# Pushing the Void to the limits: a good fit to CMB, BAO, SN and HST.

Wessel Valkenburg, RWTH Aachen
Modern Cosmology, Benasque, 2010

Biswas, Notari, WV, arXiv:1007.3065

# Outline

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- Why is a large local void interesting?
- SN
- BAO
- CMB
- $H_0$
- Matter power spectrum
- Other work
- Conclusion

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- Can a model that ignores both these assumptions fit the data?

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- Void: fine tuning in space

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# Light beam in a dust universe

Local energy density

$$\frac{1}{\sqrt{A}}\frac{d^2\sqrt{A}}{d\lambda^2} = -\frac{2}{3}\rho(r,t)\left(\frac{dt}{d\lambda}\right)^2 - \sigma^2$$

Beam area along geodesic

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# Lemaître-Tolman-Bondi

$$ds^2 = -dt^2 + S^2(r,t)dr^2 + R^2(r,t)(d\theta^2 + \sin^2\theta d\varphi^2)$$

$$S(r,t) = \frac{R'(r,t)}{\sqrt{1 + 2r^2 k(r)\tilde{M}^2}}$$

$$S(r,t) = f\left(\Omega_M(r), \Omega_k(r), t\right)$$

Each ‘isoradial shell’ obeys its own FLRW equation.

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For all the following we chose $t_{BB}(r) \equiv 0$

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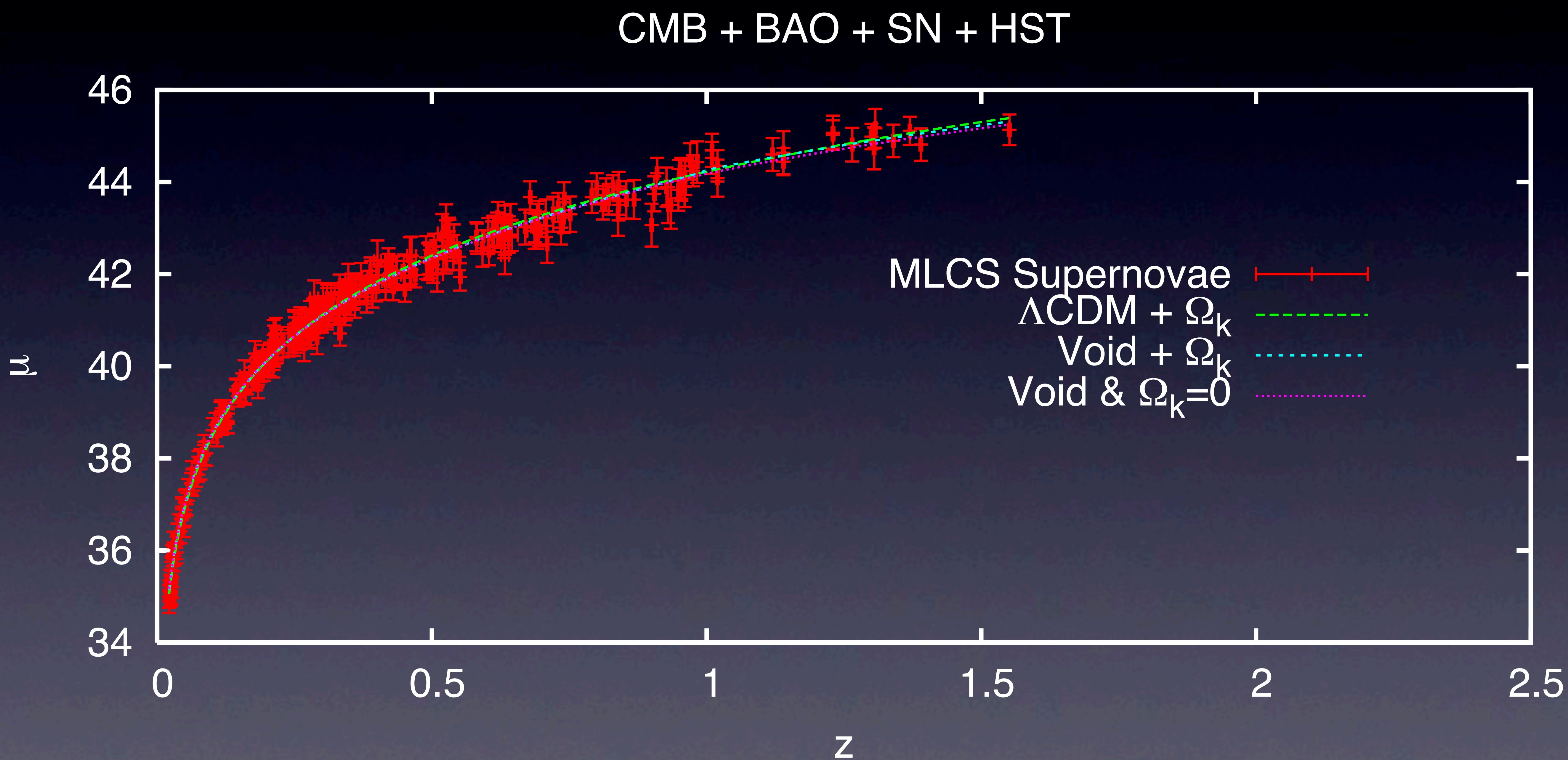
# Supernovae




LCDM Void in EdS Void in Curved FLRW

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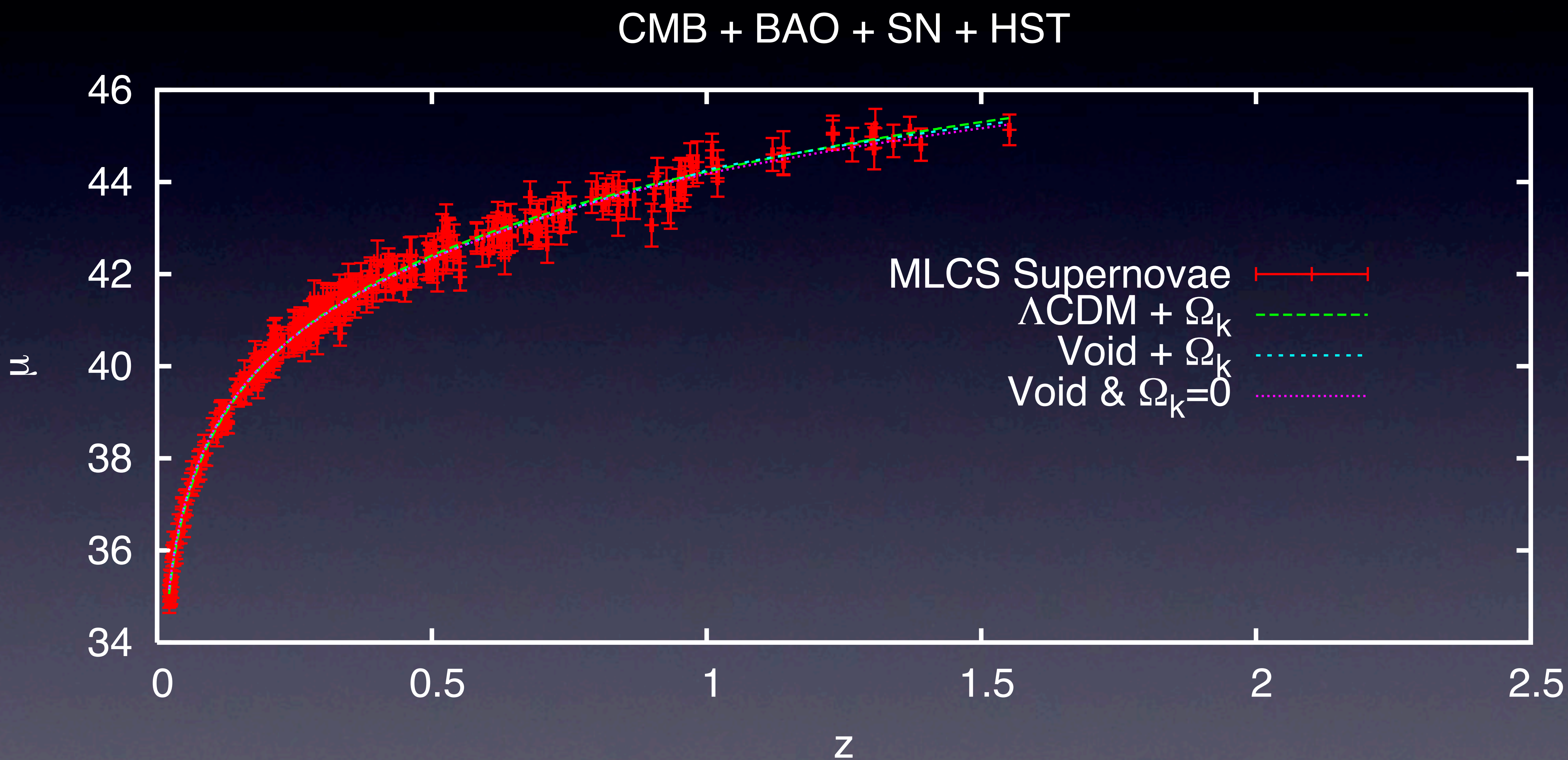


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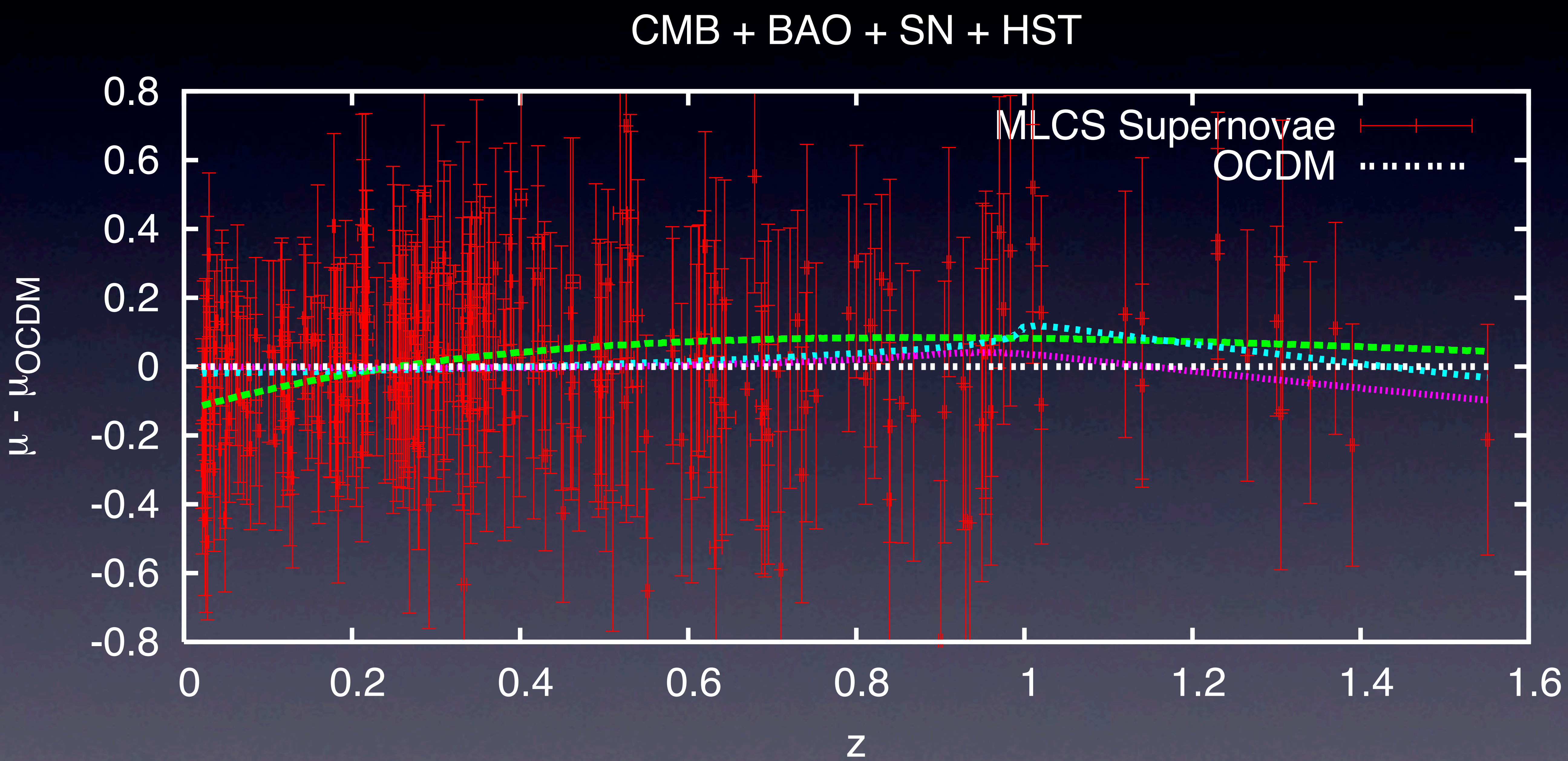


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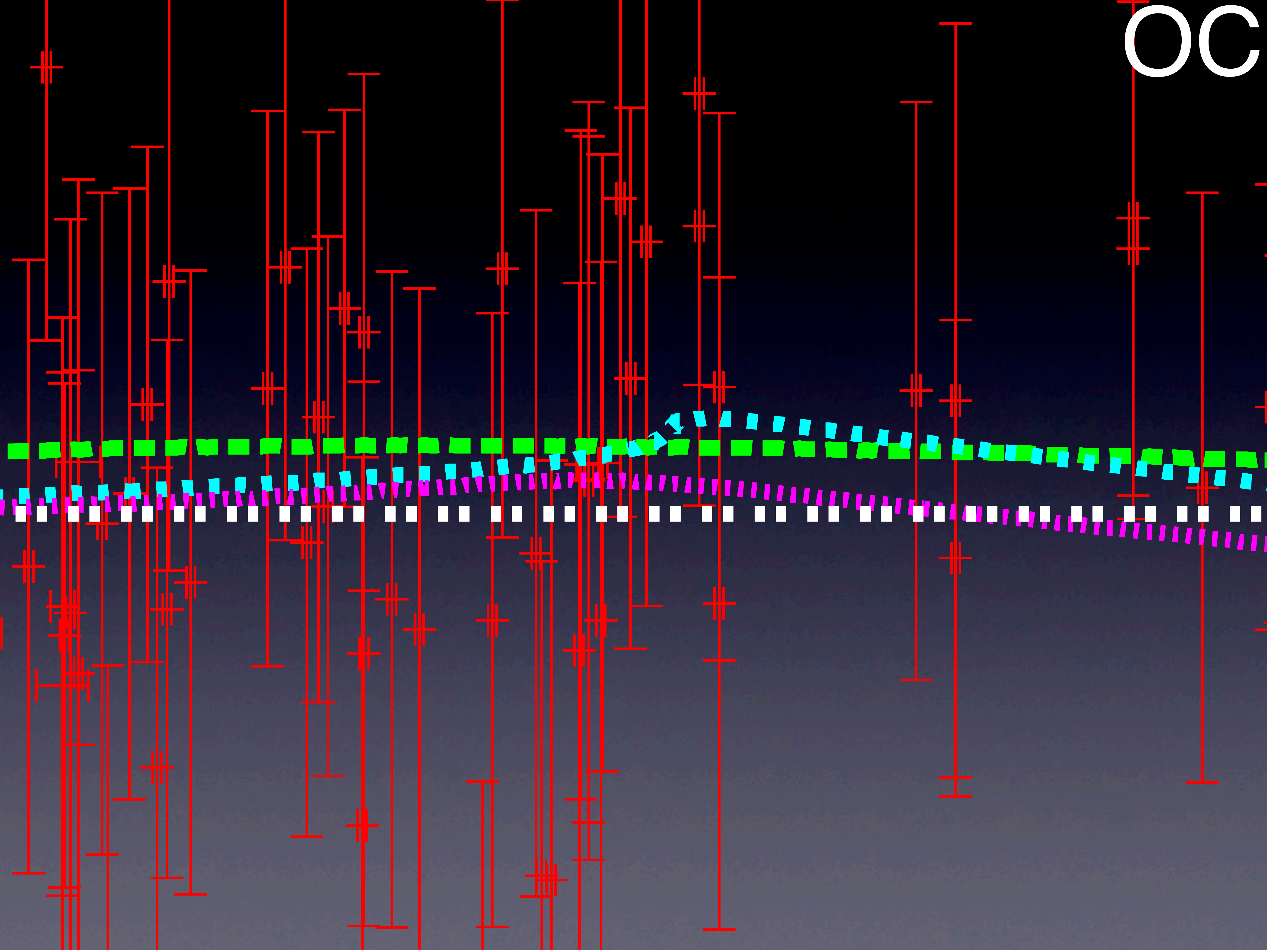
OC

# BAO

- Sound horizon at decoupling $L_S$
- imprinted in large scale structure
- subtends an angle $\Delta\theta(z)$ and redshift $\Delta z(z)$

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$$(\Delta\theta^2 \Delta z)^{1/3} = \left[(1+z_{\rm BAO})\dot{R}'_{\rm BAO}\frac{1}{R'(r(z_{\rm BAO}),t(z_{\rm rec}))R^2(r(z_{\rm BAO}),t(z_{\rm rec}))}\right]^{1/3}\frac{L_S^{\rm LTB}}{(1+z_{\rm rec})}$$

$$ds^2 = -dt^2 + S^2(r,t)dr^2 + R^2(r,t)(d\theta^2 + \sin^2\theta d\varphi^2) \qquad S(r,t) = \frac{R'(r,t)}{\sqrt{1+2r^2k(r)\tilde{M}^2}}$$

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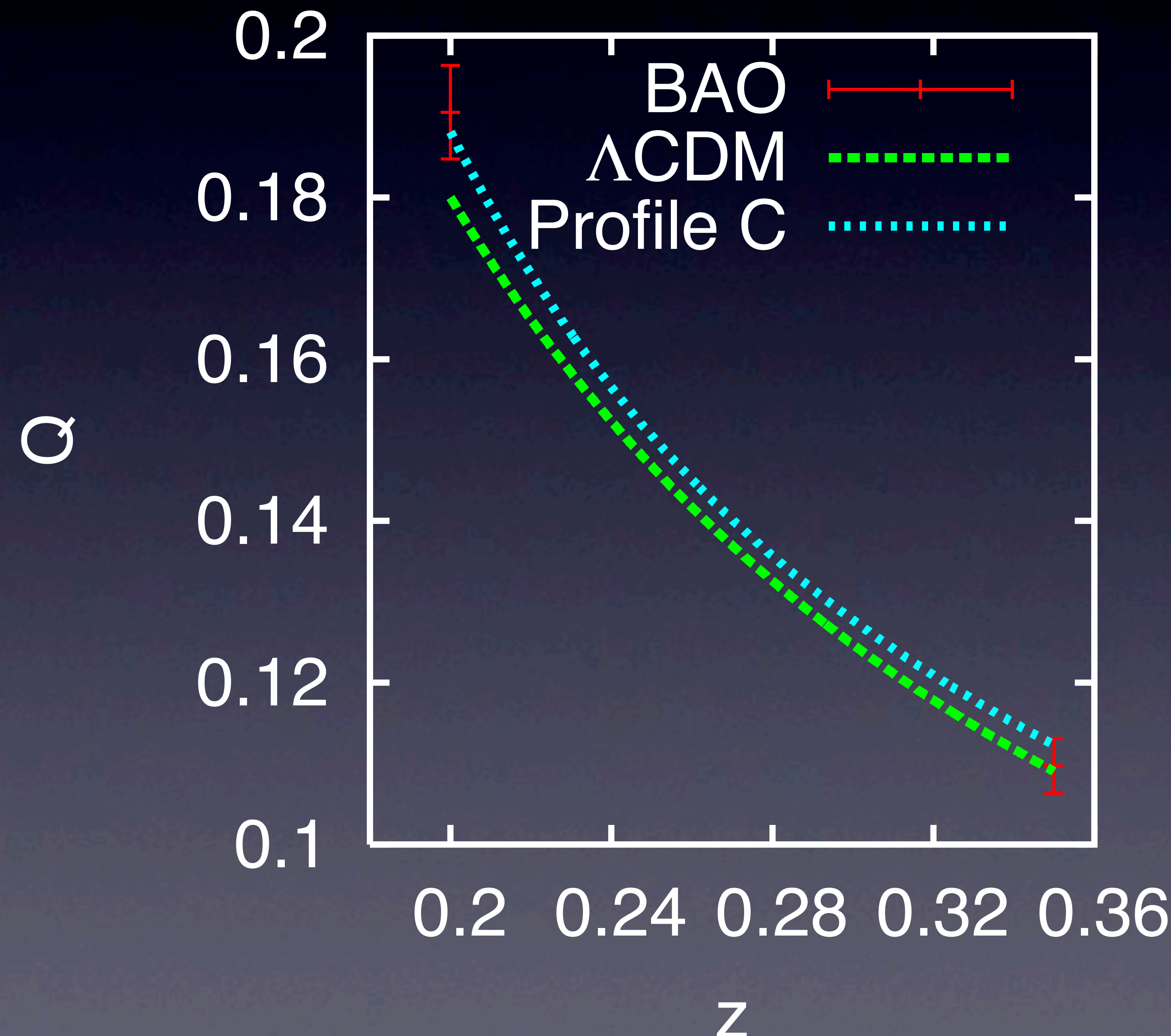

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- $T_{CMB}$ is altered
- Calculate: $$\left.\begin{array}{l} d_A \\ T_{CMB} \\ \Omega_m \\ \Omega_b \end{array}\right\} \text{to/at } z \sim 1100$$
- Construct FLRW observer with same conditions

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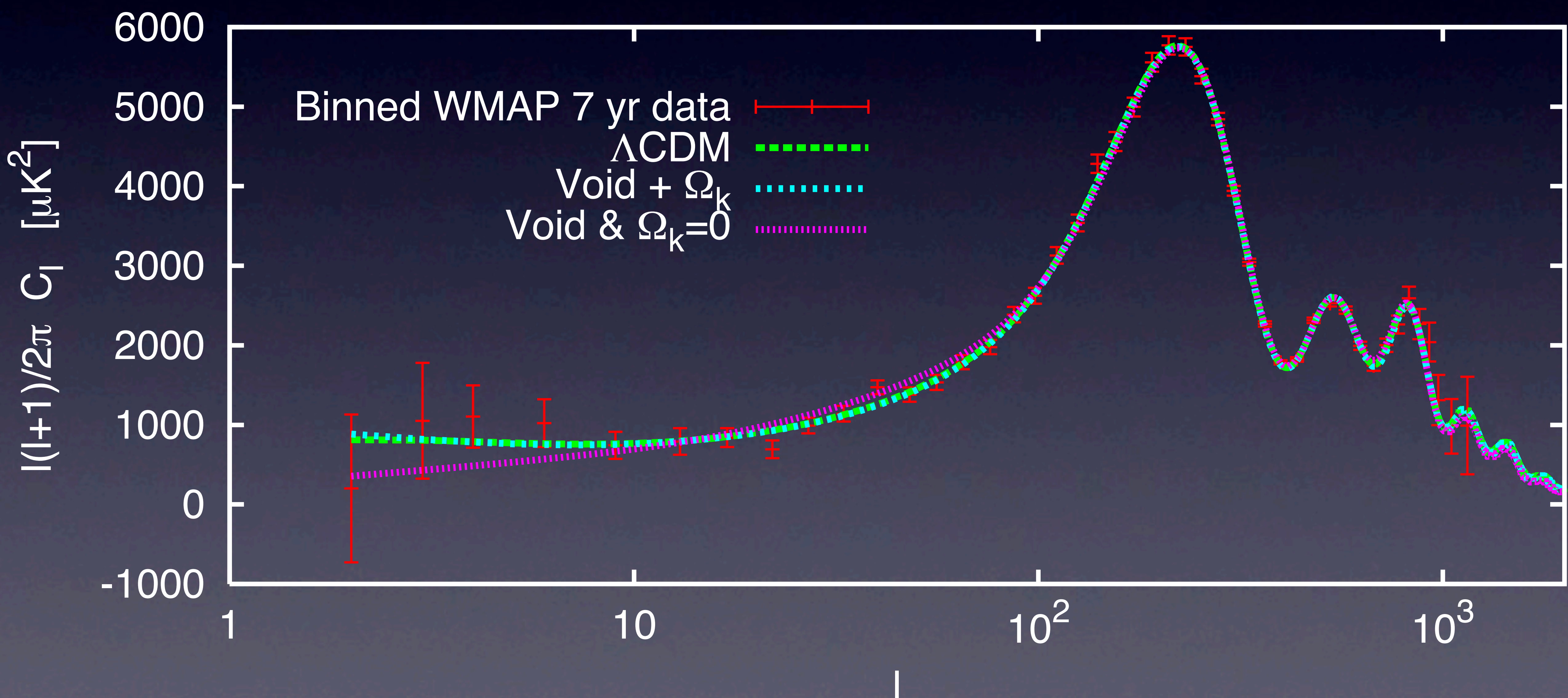
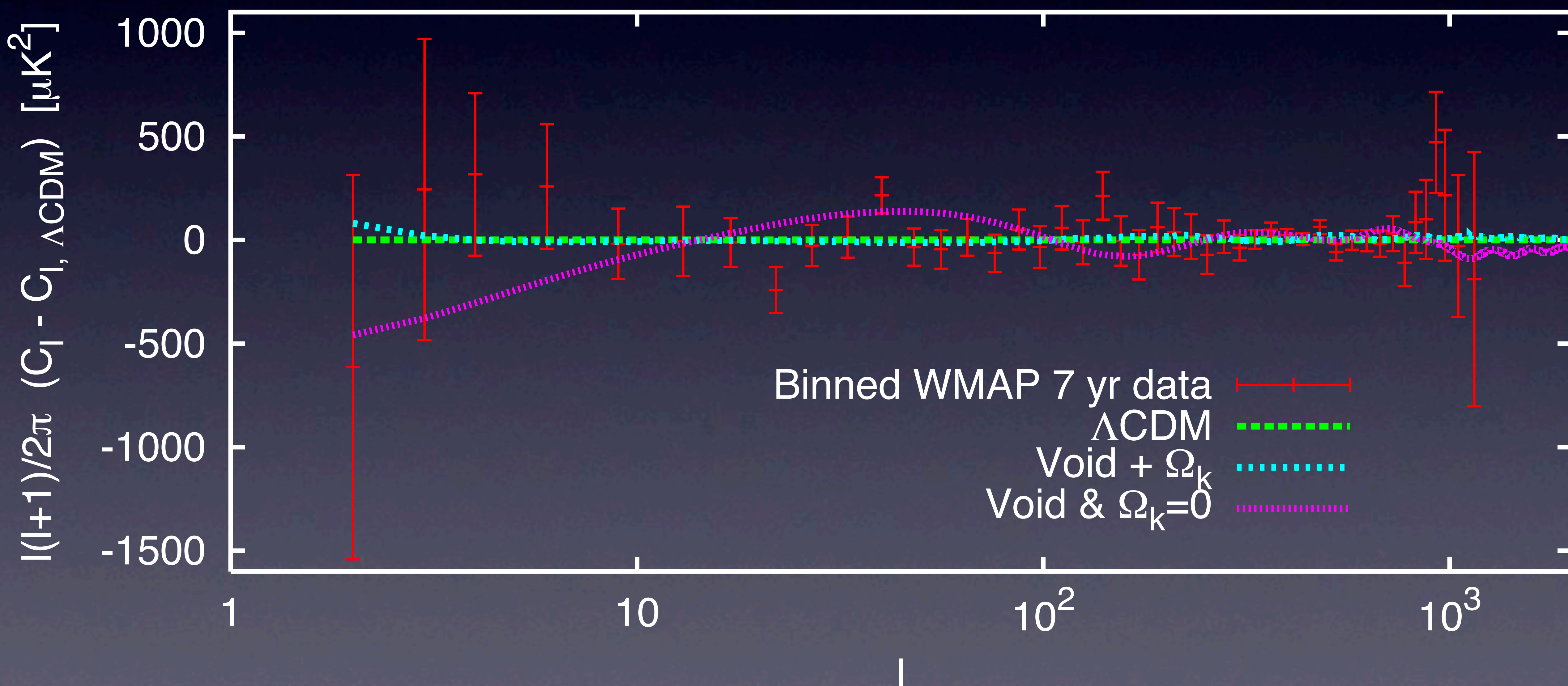
  - but not so relevant when focussing on best possible fit, and large error bars at low l
- For 'asymptotic' voids: ignoring effect of radiation on metric at high z. [Regis, Clarkson, 2010]
- Putting observer at center for simplicity (no dipole)

# CMB



Binned WMAP 7 yr data
ΛCDM
Void + $\Omega_k$
Void & $\Omega_k$=0
$l(l+1)/2\pi\ C_l\ [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
-1000
1
10
$10^2$
$10^3$
l

# CMB


1000
500
0
-500
-1000
-1500
1
10
10^2
10^3
l
l(l+1)/2π (C_l - C_l, ΛCDM) [μK^2]
Binned WMAP 7 yr data
ΛCDM
Void + Ω_k
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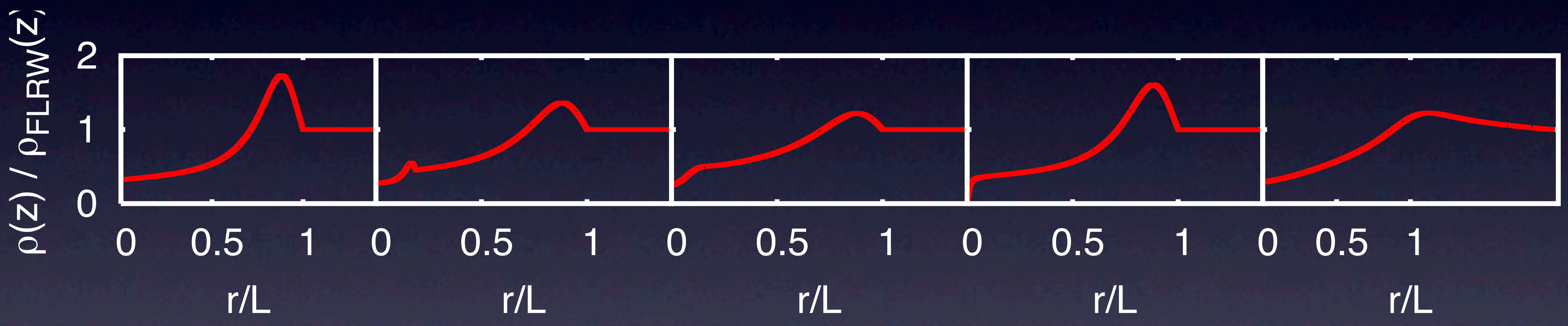
$$H_0 \equiv \lim_{z \to 0} \frac{d_A(z)}{z}$$

- ΛCDM can fit any value from 60 to 80 km/s/Mpc




| $H_{0,\mathrm{obs}}$ | 46.1 | 48.1 | 50.2 | 54.7 | 56.8 |
|---|---|---|---|---|---|

while fitting CMB+HST+BAO+SN

using $H_0 = 62 \pm 6$ [HST team, Sandage et al., 2006]

# How good is it?

| Model | CMB | BAO | SN | $HST_{62\pm6}$ | total $\chi^2$ |
|---|---|---|---|---|---|
| ΛCDM | 3371.1 | 3.1 | 239.5 | 0.4 | **3614.1** |
| Profile A | 3376.6 | 5.0 | 240.3 | 6.6 | 3628.5 |
| Profile B | 3376.7 | 0.5 | 235.2 | 5.1 | 3617.5 |
| Profile C | 3376.9 | 1.0 | 234.9 | 3.7 | **3616.5** |
| Profile D | 3376.7 | 3.8 | 233.9 | 2.2 | 3616.6 |
| Profile E | 3372.9 | 3.4 | 241.5 | 0.8 | 3618.6 |

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| Model | CMB | BAO | SN | $HST_{74\pm4}$ | total $\chi^2$ |
|---|---|---|---|---|---|
| $\Lambda$CDM | 3372.7 | 1.8 | 239.7 | 2.1 | 3616.3 |
| Profile C | 3389.8 | 0.3 | 235.4 | 27.8 | 3653.3 |
| Profile E | 3373.3 | 3.0 | 242.7 | 15.3 | 3634.3 |

$H_0 = 74 \pm 4$ from [Riess et al., 2009]

# How crazy is it?

| Profile | $z_B$ | $L$ [Mpc] | $r_{3.355\text{mK}}$ [Mpc] | $r/L$ |
|---|---|---|---|---|
| A | 1.071 | 4853.935 | 22.357 | 0.00461 |
| B | 1.241 | 5179.389 | 19.922 | 0.00385 |
| C | 2.612 | 7279.830 | 18.110 | 0.00249 |
| D | 1.092 | 4935.030 | 6.408 | 0.00130 |
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- Ignoring kSZ: better data may rule out LTB immediately

[García-Bellido, Hauboelle, 2008]

# How crazy is it?

| Profile | ($\Delta\chi^2$ vs $\Lambda$CDM) | $\Omega_{k,out}$ | $\Omega_{k,in}$ | $\delta_0$ | $t_0$ [Gyr] |
|---|---|---|---|---|---|
| A | (13.7) | -0.20 | 0.76 | -0.67 | 17.6 |
| B | (3.2) | -0.18 | 0.80 | -0.71 | 17.3 |
| C | (1.5) | -0.19 | 0.83 | -0.75 | 16.8 |
| D | (1.6) | -0.15 | 0.98 | -0.98 | 17.7 |
| E | (3.1) | +0.40 | 0.94 | -0.73 | 15.4 |

$\Omega_k > 0 \equiv$ closed

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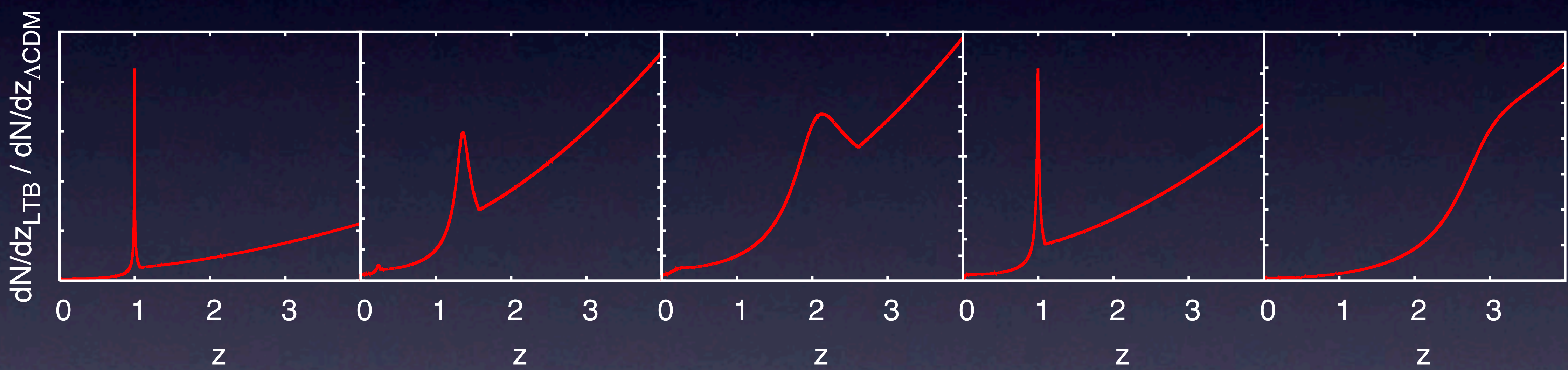

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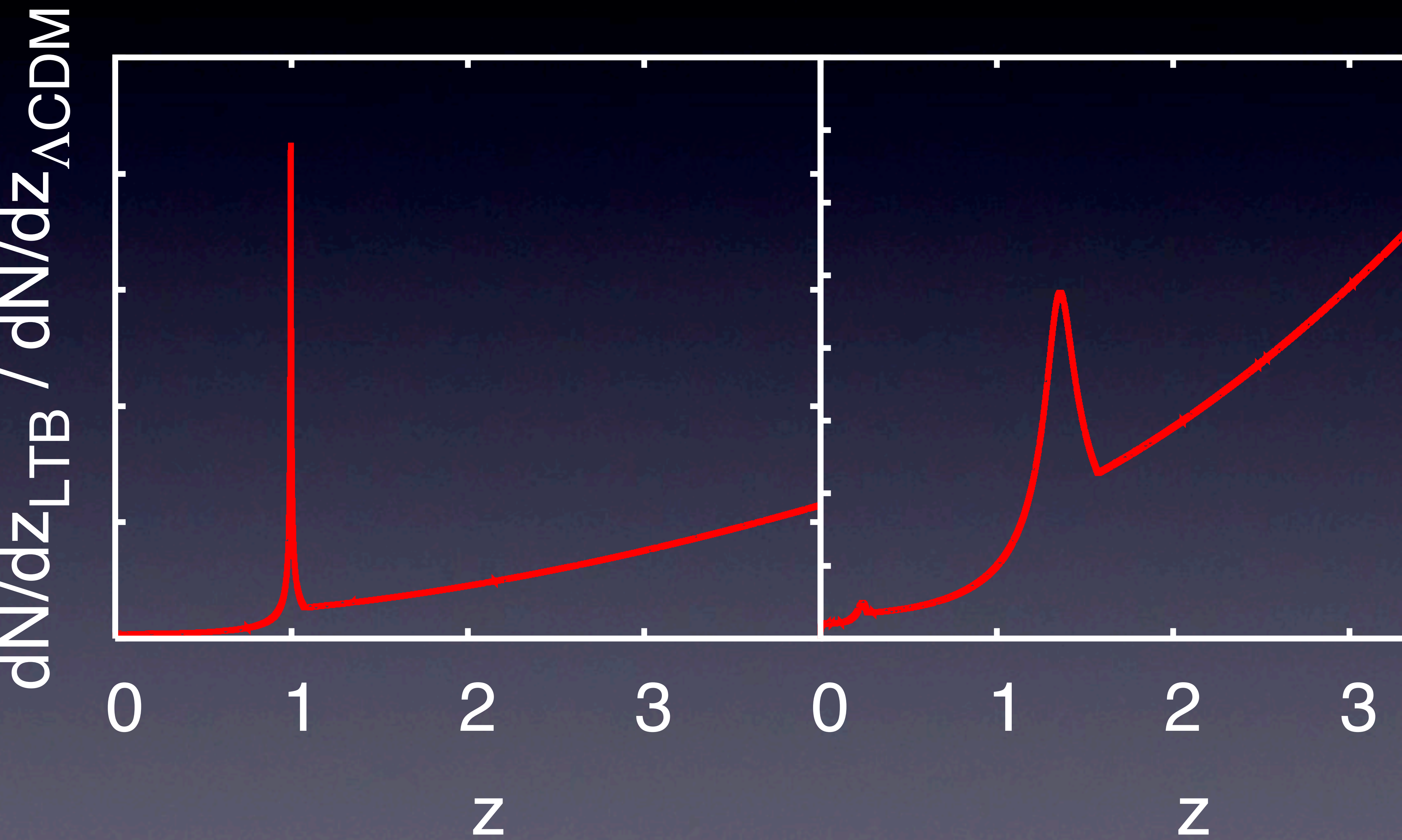

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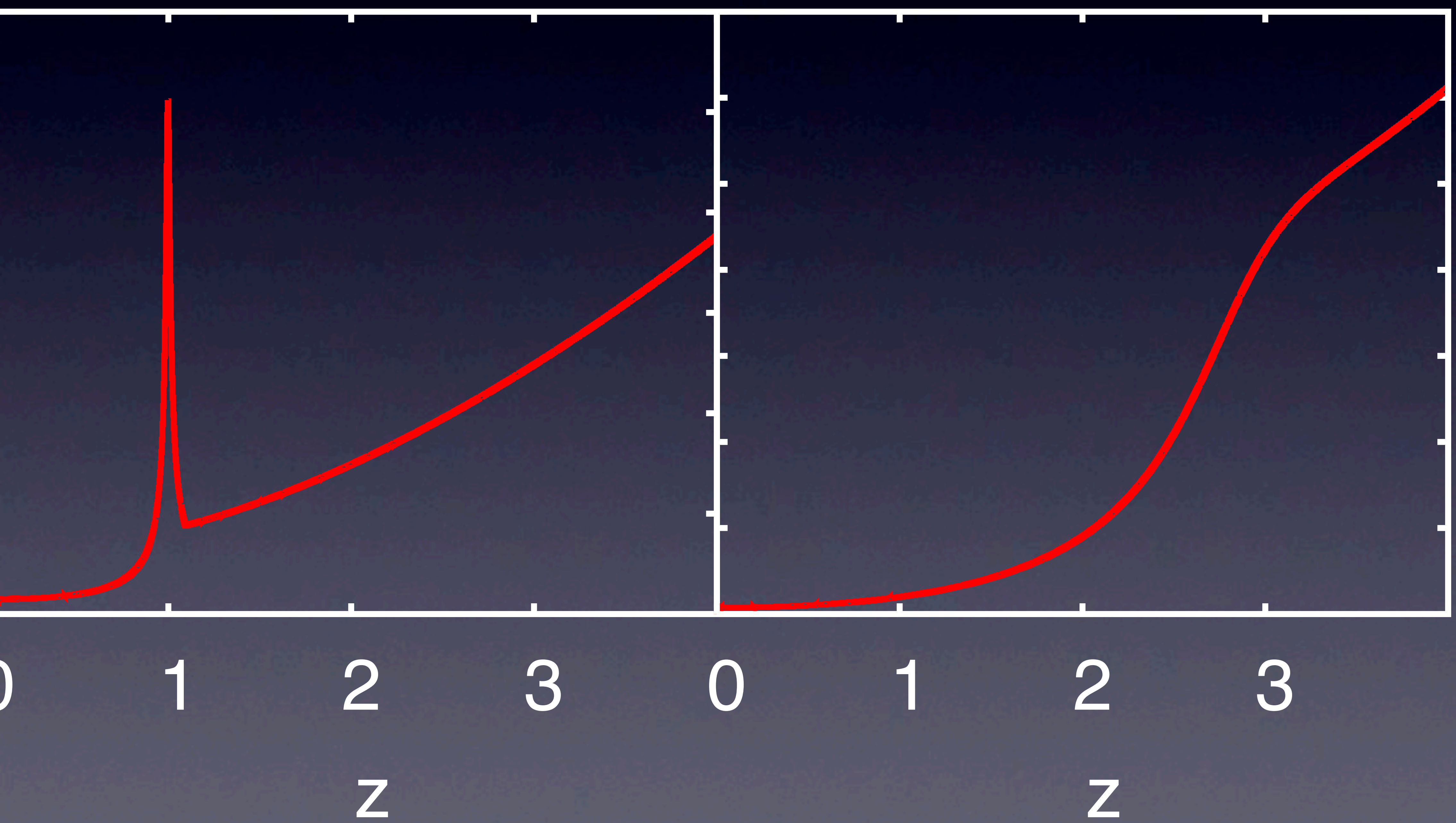

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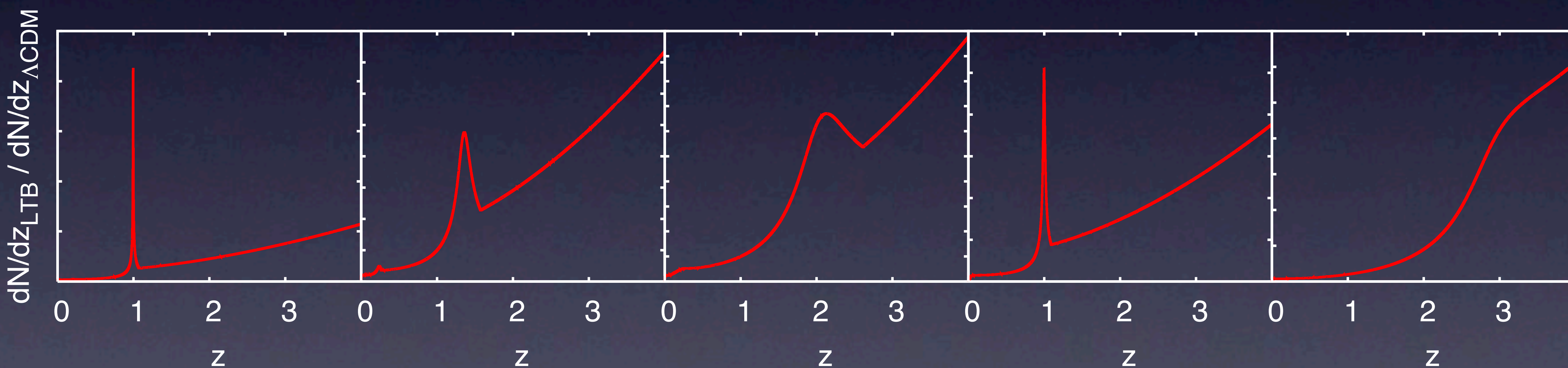

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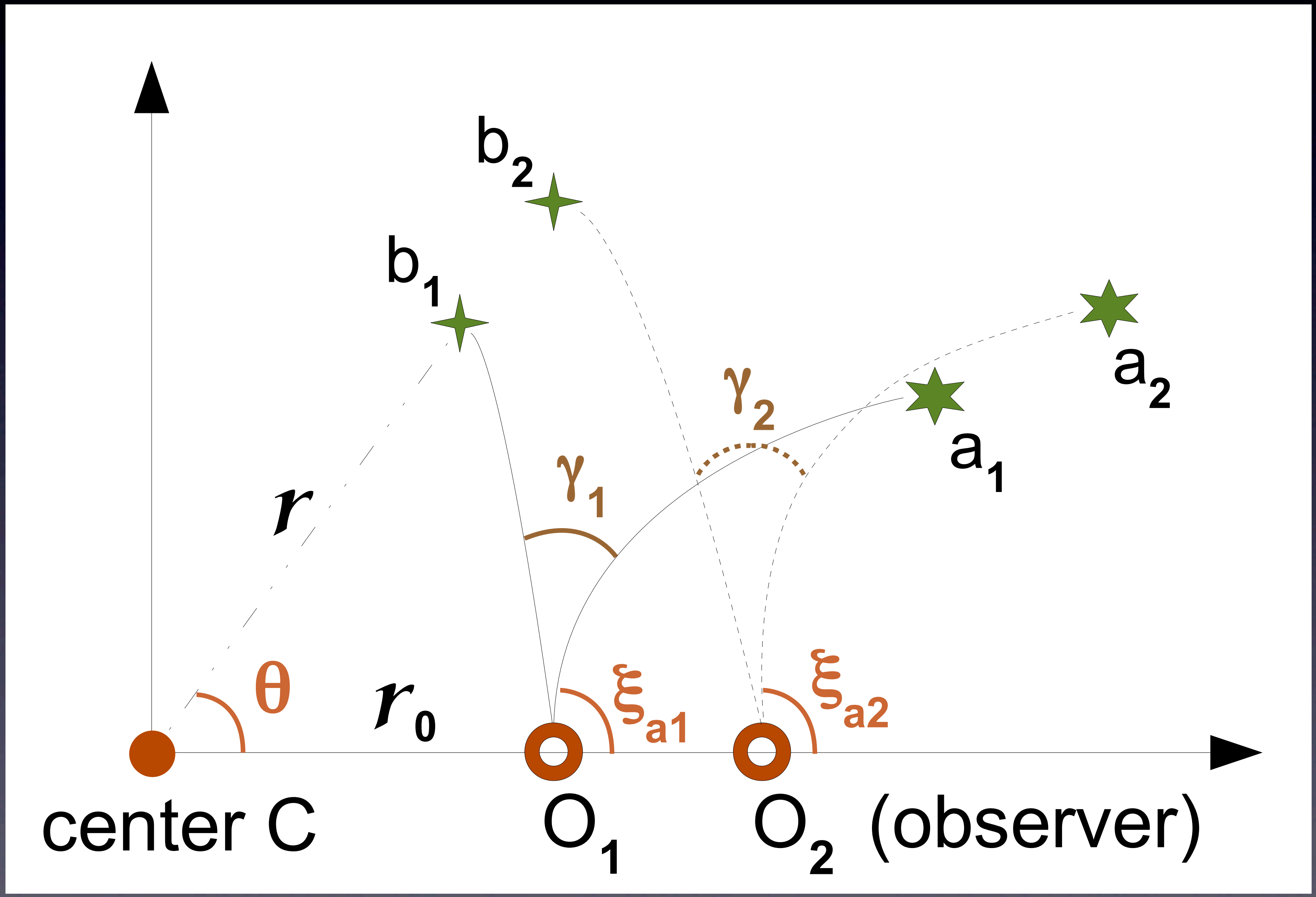
- Hence useful if isocurvature perturbations are small ($\rho_b$ / $\rho_m$ = constant throughout void)

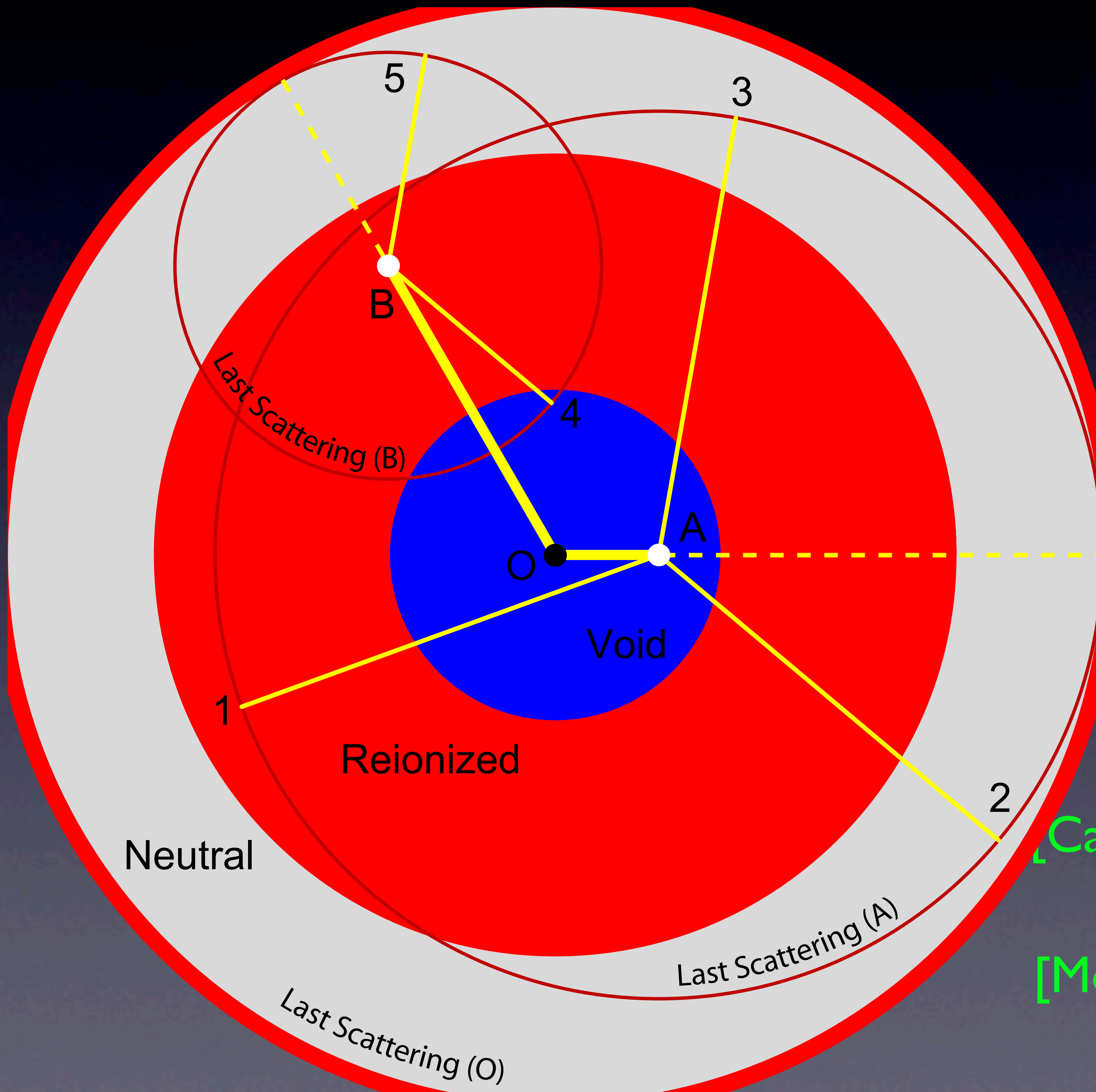
[Romano, 2009]

# Realtime cosmology




[Quartin, Amendola, 2009]

# Compton y distortion




[Caldwell, Stebbins, 2008]

[Moss, Zibin, Scott, 2010]

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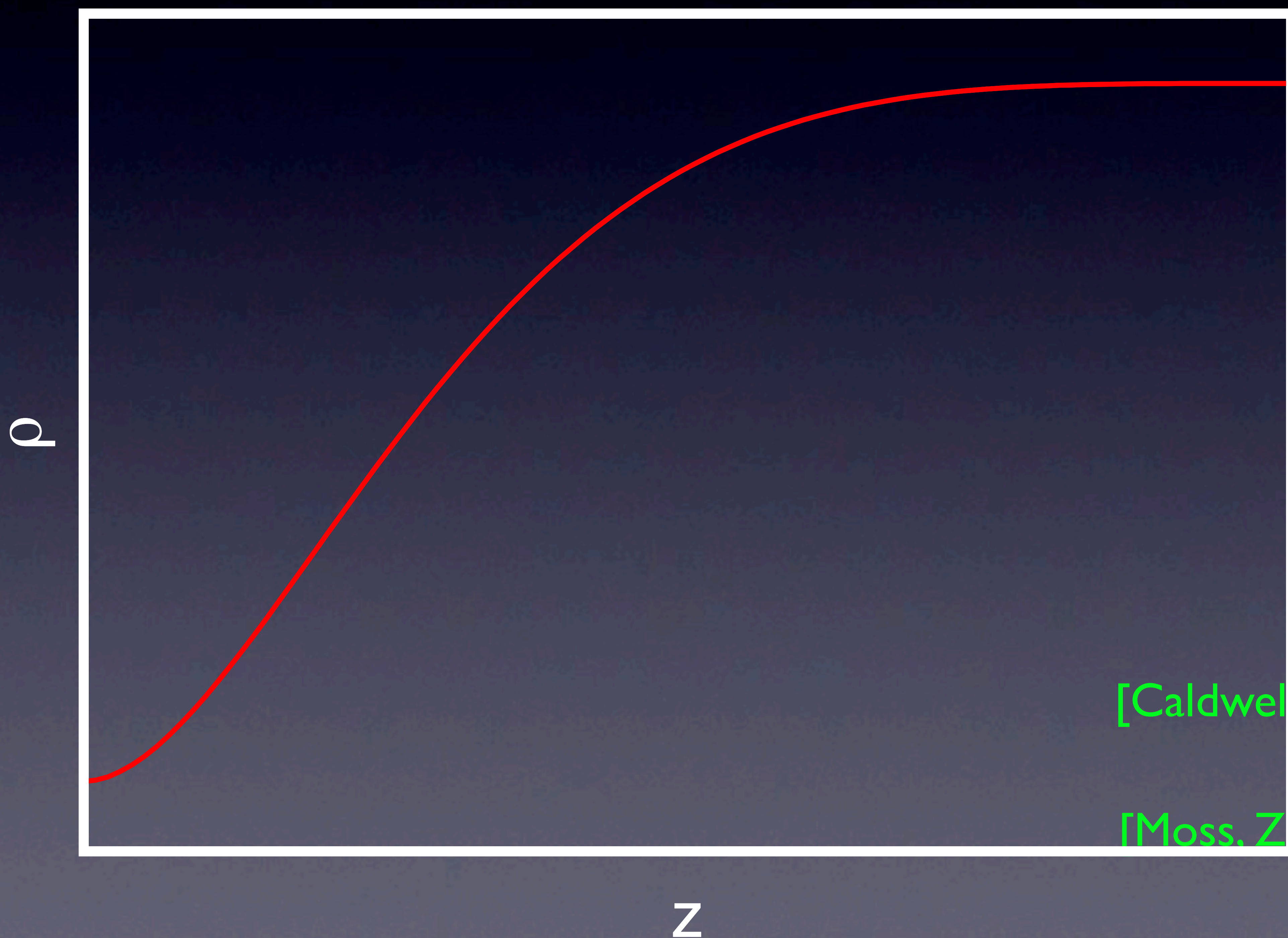


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- CosmoMC module publicly available (see paper)