Cosmology for Pedestrians

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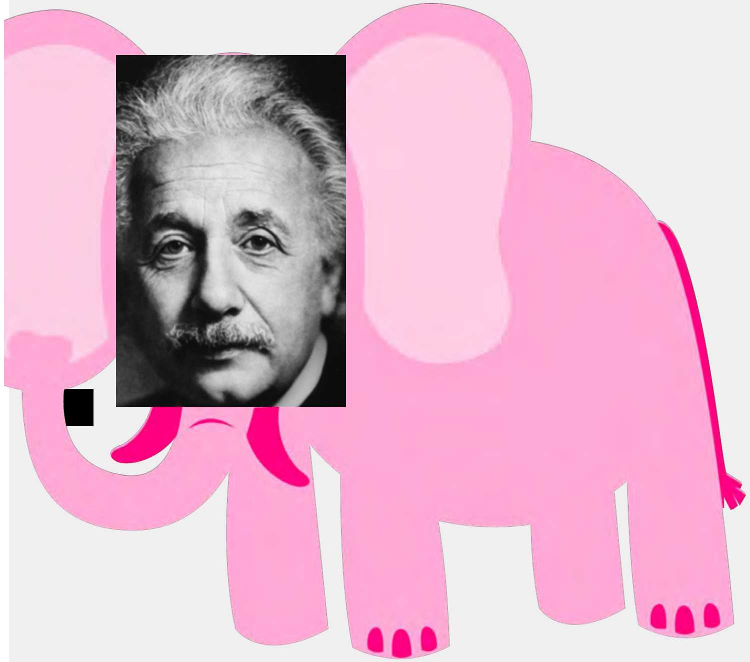
Outline

- Some ancient and not so ancient history
- Supernovae and the accelerated expansion
- The Cosmic Microwave Background
- Probing gravity and inflation

Outline: to GR or not?

- Some ancient and not so ancient history
- Concepts of General Relativity



- Supernovae and the accelerated expansion
- The Cosmic Microwave Background
- Probing gravity and inflation

cosmos

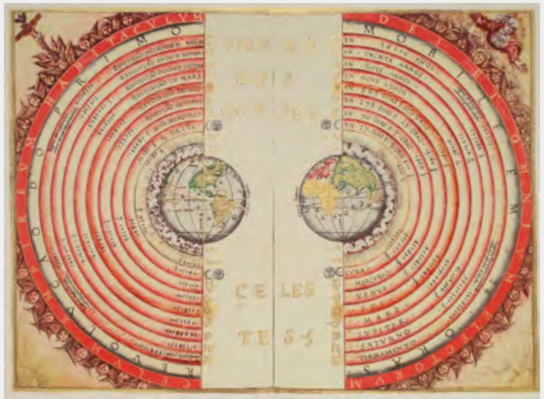
“the order of the universe”

cosmology

science of the origin and
development of the universe

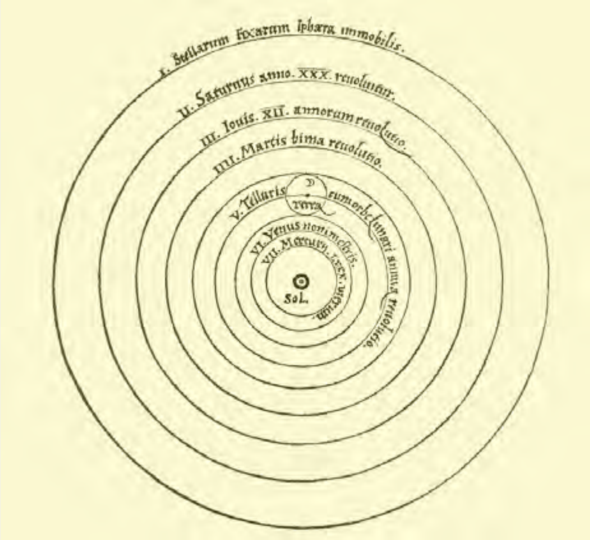
Early history

Stars arranged into constellations at least since the Babylonians



The Greek had sun and planets orbiting the Earth

Kopernikus shifted the Sun to centre.
Kopernikus principle



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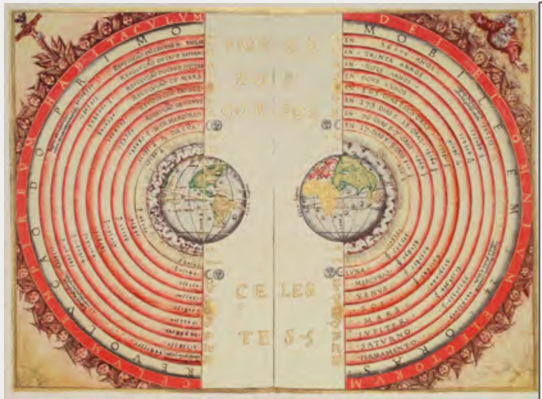

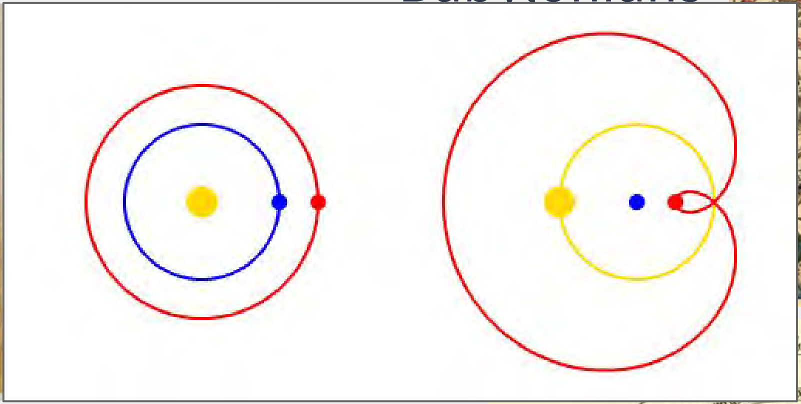

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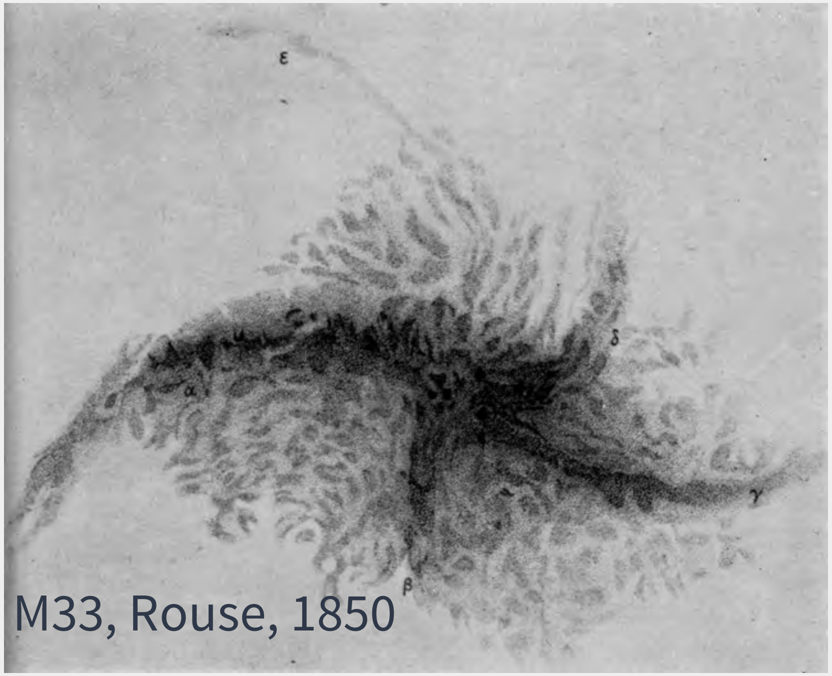
The Universe is large!



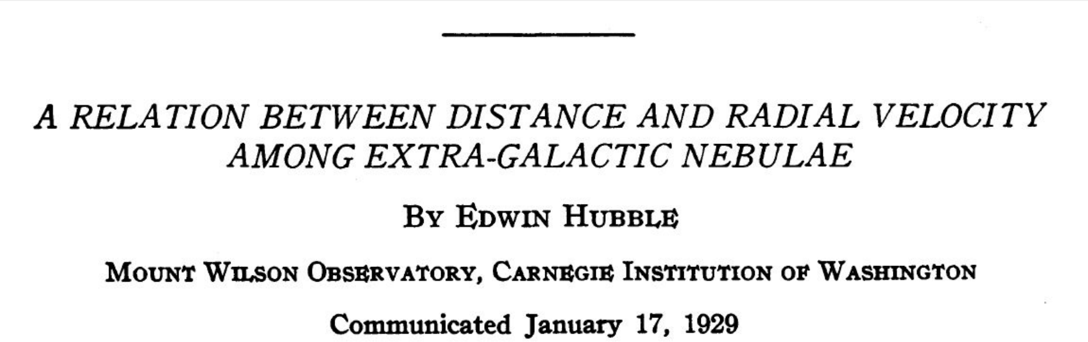
M33, Rouse, 1850

Milky Way consists of numerous distant stars (~14th century; Arabic observers).

Shape of Milky Was as rotating disk, with Sun at one edge (18th century; Wright, Kant Herschel)

Fuzzy nebulae not gas but independent galaxies far, far away (1850-1920; Rouse, Slipher, Wirtz, Hubble)

1920s - the Universe is dynamic!



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun
galactic nebulae have involved a *K* term of

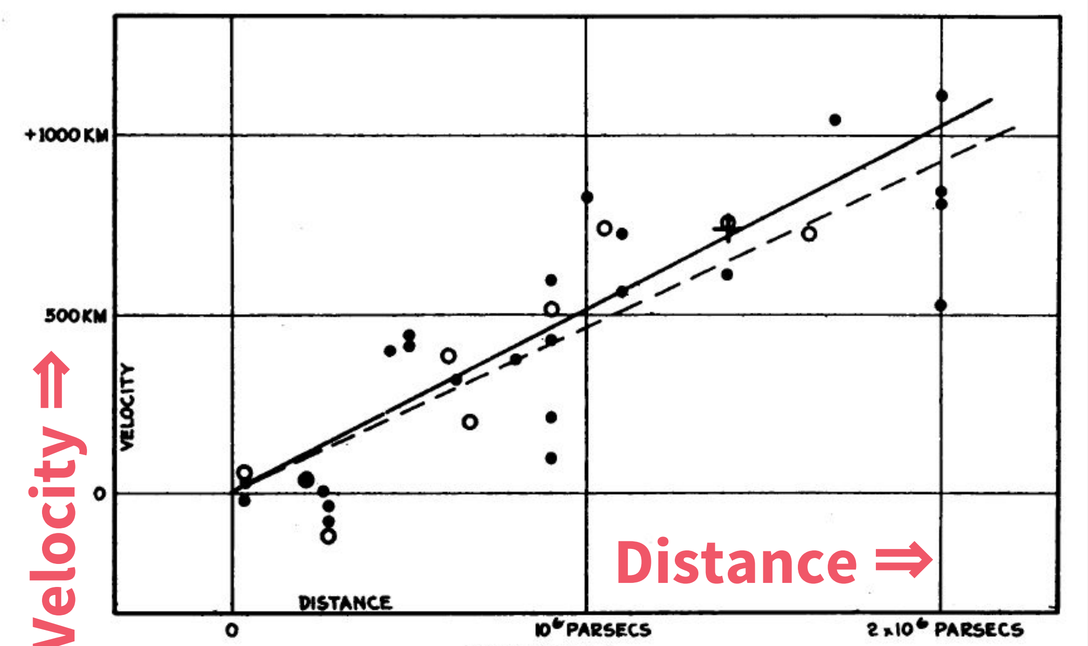


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Galaxies move away from us. Distant galaxies even faster!

Measured using Cepheid stars - standard candles

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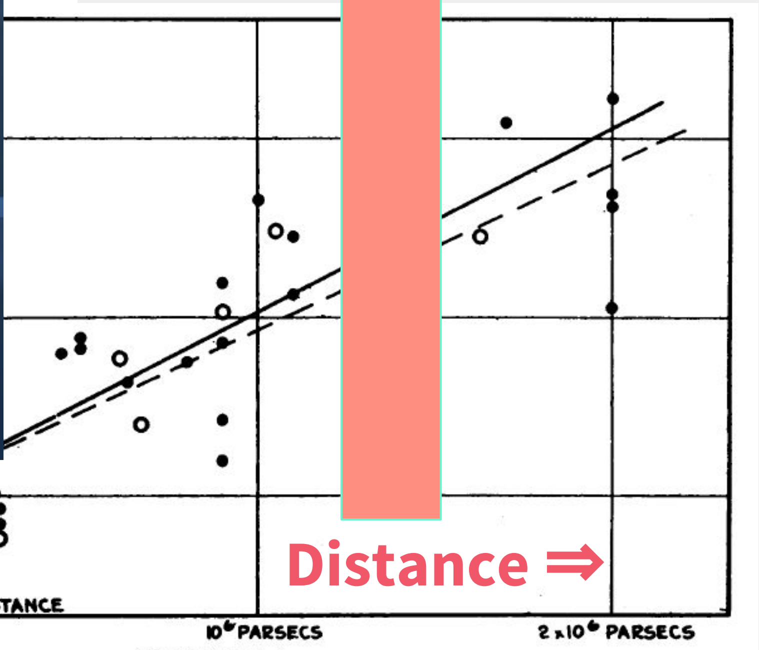
Measured using Cepheid stars - standard candles



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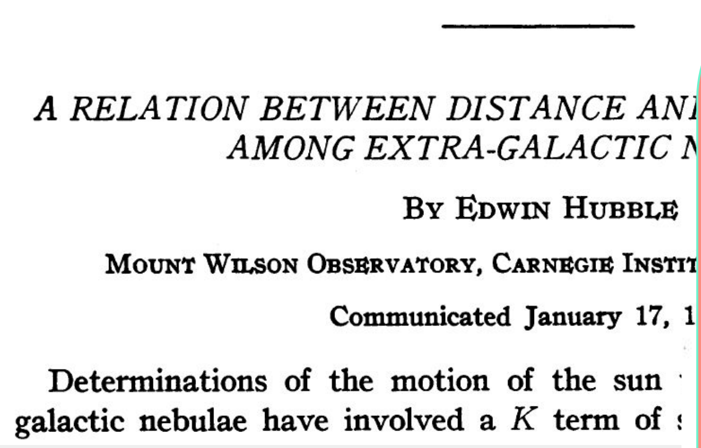

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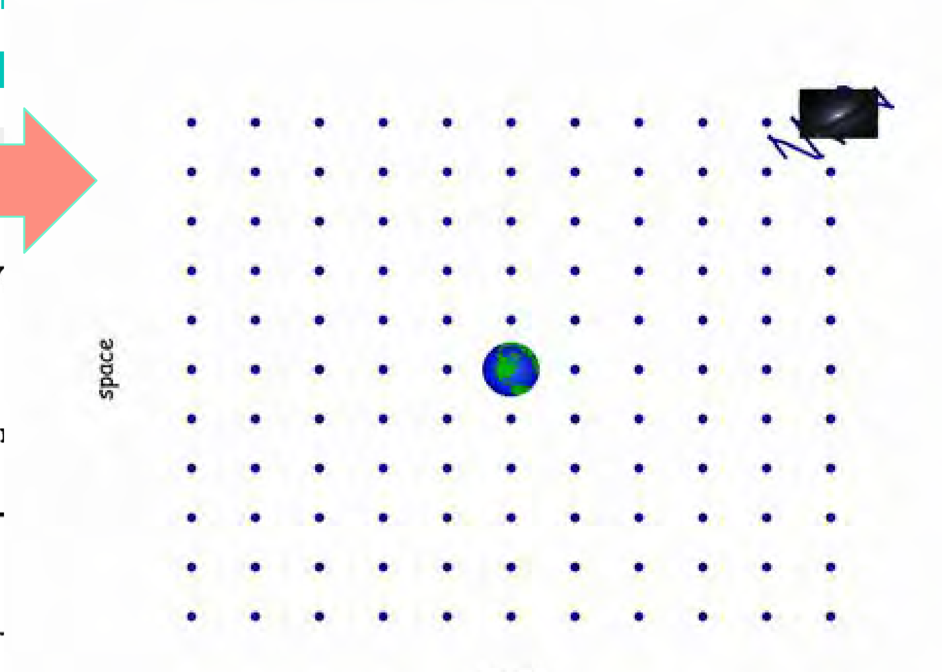
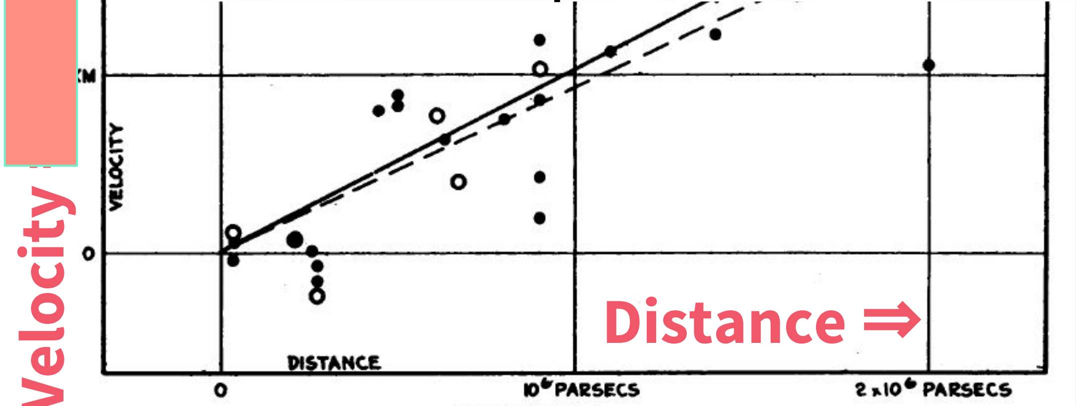


Redshift of photons



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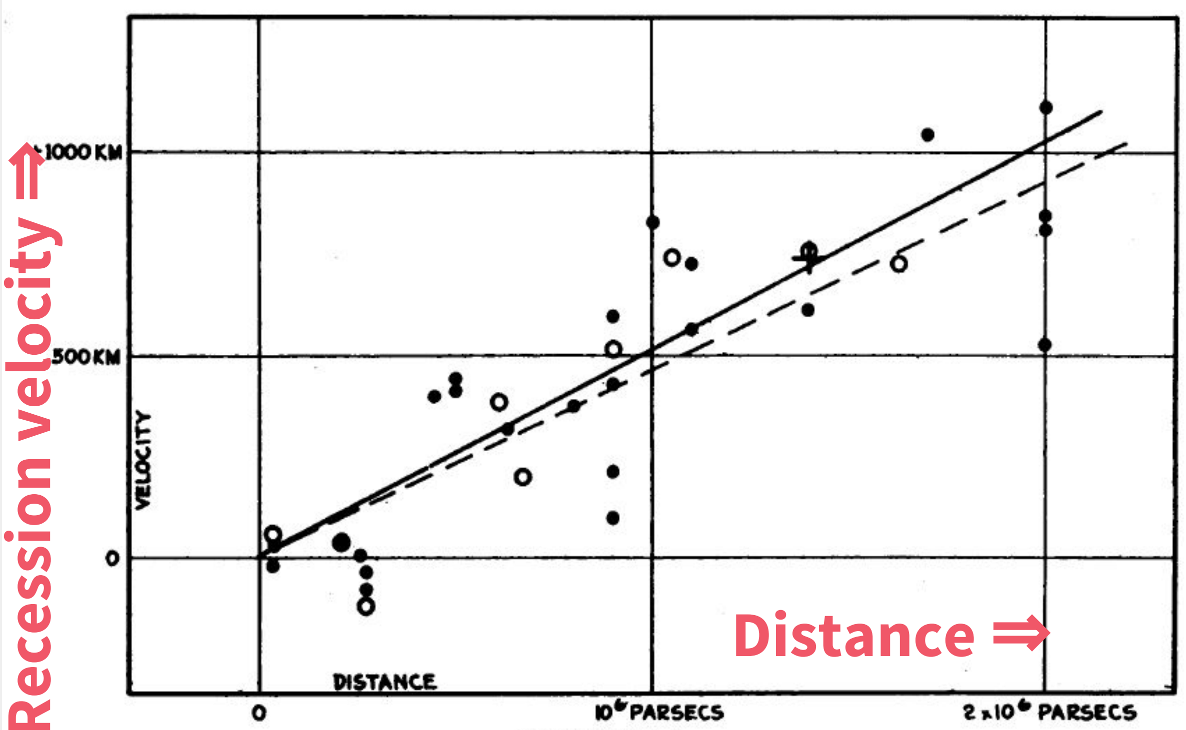
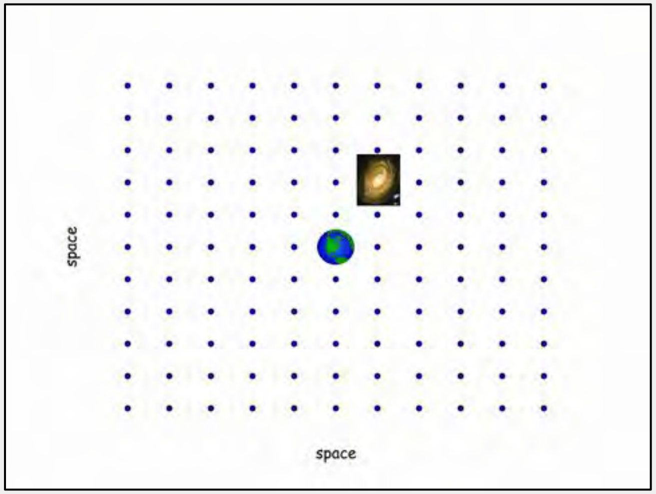


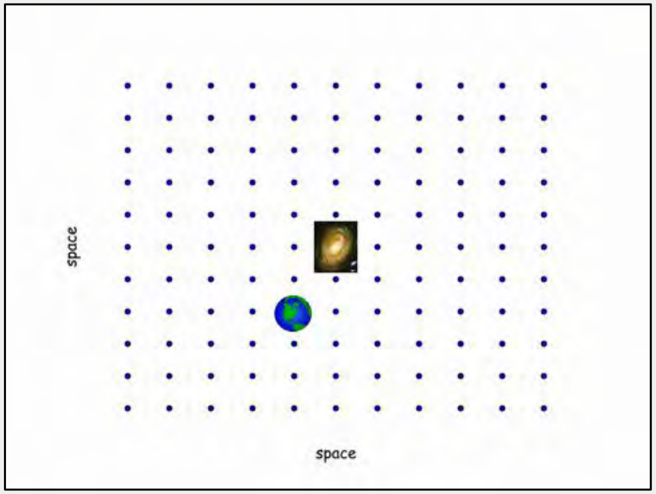
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

What does it mean??

The Big Bang

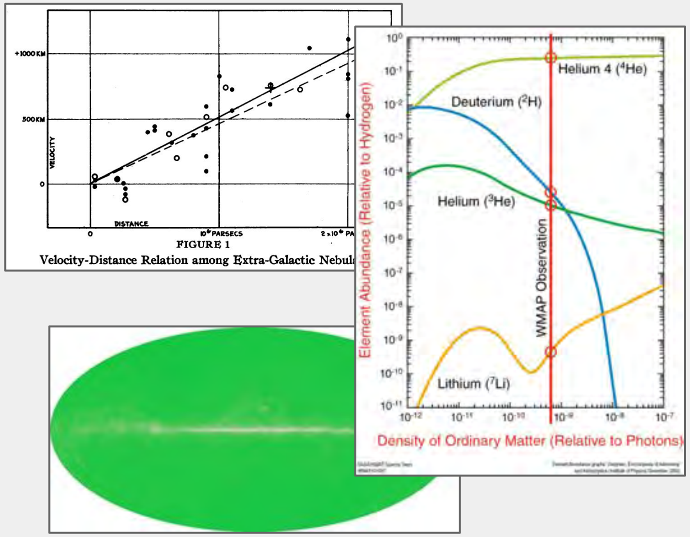




Spacetime is expanding from Big Bang

Only theory that explains the Hubble law, primordial nuclear densities and the Cosmic Microwave Background (CMB).

Formulated in GR by Lemaitre (1920s)



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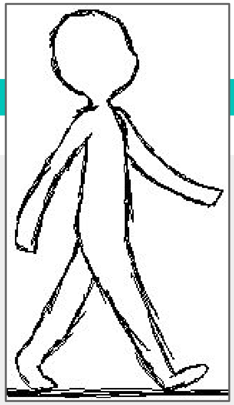
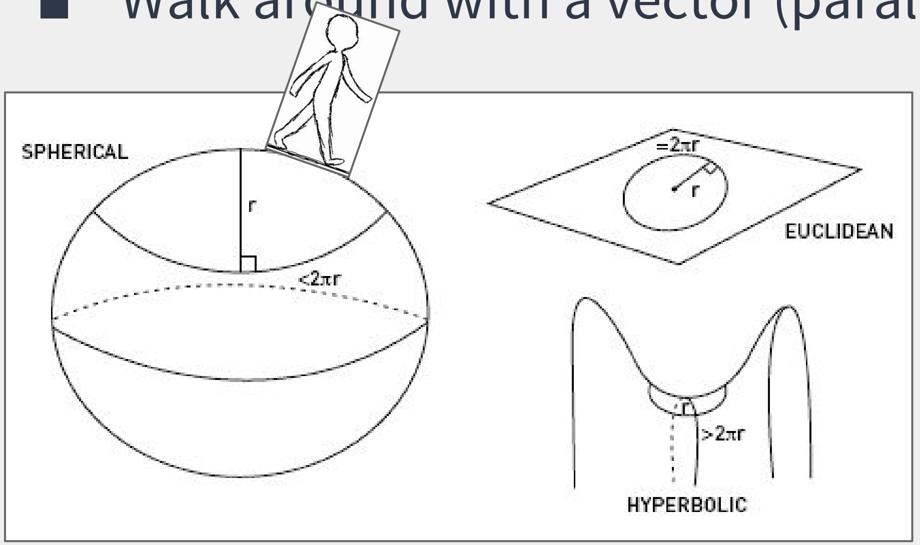
How do pedestrians do cosmology?

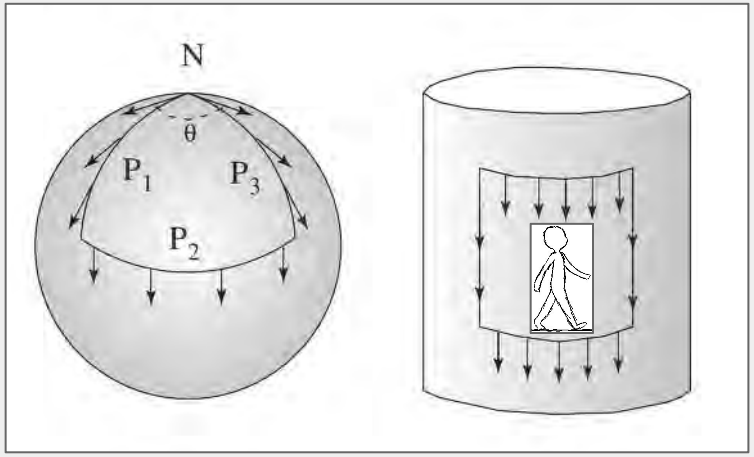


How do we measure properties of the Universe locally?

Two conceptual, pedestrian, methods:

- Compare circumference with measured radius
- Walk around with a vector (parallel transport)





Unfortunately, General Relativity needed to generalize results.

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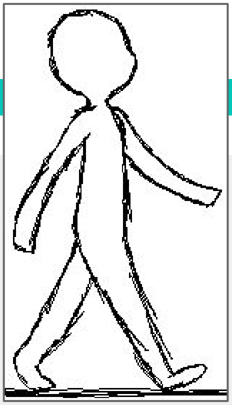

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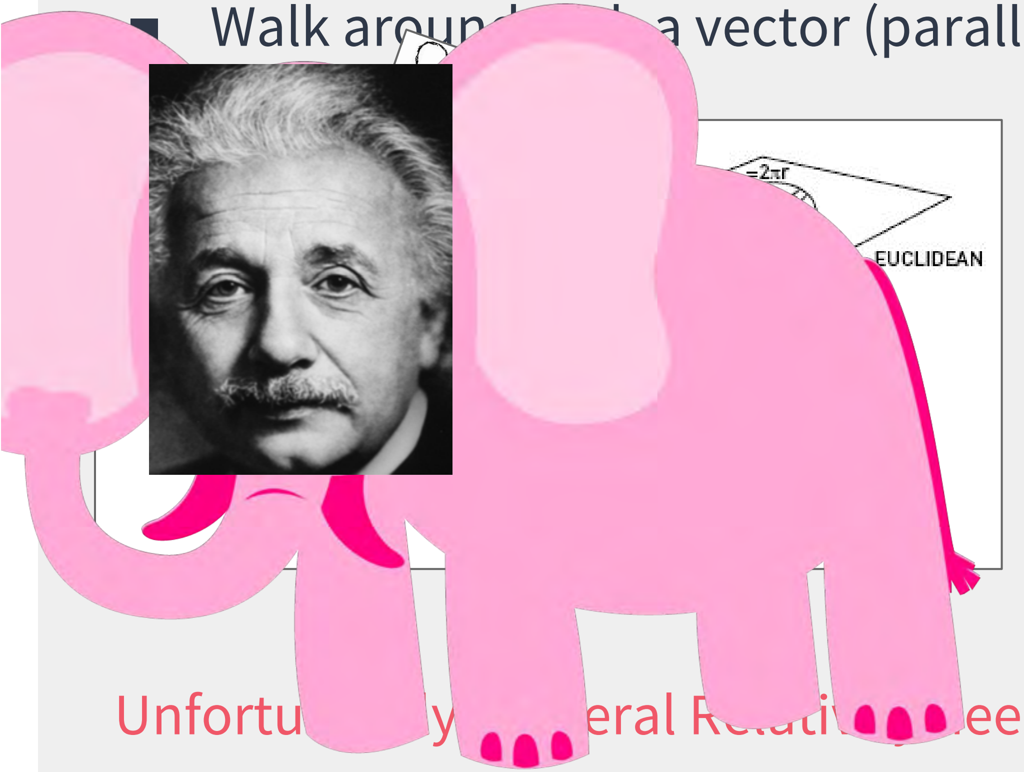
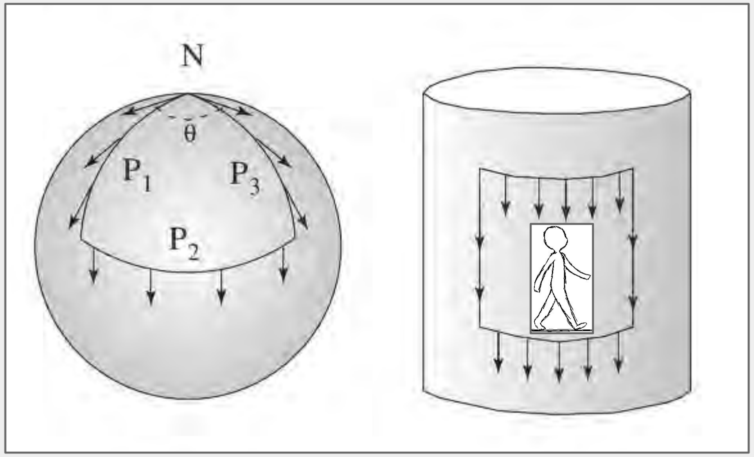




Unfortu y eral R ti eeded to generalize results.

General Relativity

Messy, not mysterious

Cosmological parameters … in a few steps

1. Define the metric connections
2. Formalize the notion of parallel transport of vectors using the Riemann tensor
3. Connection to energy/matter through equivalence principles
4. Friedmann equations (GR solutions in a perfect fluid)
5. Calculate the luminosity distance - how the brightness of an object depends on cosmological parameters

0. Special relativity, tensor notation and the metric

In Special Relativity, ds^2 is the conserved quantity.

$$ds^2 = c^2dt^2 - |\mathbf{r}|^2 = (dx^0)^2 - (dx^1)^2 - (dx^2)^2 - (dx^3)^2$$

A metric is a function that gives returns the physical (4-dimensional) distance between points in an arbitrary coordinate system.

$$ds^2 = \sum_{i,j=1}^{3} G_{ij}dx^i dx^j \equiv G_{ij}dx^i dx^j$$

$$ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$$

$$ds^2 = c^2dt^2 - dr^2 - r^2d\theta^2 - r^2sin^2\theta d\phi^2$$

0. The Stress-Energy Tensor

A compact way to describe energy and momentum conservation.

Elements of the energy-momentum 4-vector

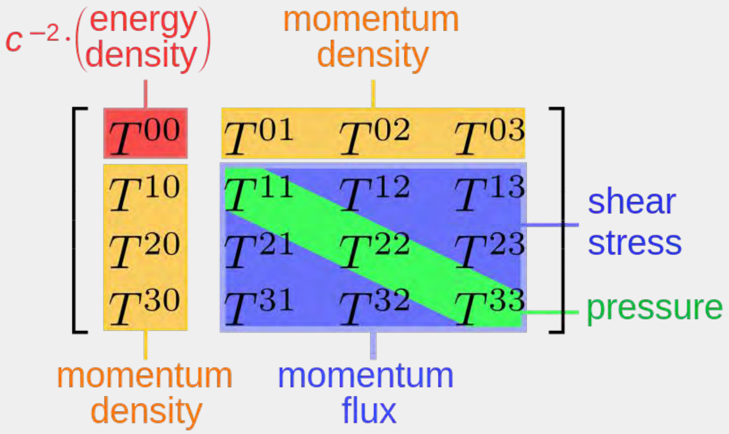
$$p^\mu = (E/c, p_x, p_y, p_z)$$

Conserved through continuity equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \vec{J} = 0$$

$$\left\{ \begin{array}{l} \dfrac{\partial}{\partial t}(\text{energy density}) = -\vec{\nabla} \cdot (\text{energy flux}) \\ \dfrac{\partial}{\partial t}(p_x \text{ density}) = -\vec{\nabla} \cdot (p_x \text{ flux}) \end{array} \right.$$

Collect these quantities in a tensor $T^{\mu\nu}$



$$\begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

And conservation of energy and momentum can be described as

$$\frac{\partial T^{\mu\nu}}{\partial x^\nu} = \frac{\partial T^{\mu 0}}{\partial t} + \partial_i T^{\mu i} = 0$$

1. The metric connection

Locally, we can define a flat (Special Relativity) metric with free fall eq:

$$\frac{d^2\xi^\mu}{d\tau^2} = 0$$

$$d\tau^2 = \eta_{\mu\nu} d\xi^\mu d\xi^\nu$$

Performing a coordinate transformation to a general coordinate system yields the *geodesic equation*:

$$d\xi^\mu = \frac{\partial \xi^\mu}{\partial x^\nu} dx^\nu$$

$$\frac{d^2 x^\sigma}{d\tau^2} + \Gamma^\sigma_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau} = 0$$

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Where the metric connection ("Christoffel symbols") given by derivatives of the metric:

$$\Gamma^\sigma_{\mu\nu} = \frac{g^{\rho\sigma}}{2} \left(\frac{\partial g_{\nu\rho}}{\partial x^\mu} + \frac{\partial g_{\mu\rho}}{\partial x^\nu} - \frac{\partial g_{\nu\mu}}{\partial x^\rho} \right)$$

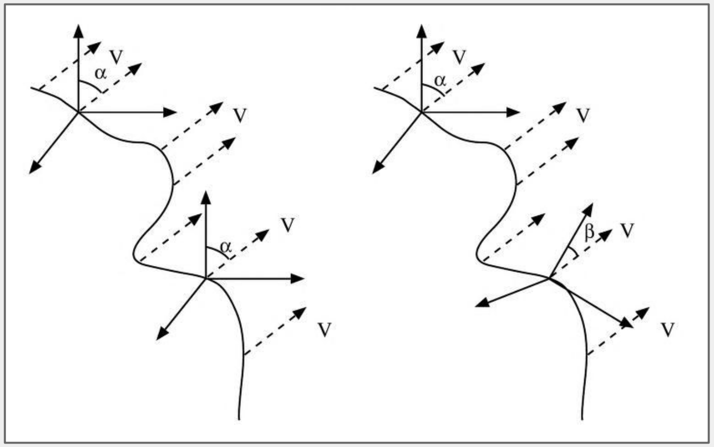
$$\frac{d^2 x^\sigma}{d\tau^2} = f^\sigma$$

(Geometric terms can be interpreted as force)

2. Parallel transport of vectors

The change of a vector decomposed into intrinsic changes to the vector field and apparent changes due to coordinate system:

$$\frac{DV^\mu}{Ds} = \frac{dV^\mu}{ds} + \Gamma^\mu_{\rho\nu} V^\rho \frac{dx^\nu}{ds}$$



A full cycle described by

$$\begin{aligned}\delta V^\mu = &-\Gamma^\mu_{\beta\nu}(x)V^\nu(x)\Delta a^\beta - \Gamma^\mu_{\beta\nu}(x+\Delta a)V^\nu(x+\Delta a)\Delta b^\beta \\ &+\Gamma^\mu_{\beta\nu}(x+\Delta b)V^\nu(x+\Delta b)\Delta a^\beta + \Gamma^\mu_{\beta\nu}(x)V^\nu(x)\Delta b^\beta\end{aligned}$$

can be rewritten using the Riemann tensor

$$\delta V^\mu = \Delta a^\alpha \Delta b^\beta V^\sigma R^\mu{}_{\sigma\beta\alpha}$$

$$R^\mu{}_{\sigma\beta\alpha} = \frac{\partial \Gamma^\mu_{\sigma\alpha}}{\partial x^\beta} - \frac{\partial \Gamma^\mu_{\sigma\beta}}{\partial x^\alpha} + \Gamma^\mu_{\rho\beta}\Gamma^\rho_{\sigma\alpha} - \Gamma^\mu_{\rho\alpha}\Gamma^\rho_{\sigma\beta}$$

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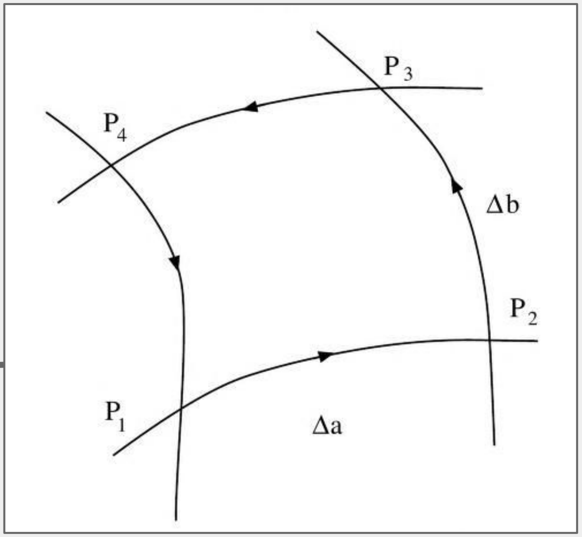

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$$\delta V^{\mu} = \Delta a^{\alpha} \Delta b^{\beta} V^{\sigma} R^{\mu}{}_{\sigma\beta\alpha}$$

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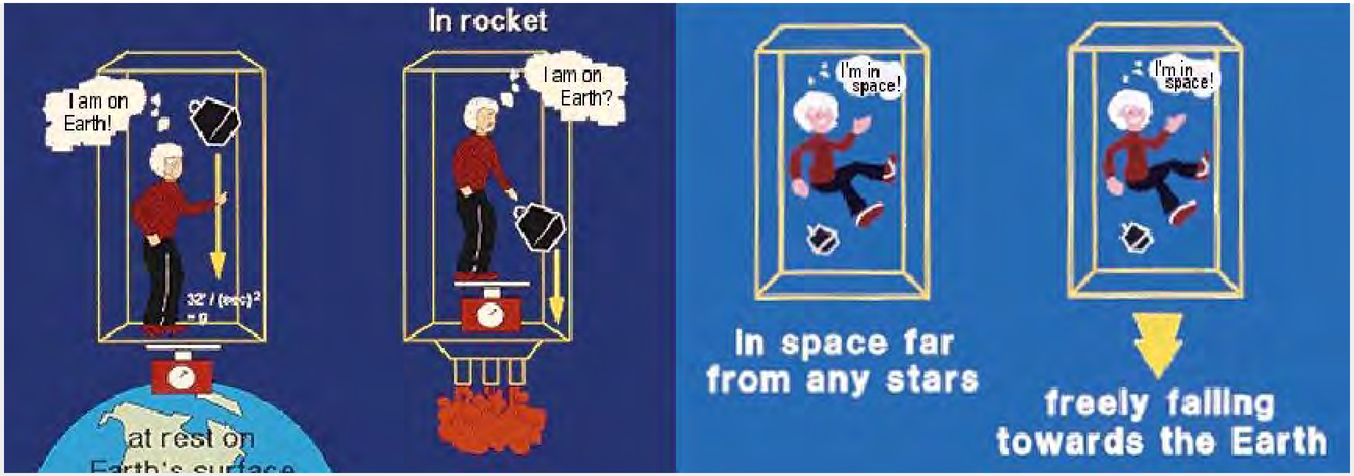
3. The equivalence principle



(inertial mass) x (acceleration) =

(intensity of the gravitational field) x (gravitational mass)

Weak and strong equivalence principles:

- (inertial mass) = (gravitational mass)
- The outcome of any local experiment (gravitational or not) in a freely falling laboratory is independent of the velocity of the laboratory and its location in spacetime.

4. General relativity

Einstein realized that if we want to take seriously the notion that mass/energy and space-time curvature are equivalent the stress-energy tensor must be related to the metric:

$$\boxed{G^{\mu\nu} = \text{const} \cdot T^{\mu\nu}}$$

Determined that only a particular combination of the Riemann tensor fulfills the continuity requirements:

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G_N T_{\mu\nu}}$$

$$\boxed{R_{\mu\nu} = g^{\alpha\gamma}R_{\alpha\mu\gamma\nu}}$$

$$\boxed{R = g^{\mu\nu}R_{\mu\nu}}$$

Equations also allow a constant term - the cosmological constant:

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}}$$

5. The Friedmann equations

On large scales, the Universe can be considered a perfect fluid, casting the stress-energy tensor into a simple form:

$$(T^{\alpha\beta})_{\alpha,\beta=0,1,2,3} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}.$$

$$T_{\mu\nu} = (p+\rho)u_\mu u_\nu - p g_{\mu\nu}$$

Using the

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

metric parameterization, the Einstein equation simplifies to:

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

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right).$$

$$\rho_{tot} = \rho_m + \rho_{rad} + \rho_{vac}.$$

6. Luminosity distance and cosmological parameters

Typically written using Ω notation:

$$\frac{H^2}{H_0^2} = \Omega_{0,R}a^{-4} + \Omega_{0,M}a^{-3} + \Omega_{0,k}a^{-2} + \Omega_{0,\Lambda}.$$

$$H'(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda}$$

$$\Omega_M = \frac{8\pi G\rho_0}{3H_0^2},$$

$$\Omega_\Lambda = \frac{\Lambda}{3H_0^2},$$

$$\Omega_M = \frac{\rho_0}{\rho^0_{crit}},$$

$$\Omega_R = \frac{8\pi G\rho_{rad}}{3H_0^2}$$

Different dependency on scale factor/redshift!

Relate to how luminous an object appears to us:

$$d_L = \sqrt{\frac{L}{4\pi\mathcal{F}}} = a(t_0)r(1+z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_K|}}\mathcal{S}\left(\sqrt{|\Omega_K|}\int_0^z \frac{dz'}{H'(z')}\right)$$

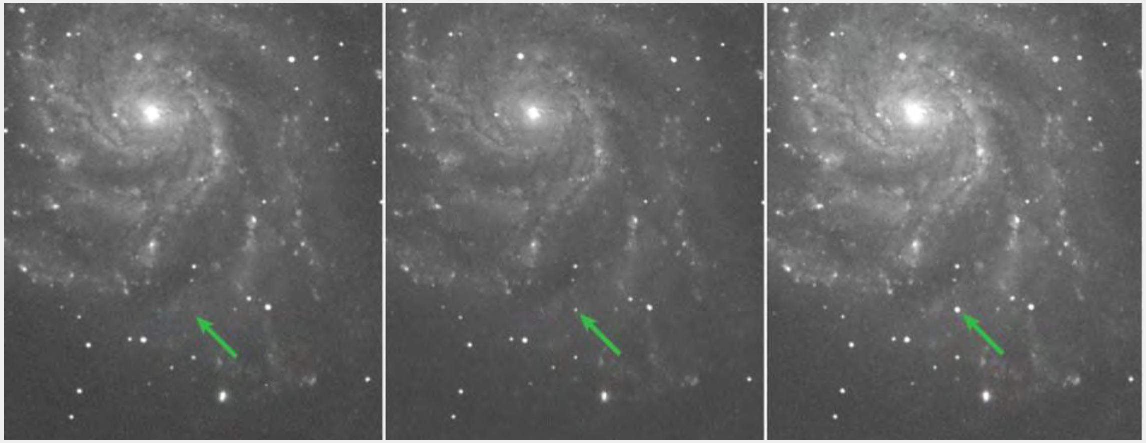
$$\frac{dr}{dt} = \frac{\sqrt{1-kr^2}}{a(t)}$$

$$H = \frac{d}{dt}\log\left(\frac{a(t)}{a_0}\right) = \frac{d}{dt}\ln\left(\frac{1}{1+z}\right) = \frac{-1}{1+z}\frac{dz}{dt}$$

Supernovae & dark energy

The accelerated expansion of the Universe

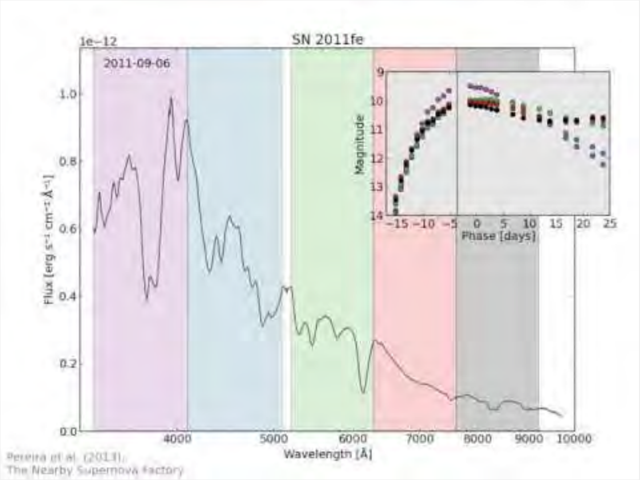
Type Ia supernovae



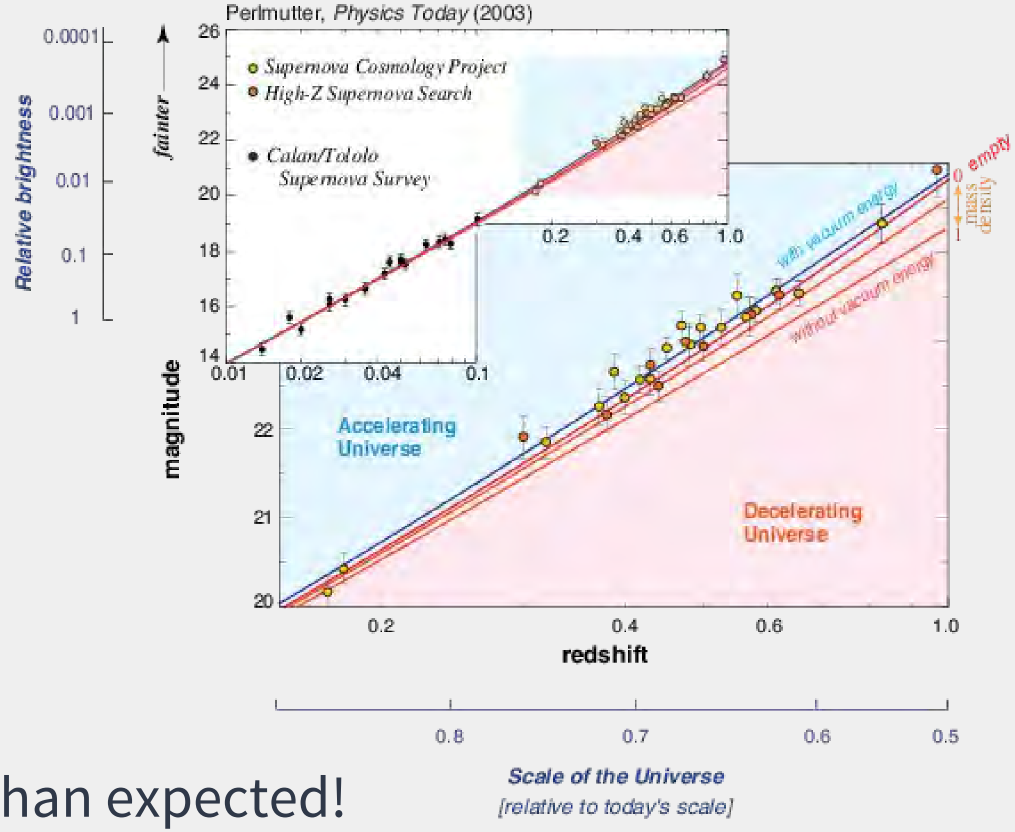
Type Ia supernovae, thermonuclear detonations of compact objects, shine as bright as galaxies for ~one month.

The uniform burning process provides an extremely bright standard(izable) candle

The discovery of dark energy



Pereira et al. (2013), The Nearby Supernova Factory



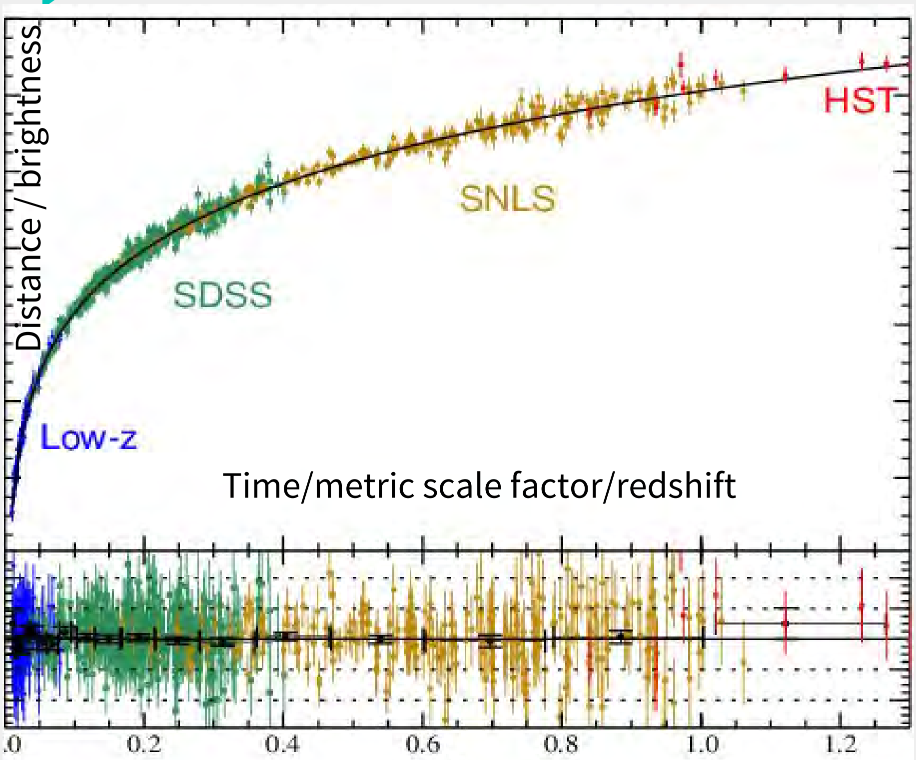
Perlmutter, *Physics Today* (2003)

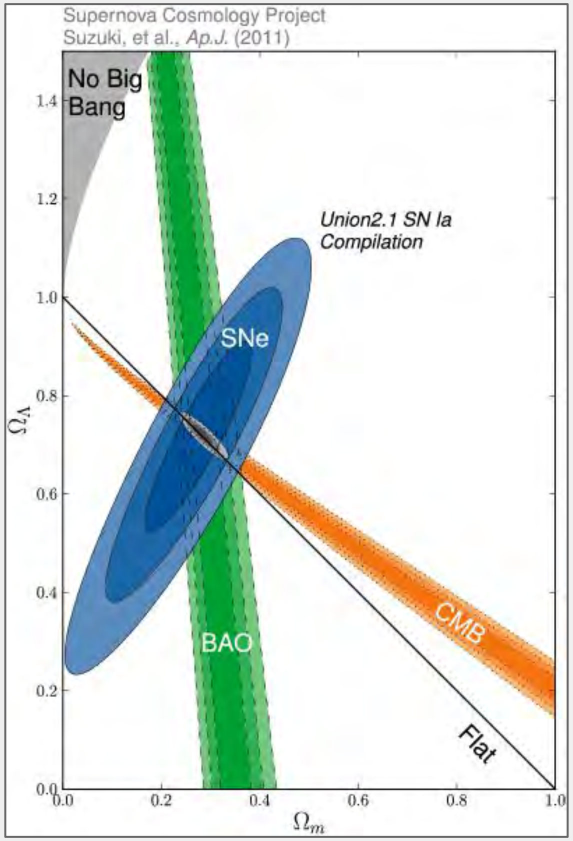
Distant supernovae fainter than expected!

The acceleration of the expansion of the Universe is increasing.

(The “circumference” over which light distributed larger than expected from the radius given by redshift - obs not curvature)

The discovery of dark energy





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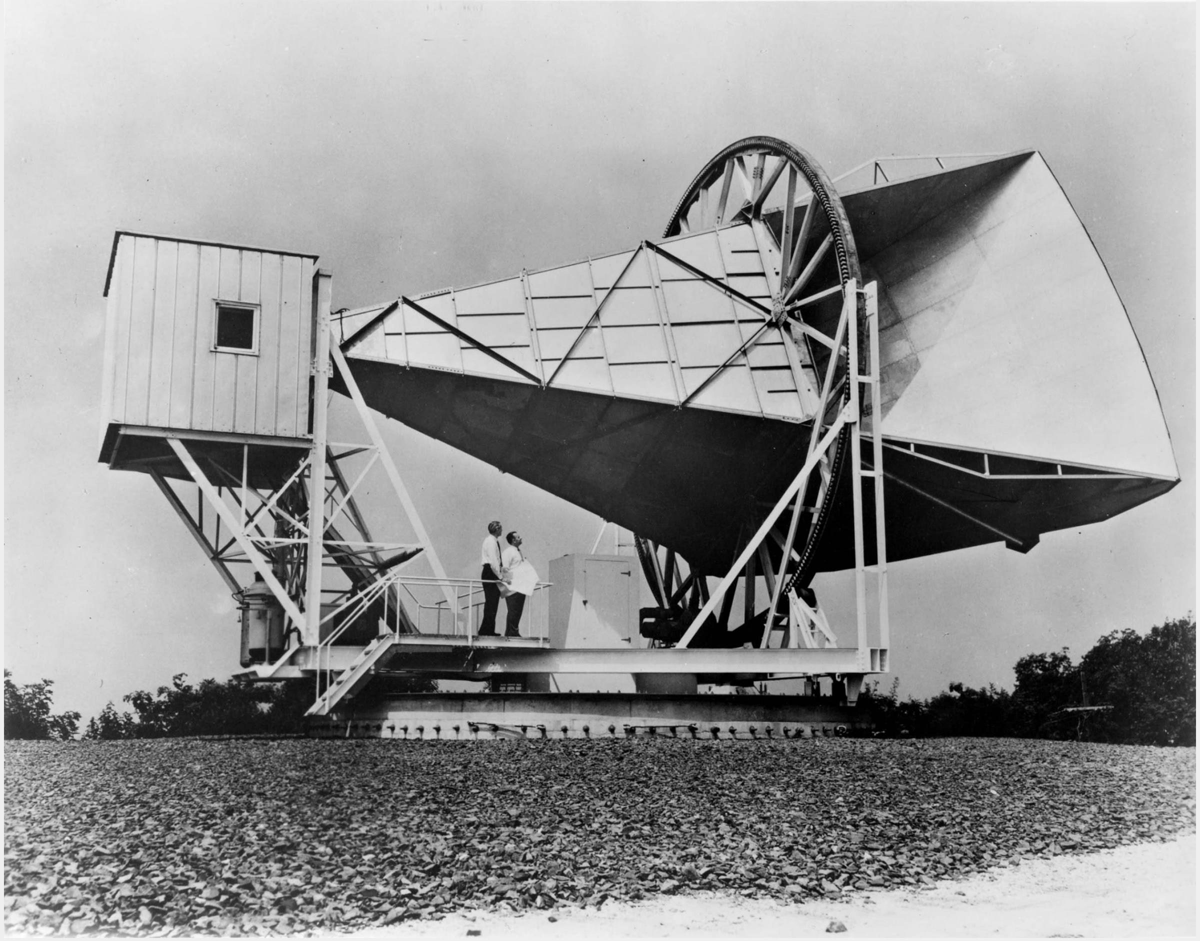
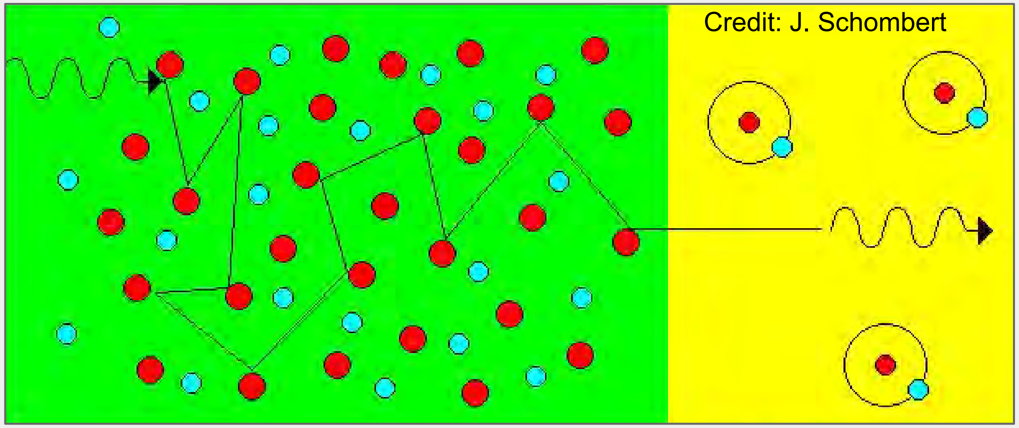
The Cosmic Microwave Background

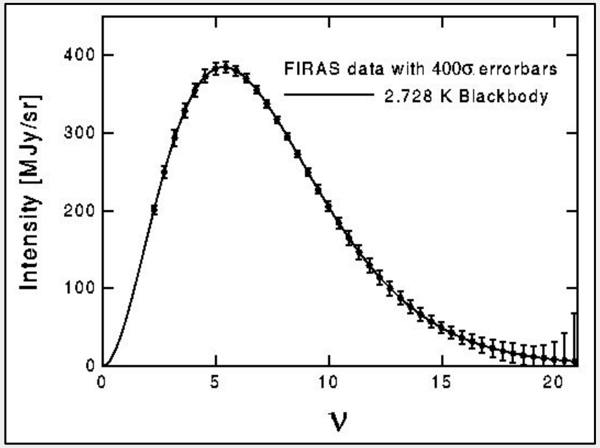


- Penzias & Wilson failed to remove background radio noise
- First measurement of relic background light from Big Bang

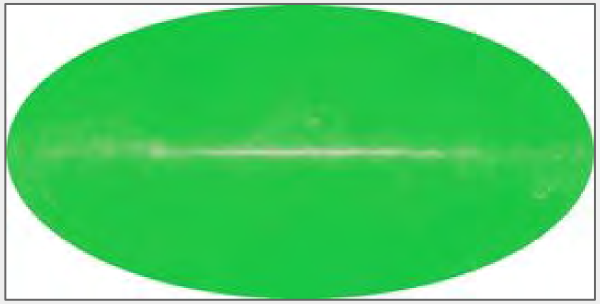
The Epoch of Recombination

In a universe that gradually cools, hydrogen must at some point go from ionized to neutral - the epoch of recombination.


Credit: J. Schombert

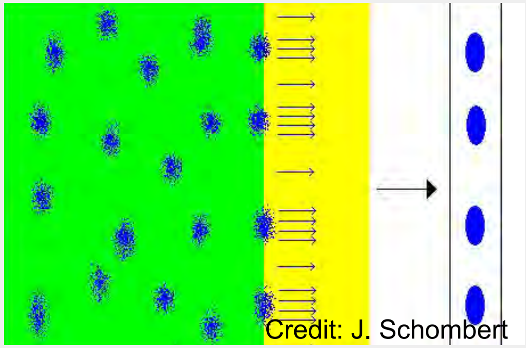


Photons emitted have propagated through a largely empty universe since. Seen as a T=2.728 (1 + z) K isotropic background radiation in all directions.



CMB fluctuations

(Dark matter) density variations prior to recombination caused temperature fluctuations at the 1e-5 scale.



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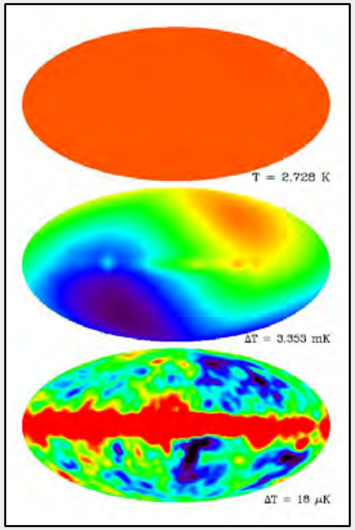
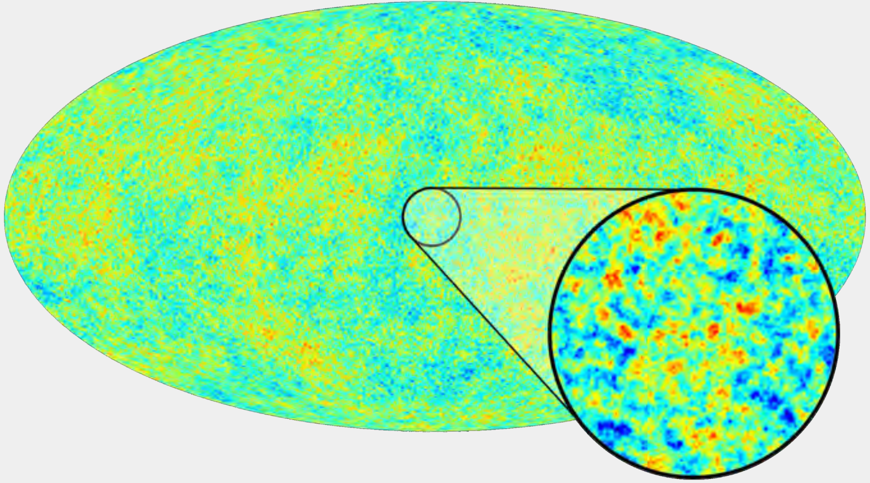
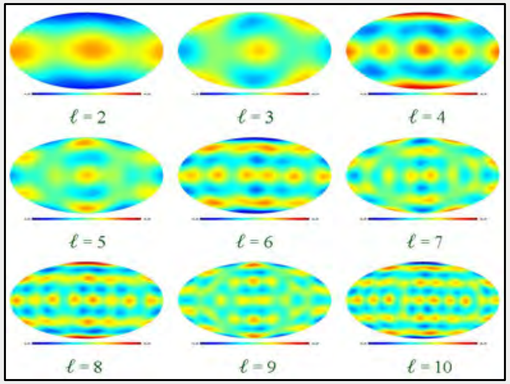


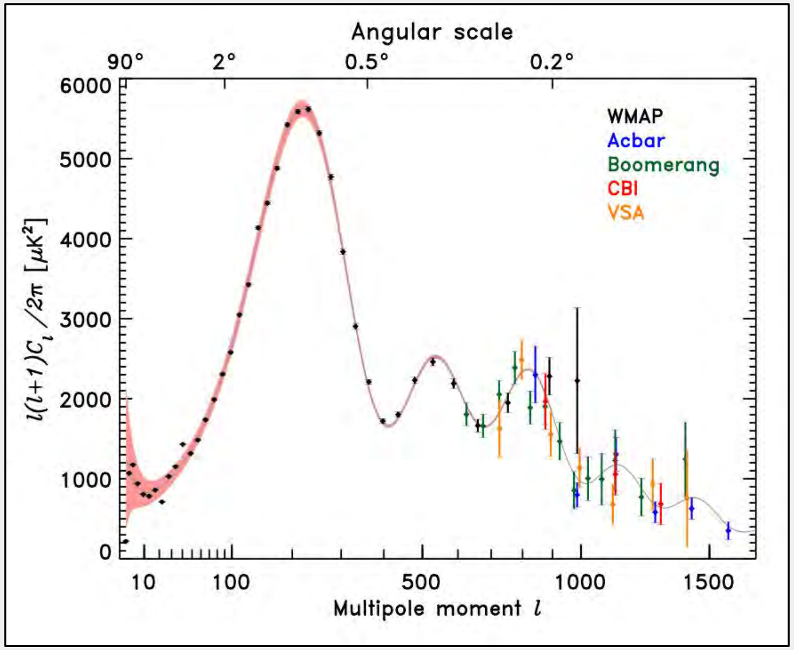


Visible after removal of mean value, dipole velocity and galactic emission in observations by COBE, WMAP & PLANCK.

The CMB power spectrum

Decomposing fluctuation map using spherical harmonics yields the CMB Power Spectrum





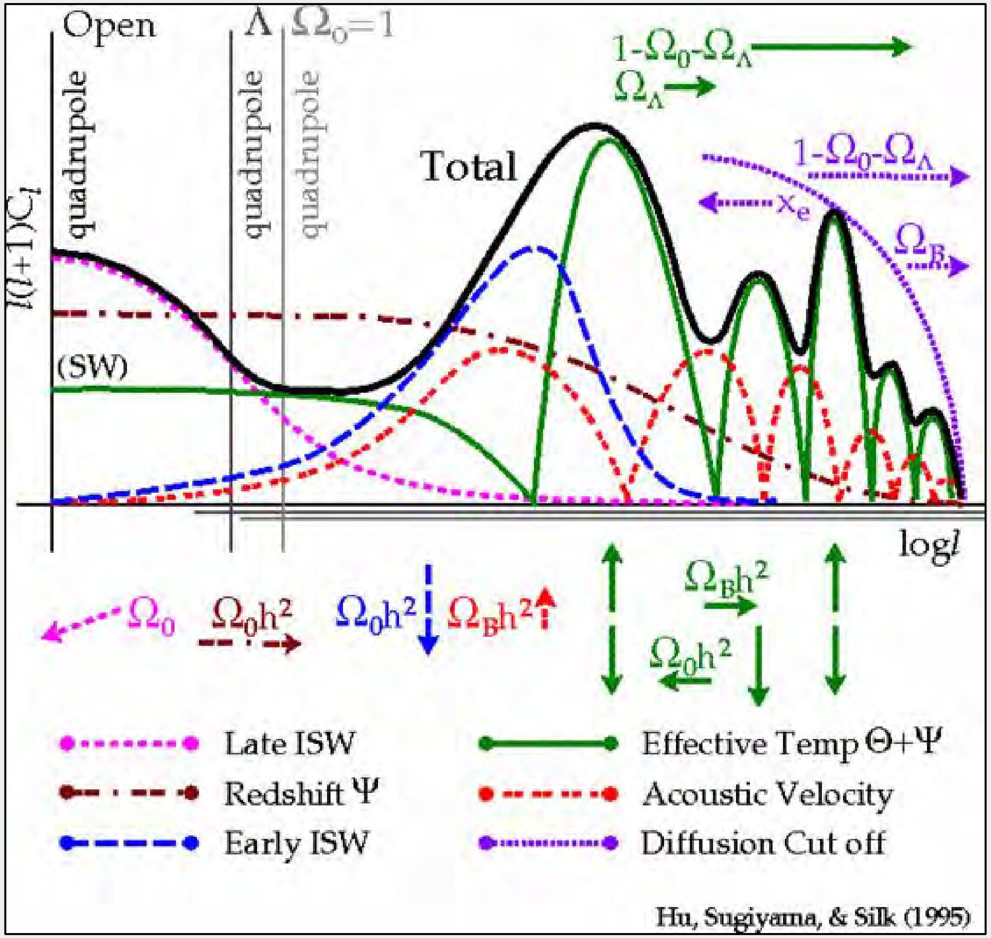
Peaks correspond to correlated density fluctuation at certain scales

$$\frac{\Delta T}{T} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

$$C_\ell \equiv \sum_m |a_{\ell m}|^2.$$

Sensitivity to multiple cosmological parameters

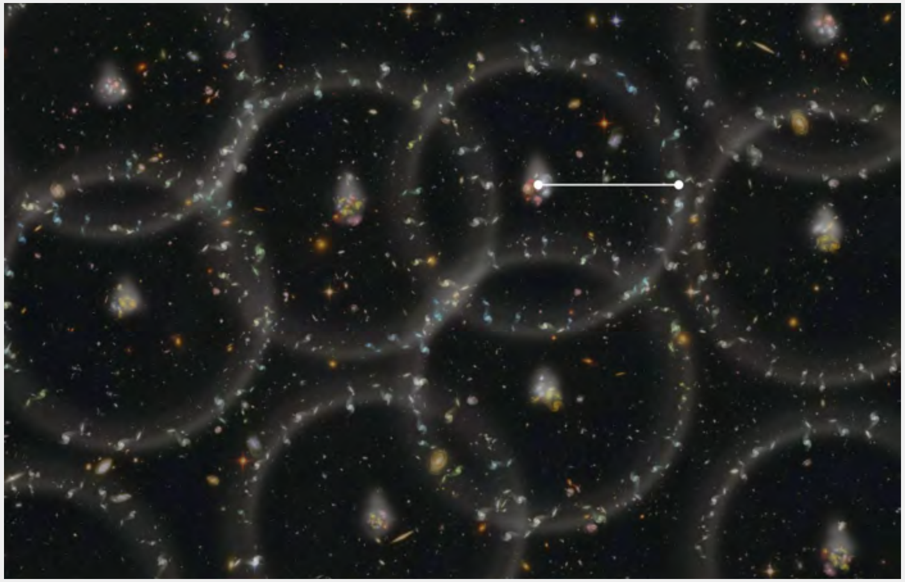
Sensitive to many parameters...

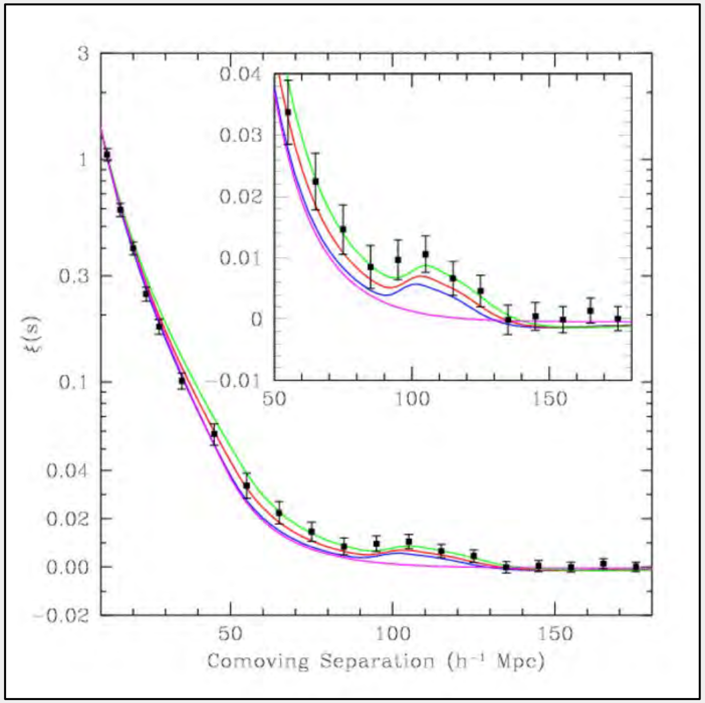


Hu, Sugiyama, & Silk (1995)

Also visible today as Baryon Acoustic Oscillations

The original density fluctuations have since grown to galaxies. Through comparing the scale of density correlations today we directly test the expansion of the Universe

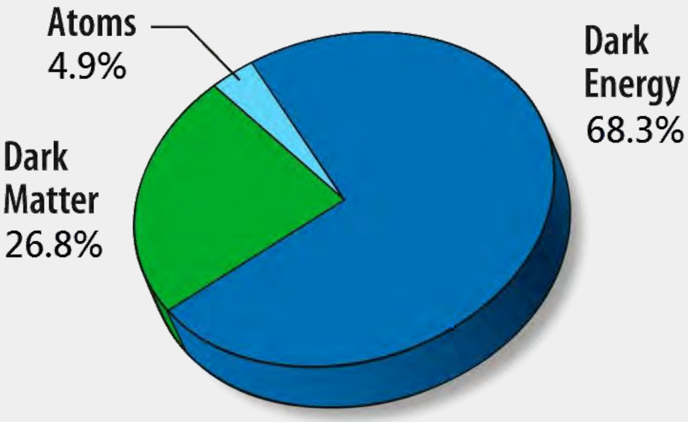


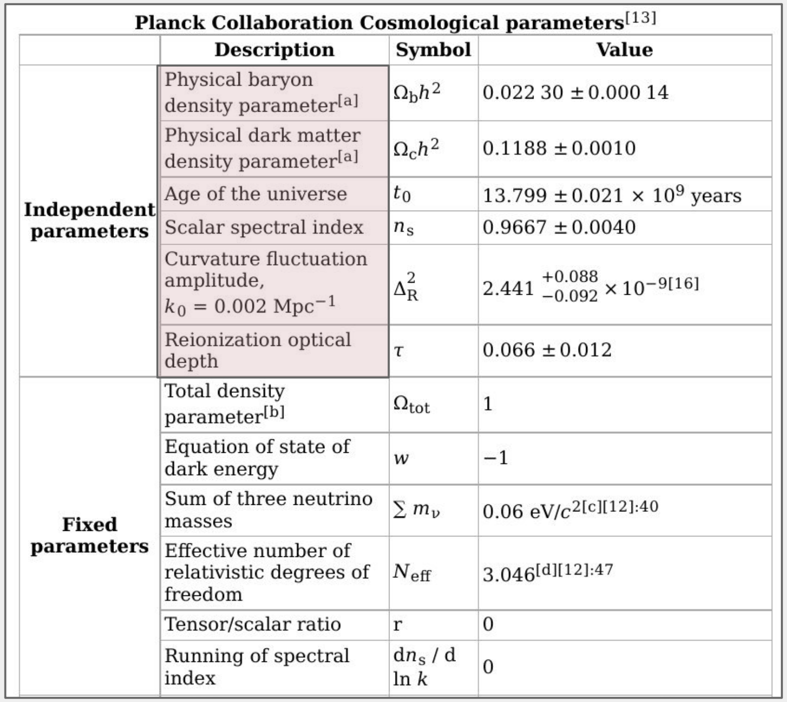


Concordance Model

A wealth of independent data is well explained by the Concordance Model

- Supernovae, CMB, cluster counting, lensing, age estimate, nucleosynthesis, structure formation ...





Planck Collaboration Cosmological parameters[13]

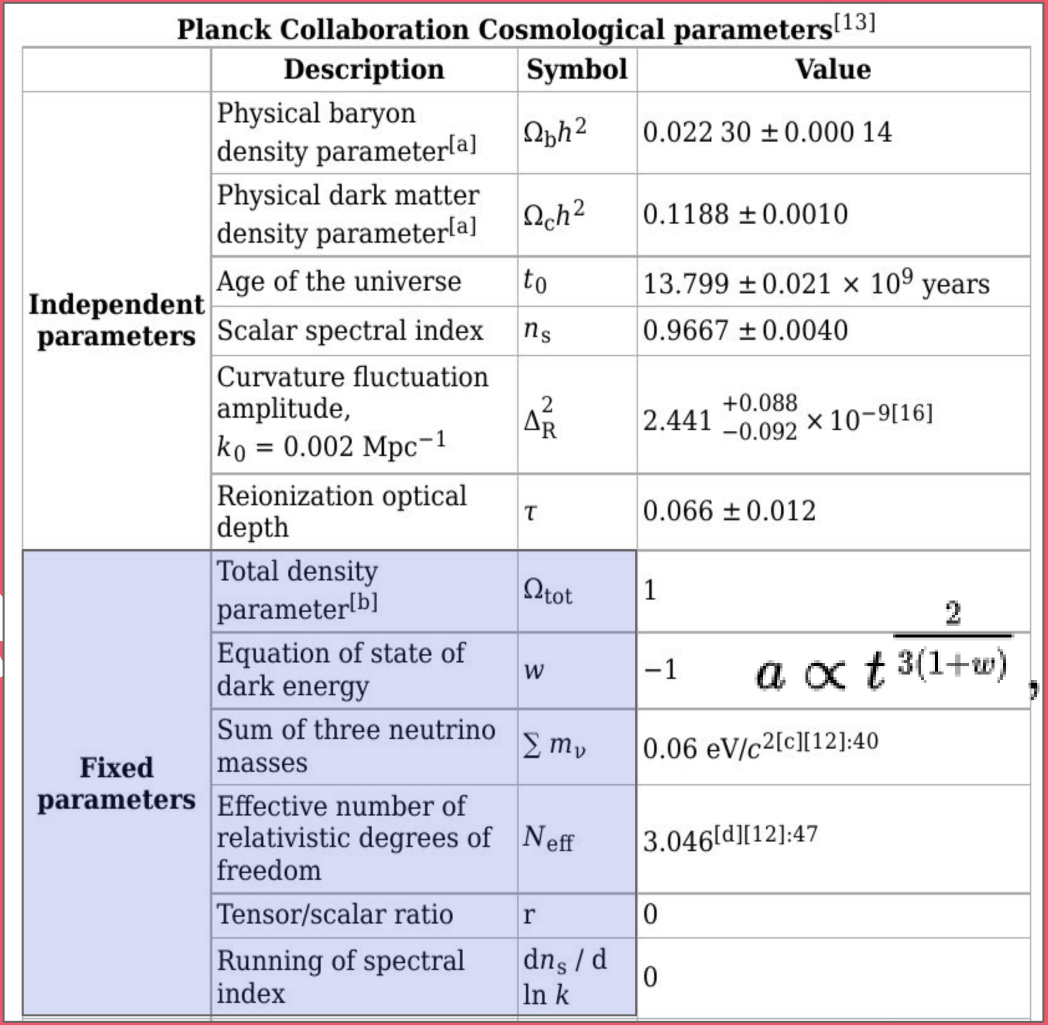
	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	$0.022\,30 \pm 0.000\,14$
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ± 0.0010
	Age of the universe	t_0	$13.799 \pm 0.021 \times 10^9$ years
	Scalar spectral index	n_s	0.9667 ± 0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[16]
	Reionization optical depth	τ	0.066 ± 0.012
Fixed parameters	Total density parameter[b]	Ω_{tot}	1
	Equation of state of dark energy	w	-1
	Sum of three neutrino masses	$\sum m_\nu$	$0.06\ \mathrm{eV}/c^2$[c][12]:40
	Effective number of relativistic degrees of freedom	N_{eff}	3.046[d][12]:47
	Tensor/scalar ratio	r	0
	Running of spectral index	$dn_s / d \ln k$	0

The Future

What we might find

The

What we mi



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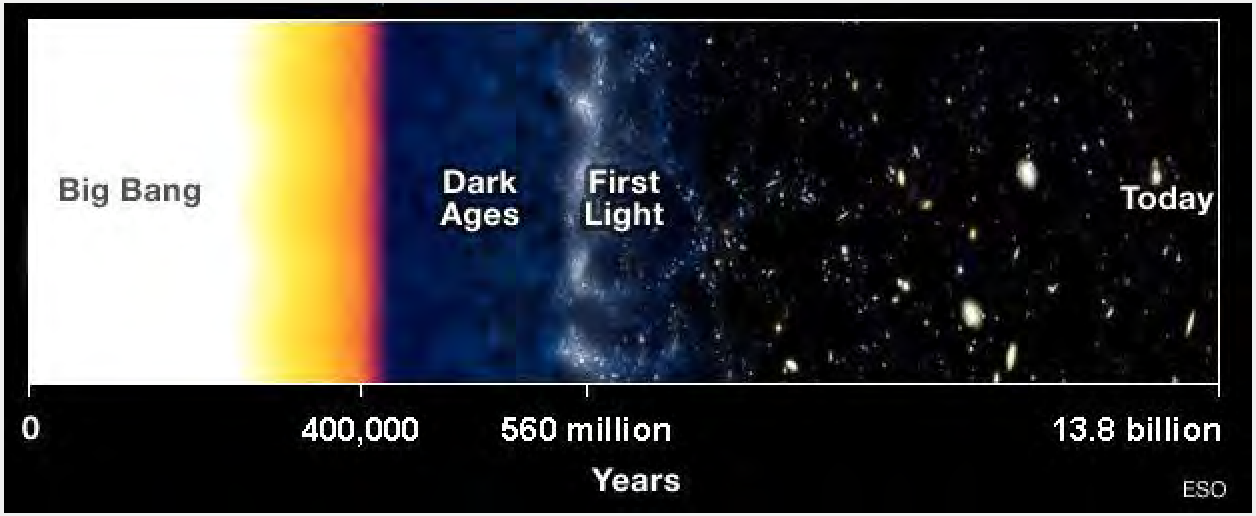
	Running of spectral index	dn_s / d ln k	0

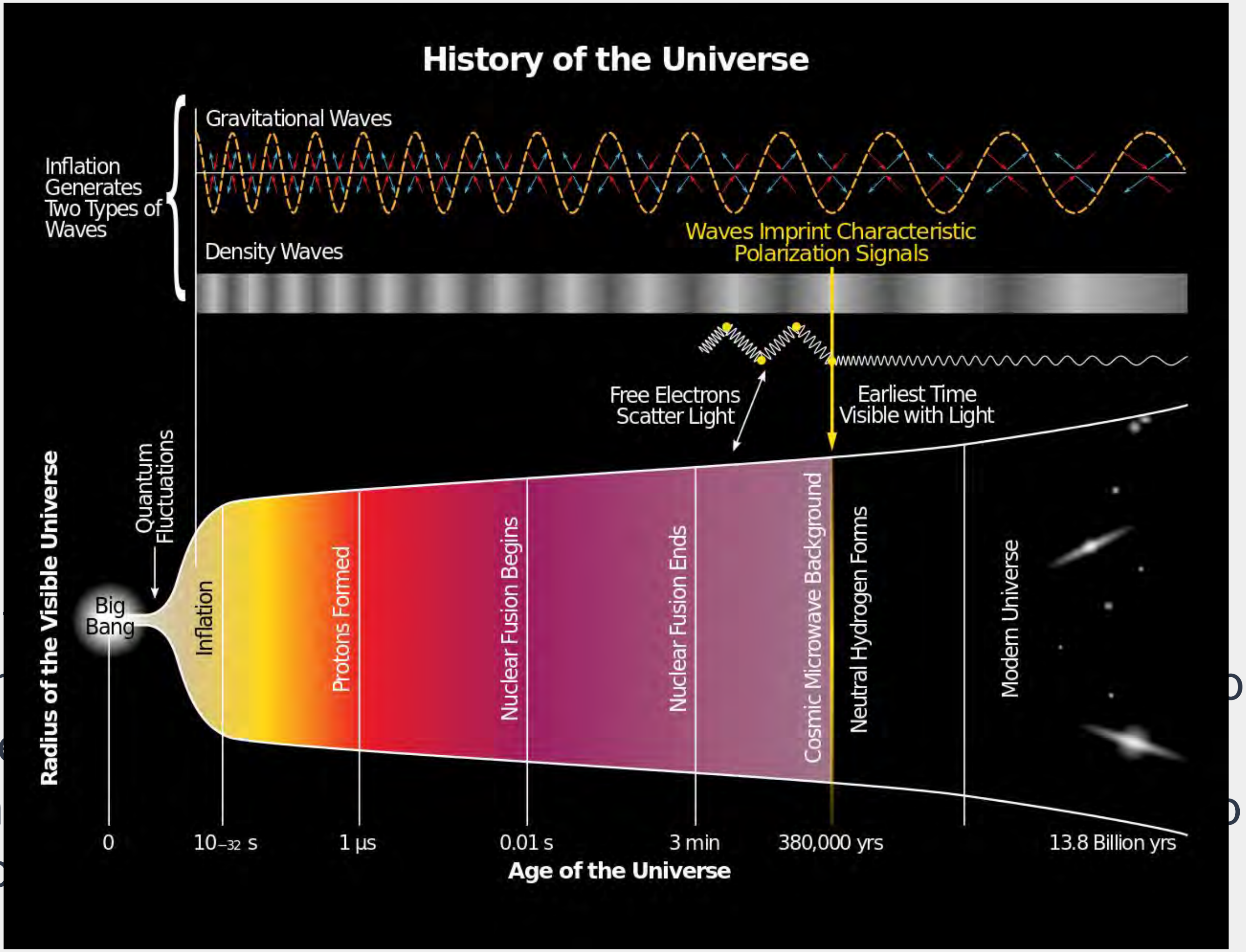
$$a \propto t^{\frac{2}{3(1+w)}},$$

Probing inflation



Inflation - exponential growth of the Universe - would allow quantum fluctuations to explain primordial density fluctuation while naturally predicting a flat universe without magnetic monopoles. Unfortunately, electromagnetic data does not go beyond recombination.

Probing inflation



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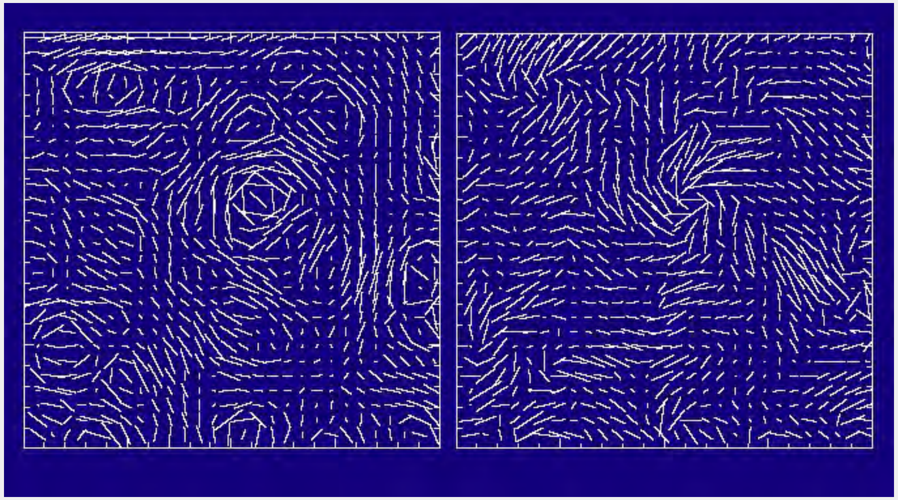
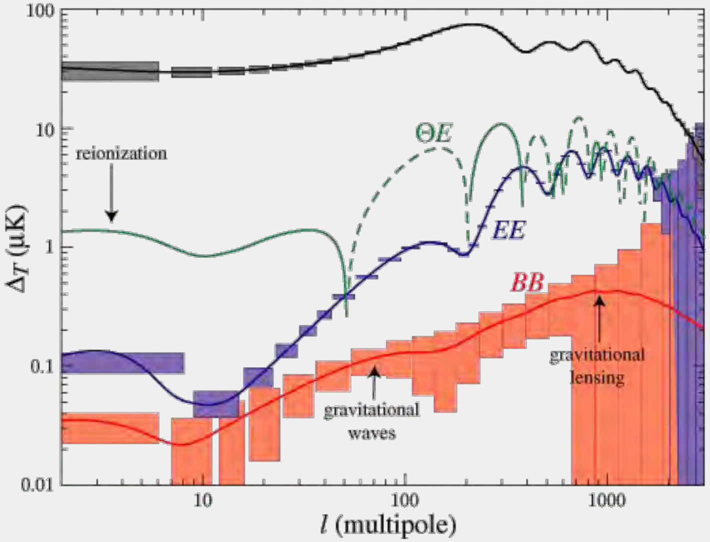
CMB polarization



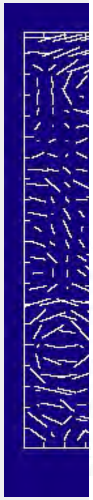


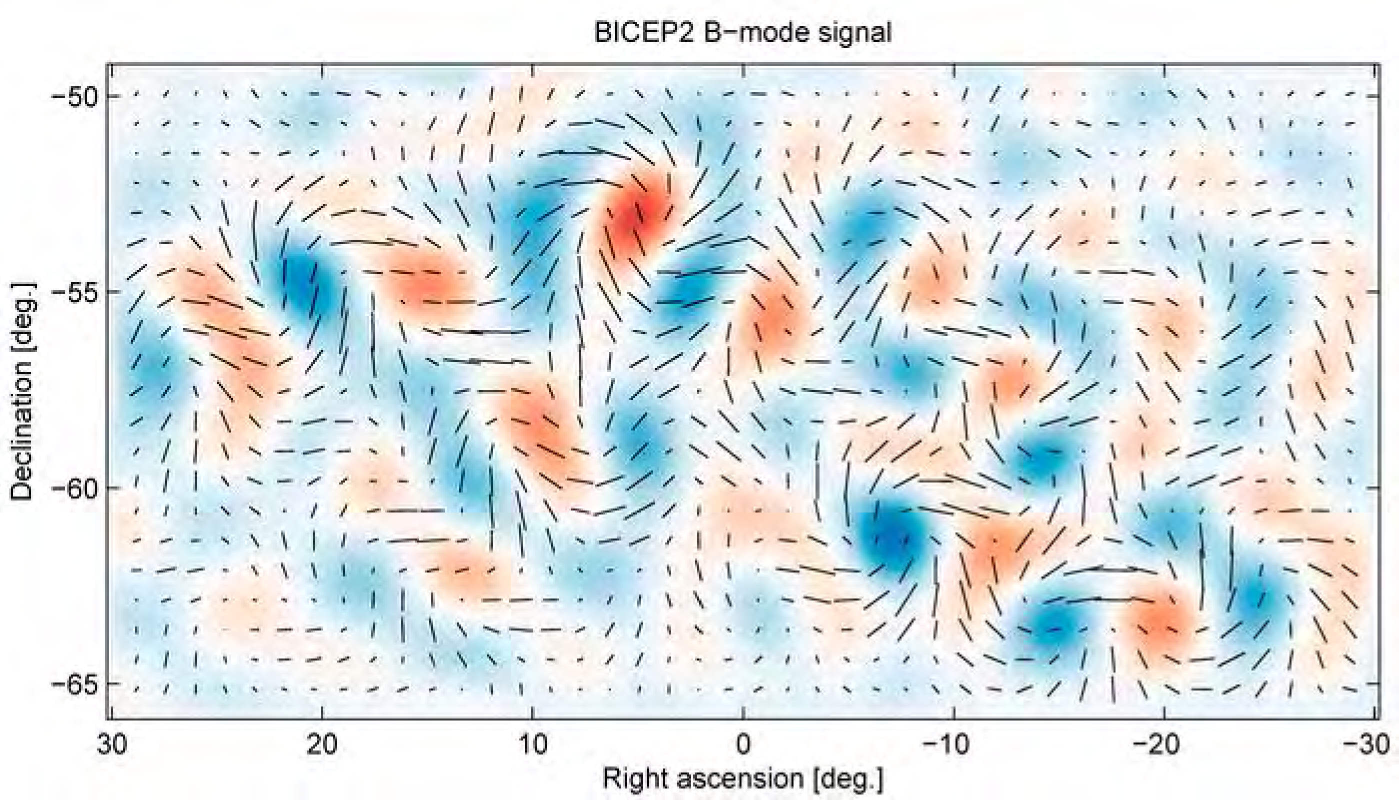
We expect CMB photons to be polarized - photons from over/under densities scatter with free electrons.

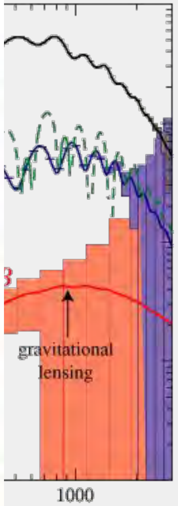
Primordial gravitational waves would also do so, but also as "tensor" perturbations.

In practice, CMB polarization decomposed into E (curl-free, electric field-like) and B (grad free, magnetic-field like)

CMB polarization




BICEP2 B−mode signal



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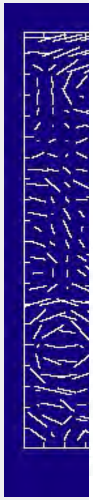
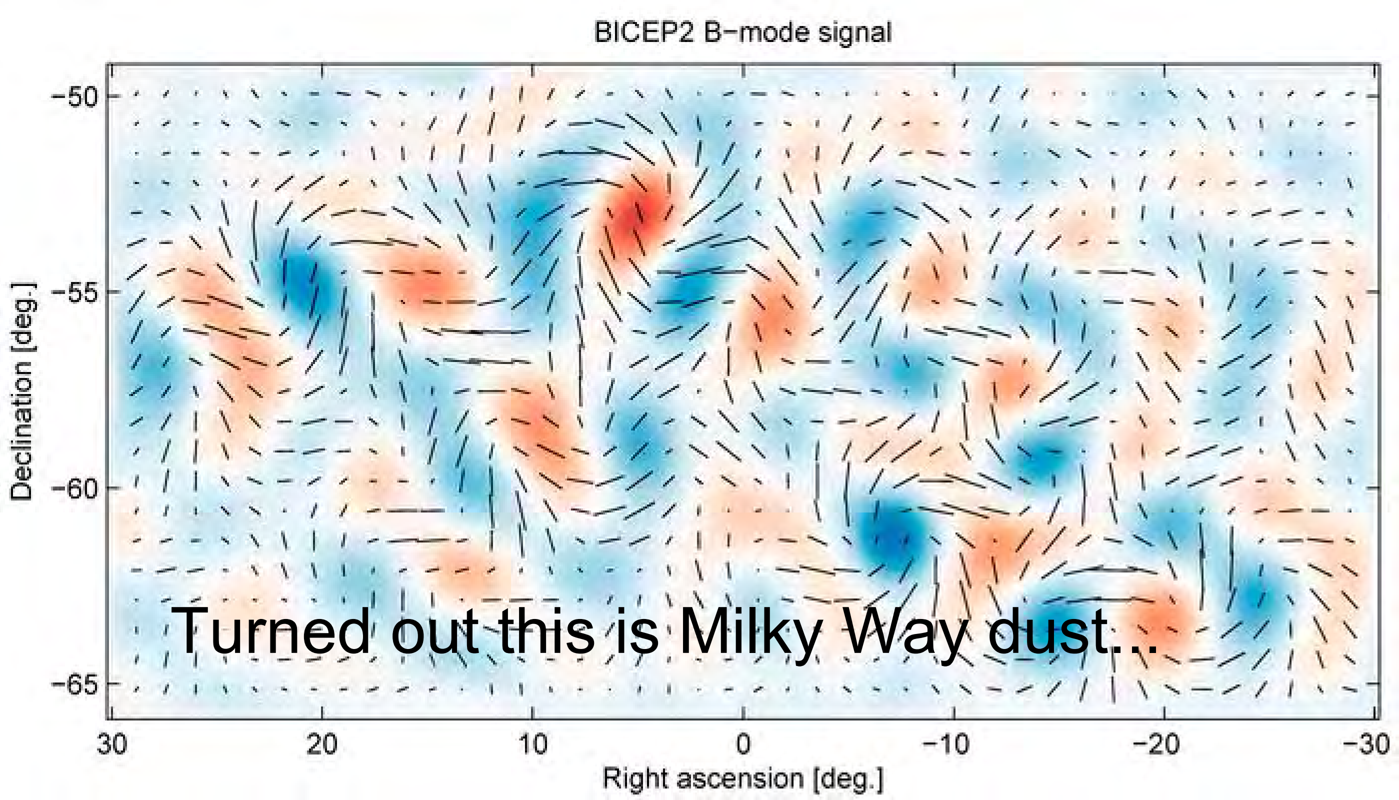
“tensor” perturbations.

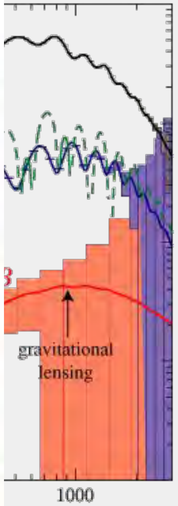
In practice, CMB polarization decomposed into E (curl-free, electric field-like) and B (grad free, magnetic-field like)

CMB polarization





Turned out this is Milky Way dust...



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In practice, CMB polarization decomposed into E (curl-free, electric field-like) and B (grad free, magnetic-field like)

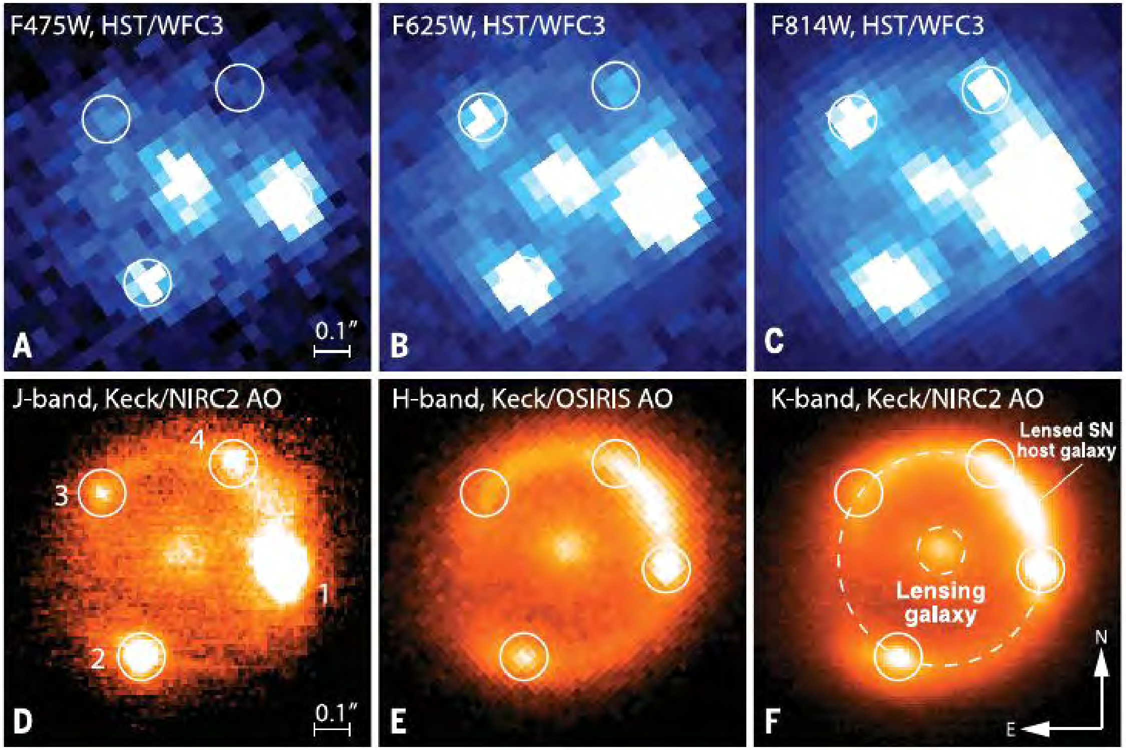
Modifying GR

From an observational point of view, dark energy can be seen either as a form of energy or a modification of GR. Suggested theories either ad-hoc phenomenological or inconsistent.

Bi-metric theory for gravitation introduces a second metric. Recently, complete (non-contradicting, ghost-free) versions have been demonstrated. This allows for creation of two gravitons - one massless and one with mass. The latter can dynamically evolve with normal mass, and cause a late-time accelerated expansion (“dark energy”) - with testable predictions.

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-f}R(f) + m^2 M_g^2\int d^4x\sqrt{-g}\sum_{n=0}^{4}\beta_n e_n(\mathbb{X}) + \int d^4x\sqrt{-g}\mathcal{L}_{\mathrm{m}}(g,\Phi_i).$$

iPTF16geu - multiply lensed SNIa

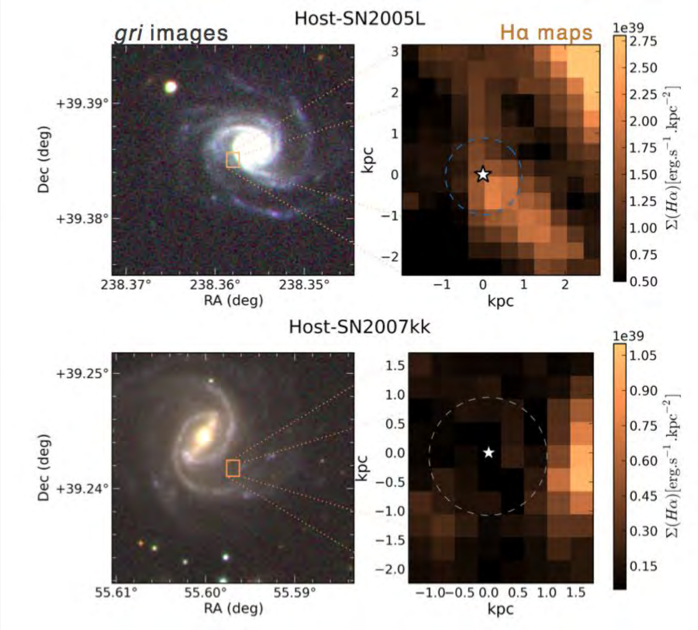


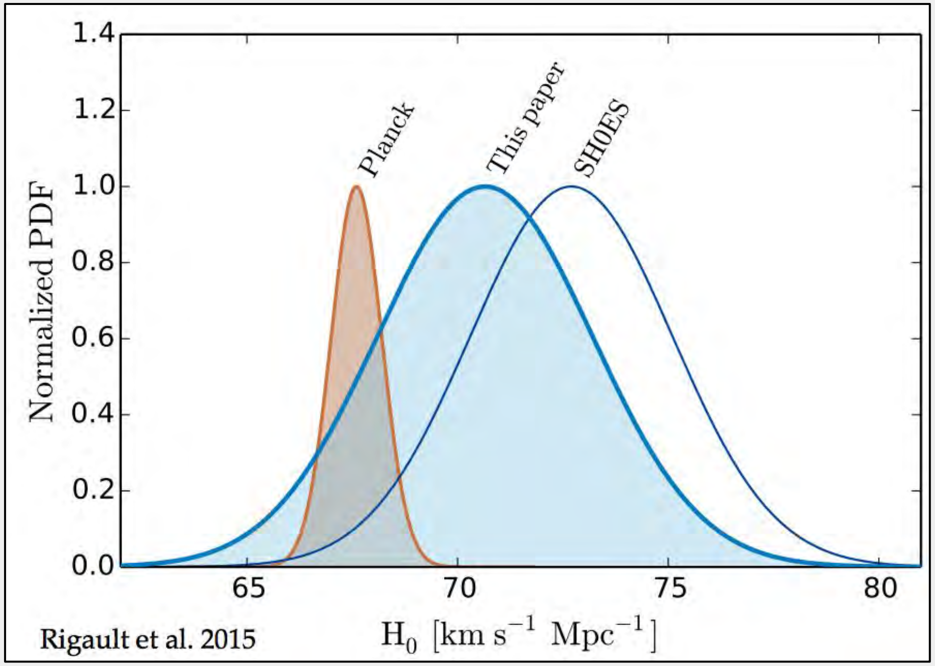
Goobar, *Amanullah*, Kulkarni et al.

A z=0.409 SNIa multiply lensed by a z=0.216 foreground galaxy.

Time delay between images directly sensitive to Hubble constant at lens.

The SNIa progenitor and the local expansion rate





Rigault et al. 2015

Overview of cosmology at HU

Supernova Factory
Spectral time series

Zwicky Transient Facility

SeeChange
HST program probing DE evolution

SN physics

SN Environment

Calibration

Anisotropies

HUMBOLDT-UNIVERSITÄT · ZU BERLIN ·

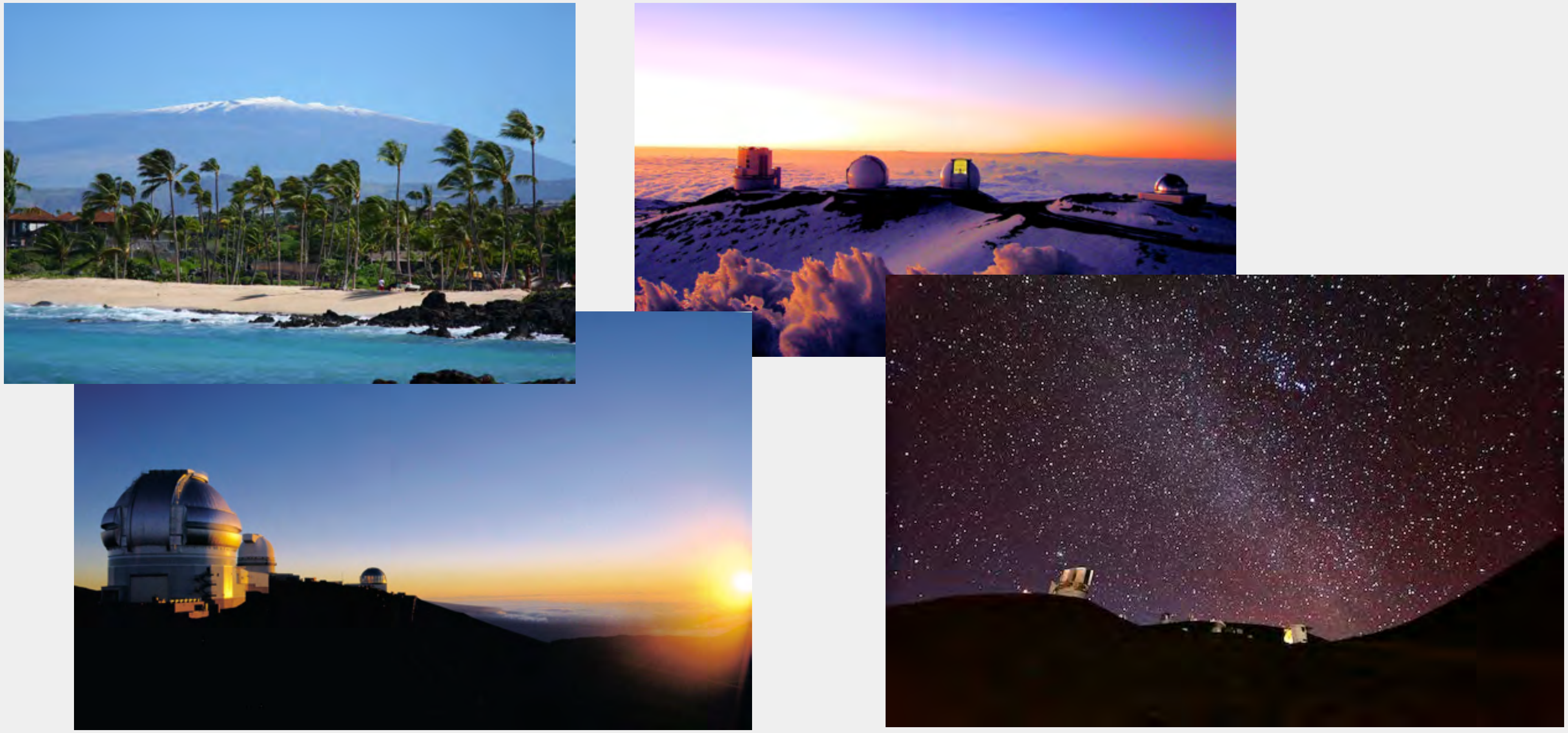
Conclusions:

- **With general relativity we can probe the Universe at it’s largest scales.**
- **Left us with mind-boggling concepts as Big Bang, dark matter and dark energy**
- **Looking for ways to probe inflation and the evolution of dark energy**

Bergstrom & Goobar; Cosmology and Astroparticle Physics
CMB: http://background.uchicago.edu/~whu/

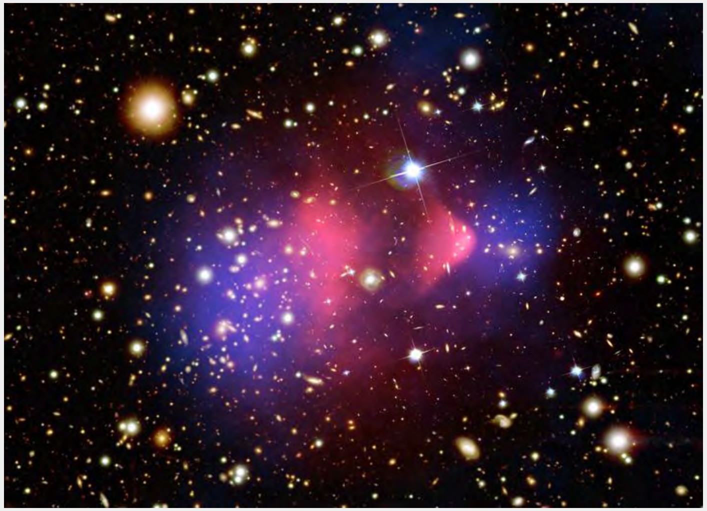
Wie findet man Supernovae?

Wie auch vor 100 Jahre suchen wir neue Lichtquellen im Himmel, deren Typ wird durch Spektroskopie bestimmt.

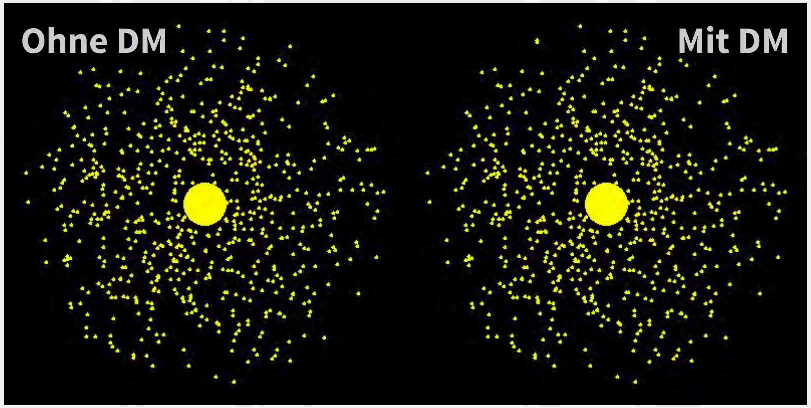


Heute brauchen wir aber die größten Teleskope und sehr dünne Atmosphäre. Der beste Ort ist auf Mauna Kea, Hawaii!

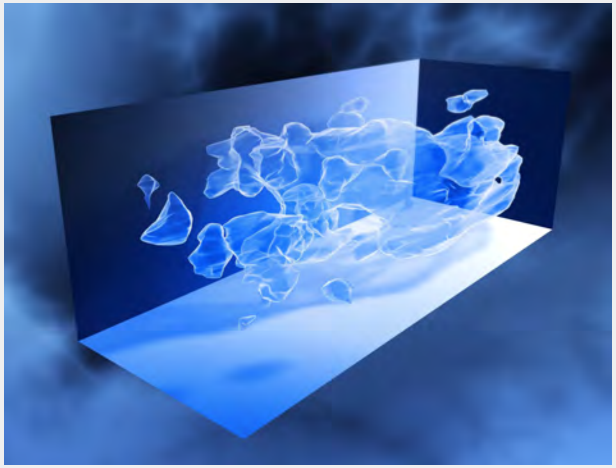
Was ist die Dunkle Materie?



Das Zentrum des Clusters ist als blau zu sehen, die normale Materie ist als rot zu sehen.



Ohne DM wurde Galaxien sich langsamer drehen.



Dunkle Materie muss uberall sein, aber wir können es nicht sehen! Trotzdem bestimmt DM wie Galaxien und Galaxiehaufen sich bewegen.

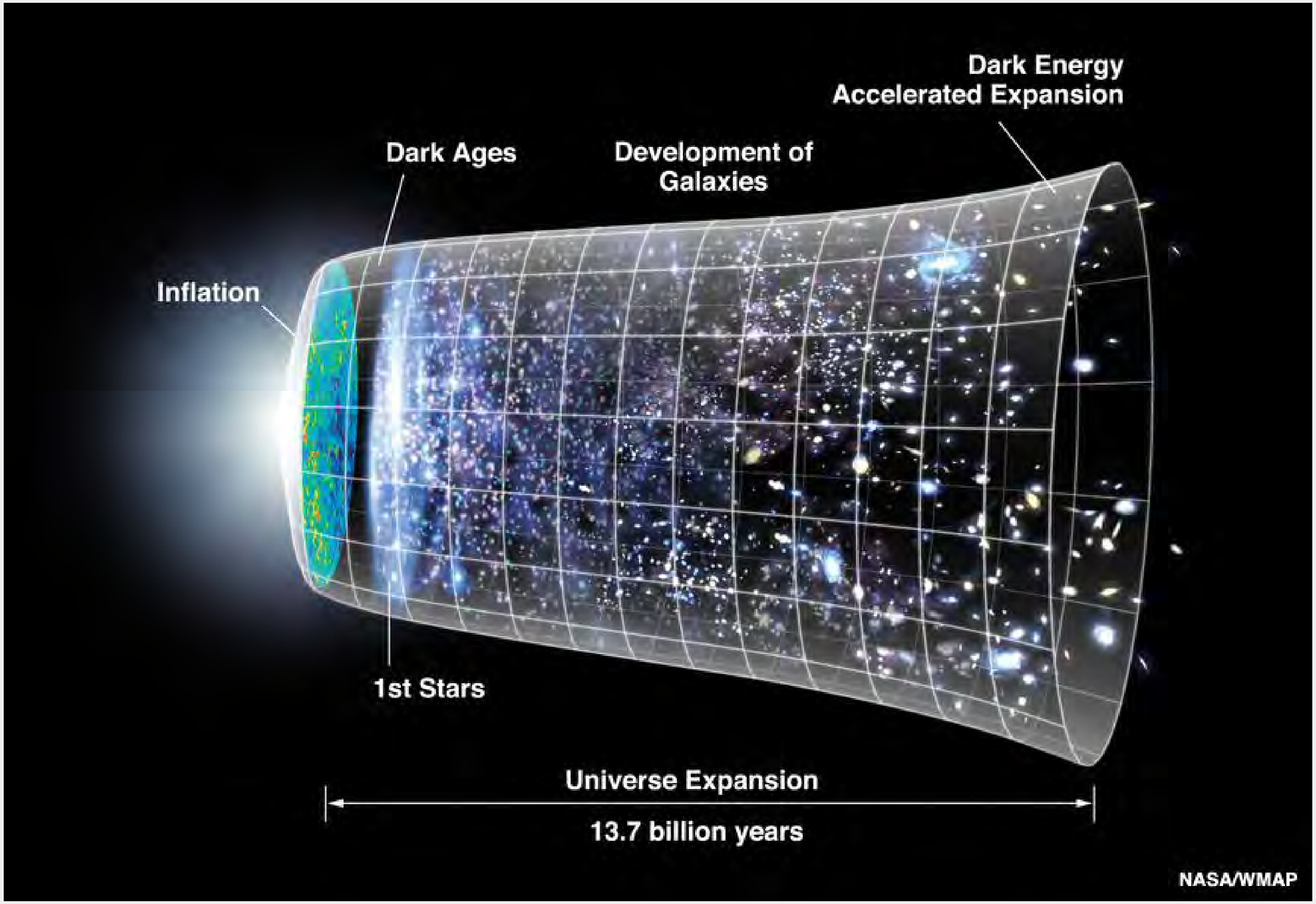
Was ist die Dunkle Energie?

WFIRST & EUCLID, zwei kunftige DE Satellitexperimente.

Wir nennen die Ursache fur die Beschleunigung des Universums “Dunkle Energie”. Sie wirkt als anti-Gravitation, aber viel mehr wissen wir nicht!

Um das zu ändern bauen wir jetzt eine neue Generation von DE Experimente.

Können wir etwas uber Big Bang entdecken?

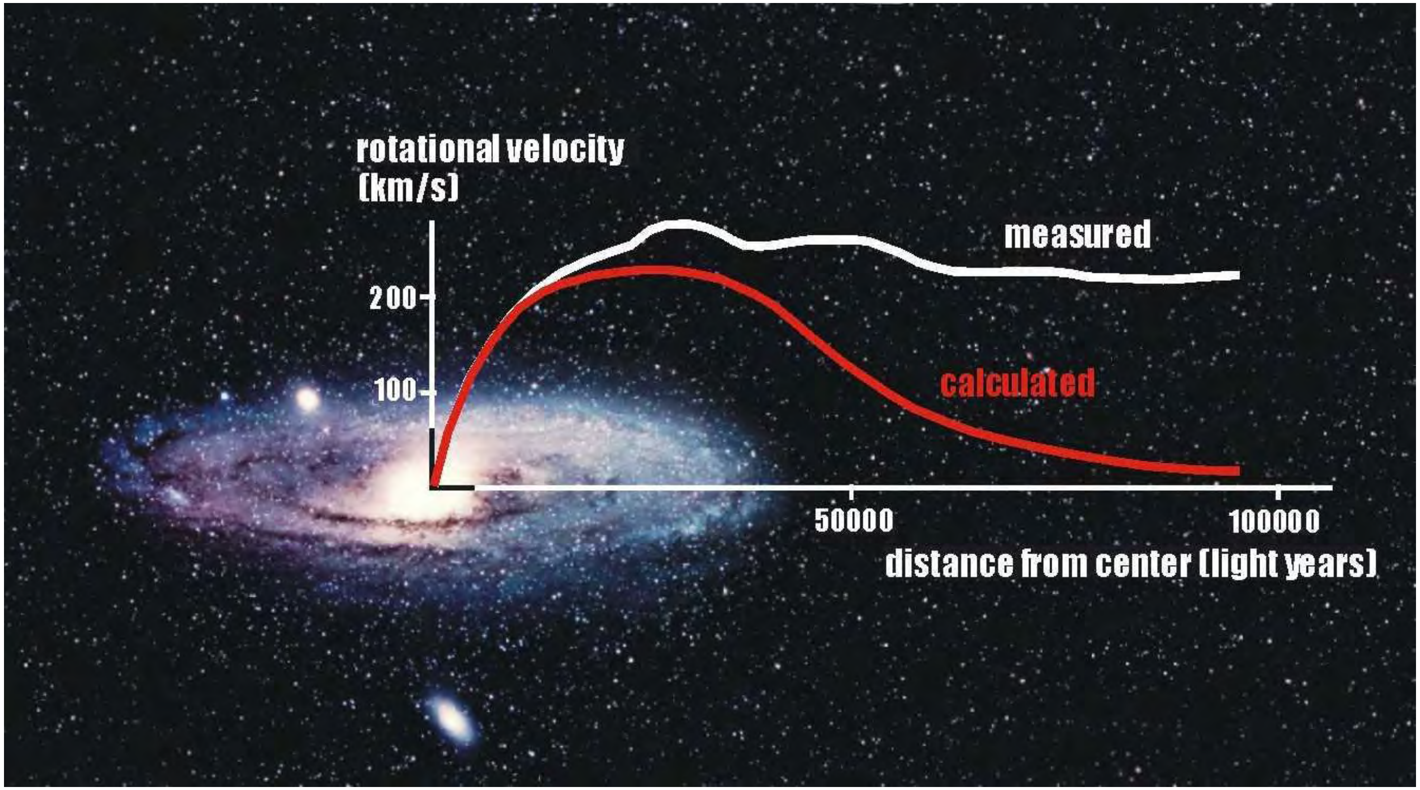


NASA/WMAP

Im nächsten Schritt wollen wir etwas uber Inflation herausfinden!

Type Ia supernovae

A thermonuclear disruption of a star, always emitting the same (enormous) amount of light.

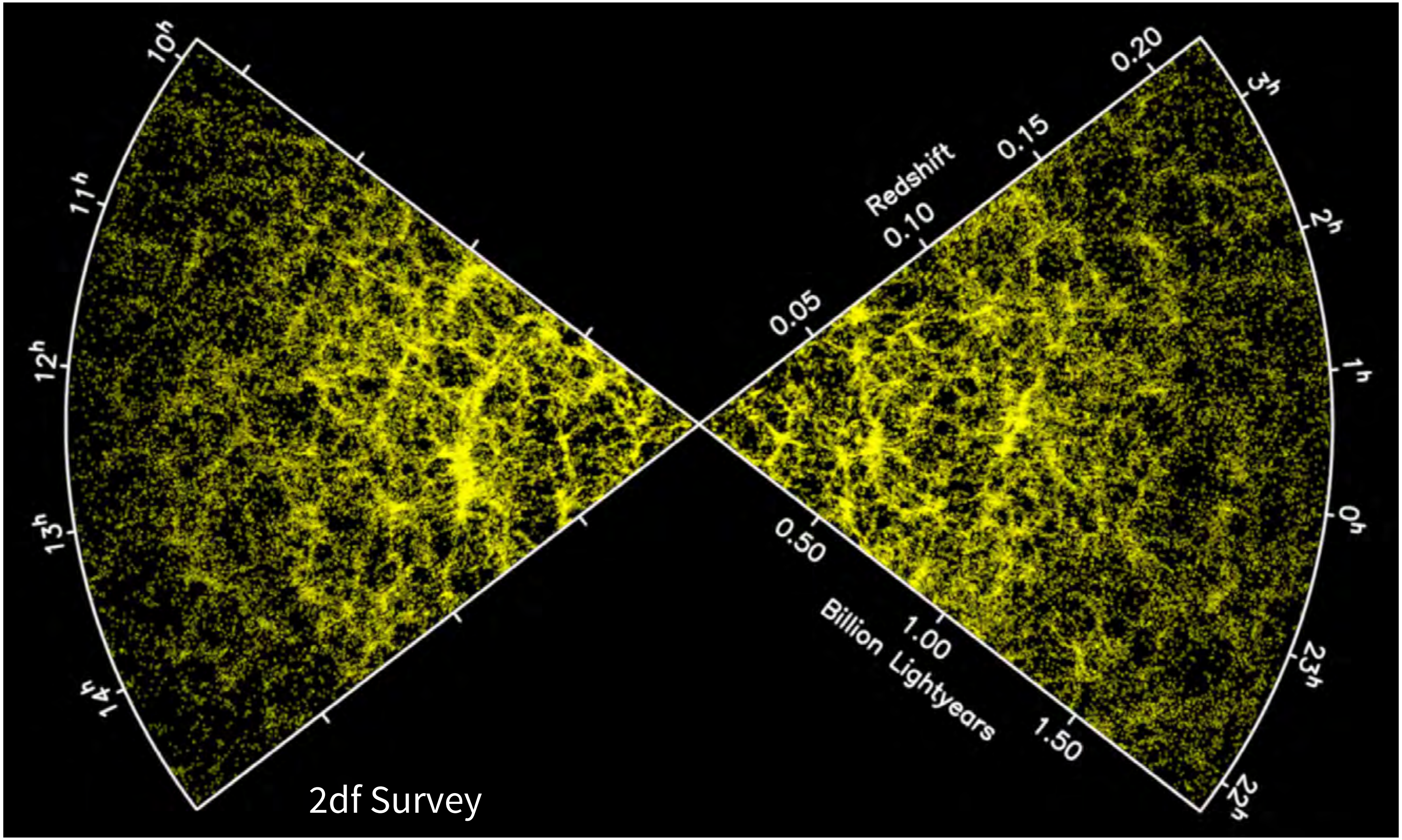

rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)

The Universe 100 years ago

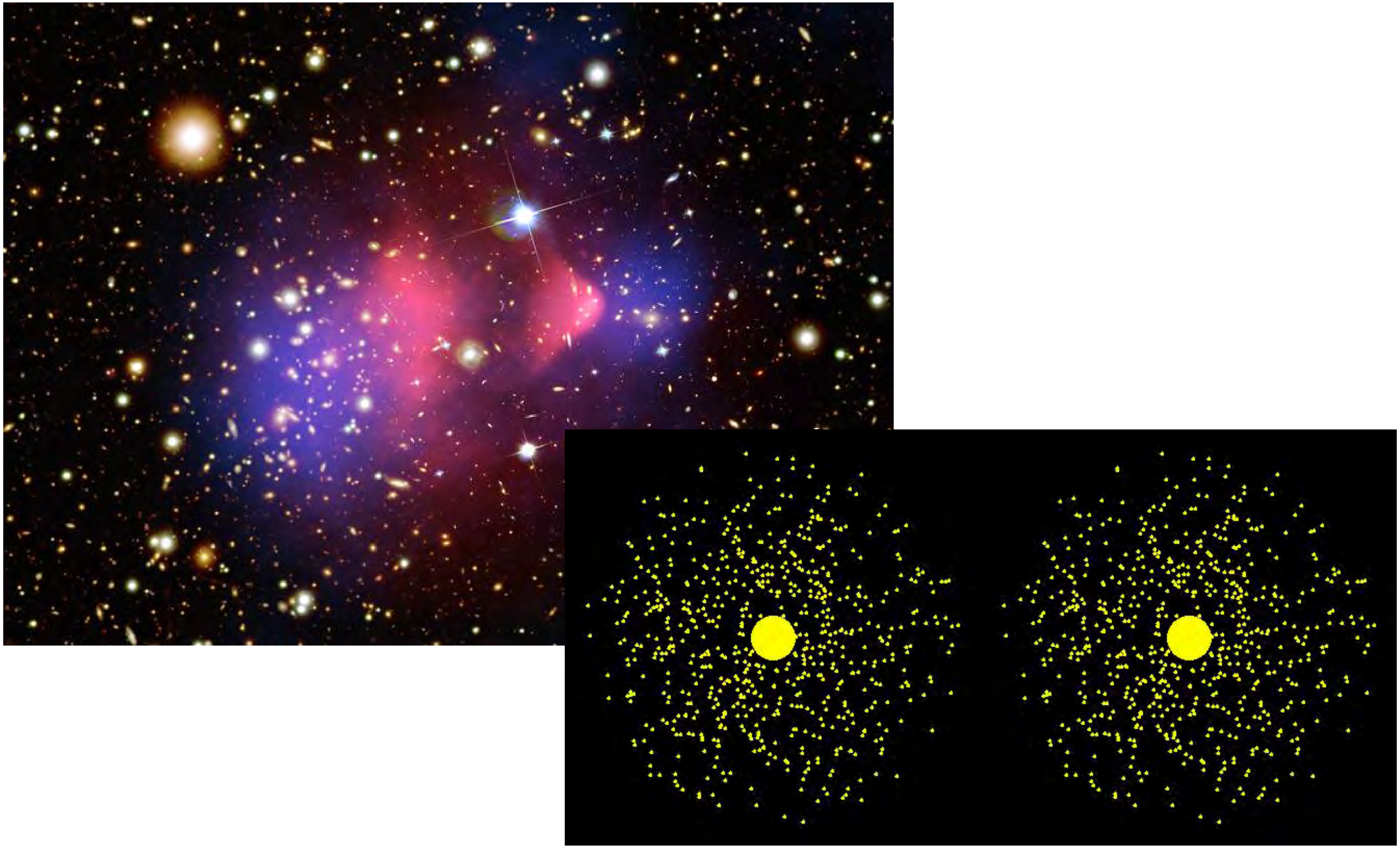
Nearby stars and distant galaxies in a statis universe

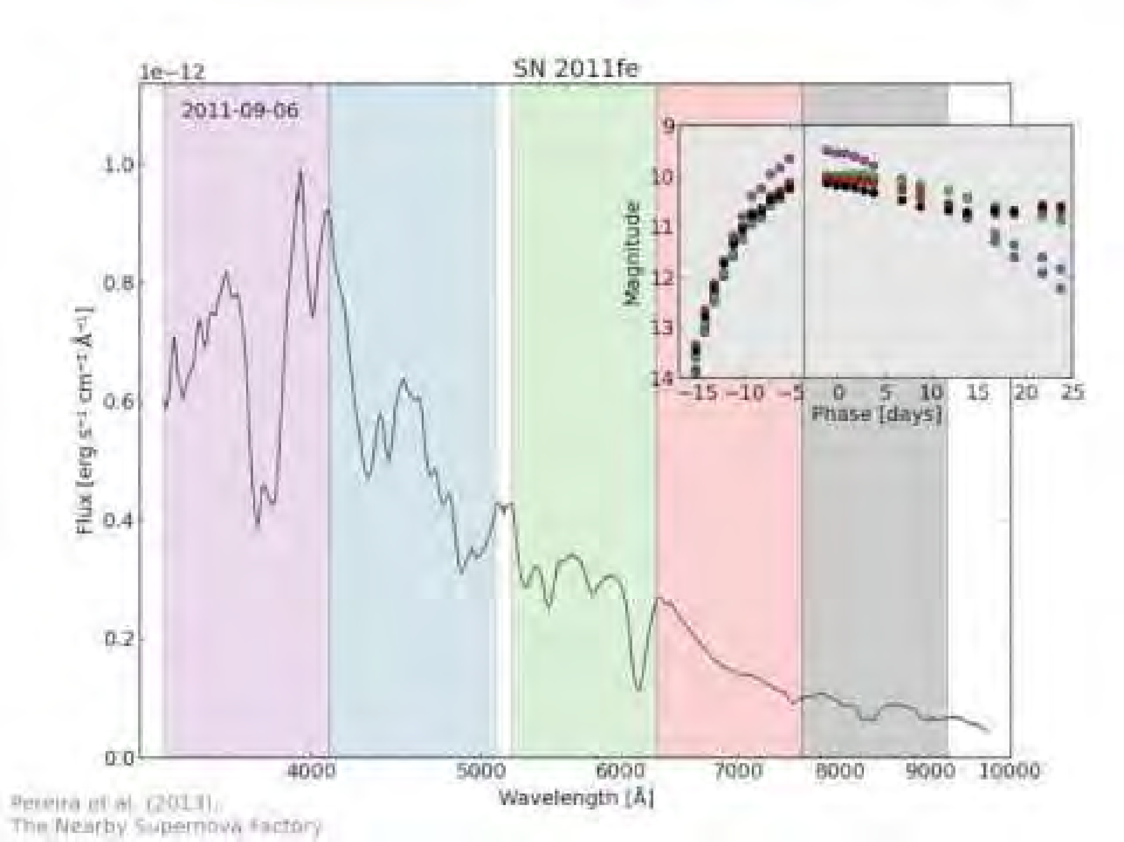
Distant light is old light

Cosmology as much history as a natural science!



- What is dark matter?
- What is dark energy?
- What happened at big bang?





- SN cosmology builds on the *standardized peak magnitude*.
    - Measure peak mag, lightcurve width and color (dust)
- Requires cadenced photometry in 3+ filters

Do we need a more complex model?

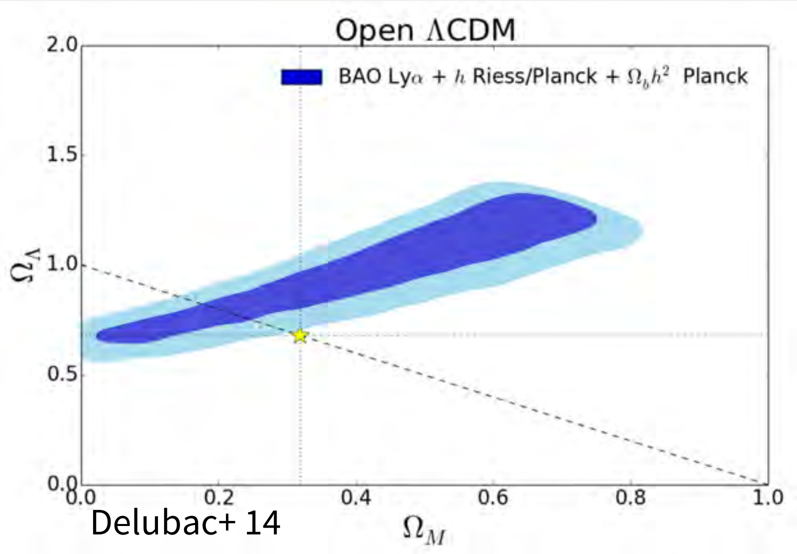
Fundamental theory

Similarly to particle physics, cosmologists are looking for a fundamental theory that explains *why* we currently experience a ΛCDM universe (coincidence problem).

Such theories typically include a dynamic dark energy-like component, implying variation with time/distance.

Data tension

The BOSS Lα-forest BAO survey at z~2.5 found correlation scales incompatible with ΛCDM at ~2σ.



Delubac+ 14

When combined with other data, this result implies time-varying Dark Energy.

1.

How to test DE evolution with SNe Ia

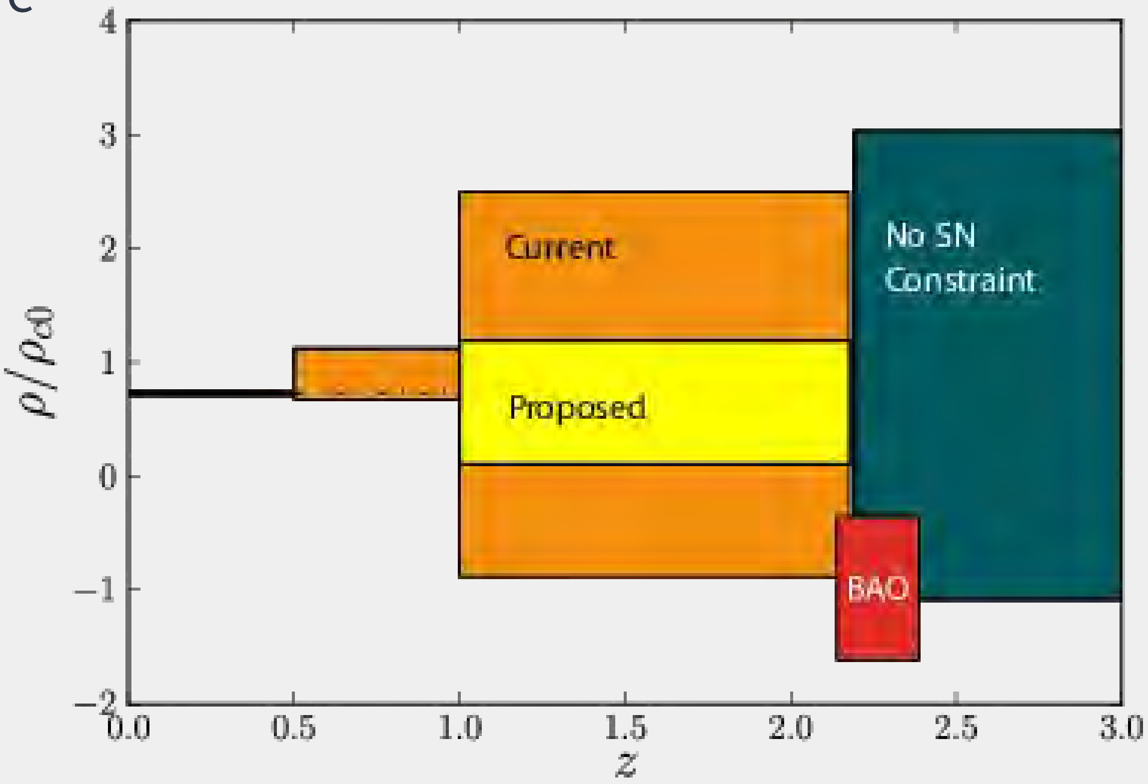
Current constraints on DE evolution

SN luminosity distances are integrated along the path and thus test the “mean” cosmology.

The dark energy density (ϱ_{DE}) is well constrained only locally.

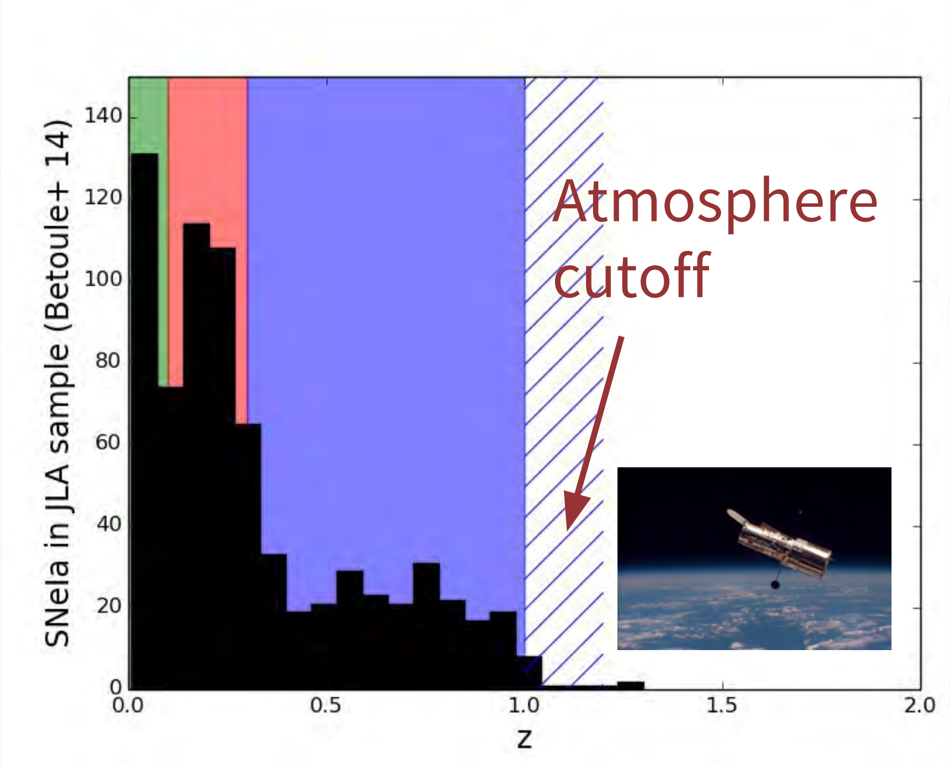
[No DE evidence z>1]

- 25 SNe at z>1.3 sufficient for constraining ϱ_{DE}(z>1).



25 SNe? We have hundreds?

- Observability from ground sharply falls off at z~1
  - True also for e.g. LSST
- Less than ten well-measured z>1 HST SNe Ia, despite hundreds of orbits
  - Goods, Candels, Clash,...

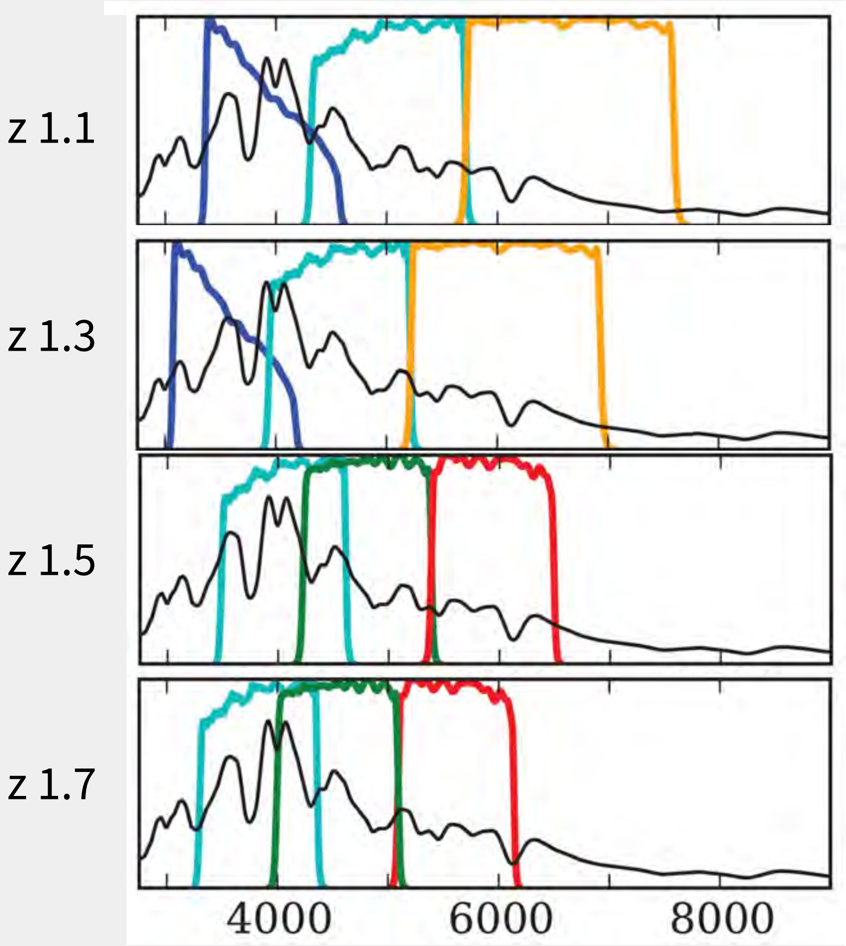


Is the 2m HST not good enough for z~2 SNe?

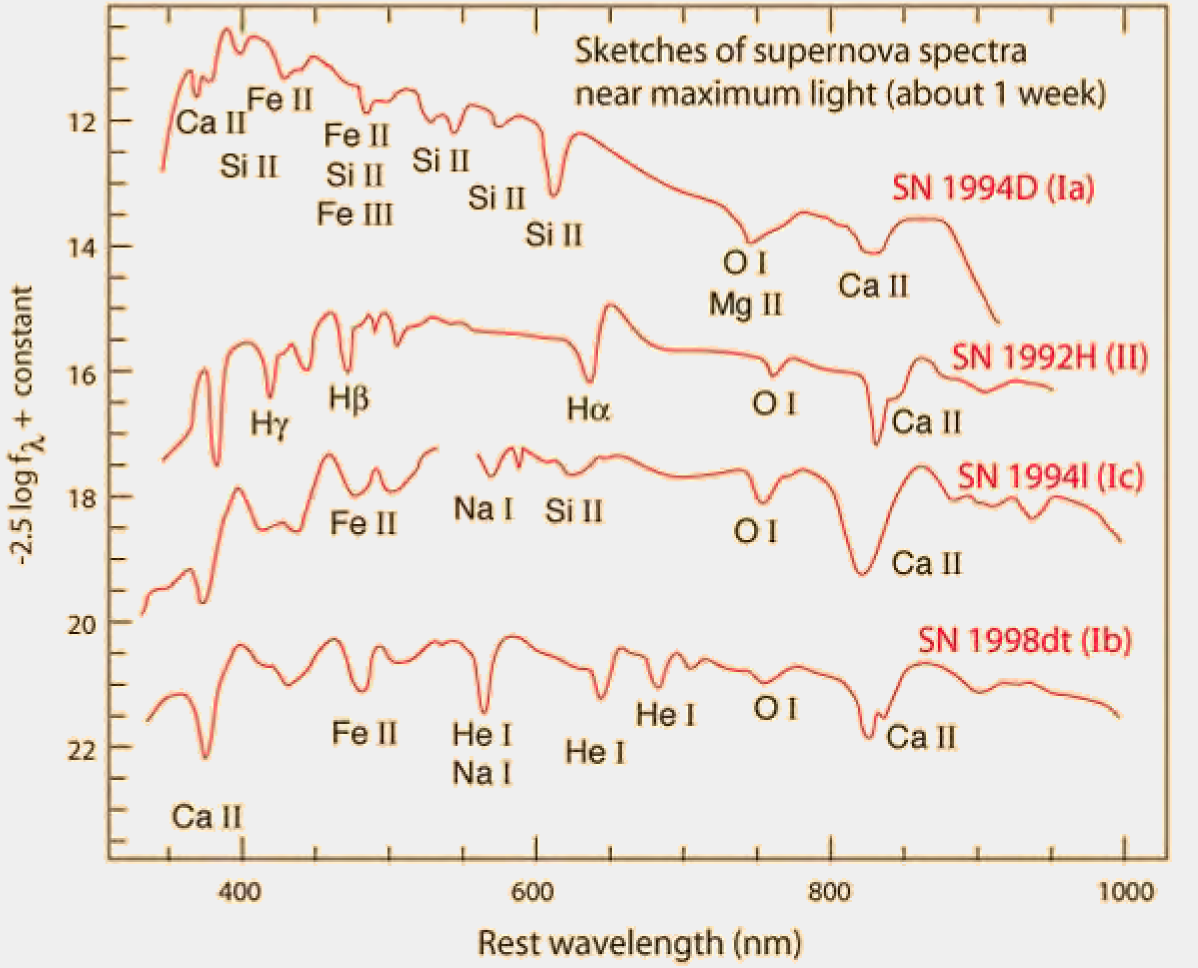
SN lightcurves can be well measured to z~2 through the combination of:

- The new IR camera WFC3
- Flat dμ/dz
- Peak (restframe) SN flux moves to wide IR bands at higher z
- No atmosphere...

[Still requires quick trigger of ToO observations of detected SNe due to slow HST visit processing. Observer frame critical.]



Filters: F814w, F105w, F125W, F140w, F160w



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Transient typing traditionally done through optical spectroscopy