Lyman-α Forest Cosmology

Lecture 1: Intro to BAO

Julian Bautista
Institute of Cosmology and Gravitation
University of Portsmouth, UK

3rd Mexican Astroparticle, Cosmology and Statistics School
June 2019

Lyman-α Forest Cosmology

Julian Bautista

Lecture 1: Intro to BAO

Lecture 2 : The Lyman-α Forest

Lecture 3 : eBOSS measurements

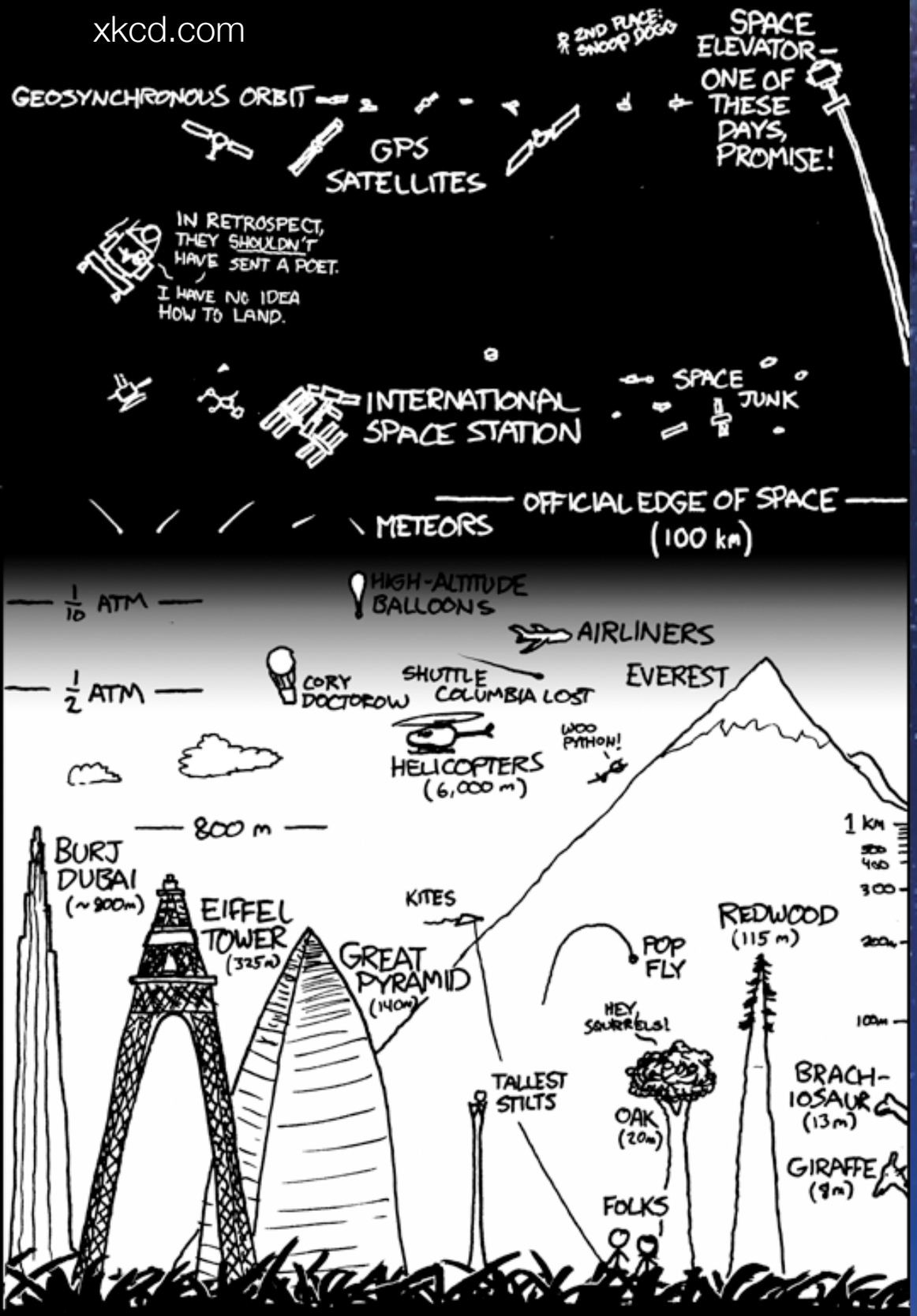
Plan of Lecture

- Cosmic trip
- Distances in astronomy
- Expansion of the Universe and dark energy
- Baryon acoustic oscillations (BAO) to measure distances

SHOOTING STAR
VENUS
SATURN
MERCURY
MT BROMO
MT BATOK
JUSTINNG
PHOTOGRAPHY

Cosmic trip

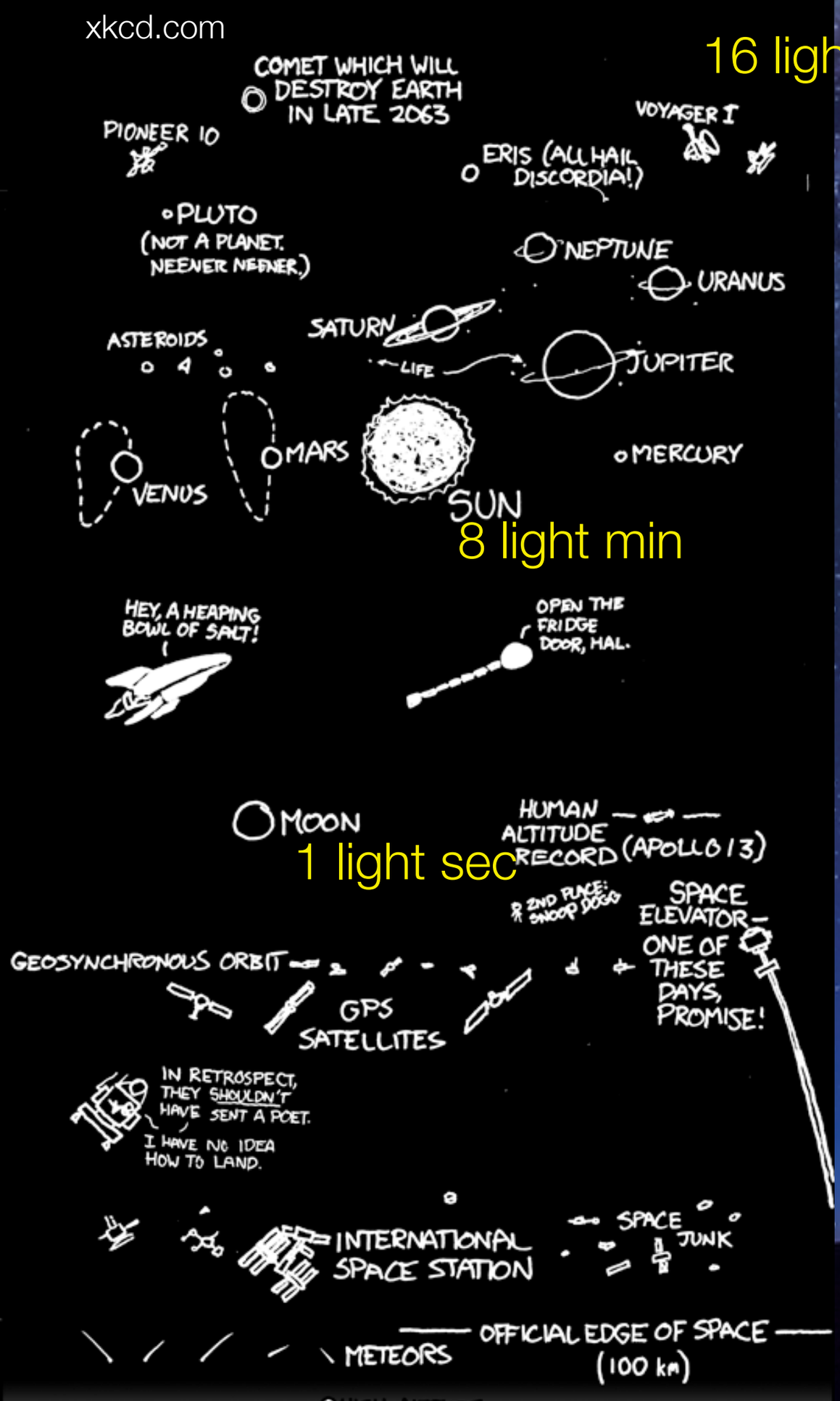
xkcd.com



THE OBSERVABLE UNIVERSE, FROM TOP TO BOTTOM

— ON A LOG SCALE —

SIZES ARE NOT TO SCALE, BUT HEIGHTS ABOVE THE EARTH'S SURFACE ARE ACCURATE ON A LOG SCALE. (THAT IS, EACH STEP UP IS DOUBLE THE HEIGHT.)

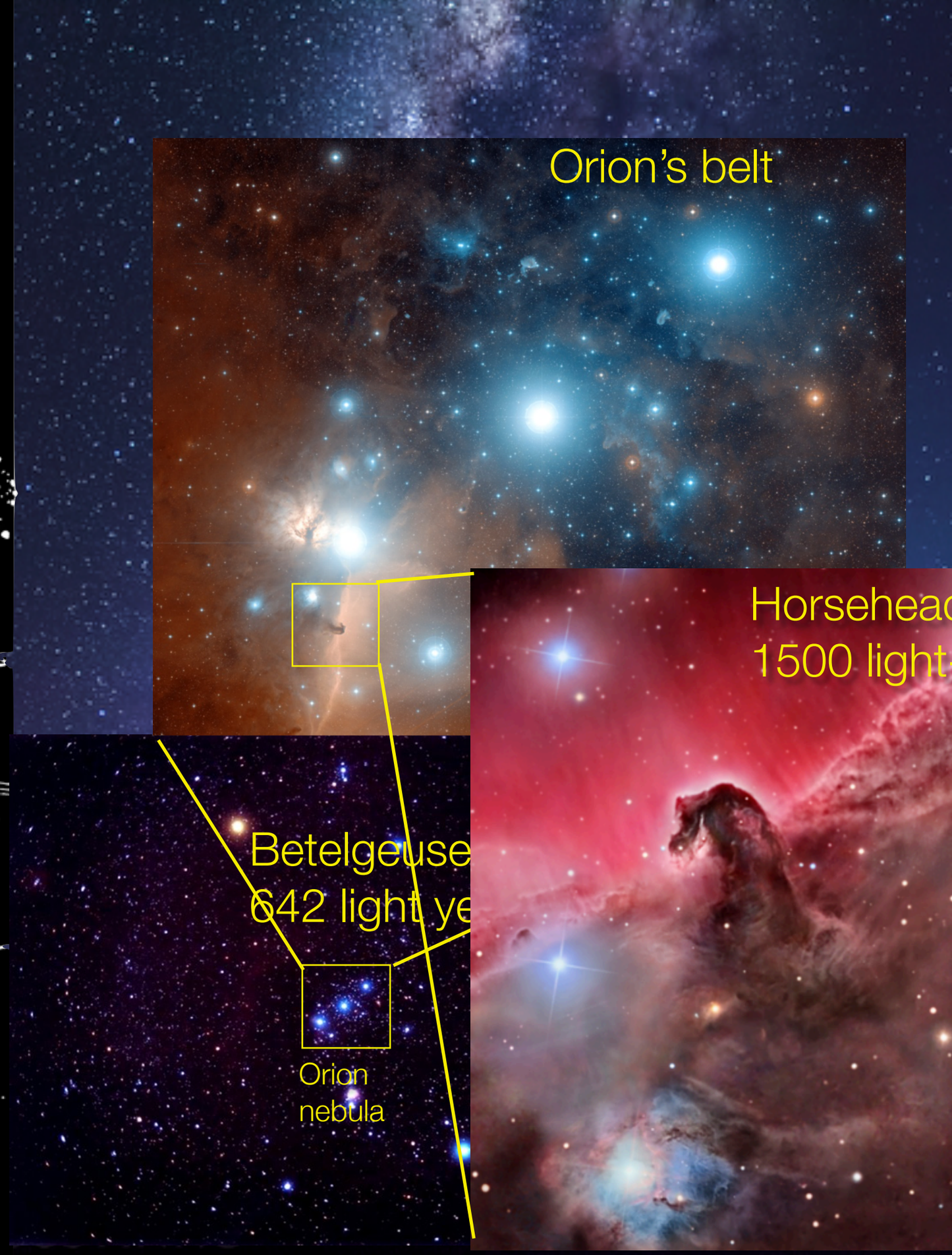

xkcd.com
COMET WHICH WILL DESTROY EARTH IN LATE 2063
16 light hours
PIONEER 10
VOYAGER I
ERIS (ALL HAIL DISCORDIA!)
PLUTO (NOT A PLANET. NEENER NEENER.)
NEPTUNE
URANUS
SATURN
ASTEROIDS
LIFE
JUPITER
VENUS
MARS
MERCURY
SUN
8 light min
HEY, A HEAPING BOWL OF SALT!
OPEN THE FRIDGE DOOR, HAL.
MOON
HUMAN ALTITUDE RECORD (APOLLO 13)
1 light sec
2ND PLACE: SNOOP DOGG
SPACE ELEVATOR
ONE OF THESE DAYS, PROMISE!
GEOSYNCHRONOUS ORBIT
GPS SATELLITES
IN RETROSPECT, THEY SHOULDN'T HAVE SENT A POET.
I HAVE NO IDEA HOW TO LAND.
INTERNATIONAL SPACE STATION
SPACE JUNK
METEORS
OFFICIAL EDGE OF SPACE (100 km)

SHOOTING STAR
VENUS
SATURN
MERCURY
MT BROMO
MT BATOK

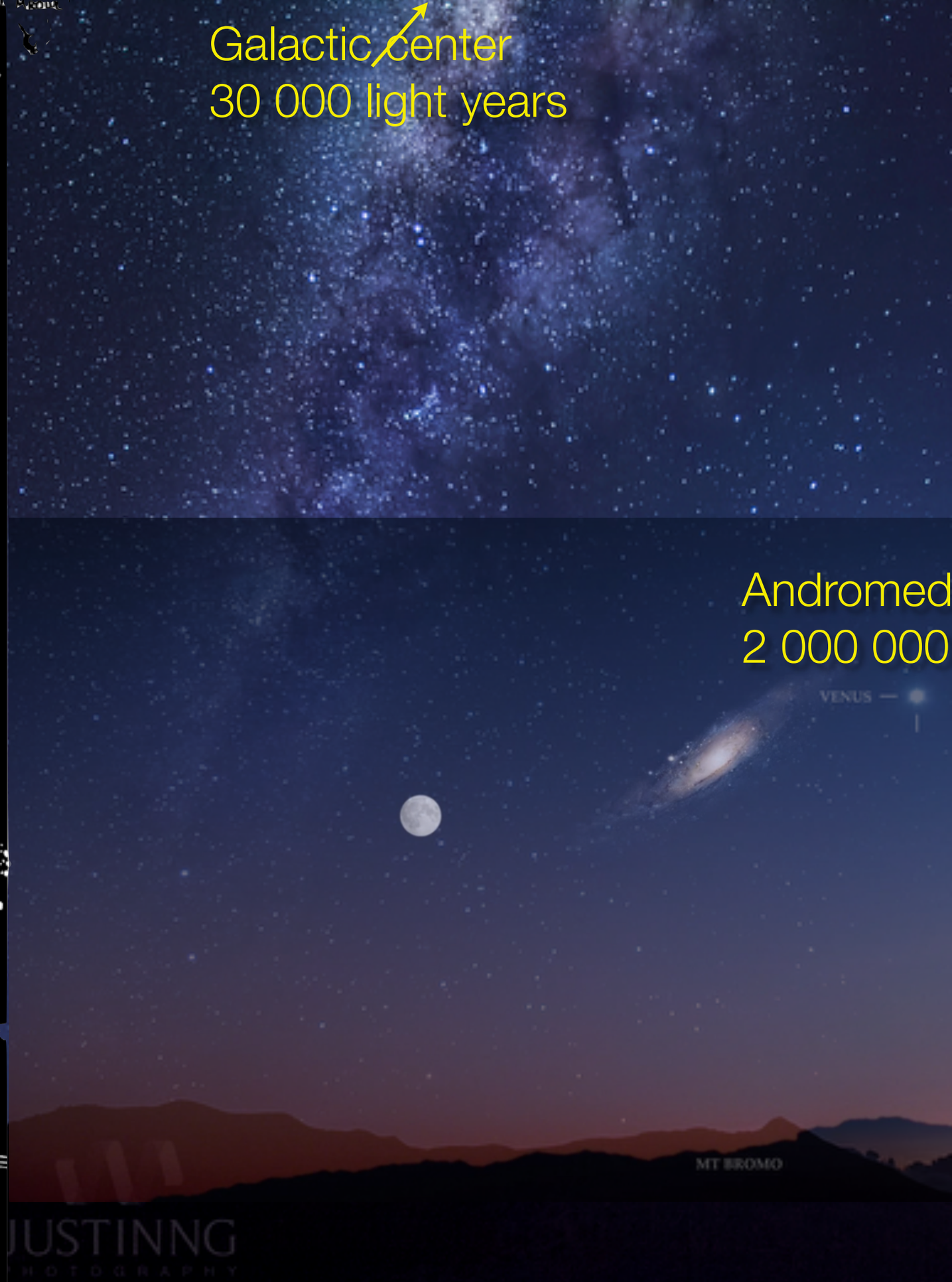
xkcd.com
ANTENNAE GALAXIES (COLLIDING)
ANDROMEDA
HOLY CRAP LOTS OF SPACE
ONE MILLION LIGHT YEARS
MAGELLANIC CLOUDS
EDGE OF GALAXY
GALACTIC CENTER
CRAB NEBULA
ORION NEBULA
HORSEHEAD NEBULA
ROMULAN NEUTRAL ZONE
THE PLEIADES, DUH.
RIGEL
BETELGEUSE
FORD PREFECT
EXPANDING SHELL OF RADIO TRANSMISSIONS
EDGE OF FEDERATION SECTOR 0-0-1
POLLUX
ARCTURUS
MISSING WINDS
SIRIUS
ALPHA CENTAURI
BARNARD'S STAR
ONE PARSEC
4 light years
ONE LIGHT-YEAR
OORT CLOUD (?)
BUPKIS

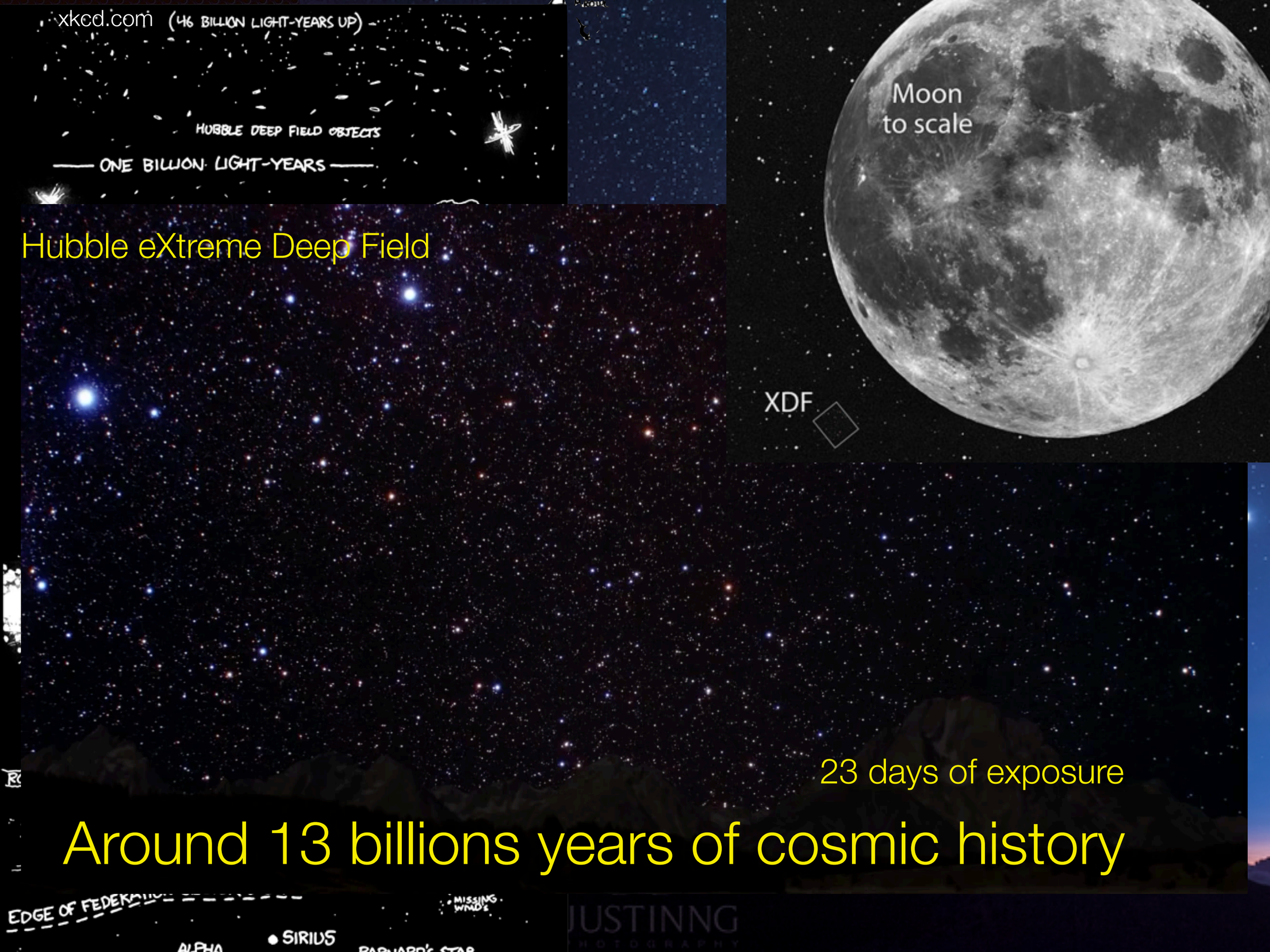
Orion constellation
Betelgeuse
642 light years
Orion
nebula
Sirius
8 light years
VENUS
MT BROMO

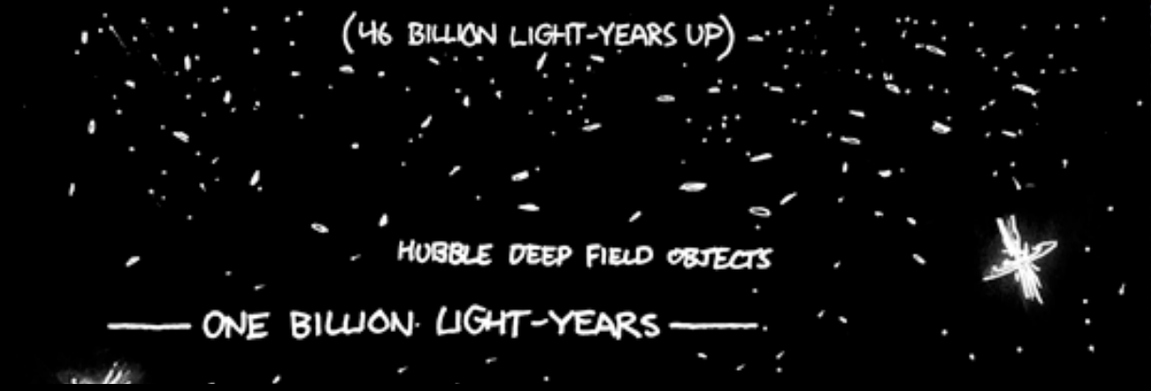
xkcd.com
ANTENNAE GALAXIES (COLLIDING)
ANDROMEDA
HOLY CRAP LOTS OF SPACE
ONE MILLION LIGHT YEARS
MAGELLANIC CLOUDS
EDGE OF GALAXY
GALACTIC CENTER
CRAB NEBULA
ORION NEBULA
HORSEHEAD NEBULA
ROMULAN NEUTRAL ZONE
THE PLEIADES, DUH.
RIGEL
BETELGEUSE
FORD PREFECT
EXPANDING SHELL OF RADIO TRANSMISSIONS
EDGE OF FEDERATION SECTOR 0-0-1
POLLUX
ARCTURUS
MISSING WINDS
SIRIUS
ALPHA CENTAURI
BARNARD'S STAR
4 light years
ONE PARSEC
ONE LIGHT-YEAR
OORT CLOUD (?)
BUPKIS


Orion's belt
Horsehead
1500 light
Betelgeuse
642 light ye
Orion
nebula

xkcd.com
(46 BILLION LIGHT-YEARS UP)
HUBBLE DEEP FIELD OBJECTS
ONE BILLION LIGHT-YEARS
GREAT ATTRACTOR
ANTENNAE GALAXIES (COLLIDING)
ANDROMEDA
HOLY CRAP LOTS OF SPACE
ONE MILLION LIGHT YEARS
MAGELLANIC CLOUDS
EDGE OF GALAXY
GALACTIC CENTER
CRAB NEBULA
ORION NEBULA
HORSEHEAD NEBULA
ROMULAN NEUTRAL ZONE
THE PLEIADES, DUH.
RIGEL
BETELGEUSE
FORD PREFECT
EXPANDING SHELL OF RADIO TRANSMISSIONS
EDGE OF FEDERATION SECTOR 0-0-1
POLLUX
ARCTURUS
MISSING WHAL'S
SIRIUS

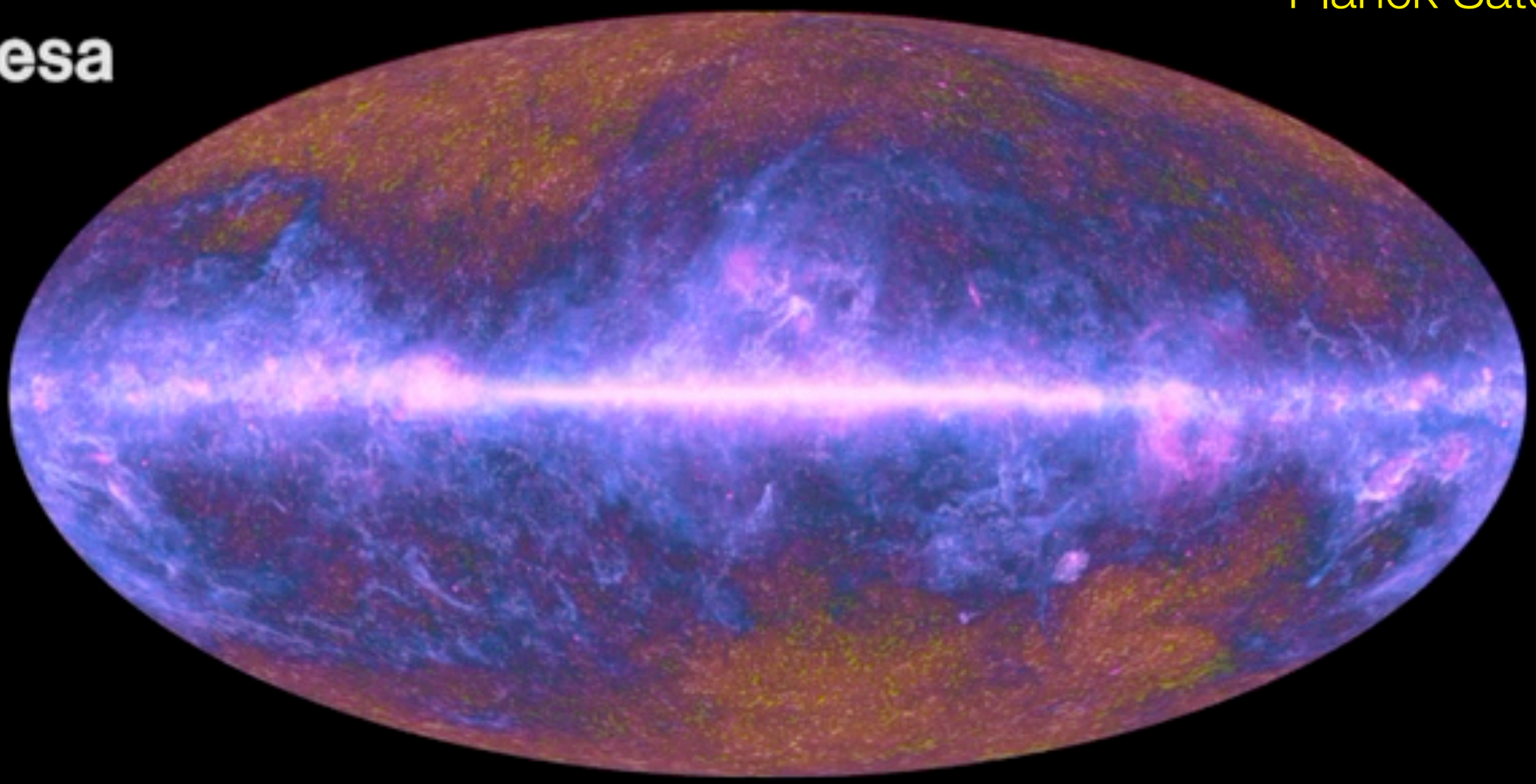

Galactic center
30 000 light years
Andromed
2 000 000
VENUS
MT BROMO
JUSTINNG


xkcd.com
(46 BILLION LIGHT-YEARS UP)
HUBBLE DEEP FIELD OBJECTS
ONE BILLION LIGHT-YEARS
Hubble eXtreme Deep Field
Moon
to scale
XDF
23 days of exposure
Around 13 billions years of cosmic history
EDGE OF FEDERATION
MISSING WINDS
SIRIUS
ALPHA
BARNARD'S STAR
JUSTINNG



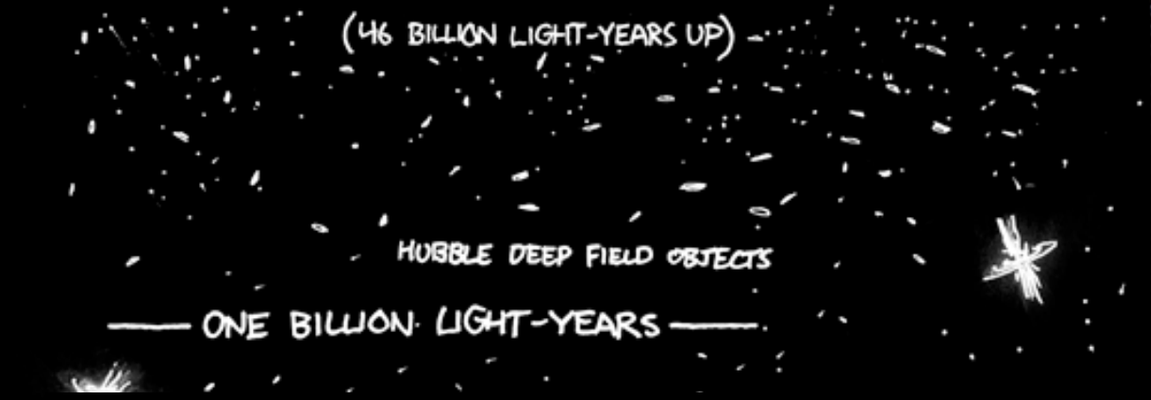
What is beyond?

Planck Satellite

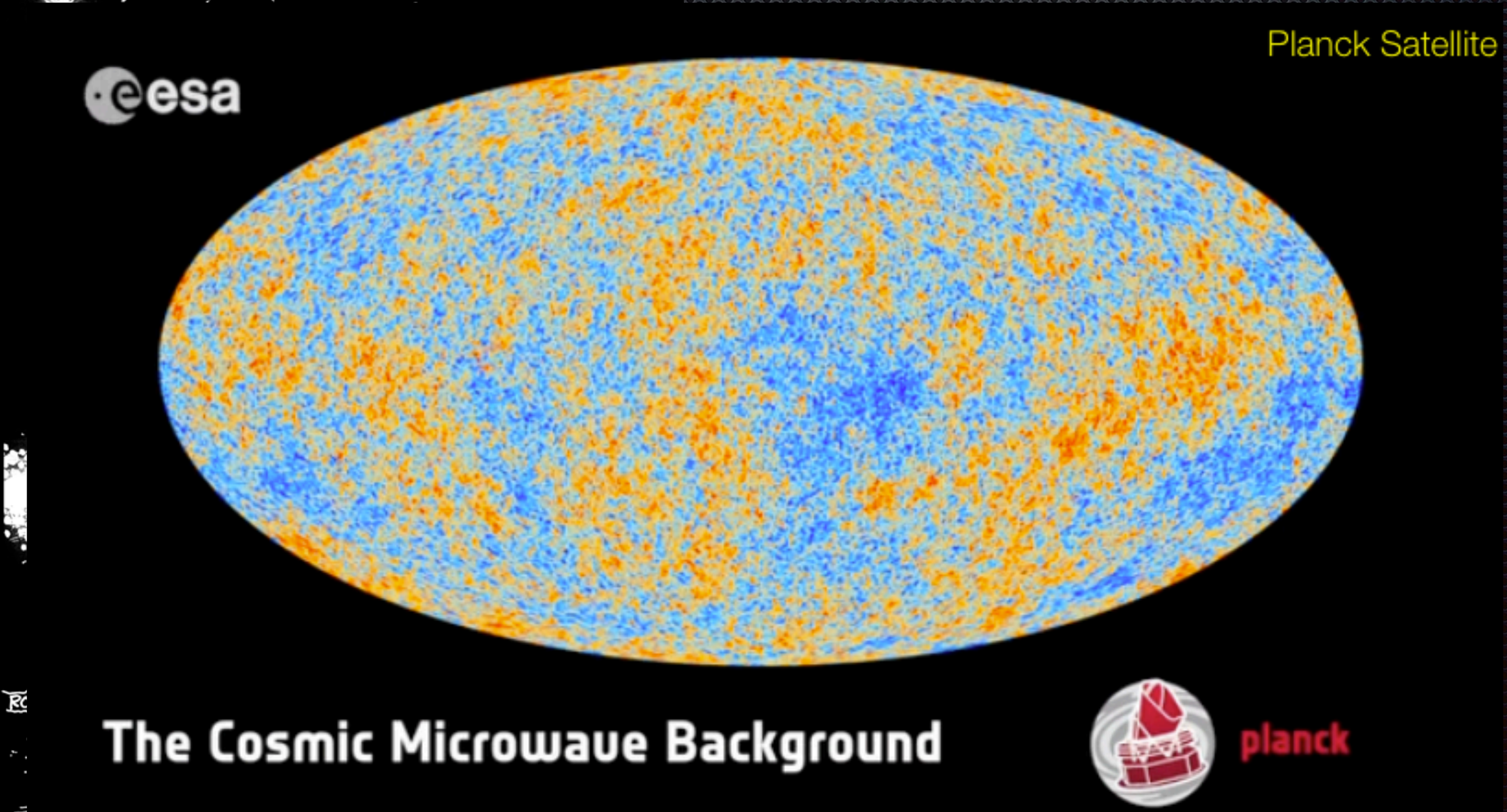


Individual sources	+	Radio emission from the Milky Way	+	Dust emission from the Milky Way	+	Cosmic Microwave Backgound

All emissions at microwave & submillimetre wavelengths

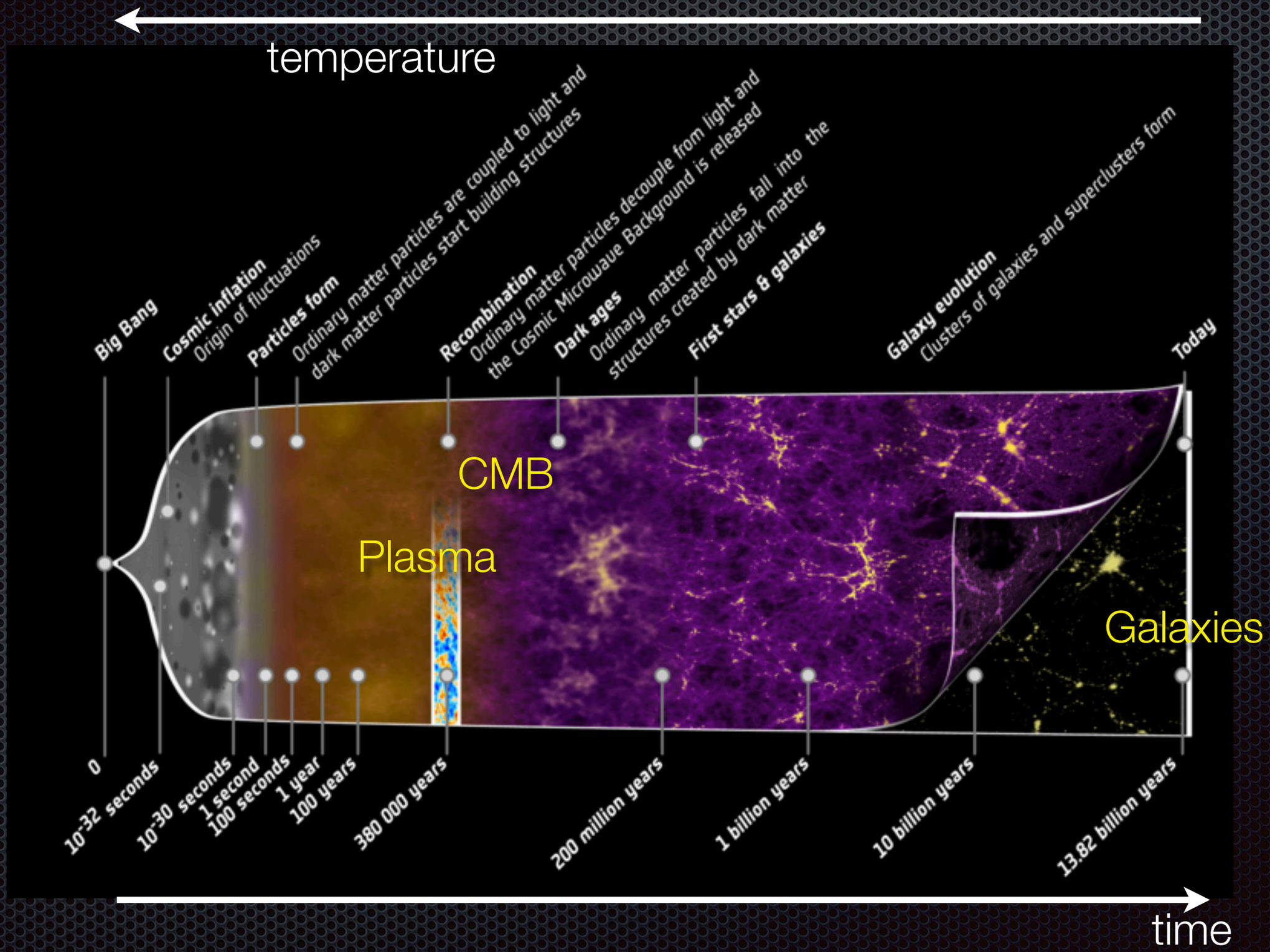


What is beyond?

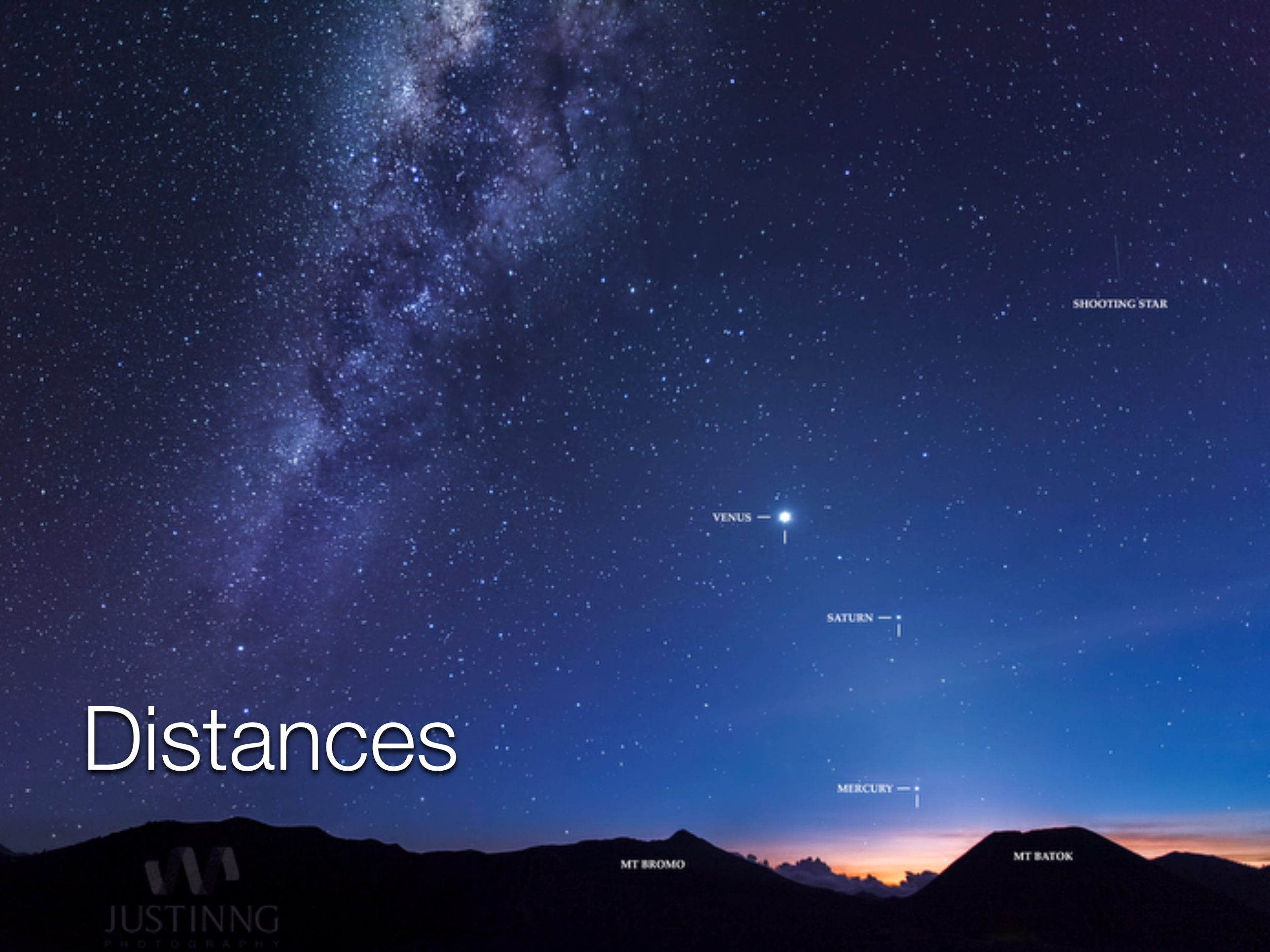


Picture of Universe 400 000 years old!

History of the Universe

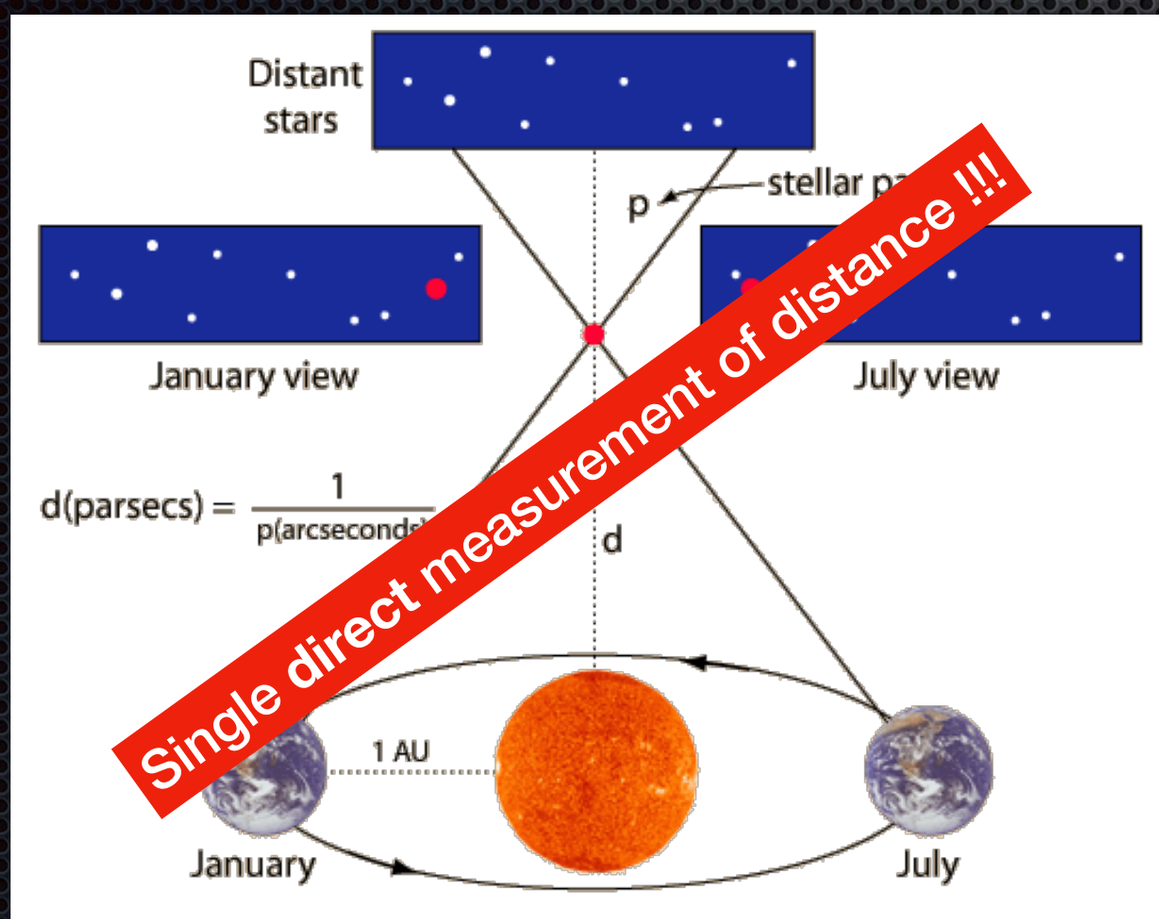


Distances


SHOOTING STAR
VENUS
SATURN
MERCURY
MT BROMO
MT BATOK
JUSTINNG
PHOTOGRAPHY

Distances

Parallax



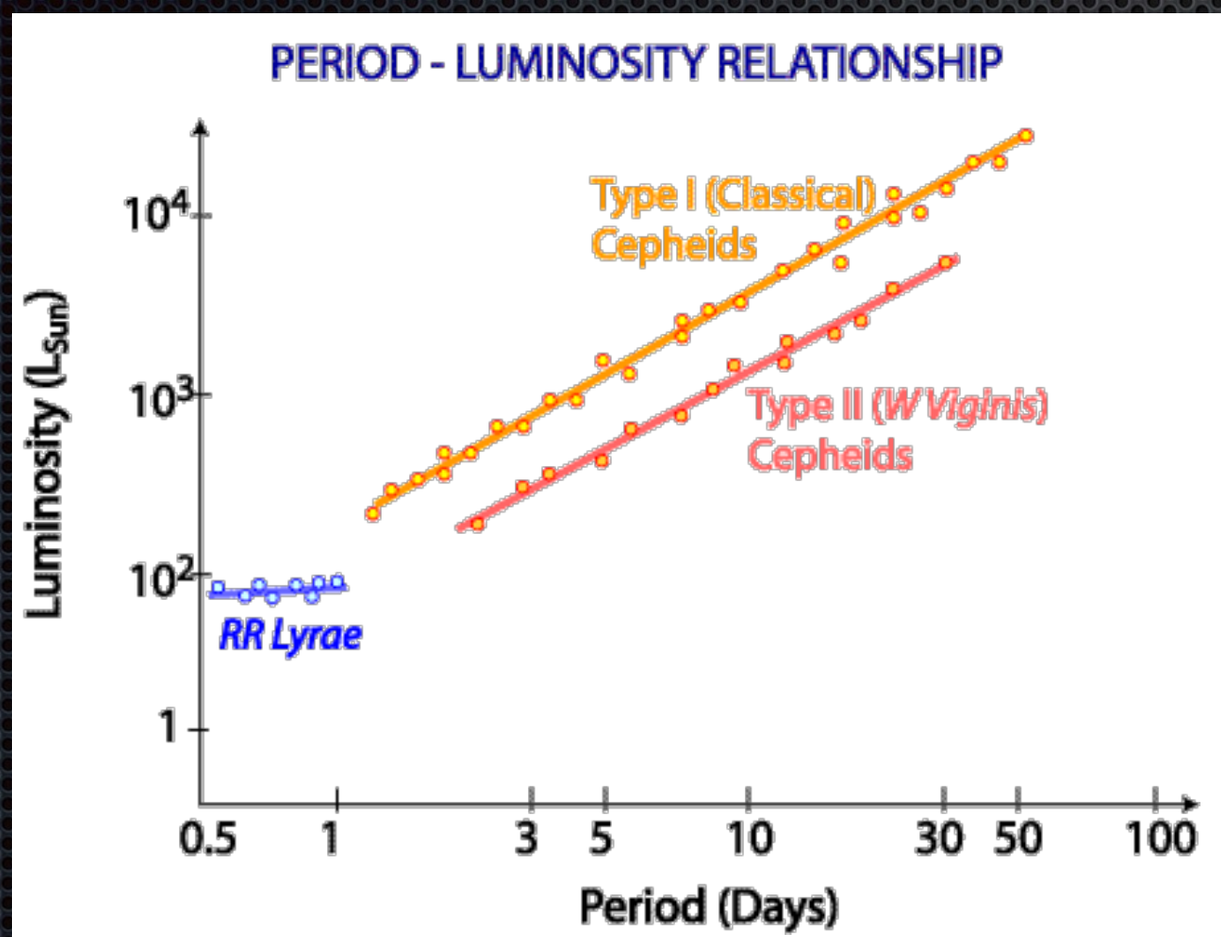
Up to 5000 light years
(inside our Galaxy!)

Standard candles

$$F = \frac{L}{4\pi d_L^2} \rightarrow d_L = \sqrt{\frac{L}{4\pi F}}$$

Distances

Variable stars



Neighbouring galaxies
Millions of light years

Standard candles

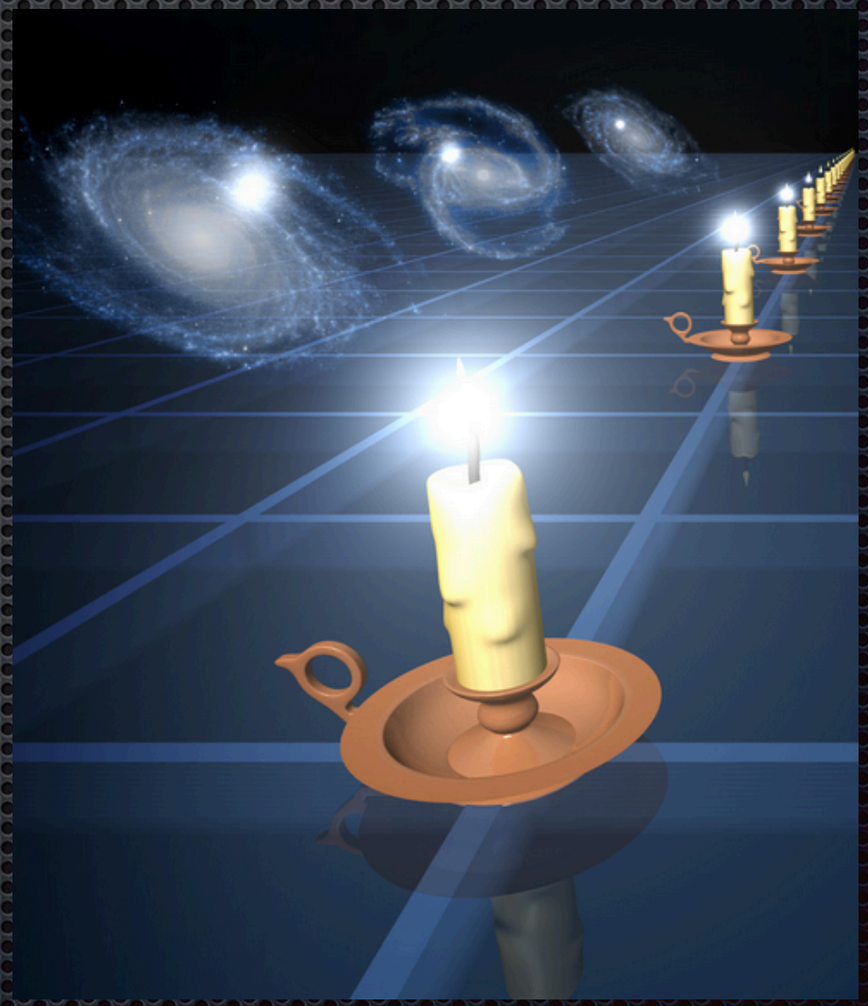
$$F = \frac{L}{4\pi d_L^2} \rightarrow d_L = \sqrt{\frac{L}{4\pi F}}$$

Distances

Supernovae Type Ia

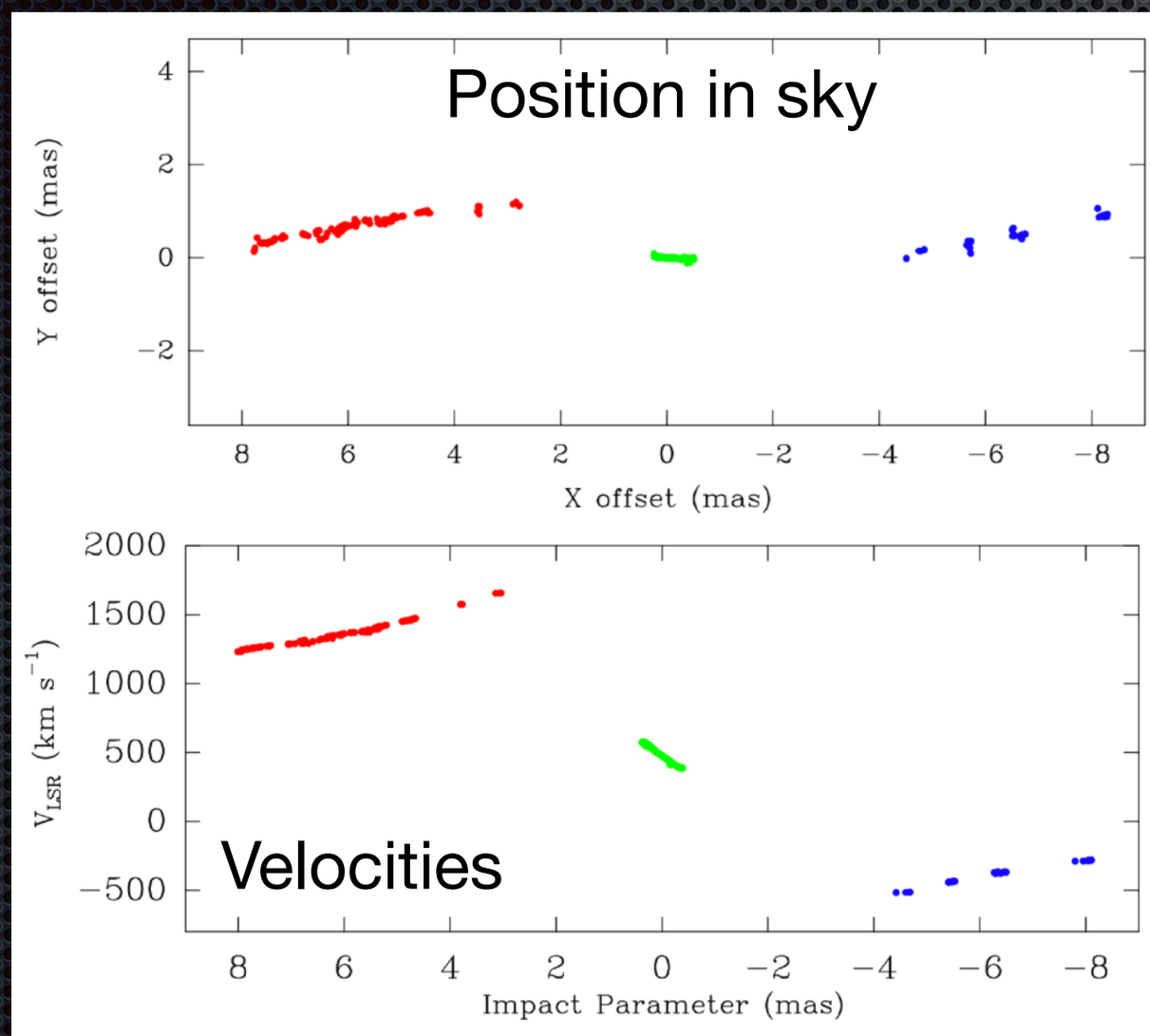
Far galaxies
Billions of light years

Standard candles



Distances

Distance to maser in NGC 4258



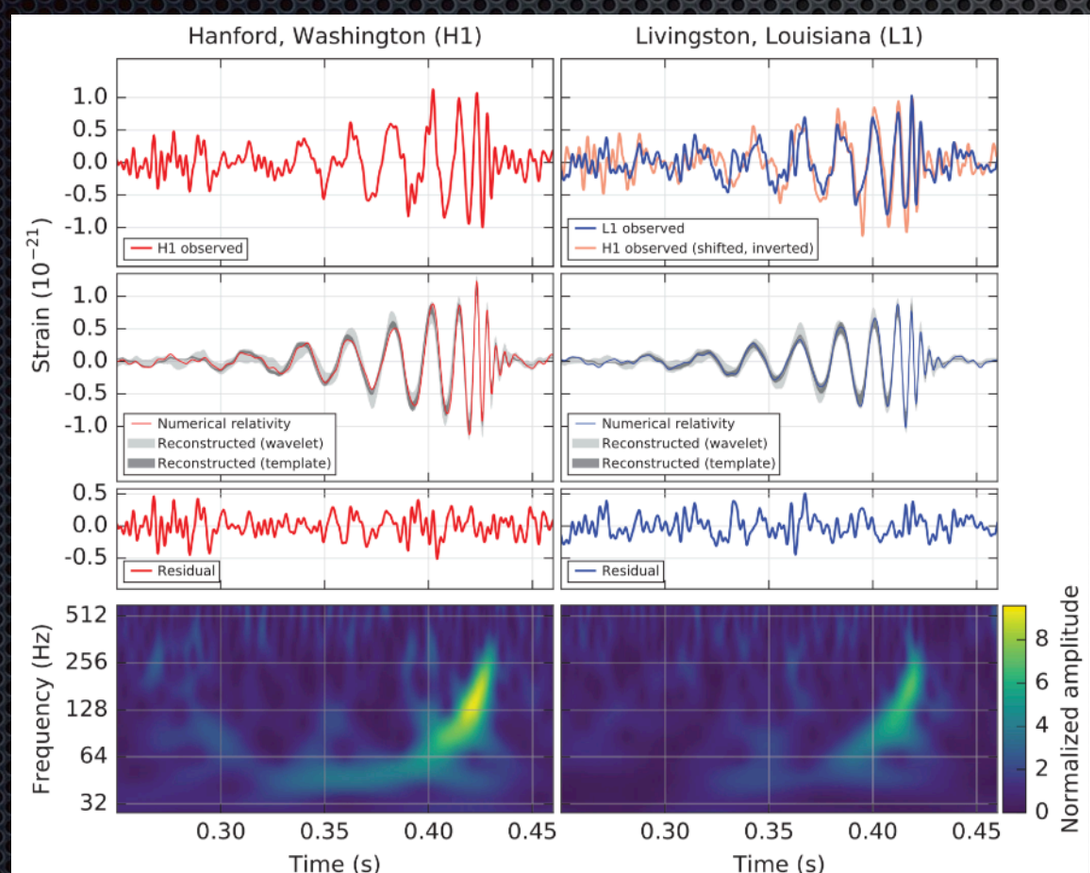
D = 7.60 ± 0.17 ± 0.15 Mpc

Hernstein et al. 1999, Humphreys et al. 2013

Distances

Distance to gravitational wave source

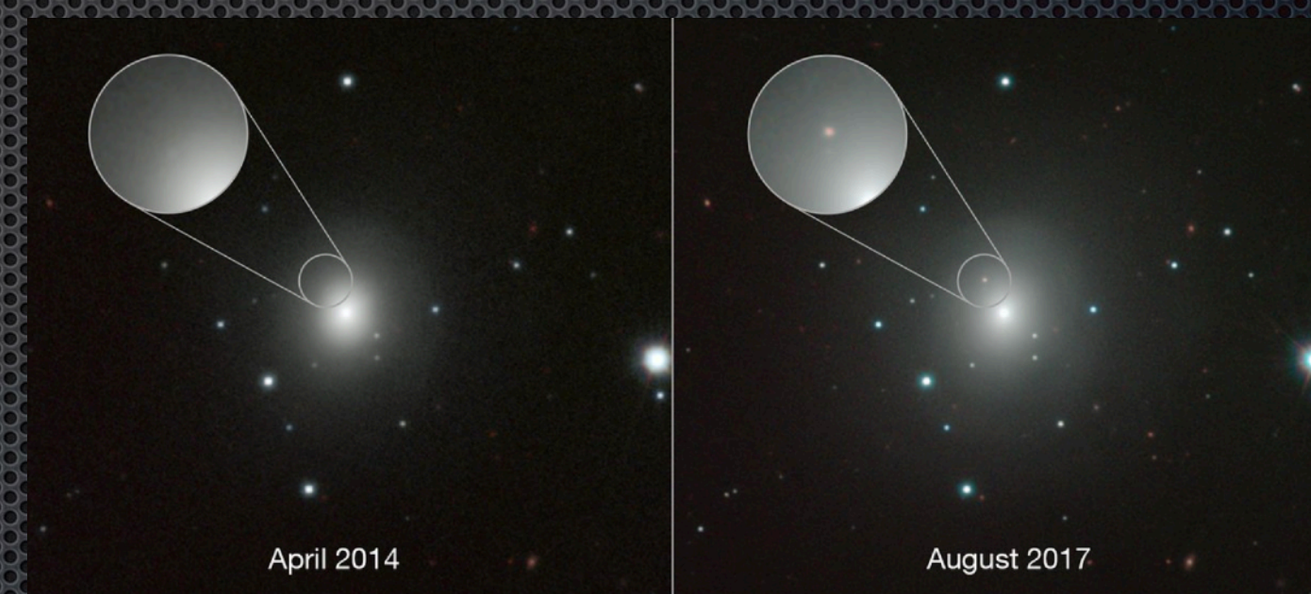
First detection!



D = 410 + (160) - (180) Mpc

LIGO and Virgo Collaboration 2015

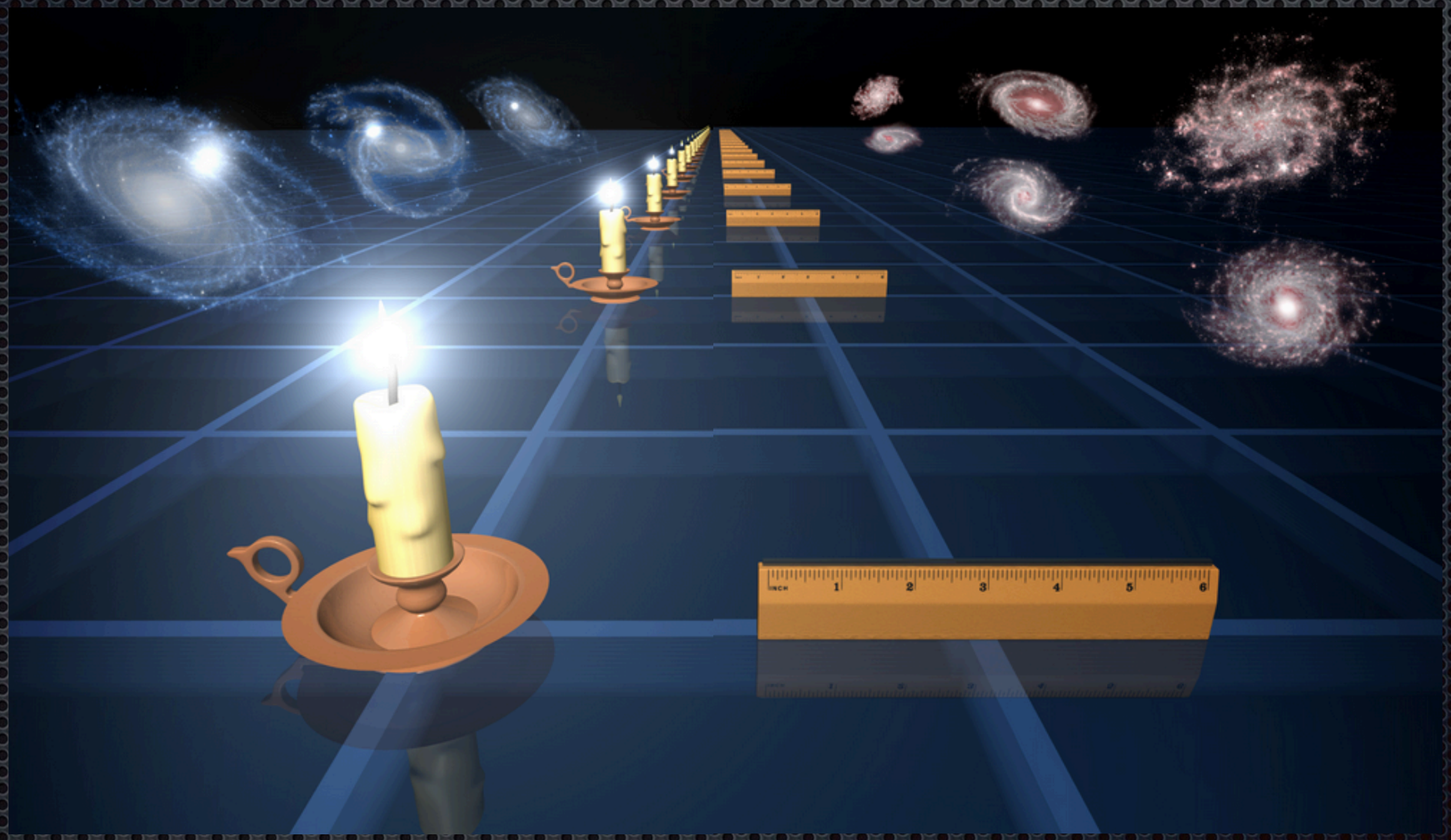
First detection with EM counterpart!!



D = 40 + (8) - (14) Mpc

LIGO and Virgo Collaboration 2017

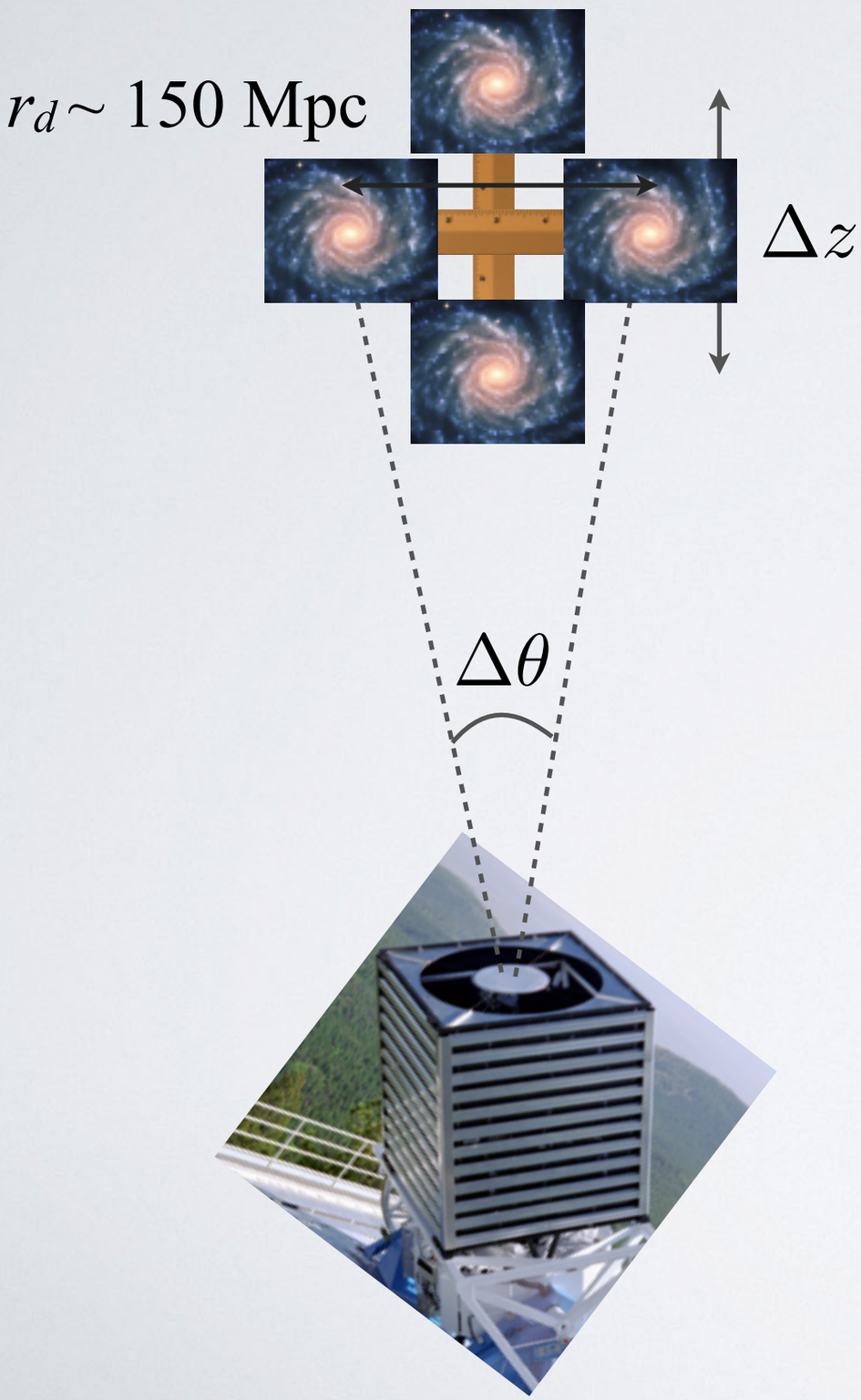
Distances



How about standard rulers?

BAO

Baryon Acoustic Oscillations



Geometry

$$\Delta\theta = \frac{r_d}{(1+z)D_A(z)} \quad \text{with} \quad D_A(z) \propto \int_0^z \frac{c\mathrm{d}z}{H(z)}$$

Hubble's law (in the past)

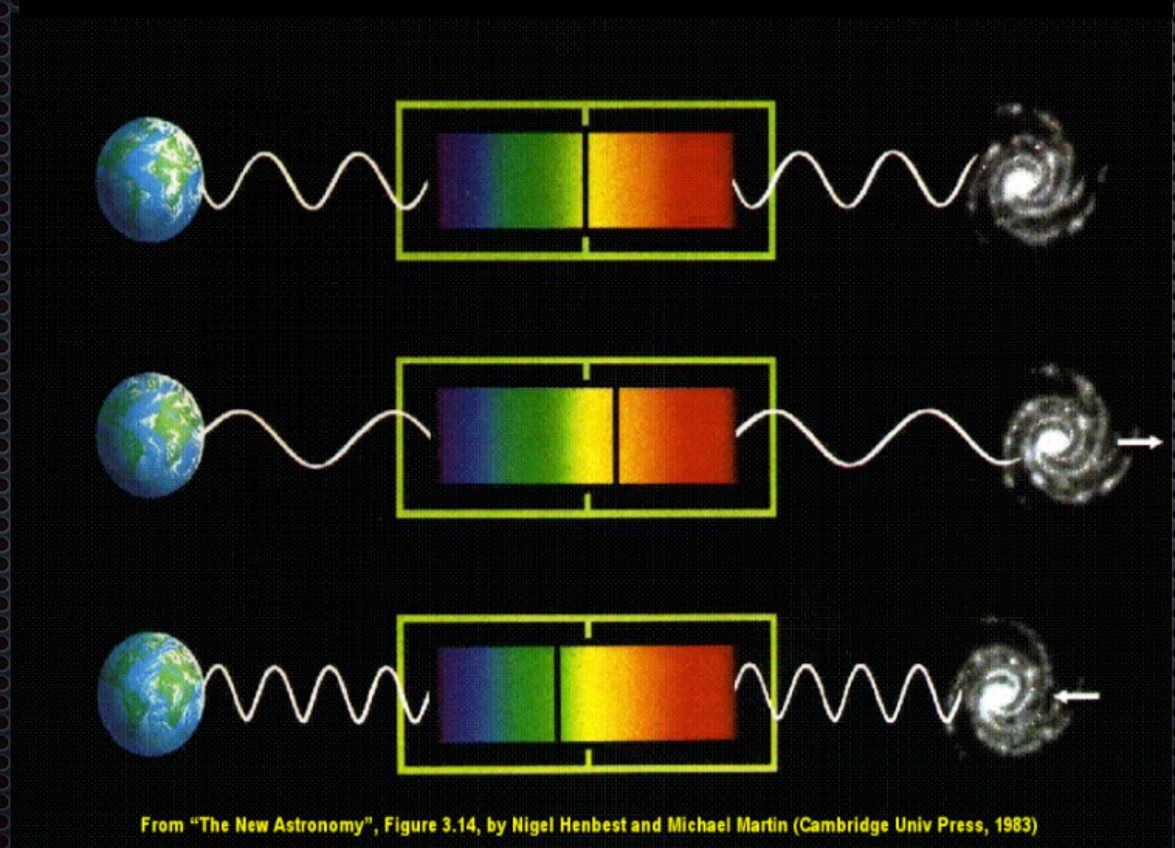
$$\Delta z = \frac{r_d}{(1+z)D_H(z)} \quad \text{with} \quad D_H(z) = \frac{c}{H(z)}$$

BAO gives few percent level distance and expansion rate measurements

Expansion of the Universe

Velocities

Spectroscopy

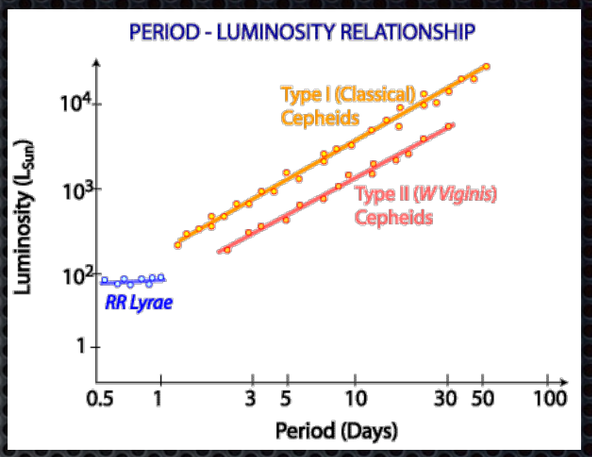


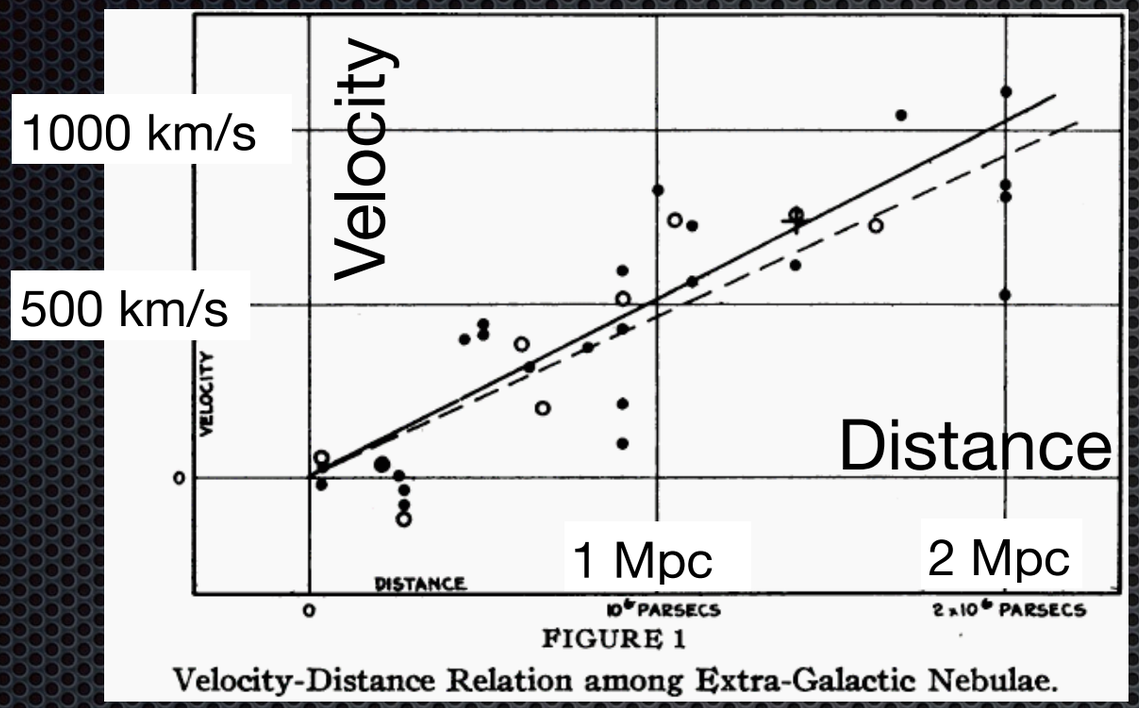
$$\frac{\lambda_{\mathrm{Obs}}}{\lambda_{\mathrm{Rest}}} = 1 + \frac{v}{c}$$

Redshift

Blueshift

Hubble's diagram



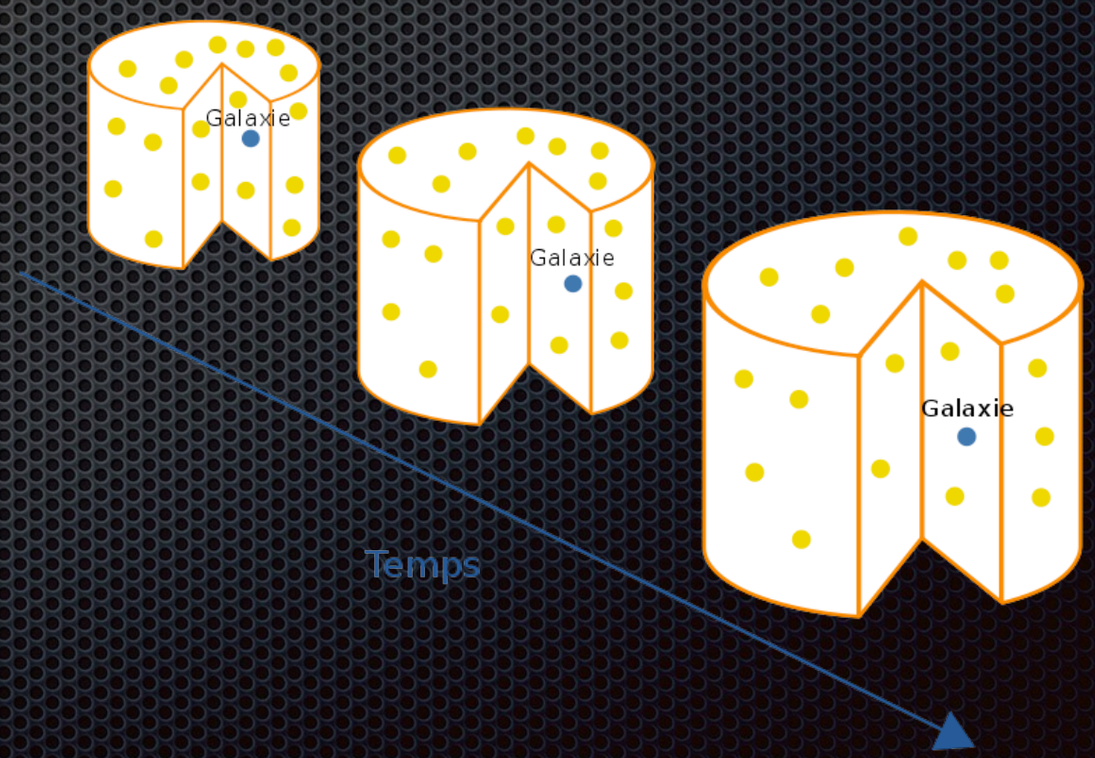


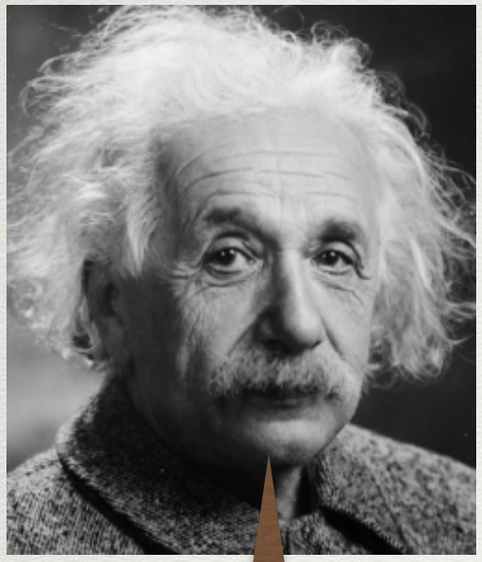
Hubble 1929

Hubble's law

$$v = H_0 \times D$$

Expanding Universe!





General Relativity

$$\Lambda g_{\mu\nu} + G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

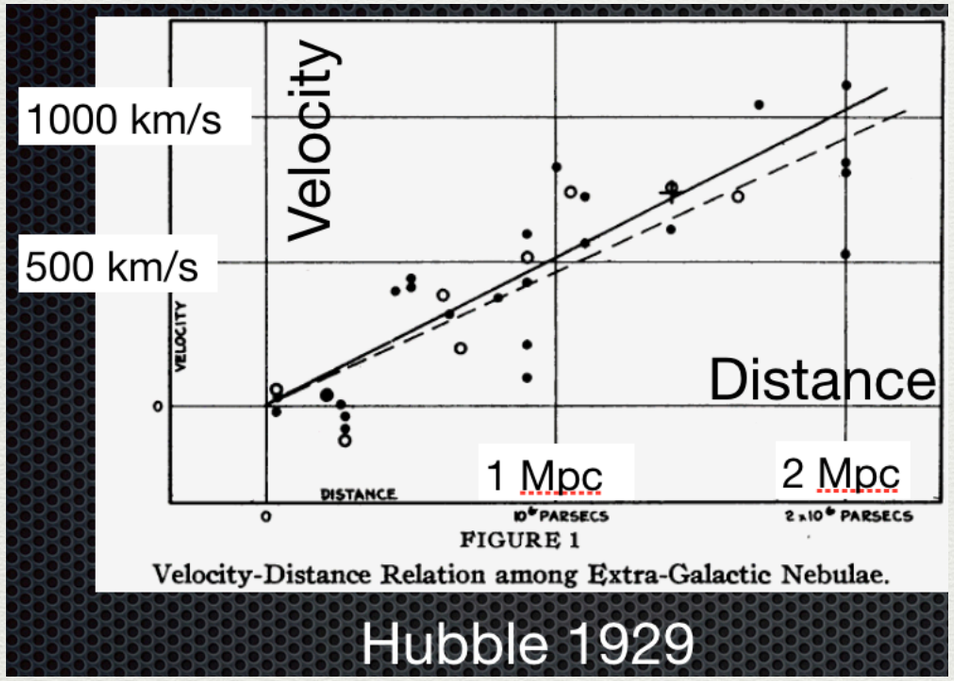
Space-time

Contents

The Universe is static!

Λ

= cosmological constant
= anti-gravity
= vacuum energy

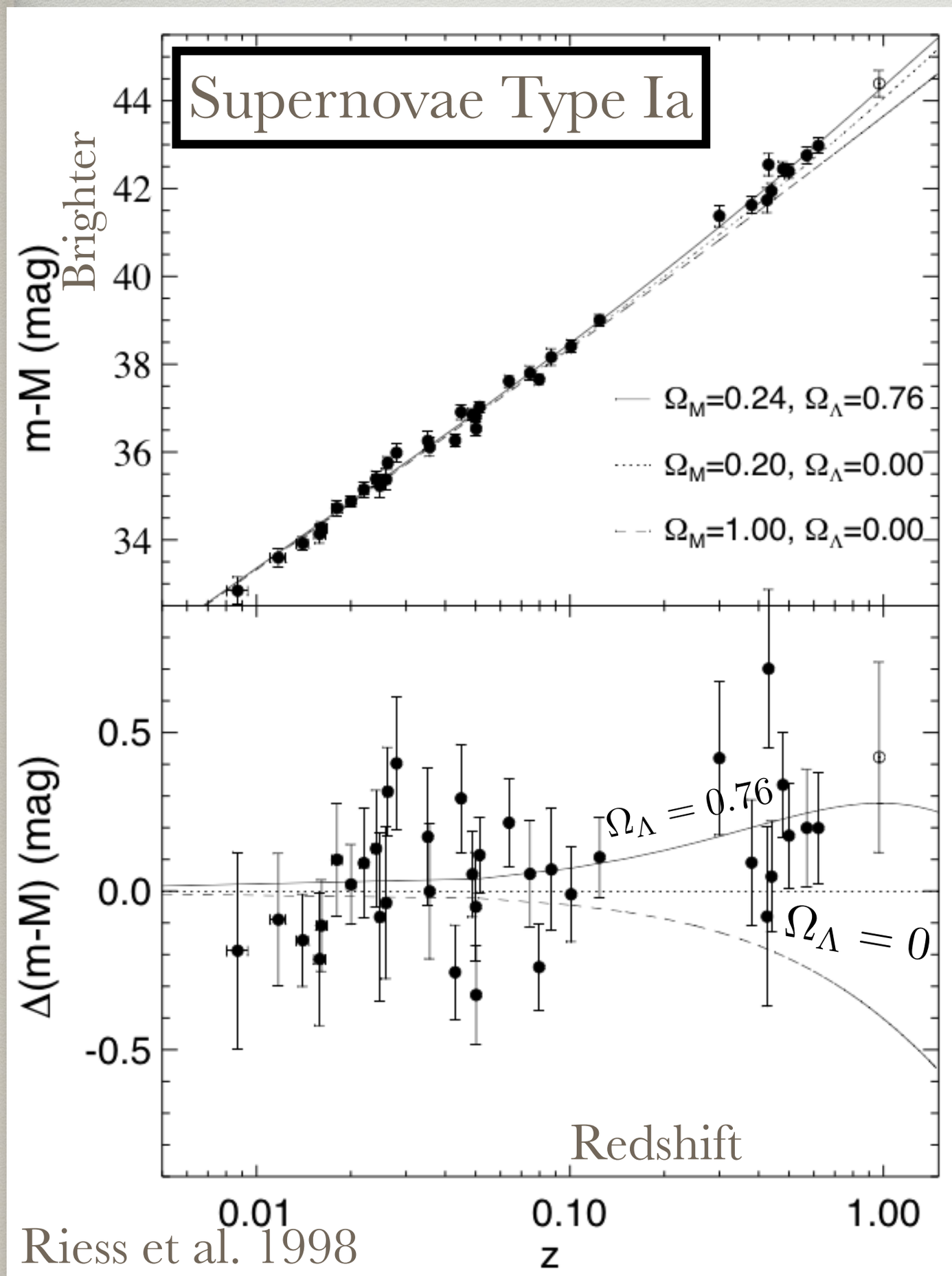


The Universe is expanding!

Edwin Hubble

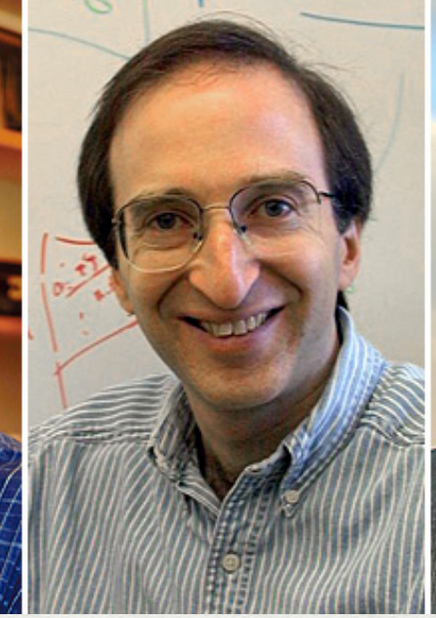
The cosmological constant is the biggest mistake of my life!

70 years later…



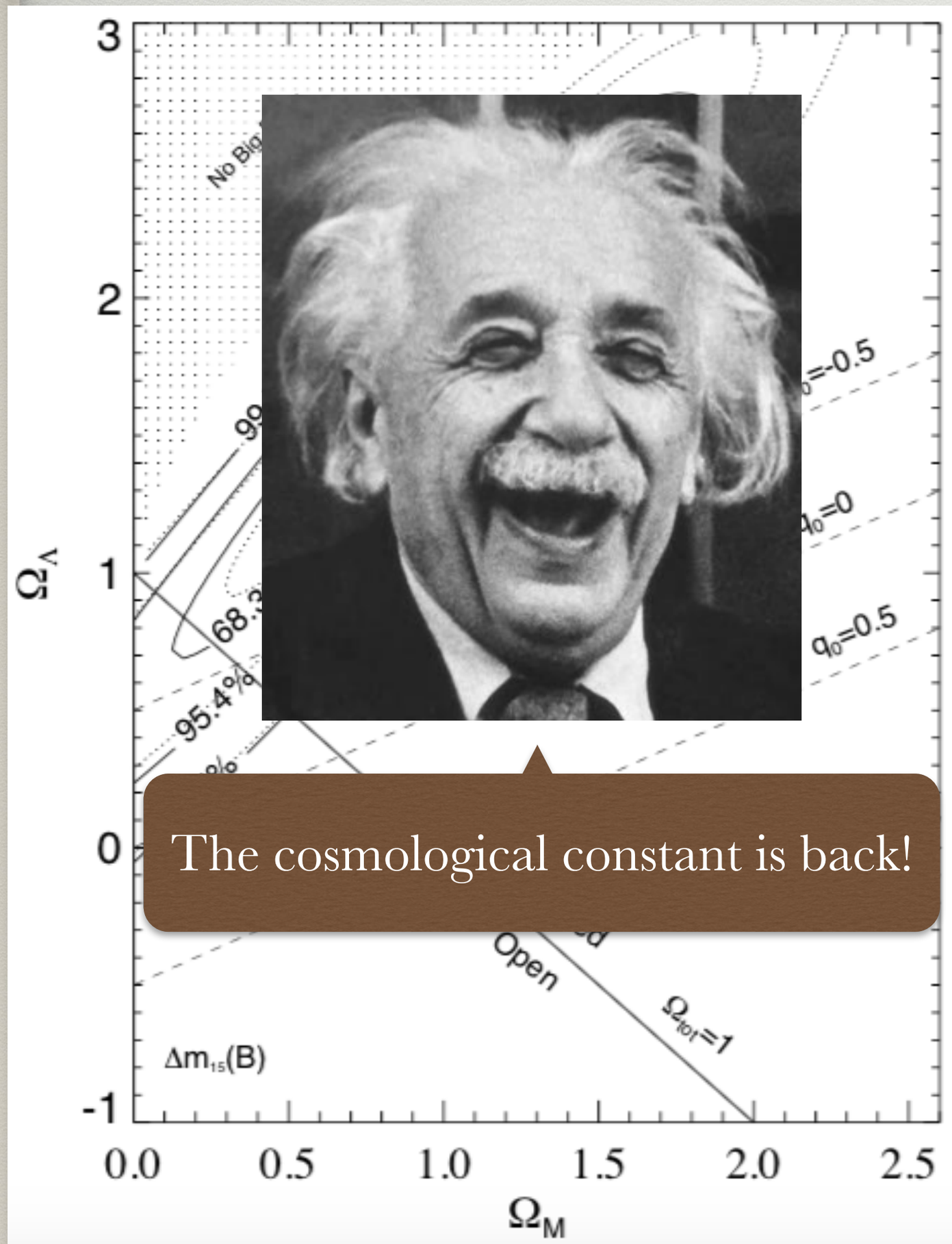
Riess et al. 1998

Riess



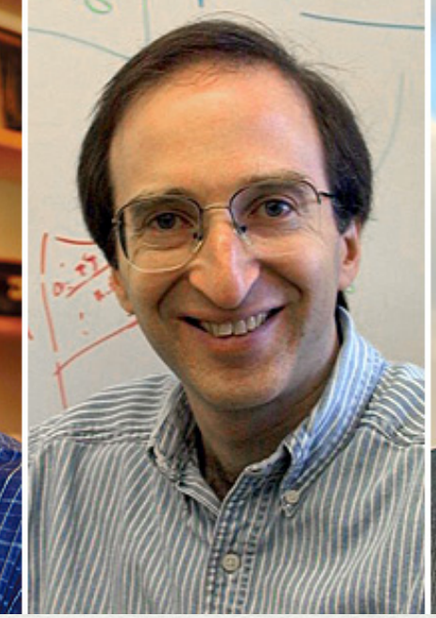
Perlmutter

Accelerated expansion!
We need the cosmological constant!



The cosmological constant is back!

Riess



Perlmutter

Accelerated expansion!
We need the cosmological constant!

2011

… and the quest
for dark energy
begins!

Observables of the expansion

$H(z)$, $D(z)$, $f(z)$, …

Observables of the expansion

- Expansion rate: $H(t) \equiv \frac{\dot{a}(t)}{a(t)}$ $\qquad t \to z \qquad$ (redshift)

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_{DE} f(z) + \Omega_k (1+z)^2 + \Omega_r (1+z)^4\right]$$

Today

Dark + baryonic matter density

Dark energy

Curvature

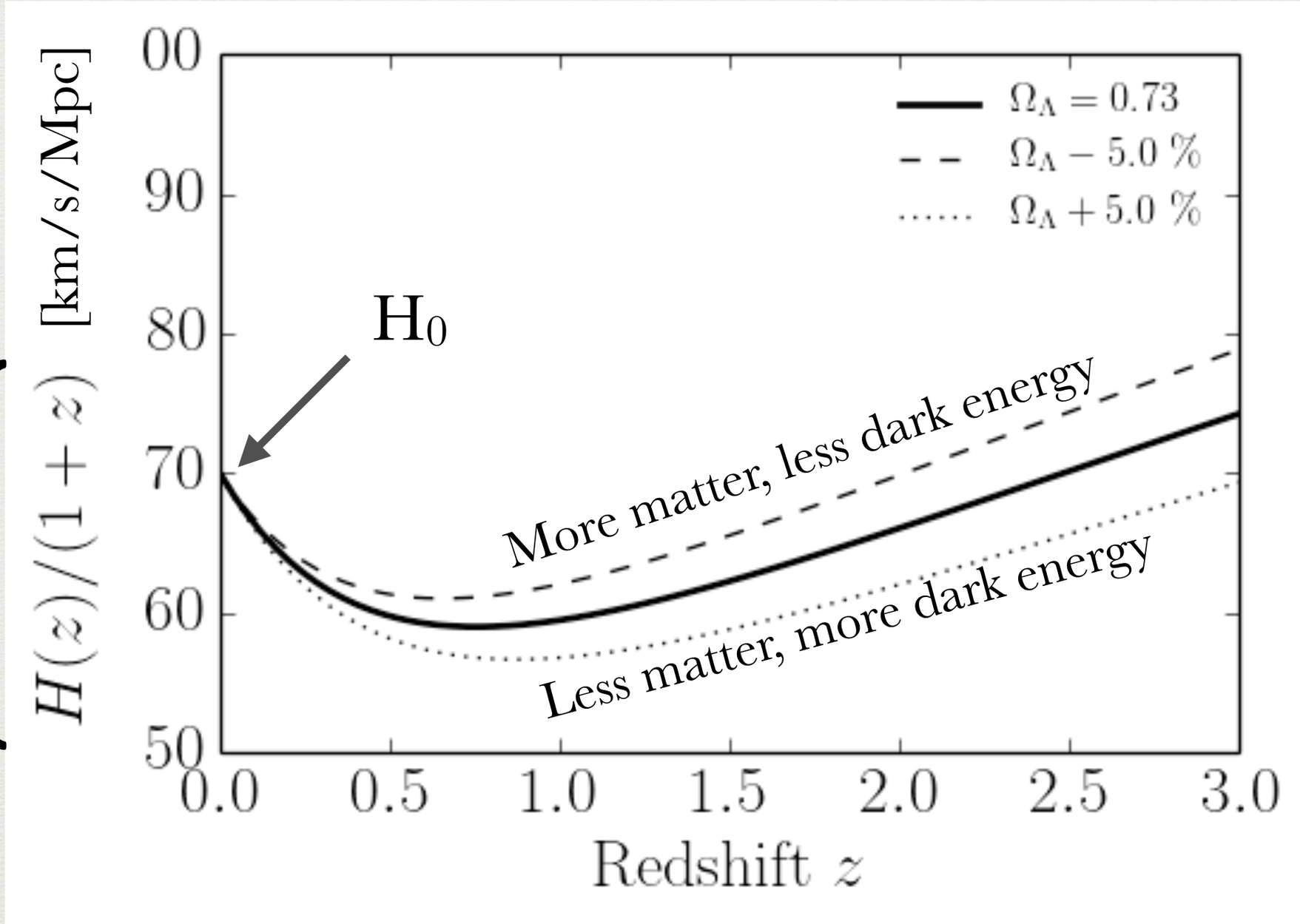
Radiation

- Distances: $$D_A(z) = \frac{c}{(1+z)} \int_0^z \frac{\mathrm{d}z'}{H(z')}$$

- Rate of structure growth: $$f(z) \equiv -\frac{d \ln G}{d \ln (1+z)} \approx \left[\Omega_{\mathrm{m}} (1+z)^3 \frac{H_0^2}{H^2(z)}\right]^{\gamma}$$

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]$$

$$\dot{a}(t) = \left\{ H(z)/(1+z) \right.$$

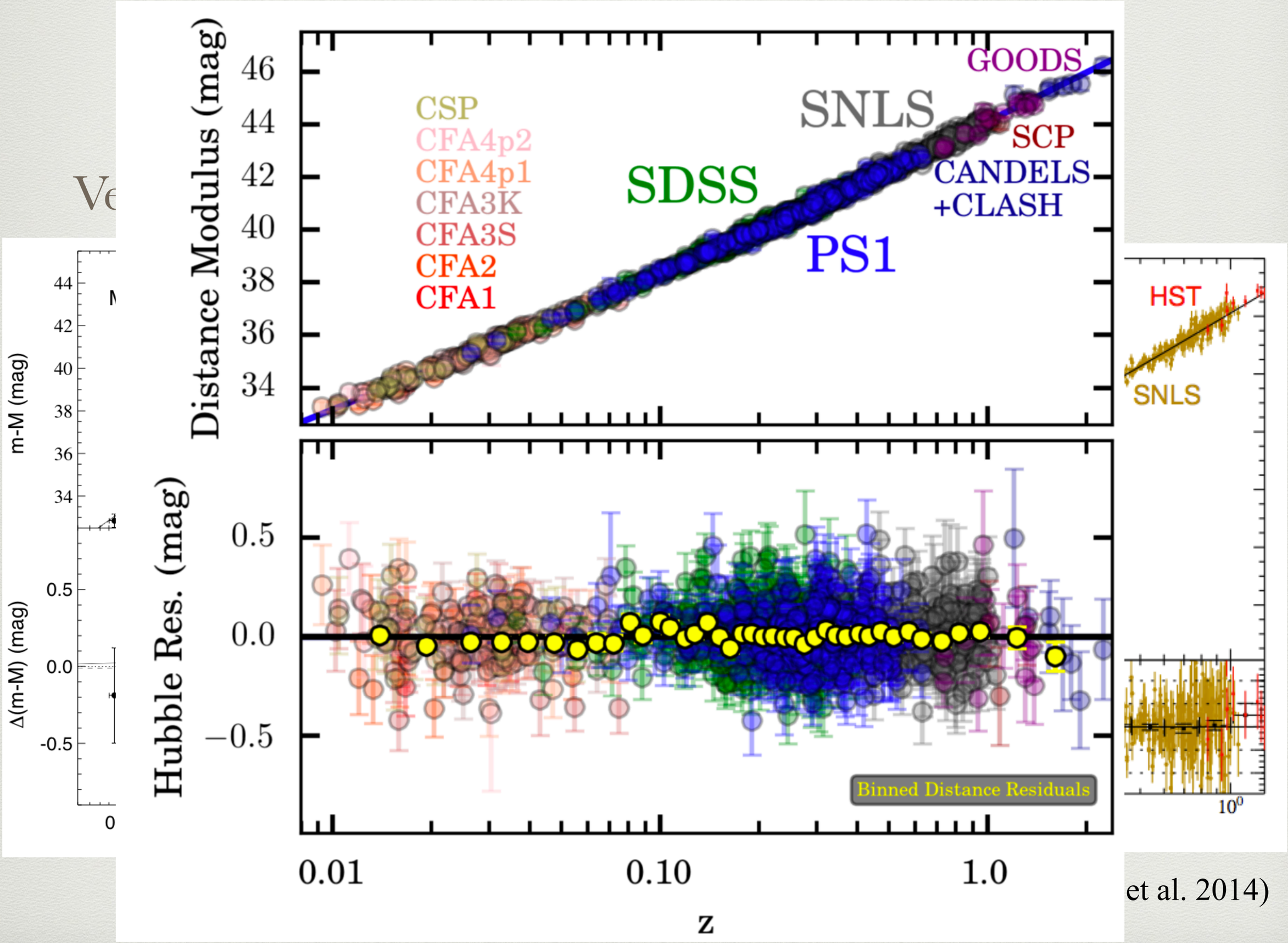


Measuring the H(z) or D(z) or f(z) at many redshifts gives us constraints on the components of the Universe

Current constraints

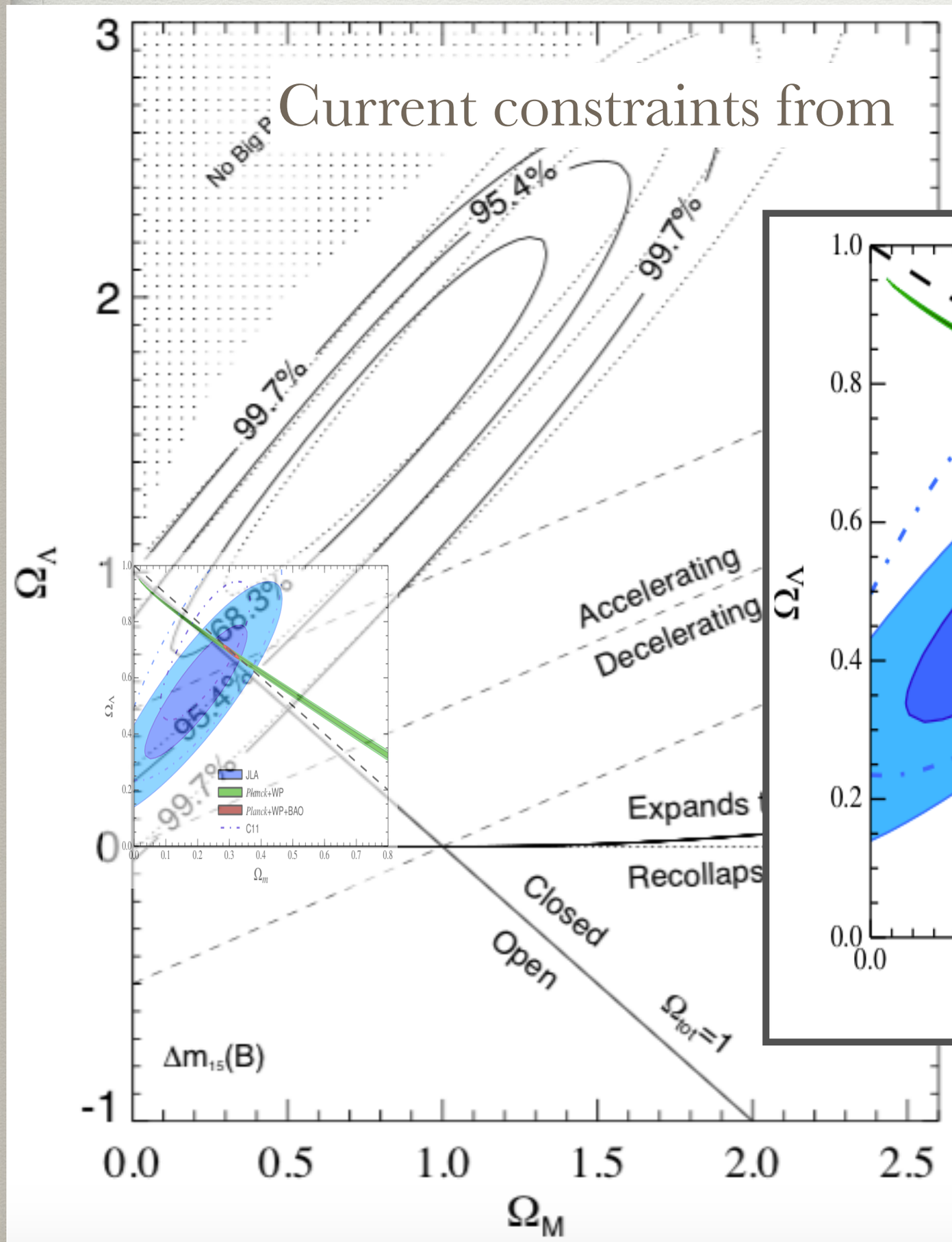
SNe, CMB, BAO, etc…

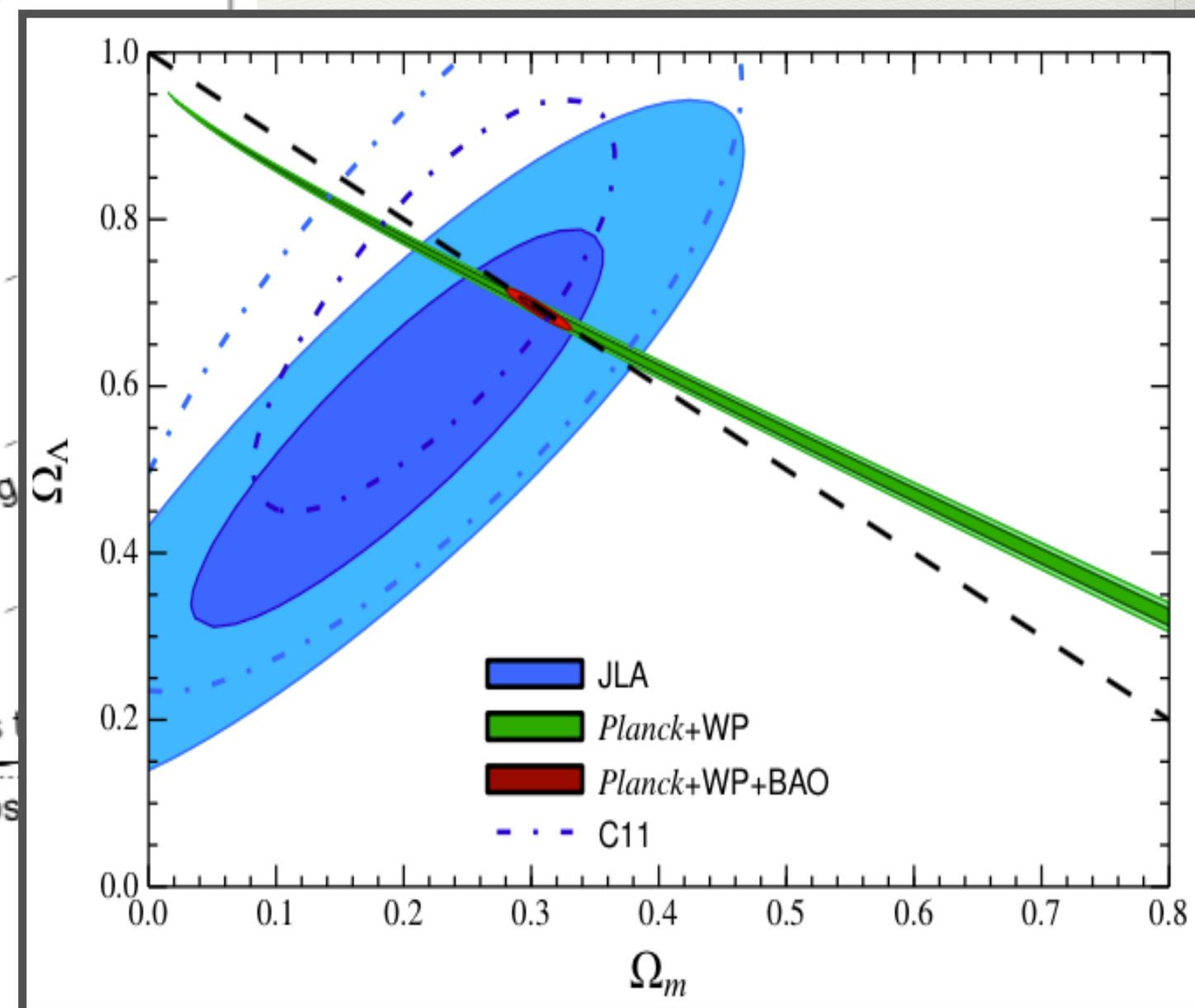
Version of 2017: Pantheon (Scolnic et al. 2017)



et al. 2014)

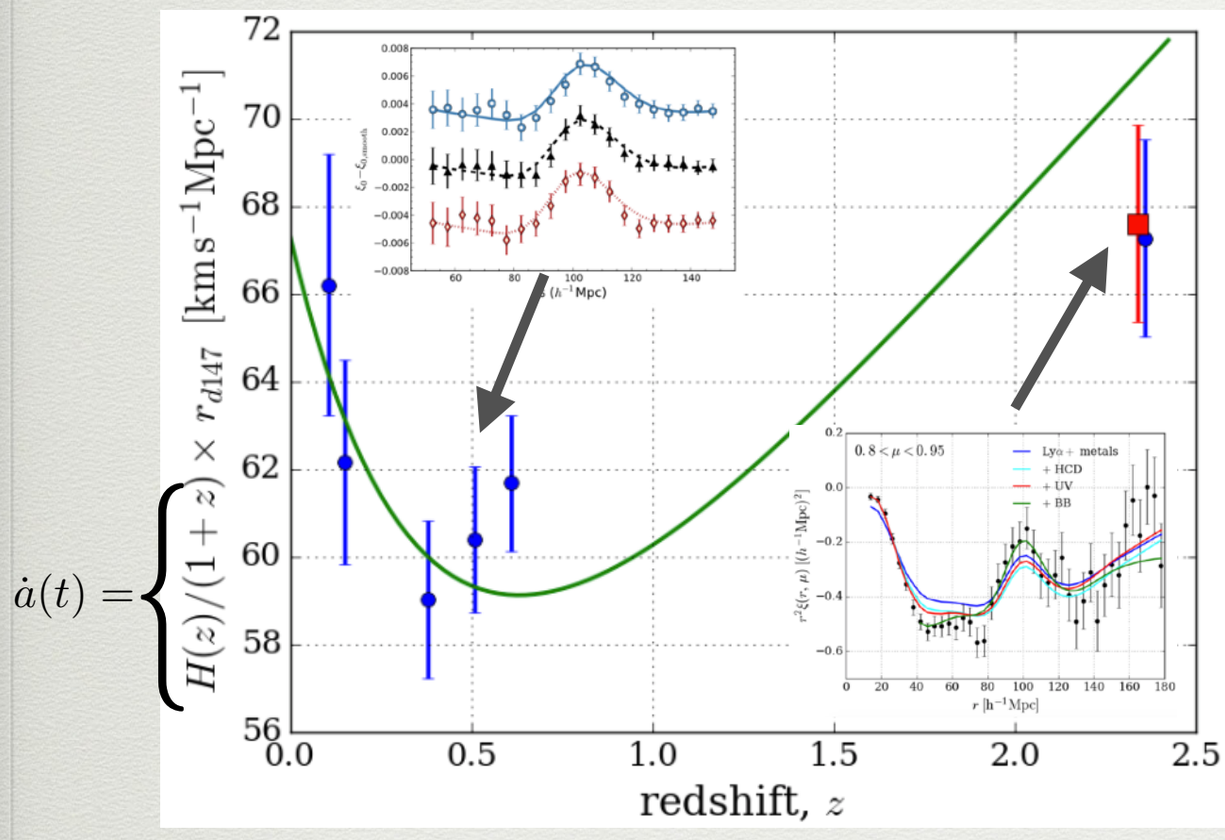
Current constraints from Supernovae

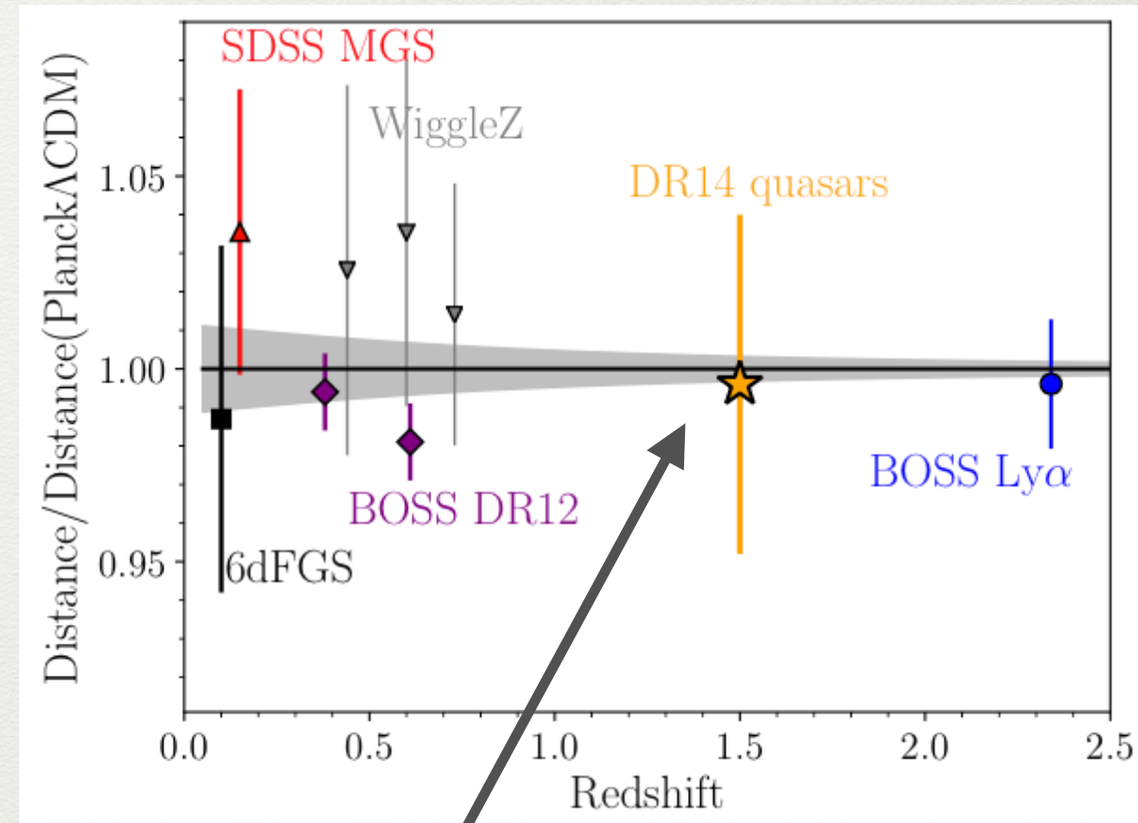




(Betoule++2014)

Current constraints from BAO in the distribution of matter

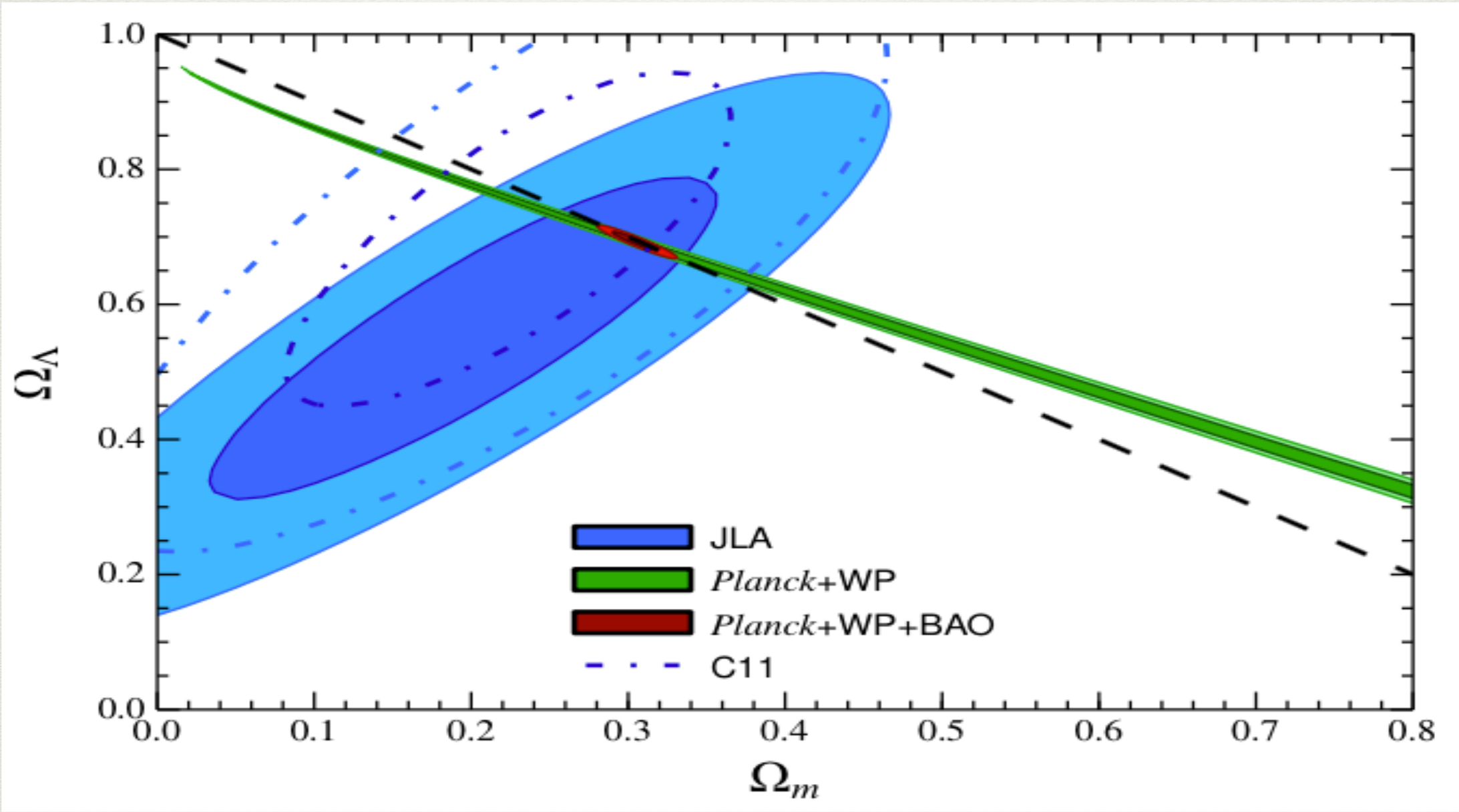




BOSS
- z = 0.11 (Beutler et al. 2011)
- z = 0.15 (Ross et al. 2015)
- z = 0.35 - 0.65 (Alam et al. 2016)
- z = 2.33 (Bautista et al. 2017)
- z = 2.34 (Font-Ribera et al. 2014)

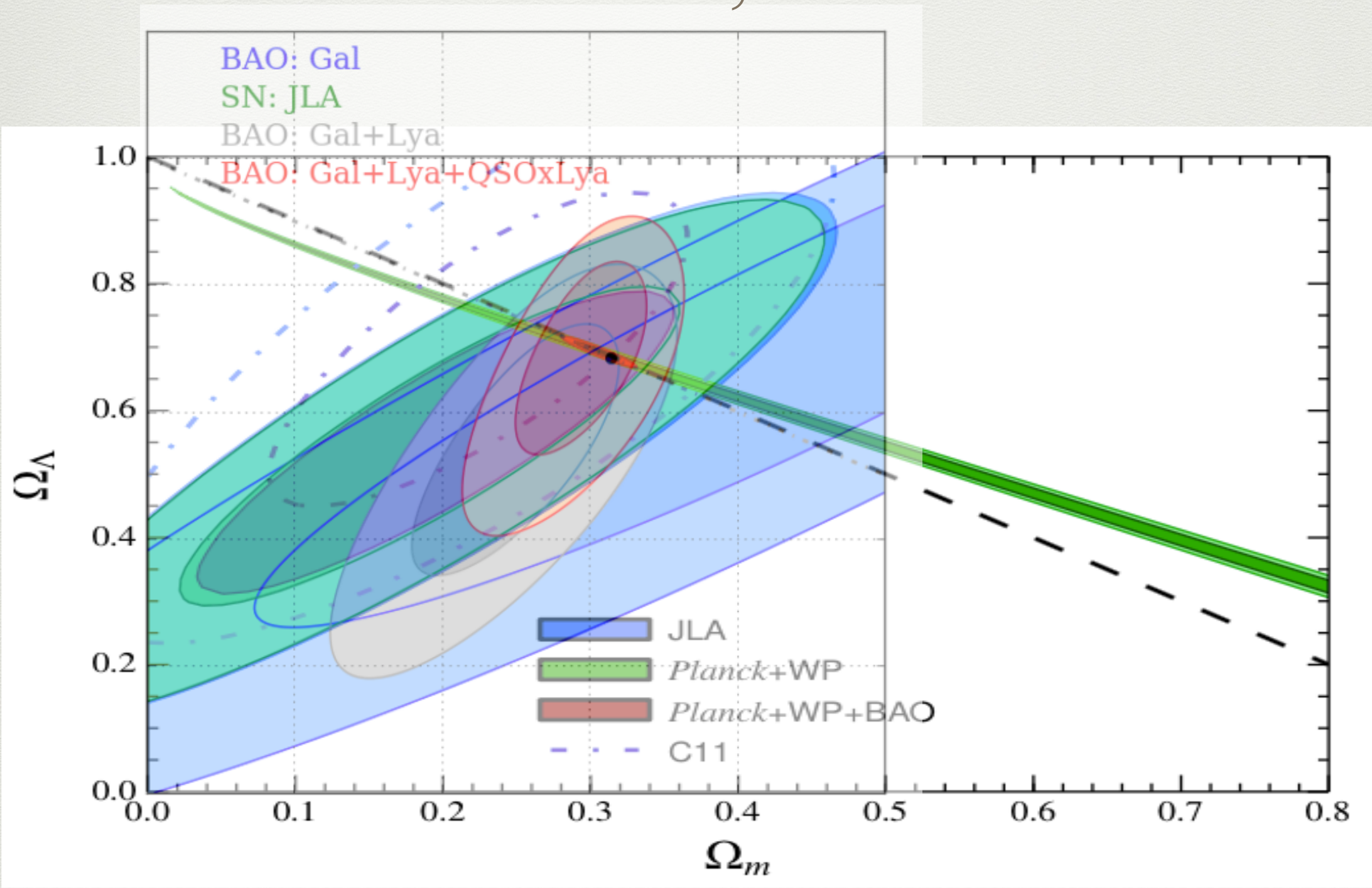
First eBOSS BAO measurement (Ata et al. 2017)

Current constraints from SNe, CMB and BAO

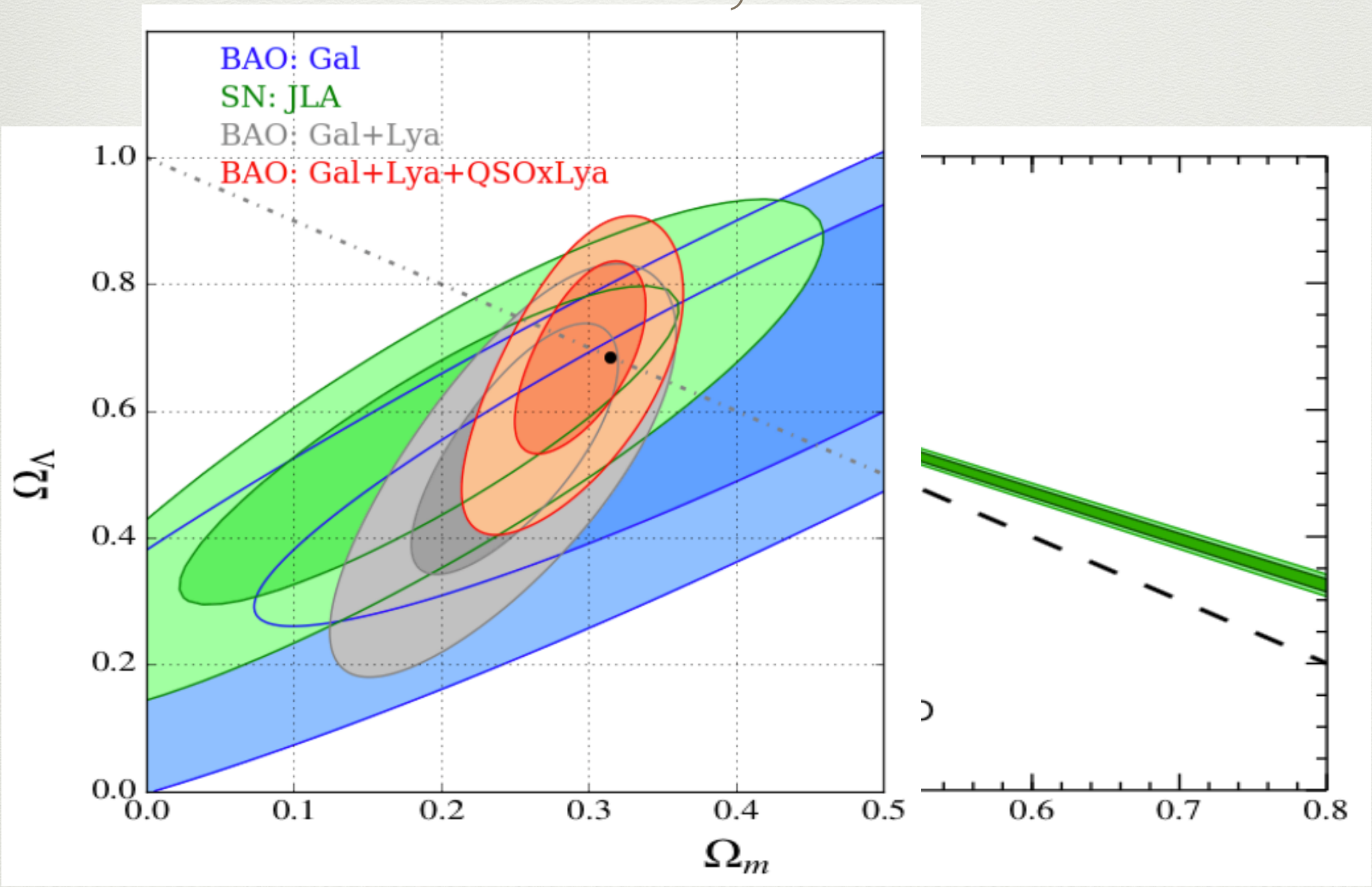


(Betoule et al. 2014)

Current constraints from SNe, CMB and BAO



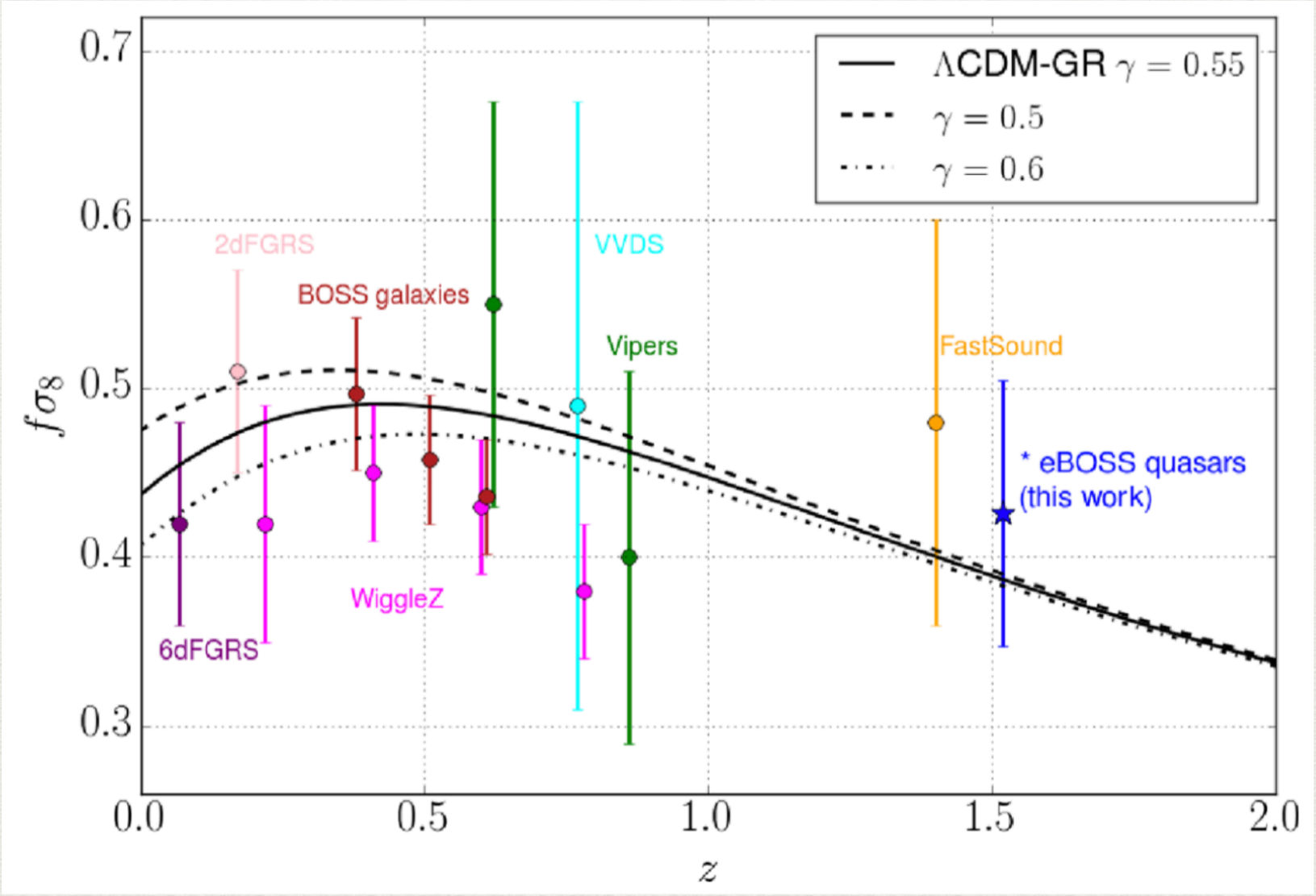
Current constraints from SNe, CMB and BAO



(Bautista et al. 2017)

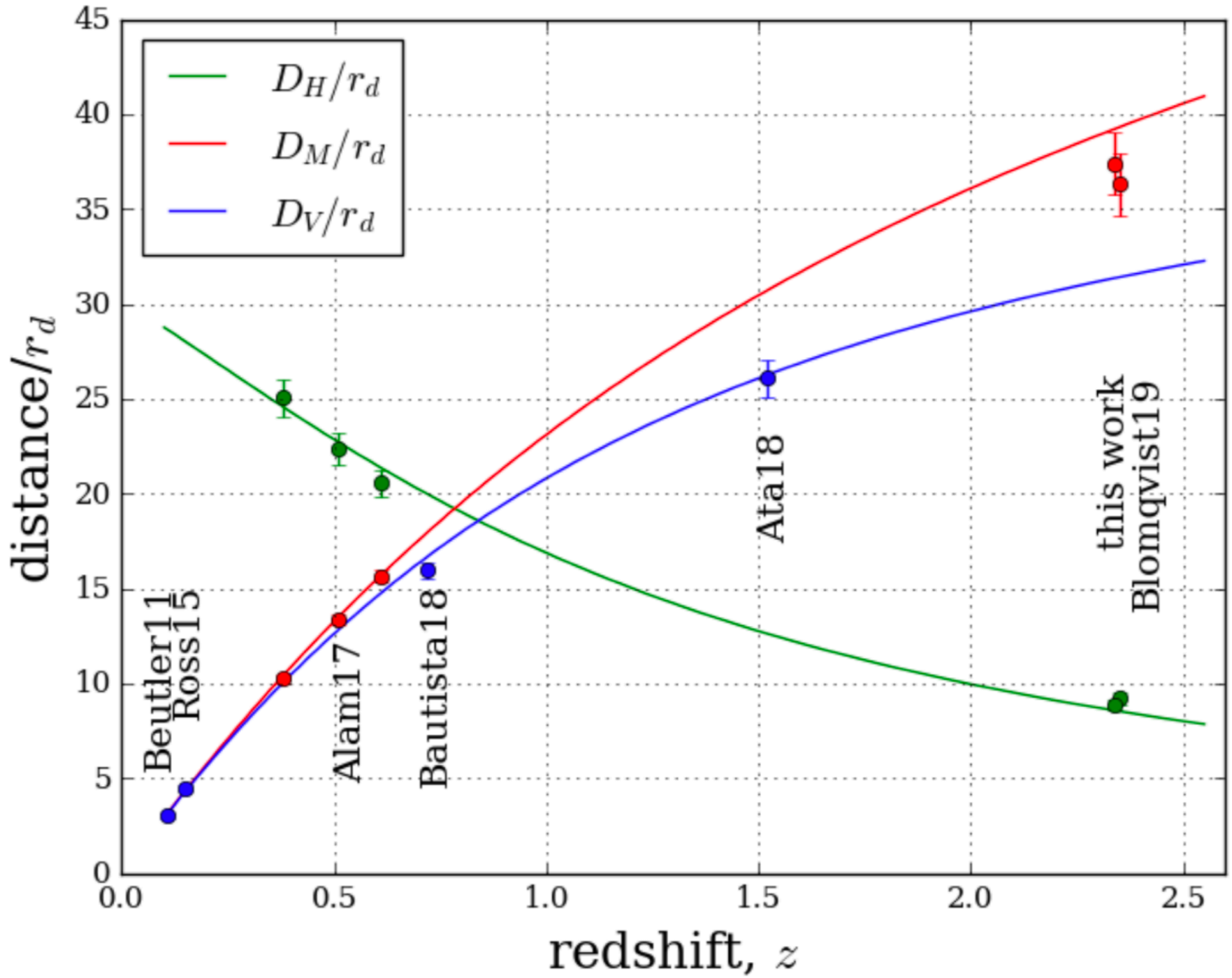
Current constraints from Growth of structures

$$f(z) \equiv -\frac{d\ln G}{d\ln(1+z)} \approx \left[\Omega_{\rm m}(1+z)^3 \frac{H_0^2}{H^2(z)}\right]^{\gamma}$$



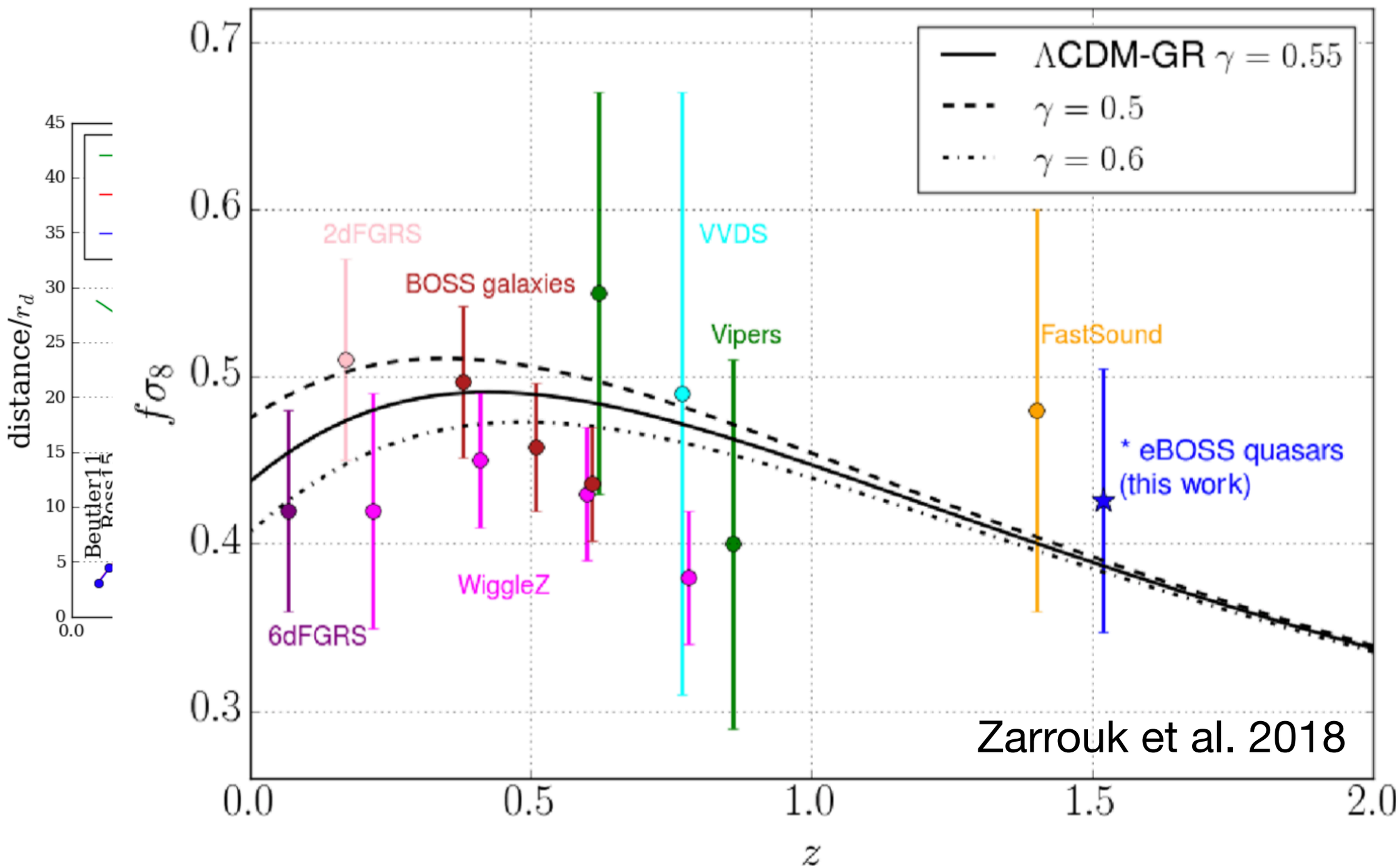
Zarrouk et al 2017

The current observational picture of the expansion of the Universe



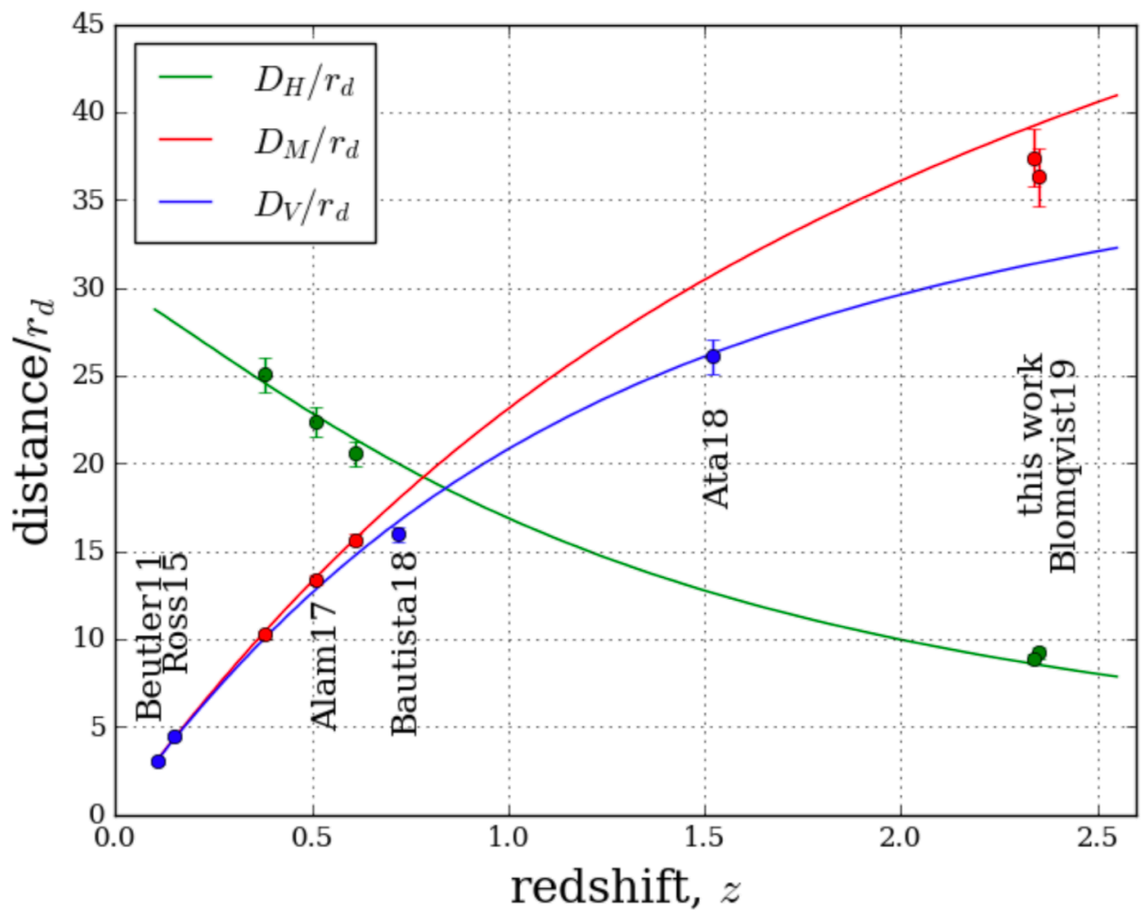
de Sainte Agathe et al 2019
Blomqvist et al. 2019

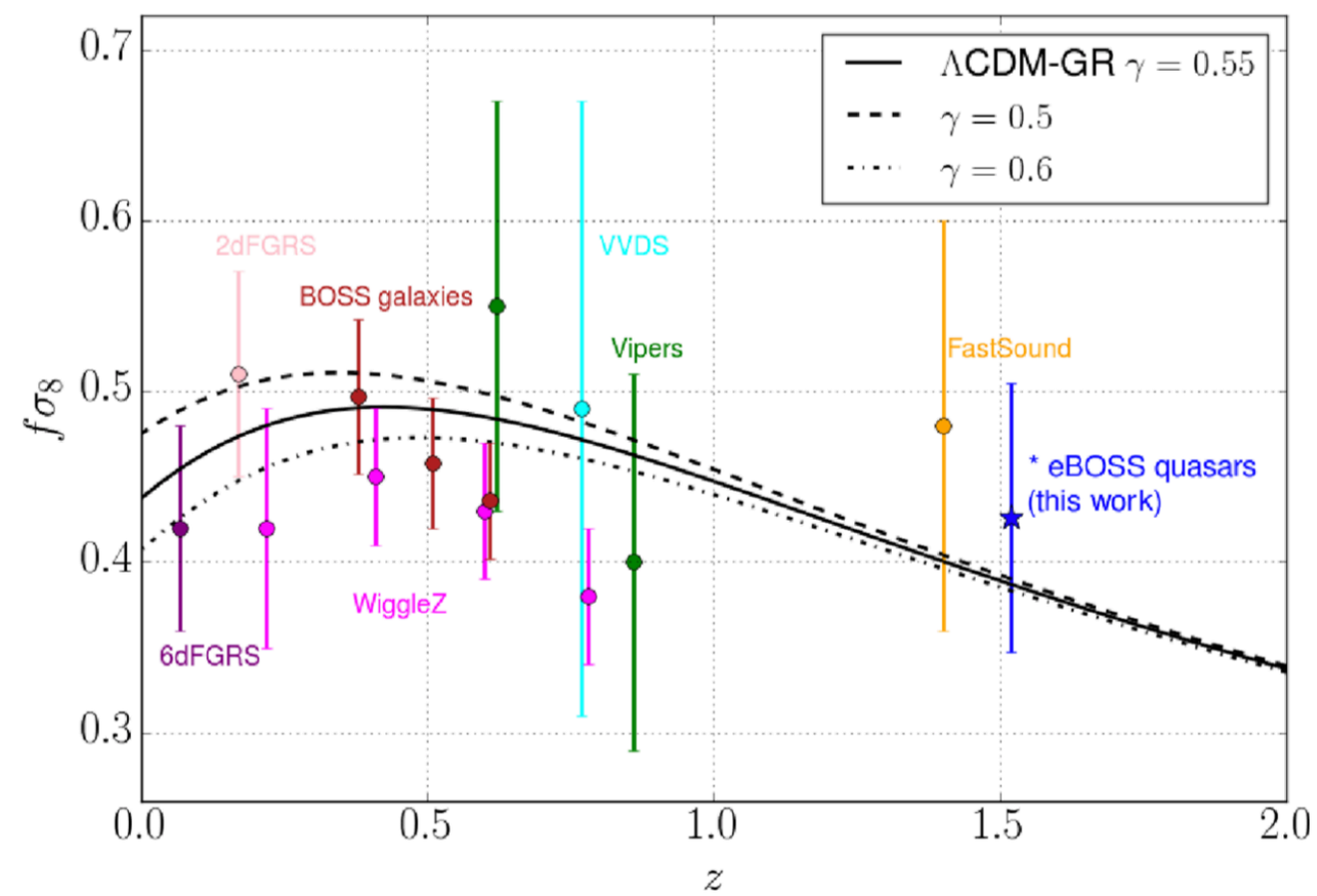
The current observational picture of the expansion of the Universe



Zarrouk et al. 2018

The current observational picture of the expansion of the Universe



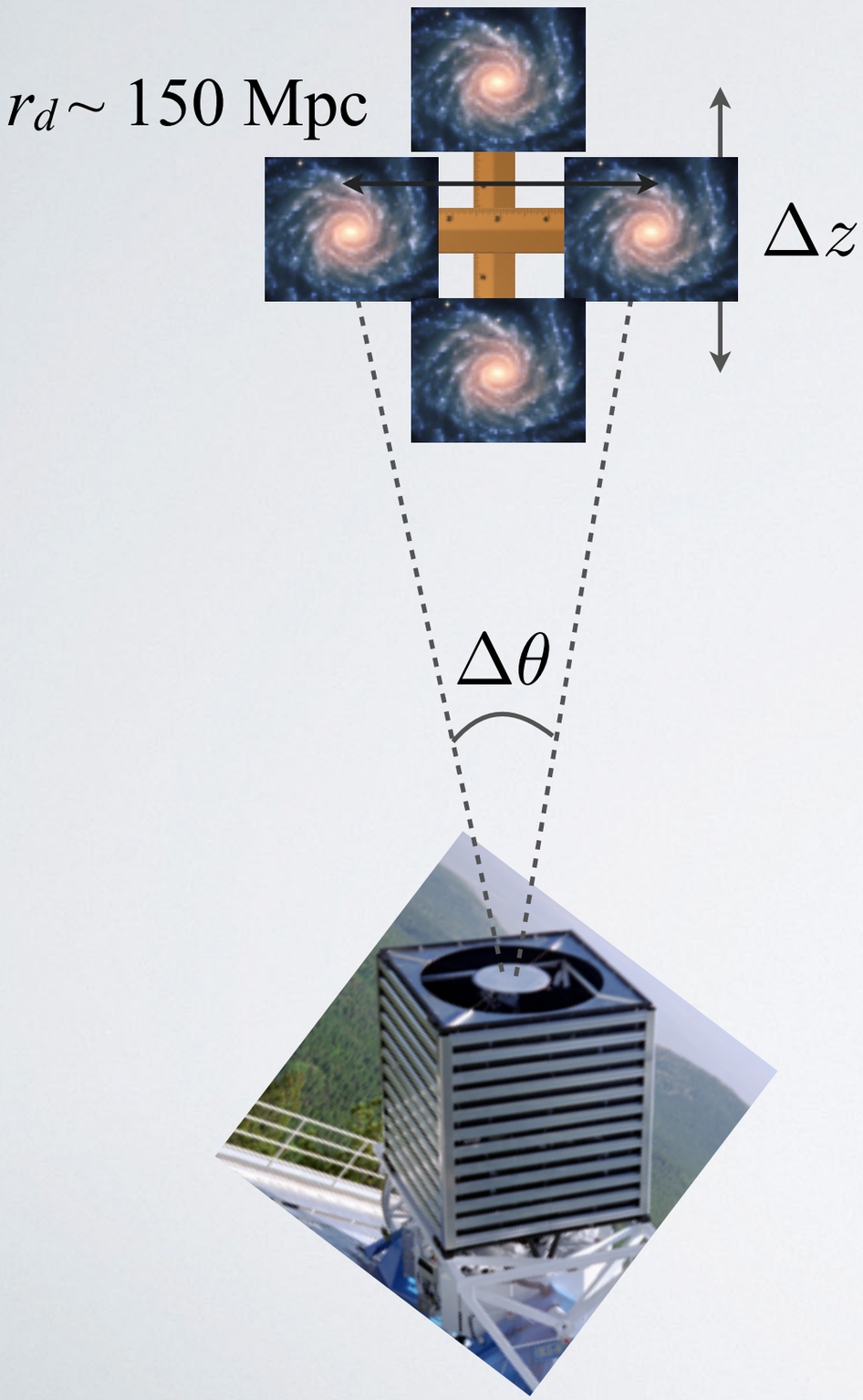


We need more data
to understand dark-energy !!

Baryon Acoustic Oscillations

BAO

Baryon Acoustic Oscillations



Geometry

$$\Delta\theta = \frac{r_d}{(1+z)D_A(z)} \quad \text{with} \quad D_A(z) \propto \int_0^z \frac{c\mathrm{d}z}{H(z)}$$

Hubble's law (in the past)

$$\Delta z = \frac{r_d}{(1+z)D_H(z)} \quad \text{with} \quad D_H(z) = \frac{c}{H(z)}$$

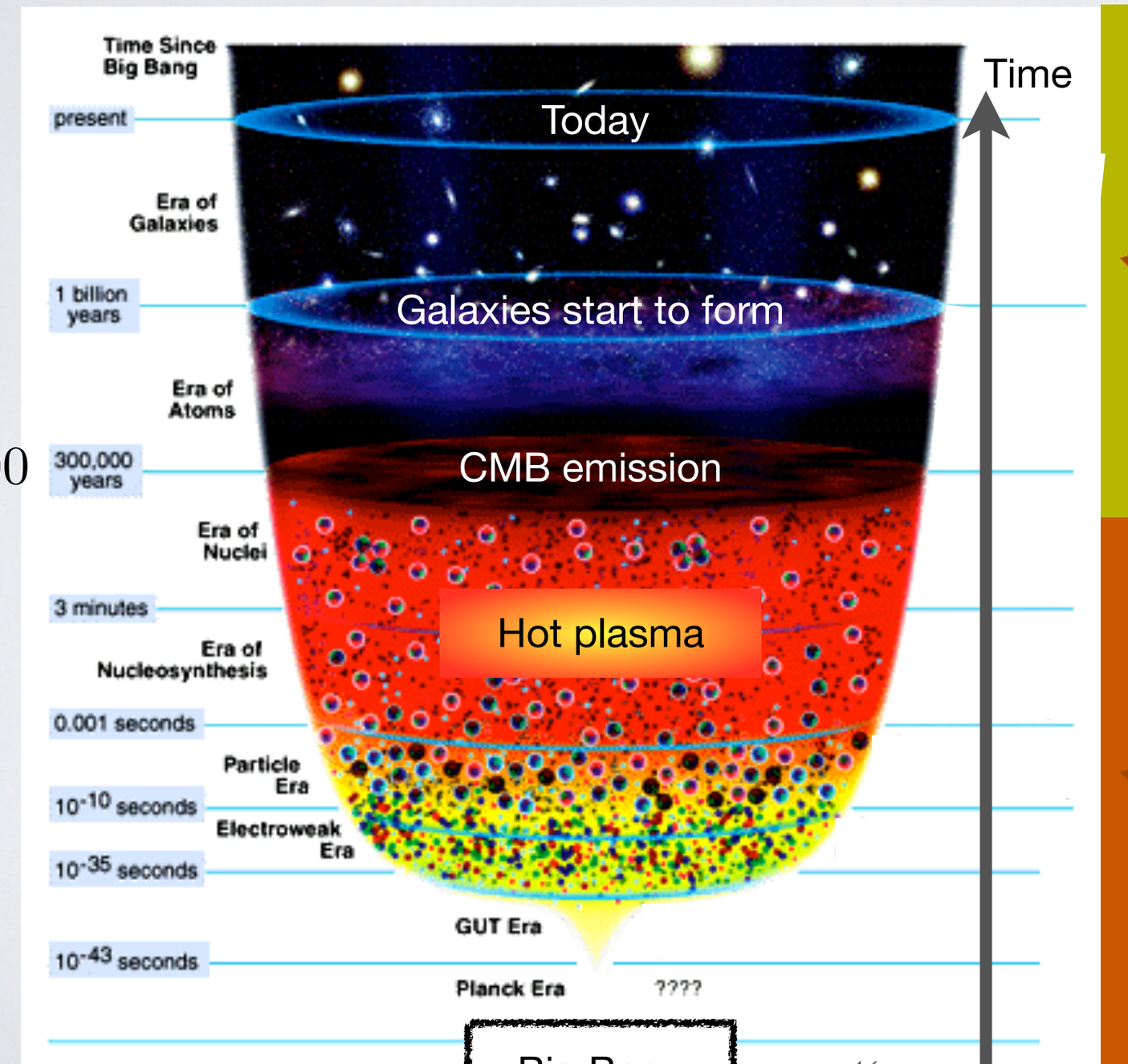
What is this standard ruler ?

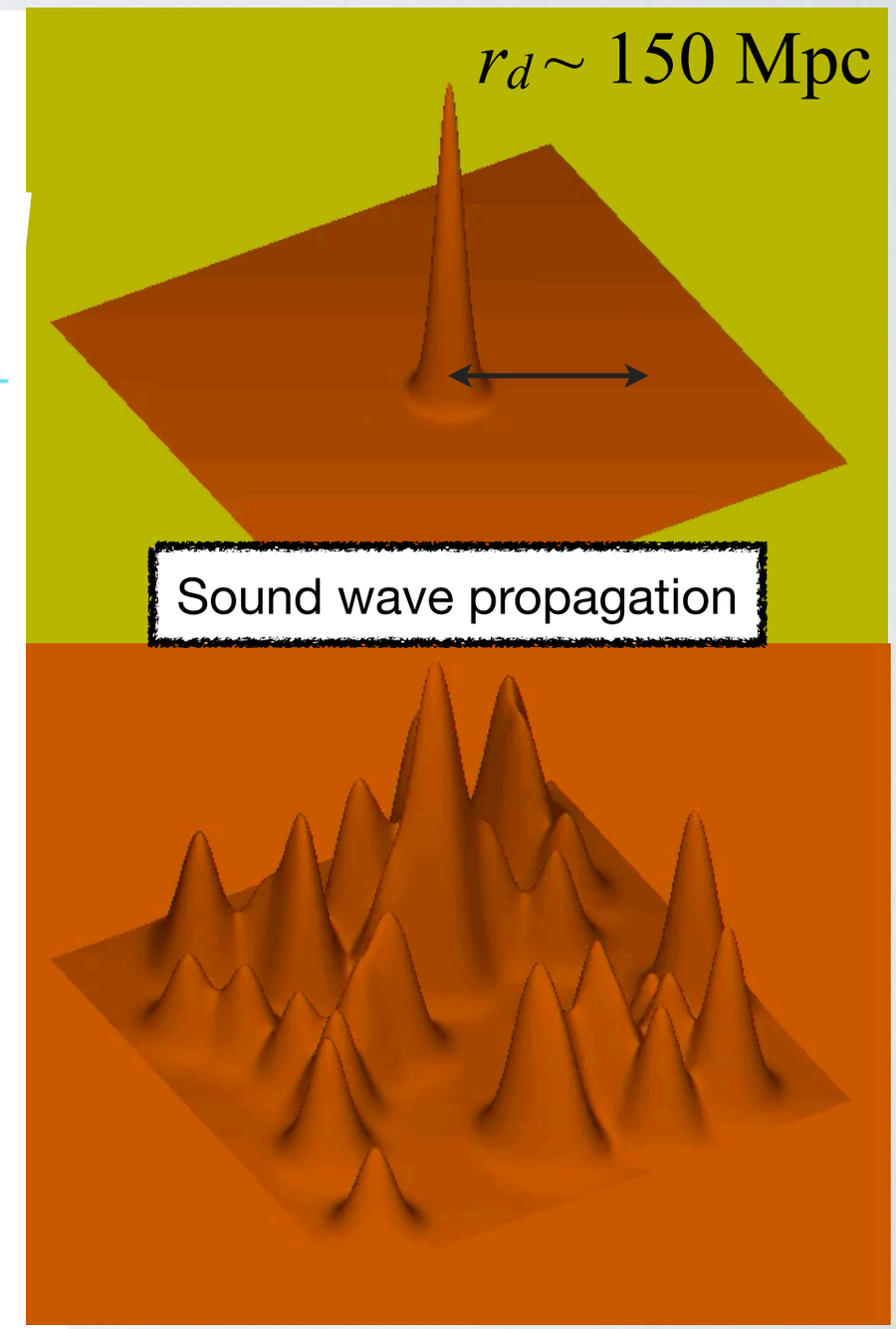
BAO

Baryon Acoustic Oscillations

$z = 0$

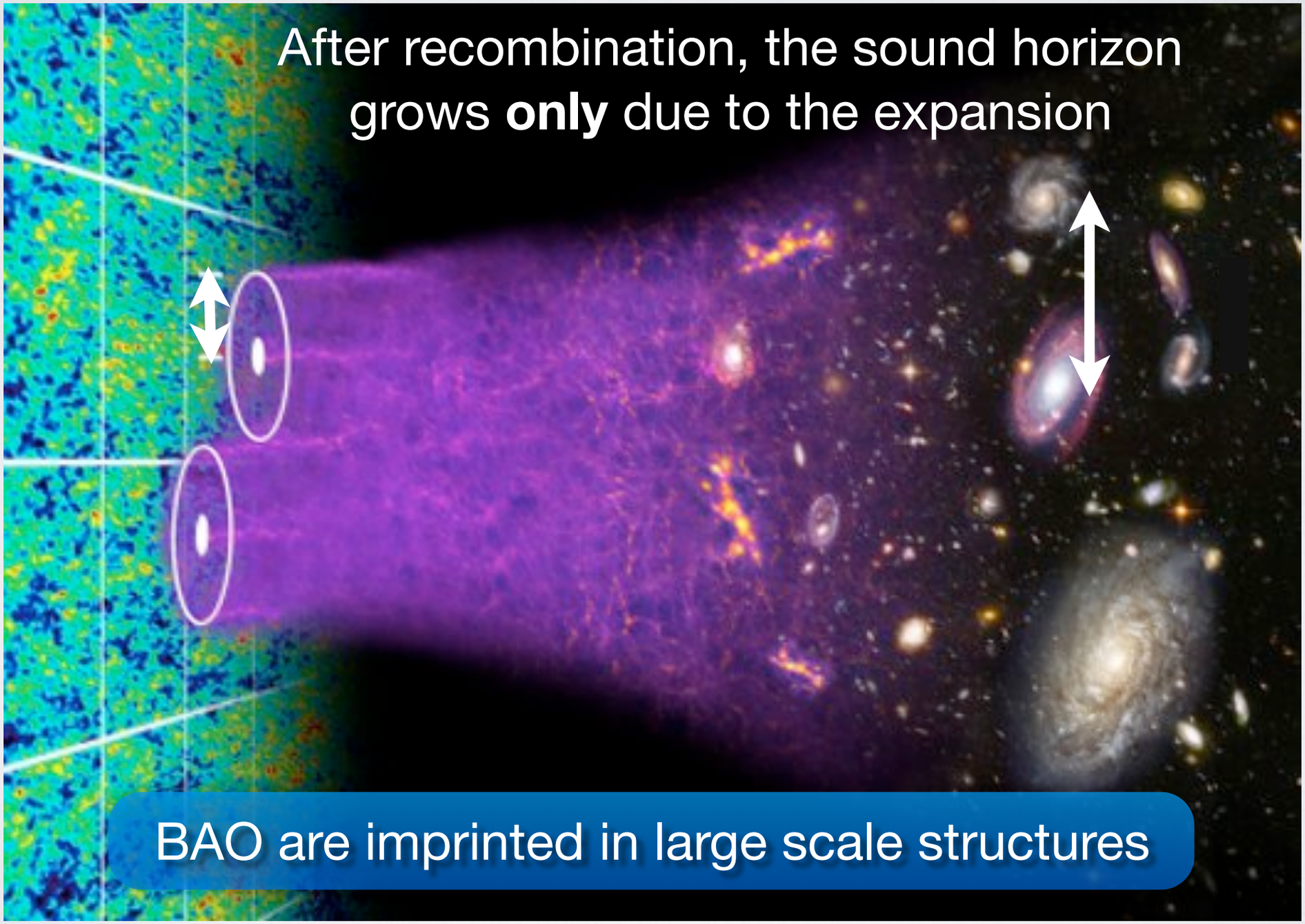
$z \sim 1100$





BAO

Baryon Acoustic Oscillations

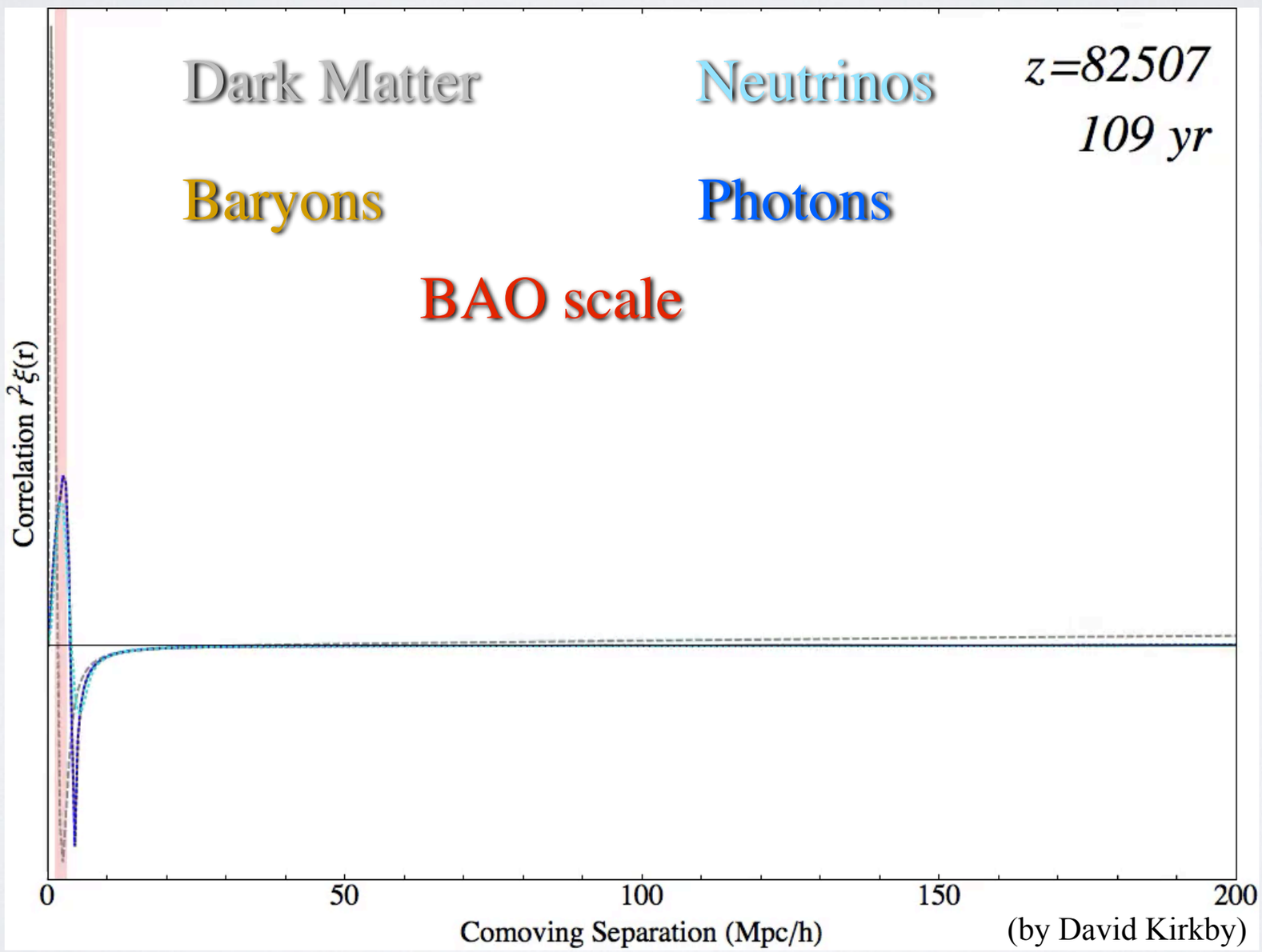


(sdss3.org)

BAO

BAO is a statistical standard ruler

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r})\rangle$



(by David Kirkby)

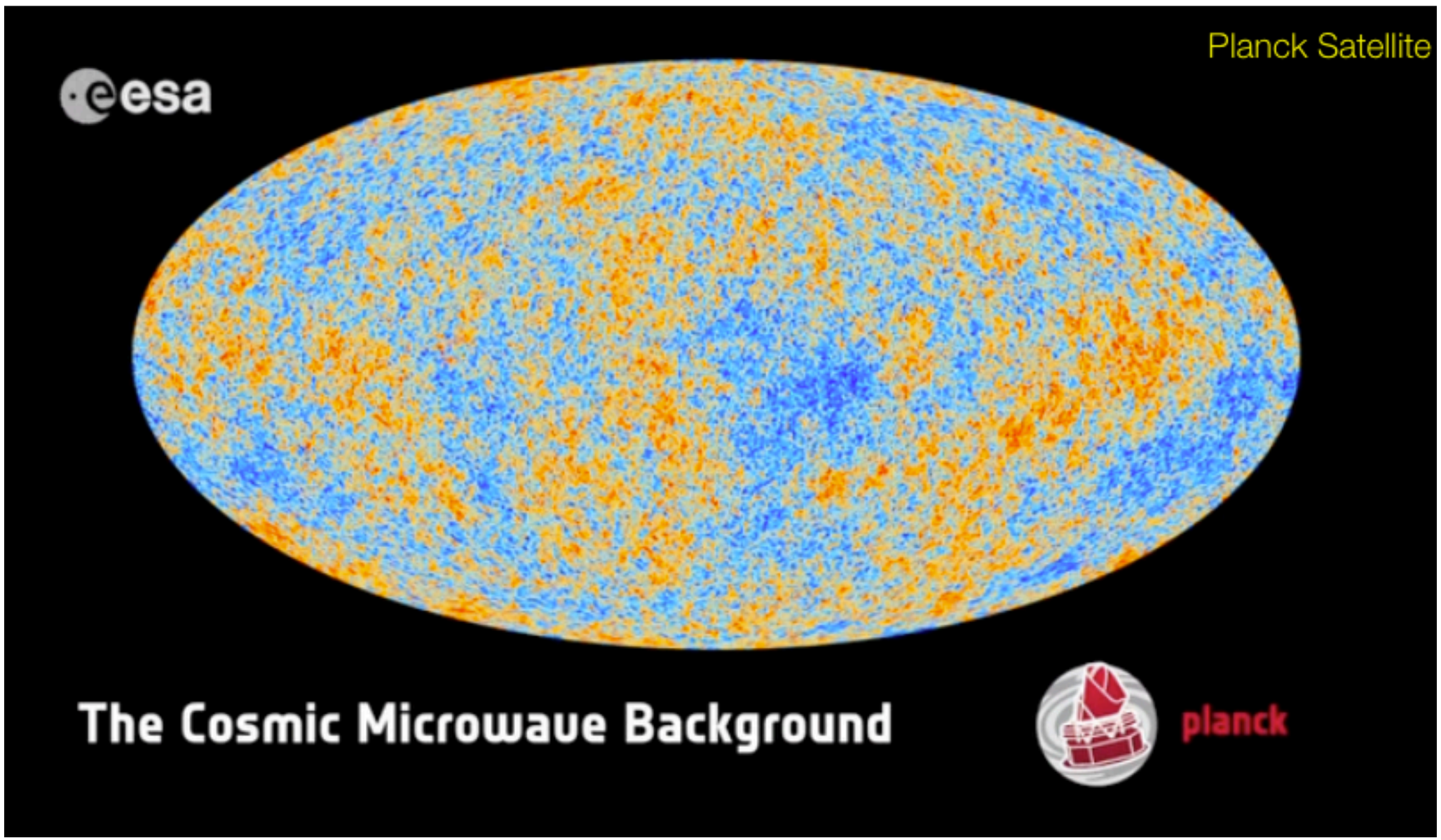
BAO in the CMB

The first detection of BAO was in the cosmic microwave background

Temperature angular power-spectrum

$$\langle \Delta T(\vec{\theta}_1) \Delta T(\vec{\theta}_2) \rangle$$

$$\Delta T(\vec{\theta}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\vec{\theta})$$



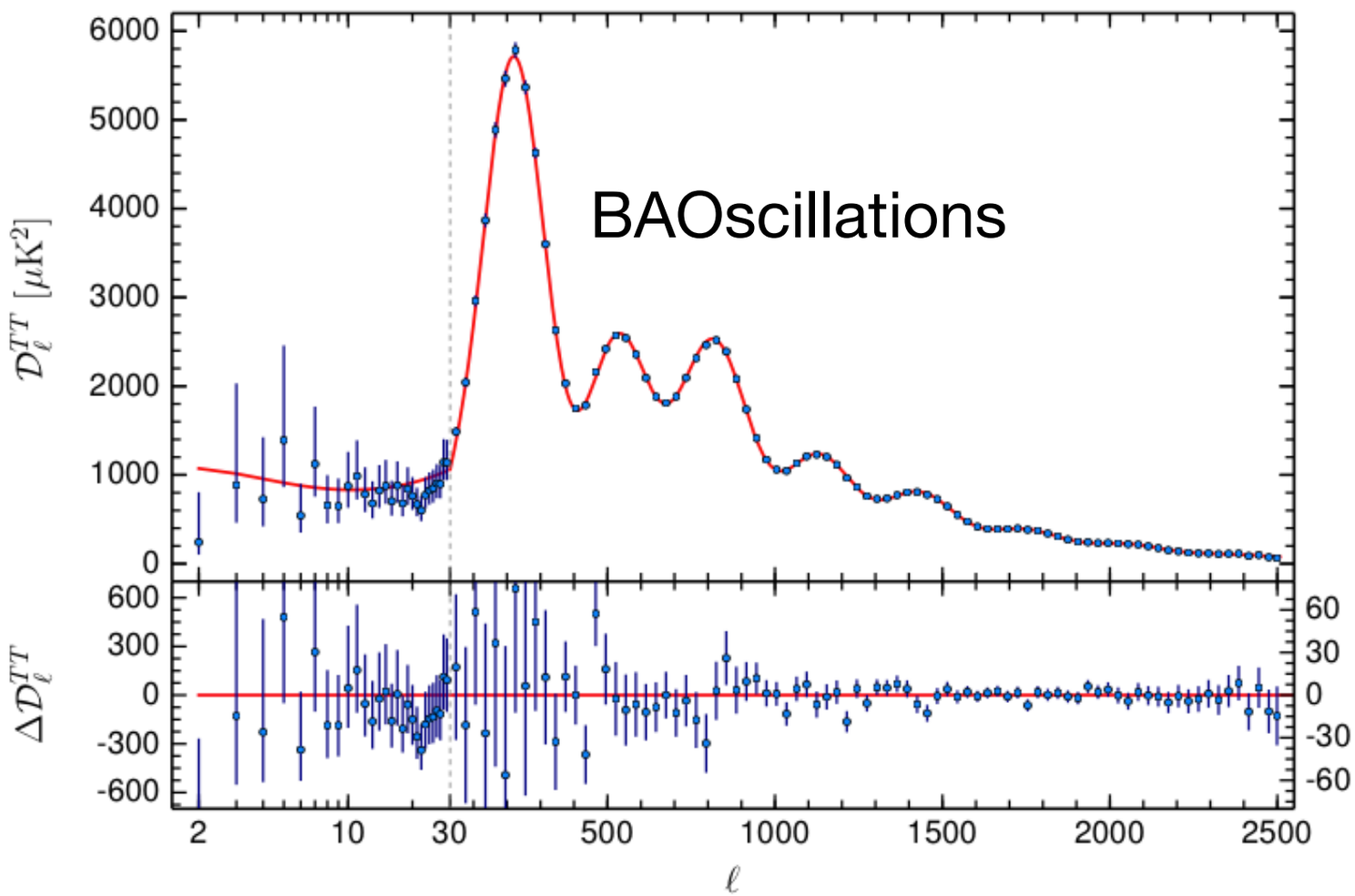
BAO in the CMB

The first detection of BAO was in the cosmic microwave background

Temperature angular power-spectrum

$$\langle \Delta T(\vec{n}) \Delta T(\vec{n} + \vec{m}) \rangle$$

$$\Delta T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$



Planck Collaboration 2018

0.05% constraint on

$$\theta_* \equiv r_* / D_{\mathrm{M}}$$

$$100\theta_* = 1.04097 \pm 0.00046$$

(68 %, *Planck* TT+lowE)

BAO in the CMB

The first detection of BAO was in the cosmic microwave background

Relating BAO and cosmological parameters

$$r_s(\eta) \equiv \int_0^{\eta} \mathrm{d}\eta' c_s(\eta') = \int_{\infty}^{z(\eta)} \mathrm{d}z' \frac{c_s(z')}{H(z')}$$

$$c_s(z) \equiv \sqrt{\frac{1}{3[1+R(z)]}}$$

$$R(z) = 3\rho_b(z)/4\rho_\gamma(z)$$

Dependency with $\Omega_m, \Omega_b, \Omega_r$

0.05% constraint on

$$\theta_* \equiv r_*/D_{\mathrm{M}}$$

$$100\theta_* = 1.04097 \pm 0.00046$$

(68 %, *Planck* TT+lowE)

BAO in the CMB

Constraints on the baseline cosmological model

Main parameters

Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	-0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	-0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	$+0.2$	0.9652 ± 0.0042

Planck Collaboration 2018 - Paper VI

BAO in the CMB

Constraints on the baseline cosmological model

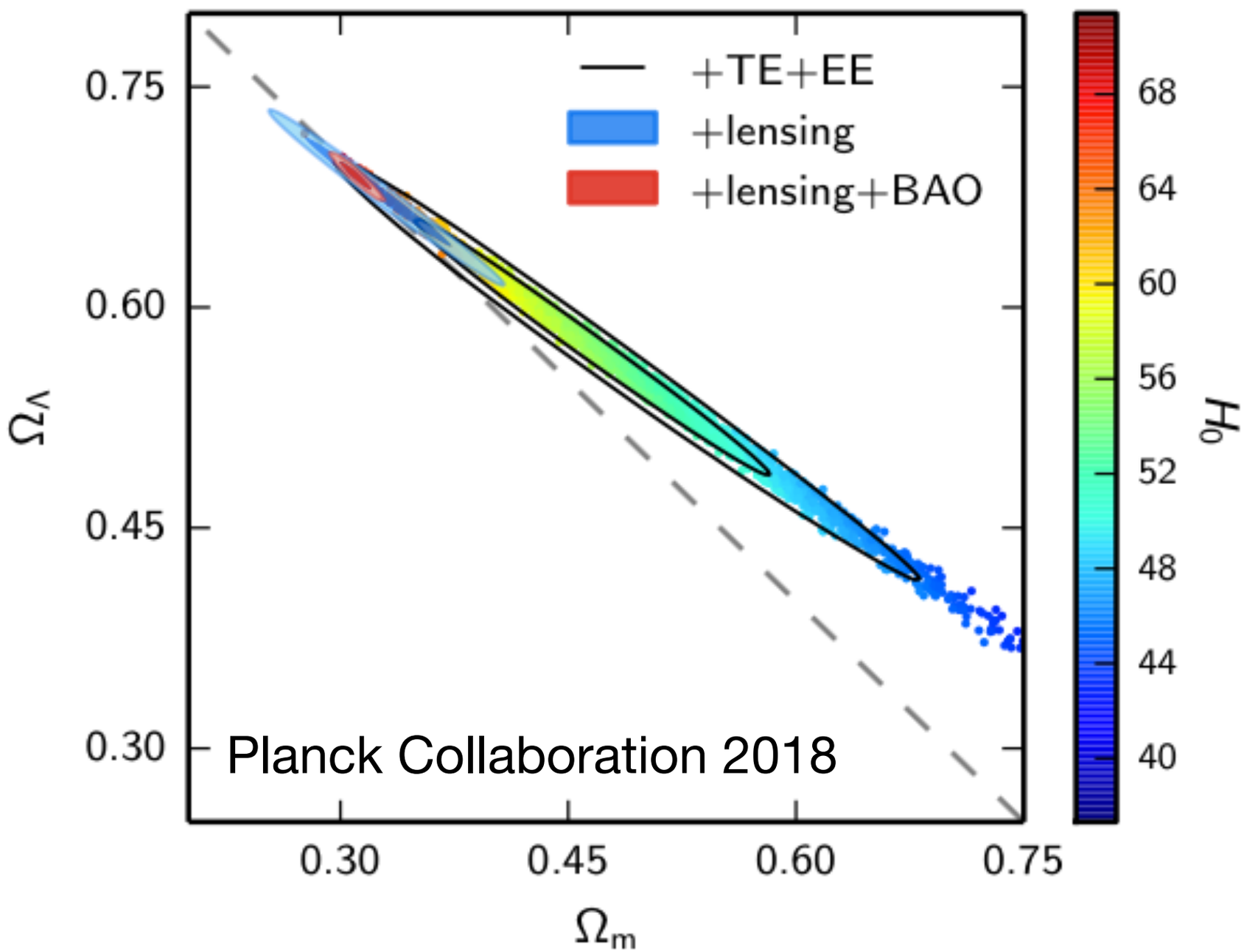
	Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
Main parameters	$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
	$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
	$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	1.04089 ± 0.00031
	τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	-0.1	0.0540 ± 0.0074
	$\ln(10^{10}A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	-0.3	3.043 ± 0.014
	n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	$+0.2$	0.9652 ± 0.0042
Derived parameters	$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	-0.3	0.1428 ± 0.0011
	H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	$+0.1$	67.37 ± 0.54
	Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	-0.2	0.3147 ± 0.0074
	Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	$+0.4$	13.801 ± 0.024
	σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	-0.3	0.8101 ± 0.0061
	$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	-0.3	0.830 ± 0.013
	z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	-0.1	7.64 ± 0.74
	$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	-0.1	1.04108 ± 0.00031
	r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	$+0.6$	147.18 ± 0.29

Planck Collaboration 2018 - Paper VI

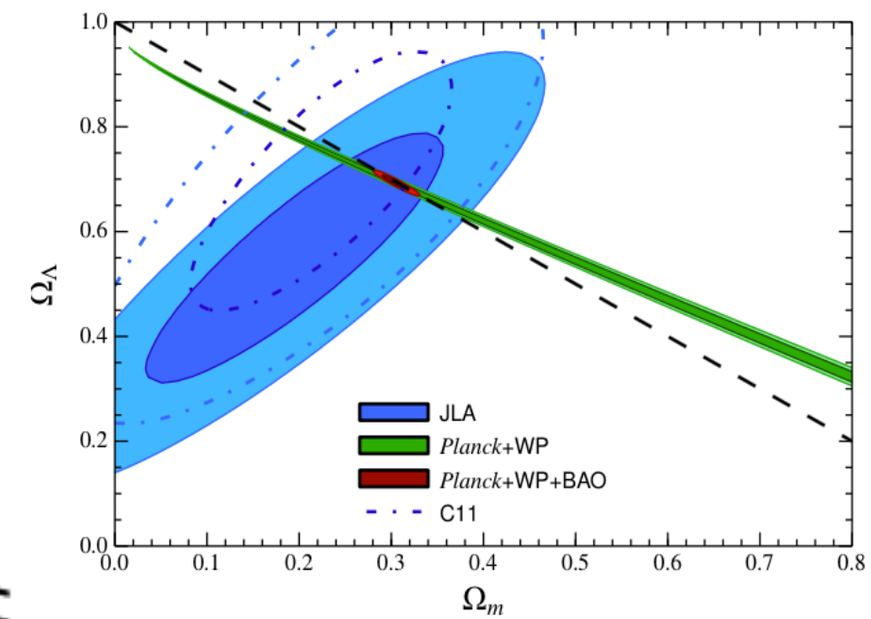
BAO in the CMB

Constraints on the baseline cosmological model

Dark-energy vs curvature degeneracy

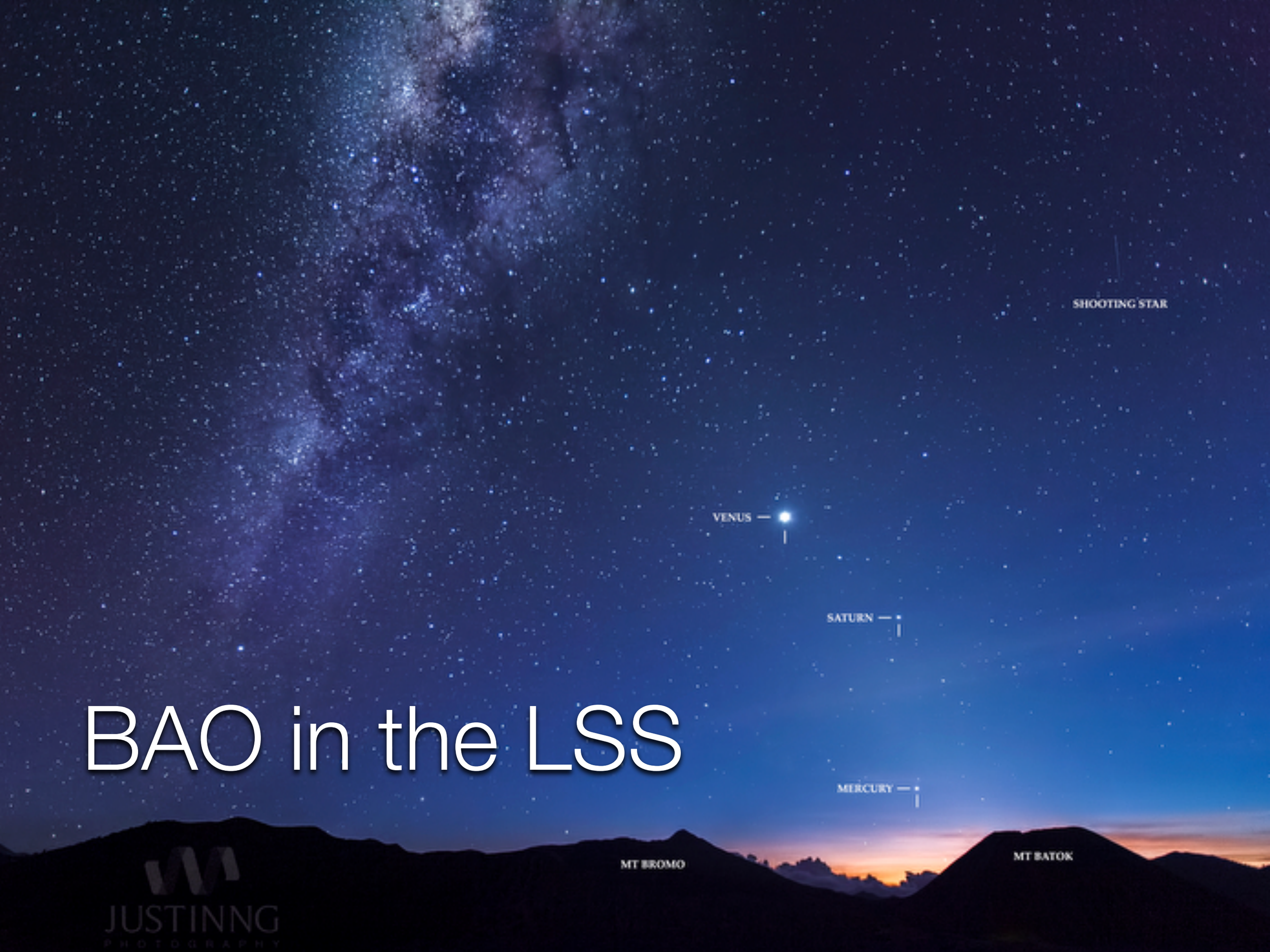


Planck Collaboration 2018

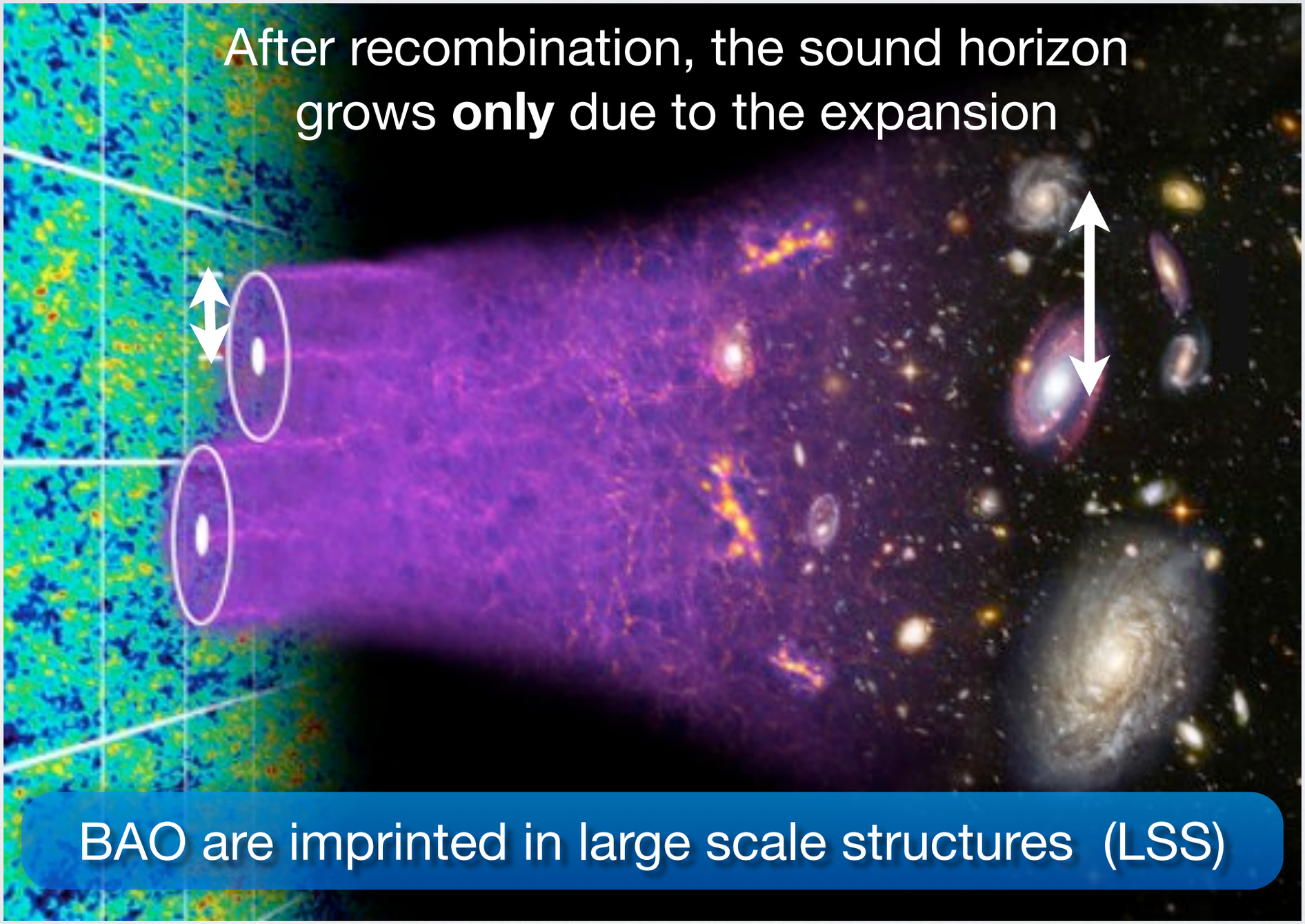


Betoule et al. 2014

BAO in the LSS



BAO in the LSS



(sdss3.org)

BAO in the LSS

Large-scale structures

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

How to trace matter overdensities δ ?

Galaxies

Trace dense regions $\delta \gg 200$

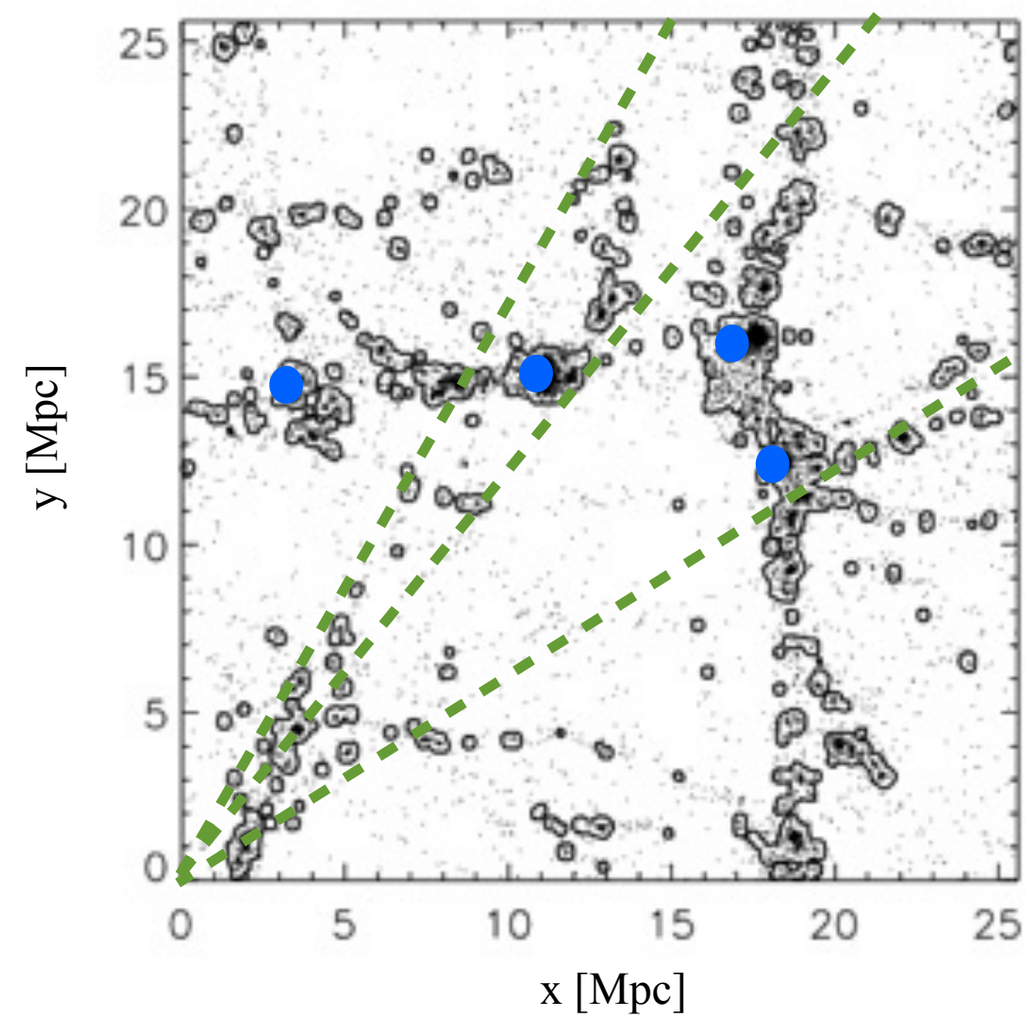
usually at low redshifts ($z < 1$)

Lyman-α Forest

Trace small over-densities $\delta \approx 1$

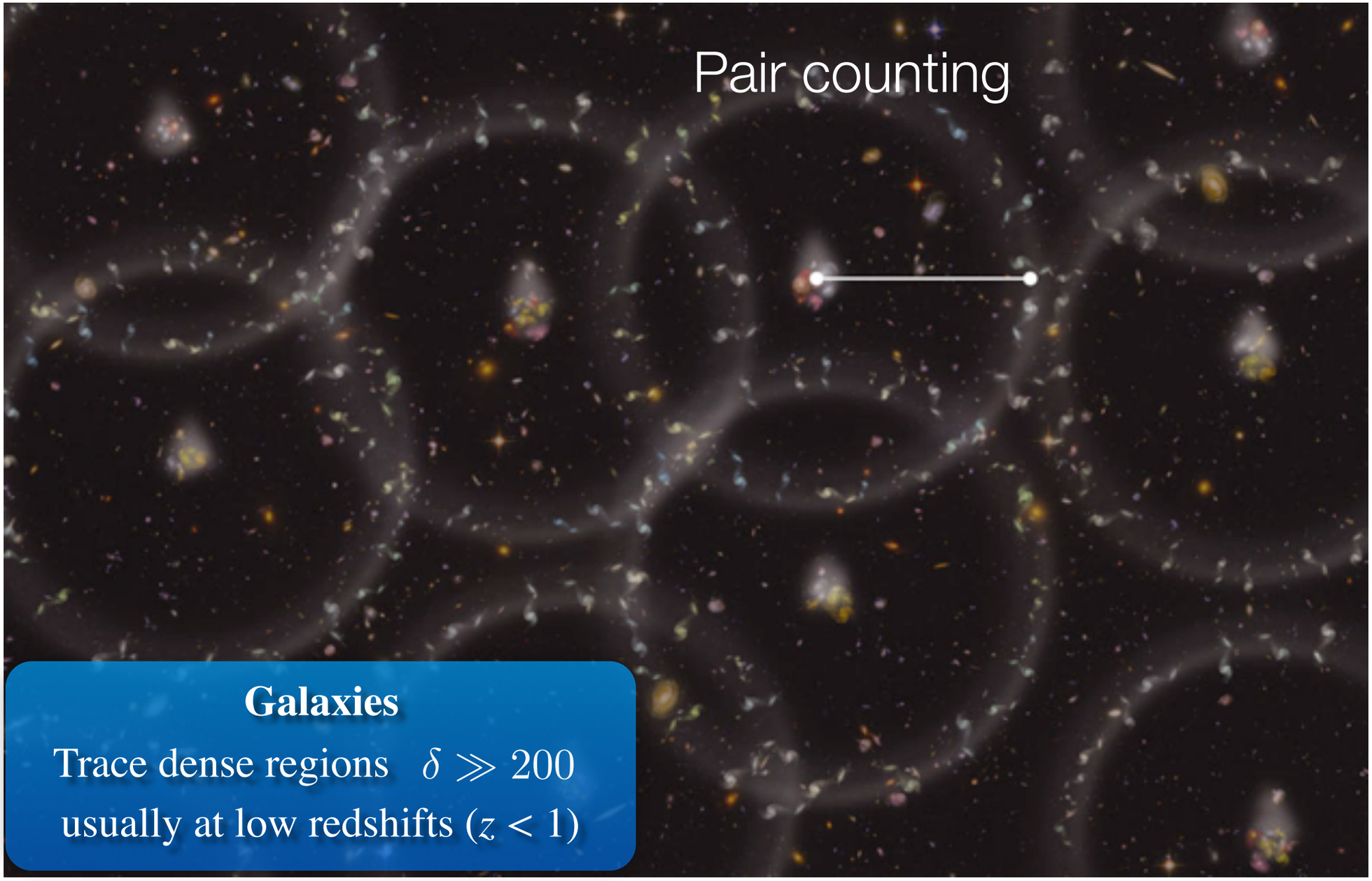
at high redshifts ($z > 2$)

(Petitjean et al. 1995)



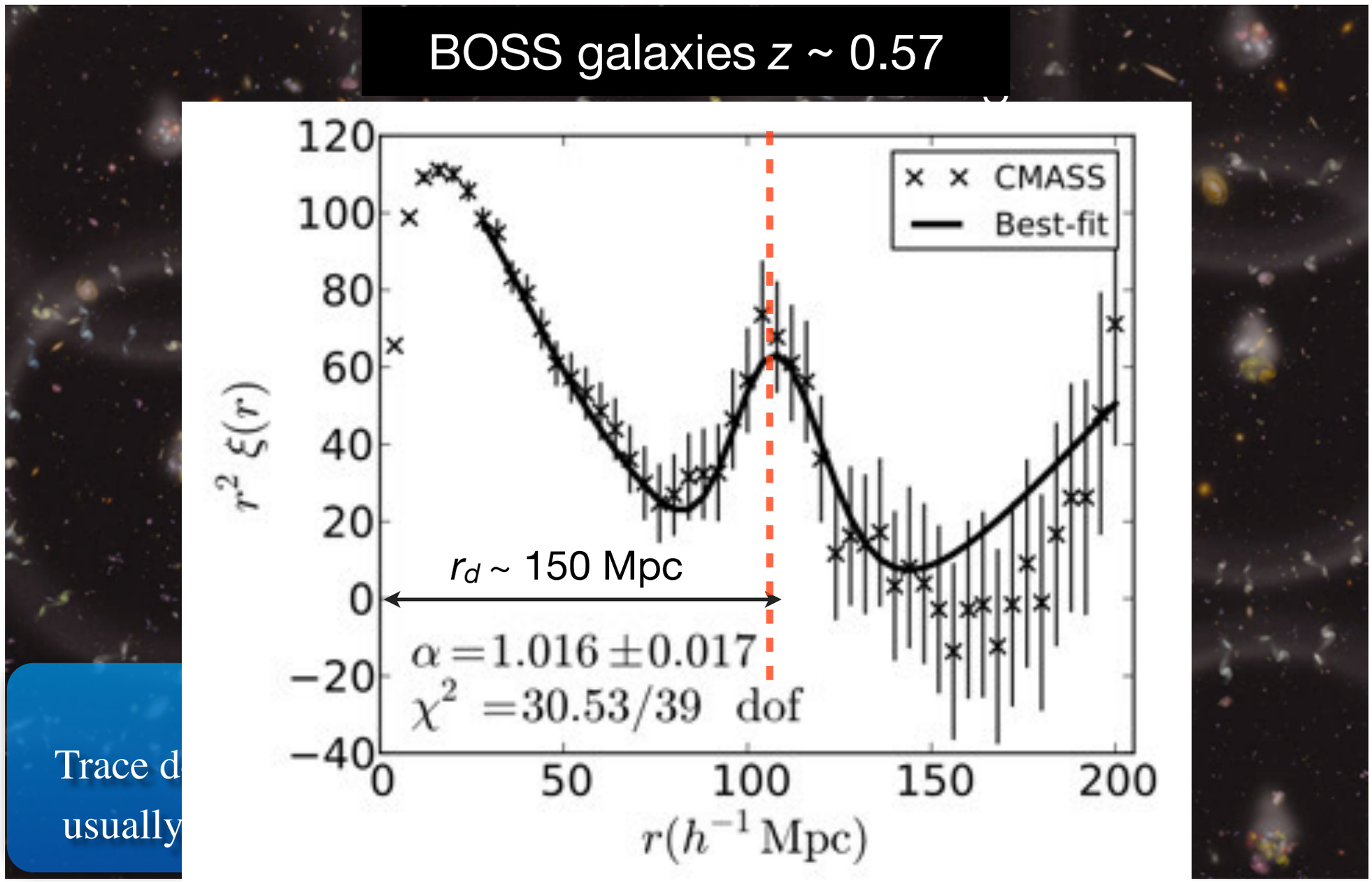
BAO with galaxies

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$



BAO with galaxies

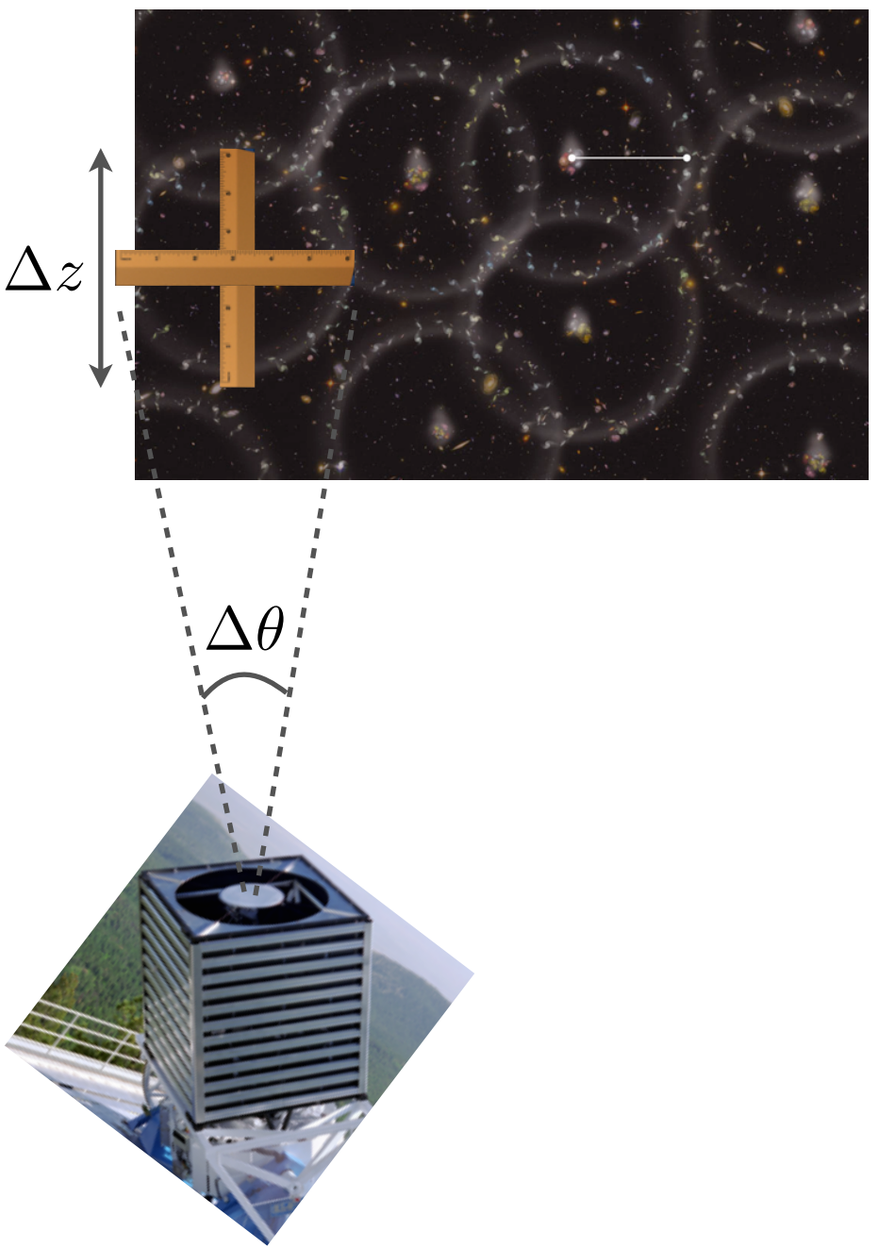
Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

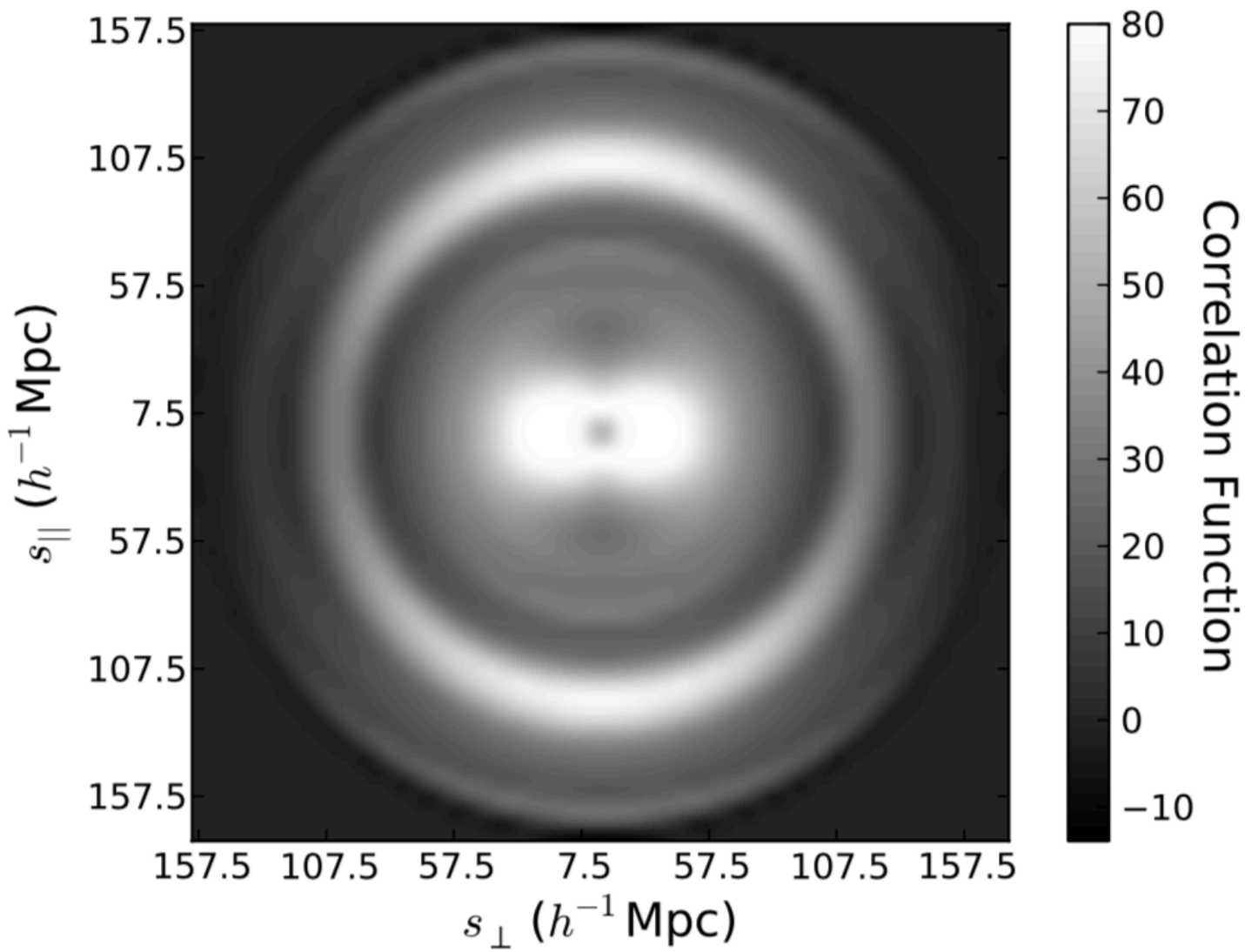


(Anderson et al. 2012)

BAO with galaxies

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

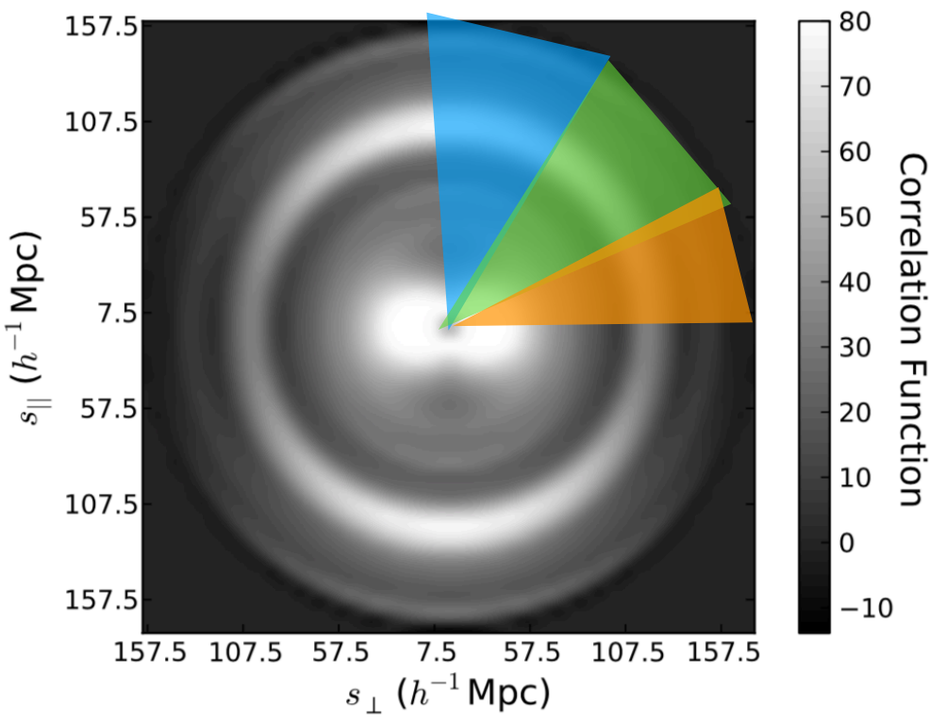


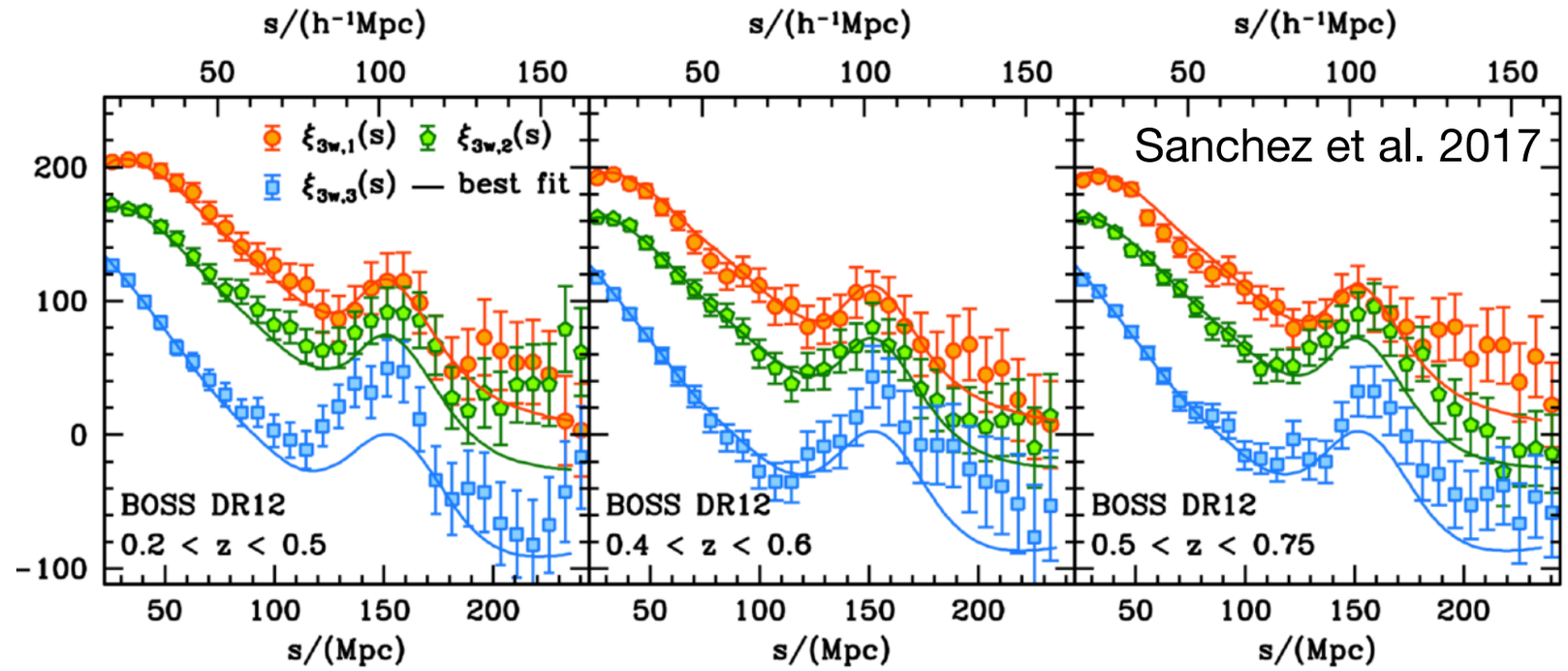


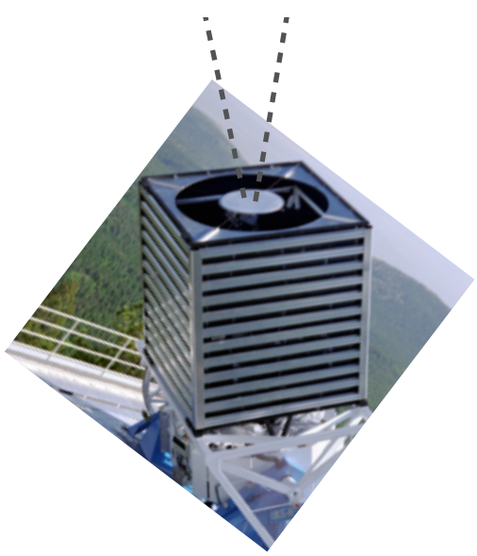
BOSS Collaboration
Alam et al. 2017

BAO with galaxies

Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$







BAO in the transverse direction

$$\Delta\theta = \frac{r_d}{(1+z)D_A(z)}$$

BAO in the radial direction

$$\Delta z = \frac{r_d}{(1+z)D_H(z)}$$

BAO with galaxies

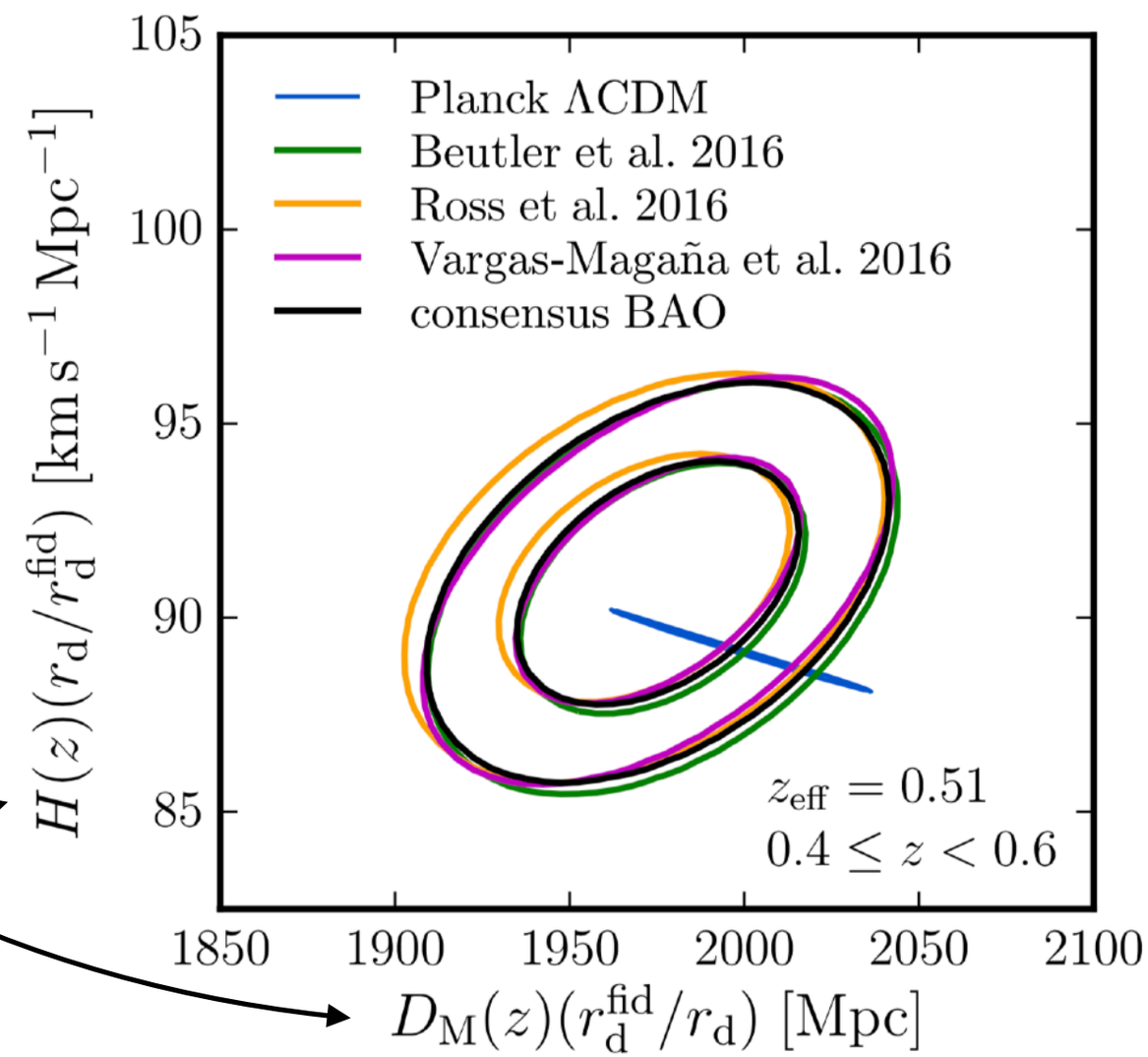
Correlation function of matter overdensities: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

BAO in the transverse direction

$$\Delta\theta = \frac{r_d}{(1+z)D_A(z)}$$

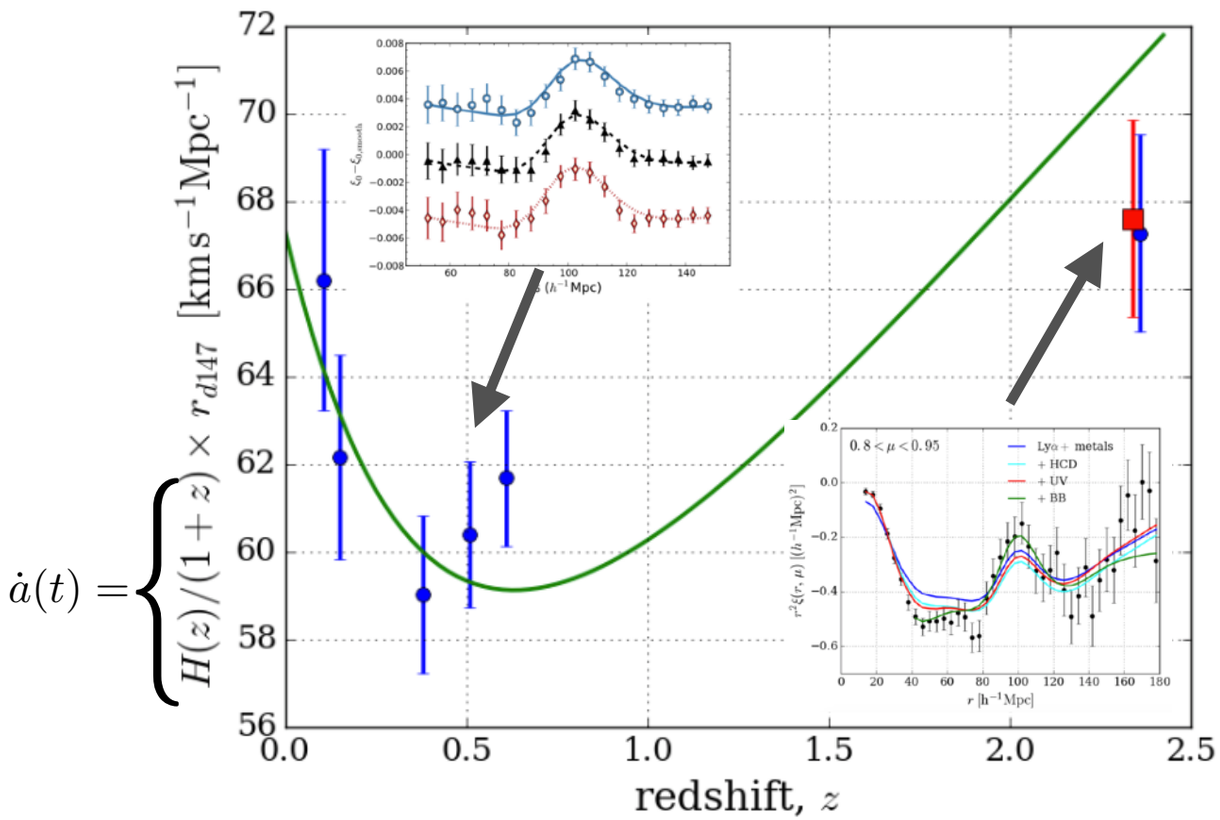
BAO in the radial direction

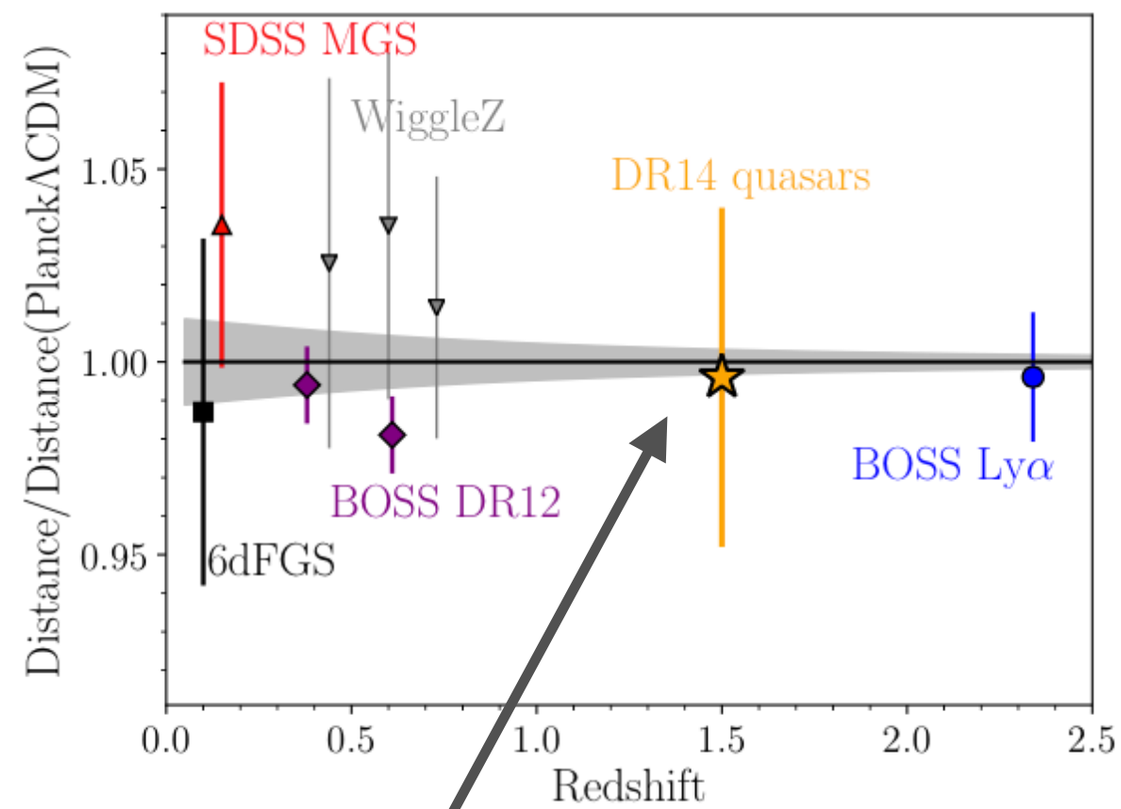
$$\Delta z = \frac{r_d}{(1+z)D_H(z)}$$



BOSS Collaboration
Alam et al. 2017

Expansion rate from BAO





BOSS
- z = 0.11 (Beutler et al. 2011)
- z = 0.15 (Ross et al. 2015)
- z = 0.35 - 0.65 (Alam et al. 2016)
- z = 2.33 (Bautista et al. 2017)
- z = 2.34 (Font-Ribera et al. 2014)

First eBOSS
BAO measurement
(Ata et al. 2017)

Summary

- Distances are not easy in astronomy
- The Universe is expanding
- The Universe's expansion is accelerating and we don't know why (although we found a cool name for it: **dark energy**)
- Baryon acoustic oscillations give us a powerful standard ruler to measure distance and the expansion rate
- BAO can be seen in the CMB, and in the large-scale structures, giving the best constraints on dark-energy