Shedding light on Dark Energy
First results of BOSS-Lyα

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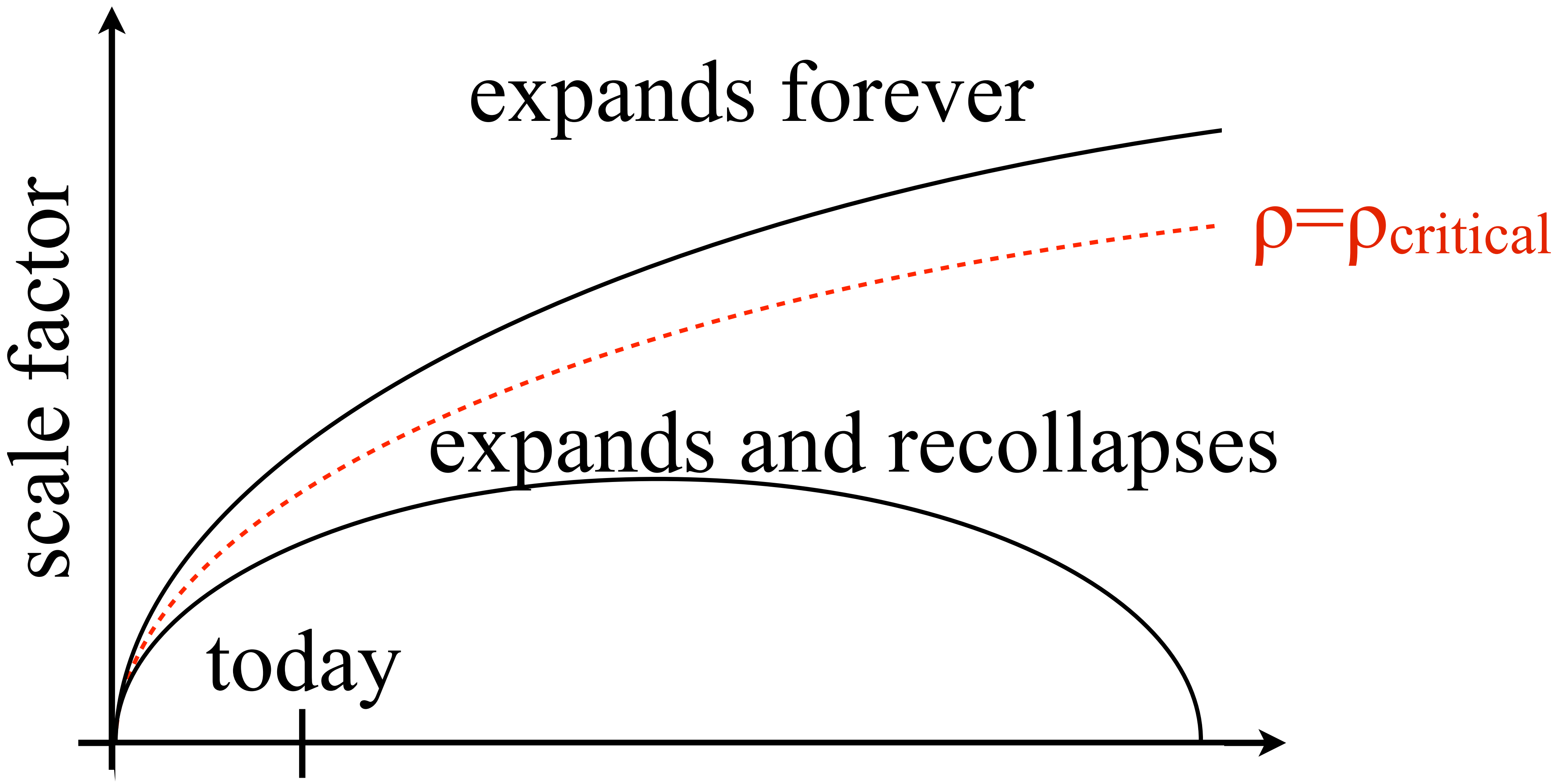
in collaboration with:
Timothée Delubac, Jim Rich

CPPM

April 22, 2013

The future of the Universe?

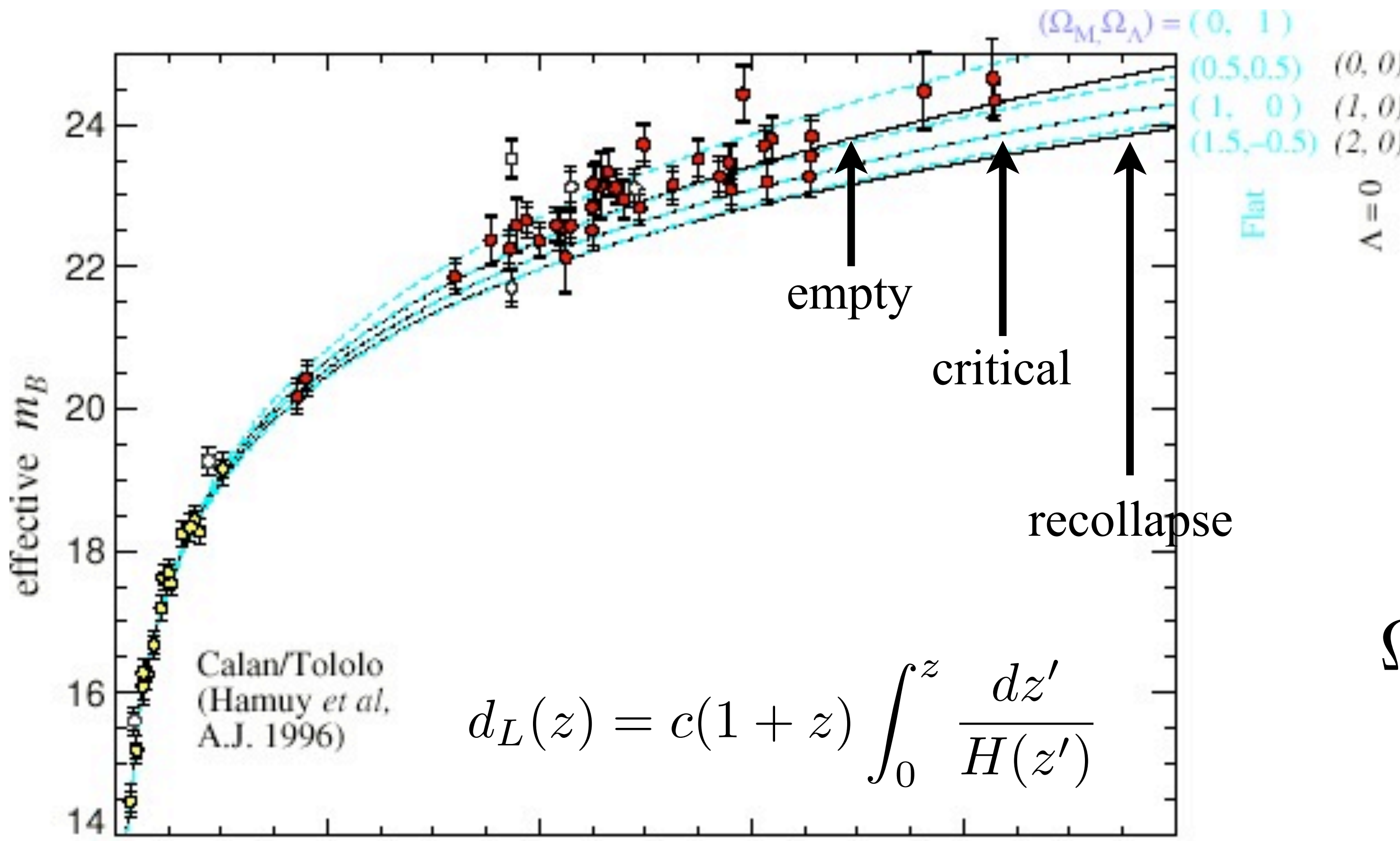
until the ~ '98



$$\frac{\dot{a}}{a} \equiv H(z) = \sqrt{\Omega_M (1+z)^3} \qquad \Omega_M = \frac{\rho_M}{\rho_c}$$

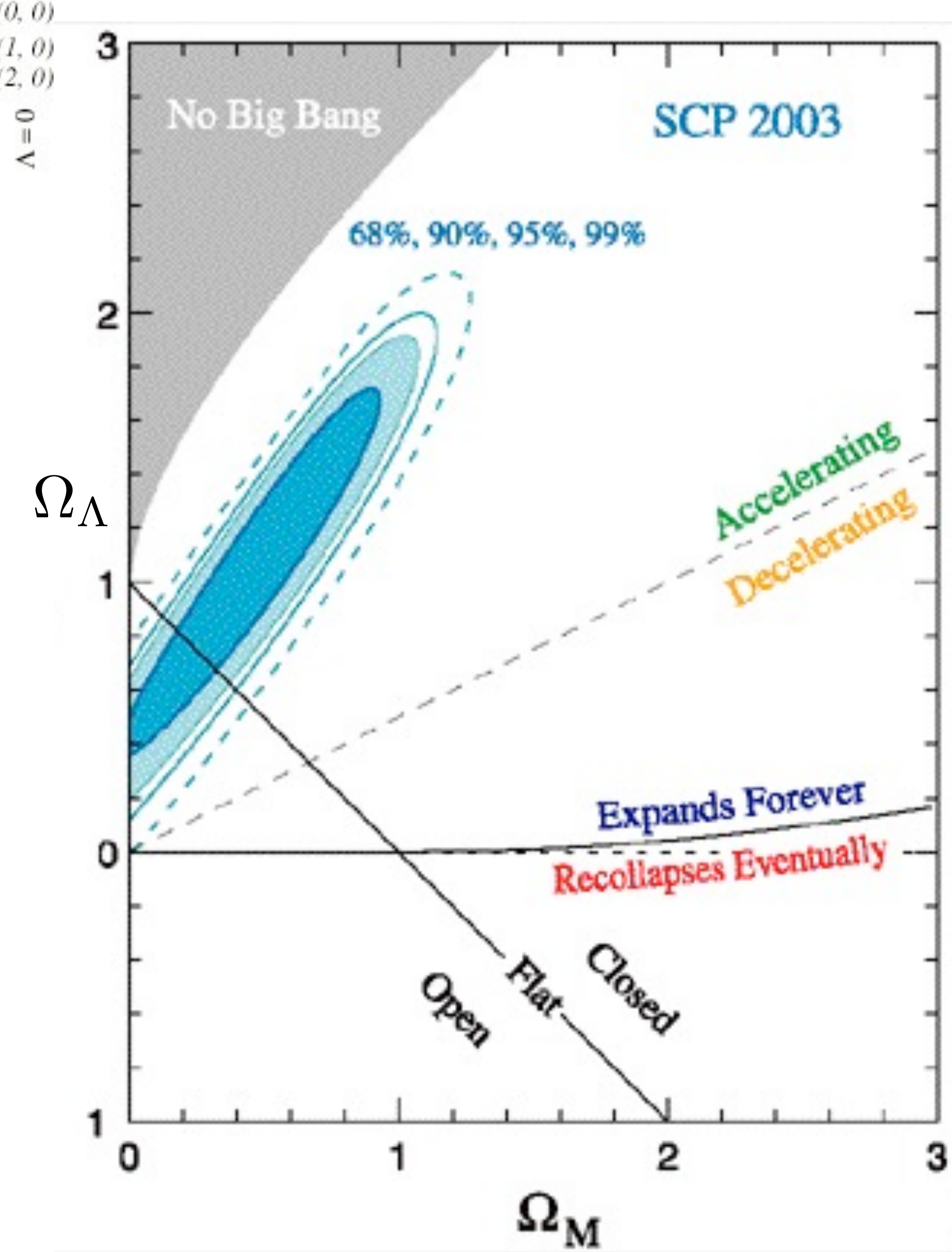
cartoon credit: Eduardo Rozo

The dawn of Dark Energy



To fit: introduce Ω_Λ

$$H(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$$



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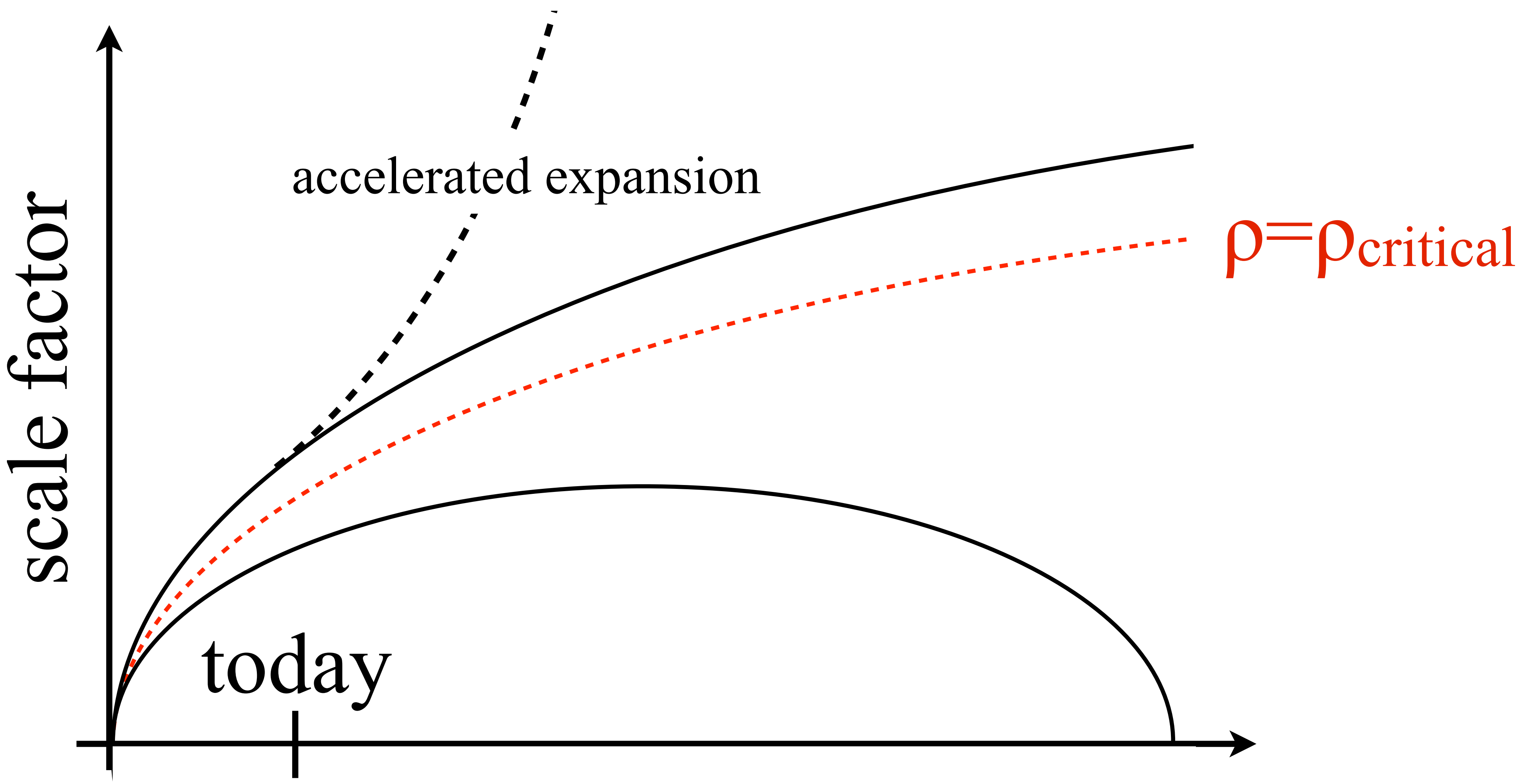

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Physical interpretation of Λ

Dark Energy:
$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Modified Gravity:
(Einstein 1920's)
$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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this seminar

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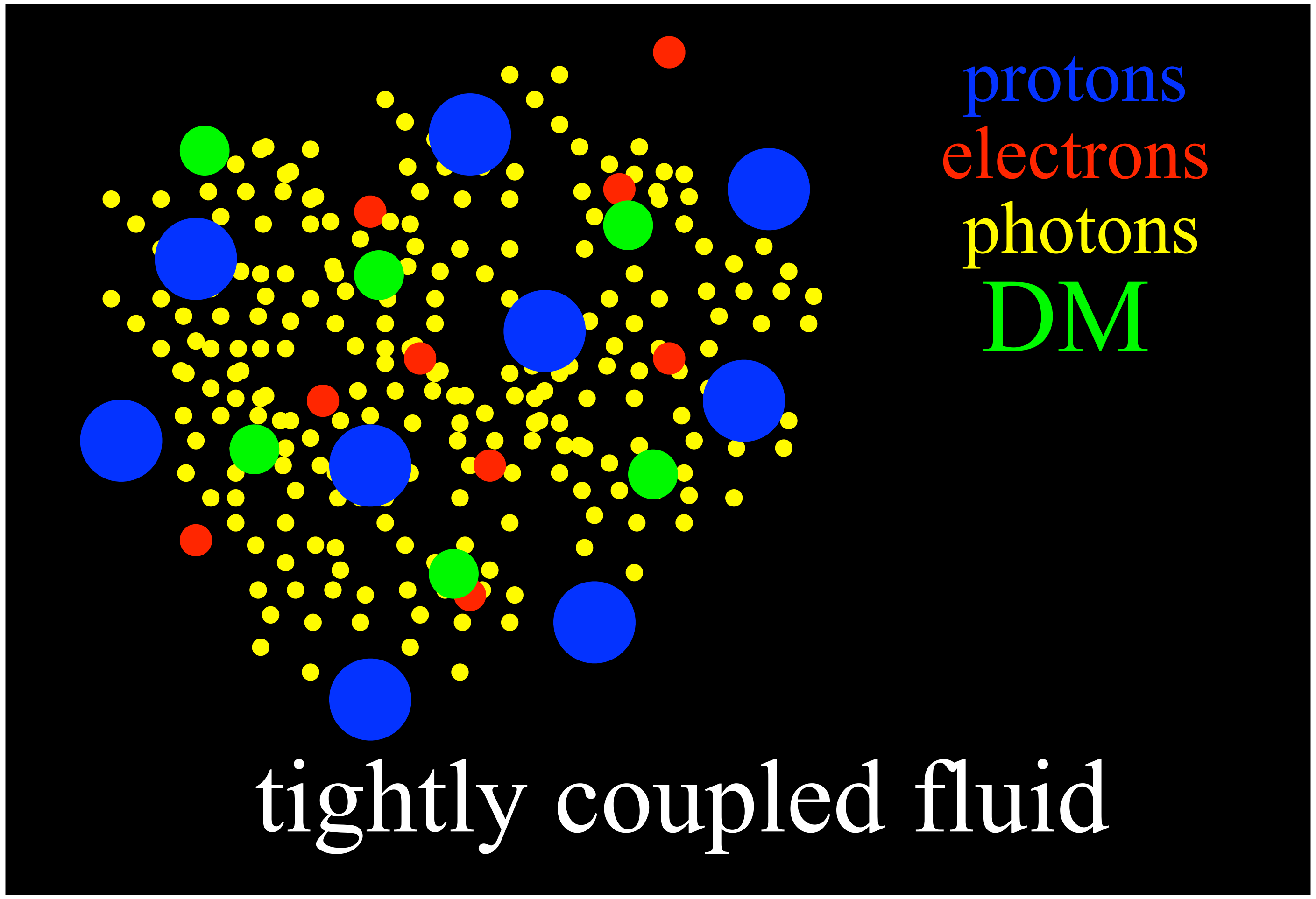
Baryon oscillations

- young Universe (age < 370.000 yrs)
- hot and ionized (T >> 3000 K)



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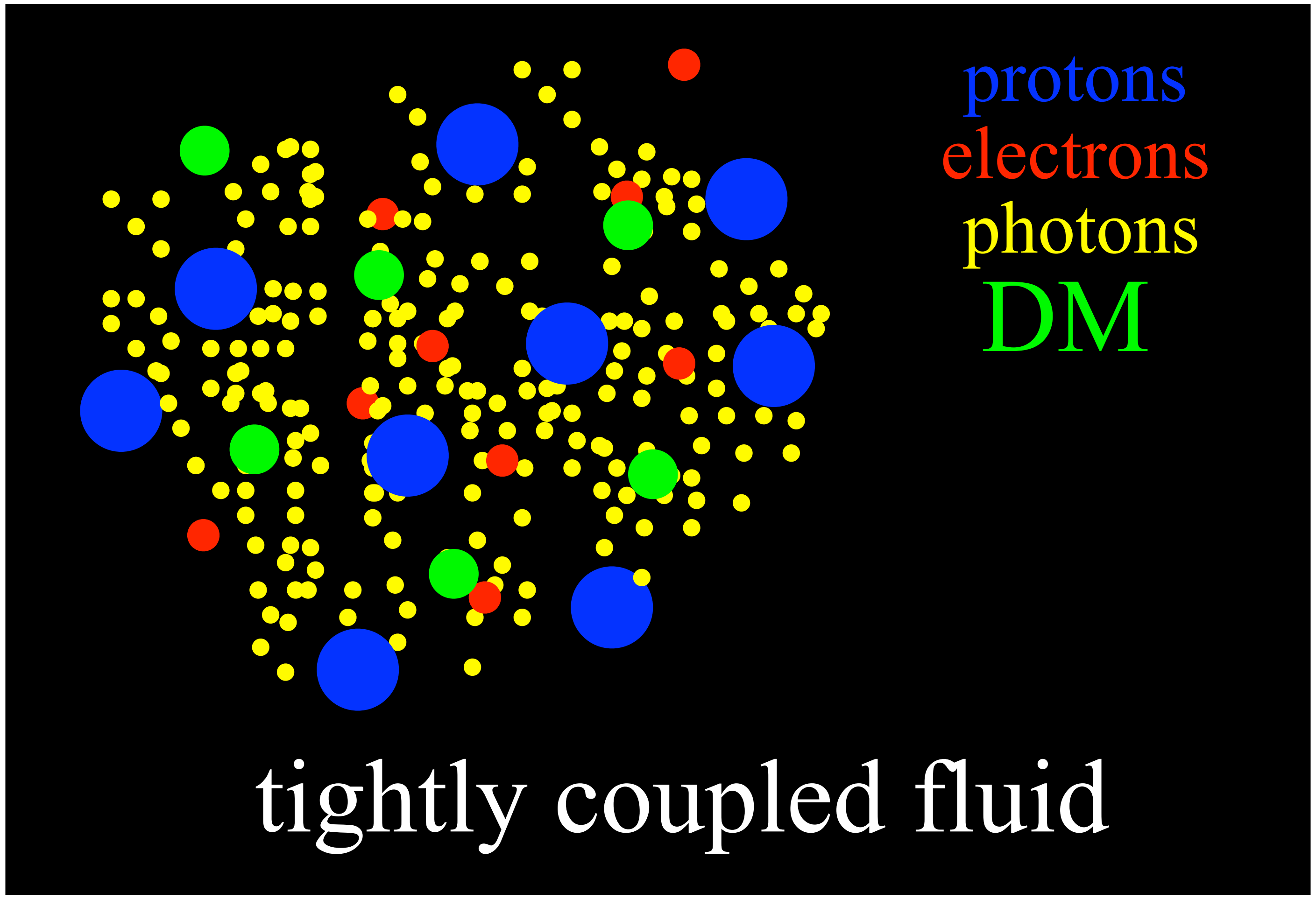
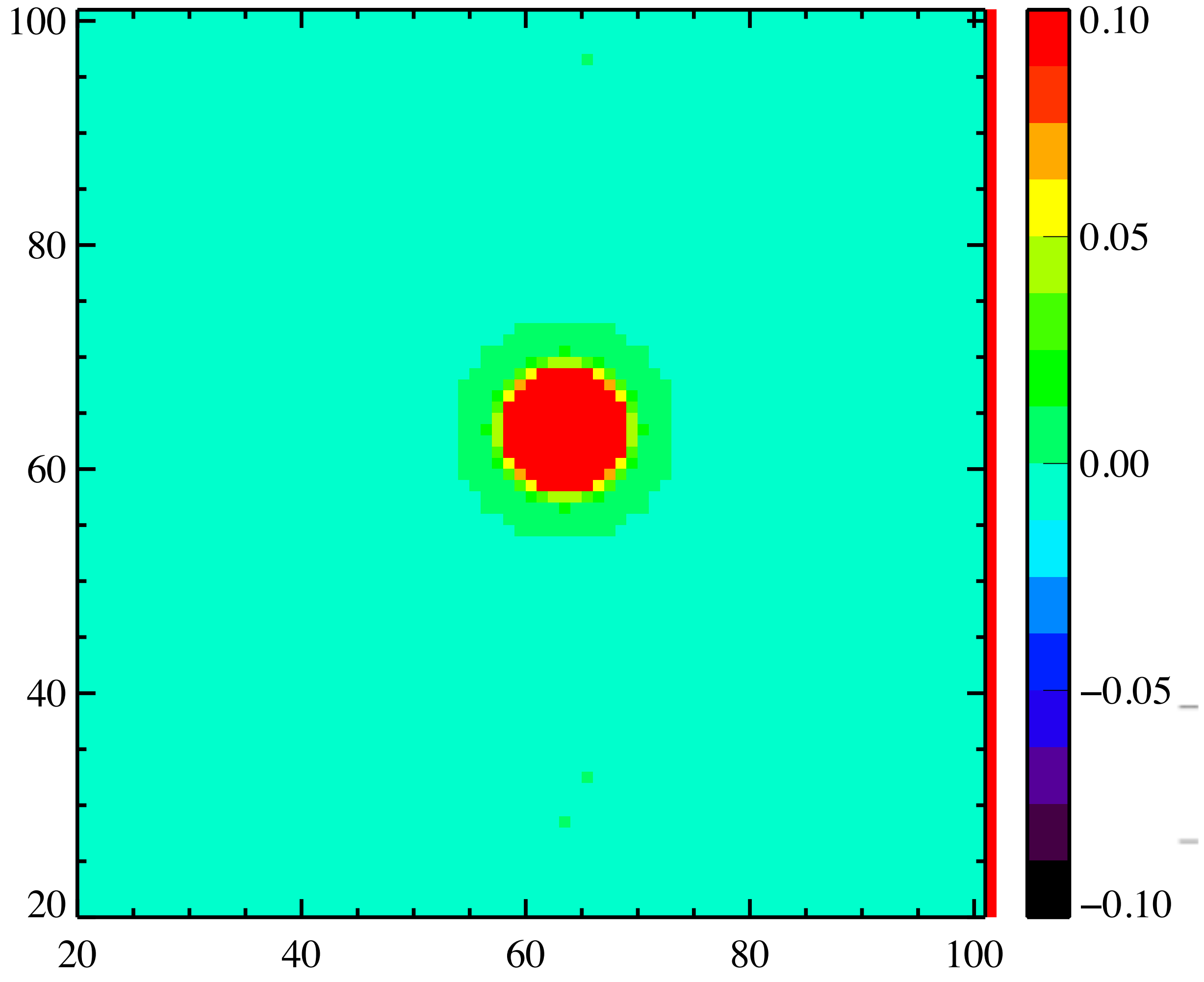


Baryon Oscillations

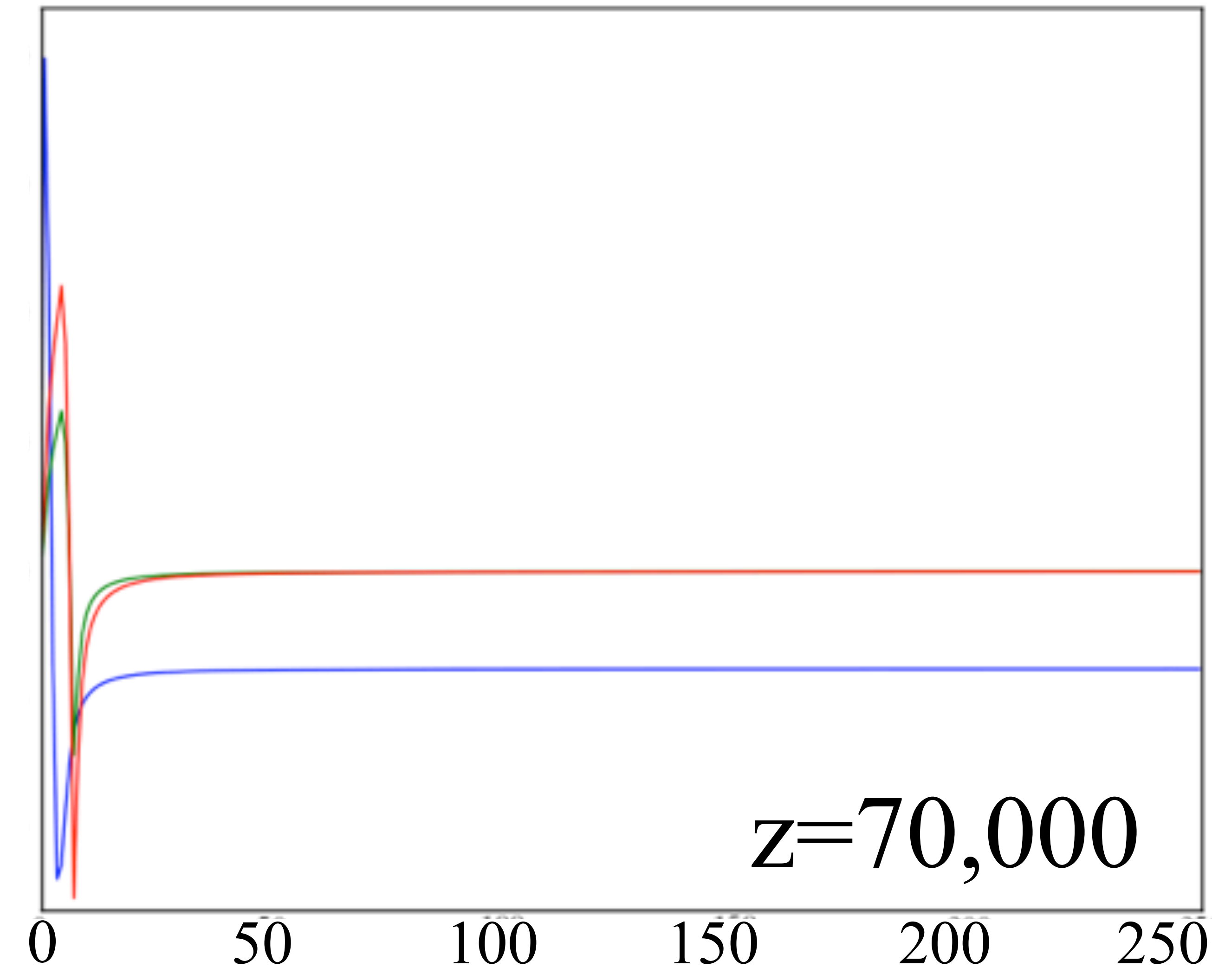
- young Universe (age < 370.000 years)
- hot and ionized (T ≫ 3000 K)
- cosmological distance scales ≫ interaction length between photons and baryons
- photons and baryons behaved as a single fluid

the fluid supports density waves

cross section of an over-density



correlation function



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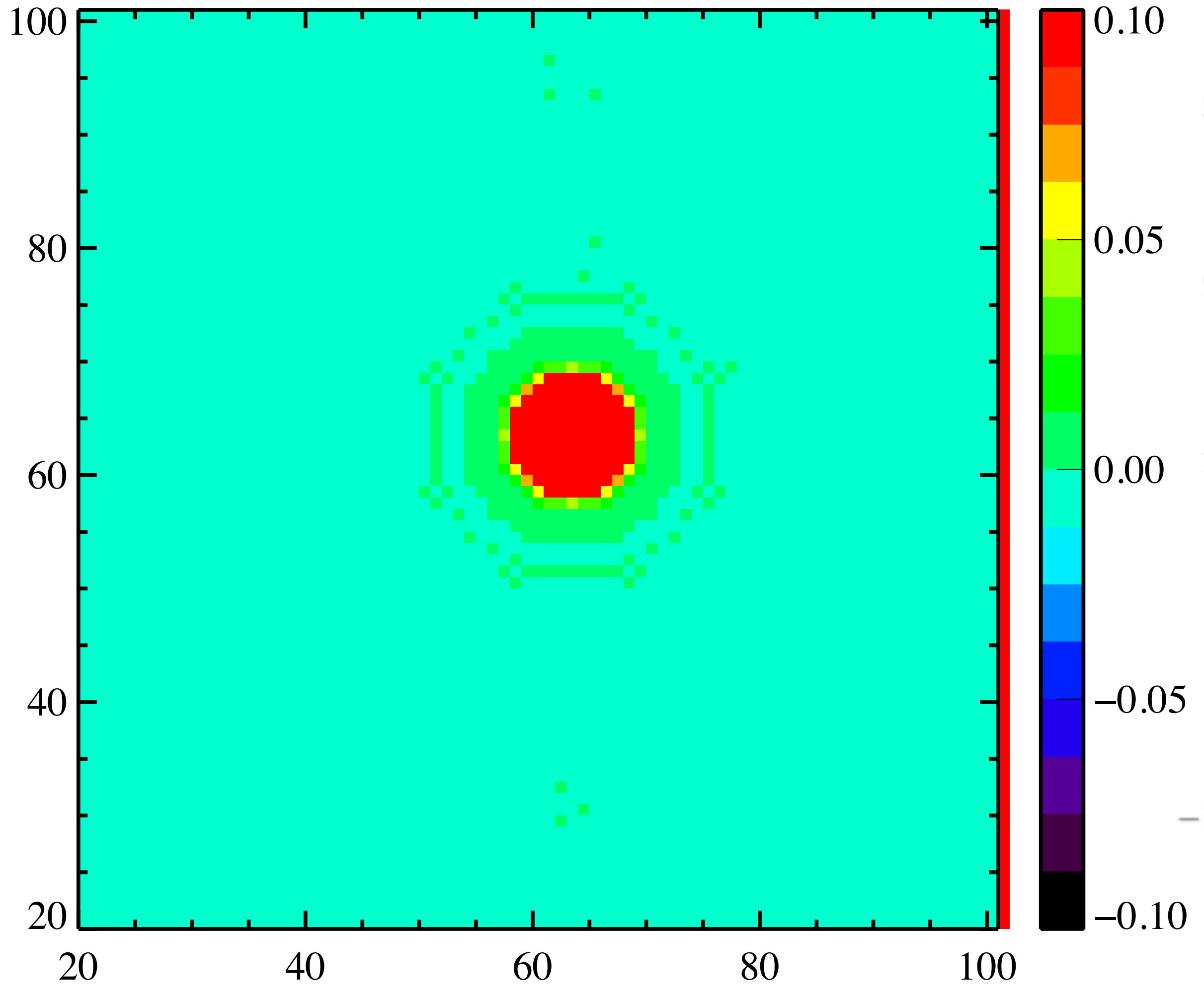

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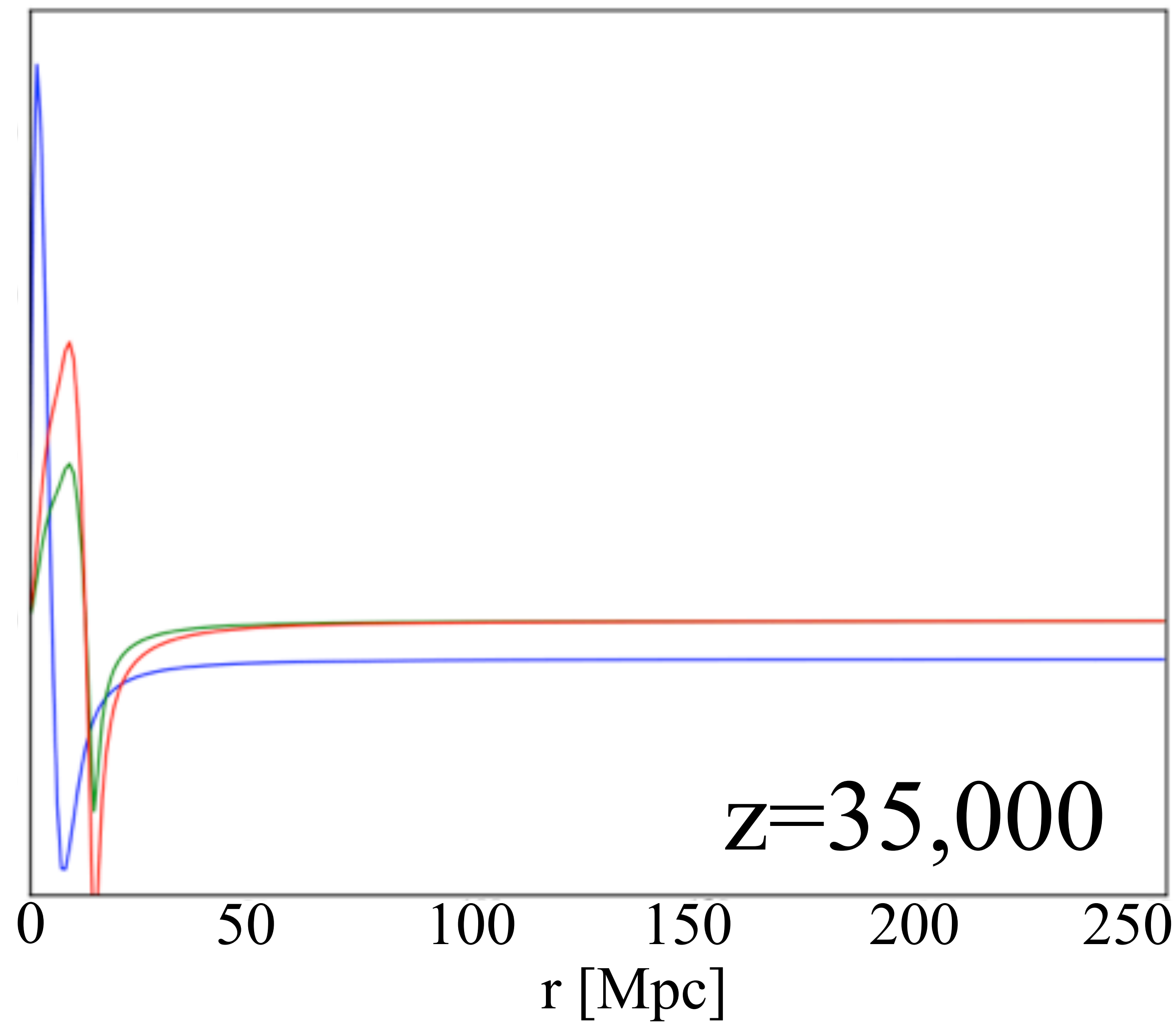

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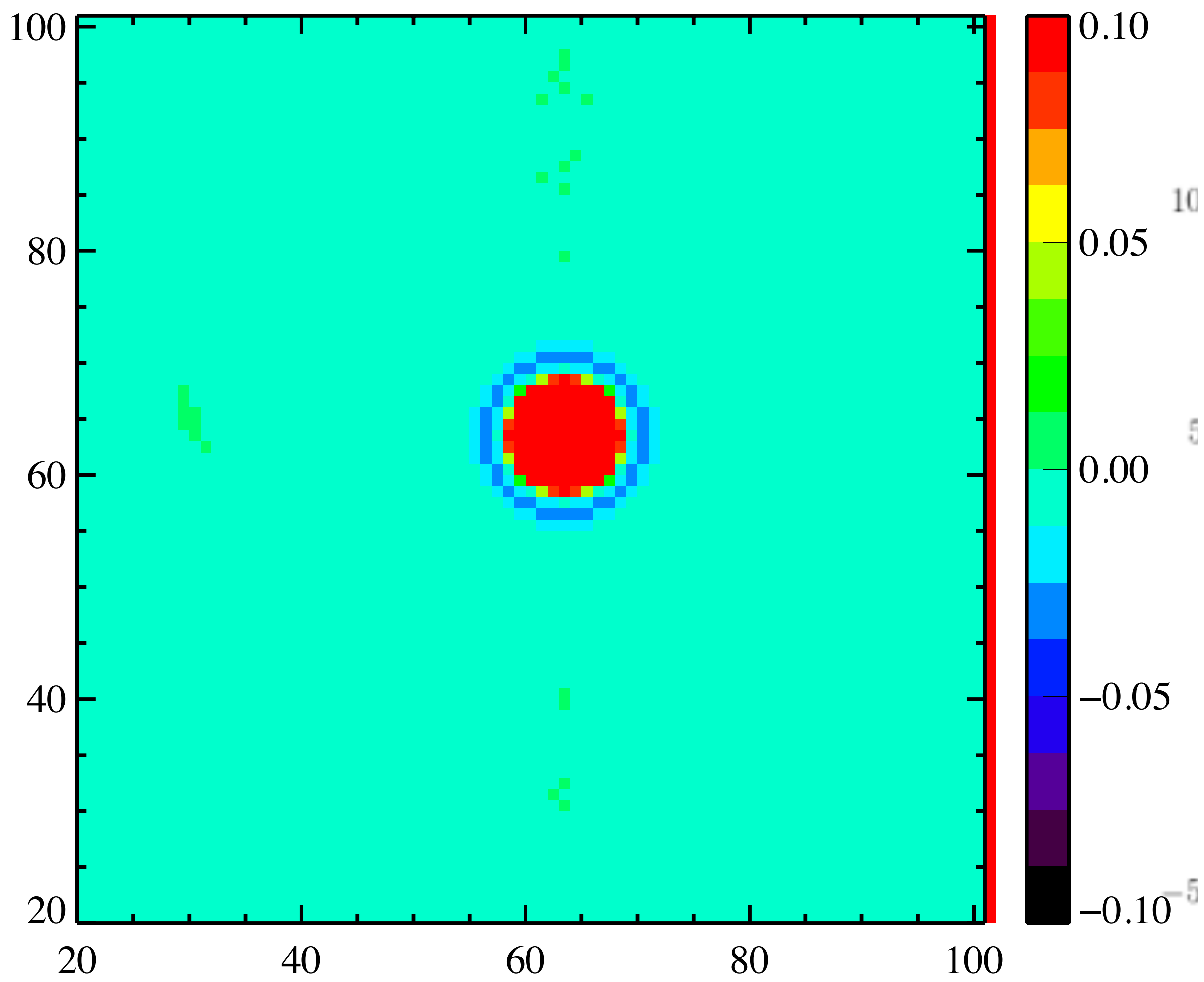

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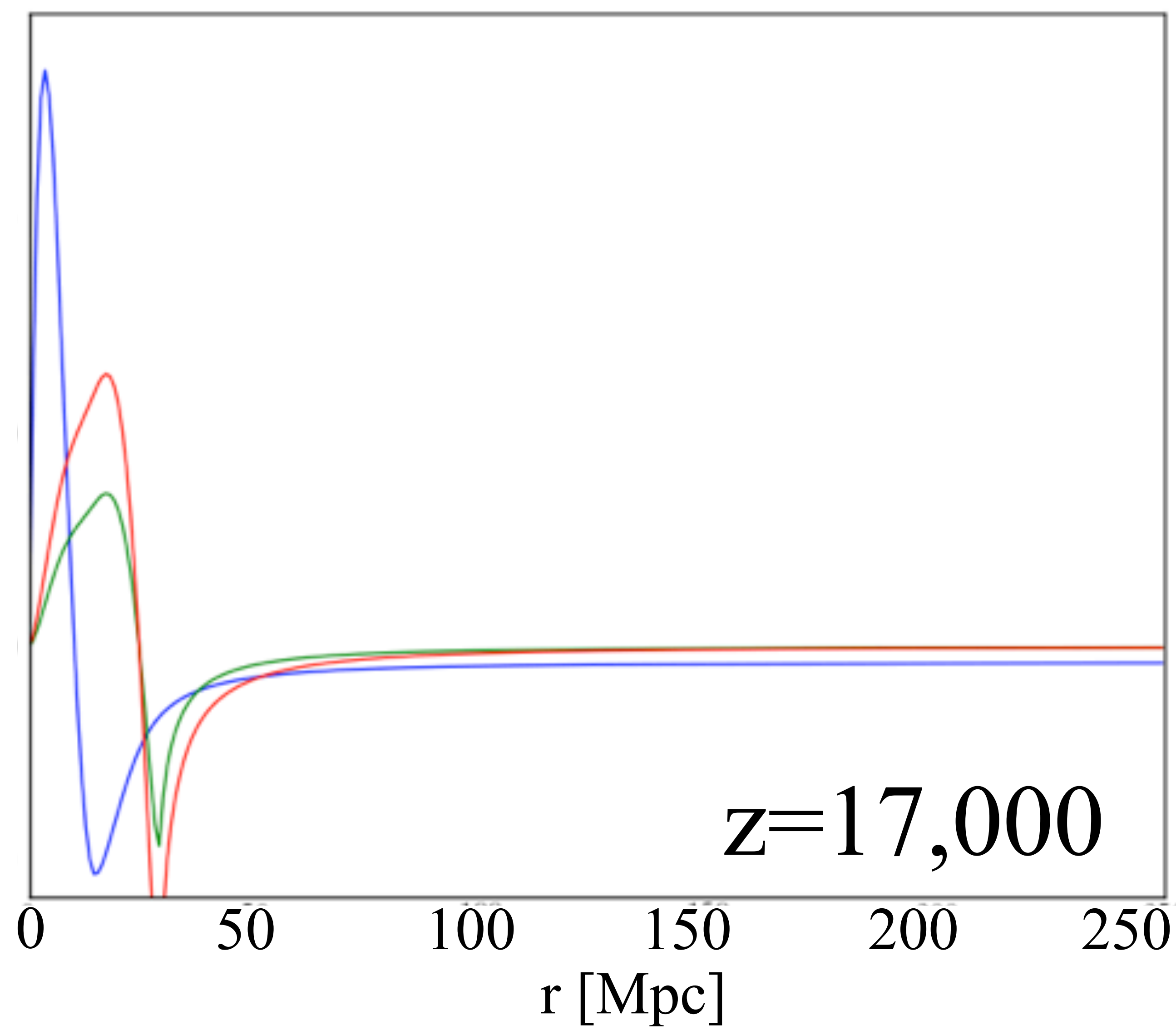

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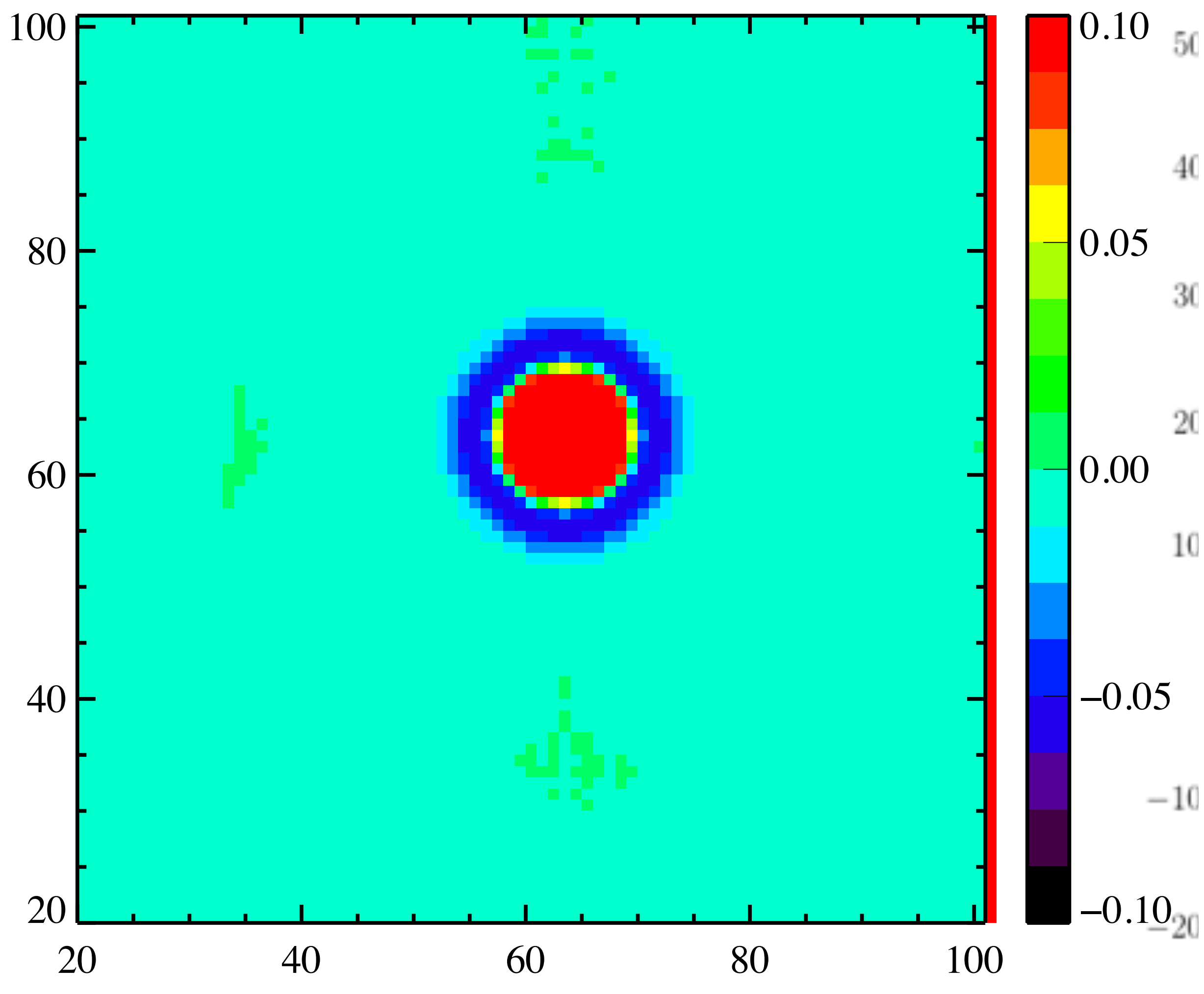

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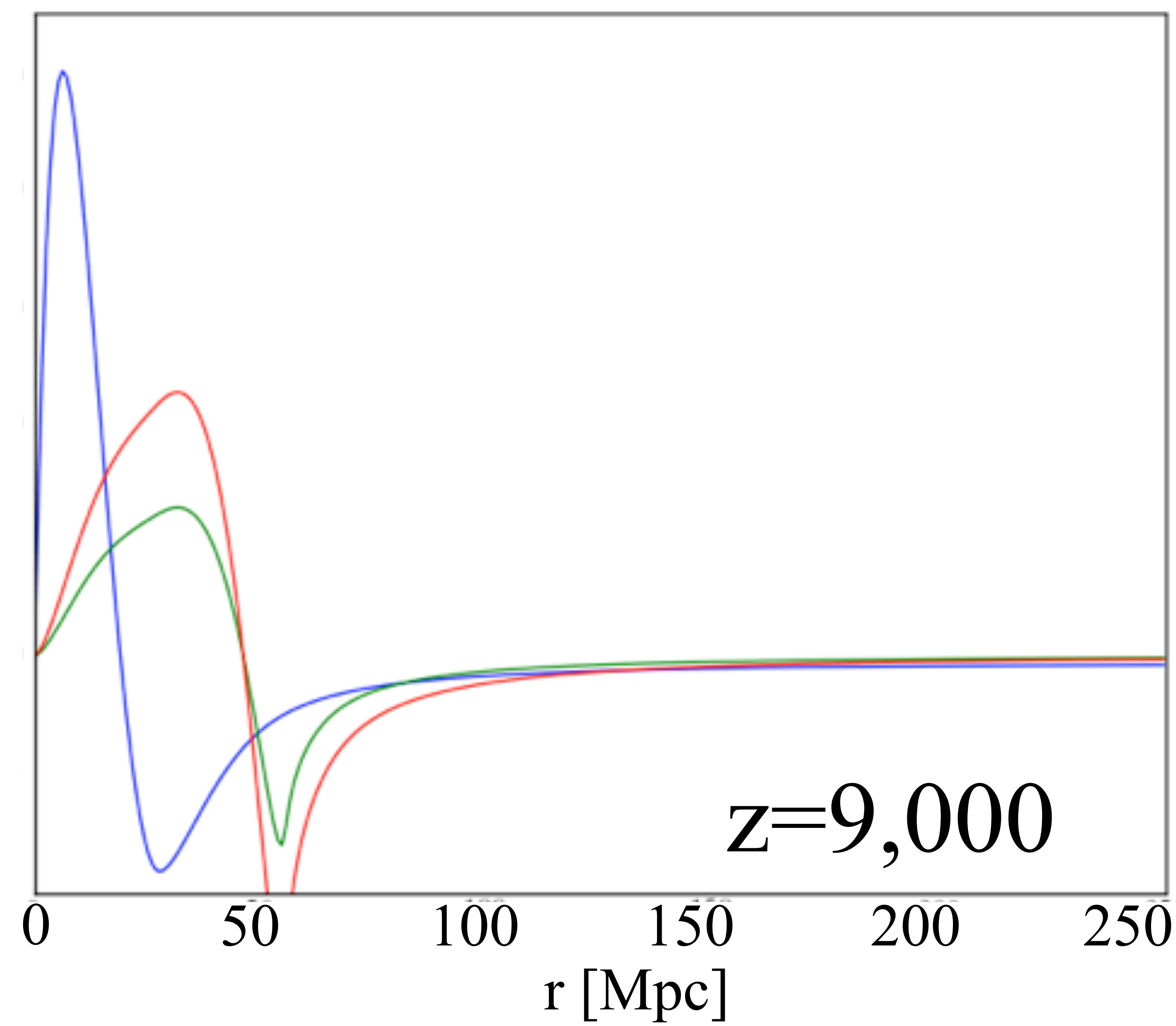

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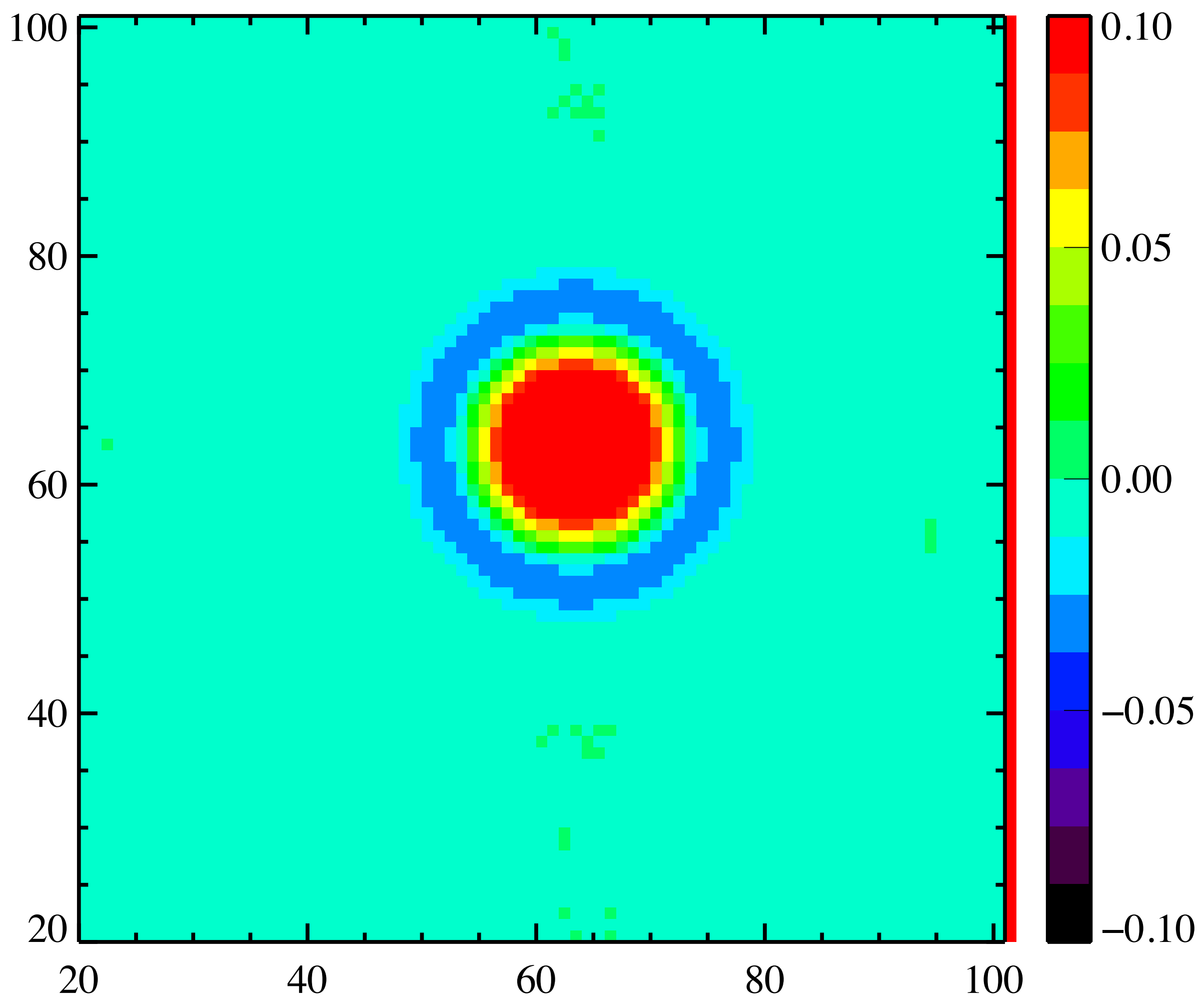

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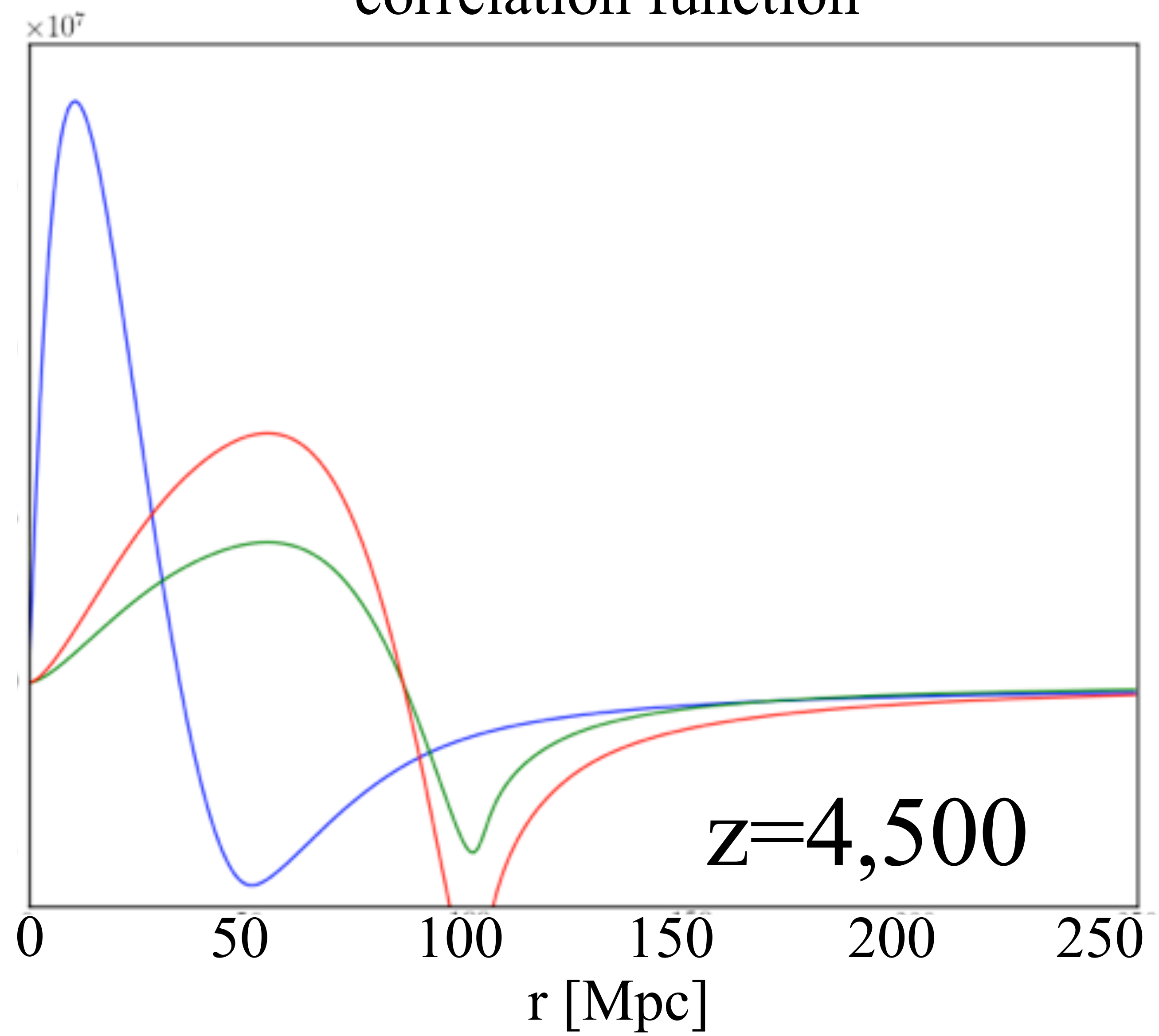

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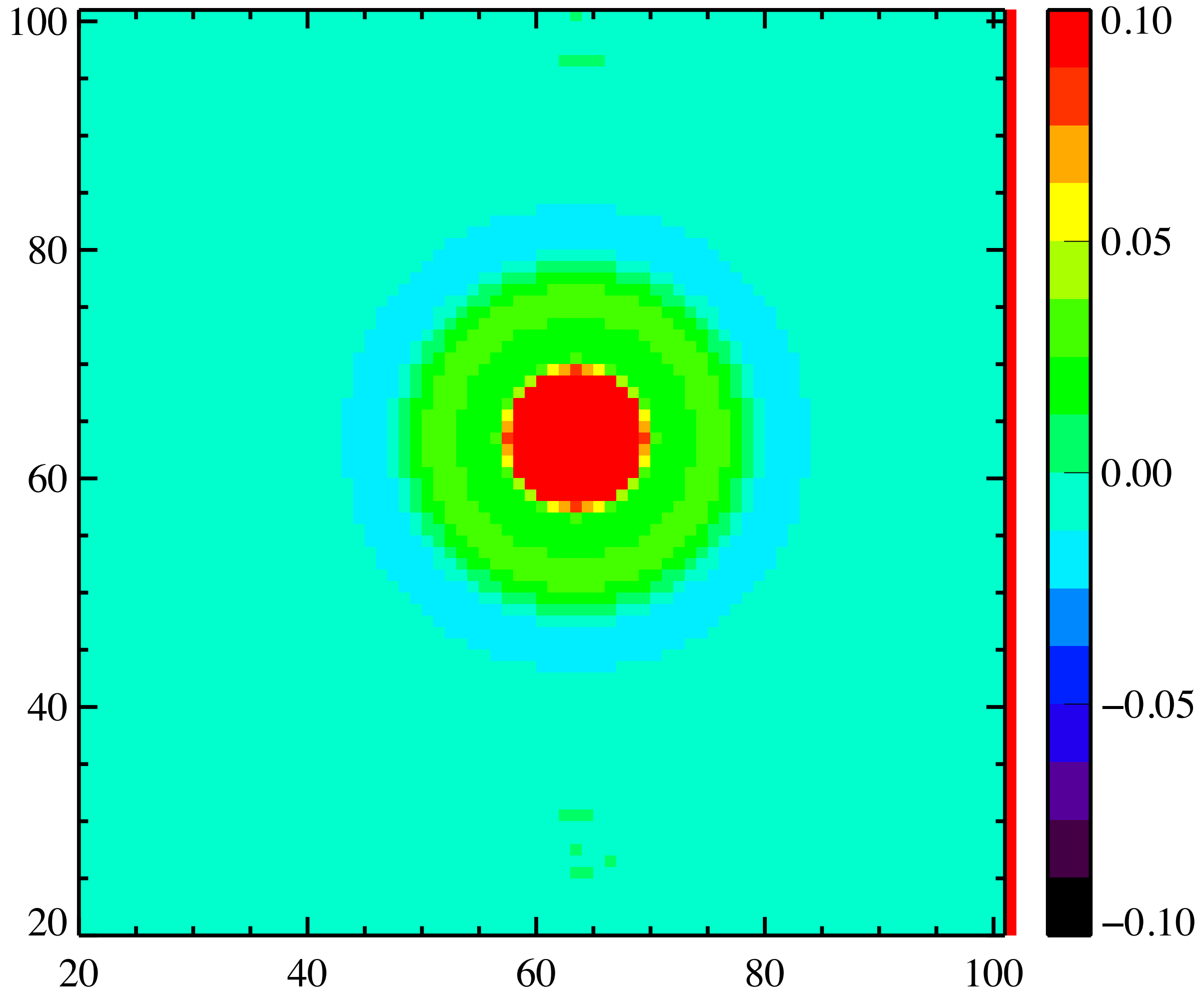

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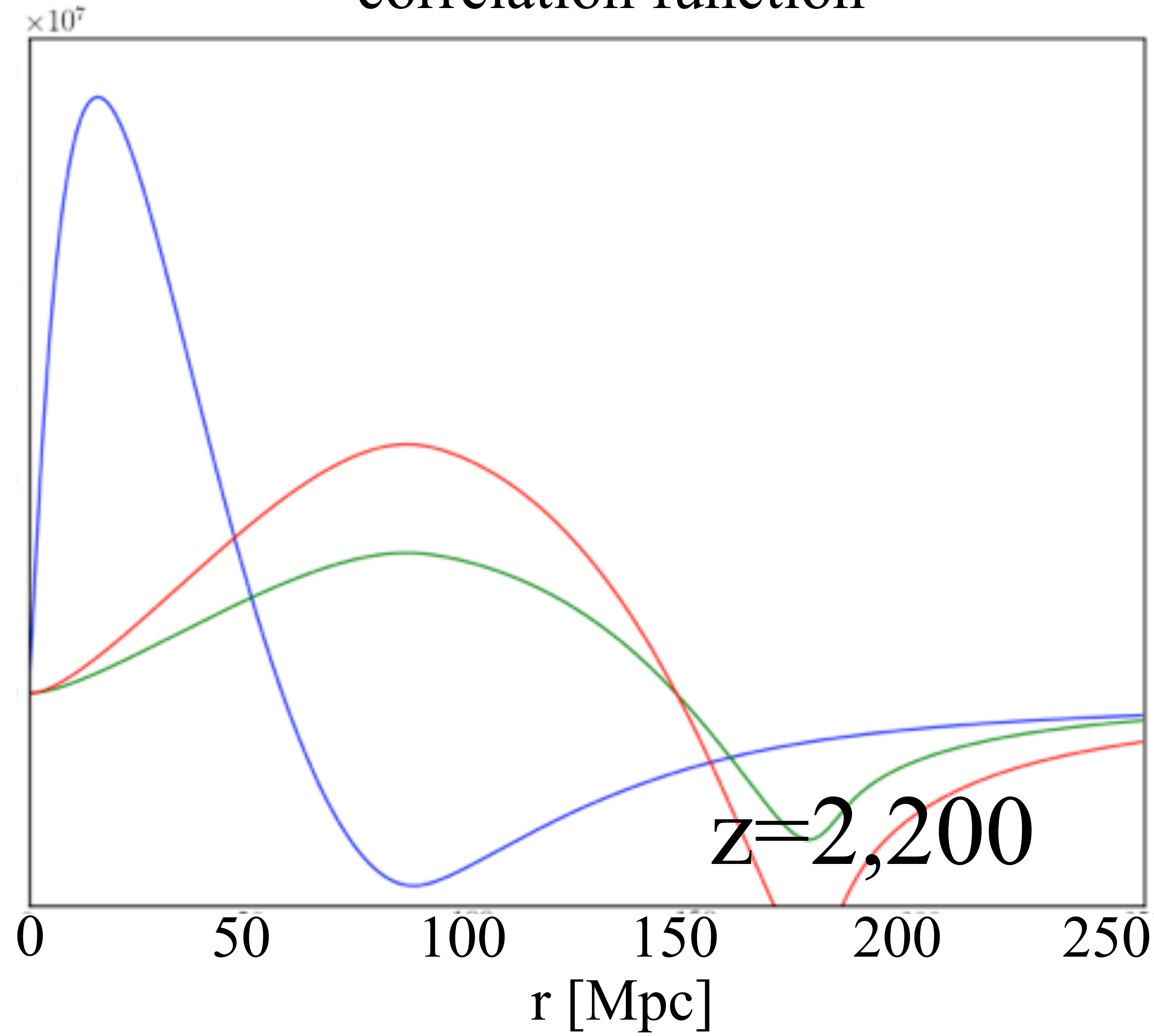

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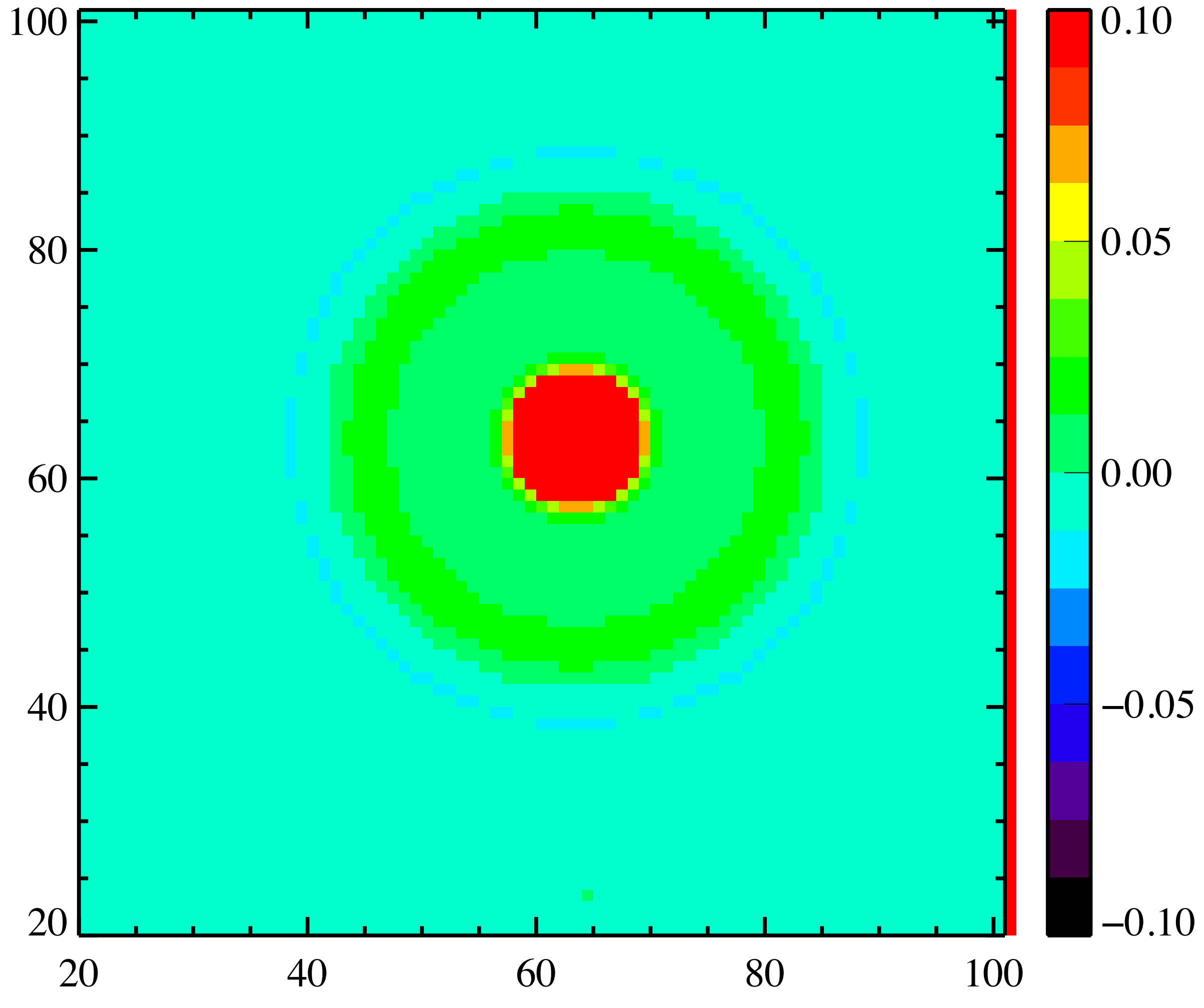

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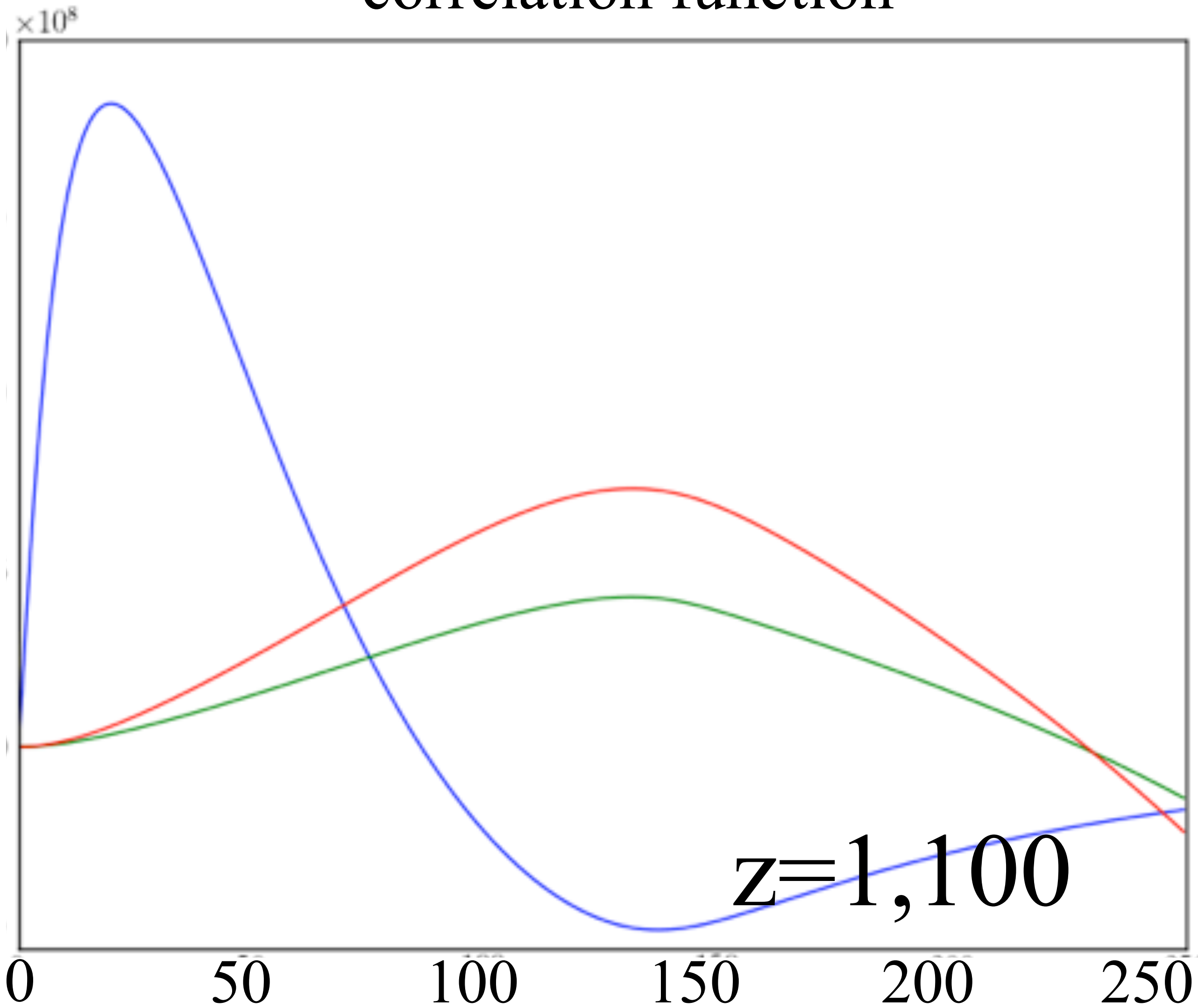

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Cosmological constrains:

in the “right” cosmology the acoustic peak has to be at the “right” position (e.g. in ΛCDM ~ 150Mpc)

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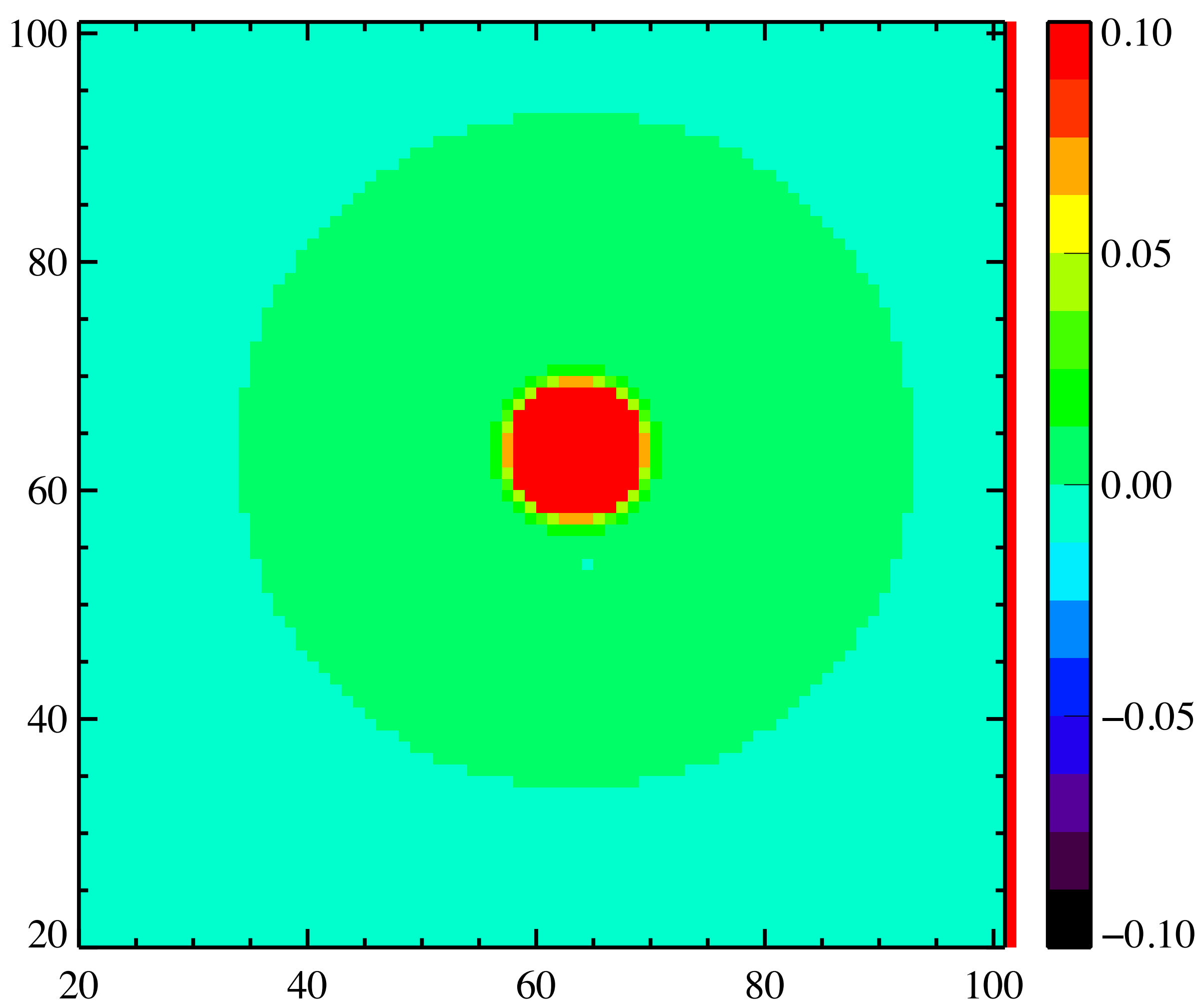

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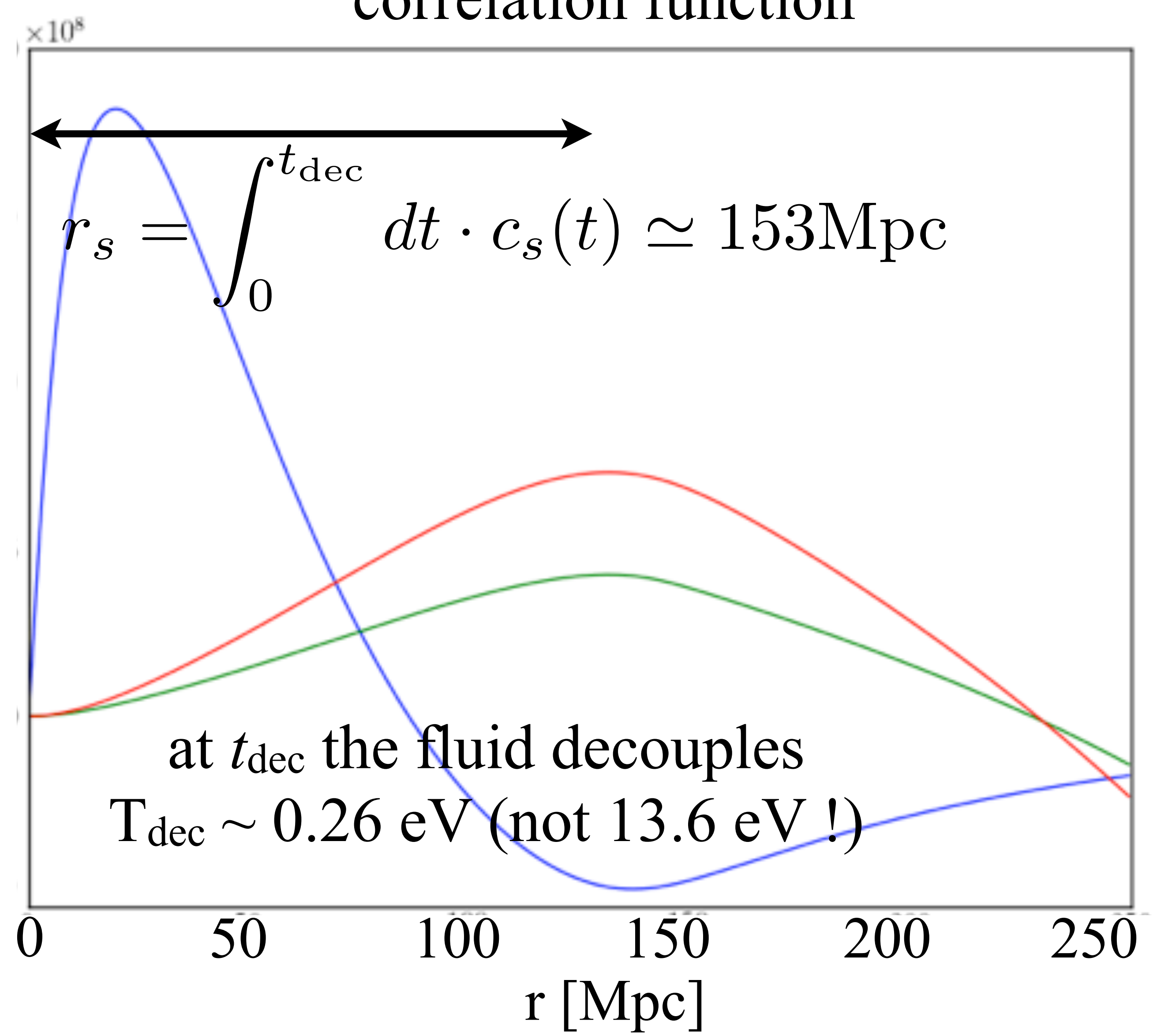

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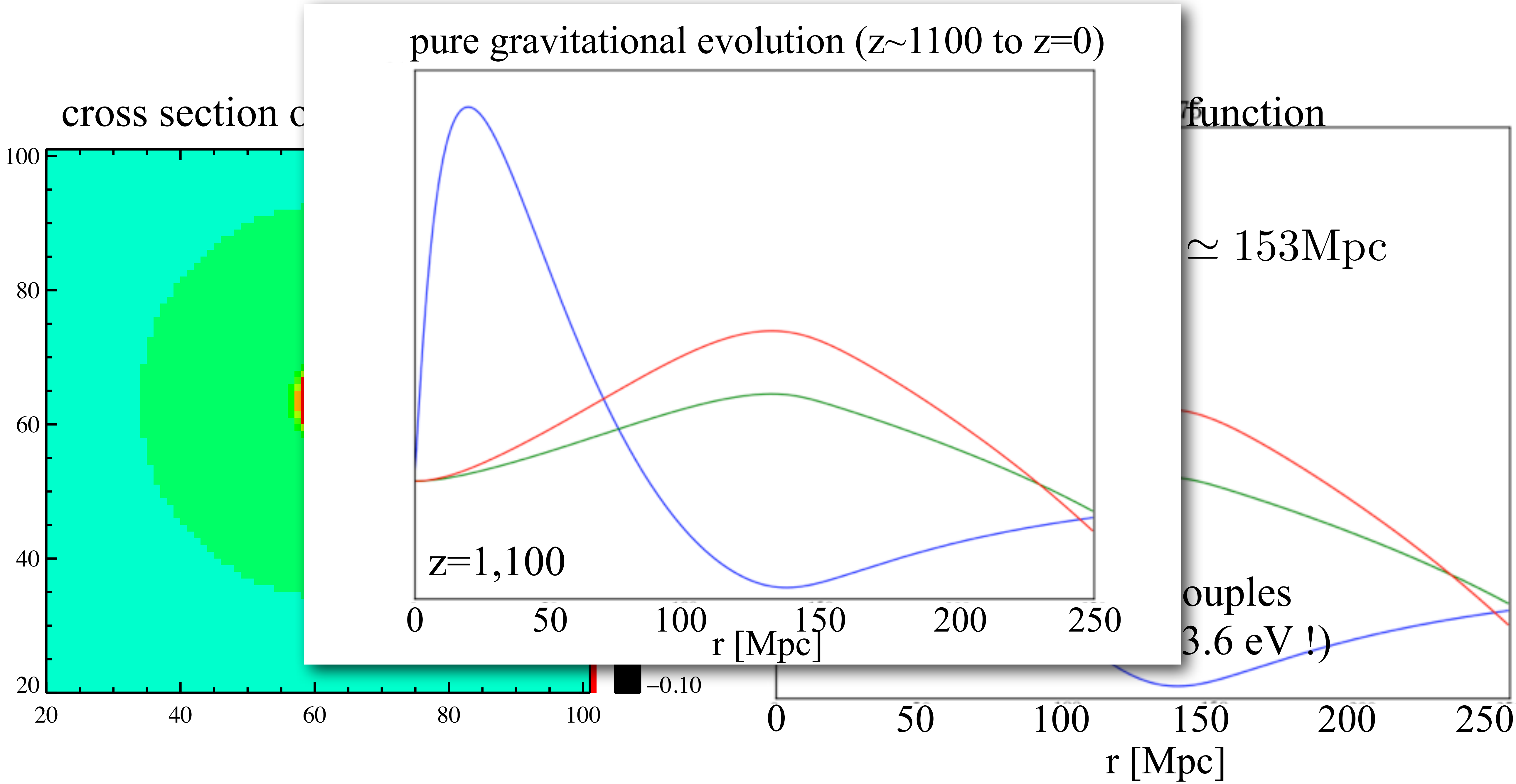

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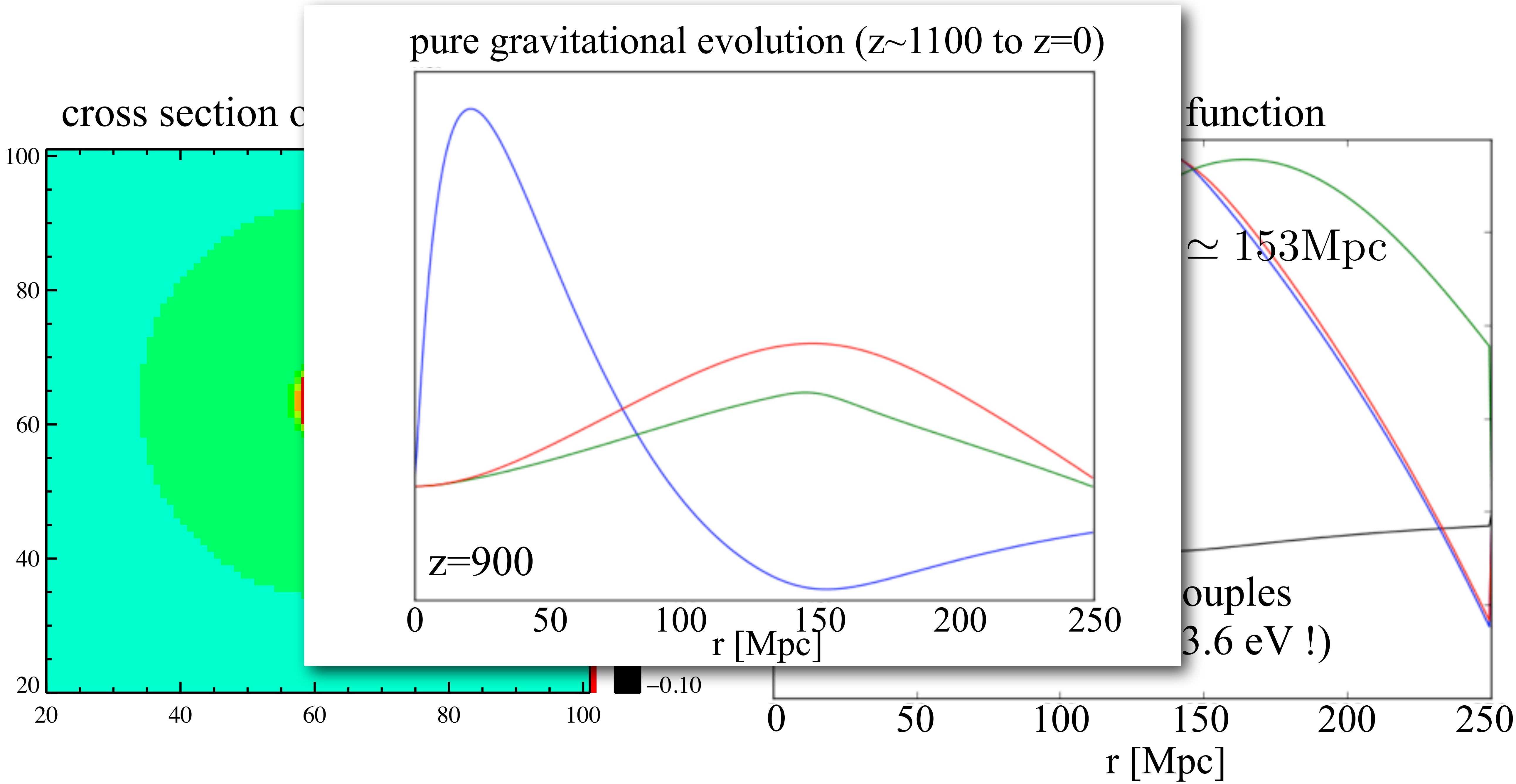

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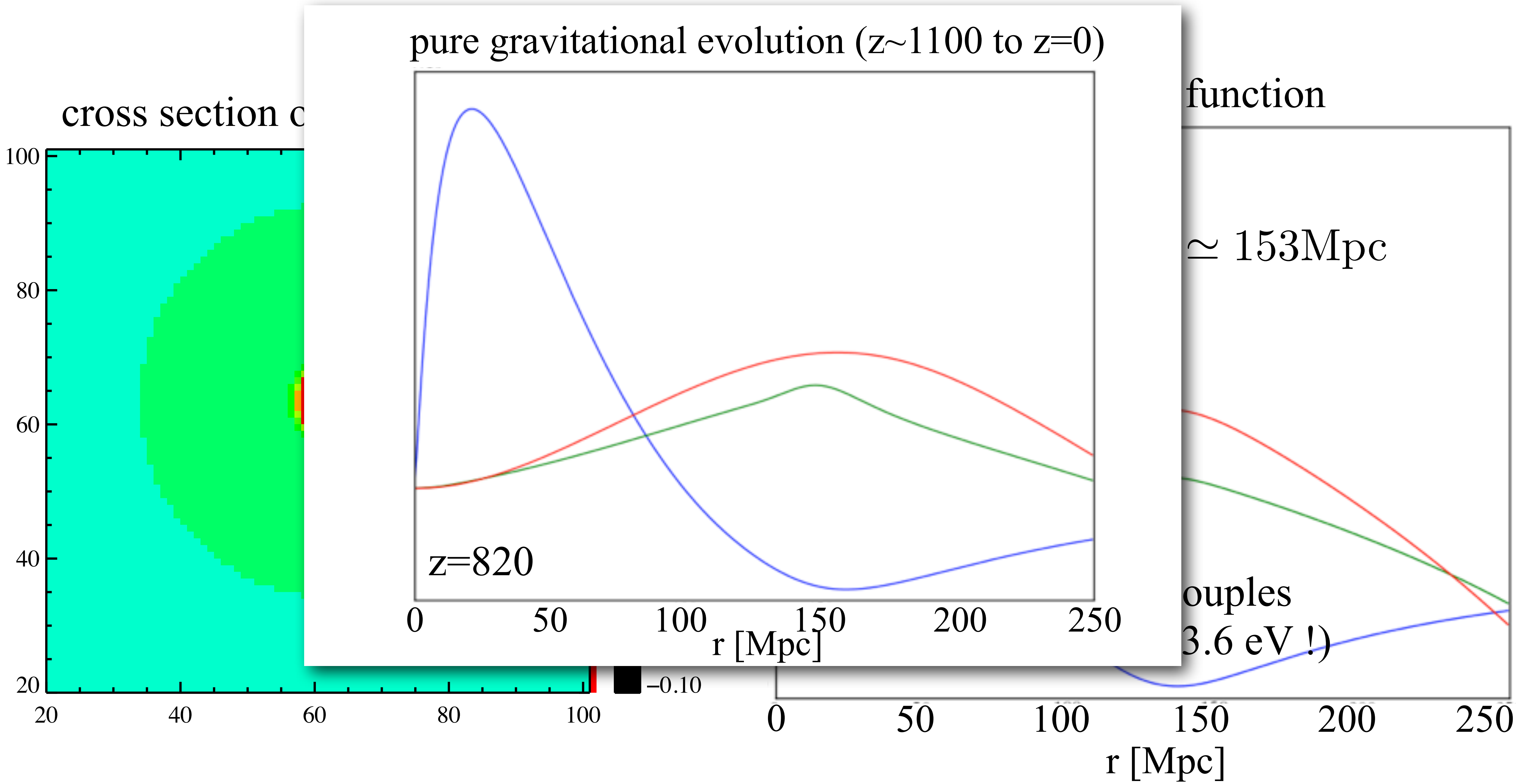

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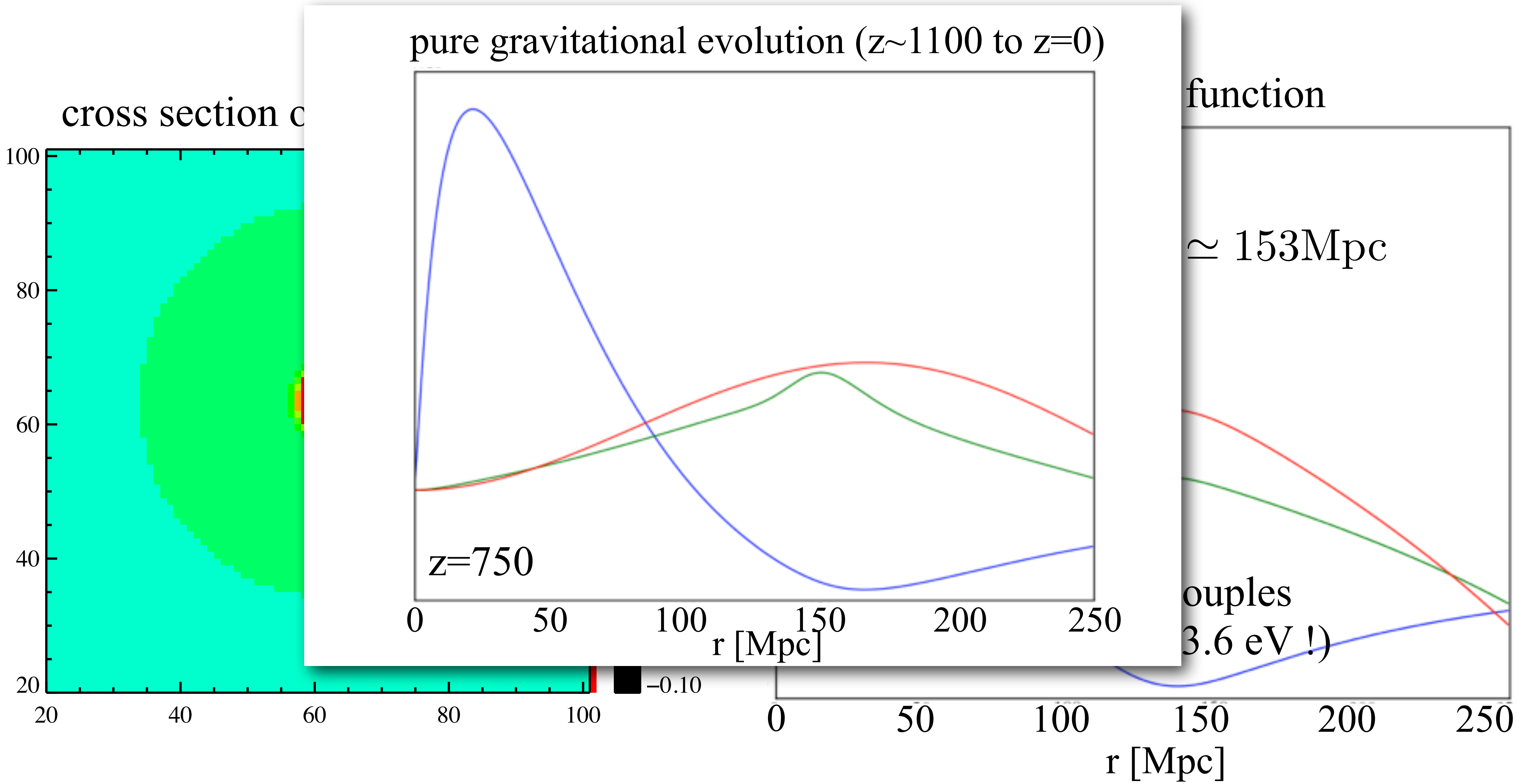

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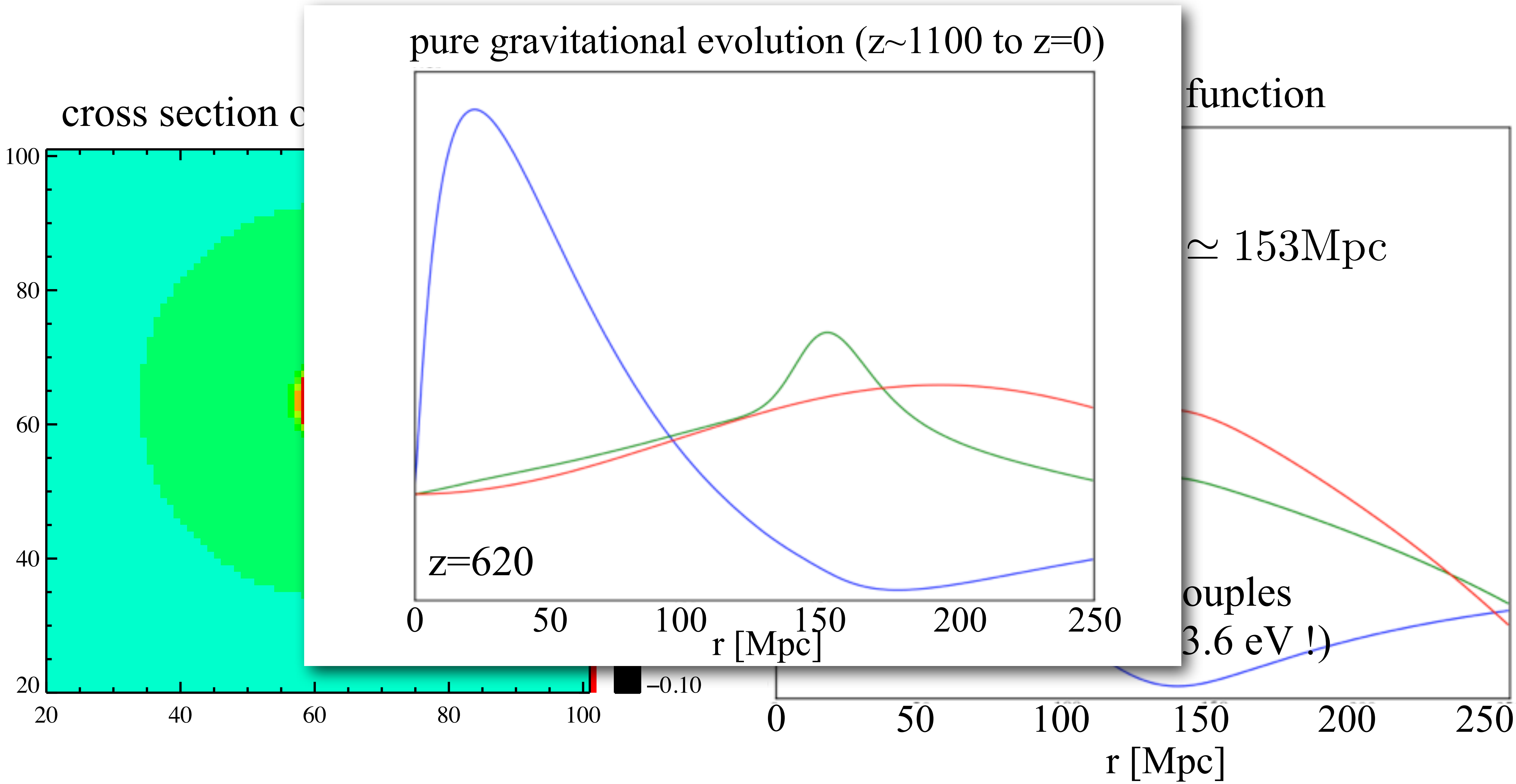

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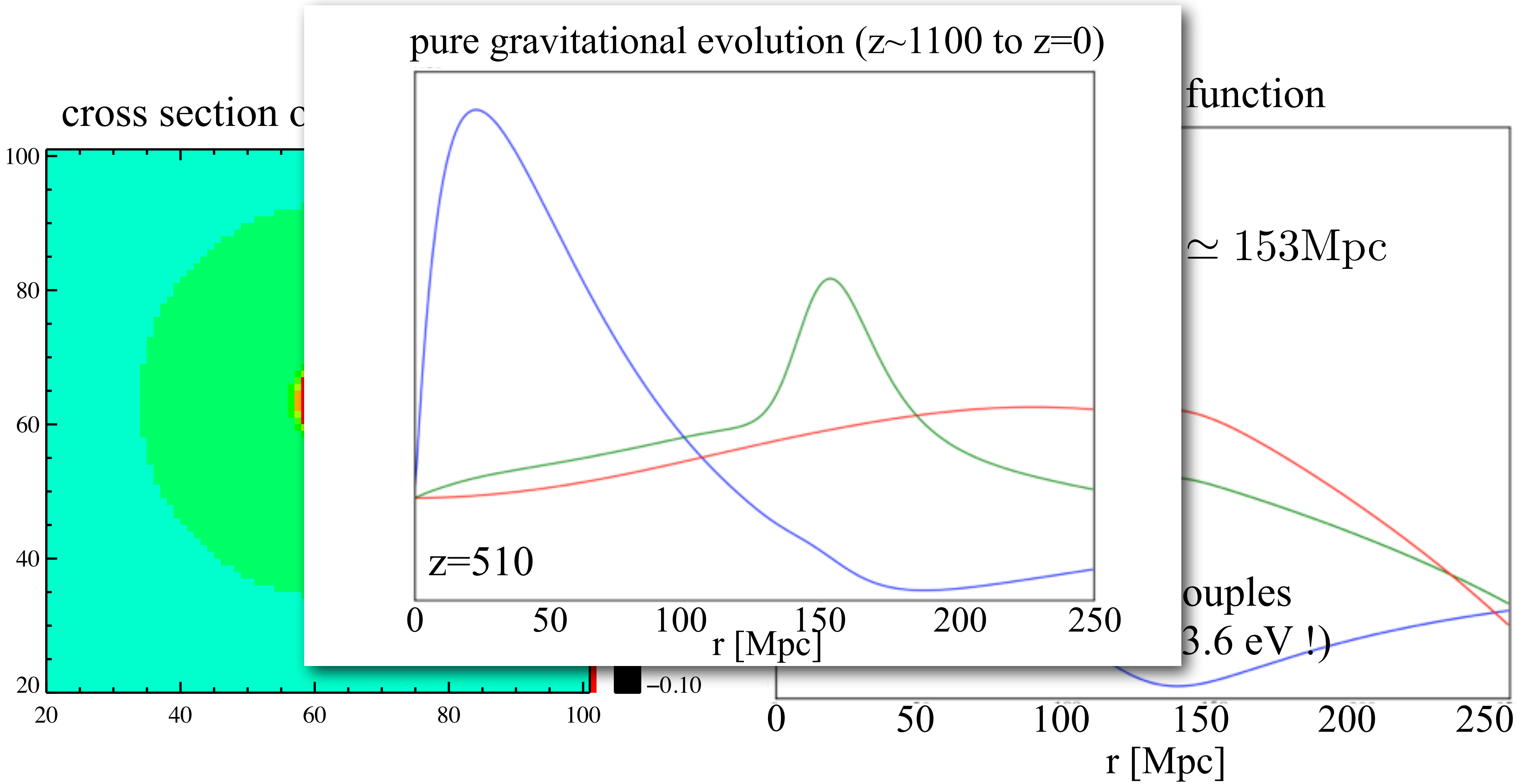

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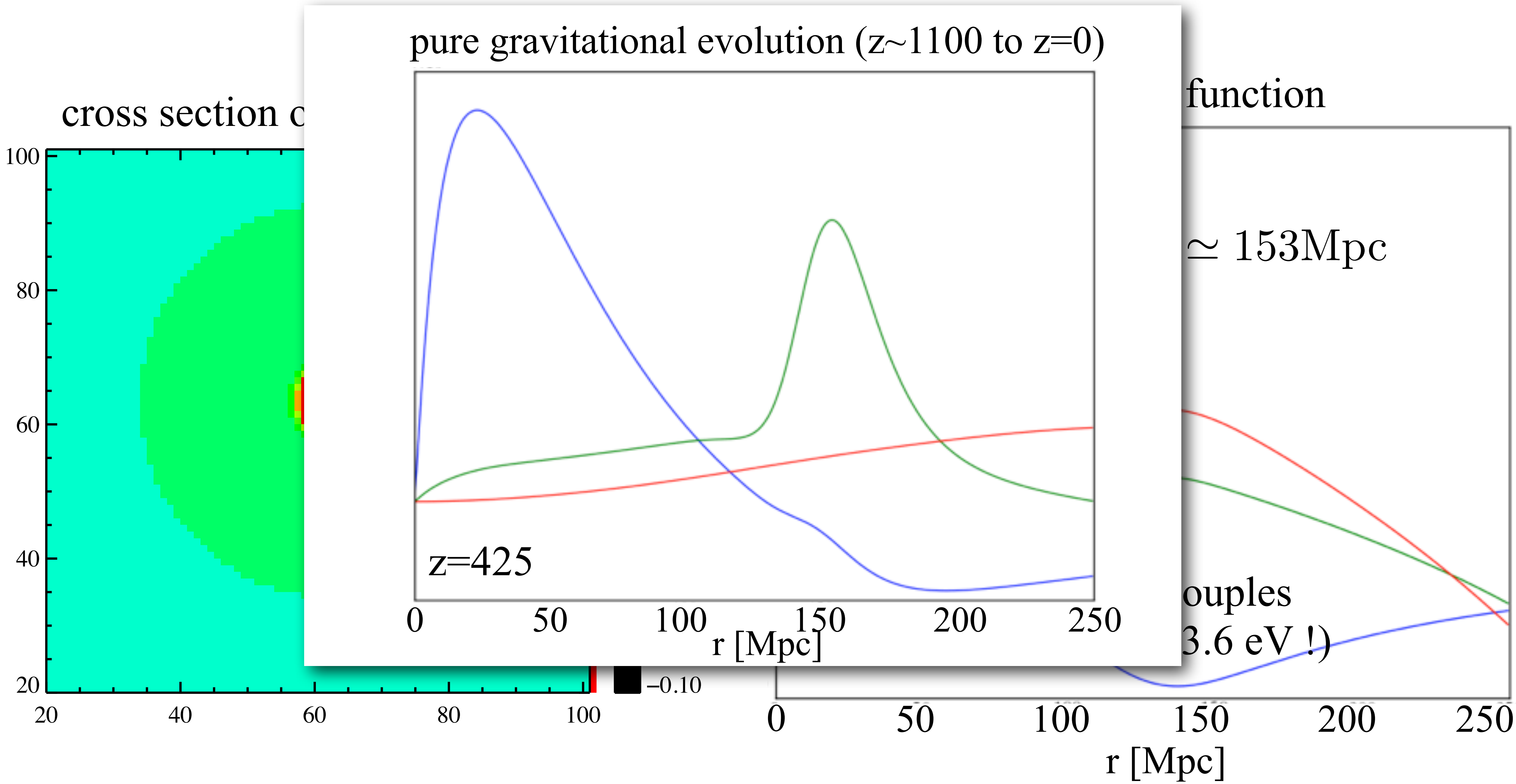

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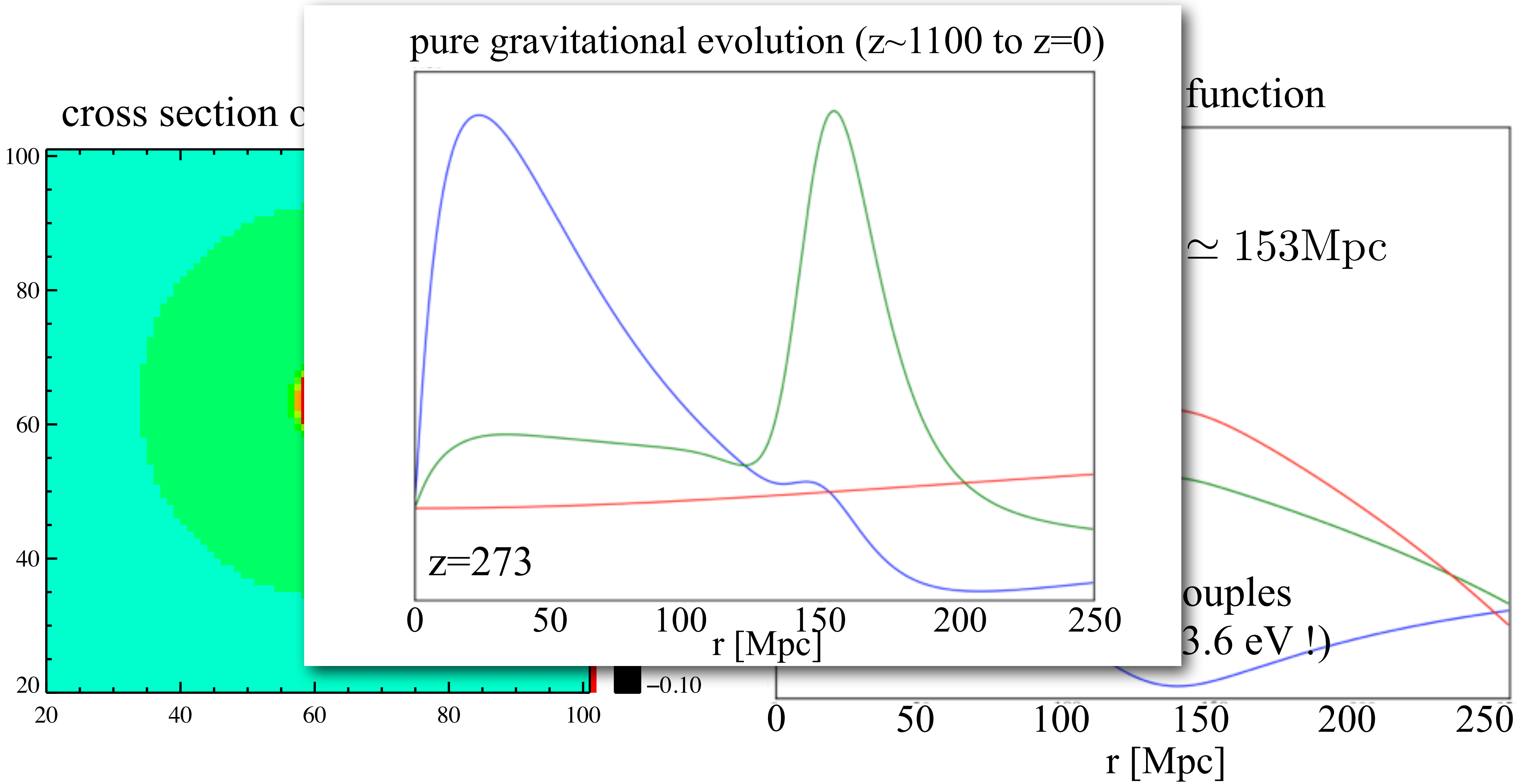

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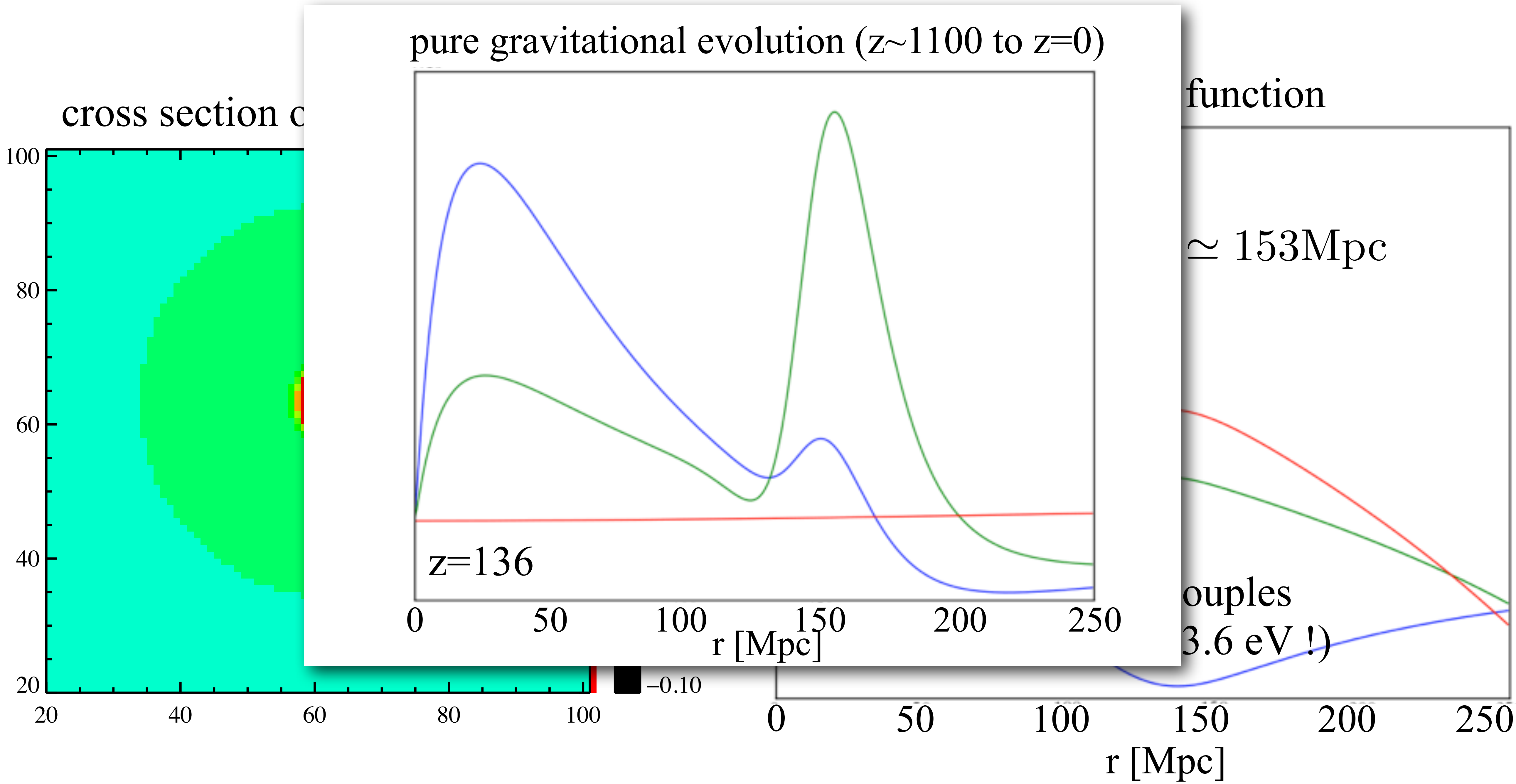

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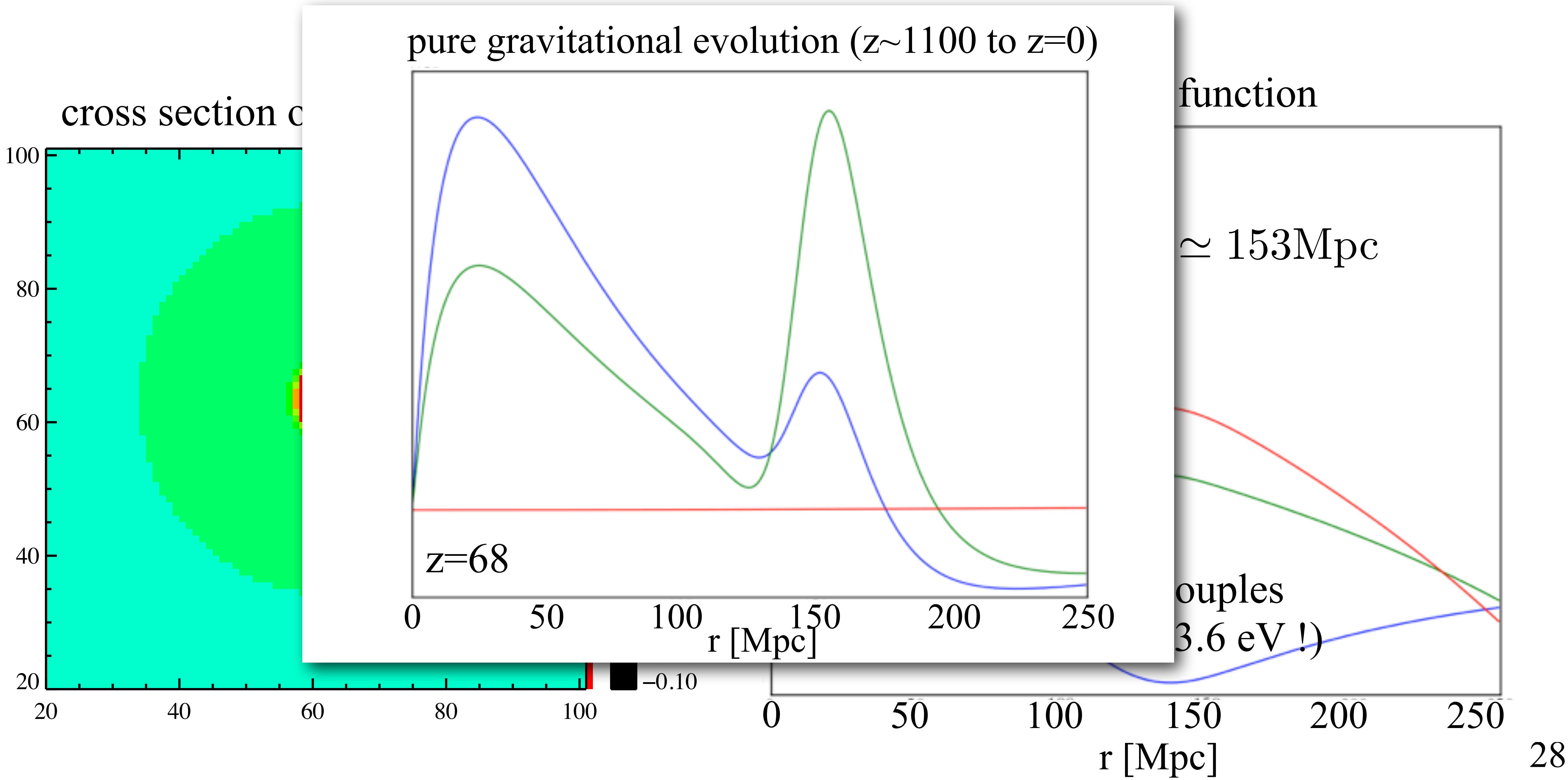

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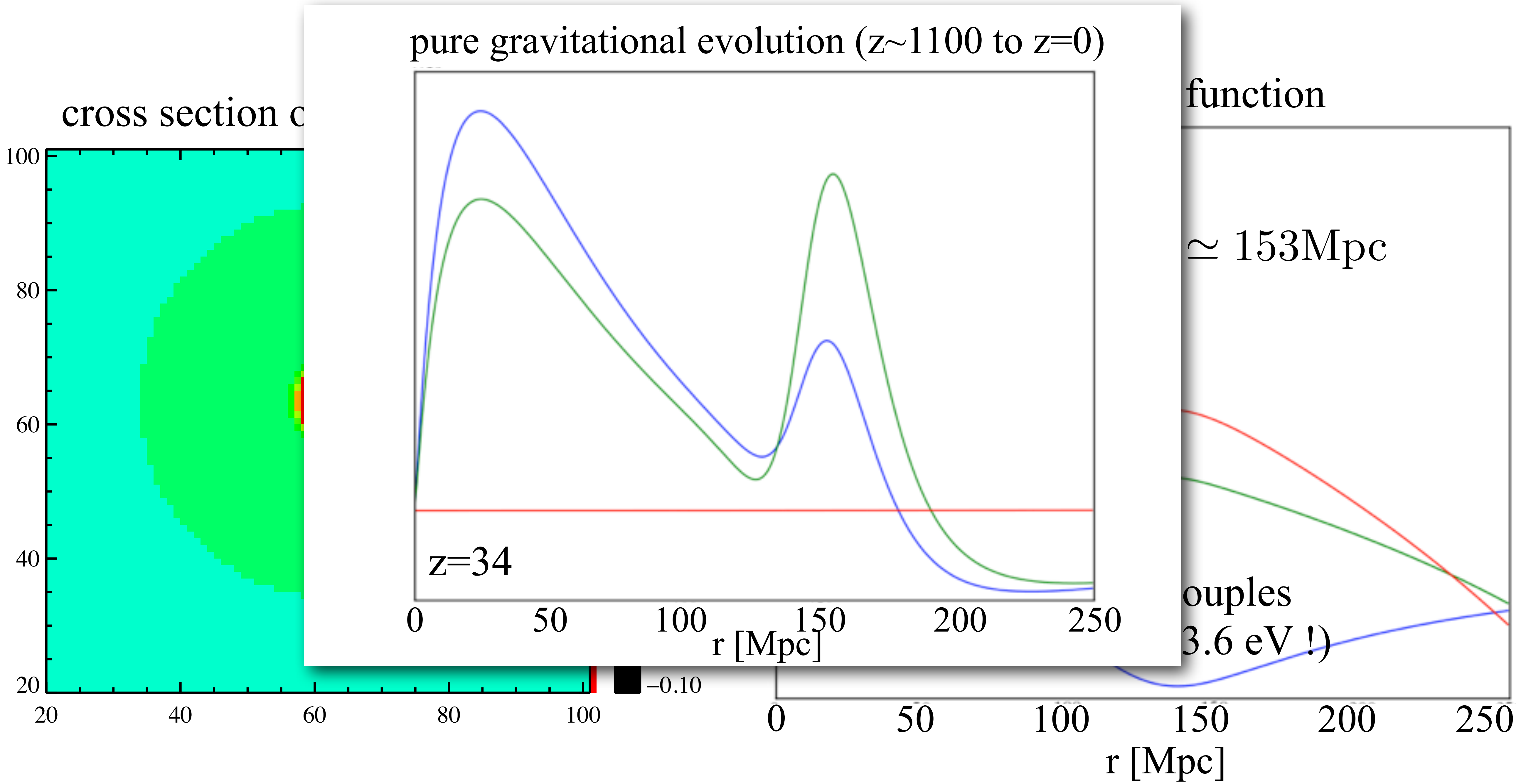

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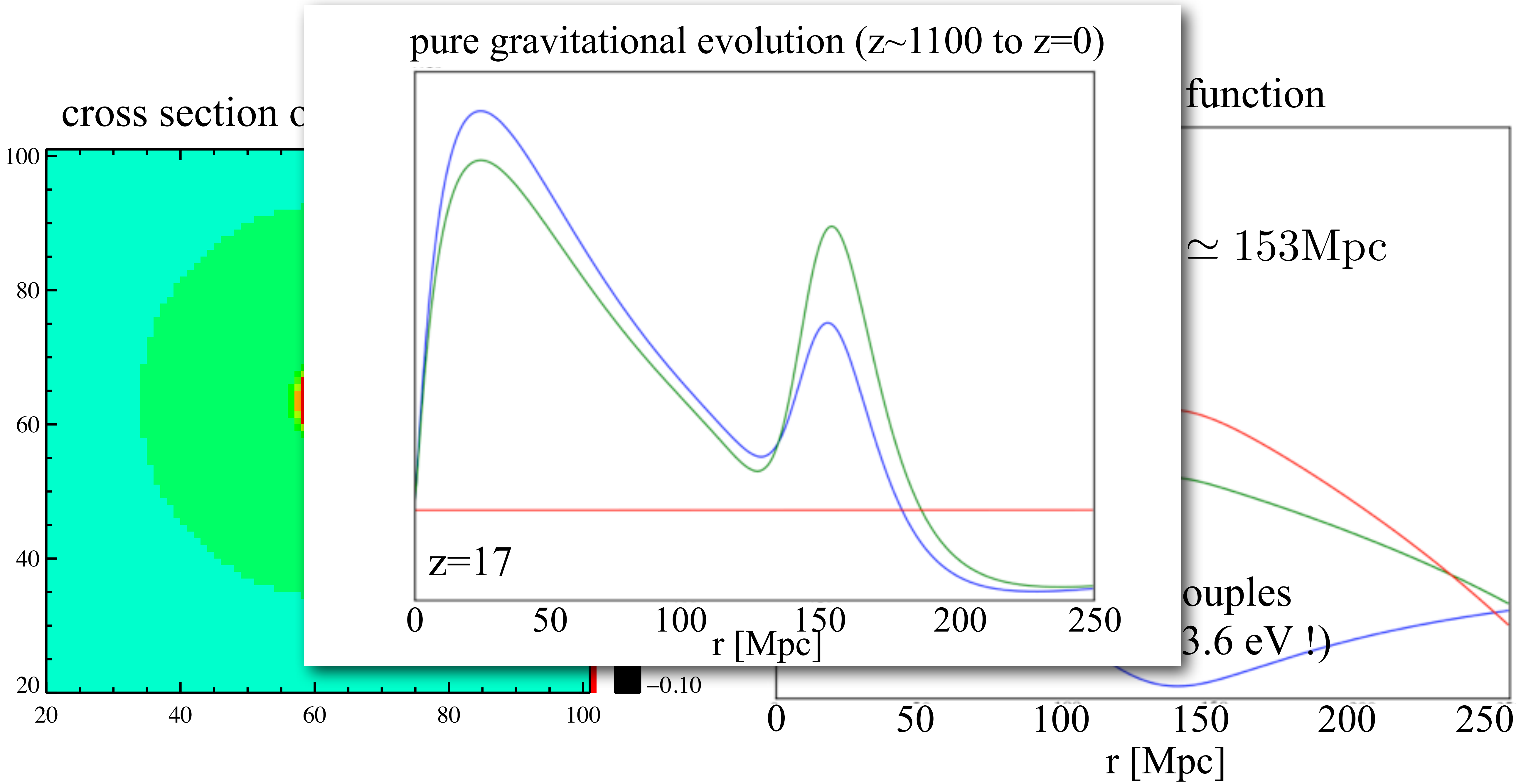

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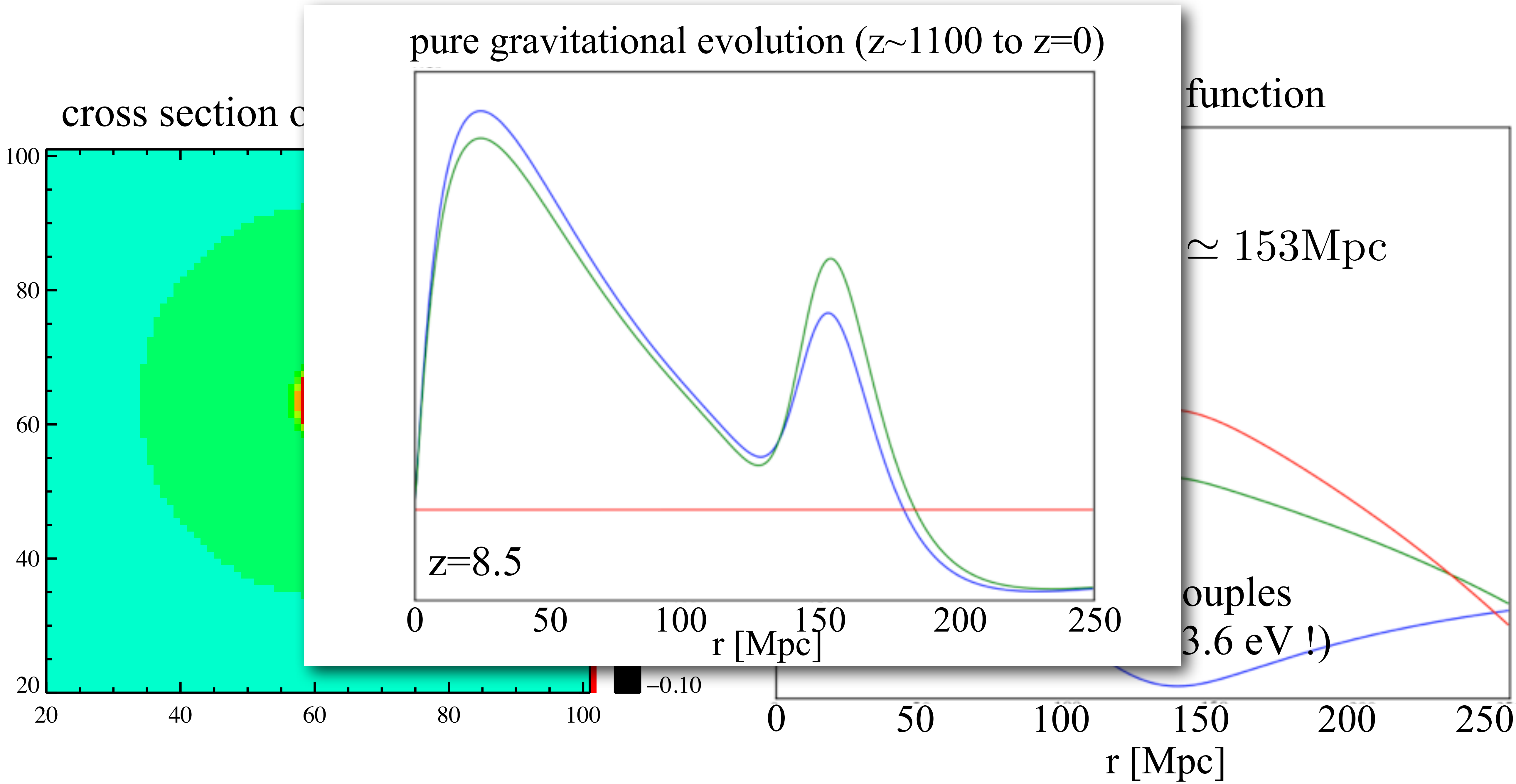

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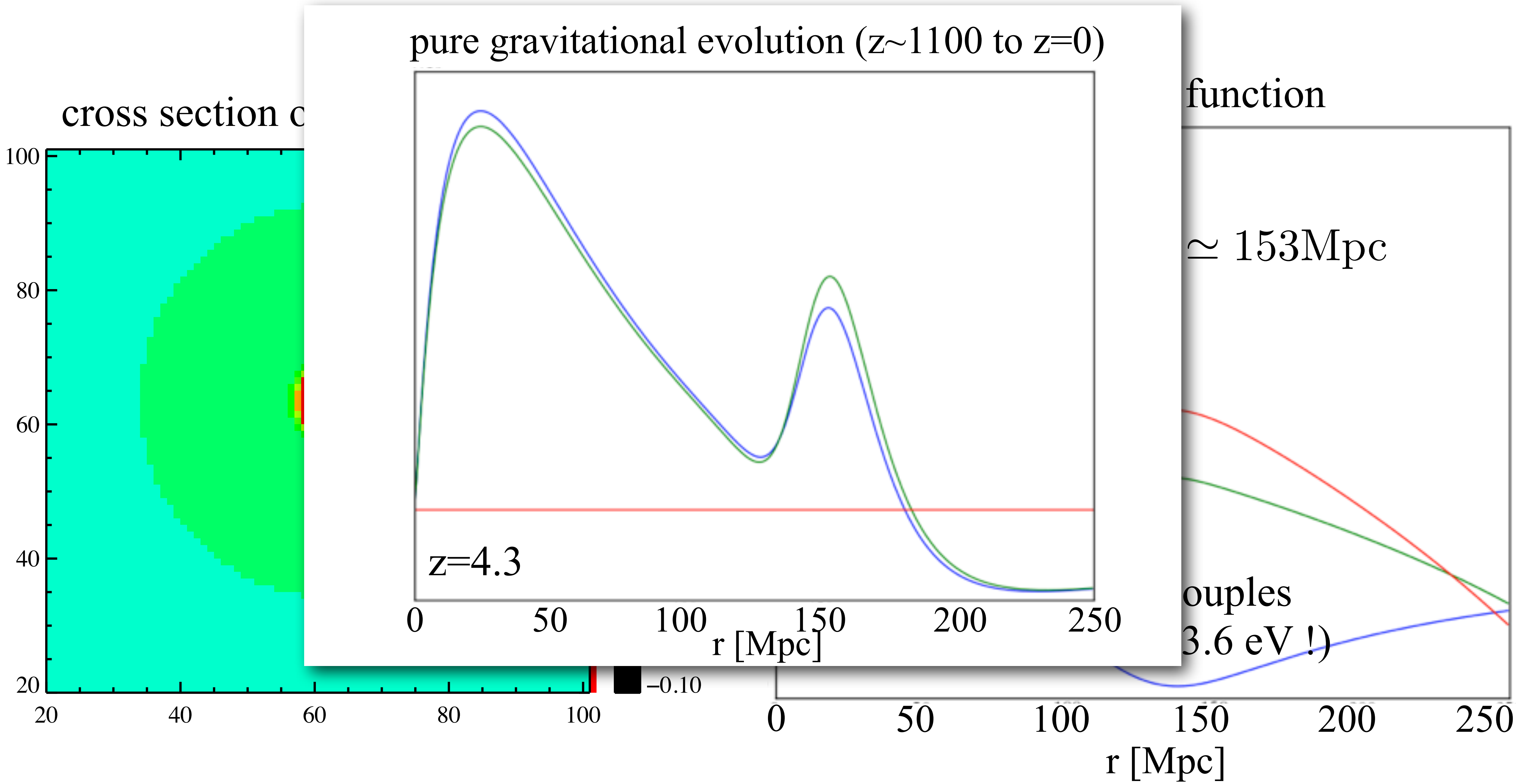

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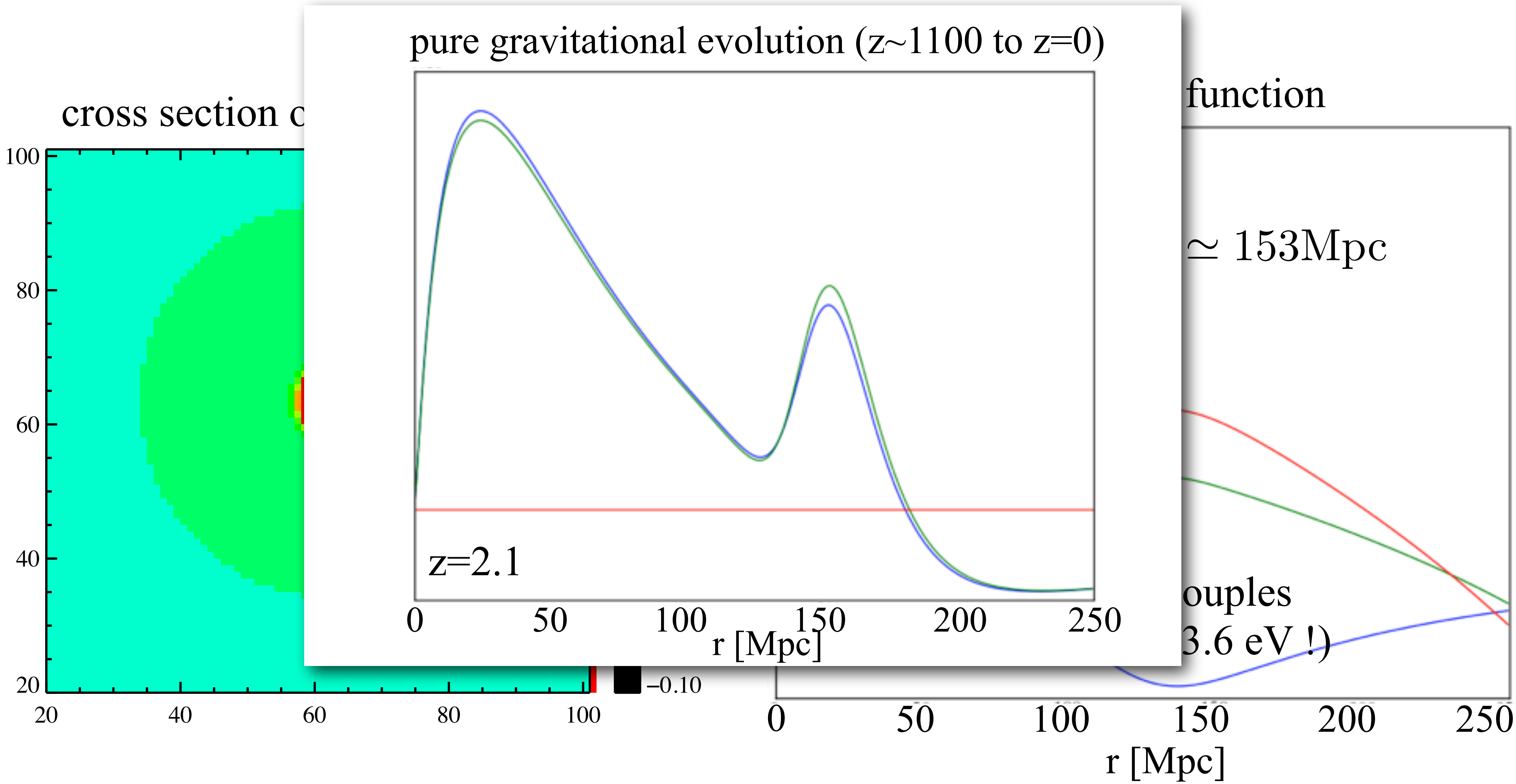

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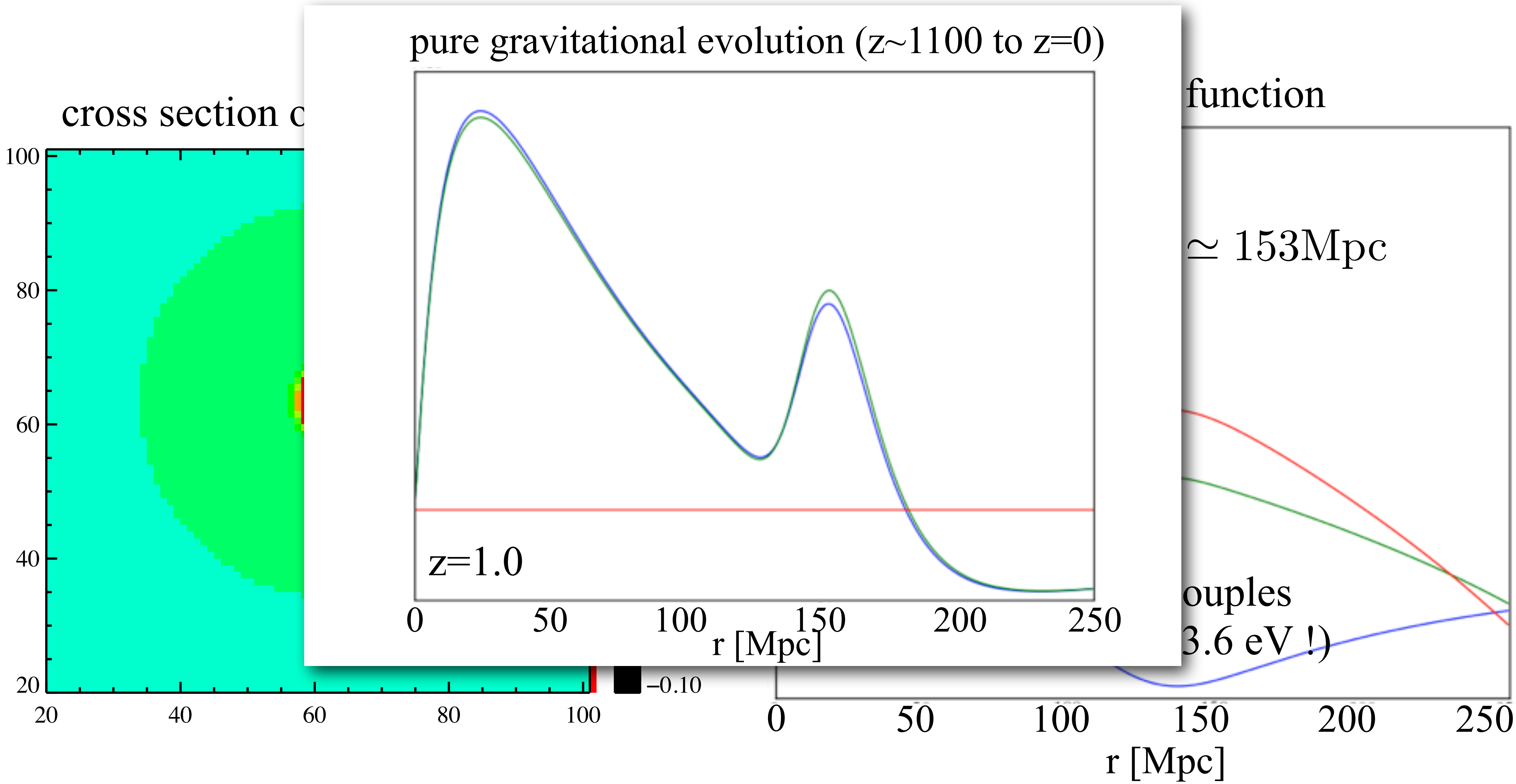

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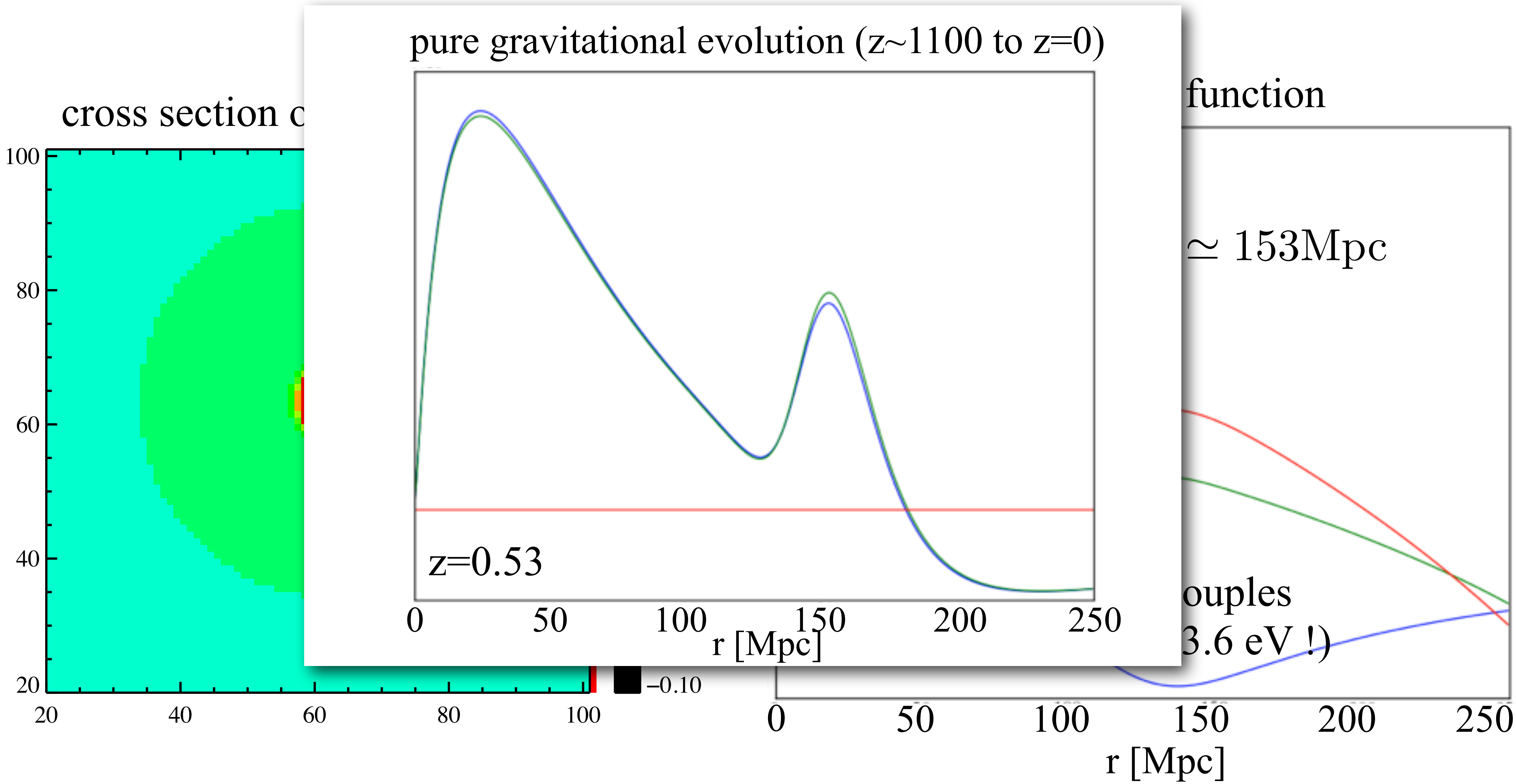

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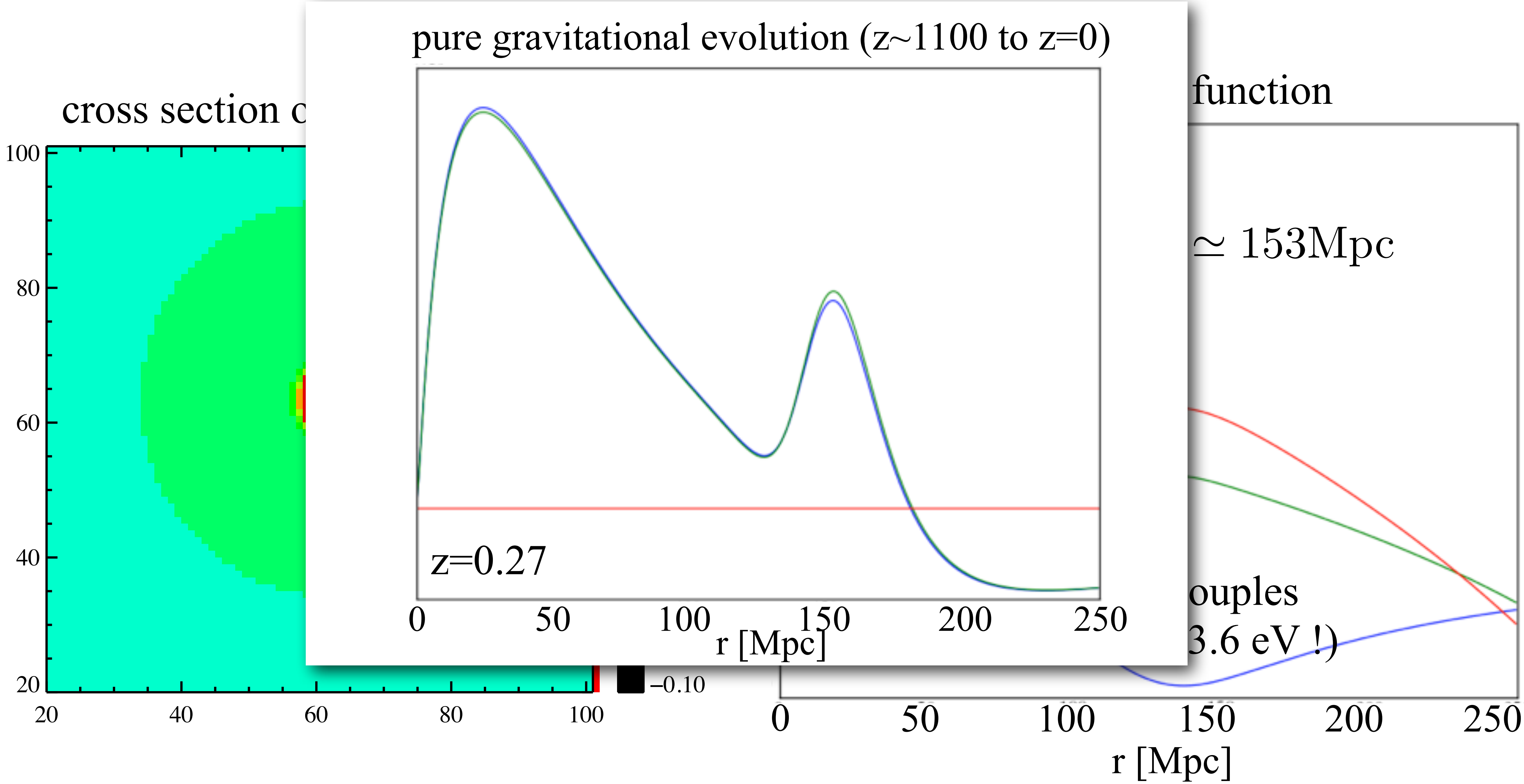

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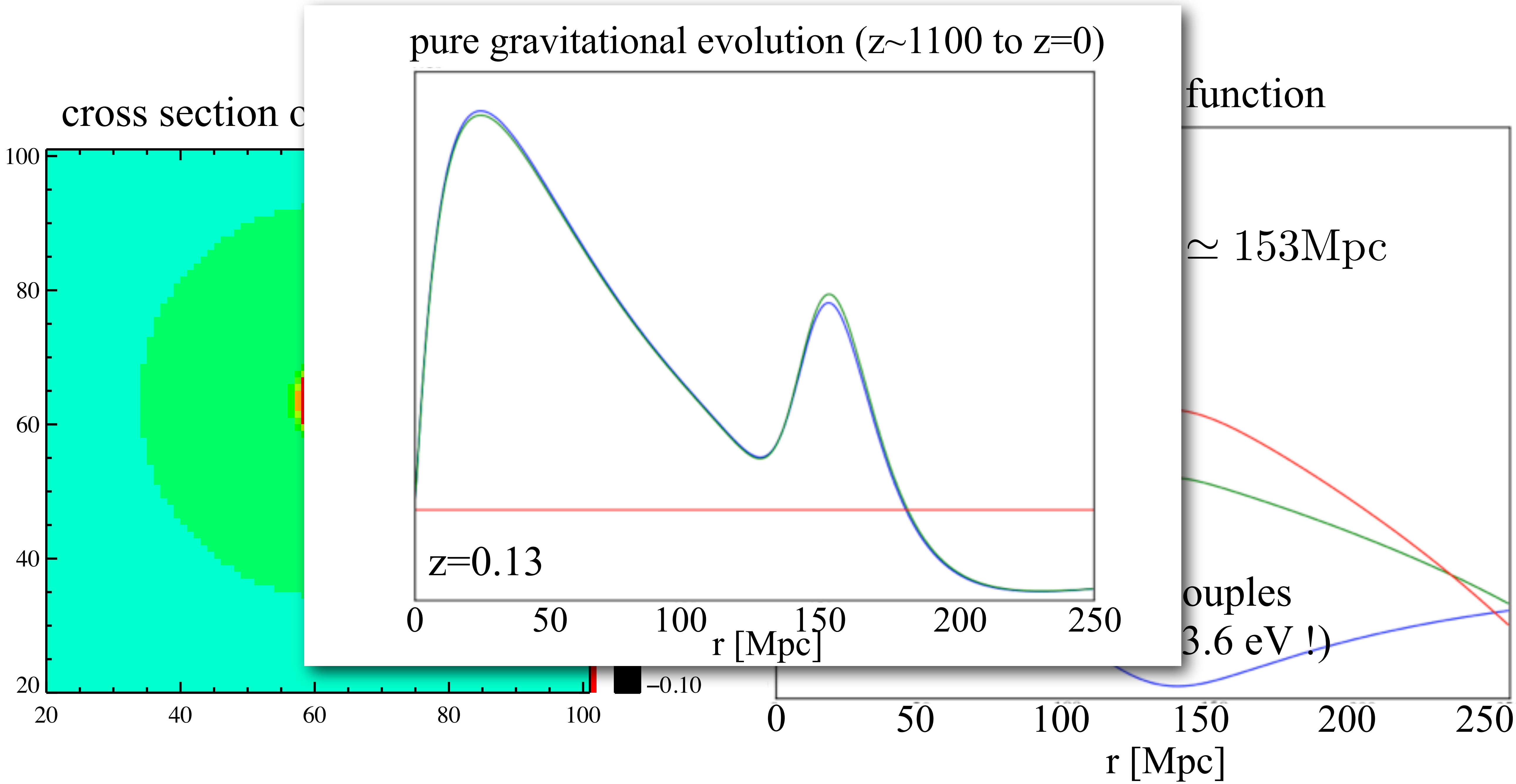

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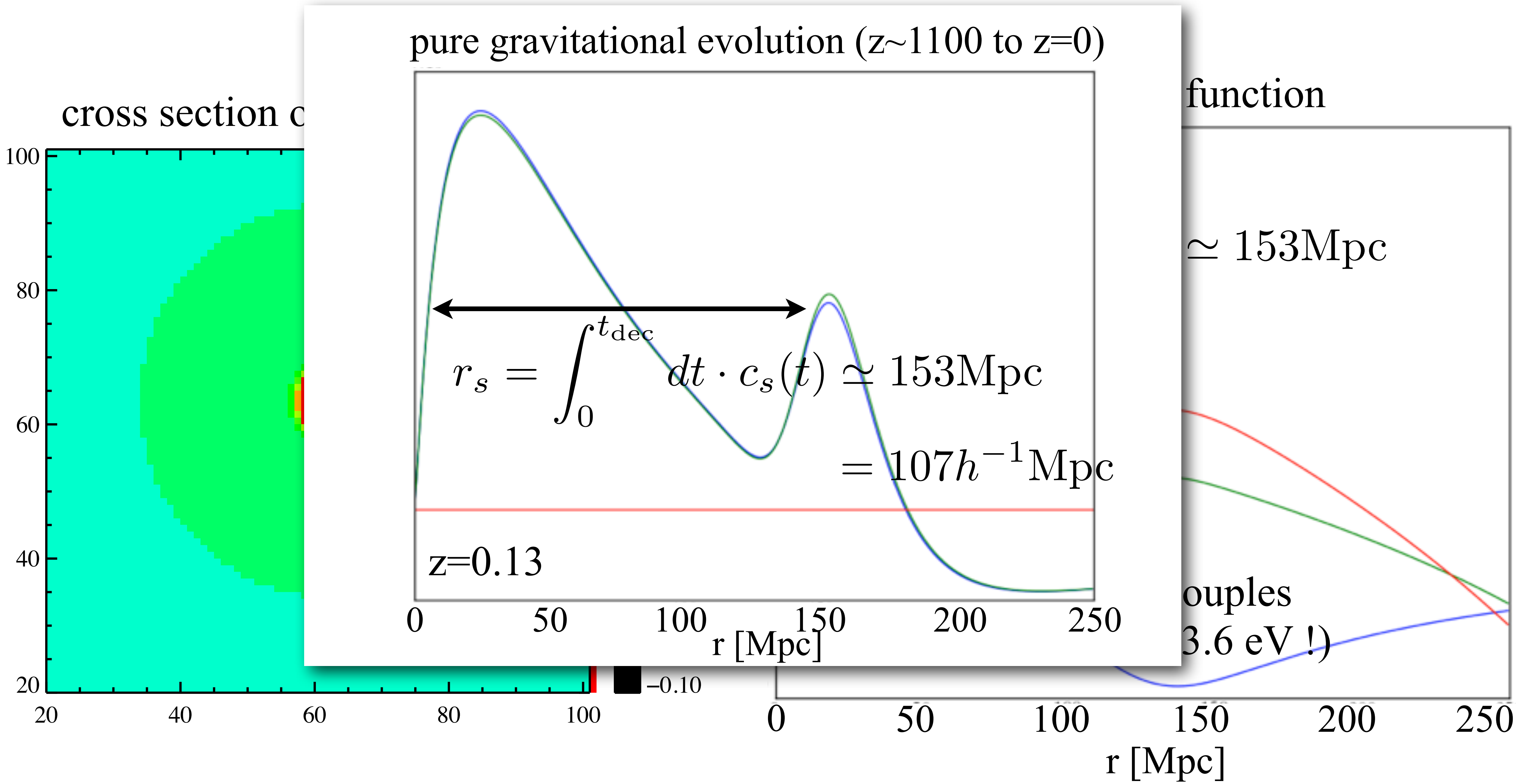
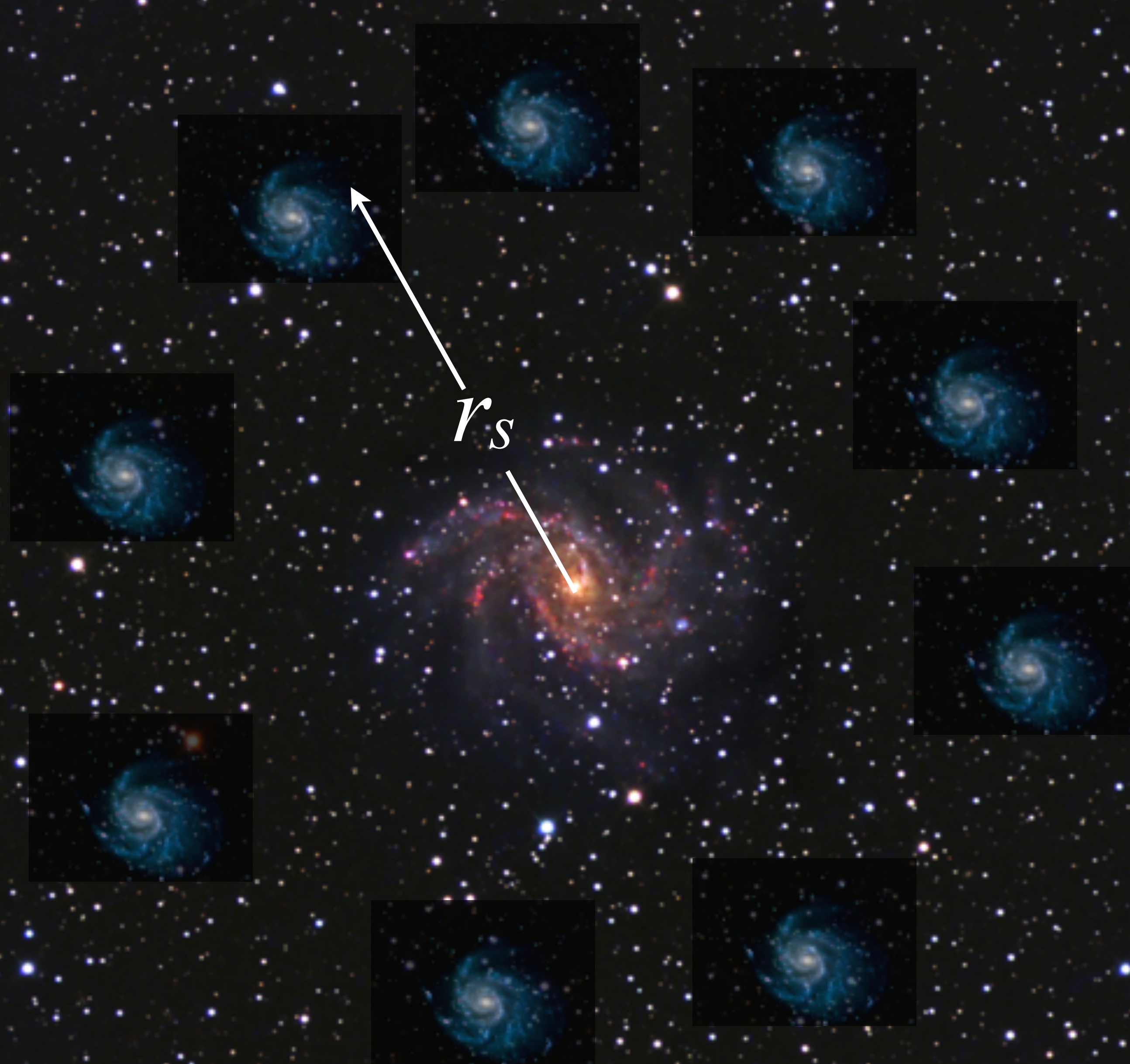


A pictorial way to do that...



$$H(z) = \frac{c\Delta z}{r_s}$$

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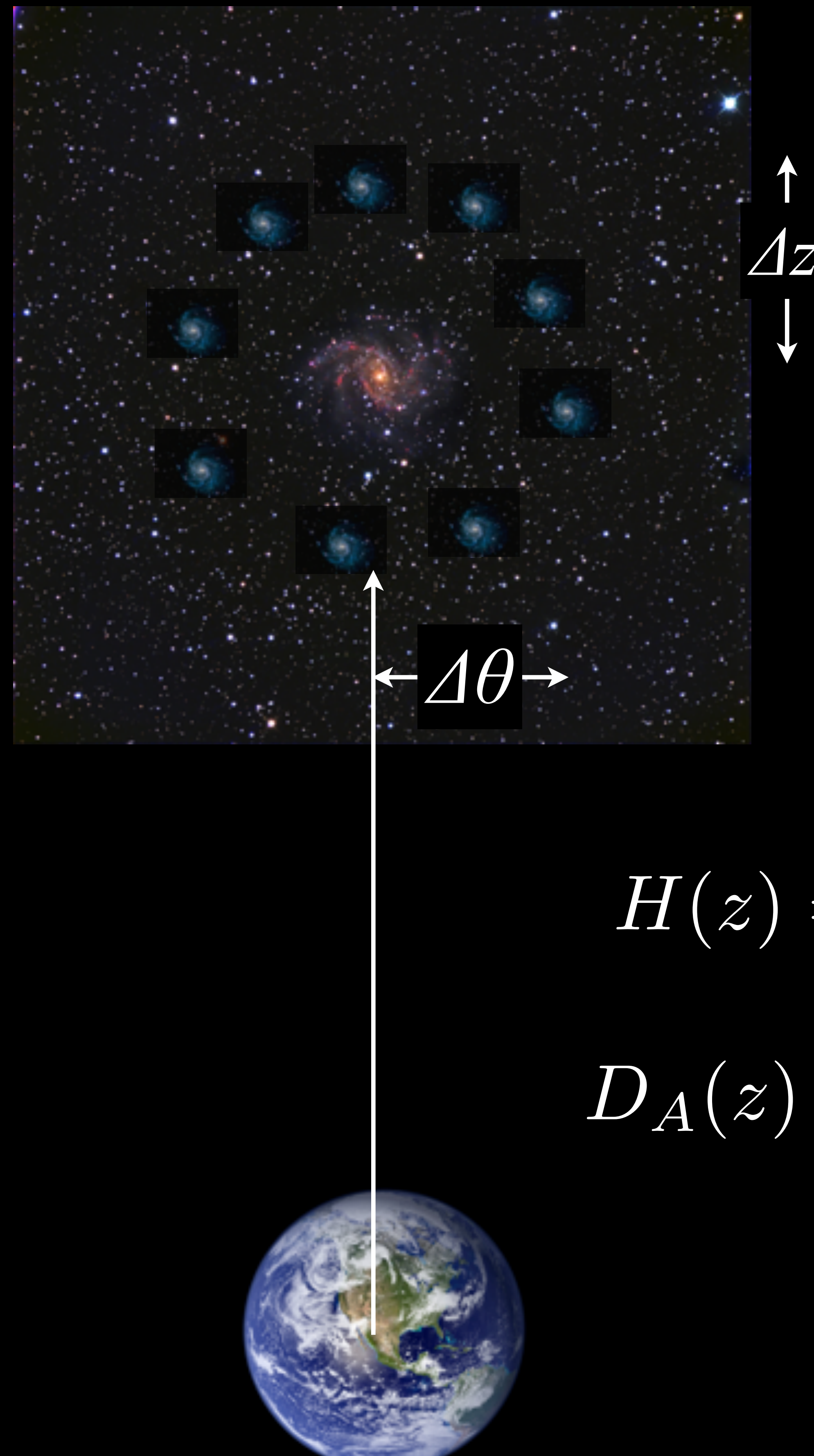
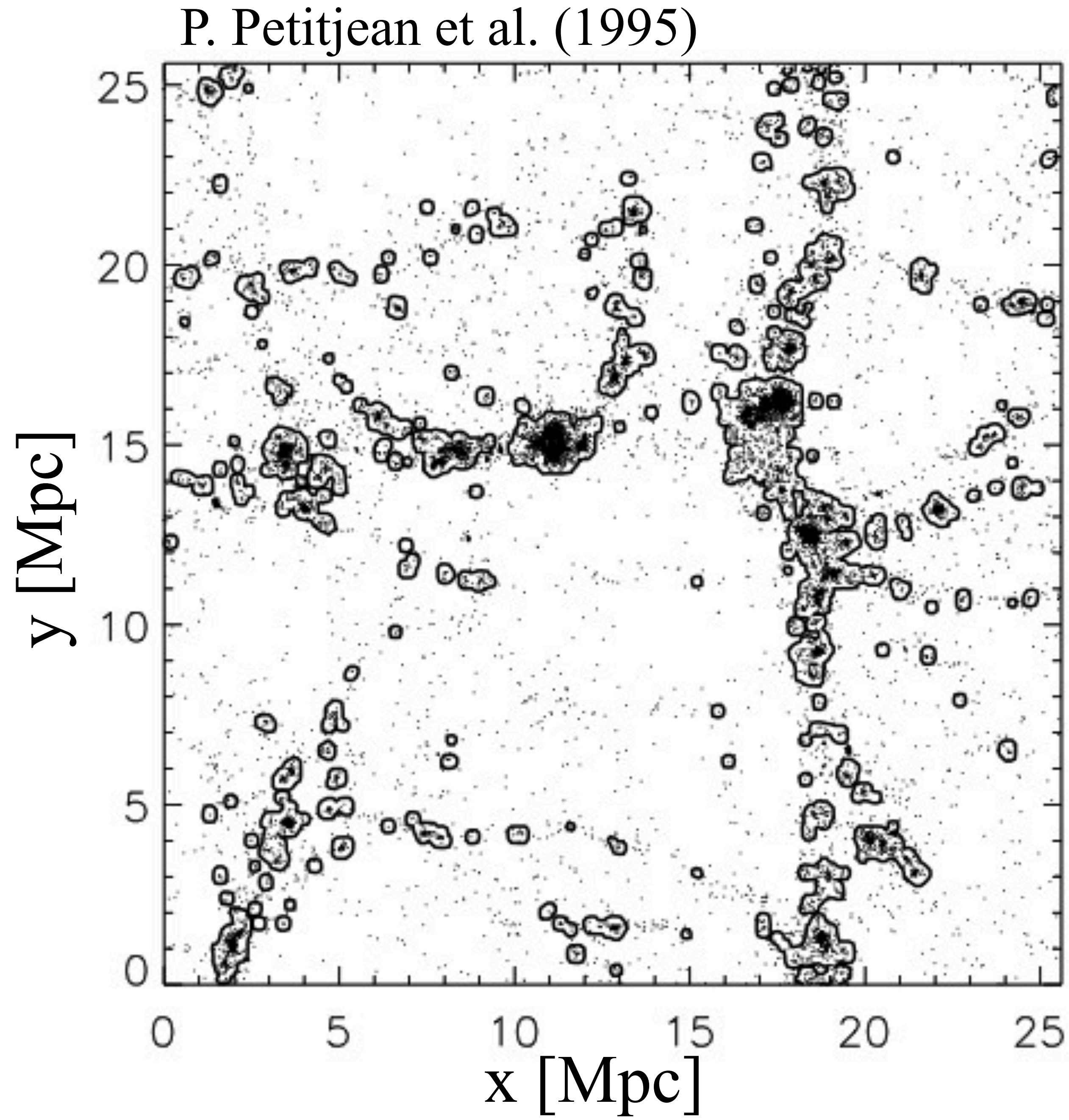


$$H(z) = \frac{c\Delta z}{r_s}$$ hubble rate

$$D_A(z) = \frac{r_s}{\Delta\theta}$$ angular diameter distance

Tracers of matter

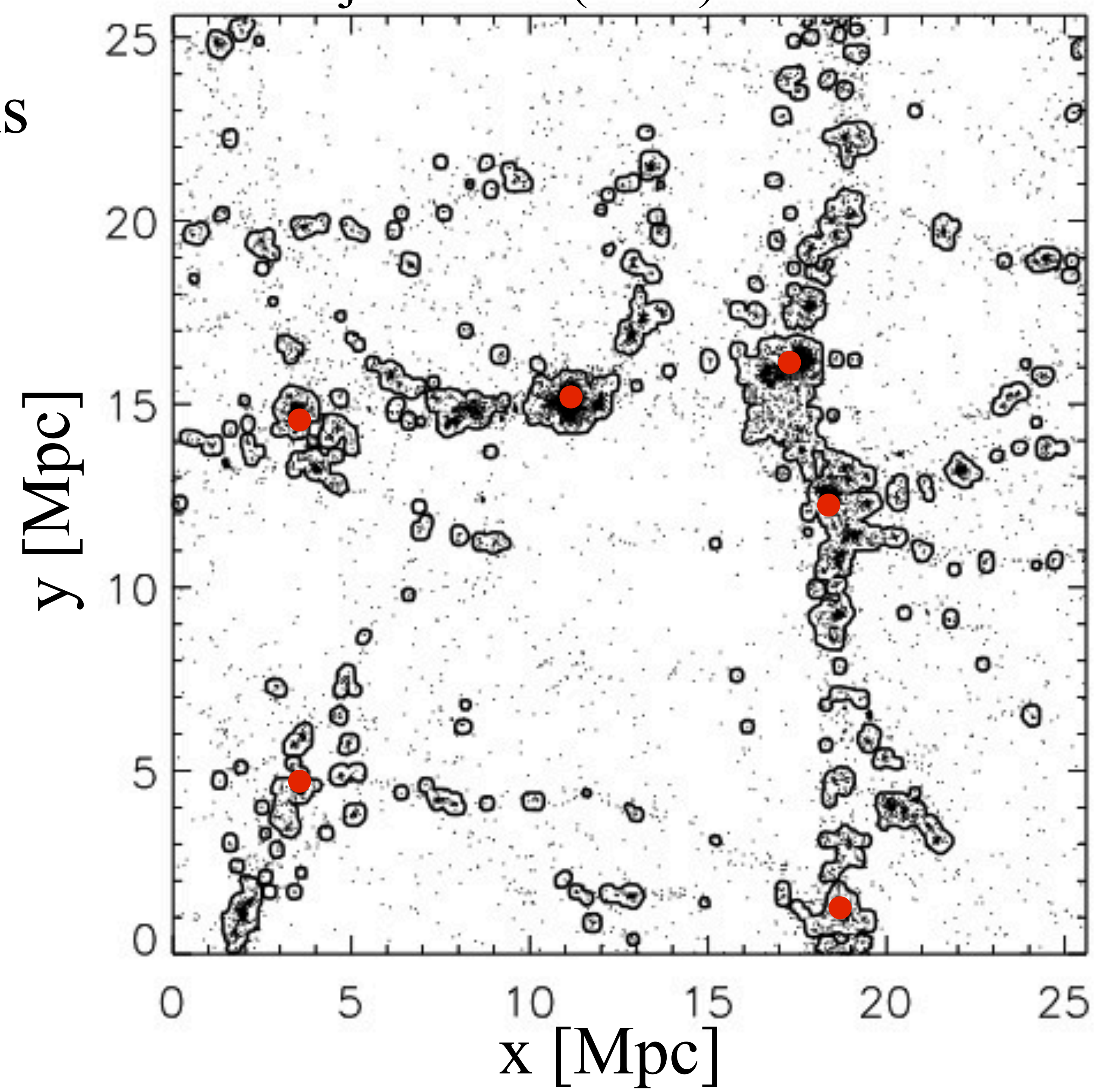
Galaxies:



Tracers of matter

Galaxies:
- trace high overdensity regions O(200)
- formation hard to simulate
- linear bias model: $\delta_{gal} = b\, \delta_{DM}$

P. Petitjean et al. (1995)



Tracers of matter

Galaxies:

- trace high overdensity regions O(200)
- formation hard to simulate
- linear bias model: $\delta_{gal} = b\, \delta_{DM}$, $b \sim O(1)$
- $z \sim$ 0-1

Lyα forest:

- trace low overdensity regions
- non-linear tracer:
$$f_\lambda = \exp\left[-\tau(z)\right]$$
- full hydro simulation possible (e.g. McDonald 2003):
- z ~ 2.5

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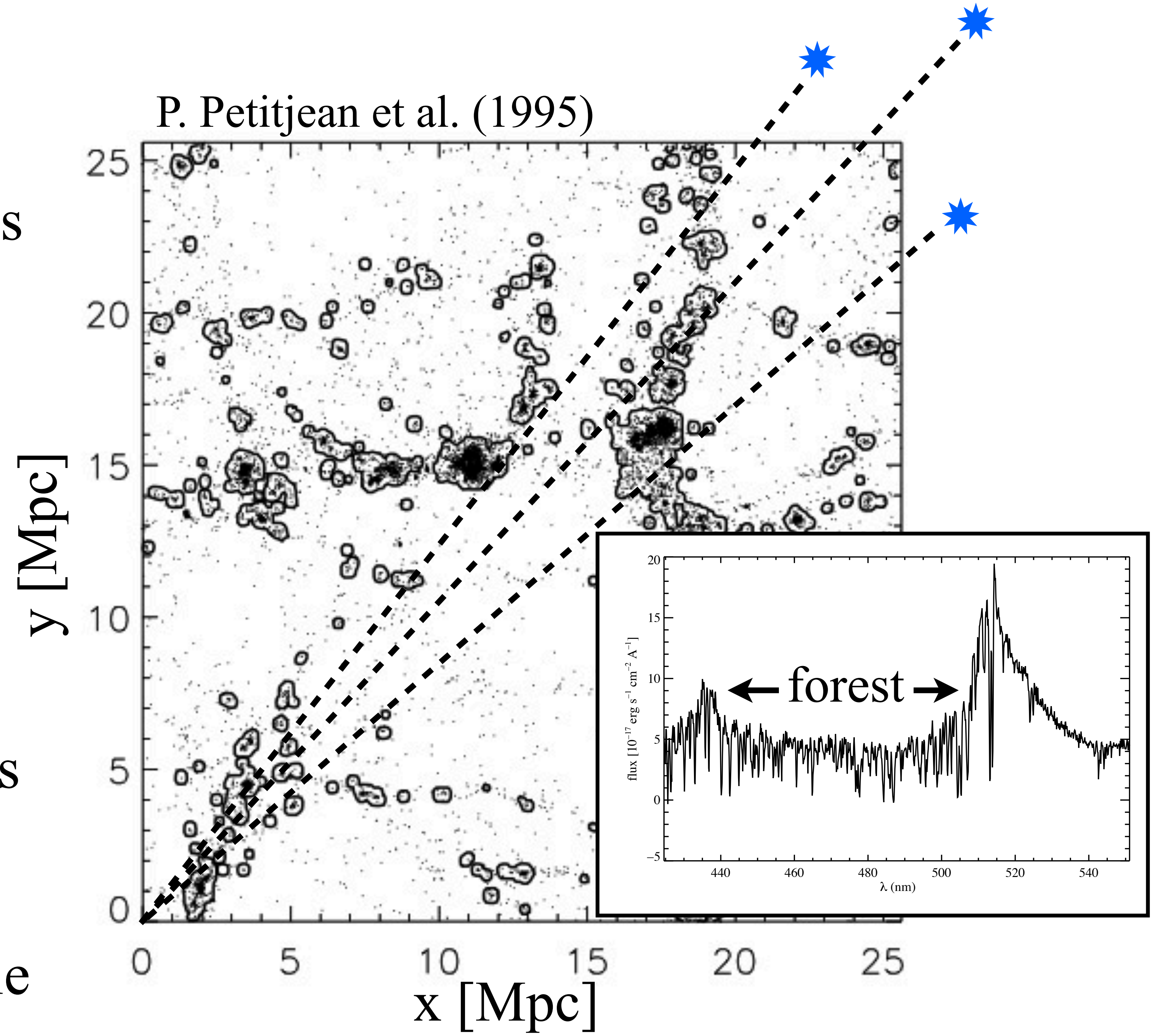


$$P_f(k, \mu_k) = b^2(1 + \beta\mu^2)^2 P_L(k)$$

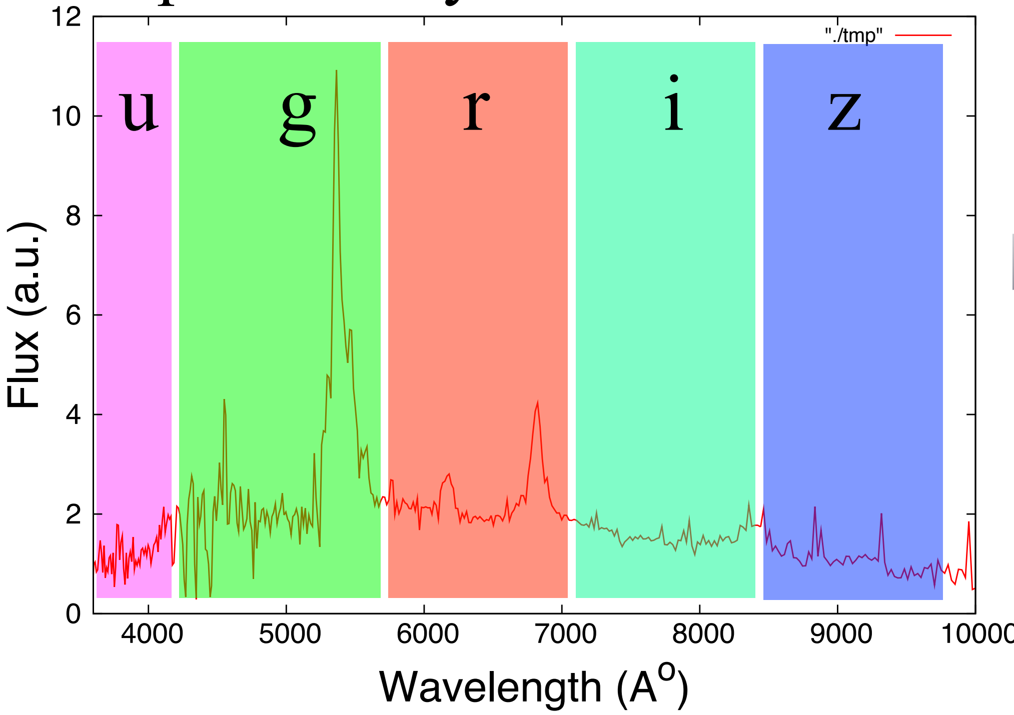
$b \sim 0.16$, $\beta \sim 1.05$

The Baryon Acoustic Oscillations Spectroscopic Survey BOSS

- one of the four surveys that share the SDSS 2.4m telescope between 2009-2014
- BOSS will observe 1/4 of the sky (10,000 deg^2)
- spectra of 1,600,000 galaxies and 150,000 quasars
- goal: to determine the position of the BAO peak with a precision of 1% at z~0.6 and 1.5% at z~2.3
- best constraints on the equation of state of dark energy until the next generation of experiments

BOSS-data taking

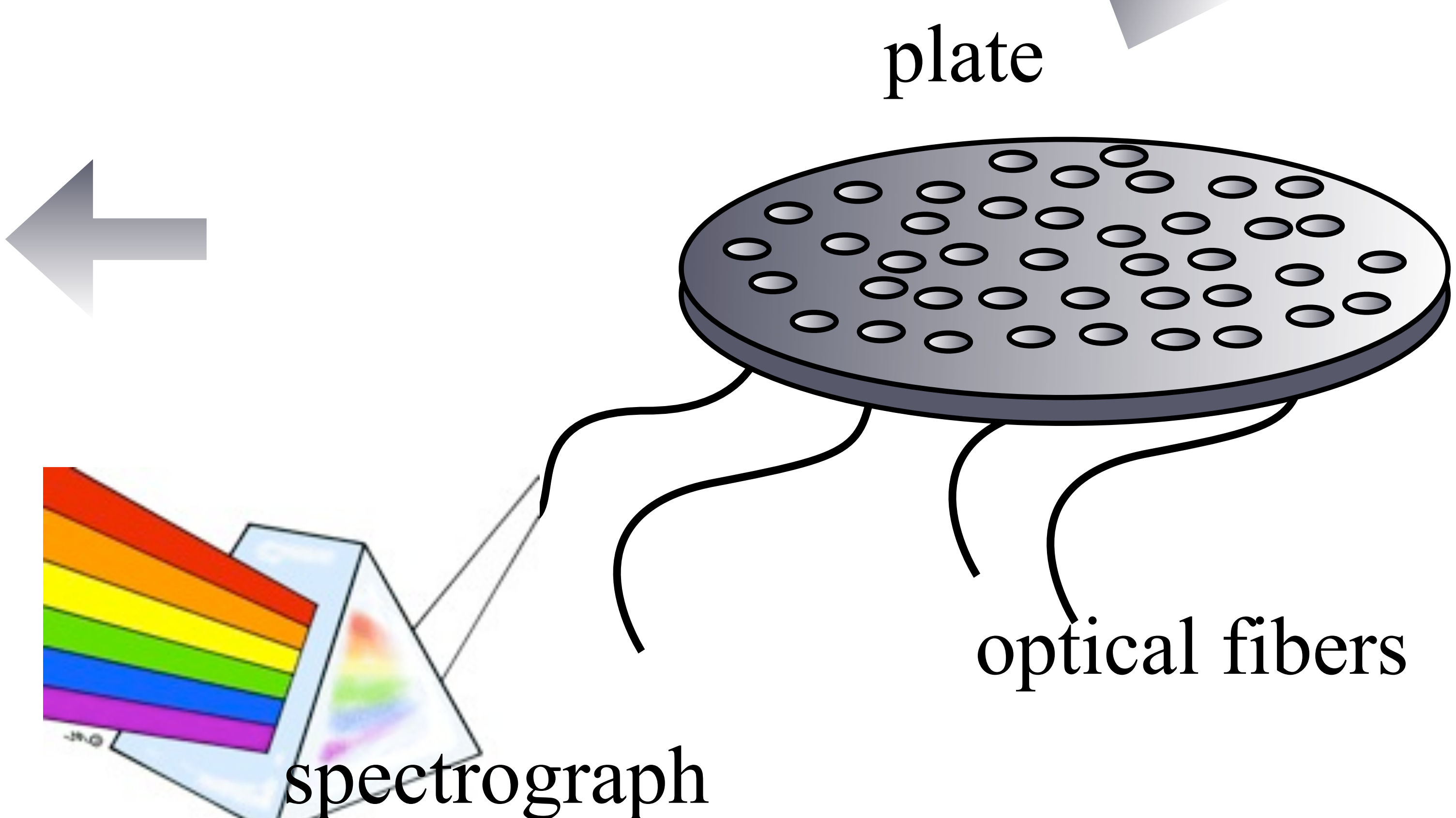
photometry from SDSS-II



target selection

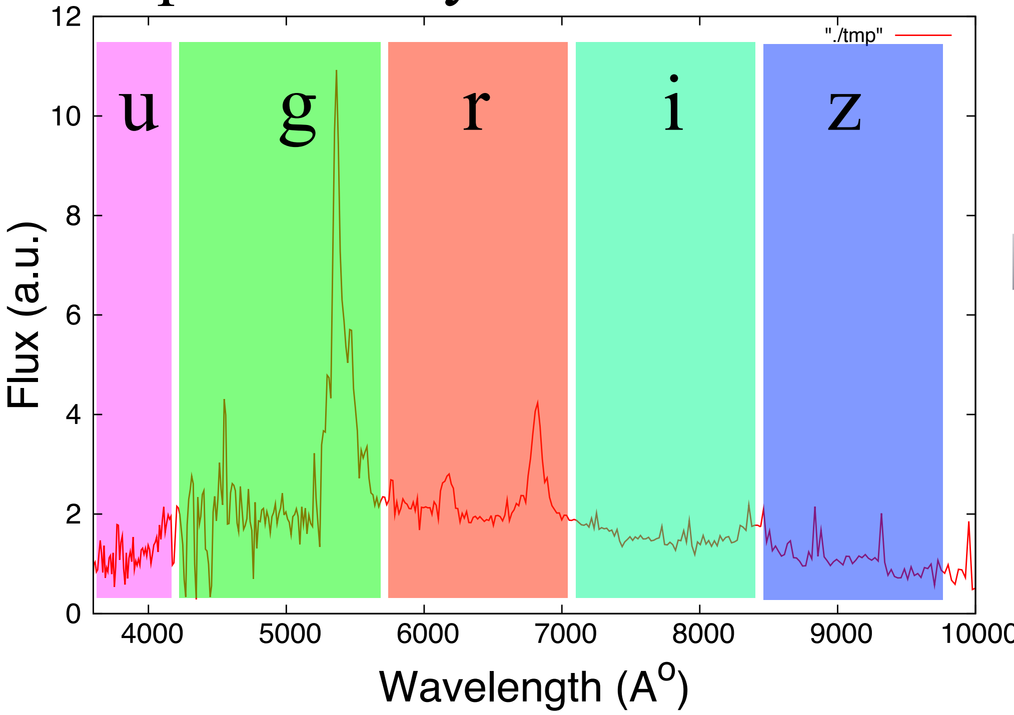
List of targets

SDSS J112253.51+005329.8
SDSSp J120441.73-002149.6
SDSSp J130348.94+002010.4
SDSSp J141205.78-010152.6
SDSSp J141315.36+000032.1
....



BOSS-data taking

photometry from SDSS-II

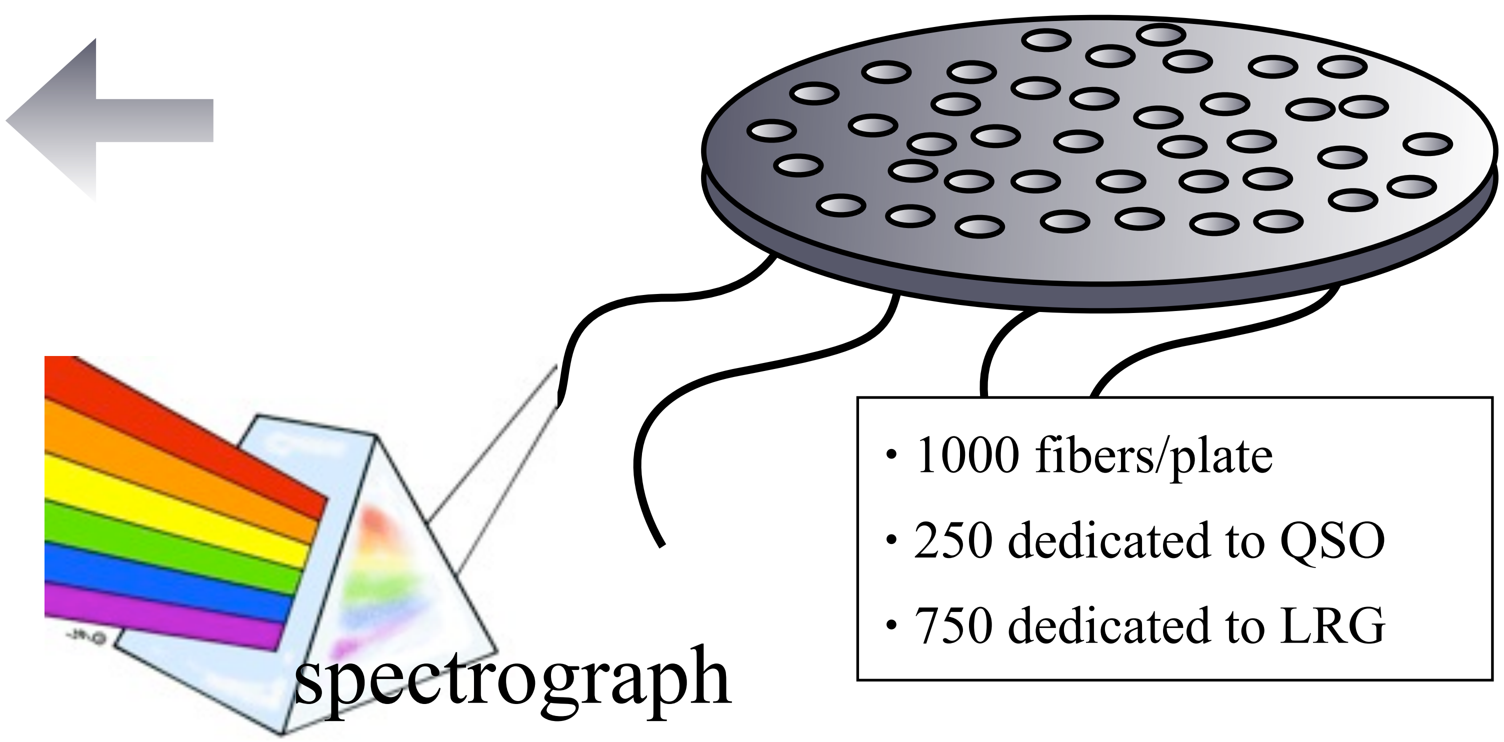


target selection

List of targets

SDSS J112253.51+005329.8
SDSSp J120441.73-002149.6
SDSSp J130348.94+002010.4
SDSSp J141205.78-010152.6
SDSSp J141315.36+000032.1
....

plate



BOSS-data taking

photometry from SDSS-II

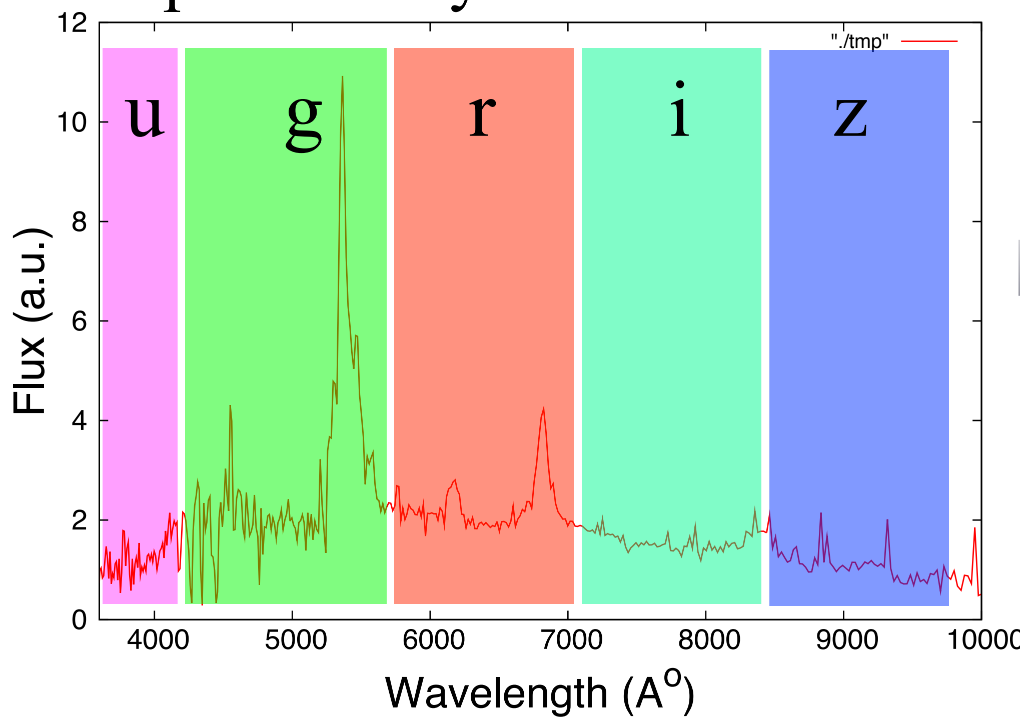


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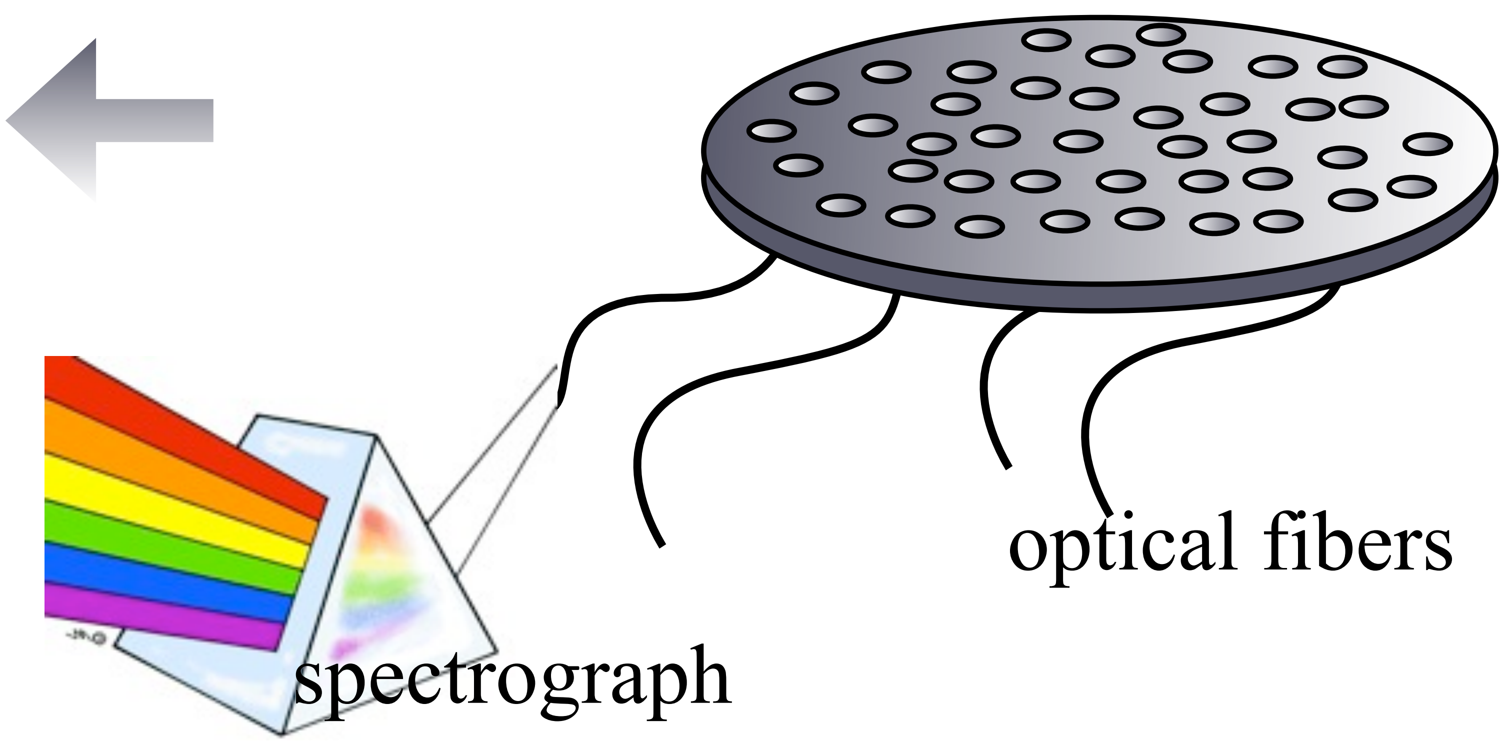
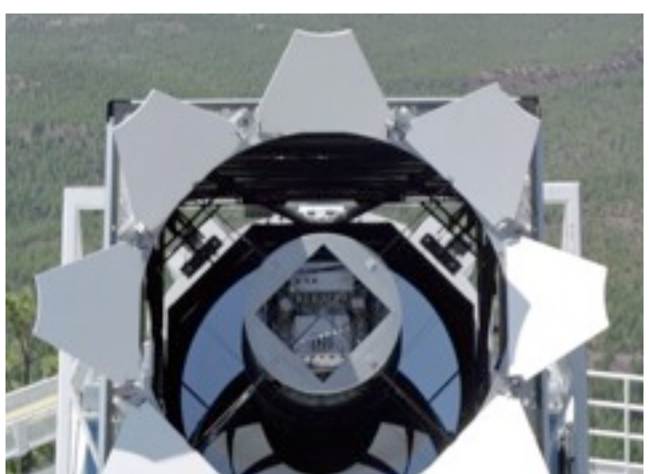
plate



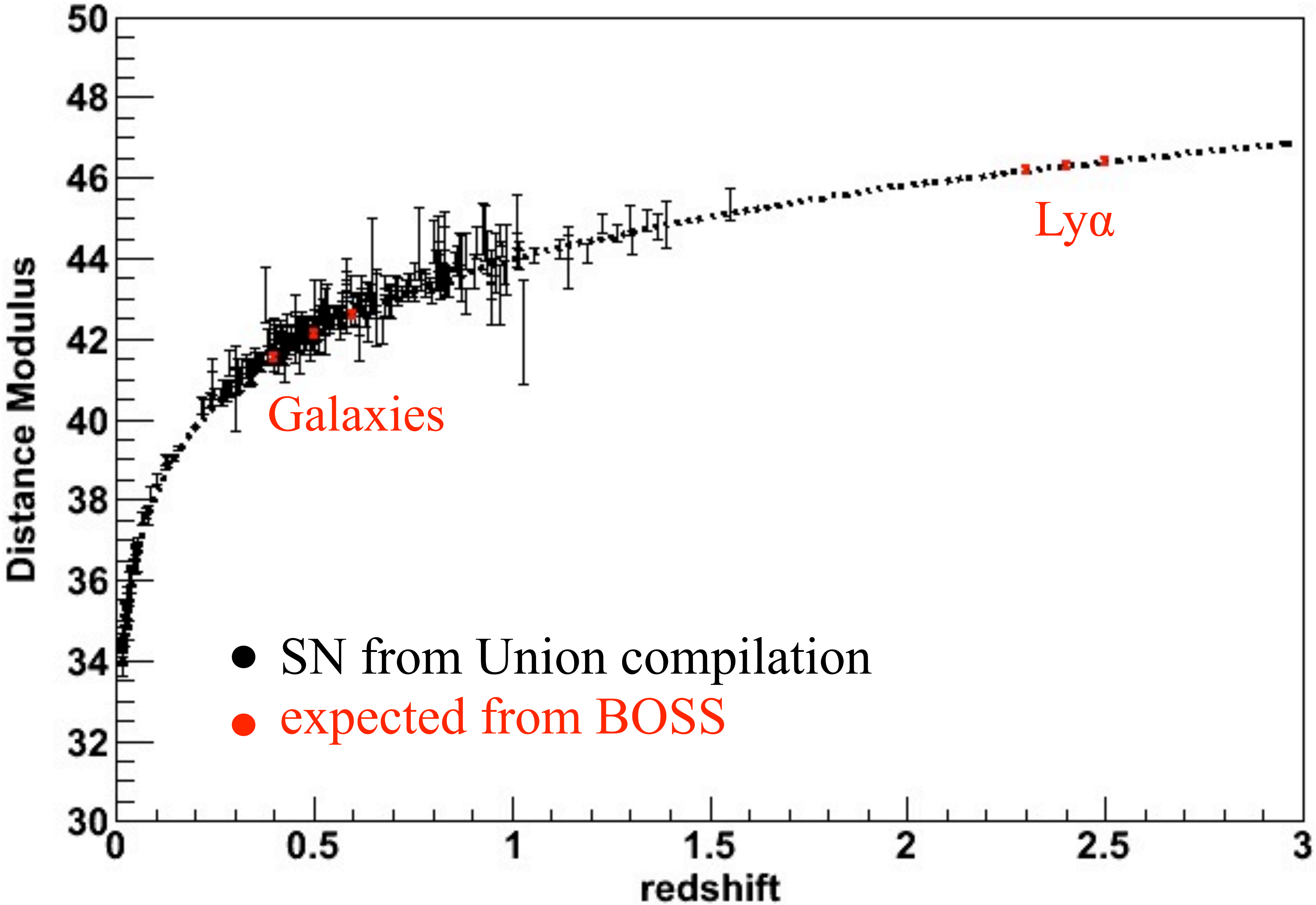


- plate goes to focal plane
- 80 min/plate
- 10min to change the plate

Expected constraints for BOSS

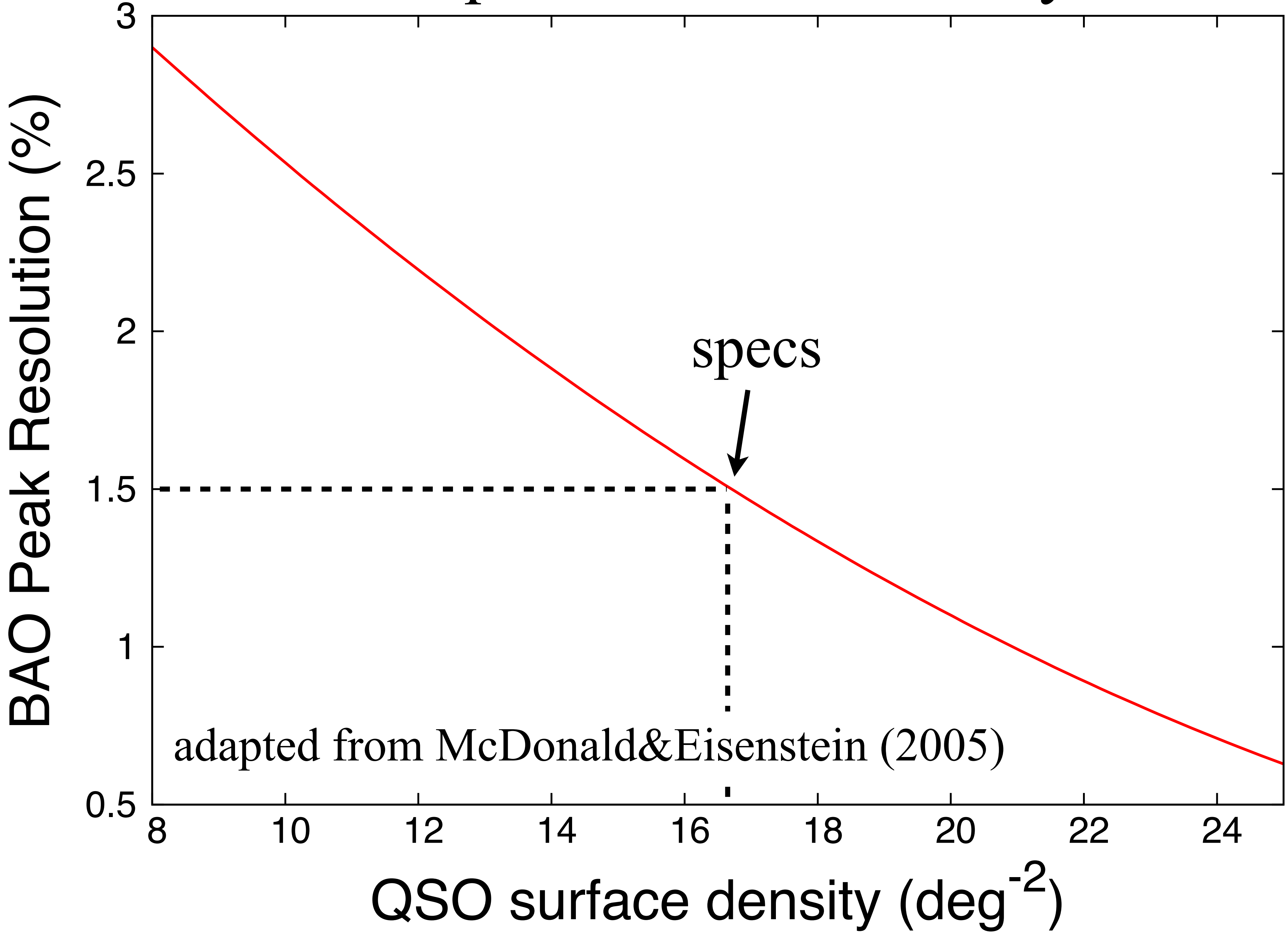
BOSS in the Hubble diagram

$$d_L^{eff}(z) = (1+z)^2 d_A(z)$$



Towards Lyα-BAO: what makes the measurement possible

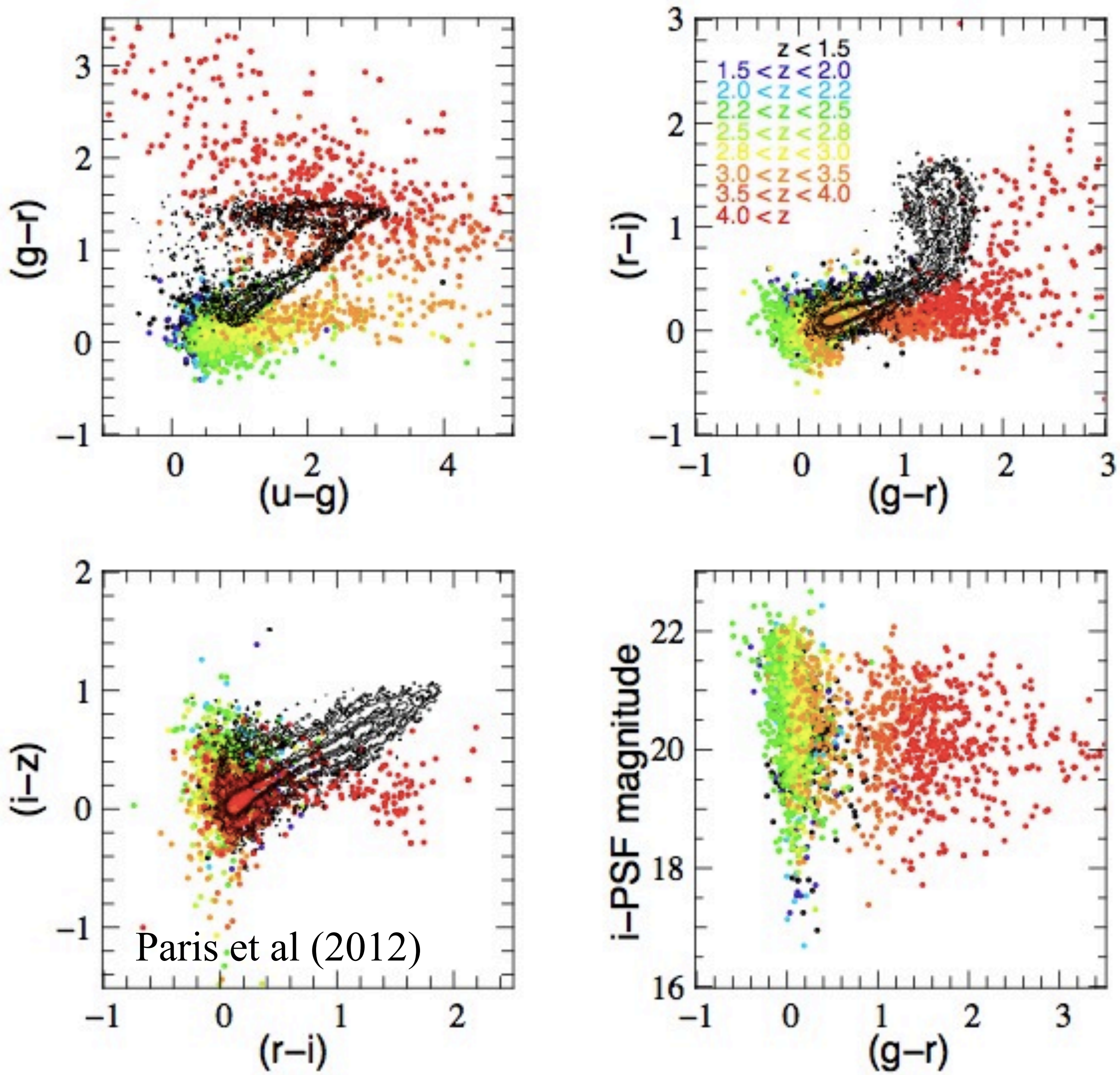
#1: quasar surface density



Towards Lyα-BAO: what makes the measurement possible

#1: quasar surface density

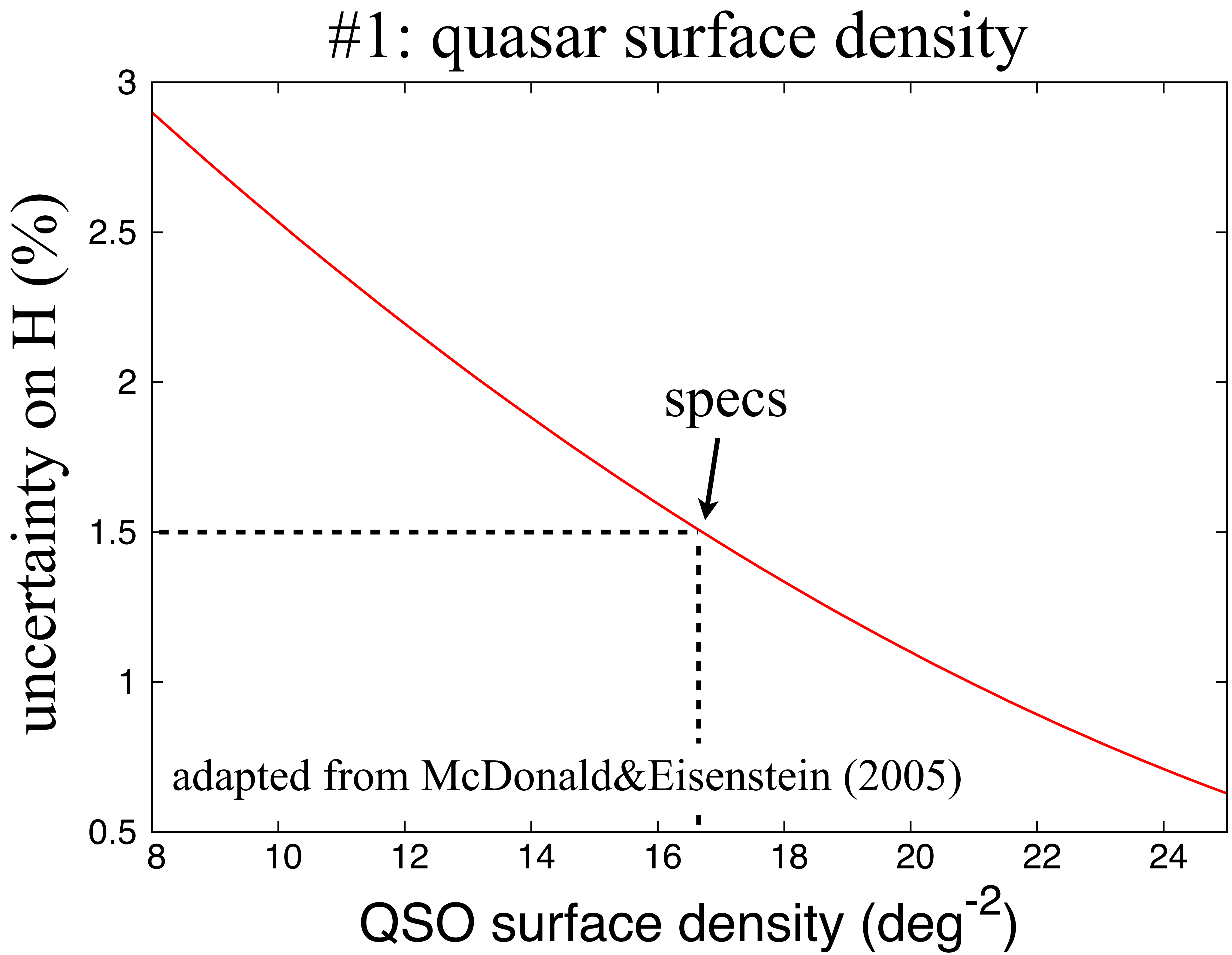
distributions of stars and quasars in color space



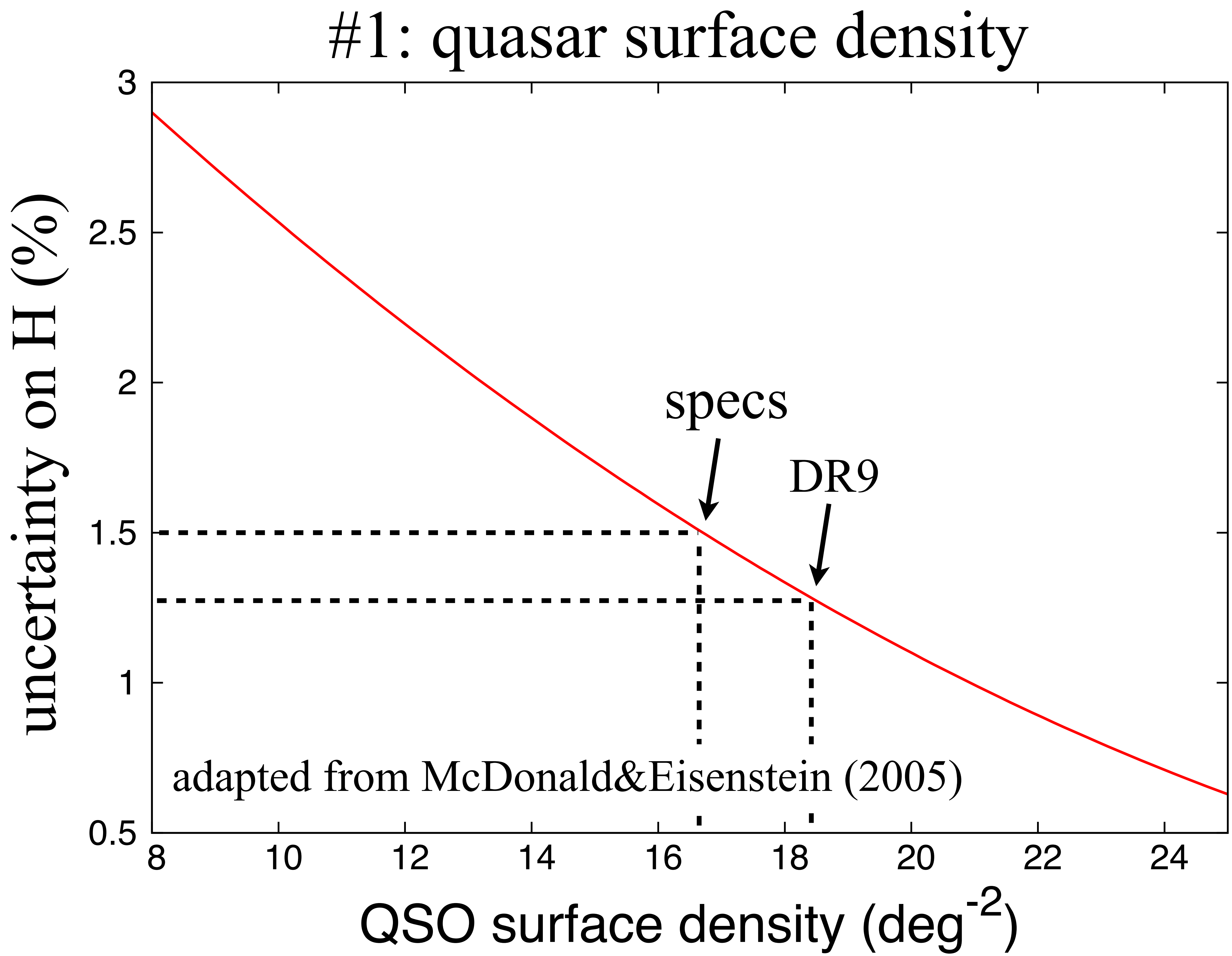
BOSS: 40 QSO targets / deg^2

- at least ~50% efficiency
- at least ~10^{-2} stelar rejection

Towards Lyα-BAO: what makes the measurement possible



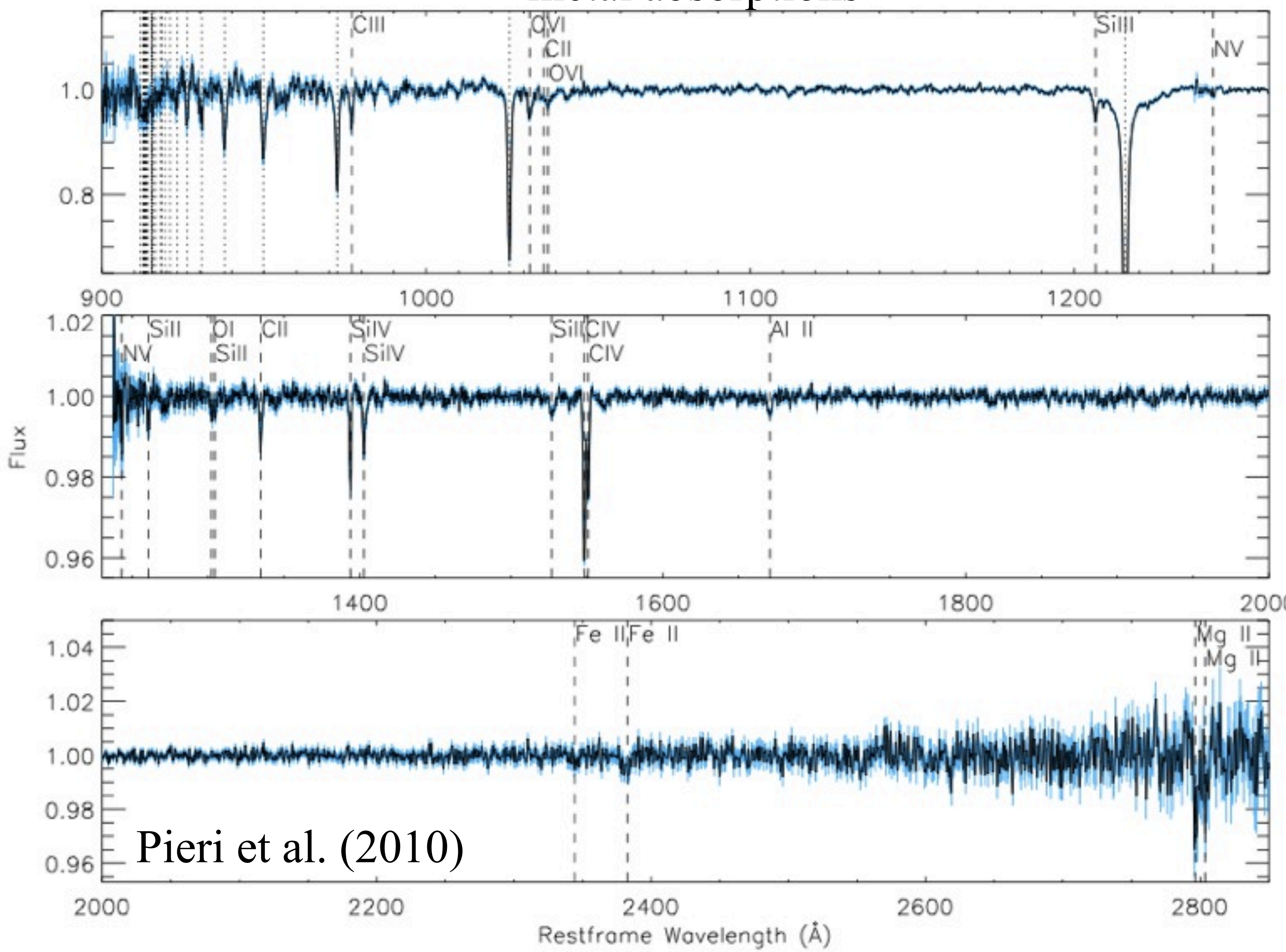
Towards Lyα-BAO: what makes the measurement possible



Towards Lyα-BAO: what makes the measurement possible

#2: non-Lyα absorptions

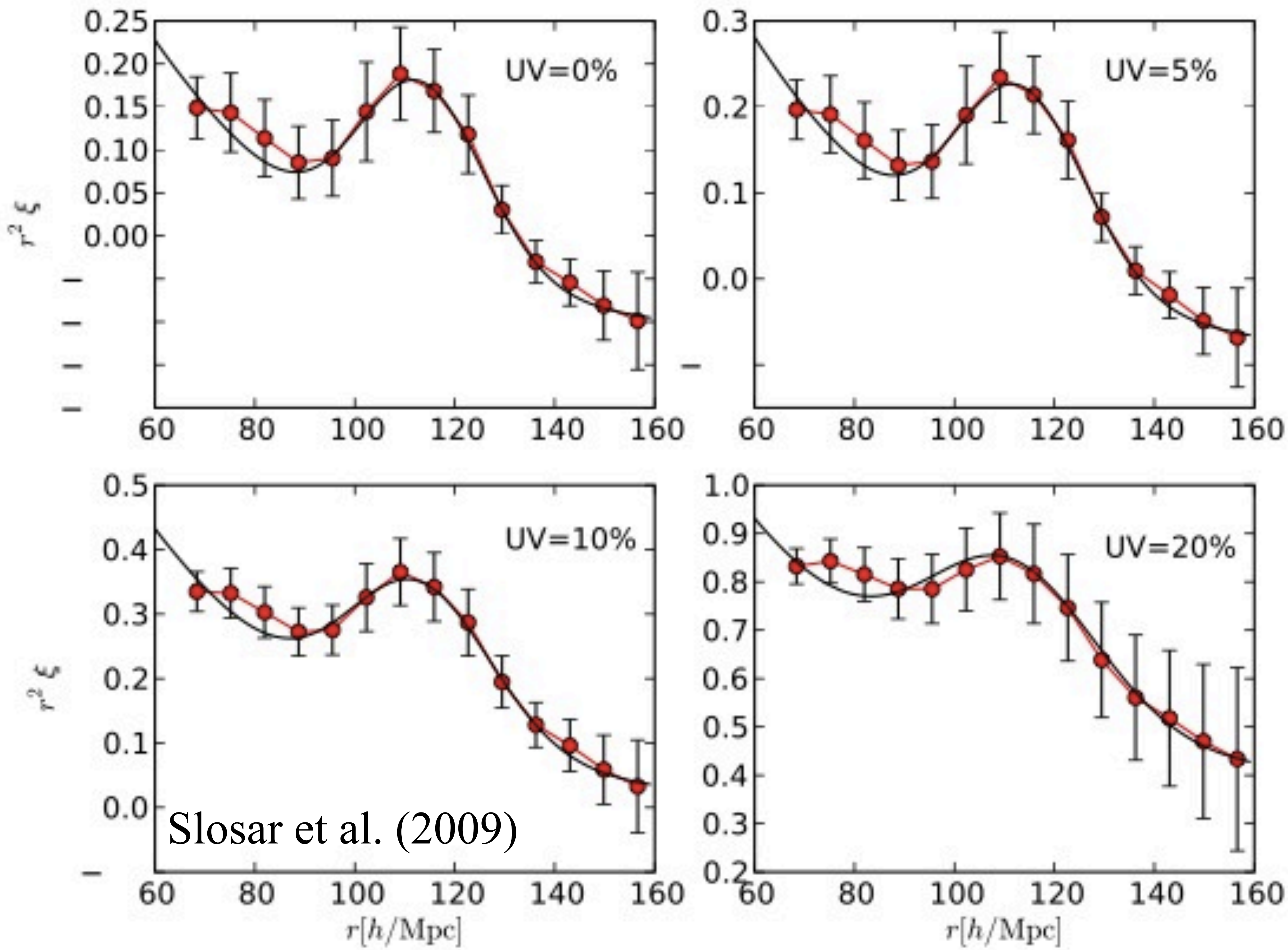
metal absorptions



Pieri et al. (2010)

Towards Lyα-BAO: what makes the measurement possible

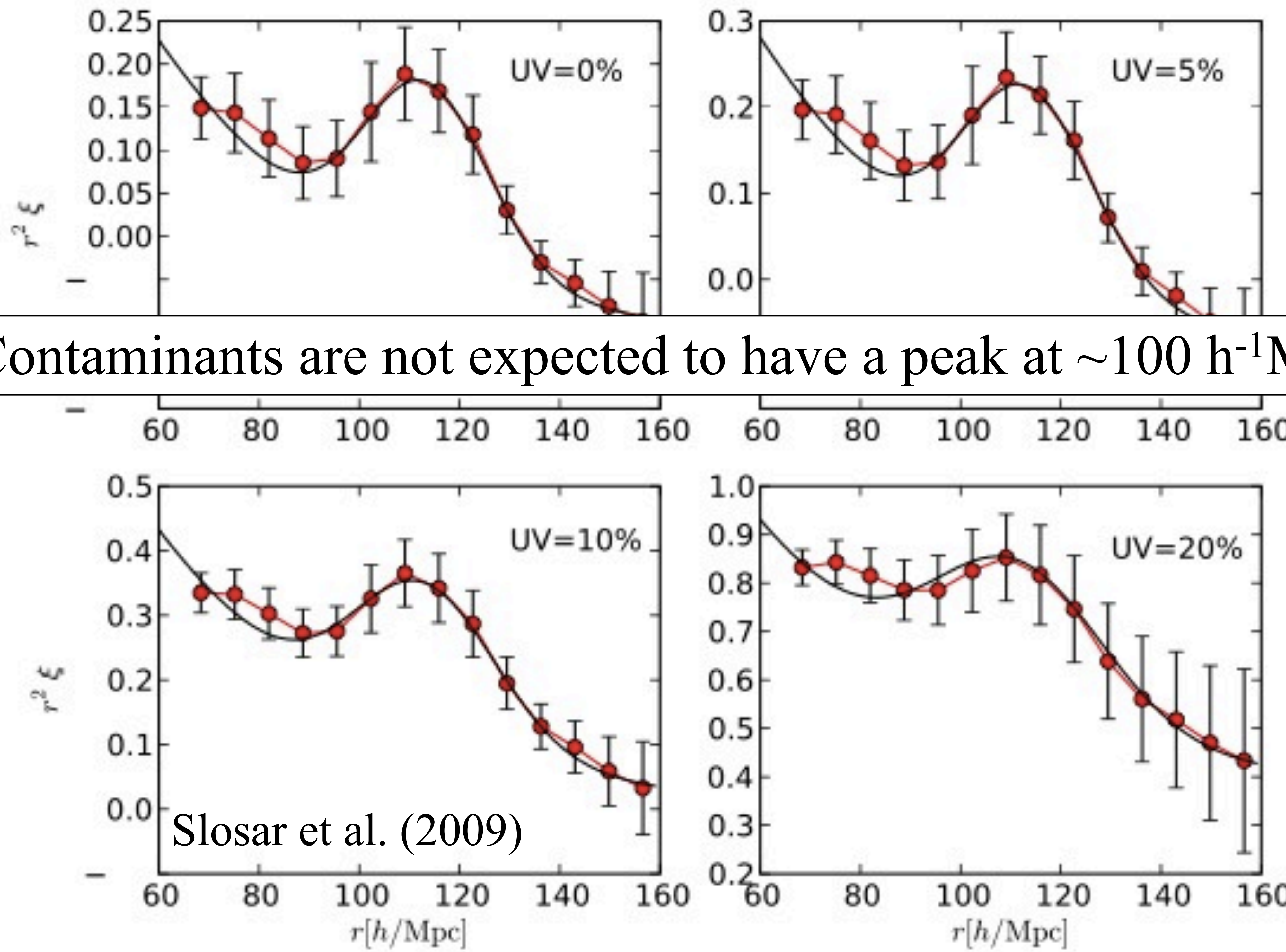
#2: UV-background fluctuations



Slosar et al. (2009)

Towards Lyα-BAO: what makes the measurement possible

#2: UV-background fluctuations



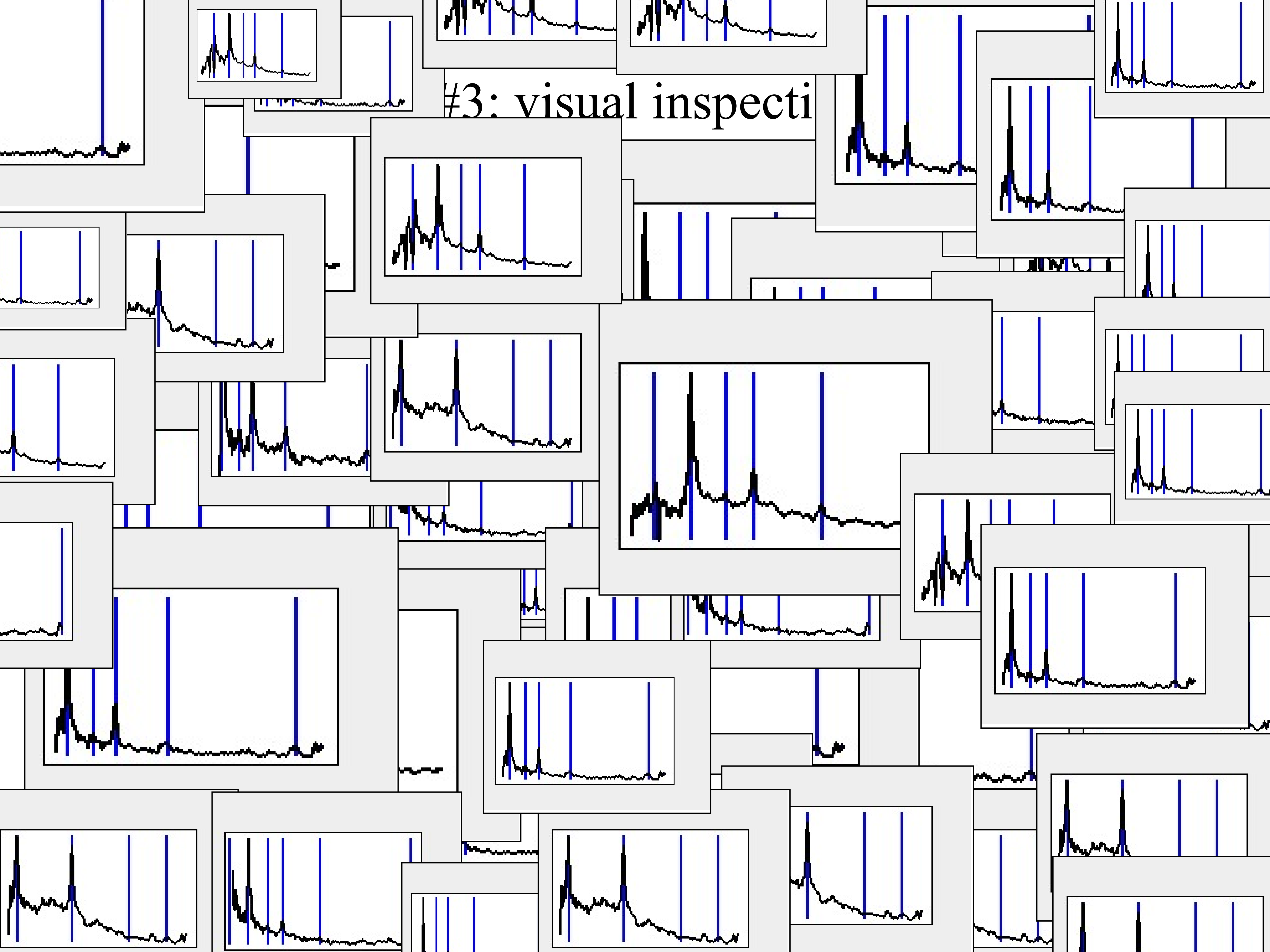
Contaminants are not expected to have a peak at ~100 h^{-1}Mpc

Slosar et al. (2009)

Towards Lyα-BAO: what makes the measurement possible

#3: visual inspection

- all DR9 180,000 quasar targets where visually inspected
- DLA and BALs tagged (~15% of the quasars)
- corrected pipeline classification and redshifts
- detect and tag reduction problems

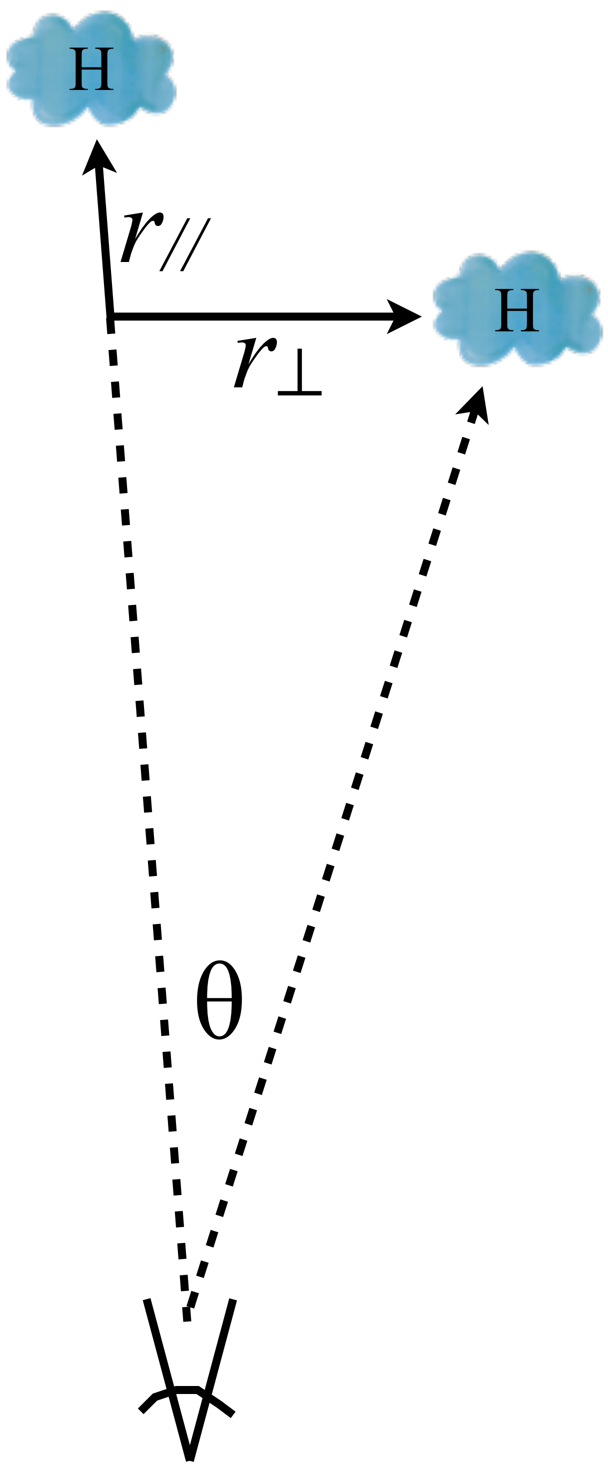

#3: visual inspecti

Towards Lyα-BAO: what makes the measurement possible

#4: mock data

- need to simulate N_{qso} x N_{pixels} ~ $O(10^6)$ correlated pixels
- based on Font-Ribera et al. (2012a): cholesky-decompose many N_{qso}^2 matrices
- weeks for O(10) simulations
- today 15 full realizations with realistic noise, DLAs, etc. (challenge for DR10)

2D correlation function



e.g. in a flat "fiducial cosmology":

$$r_\parallel = (r_1 - r_2)\cos(\theta/2)$$

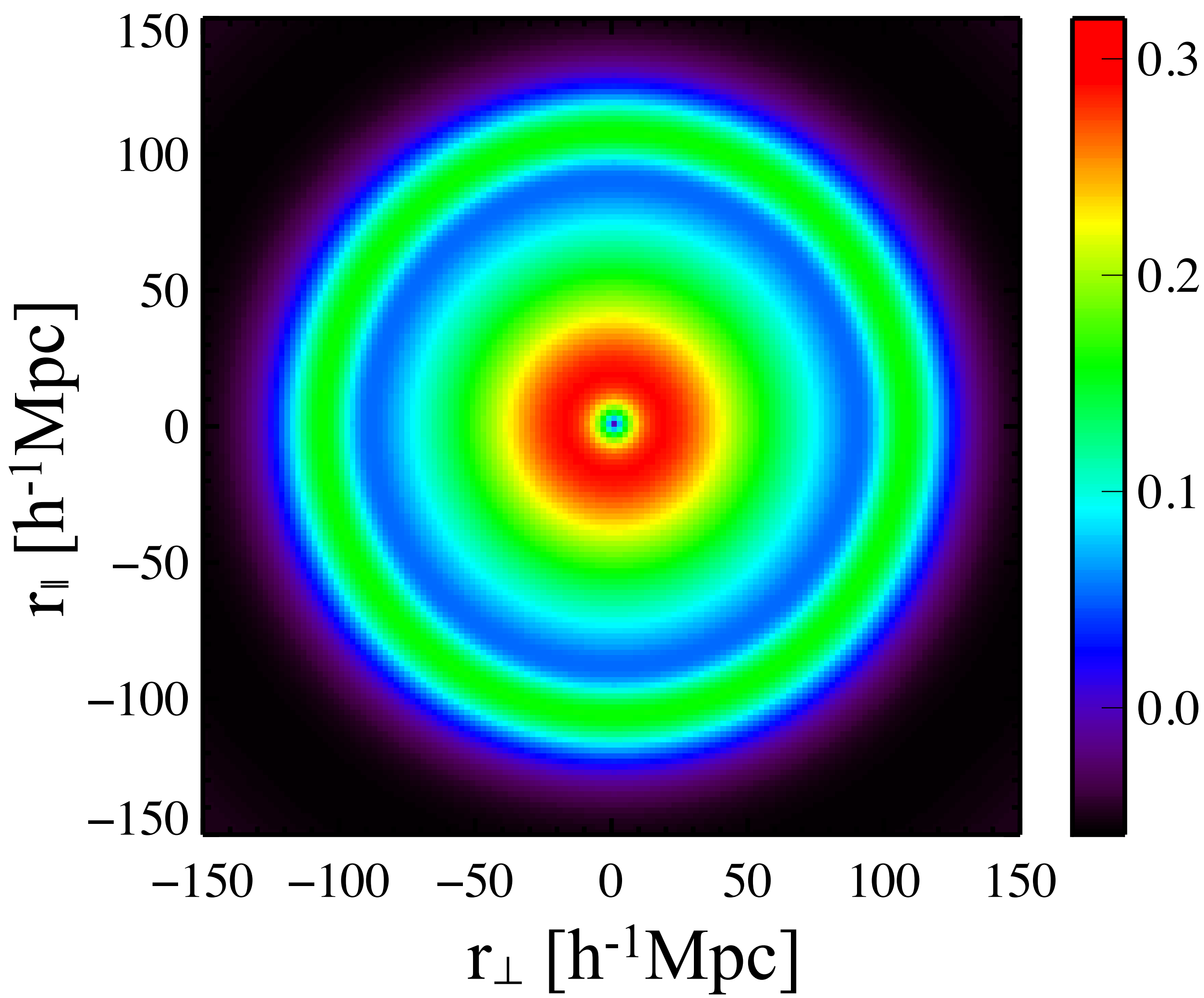
$$r_\perp = (r_1 + r_2)\sin(\theta/2)$$

$$r(z) = c\int_0^z \frac{dz}{H(z)}$$

$$\boxed{\begin{aligned} r_\parallel &= \frac{c\Delta z}{H(\bar{z})} \\ r_\perp &= (1+z)d_A(\bar{z})\theta \end{aligned}}$$

$$d_A(z) \equiv \frac{c}{1+z}\int_0^z \frac{dz}{H(z)}$$

2D correlation function



isotropy:

$$\xi(r_\perp, r_\parallel) = \xi(r_\perp^2 + r_\parallel^2)$$

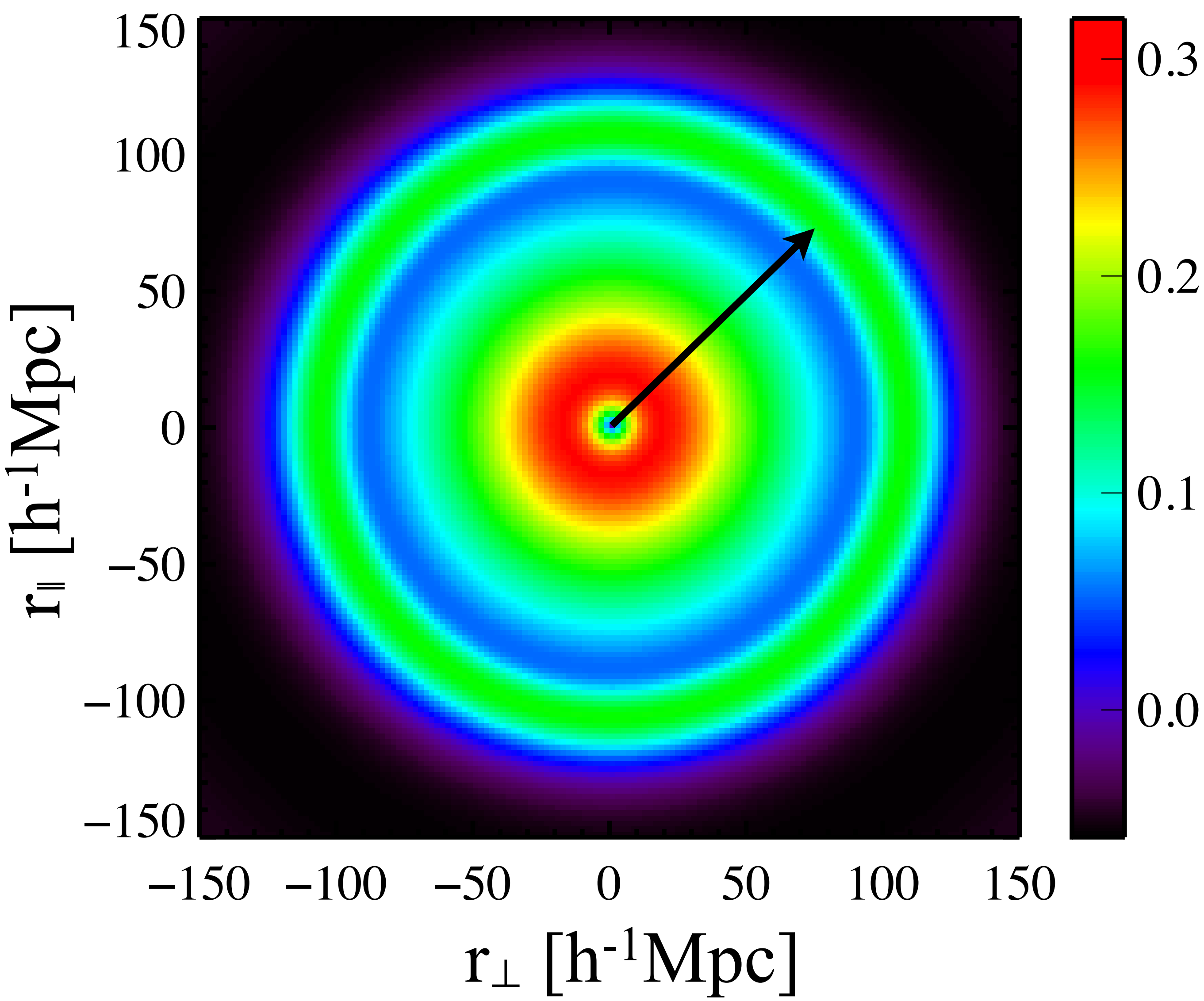
The incorrect cosmology breaks the polar symmetry

Alcock & Paczyński (1979)
(independent of BAO)

AP test measures:

$$H(z) \cdot d_A(z)$$

2D correlation function



AP test measures:

$$H(z) \cdot d_A(z)$$

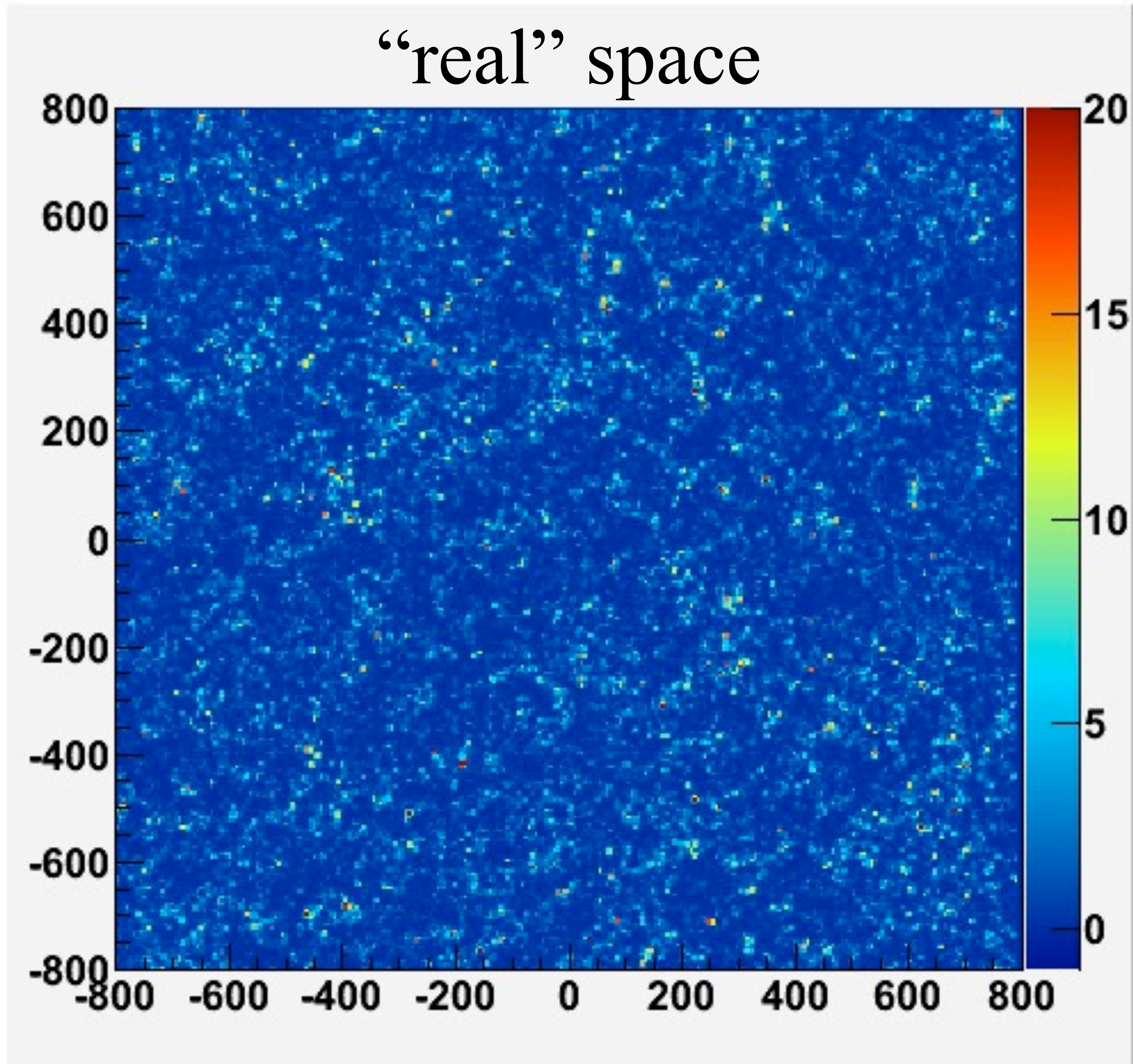
if a scale is known, two independent measurements:

$$H(z) \cdot r_s$$

$$d_A(z)/r_s$$

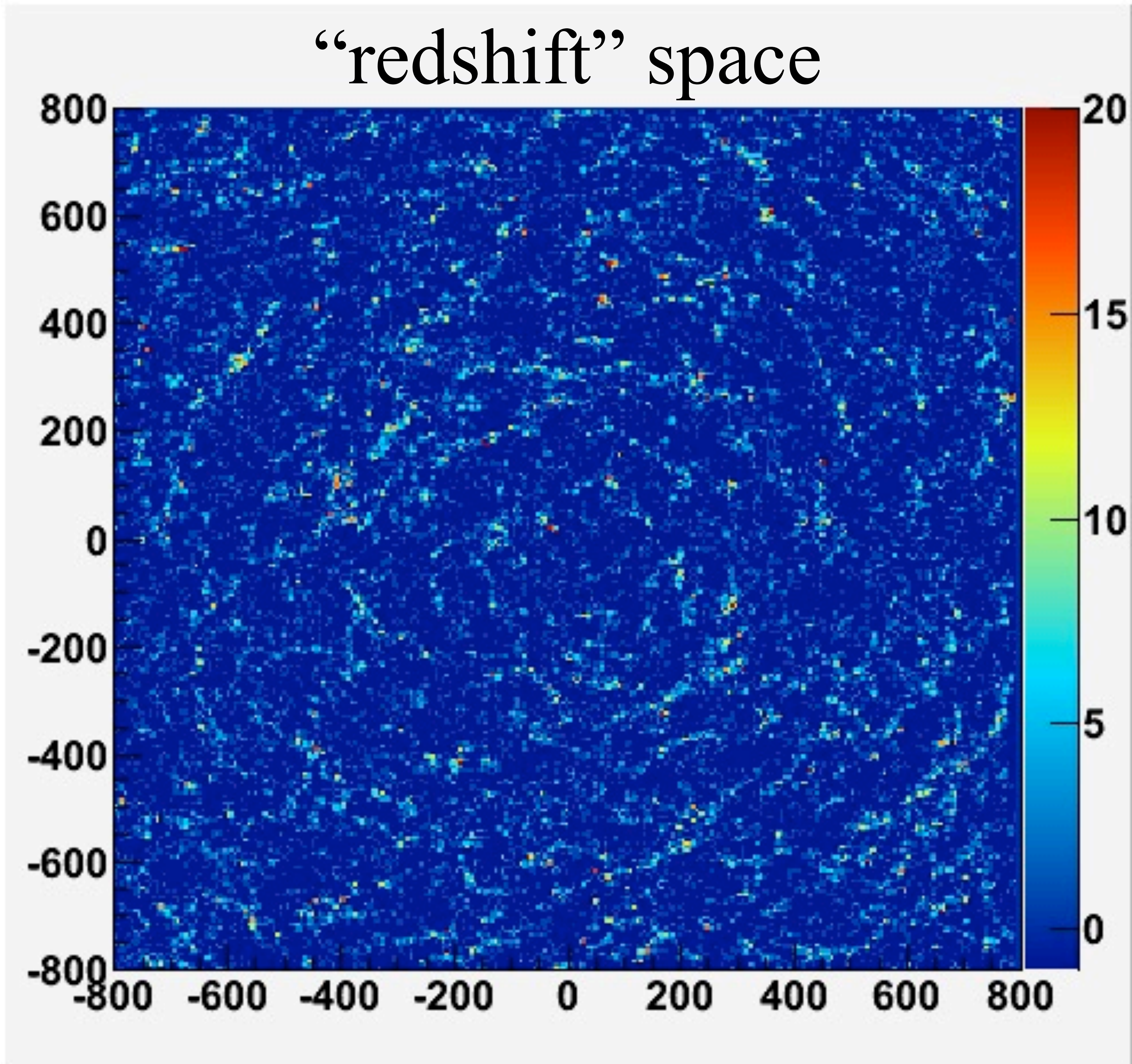
Caveat ! redshift space distortions

$$z = z_{cosmo} + z_{peculiar}$$

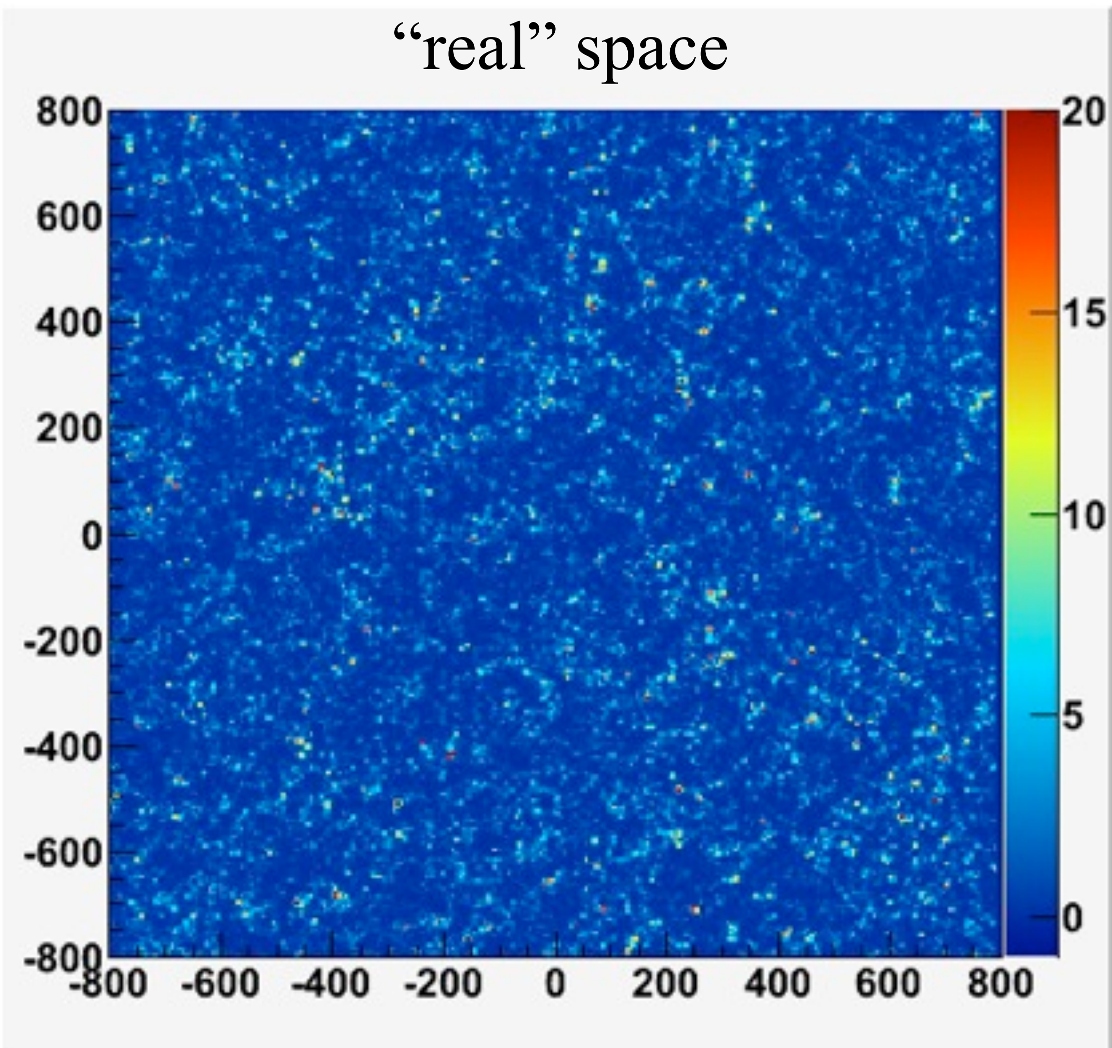


Caveat ! redshift space distortions

$z = z_{cosmo} + z_{peculiar}$

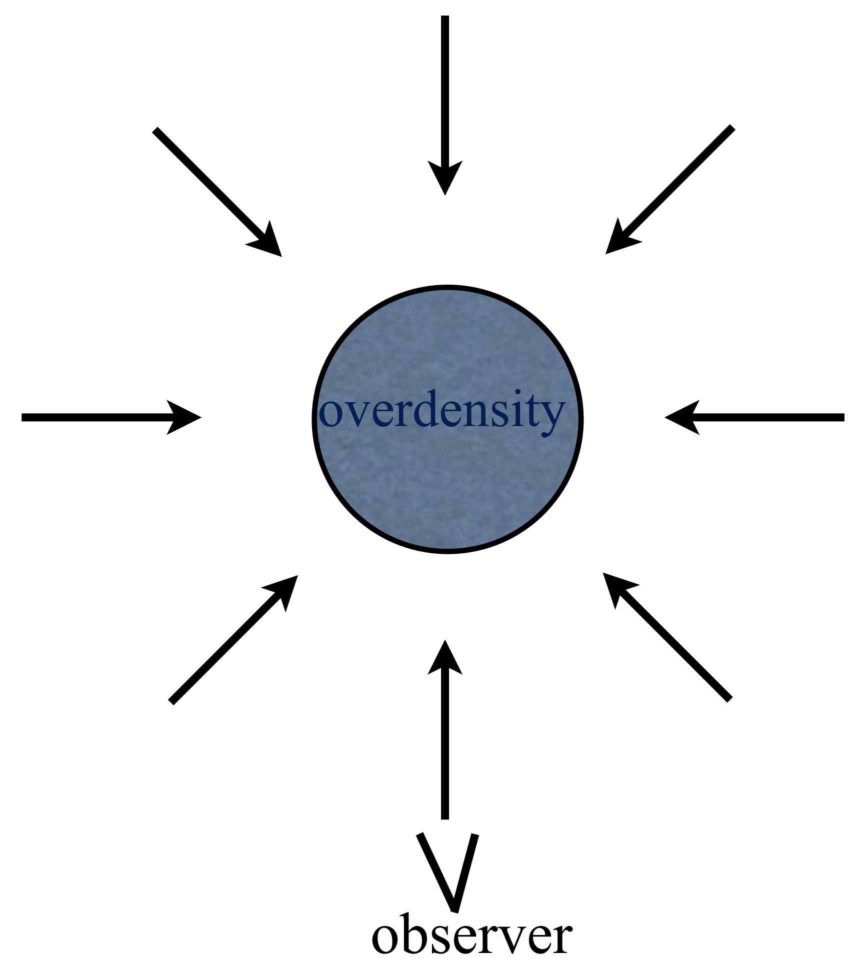


Caveat ! redshift space distortions

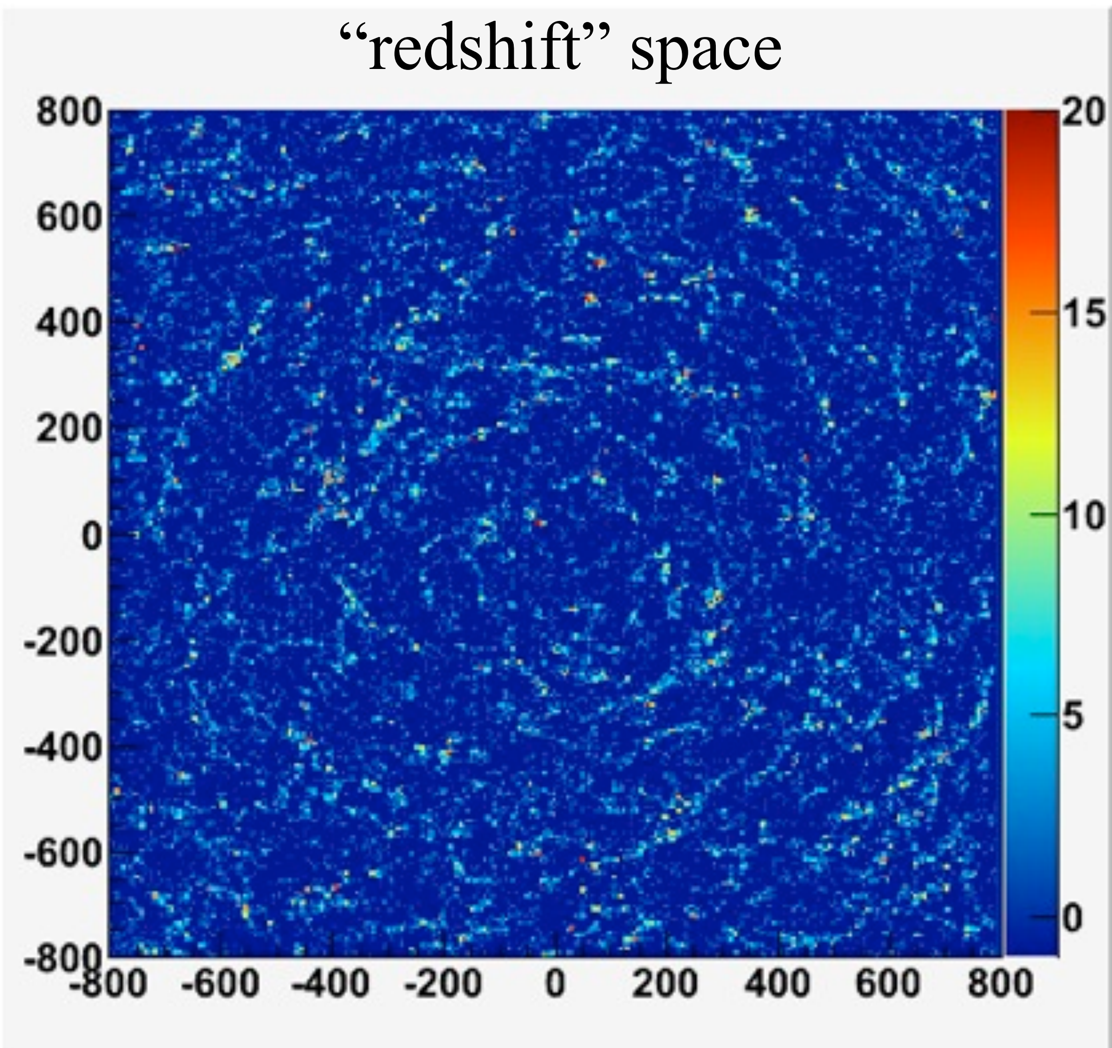


- Kaiser effect: matter falls towards potential wells

$z = z_{cosmo} + z_{peculiar}$



Caveat ! redshift space distortions



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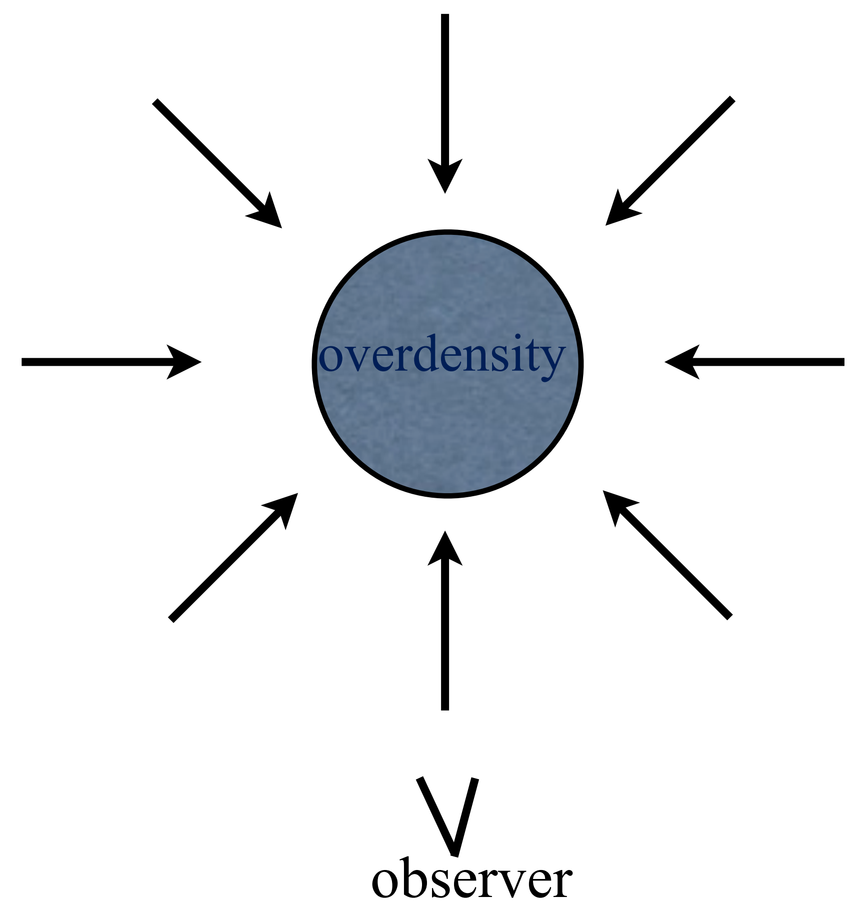
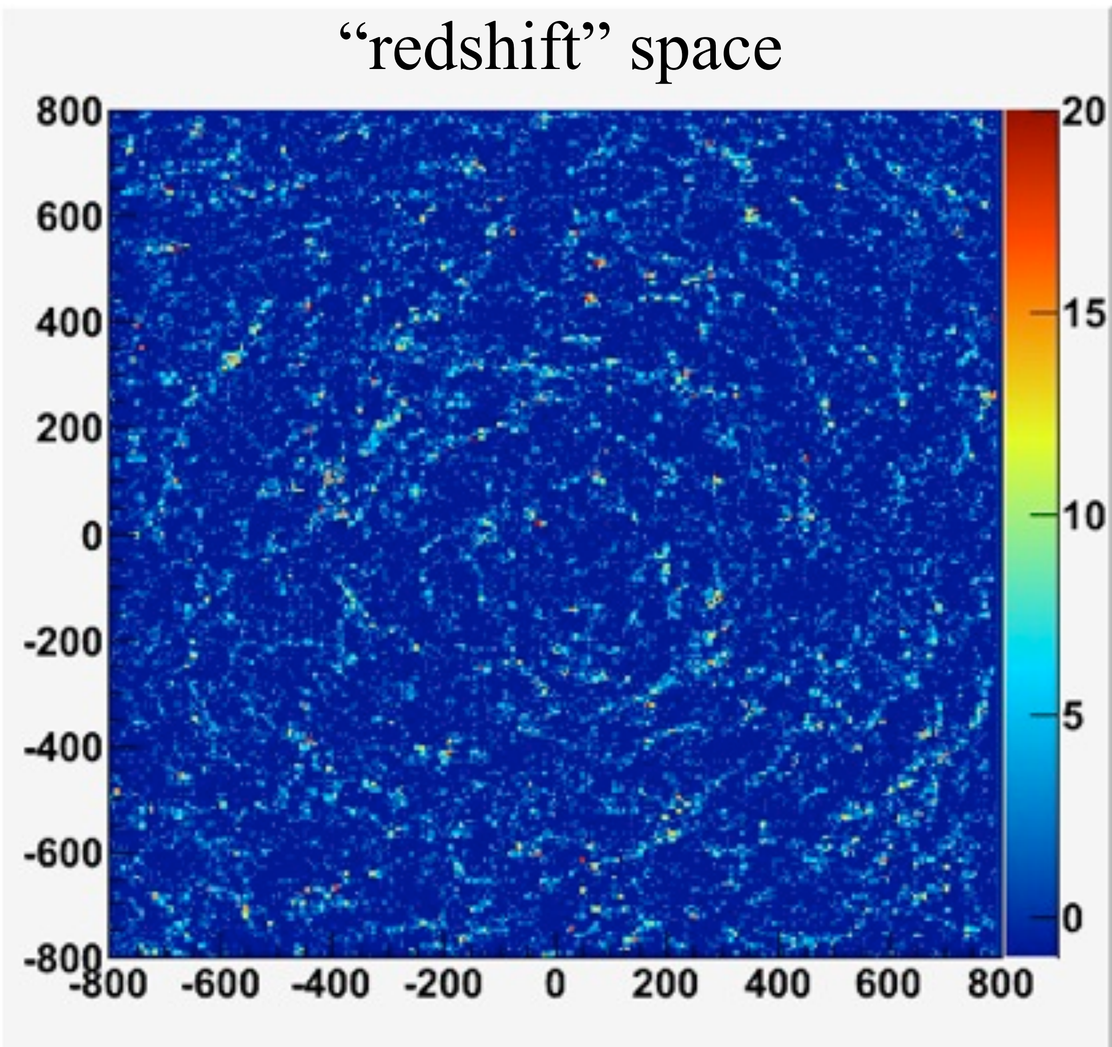
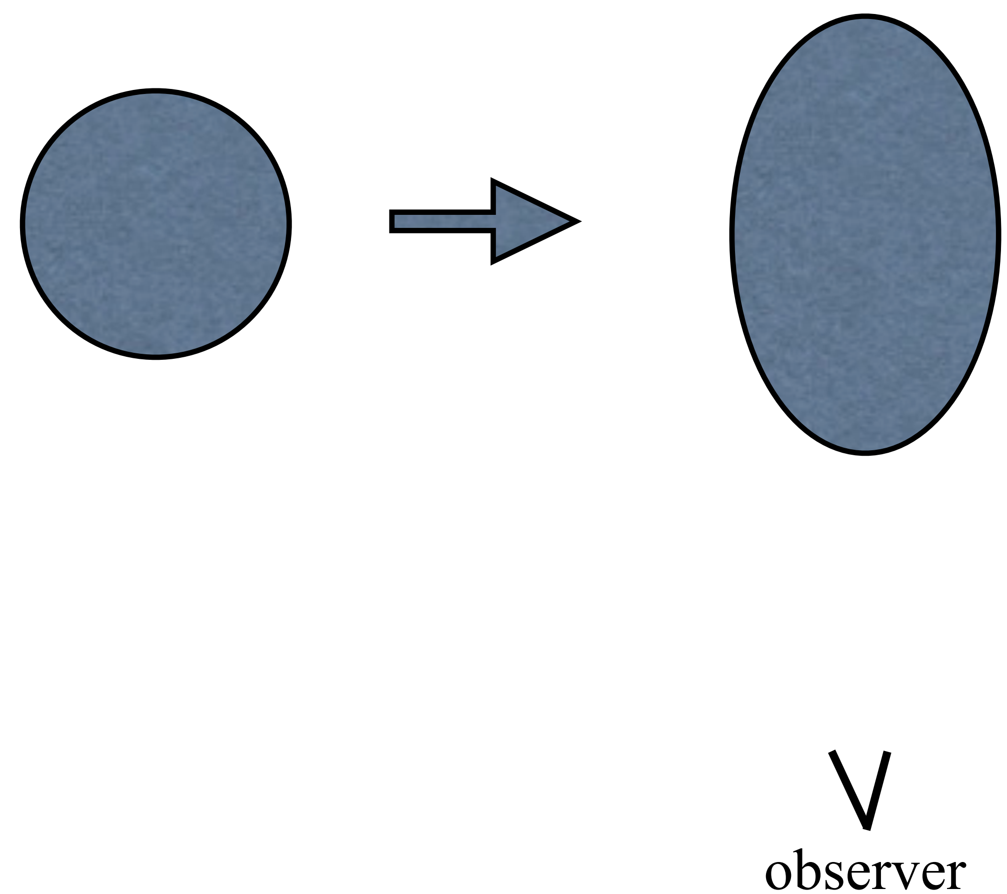


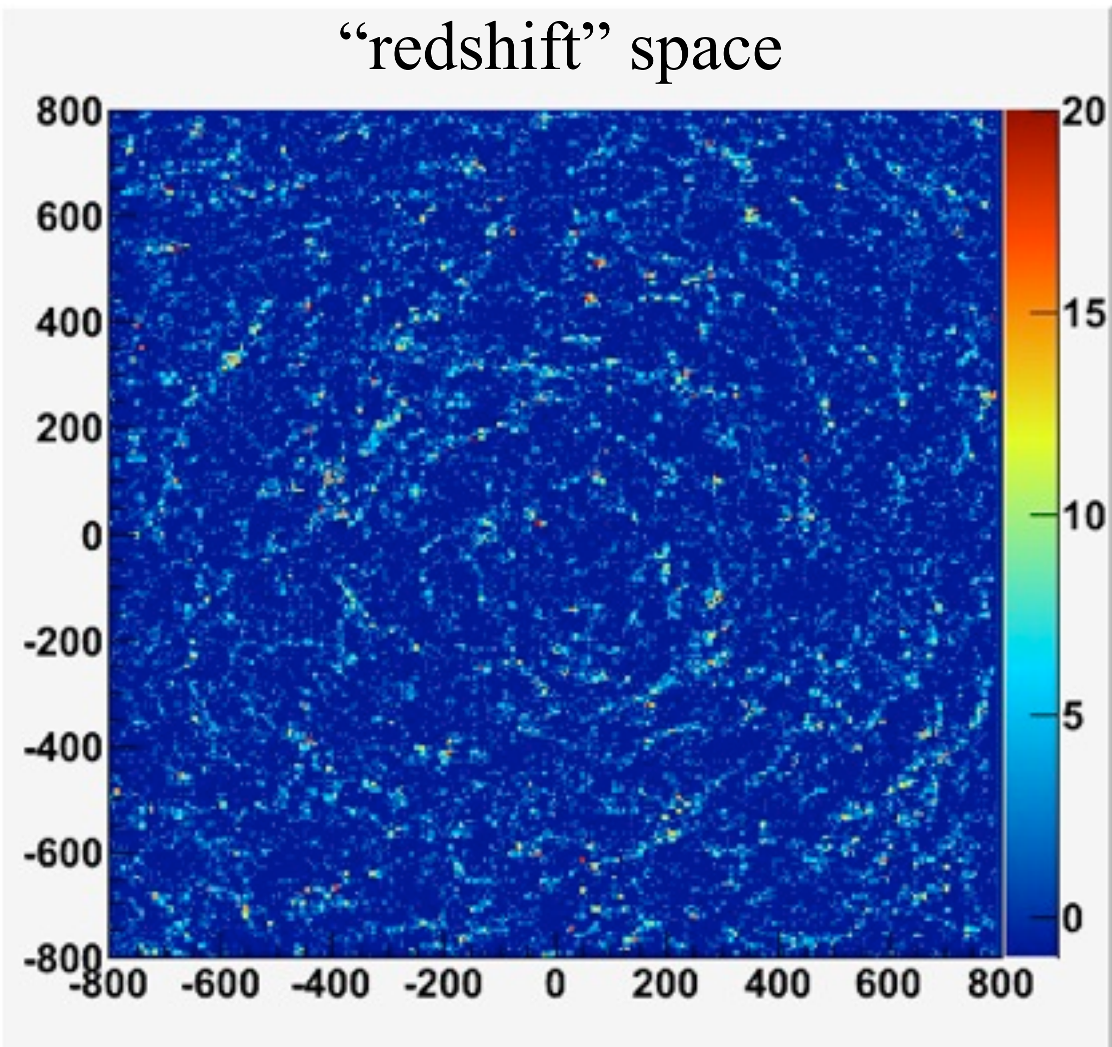
Caveat ! redshift space distortions



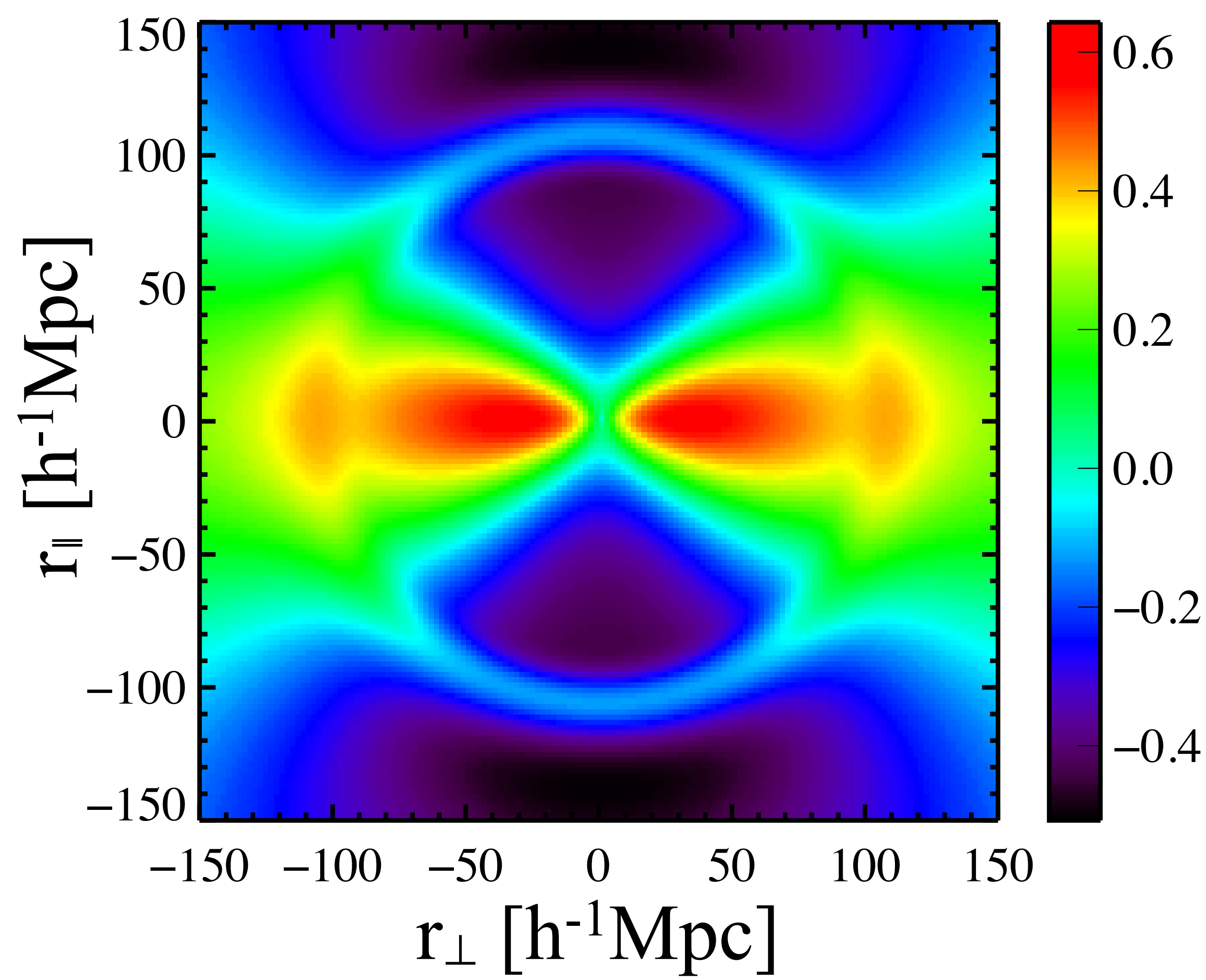
- Kaiser effect: matter falls towards potential wells
- fingers of God: random velocities in virialized clusters



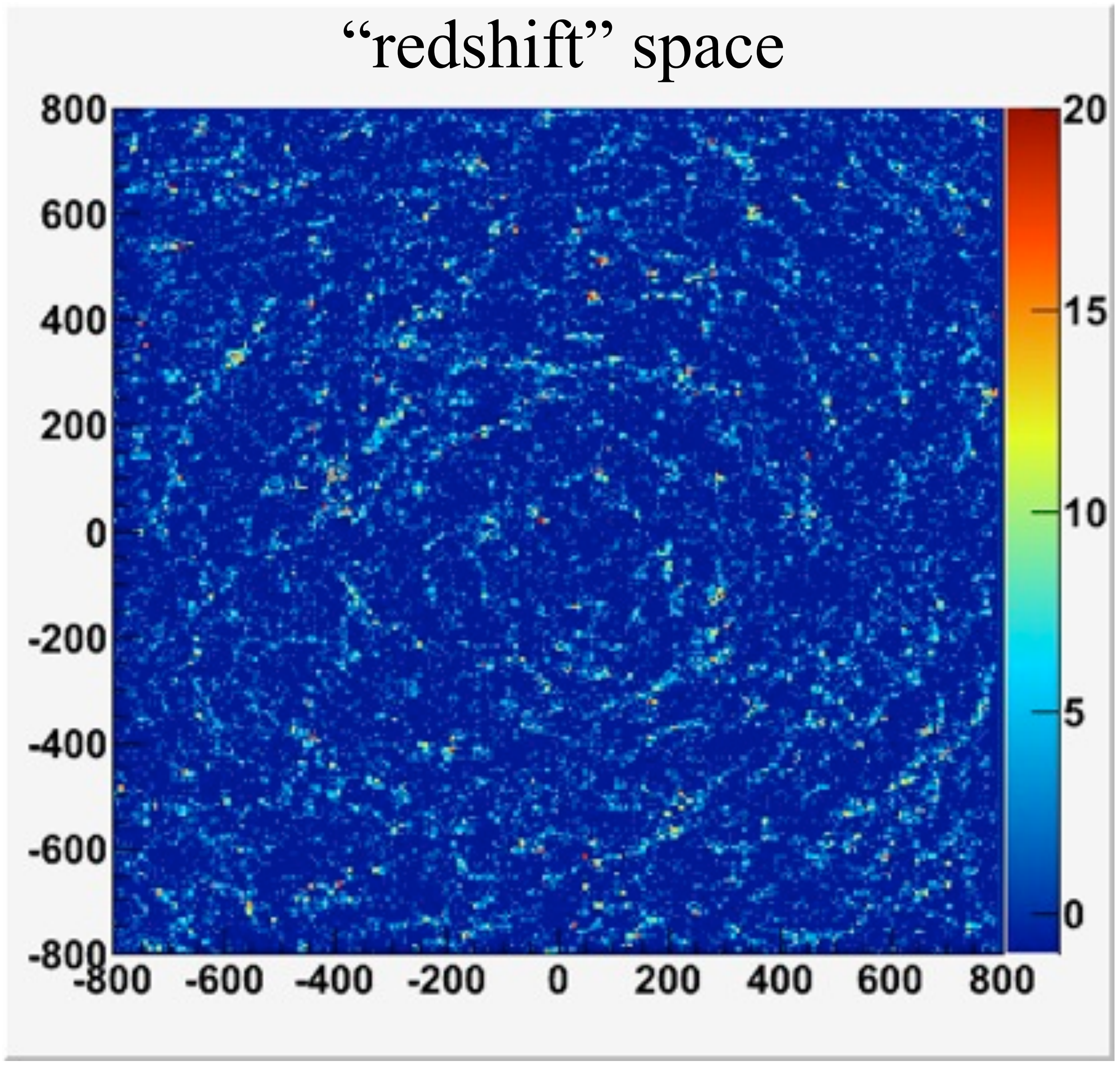
Caveat ! redshift space distortions



- Kaiser effect: matter falls towards potential wells
- fingers of God: virialized clusters



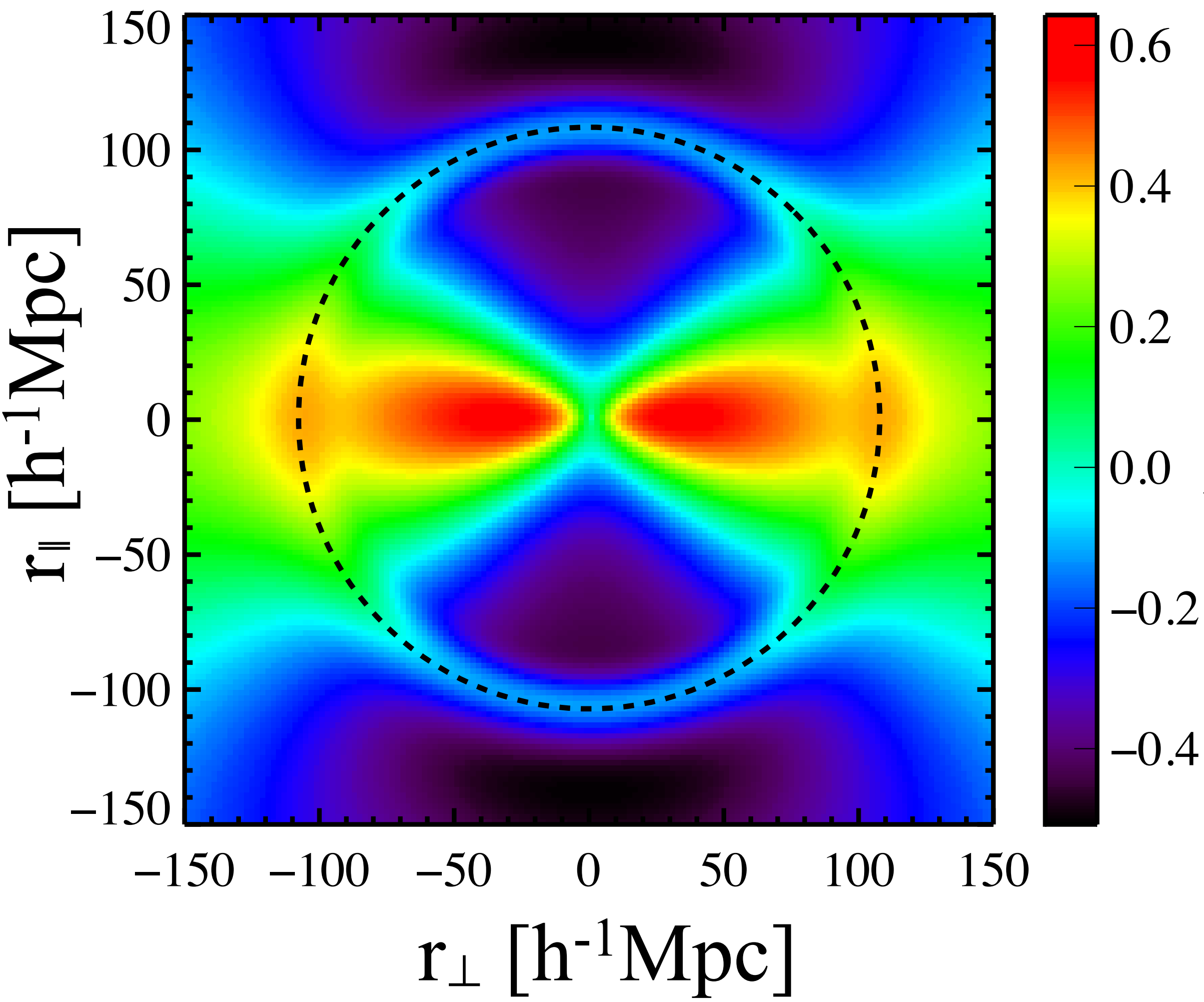
Caveat ! redshift space distortions



- Kaiser effect: matter falls towards potential wells
- fingers of God: virialized clusters

a problem for cosmology?

Caveat ! redshift space distortions



- Kaiser effect: matter falls towards potential wells
- fingers of God: virialized clusters

a problem for cosmology?

No !

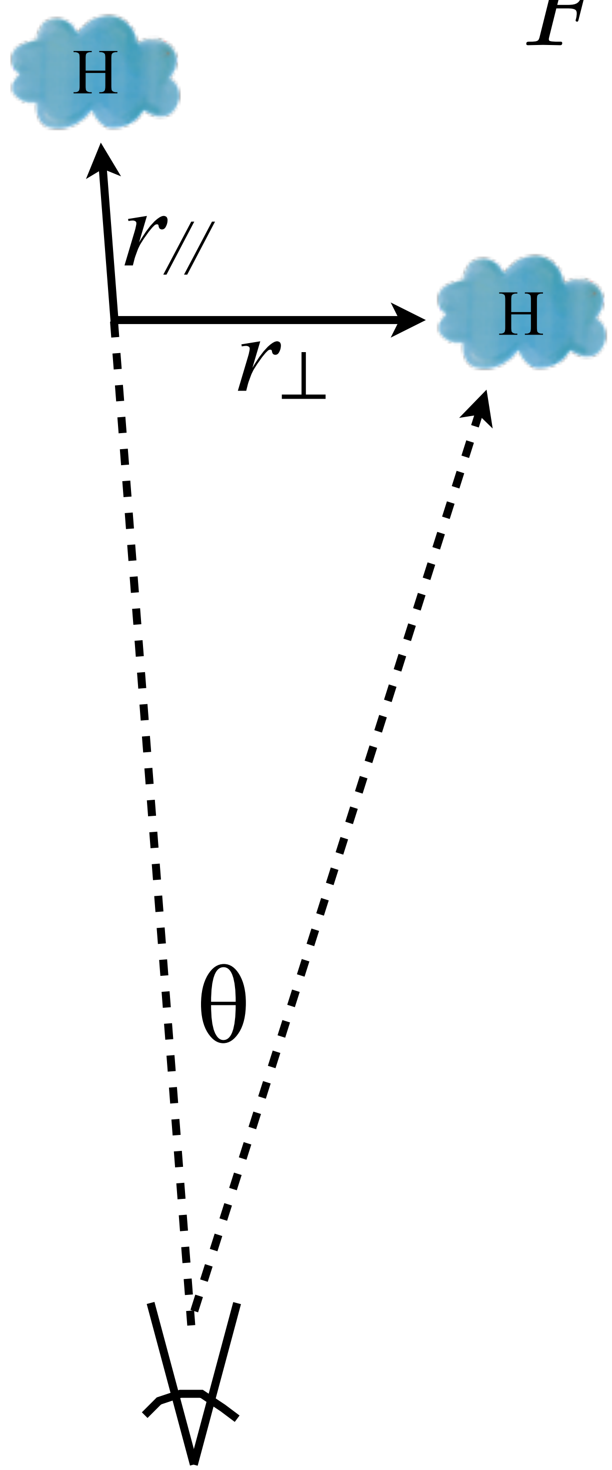
- one additional parameter:
  $P_f(k, \mu_k) = b^2(1 + \beta\mu^2)^2 P_L(k)$

β: growth function $\propto \Omega_m^{0.6}$
(for galaxy surveys)

- the position of the BAO peak is not affected

The BOSS-Lyα correlation function measurement

$$\delta(\lambda) \equiv \frac{F(\lambda)}{\bar{F}C(\lambda)} - 1$$



radial coordinate $\equiv \; r = \int_0^{z_{\rm cloud}} \frac{dz}{H(z)}$

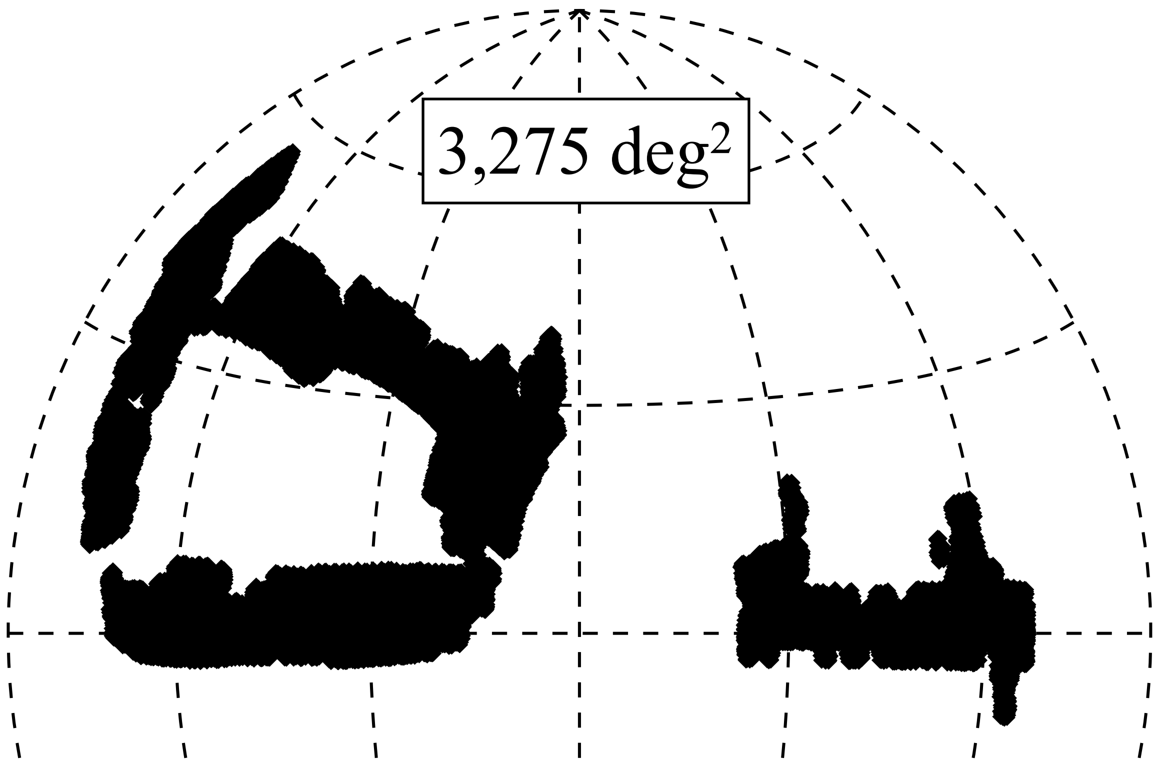
parallel distance $\equiv r_{//} \simeq \frac{\Delta z}{H(z)}$

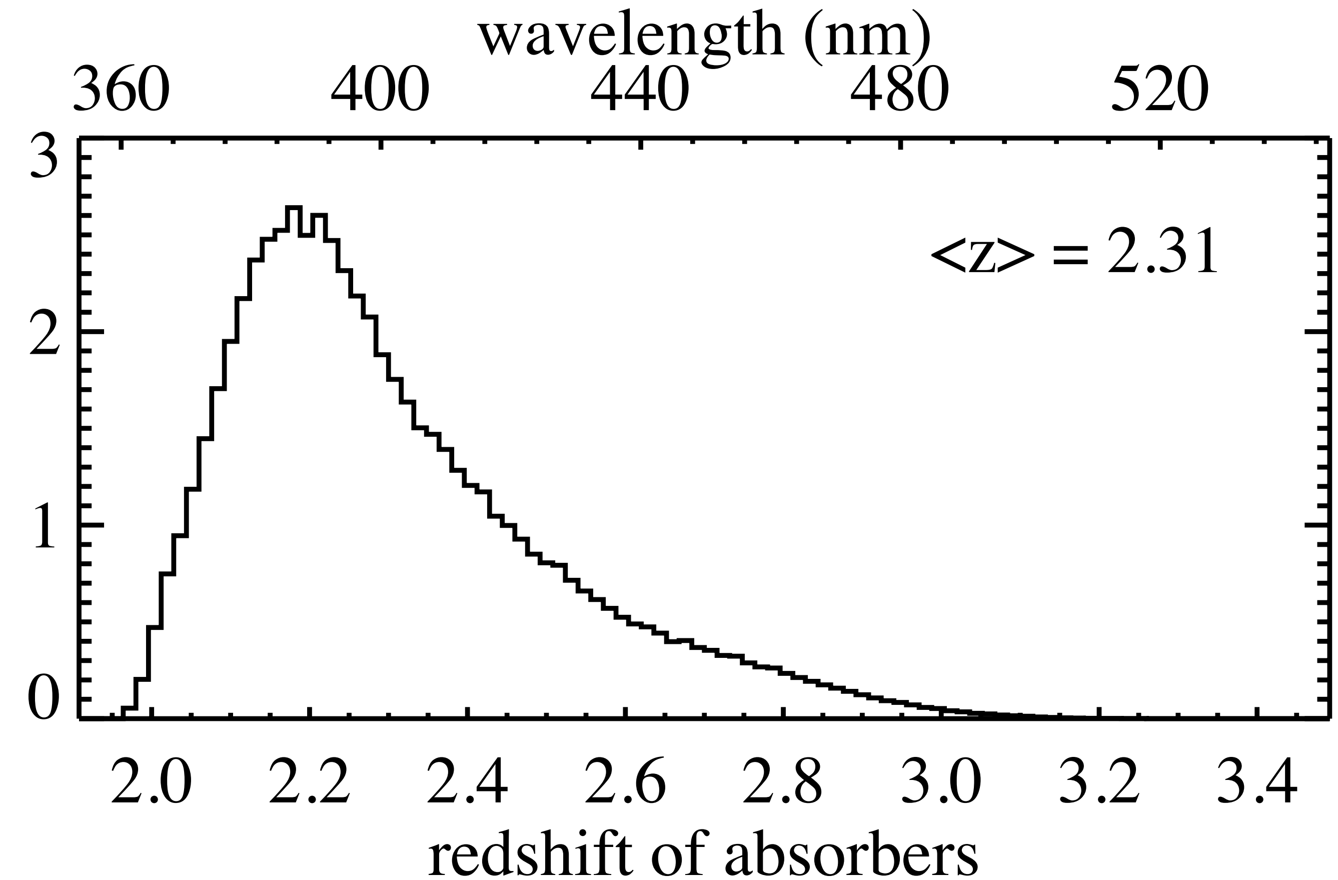
transverse distance $\equiv r_\perp = \theta \int_0^{\bar{z}} \frac{dz}{H(z)} = (1+z)d_A(\bar{z})\theta$

$$\xi(A) = \sum_{i,j\in A} w_{ij}\delta_i\delta_j$$

A: bin in $r_\parallel$, $r_\perp$
w_{ij}: weights

The BOSS-Lyα data sample



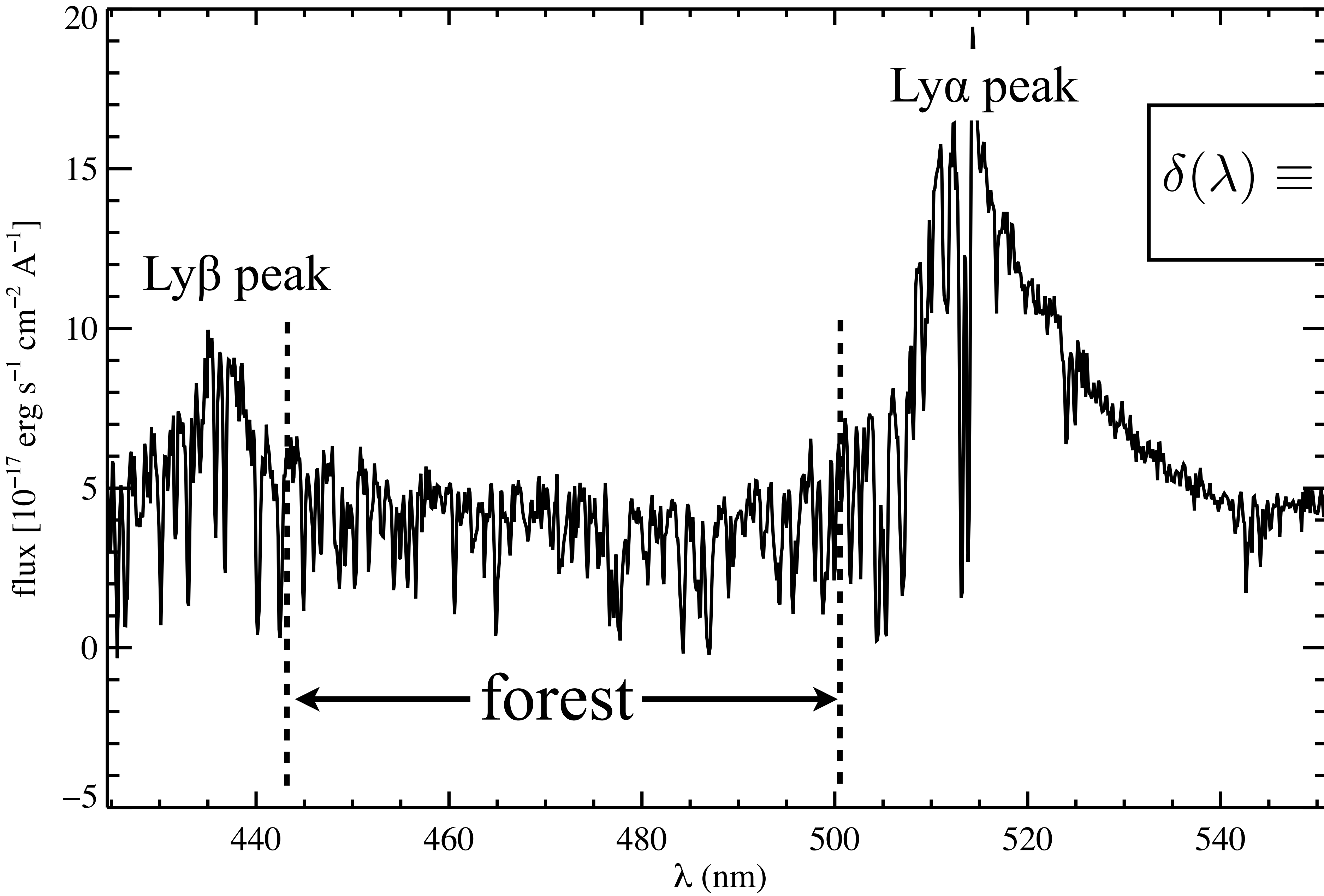


- 60,369 quasars of $2.1 \leq z \leq 3.5$
- 48,640 quasars after removal of BAL or DLA
- definition of the data sample done before looking at data
- will measure $\xi(r) \equiv \langle\delta\delta\rangle$, $\delta(z) \equiv \dfrac{F(z)}{\overline{F}(z)\, C(z)} - 1$

The BOSS-Lyα correlation function measurement

1st step: continuum fit

an example quasar spectrum

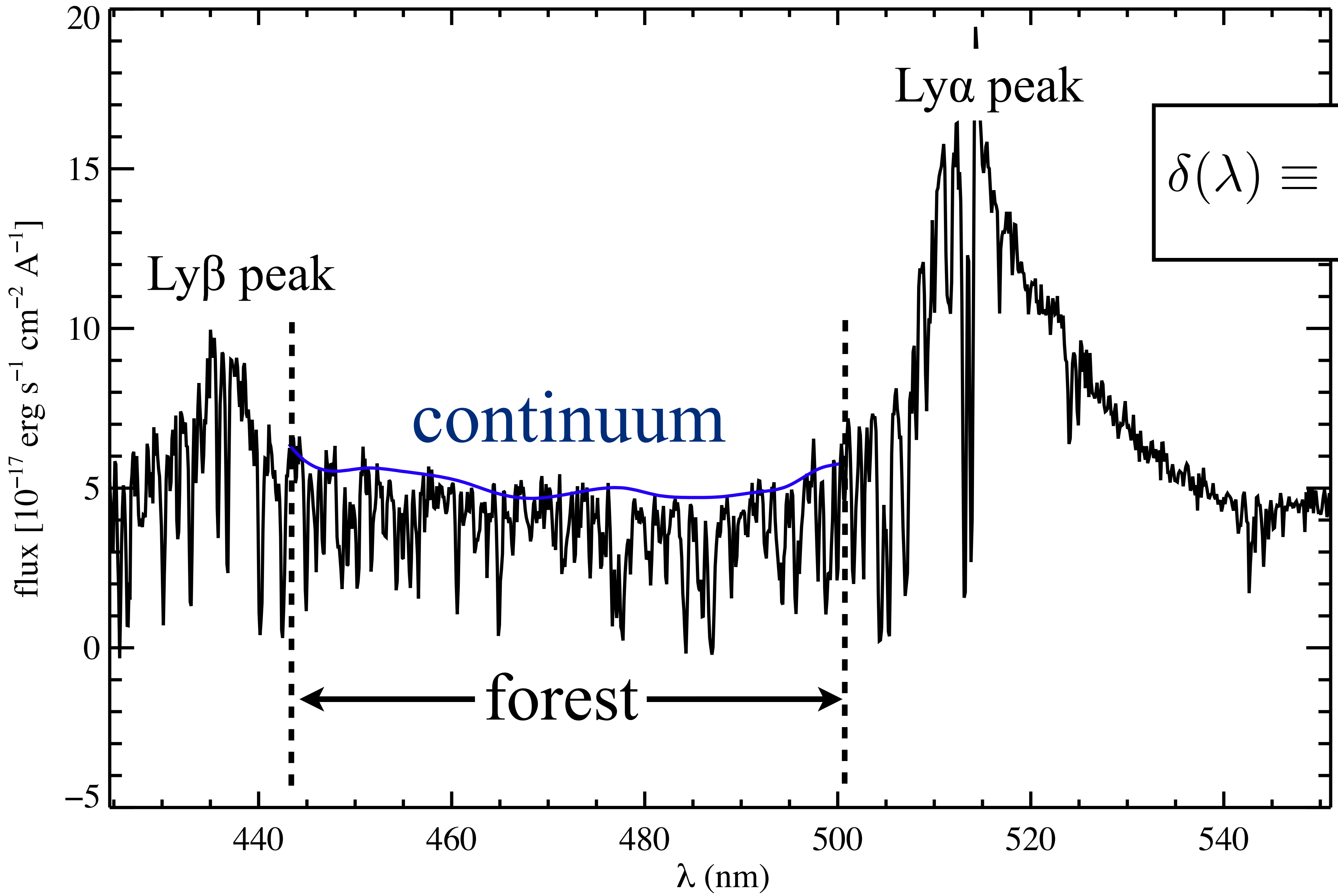


$$\delta(\lambda) \equiv \frac{F(\lambda)}{\bar{F} C(\lambda)} - 1$$

The BOSS-Lyα correlation function measurement

1st step: continuum fit

an example quasar spectrum

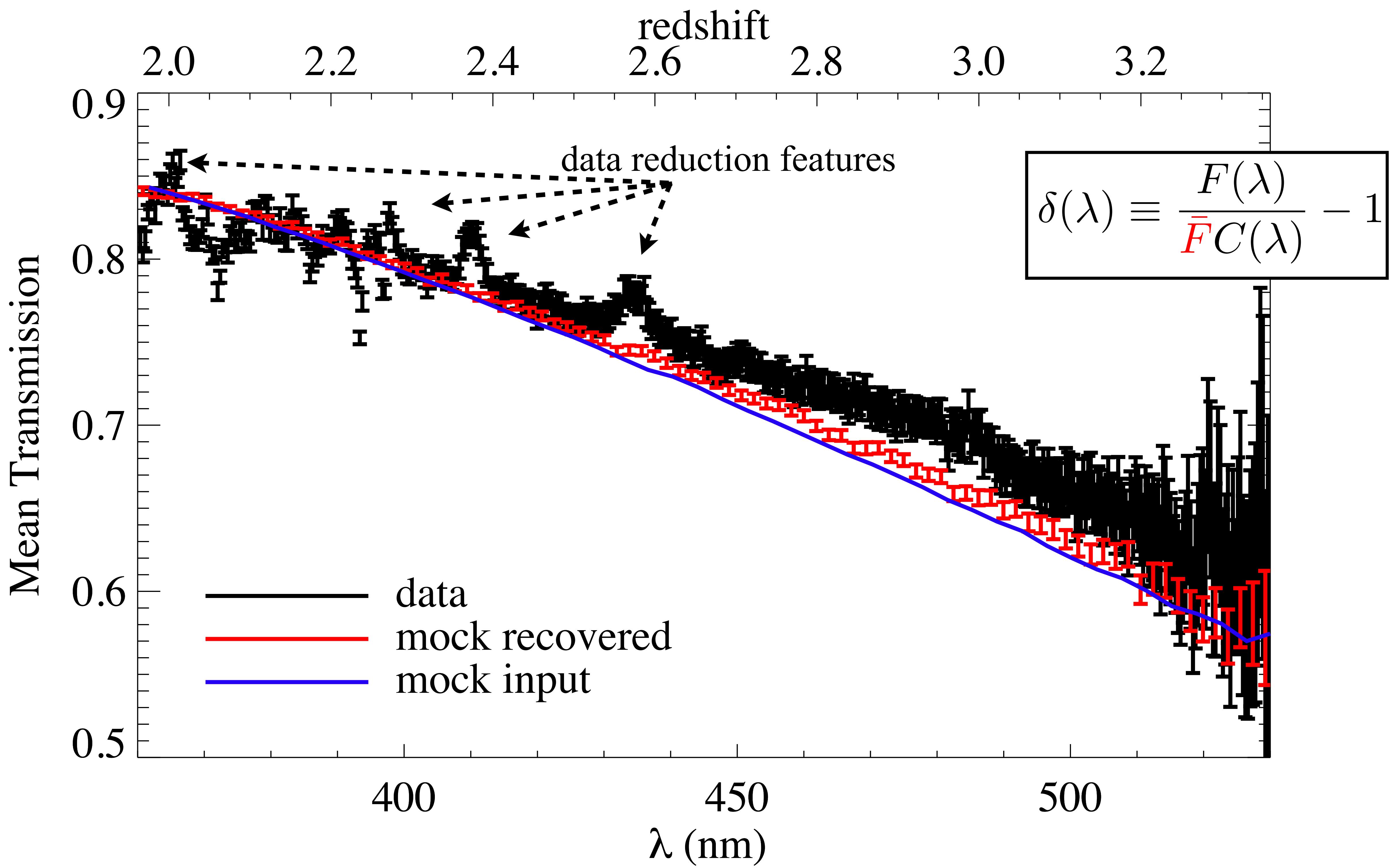


$$\delta(\lambda) \equiv \frac{F(\lambda)}{\bar{F}C(\lambda)} - 1$$

novel maximum likelihood continuum fit
(recovers the unabsorbed level)

The BOSS-Lyα correlation function measurement

2nd step: correct for mean absorption (and instrumental features)

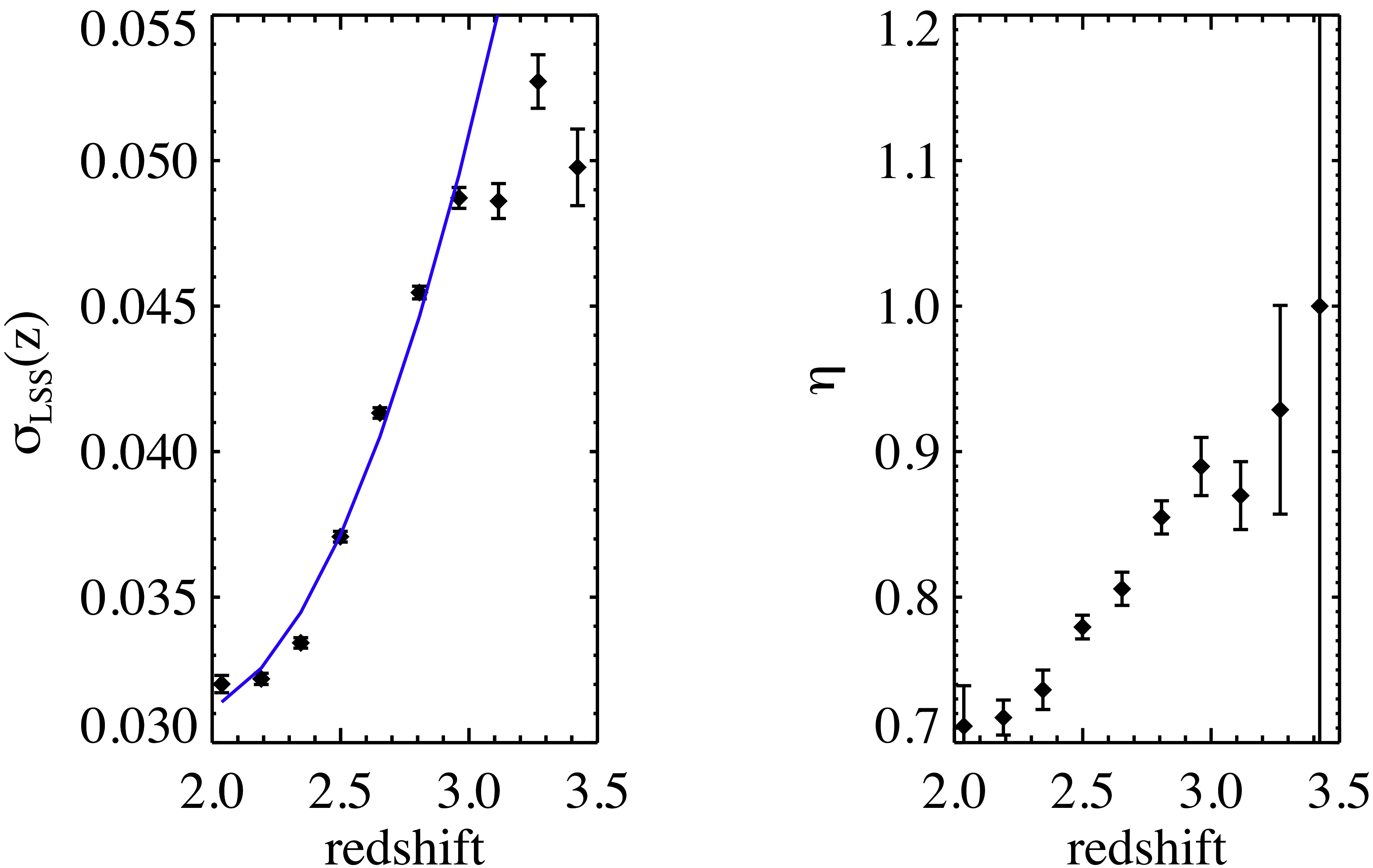


The BOSS-Lyα correlation function measurement

$$\xi(A) = \sum_{i,j \in A} w_{ij} \delta_i \delta_j$$

3rd step: calculate weights

$$\frac{1}{w} = \sigma^2_{\rm total} = \sigma^2_{\rm noise} + \sigma^2_{LSS} \rightarrow \frac{\sigma^2_{\rm pipe}}{\eta(z)} + \sigma^2_{\rm LSS}$$



(measured from data)

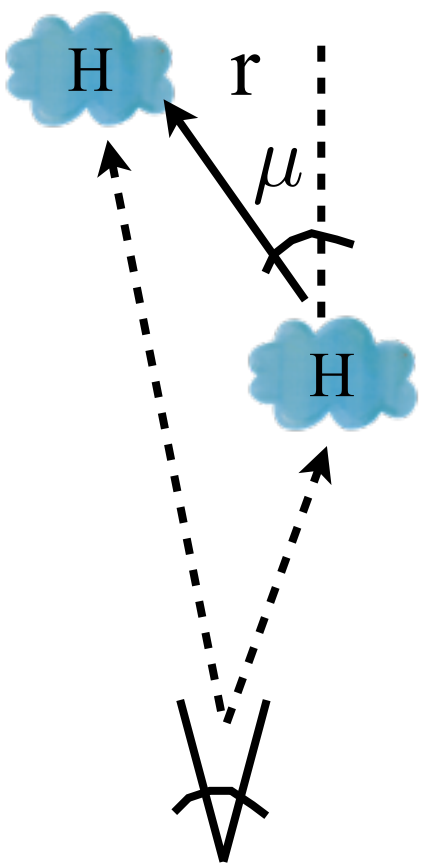
The BOSS-Lyα correlation function measurement

4th step: sum over all pairs of deltas

$$\xi(A) = \sum_{i,j \in A} w_{ij} \delta_i \delta_j$$

5th step: multipole expansion (account for redshift space distortions)

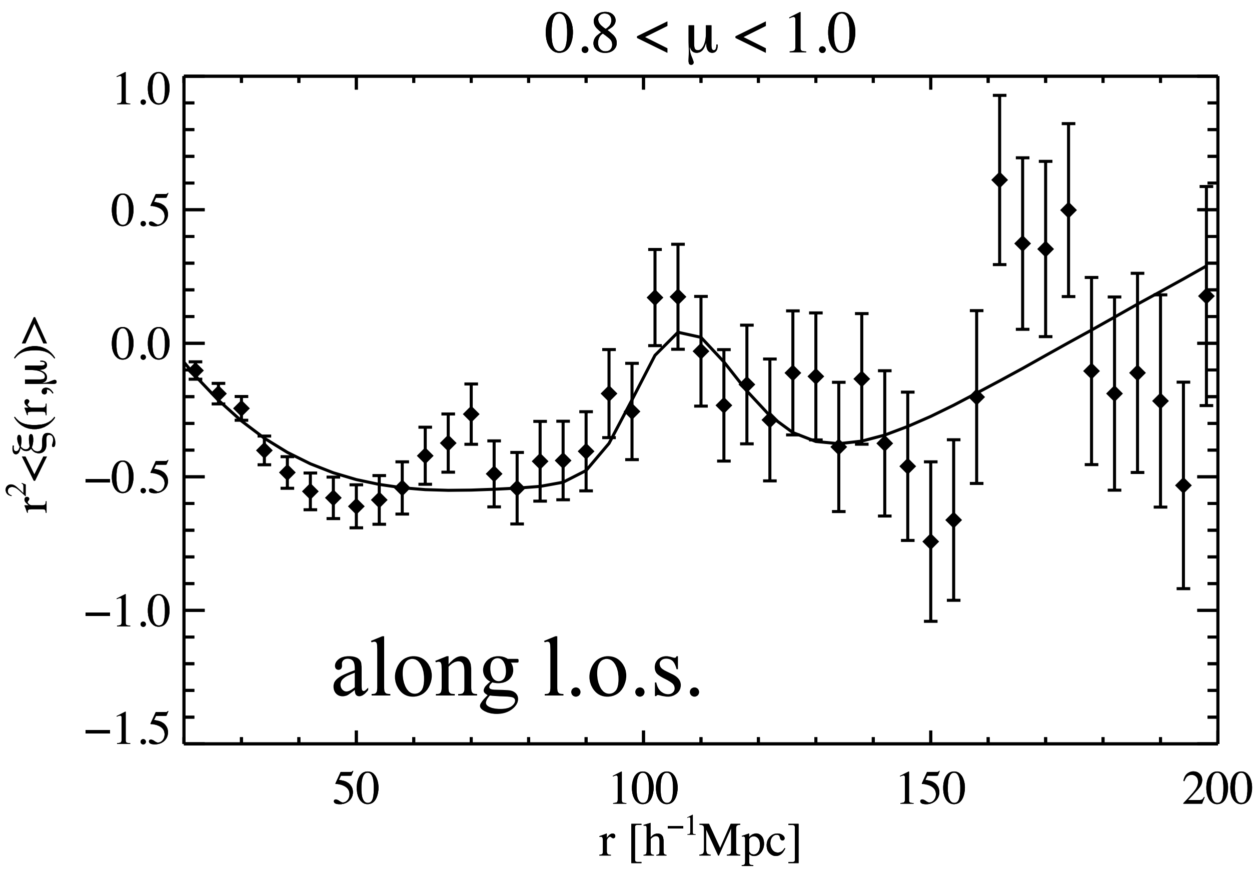
$$\xi(r_{\parallel}, r_{\perp}) = \xi_0(r) + \xi_2(r) P_2(\mu) + \xi_4(r) P_4(\mu) + ...$$

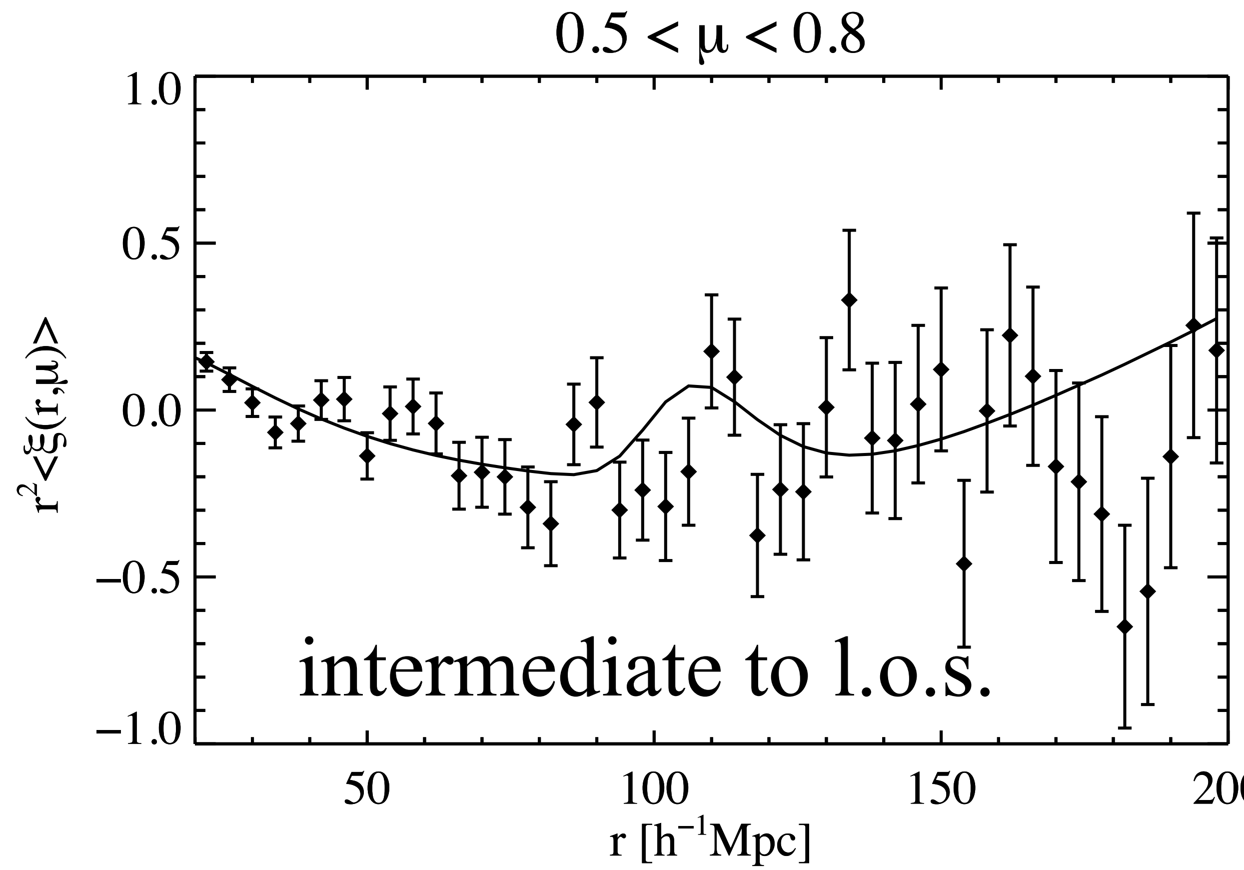


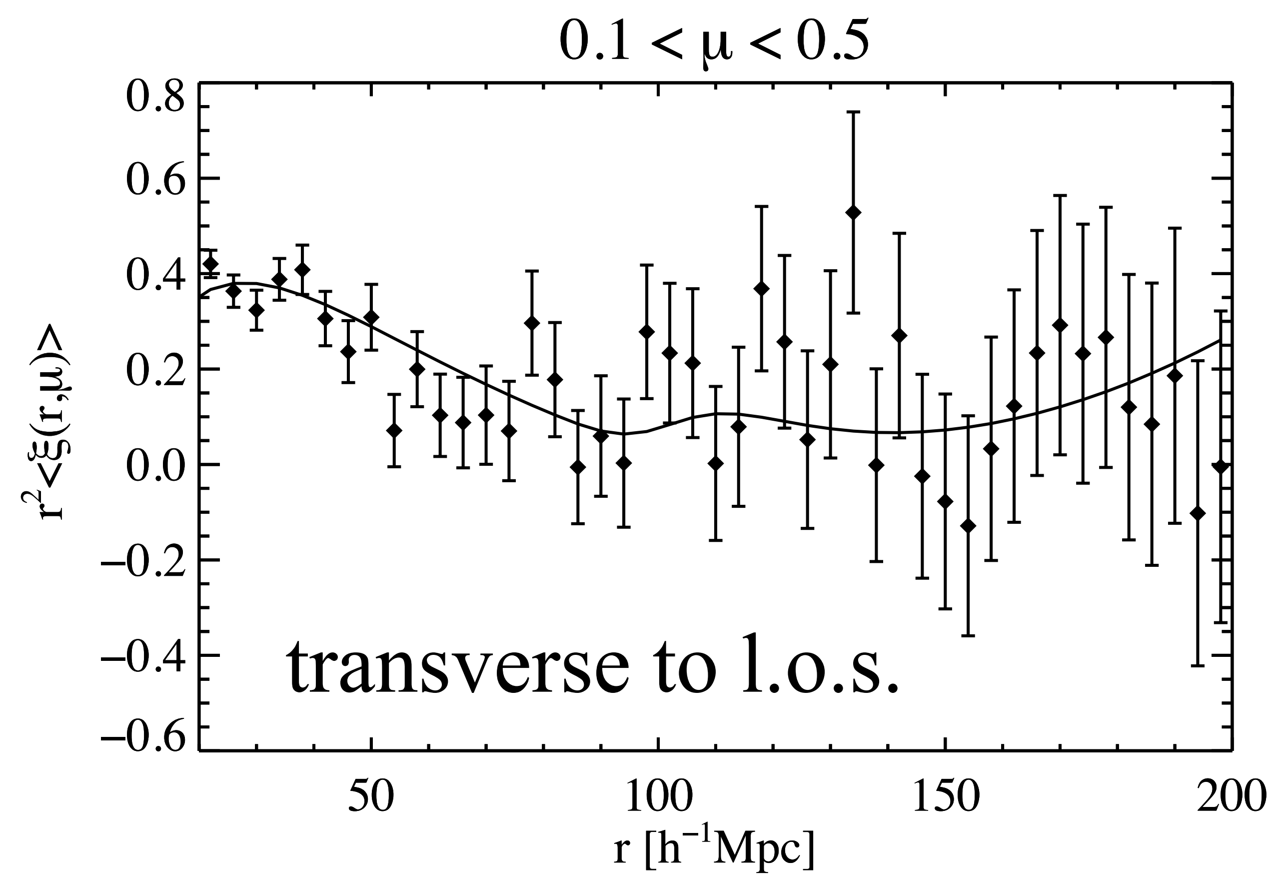
$$r = \sqrt{r_{\parallel}^2 + r_{\perp}^2}$$

$$\mu = \frac{r_{\parallel}}{r}$$

The BOSS-Lyα correlation function measurement

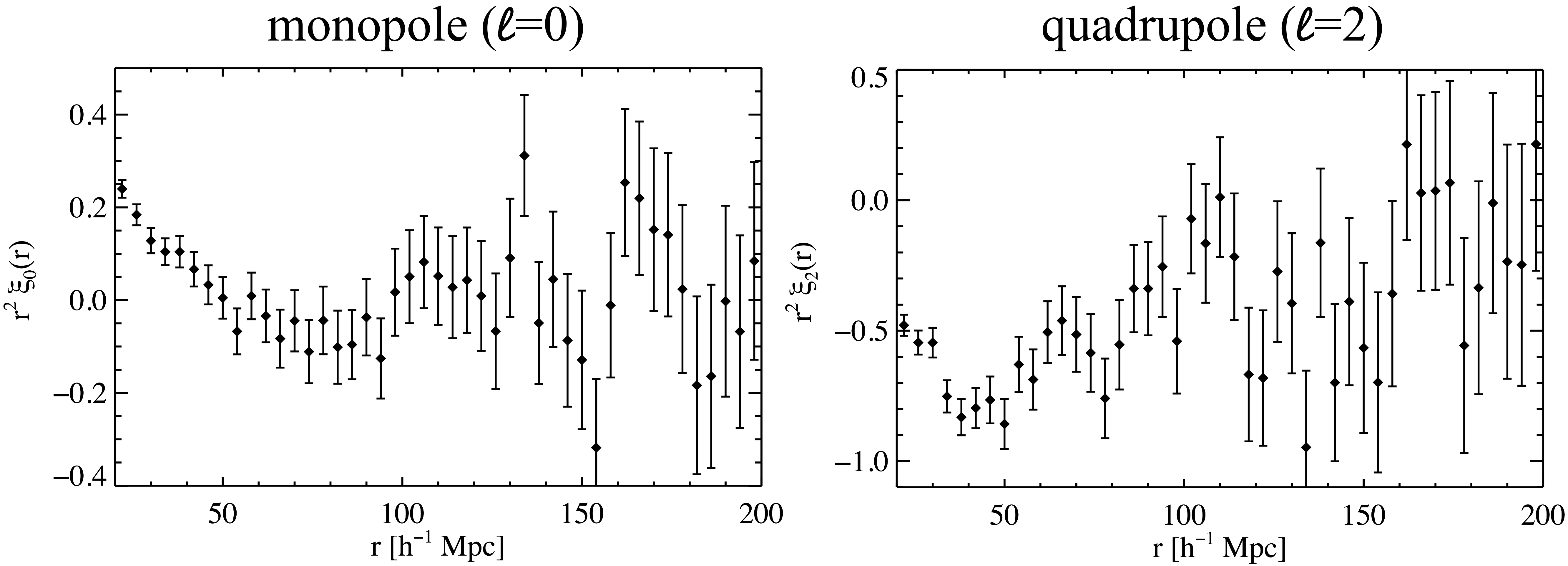






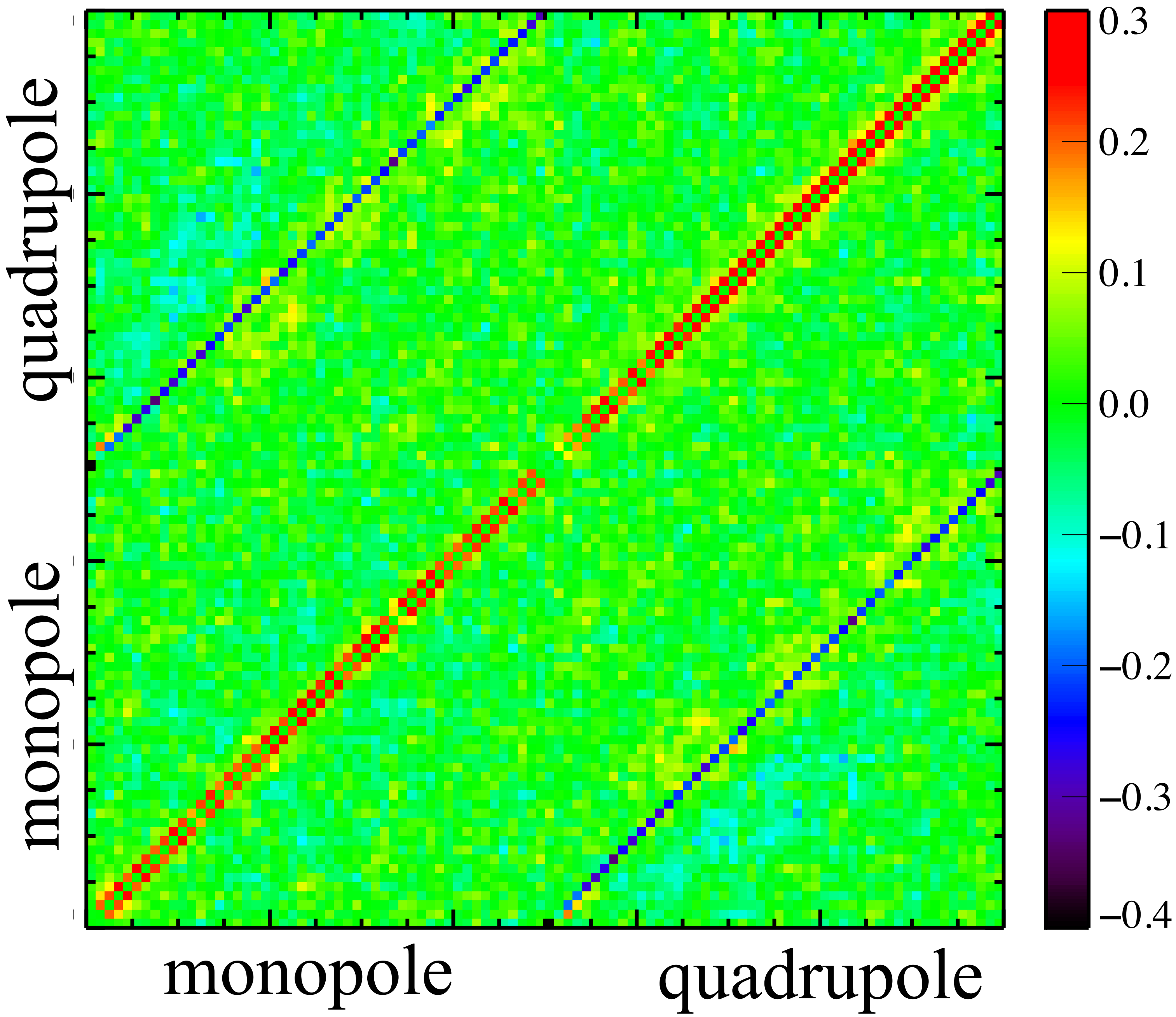
The BOSS-Lyα correlation function measurement

results: multipole expansion



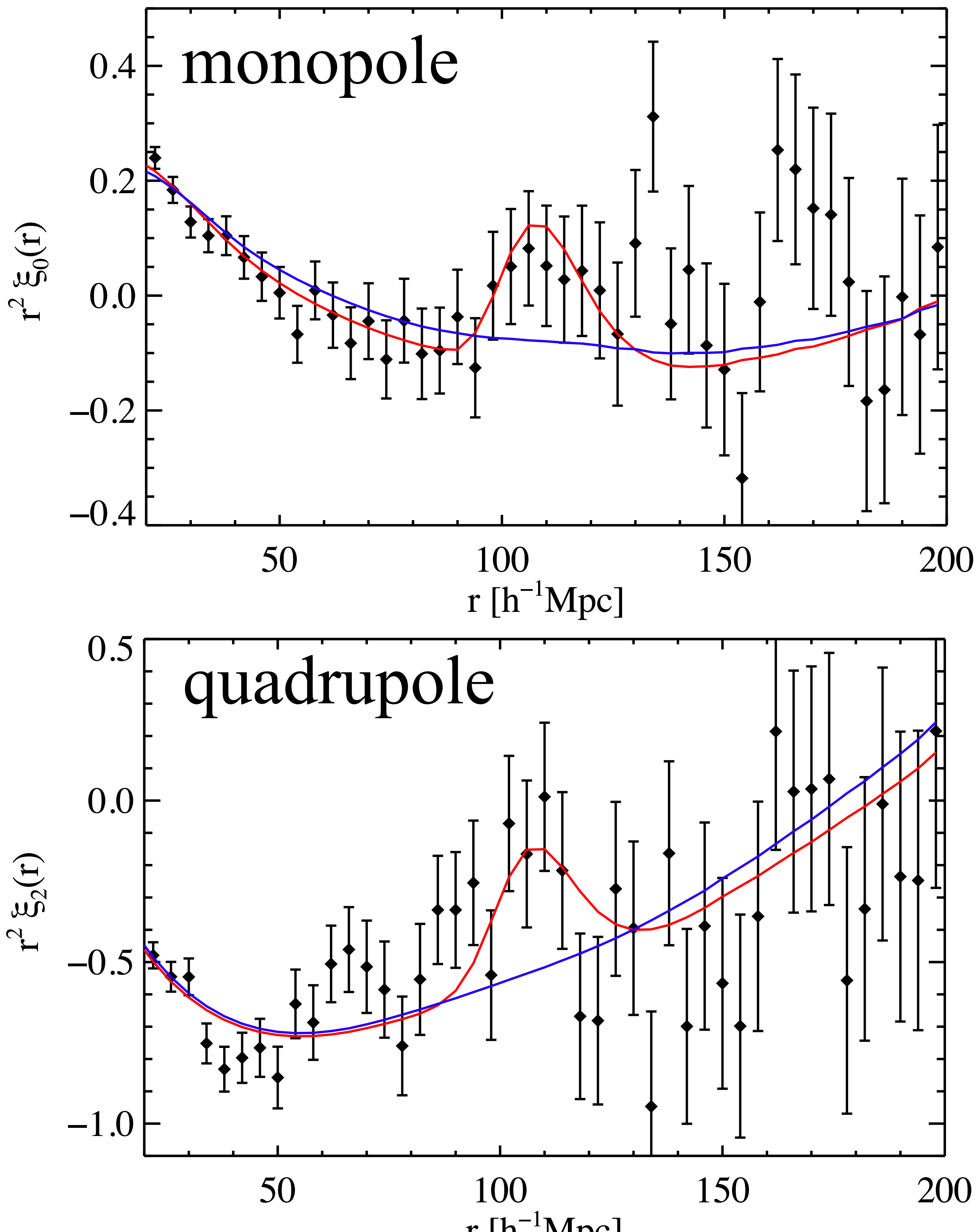
The BOSS-Lyα correlation function measurement

results: correlation matrix (from bootstrap)



- 1 in the diagonal (by construction)
- ~ 30% correlation between neighbouring bins
- ~ -25% correlation between mono-quad bins

The BOSS-Lyα correlation function measurement



peak model: fix H, d_A to fiducial values, fit peak amplitude

no peak model: fix peak amplitude to zero

χ^2_{peak} = 93.3 (83)

$\chi^2_{no\ peak}$ = 111.41 (82)

$\Delta\chi^2$ = 18.1 (significance 4.25 sigma)

(though starting the fit at higher r_{min} reduces the significance)

Fitting for cosmological parameters

Fits: cosmological fits

- Fiducial vs. true cosmology:

$$\xi'(r'_{\|}, r'_{\perp}) = \xi(\alpha_H r_{\|}, \alpha_{d_A} r_{\perp})$$

where

$$\alpha_H \equiv r_s H/(r_s H)_{\mathrm{fid}} \qquad \alpha_{\mathrm{d_A}} \equiv \frac{(d_A/r_s)_{\mathrm{fid}}}{(d_A/r_s)}$$

Fitting for cosmological parameters

Fits: cosmological fits

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where

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- Calculate mono and quad in the fiducial cosmo

$$\xi'_\ell(r') = \int_{-1}^{1} d\mu' P_\ell(\mu') \xi(\alpha_H r_{\parallel}, \alpha_{d_A} r_{\perp})$$

Fitting for cosmological parameters

Fits: cosmological fits

- Fiducial vs. true cosmology:

$$\xi'(r'_{\parallel}, r'_{\perp}) = \xi(\alpha_H r_{\parallel}, \alpha_{d_A} r_{\perp})$$

where

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- Calculate mono and quad in the fiducial cosmo

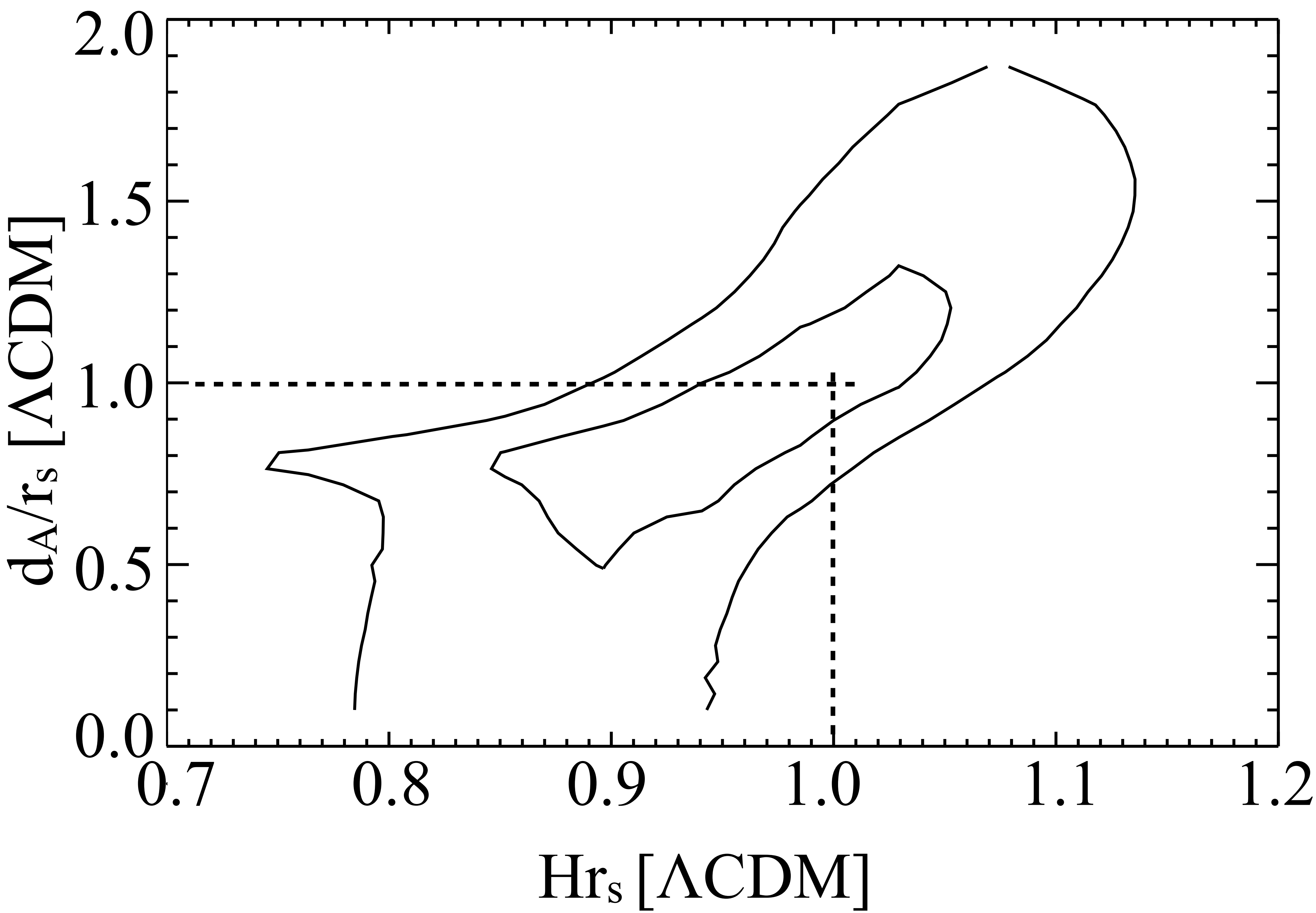
$$\xi'_\ell(r') = \int_{-1}^{1} d\mu' P_\ell(\mu') \xi(\alpha_H r_{\parallel}, \alpha_{d_A} r_{\perp})$$

- Add a "flexible broadband" (10 parameters)

$$\xi_\ell^{\mathrm{fit}}(r') = a_\ell + \frac{b_\ell}{r'} + \frac{c_\ell}{r'^2} + \frac{d_\ell}{\sqrt{r'}} + \xi'_\ell(r')$$

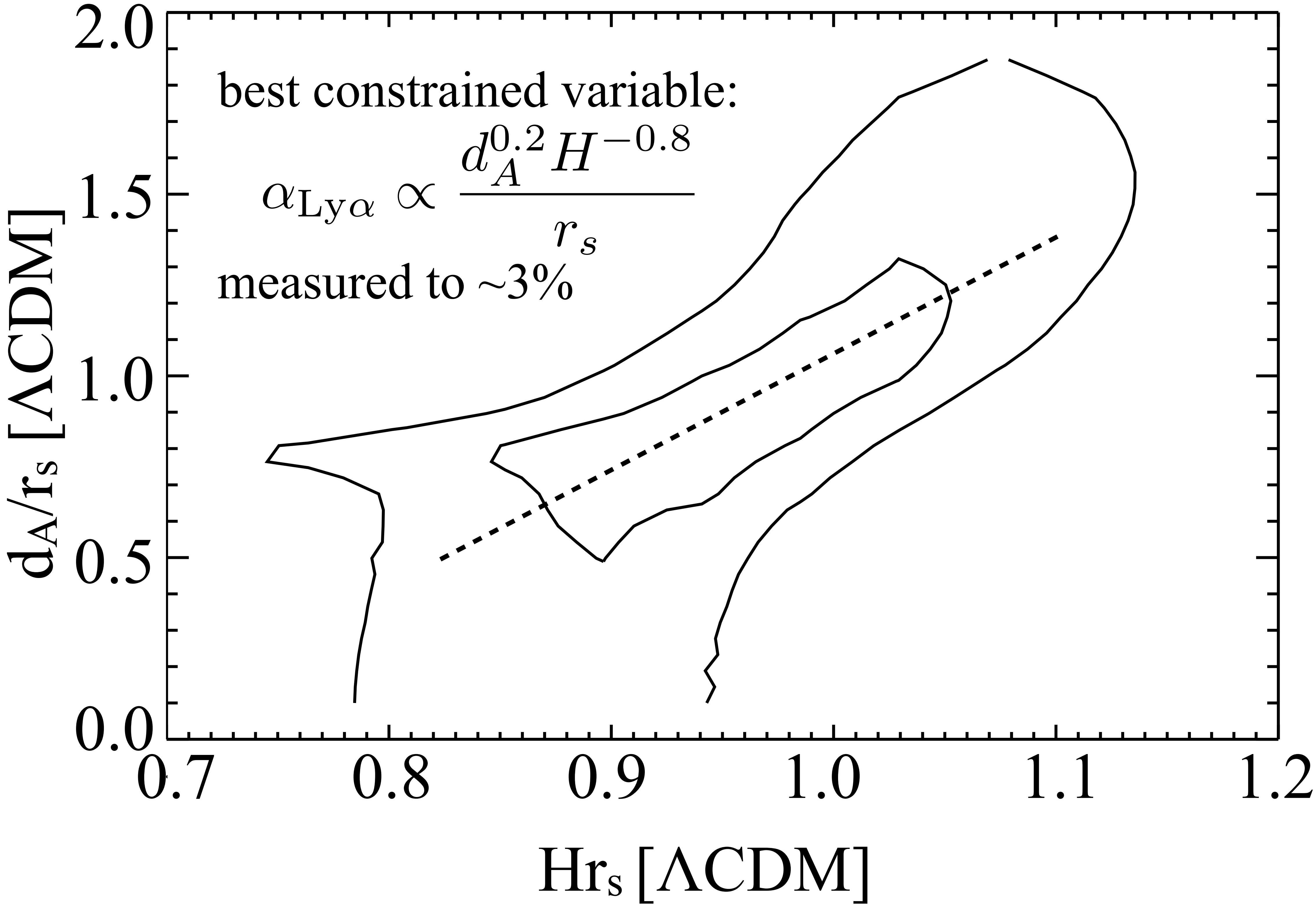
Results

contours for H, d_A (marginalized over all other parameters)



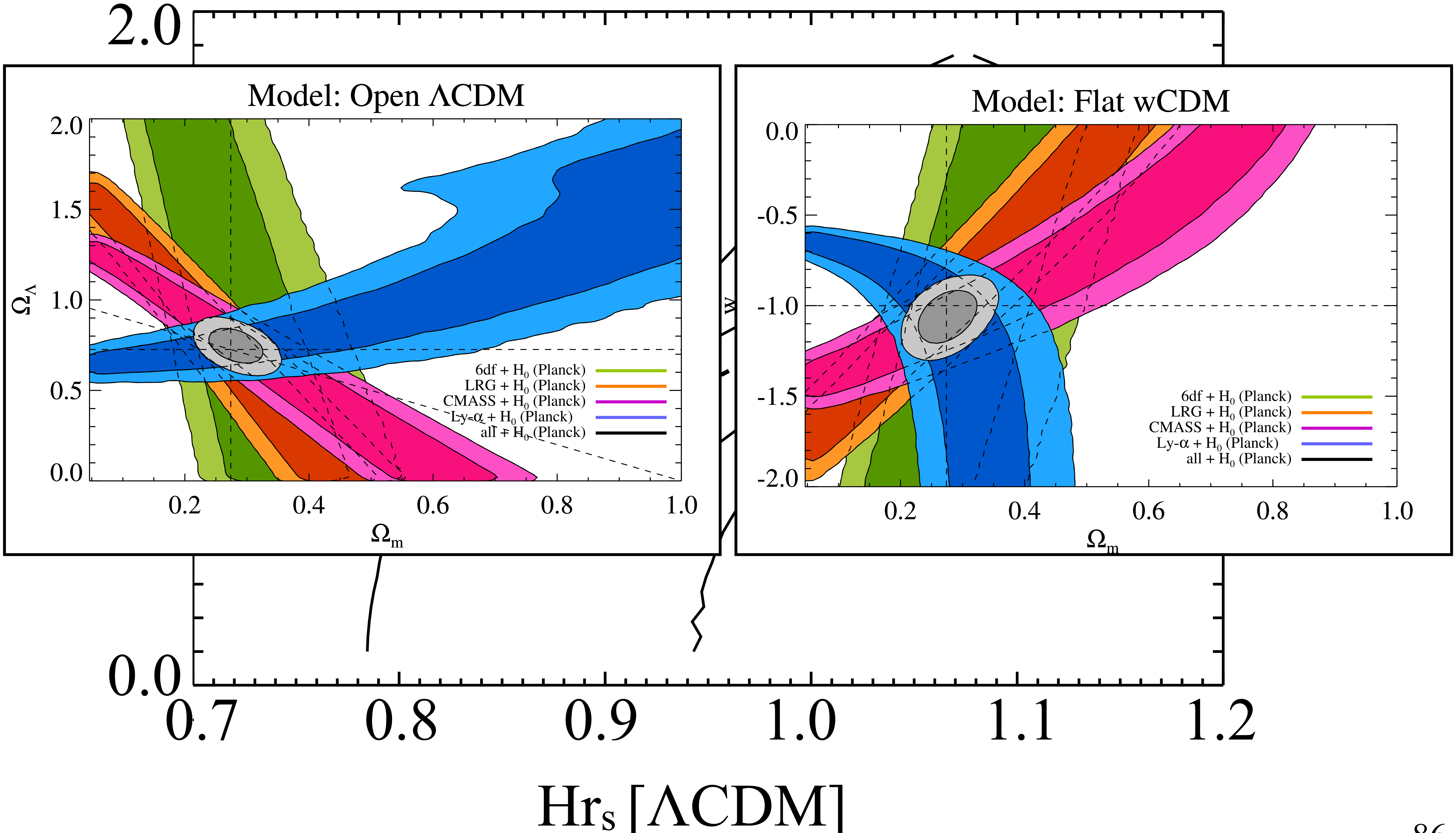
Results

contours for H, d_A (marginalized over all other parameters)

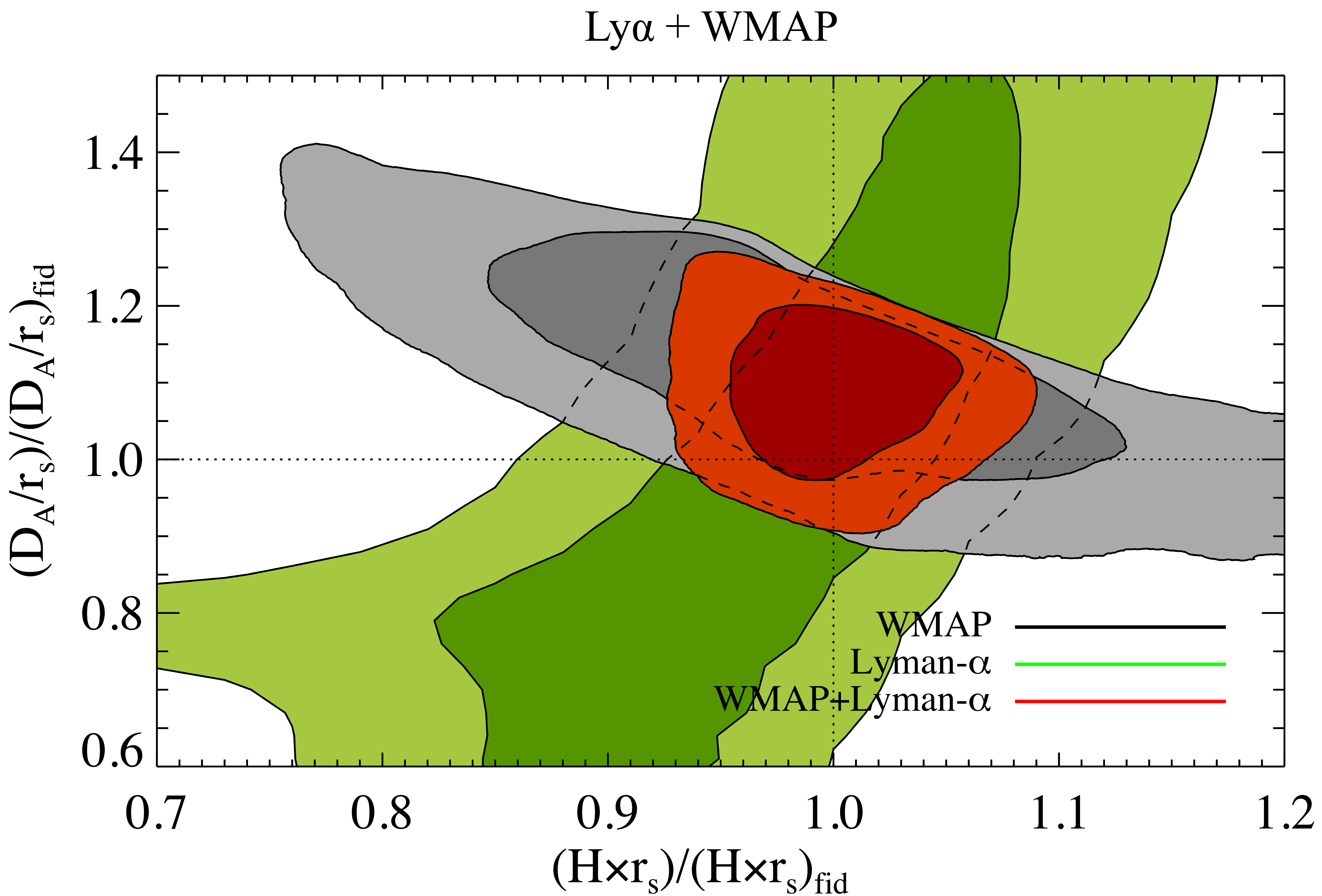


Results

contours for H, d_A (marginalized over all other parameters)

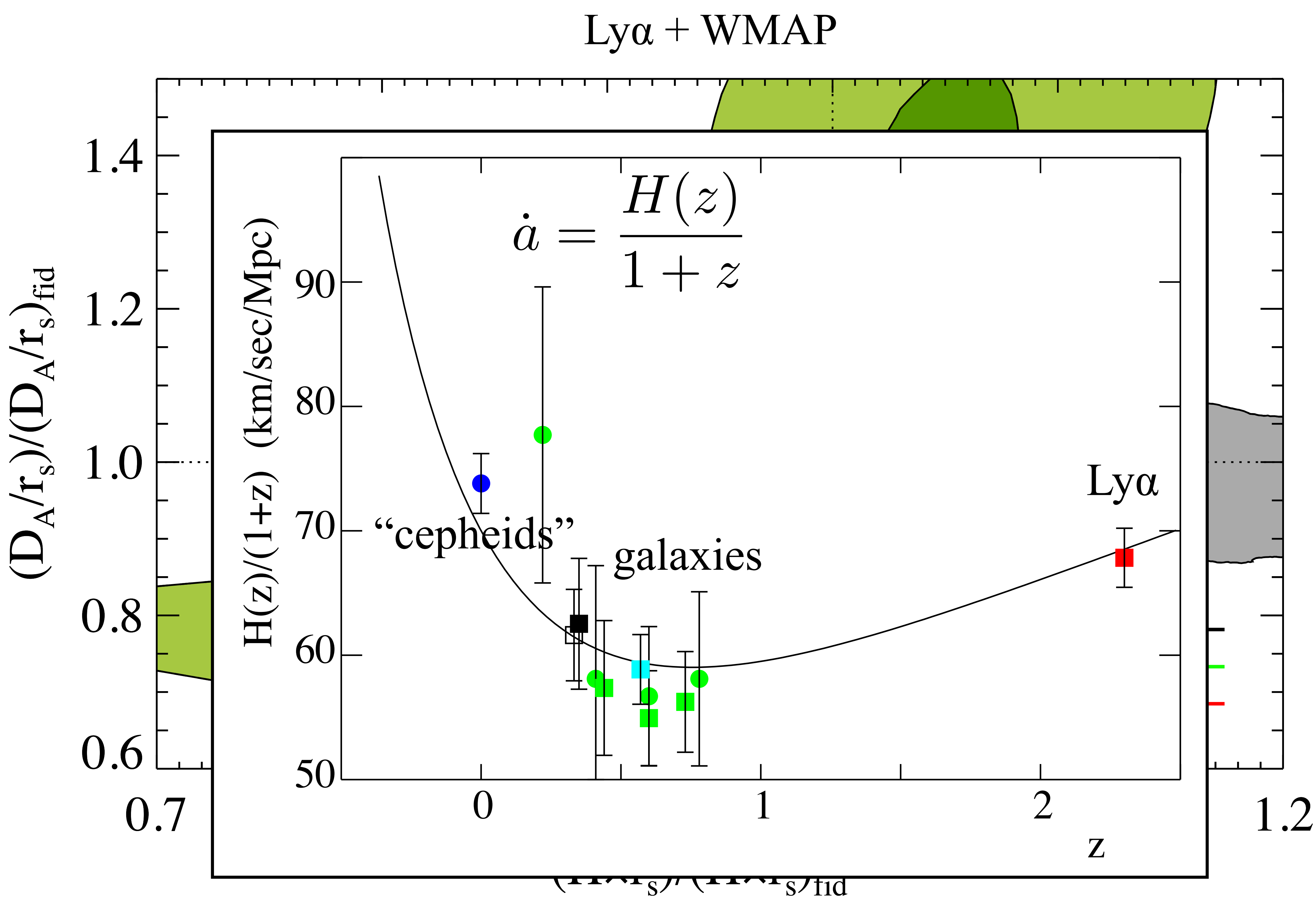


Results



Lyα + WMAP
1.4
1.2
1.0
0.8
0.6
$(D_A/r_s)/(D_A/r_s)_{fid}$
0.7
0.8
0.9
1.0
1.1
1.2
$(H\times r_s)/(H\times r_s)_{fid}$
WMAP
Lyman-α
WMAP+Lyman-α

Results



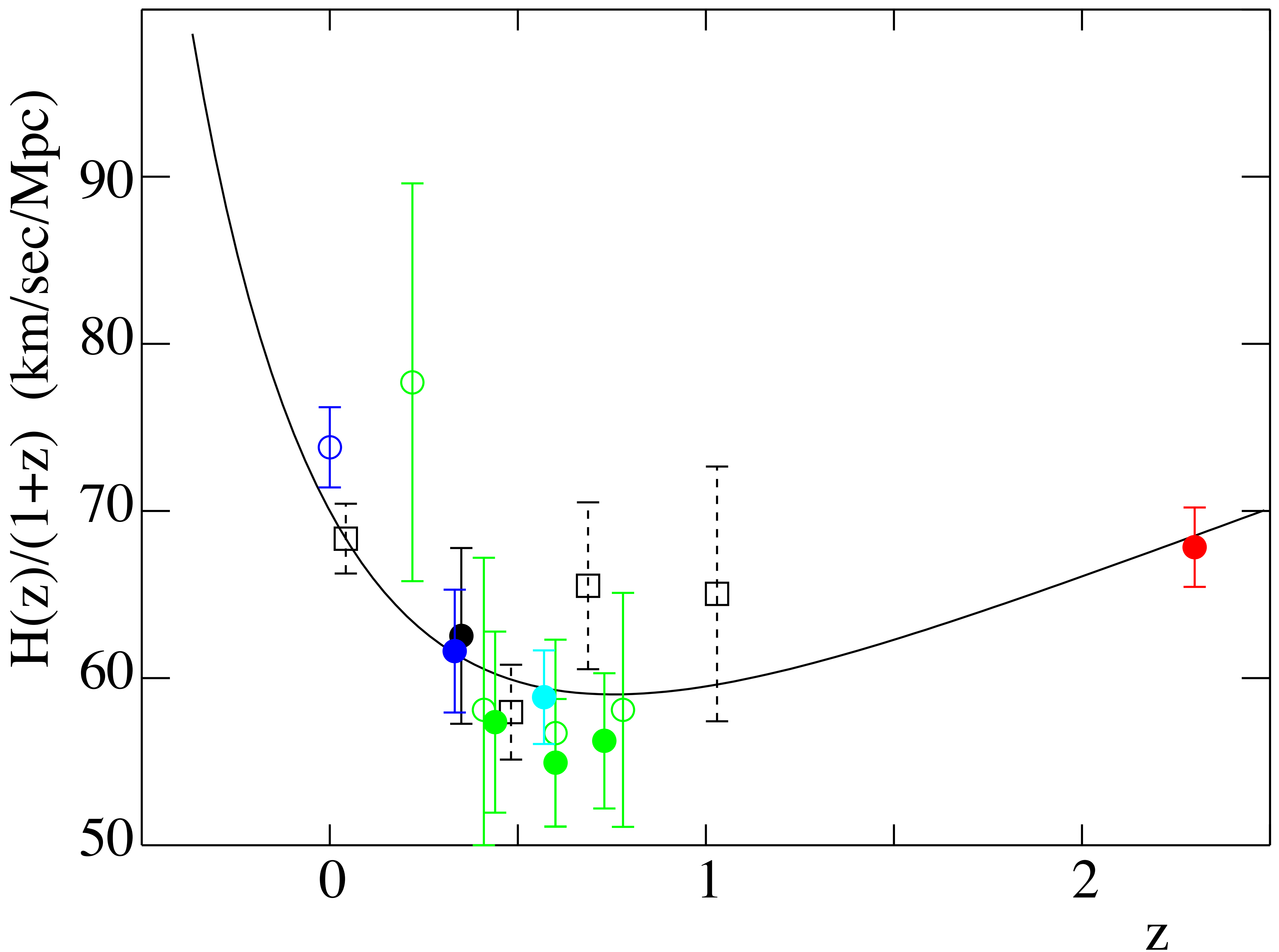
Lyα + WMAP
$(D_A/r_s)/(D_A/r_s)_{fid}$
$(H \times r_s)/(H \times r_s)_{fid}$
1.4
1.2
1.0
0.8
0.6
0.7
1.2
$\dot{a} = \frac{H(z)}{1+z}$
H(z)/(1+z) (km/sec/Mpc)
90
80
70
60
50
0
1
2
z
"cepheids"
galaxies
Lyα

Conclusions

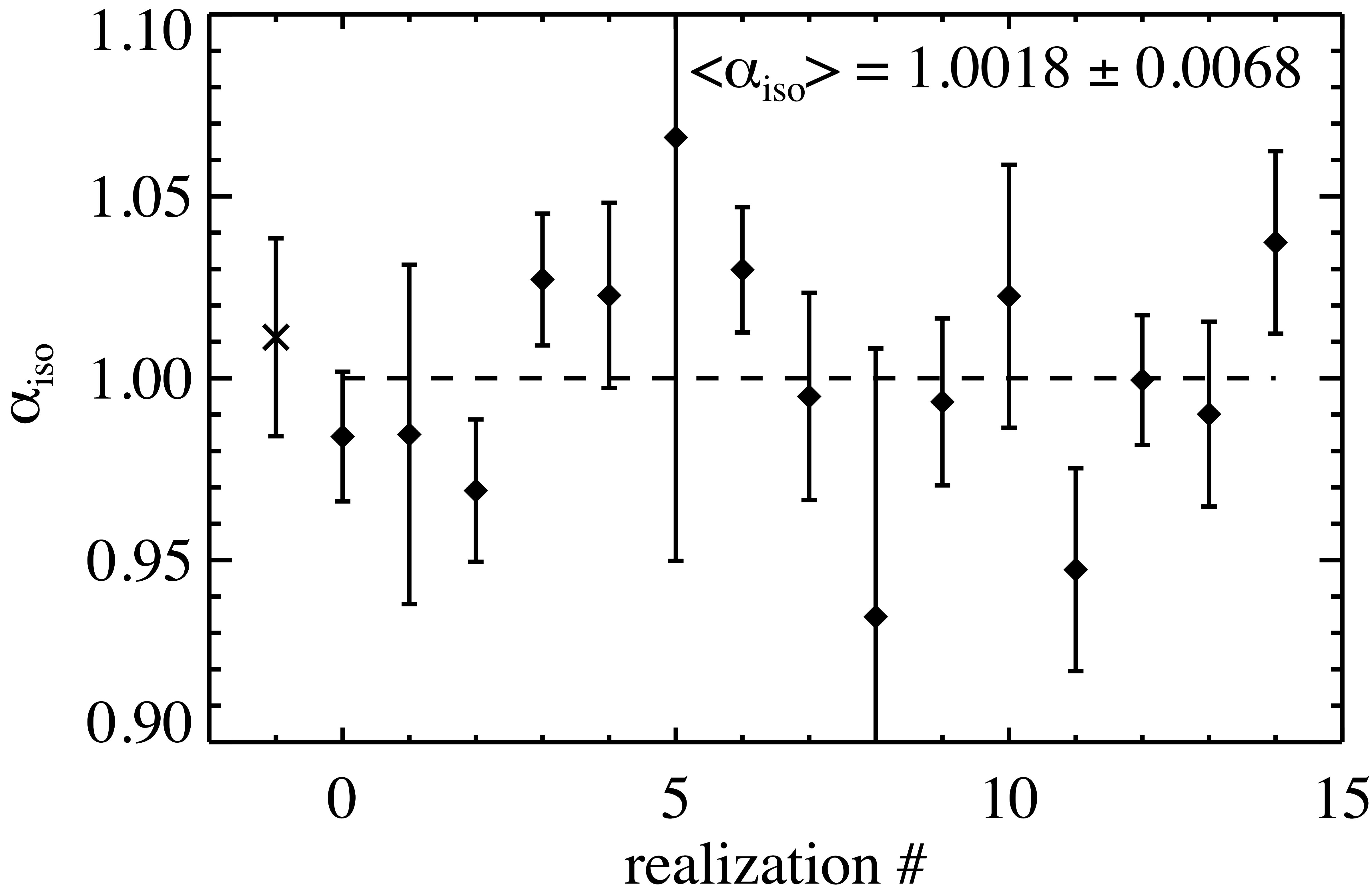
The BAO-Lyα works!

- First observation of the BAO peak at z ~ 2.3
- So far the highest z, deep in the matter domination epoch, able to measure H (with little model dependence)
- Measurement of H at high at z ~2.3 demonstrates the deceleration preceding the expansion
- Lyα data breaks degeneracies in the (Ω_m, Ω_Λ) and (Ω_m,w) plane confirming the concordance ΛCDM paradigm
- Future: full BOSS (3x this study), BigBOSS (20x full BOSS)

Backup



H(z)/(1+z) (km/sec/Mpc)
90
80
70
60
50
0
1
2
z



1.10
1.05
1.00
0.95
0.90
α_{iso}
$\langle\alpha_{iso}\rangle = 1.0018 \pm 0.0068$
0
5
10
15
realization #