Baryon Acoustic Oscillations

Marc Moniez (IJCLab), 12 oct. 2020

Cosmology in 5 minutes…

- **History** (past and future)
- **Content**
- **Structure**

}**of the Universe**

Potential of the wide field optical surveys

- Inflation theory
- Hidden matter
- Vacuum energy
- Neutrino mass

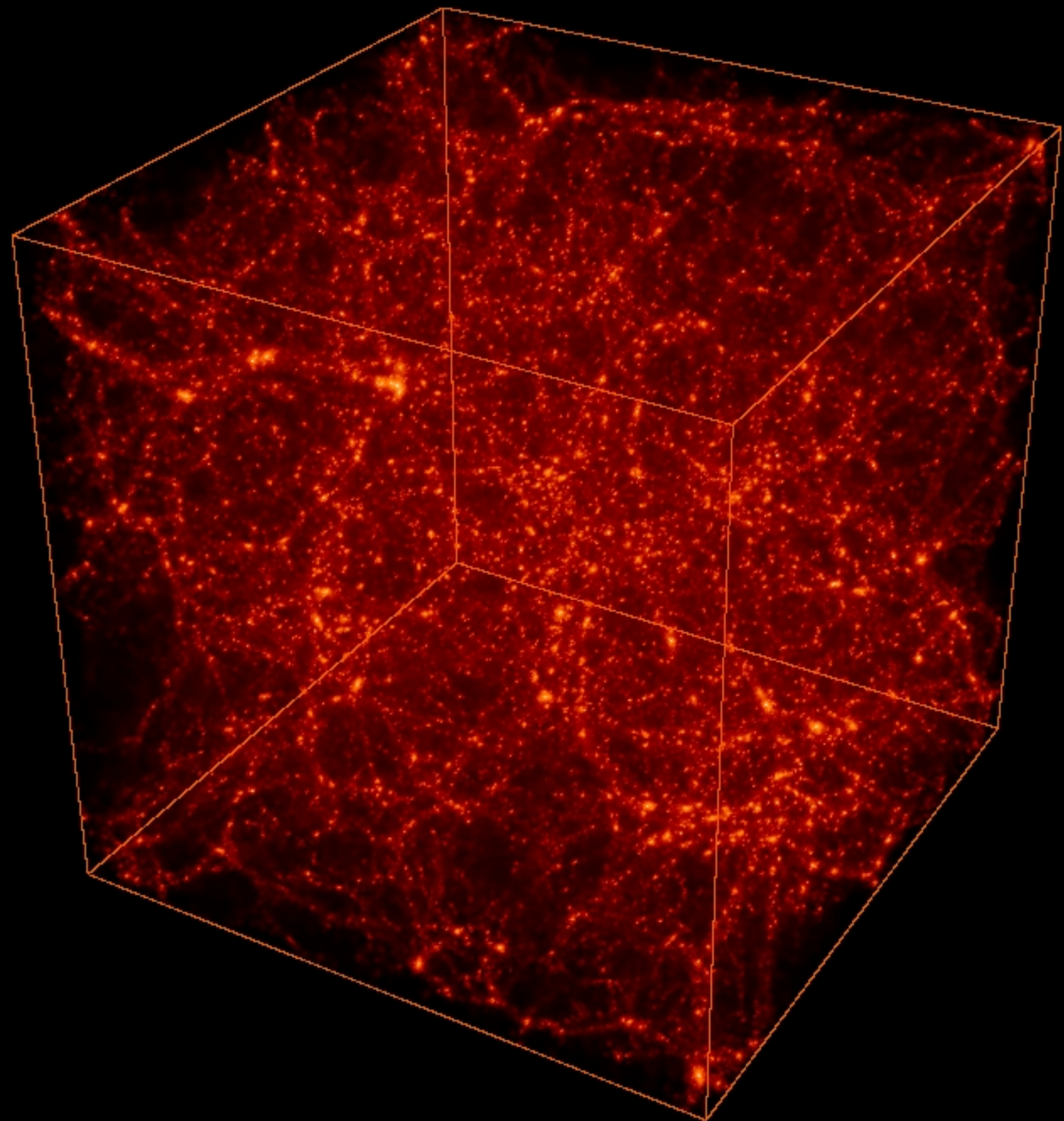
Observables:

Redshift ***z*** ***(Doppler shift due to expansion)***

Position (2 angles + Distance)

Time

BAO: Structuration



The 4 cosmological distances

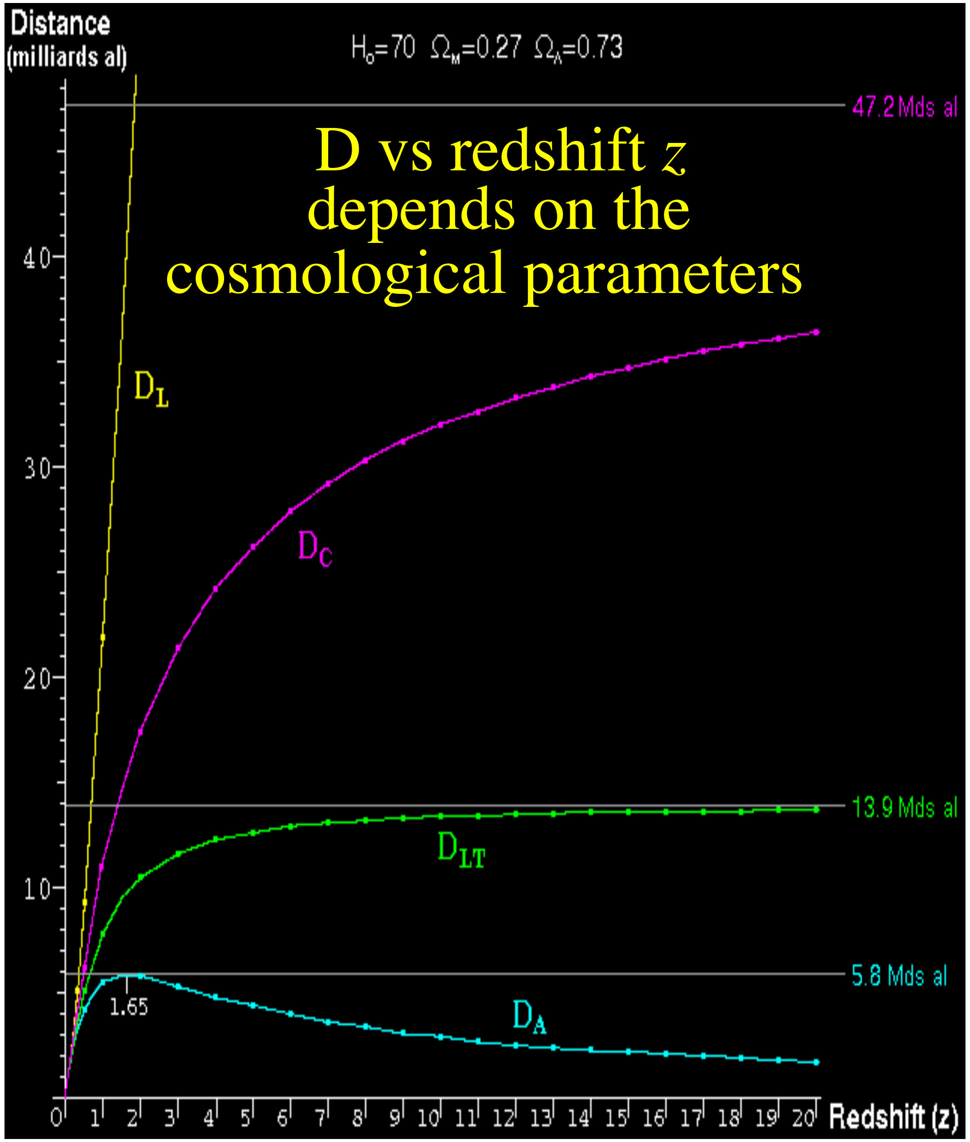
- *Comobile distance* $\mathbf{d_C}$
  Gives the present position of the object
  (even observed in a past situation)
- *Luminosity Distance* $\mathbf{d_L = d_C(1+z)}$
  depends on the repartition surface of the light
  - Used with luminosity markers

➢ ***Galaxies appear fainter than in a static Universe***

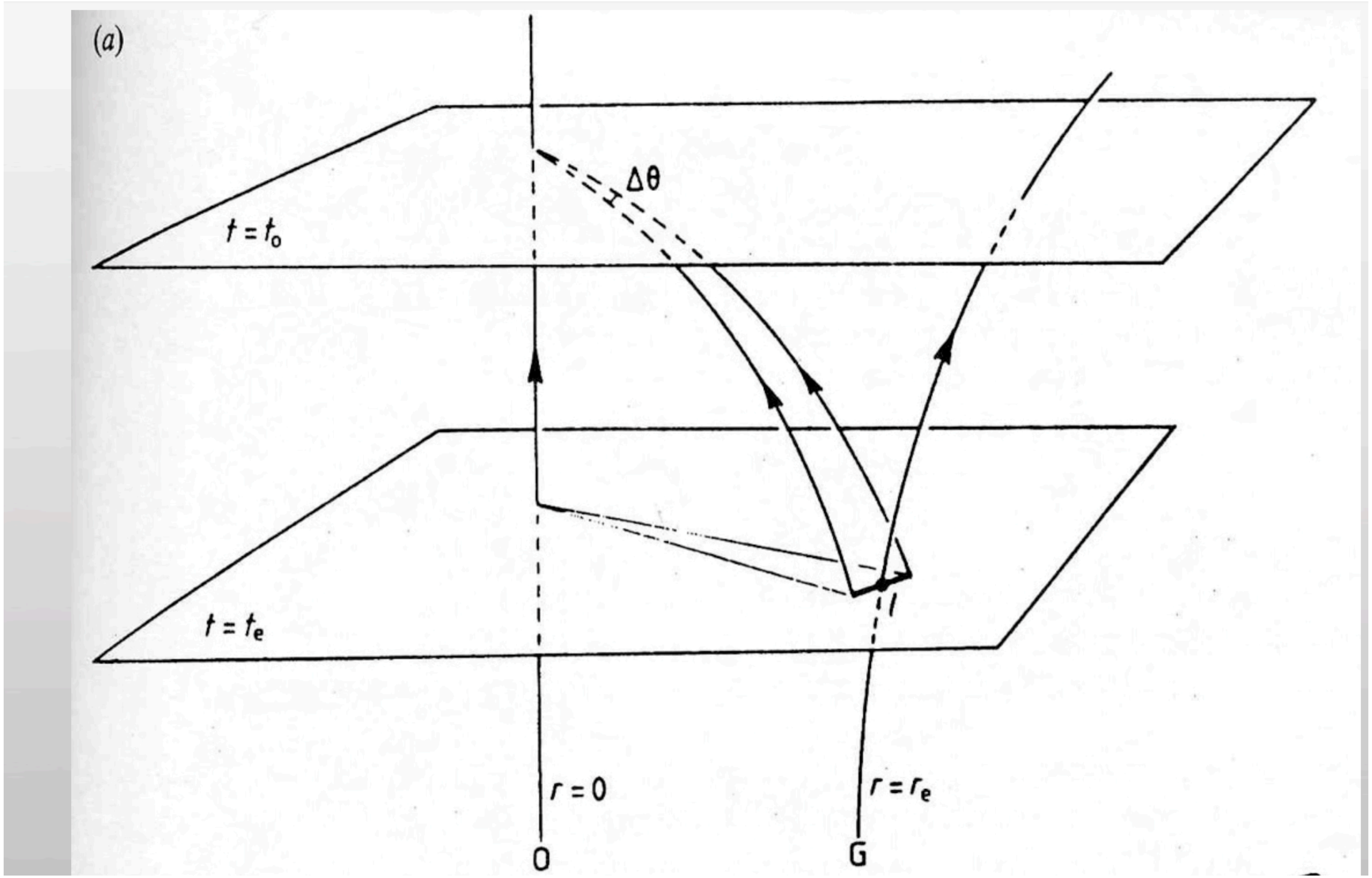
- *Angular distance* $\mathbf{d_A = d_C/(1+z)}$
  Galaxies were closer at the epoch of the light emission.
  - Used with size markers

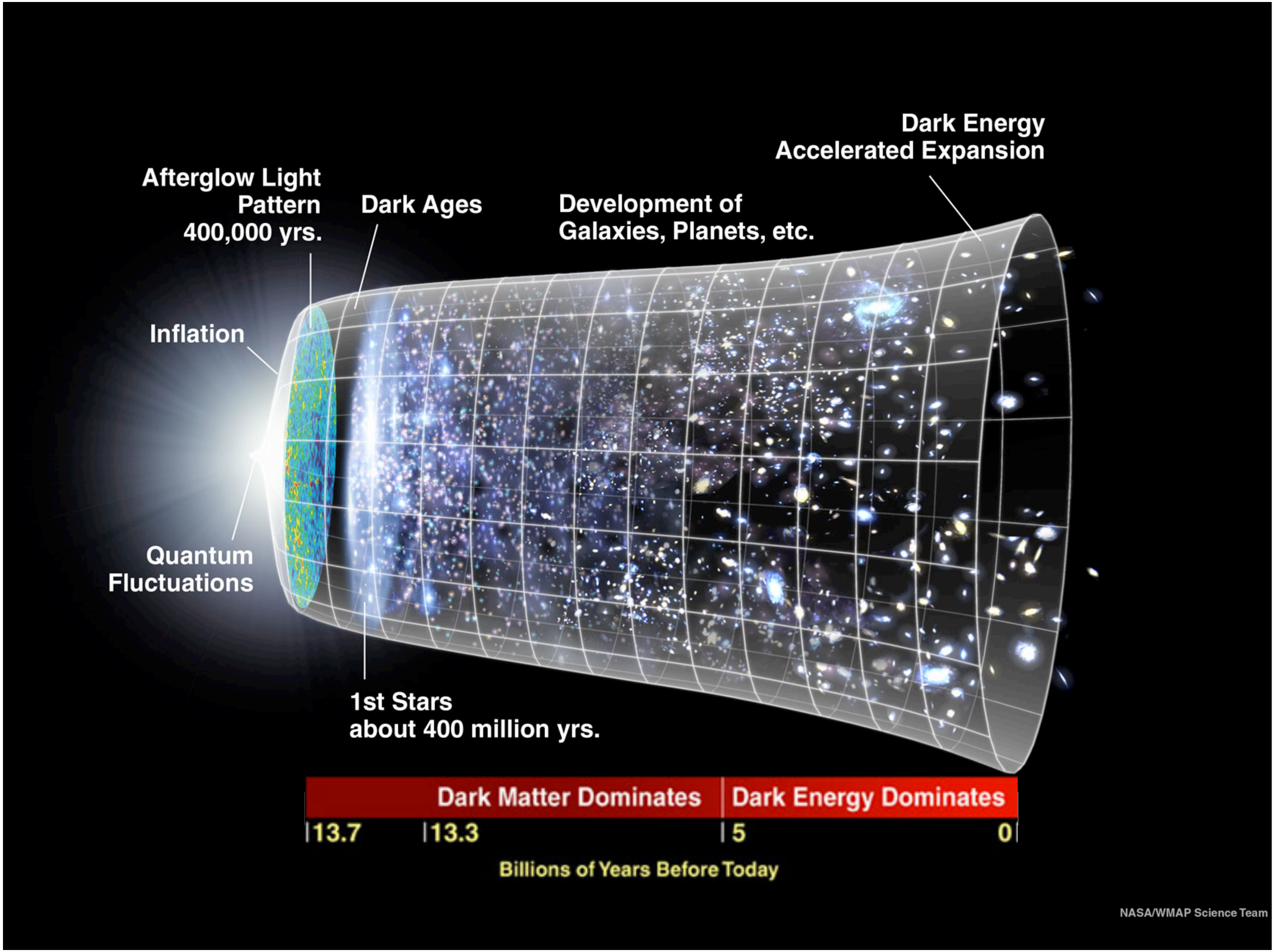
➢ ***Galaxies appear larger than in a static Universe***

- *Distance of photon propagation* $\mathbf{d_{LT}}$



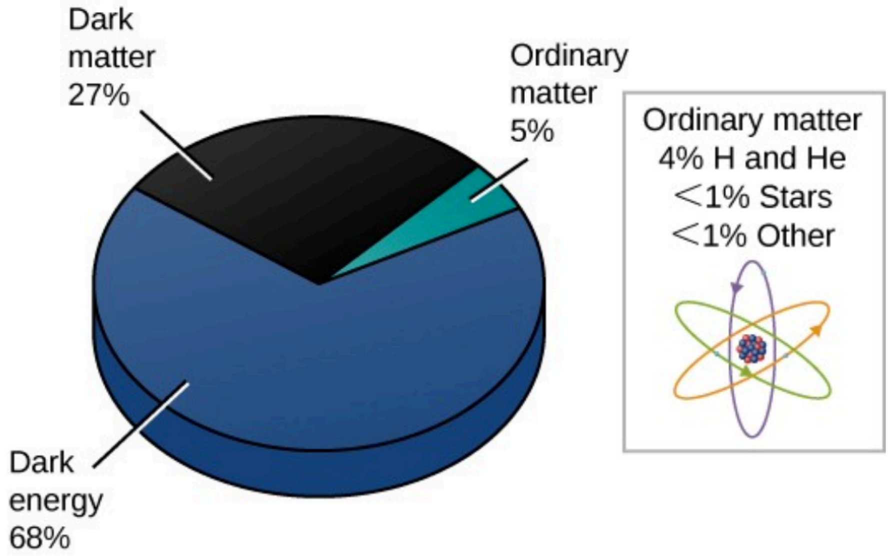
Angular diameter – redshift relation




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today
NASA/WMAP Science Team

The content of the Universe (2020)

- Current observations in favor of a flat Universe
- Energy density seems now dominated by a component that behaves like a cosmological constant Λ
- Λ acts against gravity
- Vacuum energy (quantum fluctuations) ➠ dark energy ?
- State equation for this new fluid : $p = w(z)\,\rho$
- $w(z)=-1$ for cosmological constant Λ



	Planck TT,TE,EE+lowE+lensing	+BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.1193 ± 0.0009
$100\,\theta_{MC}$	1.0409 ± 0.0003	1.0410 ± 0.0003
n_s	0.965 ± 0.004	0.966 ± 0.004
τ	0.054 ± 0.007	0.056 ± 0.007
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.044 ± 0.014	3.047 ± 0.014
h	0.674 ± 0.005	0.677 ± 0.004
σ_8	0.811 ± 0.006	0.810 ± 0.006
Ω_m	0.315 ± 0.007	0.311 ± 0.006
Ω_Λ	0.685 ± 0.007	0.689 ± 0.006

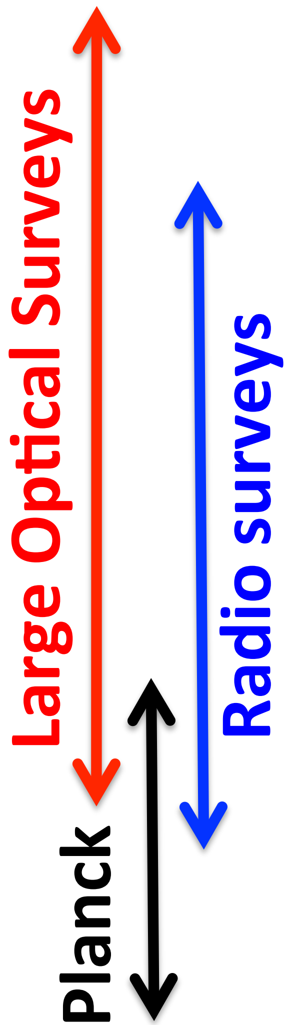
Cosmology: aims and challenges

- **History**: go to ancient times => **large redshift *z***
  - Baryonic Acoustic Oscillations
  - Supernovæ => **photometry, time**

  => ***z* determination**
- **Content**: search for mass (even local)
  - Lensing (macro, micro, weak) => **photometry, astrometry, time**
  - Other indirect signatures of matter (velocity fields…)
- **Structuration**: statistical studies of large structures
  => **large volumes**
- **Tests of the cosmological hypothesis**: check anisotropy
  => **large volumes & angular coverage**

Note: determination (z, photometry, astrometry) means *precise* determination

Cosmological probes



- **Supernovae** : measure the apparent luminosity of the SNIa as a function of z → $\mathbf{d_L(z)}$ → H(z)
- **Gravitational weak lensing** : measure distorsions of the galaxy orientation distribution → $\mathbf{d_A(z)}$ → structures
- **Strong lensing time delays** : → $\mathbf{d_{LT}}$ → H_0
- **Galaxy clusters** : cluster counting and spatial distribution → $\mathbf{d_A(z)}$ → H(z), structure formation
- **Baryonic Acoustic Oscillations (BAO)** : measure a characteristic scale in matter spatial distribution → $\mathbf{d_A(z)}$ → H(z)
- **Integrated Sachs-Wolf effect**: descent and ascent of photons in a potential well that varies over time

The BAO probe

- **Acoustic waves propagate until** the universe becomes cool enough for the **electrons and protons** to **recombine** and then the baryons and photons decouple
- The time when the baryons are "released" from the drag of the photons is known as **the drag epoch, z_d**
- From then on photons expand freely while the **acoustic waves "freeze in"** the baryons in a scale given by the size of the horizon at the drag epoch
- Progressively, **baryons fall into dark matter potential** wells but also dark matter is attracted to baryon overdendities

The BAO generation description

Description of one perturbation (Eisenstein)

- Four species:

  Dark matter, Baryons, Photons & Neutrinos

- Initial perturbations adiabatic: all species perturbed approximately same fractional amount

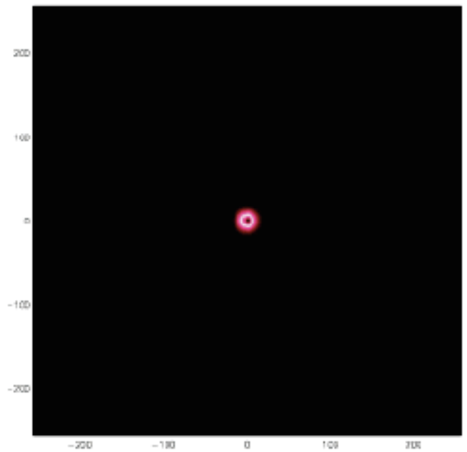
BAO : Baryonic Acoustic Oscillations

- Inprints of the oscillations of the baryon-photon fluid in the ordinary matter distribution after structure formation

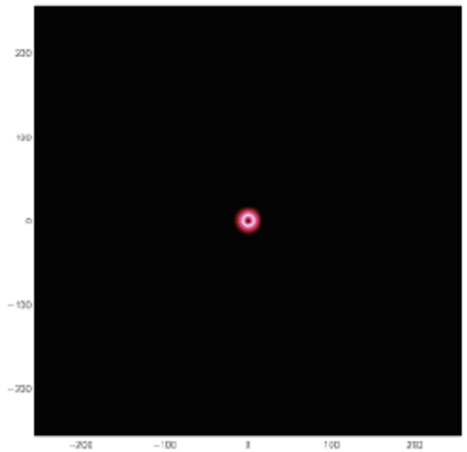
The Acoustic Wave

In the beginning (z>>1000)....

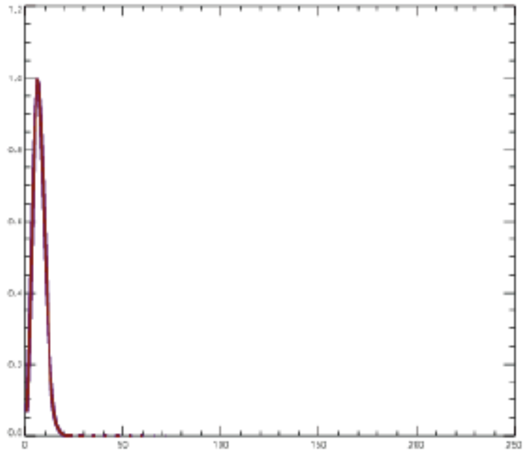
- The Universe at z>>1000 is a tightly coupled photon baryon plasma
- Consider a point overdensity - overpressured region drives out a sound wave travelling at 0.58c



Baryons

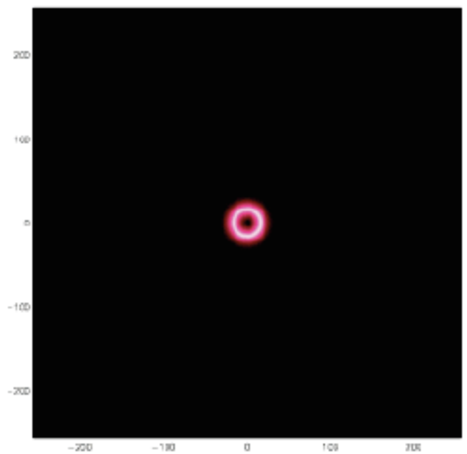


Photons



Movie credit: Martin White

The Acoustic Wave



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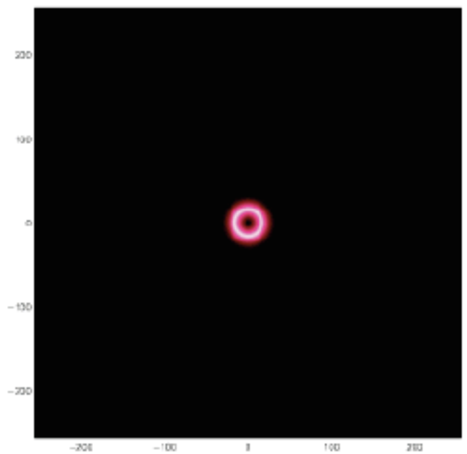

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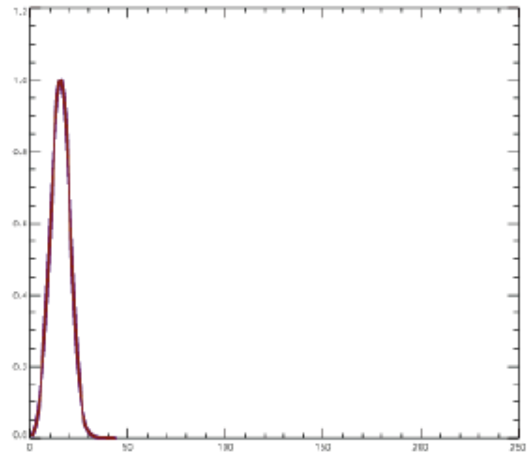

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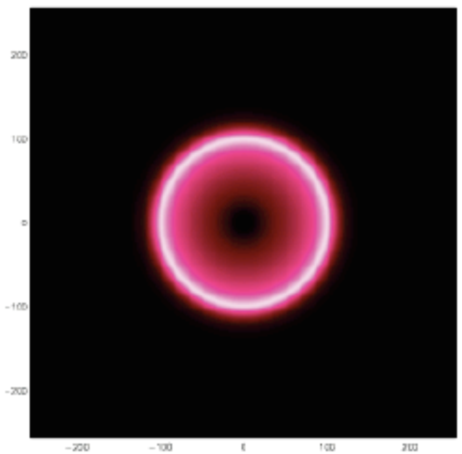
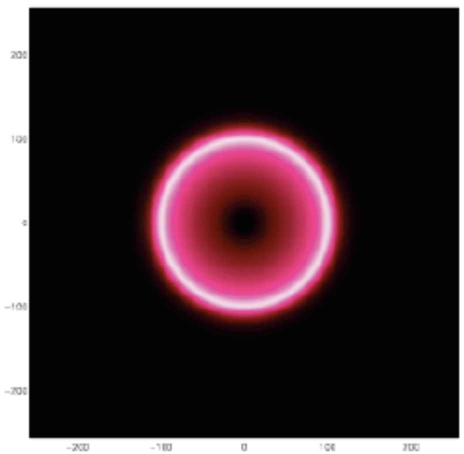
The Acoustic Wave

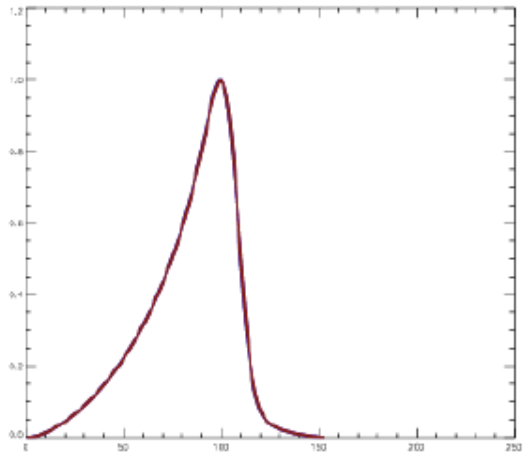
- Keeps growing at 0.58c for ~ 100,000 years



Baryons



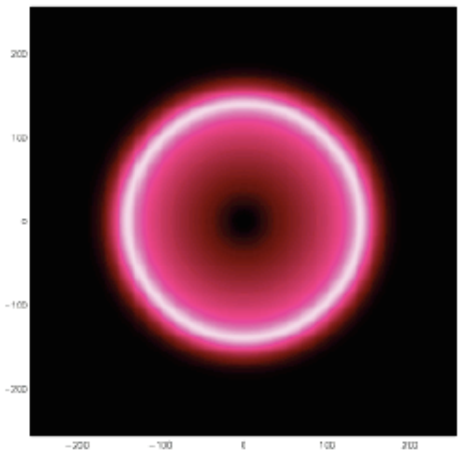
Photons



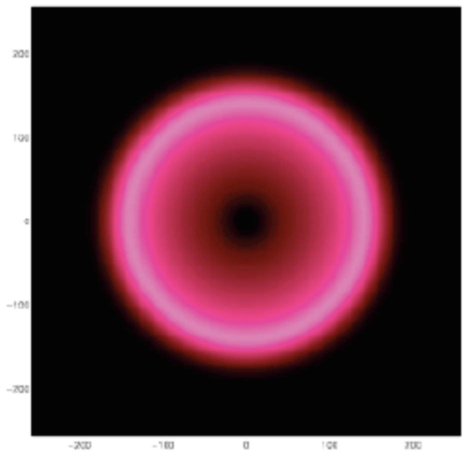
Movie credit: Martin White

The Acoustic Wave

- At z~1100, the temperature drops sufficiently to let neutral hydrogen form (***re-combination***)
- Sound speed plummets, baryon wave stalls.
- Photons free stream away.

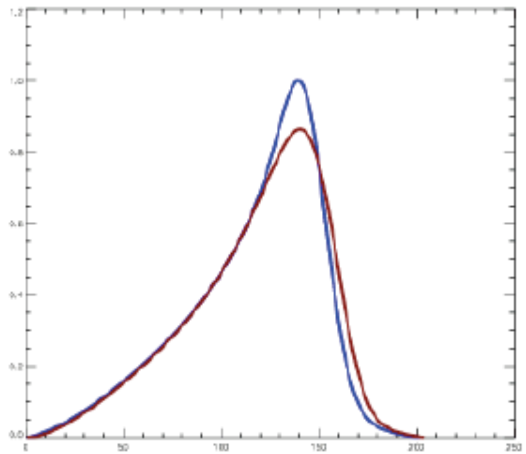


Baryons



Photons

100 h^{-1}Mpc



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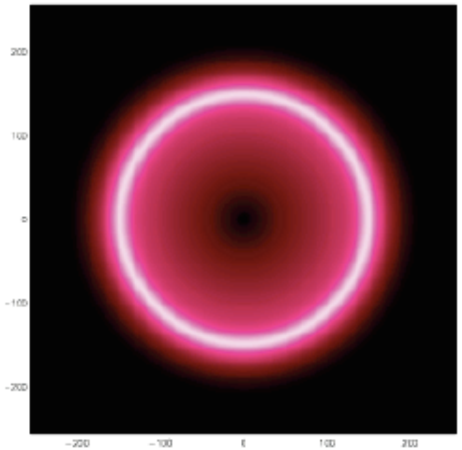

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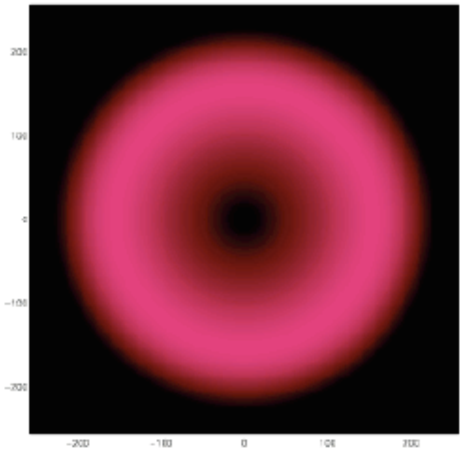
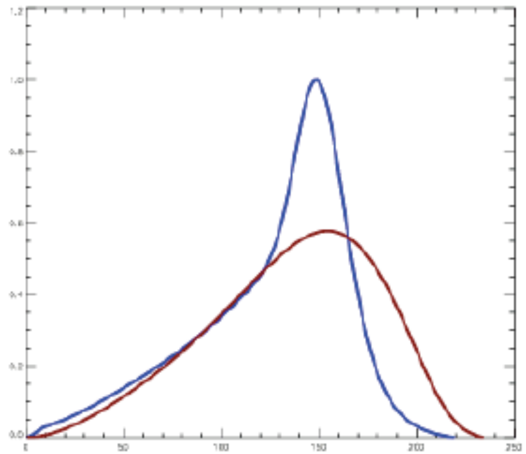


Photons



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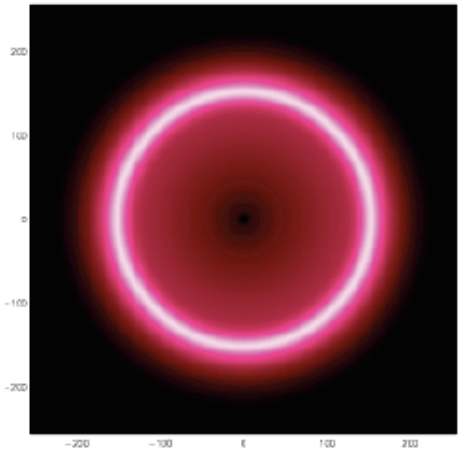
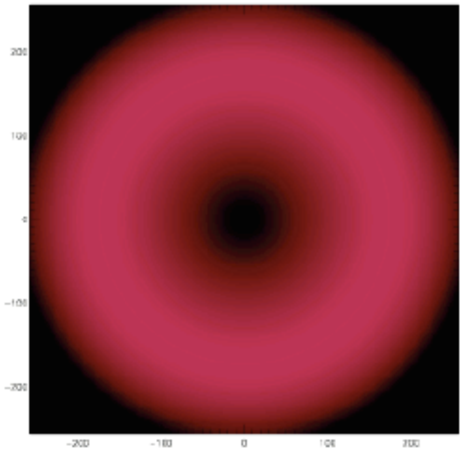
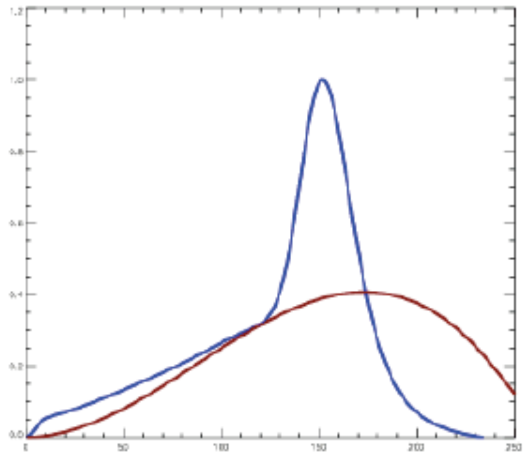
The Acoustic Wave



Baryons



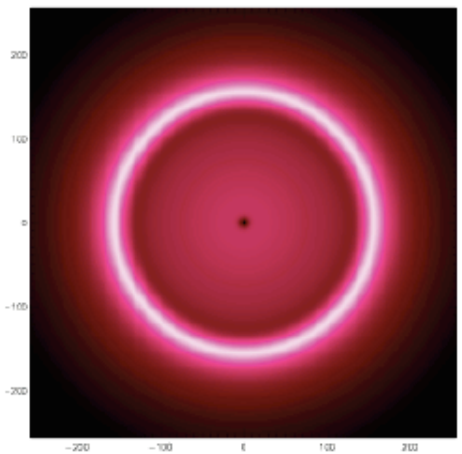
Photons



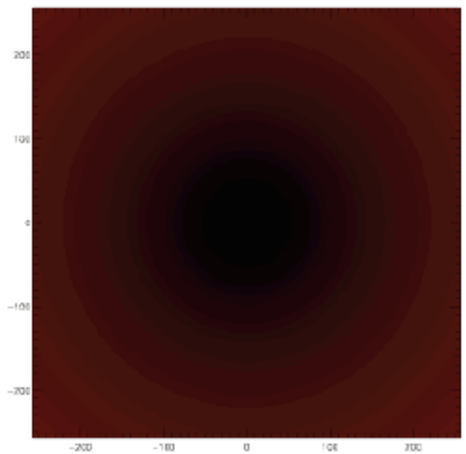
Movie credit: Martin White

The Acoustic Wave

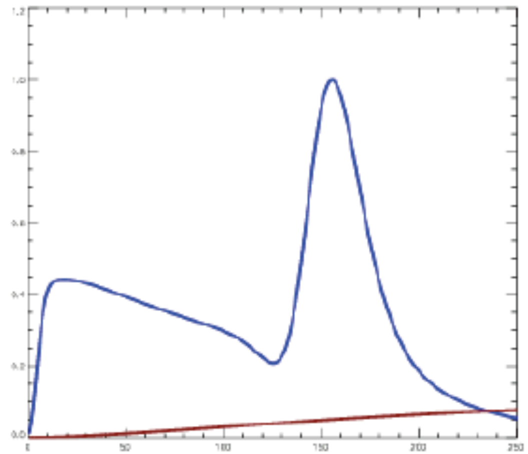
- Photons are almost uniform.
- Baryons remain overdense in a 150 Mpc shell.
- The central overdensity starts to grow.



Baryons



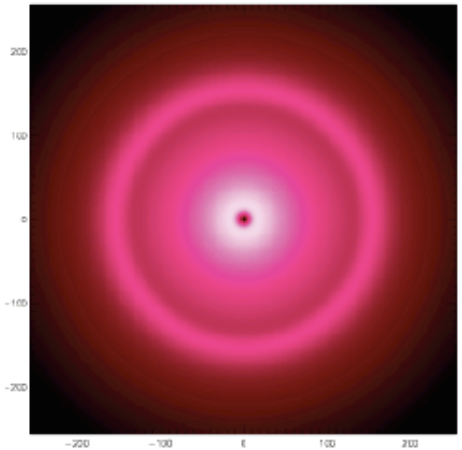
Photons



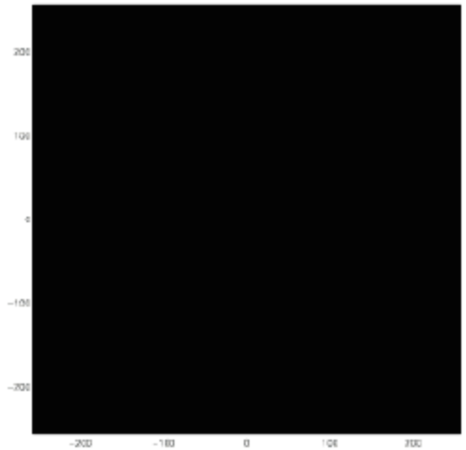
Movie credit: Martin White

The Acoustic Wave

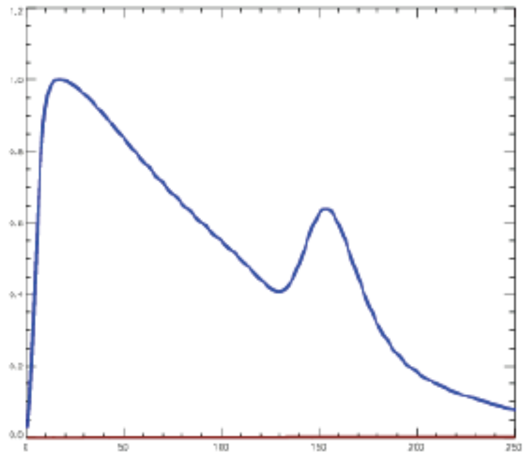
- The final configuration is the central overdensity plus an "echo" at 150 Mpc.
- Initial conditions are a random field of overdensities -- observationally, statistical correlation between matter separated by 150 Mpc.
- Nonlinear processing of the matter broadens/shifts the field.
- Galaxy formation takes place in this background, but is a local process, and is essentially decoupled.
- First predictions: Peebles & Yu (1970), Sunyaev & Zel'dovich (1970)



Baryons



Photons



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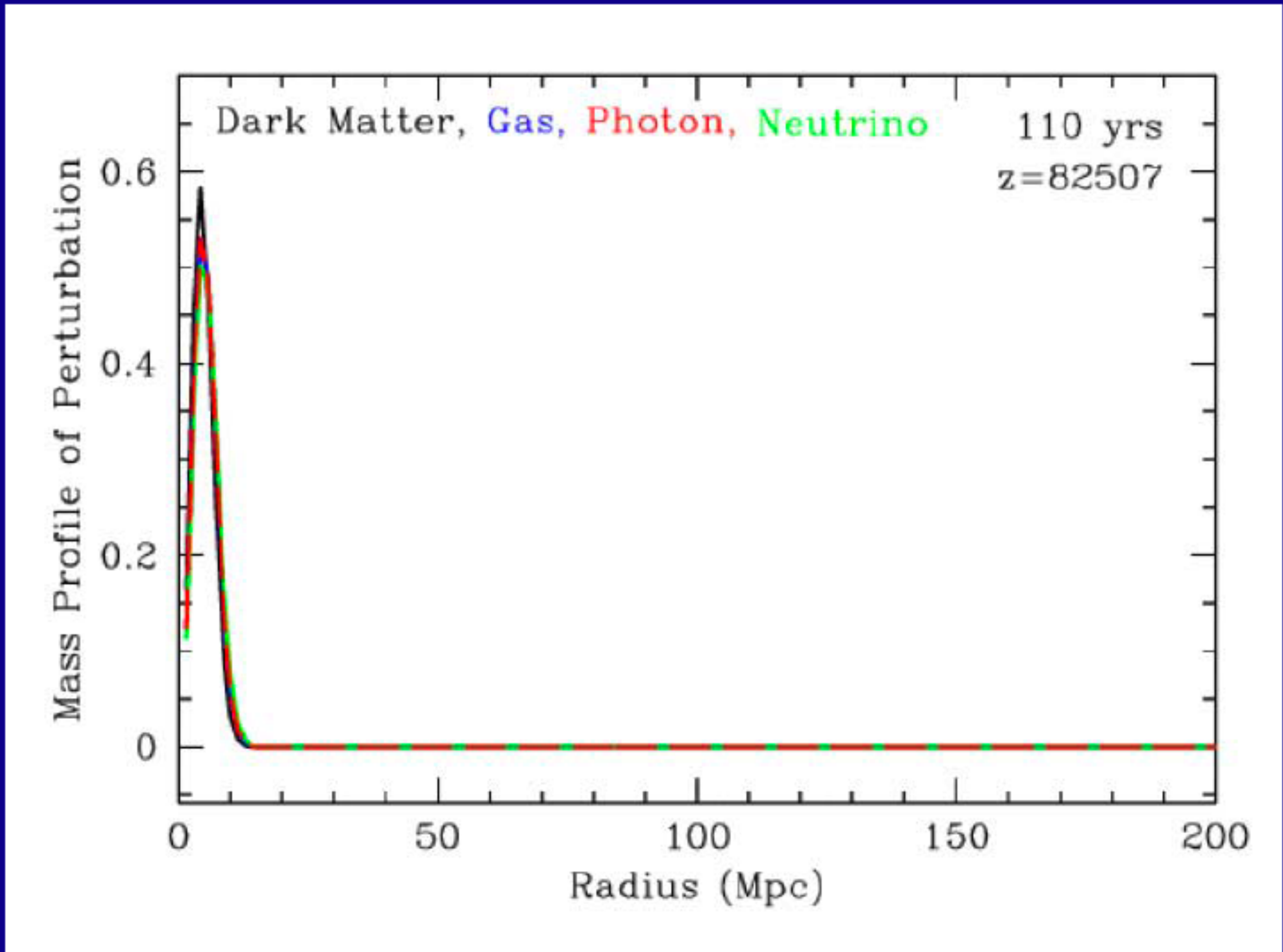
Sondes de l'énergie sombre:

les oscillations acoustiques des baryons



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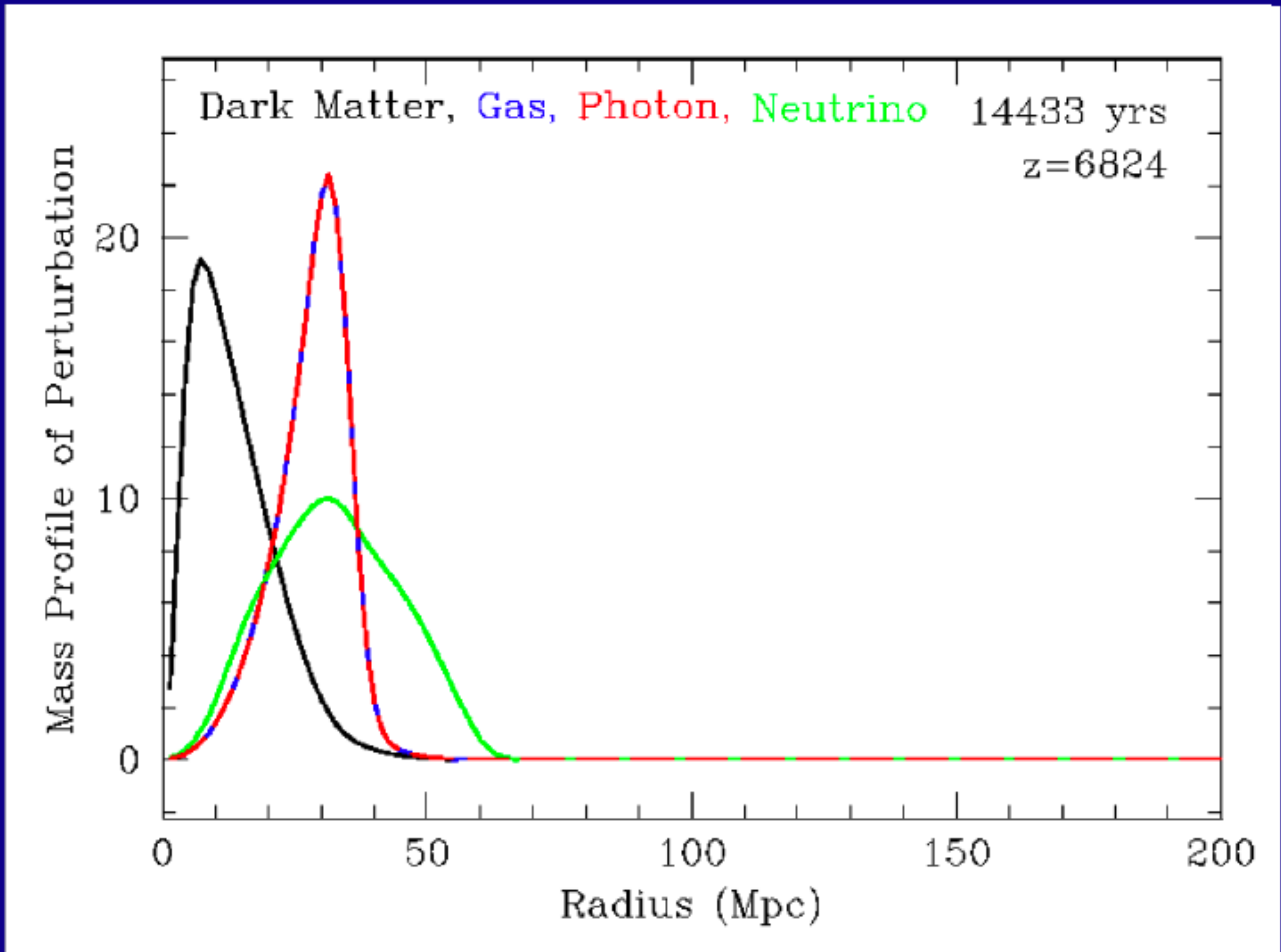

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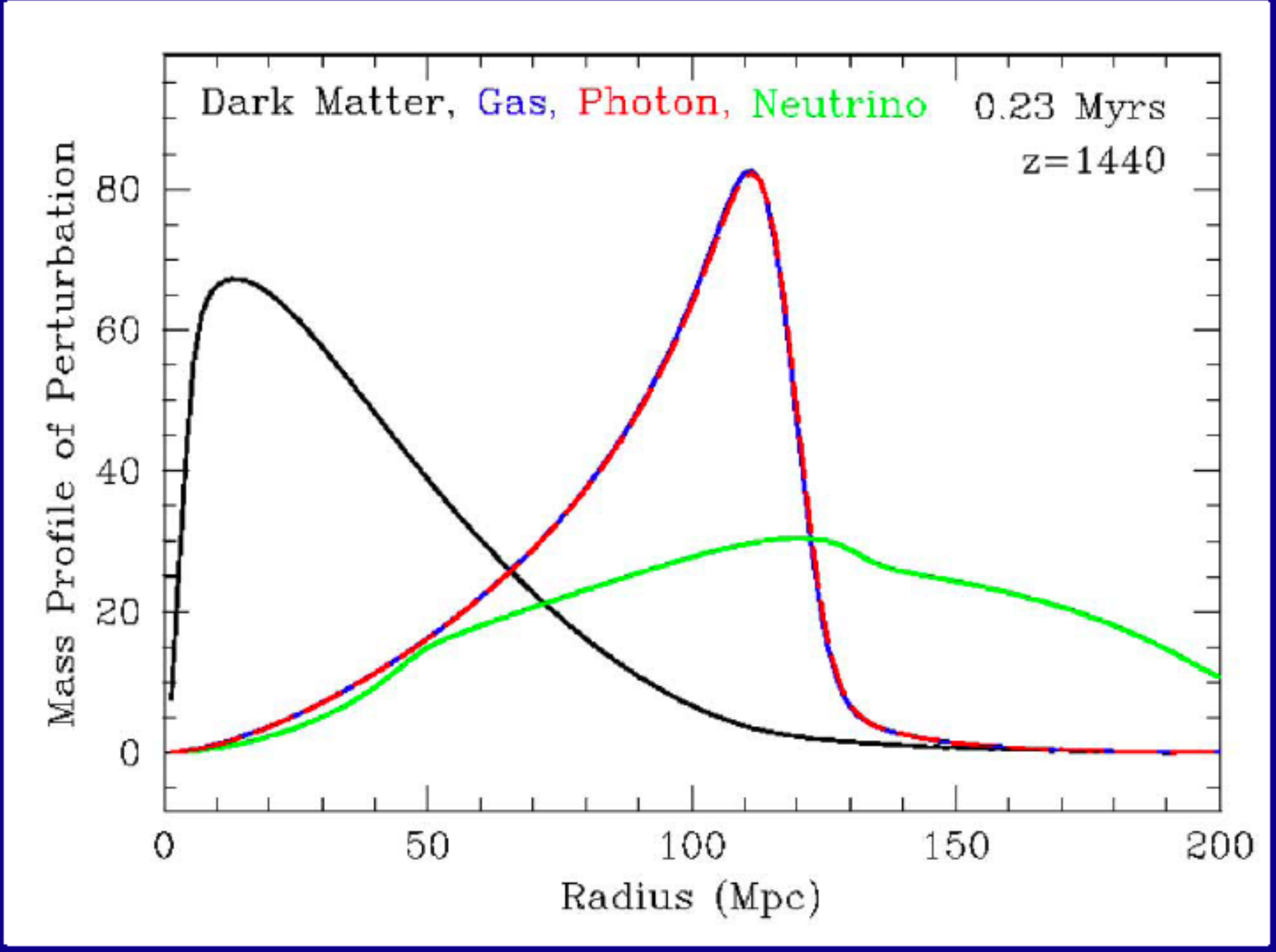

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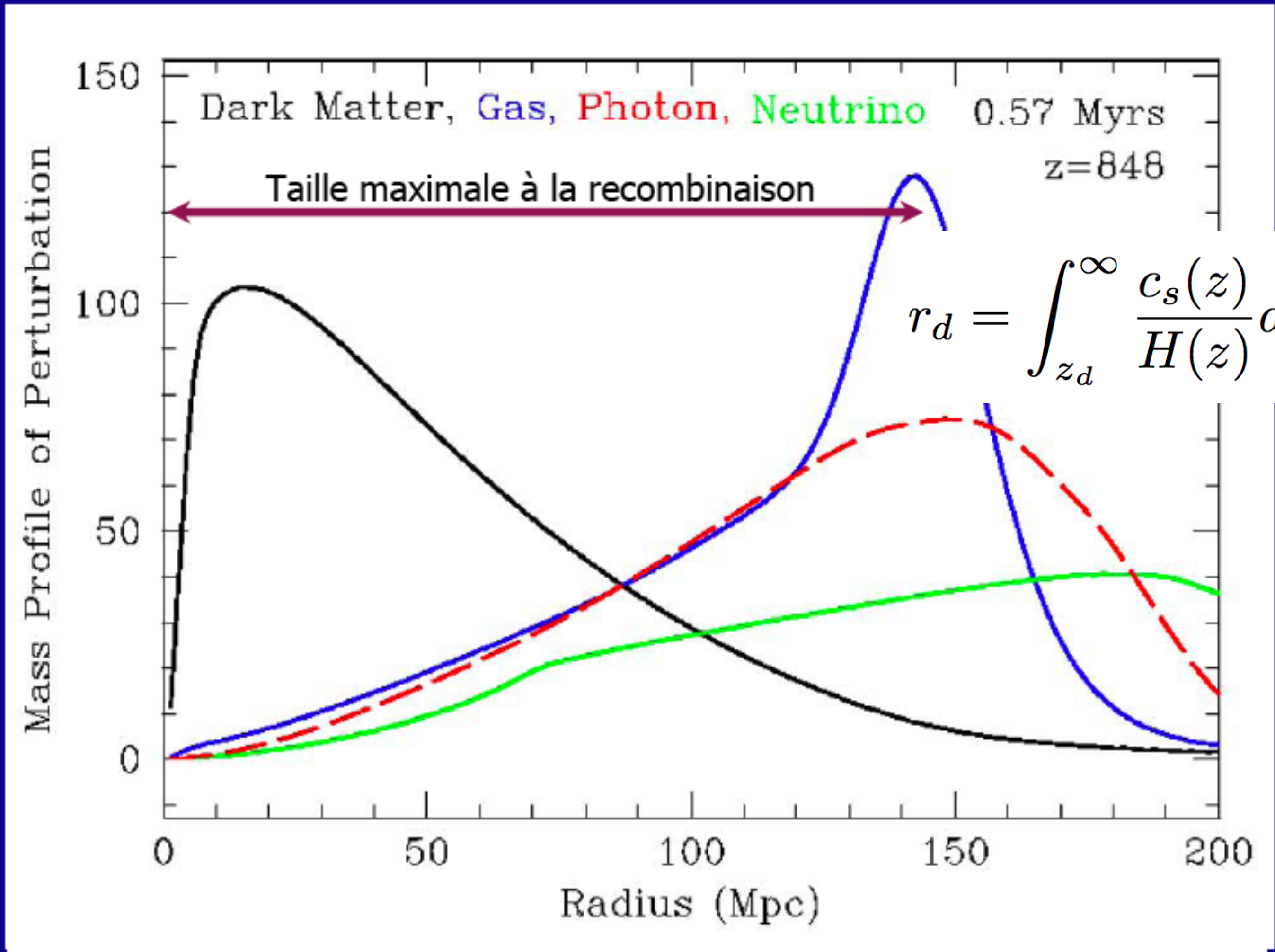
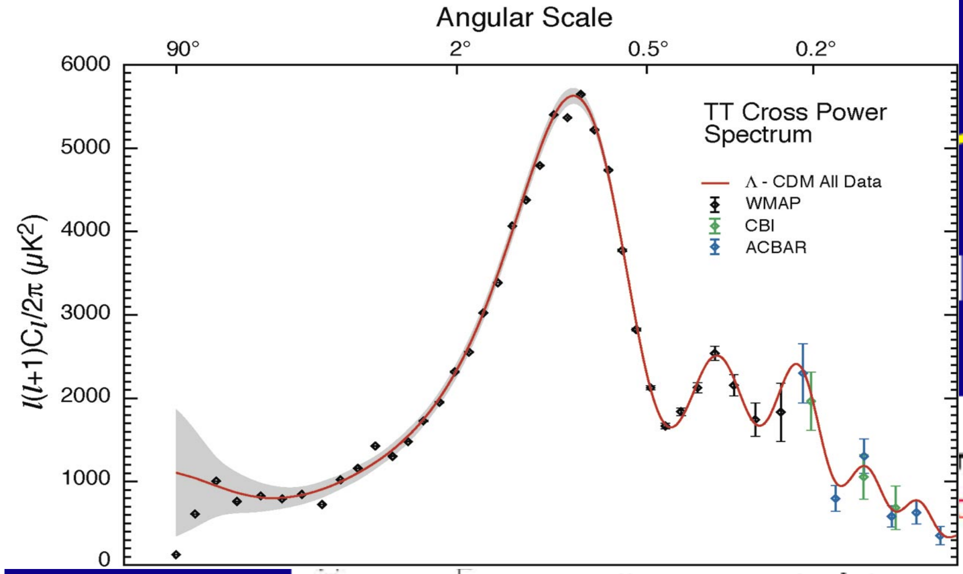
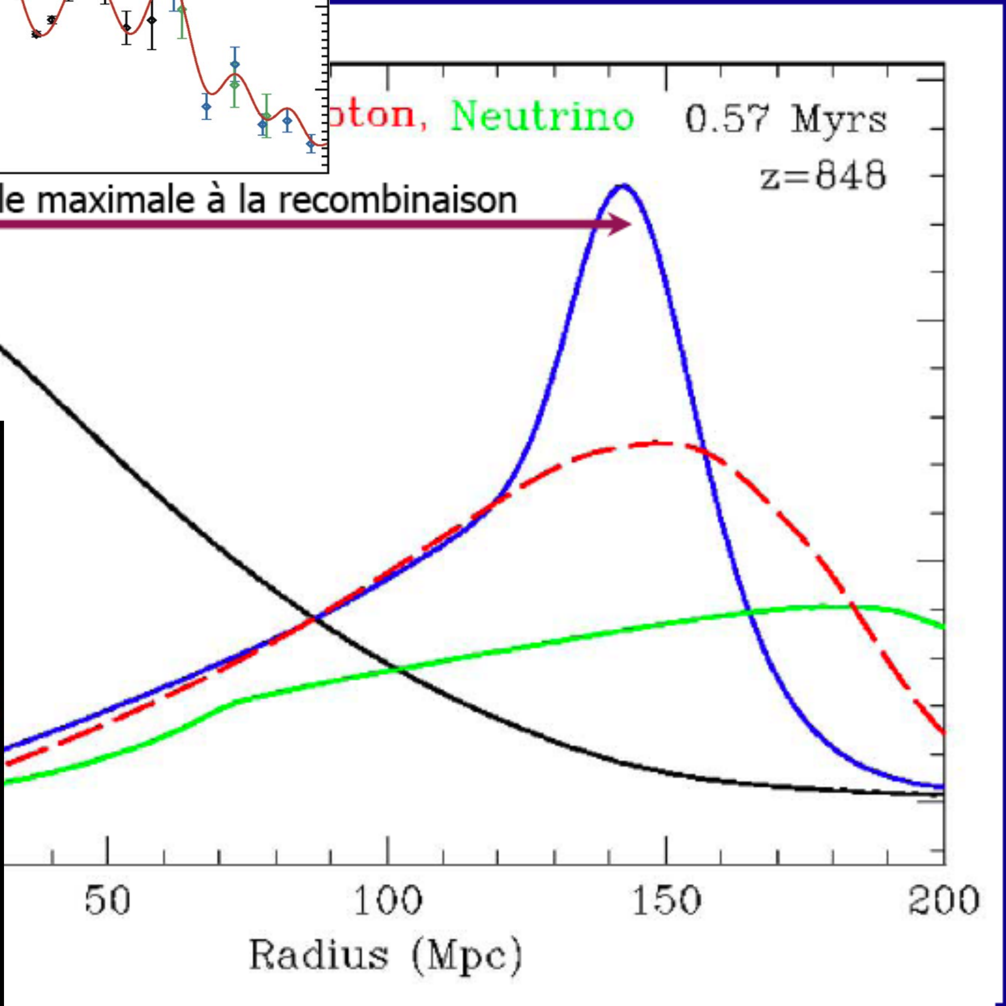


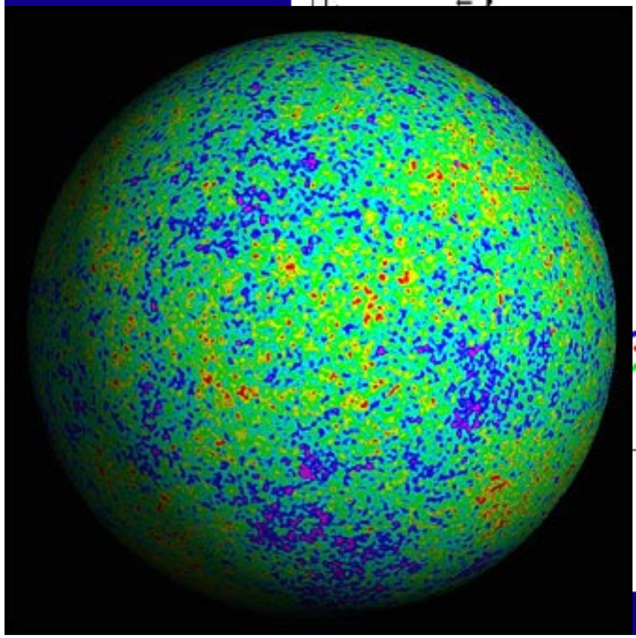
$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

nergie sombre:

stiques des baryons







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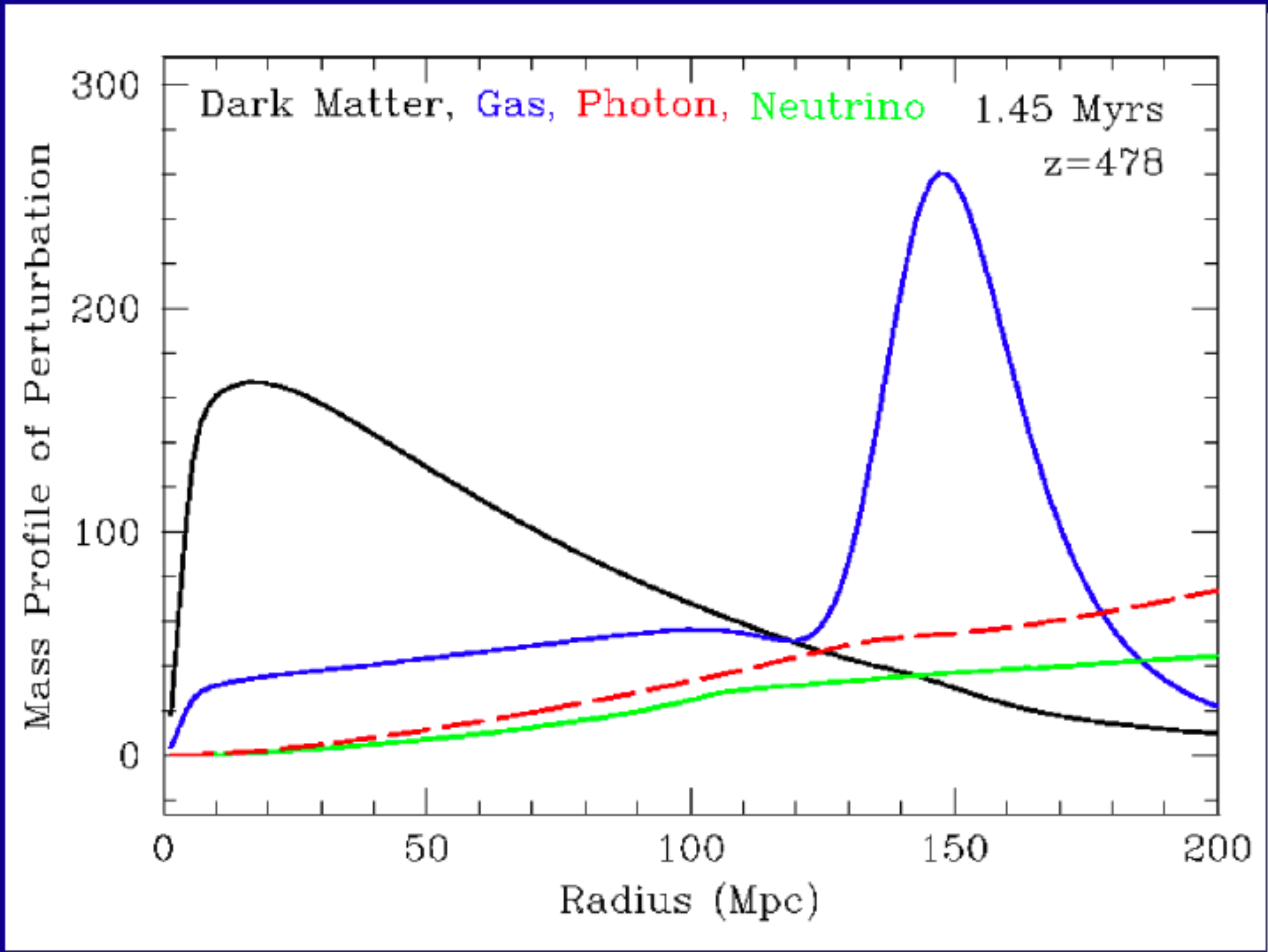

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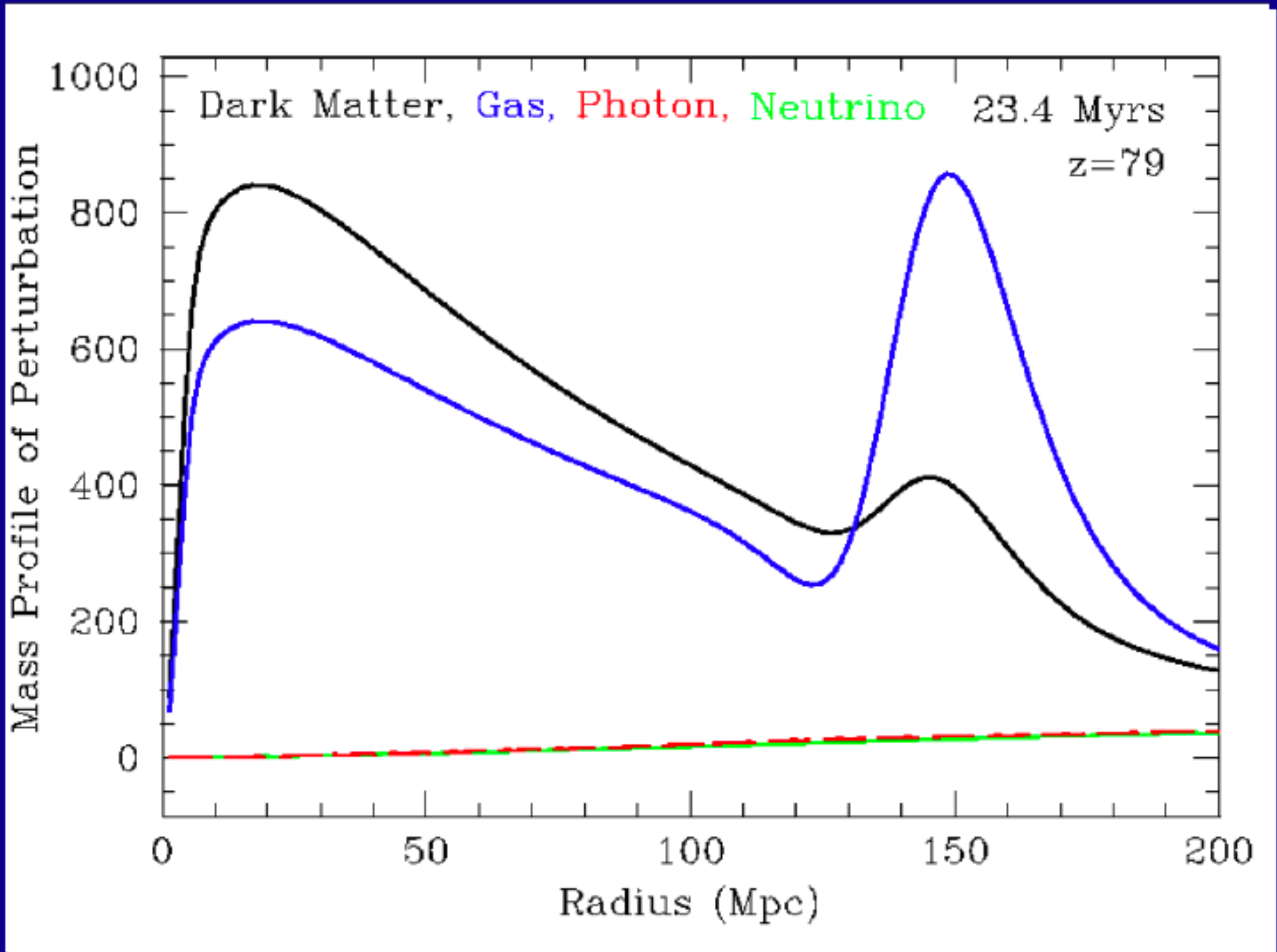
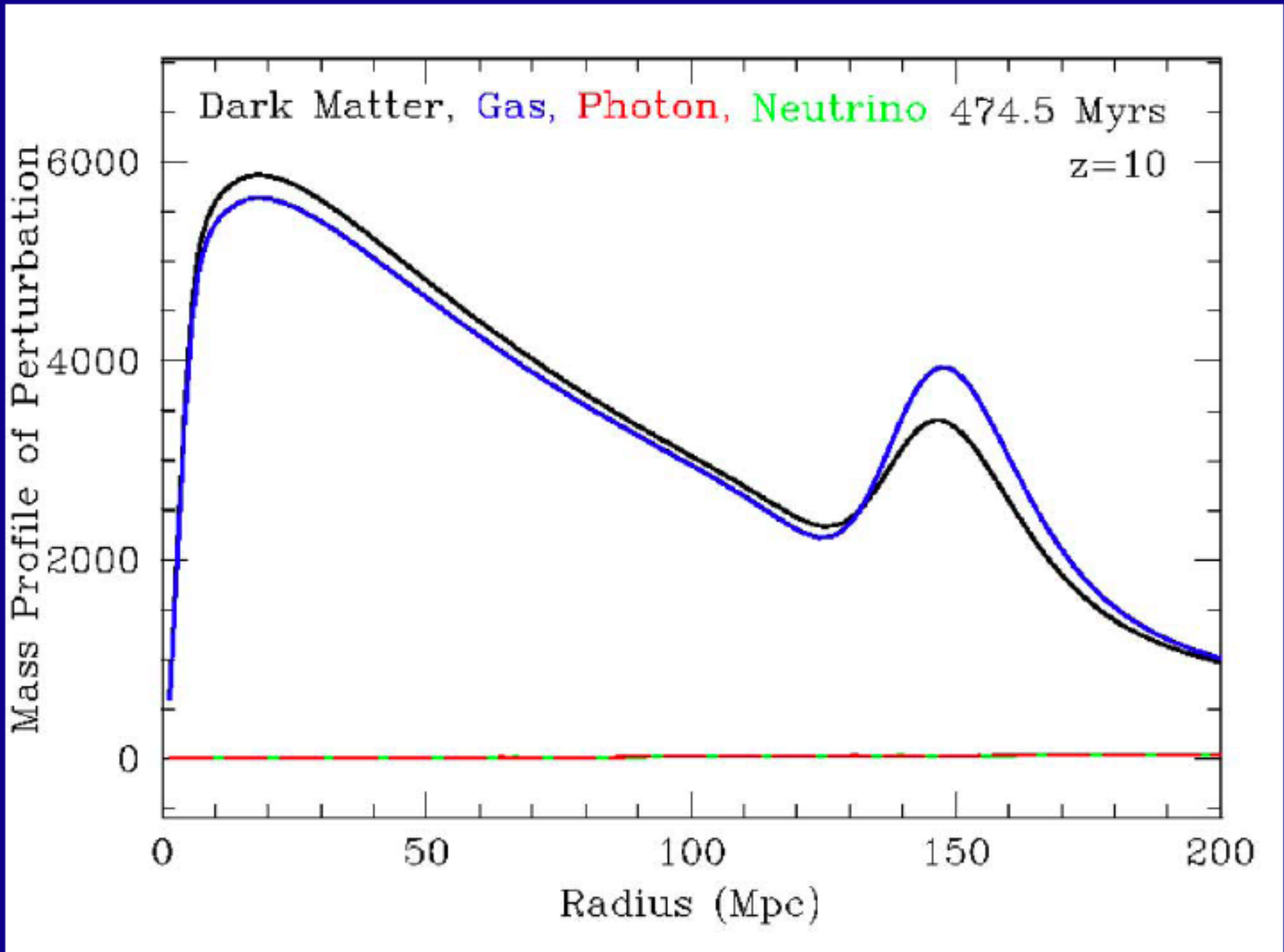


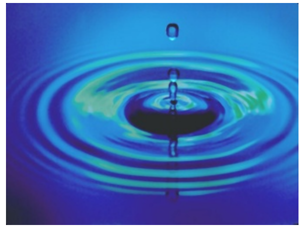
BAO : Baryonic Acoustic Oscillations

- Inprints of the oscillations of the baryon-photon fluid in the ordinary matter distribution after structure formation
- The baryonic matter distribution follows the dark matter modulation, in structures resulting from density fluctuation growing

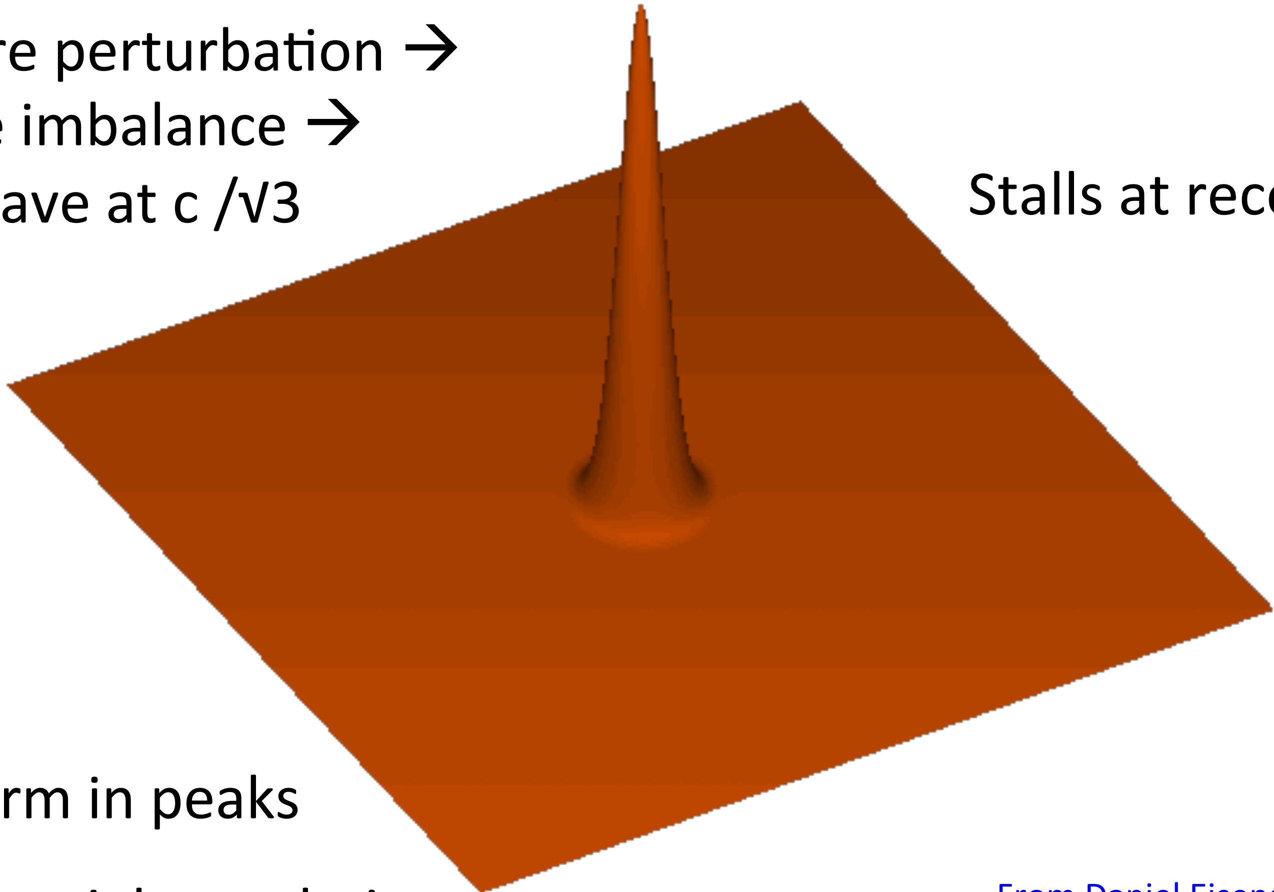
Sondes de l'énergie sombre:
les oscillations acoustiques des baryons



Three-Dimensional View



Curvature perturbation → pressure imbalance → sound wave at c /√3



Stalls at recombination

R~150Mpc

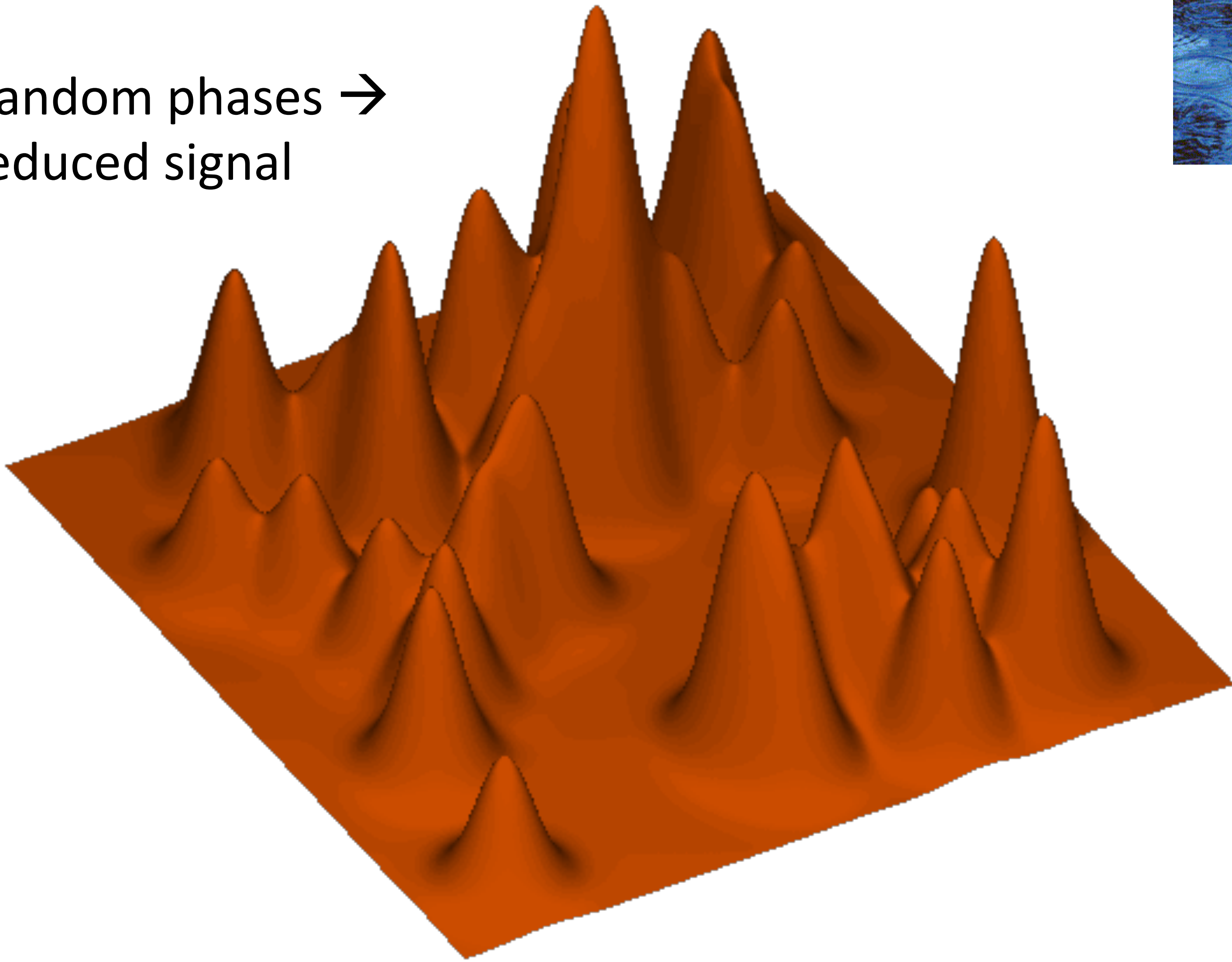
Galaxies form in peaks

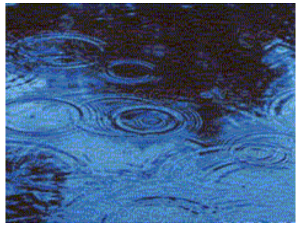
→ excess spatial correlations

From Daniel Eisenstein

Random Perturbations

Random phases → reduced signal





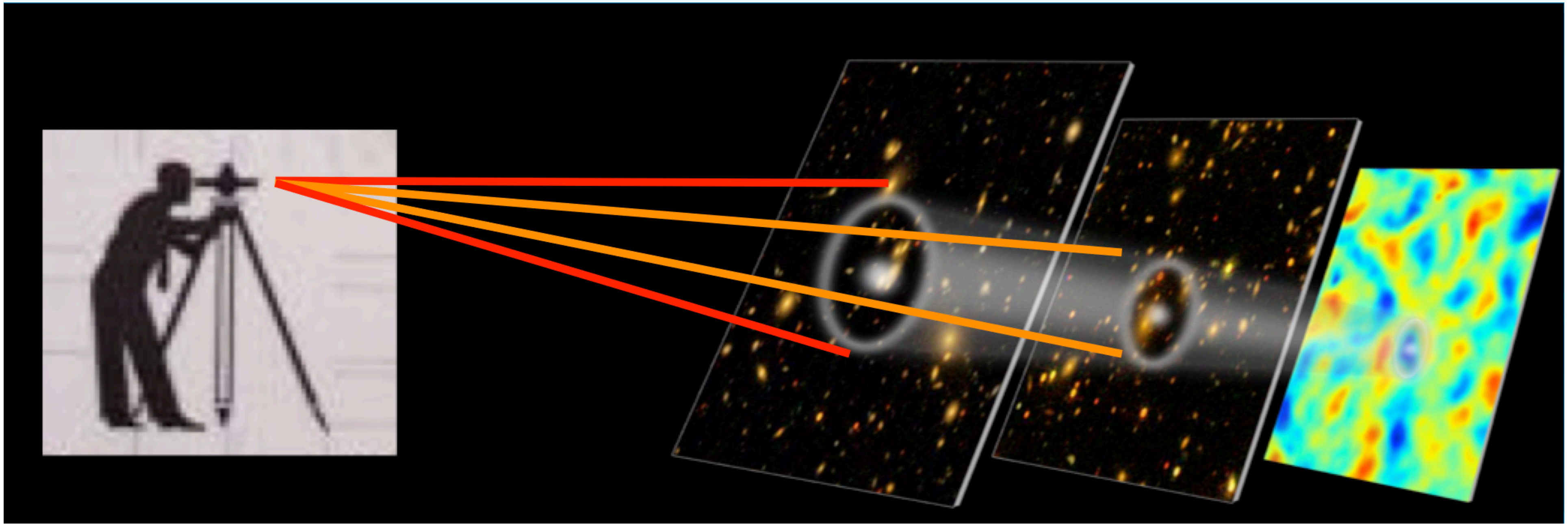
BAO : Baryon Acoustic Oscillations

- Inprints of the oscillations of the baryon-photon fluid in the ordinary matter distribution after structure formation
- The baryonic matter distribution follows the dark matter modulation, in structures resulting from density fluctuation growing
- The BAO provide a characteristic scale that is "frozen" in the galaxy distribution
- Cosmological probe of standard ruler type (**d_A**)
  - With a measurement @ z ~ 1100 as a bonus (CMB anisotropies)
- Use tracers of baryonic matter:
  galaxies (LSST), or H_I (Ly-α, radio@21cm)… with distinct biases

BAO is a standard ruler

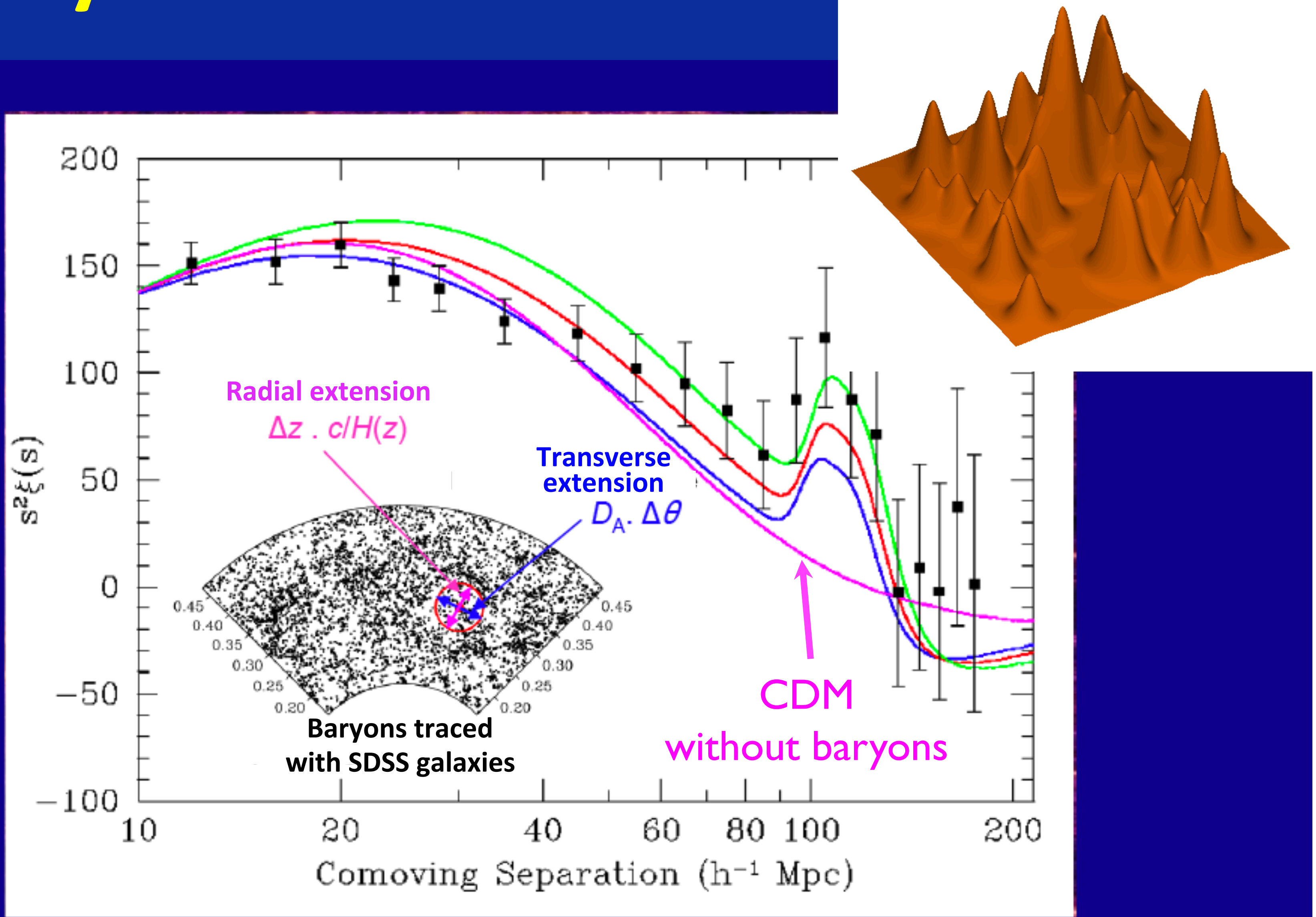
-> From the angular scale in the clustering data, we can infer the distance to the galaxies

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$



Baryonic Acoustic Oscillations

SDSS - D. Eisenstein et al.



Baryonic Acoustic Oscillations

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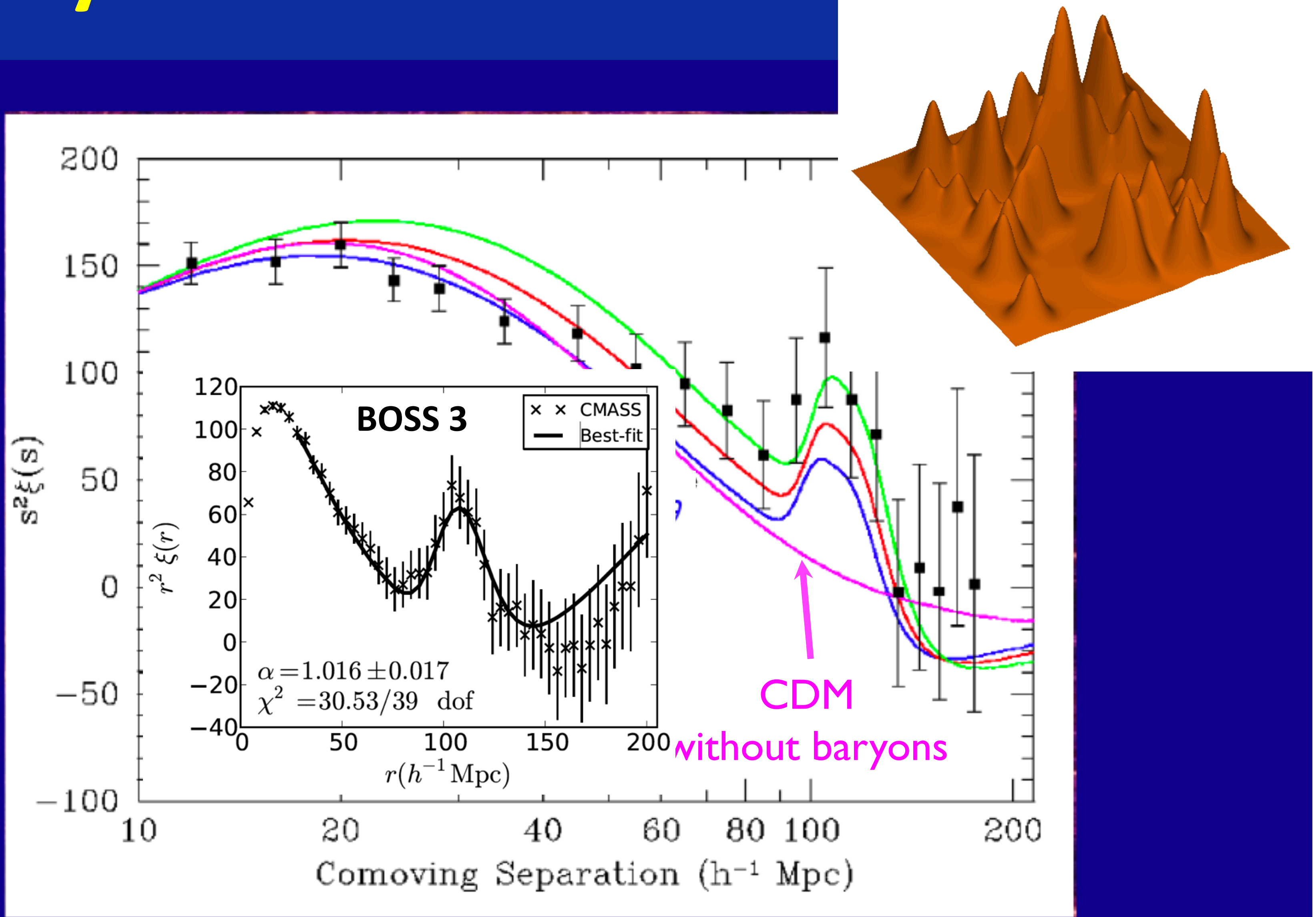
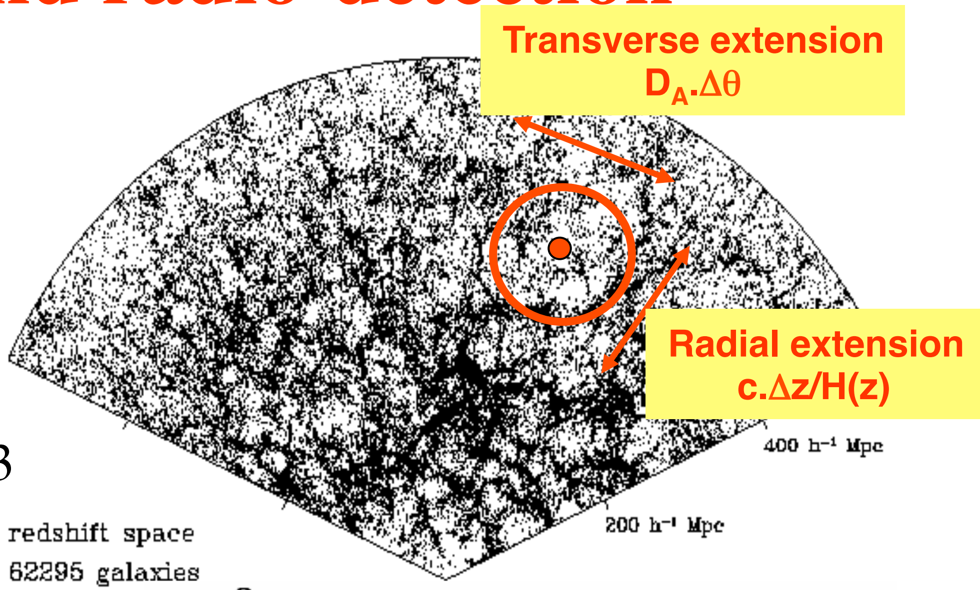
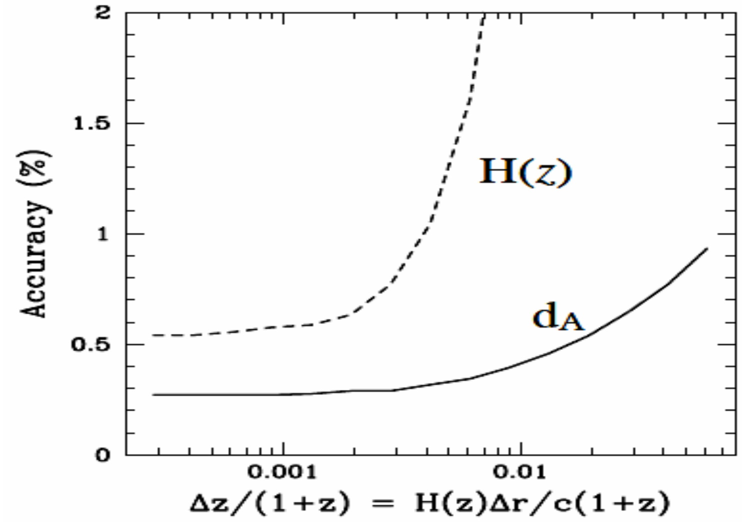


Baryonic Acoustic Oscillation with microwave, optical and radio-detection

Microwave (CMB)
measures the BAO scale at z = 1100
Optical survey (SDSS-eBOSS)
measures the BAO scale at 0.15<z<2.3
with galaxies+quasars+Ly-α
H_{21} radio-survey
can produce « low-resolution » maps of H_I (galaxies not resolved), but with excellent redshift determination (line of sight correlations easy)
-> BAO transverse+**radial** scales





BAO measurement

Principle

Search for excess in mutual distance of *objects* around 150 Mpc (comoving)

Objects = any tracer of density: galaxies, SN, emitting / absorbing gas, lenses

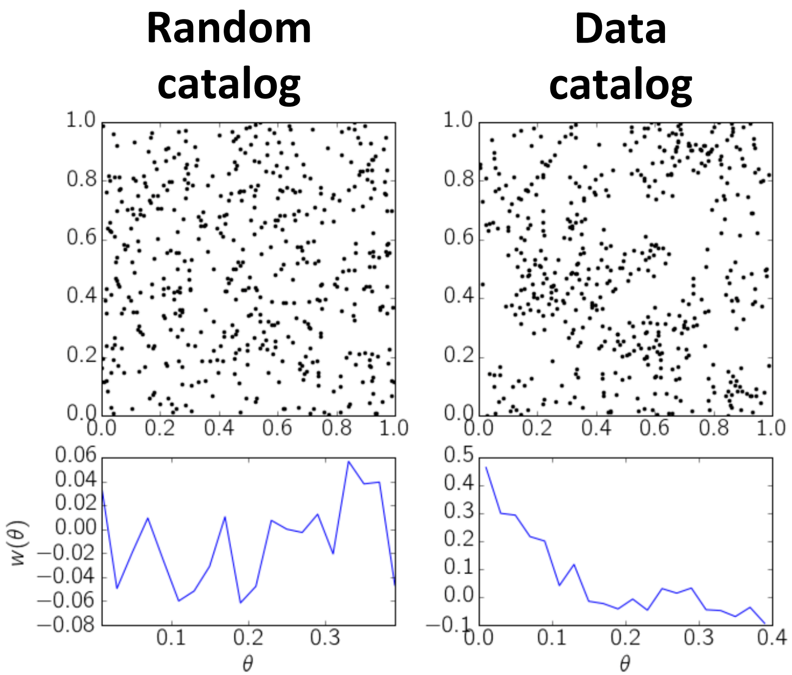
Tools

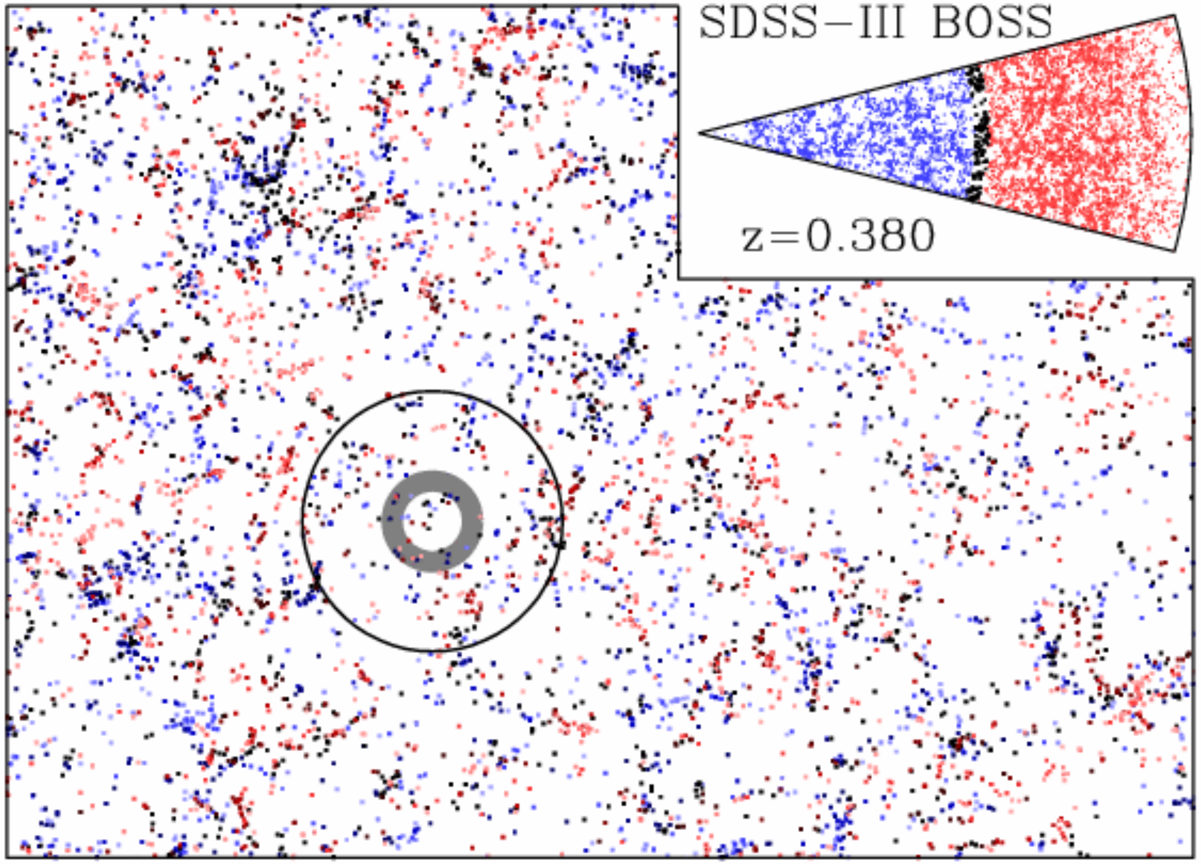
- 2-point correlation function in real space (2D or 3D)

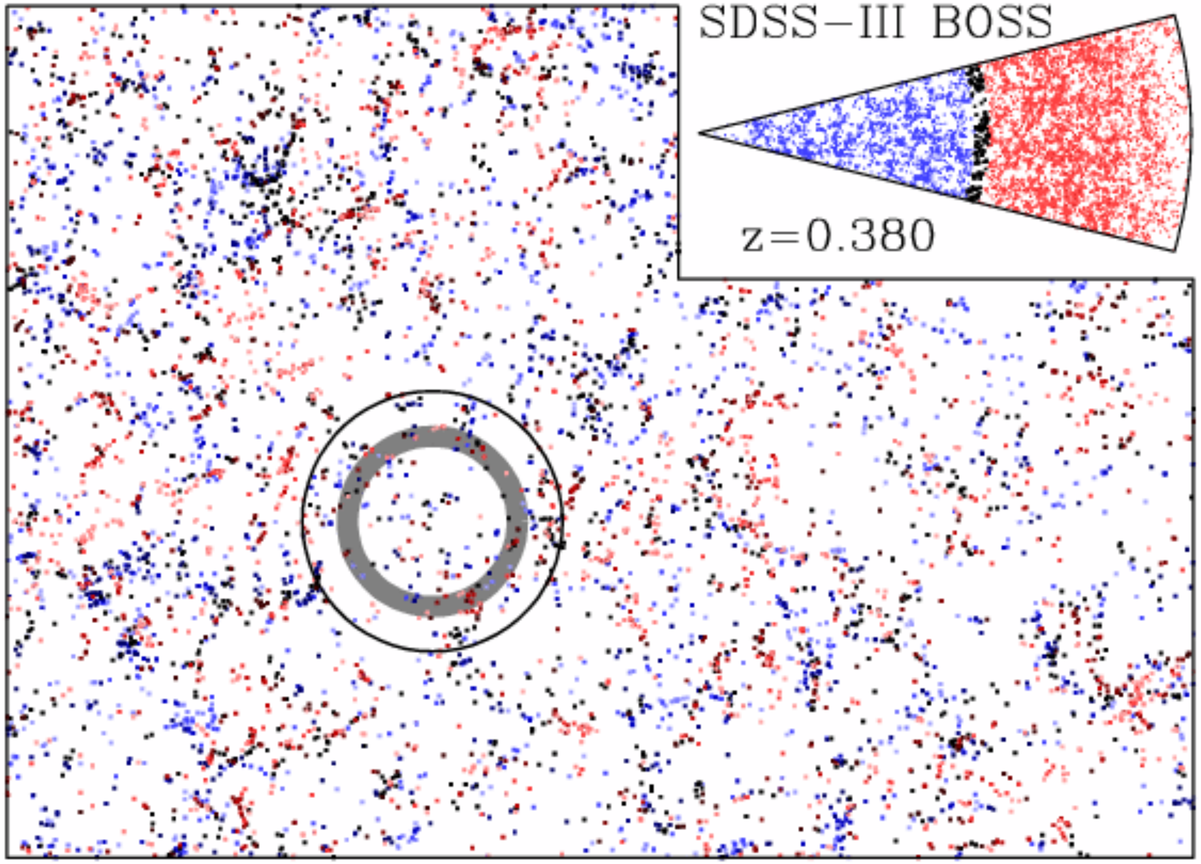
$$\xi(r) = (DD \times RR)/(DR)^2 - 1$$

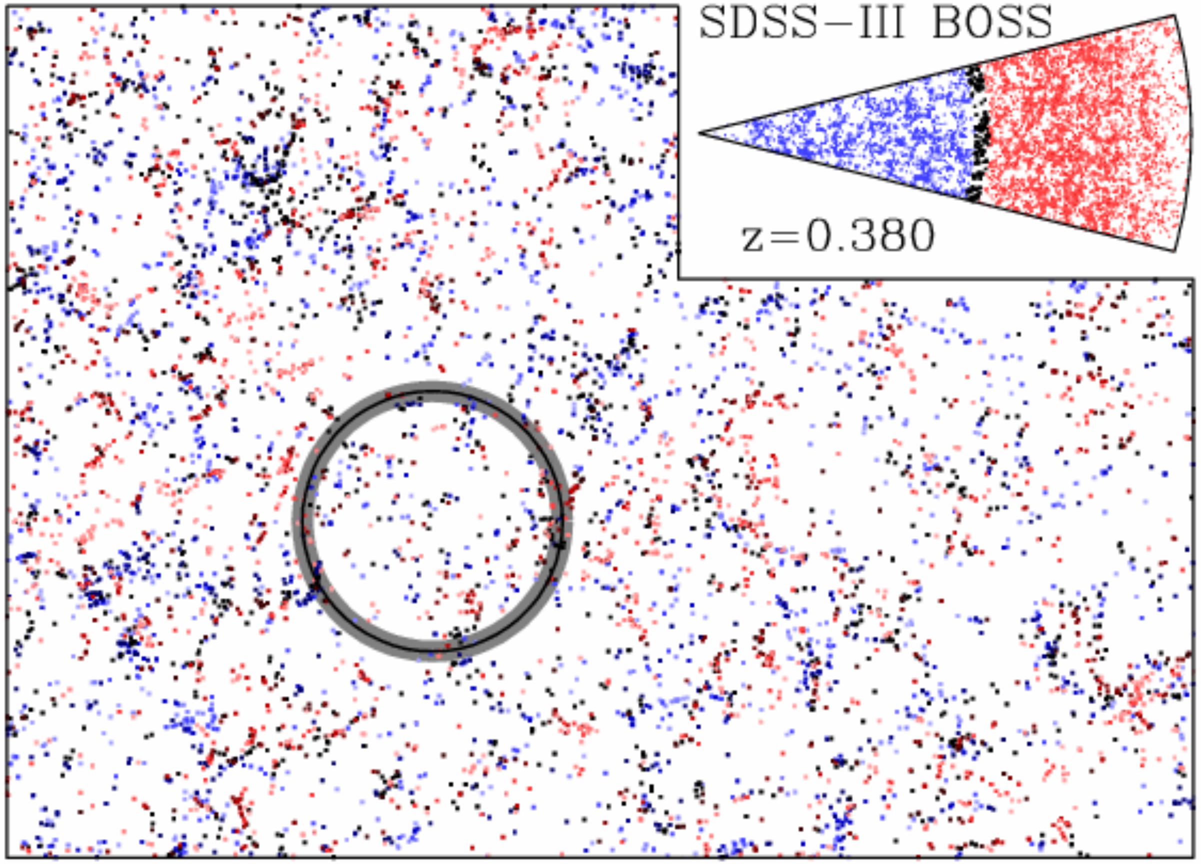
Where **DD** is # pairs in the data in bin [r,r+dr]
RR is # pairs in the random catalog
DR is # pairs data-random

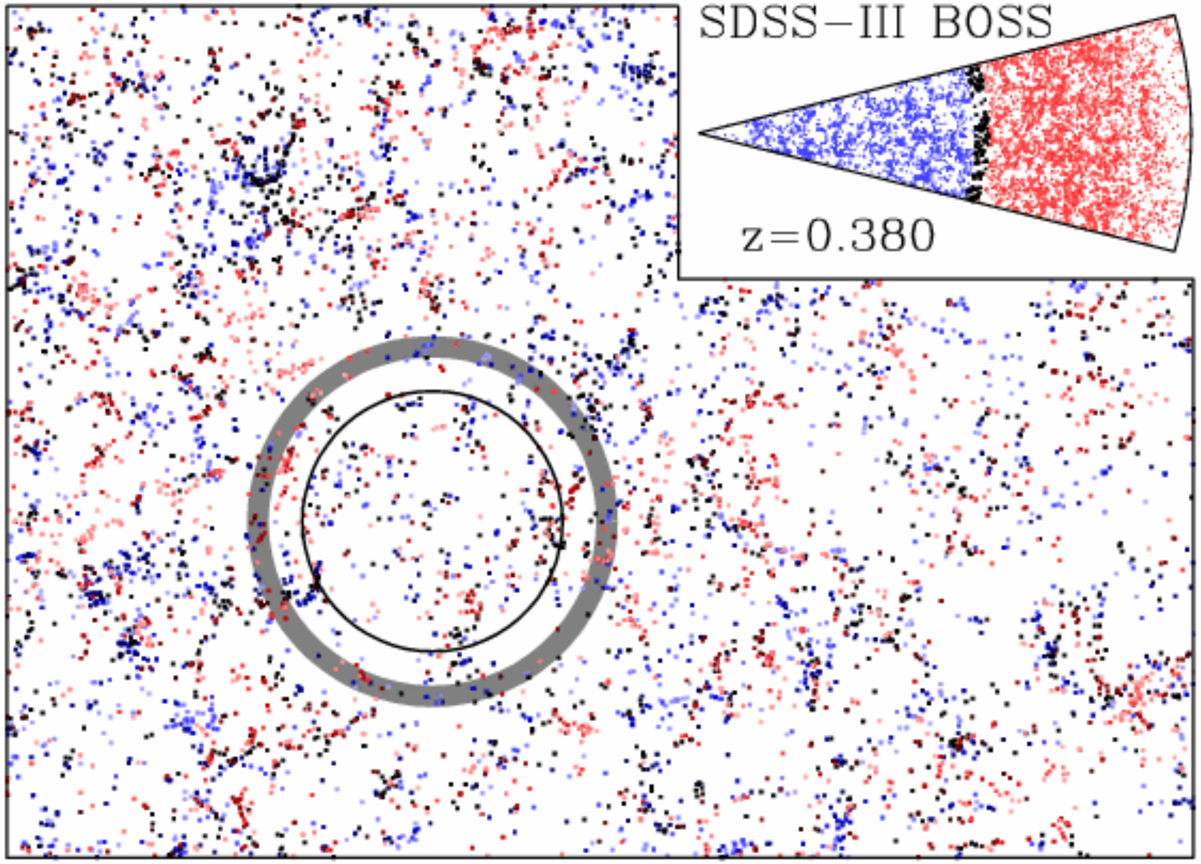
- Spherical harmonics in spatial frequency space: *density fluctuation power spectrum*

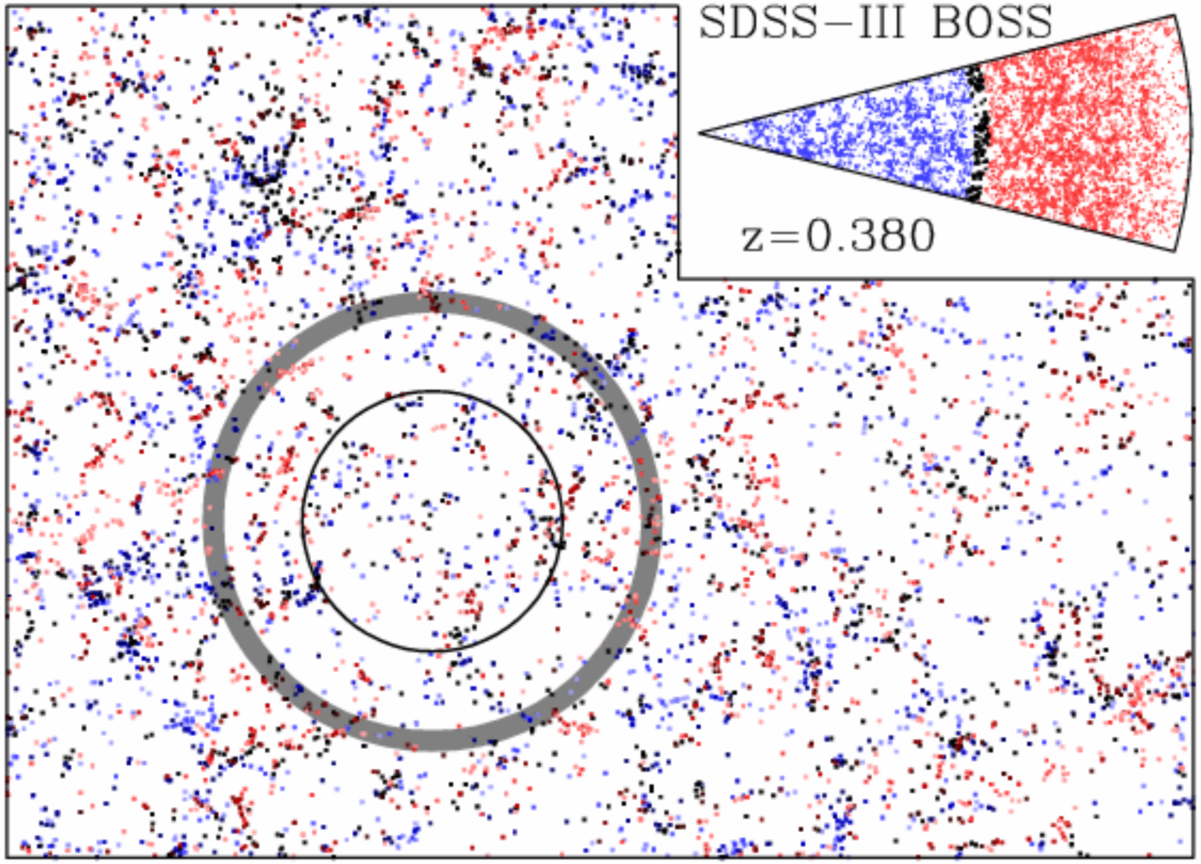



SDSS−III BOSS
z=0.380


SDSS−III BOSS
z=0.380


SDSS−III BOSS
z=0.380


SDSS−III BOSS
z=0.380


SDSS−III BOSS
z=0.380

BAO measurement

Principle

Search for excess in mutual distance of *objects* around 150 Mpc (comoving)

Objects = any tracer of density: galaxies, SN, emitting / absorbing gas, lenses

Tools

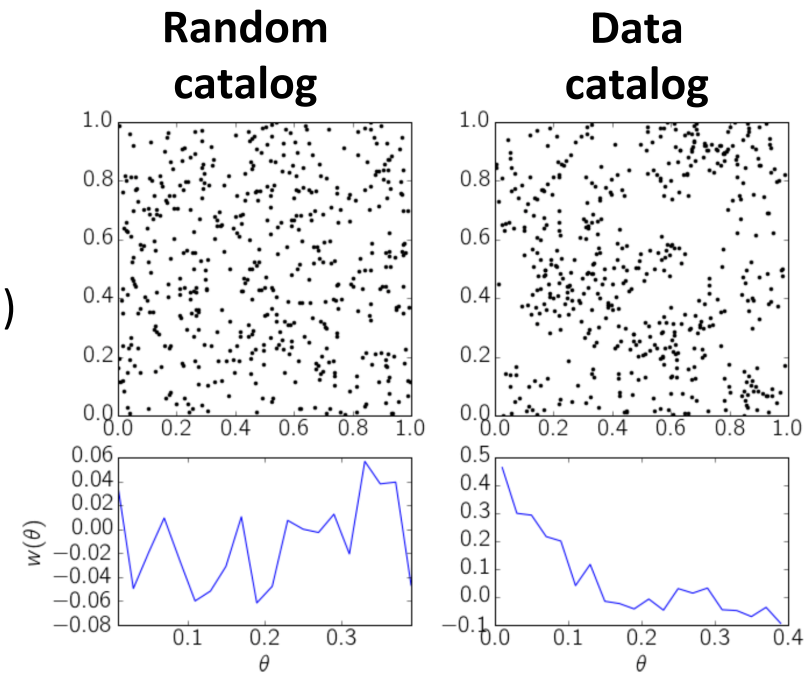
- 2-point correlation function in real space (2D or 3D)

$$\xi(r) = \mathbf{(DD \times RR)/(DR)^2 - 1}$$

Where **DD** is # pairs in the data in bin [r,r+dr]

RR is # pairs in the random catalog

DR is # pairs data-random



- Spherical harmonics in spatial frequency space: *density fluctuation power spectrum*

Issues

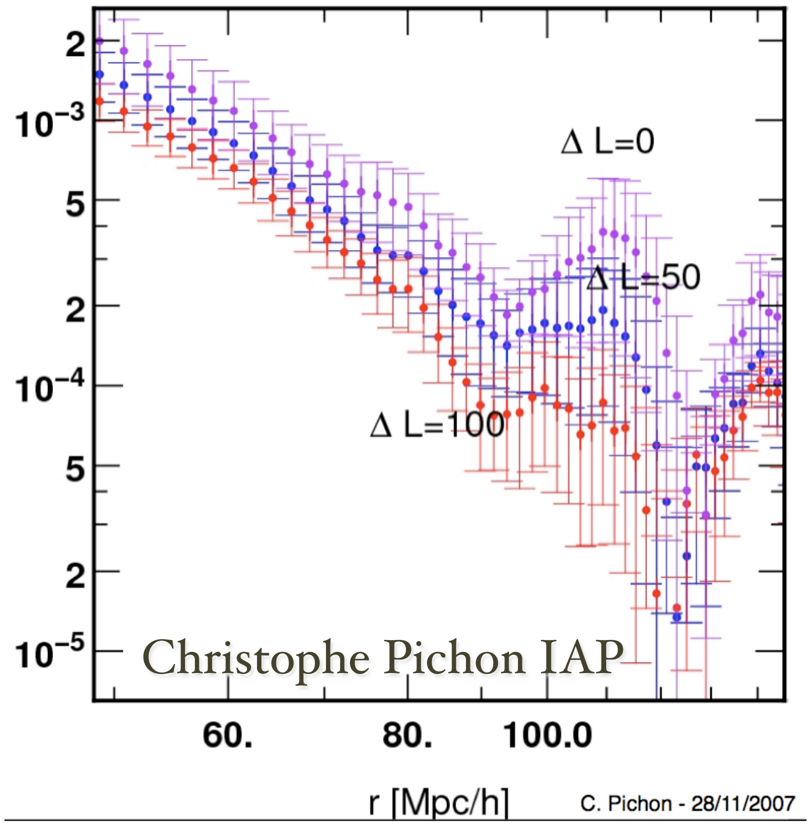
Masking / selection function (to simulate in the random catalog)

Redshift is expensive (spectra)

Redshifts instead of distance -> **RSD** (Redshift Space Distortions): Redshifts are caused by both the Hubble expansion and peculiar velocities.

Needs for a precise measurement of BAO

- Large volume (~100 Gpc^3)
- Large z domain (>1)
- Precise determination of z
  h.ΔL < 100 Mpc => Δz < 3%
- Large structures (degree)
  => No need for a very good angular precision



Scene restitution of 3D distributions

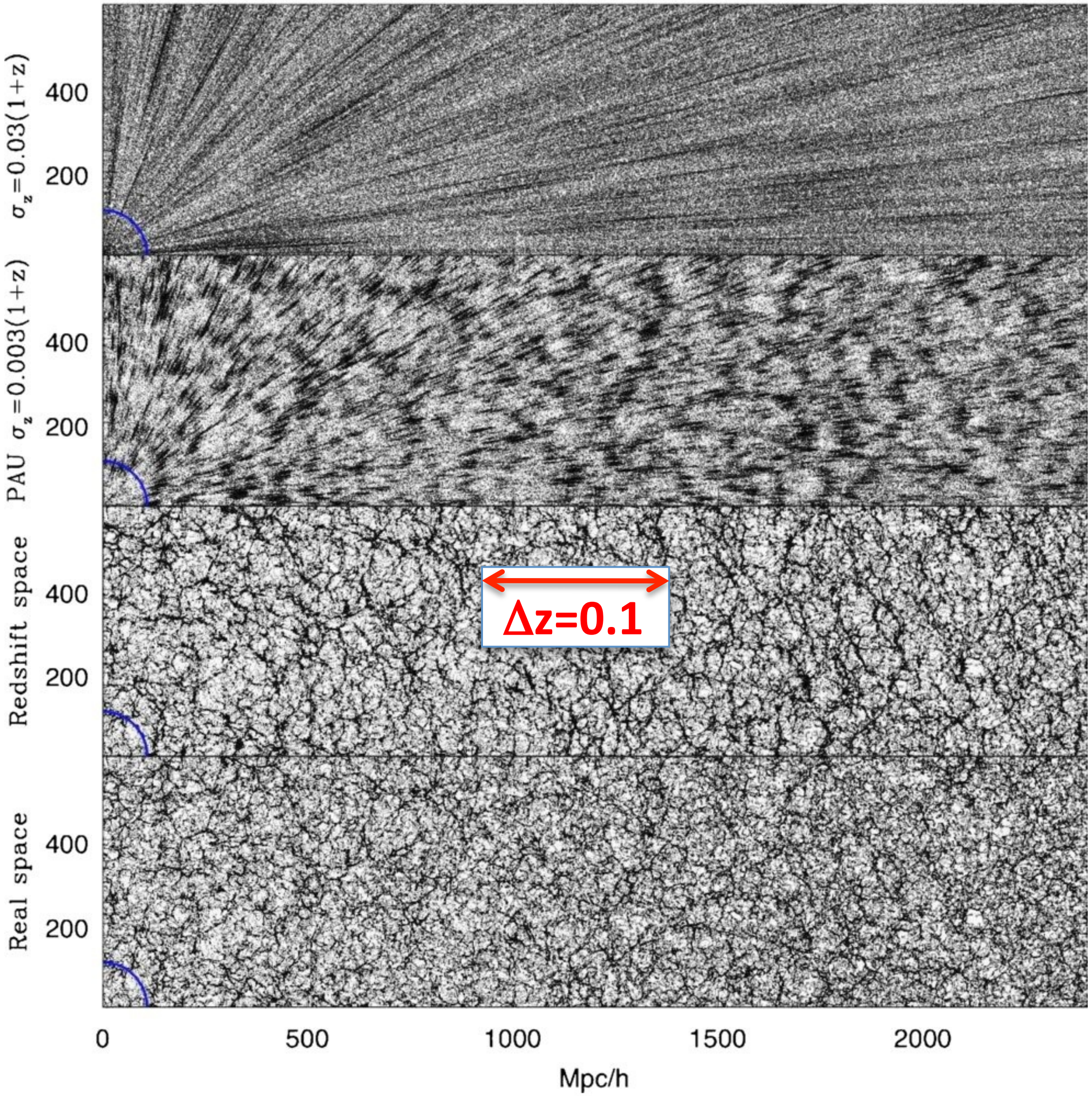
photometric survey
of galaxies

2D

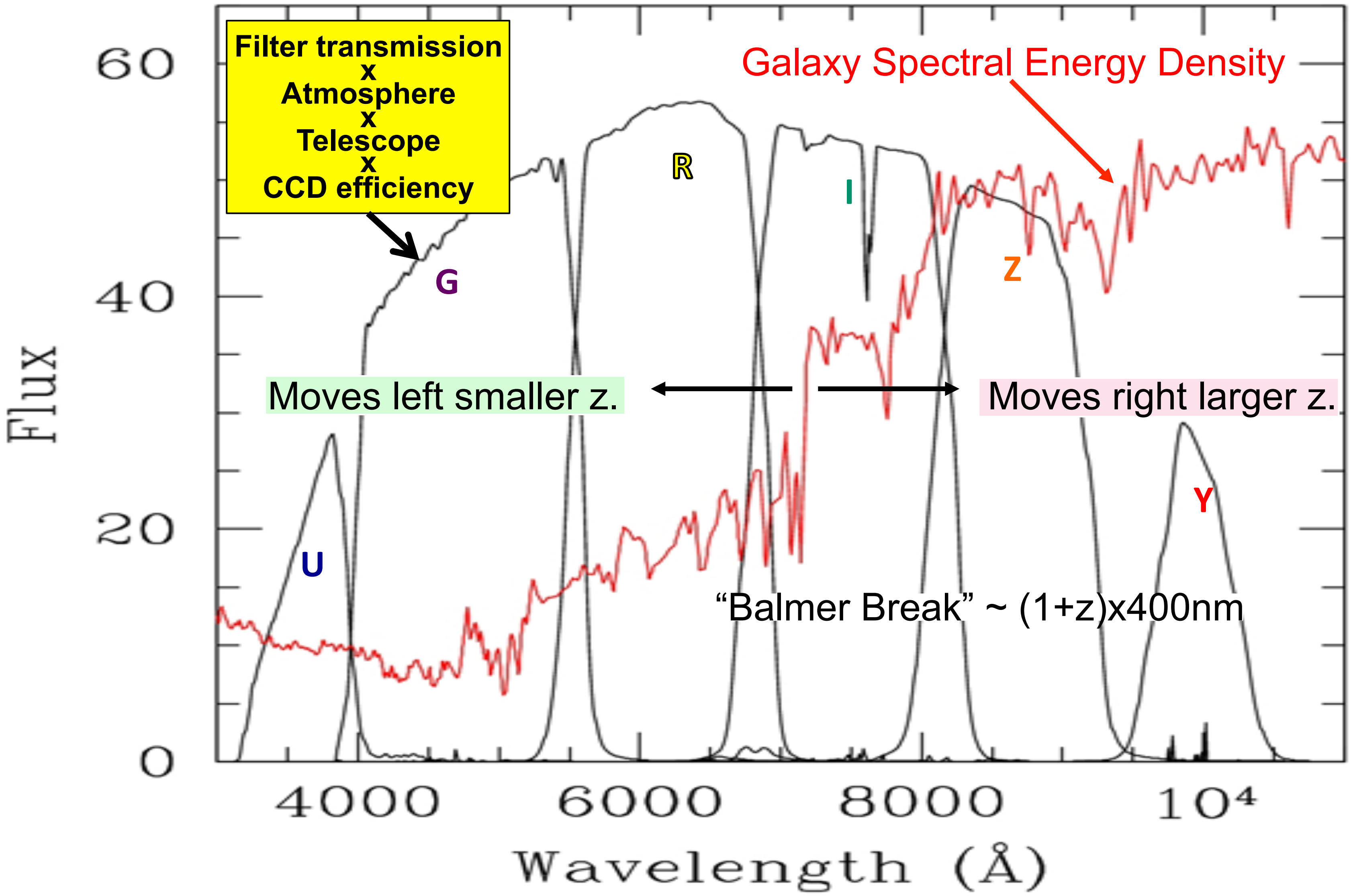
spectroscopic survey
of galaxies

BAO-radio / Ly-α

3D

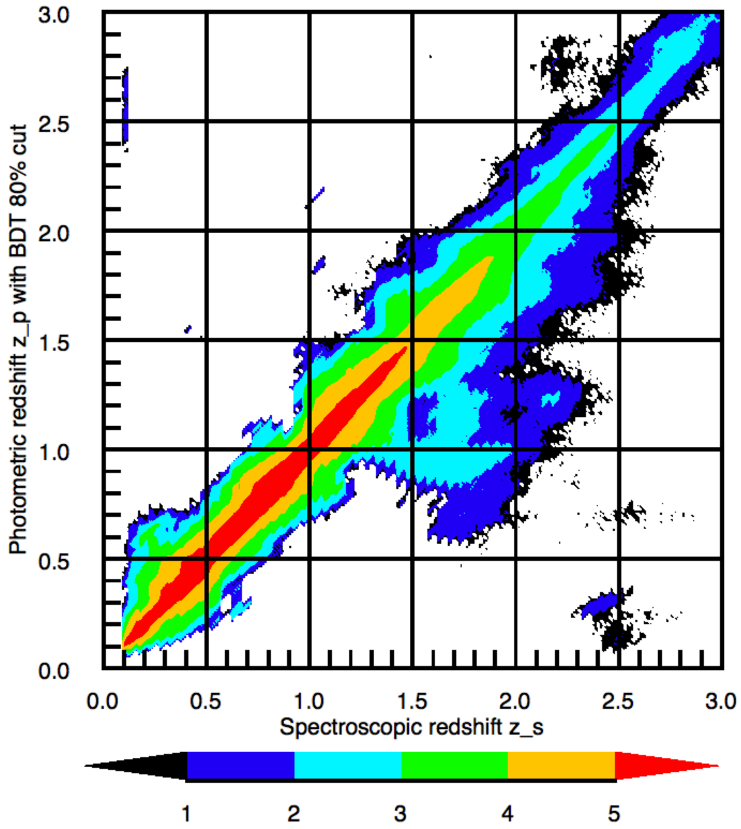


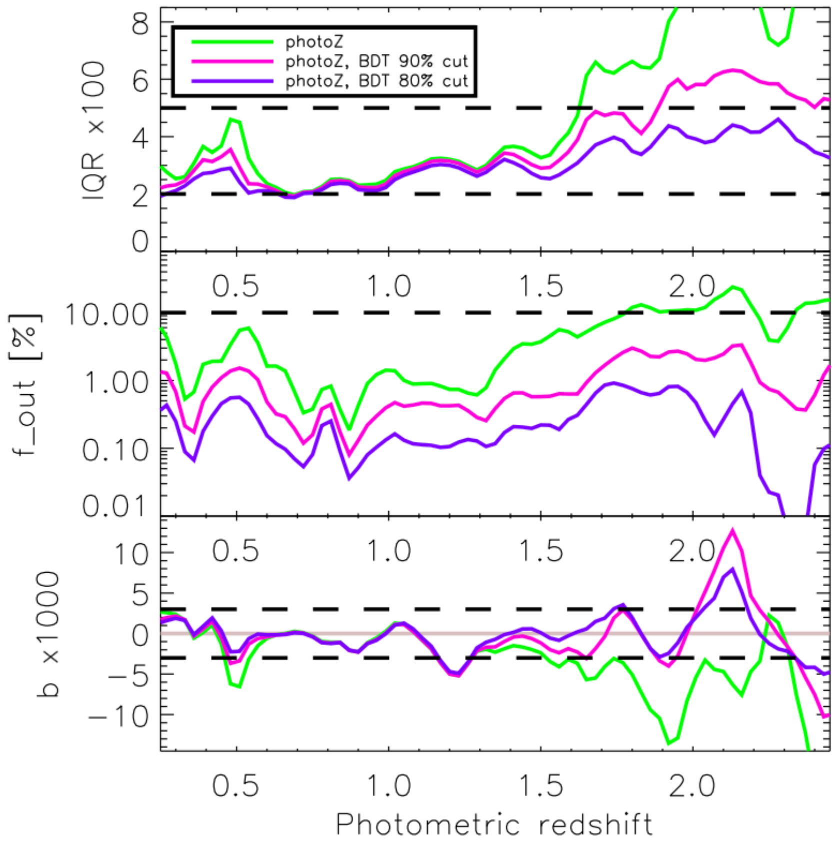
Photometric Redshift



Photometric Redshift: animation

Redshift determination (LSST)

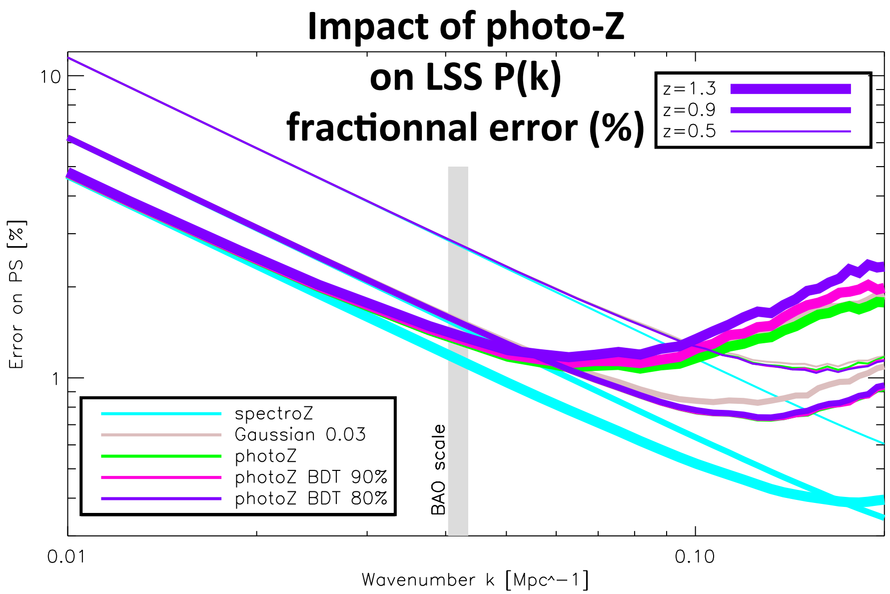


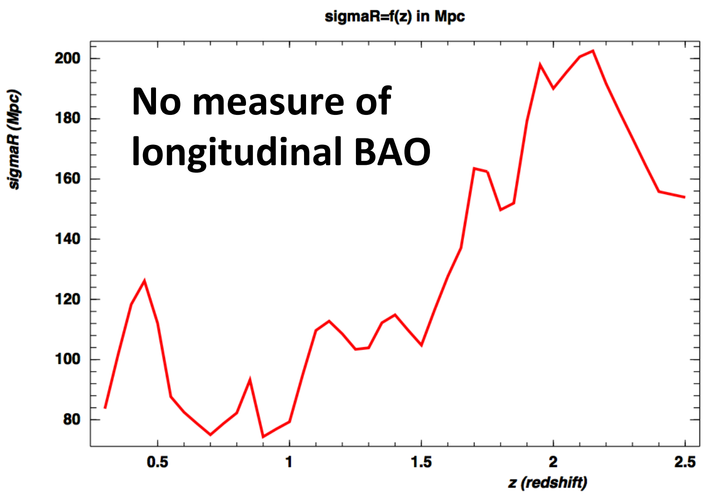


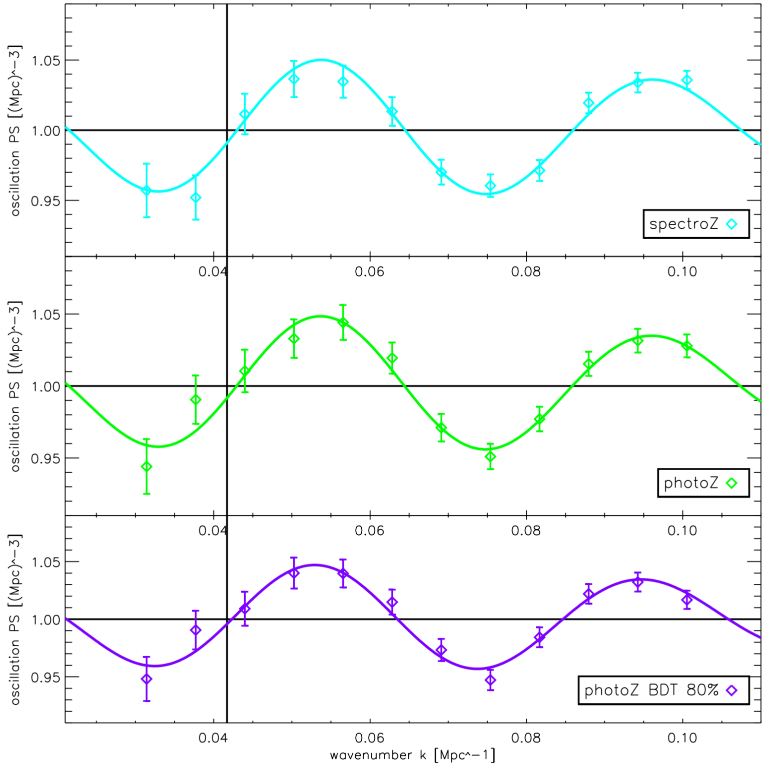
Photometric-*z* vs spectroscopic-*z*:

Simulation of photometric redshift determination with the 6 LSST passbands

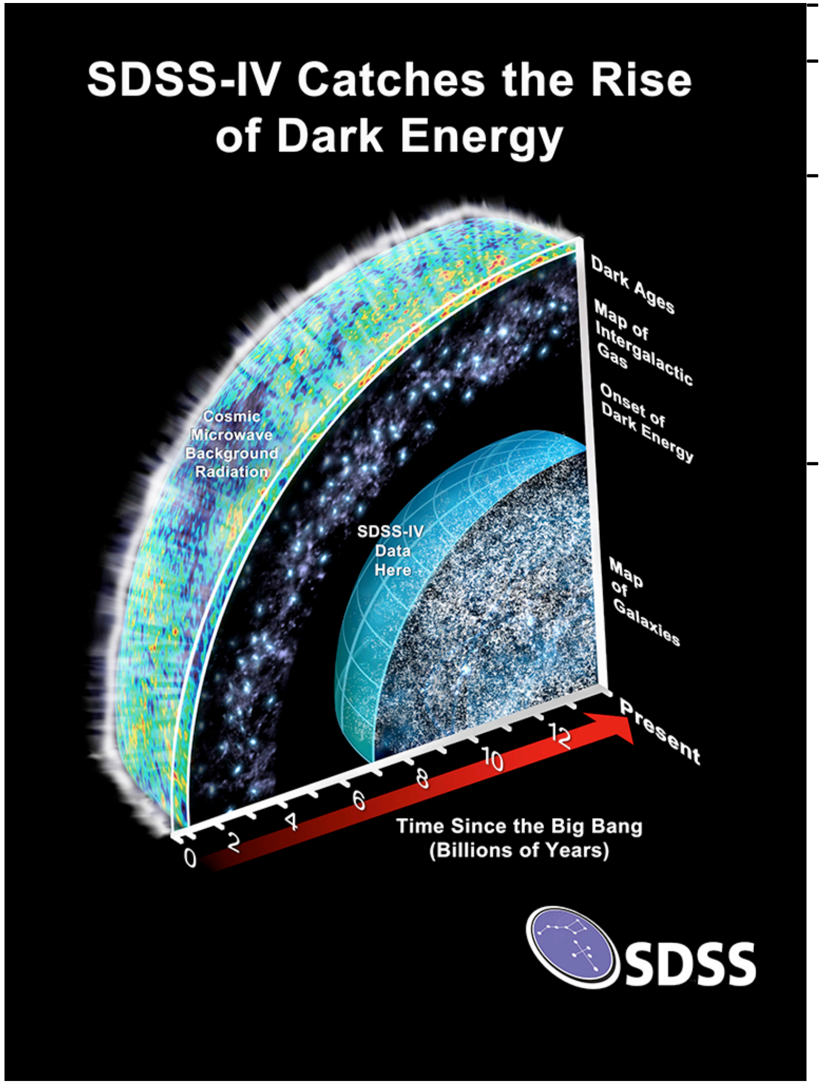
BAO: LSST expectations with photo-z



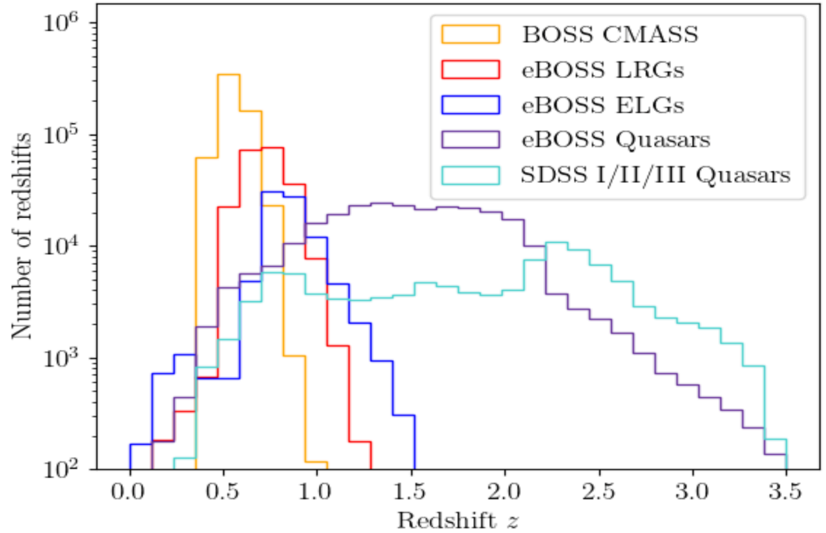




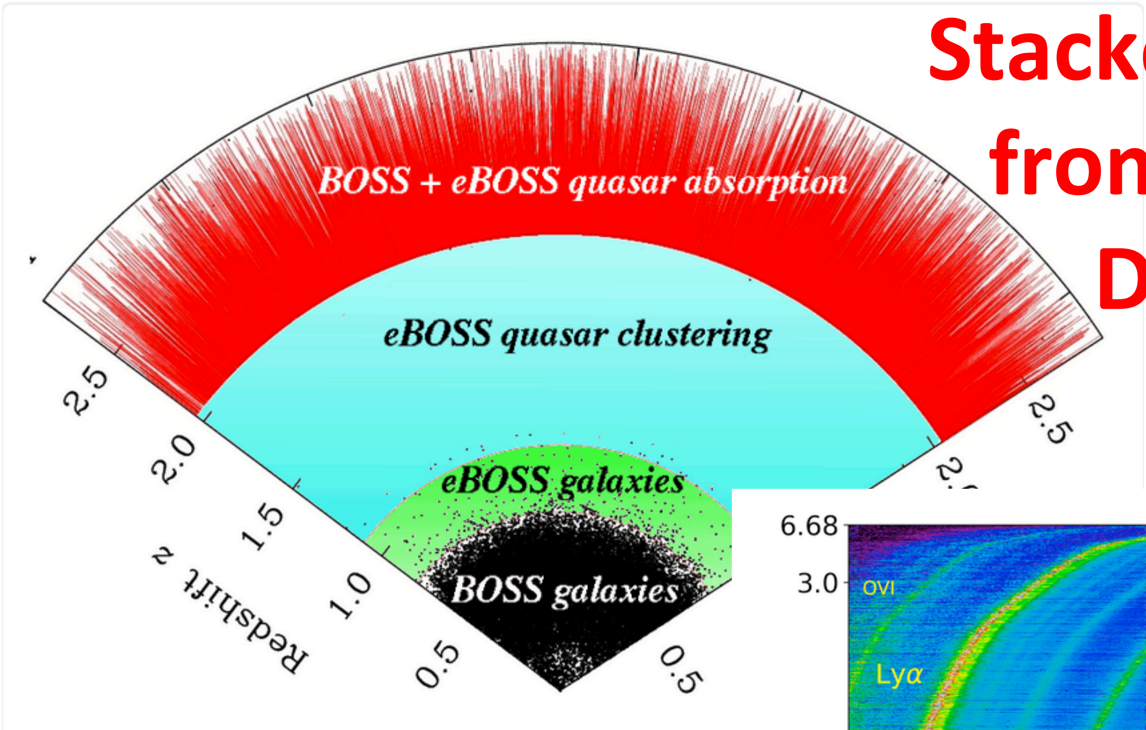
SDSS-I-II – III (BOSS) – IV (eBOSS)

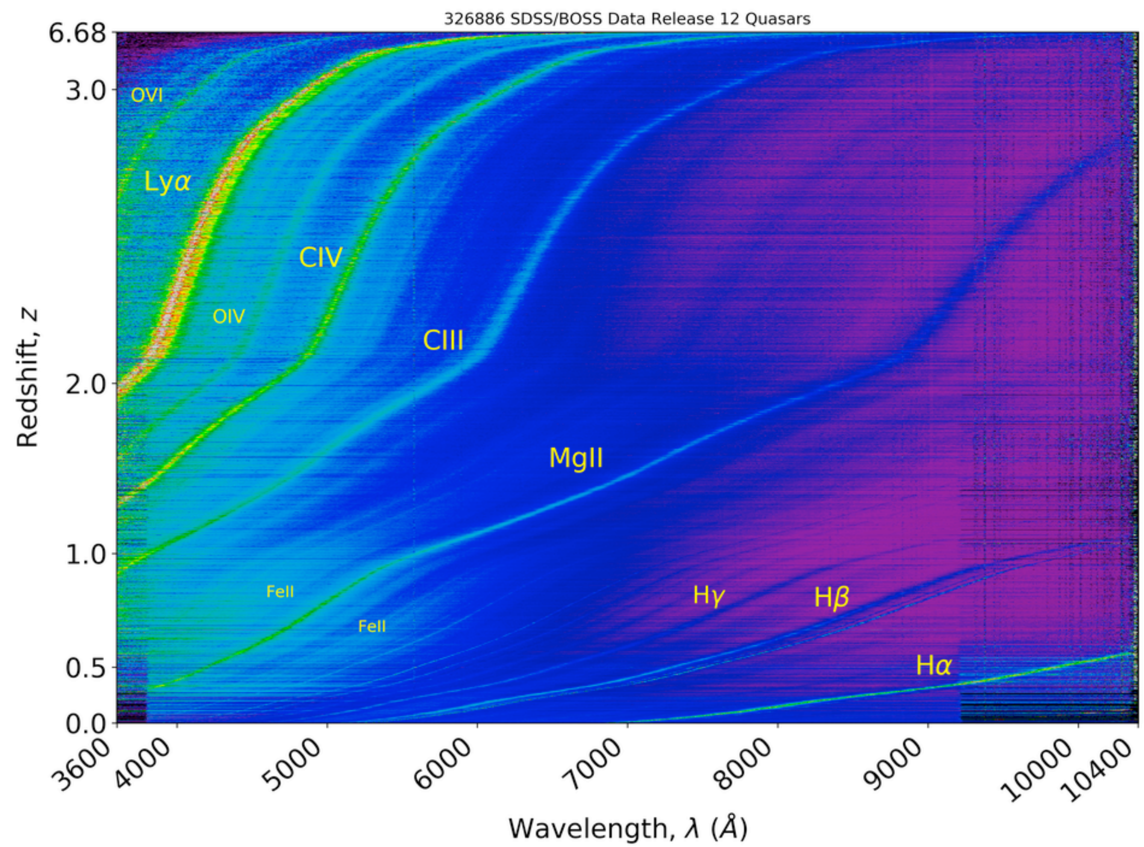


- 2.5m optical telescope in north hemisphere
- eBOSS: Spectroscopy of 1000 targets per field (fibers inserted in drilled metallic plates)
- **Luminous tracers**
  - Galaxies (all) $0.07<z<0.6$
  - Luminous Red Galaxies (LRG) $0.6<z<1.0$
  - Emission Line Galaxies (ELG) $0.6<z<1.1$
  - Quasars $0.8<z<2.2$
- **Absorbing tracer** : neutral hydrogen absorbers
  - Lyman-α forest studies within $1.8<z<3.5$ from quasar spectra (@ $2.0<z<3.5$)



Stacked Quasar Spectra from the SDSS/BOSS DR12 Database





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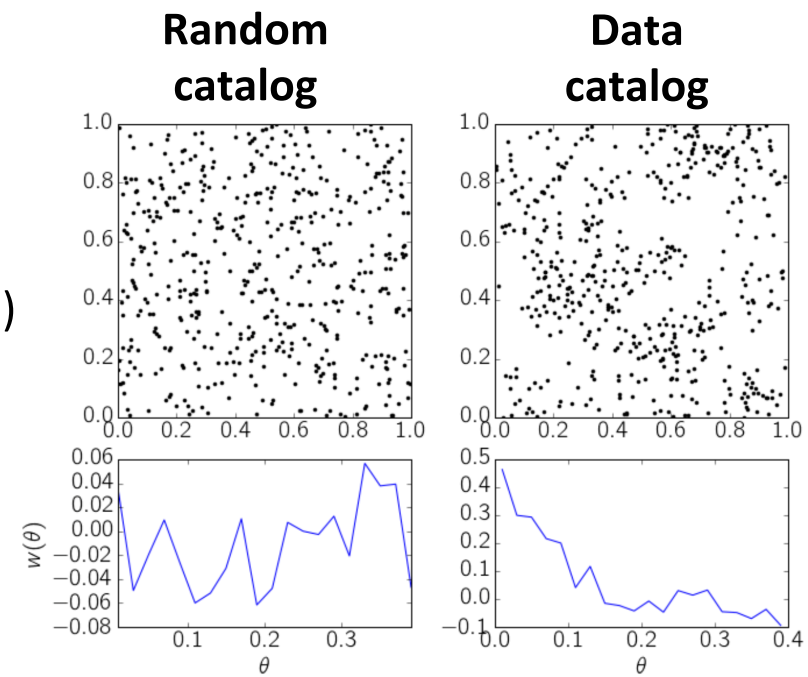

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SDSS-I-II – III (BOSS) – IV (eBOSS)

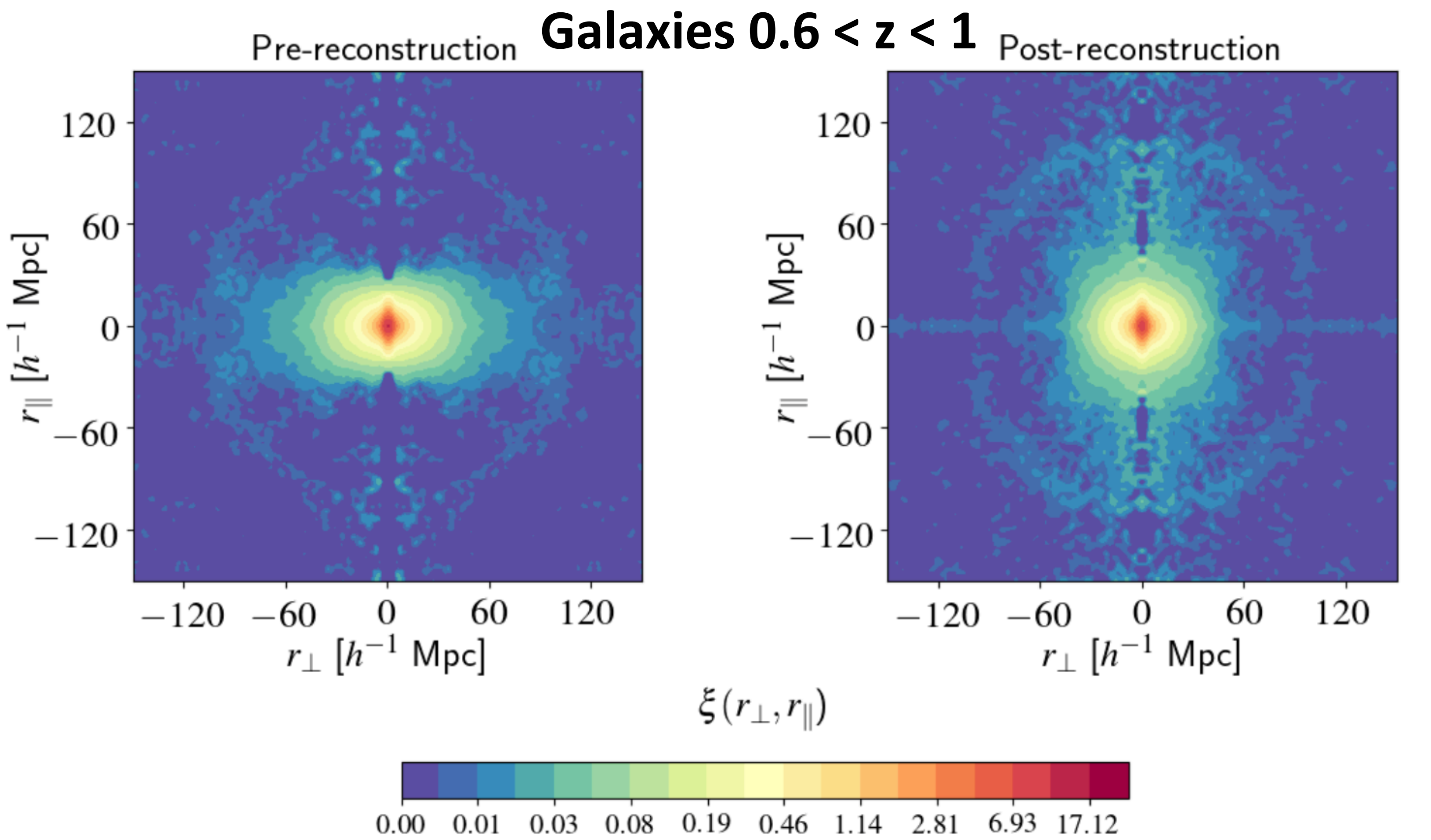
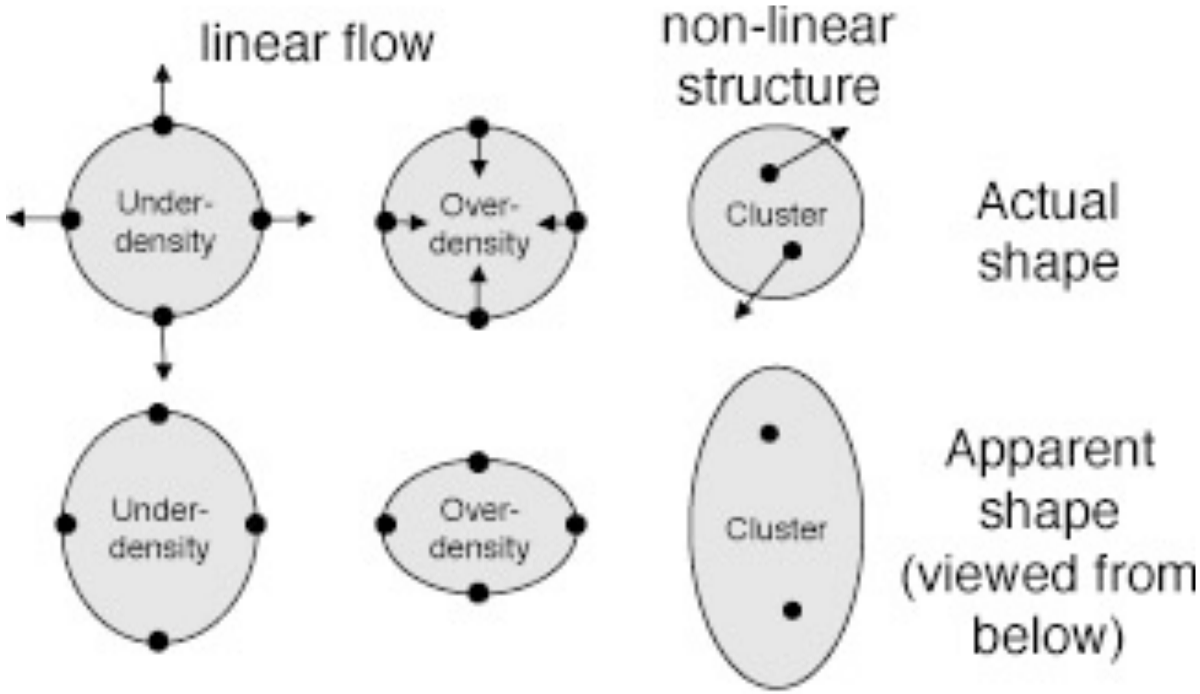


Figure 2. Anisotropic two-point correlation function of eBOSS LRG+CMASS galaxies at $0.6 < z < 1$. The left (right) panel shows the pre-reconstruction (post-reconstruction) two-point correlation function in bins of $r_\perp$ and $r_\parallel$. Bins of size 1.25 h^{-1} Mpc and a bi-cubic spline interpolation have been used to produce the contours.

Redshift Space Distortions



Large scale (few 10's Mpc):
Structures with galaxies flowing according to potential look flatened along z

Small scale (few Mpc):
Groups of nearby galaxies with peculiar velocities look elongated along z

SDSS-I-II – III (BOSS) – IV (eBOSS)

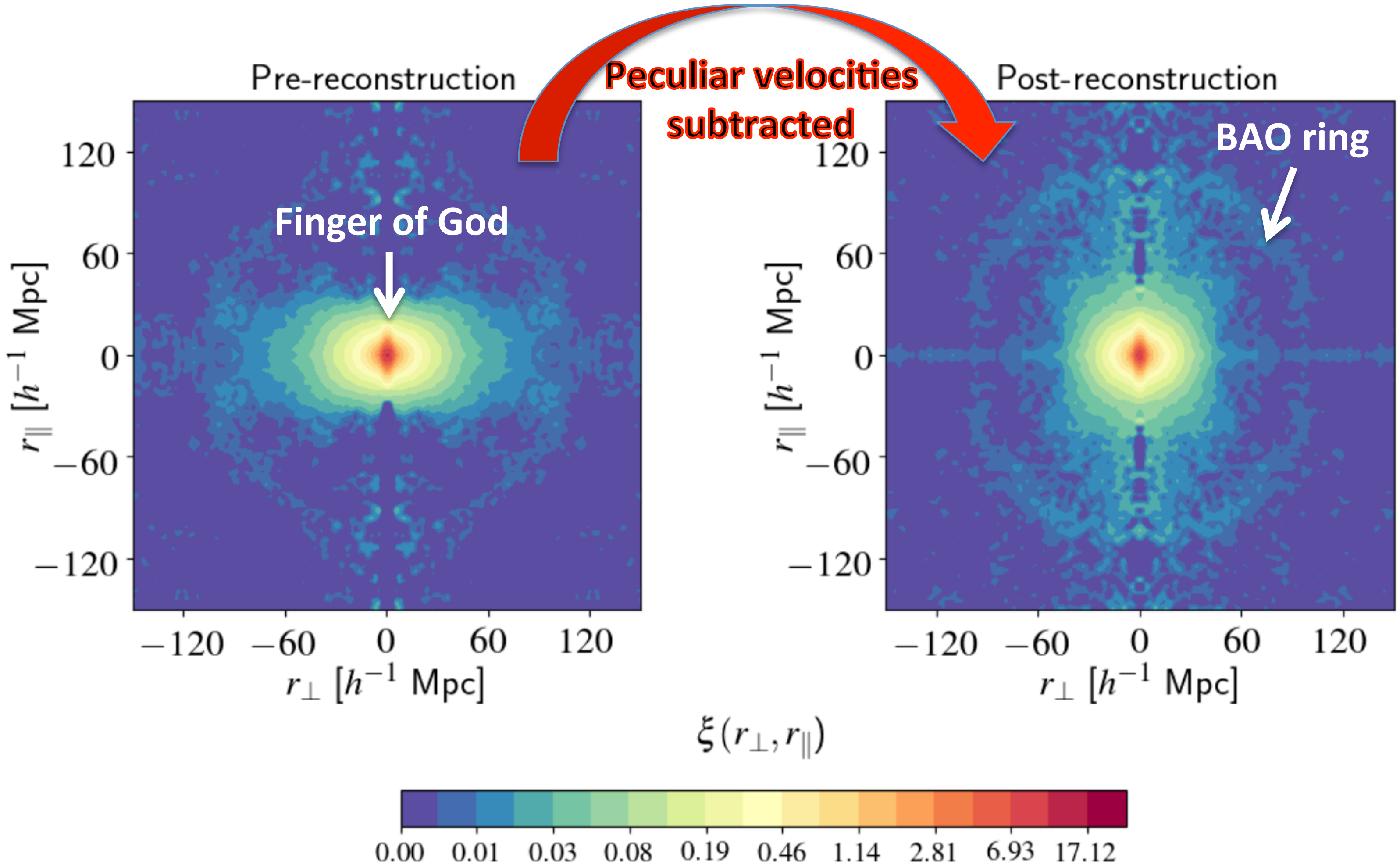
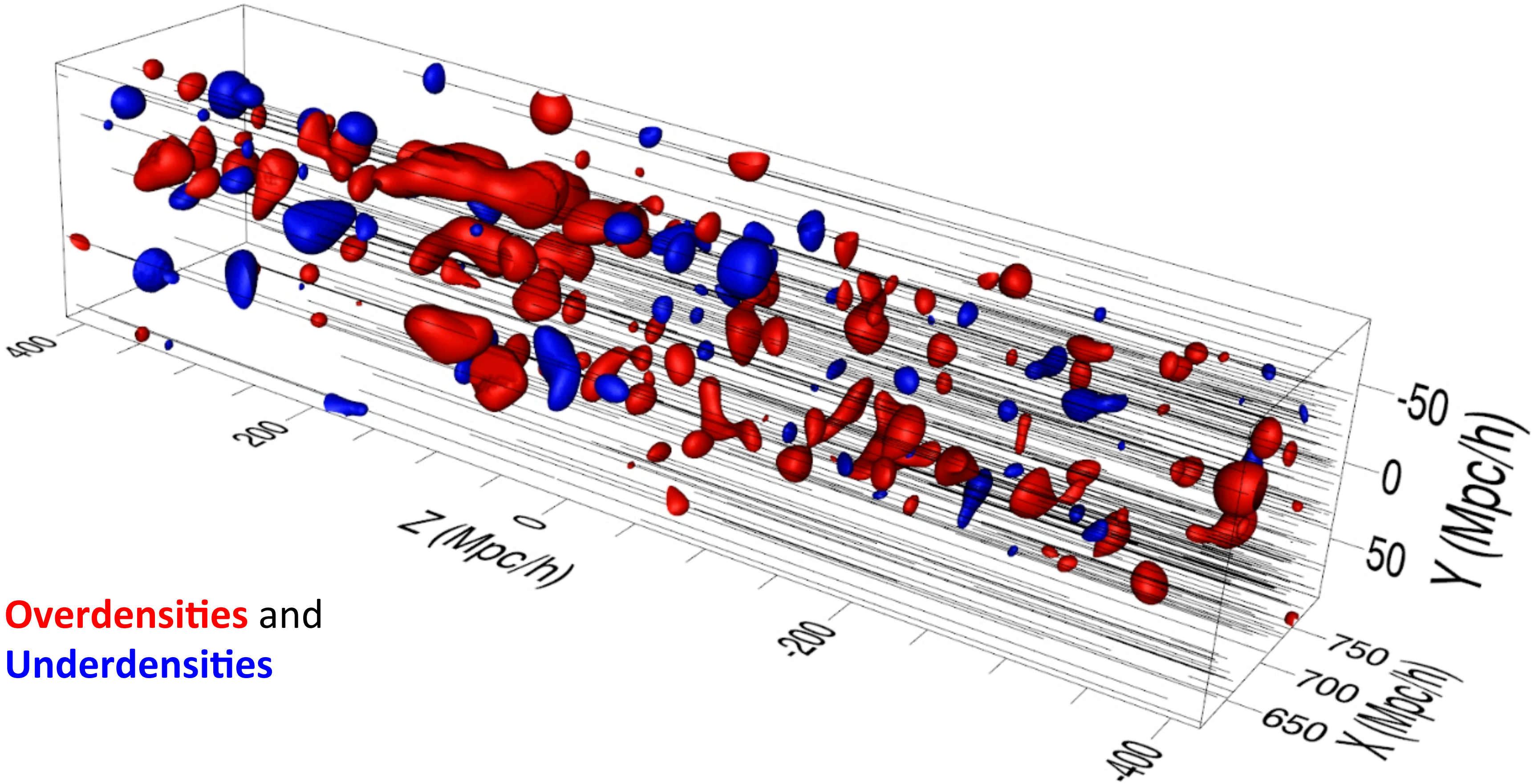


Figure 2. Anisotropic two-point correlation function of eBOSS LRG+CMASS galaxies at $0.6 < z < 1$. The left (right) panel shows the pre-reconstruction (post-reconstruction) two-point correlation function in bins of $r_{\perp}$ and $r_{\parallel}$. Bins of size 1.25 h^{-1} Mpc and a bi-cubic spline interpolation have been used to produce the contours.

Lyman-α forest: tomography of H_I

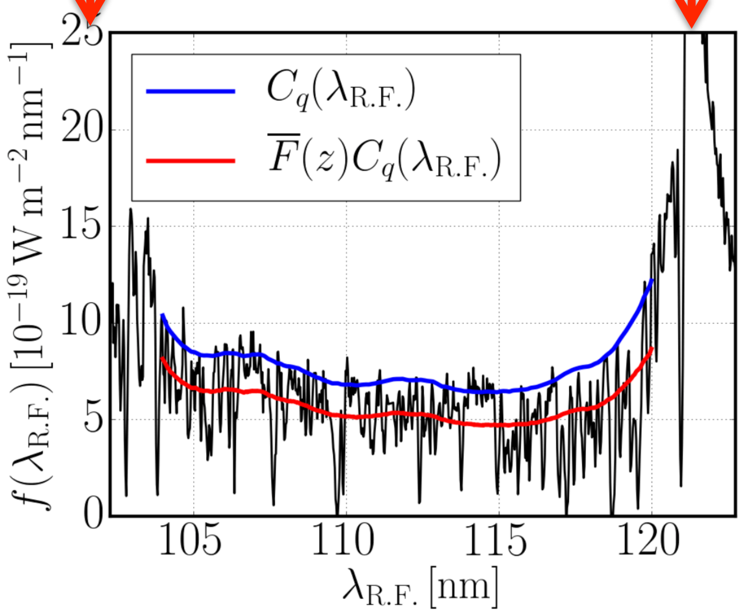


Overdensities and
Underdensities

Lyman-α forest: tomography of H_I

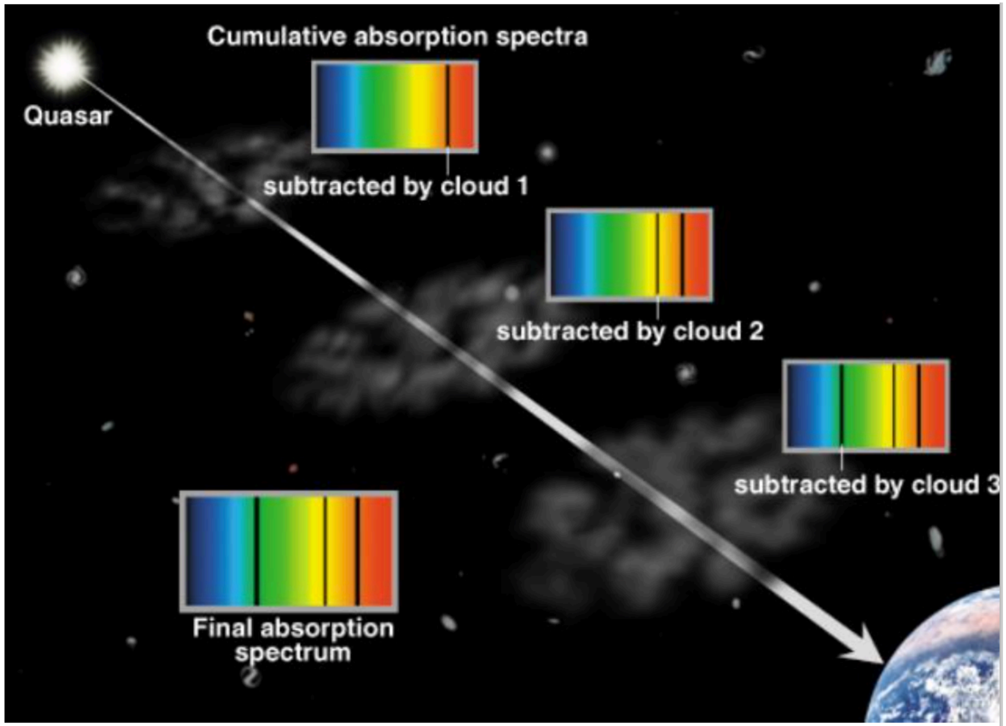
Ly-β emission line (102.57nm)

Ly-α emission line (121.57nm)



Quasar spectrum (z=2.91)

- In rest frame
- As measured by SDSS
- Resolution 0.2nm

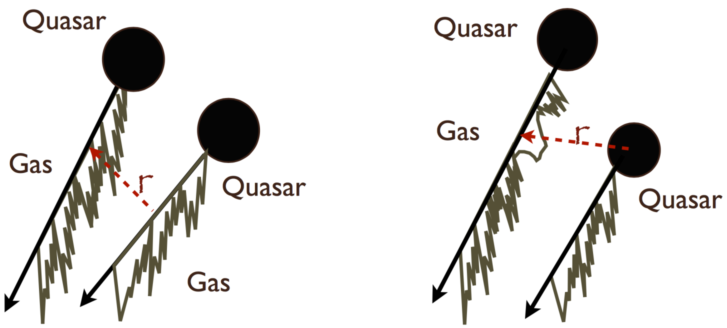


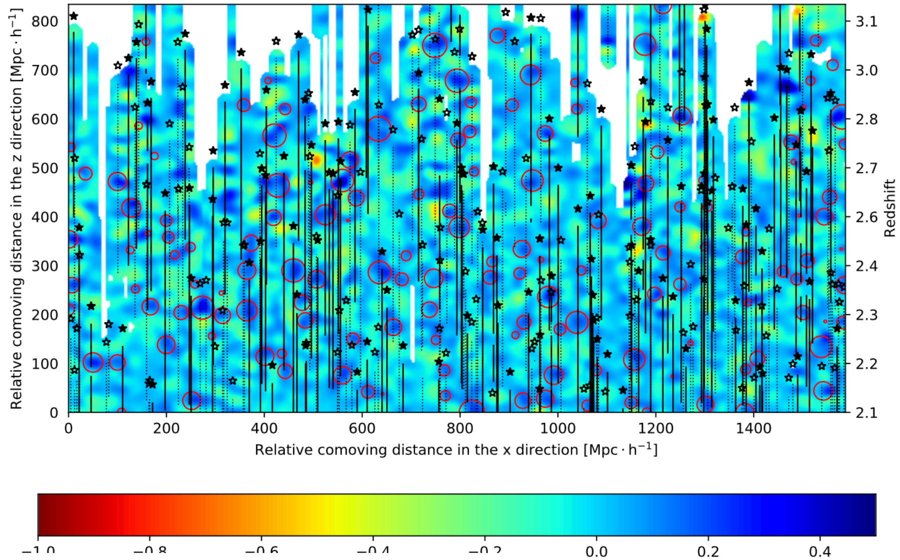
Each absorption line corresponds to an **absorbing** H_I cloud at a precise redshift -> tomography

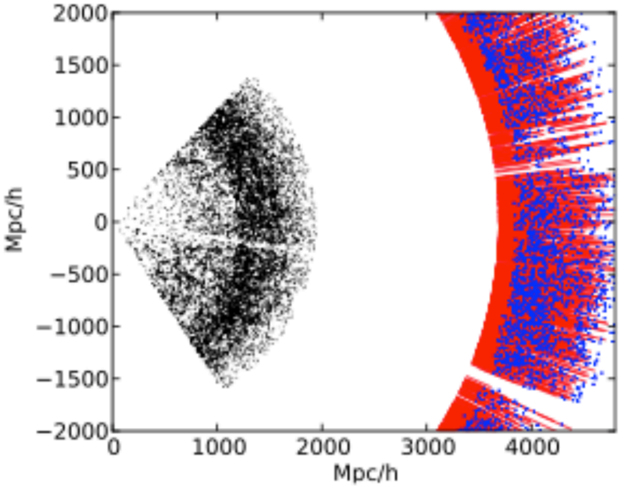
Lyman-α forest: correlation functions

Correlation functions

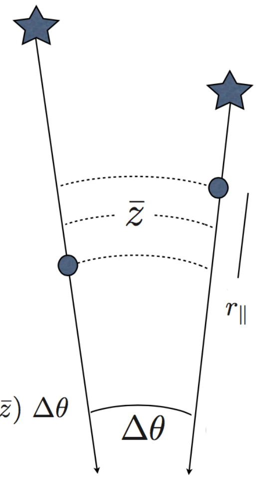
- along line-of-sight
- between lines of sight
- Cross-correlation H_I overdensities-quasars







LyaF volume : 50 (Gpc/h)^3



$$1+\bar{z} = \frac{\sqrt{\lambda_1 \lambda_2}}{\lambda_\alpha}$$

$$\bar{z} \qquad \Delta\lambda$$

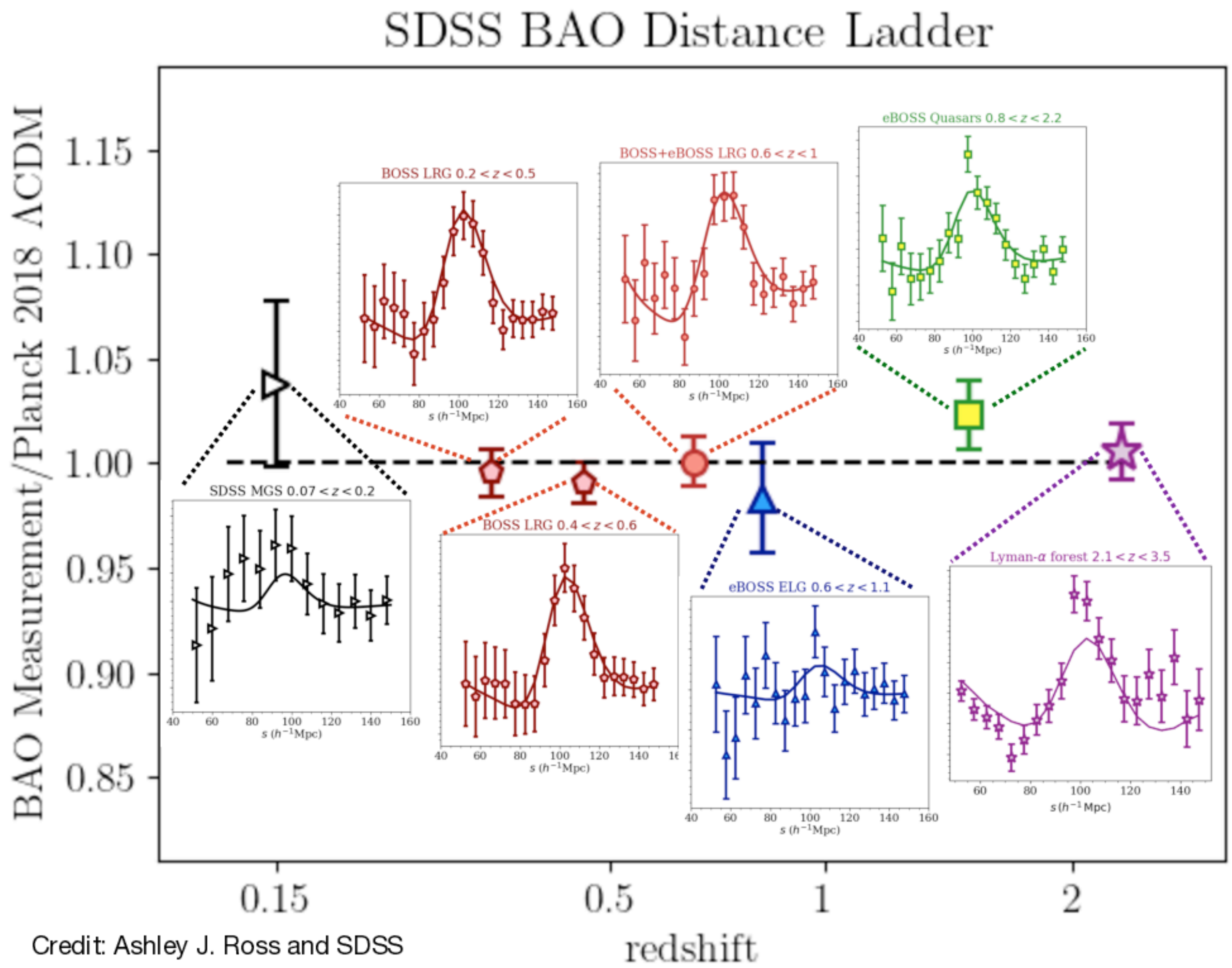
$$r_\parallel = \frac{c\,(1+\bar{z})}{H(\bar{z})\,\lambda_\alpha}\Delta\lambda$$

$$r_\perp = d_A(\bar{z})\,(1+\bar{z})\,\Delta\theta \qquad \Delta\theta$$

$1\,\mathrm{deg} \sim 70\,h^{-1}\,\mathrm{Mpc}$ $\quad$ $1\mathring{A} \sim 70\,\mathrm{km\,s^{-1}} \sim 0.7\,h^{-1}\,\mathrm{Mpc}$

SDSS-I-II – III (BOSS) – IV (eBOSS)

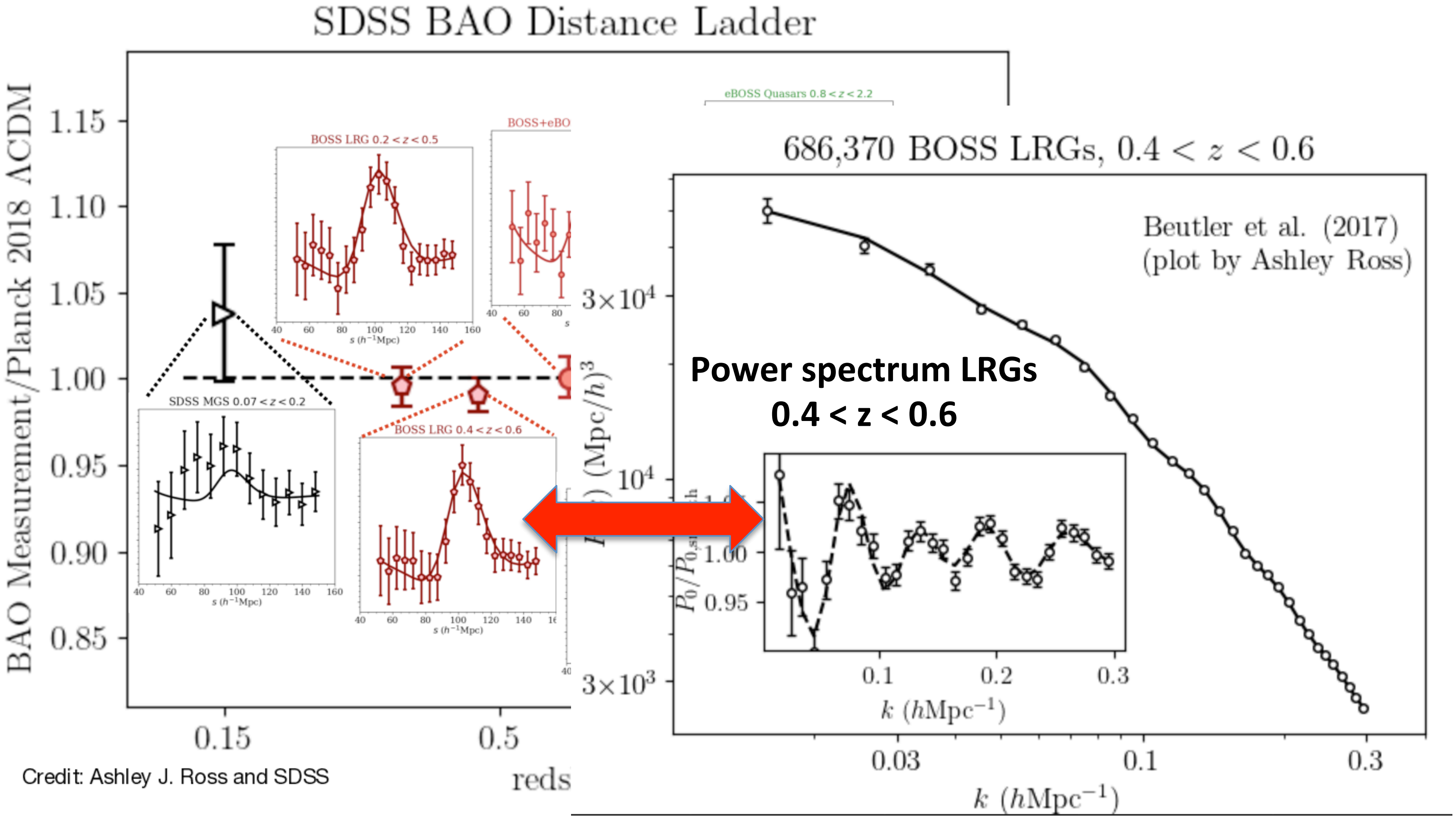
BAO results from SDSS, normalized by the Planck ΛCDM prediction



Credit: Ashley J. Ross and SDSS

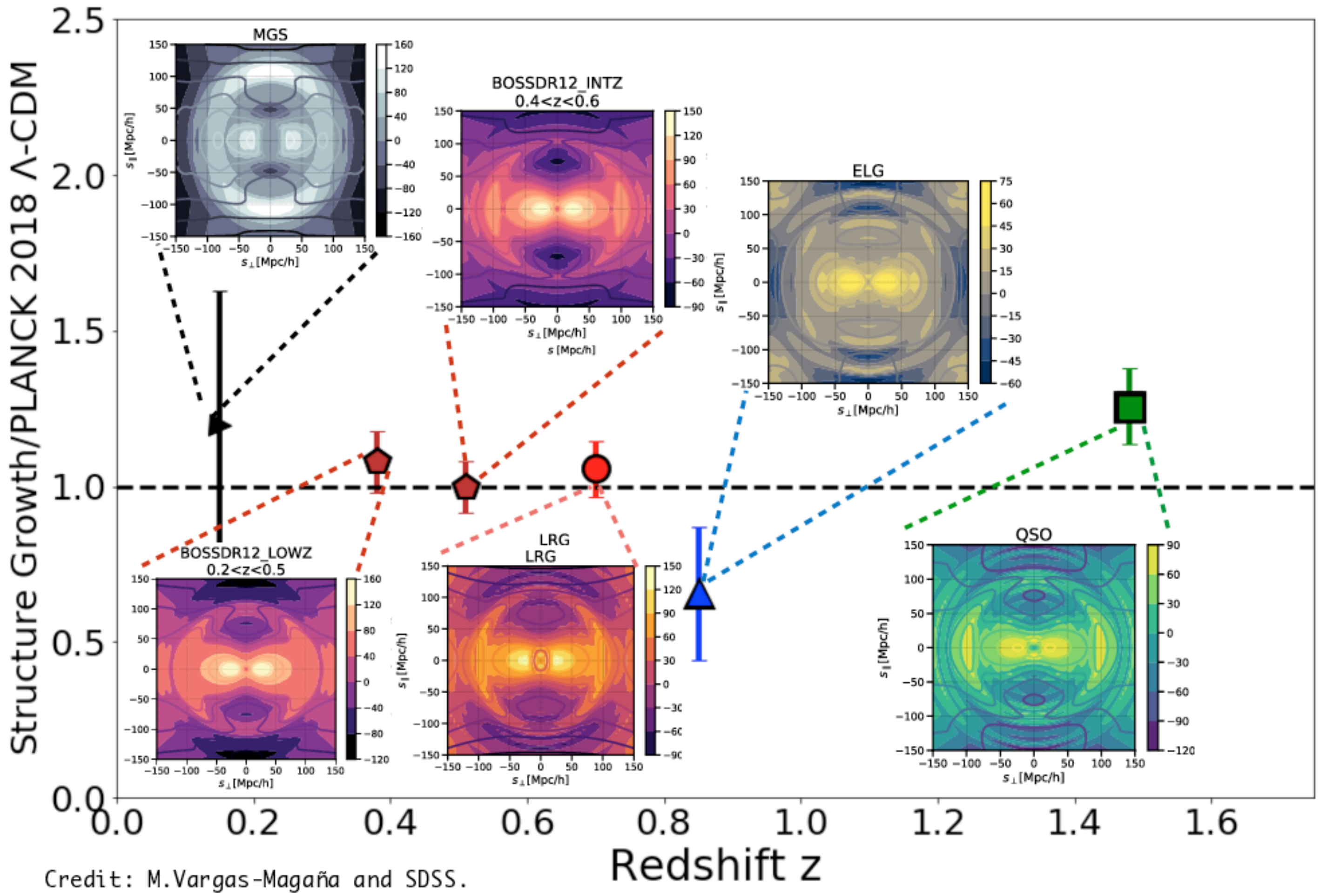
SDSS-I-II – III (BOSS) – IV (eBOSS)

BAO results from SDSS, normalized by the Planck ΛCDM prediction



SDSS-I-II – III (BOSS) – IV (eBOSS)

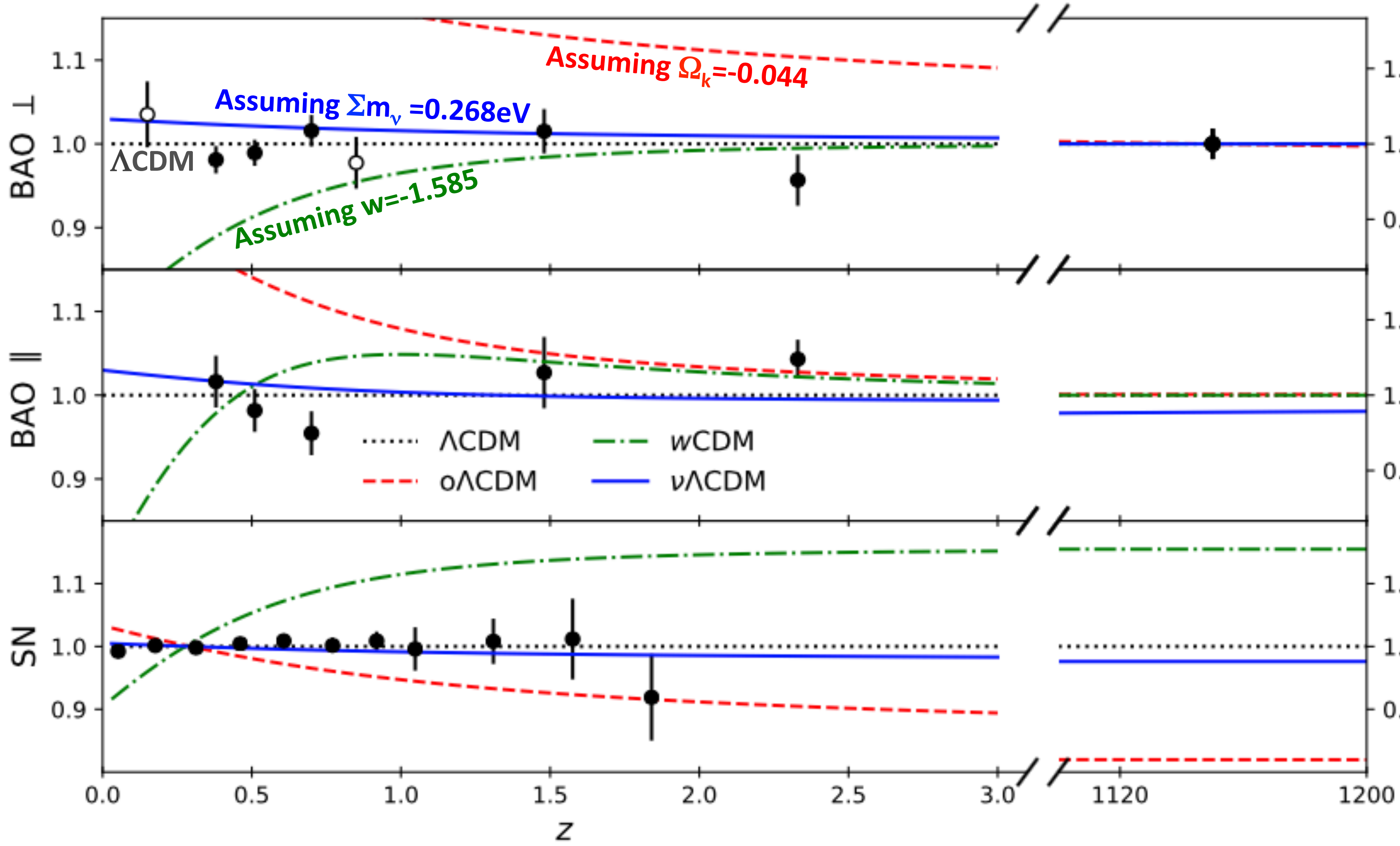
RSD measurements from SDSS, normalized by the Planck ΛCDM prediction



Credit: M.Vargas-Magaña and SDSS.

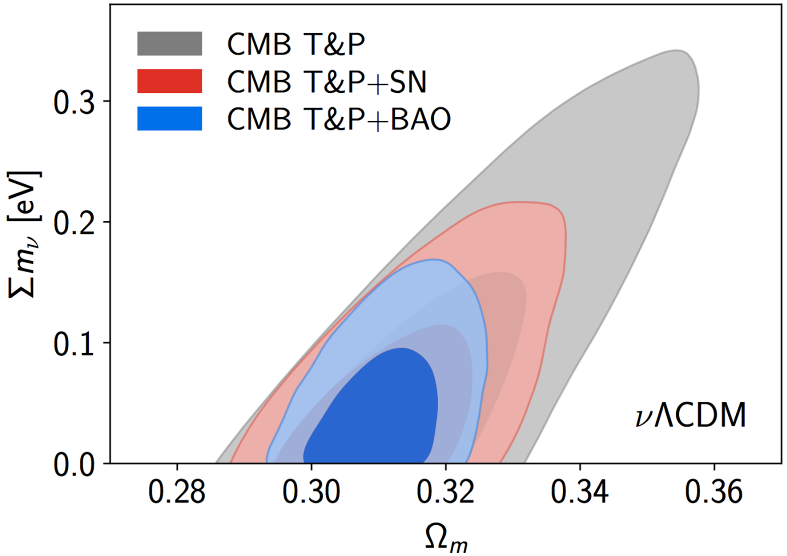
BAO results / status

Residuals relative to best-fit ΛCDM from CMB alone



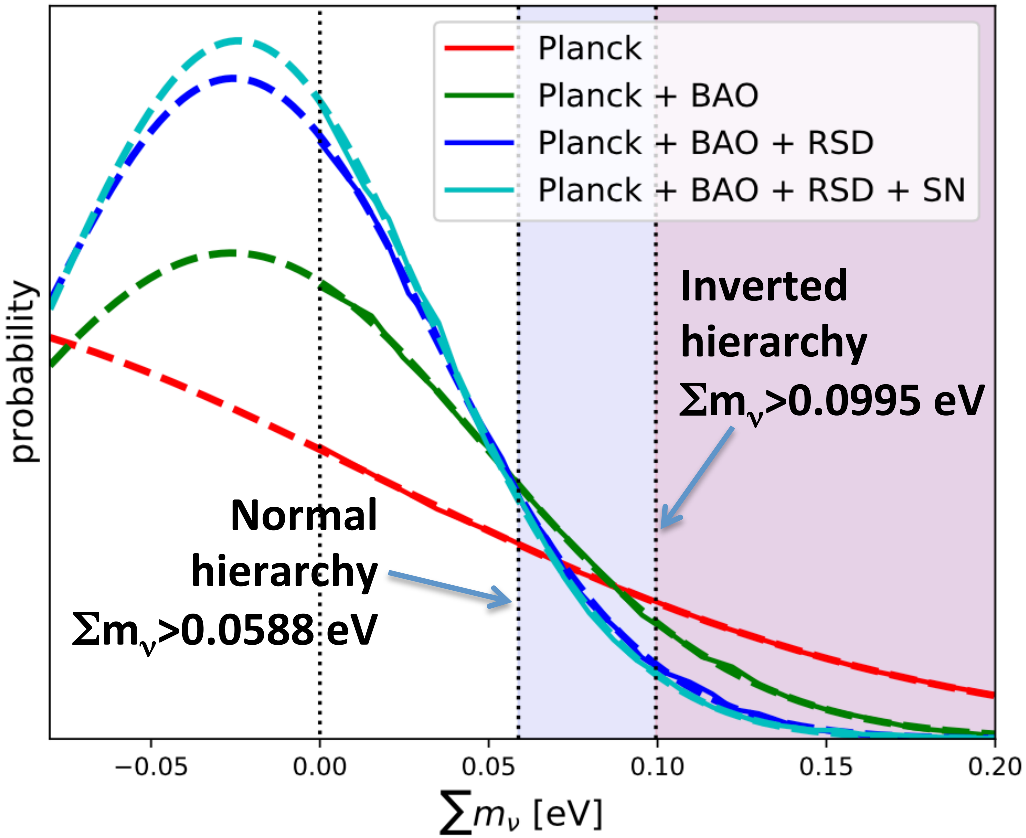
SDSS-I-II – III (BOSS) – IV (eBOSS)

Neutrino mass: contribution to density: $\Sigma m_\nu = 94\text{eV} \times \Omega_\nu h^2$



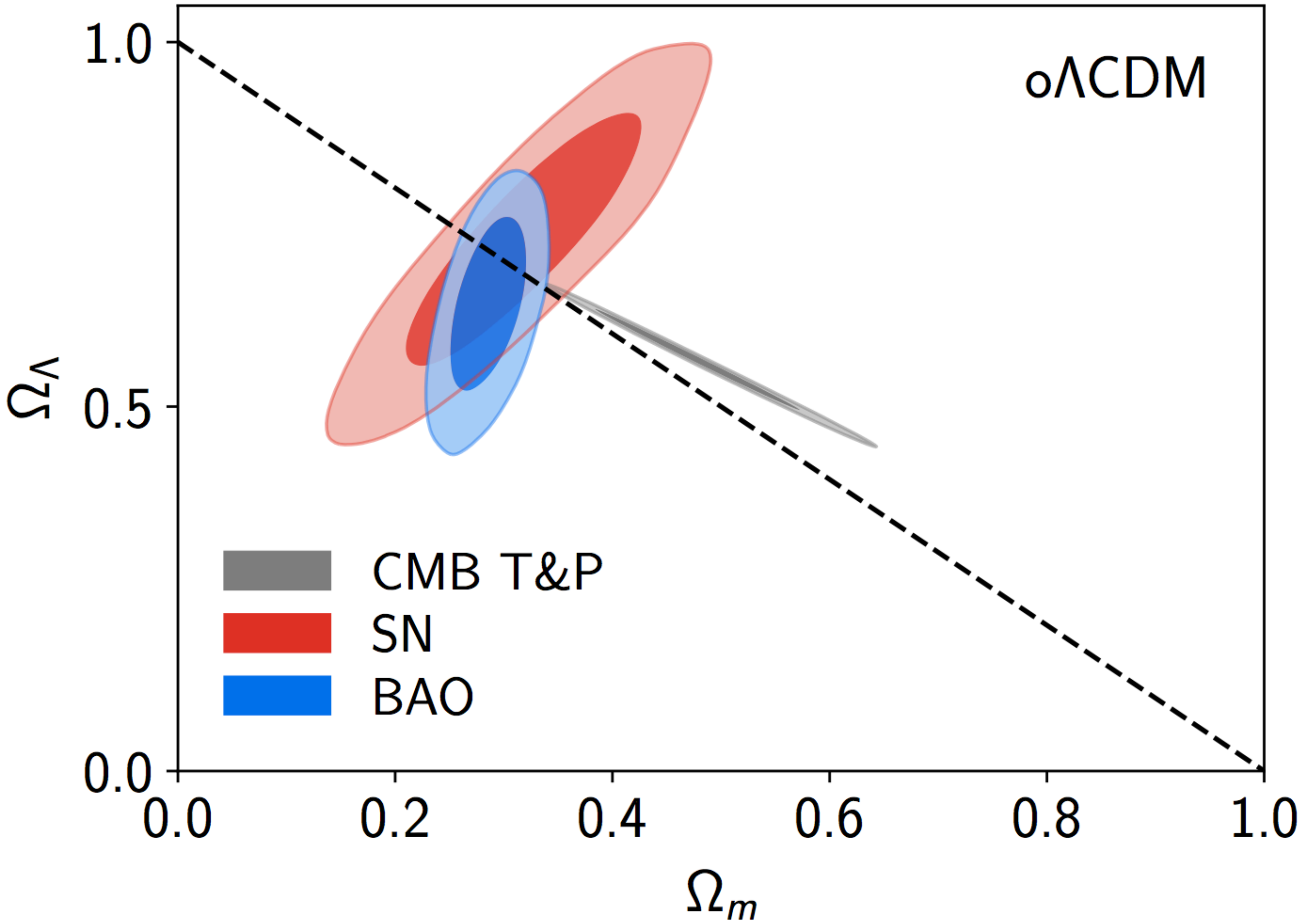
Growth rate of structures is sensitive to the neutrino mass.
Large $L_{jeans}(\nu)$ =>

- **power spectrum reduced for small structures**
- **Impact small scale clustering**



SDSS-I-II – III (BOSS) – IV (eBOSS)

Constraint on dark energy



SDSS-I-II – III (BOSS) – IV (eBOSS)

BAO scale

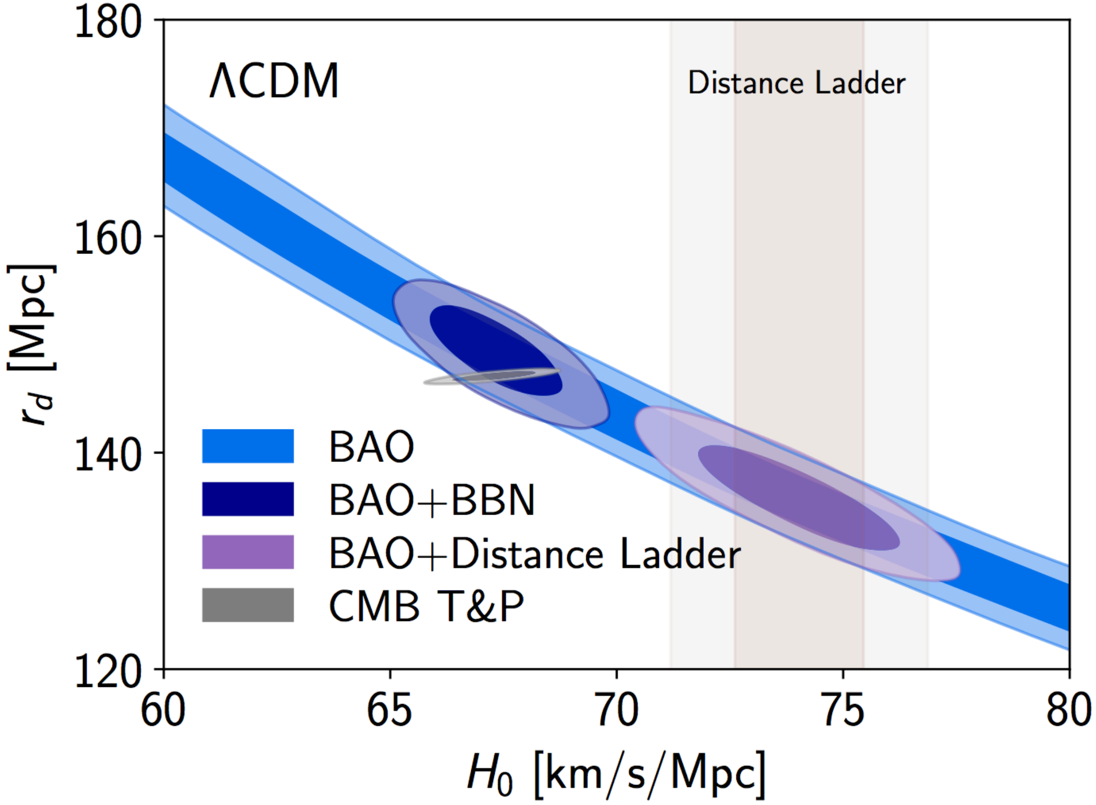
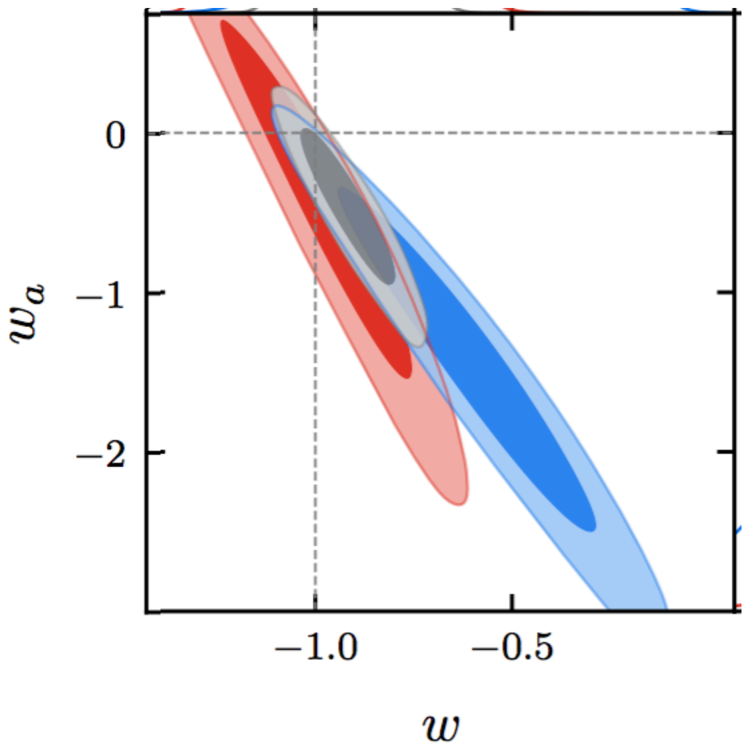


FIG. 6.— Cosmological constraints on H_0 and r_d under the assumption of the ΛCDM model using BAO data (blue) in combination with H_0 distance ladder measurements (purple) and BBN data (dark blue) in contrast to CMB measurements (grey). The shaded band refers to the H_0 distance ladder measurement.

Dark Energy state equation

State equation
$p/\rho = w(z) = [w_0 + w_a . z/(1+z)]$

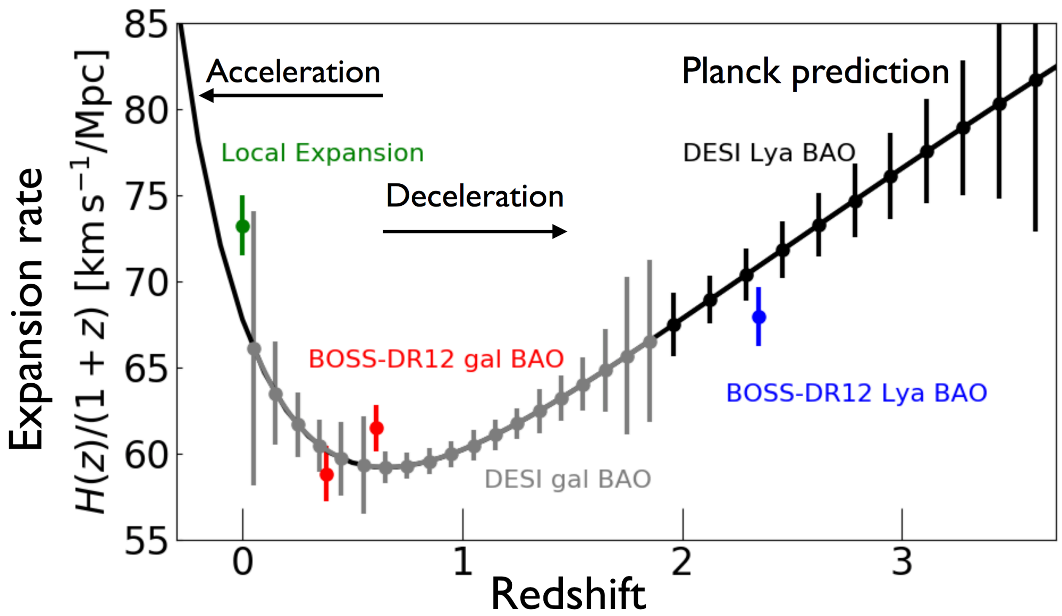
Red = Planck + SNe
Blue = Planck + SDSS
Grey = All



DESI: next to come in optics

- Multi-object spectrograph (5000 robotic fibers)
  - To measure redshifts of 30M galaxies
- Field 8 sq. deg.
- Construction finished since may 2020
- On-sky commissioning demonstrated.

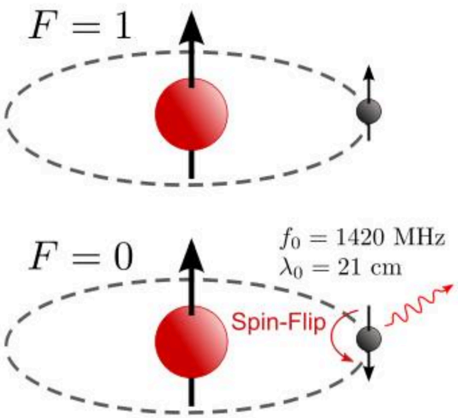
-> Data taking?



BAO in radio-astronomy

- Objective: produce a 3D intensity mapping of H_{21} hyperfine emission line
  - The longest wavelength (21cm at rest) in the Universe (emission line)
  - AGN main source of background (continuum)
  - Mapping of H abundance as a function of (α,δ,z)
  - Power spectrum P(k) for LSS studies
  - This hydrogen **traces the BAO**
- Wide field large passband radio-astronomy under development

The H_{21} emission line



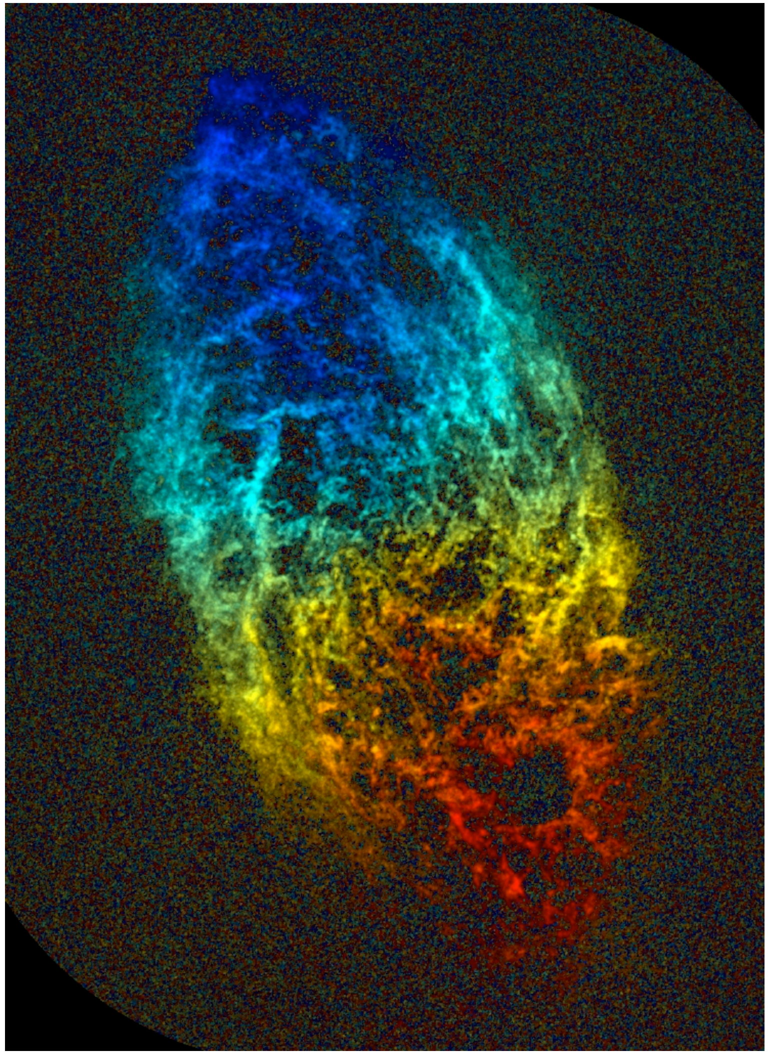
spin- flip transition at 21 cm (1420.4 MHz in radio).

If line is redshifted, its frequency gives directly the redshift

Power received from a galaxy at z=0.3 (1500Mpc):

- optics: 10^{-16} W/m^2 in standard band (~ **10 photons/m^2/s**)
- 21cm (very narrow band): 10^{-24} W/MHz.m^2. Few photons/m^2/s in 1MHz band (assuming ~200km/s velocity dispersion)

The integrated emission of HI of a galaxy traces its ***mass***



The HI radial velocity field of M33 shown by colors corresponding to Doppler redshifts and blueshifts relative to the center of mass; brightness is proportional to HI column density.

BAO in radio detection

Like the optical surveys : source by source

- H_I (21 cm) source identification
- determination of the angular position and the redshift
- determination of the 2-point correlation function
  or of the P(k) spectrum from the source catalog

Like the CMB observations : intensity mapping

- 3D mapping of H_I (21 cm) sources $T_{21}(\alpha,\delta,z)$
- foreground estimate for subtraction
- determination of the P(k,z) spectrum from the 3D data

Radio imagery

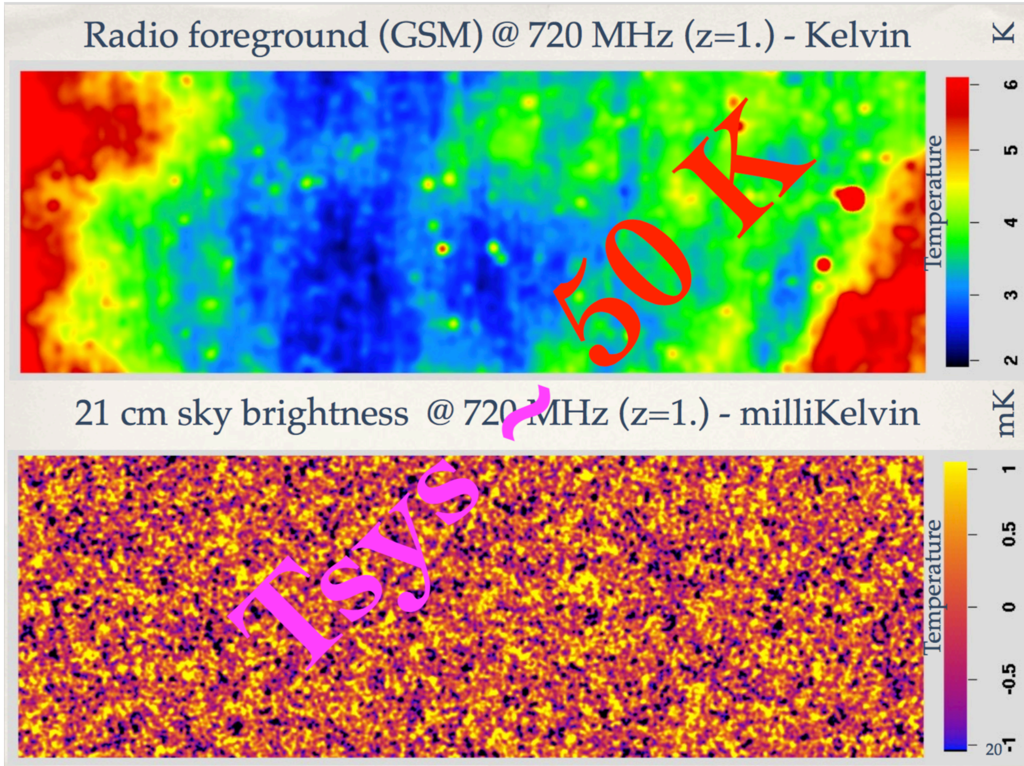
- **Band**: ~ 100 MHz ... 1500 MHz - ν = f(z) , z: 0 ... 10
1420 MHz @ z=0 , 946 MHz @ z=0.5 , 720 @ z=1 , 284 @ z=5, 129 @ z=10

- Radio instruments are **diffraction limited**:
700 MHz: D=100 m → ~20' , D=1km → ~2' , D=100 km → ~1" , 2' → 1 Mpc @ z = 1

- Intensity measurement in optical, **amplitude & phase** in radio;
➡ Interferometry and spectroscopy

- Instrumental/electronic noise (<5 e) usually negligible in optical, **dominant in radio** (Tsys~20-100 K)

- Light pollution, atmosphere in optical / EM pollution (RFI) and ionosphere (lower frequencies) in radio



H_{21} radio survey. Cylinders(1)

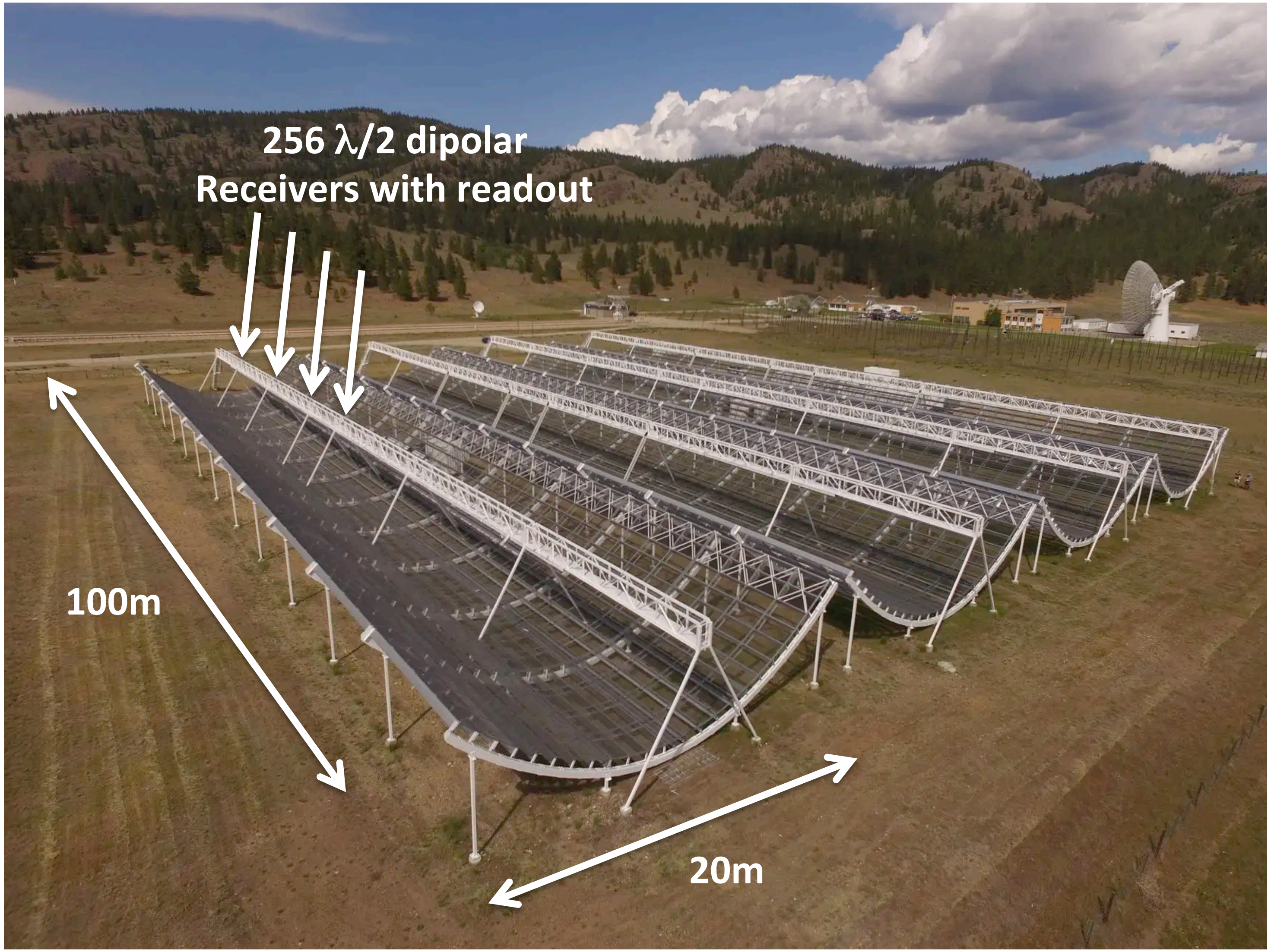
- **Wide Band 0.4 … 0.8 GHz GHz (to measure H_{21} from z = 0.8 to 2.5)**
- **Wide field thanks to the detector multiplicity**
- Series of N_{cyl} static cylindrical reflectors (Surface ~ 10^4 m^2) : the sky passes over the cylinder lobe (E-O)
- Each cylinder is equipped along the axis with ~1 receiver / 30cm (N_R dipolar antennas $\lambda/2$).

  ➠ Measure of **amplitude** and phase for each polarization and frequency component → redshift z
- Simultaneous restitution of ~ $N_R \times N_{Cyl}$ lobes (directions) on sky : Resolution ~ (15 arcmin) × (15 arcmin) × (δz ~ 0.001)

  ➠ mapping of a 3D piece of Universe (α,δ,z)

  ➠ ~ 10^6 instantaneous redshift measurements $0.8 \le z \le 2.5$

21cm radio survey with cylinders



H_{21} radio survey. Cylinders (2)

- Wide Band 0.4 … 0.8 GHz sliced into several bands
- Frequency shift : $\sin[\omega t] \times \sin[\omega' t] = \cos[(\omega+\omega')/2] + \cos[(\omega-\omega')/2]$
- If signal digitization @ 500 MHz (ADC 8 bits , ~ 10000 channels) -> $s(t,x_i)$
- $S(\nu,x_i)=TF_t(s(t,x_i))$ separates the frequency components (~ redshift z)
- The measurements from all receivers of one cylinder are grouped for each frequency component
- $TF_x(S(\nu,x_i))$ separates the (N-S) directions (multi-lobe)
- Instantaneous field of view: 200 sq. deg.
- Combine signals from the cylinders to get E-O separation
- On-line processing ~ 100 Tbytes/day

Radio H_{21} survey with paraboles

100's of **orientable** paraboles of 5m (Area ~ $20m^2$ x #paraboles)

- **Not too large** to get a wide lobe able to contain 500 beams of ~10 Arcmin
- **Short base:** interferometry (<100m) to cover domain around k=1 deg^{-1}
- **Scalable cost**: mecanics+command + 1 electronic channel /polarisation
- No crosstalk between dishes
- Positions can be changed
- Measure **amplitude and phase** for each frequency (or redshift z)
- Wide band 0.4 … 1.4 GHz for wide redshift z domain
- Measure of $N_{paraboles}$x($N_{paraboles}$-1)/2 visibilities per frequency band:
  - $A_\nu(\mathbf{x_i}, t_s)=TF_t(s(t,\mathbf{x_i}))$ splits the frequencies (~ redshift z) (on-line).
  - Measures from all receivers are grouped by frequency
  - Visibilities $\langle A_\nu(\mathbf{x_i},t_s)\, A_\nu(\mathbf{x_j},t_s)^* \rangle$ (averaged over t_s) produce the (u,v) plane intensity map
- Numerical correlators: huge data flow

One of the precursor experiments

PAON-4 @ Nançay

4 x 5m dishes, in compact transit interferometer configuration
L-band (~ 1250-1500 MHz → 1275 - 1475 MHz)

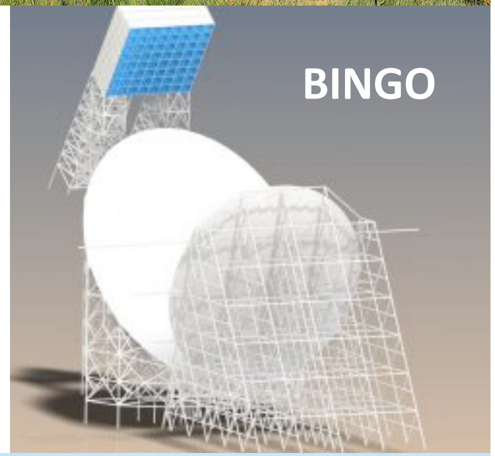
Bao radio transit telescopes

HIRAX: dense array of 1000 small dishes in South Africa

- Collecting area: 28000m^2
- Measure BAO at 0.75<z<2.55

BINGO: large single dish with multifeed receiver array (Brazil)

- Measure BAO at 0.13<z<0.48 with 2% accuracy



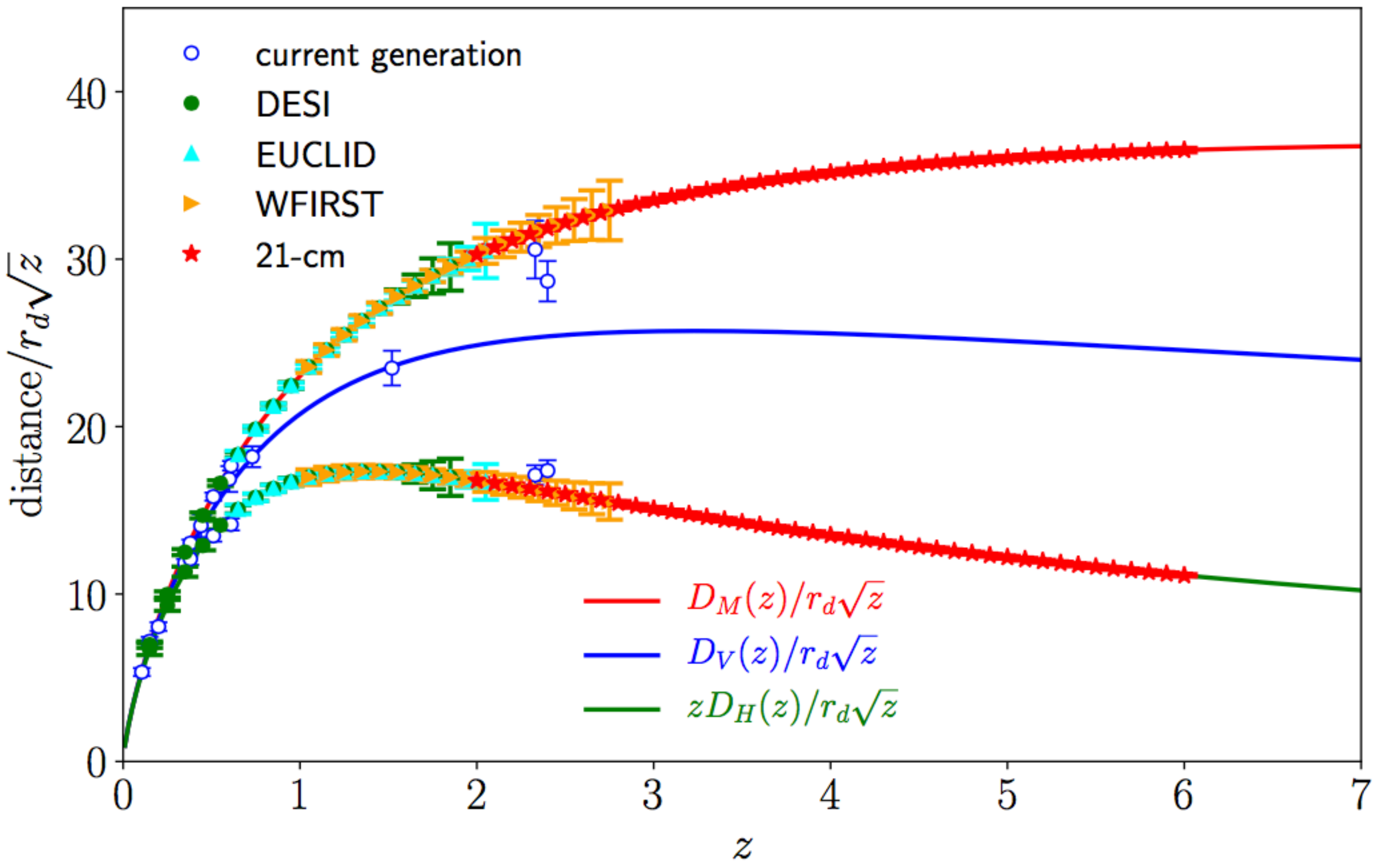
CHIME: cylinders in Canada, dense interferometer

- 200 sq. deg. on sky
- Collecting area: 8000m^2
- Measure BAO at 0.77<z<2.55

TIANLAI: cylinders and 16 dishes array in China (14400m^2)

- 200 sq. deg. on sky

Projected BAO sensitivity



Distances as a function of z - expressed in r_d

note scaling by 1/sqrt(z))

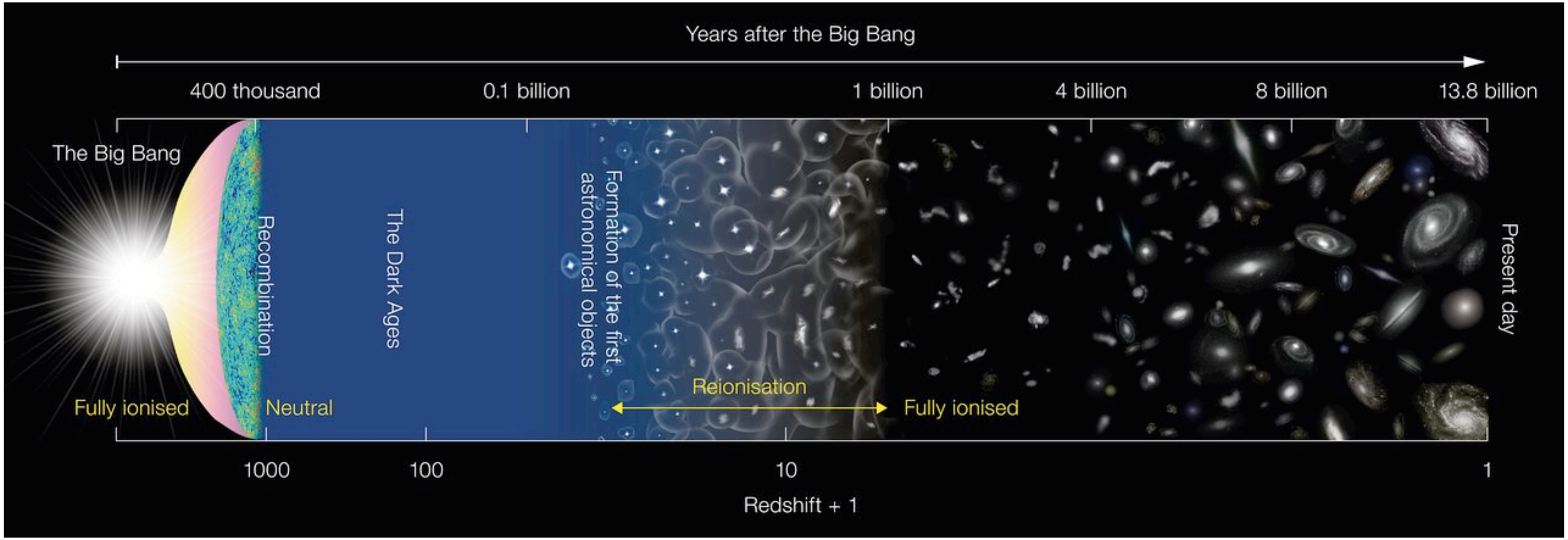
Conclusions

- BAO is a robust cosmological probe
  - With bonus RSD probe of small structure formation history
- Applies to any baryon tracer:
  - Galaxies (several types)
  - Gas (Ly-α, H_{21})
  - But also voids, lenses, SNs…
- Perspectives to probe up to the reionisation epoch with large radio-telescopes

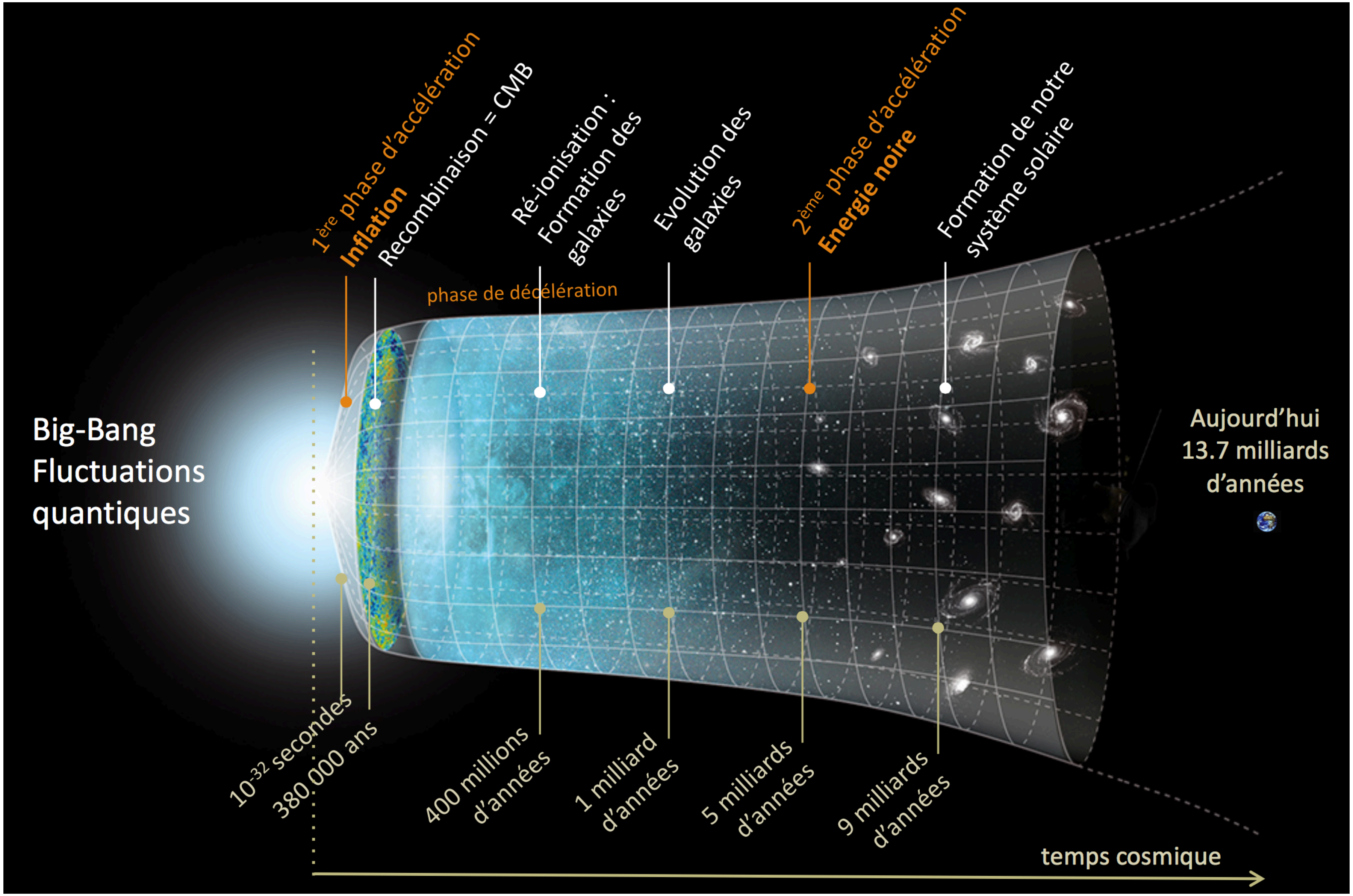
COMPLEMENTS

Cosmological parameters (2020)

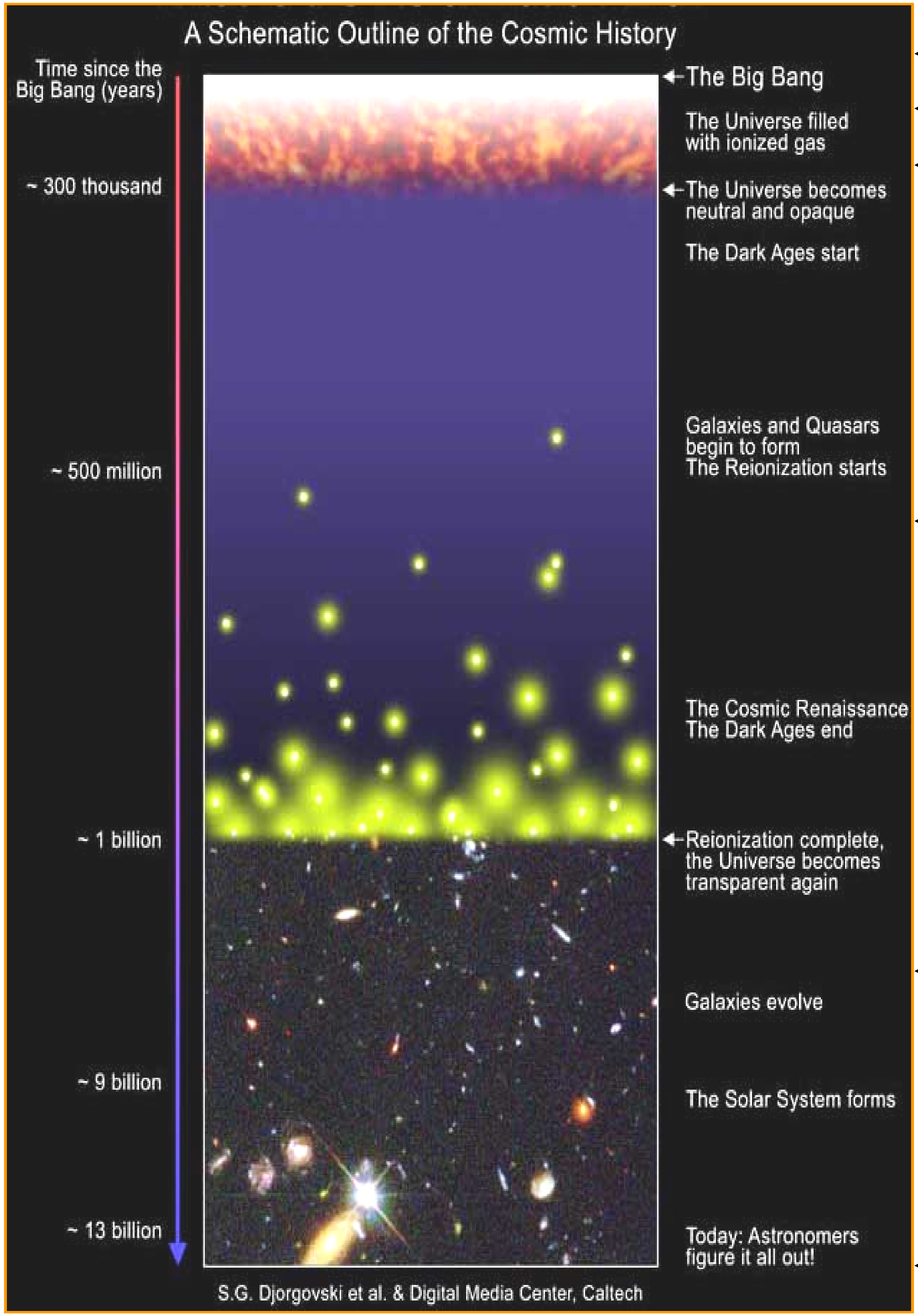
	Planck TT,TE,EE+lowE+lensing	+BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.1193 ± 0.0009
$100\,\theta_{MC}$	1.0409 ± 0.0003	1.0410 ± 0.0003
n_s	0.965 ± 0.004	0.966 ± 0.004
τ	0.054 ± 0.007	0.056 ± 0.007
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.044 ± 0.014	3.047 ± 0.014
h	0.674 ± 0.005	0.677 ± 0.004
σ_8	0.811 ± 0.006	0.810 ± 0.006
Ω_m	0.315 ± 0.007	0.311 ± 0.006
Ω_Λ	0.685 ± 0.007	0.689 ± 0.006



Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Neutral
Reionisation
Fully ionised
1000
100
10
1
Redshift + 1



1ère phase d'accélération
Inflation
Recombinaison = CMB
Ré-ionisation : Formation des galaxies
Evolution des galaxies
2ème phase d'accélération
Energie noire
Formation de notre système solaire
phase de décélération
Big-Bang
Fluctuations quantiques
Aujourd'hui
13.7 milliards d'années
10-32 secondes
380 000 ans
400 millions d'années
1 milliard d'années
5 milliards d'années
9 milliards d'années
temps cosmique



Inflation ? → Spectre initial des perturbation de densité

Nucléosynthèse primordiale → BBN

Découplage matière-rayonnement → CMB
Les ondes de fluctuation de densite baryoniques se figent

Formation des premières étoiles et quasars → Réionisation

Formation des galaxies

Aujourd'hui z=0

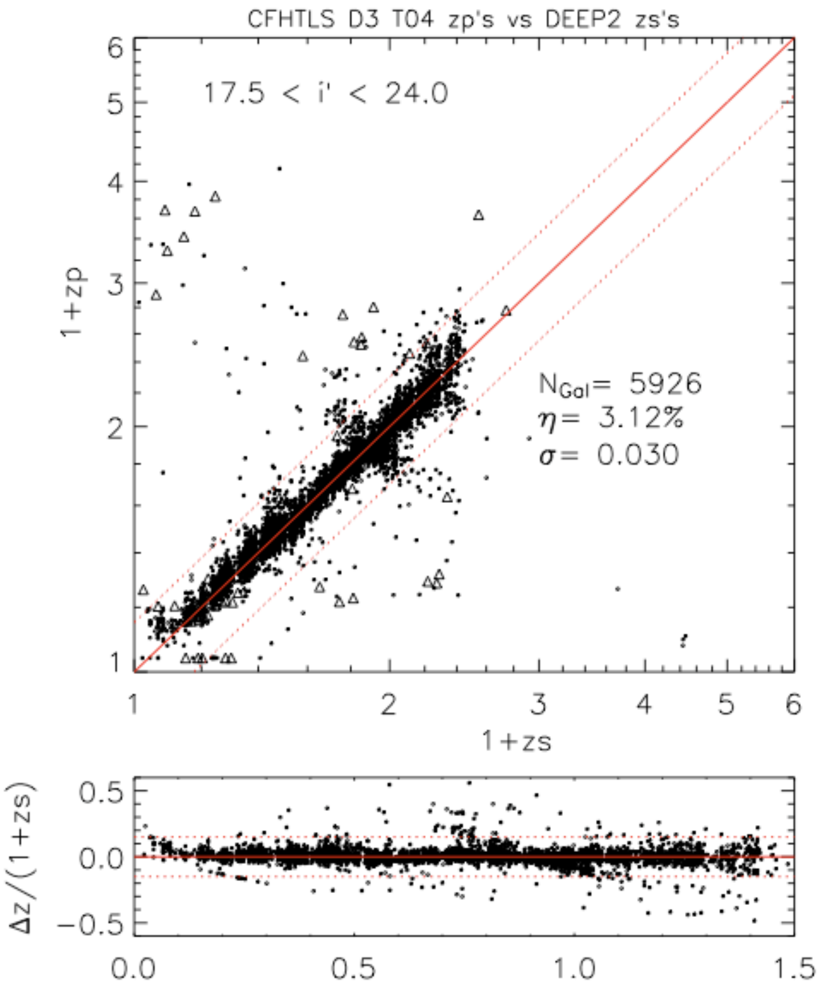
Domination de l'énergie noire / Λ

Cosmological Surveys

- **Running / Near-future**
  - **SDSS-eBOSS**: 10000 deg^2, tel. 2.4m, BAO 0.6<**spectro**-z<2.3
- **After 2022**
  - **LSST**: 20000 deg^2, tel. 8.4m -> SN, BAO, weak-lensing
  - EUCLID (space) -> BAO
  - SKA (radio) -> BAO

BAO: LSST vs HSHS

	LSST	**Radio**
Large volume	OK	OK
Precision on z	Photo-z?	$<10^{-3}$ (longitudinal BAO)
z domain	0 - 1	0 - 1.5
Limiting factor	Cosmic variance	Background
Remarks		Galaxies not resolved



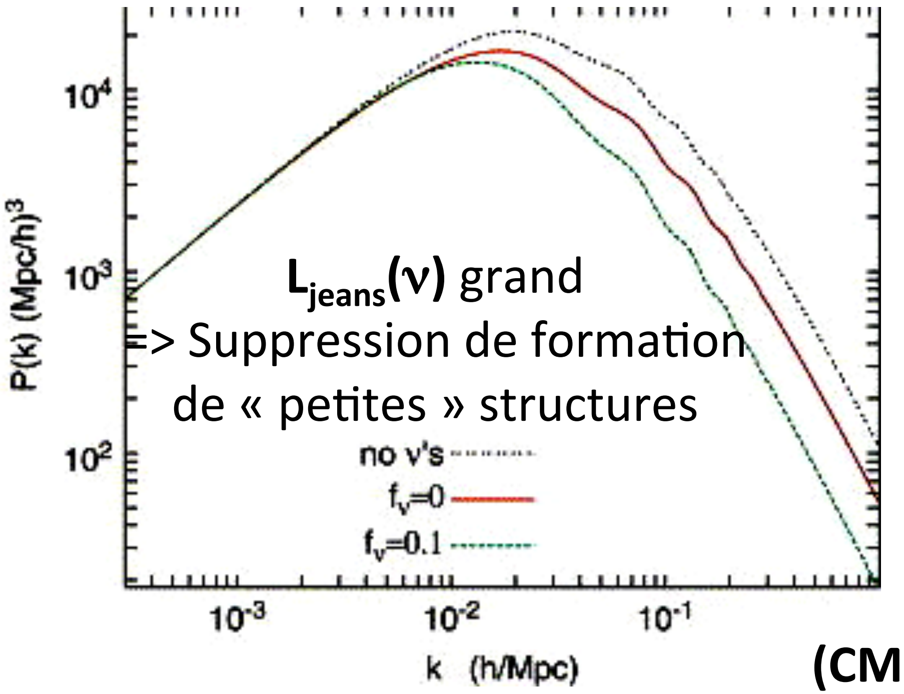
- Correlation between the 2 surveys
- H1 vs light as a function of z

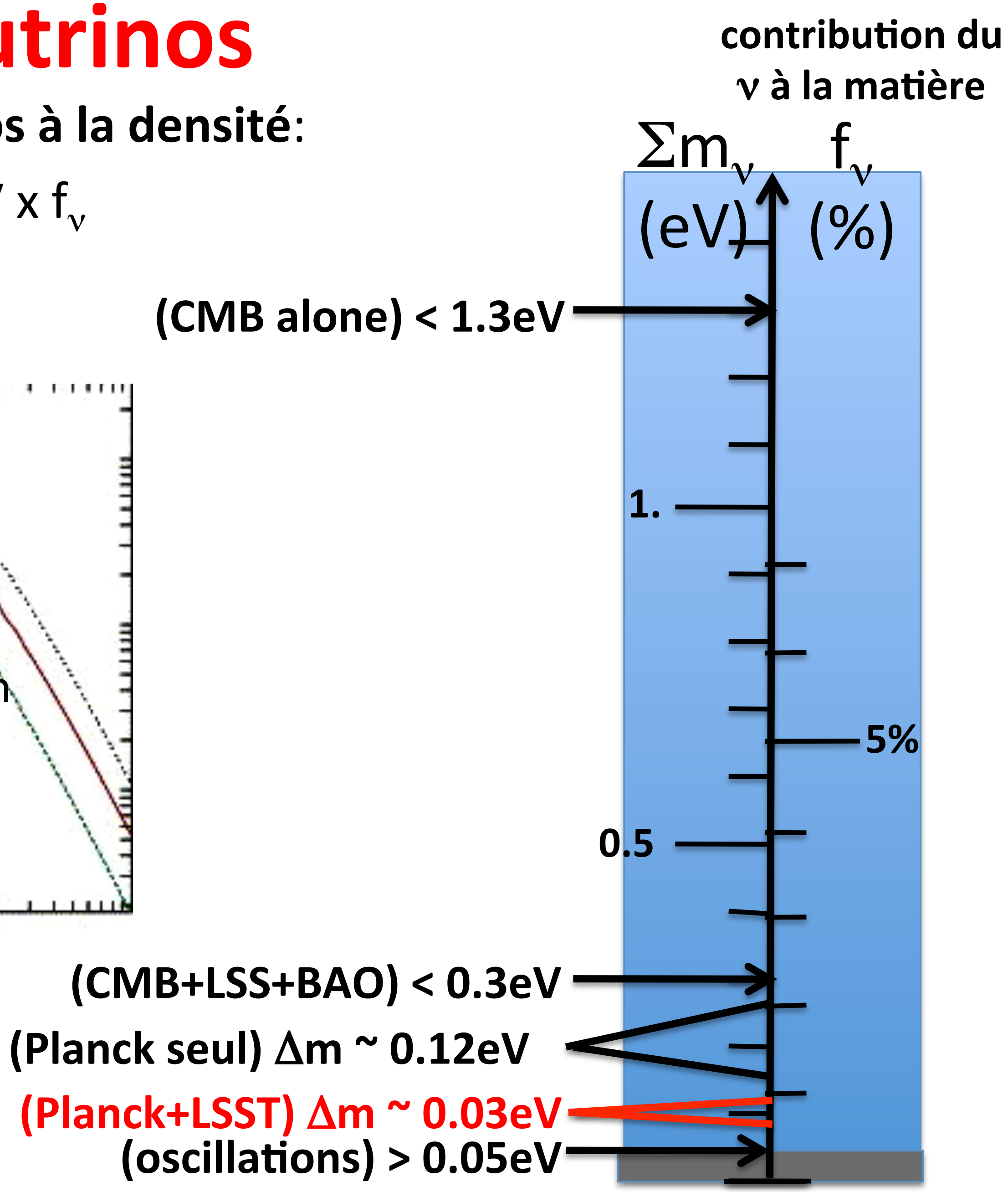
Jean Coupon et al. IAP

Masse des neutrinos

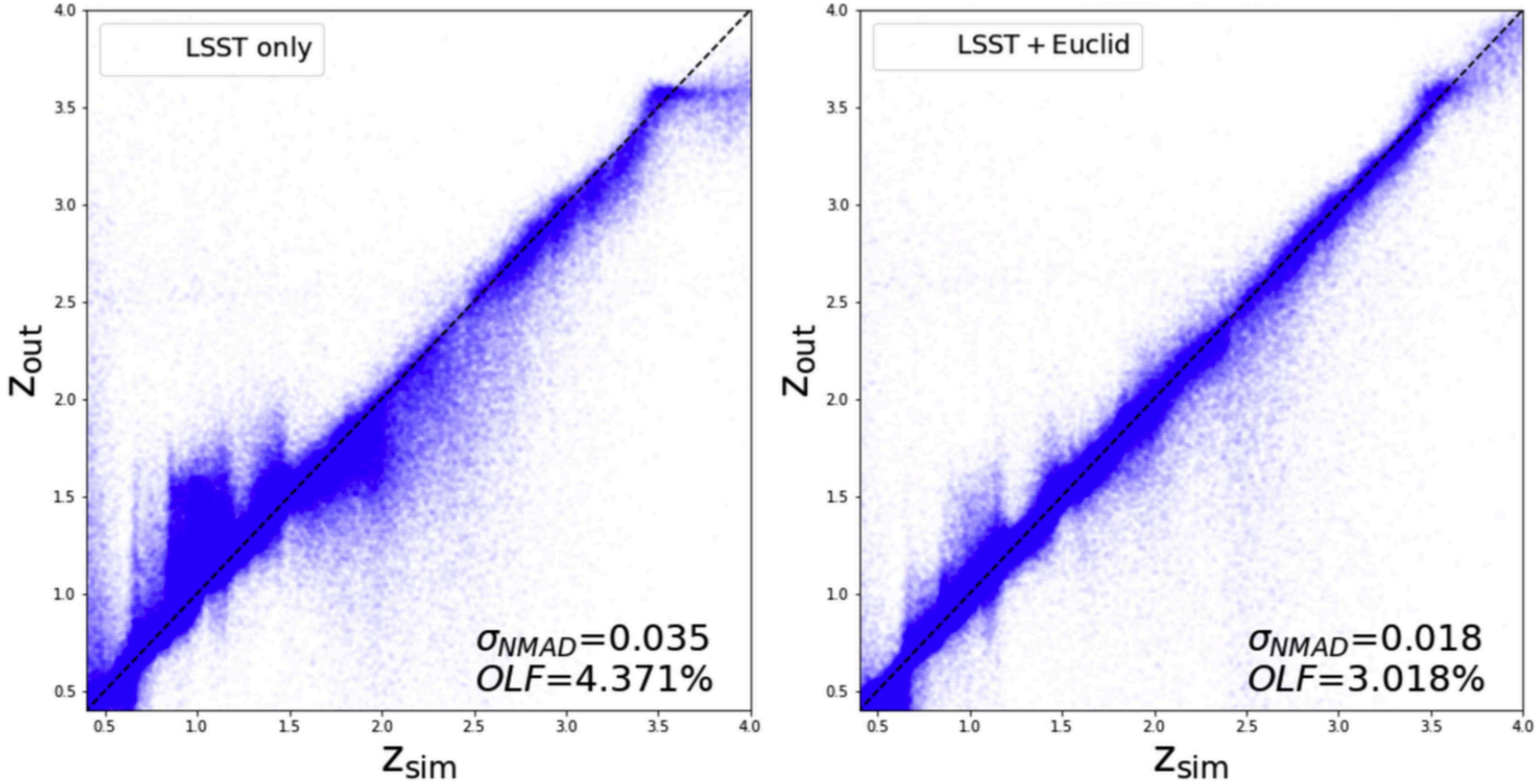
contribution des neutrinos à la densité:

$\Sigma m_\nu = 94 eV \times \Omega_\nu h^2 = 13 eV \times f_\nu$





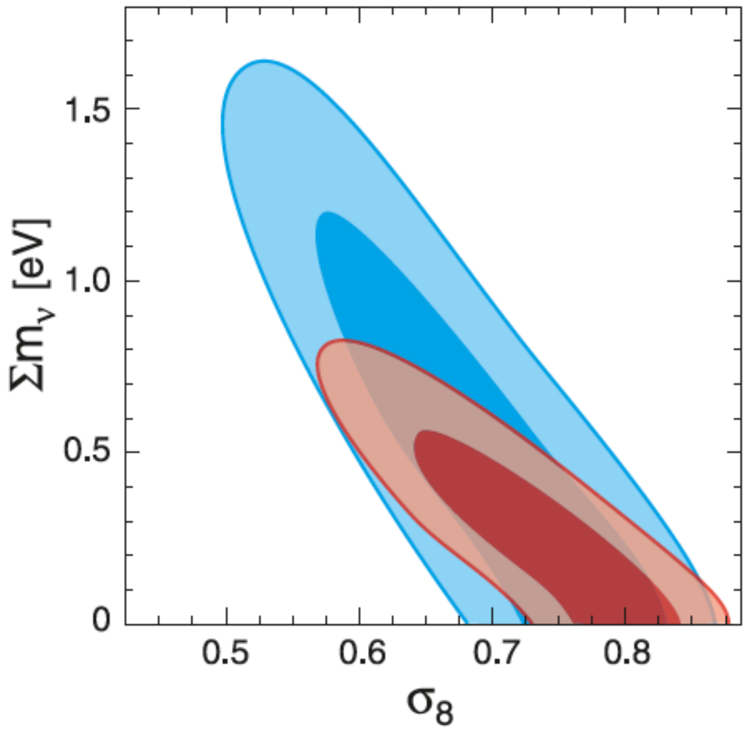
Redshift determination



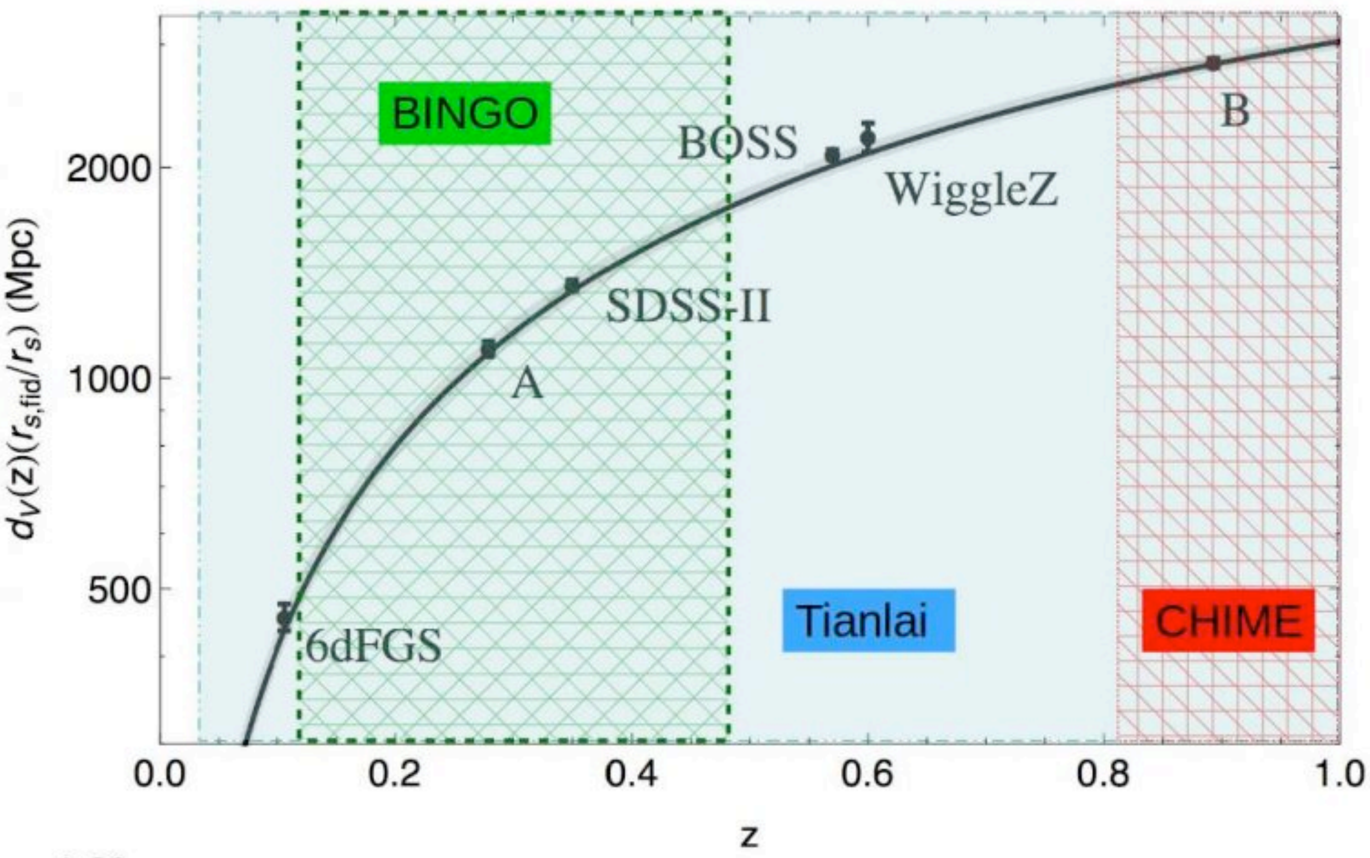
Expected Photometric-*z* vs Spectroscopic-*z*

BAO: Optical vs Radio surveys

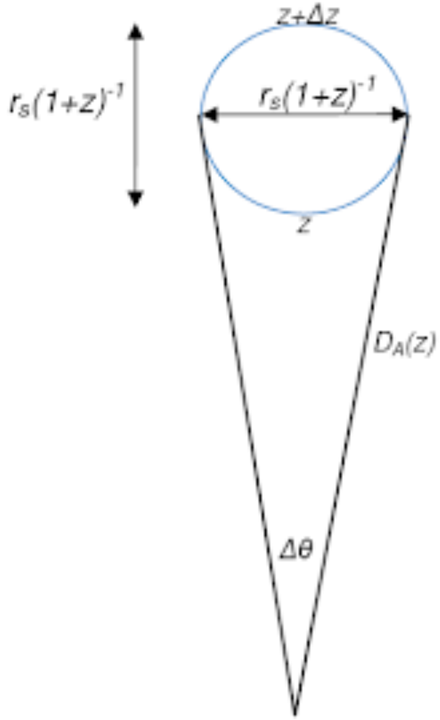
	Optical	Radio
Large volume	OK	OK
Precision on z	Photo-z?	$<10^{-3}$ (longitudinal BAO)
z domain	0 - 1	0 - 1.5
Limiting factor	Cosmic variance	Background
Remarks		Galaxies not resolved



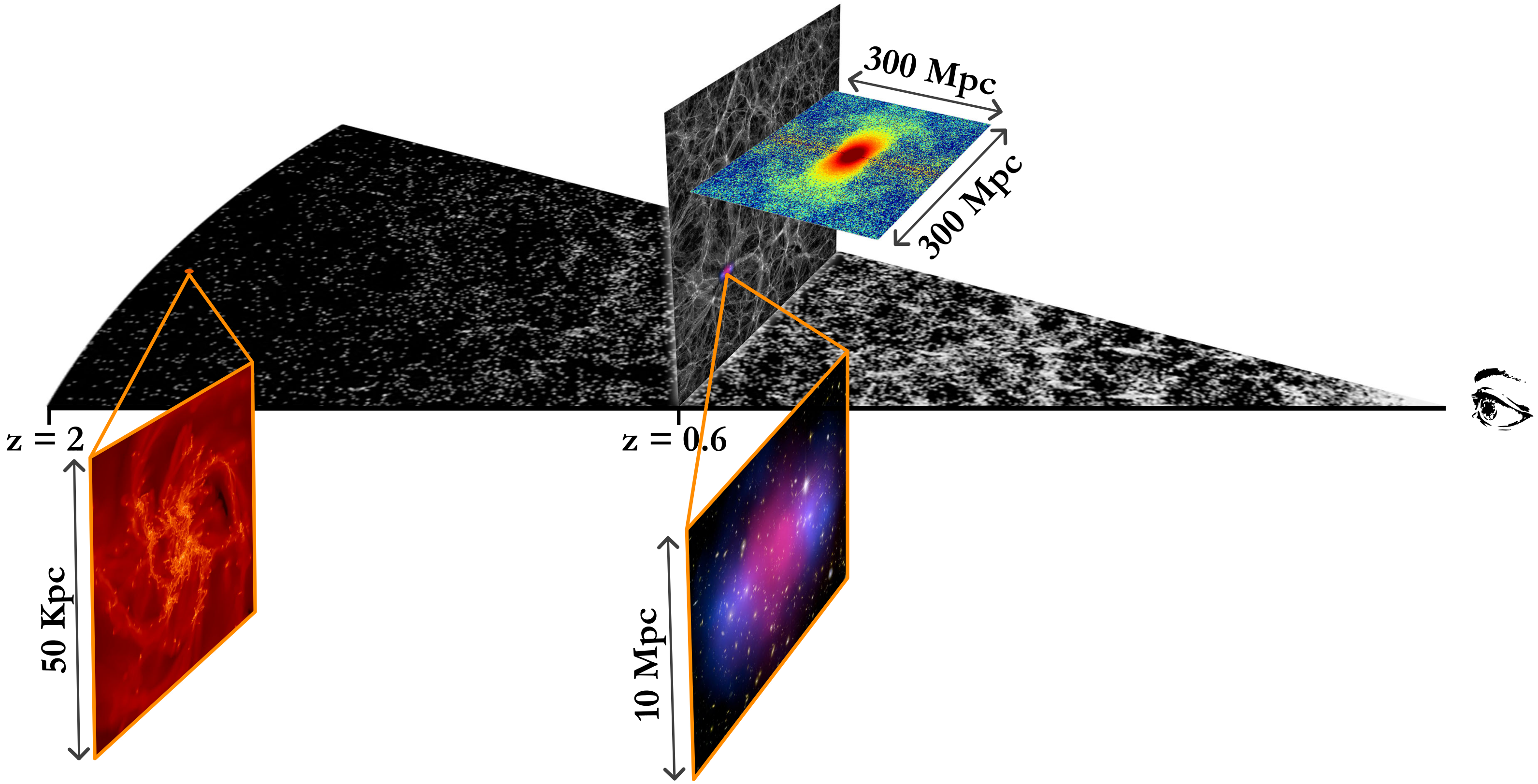
- Correlation between the 2 surveys
- H_1 vs light as a function of z: bias σ_8



BAO Hubble Diagram: distance-redshift relation from different BAO measurements, adapted from Anderson et al 2012. The redshift probed by the different HI intensity mapping radio projects is marked: BINGO 0.13-0.48, Tianlai 0-3 CHIME 0.8-2.5



z+Δz
$r_s(1+z)^{-1}$
$r_s(1+z)^{-1}$
z
$D_A(z)$
Δθ



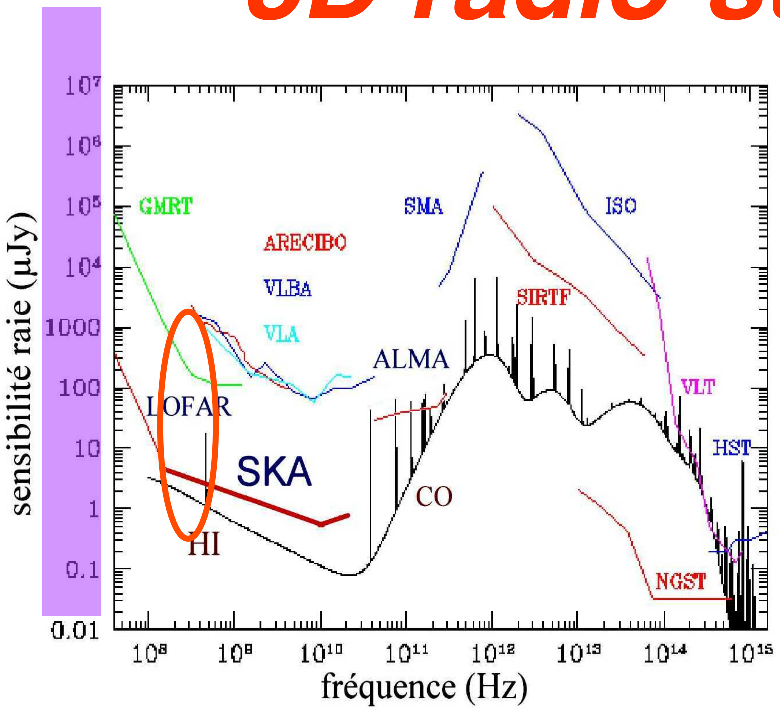
300 Mpc
300 Mpc
z = 2
z = 0.6
50 Kpc
10 Mpc

BAO with T21(α,δ,z) mapping

Total Intensity Mapping

- ✓ Needs angular resolution of only 10-15 arcmin
- Instrumental noise
- Difficulty: subtraction of foreground emission and radio sources

3D radio-survey for BAO



Principle

➢ Simultaneous determination of position and redshift with the 21cm atomic hydrogen emission line (1.4 GHz @ z=0)

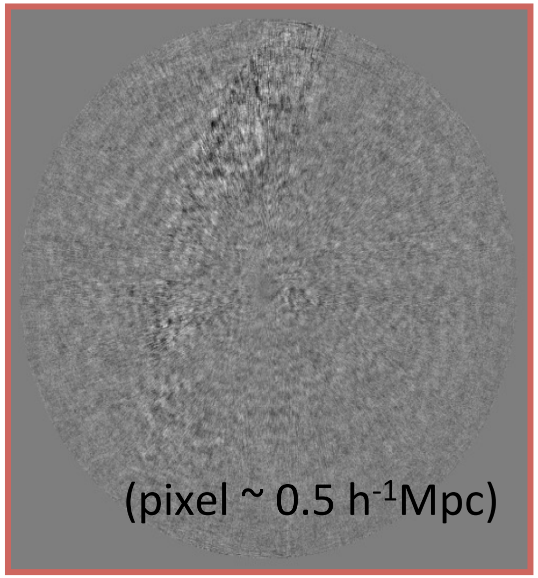
➢ **H_{21} line dominates** below 1.4 GHz

➢ **No need for one-by-one galaxy detection**

$\Rightarrow$Pixel map of H_{21} flux

$\Rightarrow$Brightness temperature variation

$\Rightarrow$pixels should be smaller than 20-30Mpc to measure 150 Mpc structures **σ_θ~20'**



HIPASS survey