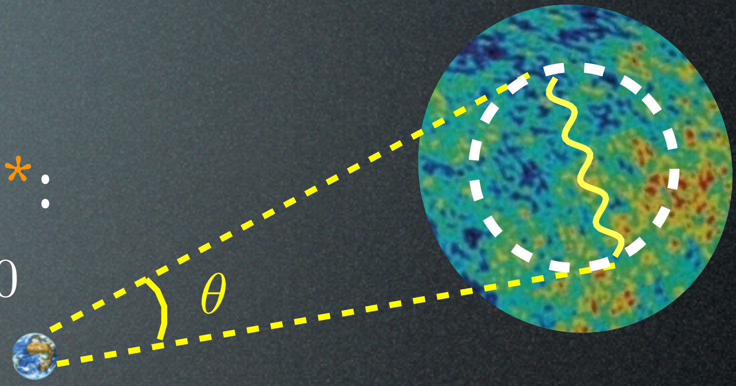

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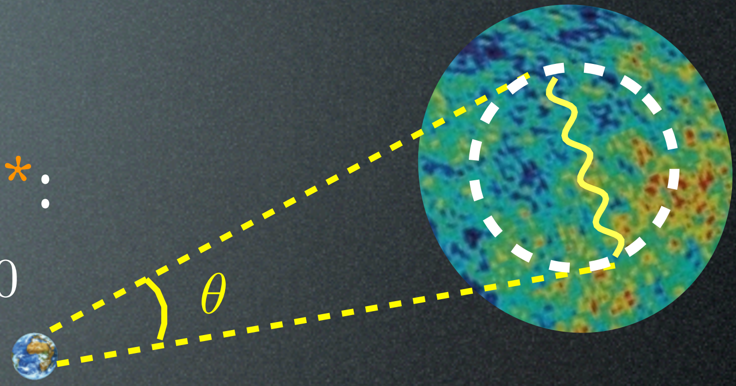

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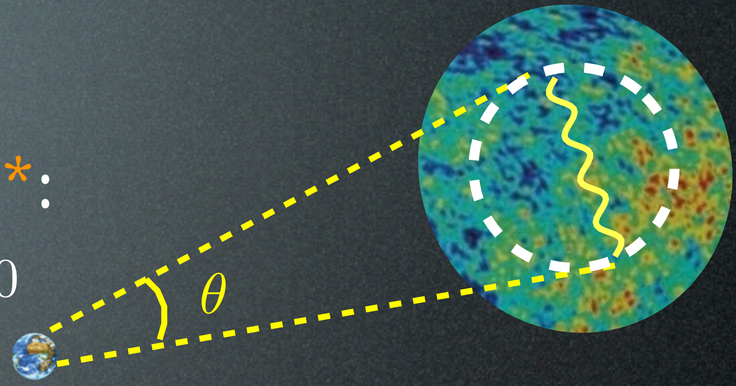

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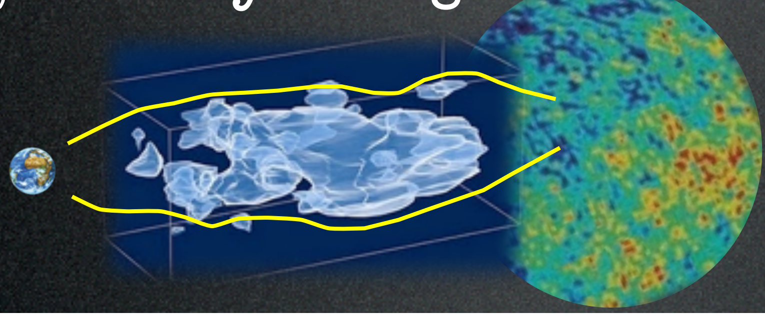
Moreover, recently: using weak lensing of CMB light



$$\Omega_\Lambda = 0.61^{+0.14}_{-0.06}$$

Sherwin et al., ACT Atacama Cosmology Telescope, 1105.0419

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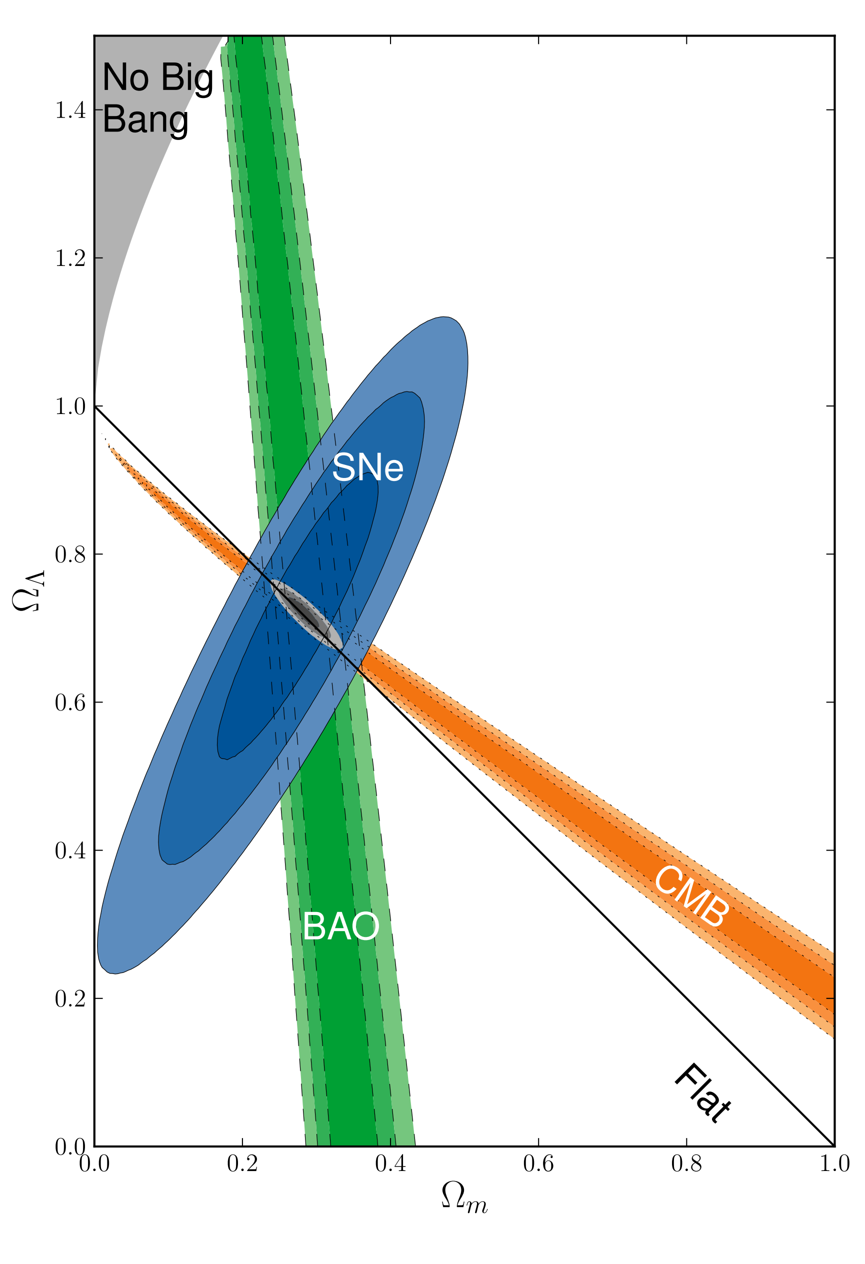

Suzuki et al., 1105.3470

- complementarity
- concordance

$$\Omega_\Lambda = 0.725 \pm 0.016$$

$$\Omega_M = 0.274 \pm 0.007$$

Komatsu et al., WMAP7, 1001.4538

Other probes played / will play a role:

- cluster counts
- weak lensing...

What do we know of the (particle physics) properties of Dark Energy?

Nature of DE

Λ cosmological constant, $w = -1$

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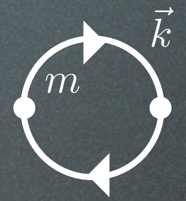
estimate
$$\rho_{\rm vac} = \frac{1}{2} \sum_{\rm particles} g_i \int_0^{k_{\rm max}} \frac{d^3k}{(2\pi)^3} \sqrt{k^2 + m^2}$$
$$\simeq \sum_{\rm particles} \frac{g_i\, k_{\rm max}^4}{16\, \pi^2}$$



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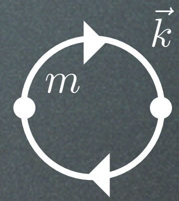

if $k_{\rm max} \sim M_{\rm Pl}$ $\quad \rho_\Lambda \sim 10^{74}\ \mathrm{GeV}^4$

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Λ cosmological constant, $w = -1$

measured value $\rho_\Lambda = 2.5\ 10^{-47}\ \mathrm{GeV}^4$

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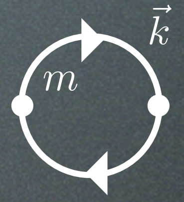

if $k_{\mathrm{max}} \sim M_{\mathrm{Pl}}$ $\rho_\Lambda \sim 10^{74}\ \mathrm{GeV}^4$

121 orders
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Nature of DE

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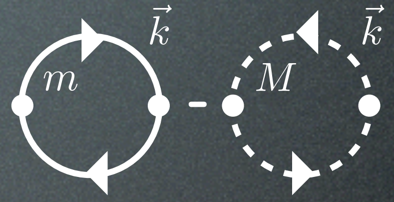

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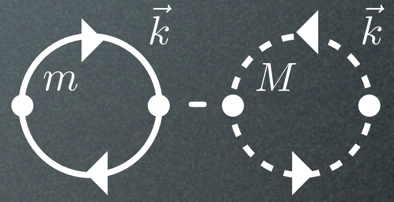

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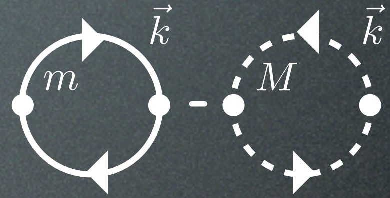

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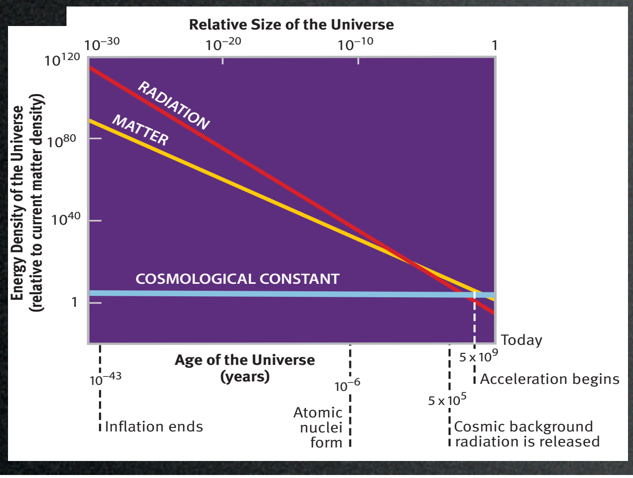

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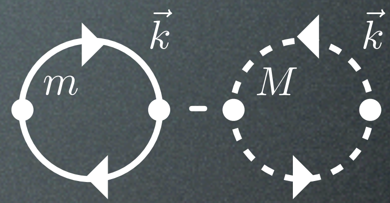

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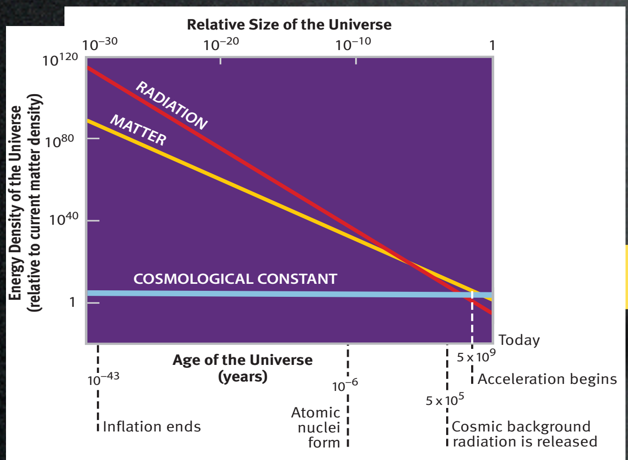

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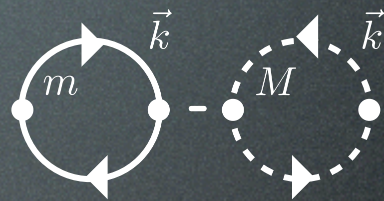

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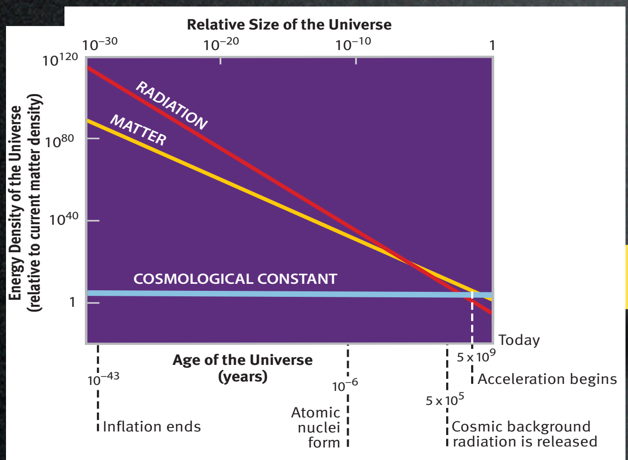

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Anthropism?

Multiverse?

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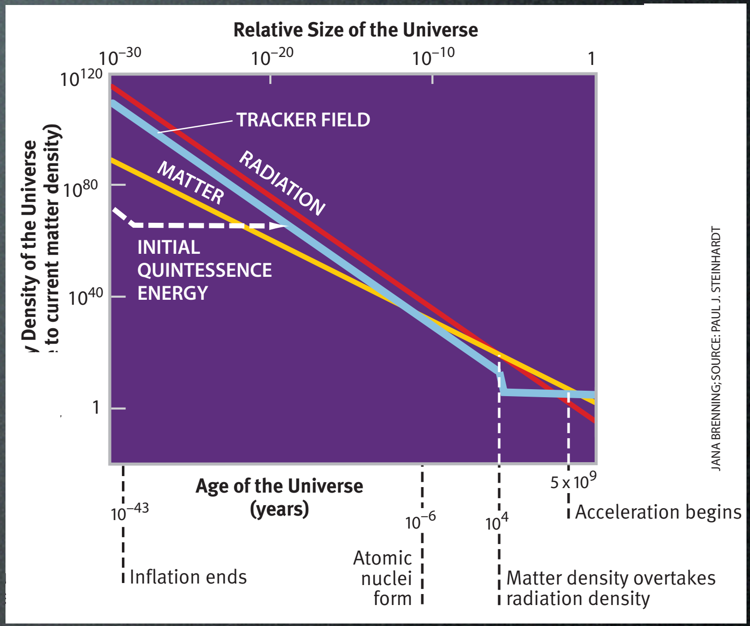

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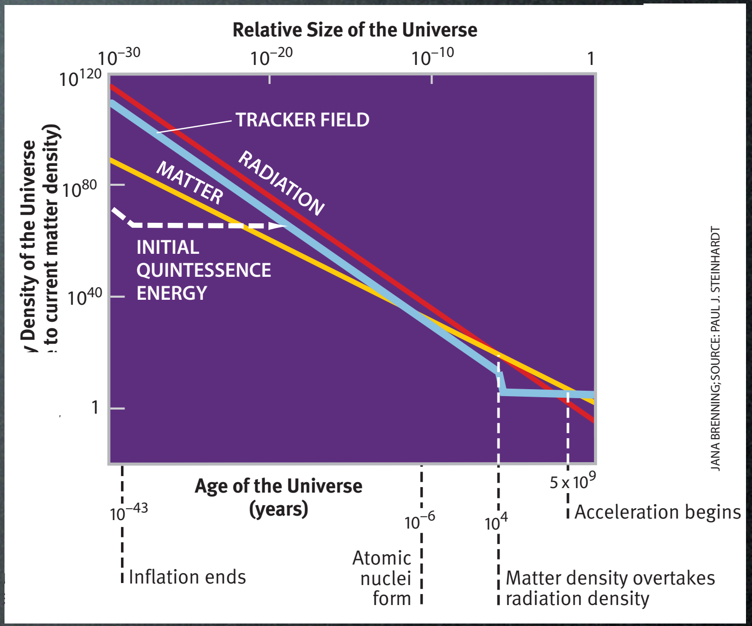

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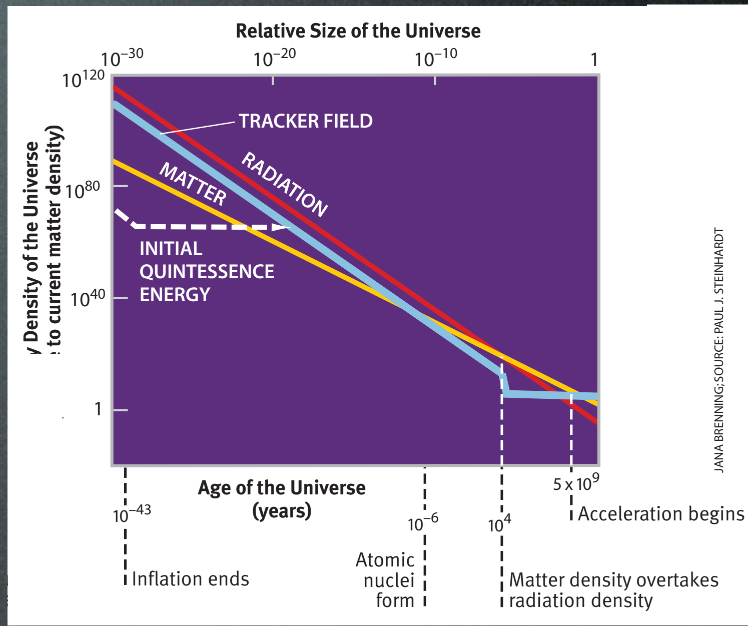

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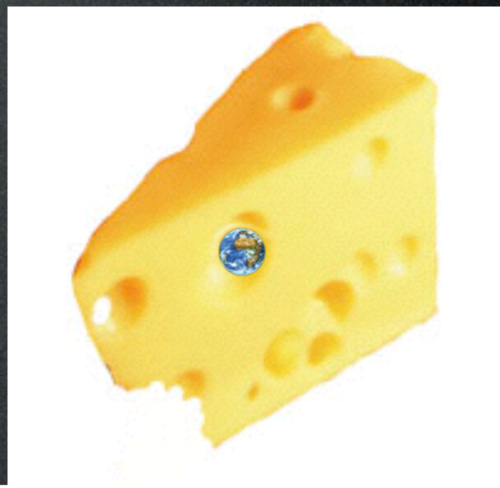

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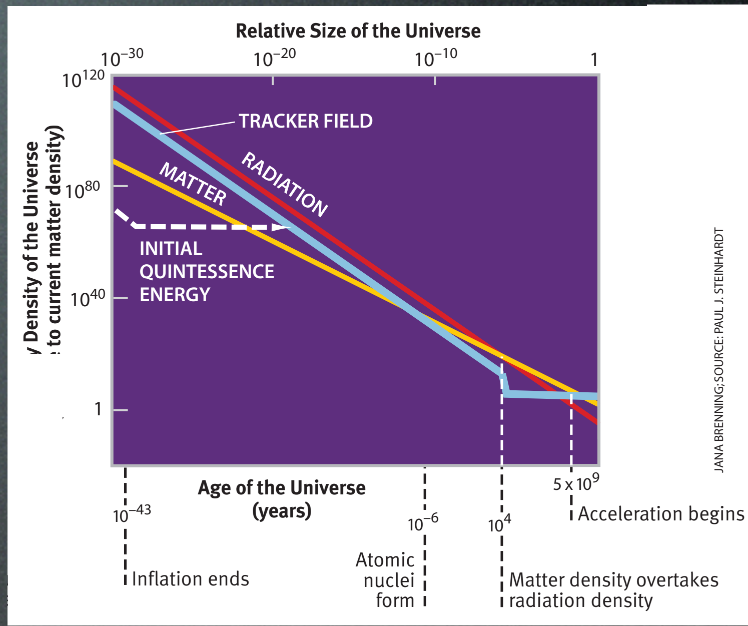

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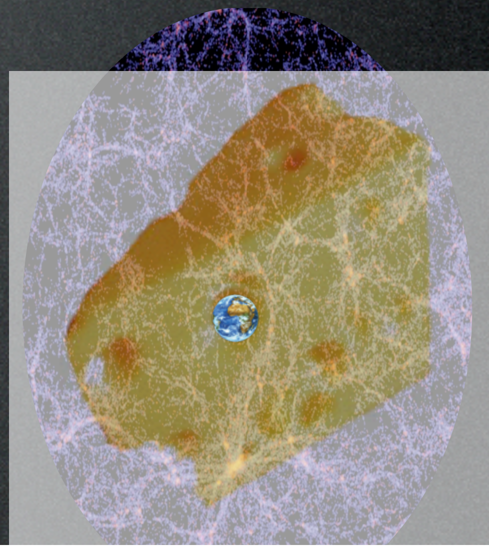

Conclusions (for today)

Dark Matter exists

Dark Energy exists

We have (almost) no clue of what they are,
but many hints and many ideas.

The 'era of data'
is now for DM.

The 'era of data'
is coming for DE.

May you live in exciting times.