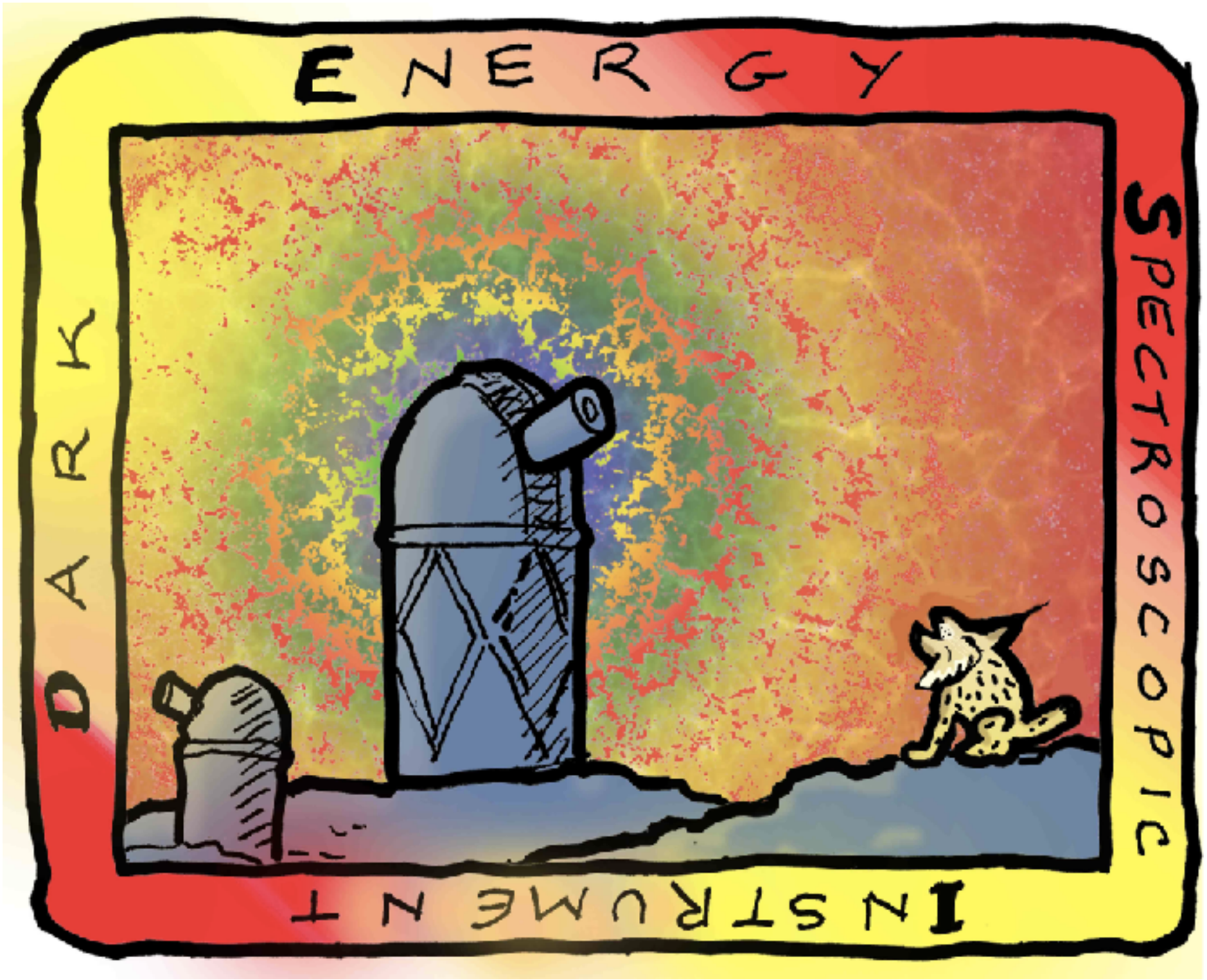
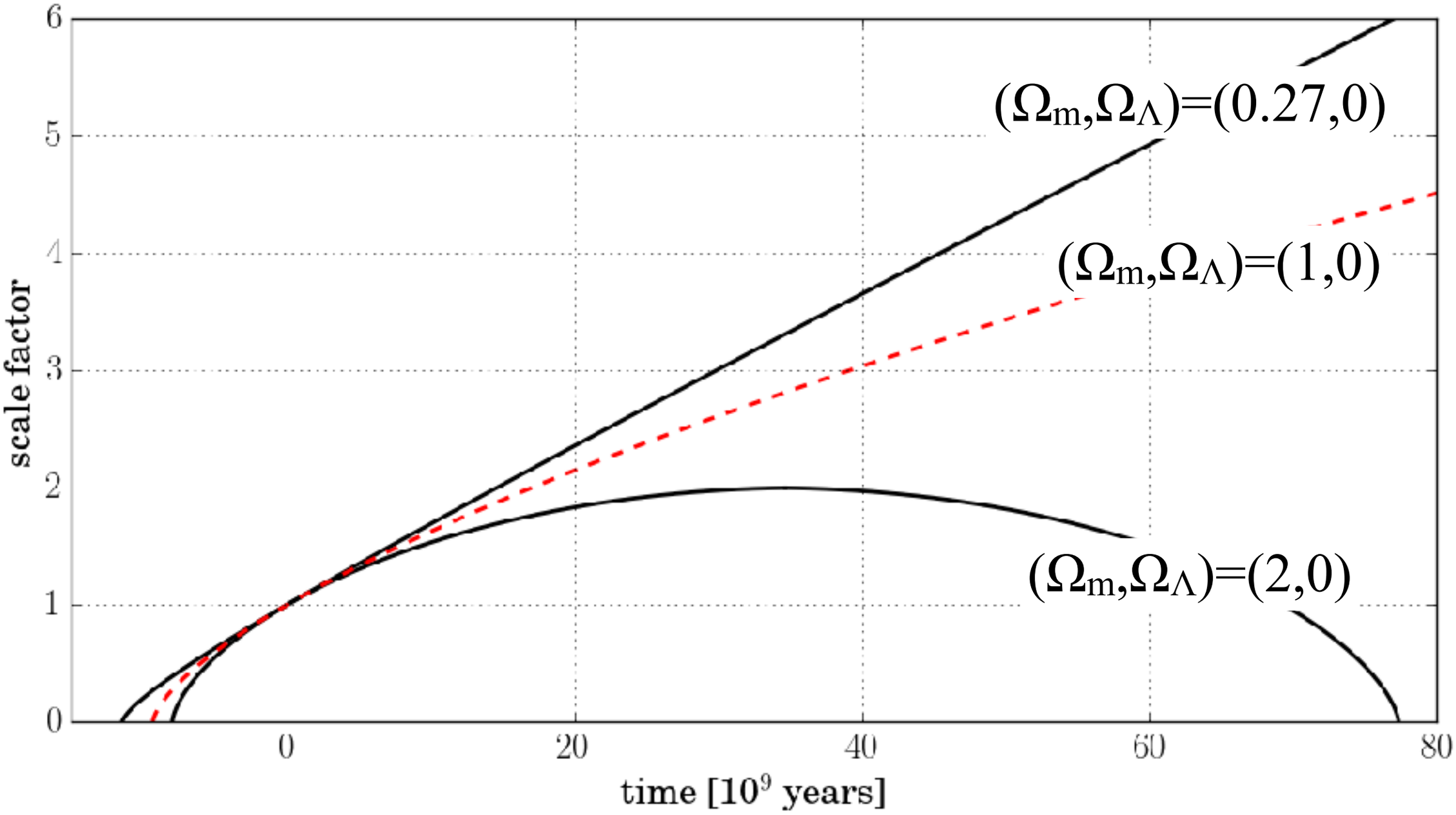
The Dark Energy Spectroscopy Instrument



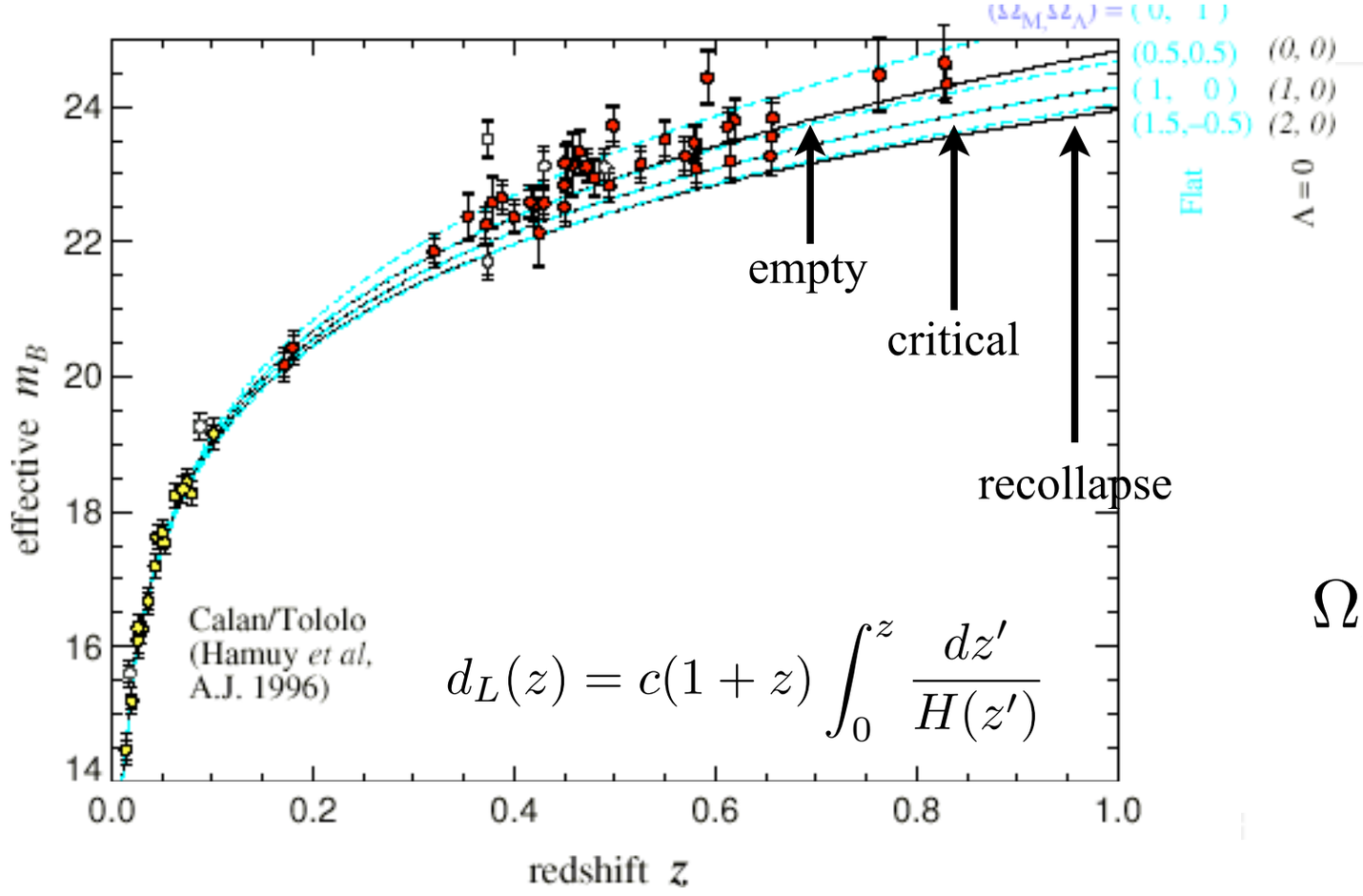
Colloque Énergie Sombre **LAL - 12 Octobre 2017**

The future of the Universe?



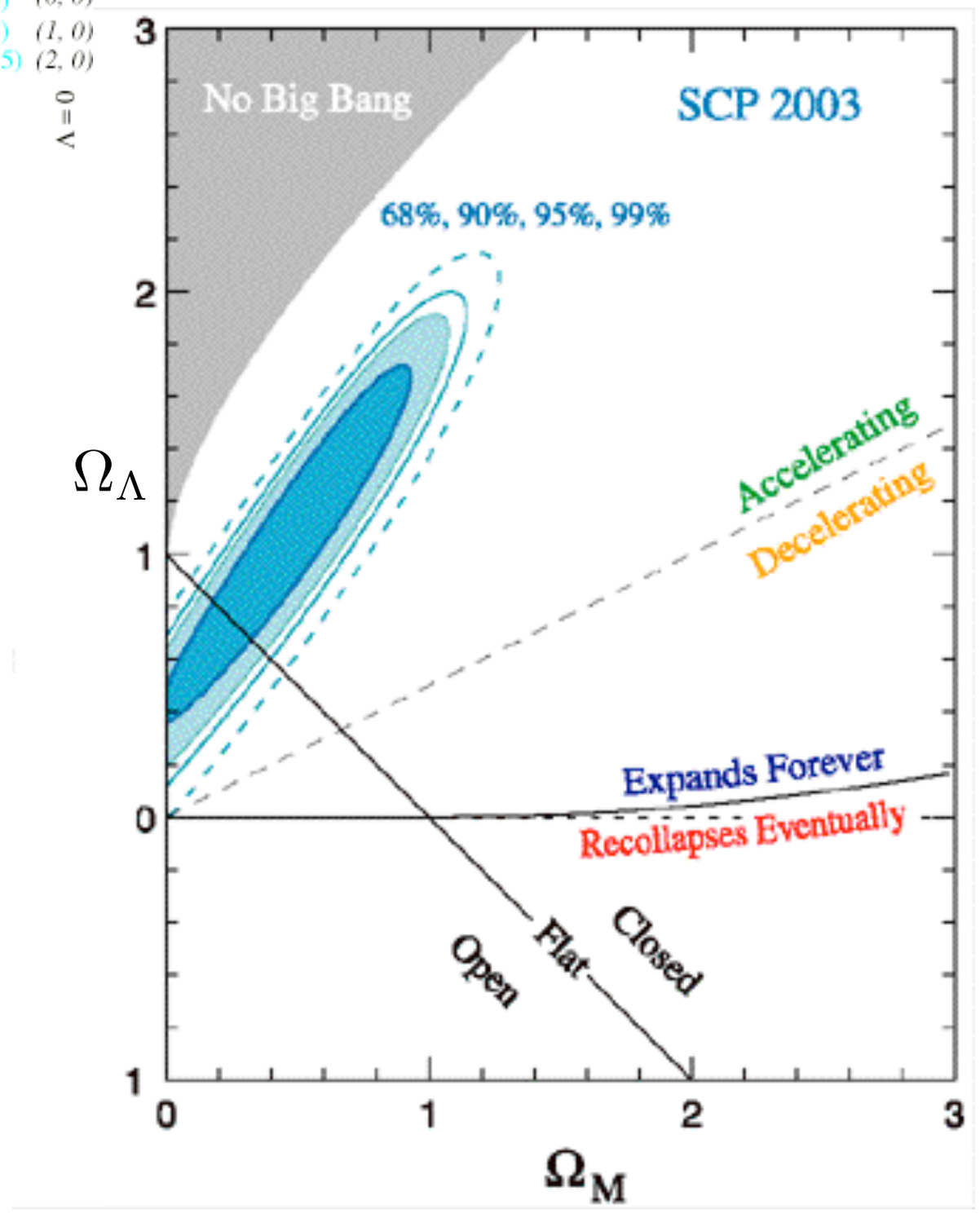
$$\frac{\dot{a}}{a} \equiv H(z) = \sqrt{\Omega_M (1+z)^3} \qquad \Omega_M = \frac{\rho_M}{\rho_c}$$

First detection of accelerated expansion



the data require Λ

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



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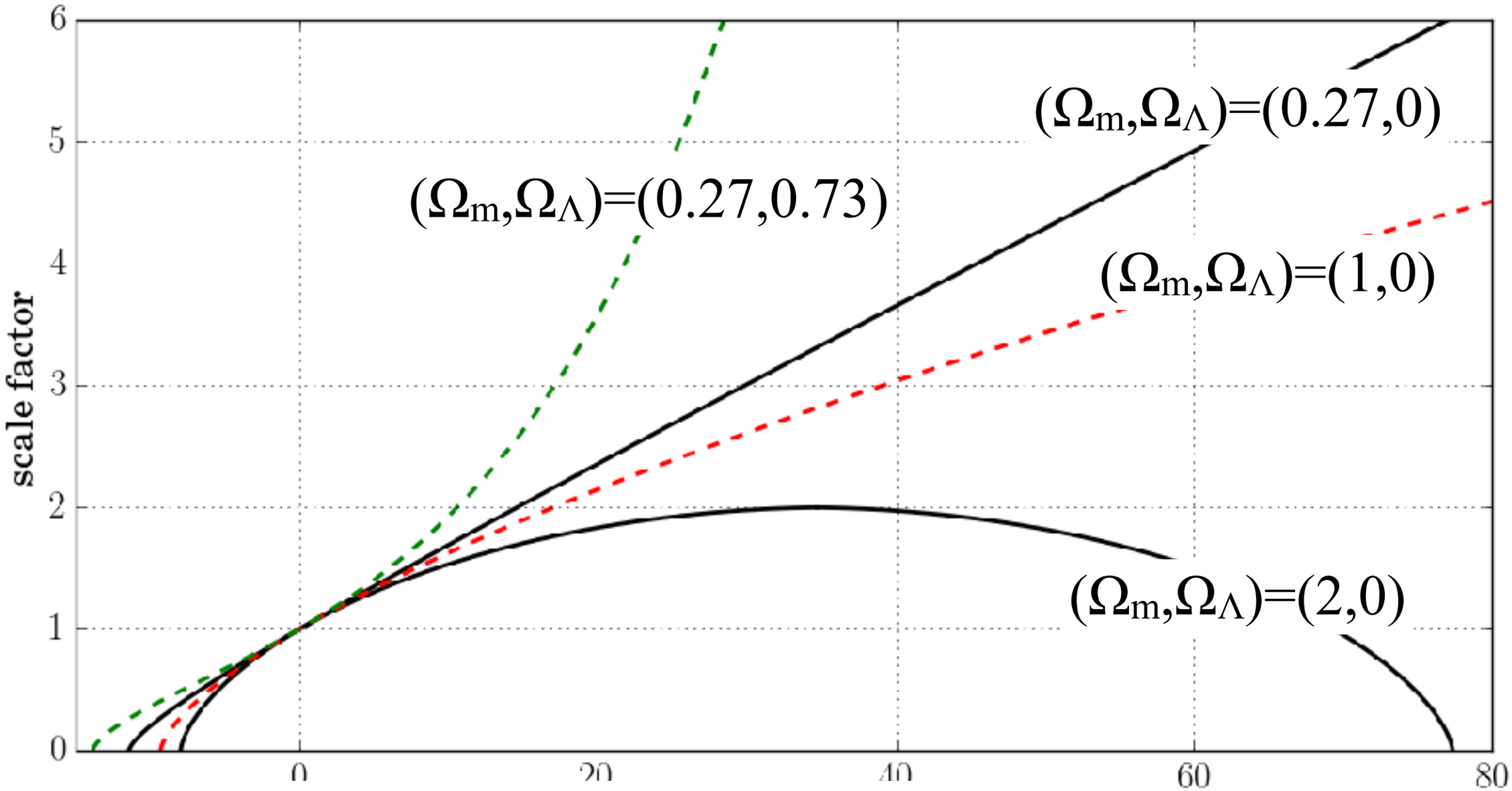

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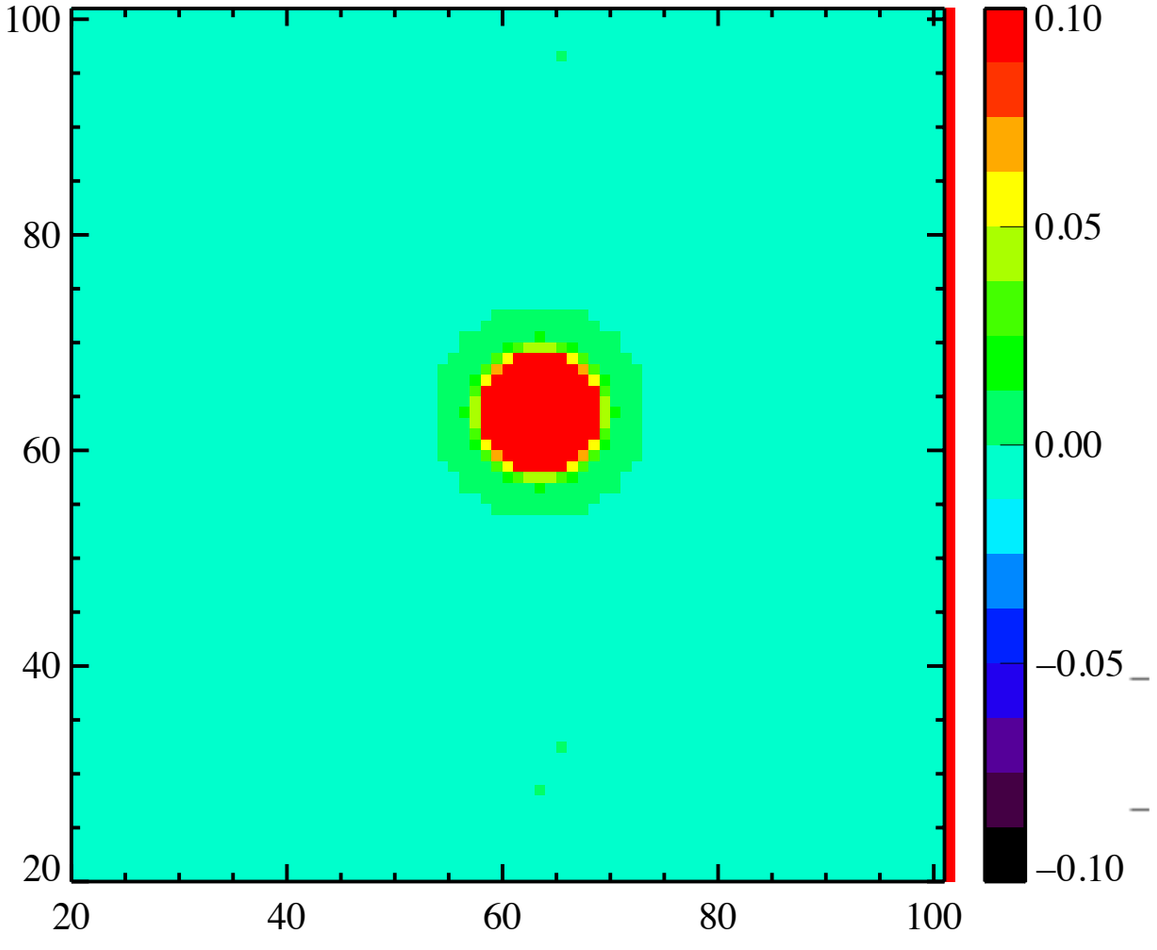
Baryon acoustic oscillations

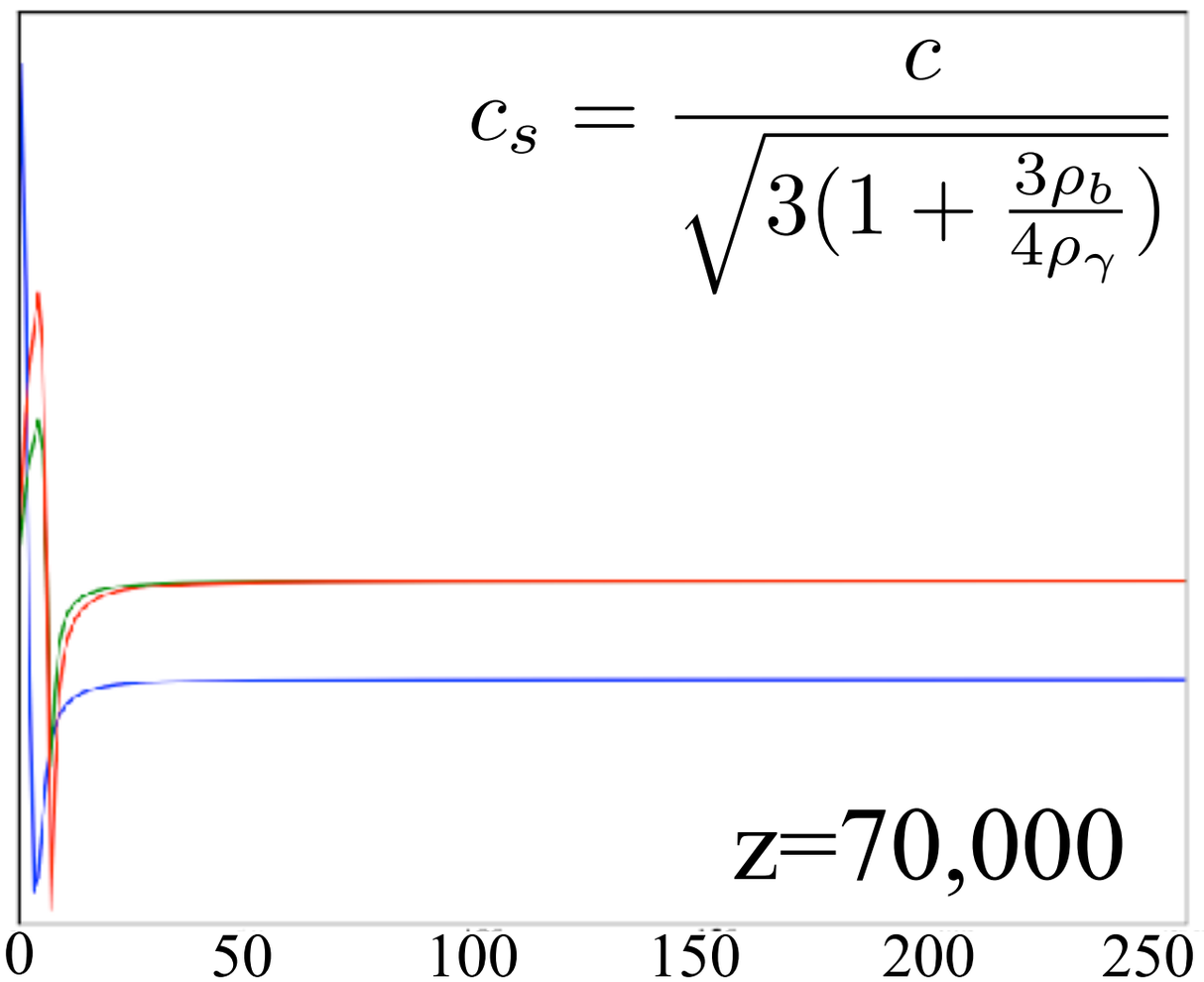
- pressure waves in the early Universe (< 400.000 years after the Big Bang)
- hot and ionized (T ≫ 13.6 eV)
- cosmological scales (c/H(z)) ≫ photon-baryon interaction length

cross-section of a perturbation



correlation function

$$c_s = \frac{c}{\sqrt{3(1+\frac{3\rho_b}{4\rho_\gamma})}}$$



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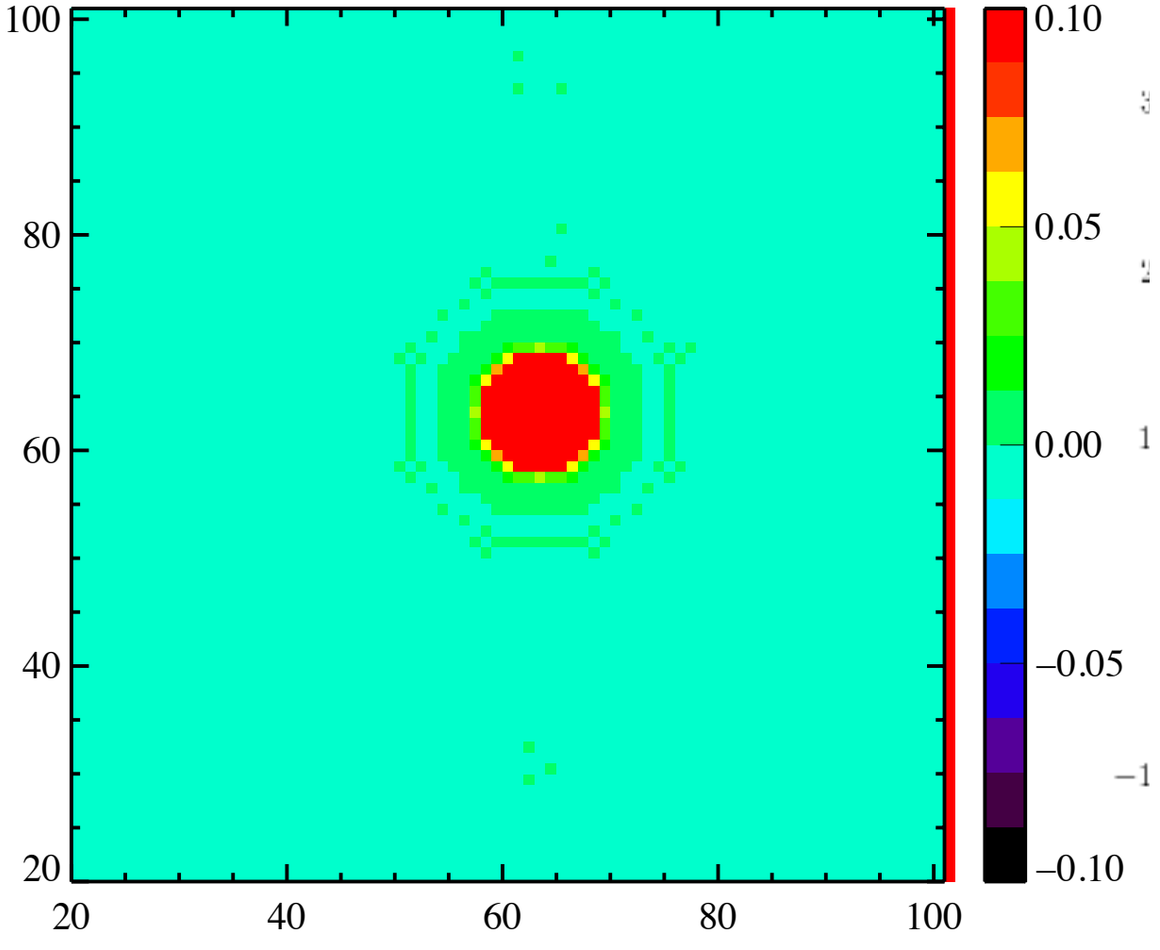

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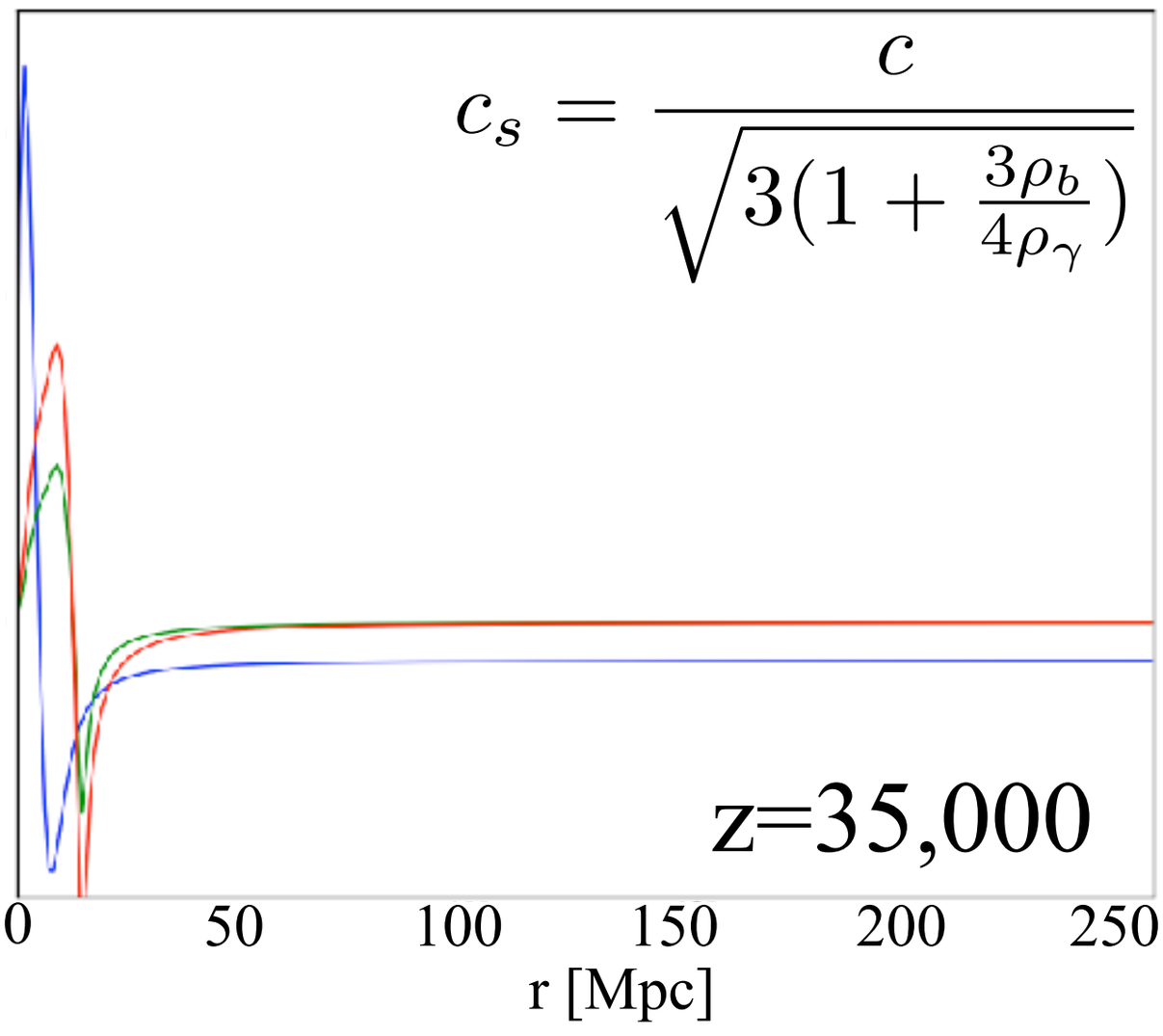

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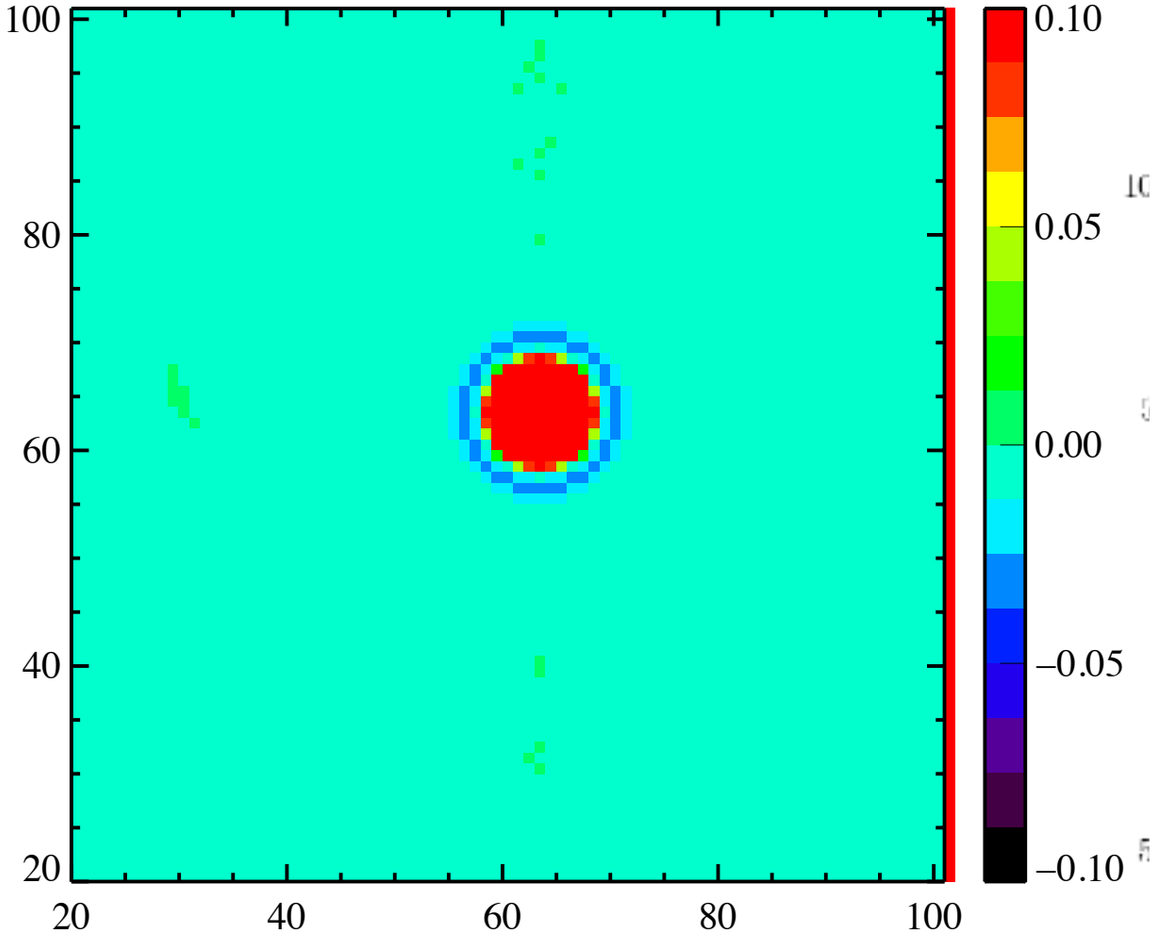

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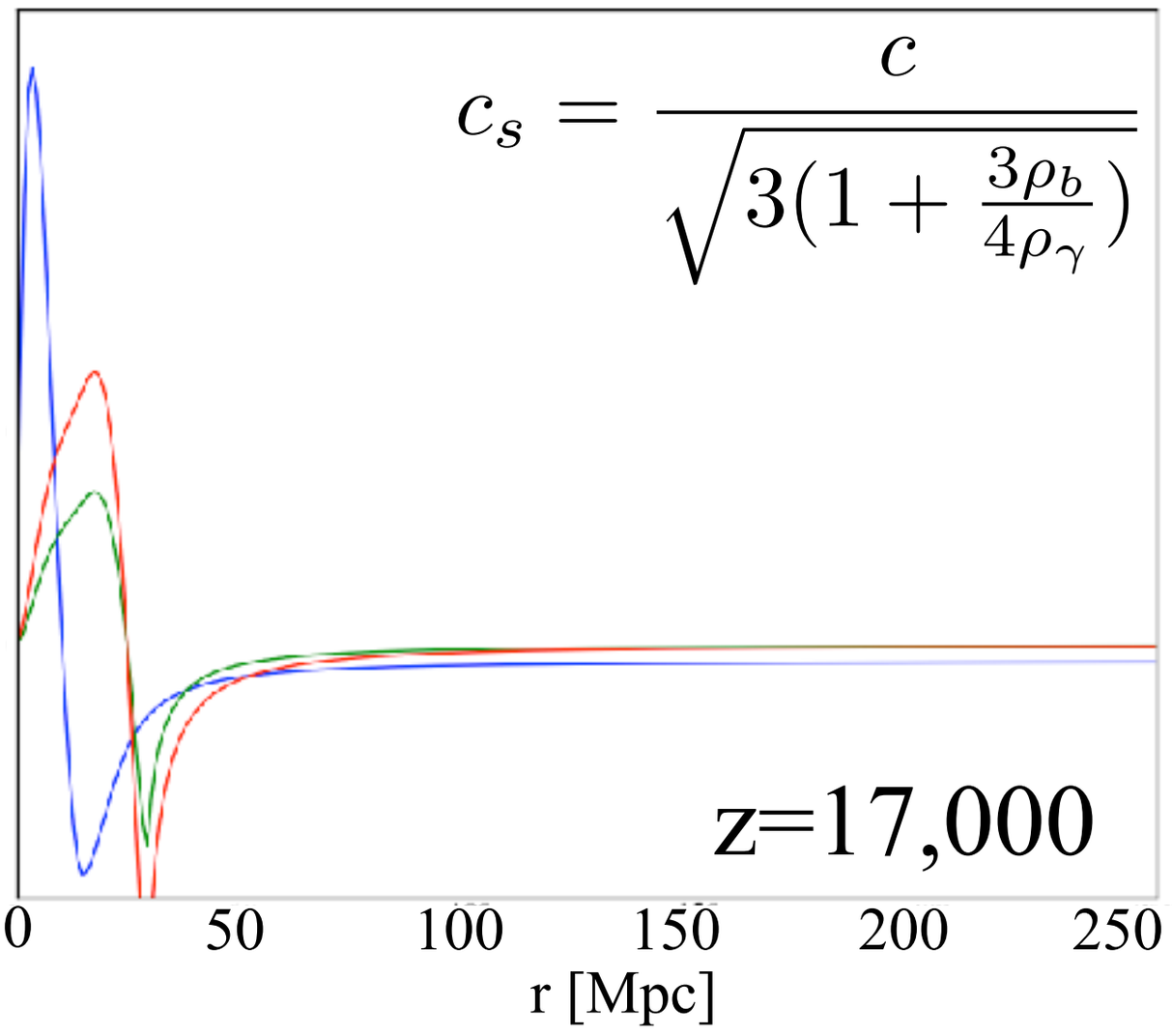

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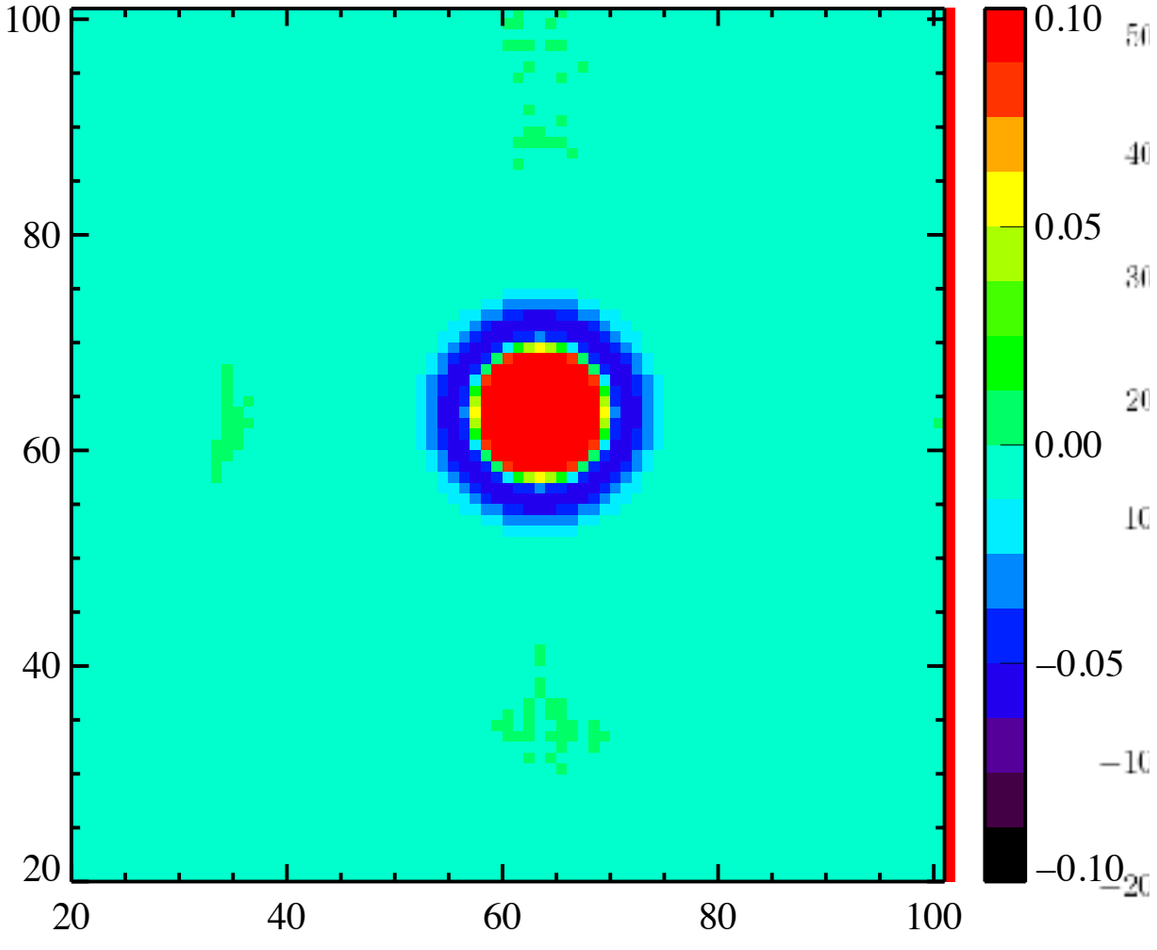

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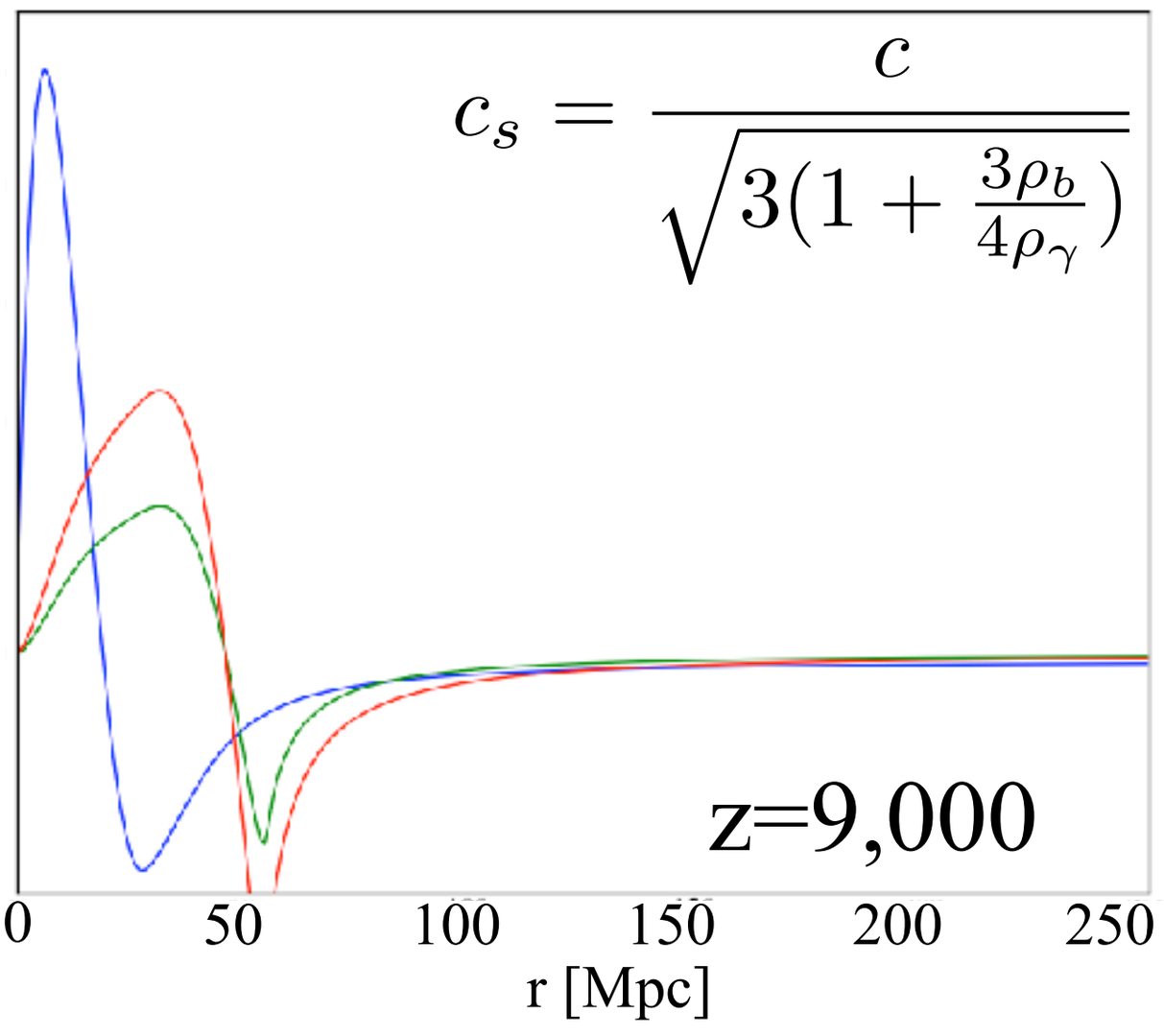

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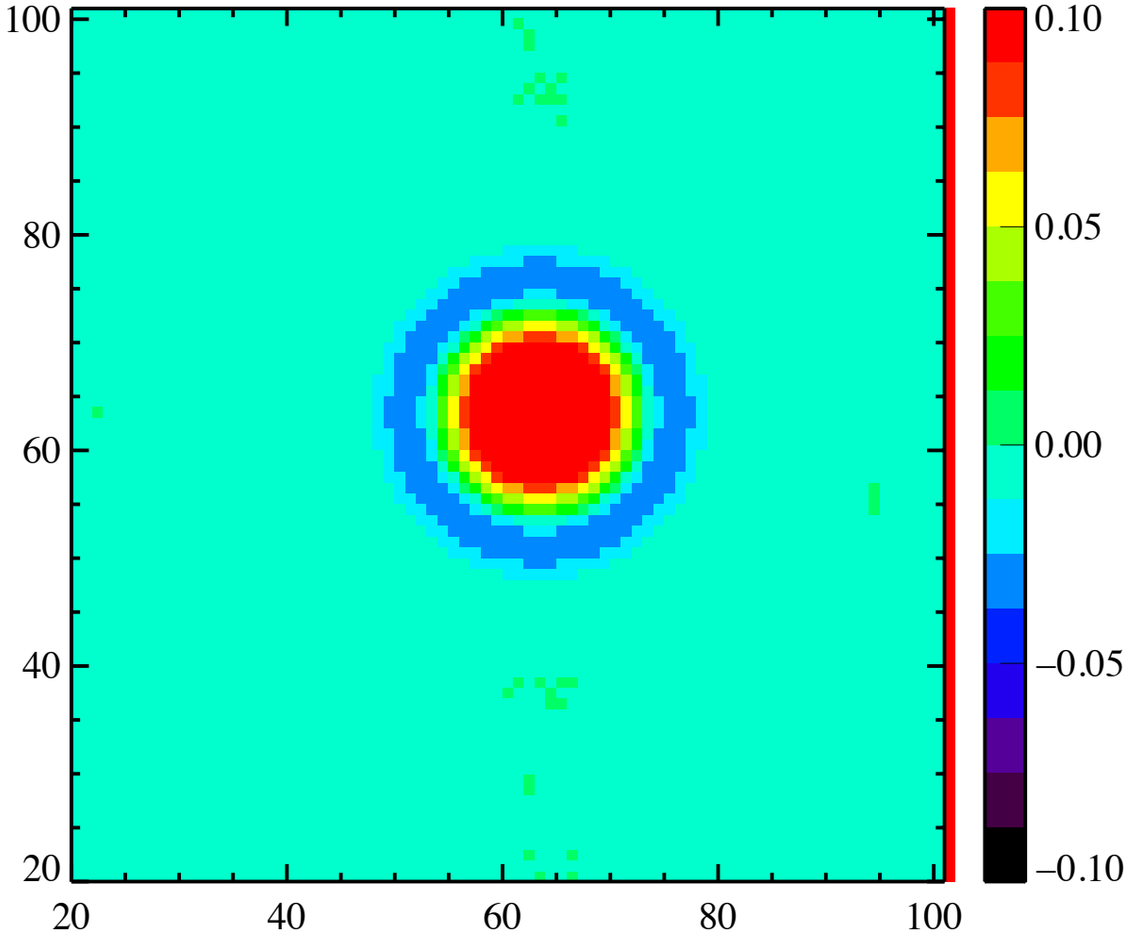

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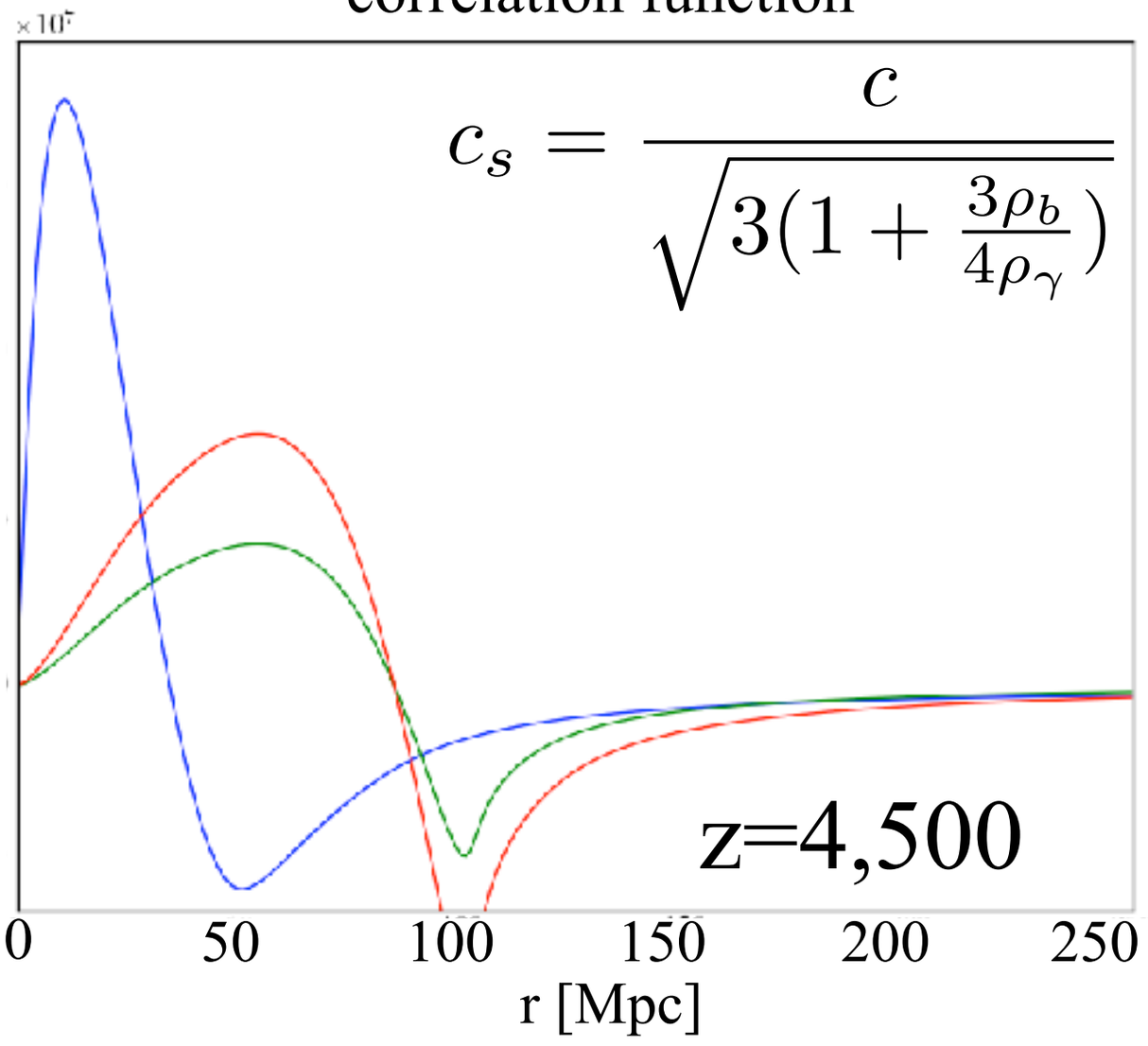

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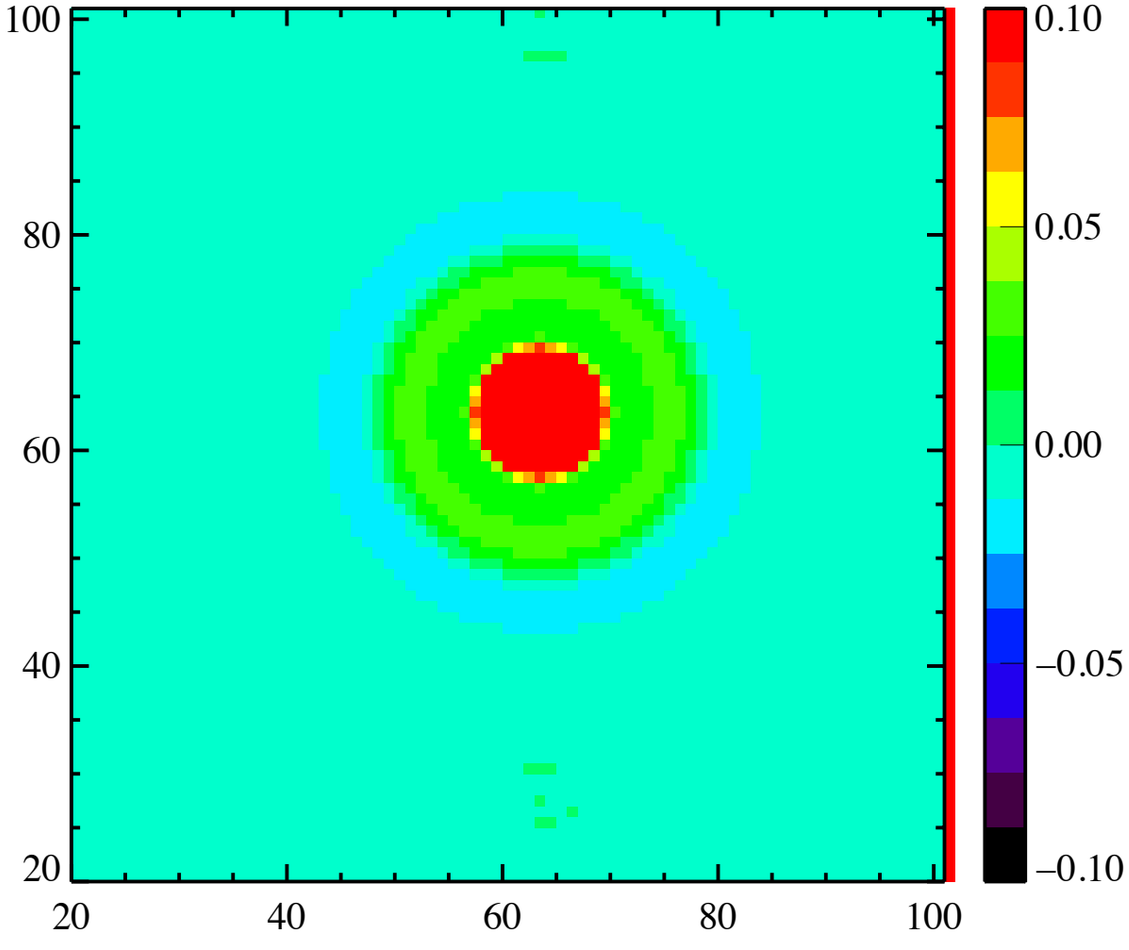

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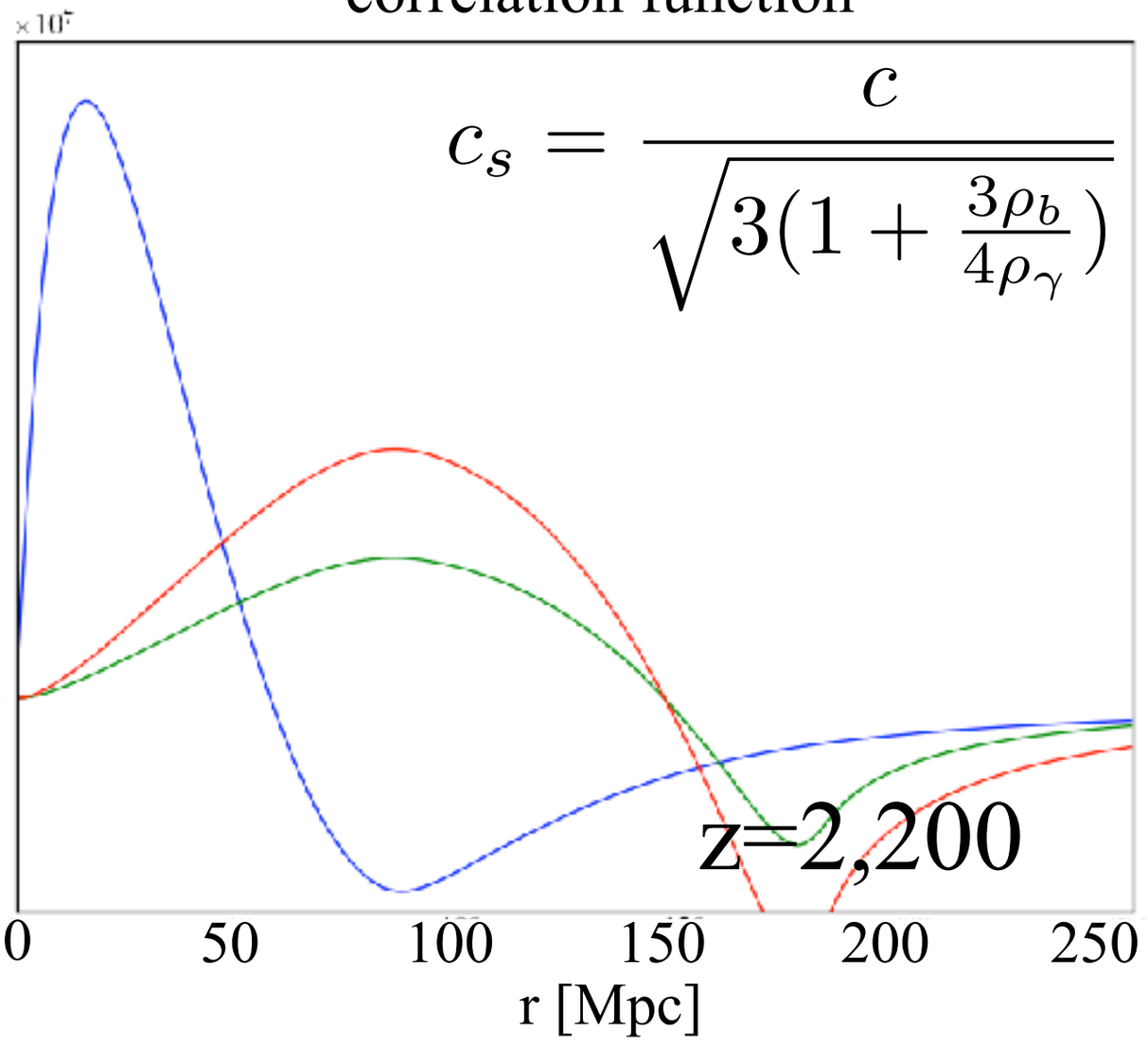

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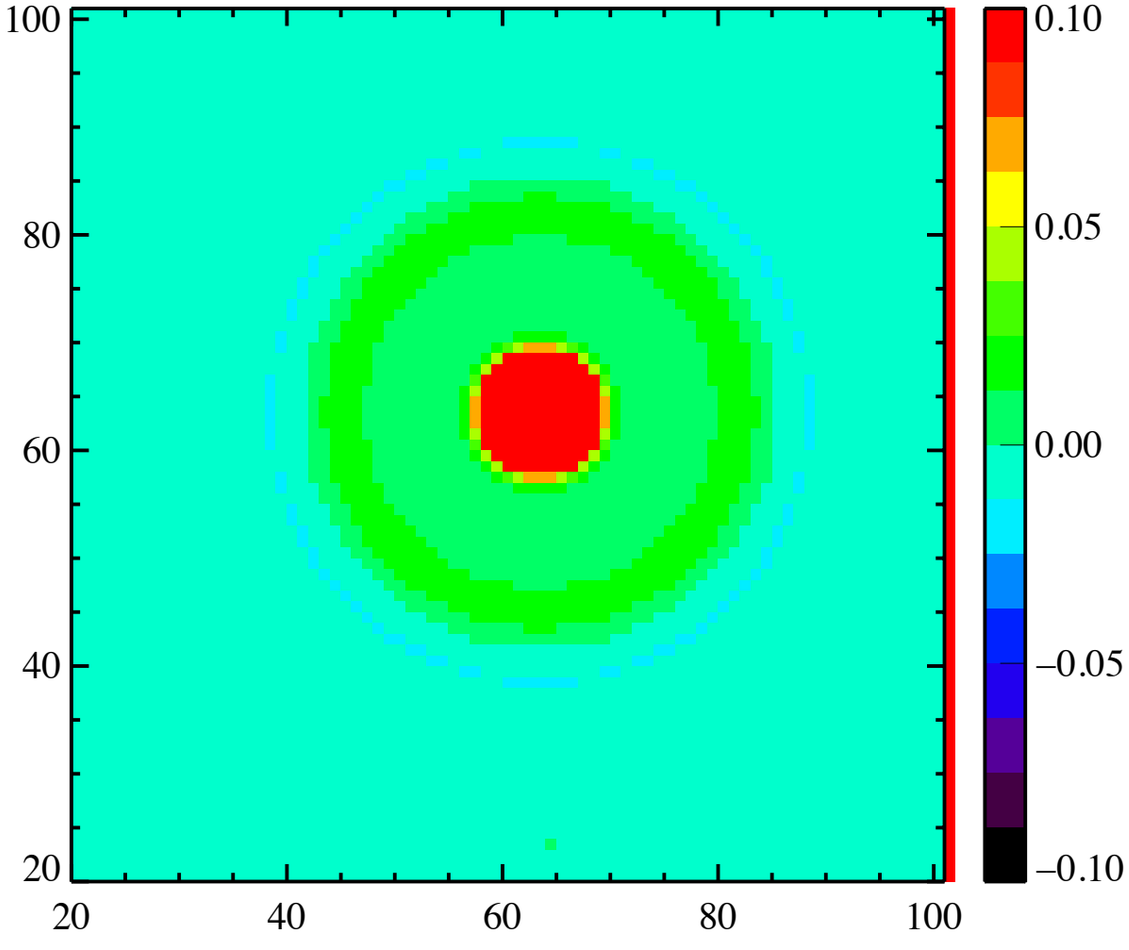

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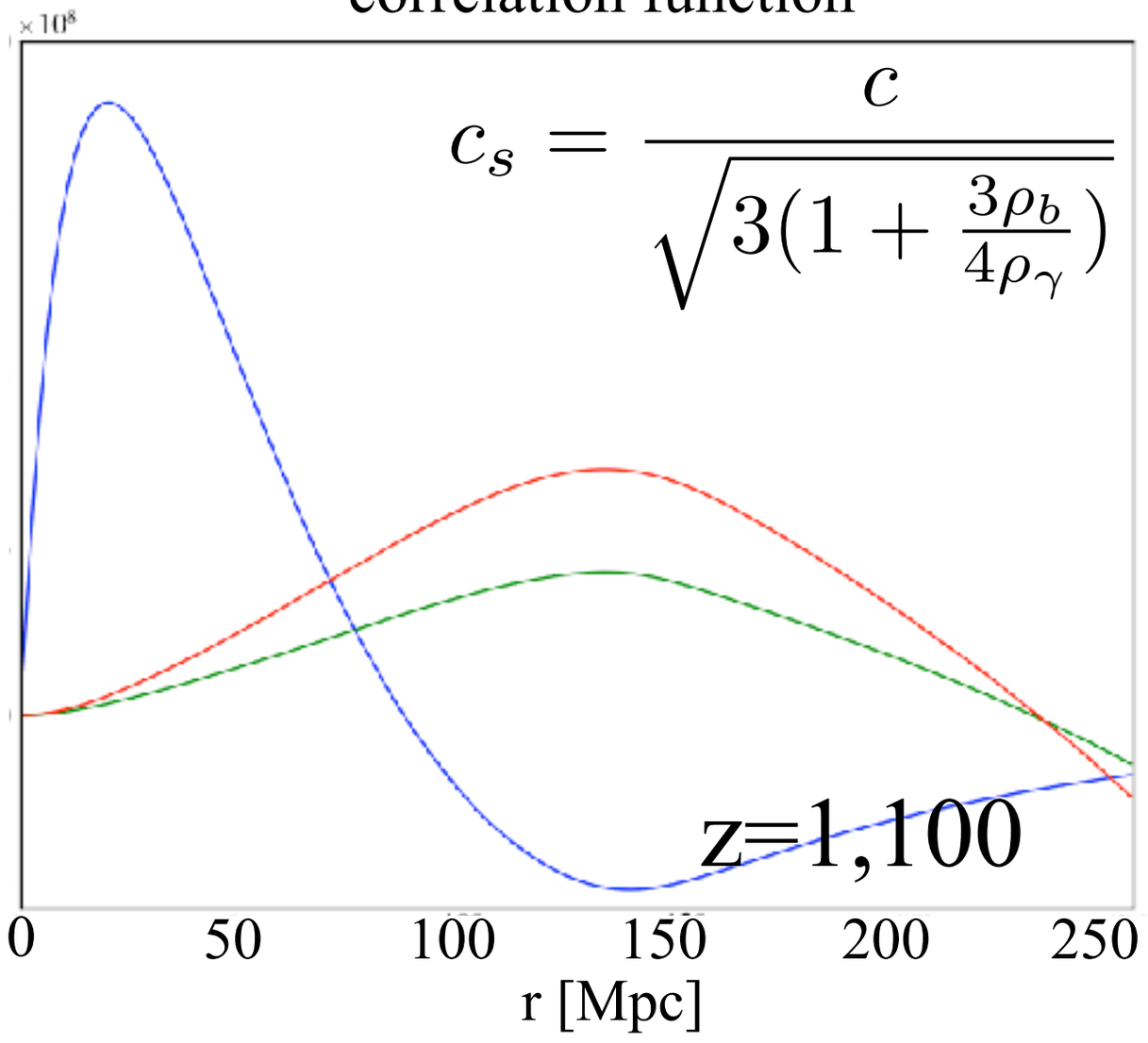

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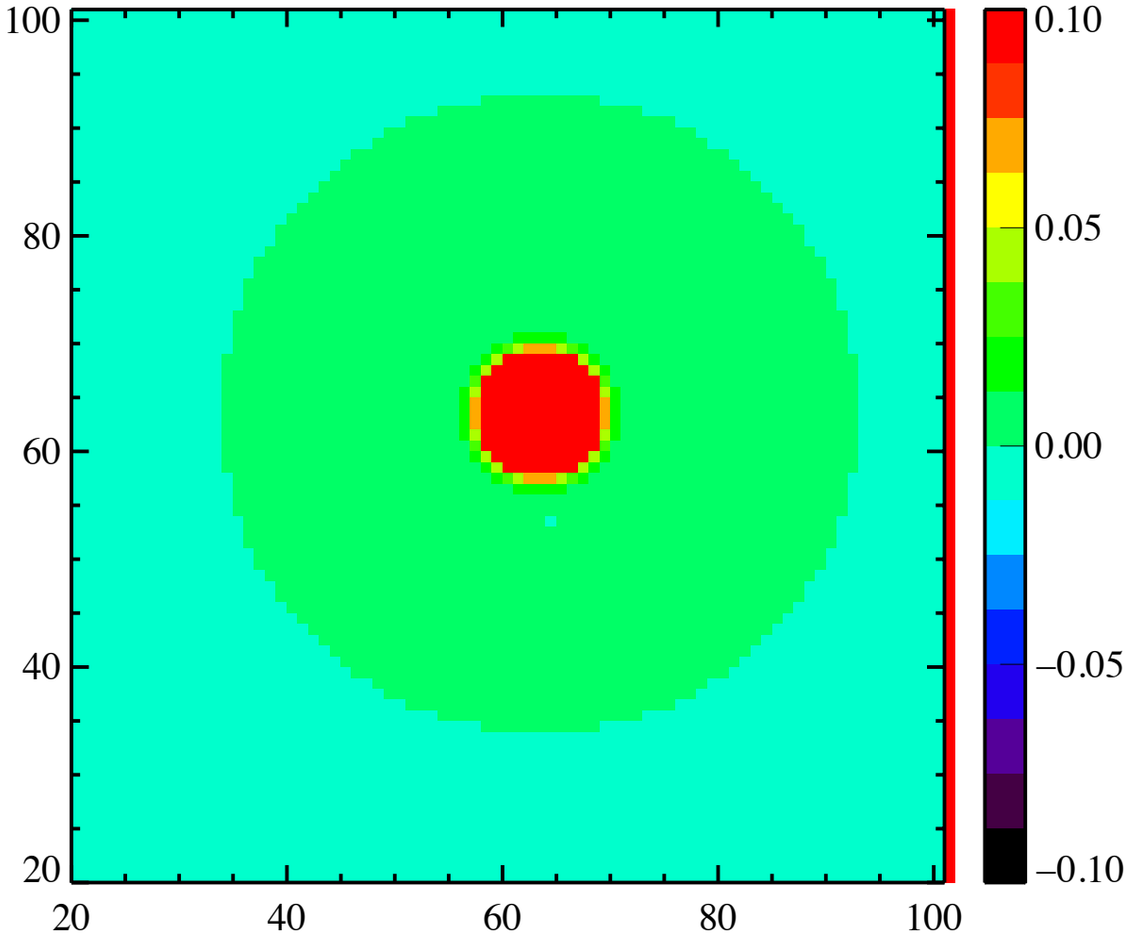

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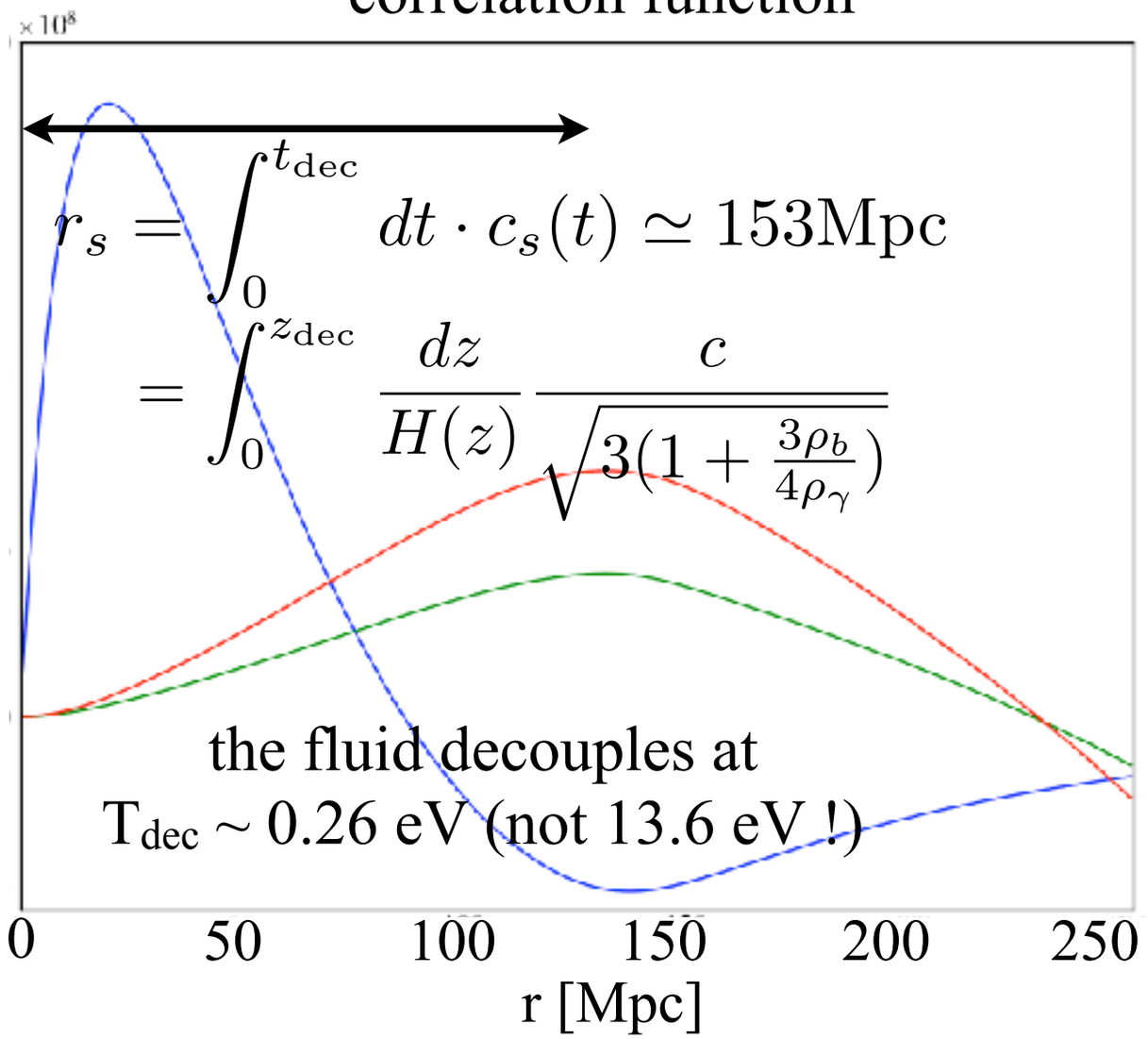

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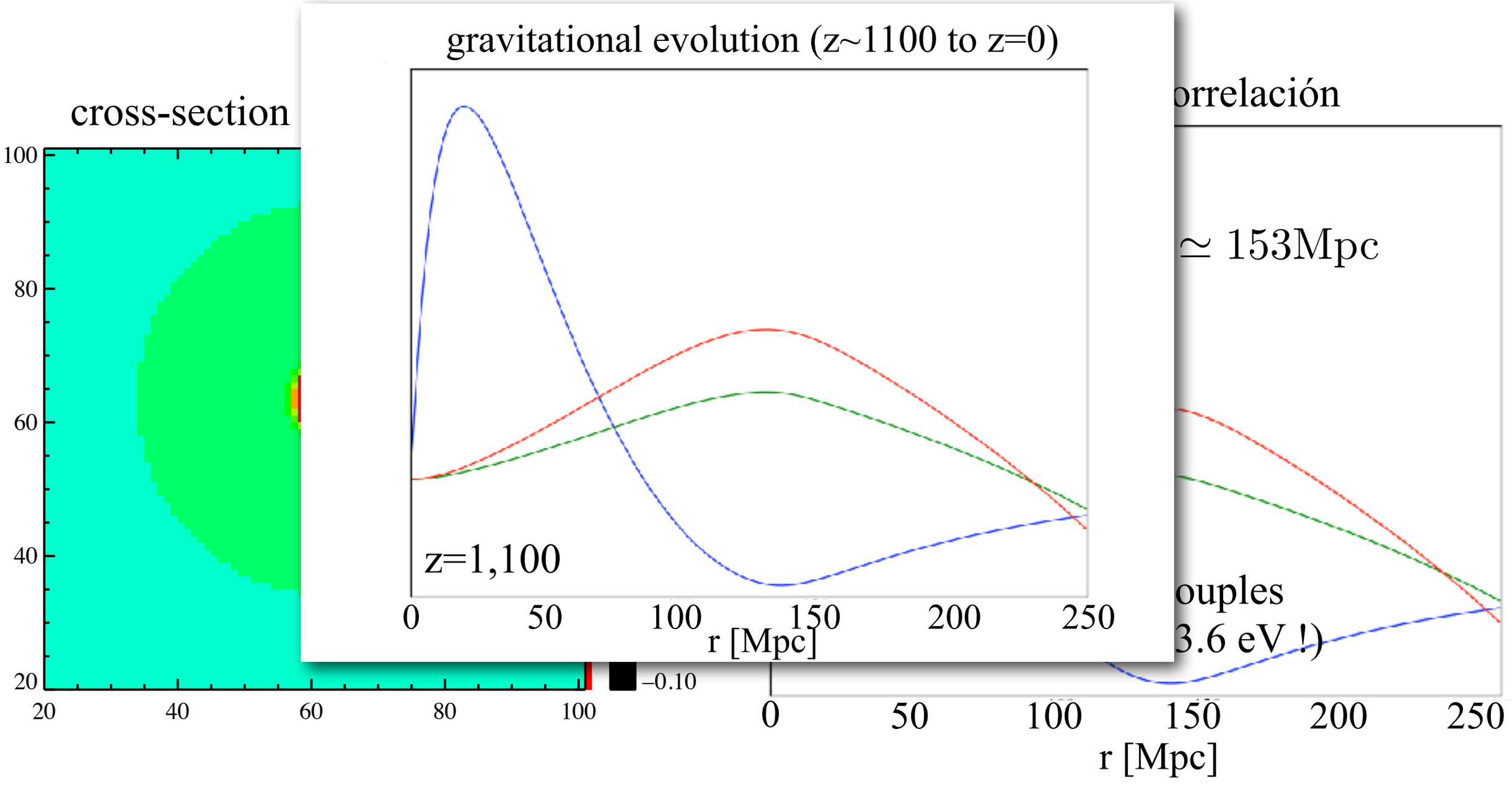

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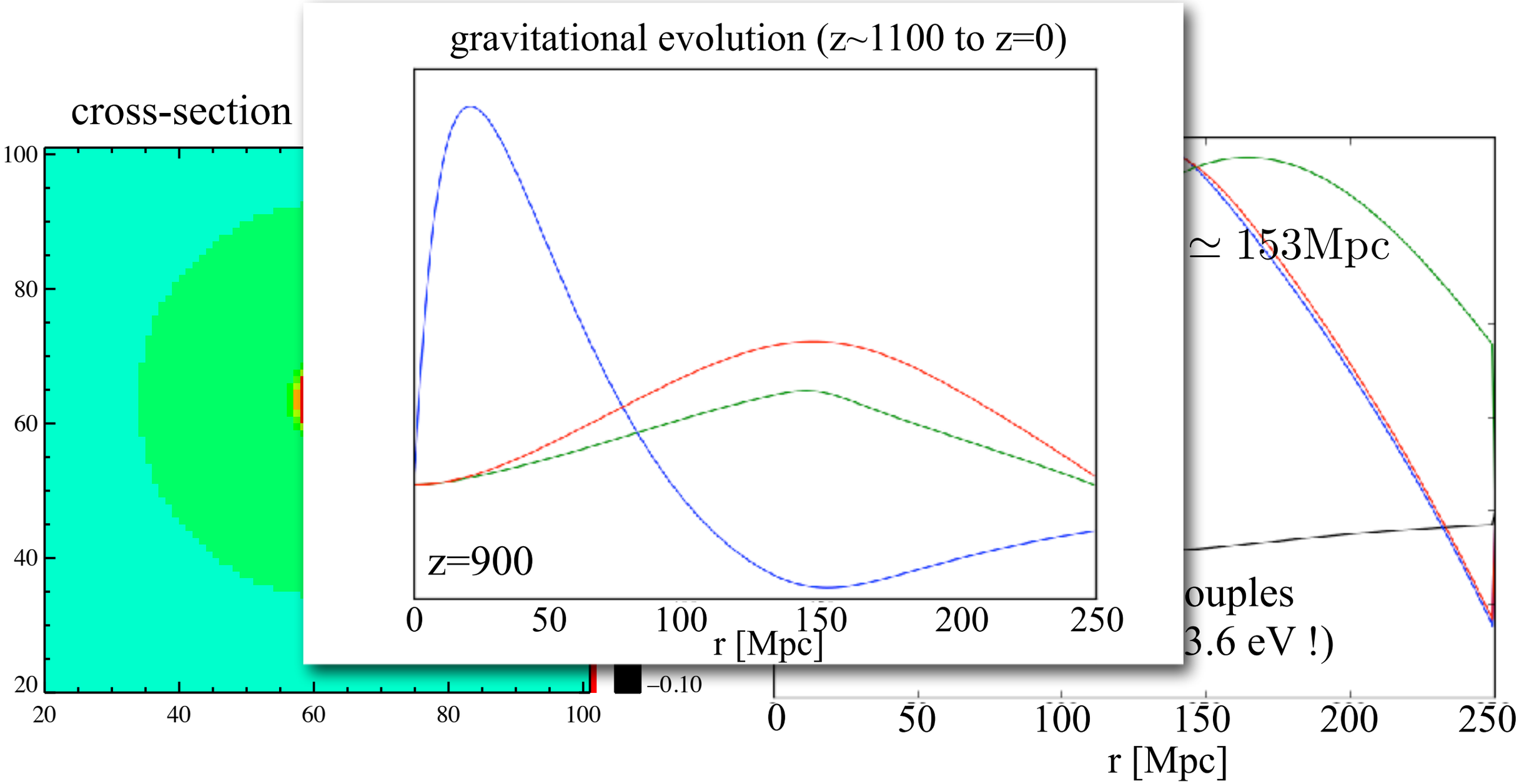

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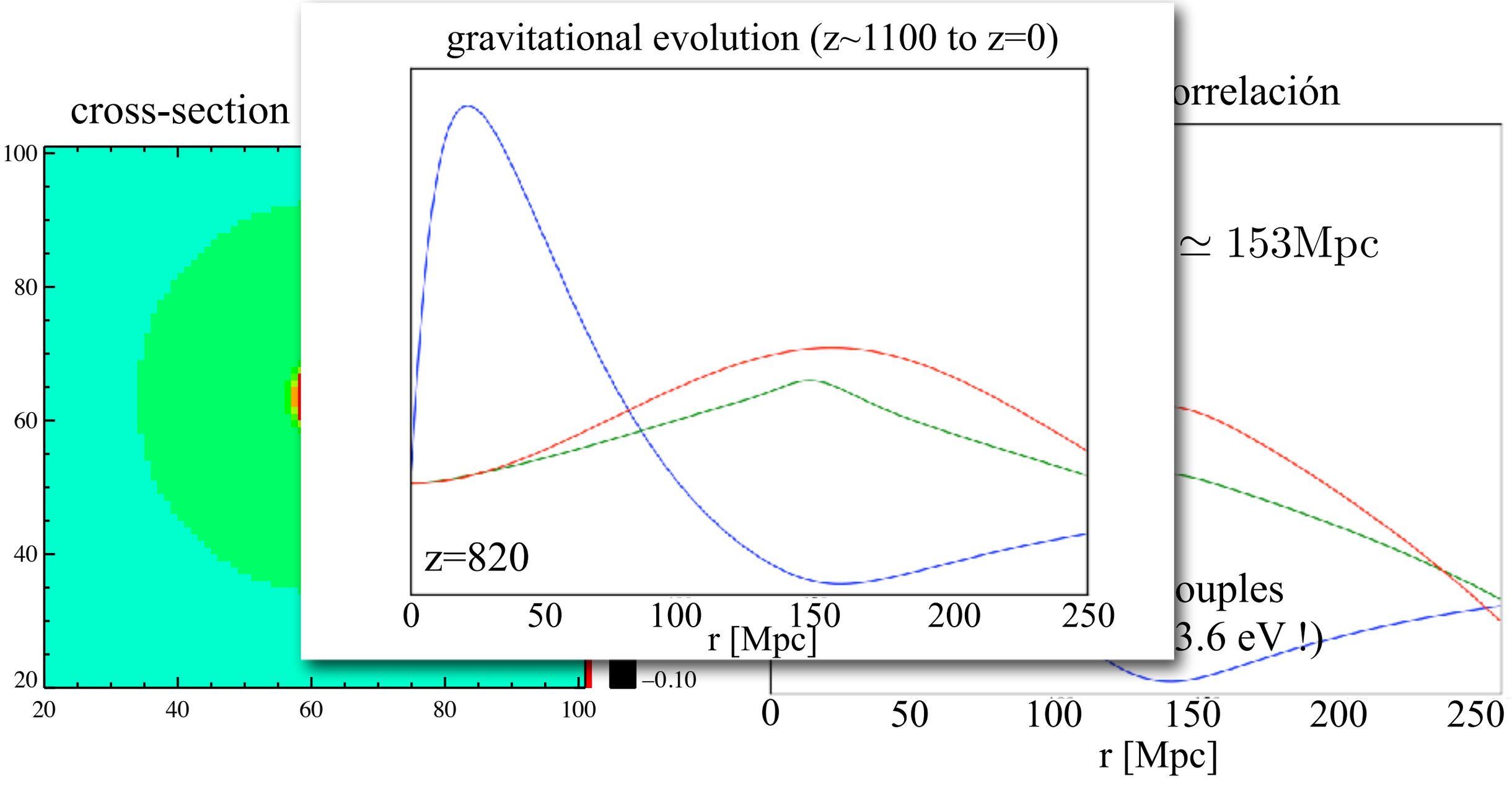

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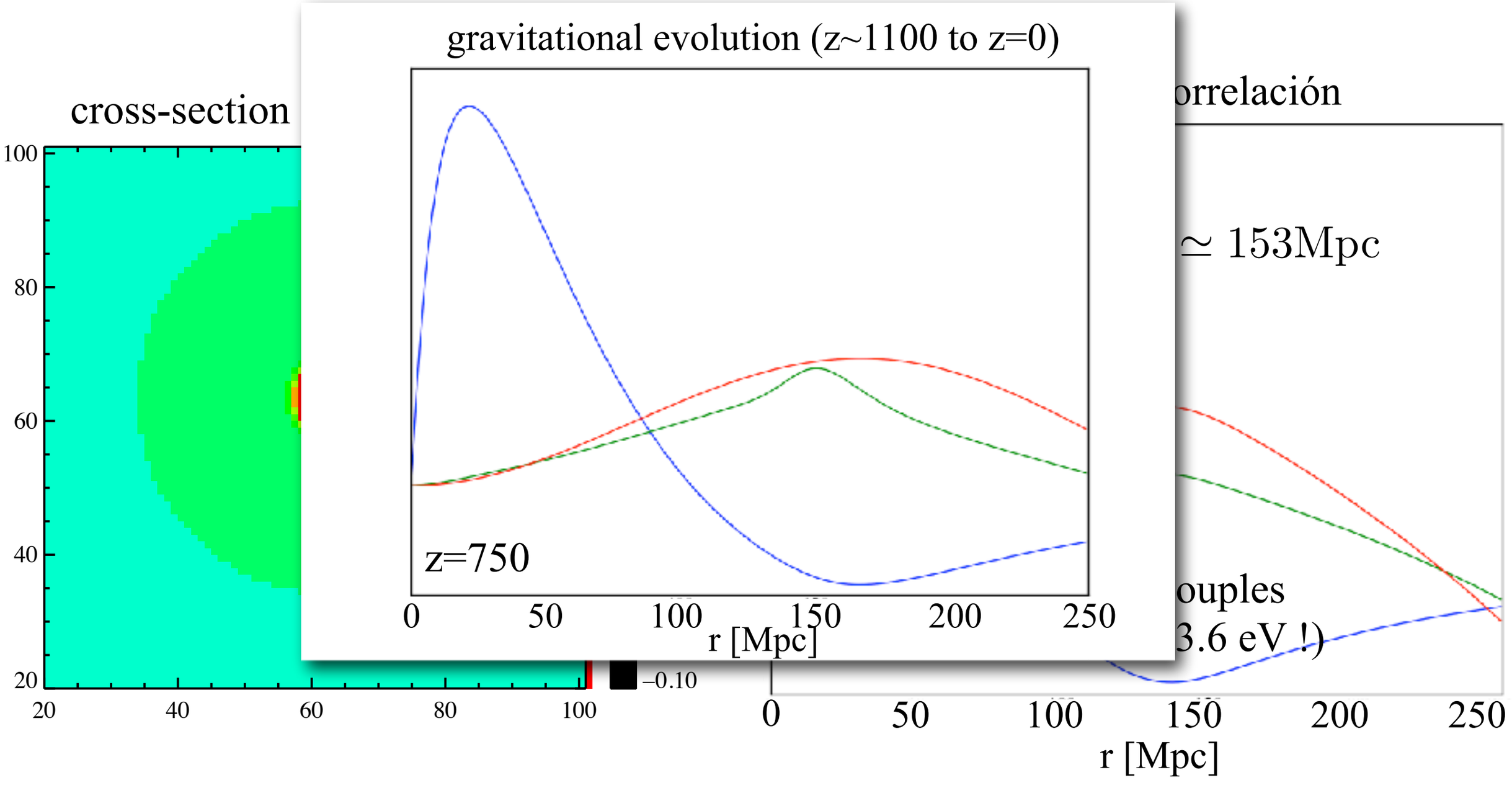

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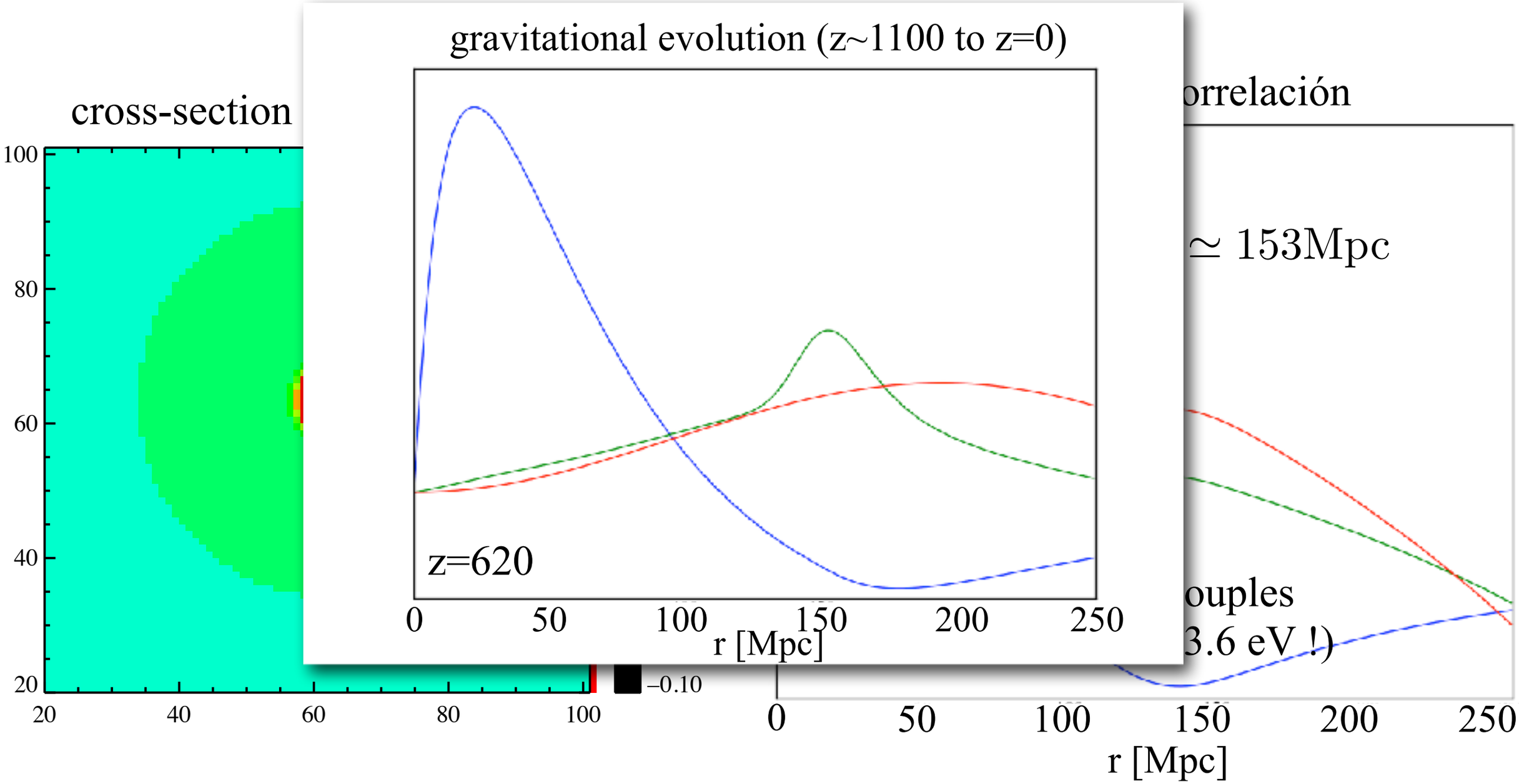

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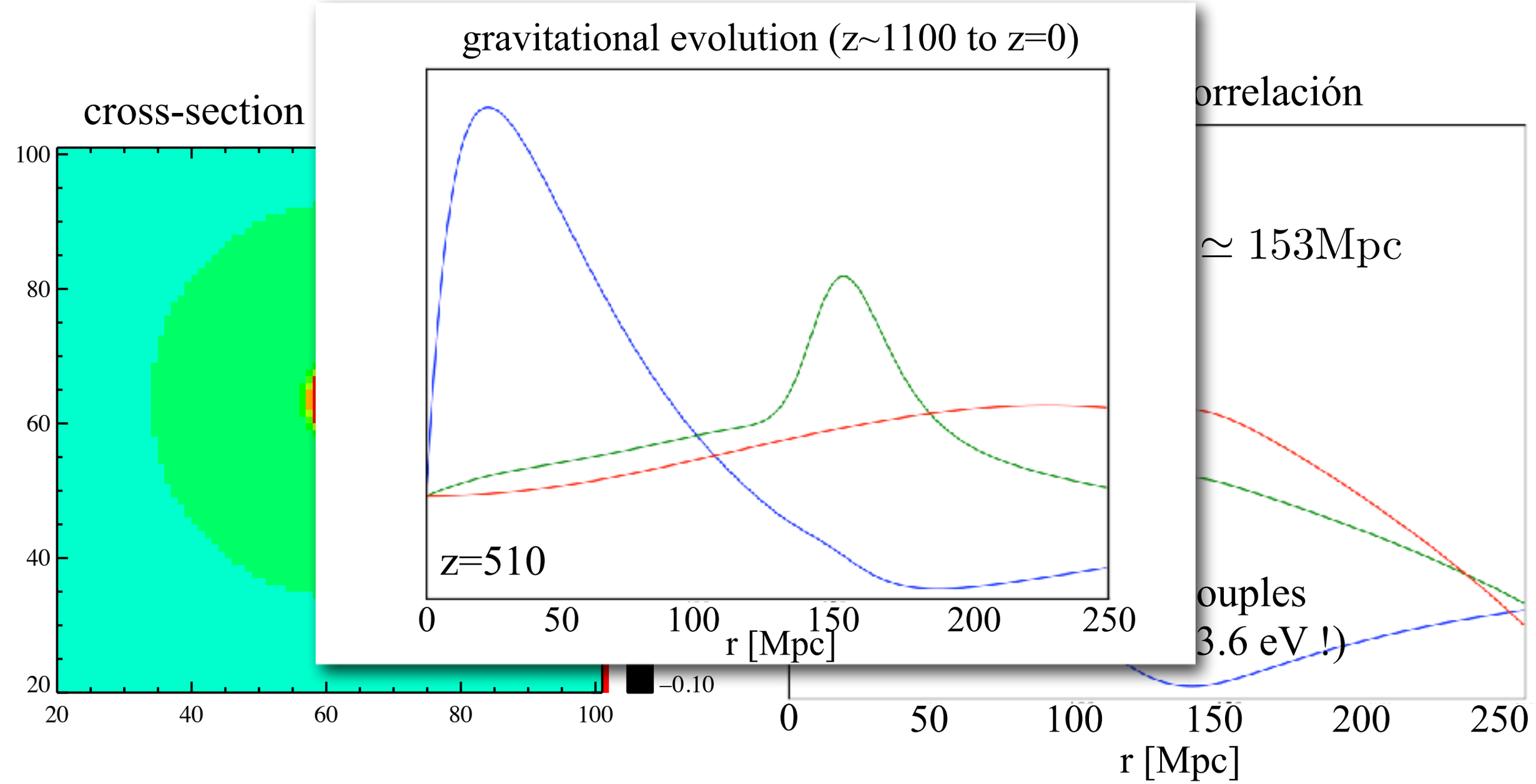

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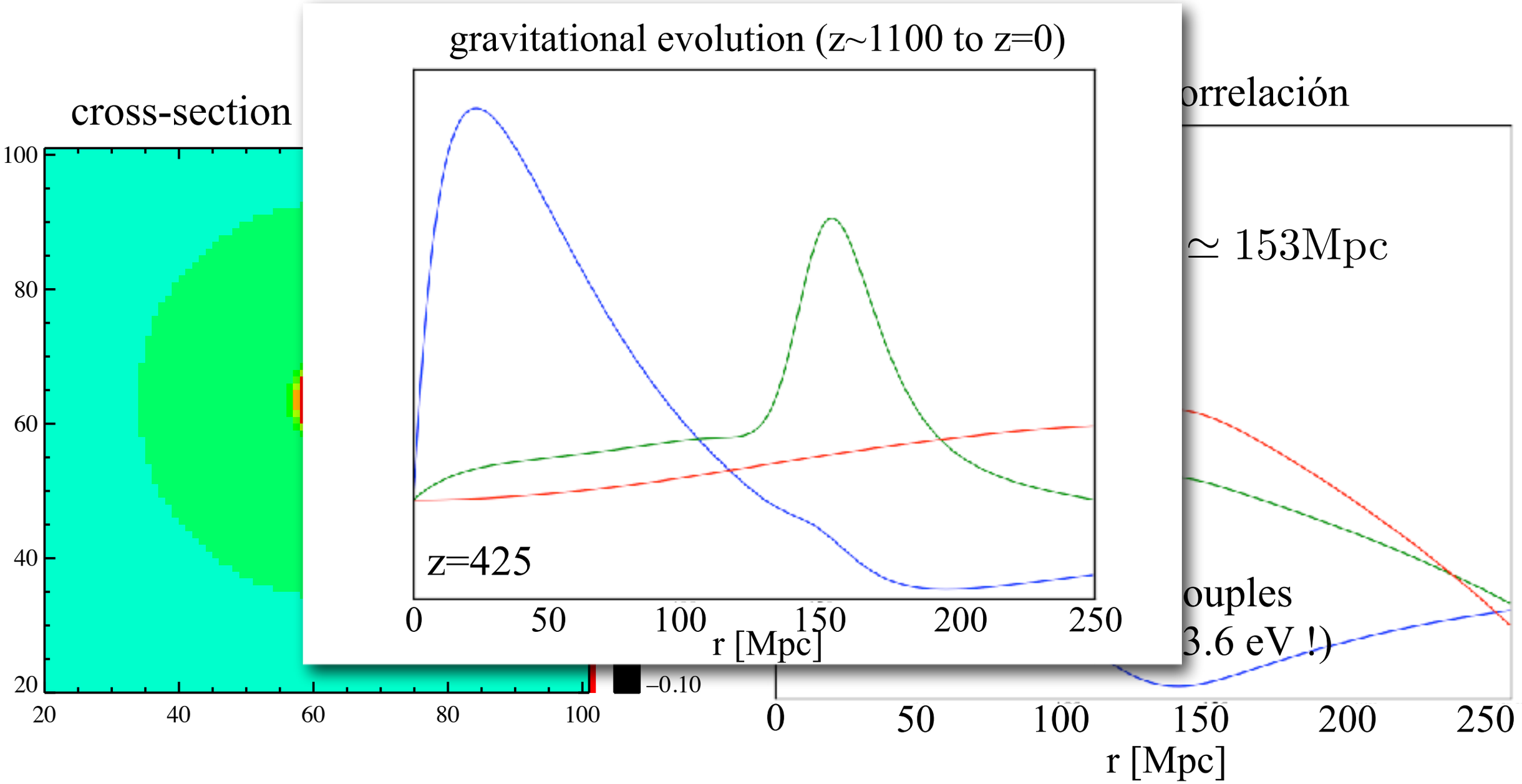

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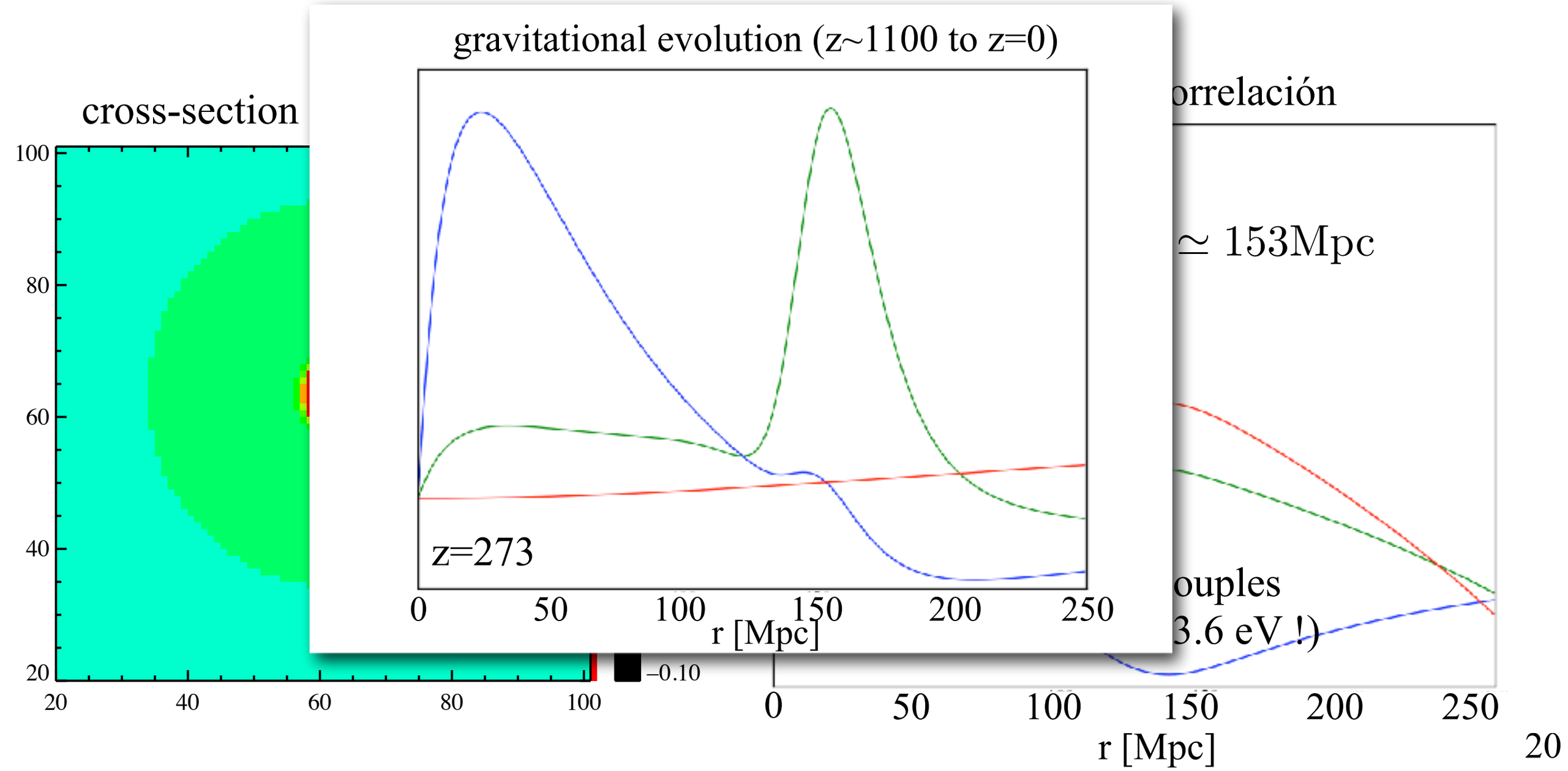

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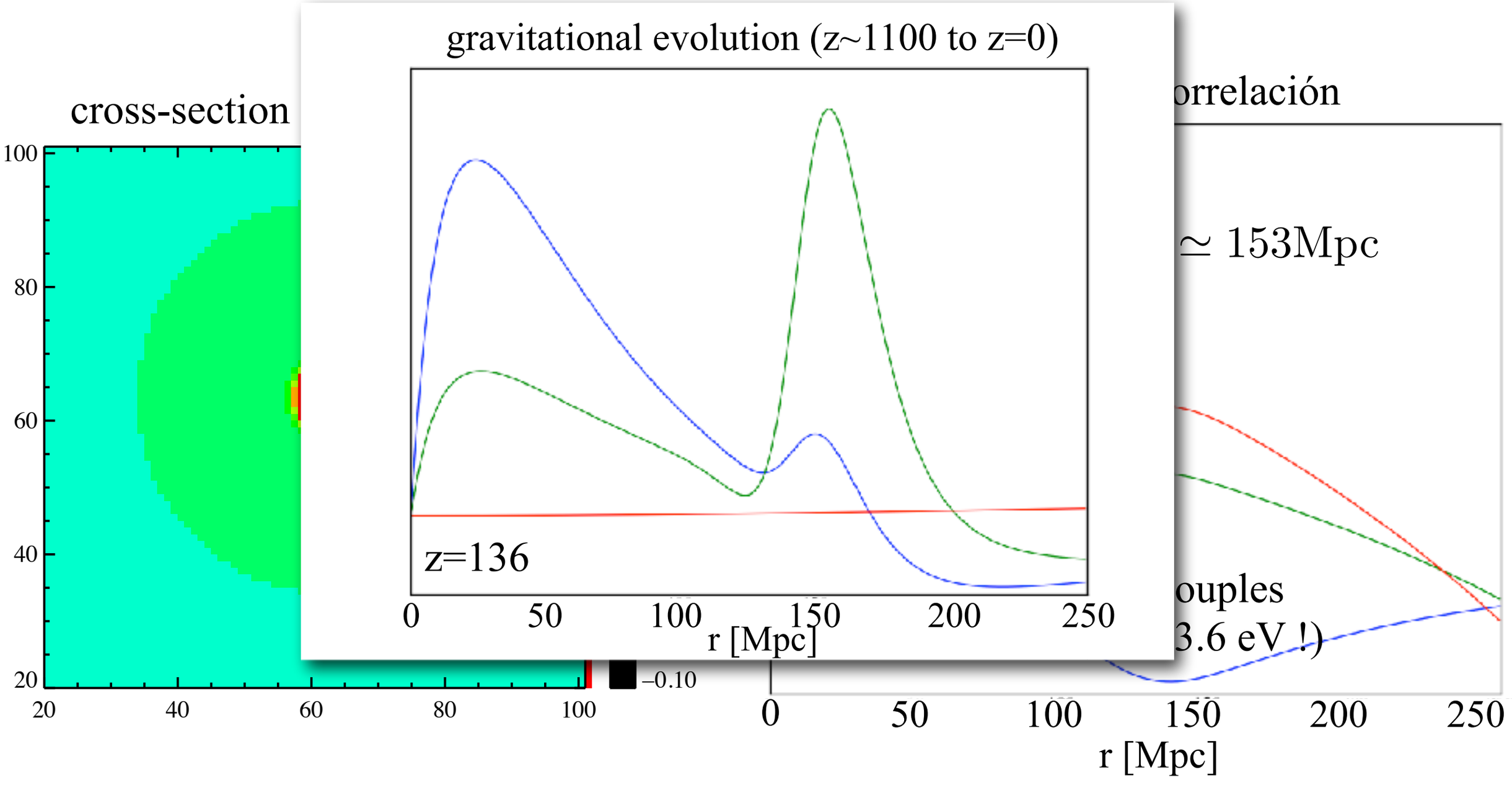

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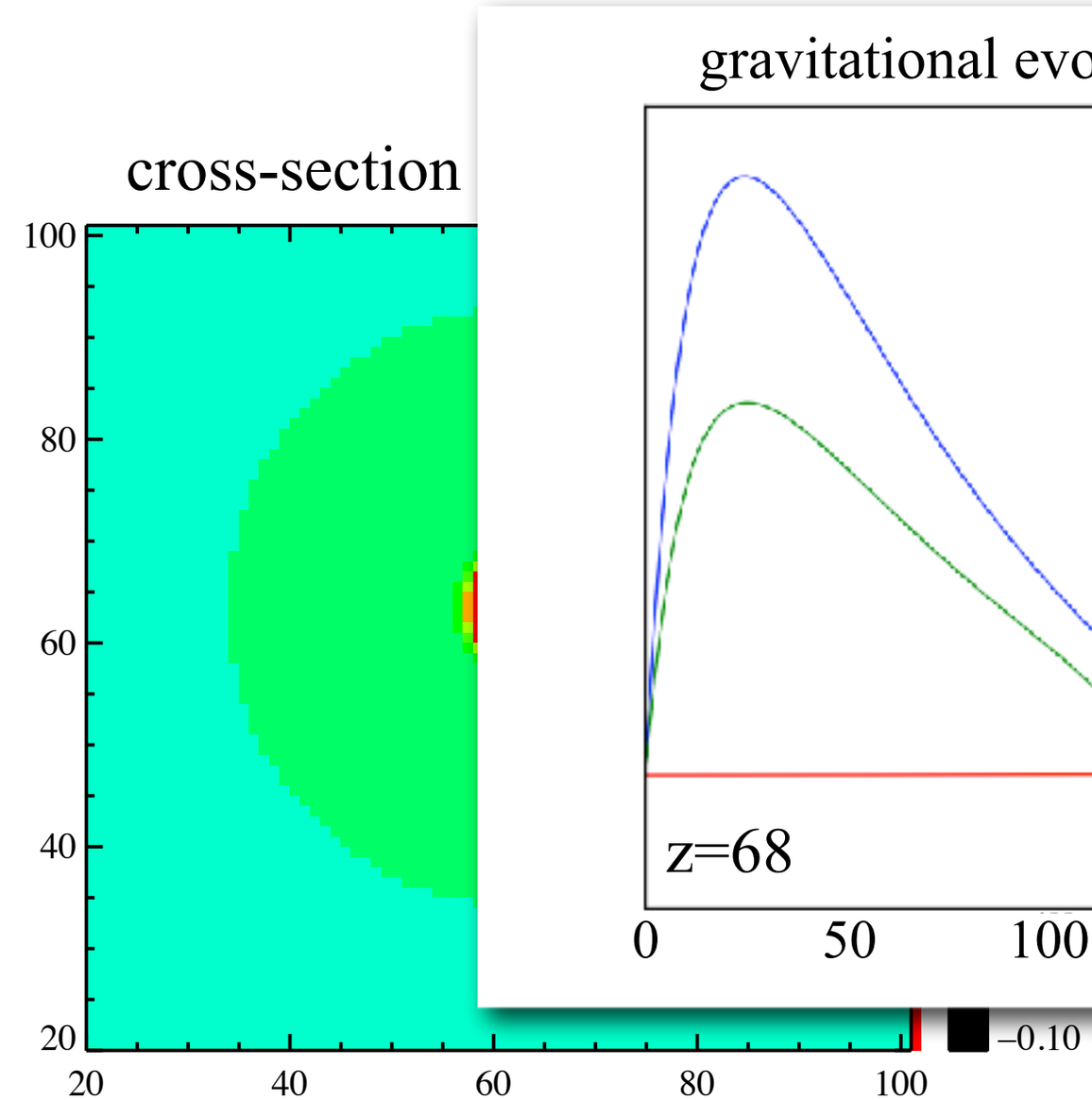

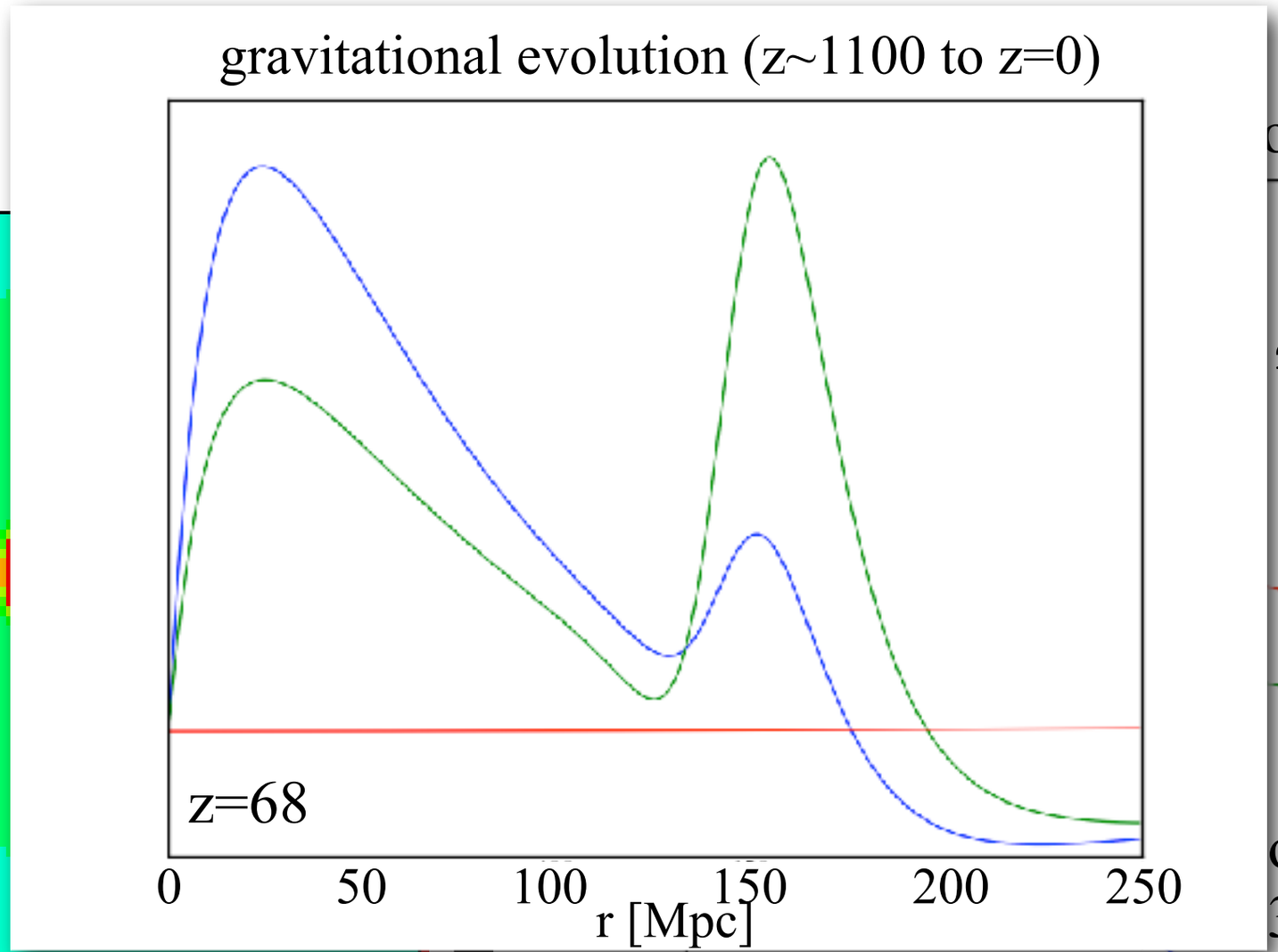

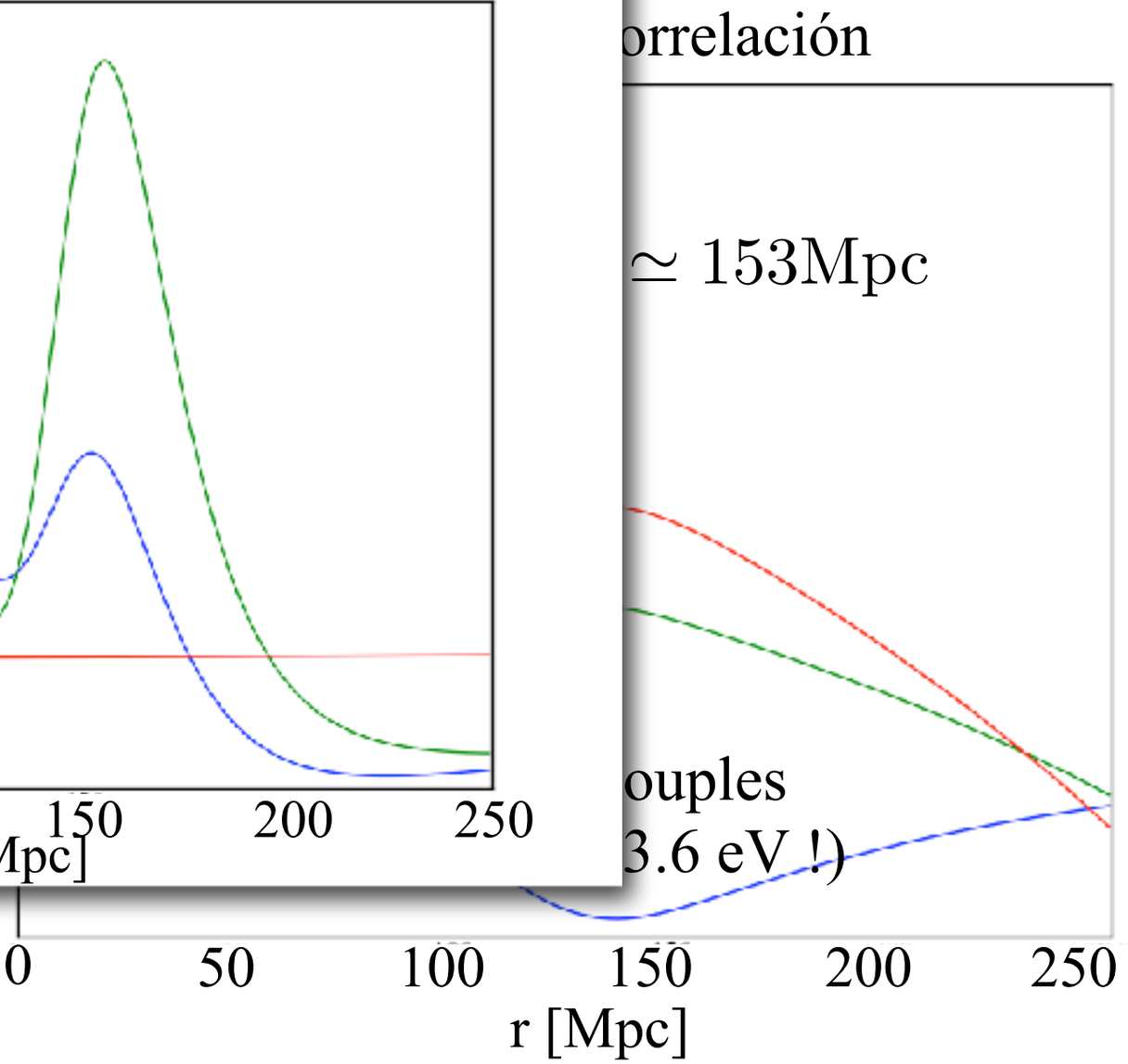

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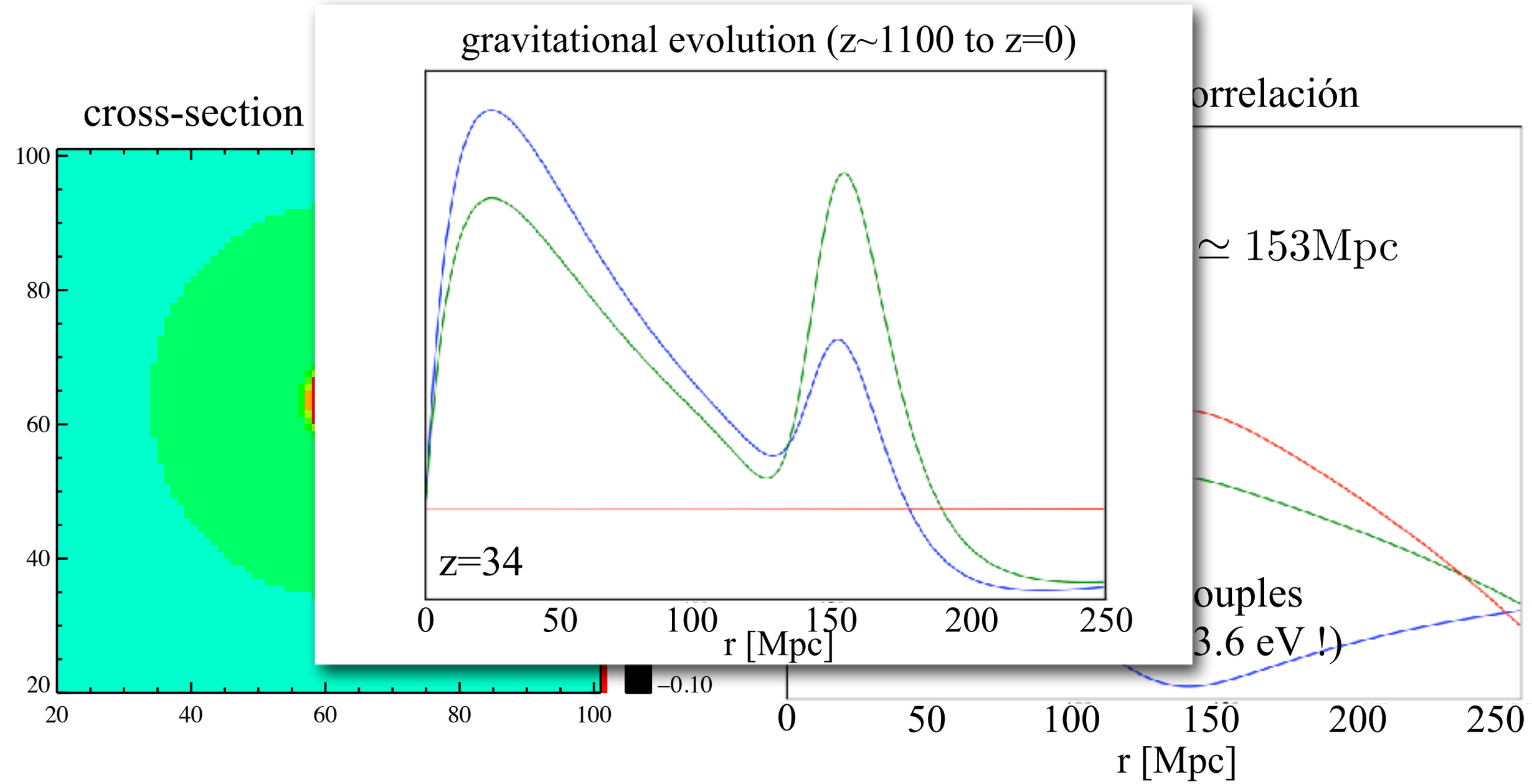

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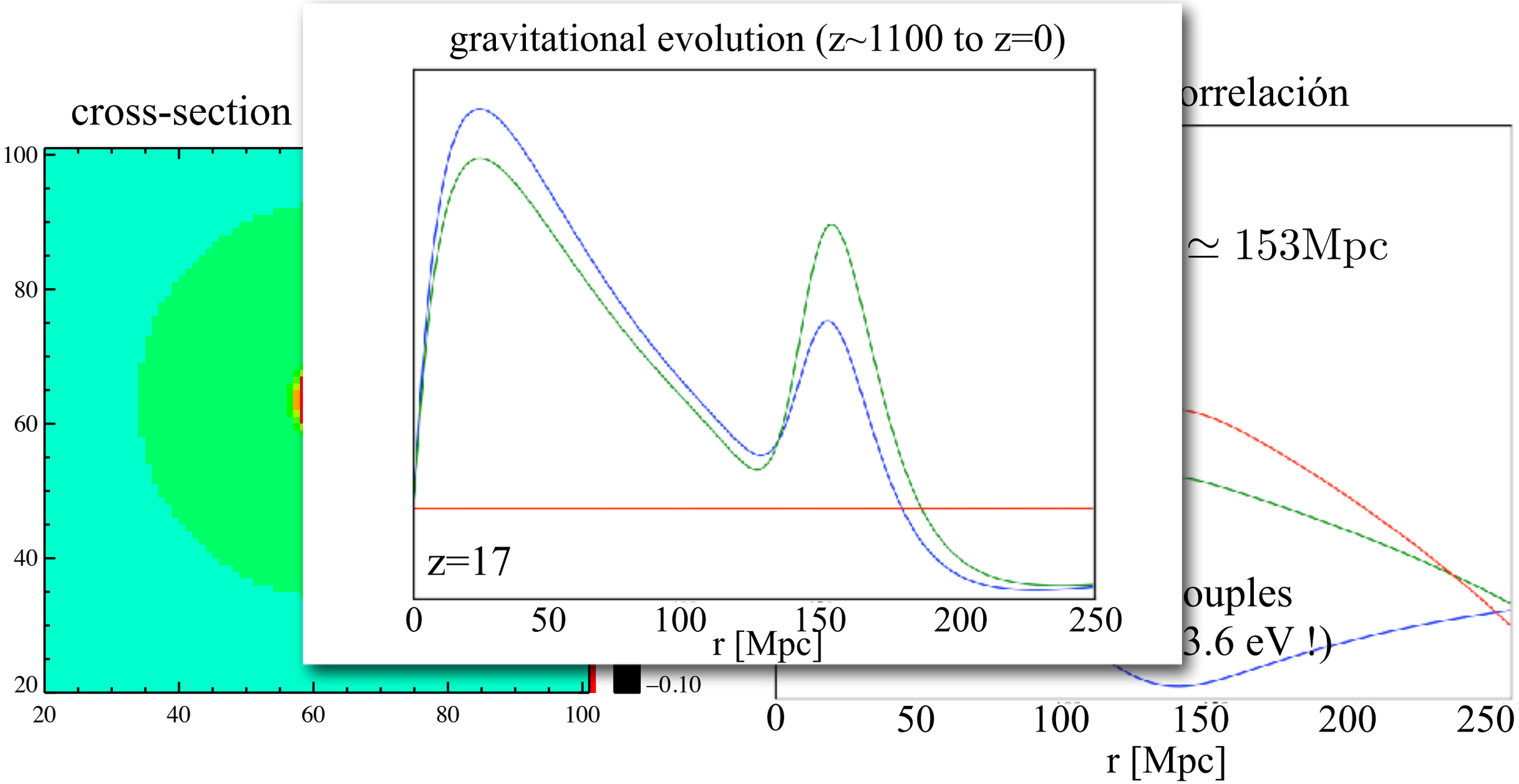

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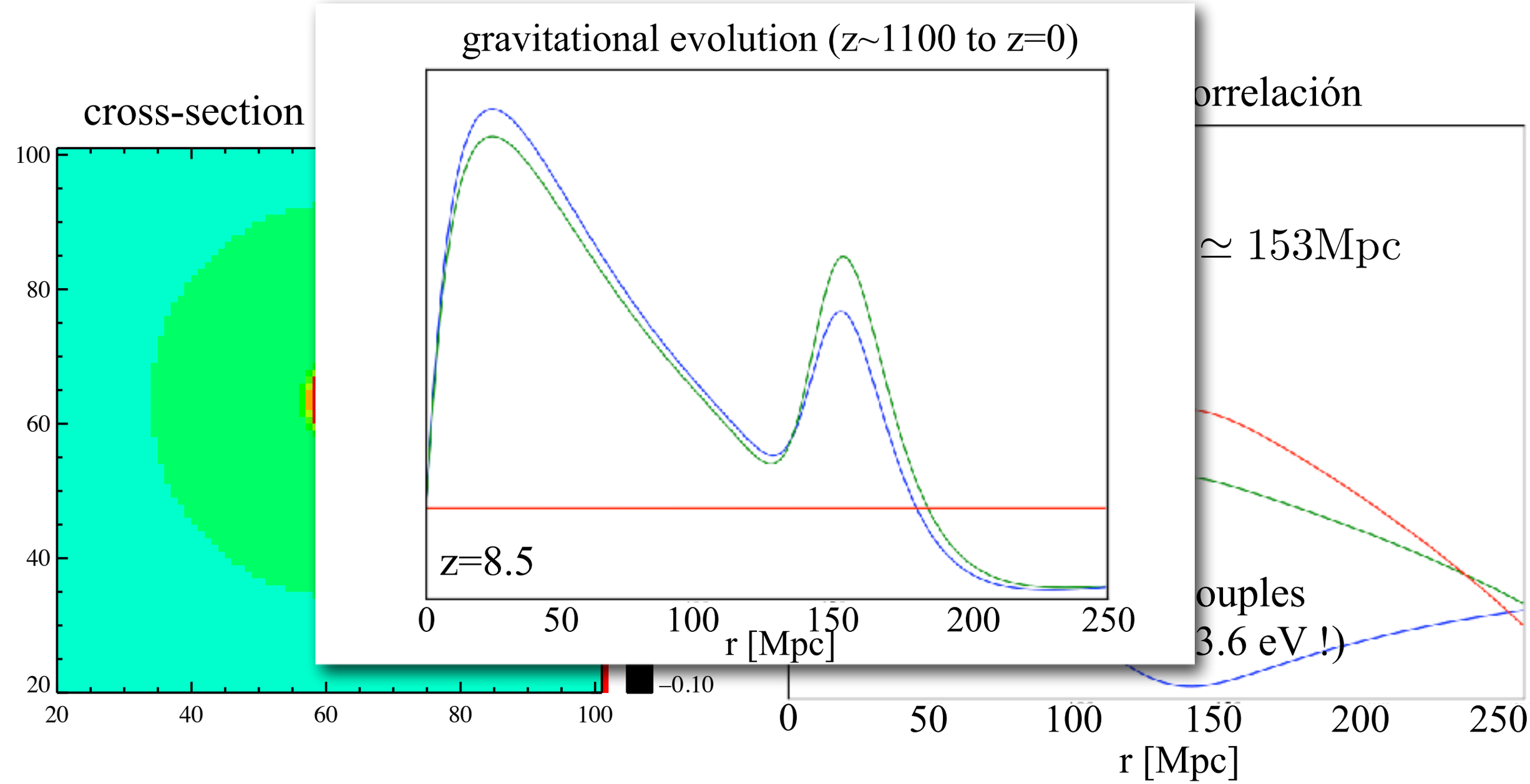

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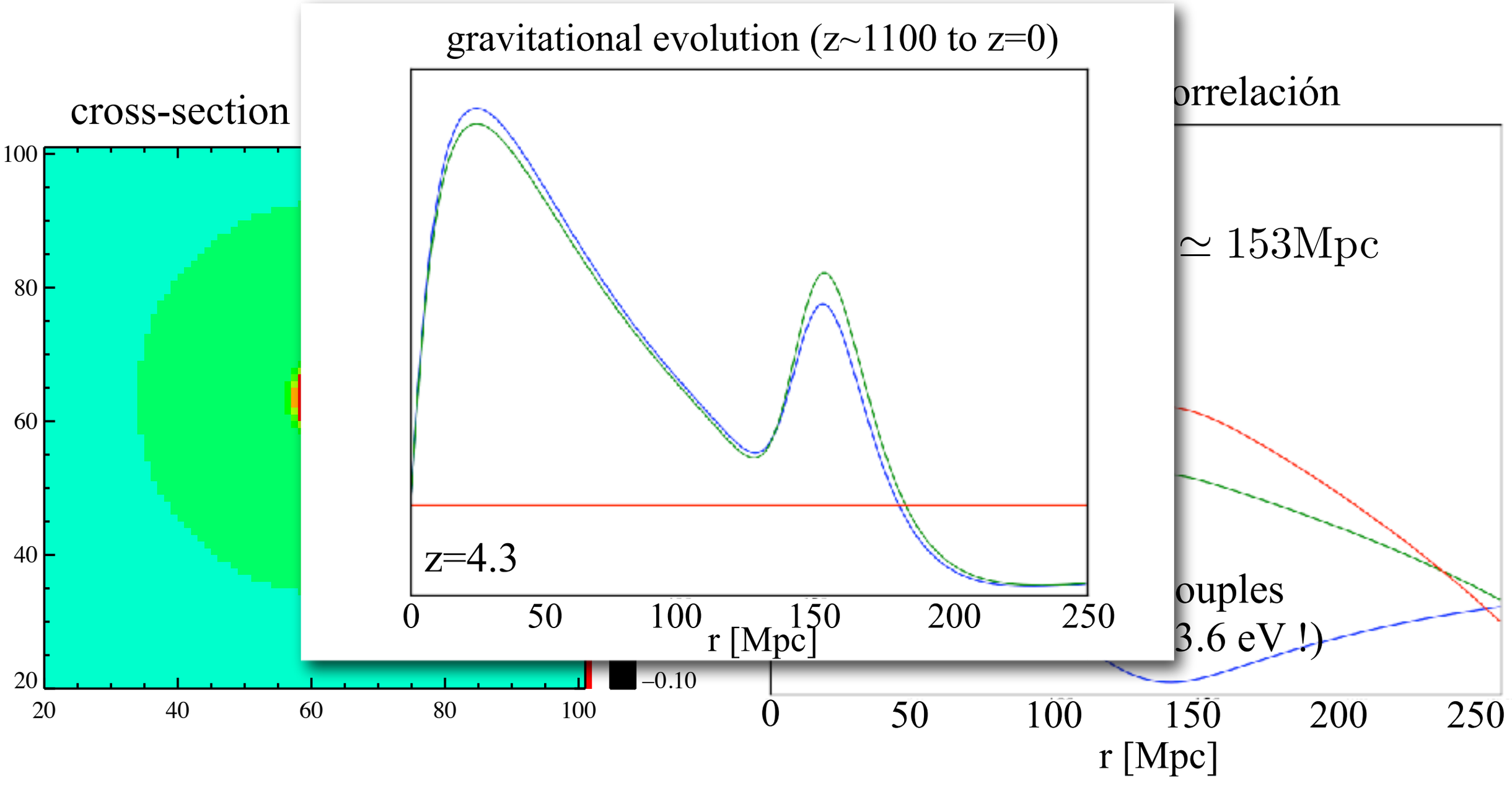

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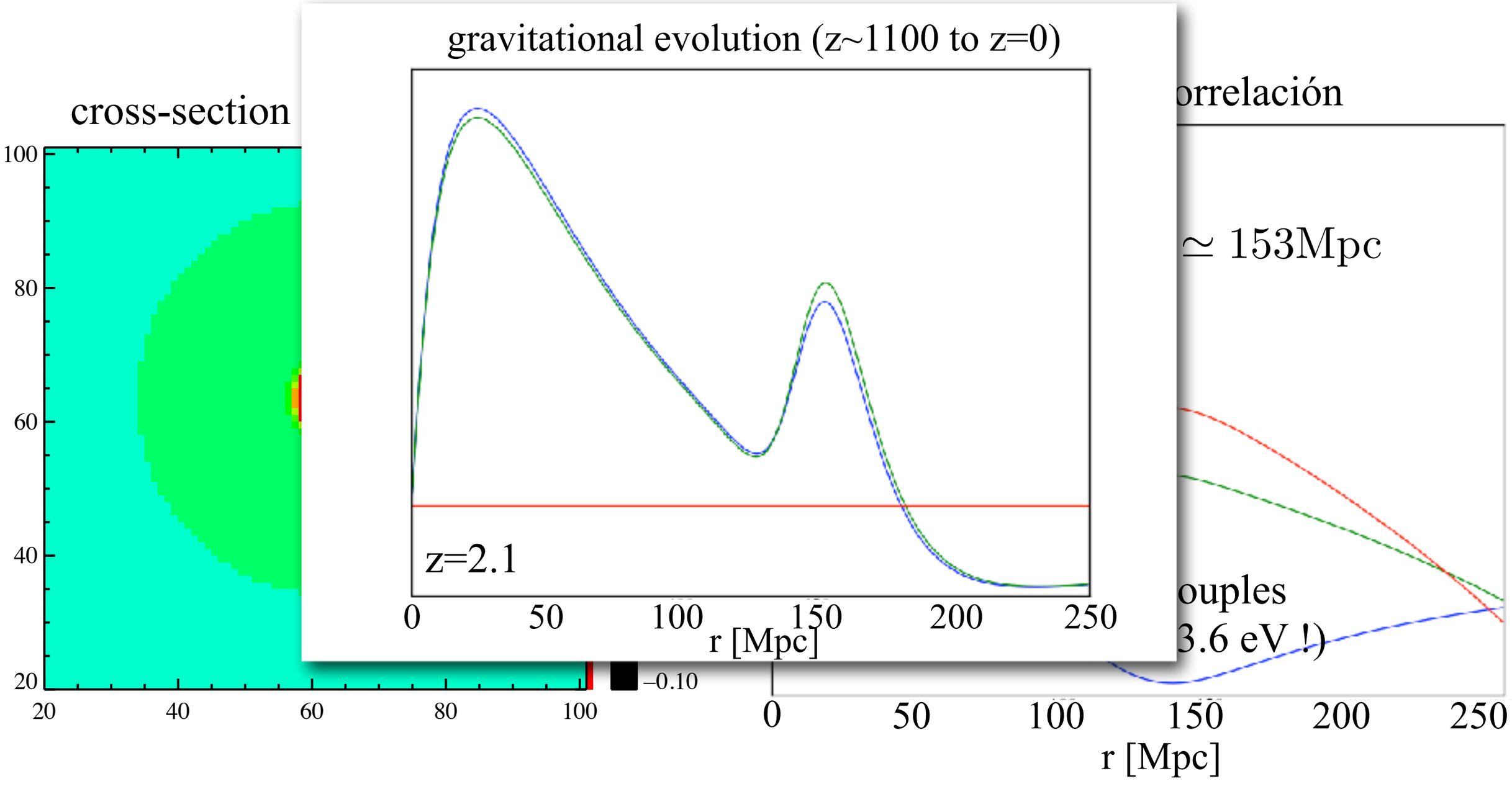

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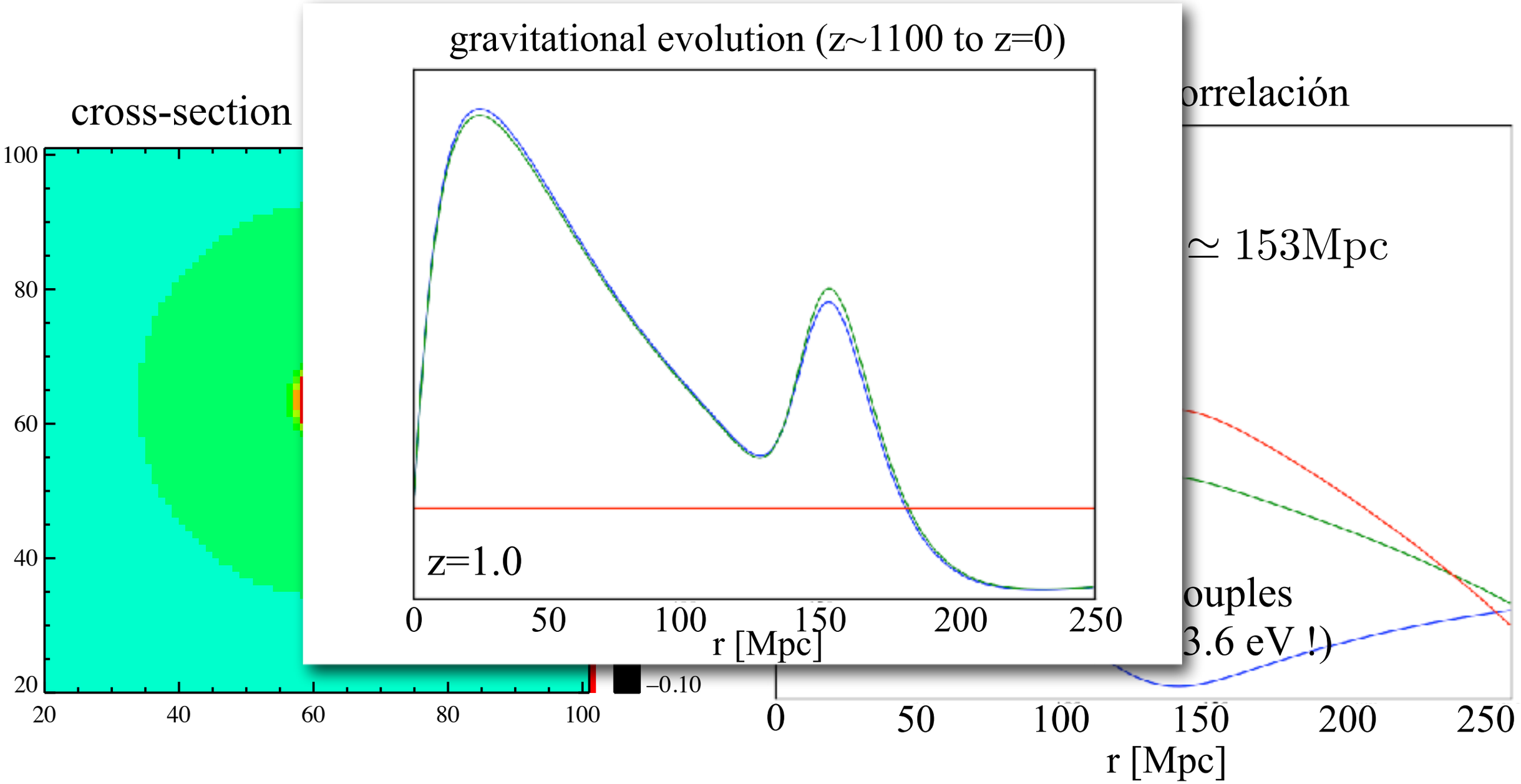

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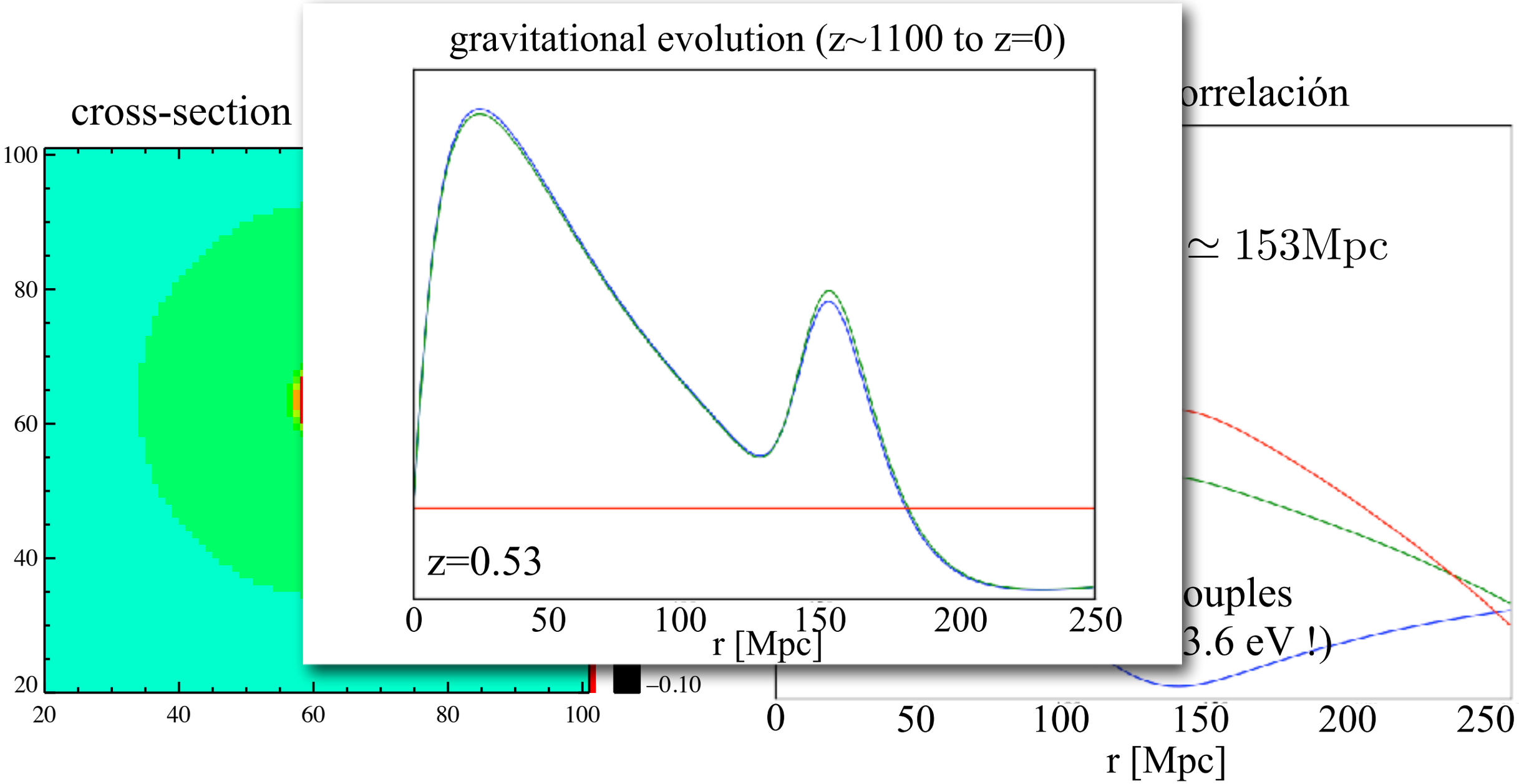

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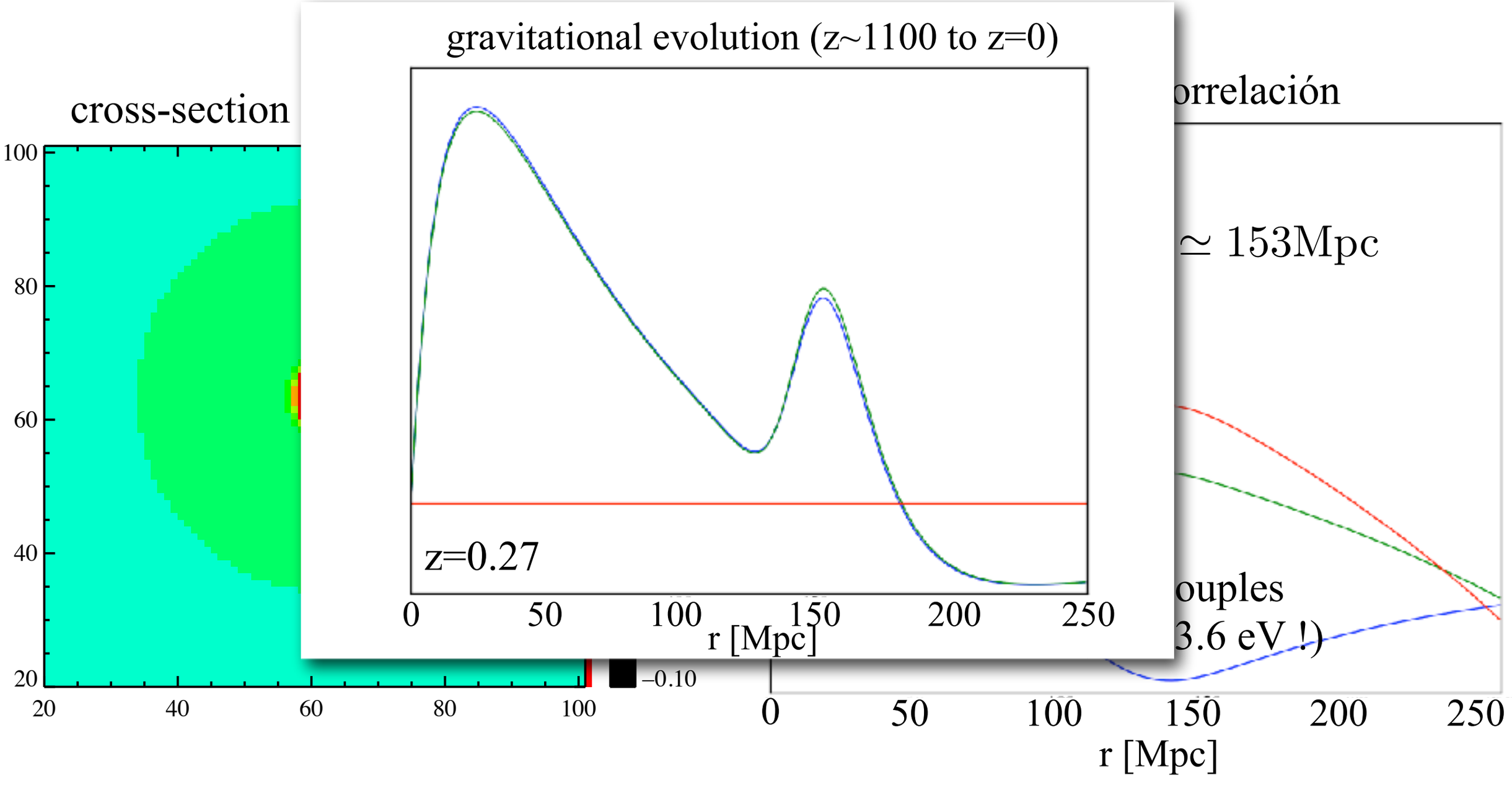

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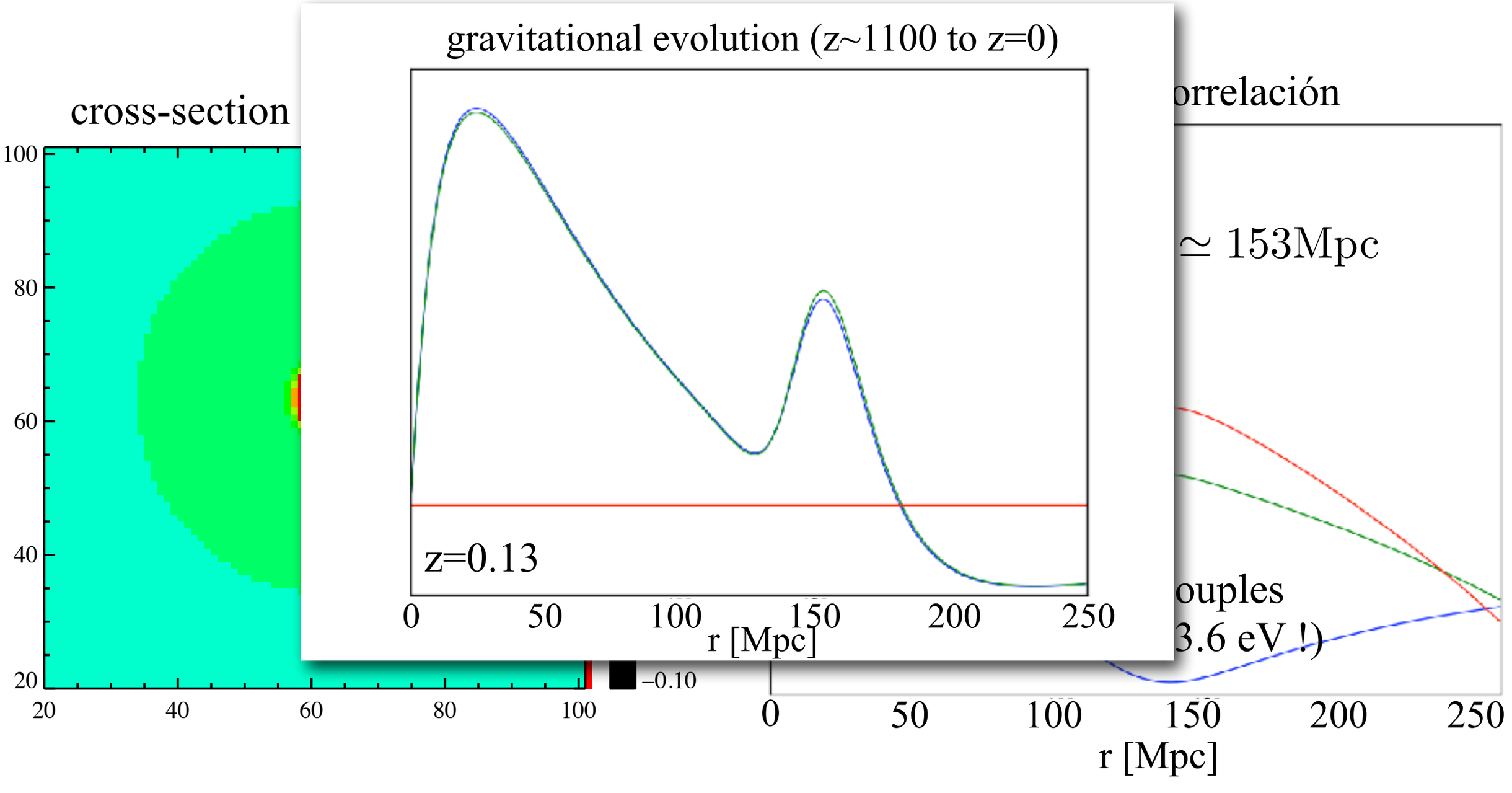

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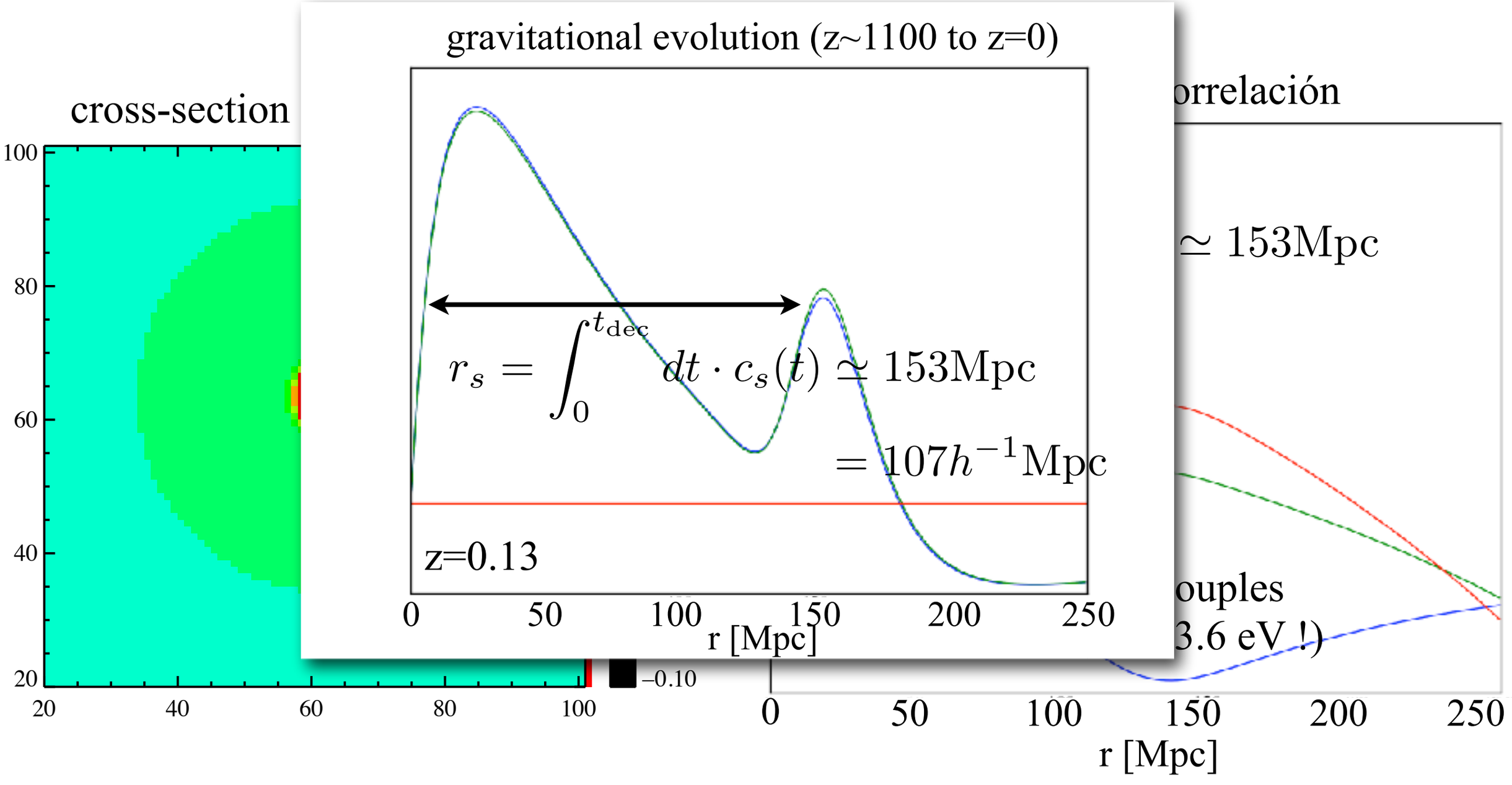
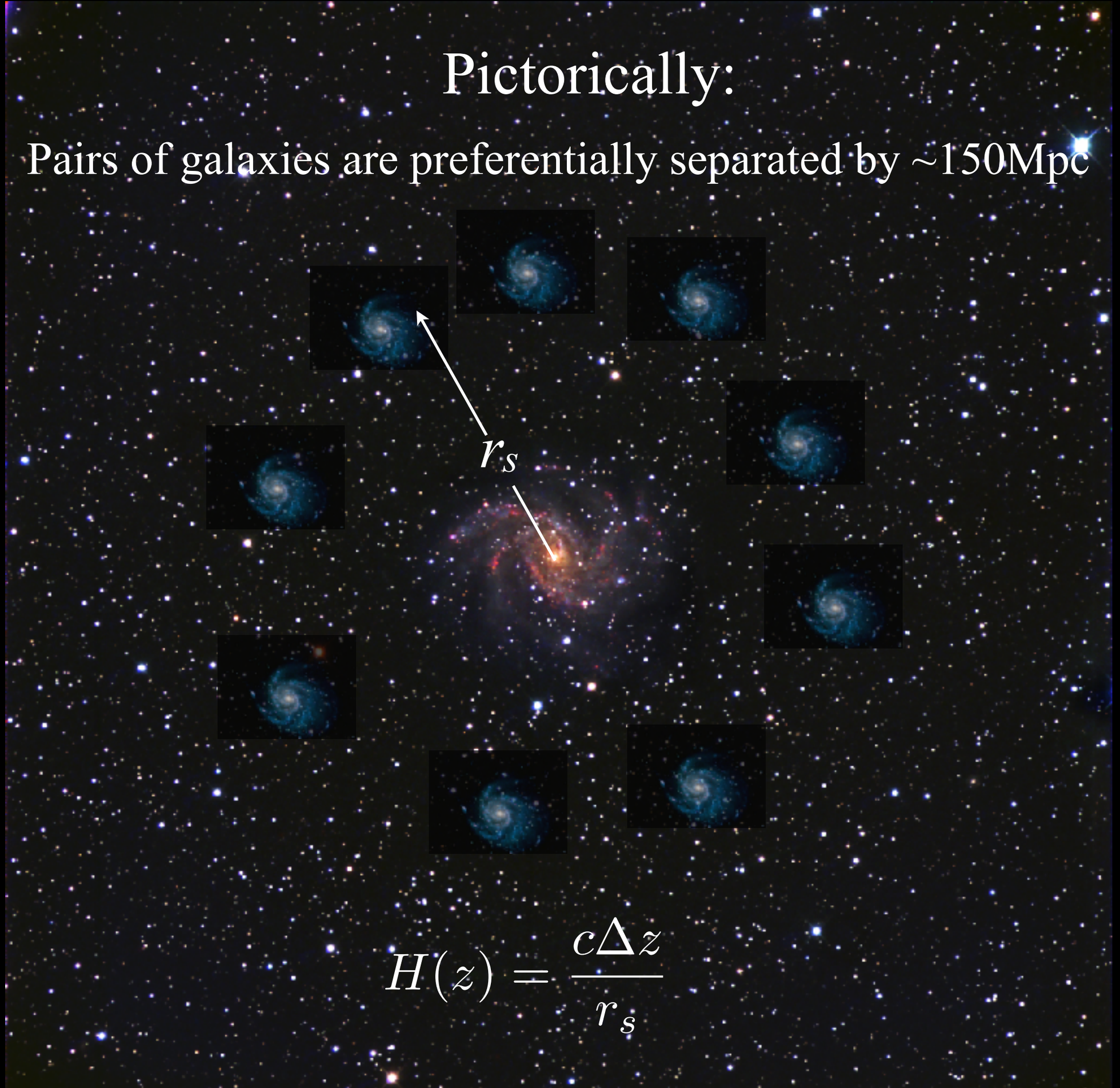


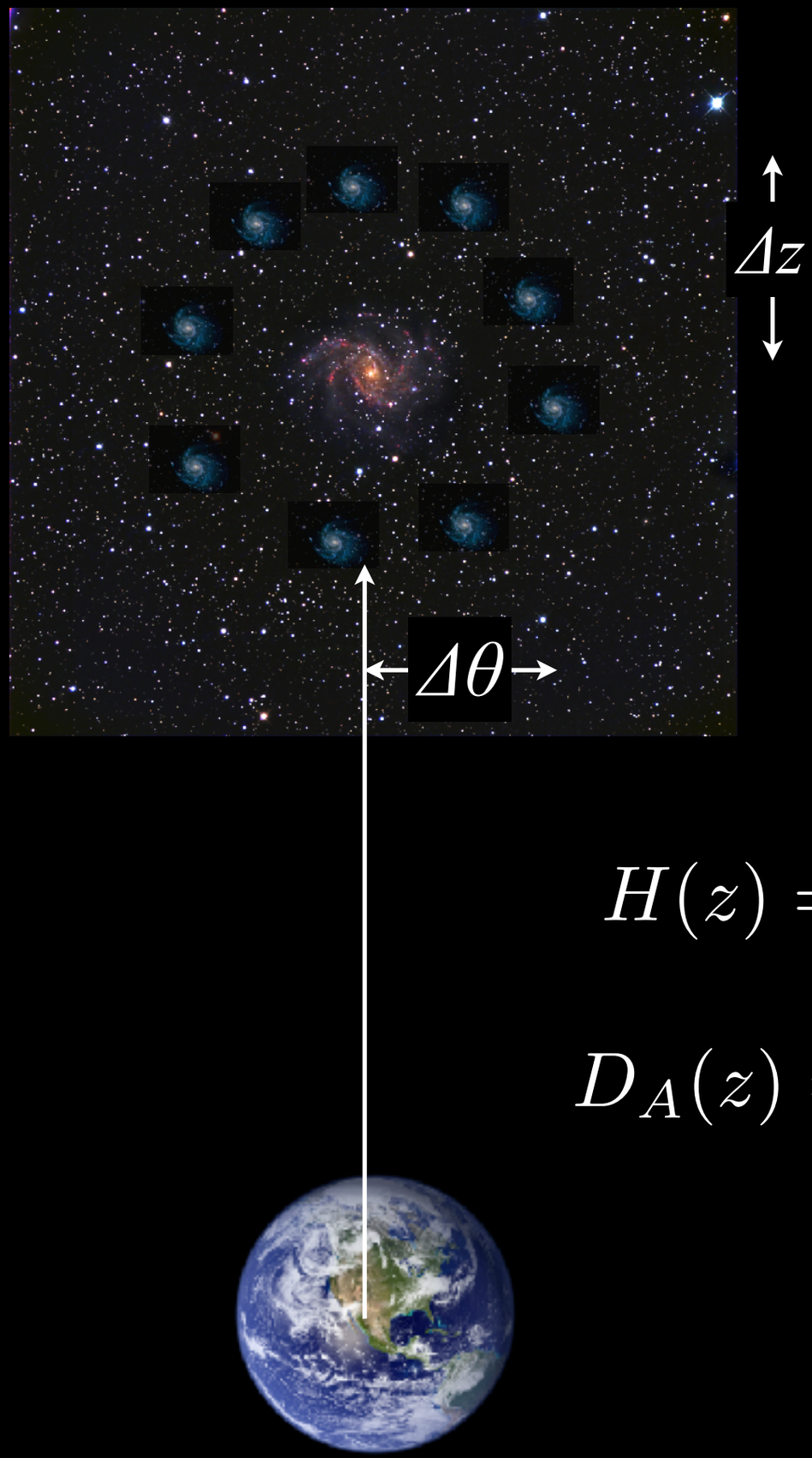
Pictorically:

Pairs of galaxies are preferentially separated by ~150Mpc



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

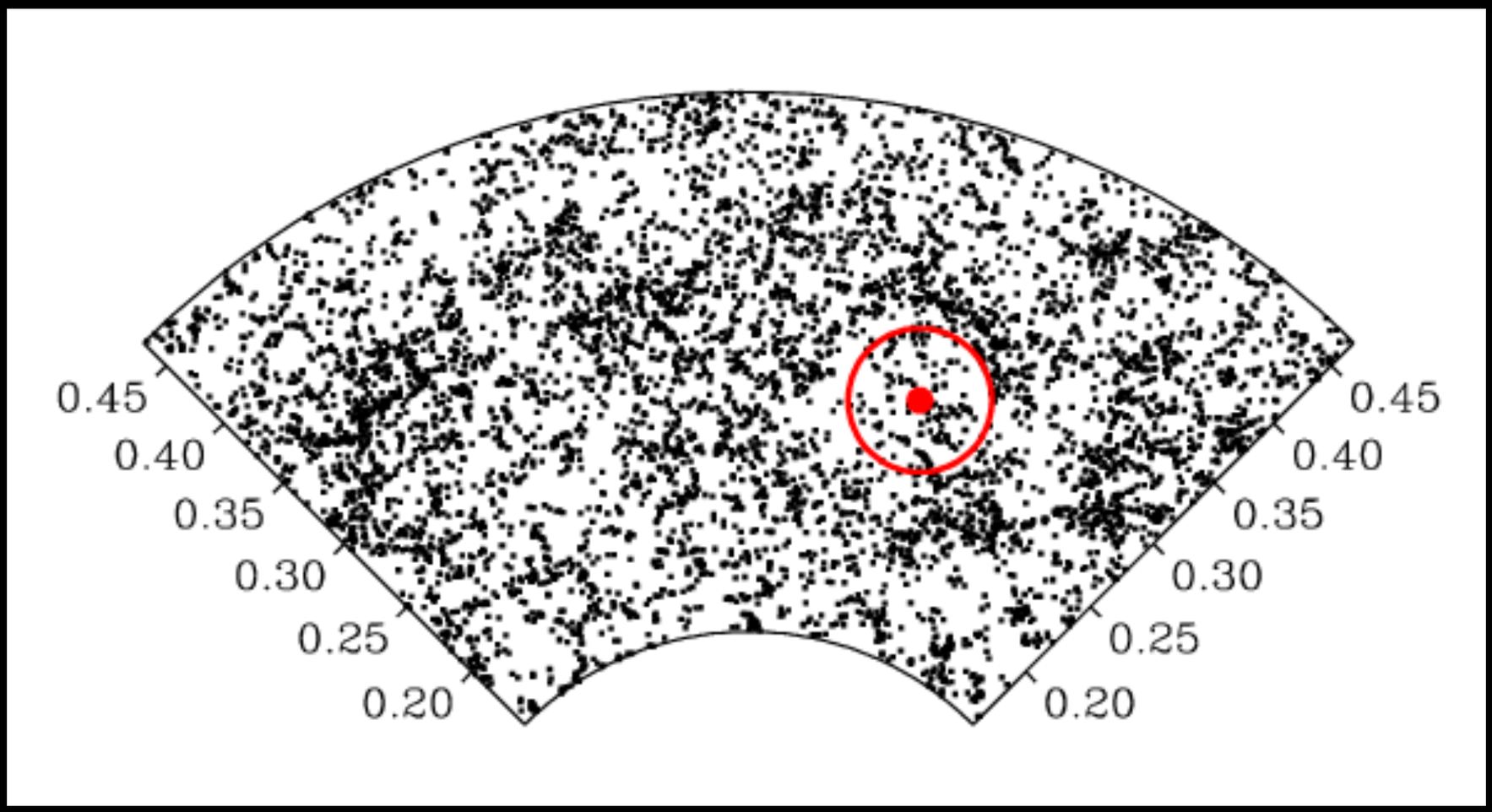
Pictorically



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

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

In practice…

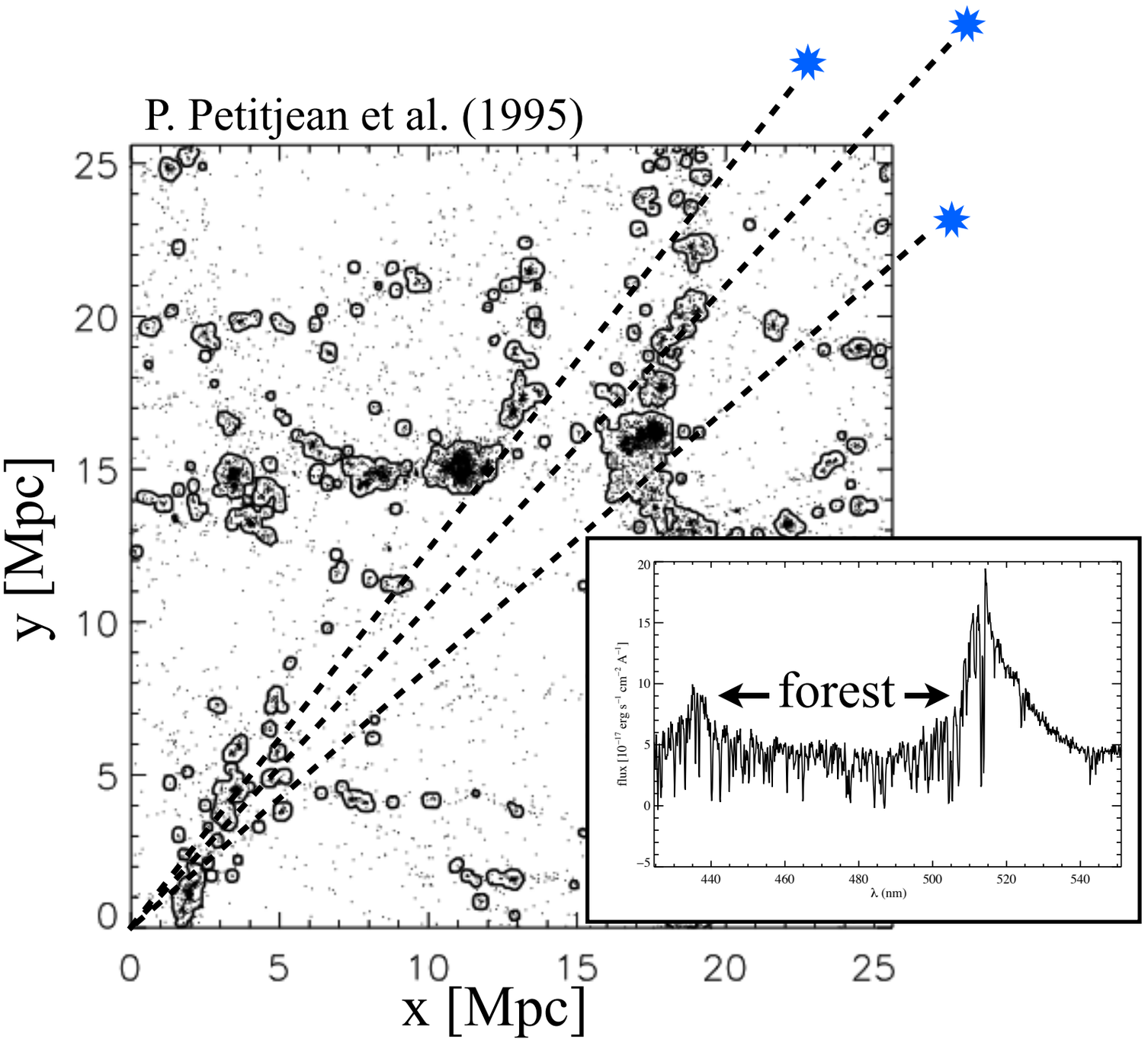


- The large scale structure results from a superposition of these shells
- The acoustic scale can be observed as a ~1% excess in the 2pt-correlation function

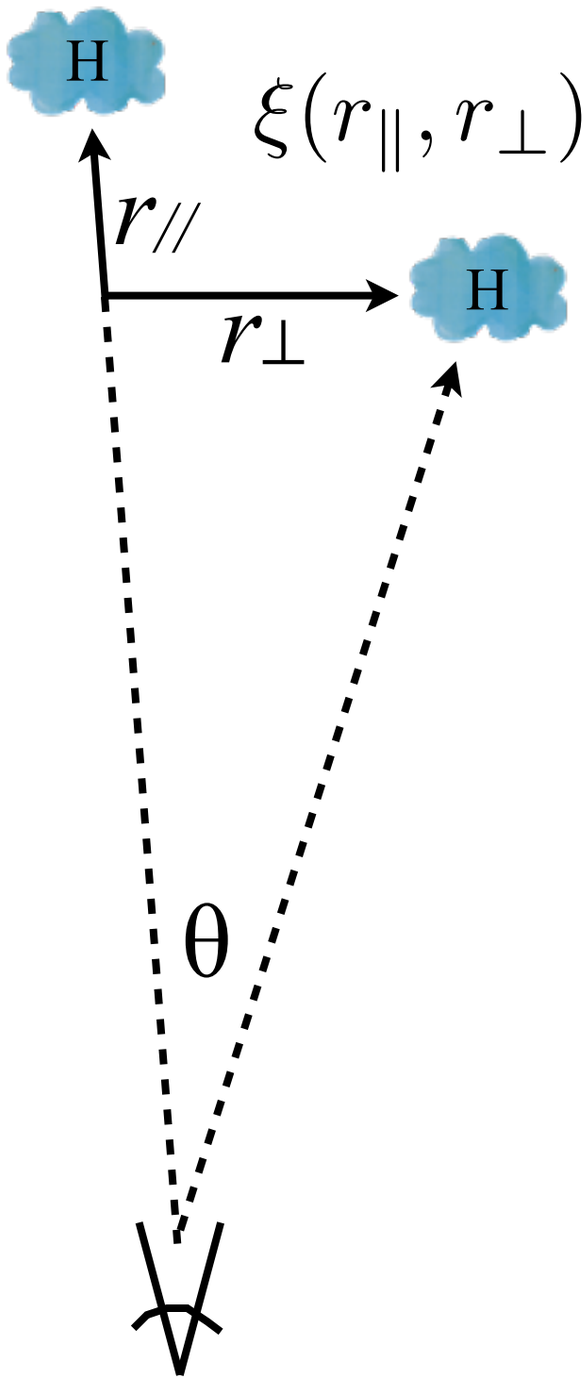
How to measure the matter distribution

Galaxies:
- high density contrast O(200)
- bias model
  (how light follows matter):
  $\delta_{gal} = b\, \delta_{DM}$
- z ~ 0-1.

Lyα forest:
- low density constrast
- non-linear tracer:
  $$f_\lambda = \exp\left[-\tau(z)\right]$$
- first principle calculations
- z ~ 2.5



Measurement of the correlation function in terms of a "fiducial cosmology"



$$\xi(r_\parallel, r_\perp) = \langle \delta\delta \rangle$$

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

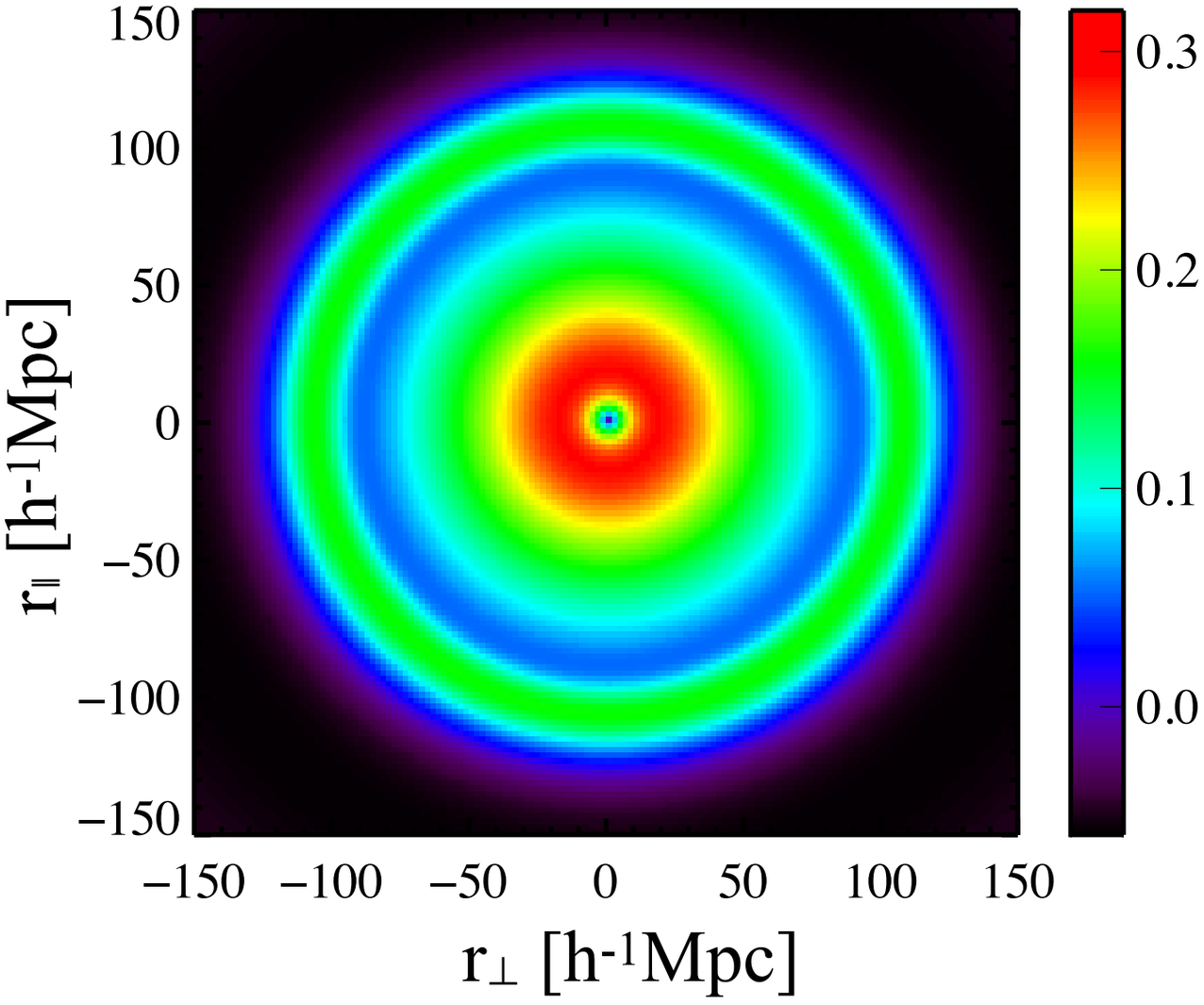
$$r_\perp = (r_1 + r_2)\sin(\theta/2)$$

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

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

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

Measurement of the correlation function



Isotropy:

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

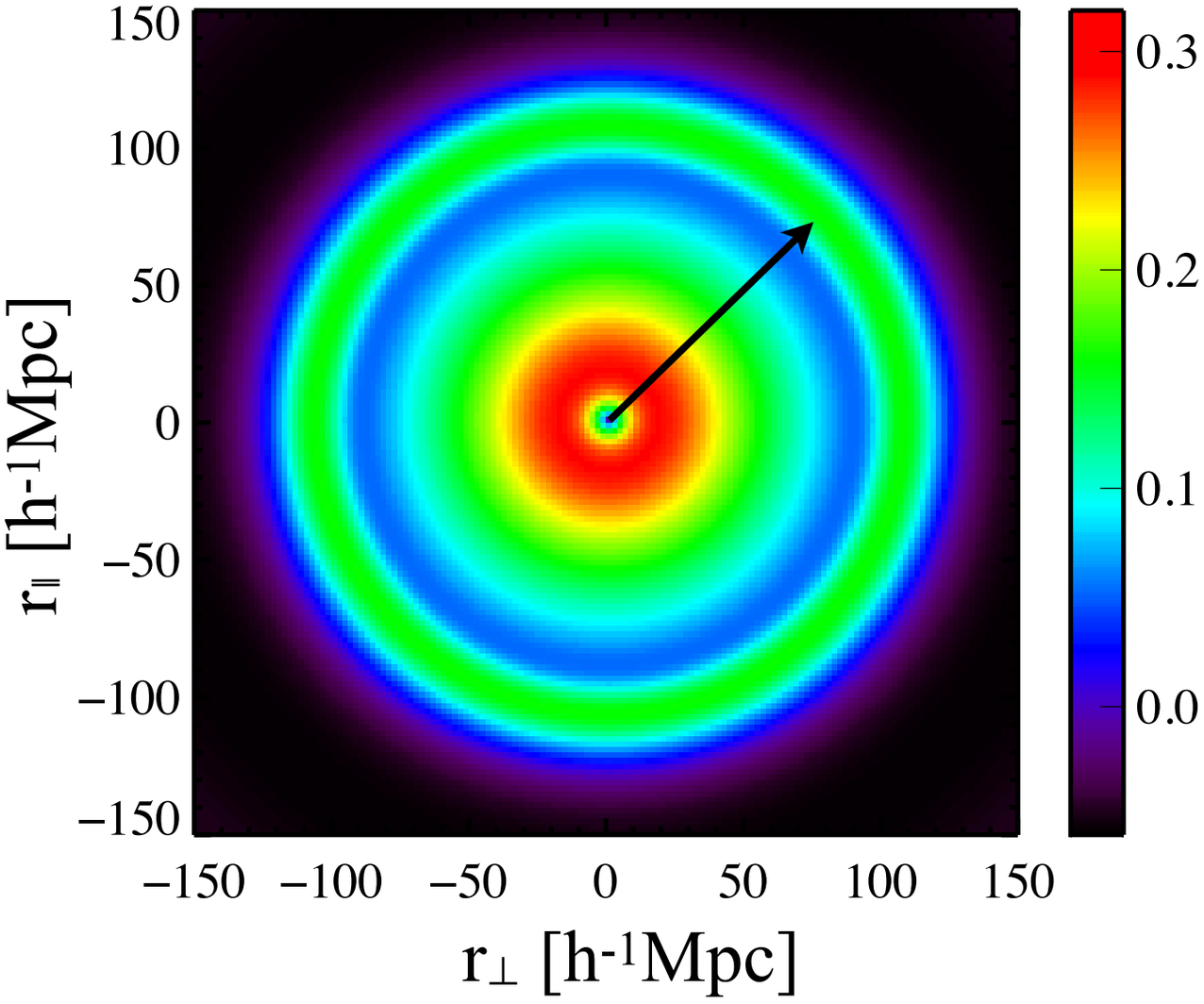
An incorrect fiducial cosmology breaks the polar symmetry

Alcock & Paczyński (1979)
(independiente de las BAO)

AP measures:

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

Measurement of the correlation function



AP measures:

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

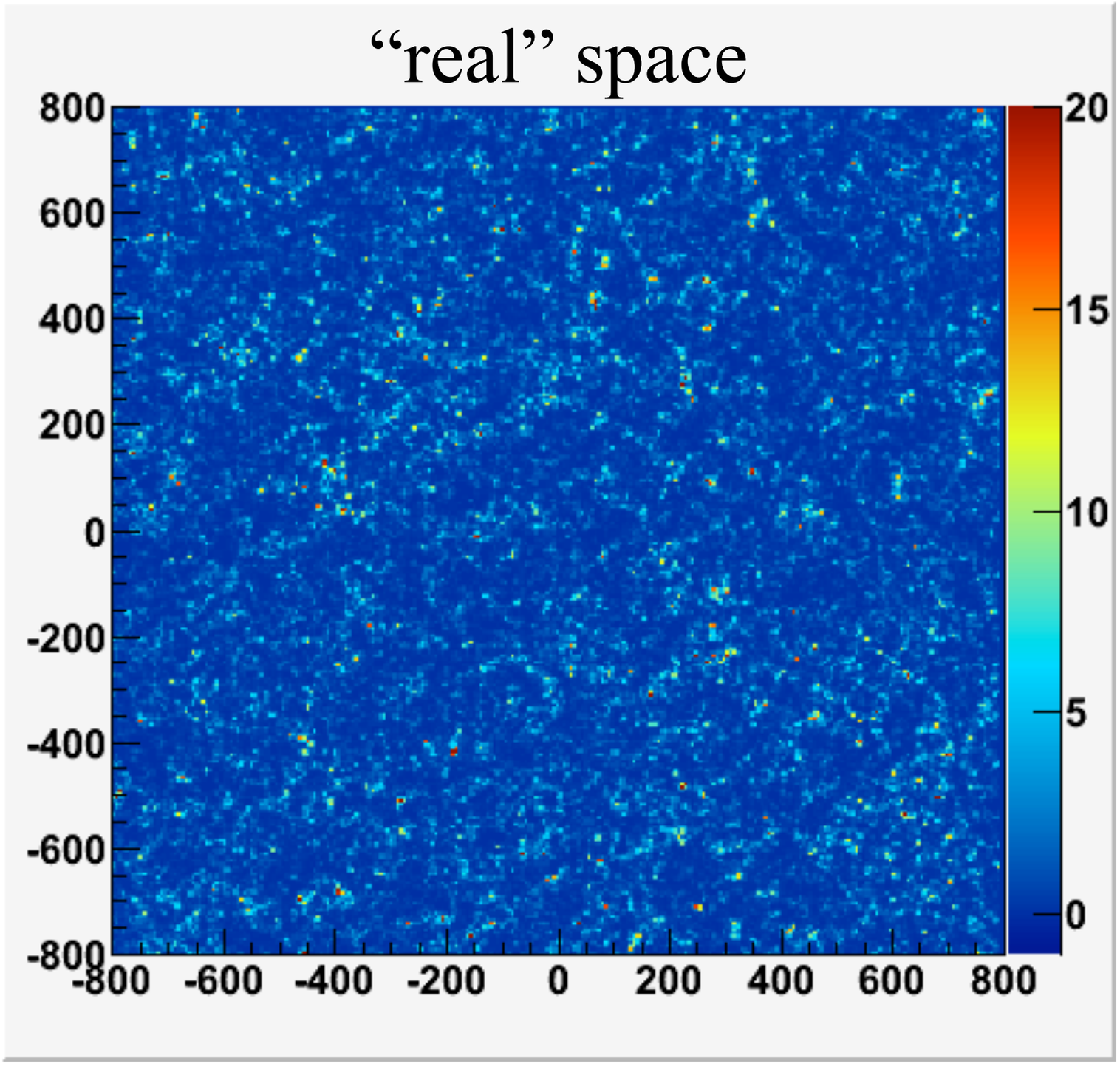
The BAO scale allows one to break the degeneracy:

$$H(z) \cdot r_s$$

$$d_A(z)/r_s$$

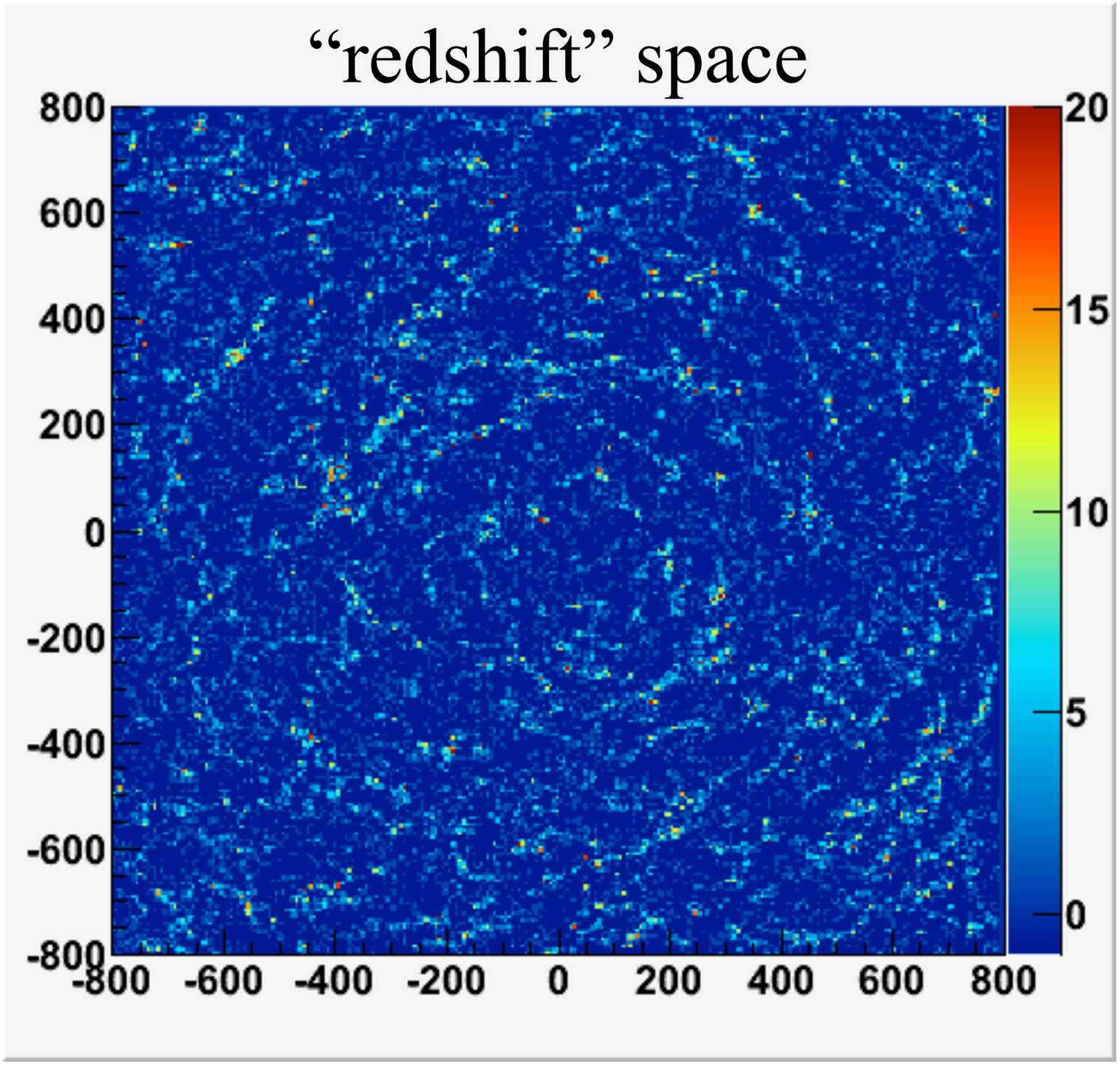
Caveat ! redshift space distortions

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

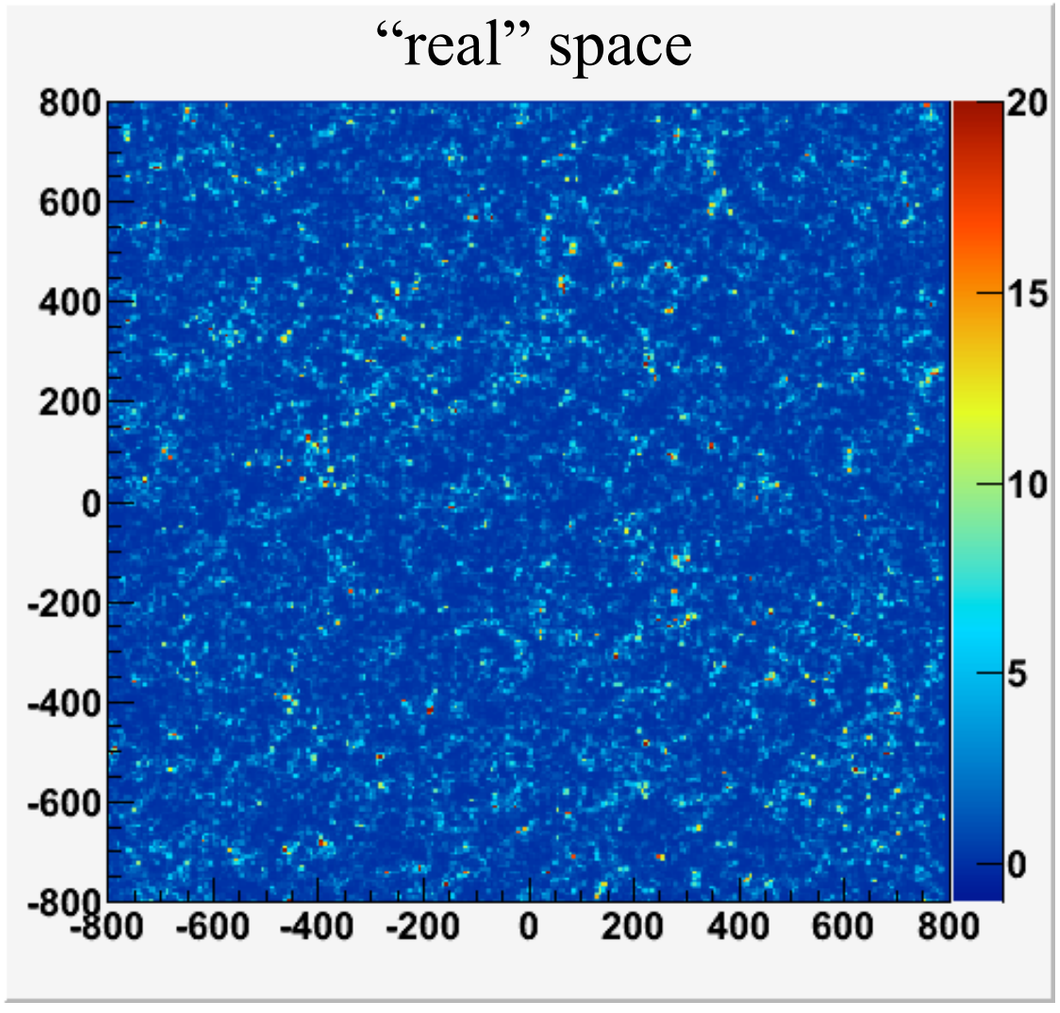


Caveat ! redshift space distortions

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

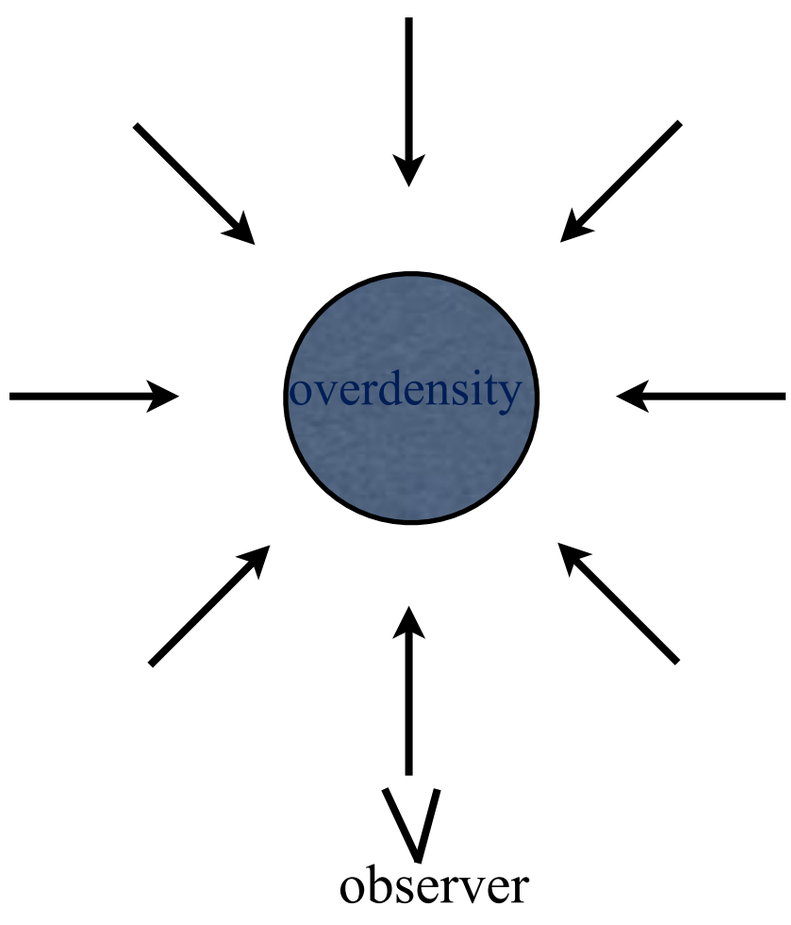


Caveat ! redshift space distortions

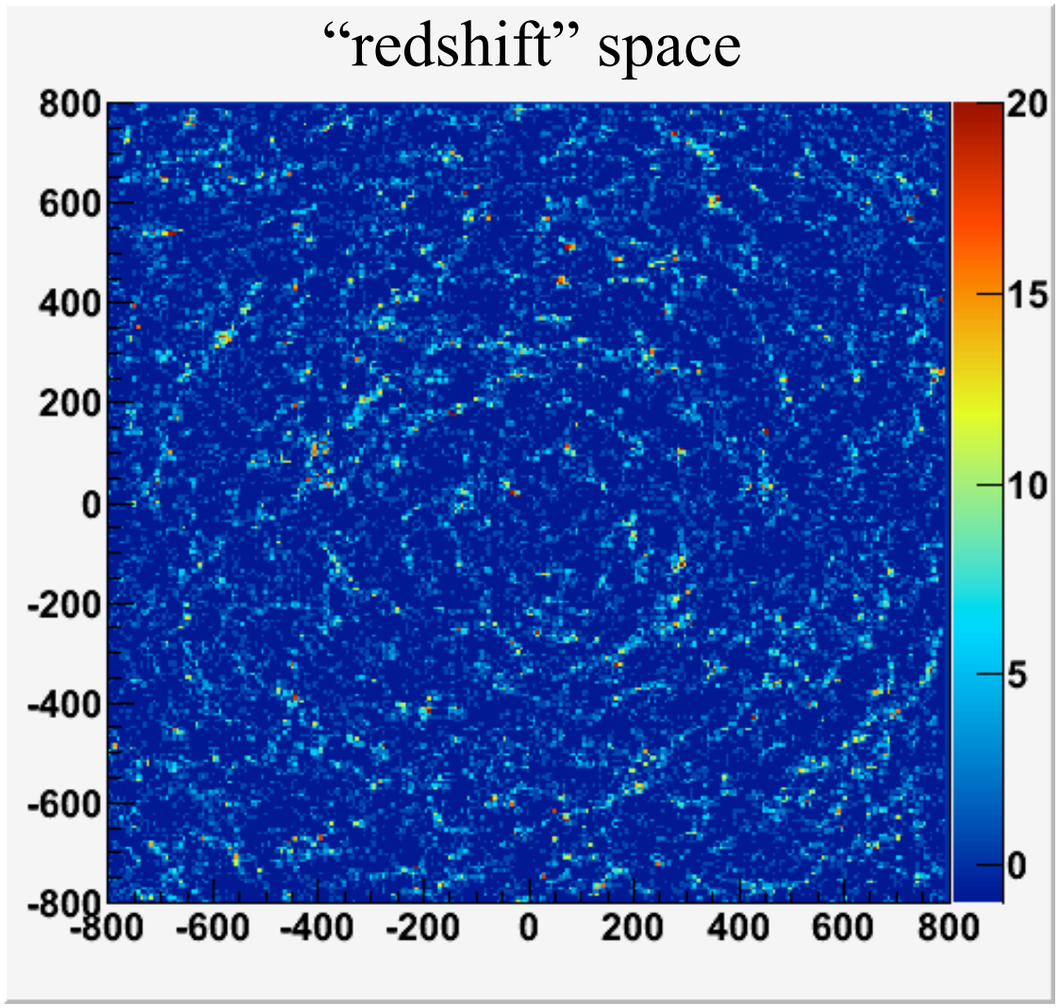


- Kaiser effect: matter falls into potential wells

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



Caveat ! redshift space distortions



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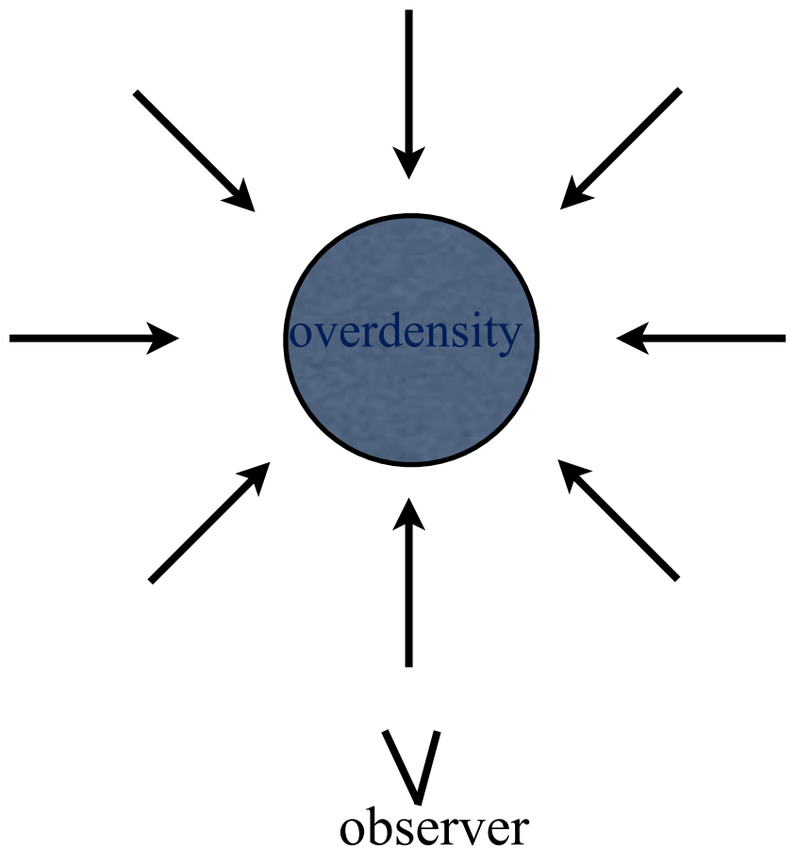
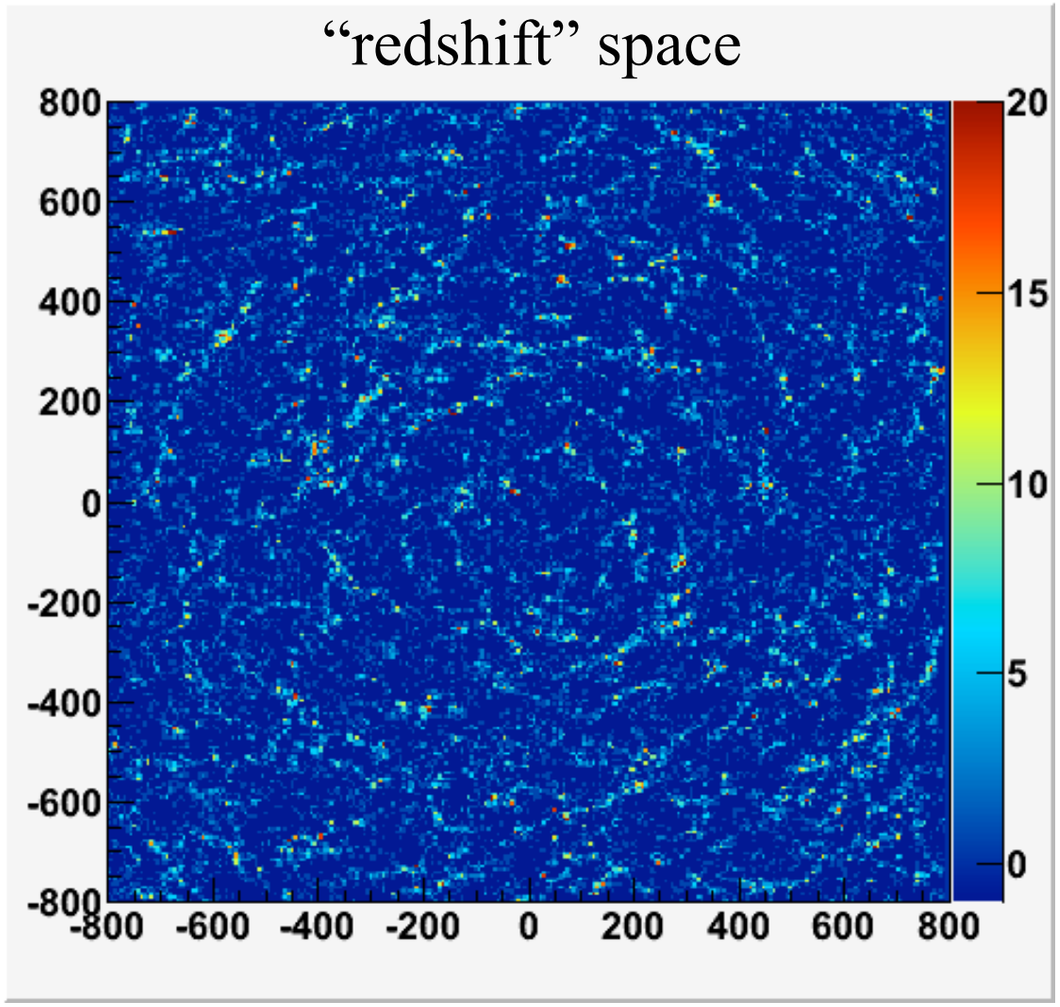


Caveat ! redshift space distortions



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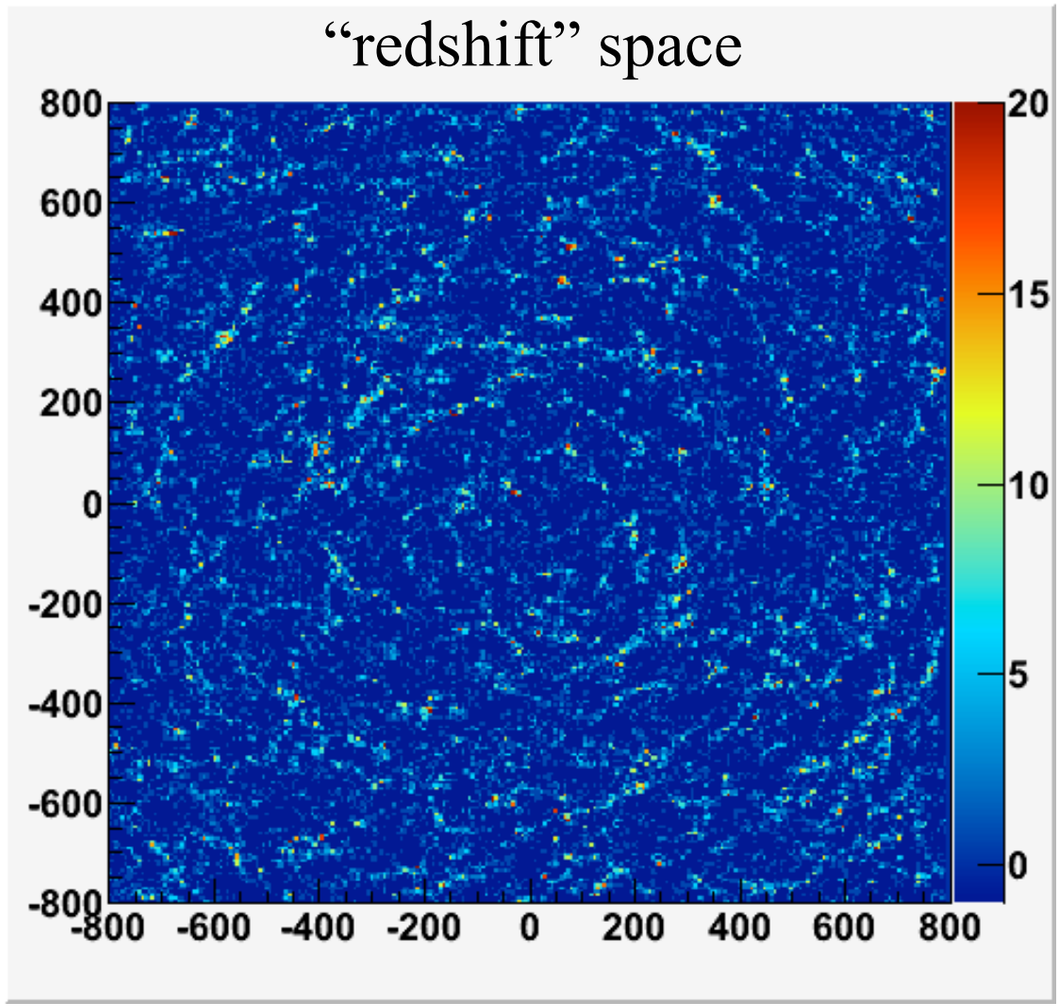
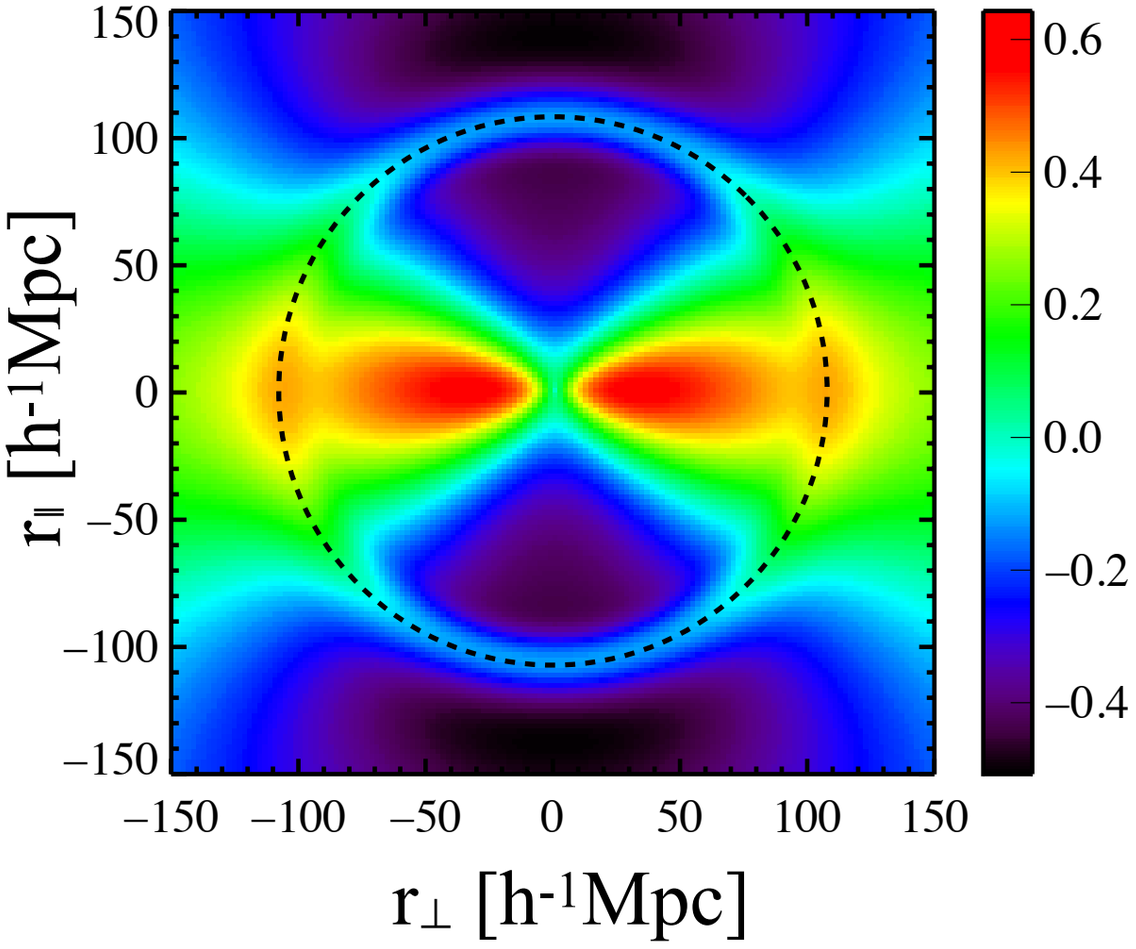
Caveat ! redshift space distortions



- Kaiser effect: matter falls into potential wells

a problem for cosmology?

Caveat ! redshift space distortions



- Kaiser effect: matter falls into potential wells

a problem for cosmology?

No !

- one additional parameter

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

$\beta \propto \Omega_m^{0.6}$ (in general relativity)

- the BAO position is not affected

(e)BOSS: (extended) Baryon acoustic oscillations survey

- Survey bases on the 2.5 m SDSS telescope (APO, New Mexico)
- BOSS observed 10 kdeg^2 1.2 MGalaxies, $0.3 < z < 0.8$
- Will reobserve the BOSS footprint to focus on the $1 < z < 2$ region
- Extend the high-redshift Lyα sample by ~60,000 new quasars (originally ~200,000) and improving the S/N of ~60,000 known quasars from BOSS

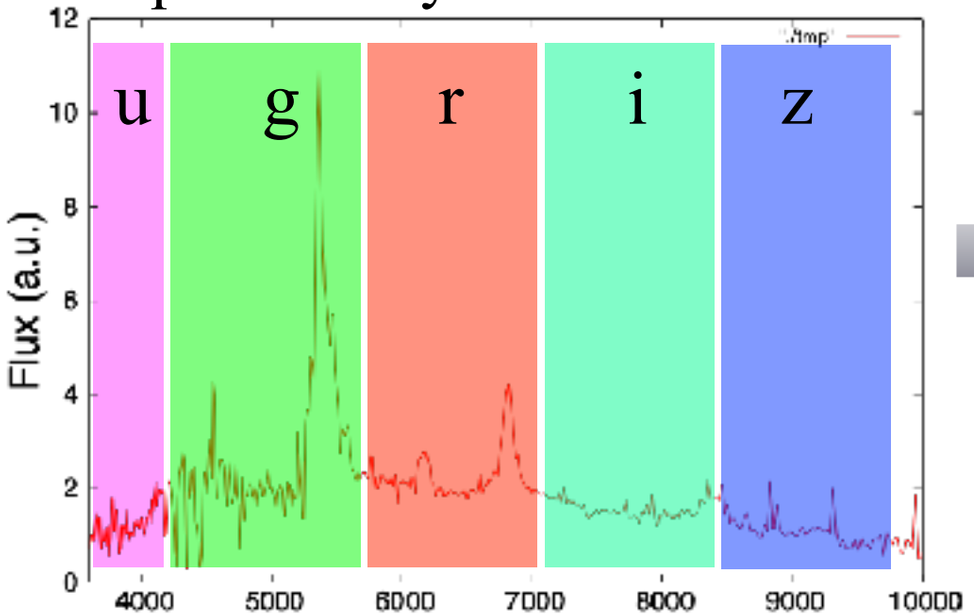
DESI: Dark Energy Spectroscopic Instrument

Mayall 4-Meter Telescope

- Dedicated survey at the Mayall Telescope
- 4m telescope located in Kitt Peak (Arizona)
- Will observe 14 kdeg^2 and $0 < z < 4$
- ~5x eBOSS

(e)BOSS - data taking

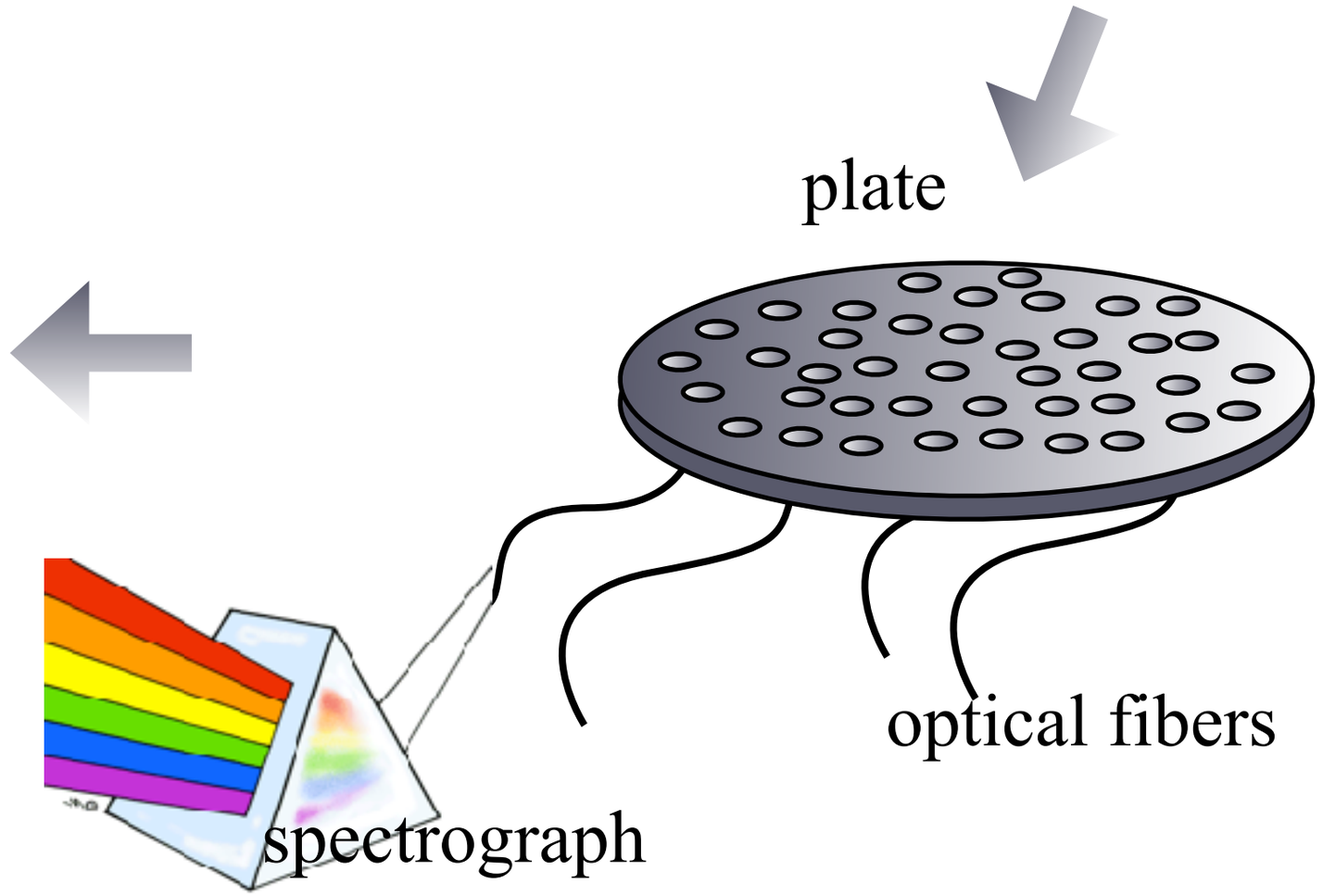
photometry from SDSS-II



target selection

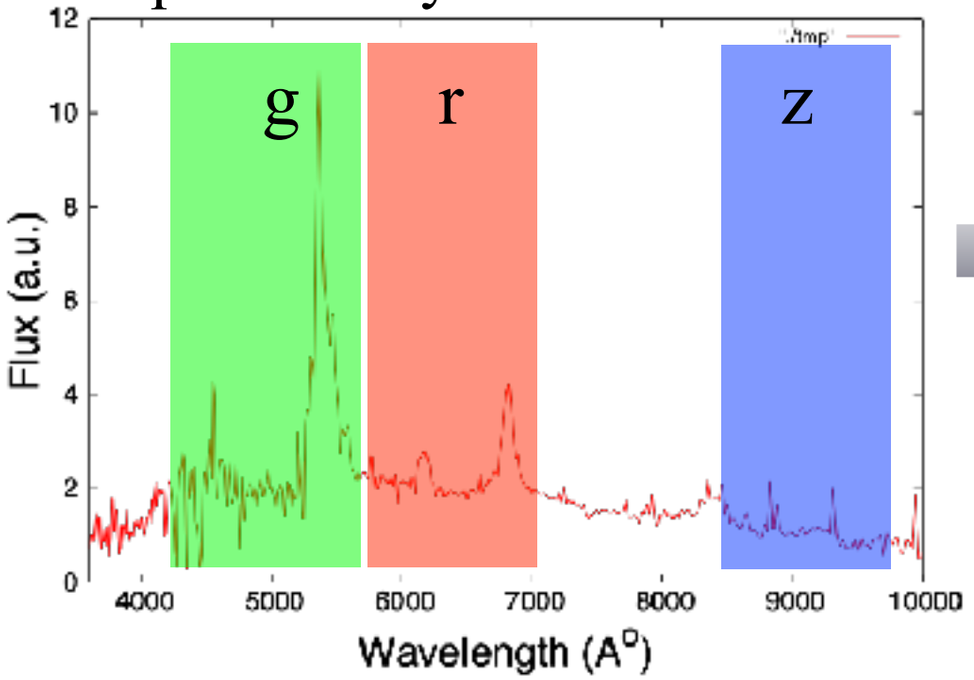
List of targets

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
....



DESI - data taking

photometry from SDSS-II



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SDSSp J120441.73-002149.6
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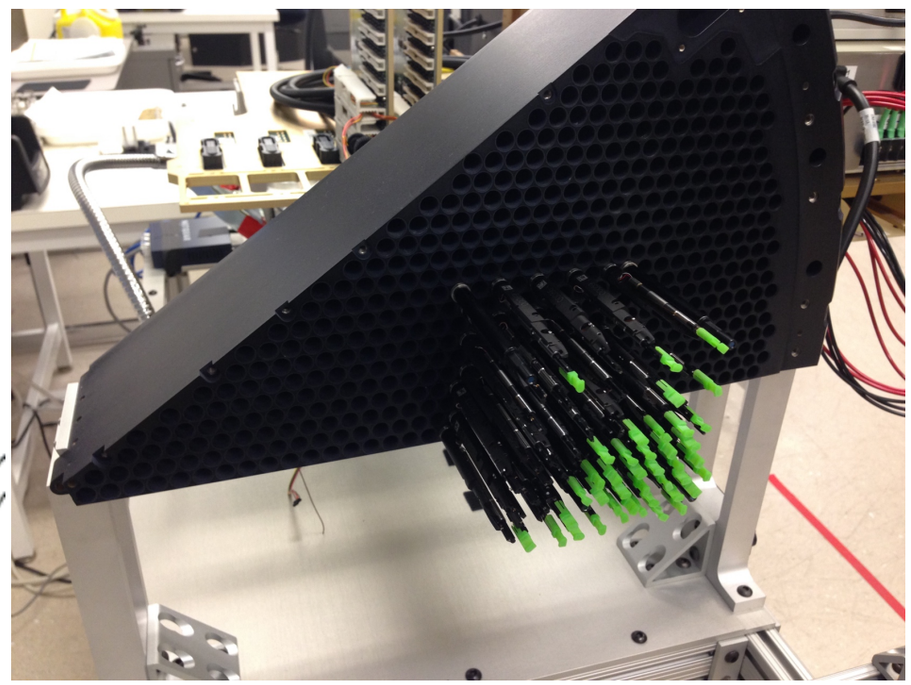
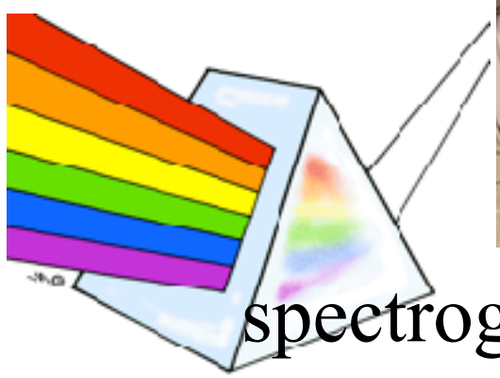
SDSSp J141205.78-010152.6
SDSSp J141315.36+000032.1
....

a “petal”



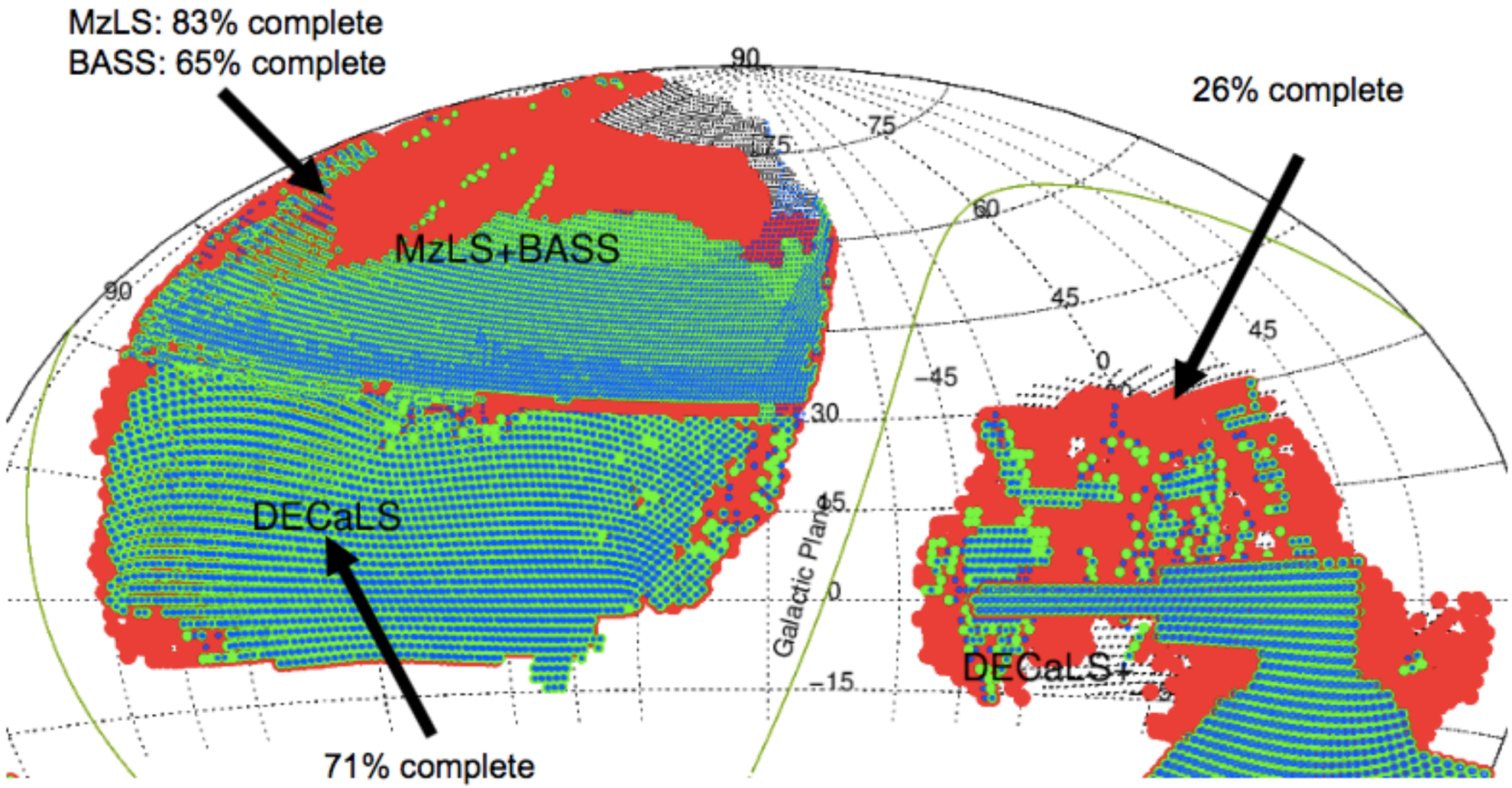


spectrograph

DESI - photometric survey

Current Status

2017 June 15



MzLS: Mayall z-bang legacy survey (z-band Mayall telescope, Kitt Peak)

needs to finish by the end of the year!!

BASS: Beijing Arizona Sky Survey (r and g bands, Bok telescope, Kitt Peak)

DECaLS: Dark Energy Camera Legacy Survey (r, g, z bands, Blanco telescope, Cerro Tololo)

data publicly accessible at http://legacysurvey.org

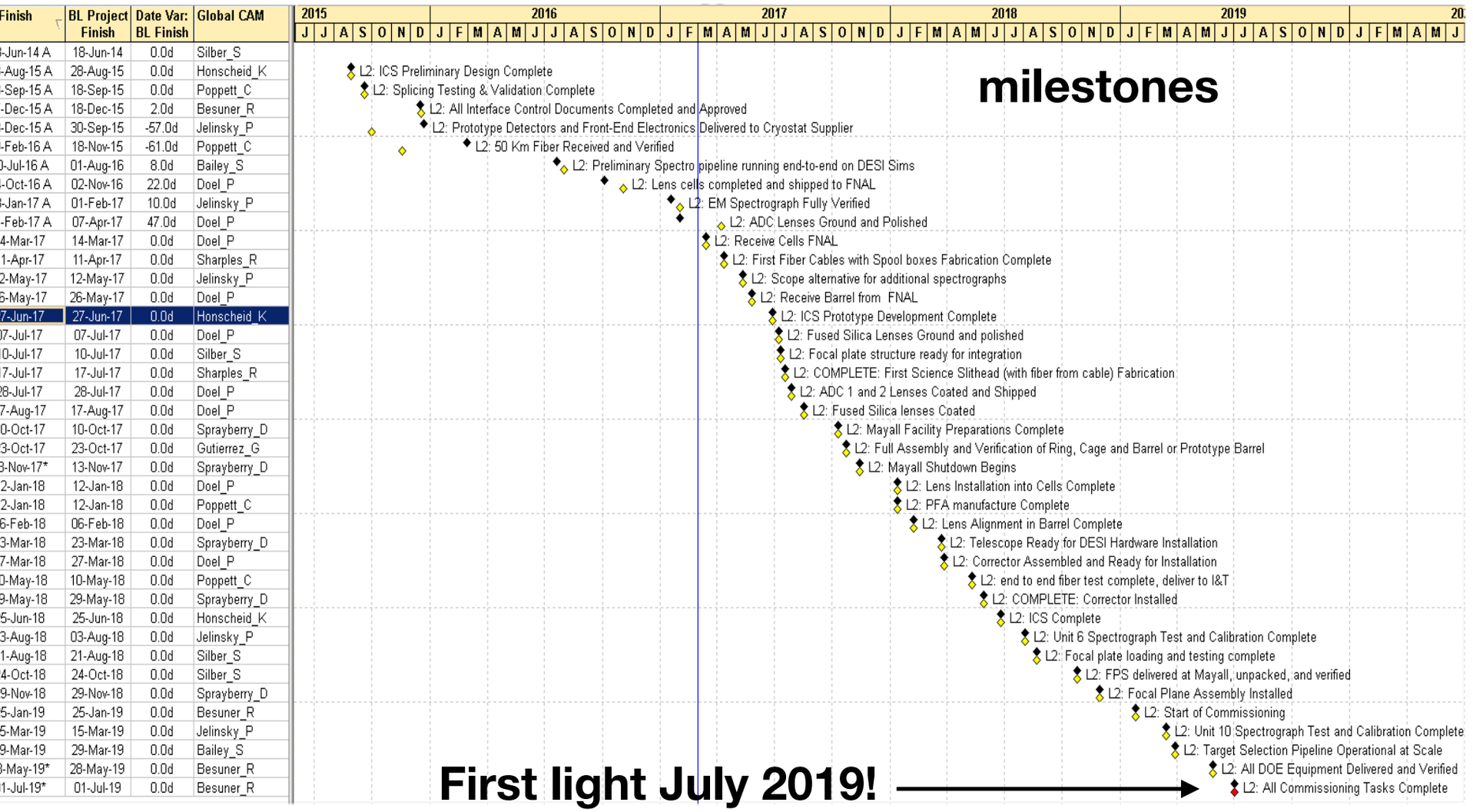
DESI - photometric survey

Current Status

2017 June 15

MzLS: 83% complete

Finish	BL Project Finish	Date Var: BL Finish	Global CAM
18-Jun-14 A	18-Jun-14	0.0d	Silber_S
28-Aug-15 A	28-Aug-15	0.0d	Honscheid_K
18-Sep-15 A	18-Sep-15	0.0d	Poppett_C
17-Dec-15 A	18-Dec-15	2.0d	Besuner_R
23-Dec-15 A	30-Sep-15	-57.0d	Jelinsky_P
29-Feb-16 A	18-Nov-15	-61.0d	Poppett_C
20-Jul-16 A	01-Aug-16	8.0d	Bailey_S
04-Oct-16 A	02-Nov-16	22.0d	Doel_P
18-Jan-17 A	01-Feb-17	10.0d	Jelinsky_P
01-Feb-17 A	07-Apr-17	47.0d	Doel_P
14-Mar-17	14-Mar-17	0.0d	Doel_P
11-Apr-17	11-Apr-17	0.0d	Sharples_R
12-May-17	12-May-17	0.0d	Jelinsky_P
26-May-17	26-May-17	0.0d	Doel_P
27-Jun-17	27-Jun-17	0.0d	Honscheid_K
07-Jul-17	07-Jul-17	0.0d	Doel_P
10-Jul-17	10-Jul-17	0.0d	Silber_S
17-Jul-17	17-Jul-17	0.0d	Sharples_R
28-Jul-17	28-Jul-17	0.0d	Doel_P
17-Aug-17	17-Aug-17	0.0d	Doel_P
10-Oct-17	10-Oct-17	0.0d	Sprayberry_D
23-Oct-17	23-Oct-17	0.0d	Gutierrez_G
13-Nov-17*	13-Nov-17	0.0d	Sprayberry_D
12-Jan-18	12-Jan-18	0.0d	Doel_P
12-Jan-18	12-Jan-18	0.0d	Poppett_C
06-Feb-18	06-Feb-18	0.0d	Doel_P
23-Mar-18	23-Mar-18	0.0d	Sprayberry_D
27-Mar-18	27-Mar-18	0.0d	Doel_P
10-May-18	10-May-18	0.0d	Poppett_C
29-May-18	29-May-18	0.0d	Sprayberry_D
25-Jun-18	25-Jun-18	0.0d	Honscheid_K
03-Aug-18	03-Aug-18	0.0d	Jelinsky_P
21-Aug-18	21-Aug-18	0.0d	Silber_S
24-Oct-18	24-Oct-18	0.0d	Silber_S
29-Nov-18	29-Nov-18	0.0d	Sprayberry_D
25-Jan-19	25-Jan-19	0.0d	Besuner_R
15-Mar-19	15-Mar-19	0.0d	Jelinsky_P
29-Mar-19	29-Mar-19	0.0d	Bailey_S
28-May-19*	28-May-19	0.0d	Besuner_R
01-Jul-19*	01-Jul-19	0.0d	Besuner_R



MzLS: Mayall z-bang legacy survey (z-band Mayall telescope, Kitt Peak)
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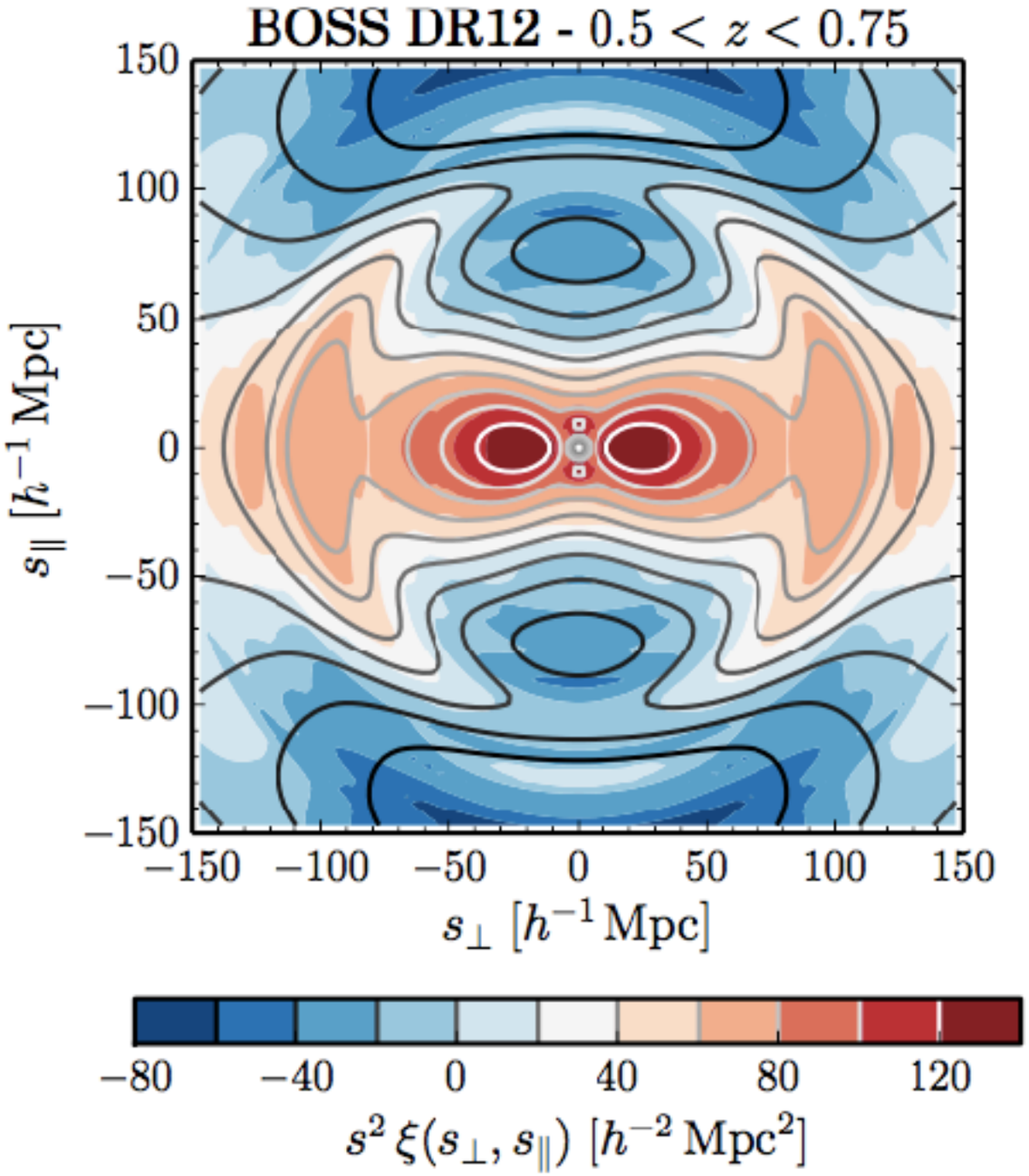
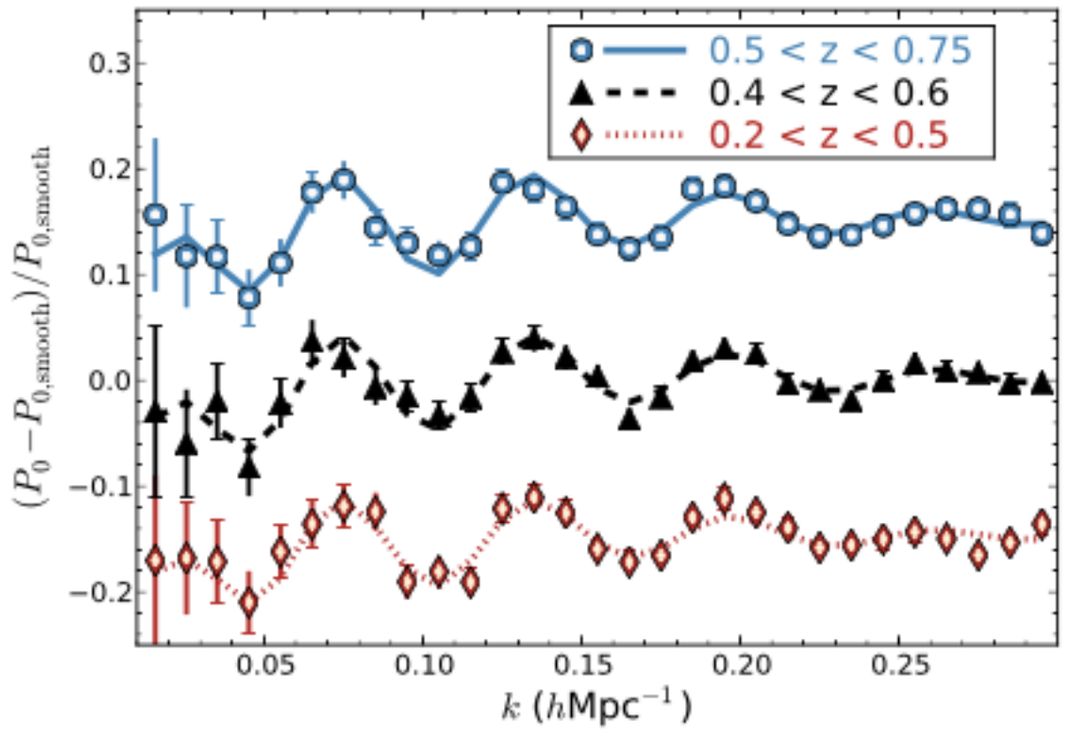
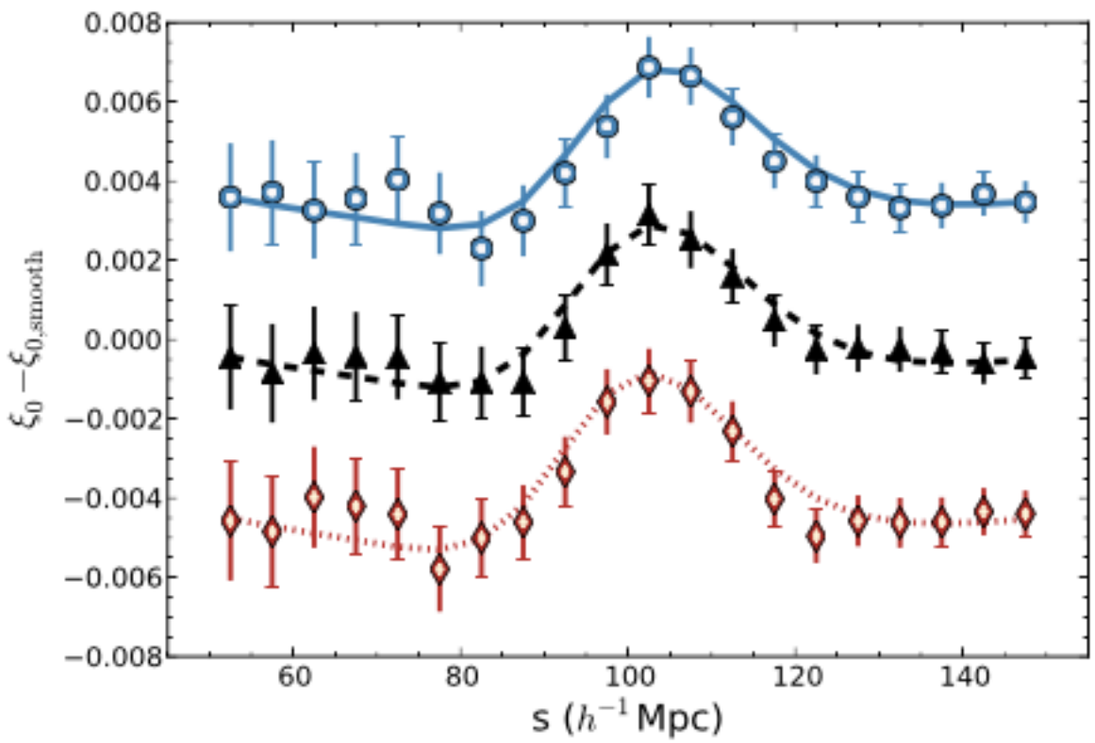
Latest Cosmological Results - BOSS DR12

Latest Cosmological Results - BOSS DR12

Galaxy-Galaxy correlation function

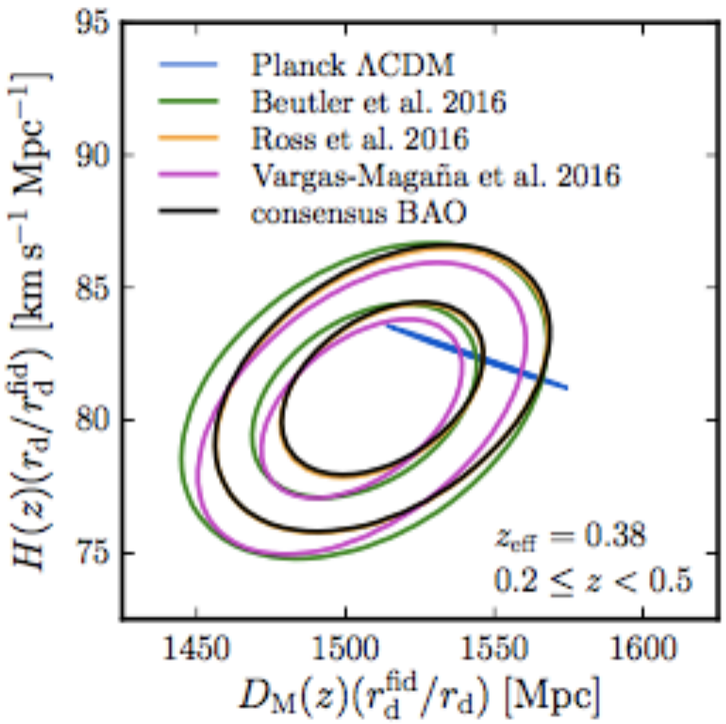


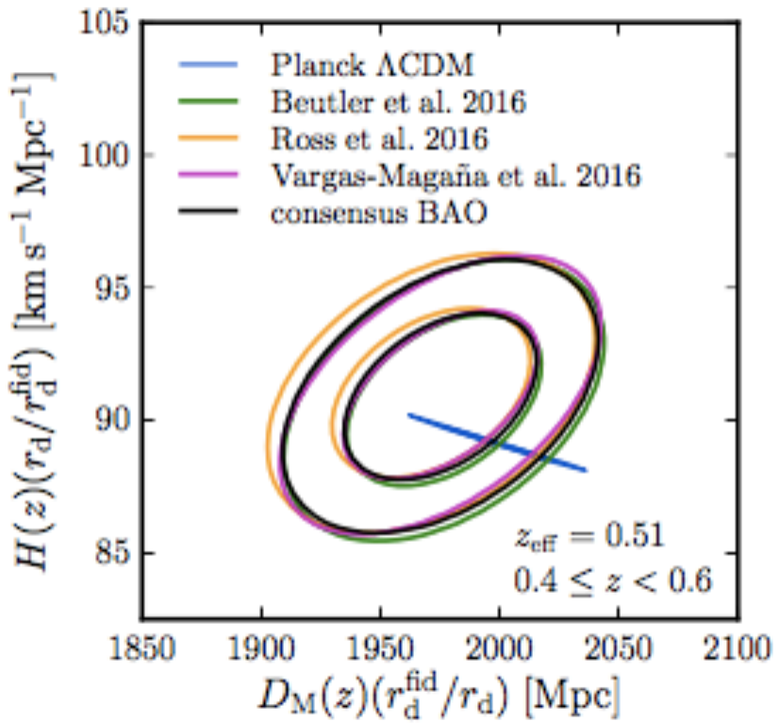


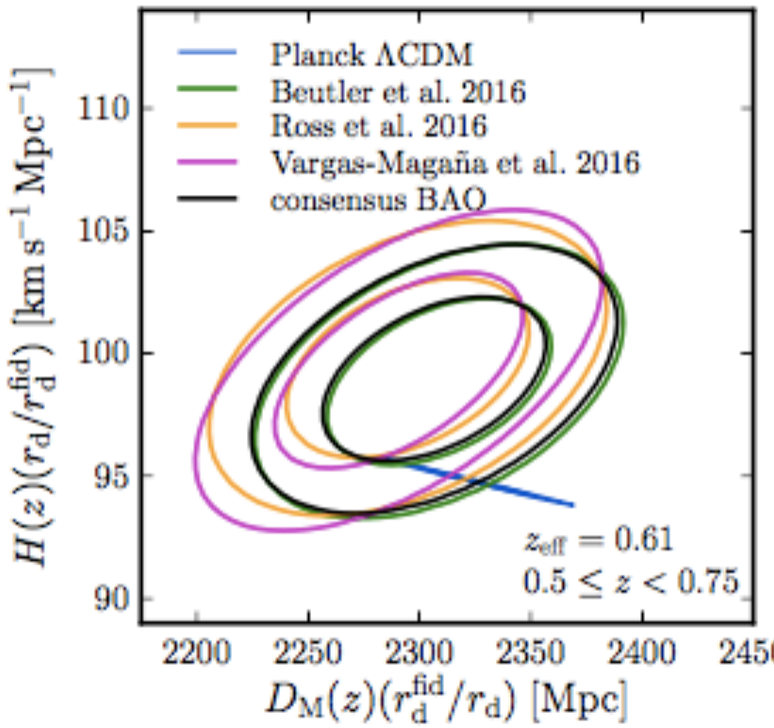


Latest Cosmological Results - BOSS DR12

Alam et al. 2016







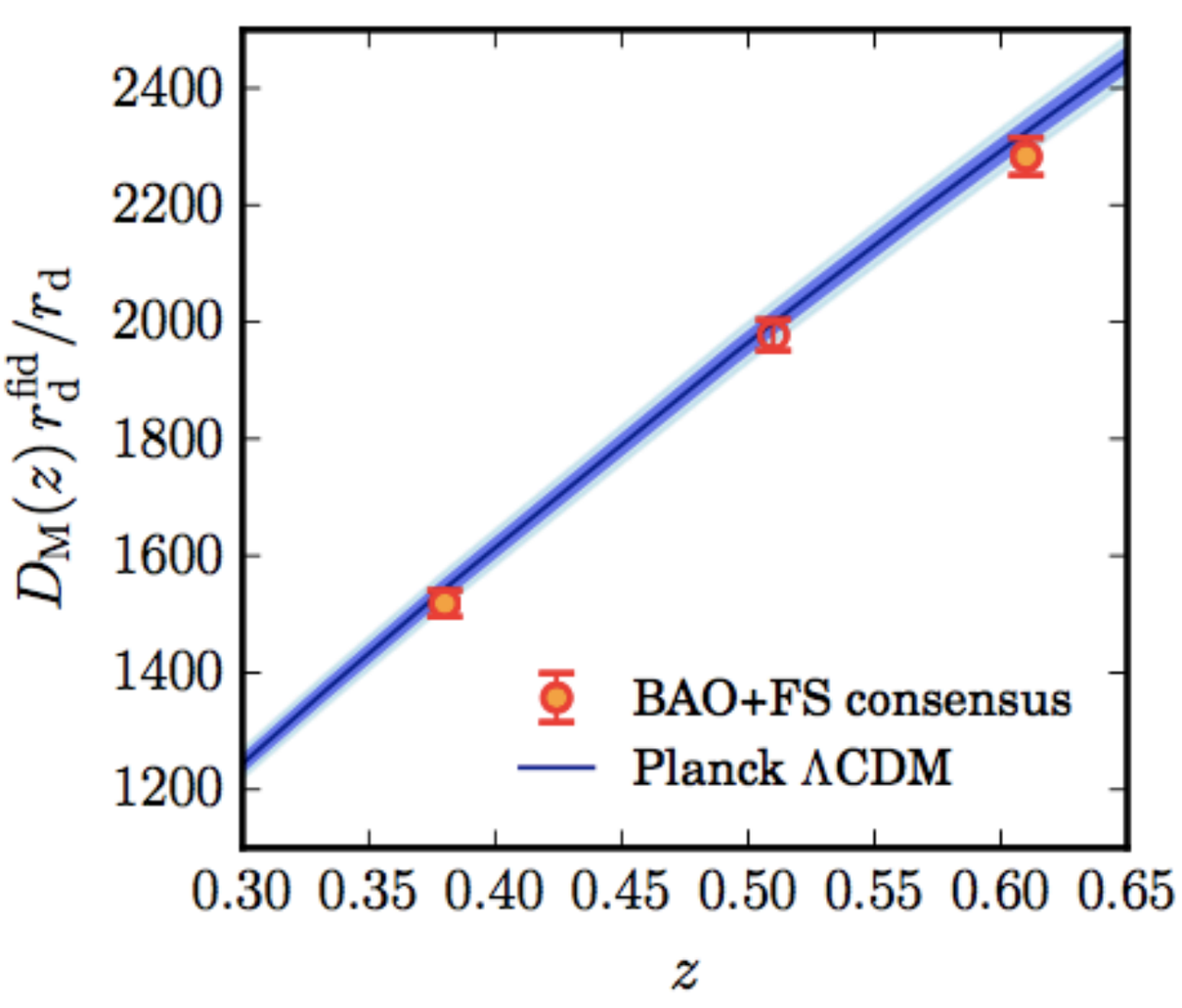
Measurement	redshift	Beutler et al. (b) $P(k)$	Vargas-Magaña et al. $\xi(s)$	Ross et al. $\xi(s)$
$D_M \times (r_{d,\rm fid}/r_d)$ [Mpc]	$z = 0.38$	1507 ± 25	1507 ± 22	1512 ± 23
$D_M \times (r_{d,\rm fid}/r_d)$ [Mpc]	$z = 0.51$	1976 ± 29	1975 ± 27	1971 ± 27
$D_M \times (r_{d,\rm fid}/r_d)$ [Mpc]	$z = 0.61$	2307 ± 35	2291 ± 37	2296 ± 37
$H \times (r_d/r_{d,\rm fid})$ [km s^{-1} Mpc^{-1}]	$z = 0.38$	80.7 ± 2.4	80.4 ± 2.4	81.1 ± 2.2
$H \times (r_d/r_{d,\rm fid})$ [km s^{-1} Mpc^{-1}]	$z = 0.51$	90.8 ± 2.2	91.0 ± 2.1	91.1 ± 2.1
$H \times (r_d/r_{d,\rm fid})$ [km s^{-1} Mpc^{-1}]	$z = 0.61$	98.8 ± 2.3	99.3 ± 2.5	99.4 ± 2.2

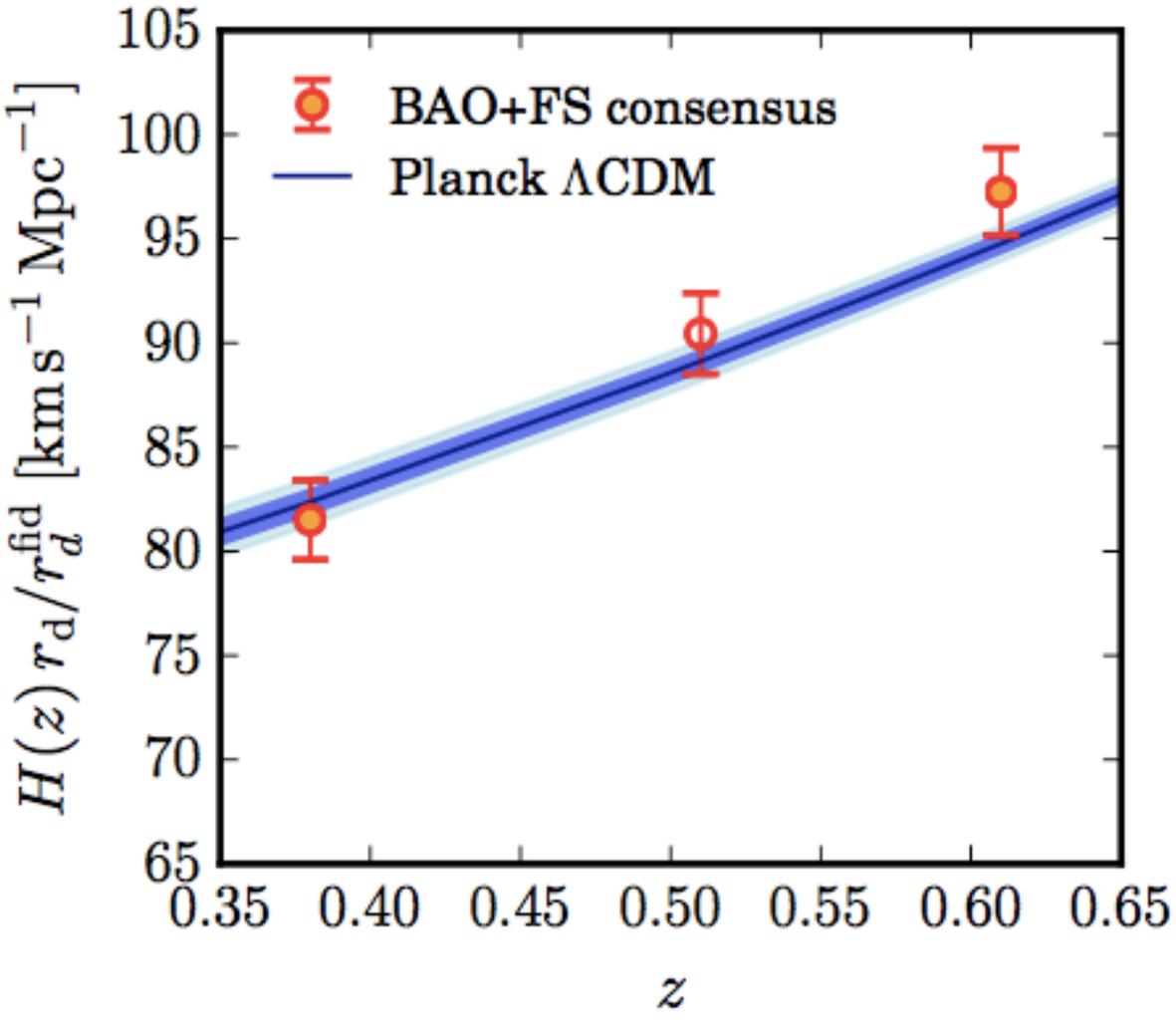
1.5% in D_M

2.5% in H

Latest Cosmological Results - BOSS DR12

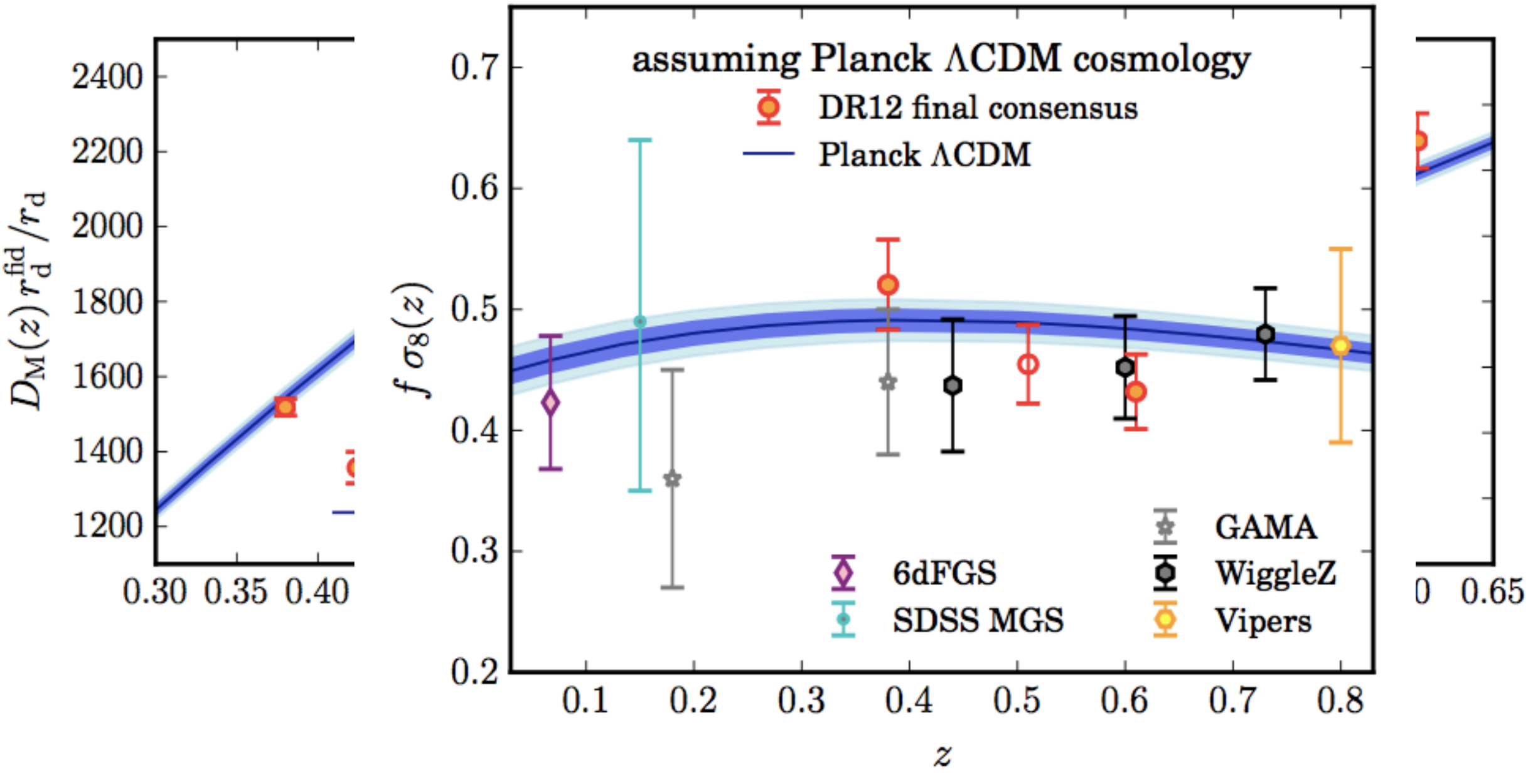
Alam et al. 2016





Latest Cosmological Results - BOSS DR12

Alam et al. 2016



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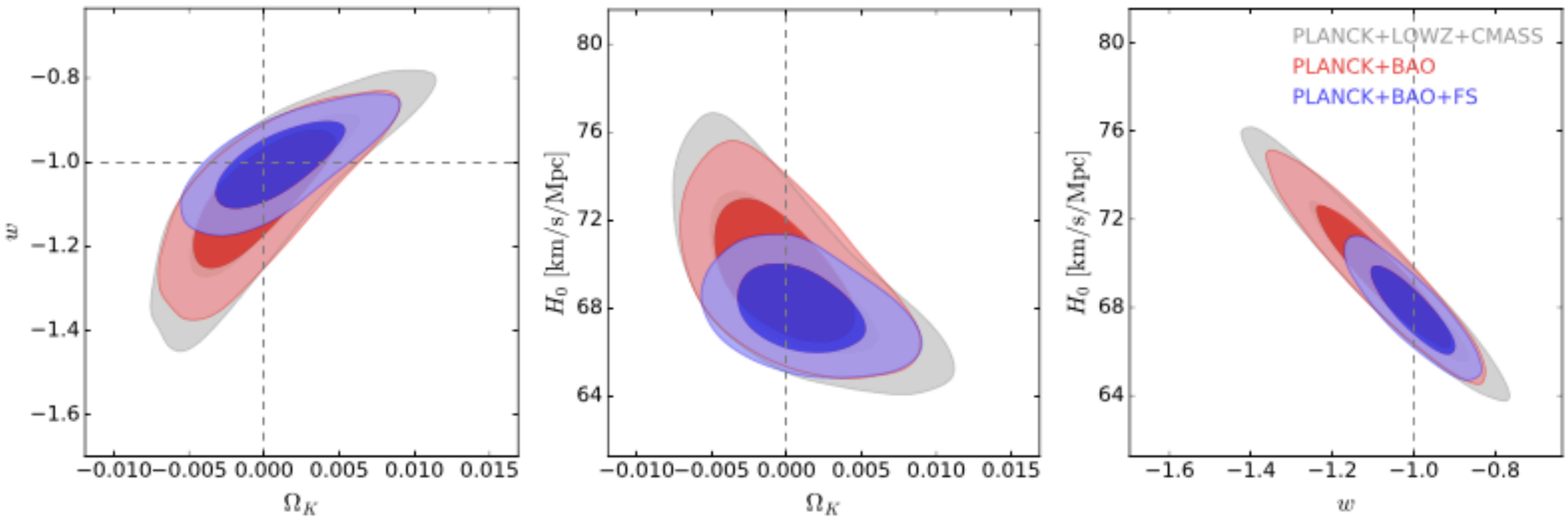
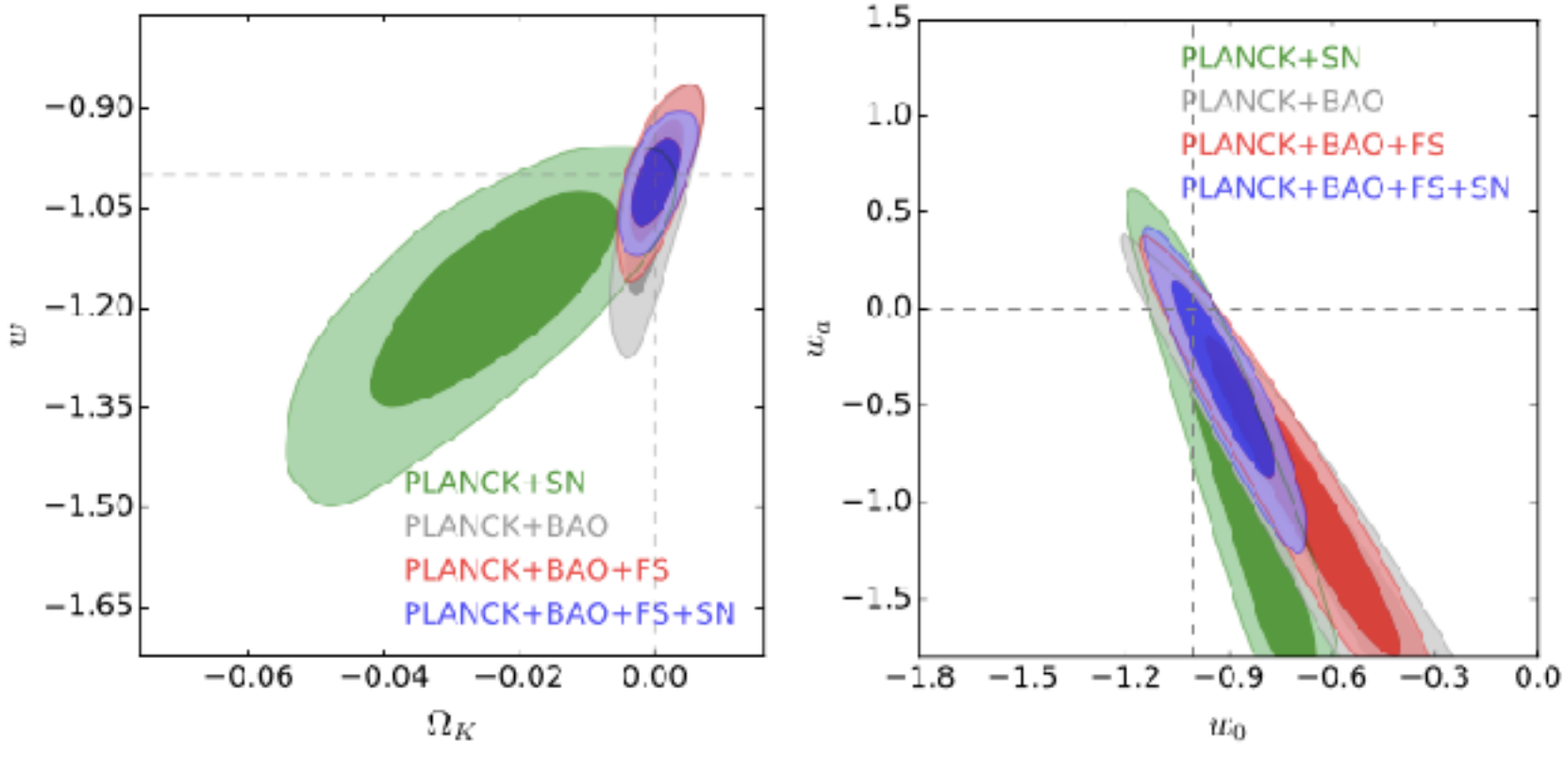
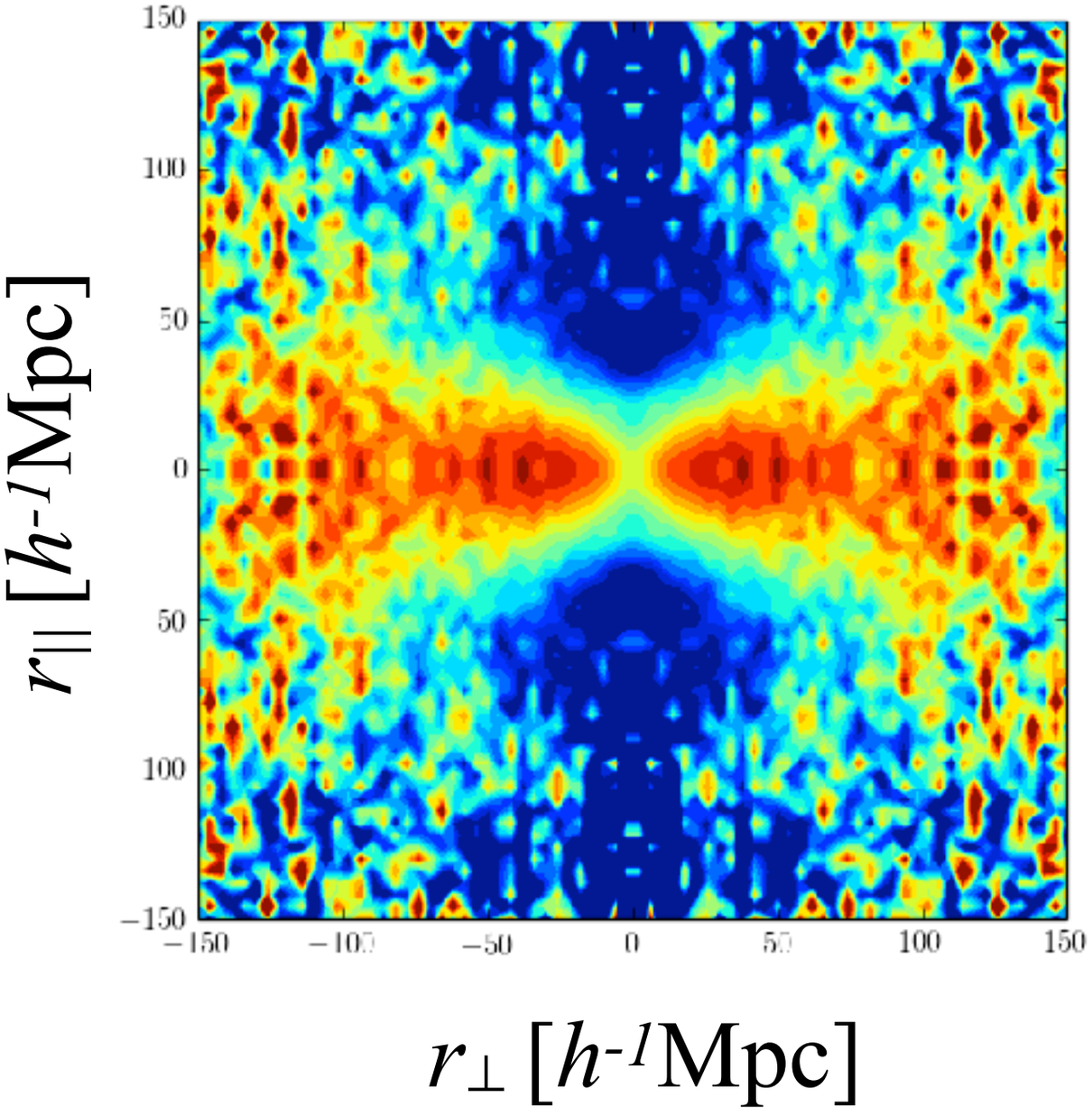


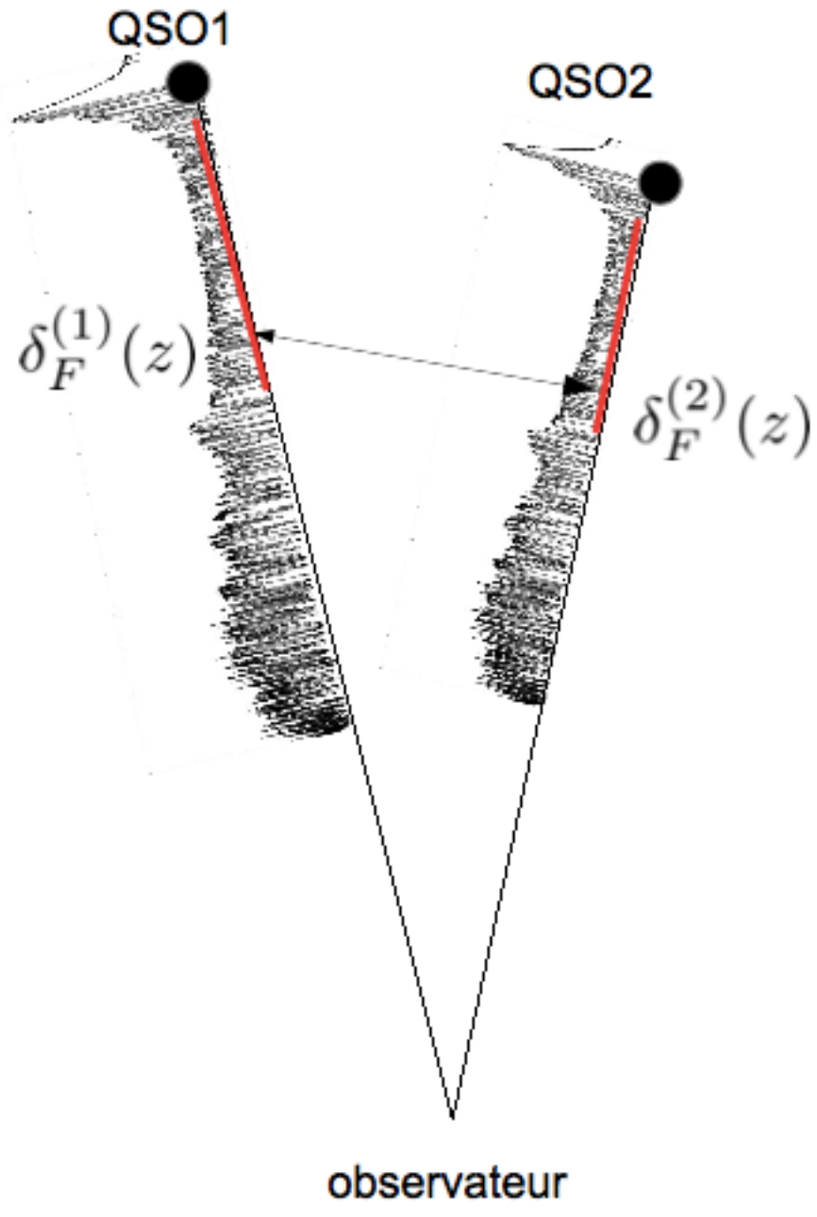


Latest Cosmological Results - BOSS DR12

Bautista et al. (2017)

Lyman-alpha autocorrelation





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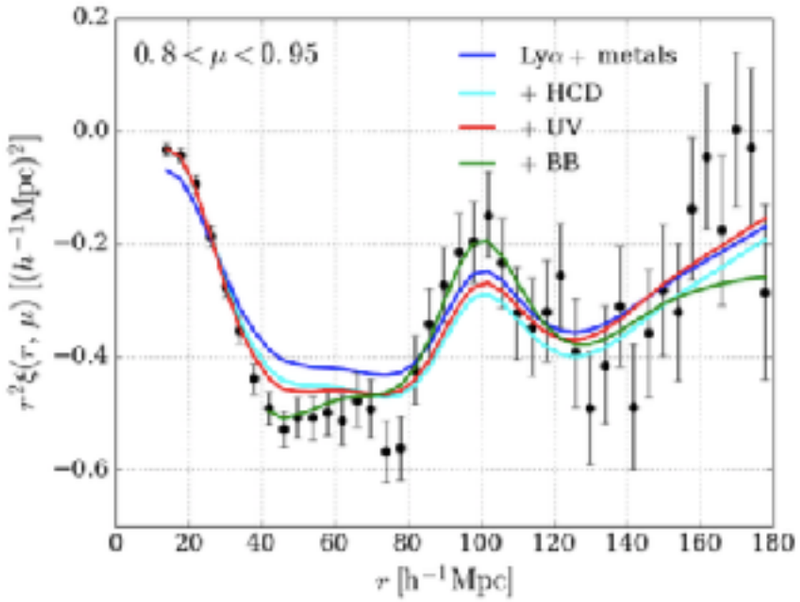
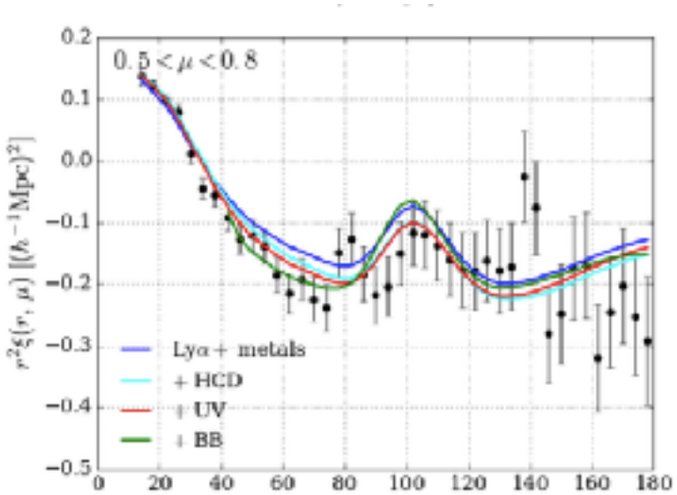
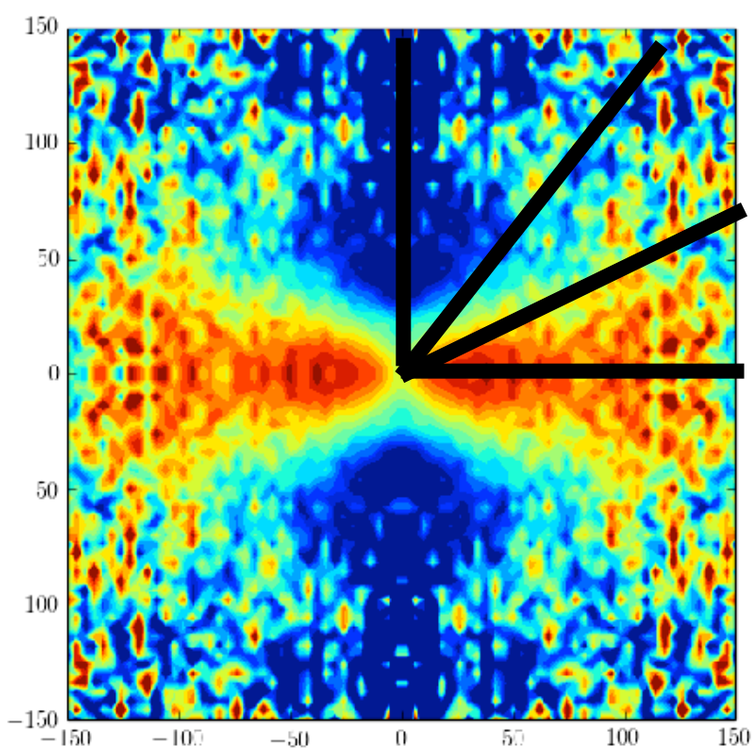
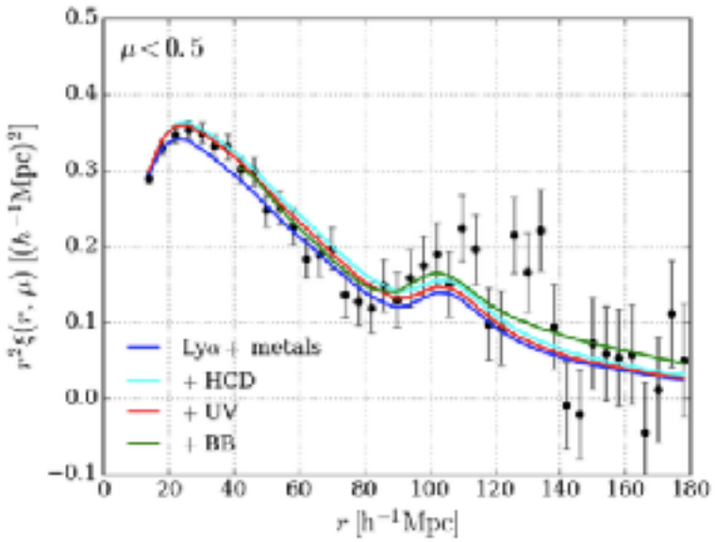


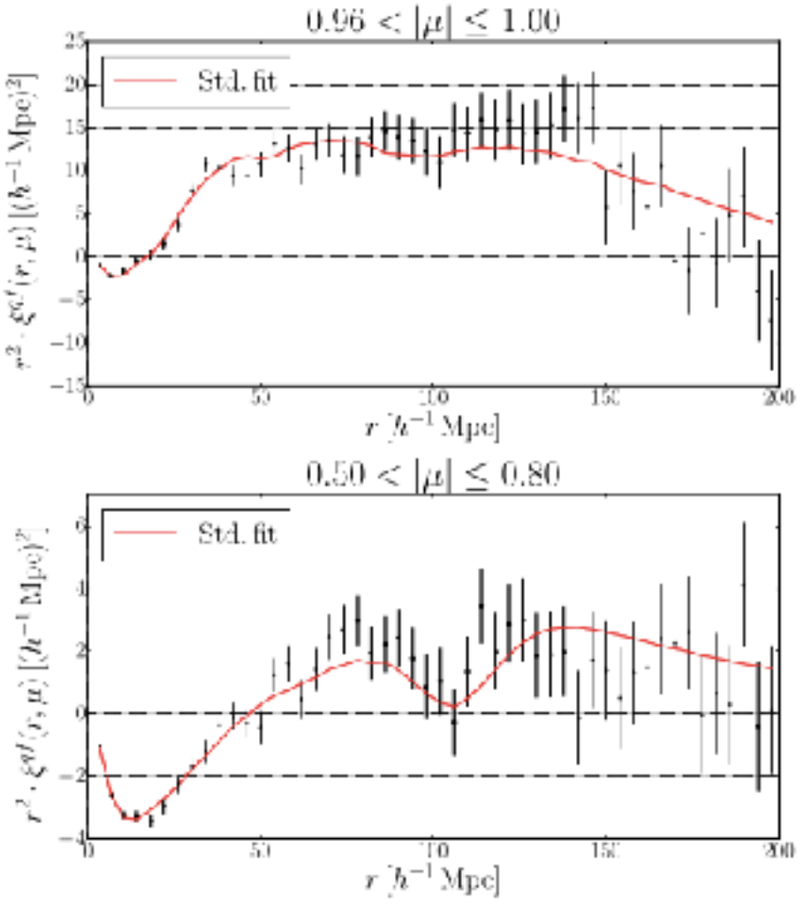


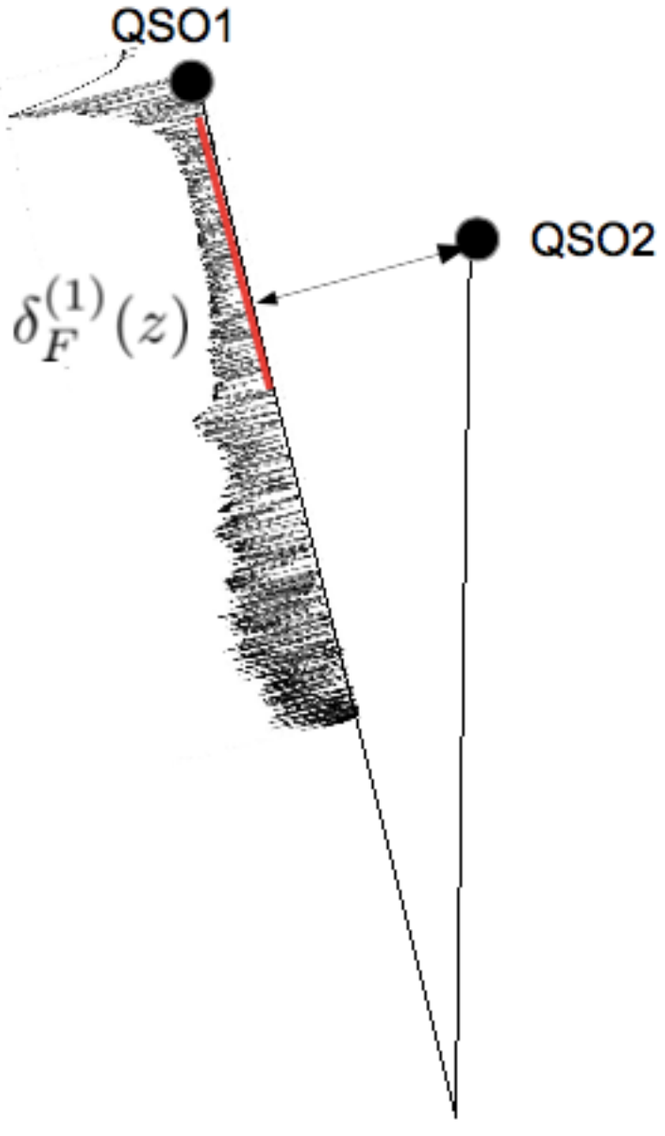




Latest Cosmological Results - BOSS DR12

Lyman-alpha x QSO cross correlation



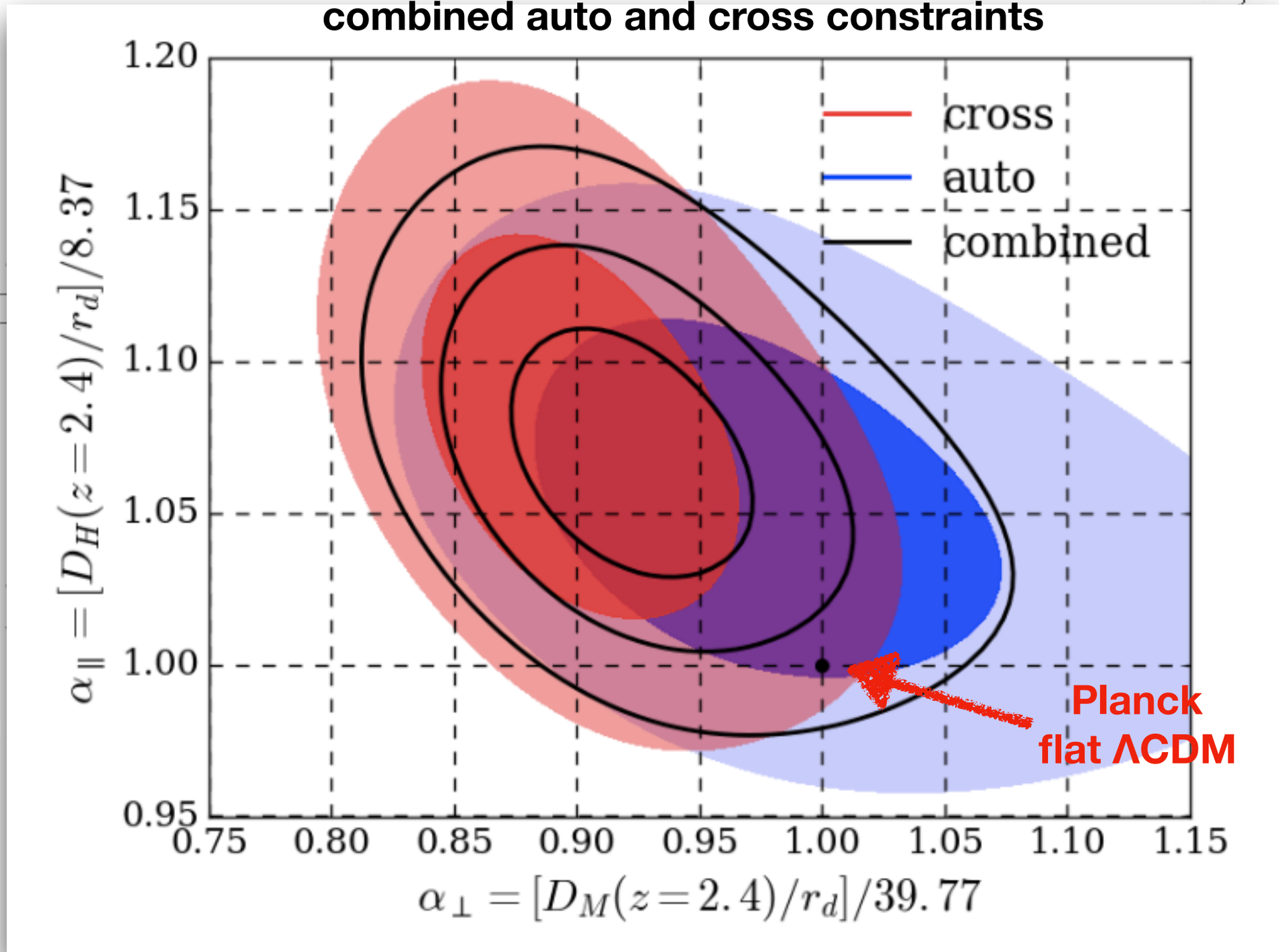


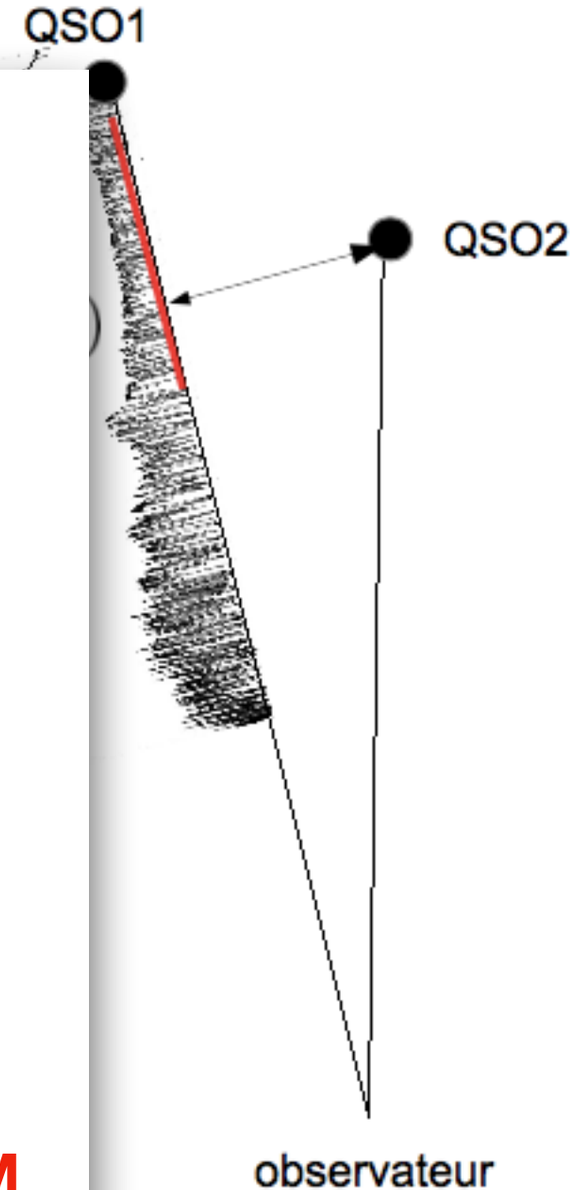
du Mas des Boboux et al. (2017)

Latest Cosmological Results - BOSS DR12

Lyman-alpha x QSO cross correlation

combined auto and cross constraints

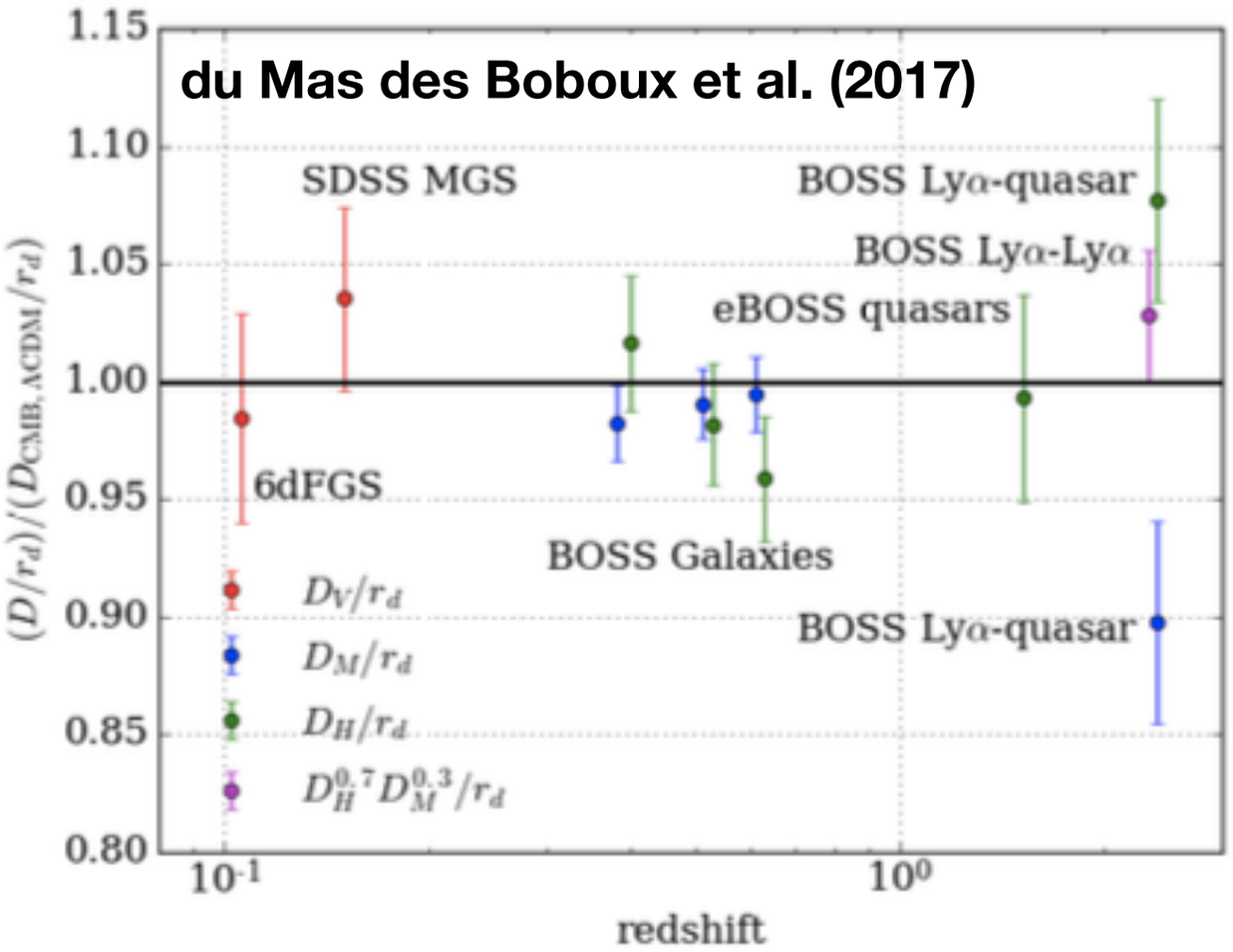


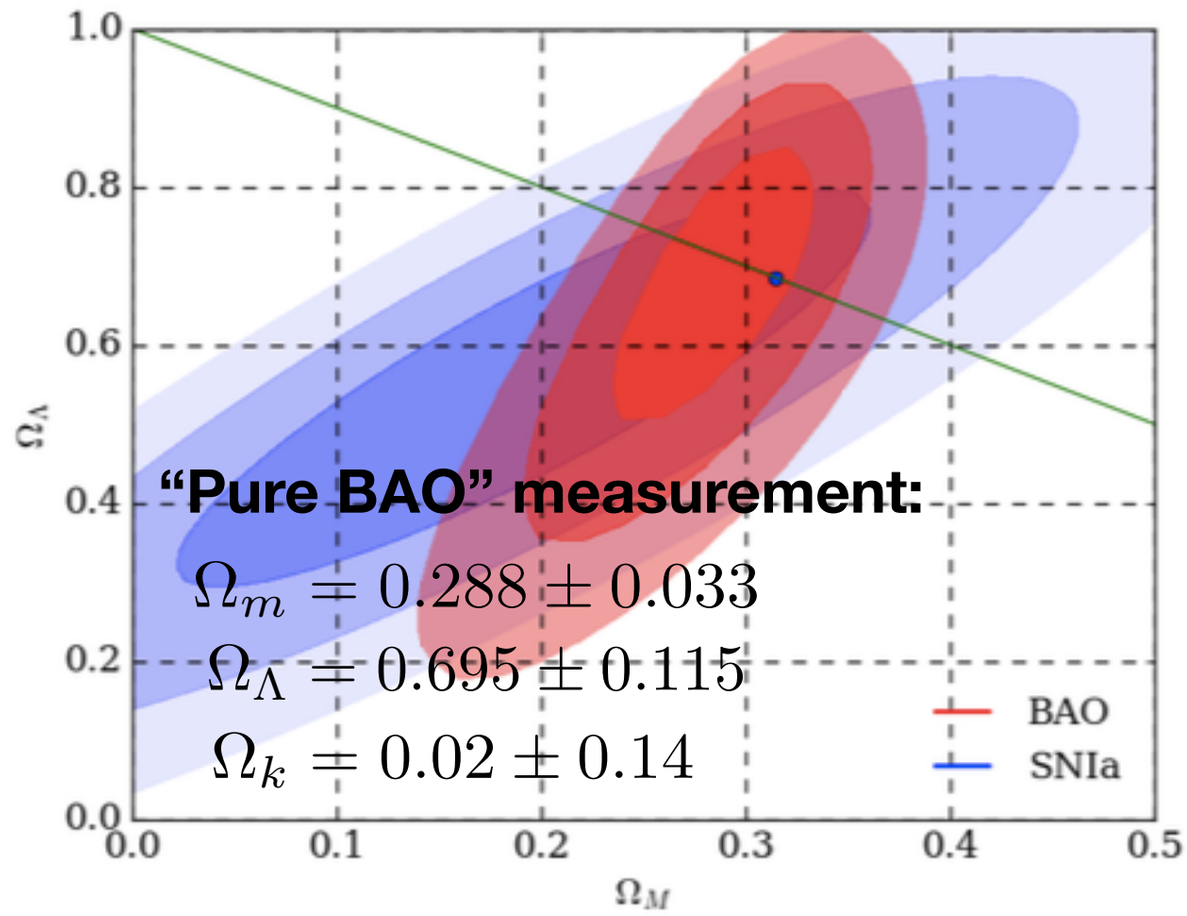


du

Latest Cosmological Results - BOSS DR12

All BAO combined!





“Pure BAO” measurement:

$$\Omega_m = 0.288 \pm 0.033$$
$$\Omega_\Lambda = 0.695 \pm 0.115$$
$$\Omega_k = 0.02 \pm 0.14$$

c.f. Planck flat LCDM:

$$\Omega_m = 0.315 \pm 0.017$$
$$\Omega_\Lambda = 0.685 \pm 0.017$$

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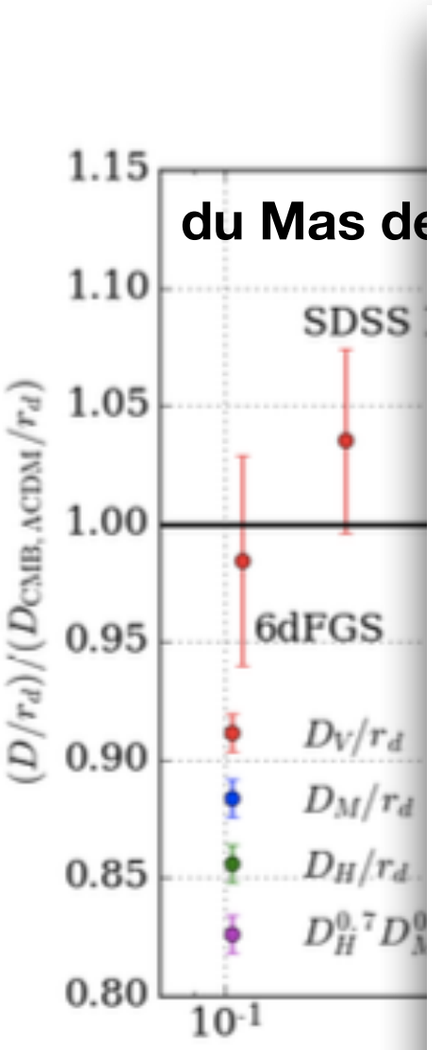

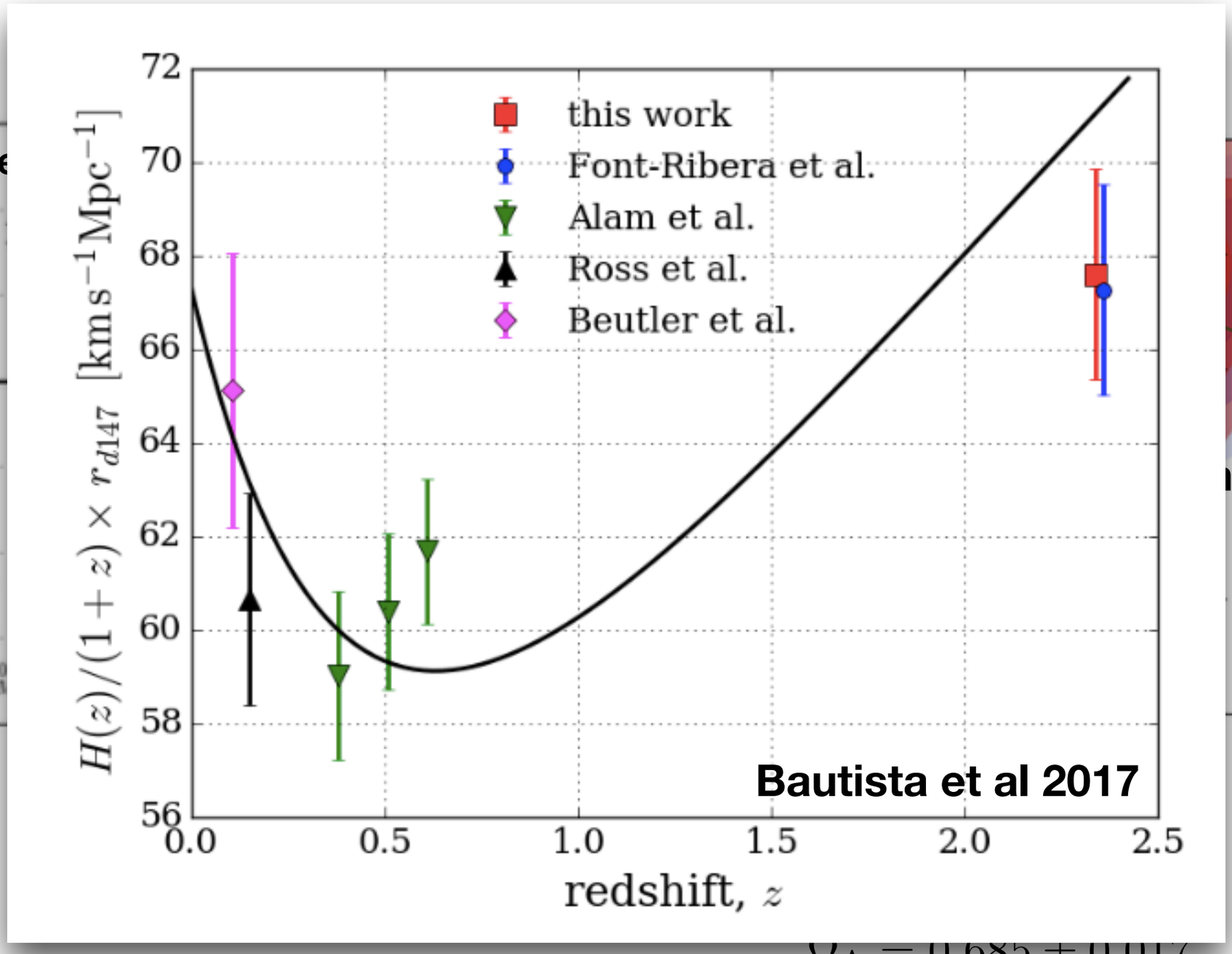

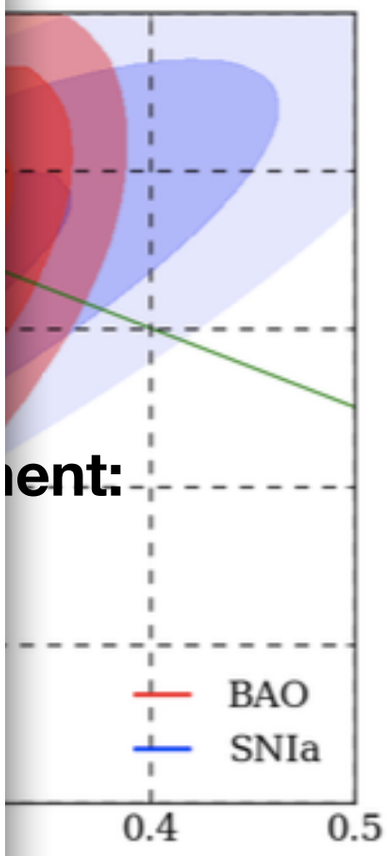

ent:

$$\Omega_\Lambda = 0.685 \pm 0.017$$

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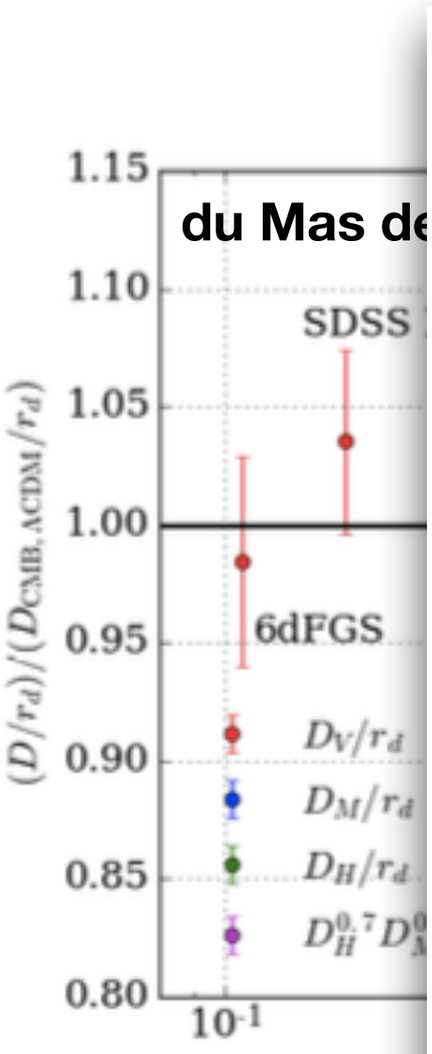
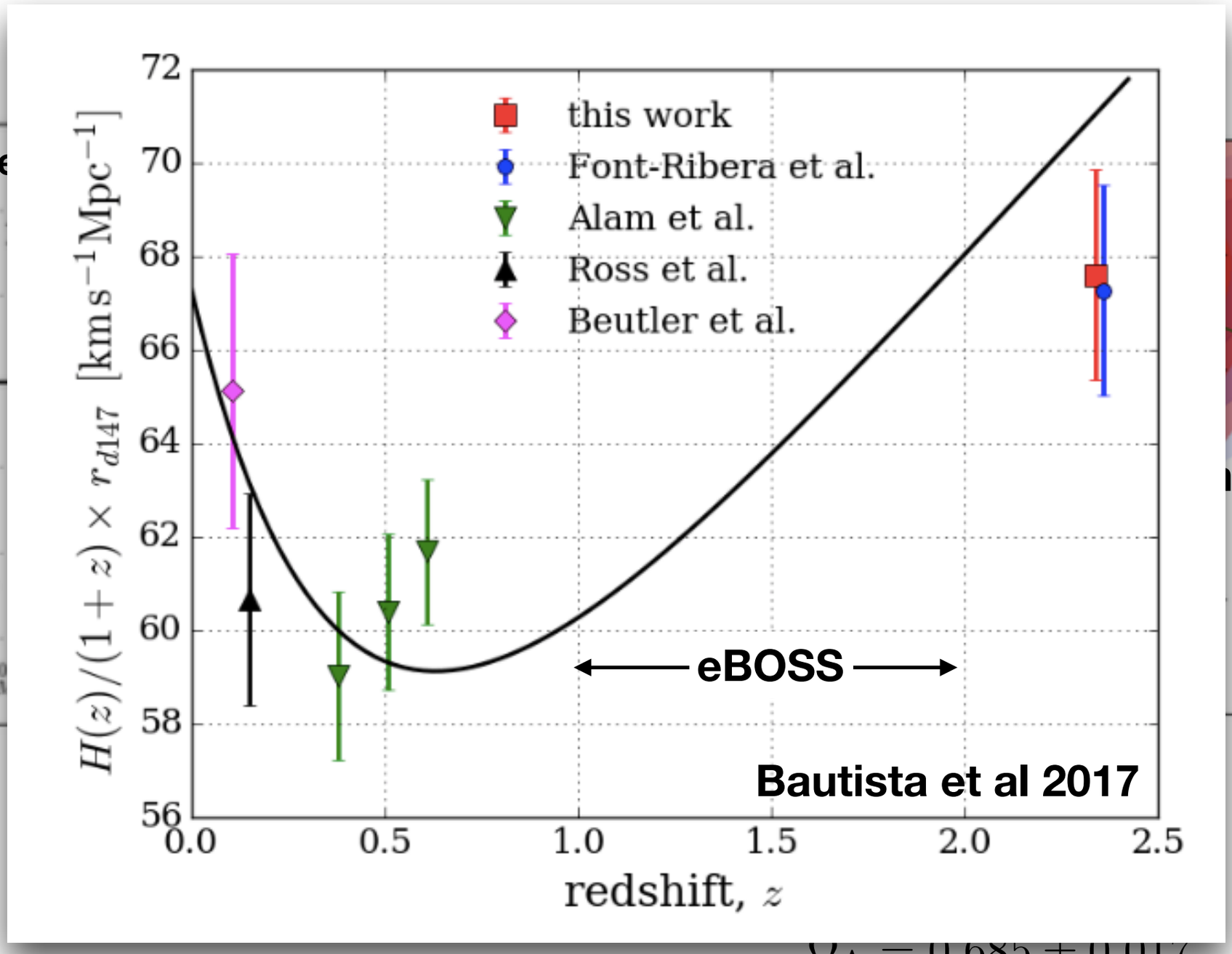
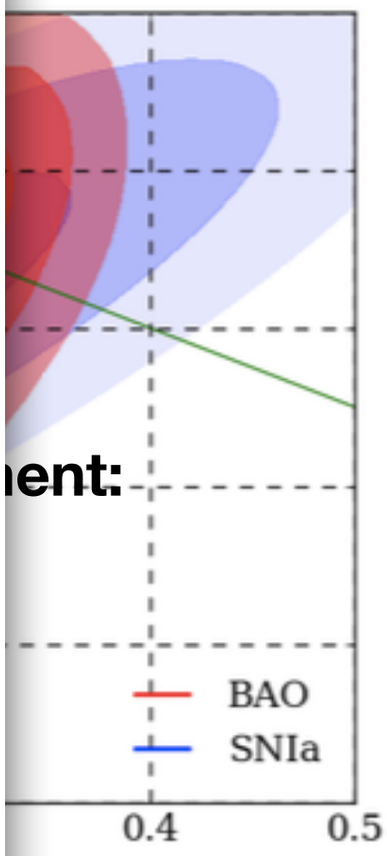
All BAO combined!



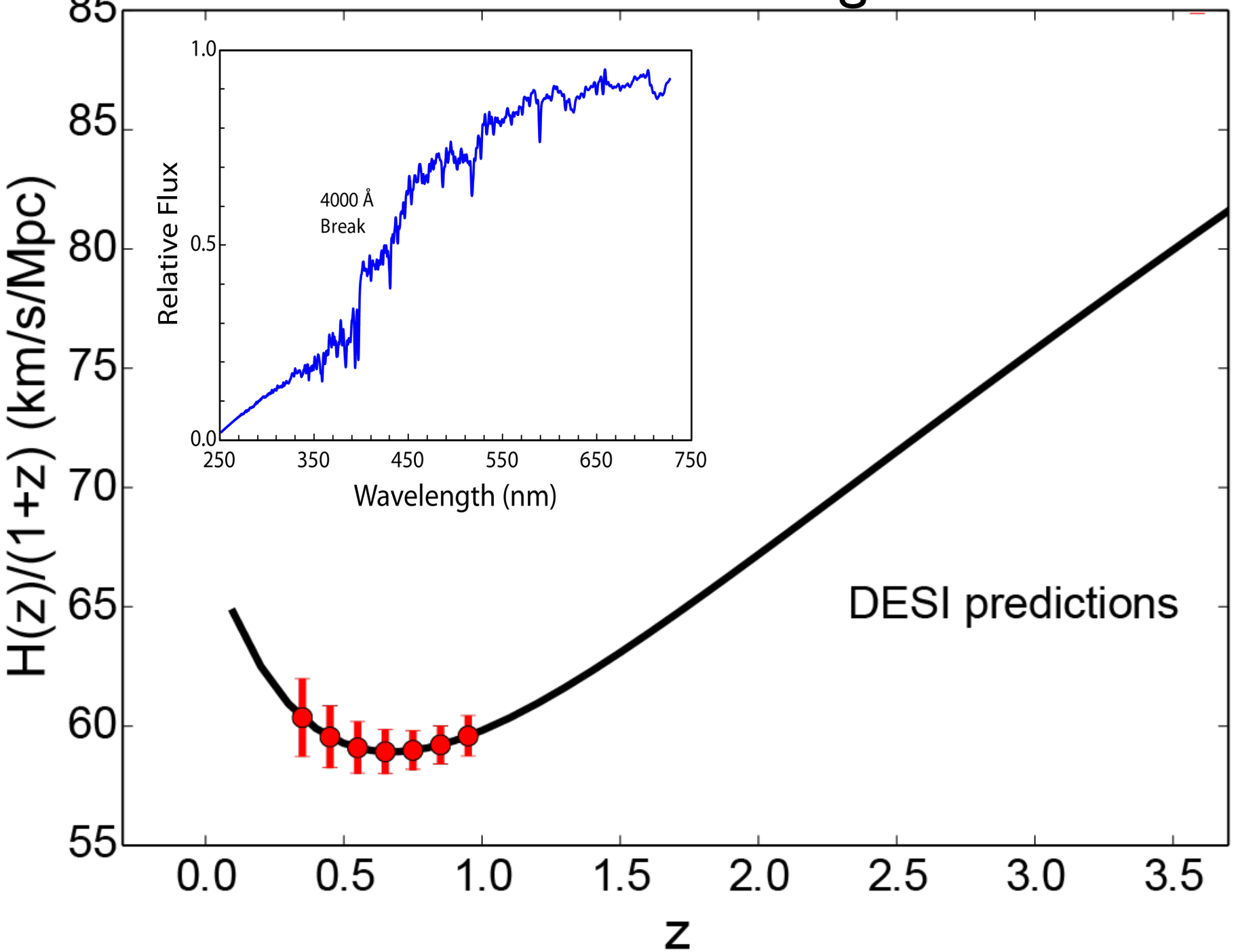




$\Omega_\Lambda = 0.685 \pm 0.017$

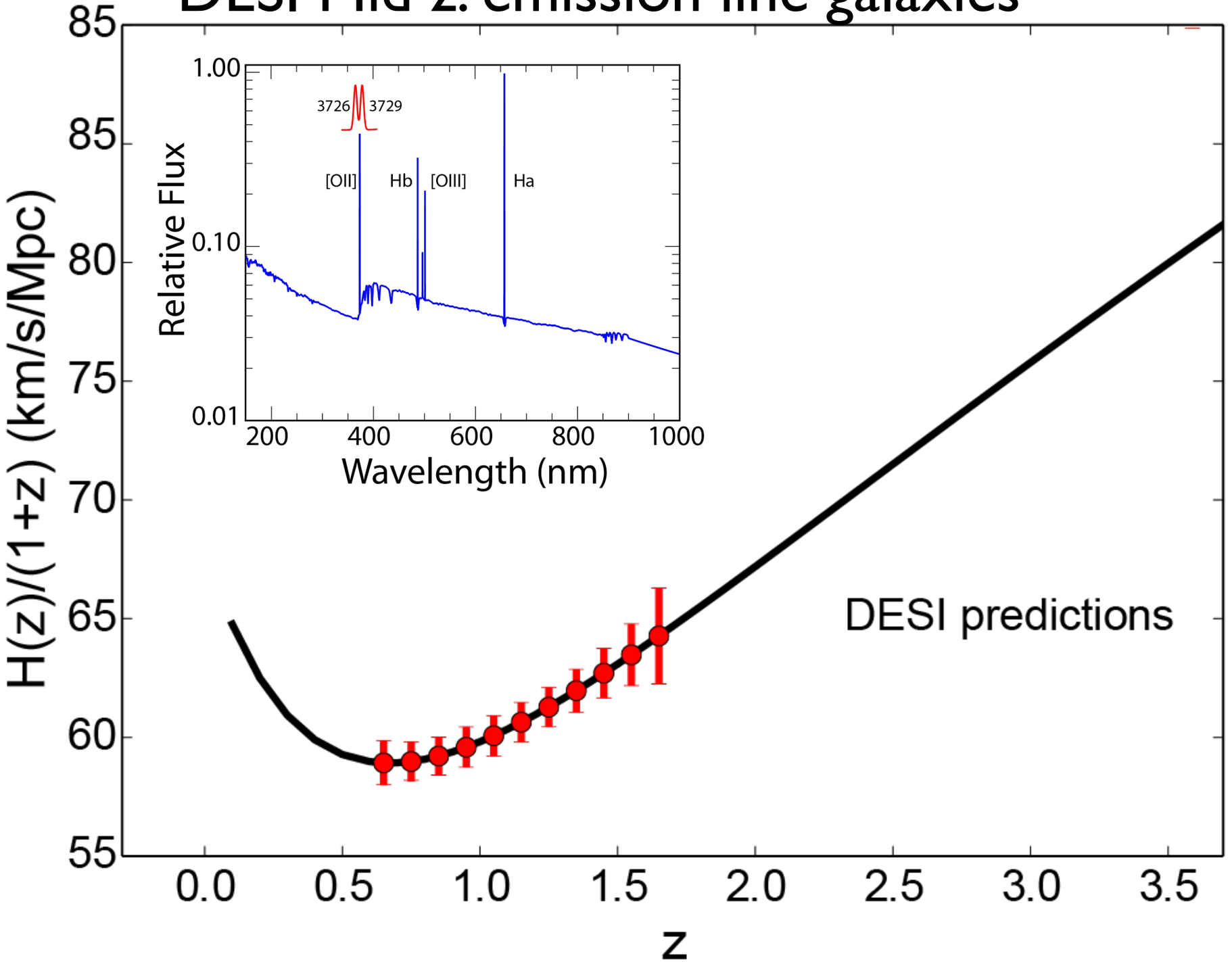
DESI

DESI Low z: luminous red galaxies

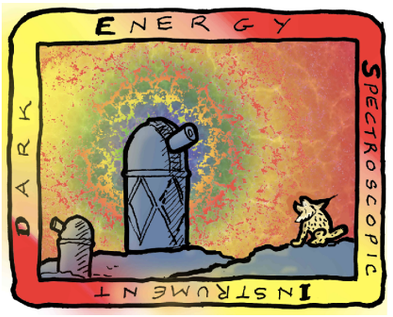


DESI

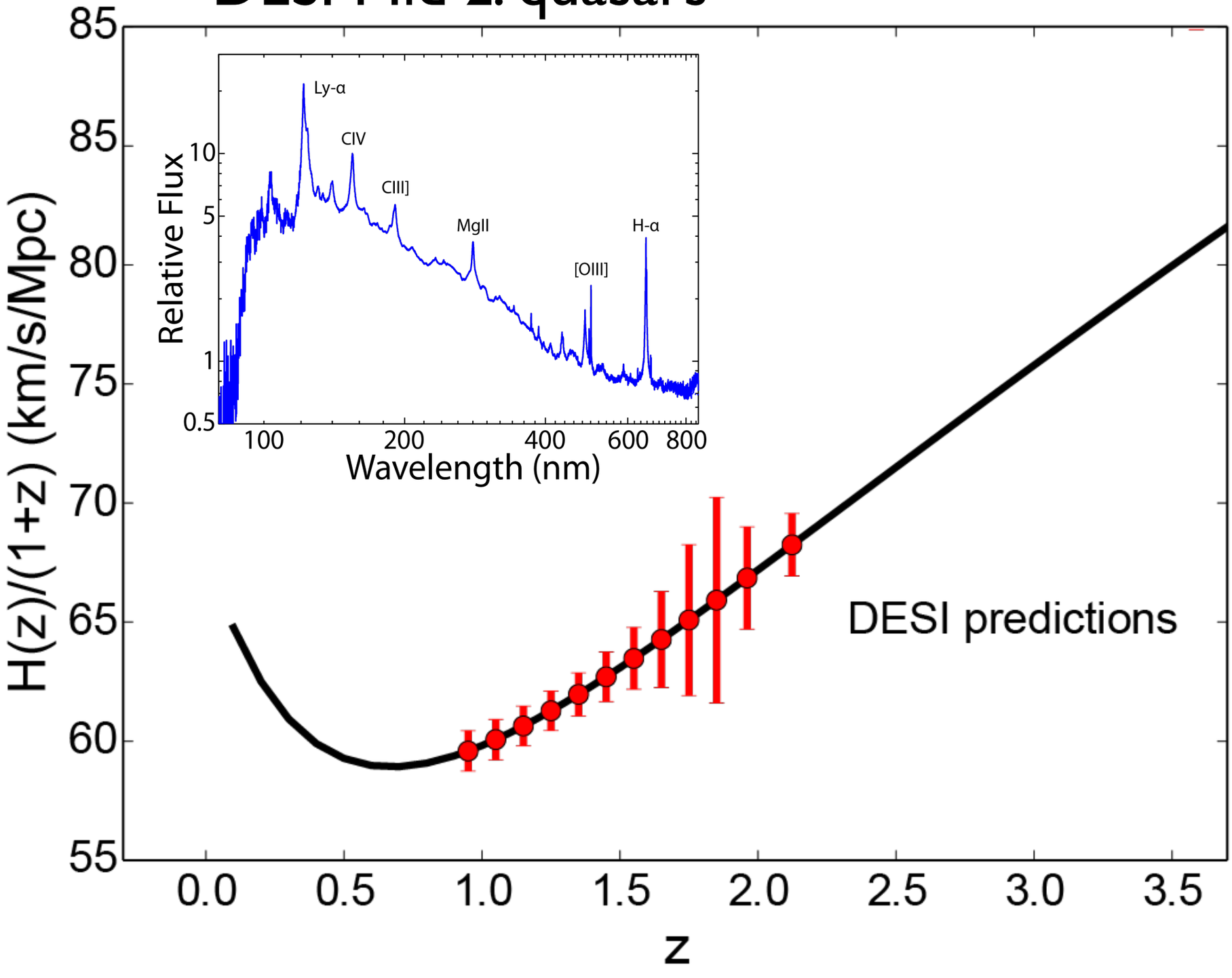
DESI Mid z: emission line galaxies



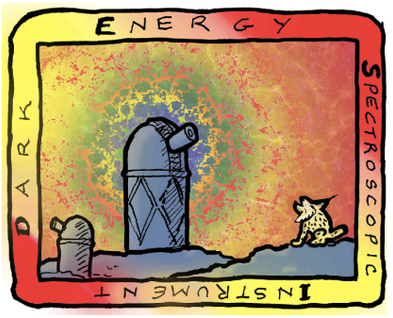
DESI



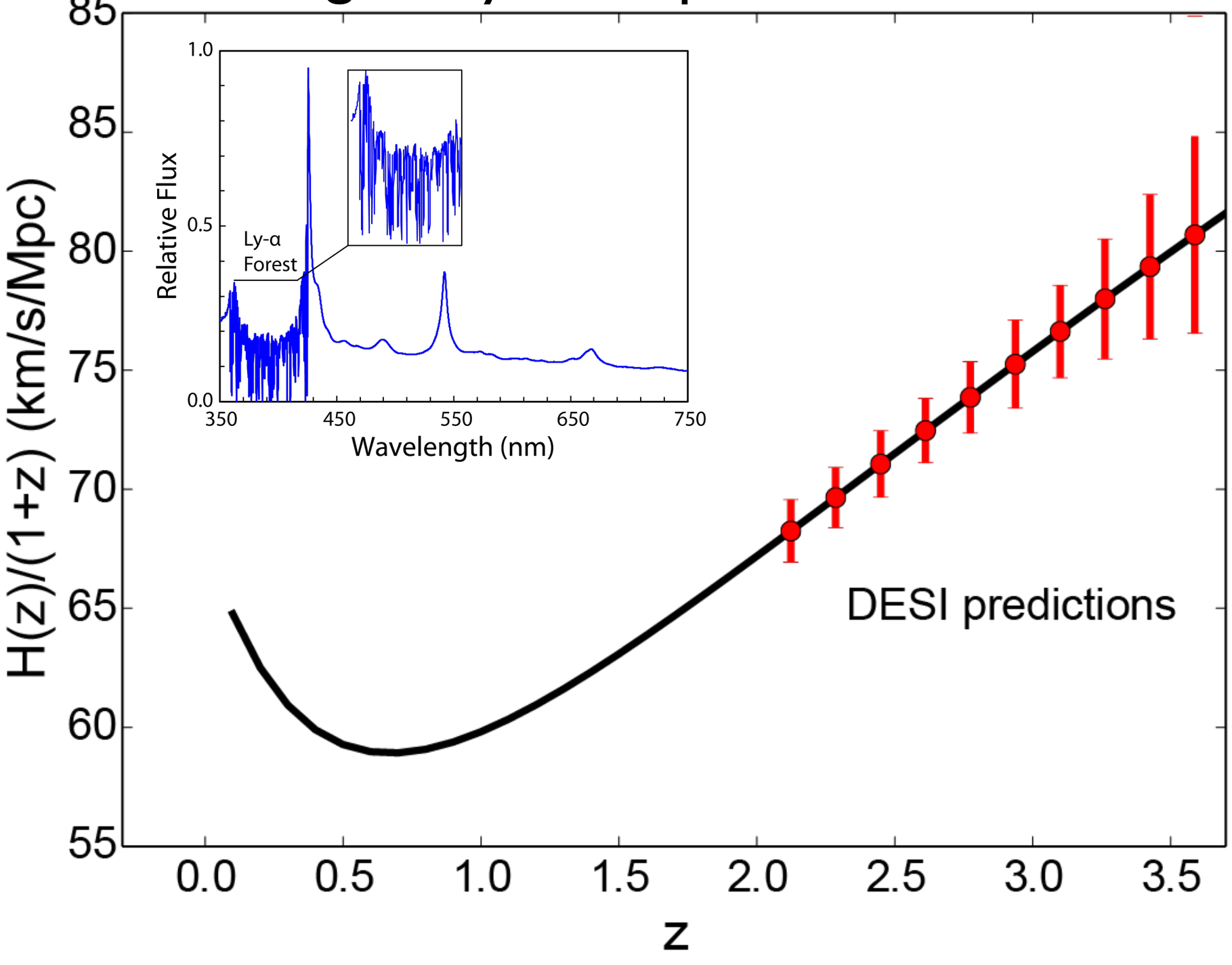
DESI Mid z: quasars



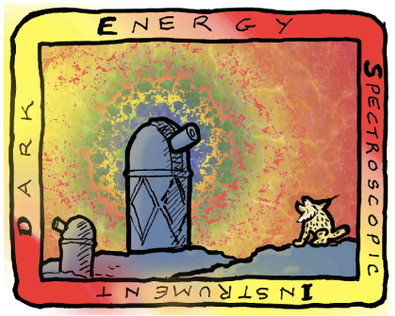
DESI

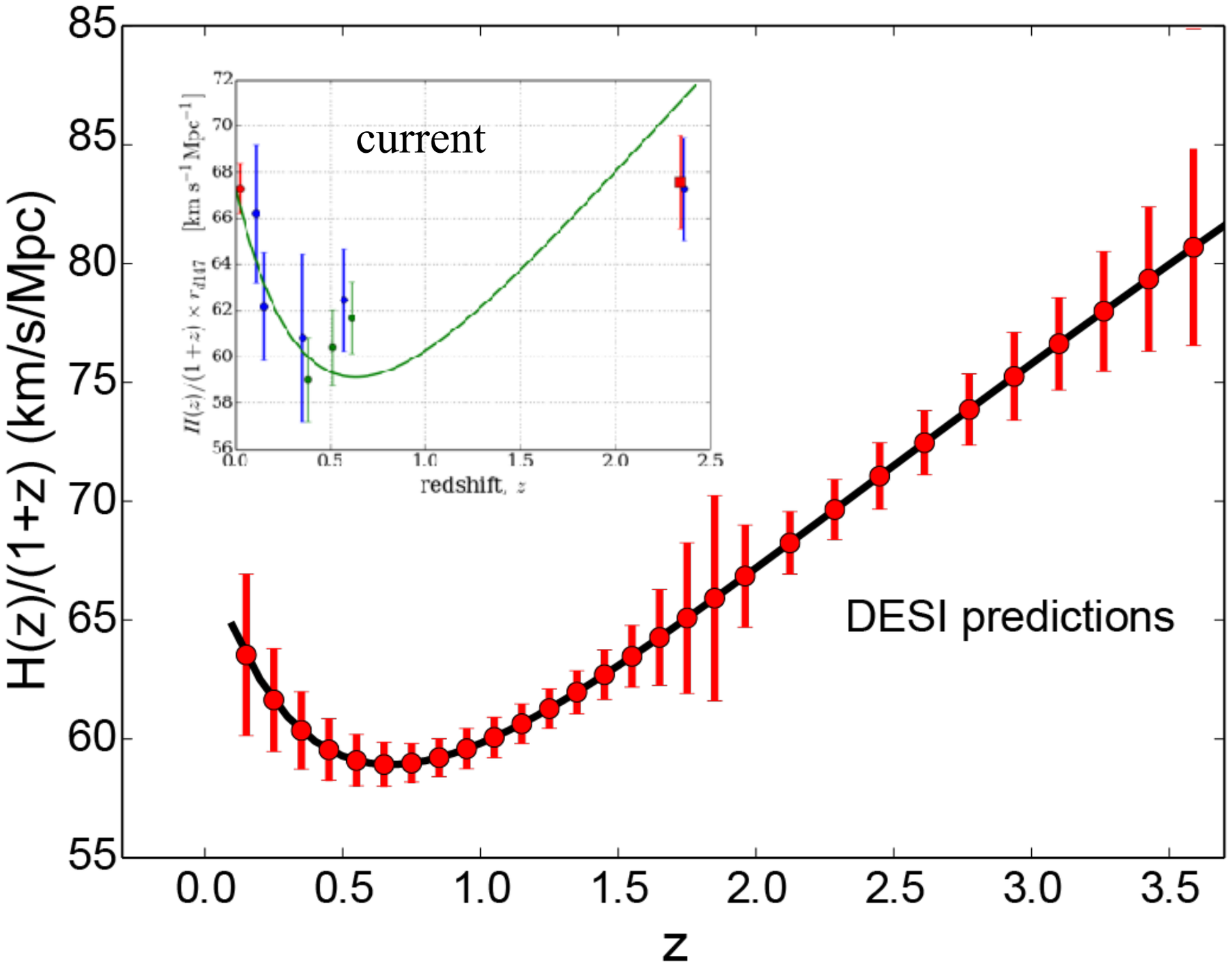


DESI high z: Lyman-alpha forest

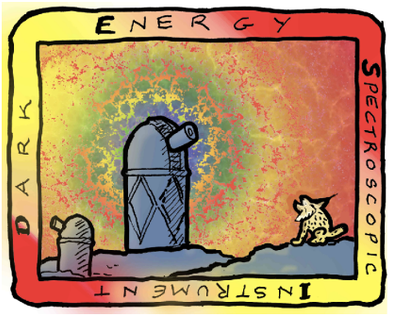


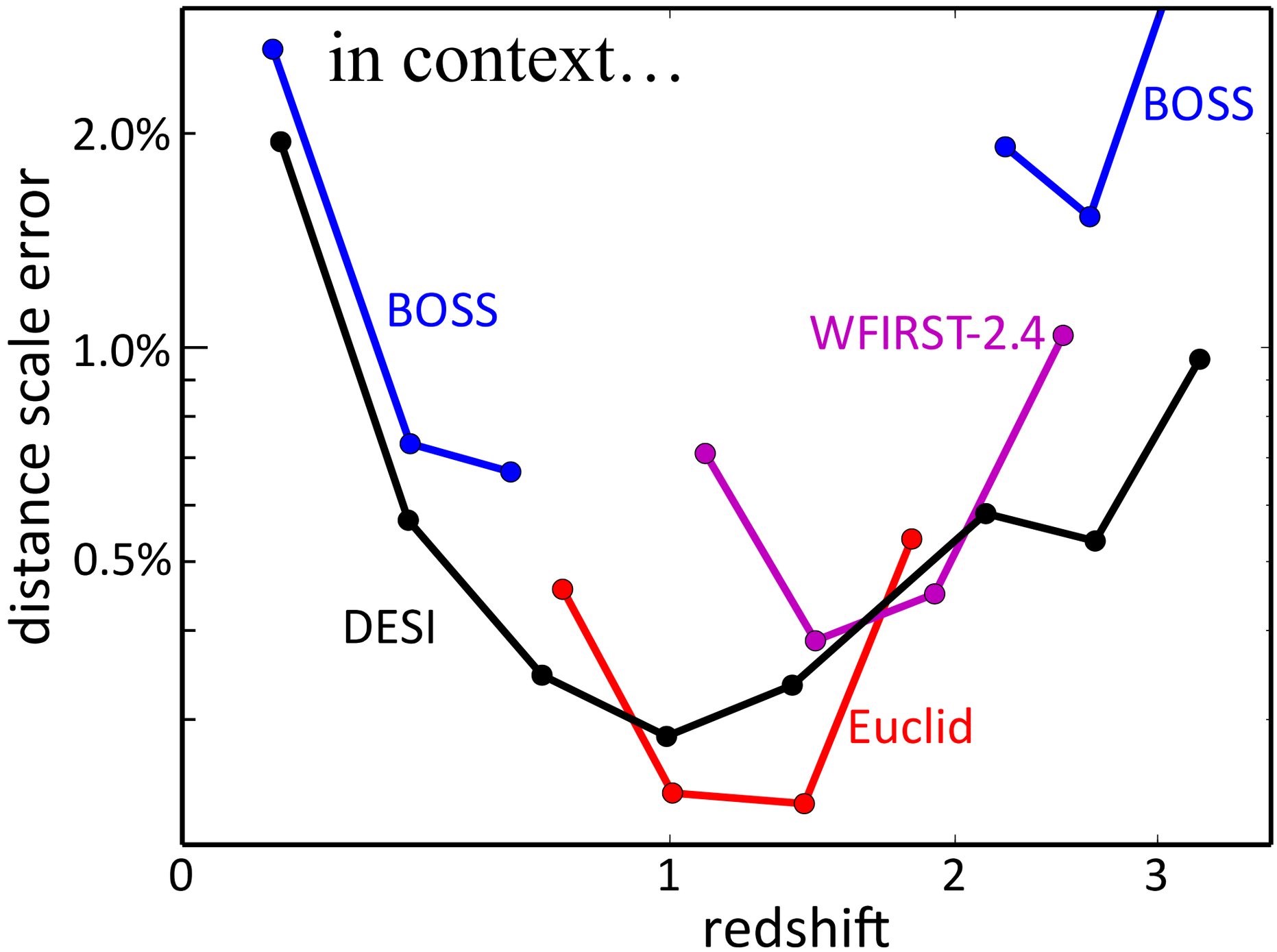
DESI


ENERGY
DARK
SPECTROSCOPIC
INSTRUMENT


current
redshift, z
DESI predictions
H(z)/(1+z) (km/s/Mpc)
z

DESI


ENERGY
SPECTROSCOPIC
INSTRUMENT
DARK


in context…
2.0%
1.0%
0.5%
distance scale error
BOSS
BOSS
WFIRST-2.4
DESI
Euclid
0
1
2
3
redshift

Conclusions

- Spectroscopic surveys measuring the large scale structure have reached per-cent precision
- We are already sampling the history of the expansion rate through the dawn of dark energy
- DESI will complete the picture out to redshift 4 with tomographic per-cent level measurements