Classical cosmological tests

(Master NPAC)

N. Regnault
(LPNHE, Paris)

- Age of the Universe
- Standard candles (d_L vs. z)
  - $\rightarrow$ type Ia supernovae
- Standard rulers (d_A vs. z)
  - $\rightarrow$ BAO
- Volumes / counting objects
  - clusters

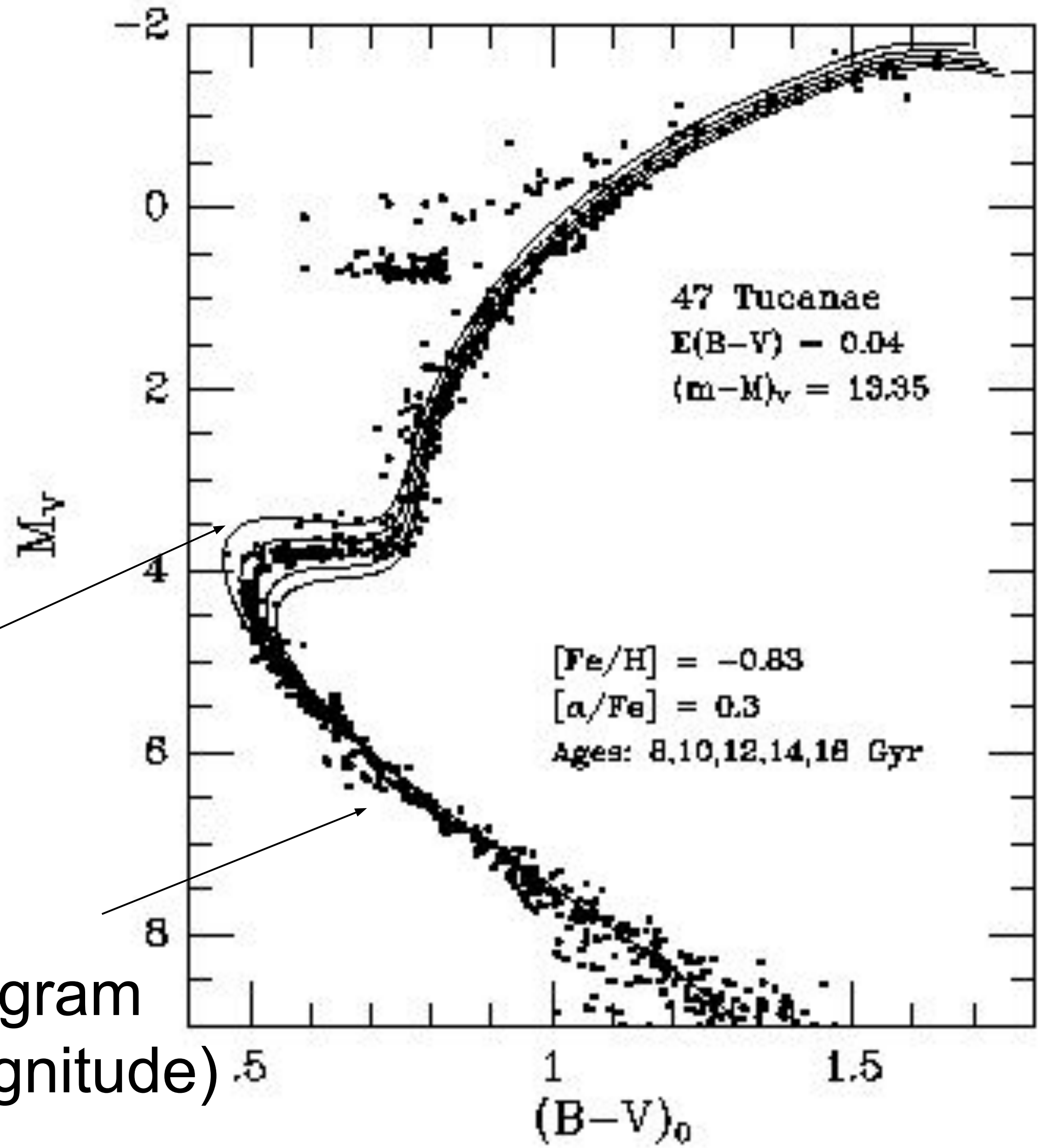
Age of the Universe

$$t = \frac{1}{H_0} \int_0^1 \frac{dx}{[\Omega_m x^{-1} + \Omega_\Lambda x^2 + (1 - \Omega_m - \Omega_\Lambda)]^{1/2}}$$

- ~ Hubble time x correction(Ω)
  - Decreasing function of Ω_m (deceleration)
  - Increasing function of Ω_Λ (acceleration)
- Lower limits from inferred ages of old objects in the universe (e.g. globular clusters)
  - Historically gave interesting upper limits on Ω_m
  - $t > 1.1\ 10^9 \Rightarrow \Omega_m < 0.3$ (no Λ) → "age problem"

Globular clusters

- Low metallicity (old) star systems
- Can be dated
  - from their HR diagram
  - WD temperatures



Isochrones (model)

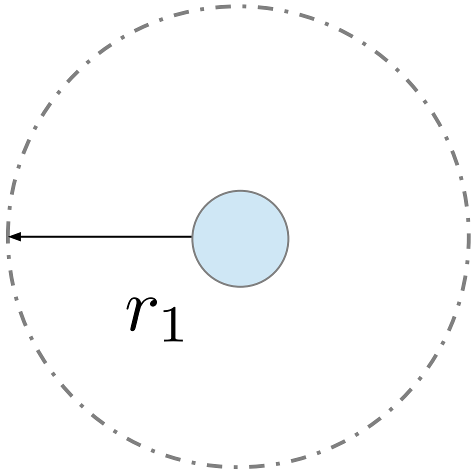
HR diagram (color,magnitude)

~ can be as old as ~ 12 Gyr

Distances and Volumes

- Obtained directly from the Friedmann equation

$$d_L^2 = \frac{\mathcal{L}}{4\pi\phi} = a_0^2 {r_1}^2 (1+z)^2$$

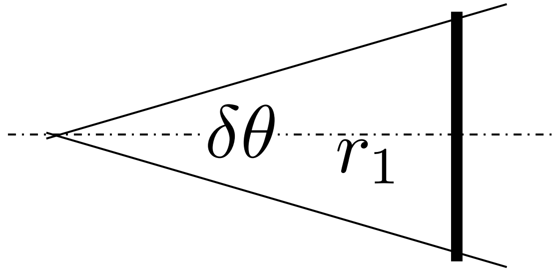


What we measure

What we predict

$$\propto \int \frac{dz}{H(z)}$$

$$d_A = \frac{\delta S}{\delta\theta} = \frac{a_0 r_1}{1+z}$$



$$\delta S = a_1 r_1 \delta\theta$$

Luminosity distance vs. z

- Astronomers use magnitudes

$$m = -2.5 \log_{10} \frac{f}{f_{ref}}$$

measured flux

reference flux

Absolute flux <-> “flux at 10 pc”

$$\frac{f(z)}{f_{10}} = \frac{L}{4\pi d_L^2(z)} \times \frac{4\pi d_{10}^2}{L} = \frac{d_{10}^2}{d_L^2}$$

In magnitudes

$$\underbrace{m - M}_{\mu} = 5 \log_{10} \frac{d_L}{10pc} = 5 \log_{10} \frac{d_L 10^6}{10} = 25 + 5 \log_{10} d_L$$

Can factor out H0 (and M)

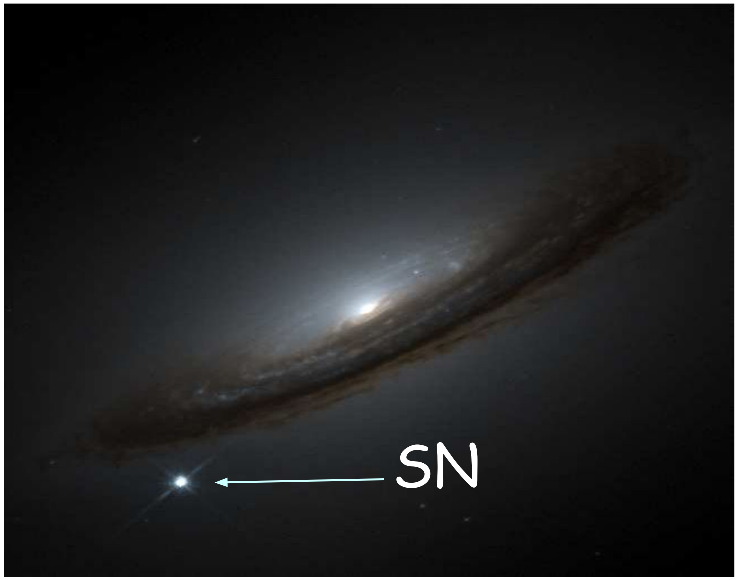
$$5\log_{10} d_L = 5\log_{10}\frac{c}{H_0} + 5\log_{10}\mathcal{D}(z, \Omega_i \ldots)$$

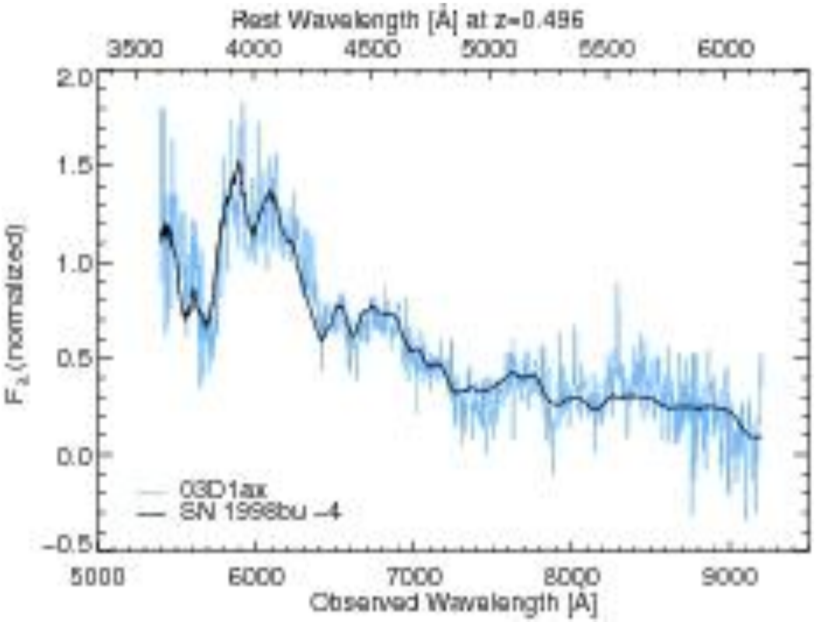
something that does not depend on H0

$$m = \underbrace{(M + 5\log_{10}\frac{c}{H_0})}_{\mathcal{M}} + 5\log_{10}\mathcal{D} + 25$$

On the other hand, measuring H0 requires to know M (distance ladder)

Type Ia Supernovae



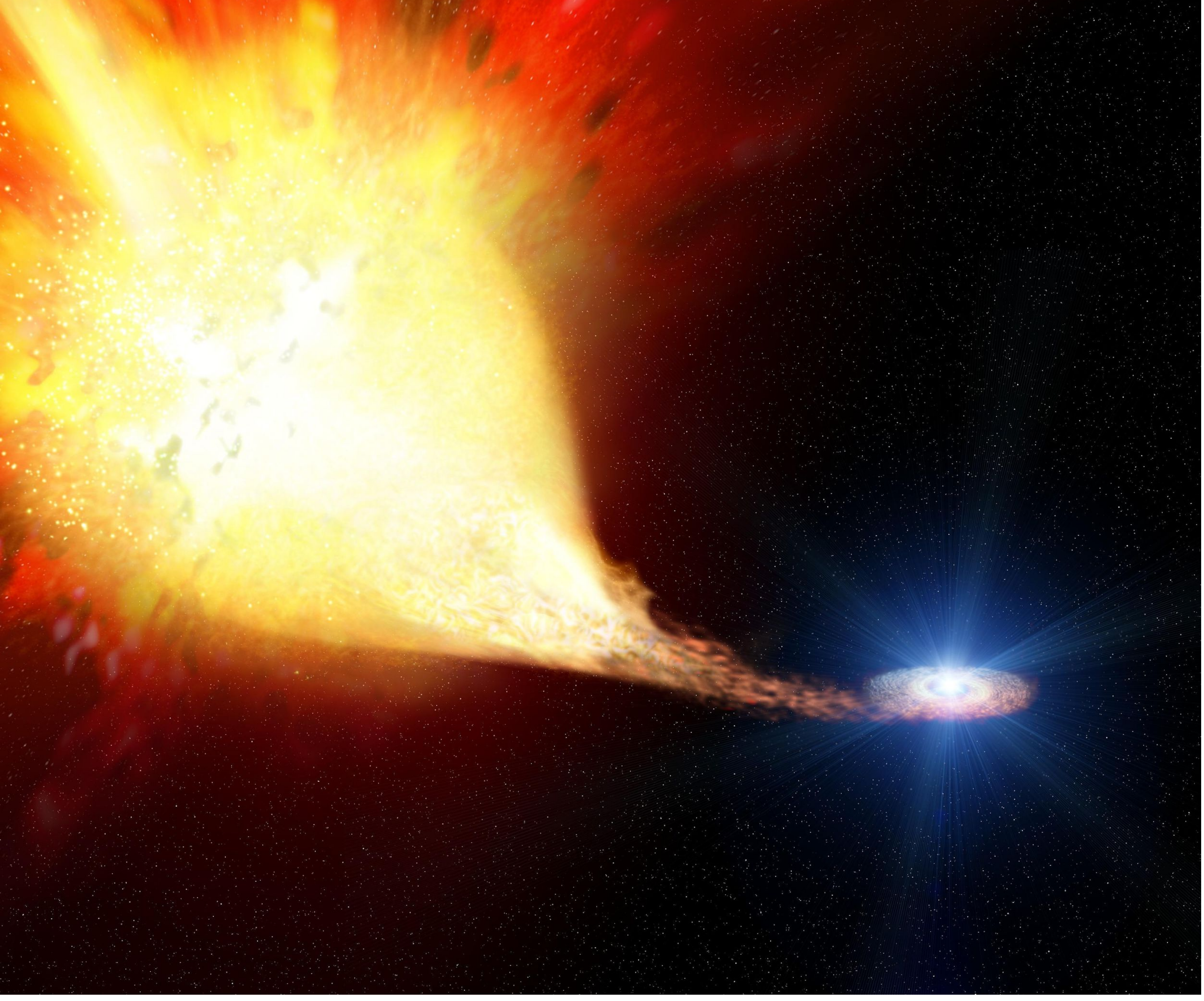


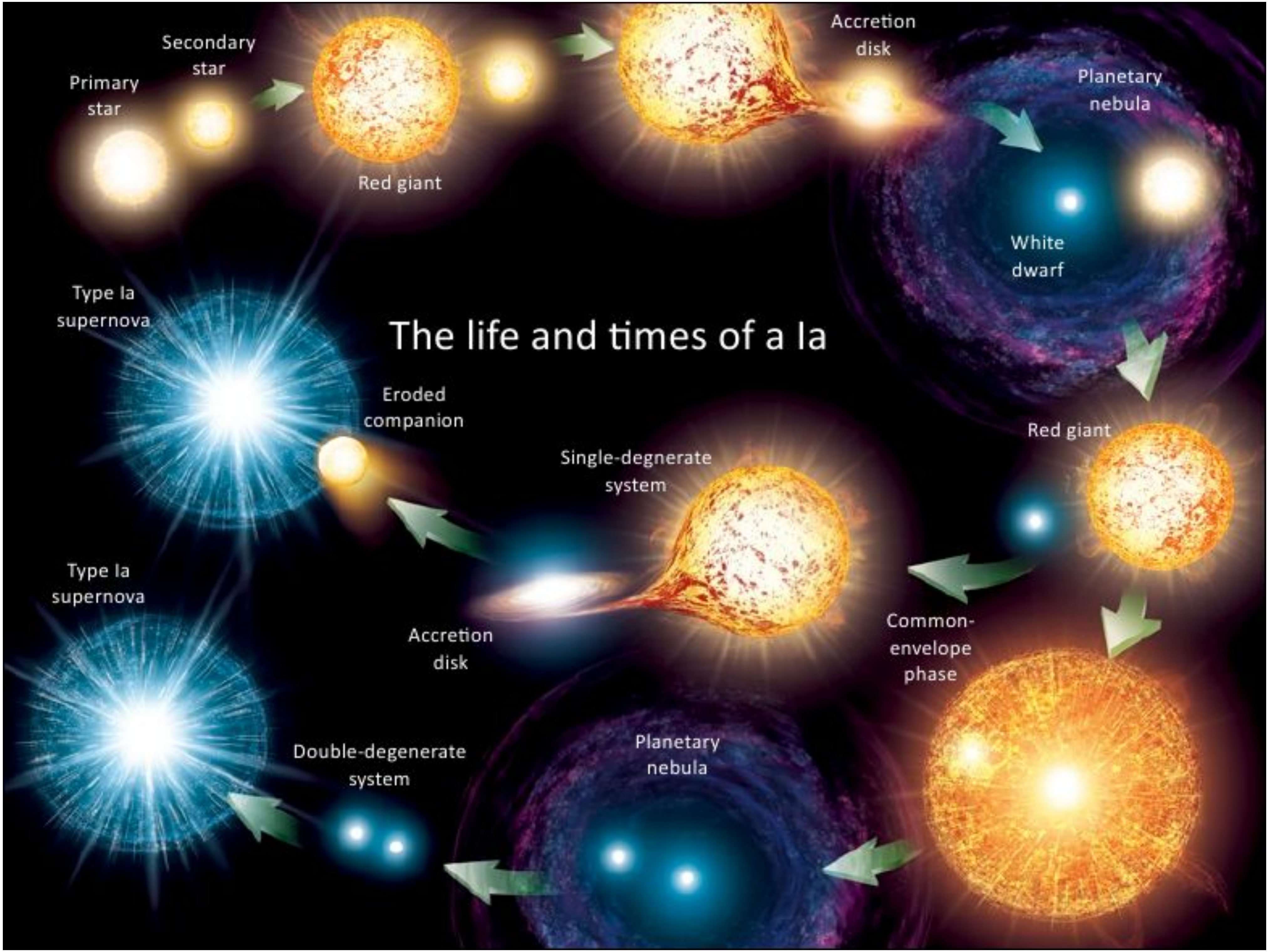
- Thermonuclear explosion of WD
  - Rare events (~1 / Gal / 1000 yr)
  - Very bright (~10^{10} solar luminosities)
  - Transients (~ 1 month)
  - $\sigma(L_{max})$ ~ 40%
    - Standardizable → σ(Lmax) ~ 15%

- Spectroscopy
  - Identification (broad features)
  - Chemical composition & velocities

Hillebrandt & Niemayer, 2000

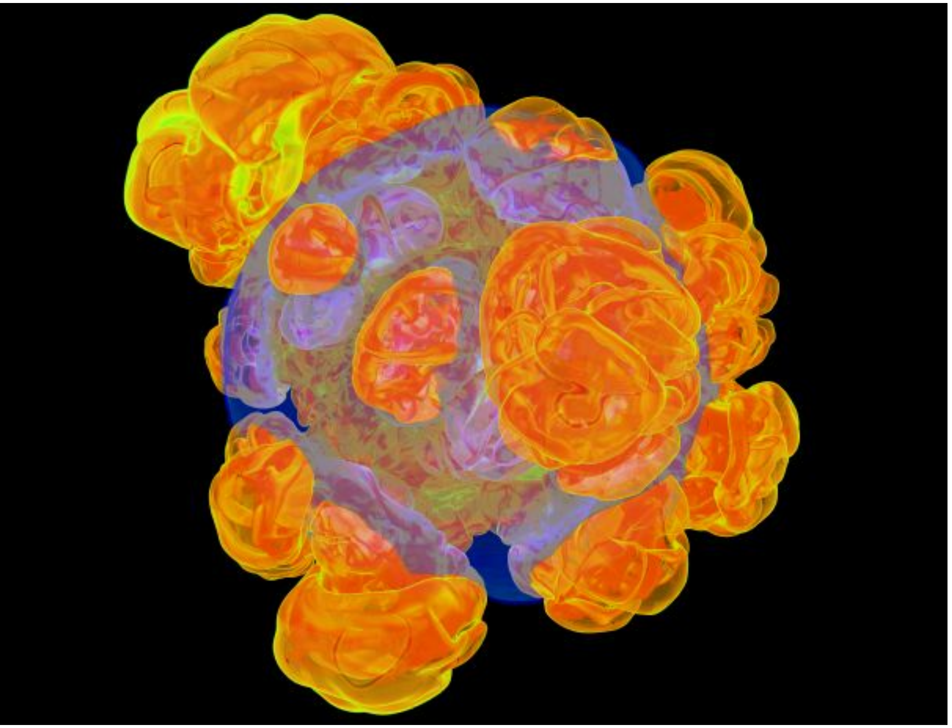
Maoz et al 2014



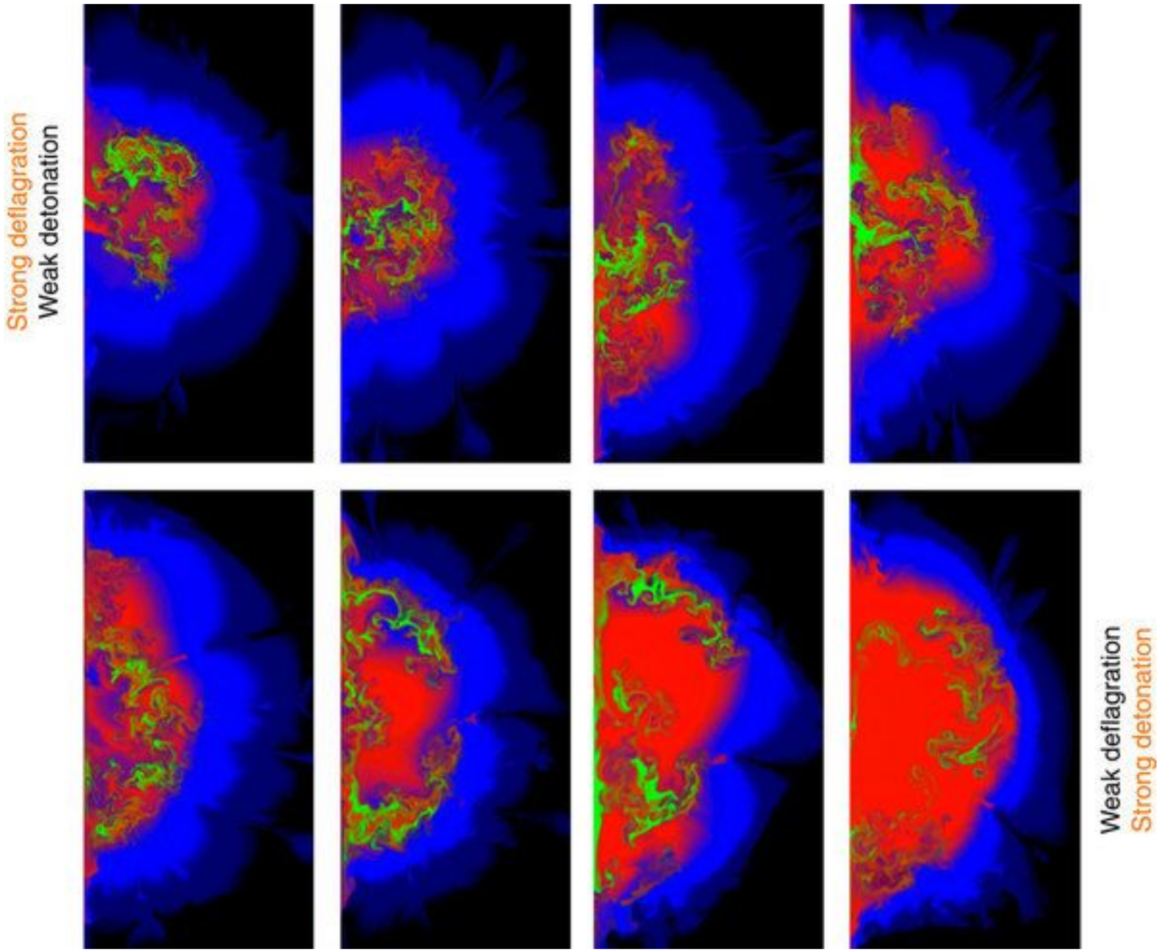


The life and times of a Ia
Primary star
Secondary star
Red giant
Accretion disk
Planetary nebula
White dwarf
Red giant
Common-envelope phase
Planetary nebula
Double-degenerate system
Type Ia supernova
Single-degenerate system
Accretion disk
Eroded companion
Type Ia supernova

SNIa Models



Jordan et al, astro-ph/0703573



Kasen et al, 0907.0708

- Thermonuclear explosion of C/O white dwarf fed by companion star
- Lots of non-linear physics going on...

However

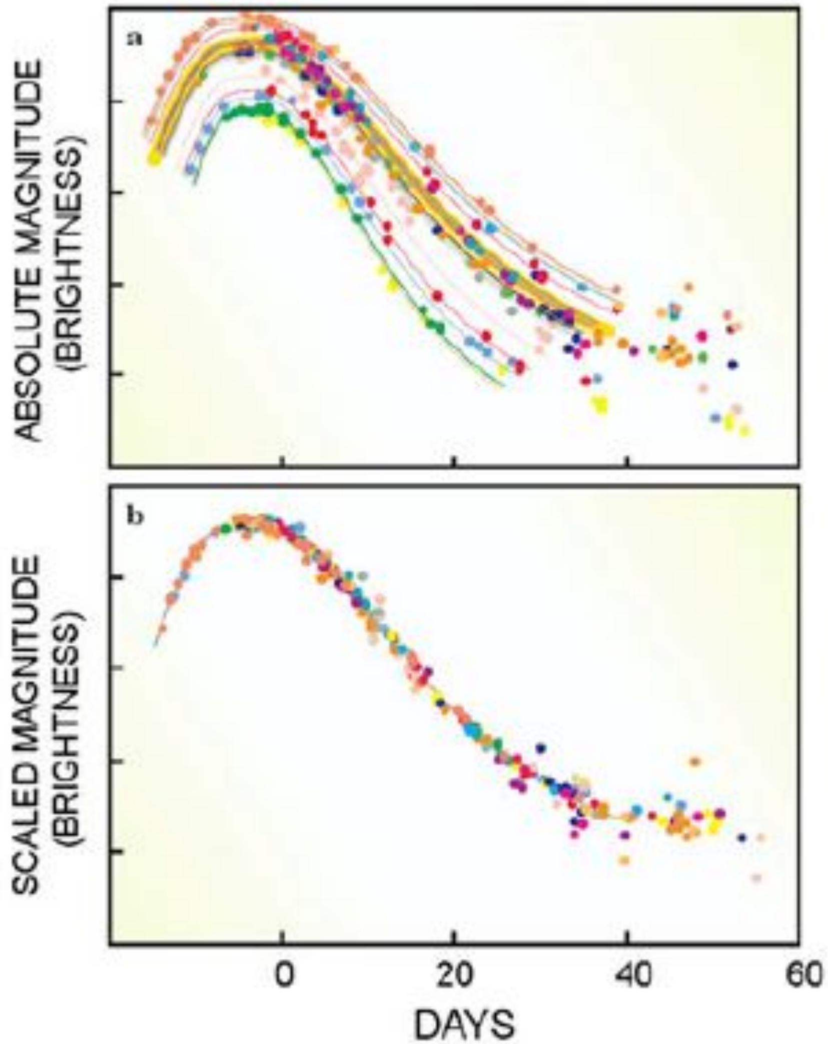
- SNe Ia seem to form a very uniform family
- Standardization
    - “Brighter bluer”
    - “Brighter slower”

$$M_{cor} = M_0 + \alpha(s-1) - \beta c$$

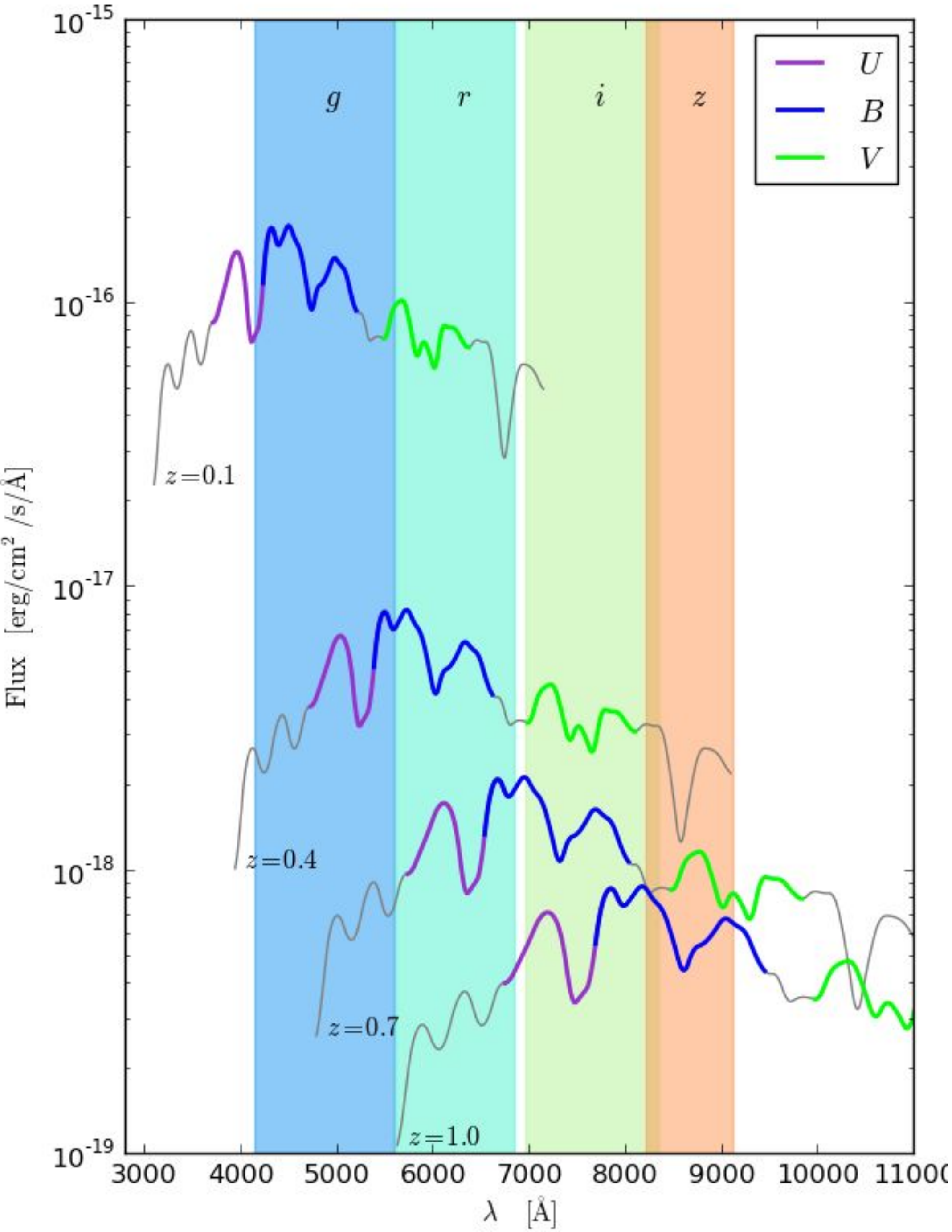
~ log(flux)

Light curve shape

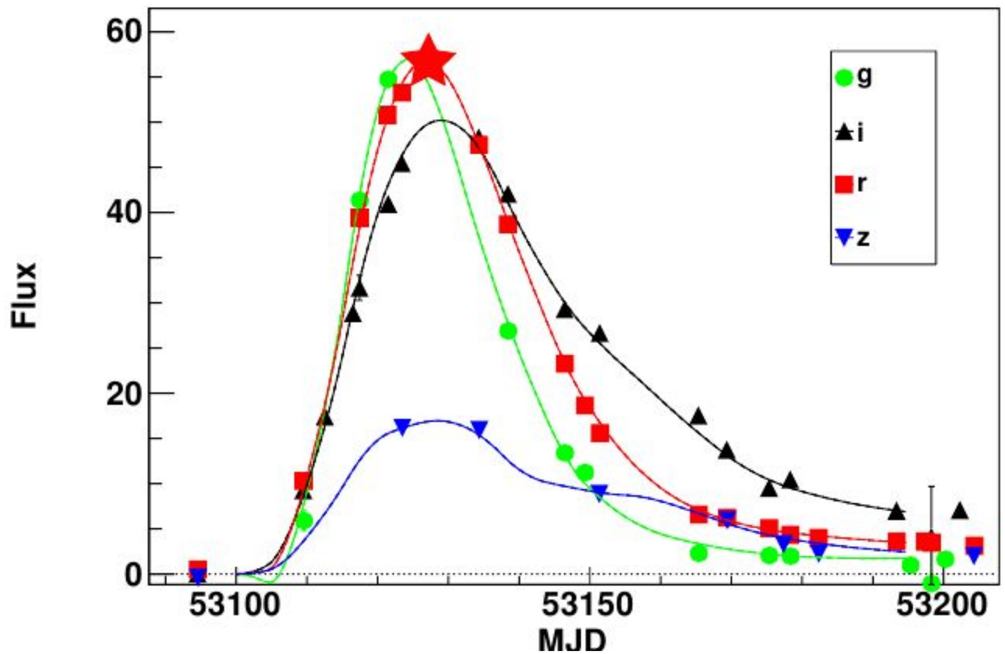
restframe color



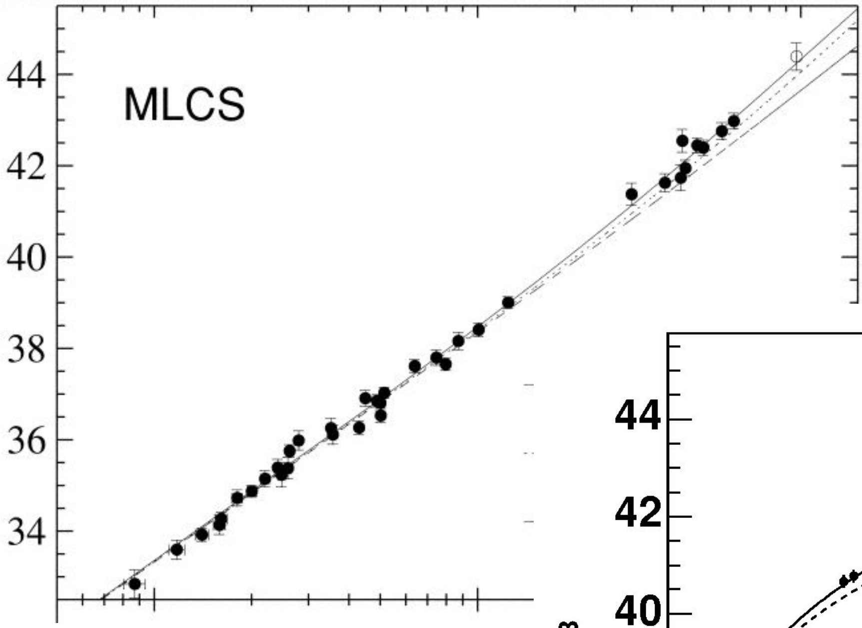
Principle

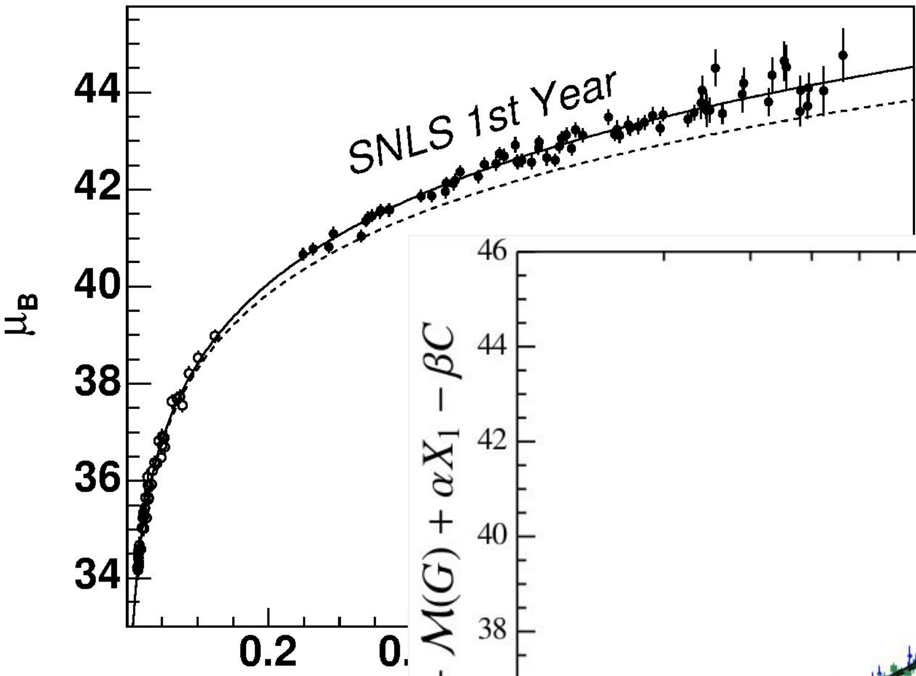


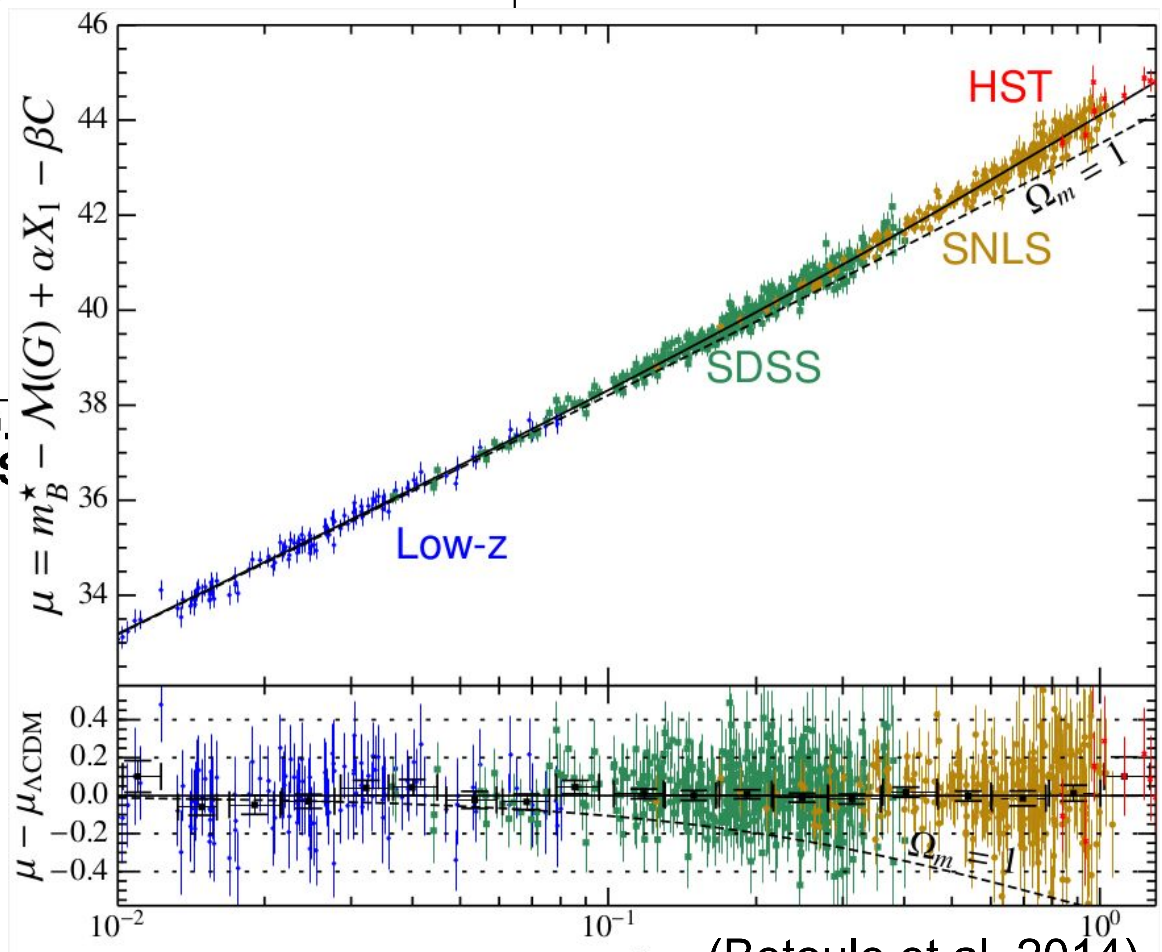
- Ingredients
  - Flux ratios between (observer) bands
  - → (relative) flux calibration
  - Interpolate in time and wavelength
  - → Light curve model



Supernovae







(Betoule et al, 2014)

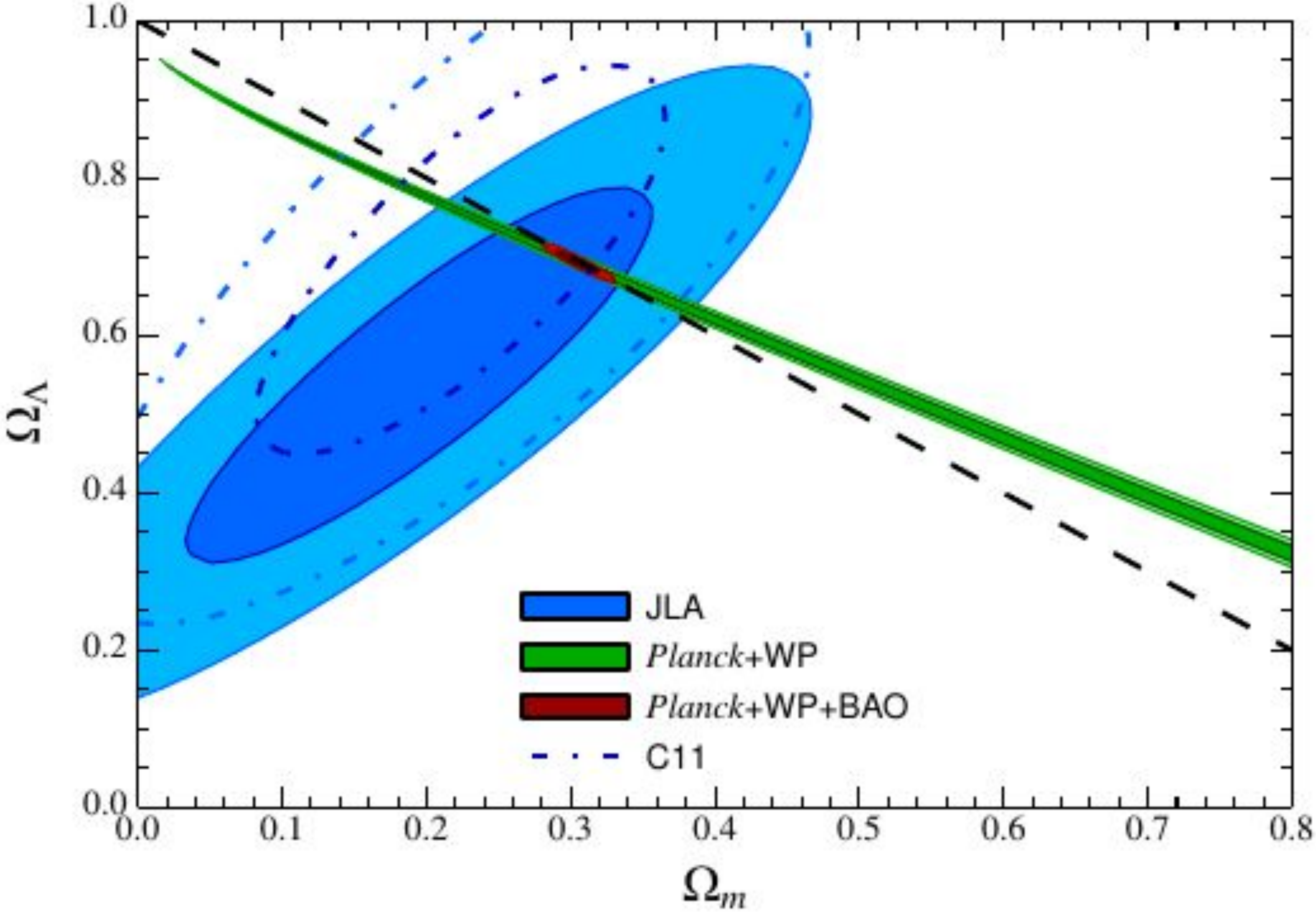
- 1998 : O(50) SNe
- 2005 : O(100) SNe
- 2014 : O(1000) Sne
- (x 20 in statistics)

Constraints on

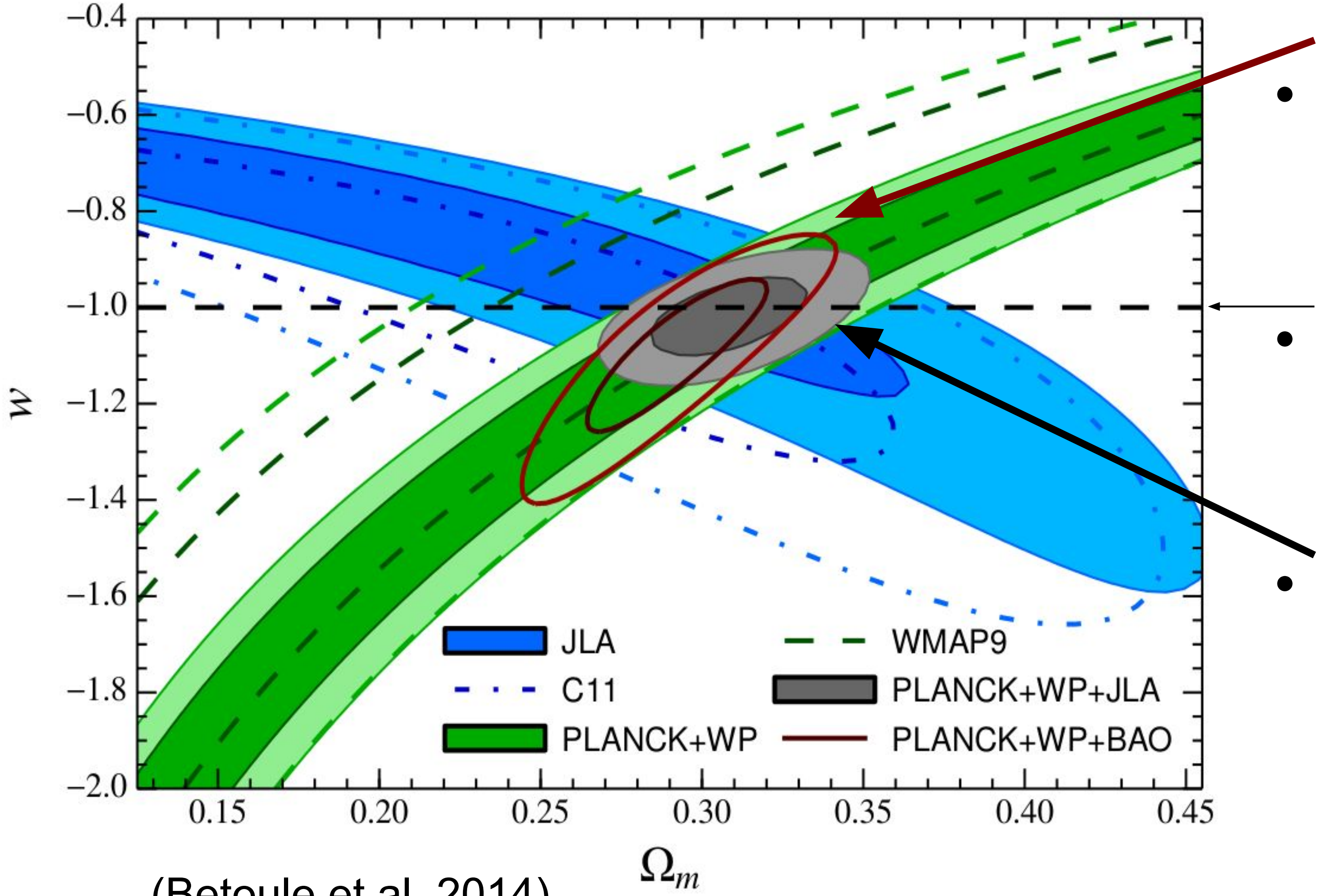
- ΛCDM
- And minimal extensions of ΛCDM
  - Add curvature (Ωk)
  - Add dark energy with arbitrary (constant) EoS (in a spatially flat universe)
  - Add dark energy with time varying EoS

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

Constraints in Ω_m-Ω_{Λ} plane



Flat wCDM

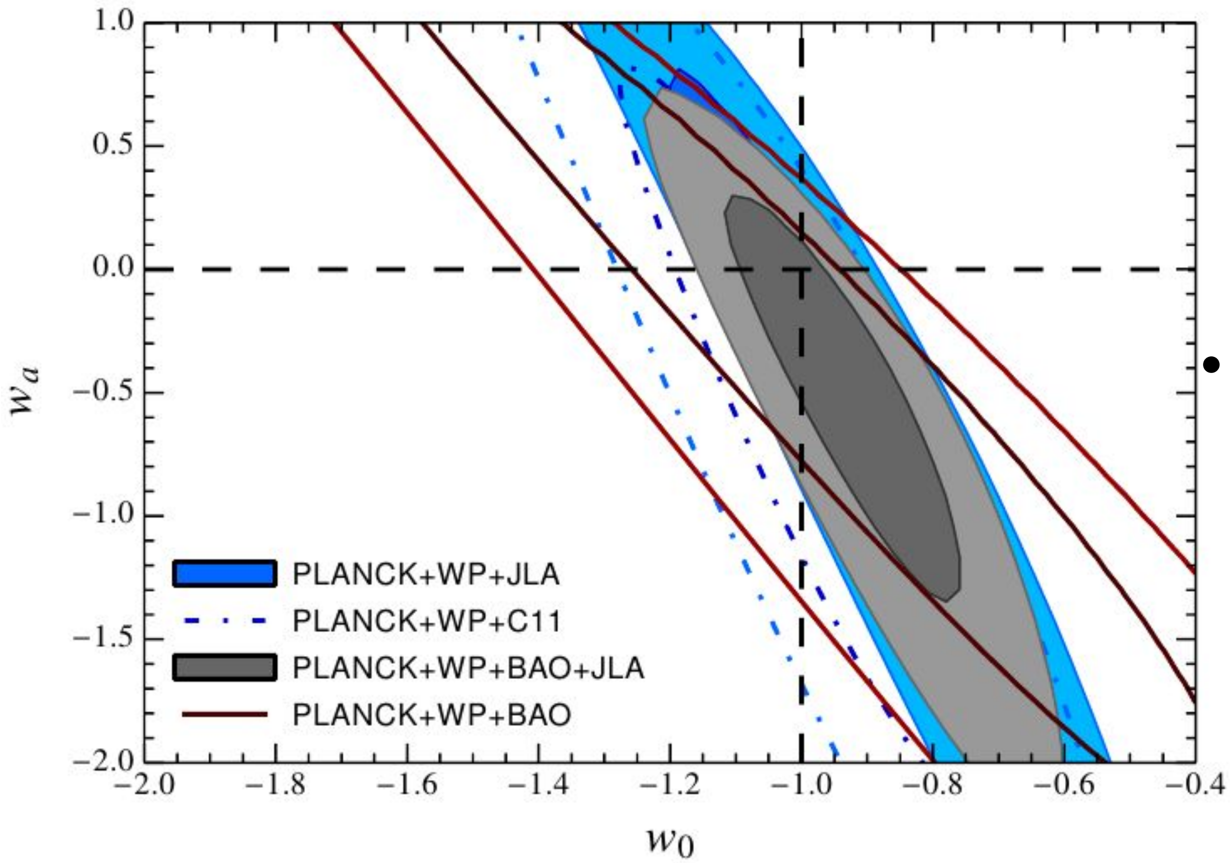


(Betoule et al, 2014)

- Planck + BAO
  - w = -1.01 ± 0.08
- Λ
- Planck + SNe
  - w = -1.018 ± 0.057

(see also Suzuki et al '12,
Rest et al '13, Scolnic et al '13...)
Scolnic et al '17

Marginal constraints on (w_p, w_a)



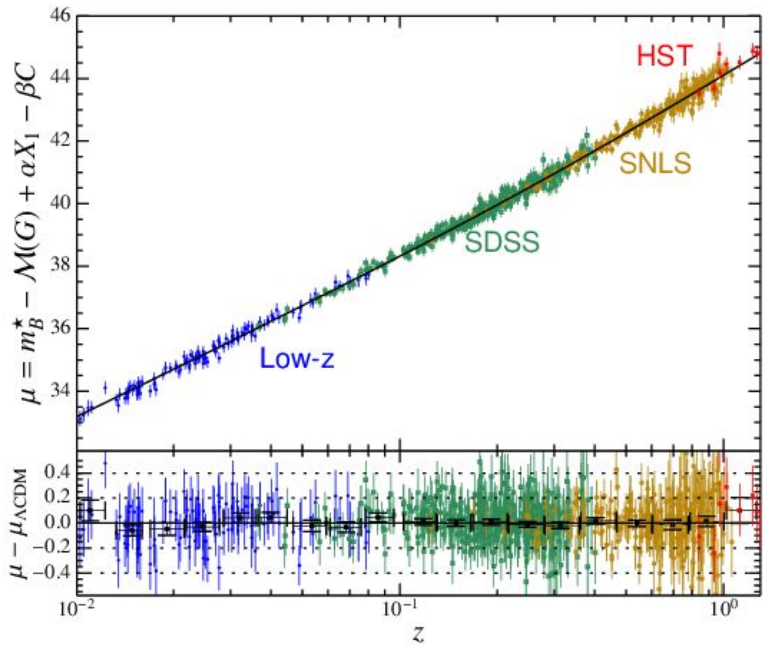
$$FoM = \frac{1}{\sigma(w_p) \times \sigma(w_a)}$$

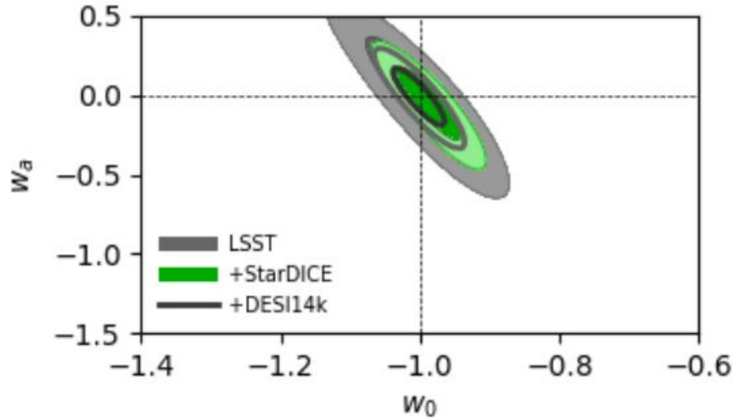
DETF : Albrecht et al '06
See also: Peacock et al '06

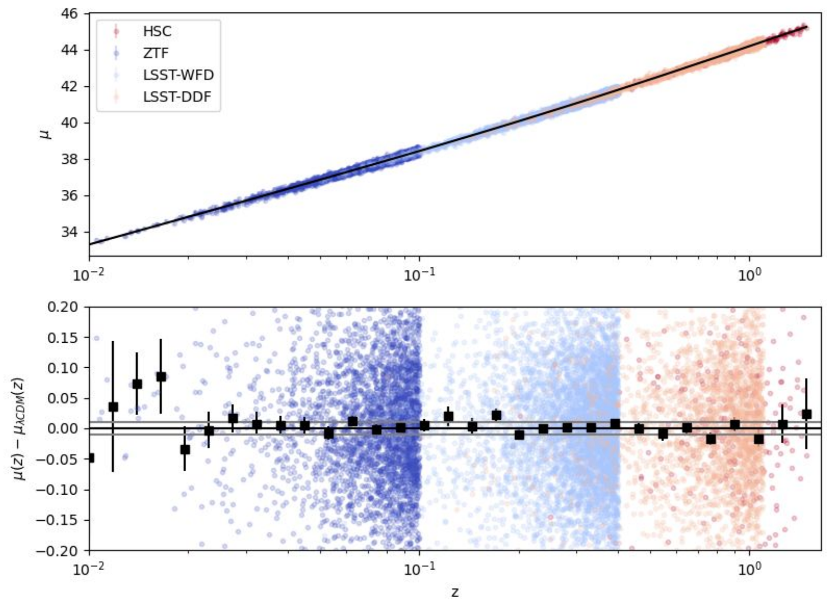
- DETF FoM ~ 15
- Ingredients
  - Large SDSS dataset
  - Calibration accuracy
  - Better CMB + BAO

Goals for next decade:
FoM > 400

The future

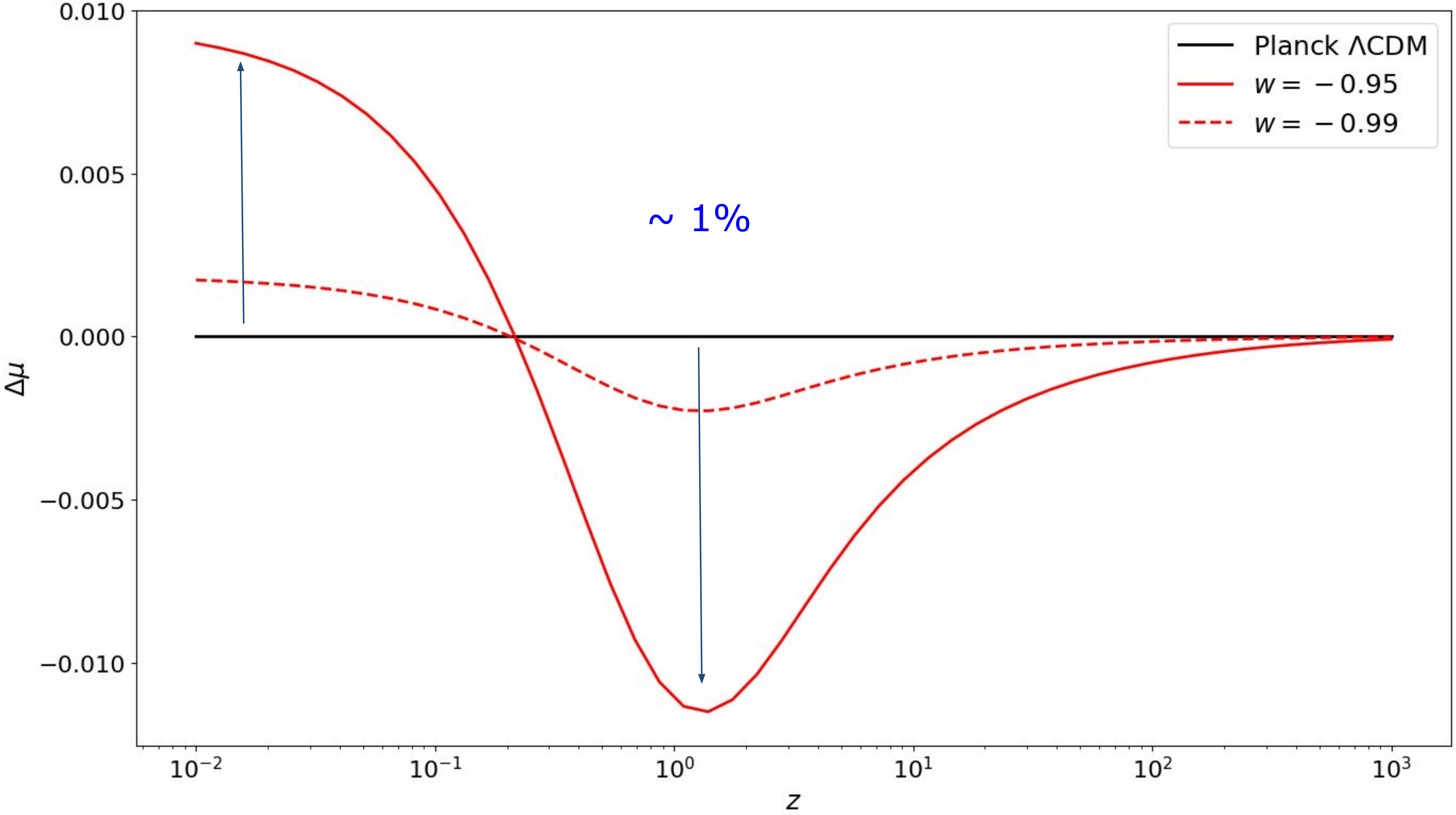




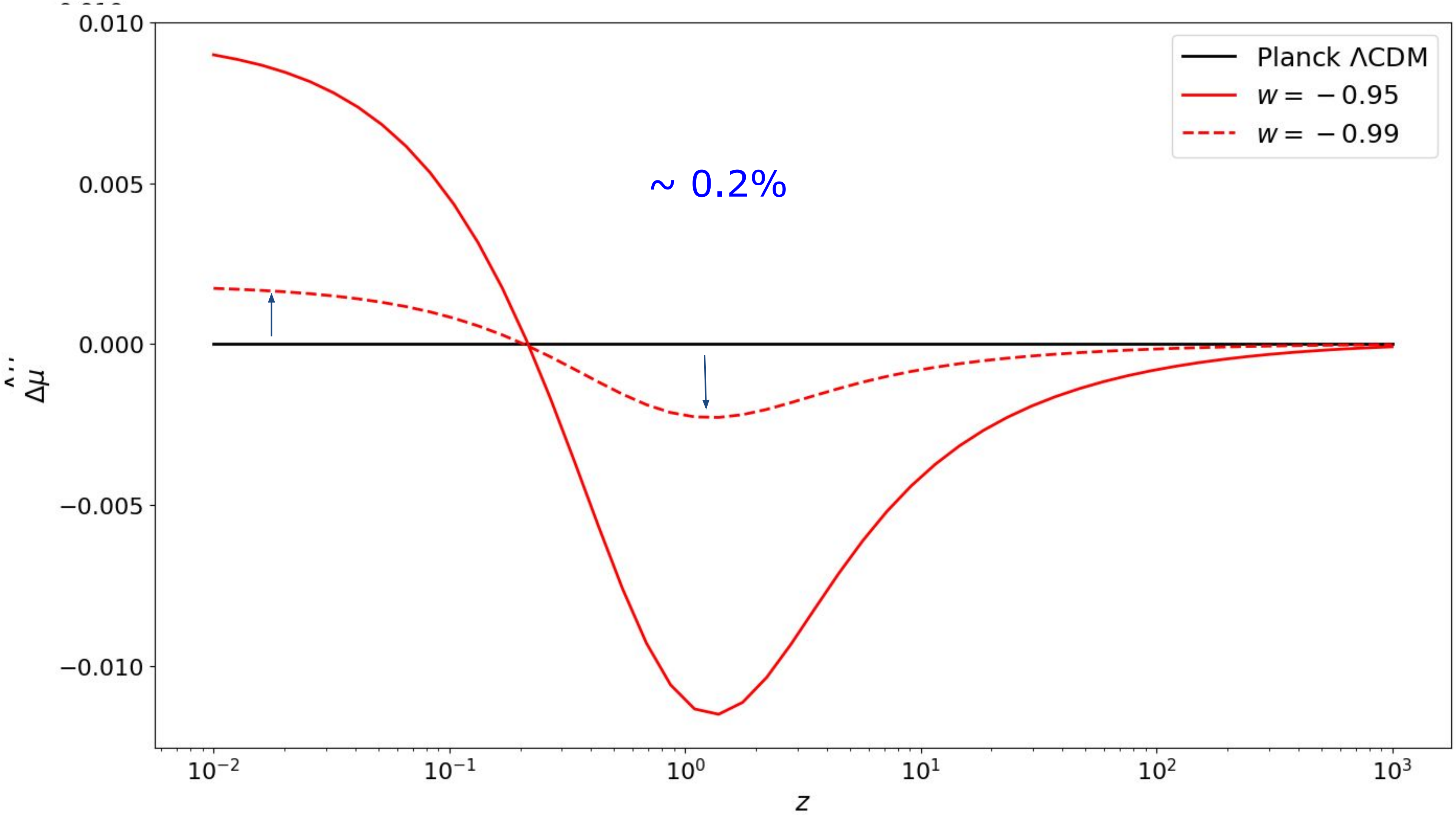


- 2014 : O(1000) SNe (JLA++)
- 2022 : O(5000) SNe
- 2025 : O(10000) SNe

Precision measurement

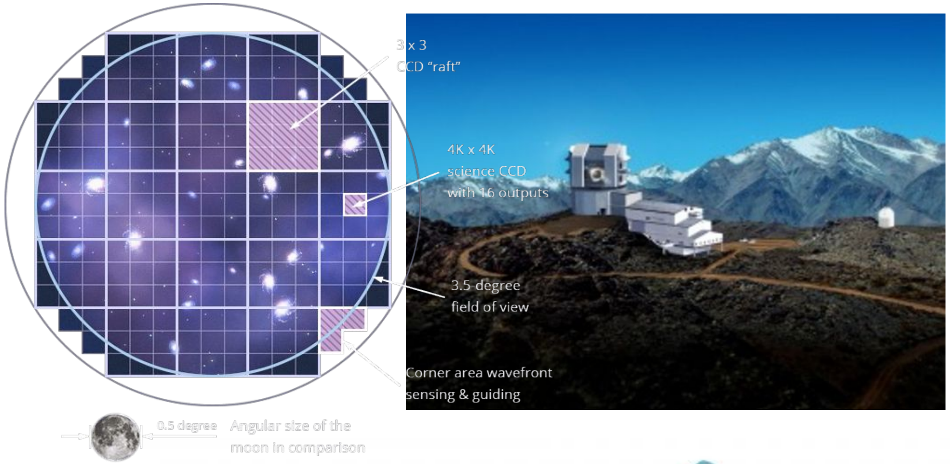


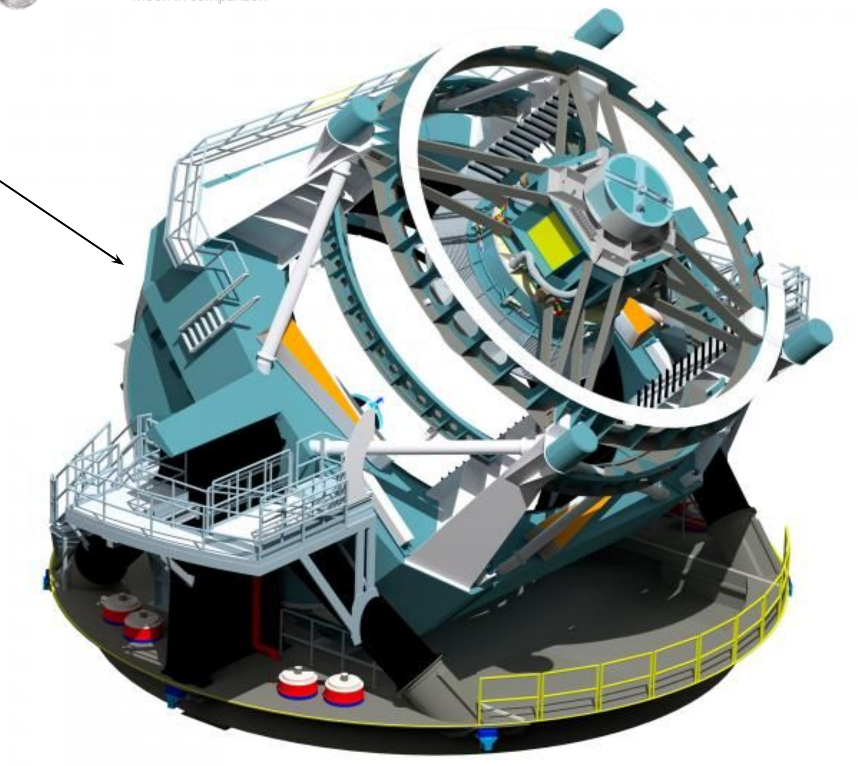
Precision measurement

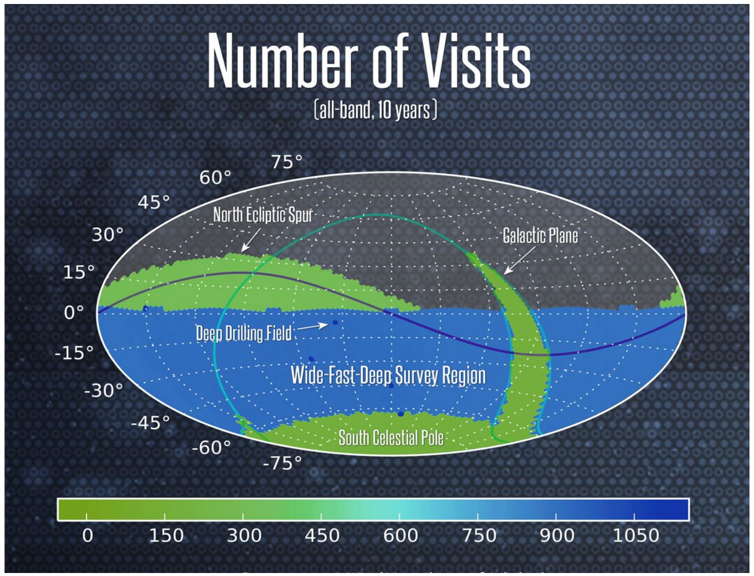


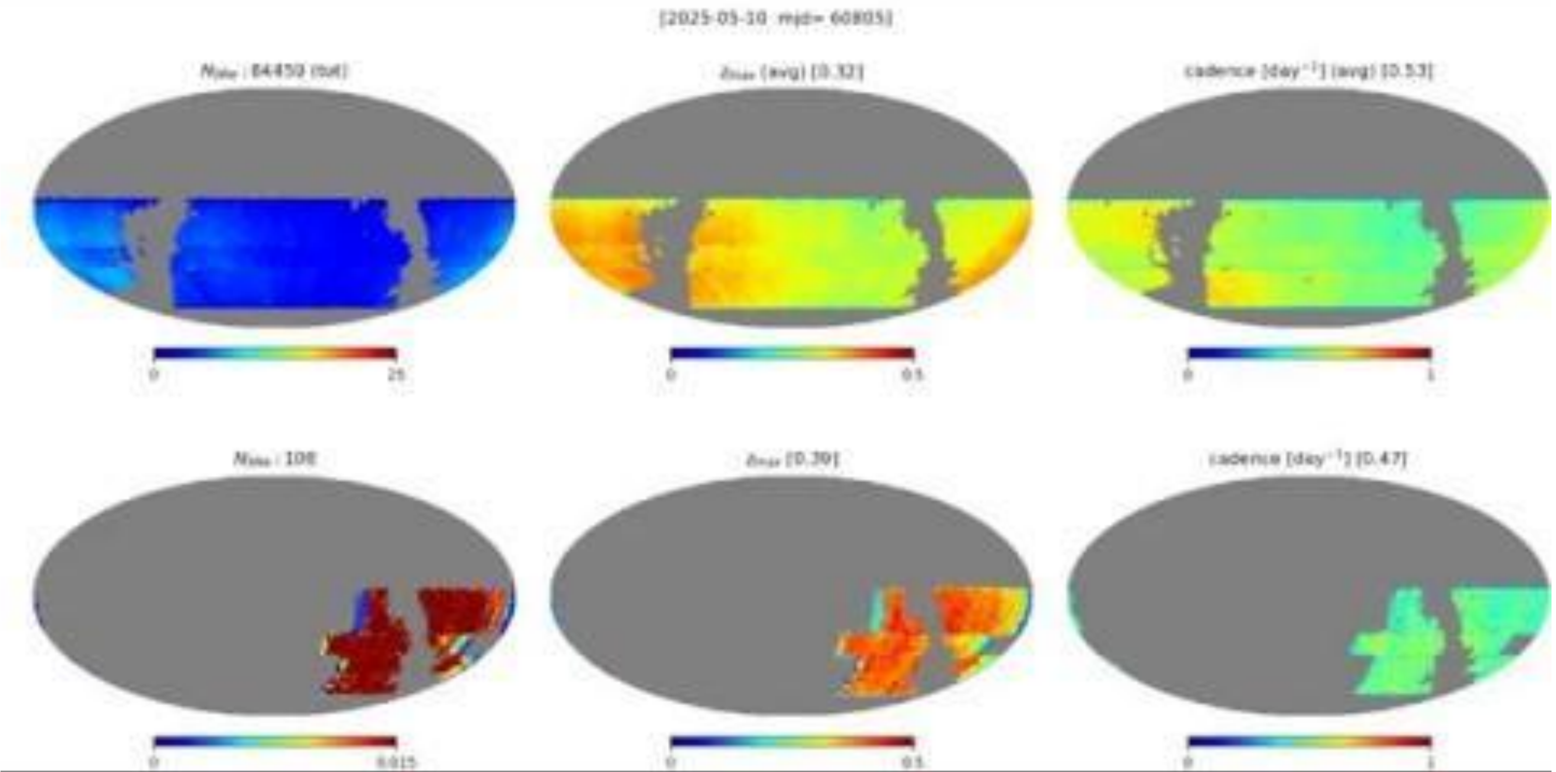
LSST

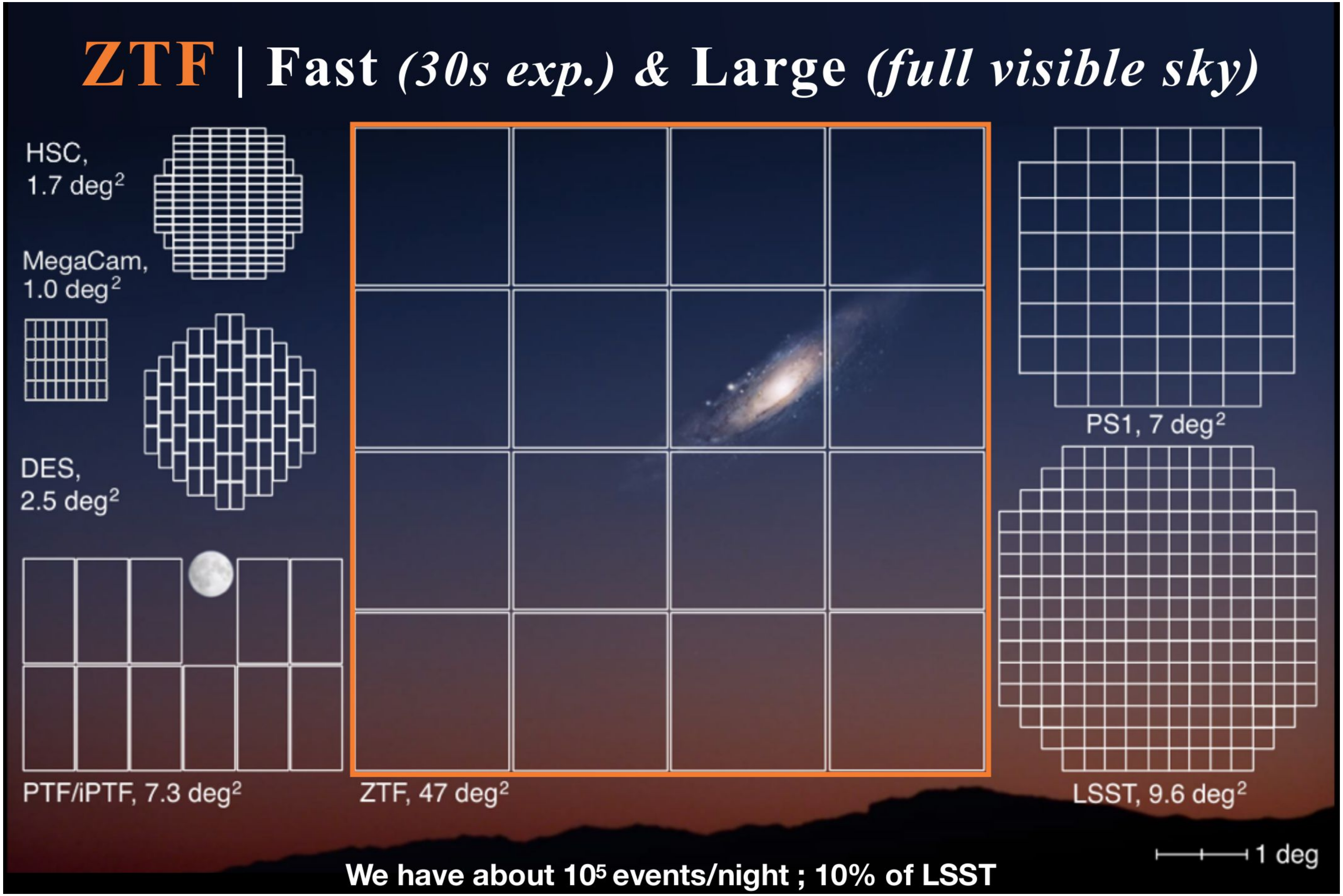
- LSST
- 8.4-m, 9.6 deg^2
- Chile



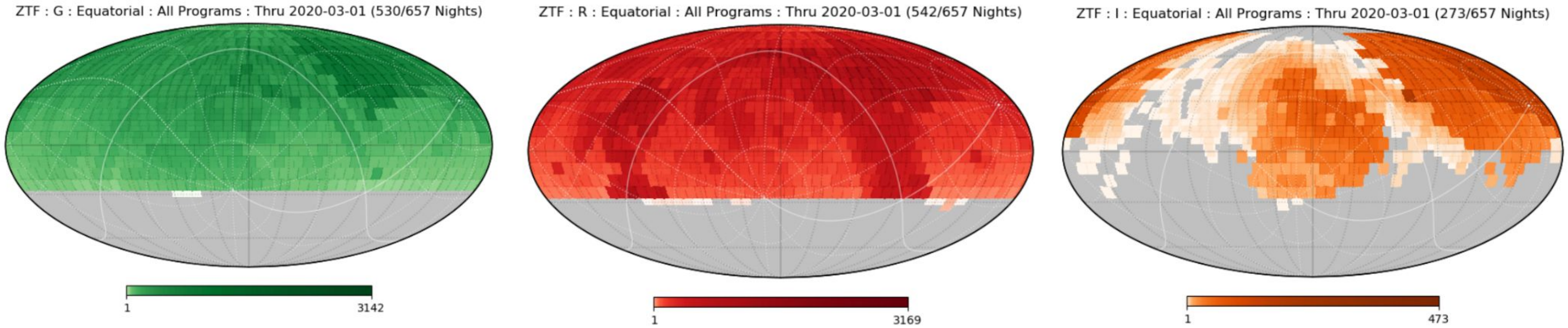





[2025-05-10 mjd= 60805]
N_{obs} : 84450 (tot)
z_{lim} (avg) [0.32]
cadence [day^{-1}] (avg) [0.53]
0
25
0
0.5
0
1
N_{obs} : 108
z_{lim} [0.30]
cadence [day^{-1}] [0.47]
0
0.015
0
0.5
0
1


ZTF | Fast (30s exp.) & Large (full visible sky)
HSC, 1.7 deg²
MegaCam, 1.0 deg²
DES, 2.5 deg²
PTF/iPTF, 7.3 deg²
ZTF, 47 deg²
PS1, 7 deg²
LSST, 9.6 deg²
1 deg
We have about 10⁵ events/night ; 10% of LSST

Survey of the full northern sky



- 3 bands
  - g,r & I
- "MSIP" survey
  - LSST-like survey of northern sky in g & r (2-3 day cadence)
- Partnership survey
  - High cadence observations of 10% of the sky (5-6 visits/night)
  - I-band observations of 50% of the sky (~5 day cadence)
- + other partnership programmes (solar system, ToO monitoring of GW events …)

BAO

- Measuring
  - angular distances

$$\int \frac{dz}{H(z)}$$

$$d_A = \frac{a_0 r}{1+z} = \frac{a_0 S_K(\chi)}{1+z}$$

  - longitudinal separation :

$$\delta z = \frac{1}{c} H(z)(1+z)\delta\ell$$

measured

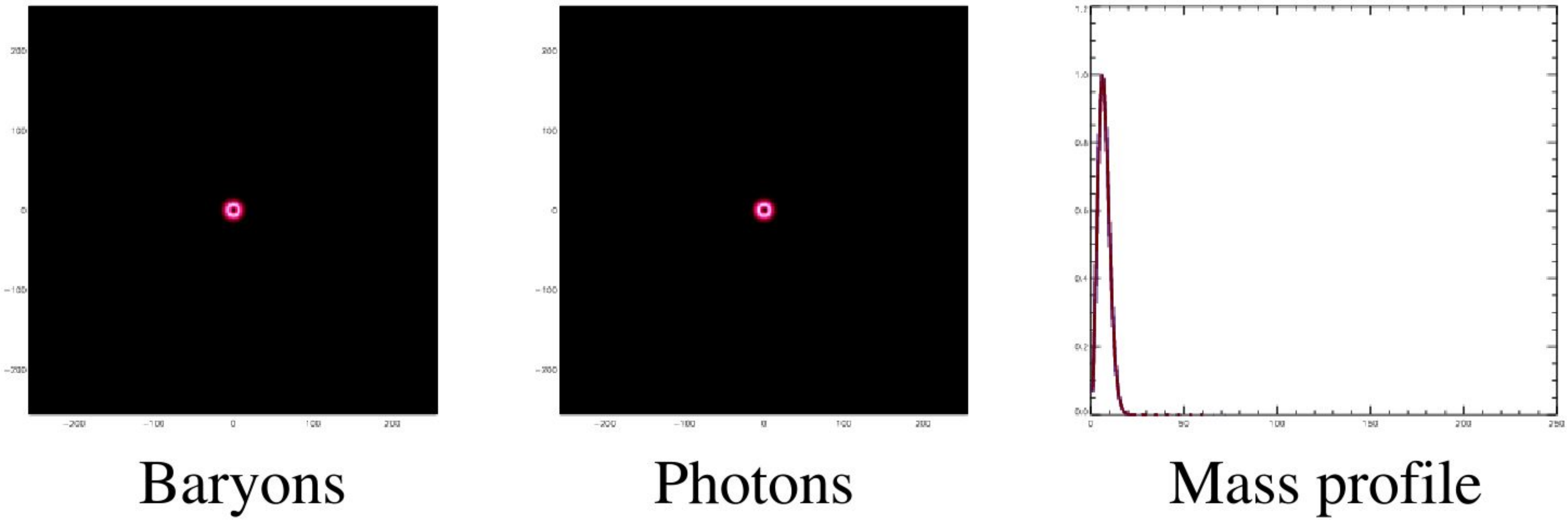
Theory

measured

known (theory or measurement)

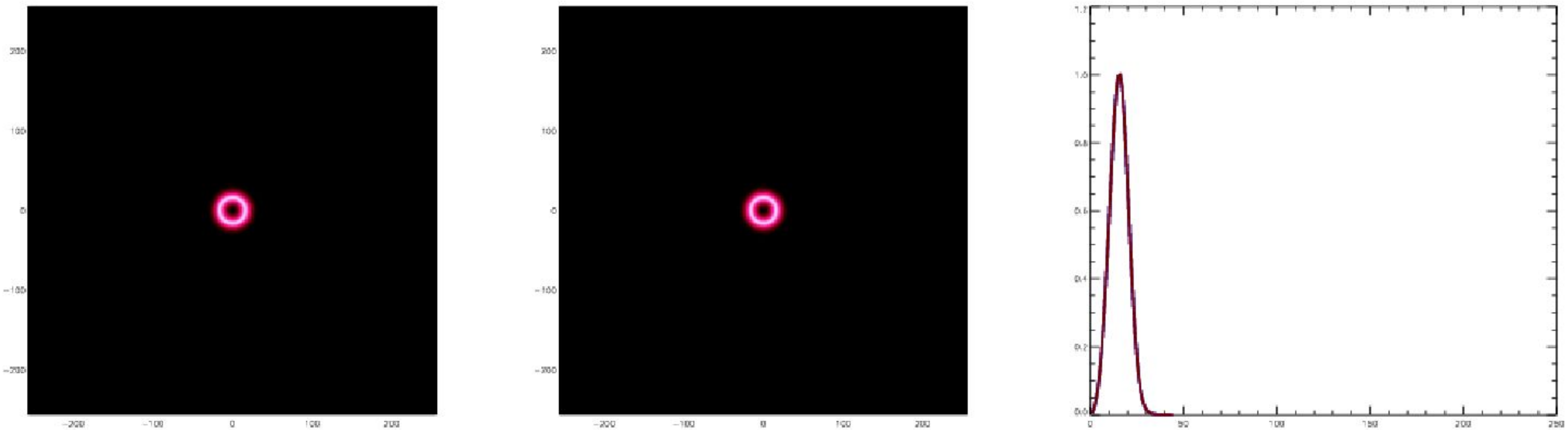
Direct measurement of H(z)

The acoustic wave



Uniform plasma. Single perturbation (excess of matter) at the origin.
High pressure -> gas + photon fluid pushed outwards (v ~ c/sqrt(3))

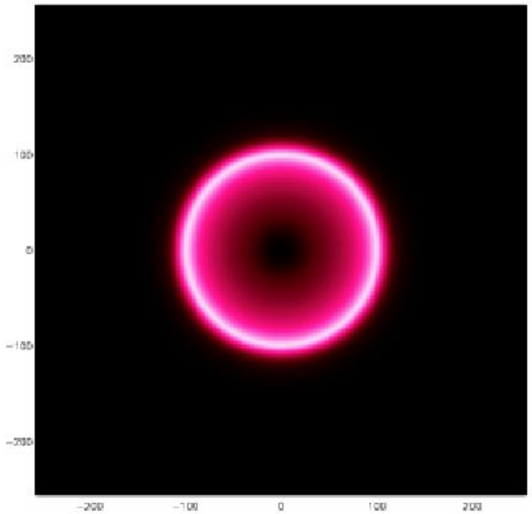
The acoustic wave

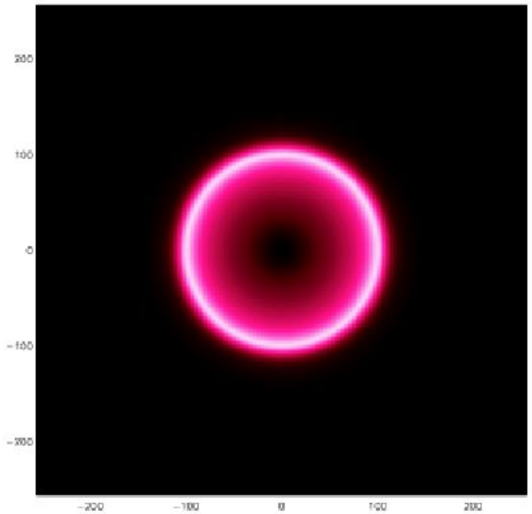


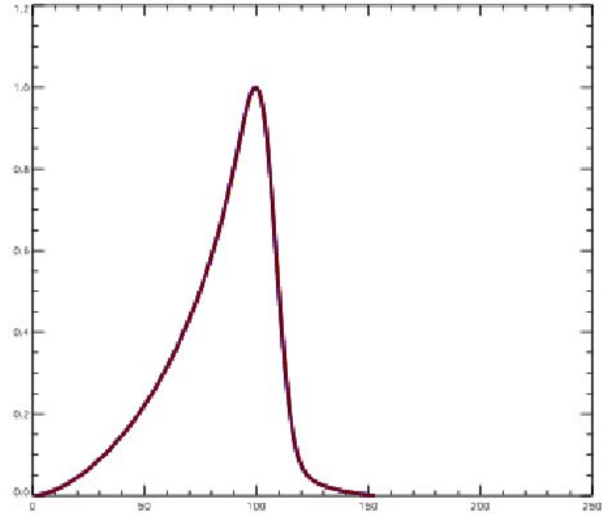
Baryons Photons

Photons and baryons expand together.

The acoustic wave

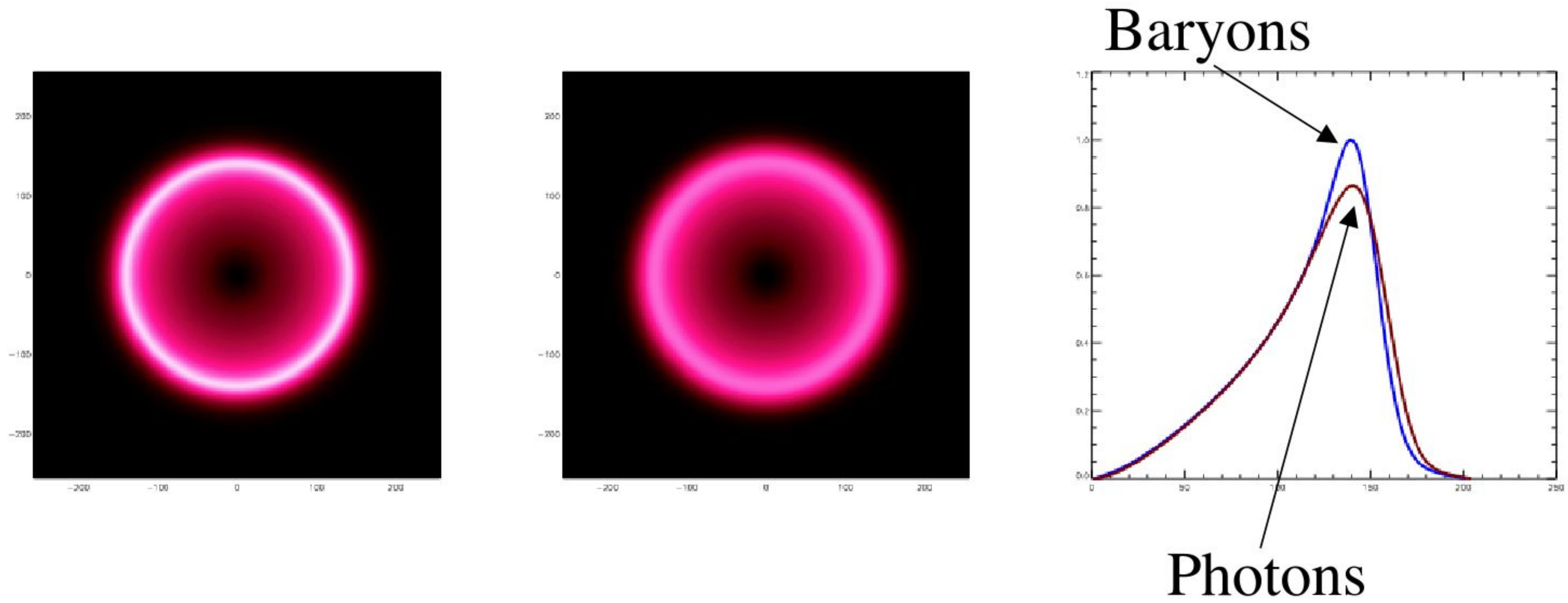






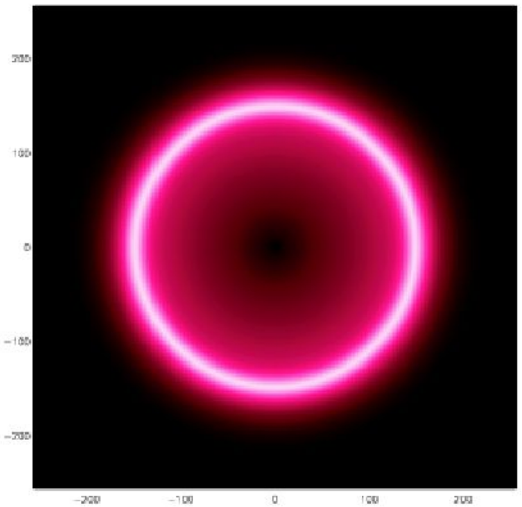
Expansion continues for 10^5 years (until recombination)

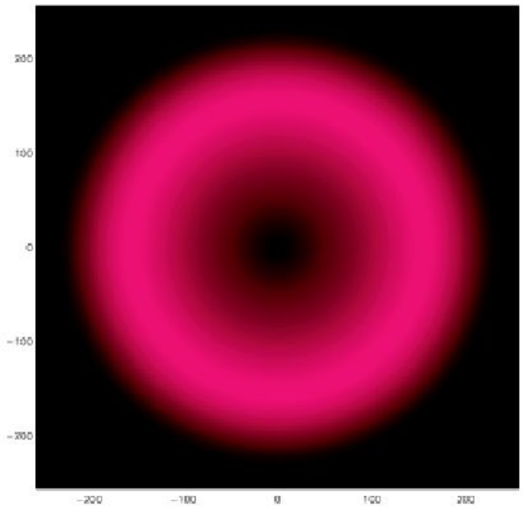
The acoustic wave

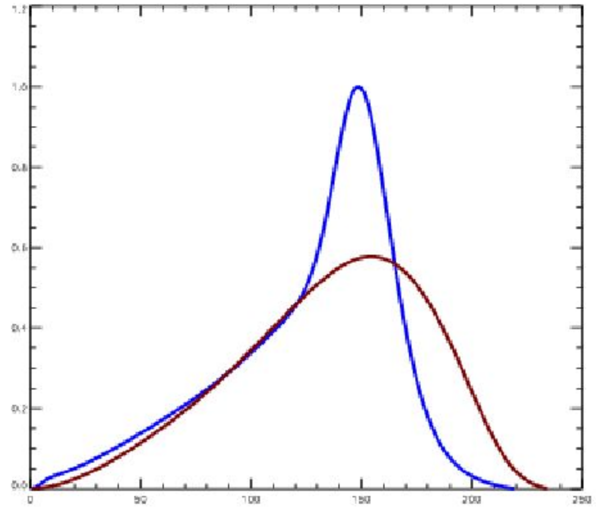


At recombination (10^5 years), Universe has cooled enough -> form H atoms. Photons and baryons decouple. Photons stream away. Baryon perturbation remains in place.

The acoustic wave

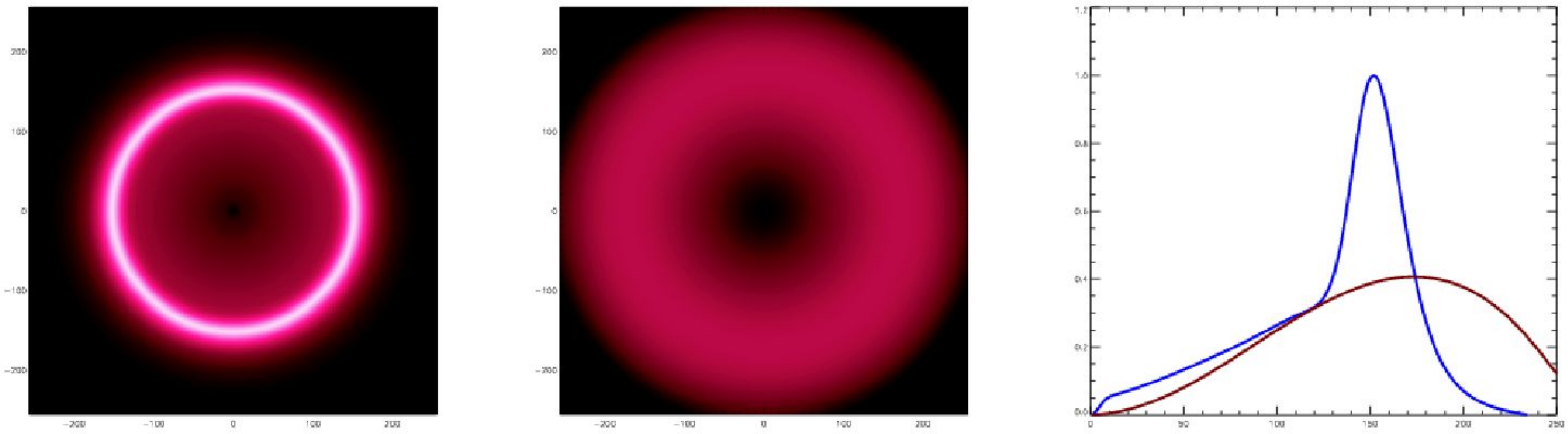






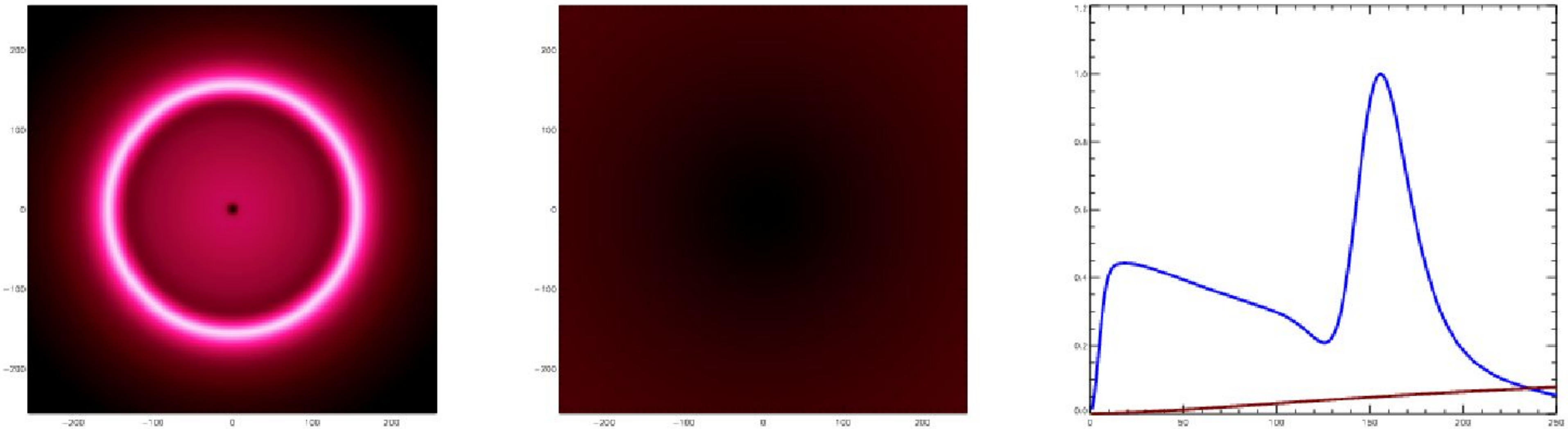
Process goes on.

The acoustic wave



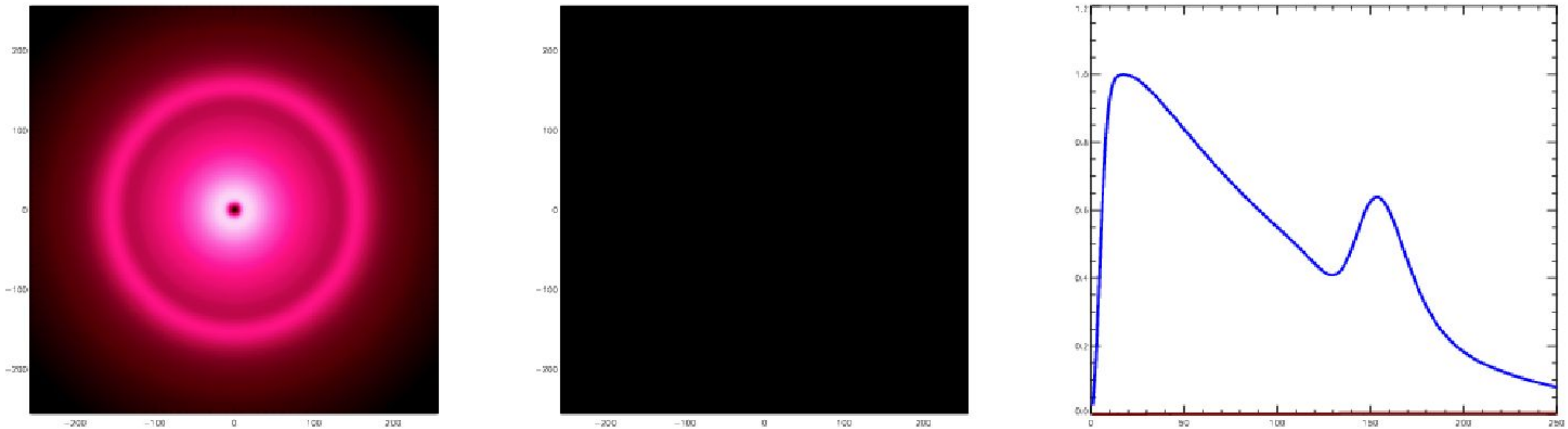
… and on

The acoustic wave

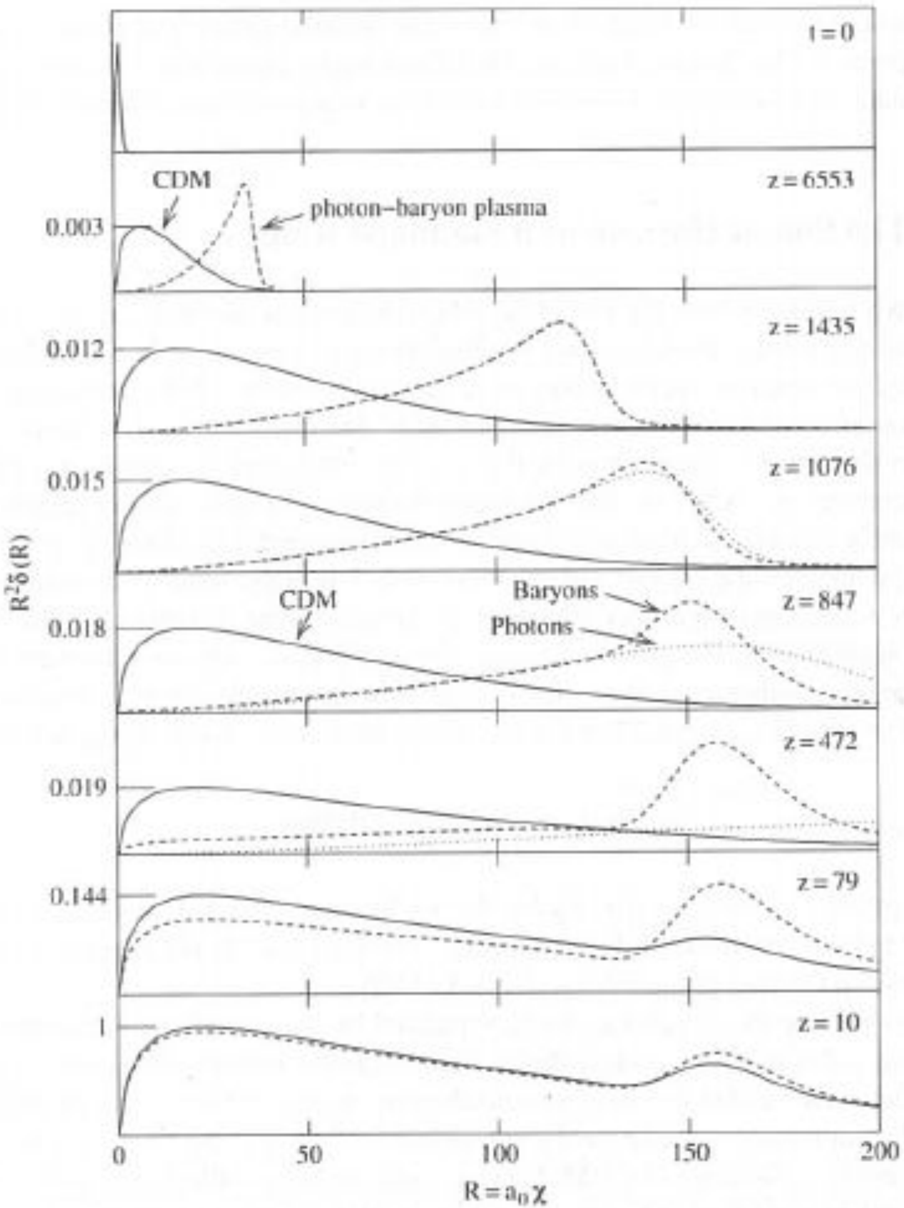


Photons now uniform. Baryons remain in a shell ~ 100 Mpc in radius. Gravity starts pulling material back into potential wells.

The acoustic wave



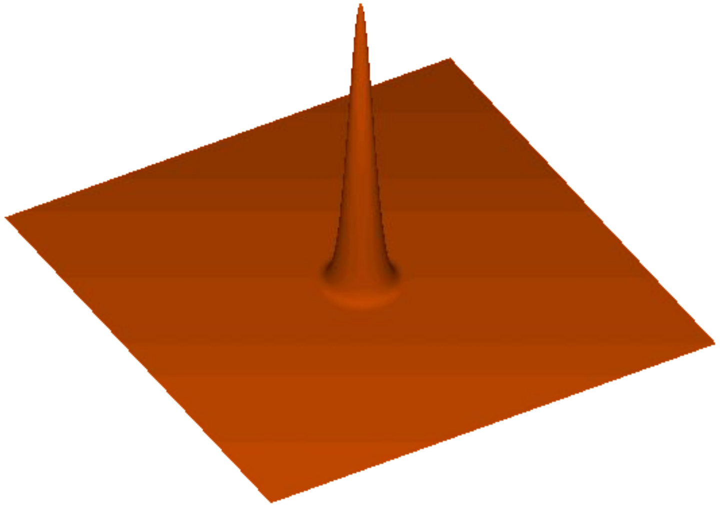
Final configuration. Shell of overdense baryons around initial perturbation.
100Mpc in radius. Non linear effects broaden and (slightly) shift the peak



t = 0
z = 6553
CDM
photon–baryon plasma
0.003
z = 1435
0.012
z = 1076
0.015
z = 847
CDM
Baryons
Photons
0.018
z = 472
0.019
z = 79
0.144
z = 10
1
$R^2\delta(R)$
0
50
100
150
200
$R = a_0\chi$

Baryon accoustic oscillations

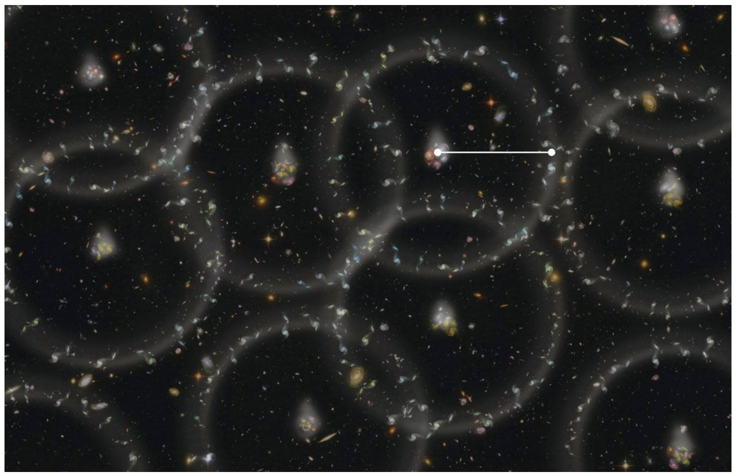
- Oscillations in primordial plasma

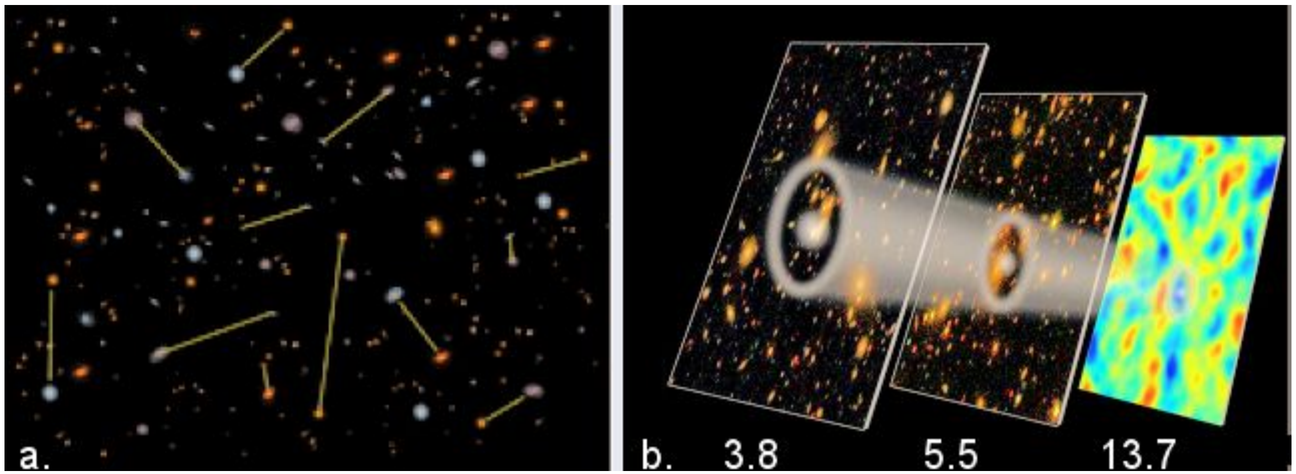


$$r_s = \int_0^{t_\star} \frac{c_s(t)}{a(t)} dt$$ = 147.5 ± 0.6 Mpc

(Planck Coll XVI)

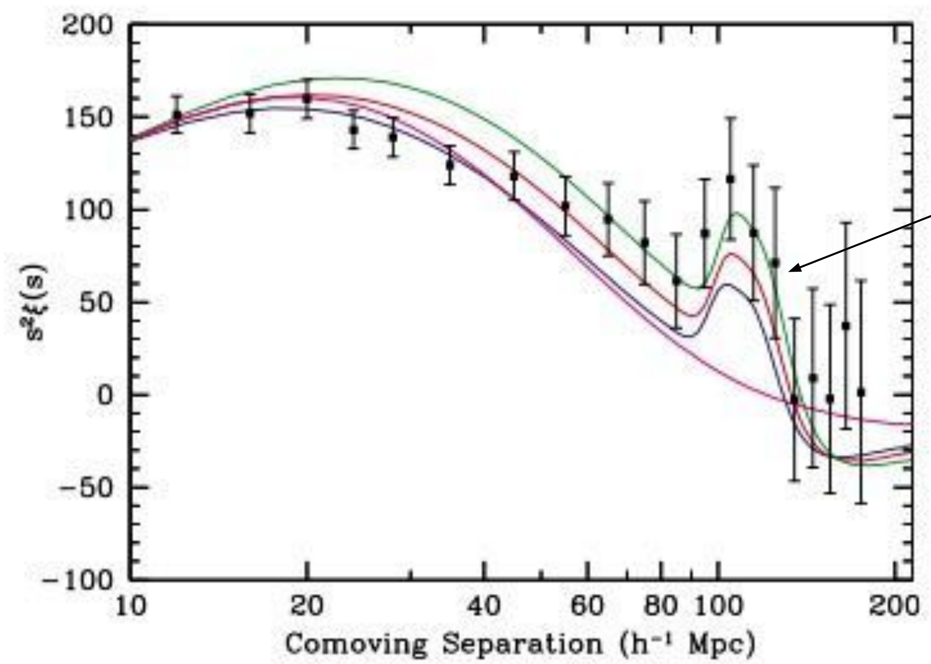
Simple, linear physics





Baryon accoustic oscillations

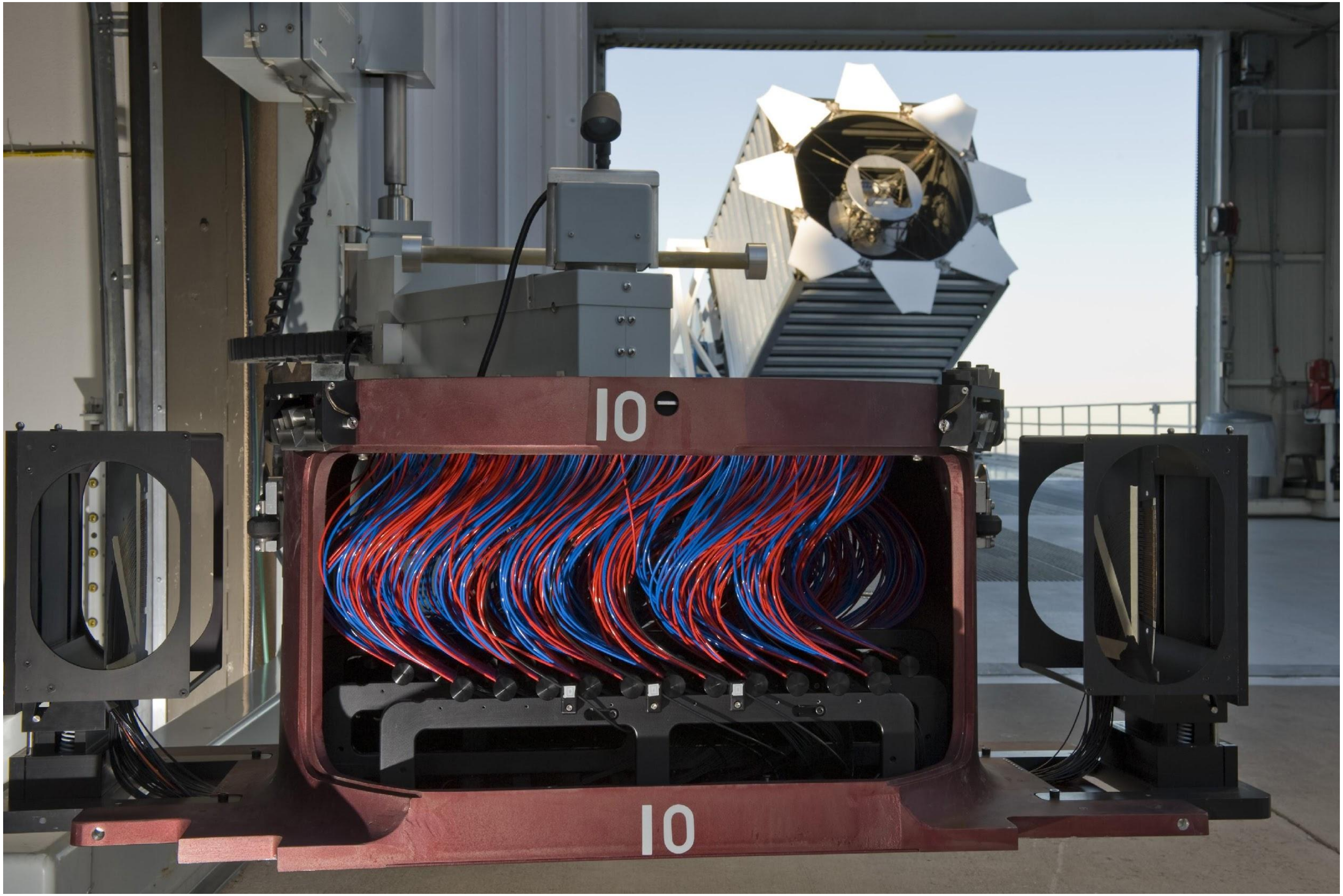
- With a massive spectroscopy survey, one can measure the positions (θ, φ, z) of enough ($\sim 10^5 - 10^6$) galaxies and histogram their distances :



Baryon accoustic peak !

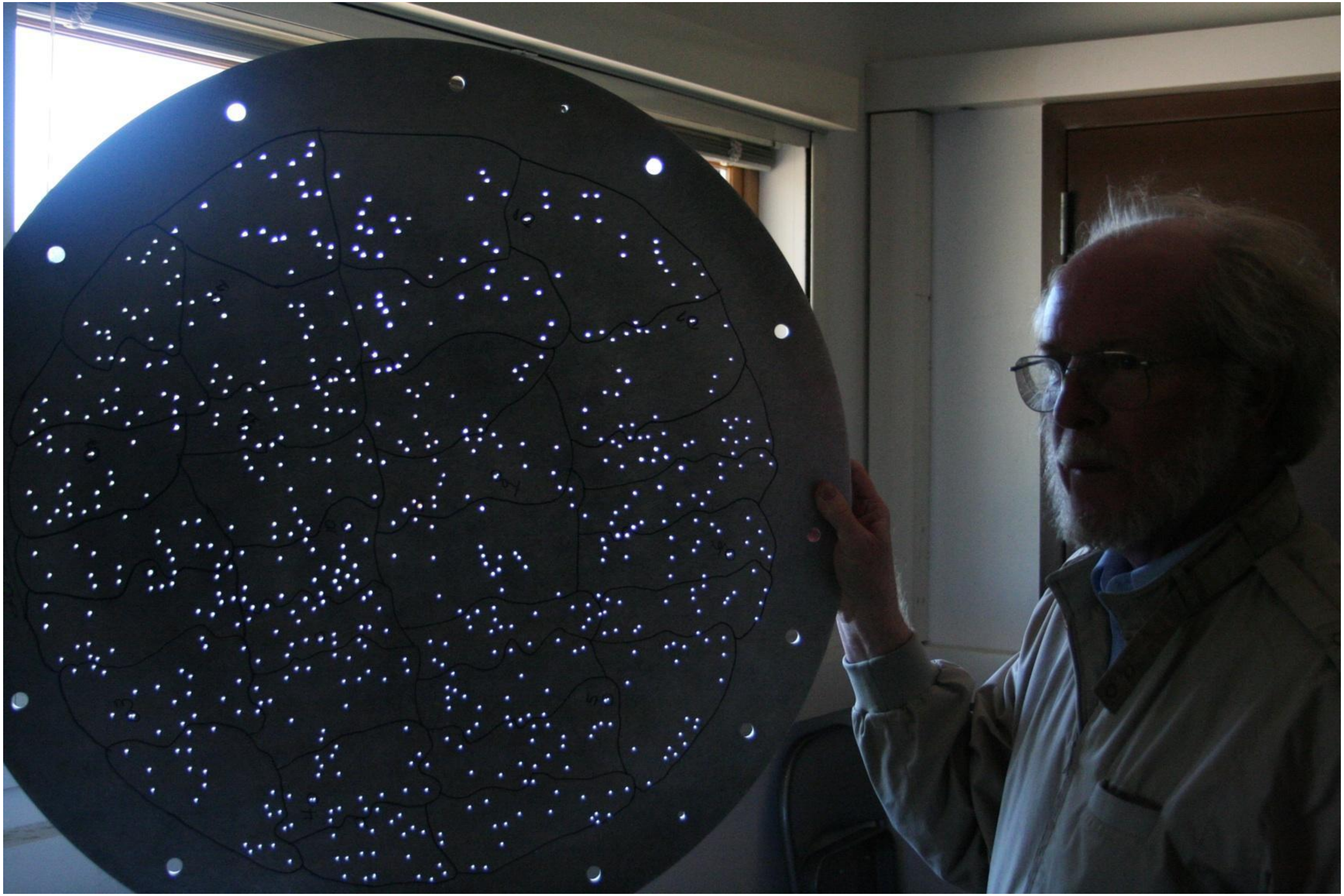
(Eisenstein et al, '05 Cole et al

Massive spectroscopic survey

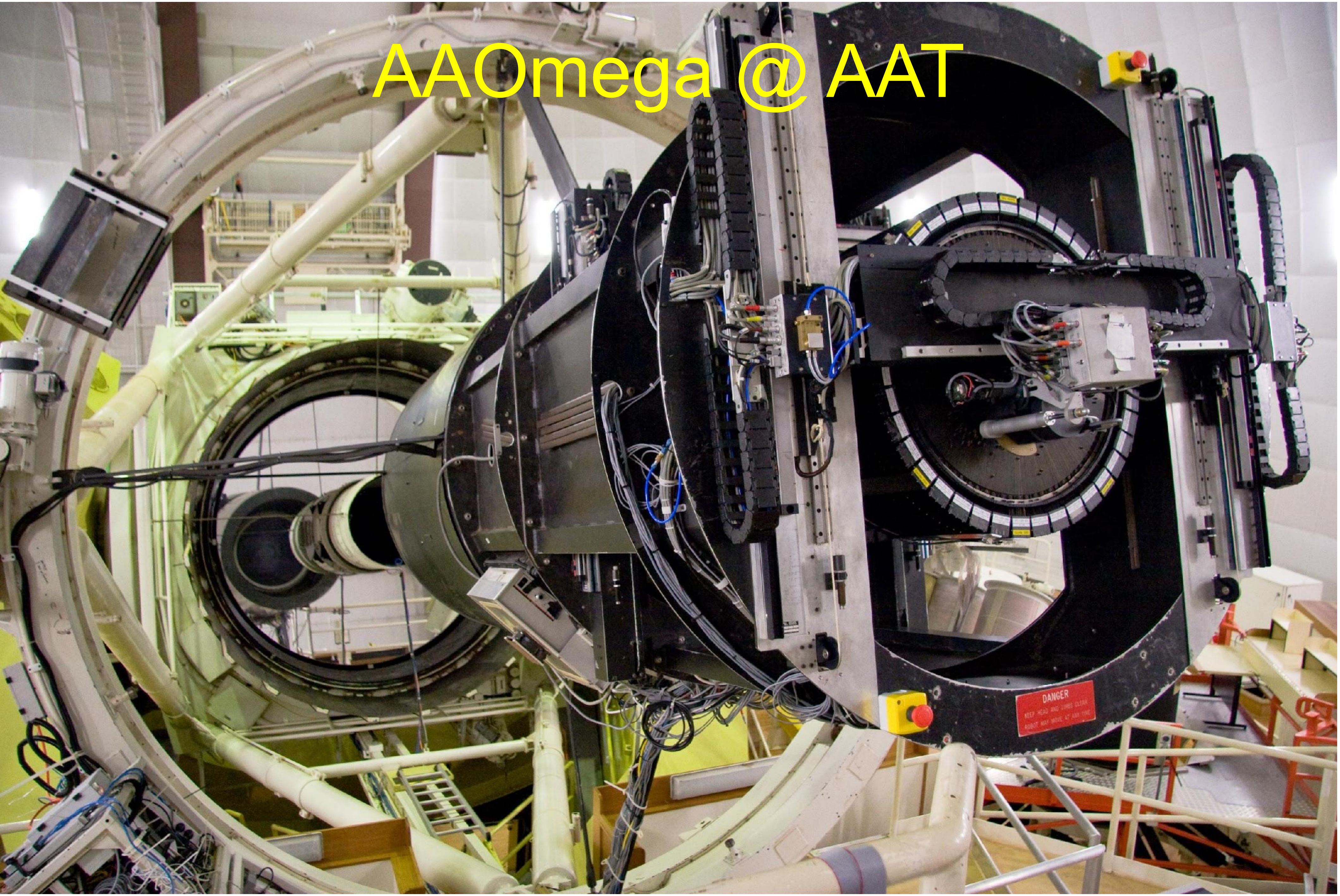


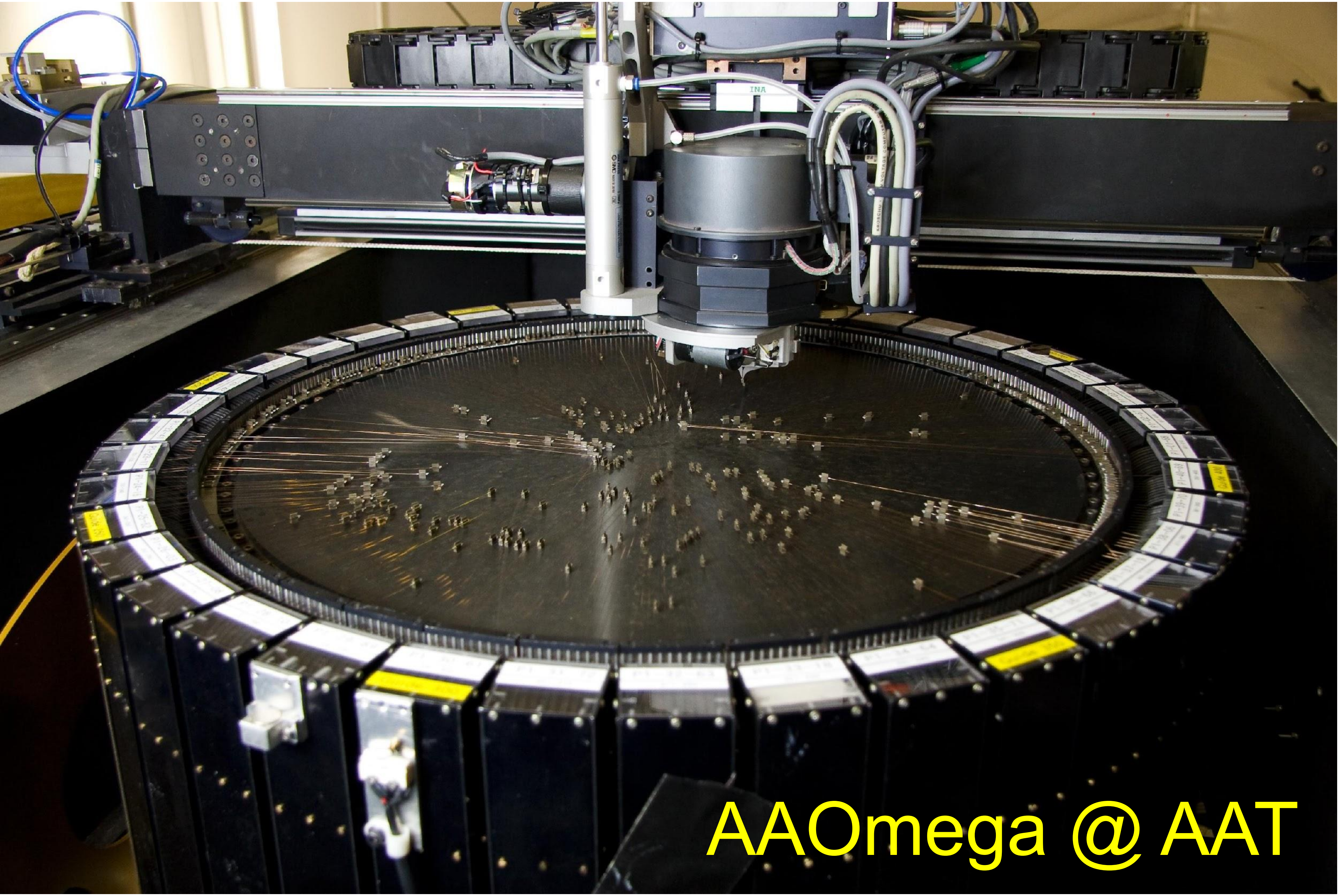
SDSS-III/BOSS

Massive spectroscopic survey

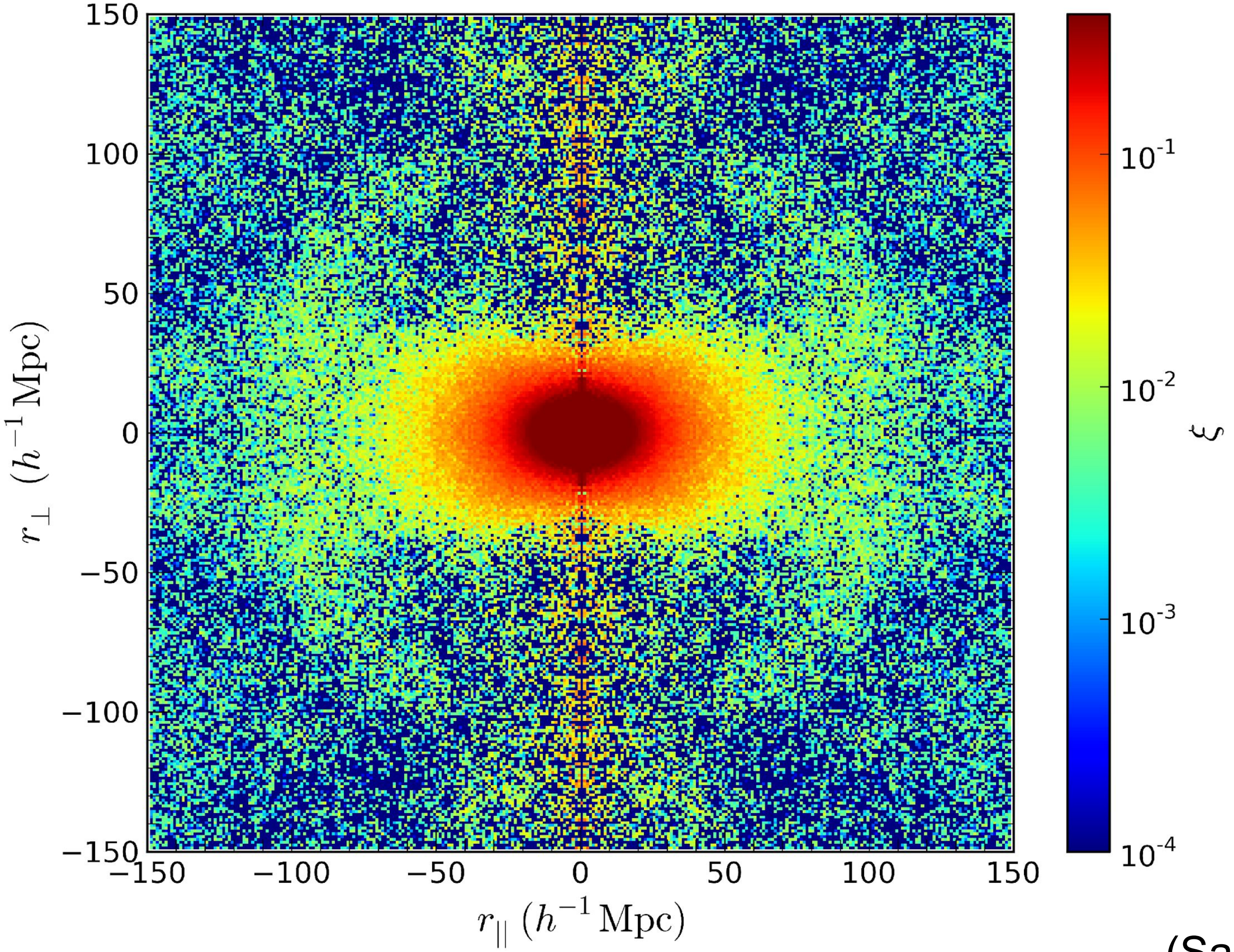


AAOmega @ AAT



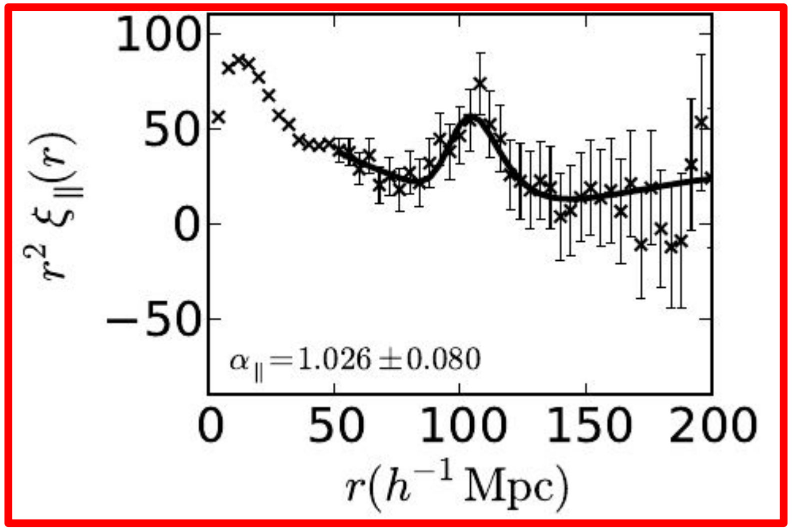

AAOmega @ AAT

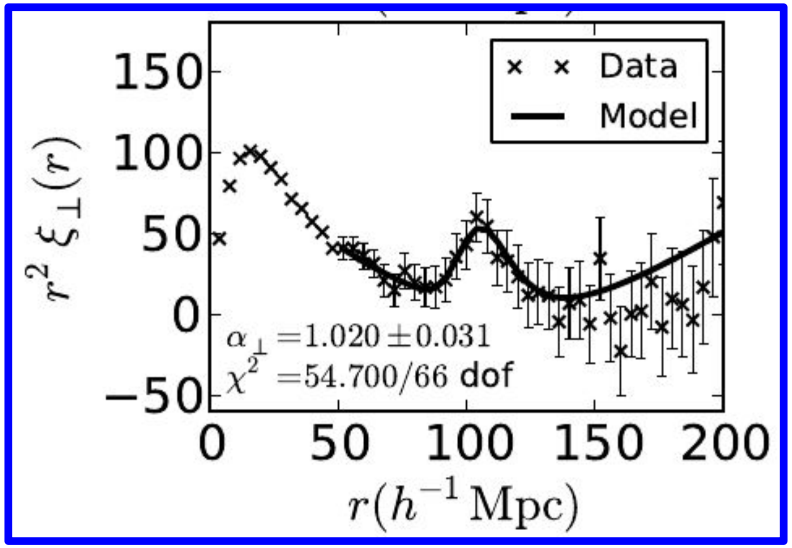
2D correlation function



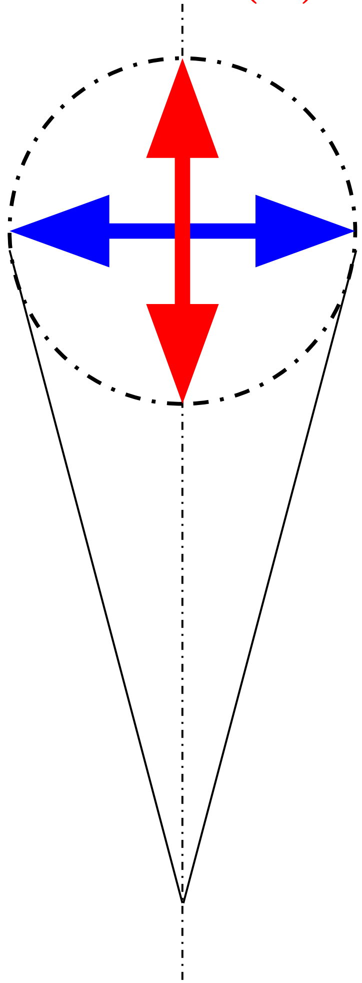
(Samushia et al, 2013)

Not just angular distances...





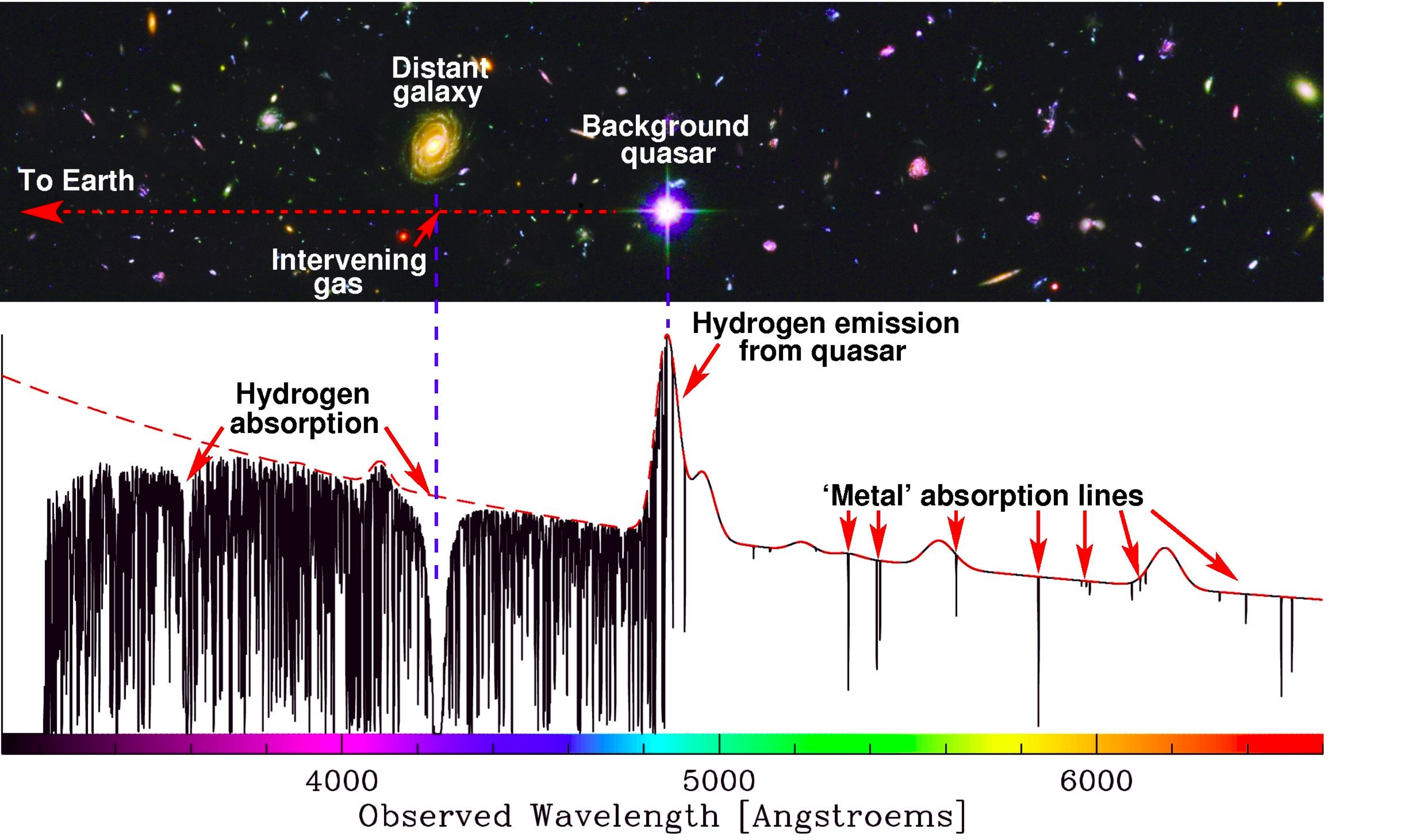
$$\delta r_{\parallel} = \frac{c}{H(z)}\Delta z$$



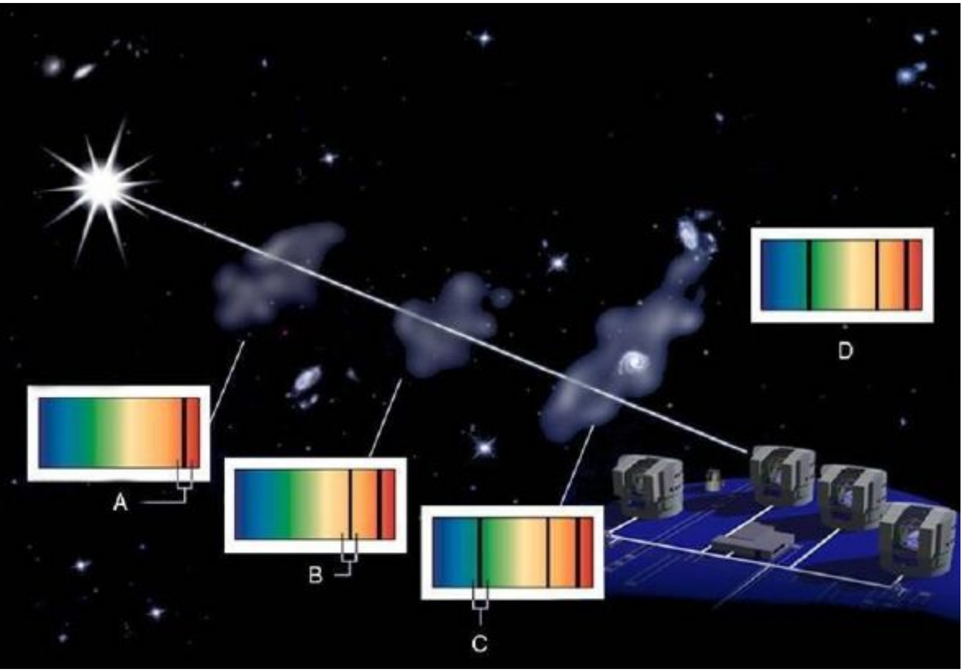
$$\delta r_{\perp} = D_A \delta\theta$$

$$\propto \int \frac{dz}{H(z)}$$

BAO in the Ly-α Forest

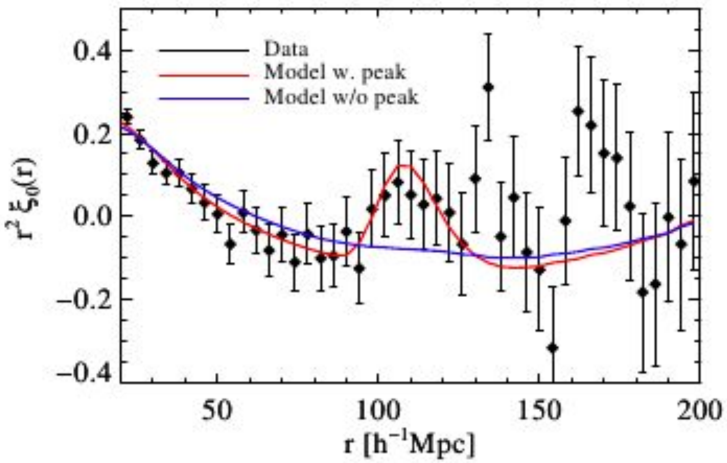


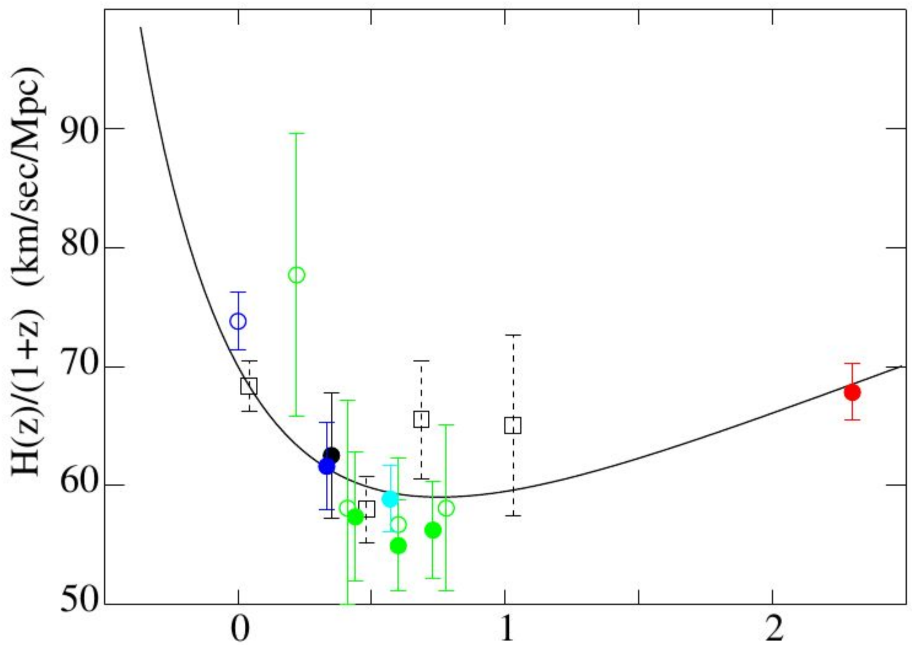
BAO in the Ly-α Forest



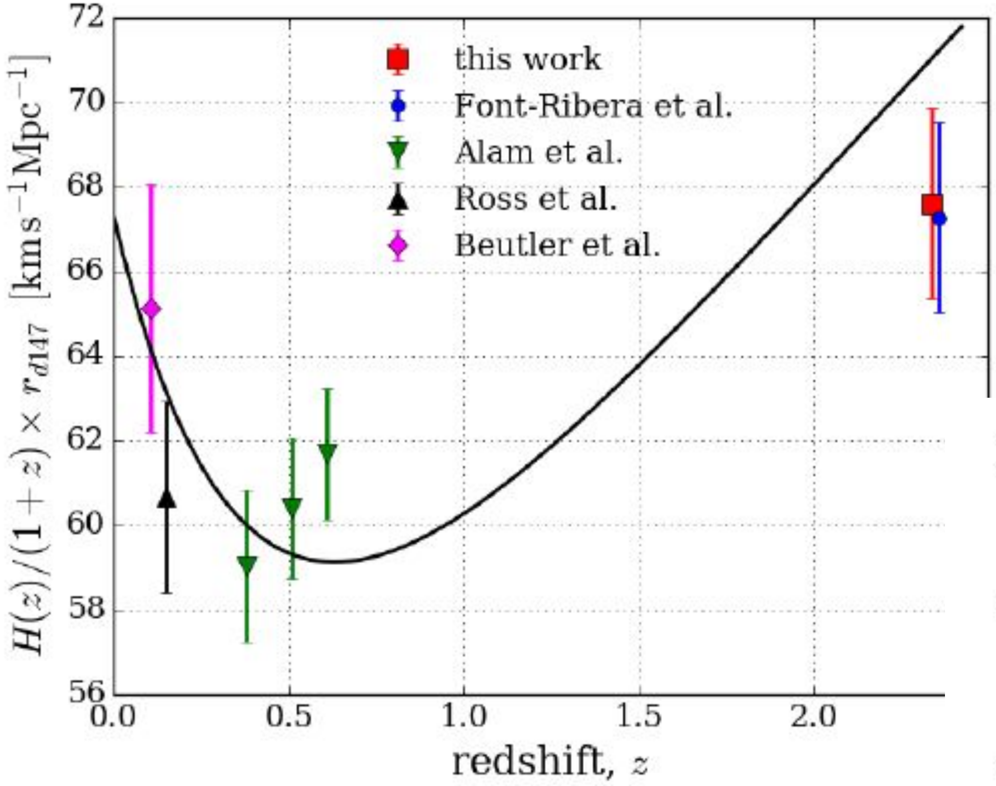
- Background quasars
- Light travels through the intergalactic medium (ionized H)
- Ly-α, absorption line

$\lambda = 1215Å$

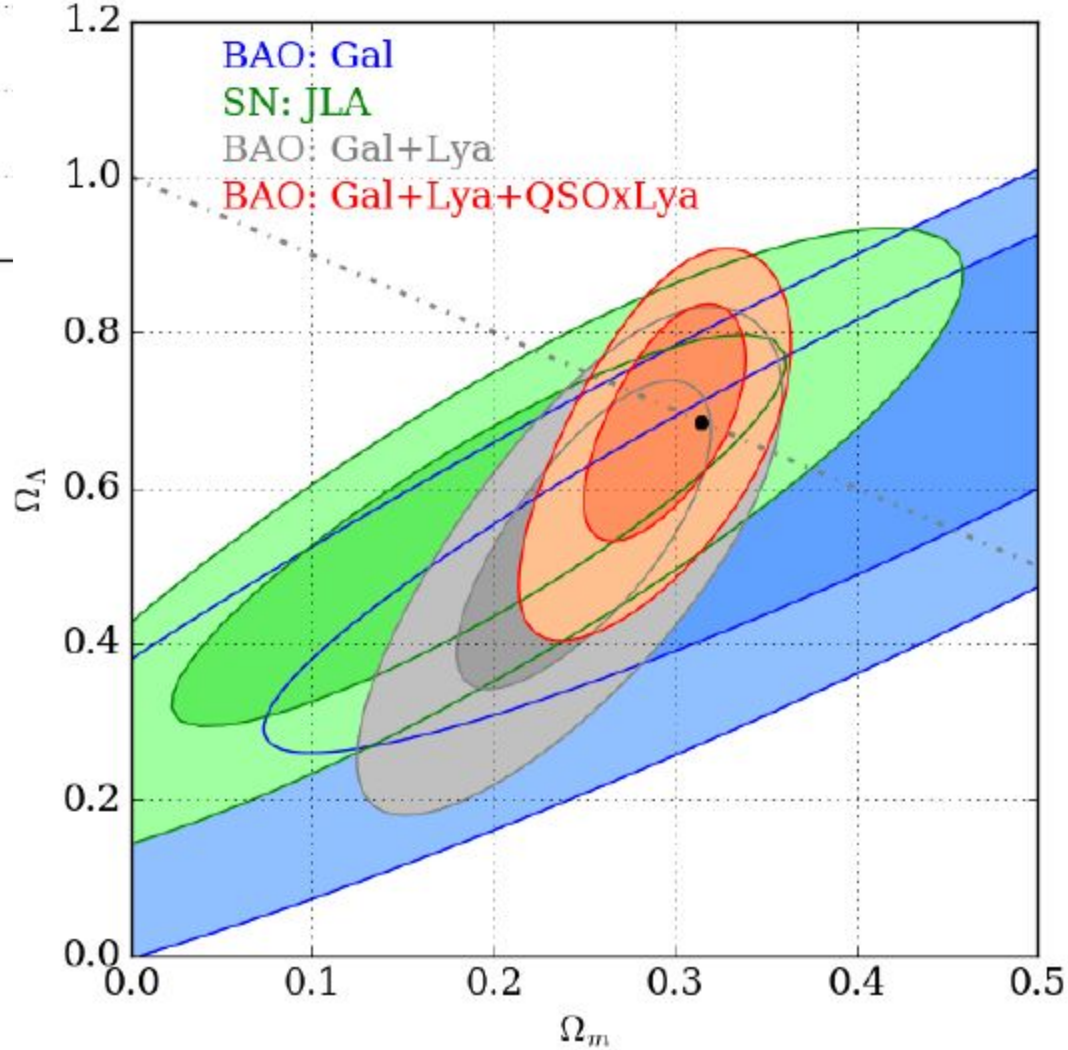




(See e.g. Busca et al, '12, Delubac et al, '15, Font Ribeira et al, '14)



this work
Font-Ribera et al.
Alam et al.
Ross et al.
Beutler et al.
$H(z)/(1+z) \times r_{d147}$ [km s^{-1}Mpc^{-1}]
redshift, z

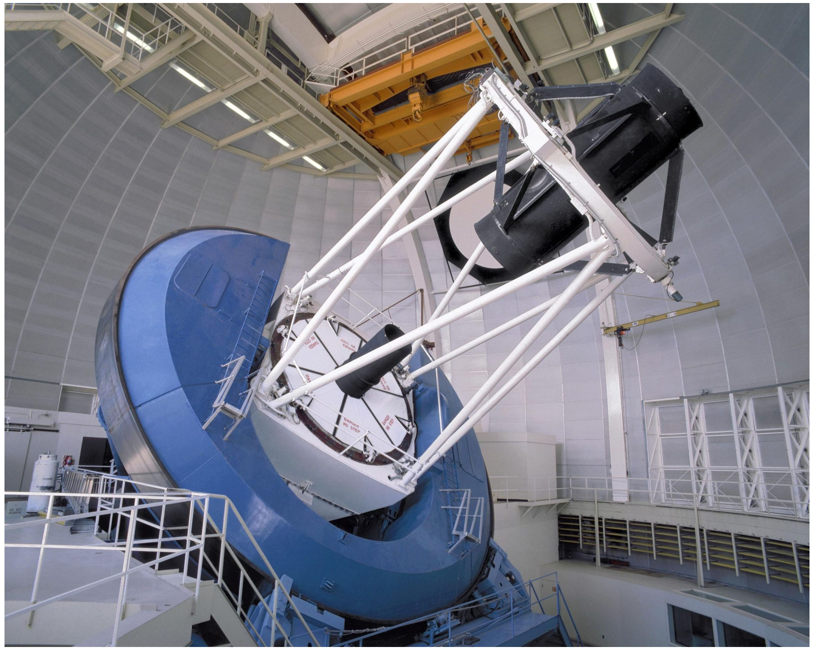


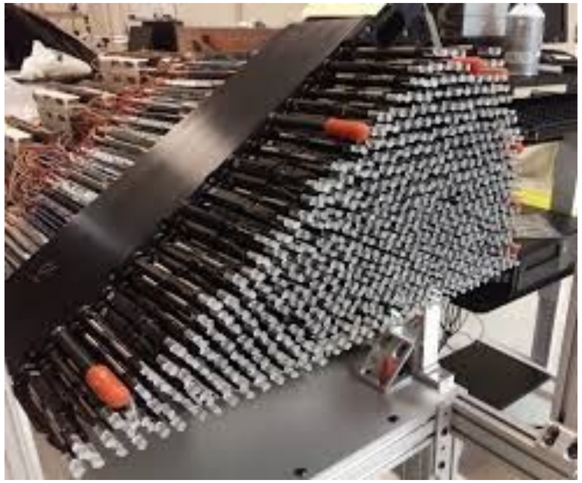
BAO: Gal
SN: JLA
BAO: Gal+Lya
BAO: Gal+Lya+QSOxLya
Ω_Λ
Ω_m

Baryon acoustic oscillations

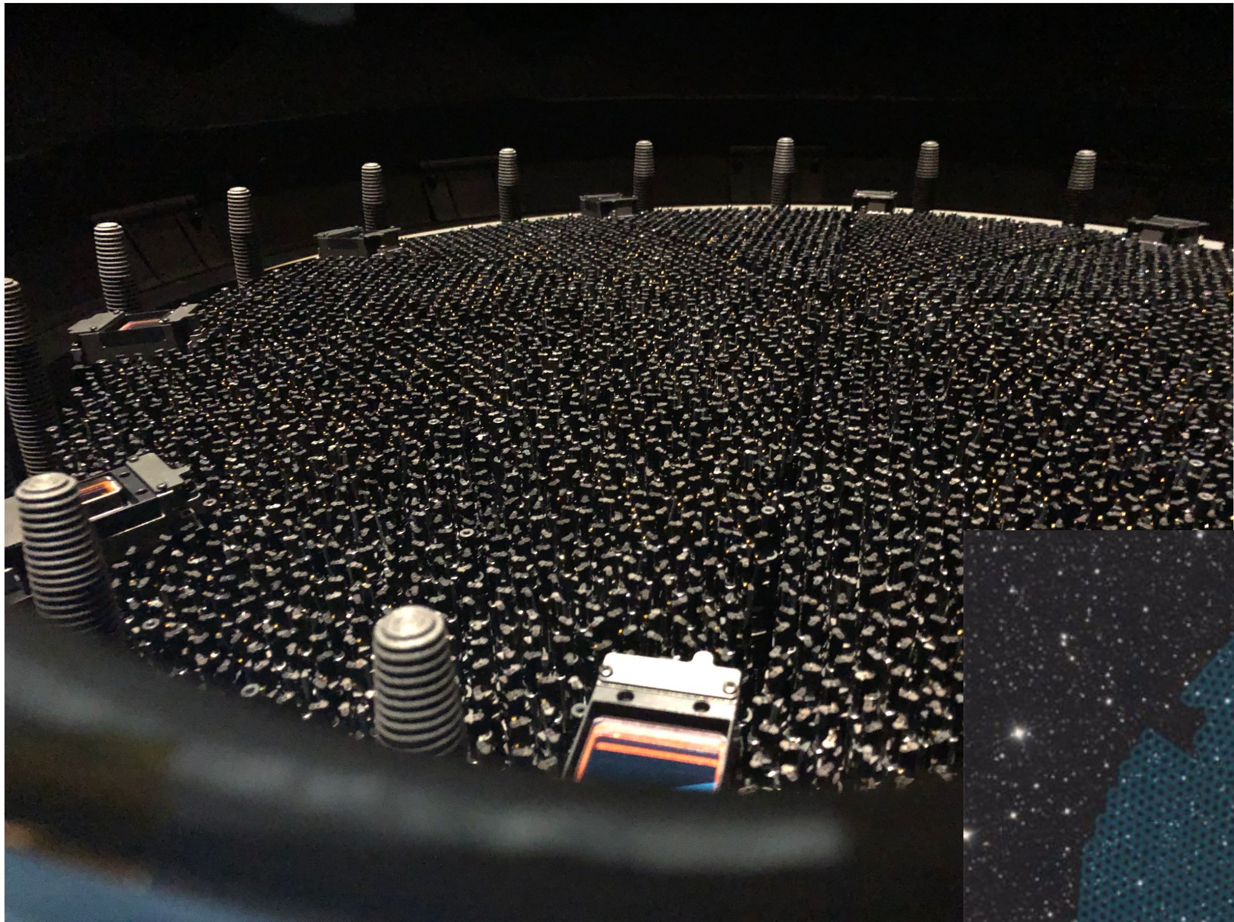
- Geometric measurement
- *Absolute* angular distances (r_s is known)
- Sensitivity to H(z)
- Measurable wherever there are baryons
  - (Galaxies, Ly-α forest, quasars…)
- Expensive probe : millions of redshifts needed
- Cosmic variance at low redshift
- Target selection : photometric catalog needed before the survey starts !
- Strong implication FR community (BOSS/eBOSS/DESI/4MOST)

Dark Energy Spectroscopic Instrument

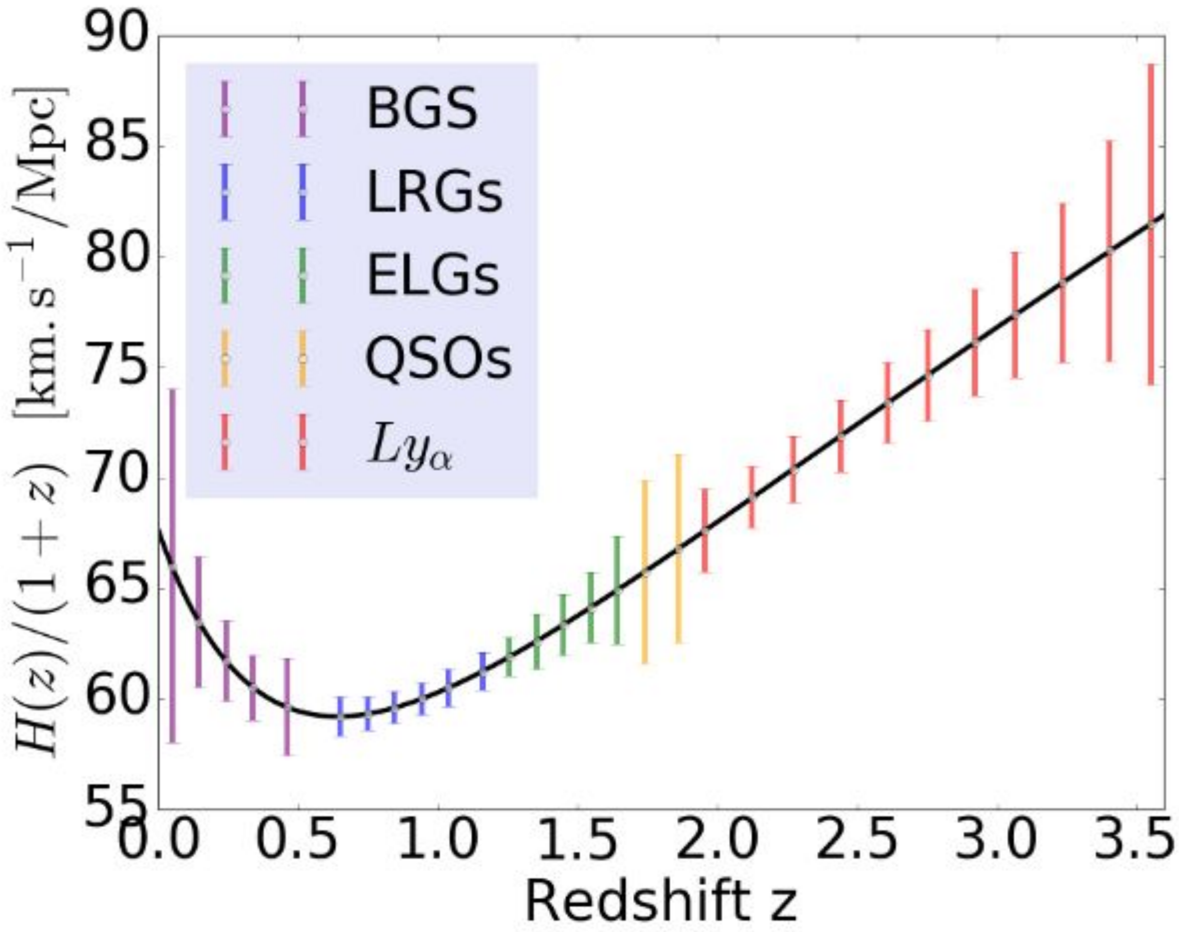




The DESI focal plane



BAO in the Ly-α Forest

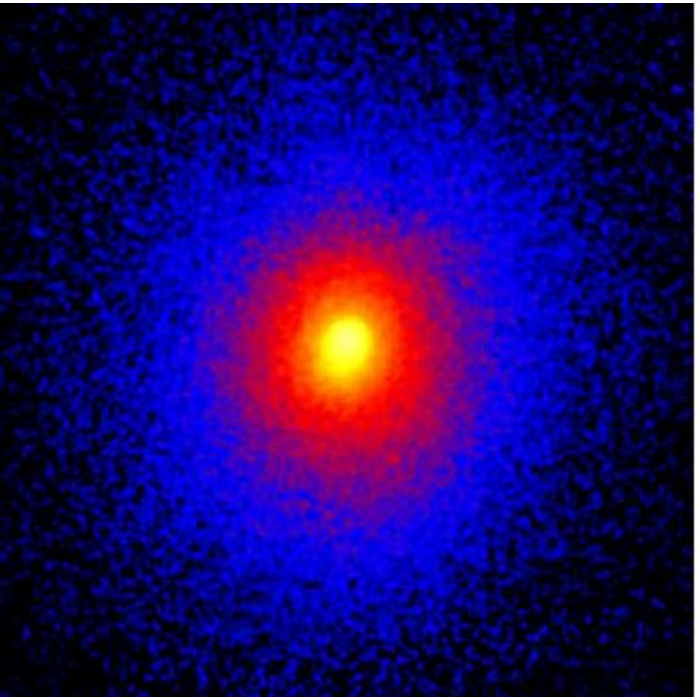


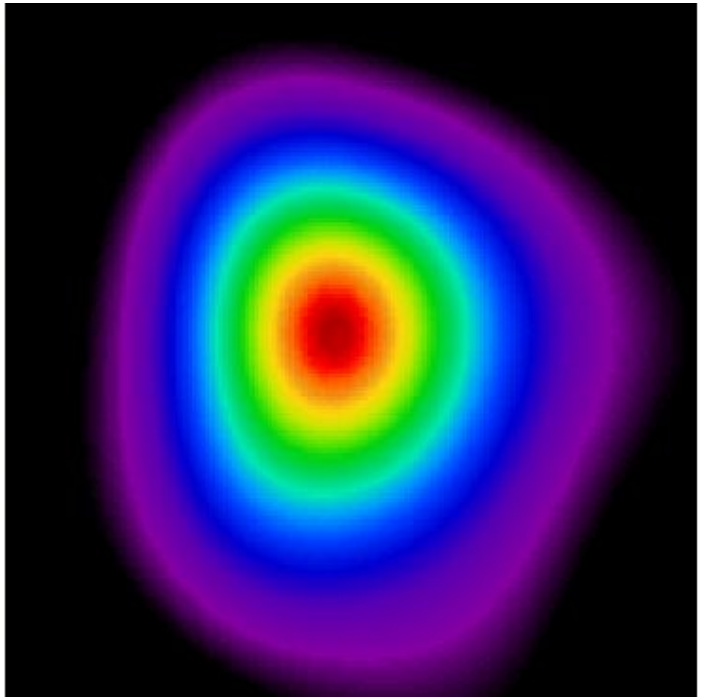
Volumes

$$V = \Delta\Omega \int_{z}^{z+\Delta z} \frac{1}{1+z} \frac{d_A^2(z)}{H(z)} dz$$

Can be probed, either with objects with constant comoving density (n ~ n0 (1+z)^3) or with objects for which we have a prediction of comoving density.

Galaxy clusters





- X
- Optical
- SZ

(Abell 1835, z = 0.25)

(Allen, Evrard, Mantz, '11)

Abell http://apod.nasa.gov/apod/image/0301/abell1689_hstacs_

Clusters

- Clusters
  - Largest virialized structures in the Universe
  - $10^{14} – 10^{15}$ solar masses
  - most of the baryons as hot intracluster gaz
    - → T ~ 1-15 keV
    - → X-ray emission
    - → inverse Compton scattering on CMB photons

↑

Sunayev-Zel'dovich effect
(SZ)

Cluster counts

- Cluster counts are sensitive to
  - V(z) [geometrical test]
  - Growth of structures

$$\frac{dN}{dz\,d\ln M} = f(\sigma)\frac{\rho_m}{M}\left|\frac{d\ln\sigma^{-1}}{d\ln M}\right|\frac{dV}{dz}$$

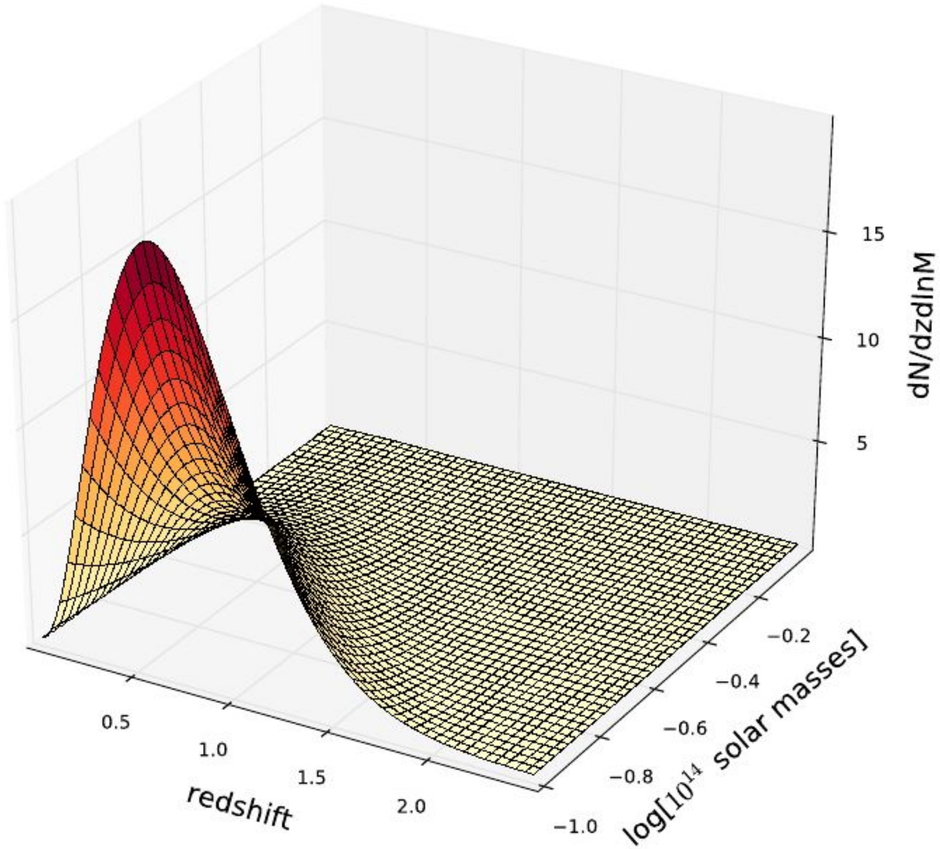
Density of clusters

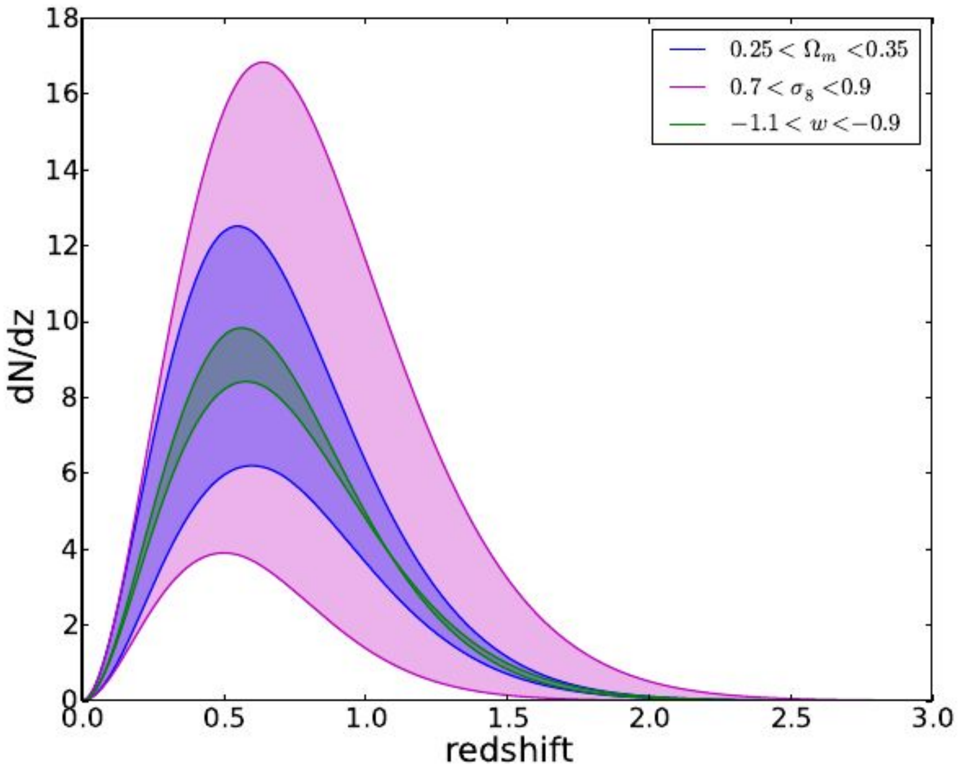
Variance of density fluctuations σ (z,M)

Geometry

$$\sigma^2 = \frac{1}{2\pi}\int dk k^2 P(k,z)\left|W(kR)\right|^2$$

Cluster counts

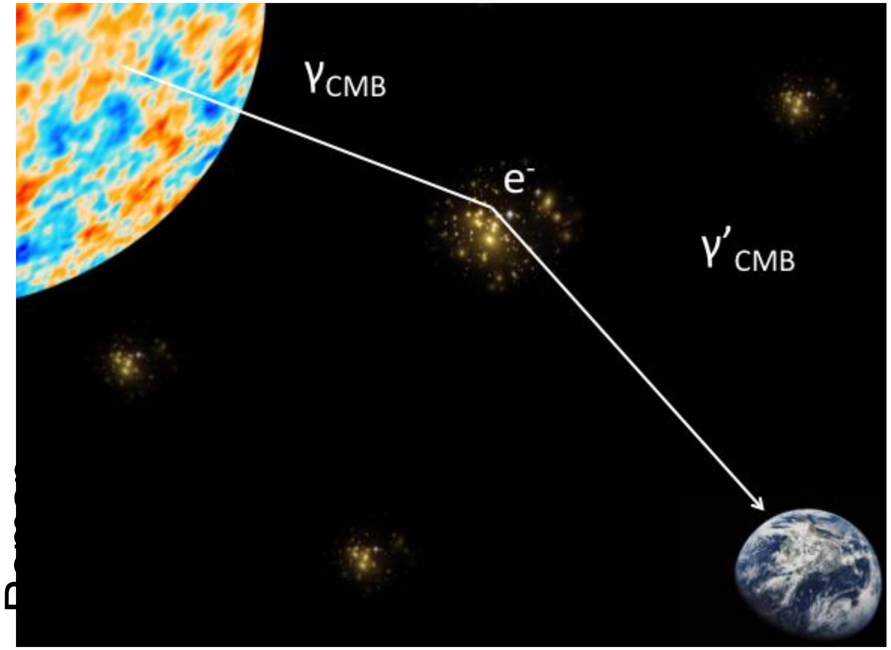




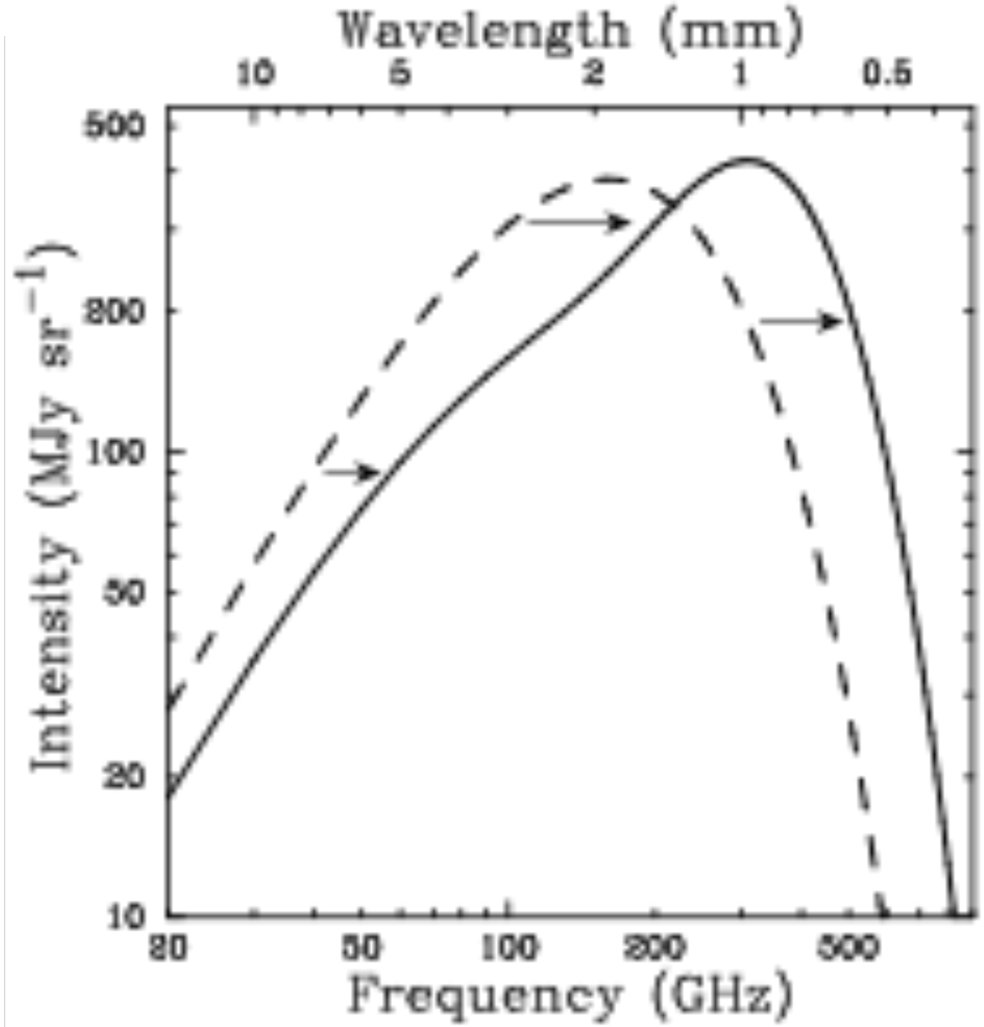
Cluster detection

- Optical observations
  - SDSS, Dark Energy Survey (Rozzo et al, 2010, Rozzo & Rykoff 2014)
- Sunayev-Zel'dovich effect
  - *Planck*
  - Atacama Cosmology Telescope (ACT)
  - South Pole Telescope (SPT)
  - APEX-SZ
  - NIKA2@
  - …

SZ effect



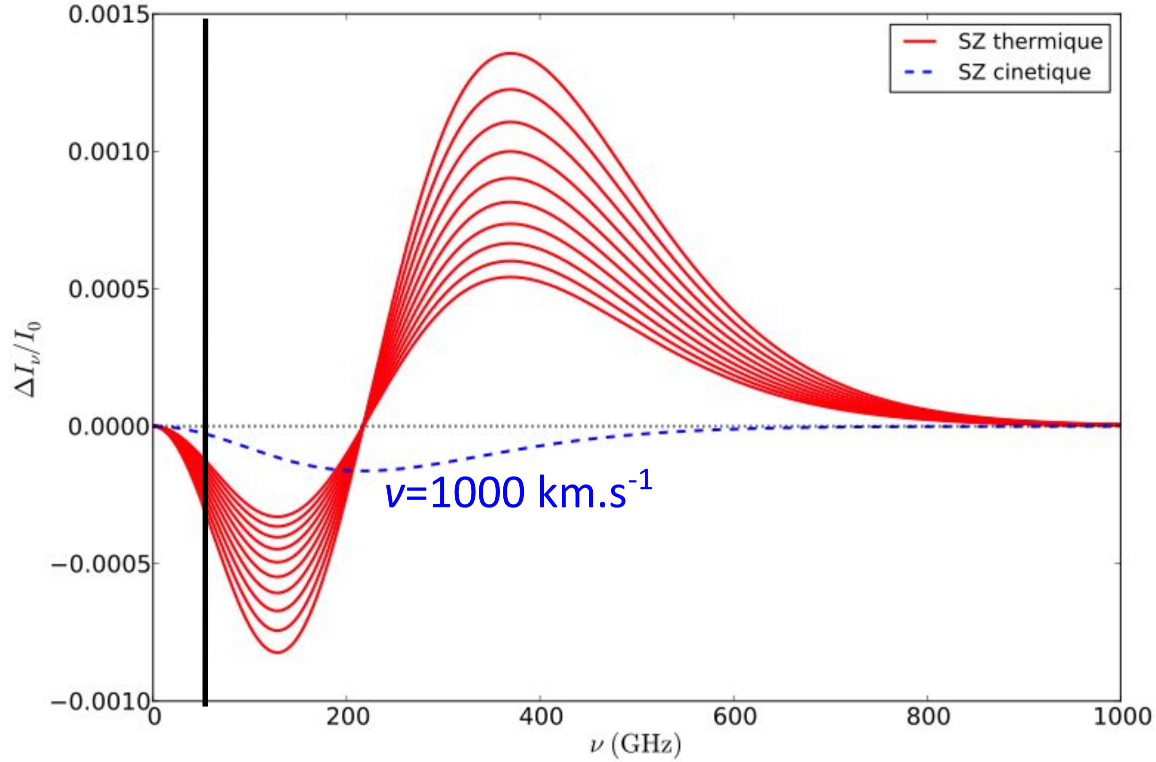
- Inverse-Compton interaction of CMB photons on thermally distributed intracluster gas
- Net energy transfer → γ
- CMB black body distortion
- Does not depend on redshift



[Carlstrom et al., *Cosmology with the Sunyaev-Zel'dovich Effect*, A&A, Vol.40, p.643-680, 2002]

SZ effect

30 GHz



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

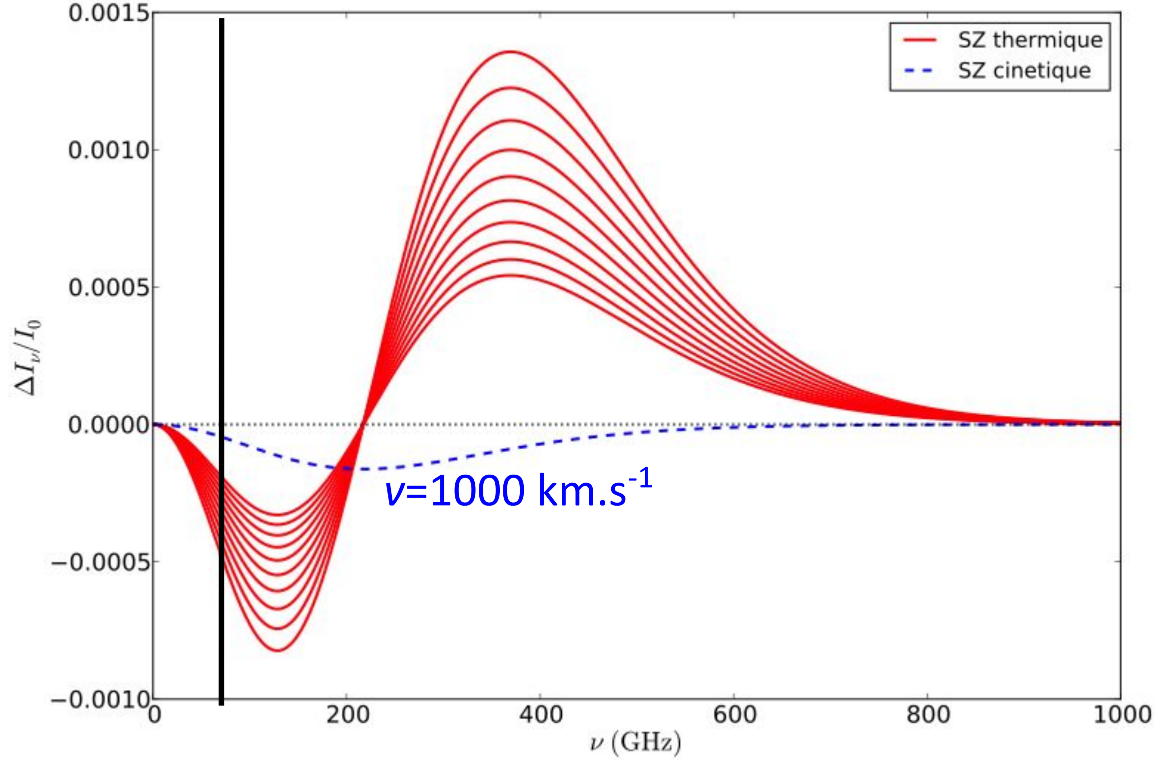
y=2x10^{-4}

↓

y=8x10^{-5}

SZ effect

44 GHz



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

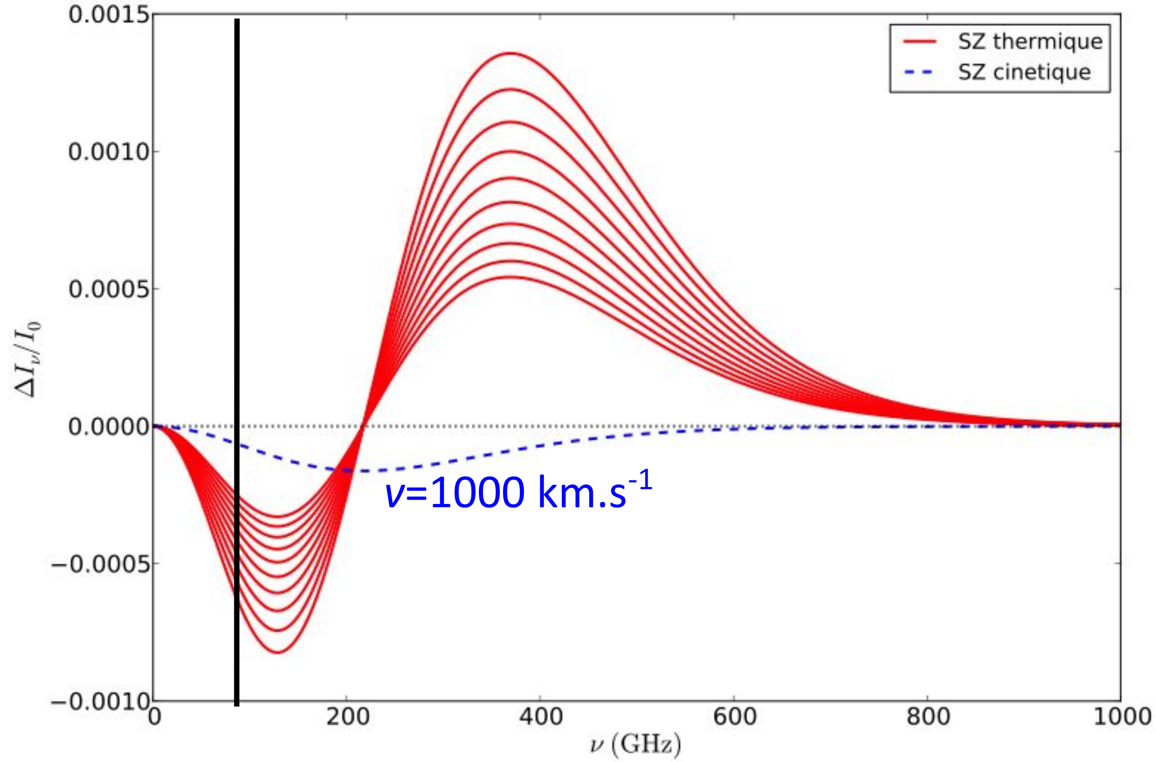
$y=2\times10^{-4}$

↓

$y=8\times10^{-5}$

SZ effect

70 GHz



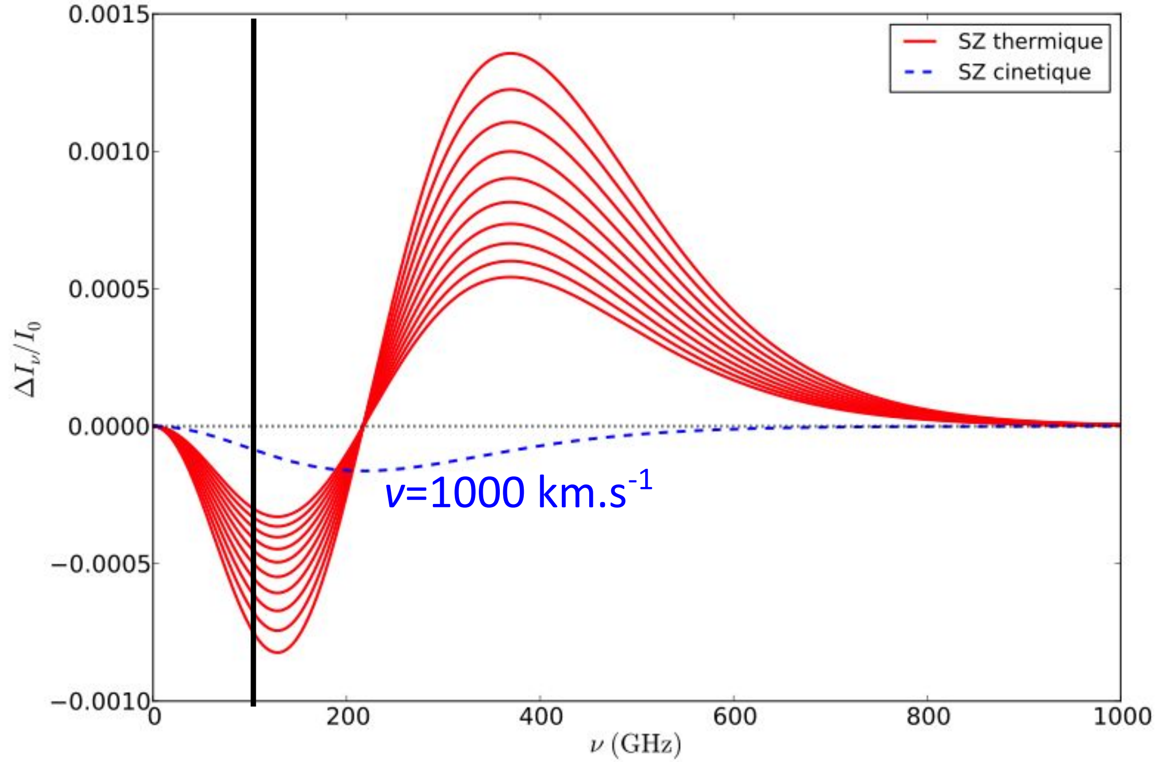
[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

$y=2\text{x}10^{-4}$

$y=8\text{x}10^{-5}$

SZ effect

100 GHz



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

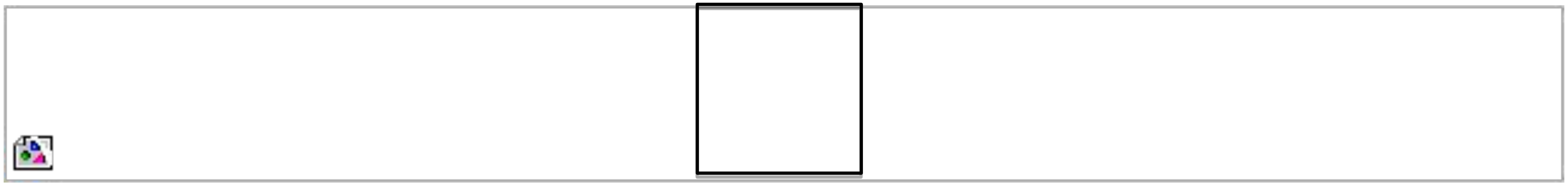
y=2x10^{-4}

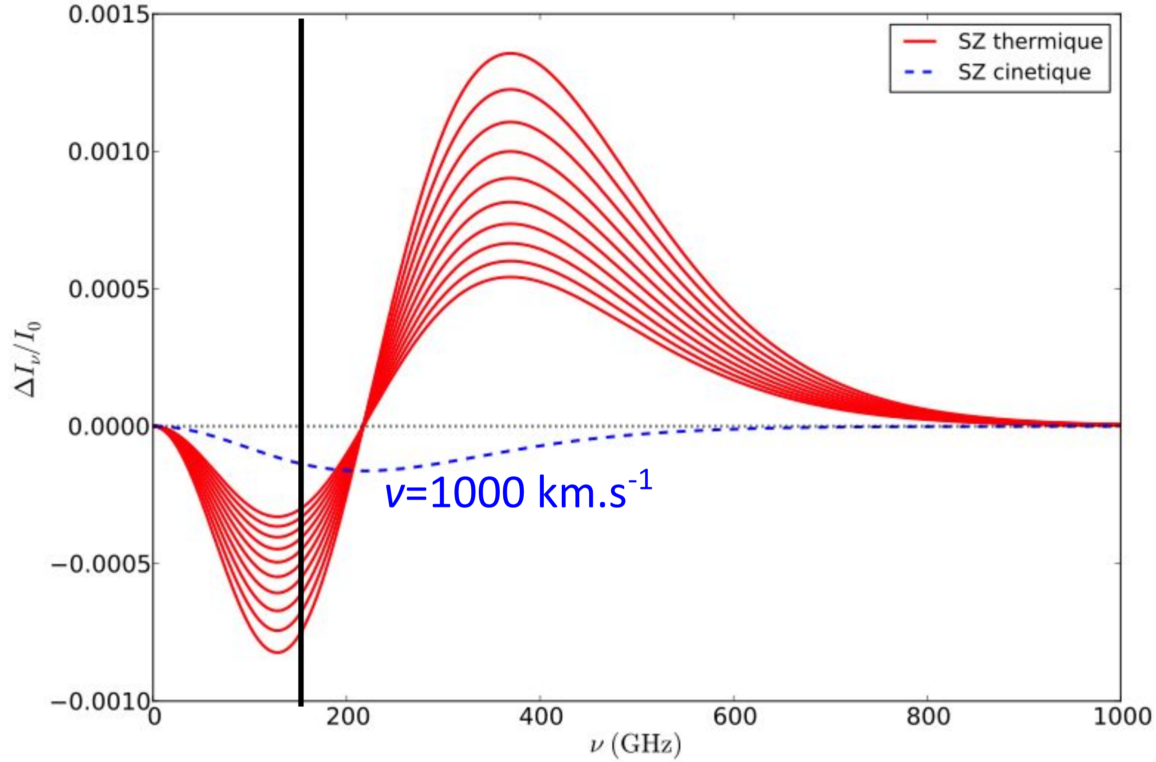
↓

y=8x10^{-5}

SZ effect

143 GHz





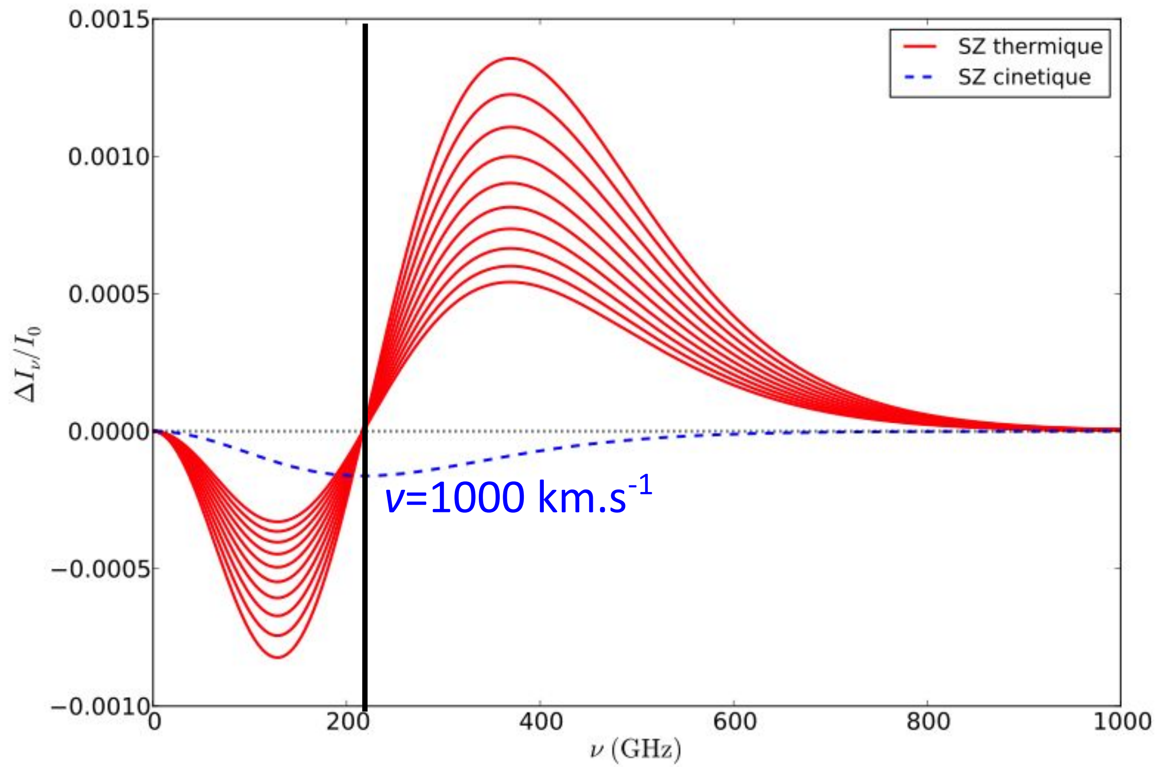
[Planck Collaboration.
Planck 2013 results. *XXIX.*
The Planck catalogue of
Sunyaev-Zeldovich sources.
A&A 571, A29, 2014]

$y = 2\text{x}10^{-4}$

↓

$y = 8\text{x}10^{-5}$

SZ effect



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

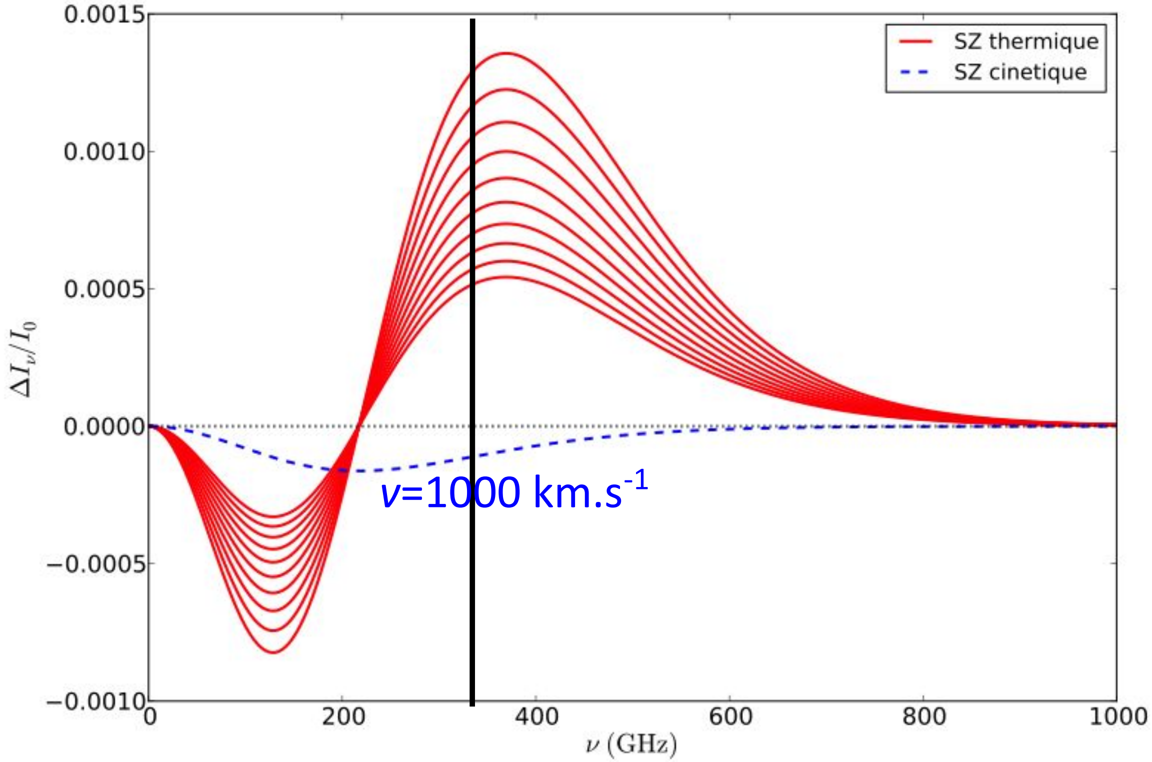
$y=2\text{x}10^{-4}$

↓

$y=8\text{x}10^{-5}$

SZ effect

353 GHz



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

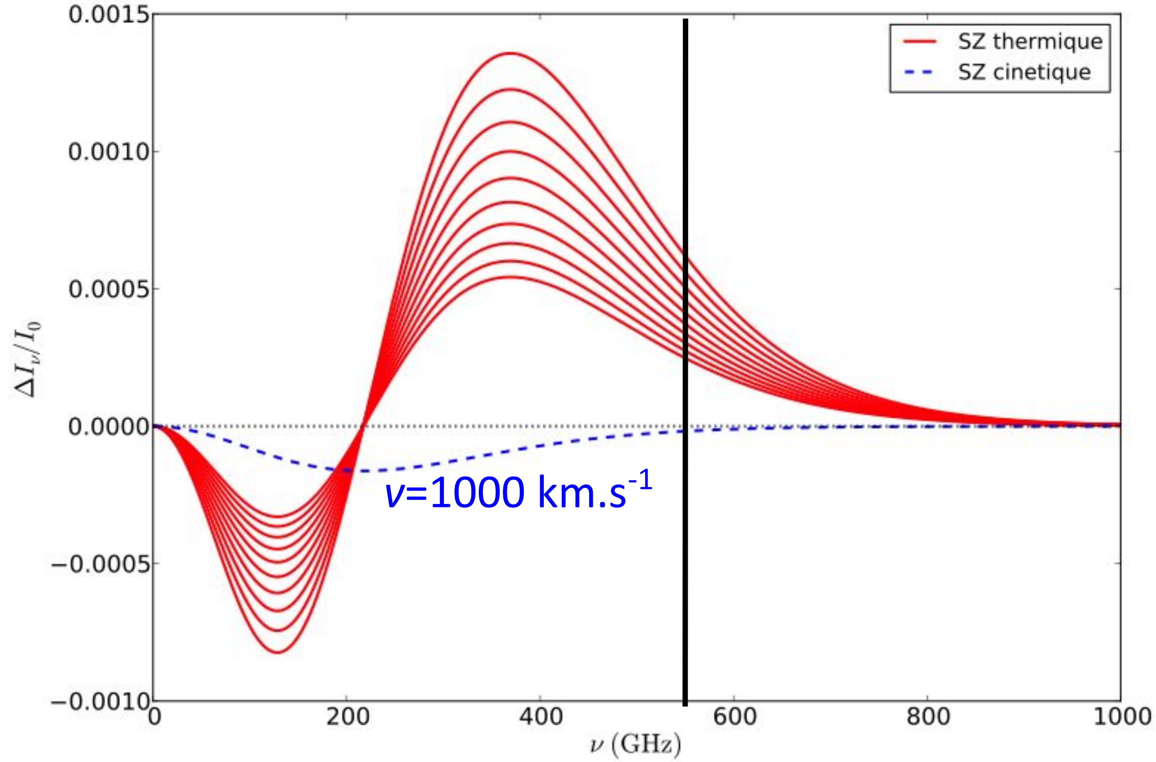
$y=2\times10^{-4}$

↓

$y=8\times10^{-5}$

SZ effect

545 GHz



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

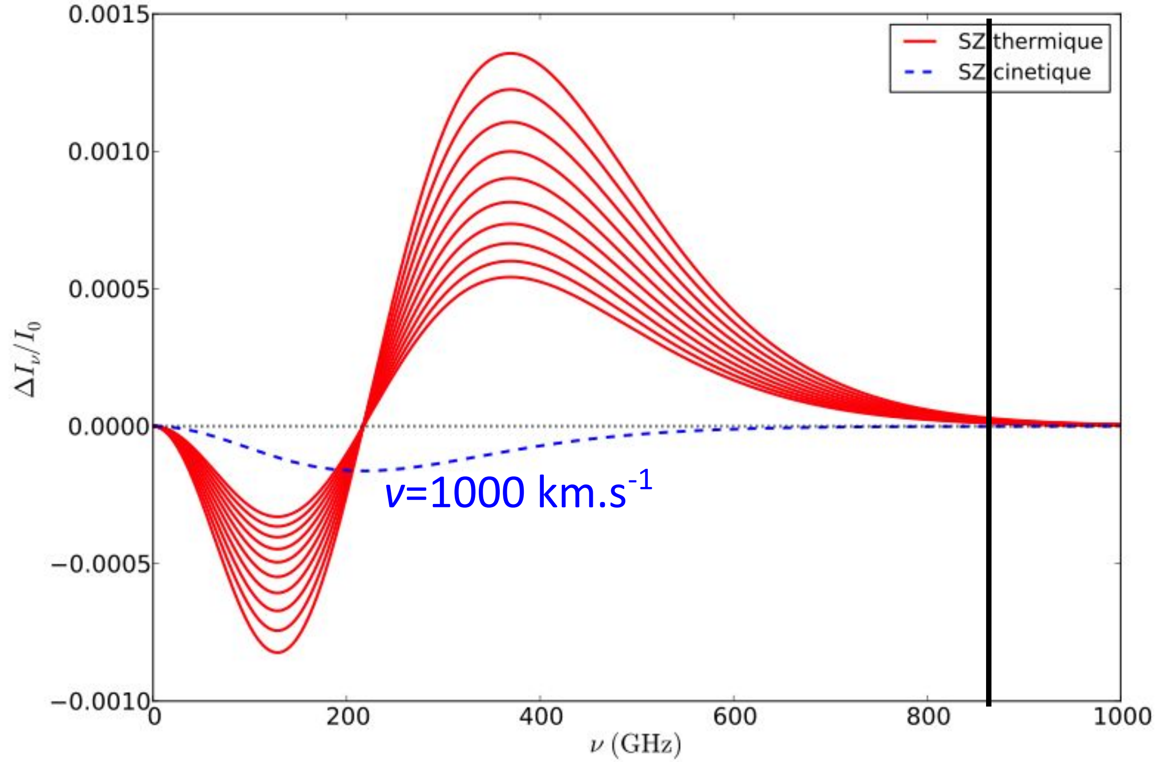
$y=2\times10^{-4}$

↓

$y=8\times10^{-5}$

SZ effect

857 GHz



[Planck Collaboration. Planck 2013 results. *XXIX. The Planck catalogue of Sunyaev-Zeldovich sources.* A&A 571, A29, 2014]

y=2x10^{-4}

↓

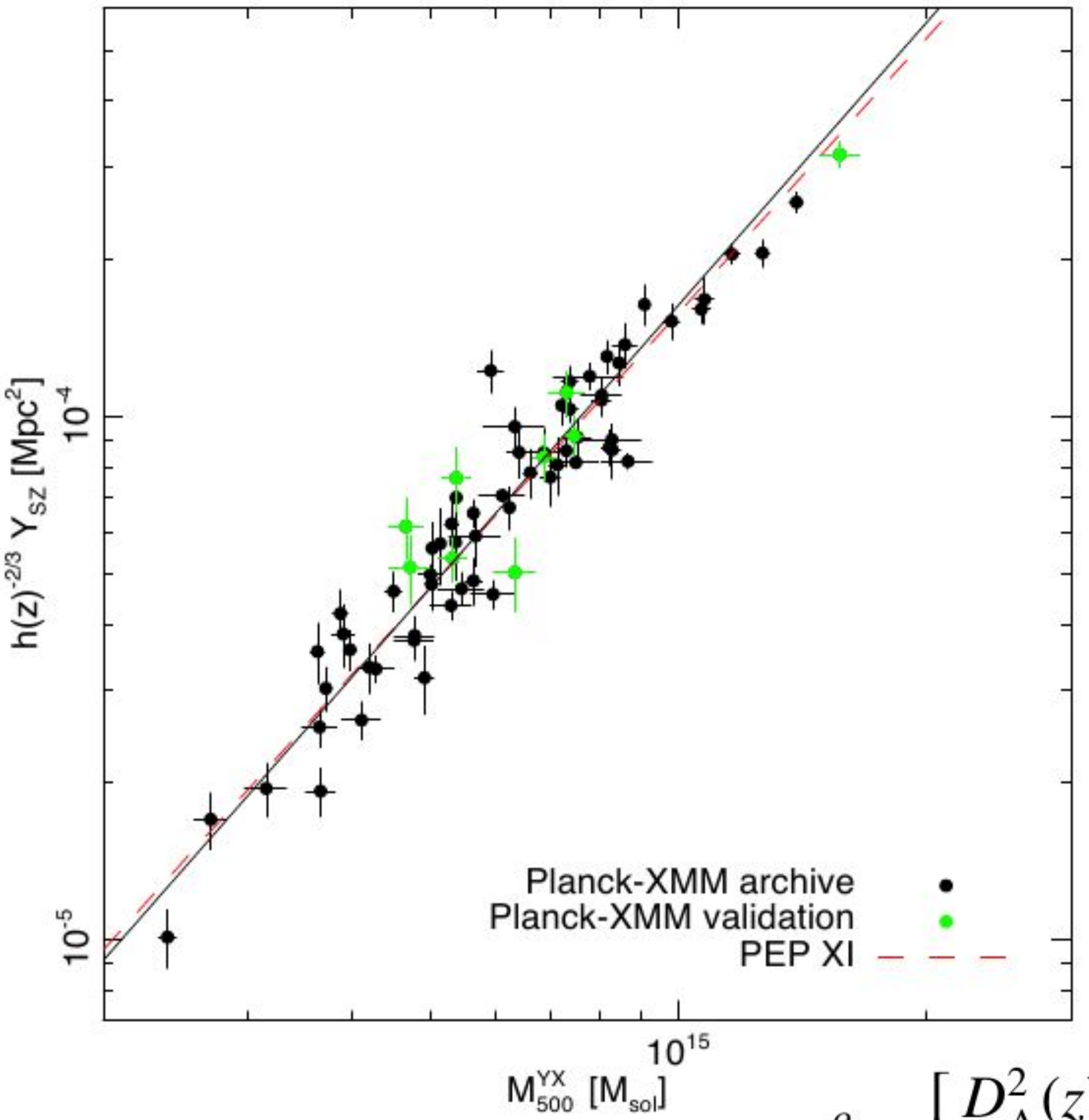
y=8x10^{-5}

What do we measure ?

- Integrated compton parameter Y_{500}
- Cluster size θ_{500}
- We need information on mass & redshift !
  - redshift : optical follow-up
  - mass : X-ray, lensing (CMB or galaxy)

Build and calibrate a
relation
between Y_{500} and mass...

Cluster masses



- Relate the mass of the clusters to an observable
  - richness
  - SZ flux (Y)
  - X-ray ($Y_X = M_{gas} \times T_X$)
  - Lensing

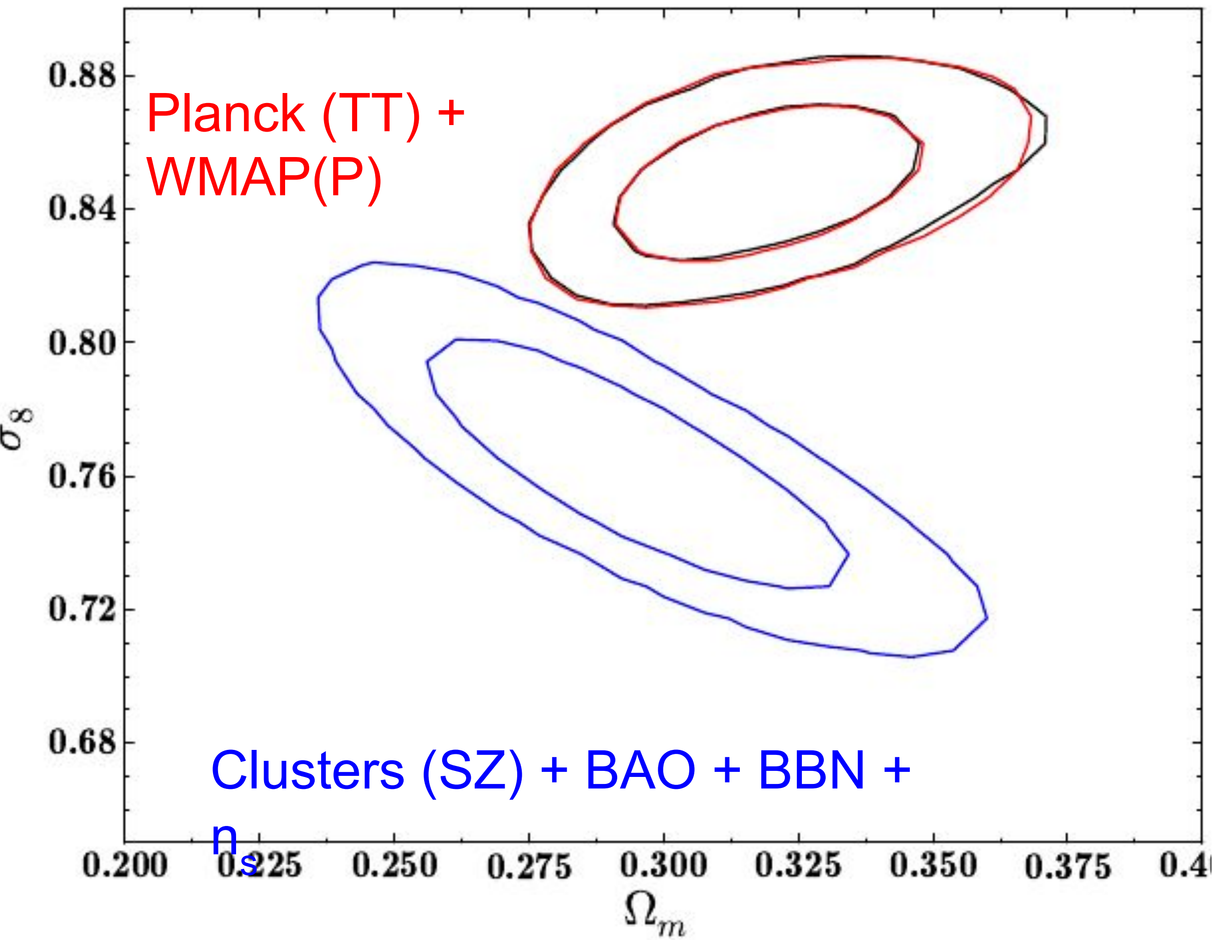
Bias factor

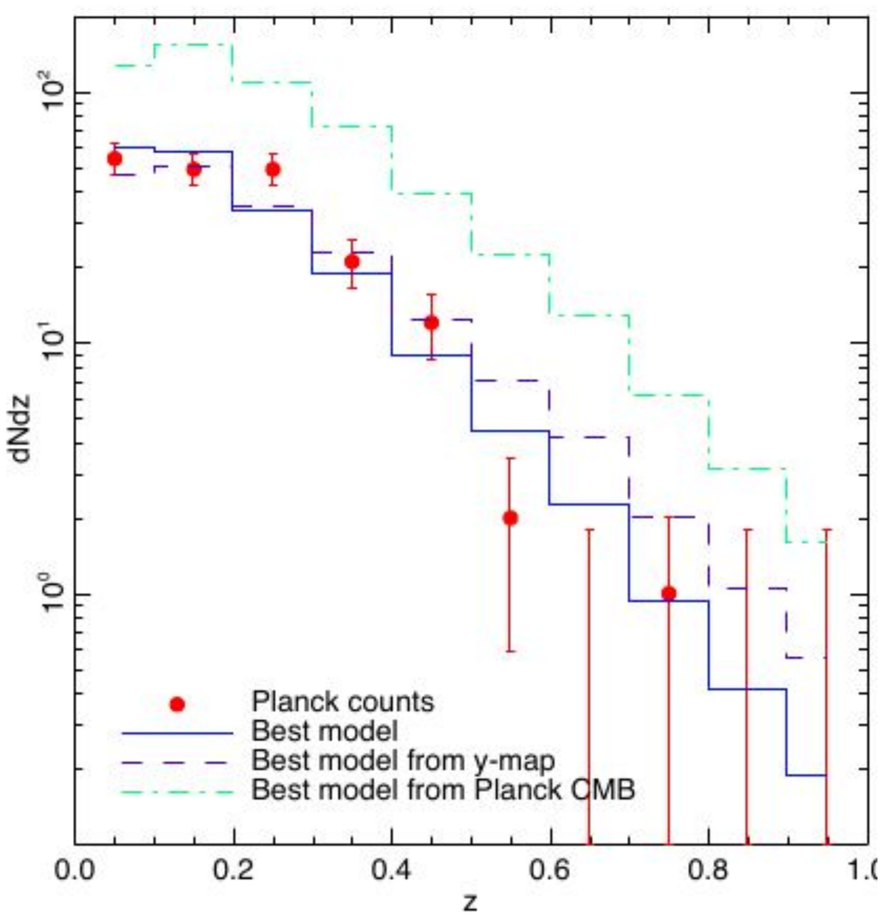
true mass ↔ mass estimate

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,\mathrm{M_{sol}}}\right]^{\alpha}$$

(Planck results 2013 XX)

Planck (2013)



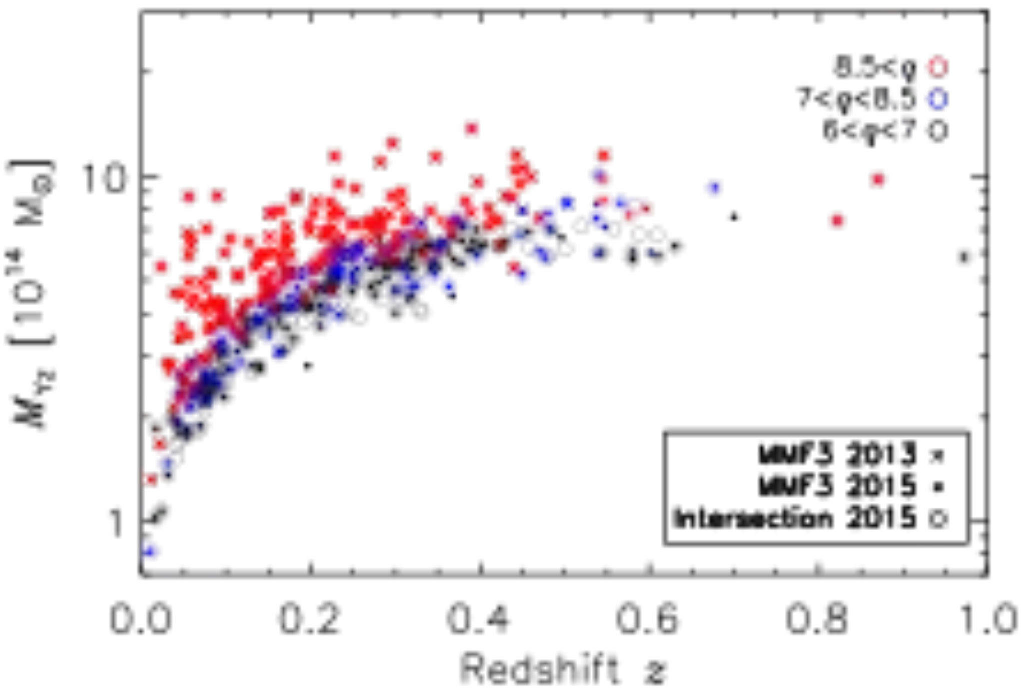


189 SZ clusters
(with high SNR)

Tension with CMB on σ_8

- → Mass bias ?
- → Massive ν's

(Planck results 2013 XX)



Planck 2015

- Bias values :
  - Baseline 2013: 1-b = 0.8
  - WtG : 1-b = 0.688 ± 0.072
  - CCCP : 1-b = 0.780 ± 0.092
- Persisting tensions w/ CMB
- Goal : calibration mass relation at ~ 1% (from 10% now)