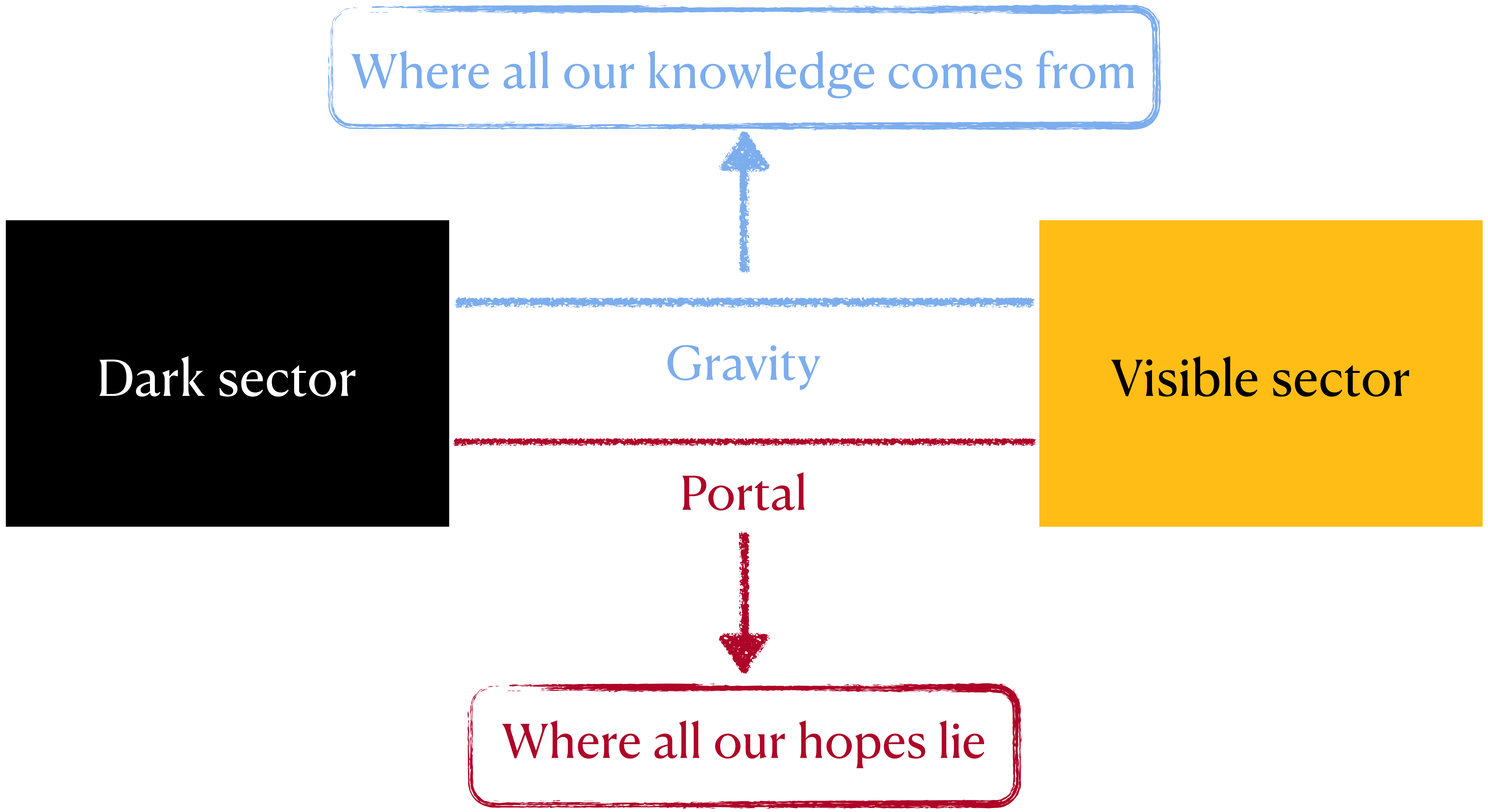
Hunting for New Physics with LSS and Linear Cosmology

Salvatore Bottaro

WEIZMANN INSTITUTE OF SCIENCE

26th June 2026 - Sheffield - PASCOS

Can we see in the dark?



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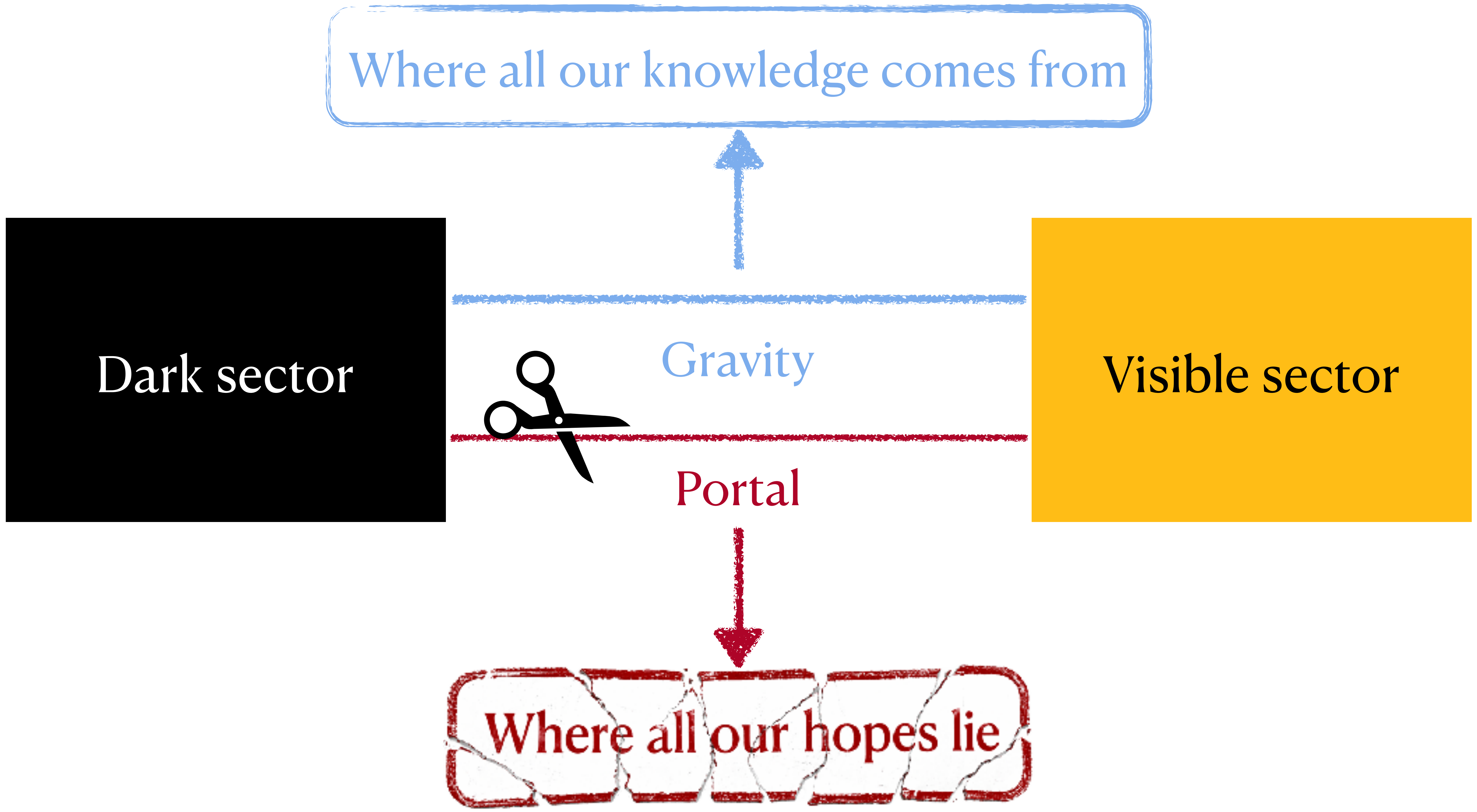

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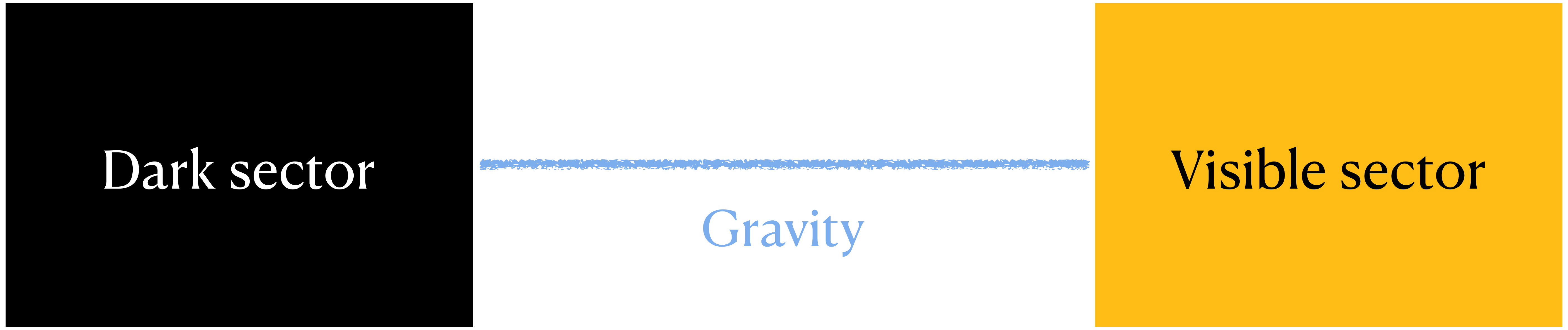
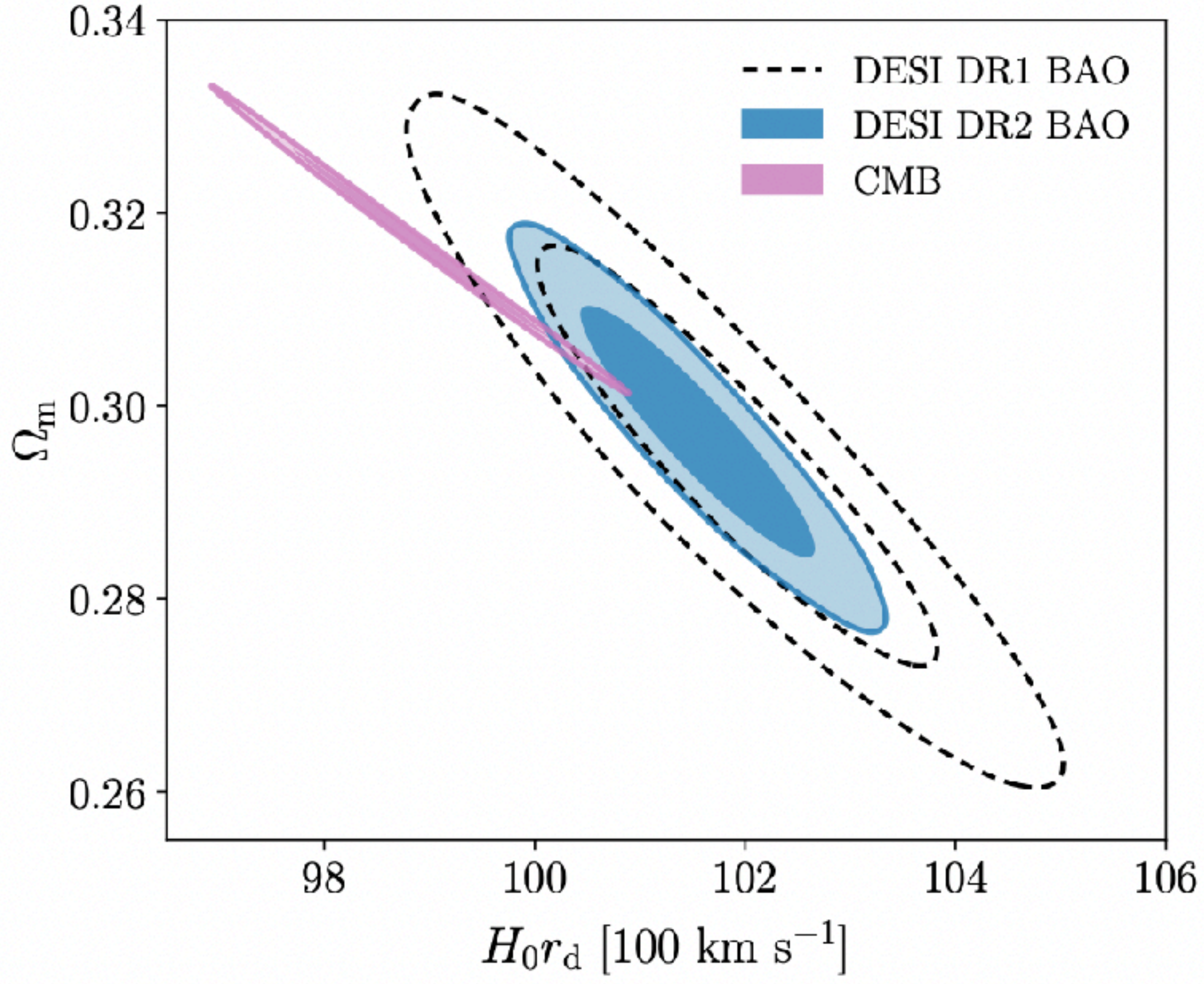
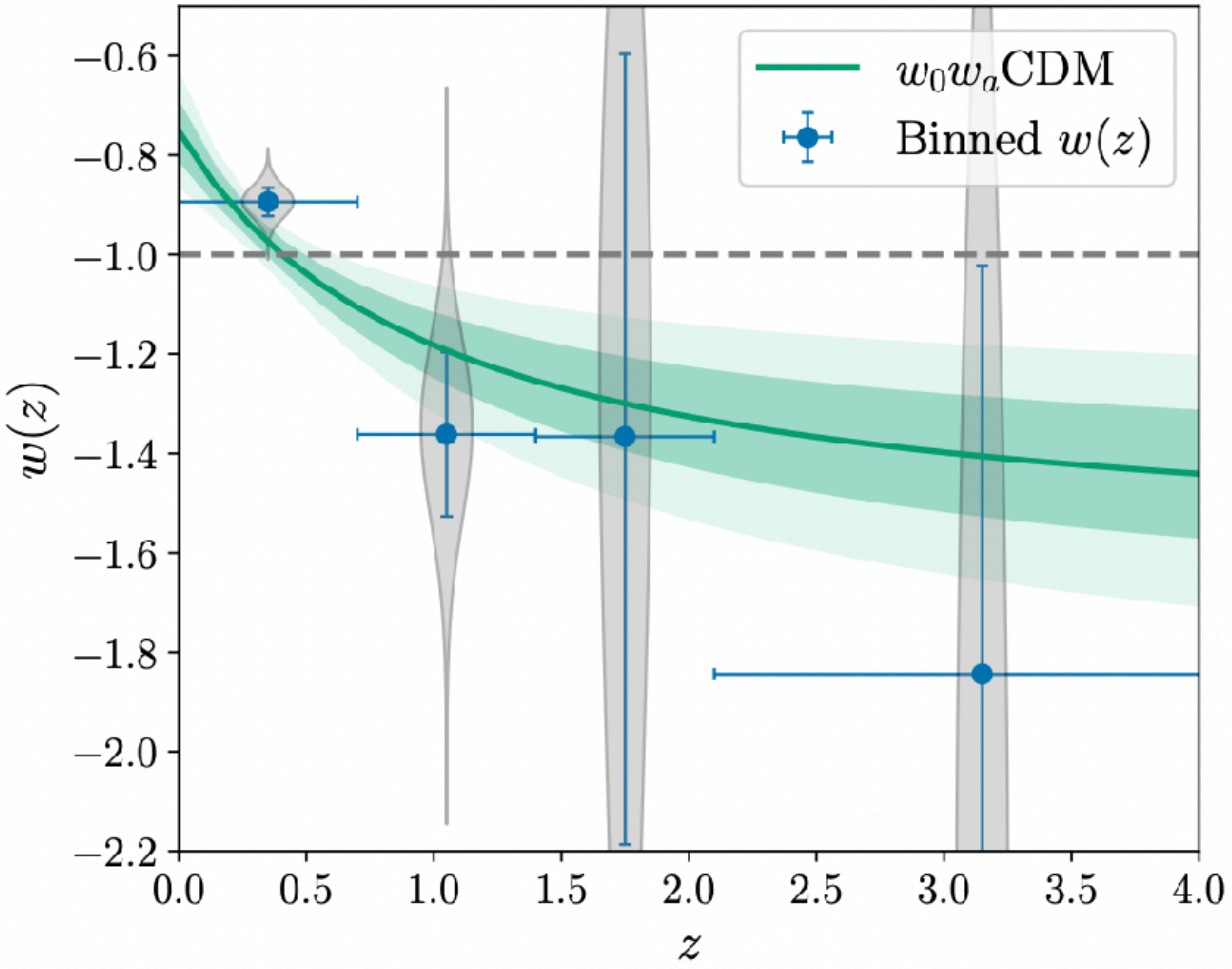


What can we infer on Dark Energy and Dark Matter using purely gravitational probes?

Hints of New Physics from data?



Evolving Dark Energy?



DESI collaboration, 2503.14738

Where can NP hide?

Cosmological observables

Production + Dynamics + Collapse

Production

$\delta_{\rm ini},\ z_{\rm NP},\ f_{\rm NL},\ \cdots$

- Isocurvature
- Non-Gaussianities
- ...

Dynamics

$c_s^2,\ \Delta H,\ \Delta G_N,\ \cdots$

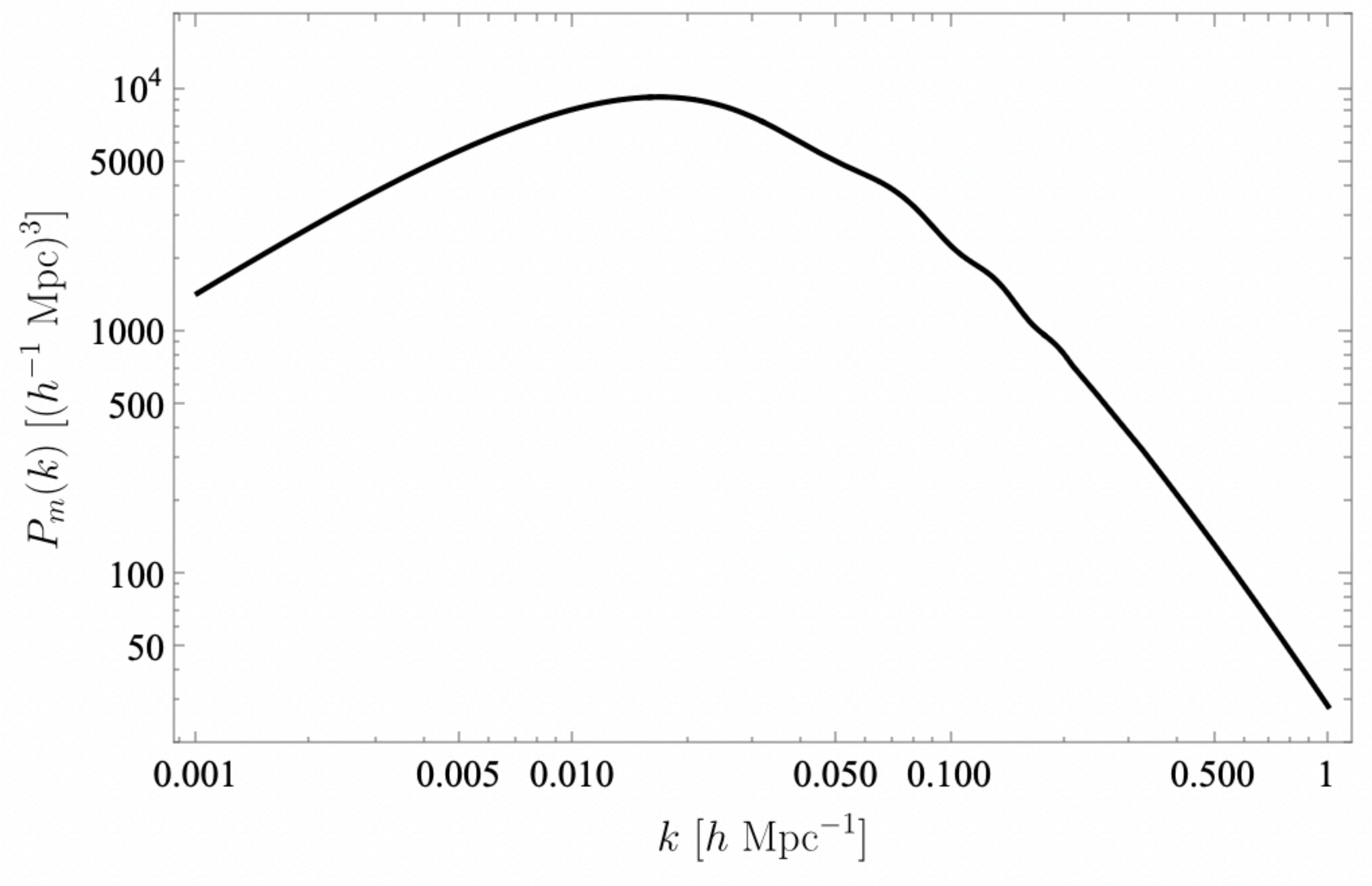
- Pressure
- Modified bkg
- New forces
- Late-time injection of fluctuations

Collapse

$\sigma,\ \lambda_{\rm dB},\ \cdots$

- Self-interactions
- Large De Broglie wavelength
- ...

What can we find in the Power Spectrum?



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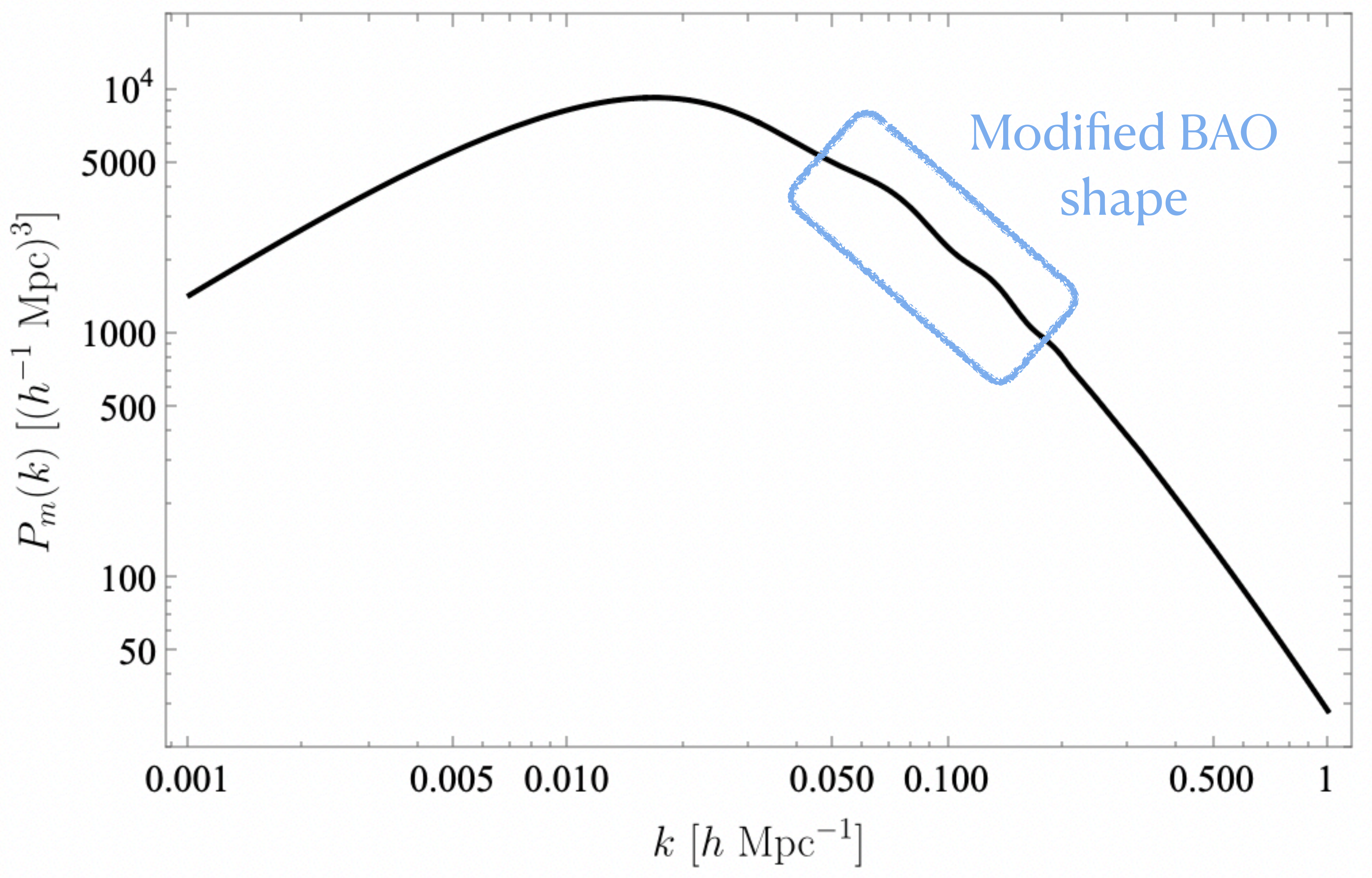

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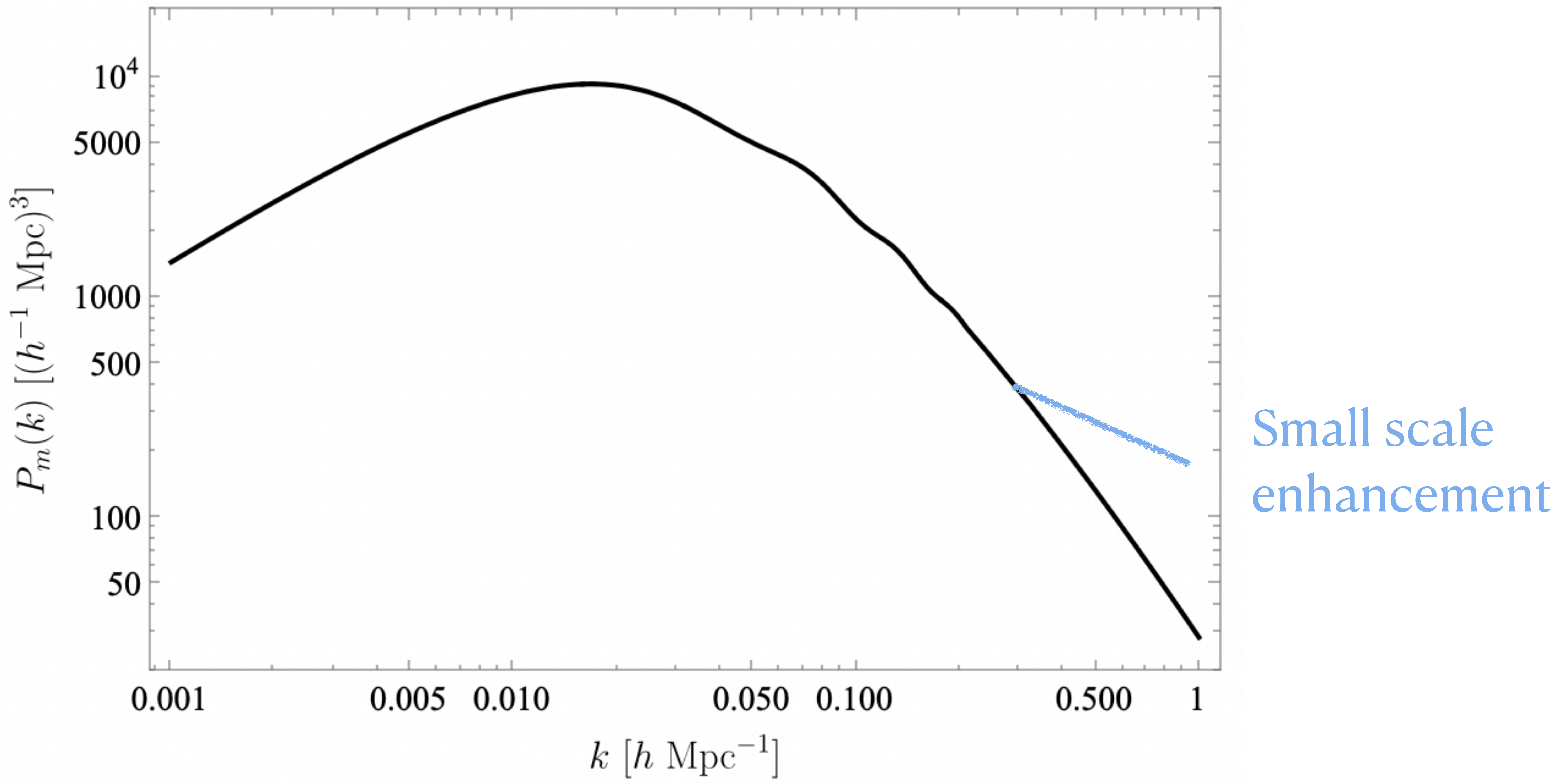

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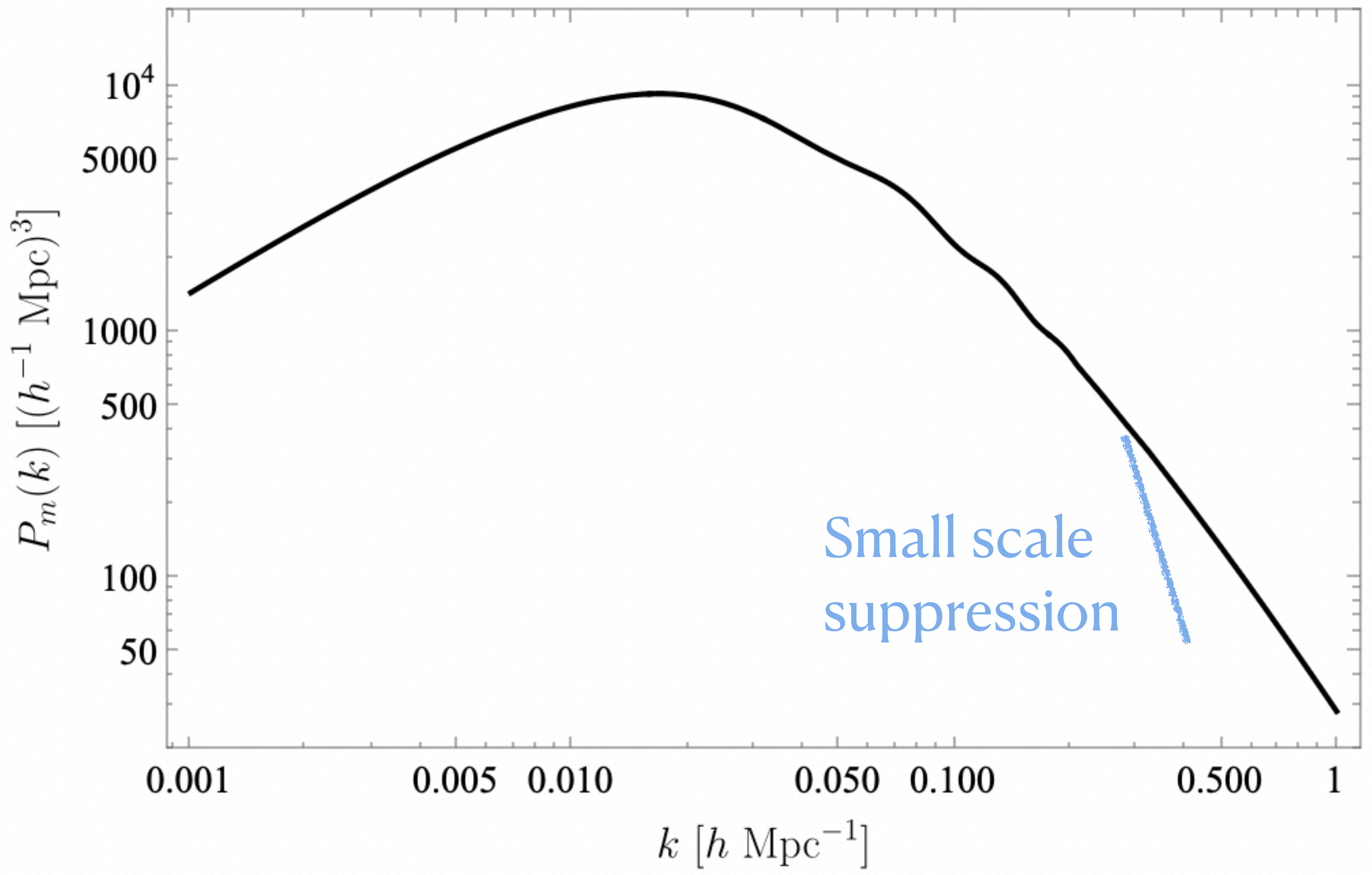

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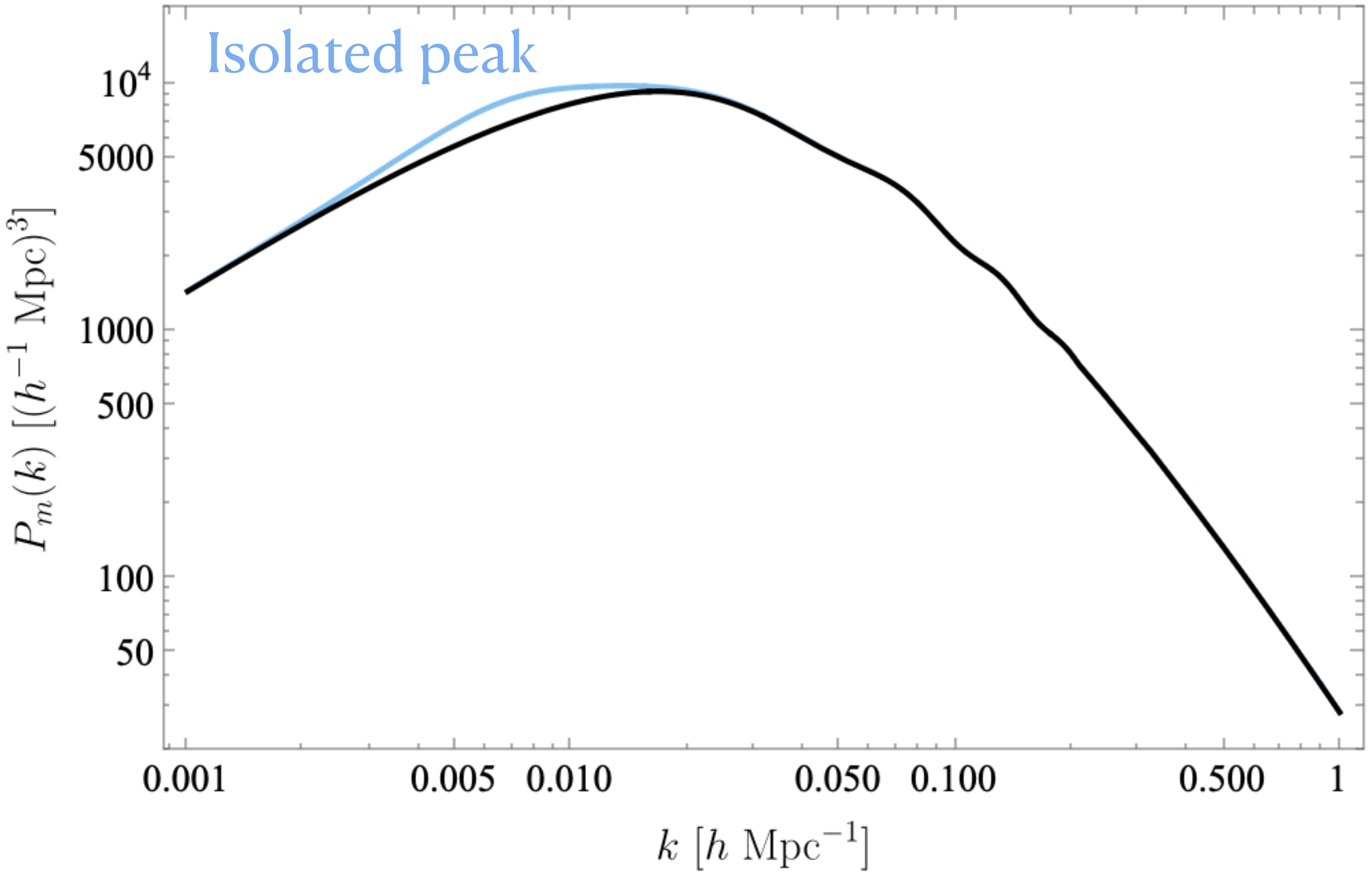

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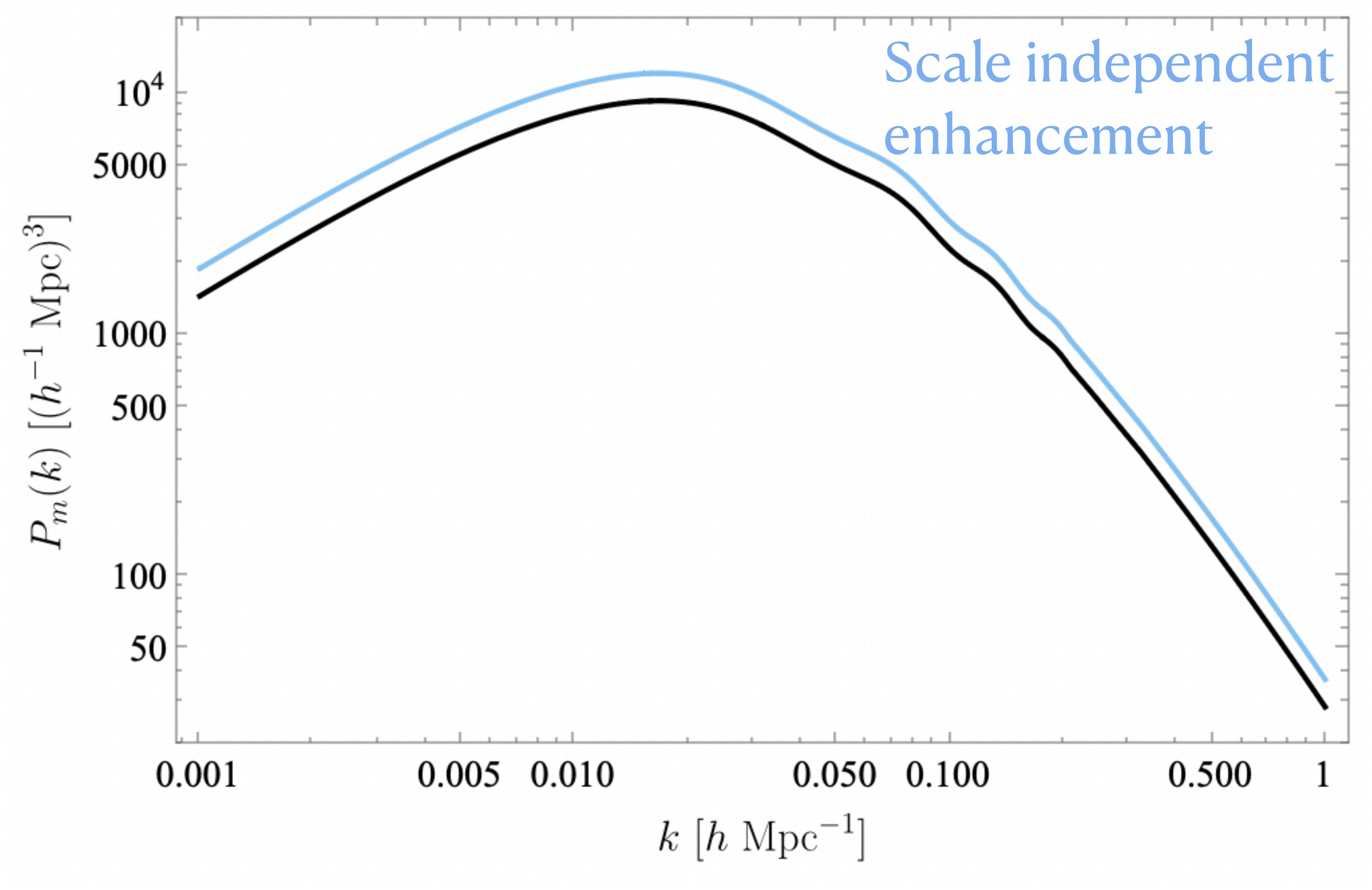

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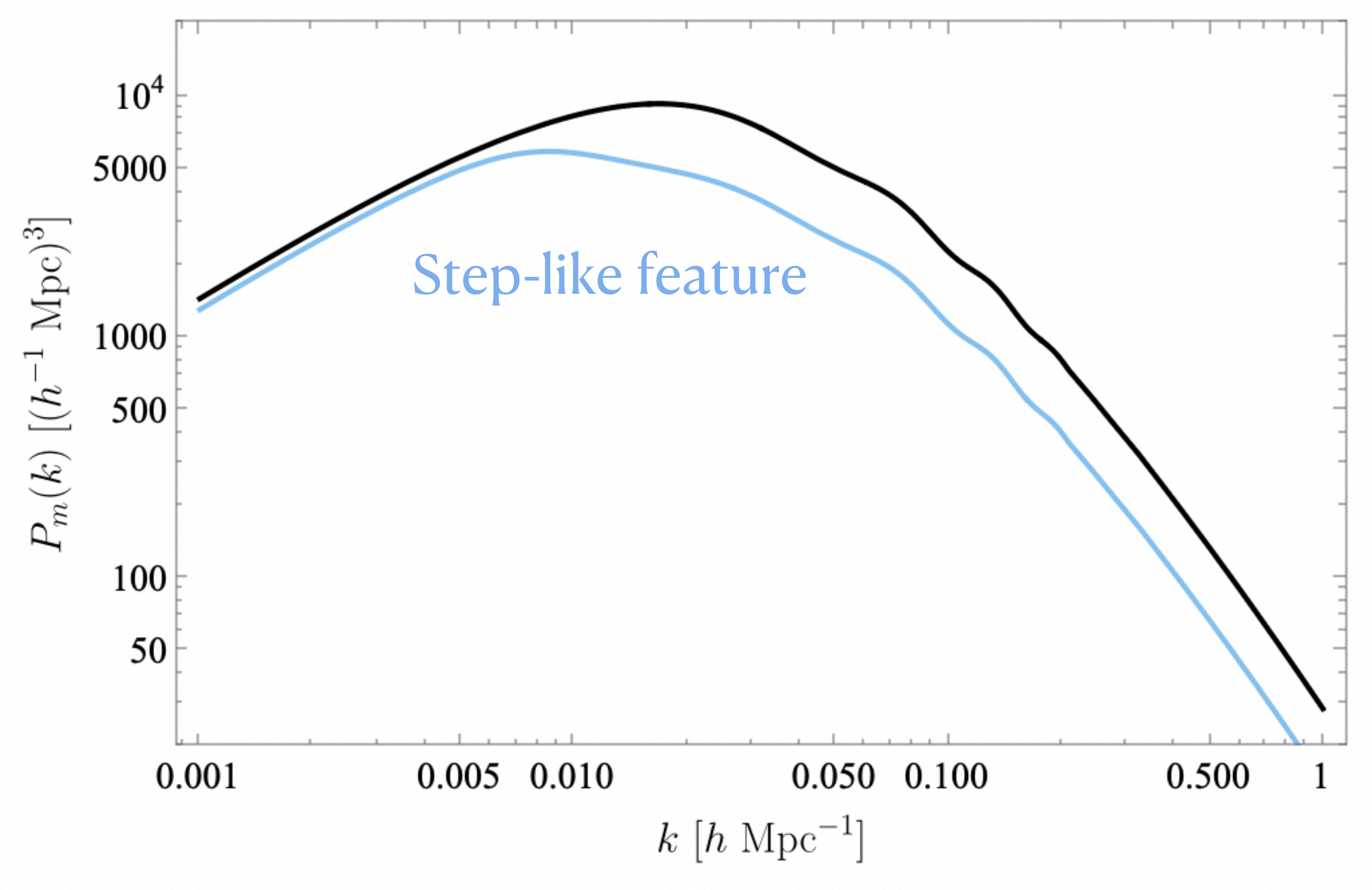

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Production + **Dynamics** + **Collapse**

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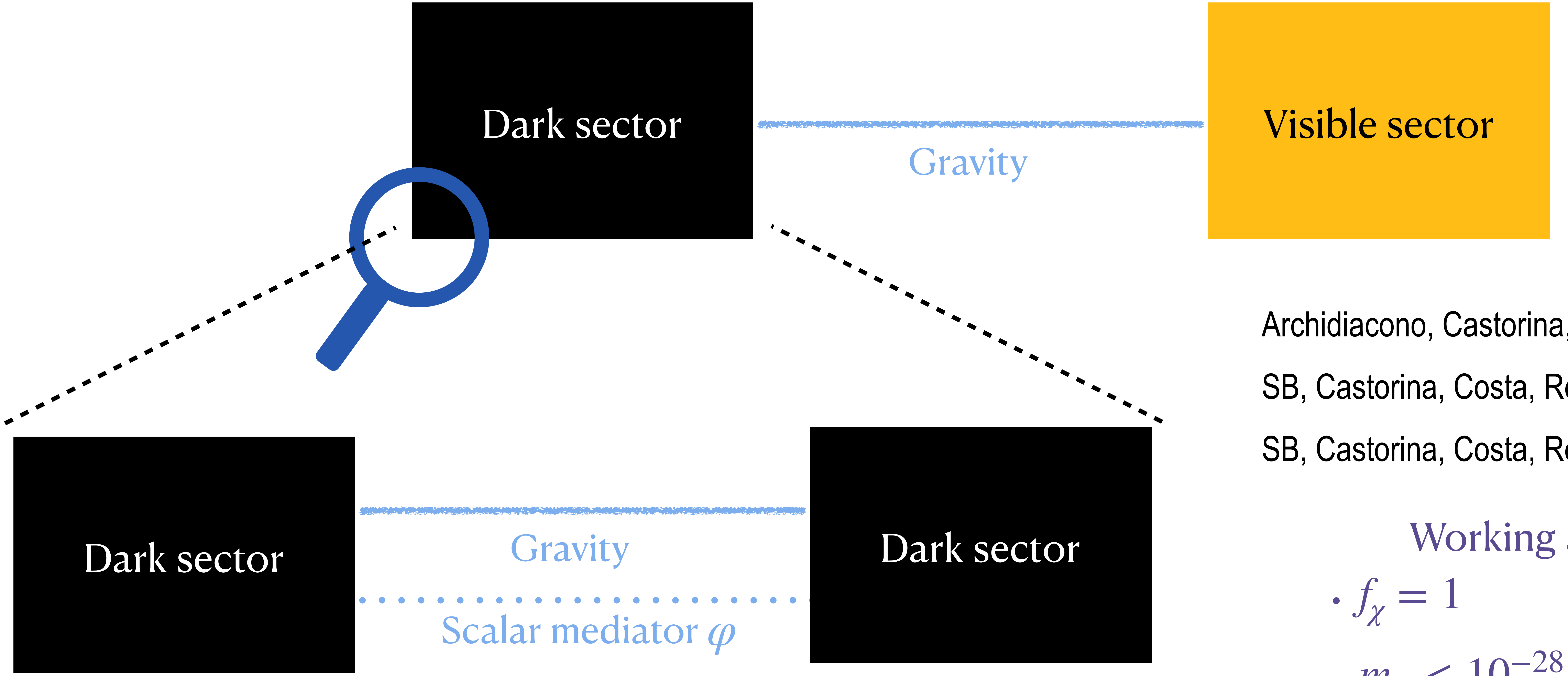
Long-range forces in the DS



Archidiacono, Castorina, Redigolo, Salvioni - 2204.08484

SB, Castorina, Costa, Redigolo, Salvioni - 2309.11496

SB, Castorina, Costa, Redigolo, Salvioni - 2407.18252

Working assumptions

- $f_\chi = 1$
- $m_\varphi < 10^{-28}$ eV

$$\mathscr{L} \supset \frac{1}{2} m_\chi^2 \left(1 + \sqrt{4\pi\beta G_N}\varphi\right)\chi^2 \longrightarrow V_\chi = -G_N\left(1 + \beta e^{-m_\varphi r}\right)\frac{m_\chi^2}{r}$$

Keep your feet on the (back)ground

Time dependent DM mass

φ $\qquad\qquad \varphi\chi^2 \qquad\qquad$ χ

Evolution of φ sourced by
the DM number density

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φ $\qquad$ $\varphi\chi^2$ $\qquad$ χ

Evolution of φ sourced by
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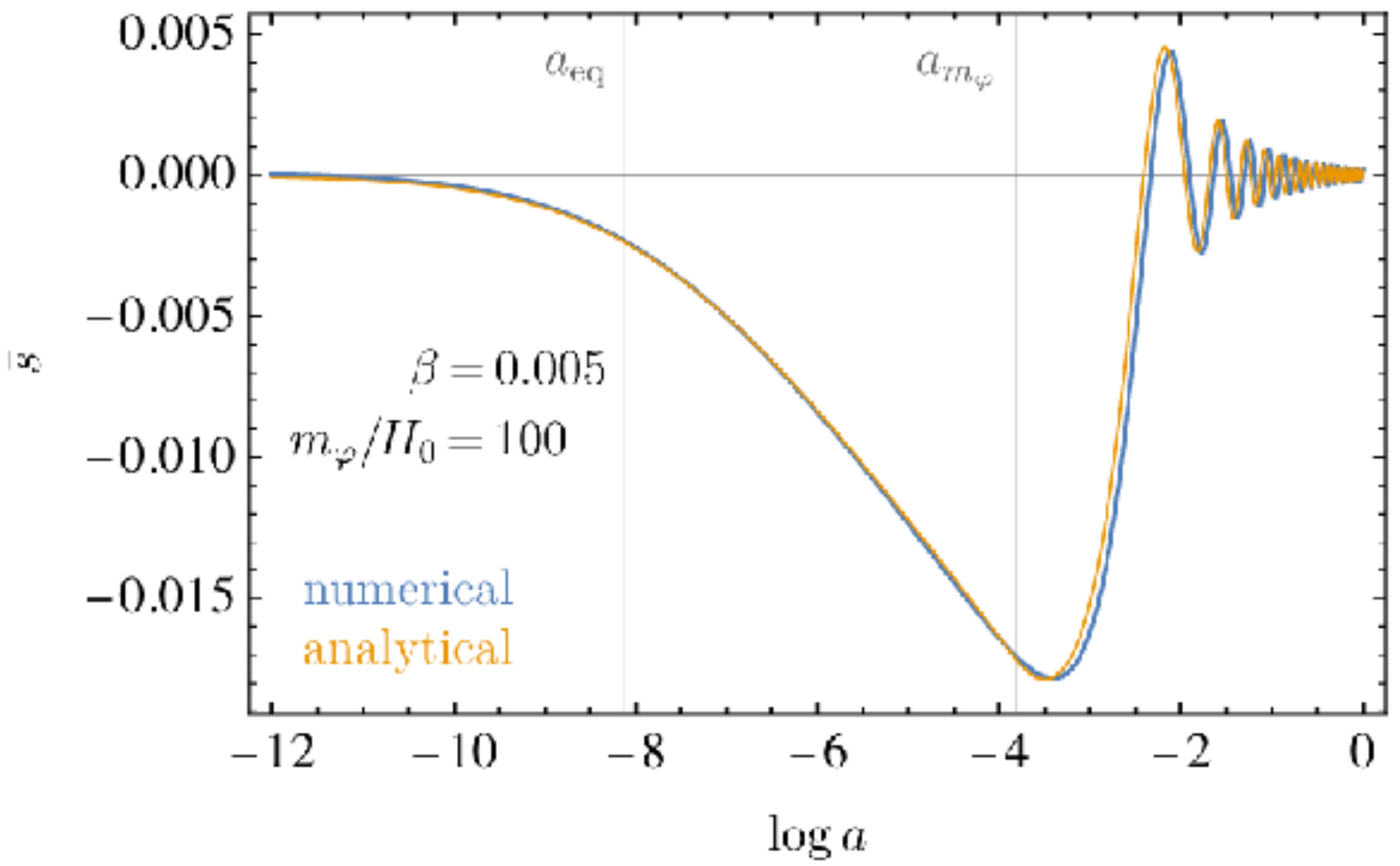


Keep your feet on the (back)ground

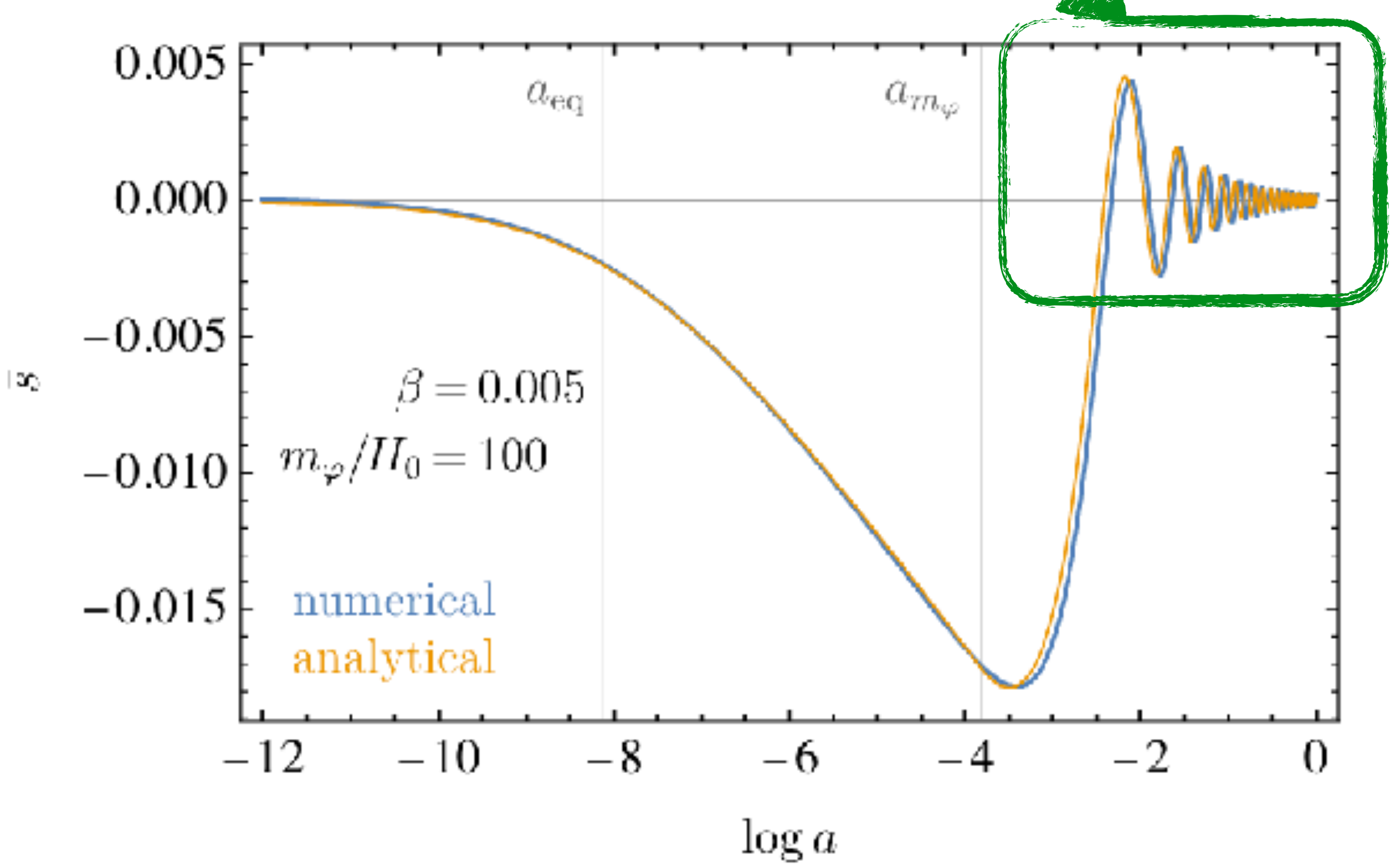
Time dependent DM mass

φ $\qquad$ $\varphi\chi^2$ $\qquad$ χ

Evolution of φ sourced by the DM number density

Mediator becomes DM

$f_\varphi \sim \beta \log^2(H_{\rm eq}/m_\varphi)$



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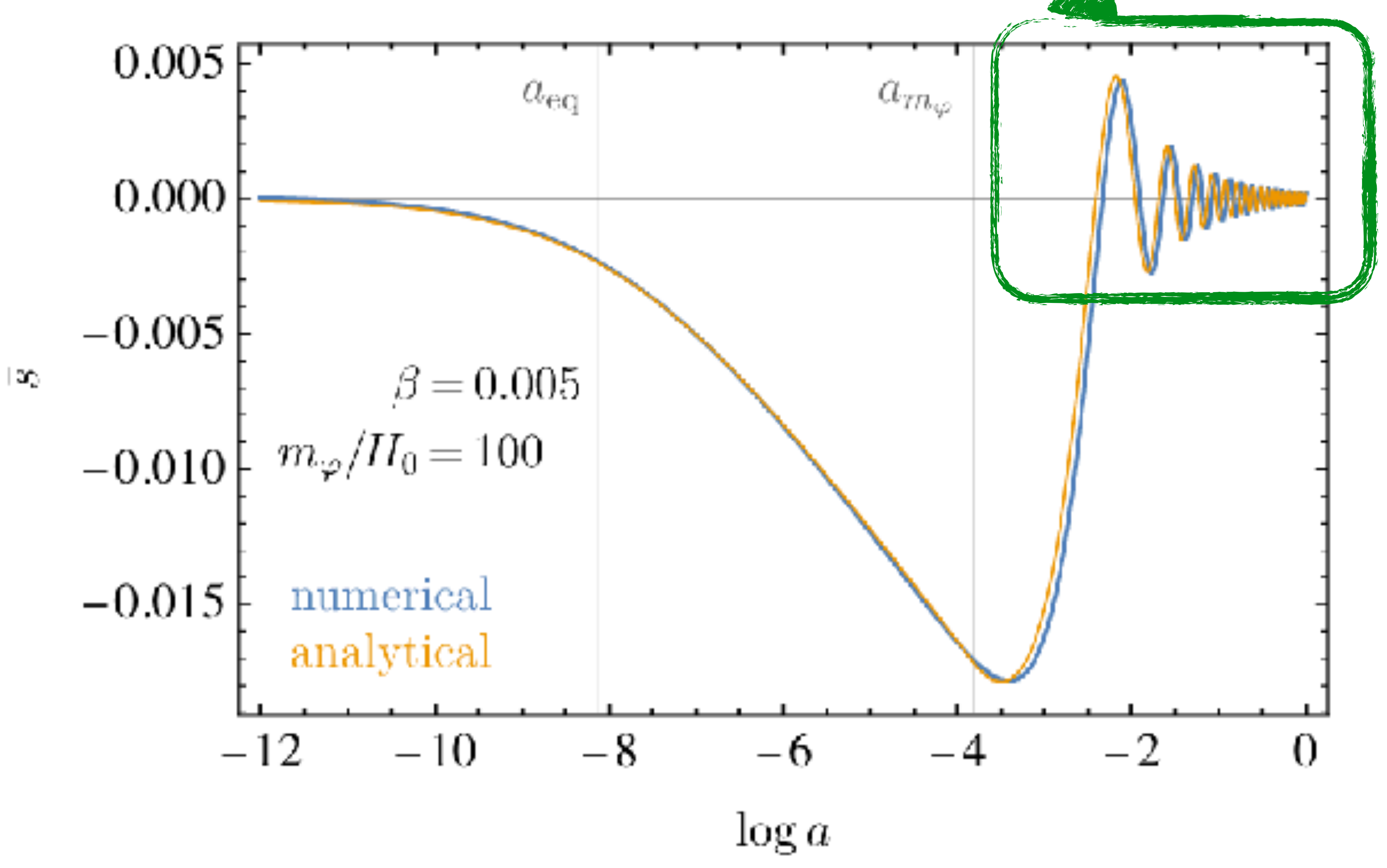
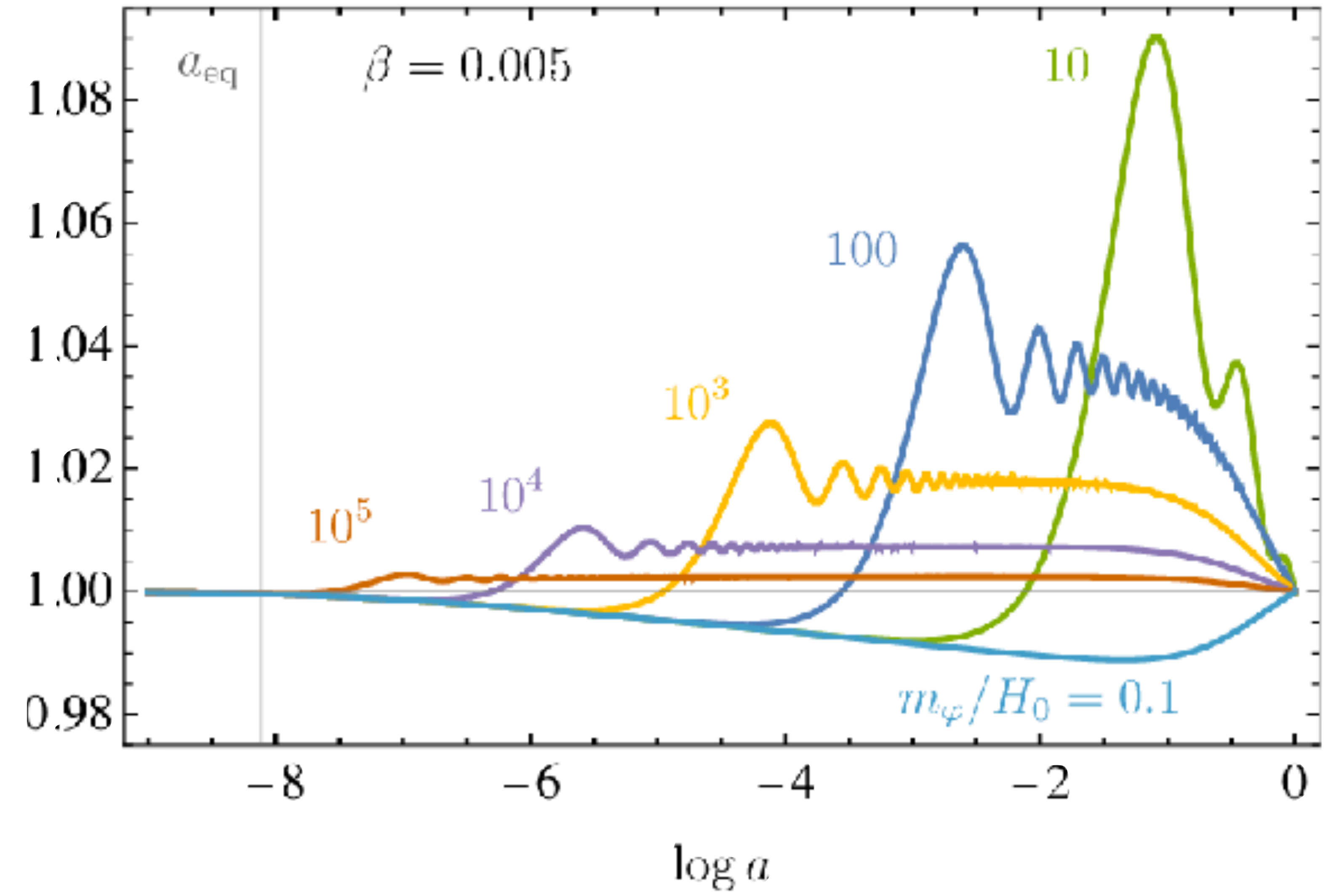


Evolution of φ sourced by the DM number density

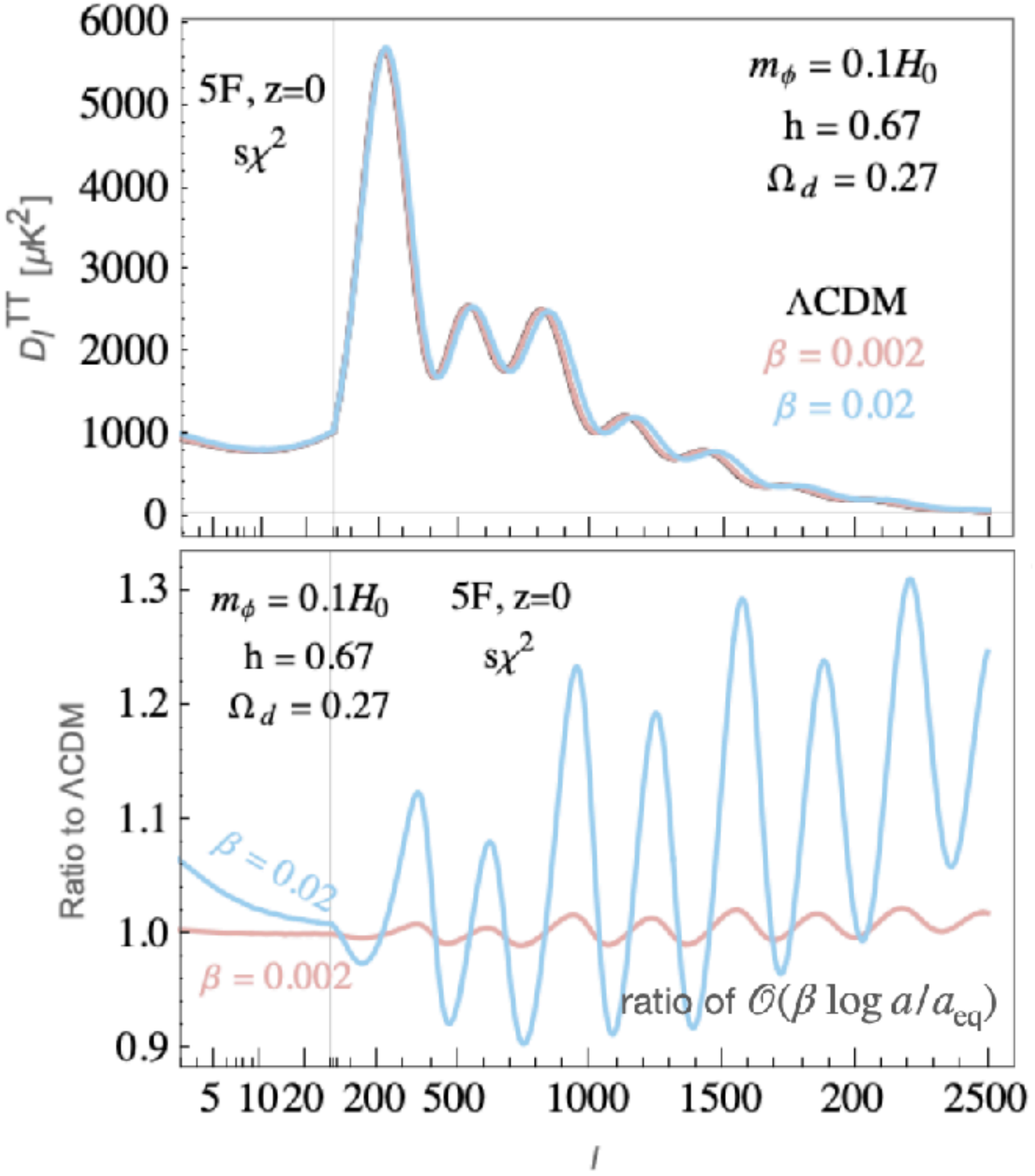
Modified distances

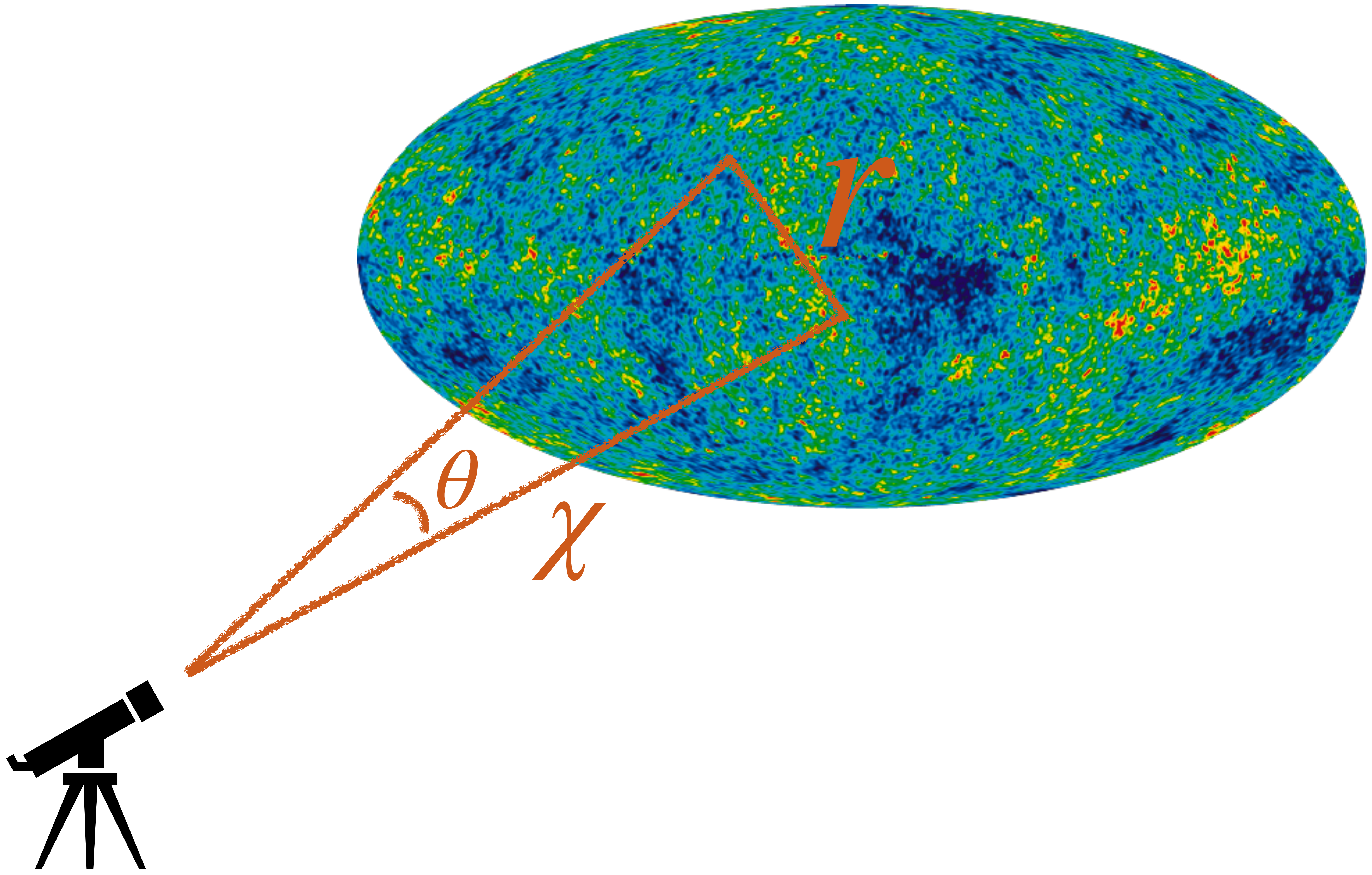


Effects on CMB: what matters is the journey

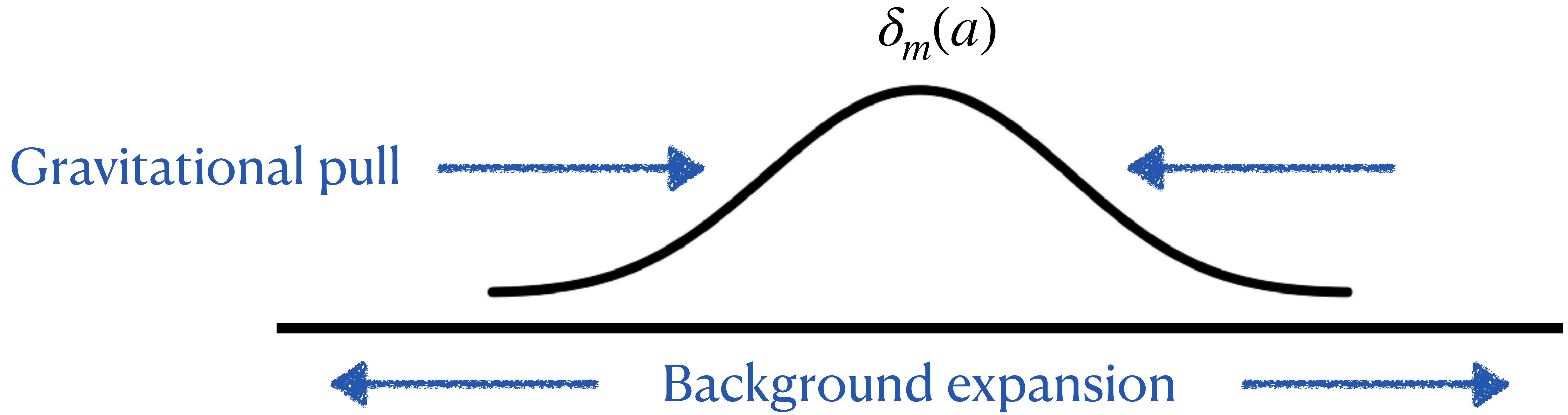
Shifts in the peaks due to modified distances

$$\ell \sim \frac{2\pi}{\theta} \sim \frac{\chi}{r} = \frac{1}{r}\int \frac{\mathrm{d}z}{H(z) + \Delta H(z)}$$





What's the Matter (Power Spectrum)?



$$\delta_m(a) \propto a$$

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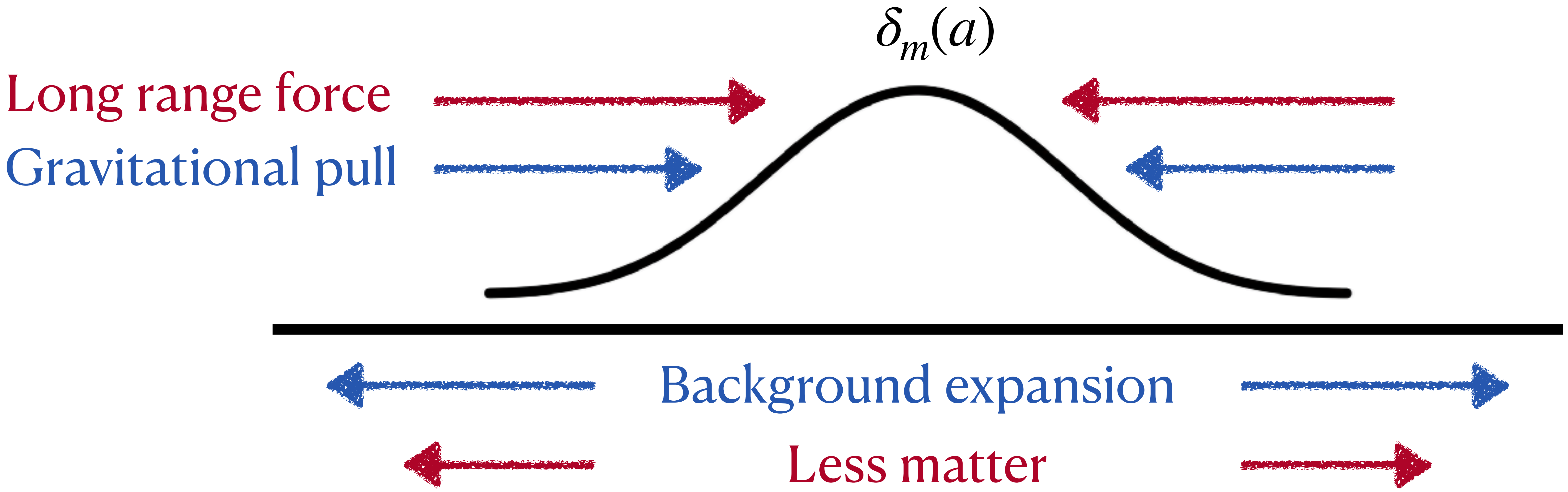

$$\delta_m(a) \propto a\left(1+\beta\log(a/a_{\mathrm{eq}})\right)$$

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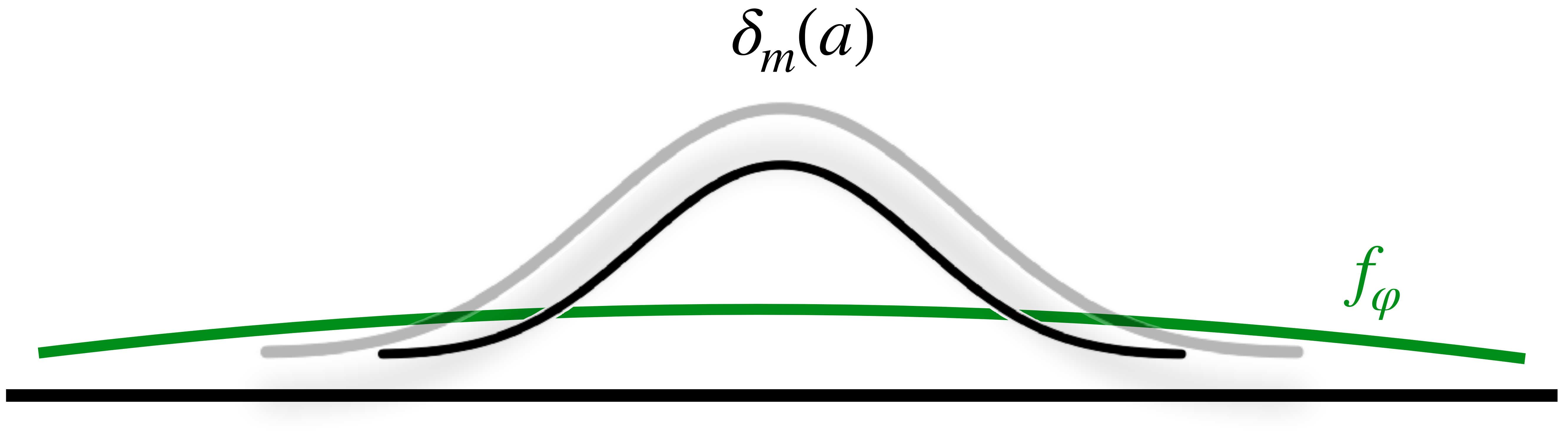
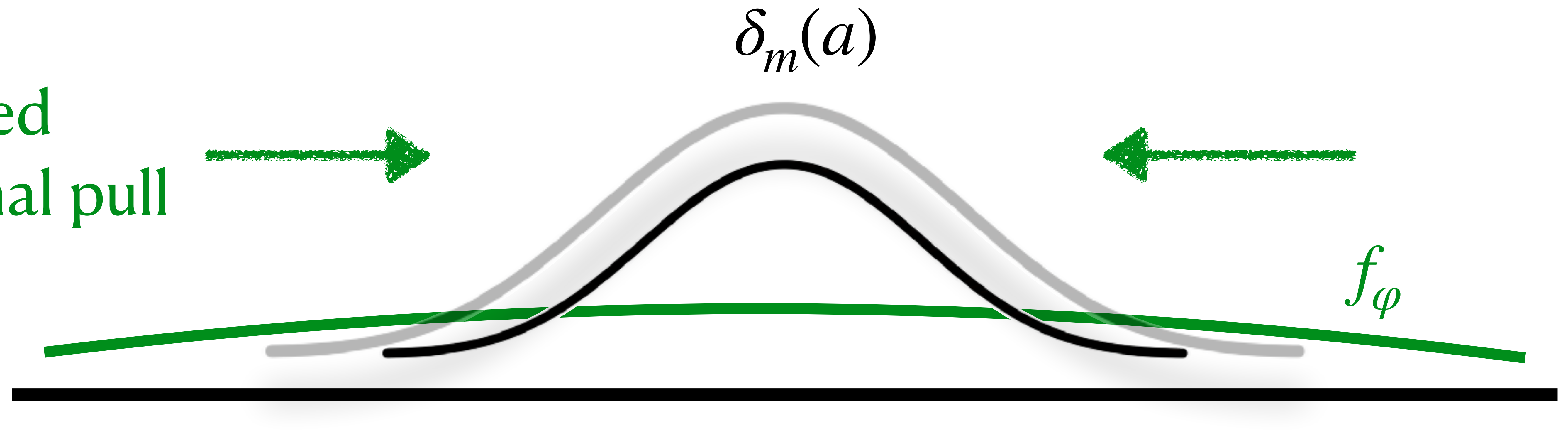


Mediator not clustering at scales $k > k_J \sim \lambda_{\rm dB}^{-1}$

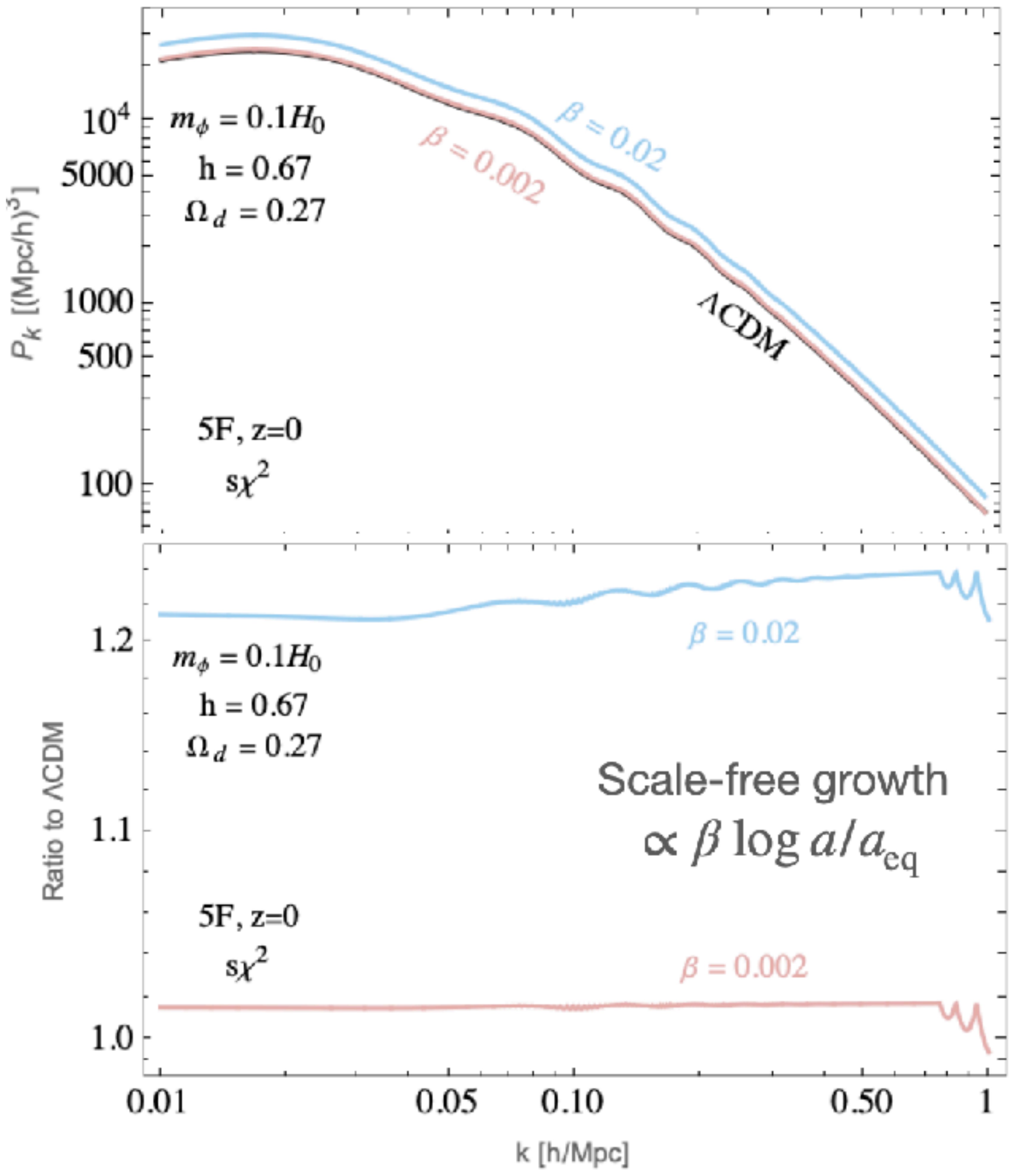
$$\delta_m(a) \propto a\left(1+\beta\log(a_{m_\varphi}/a_{\rm eq})-f_\varphi\right.$$

What's the Matter (Power Spectrum)?

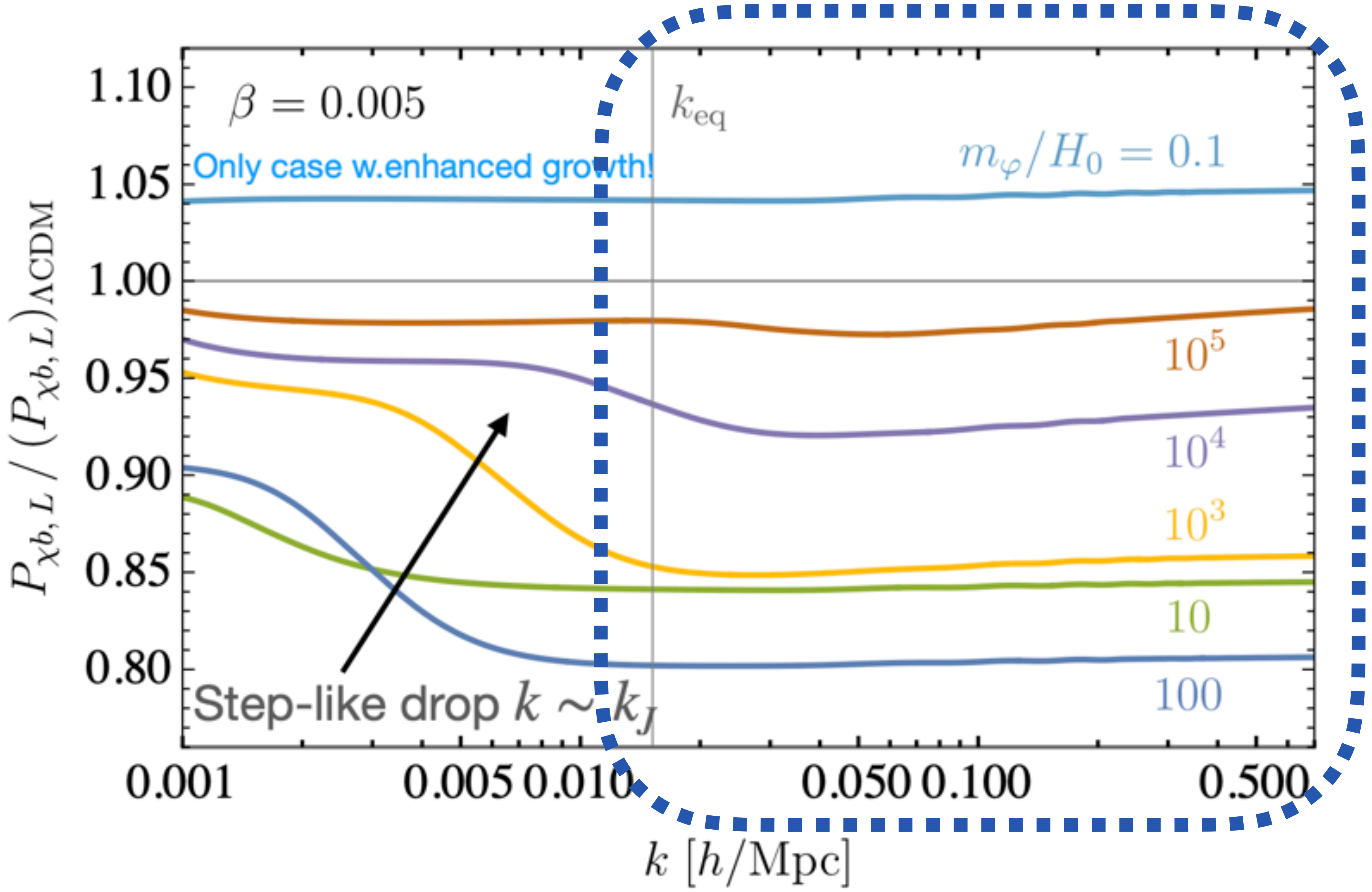


$$\delta_m(a) \propto a \left(1 + \beta \log(a_{m_\varphi}/a_{\rm eq}) - f_\varphi - f_\varphi \log(a/a_{m_\varphi})\right)$$

What's the Matter (Power Spectrum)?



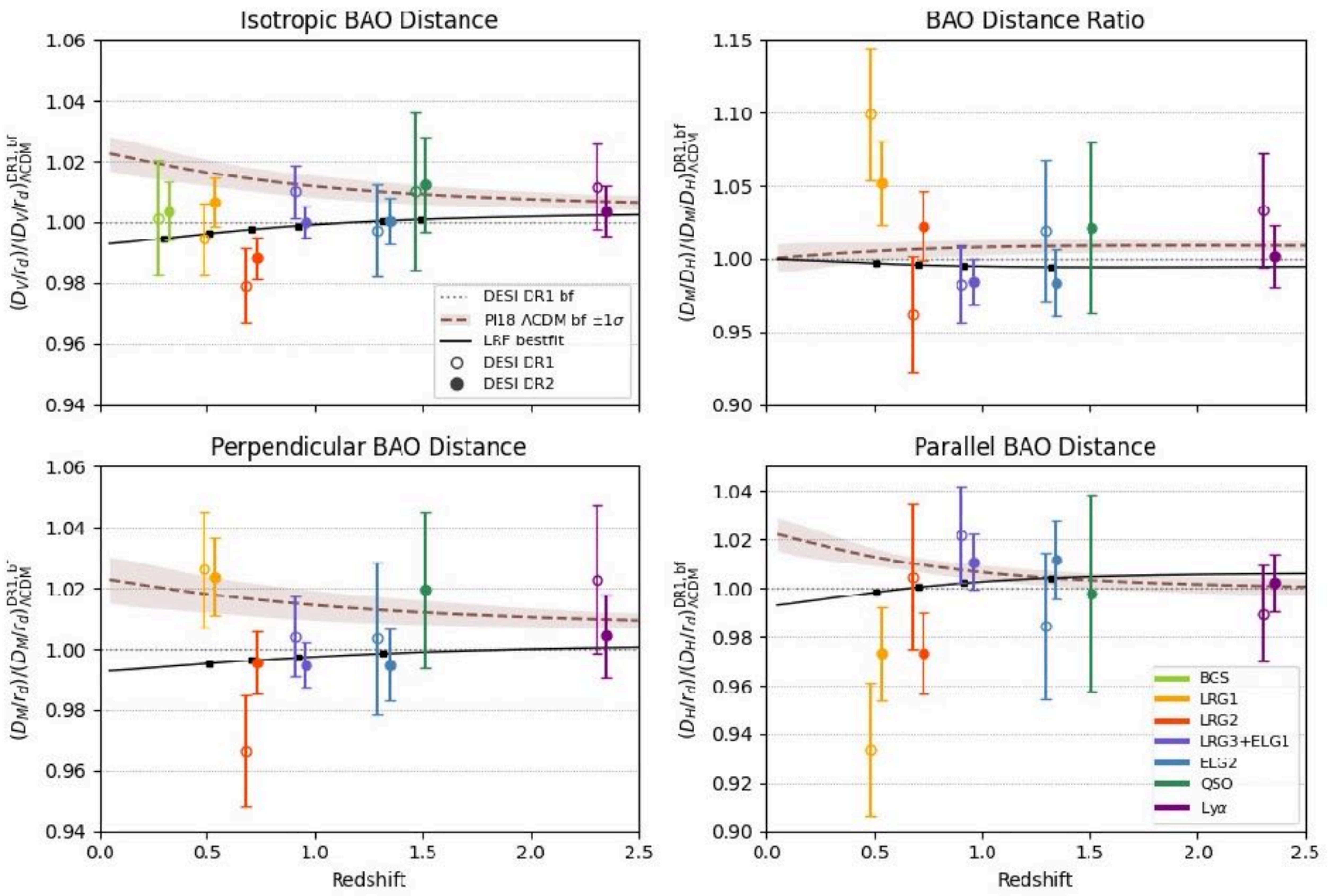
Scale-free growth factor at scales relevant for LSS

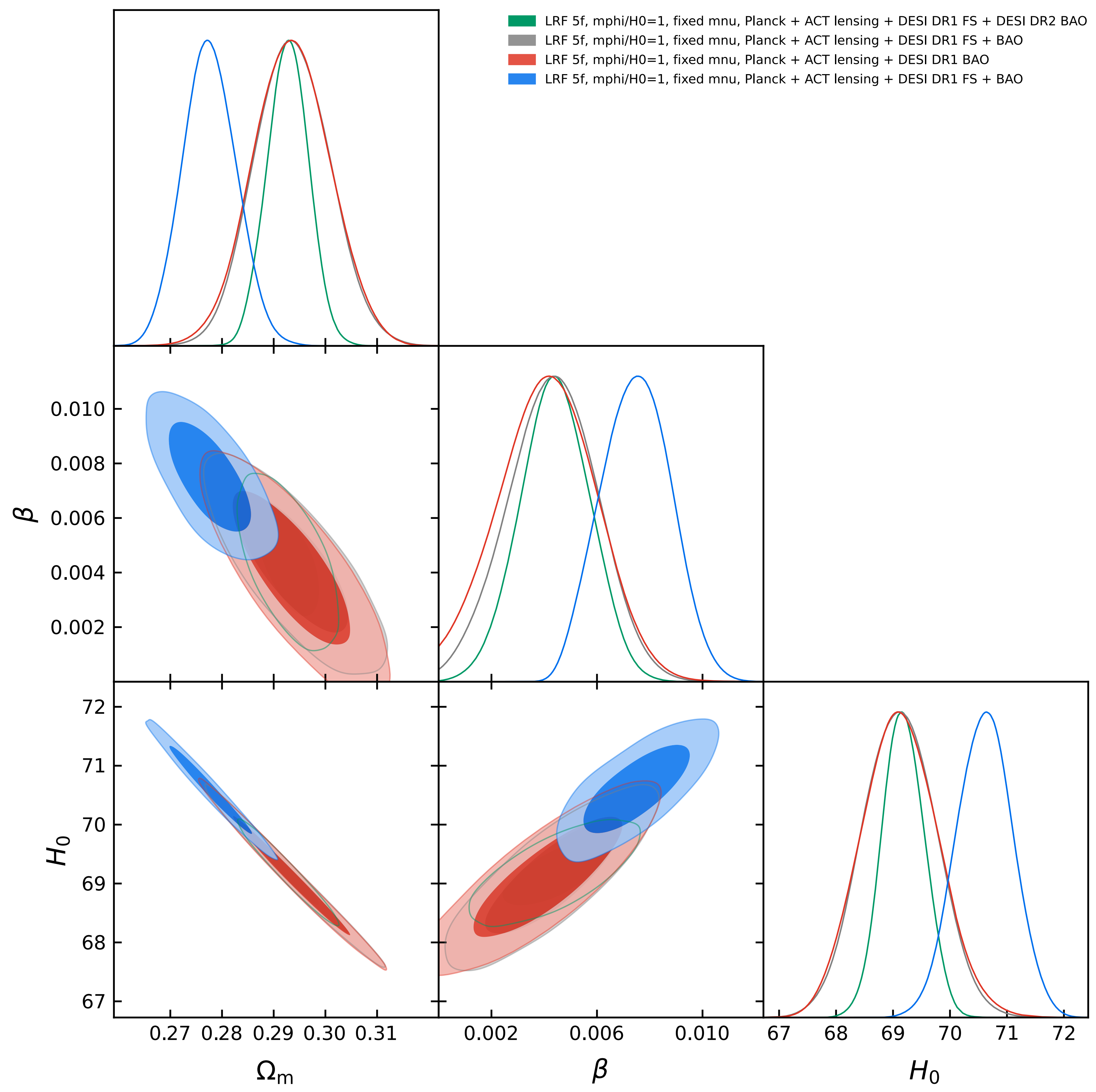


$$\frac{\delta_m(a)}{\delta_m^{\rm CDM}(a)} - 1 \simeq \frac{6}{5}\beta \log \frac{a_{m_\varphi}}{a_{\rm eq}} - f_s - \frac{3}{5} f_s \log \frac{a}{a_{m_\varphi}}$$

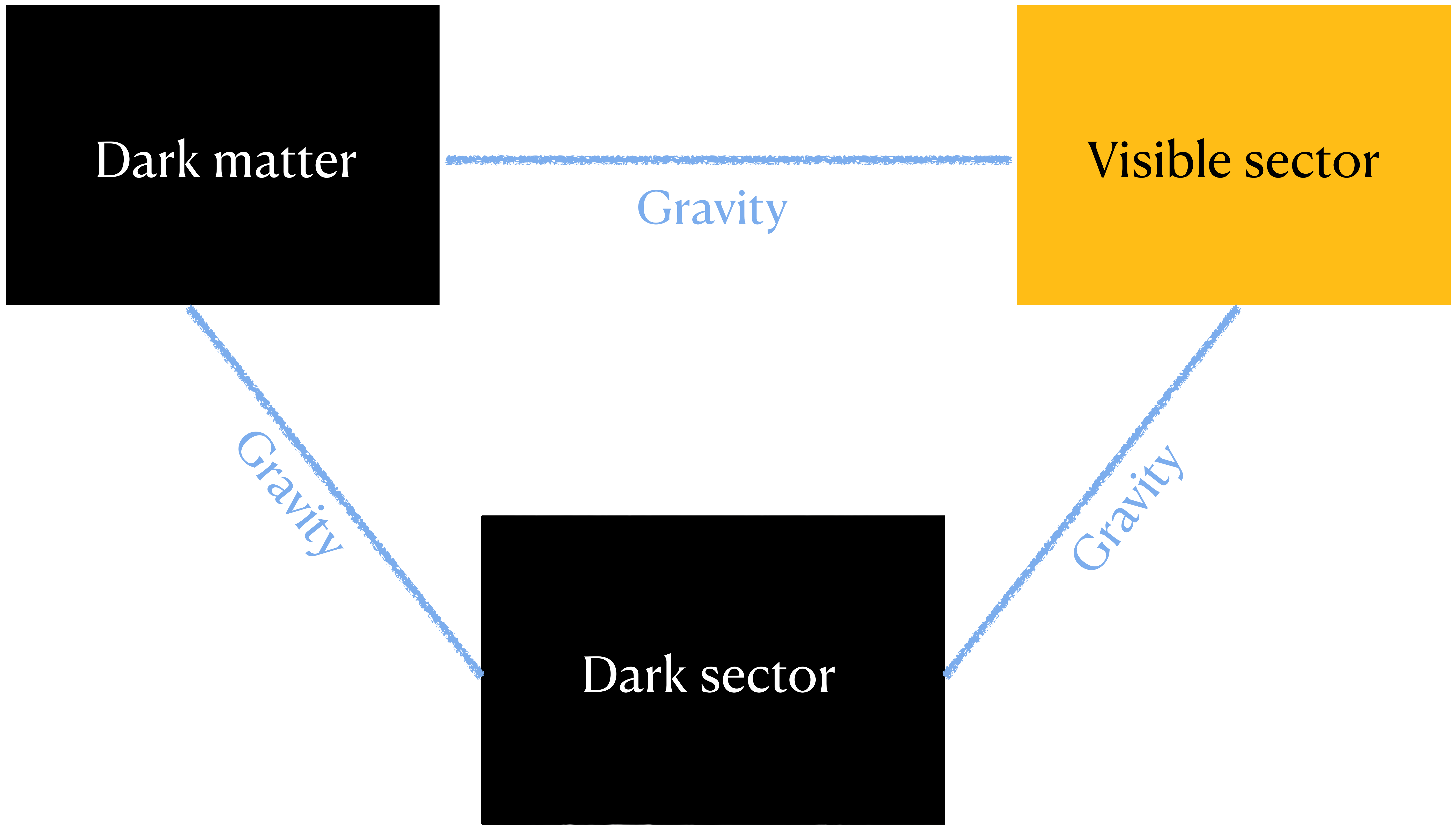
The most DESIrable model?

Analysis by **Andrea Clini**, with
Archidiacono, Castorina, Zhang





Instantaneous injection of fluctuations



Secluded Dark Sector that sources fluctuations

SB, Geller, Redigolo, Tsur - 2605.03007

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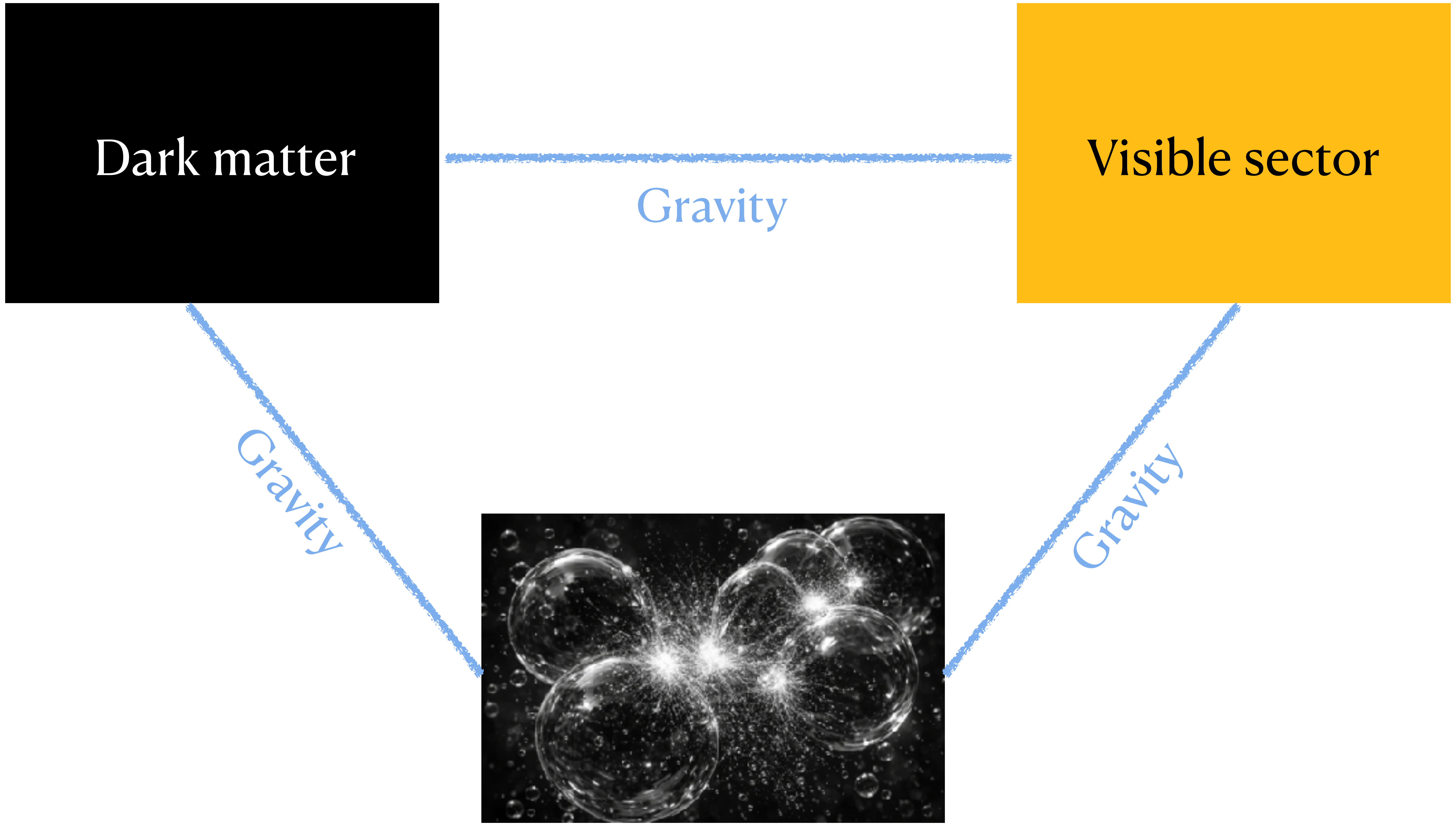

Example: First order phase transition after recombination

SB, Geller, Redigolo, Tsur - 2605.03007

Boiling after Recombination

From Producer to Consumer

$$G^{\mu\nu} = 8\pi G_N \left(T^{\mu\nu}_{\Lambda\mathrm{CDM}} + T^{\mu\nu}_{\mathrm{DS}} \right)$$

How to characterise the Stress-Tensor?

Covariant conservation + Instantaneous approx.

$$\nabla_\mu T^{\mu\nu}_{\mathrm{DS}} = 0$$

Fixes the bkg

Constrains $T^{\mu\nu}_{DS}$

$$\bar{T}^{0,\mathrm{DS}}_{0} = \rho_{\mathrm{DS}} \left(\left(\frac{a_*}{a}\right)^{3(1+w_<)} \theta(a_* - a) + \left(\frac{a_*}{a}\right)^{3(1+w_>)} \theta(a - a_*) \right)$$

$$T^0_0 \propto T^0_i \propto \rho_{\mathrm{DS}} \theta(\eta - \eta_*)$$

$$T^j_i \propto \frac{\rho_{\mathrm{DS}}}{a_* \beta} \delta(\eta - \eta_*) \hat{T}^j_i(\vec{k})$$

From Producer to Consumer

$$\boxed{G^{\mu\nu} = 8\pi G_N \left(T^{\mu\nu}_{\Lambda\mathrm{CDM}} + T^{\mu\nu}_{\mathrm{DS}} \right)}$$

How to characterise the Stress-Tensor?

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$$\nabla_\mu T^{\mu\nu}_{\mathrm{DS}} = 0$$

General set of transfer functions

Fixes the bkg

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From Producer to Consumer

Jinno, Takimoto - 1605.01403

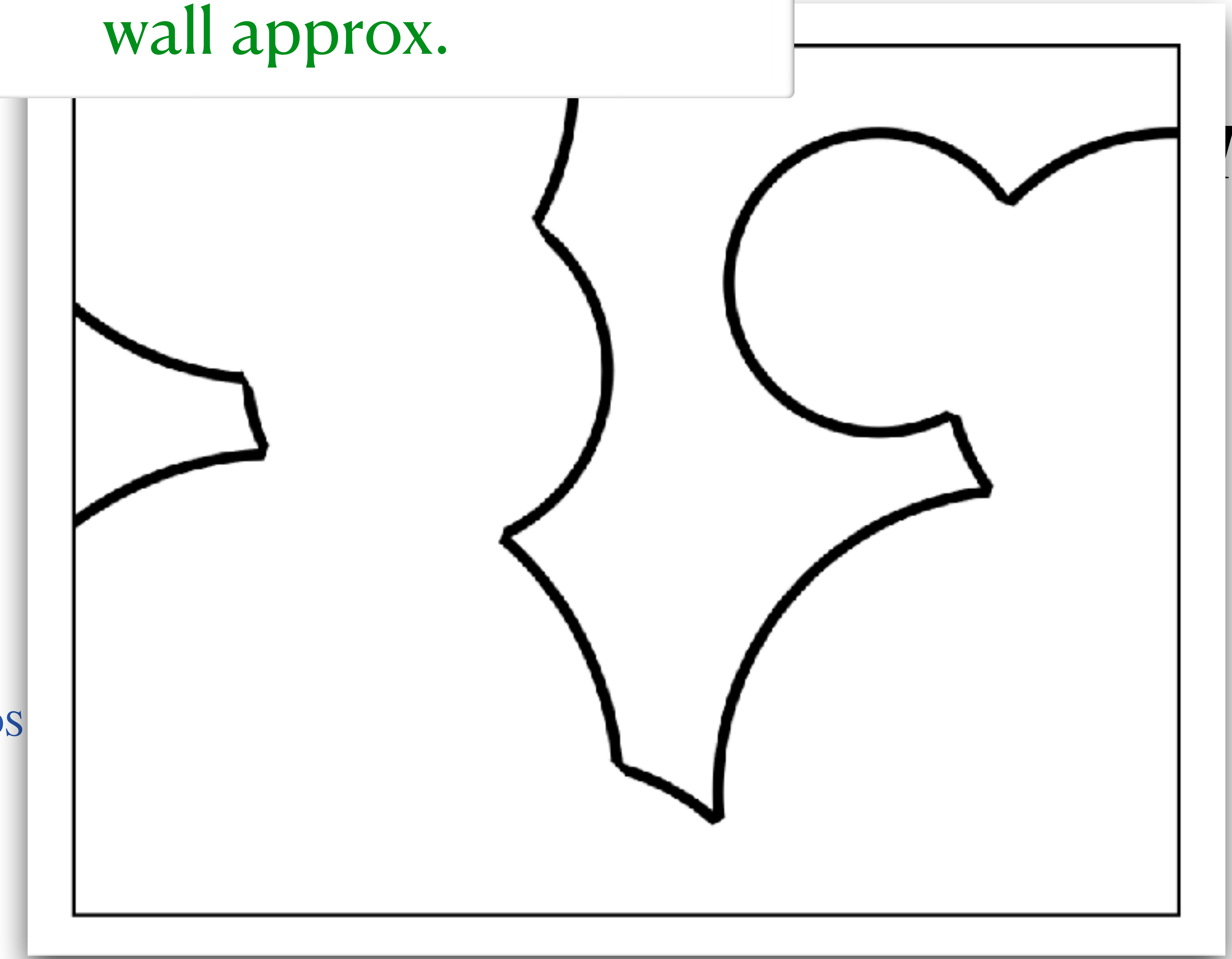
Kosowsky, Turner - *Phys.Rev.D* 47 (1993) 4372-4391

Kosowsky, Turner, Watkins - *Phys.Rev.D* 45 (1992) 4514-4535

$$G^{\mu\nu} = 8\pi G_N \left(T^{\mu\nu}_{\Lambda\text{CDM}} + T^{\mu\nu}_{\text{DS}} \right)$$

How to characterise the Stress-Tensor?

Example: PT with envelope +thin-wall approx.



+ Instantaneous approx.

$T^{\mu\nu}_{\text{DS}} = 0$

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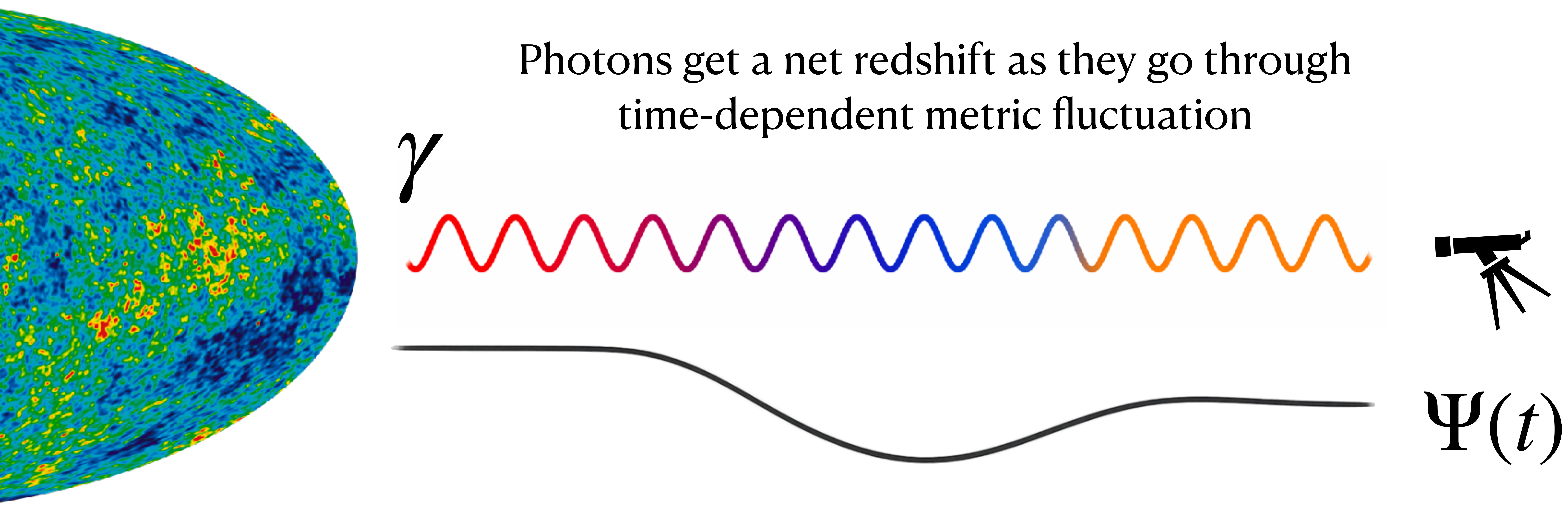
The Integrated Sachs-Wolfe effect

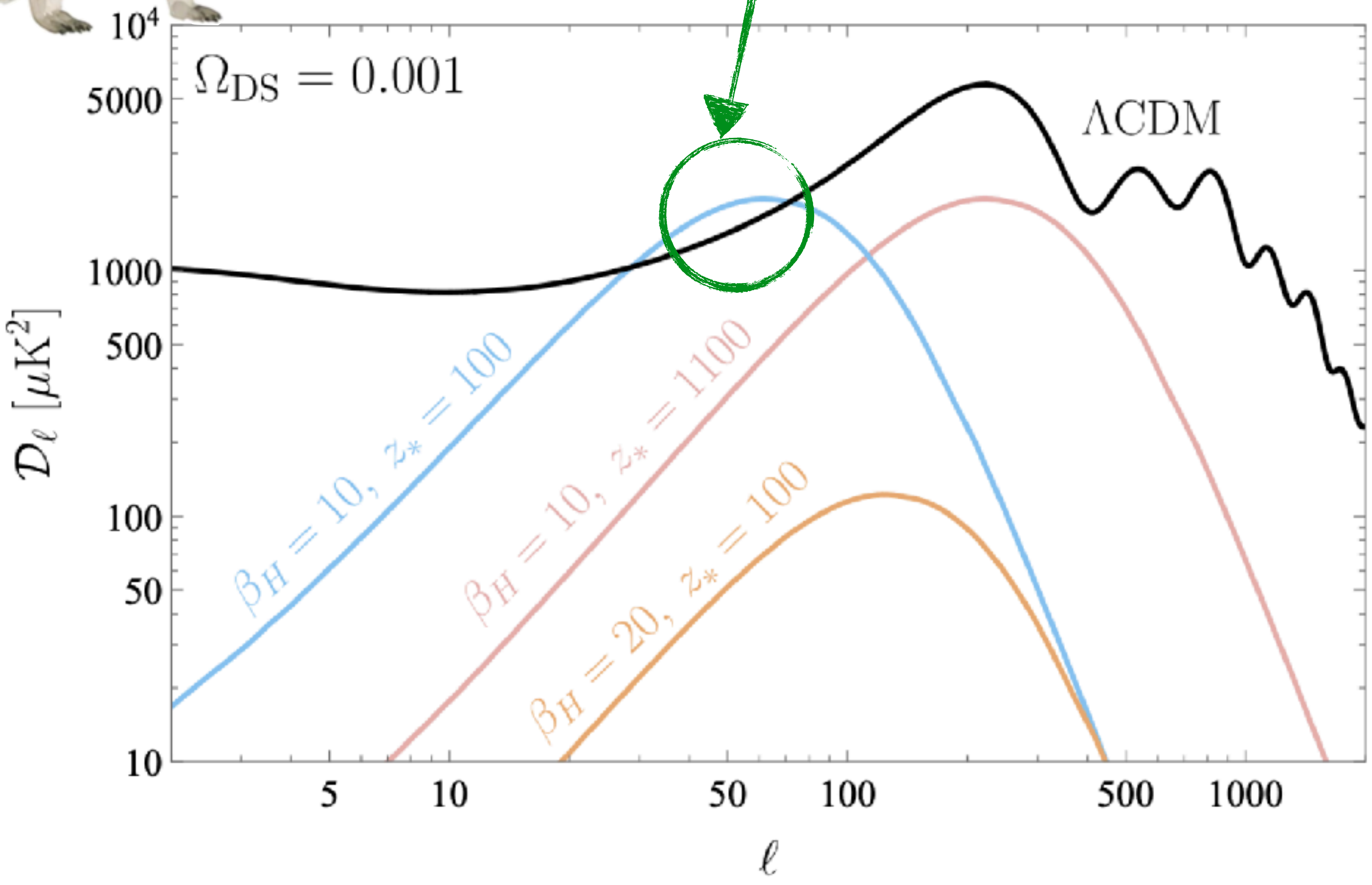
$$\frac{\delta T(\hat{n})}{\bar{T}} = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \int_{\eta_*}^{\eta_0} \mathrm{d}\eta \; e^{i(\eta_0 - \eta)\vec{k}\cdot\hat{n}} \left(\underbrace{\boxed{\Phi' - \Psi'}}_{\text{Scalar}} + \underbrace{\boxed{n_i n_j \partial_j W_i'}}_{\text{Vector}} - \underbrace{\boxed{\frac{1}{2} n_i n_j h_{ij}'}}_{\text{Tensor}} \right) .$$

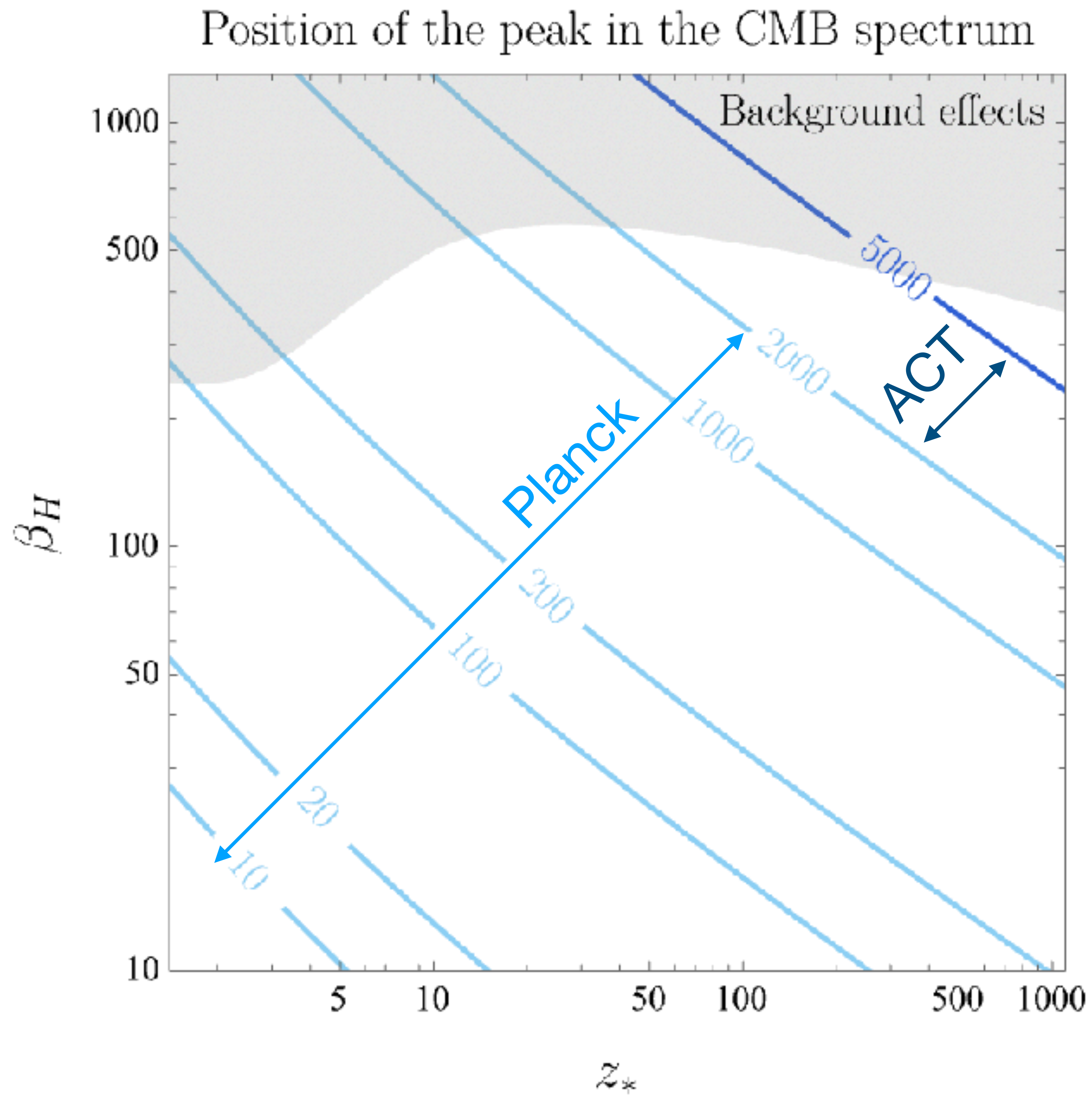
Photons get a net redshift as they go through time-dependent metric fluctuation



The Integrated Sachs-Wolfe effect

Signal peaks at the angular size of the bubbles

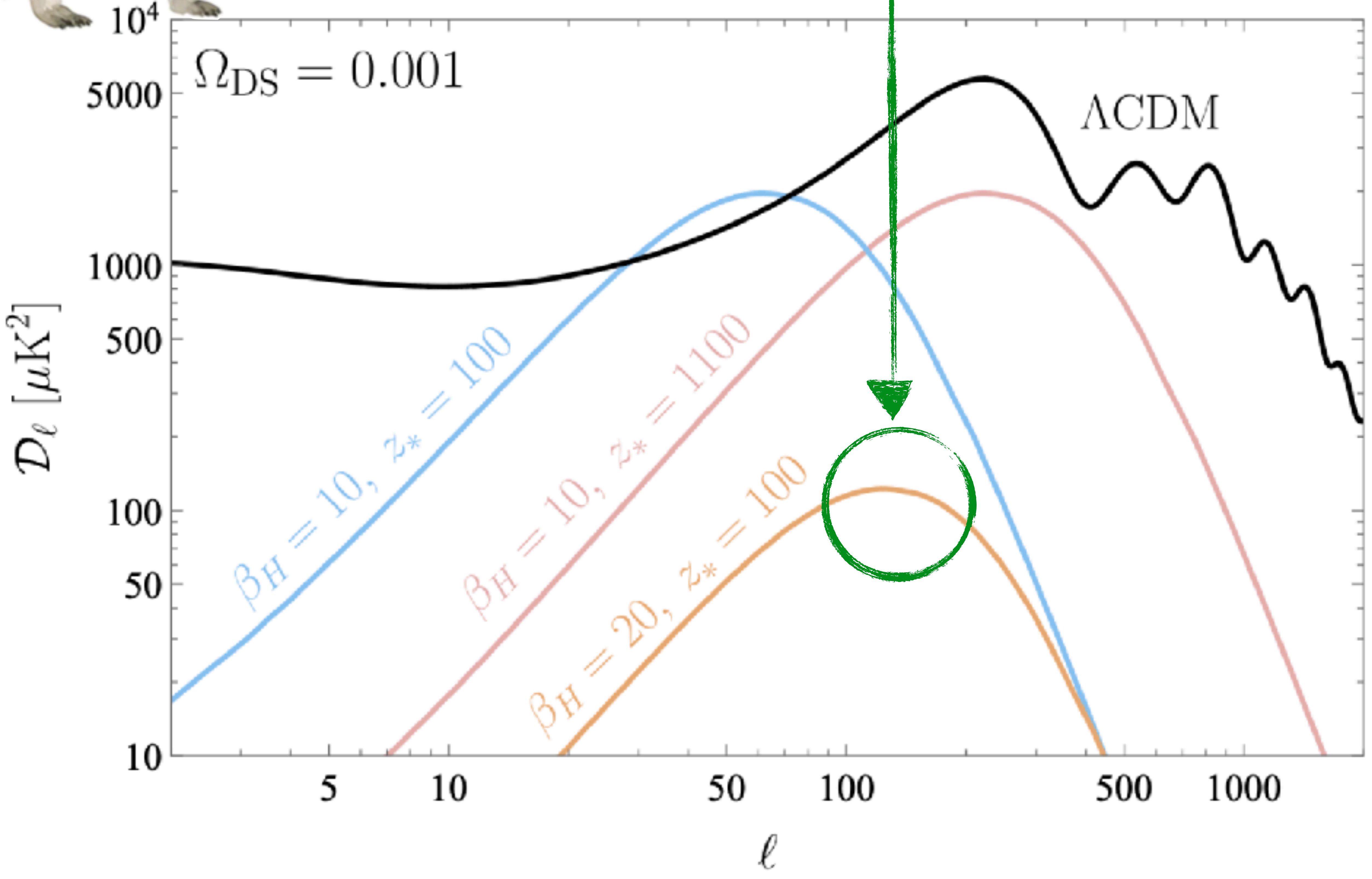




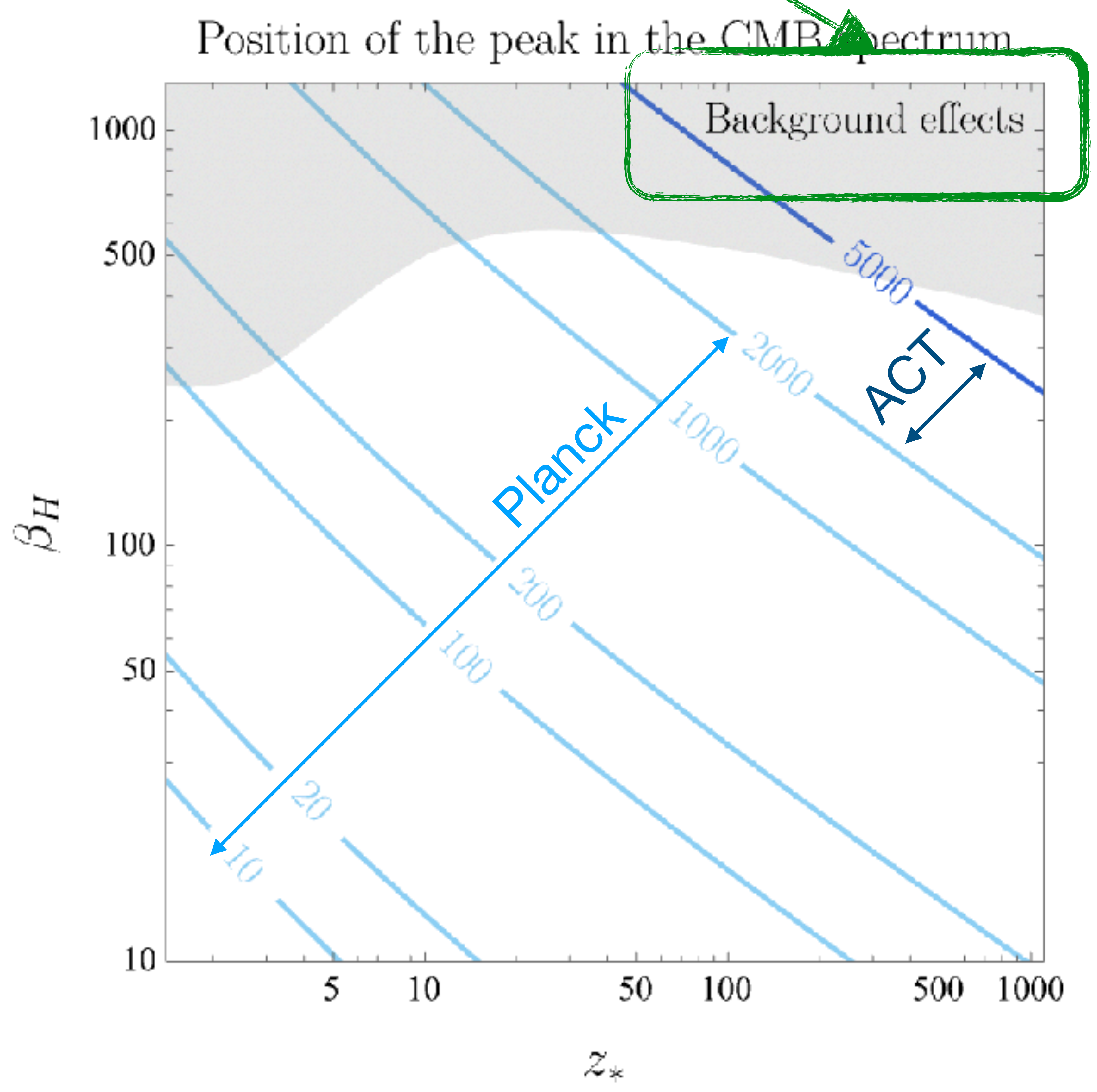
$\beta_H = \beta / H_{\rm PT}$

The Integrated Sachs-Wolfe effect

Signal scaling like $\Omega_{\rm DS}^2/\beta^4$



Energy released by the PT modifies Hubble



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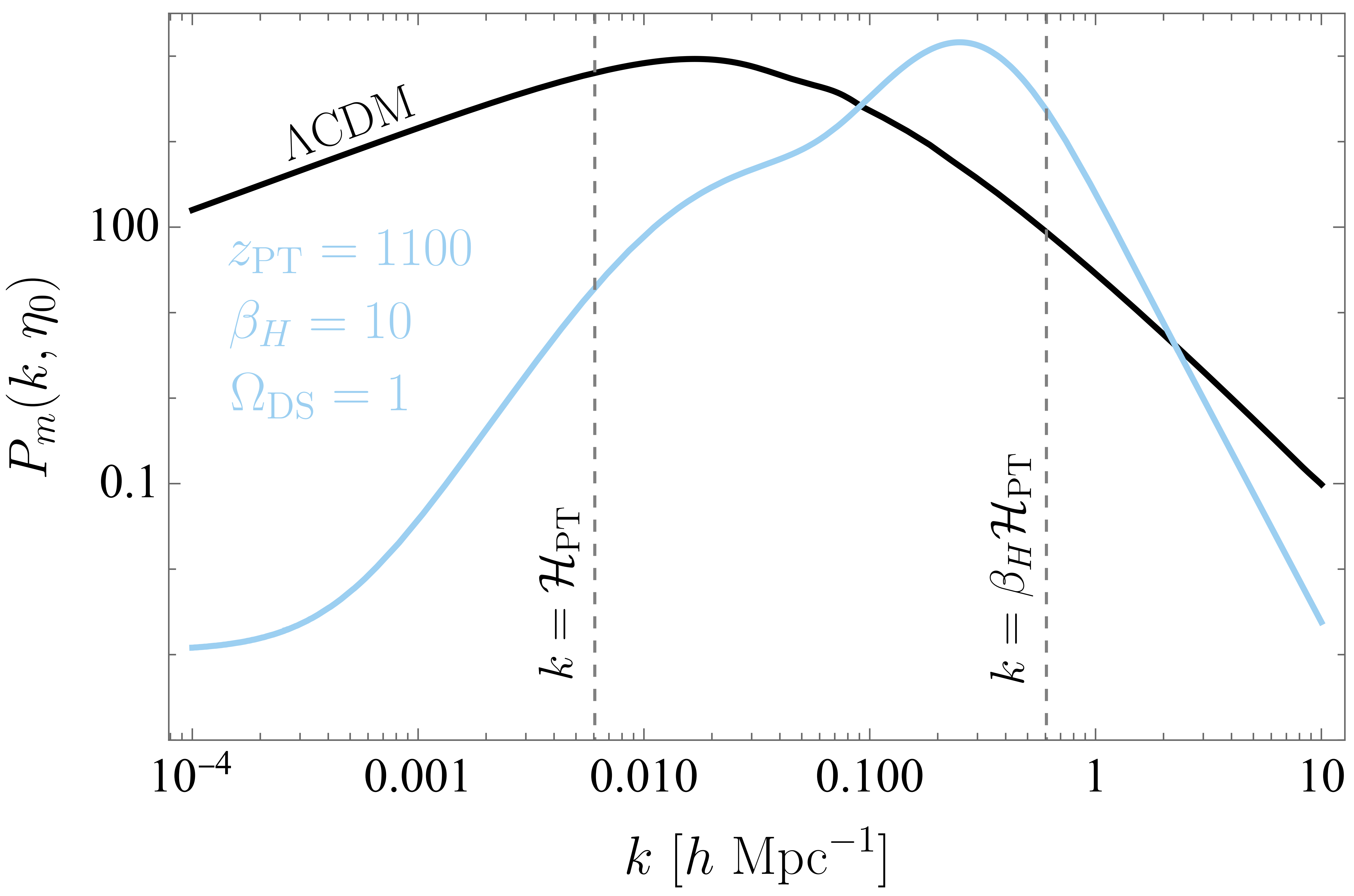
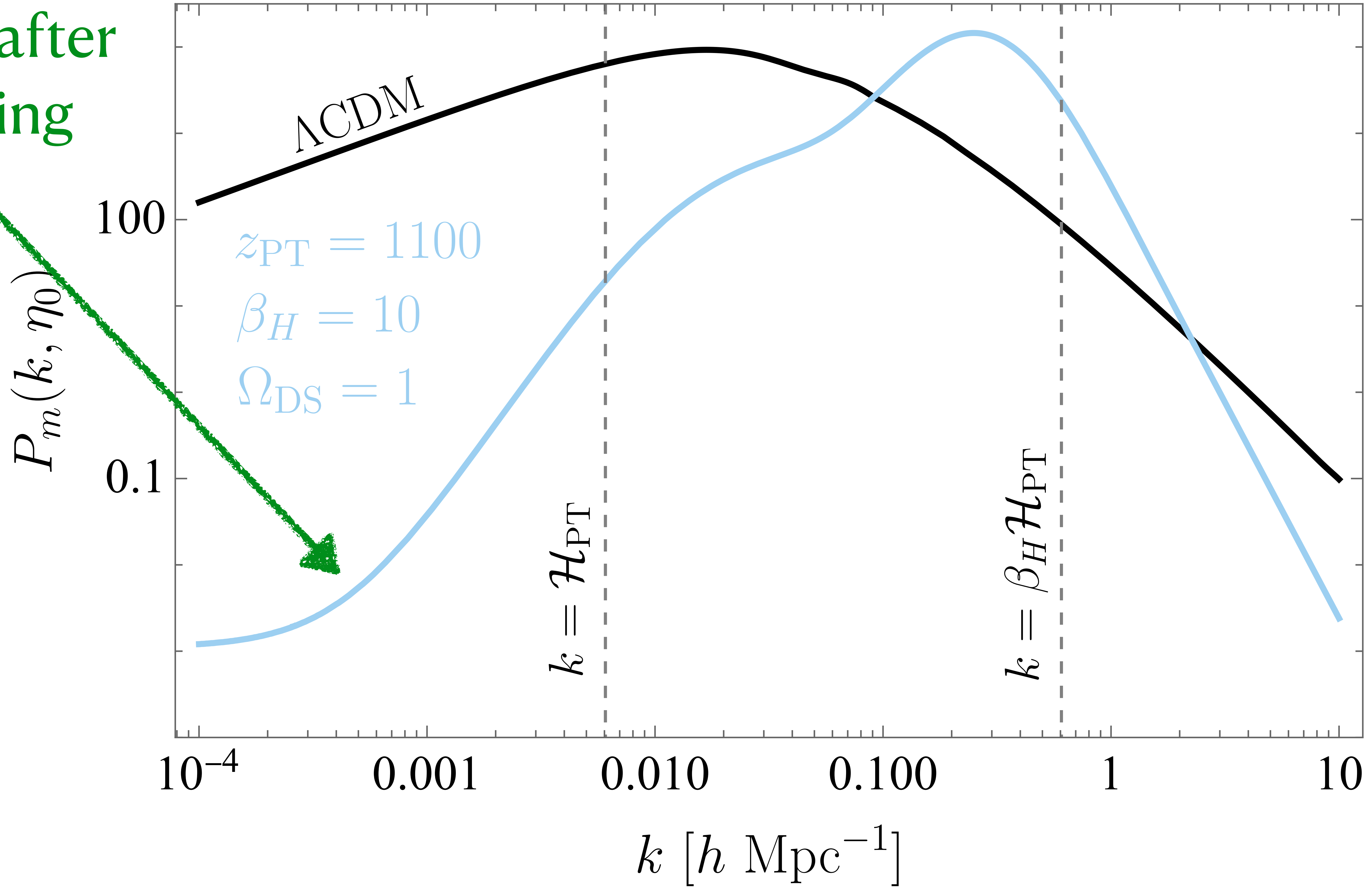
Matter Power Spectrum



Matter Power Spectrum

Modes produced outside the horizon: they grow only after horizon crossing



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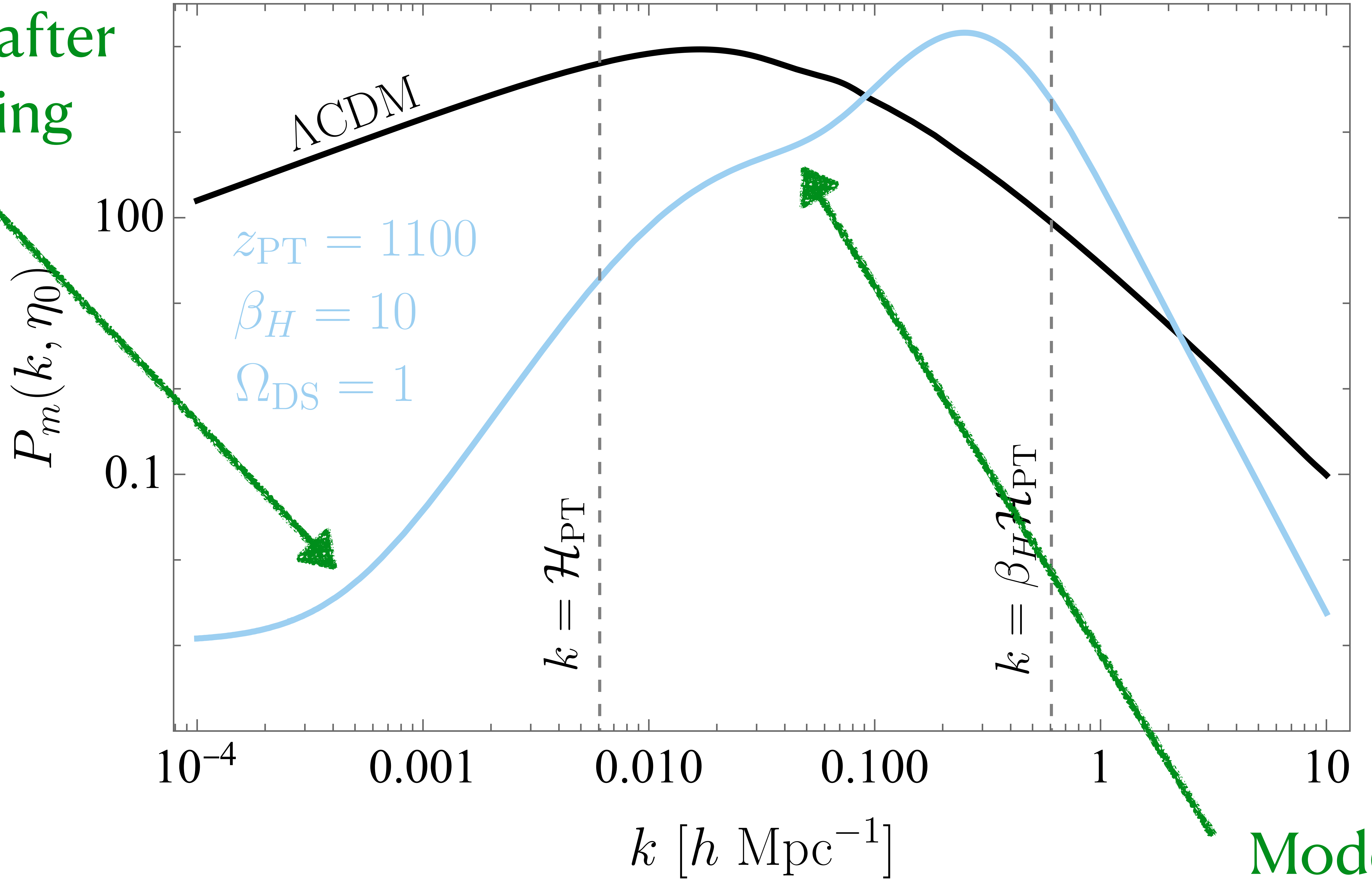
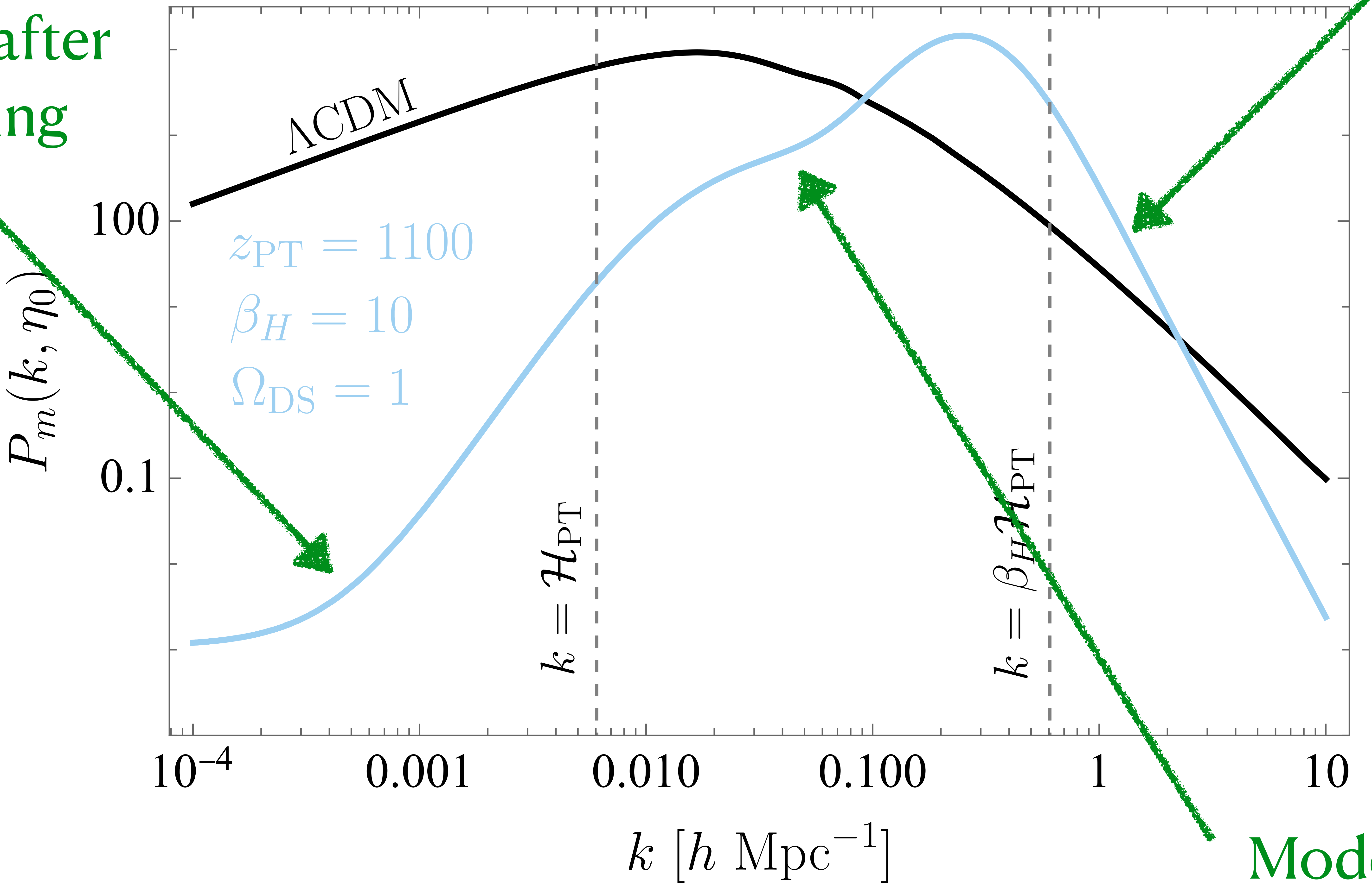


Modes produced inside the horizon

Matter Power Spectrum

Modes produced outside the horizon: they grow only after horizon crossing

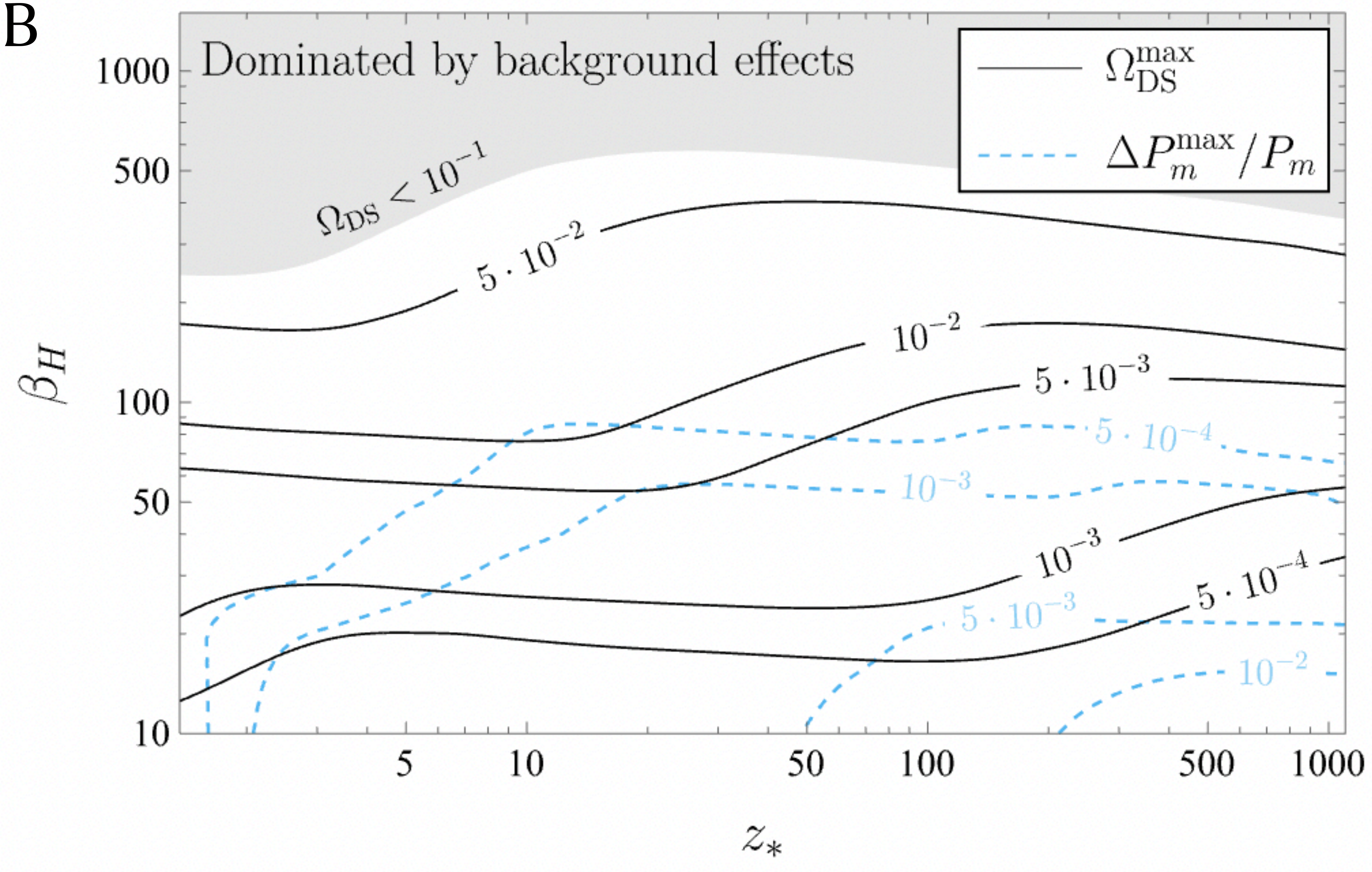
Suppressed by the source



Modes produced inside the horizon

Results

Energy fraction is constrained to be at most 10^{-2} by CMB



Only percent corrections to the matter power spectrum

Outlook

Higher-order correlation functions

Bispectrum

Non-Gaussianities

Pre-recombination dynamics

All CMB components are affected

Power Spectrum as powerful as CMB

Significant B-modes

Characterising the source

$\langle TT \rangle \supset$ Scalar - Vector - Tensors

$\langle BB \rangle \supset$ Vector - Tensors

$\langle BT \rangle \supset$ Vector ?

Conclusions

Hunting for NP with LSS and Linear Cosmology

Opportunity

Necessity

Tons of new data

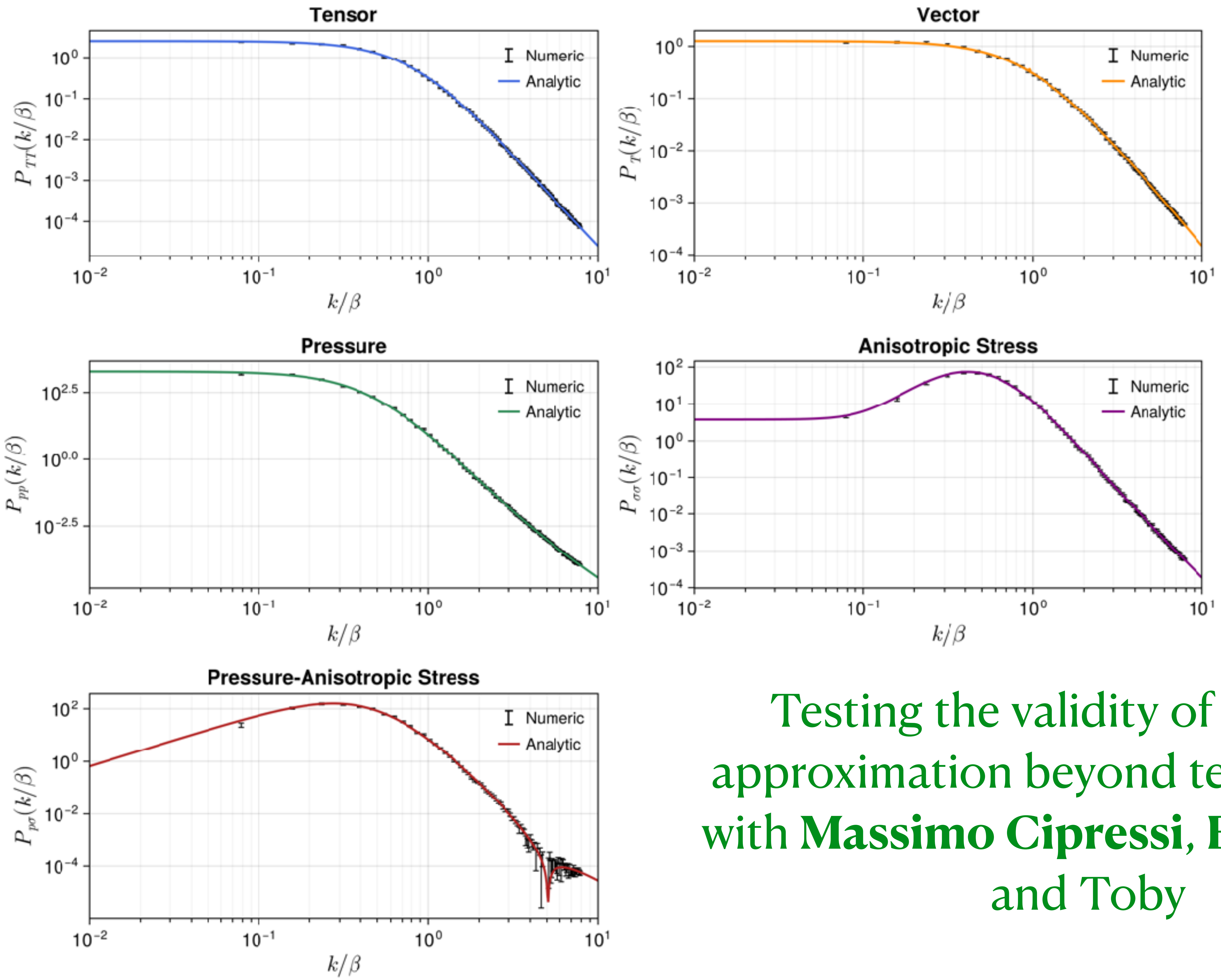
Secluded DS

Unprecedented sensitivity. Hints of new dynamics?

Plenty of new features imprinted in cosmological observables

Future can be bright even if completely dark!

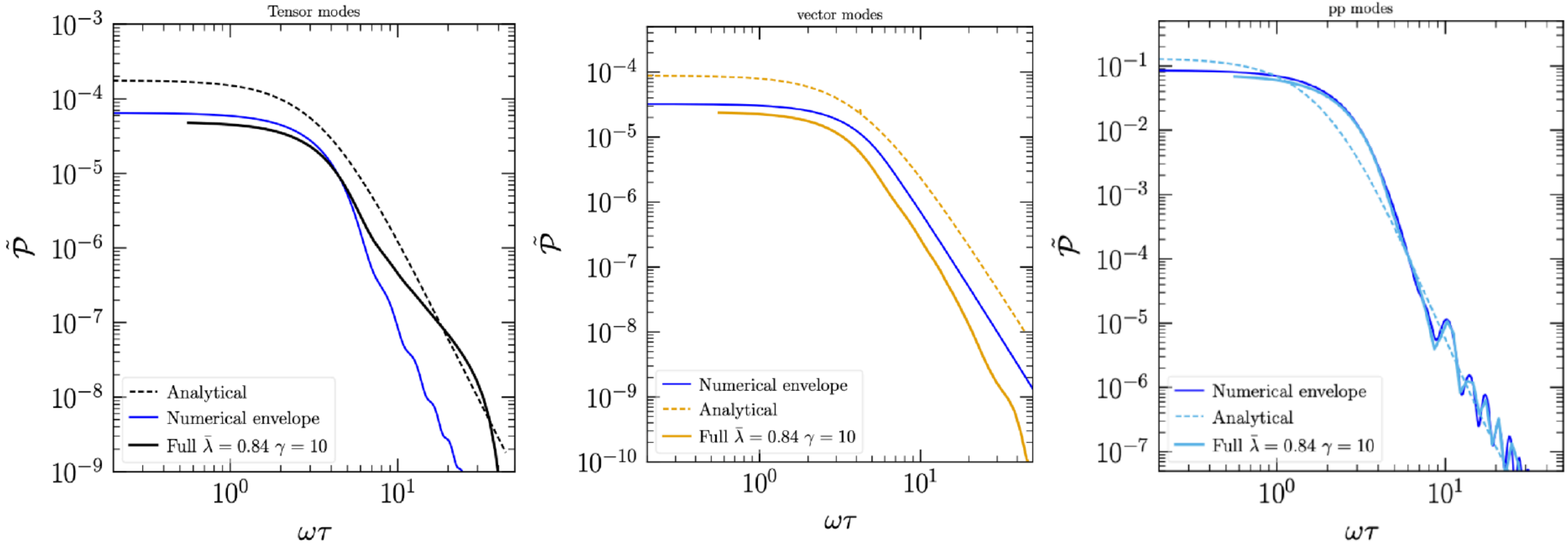
From Producer to Consumer



Numerical code by **Ben Hatzofe**

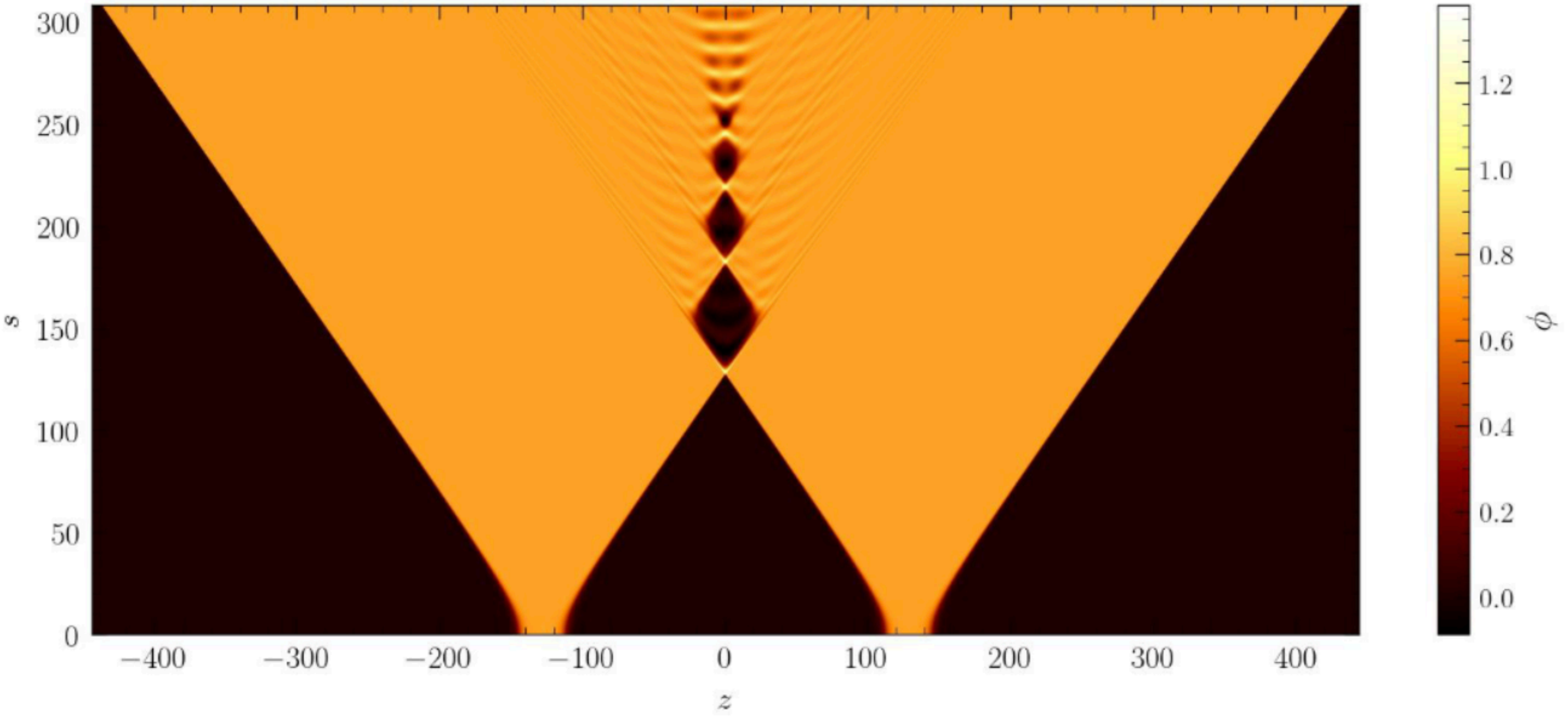
Testing the validity of envelope approximation beyond tensor modes with **Massimo Cipressi**, **Ben Hatzofe** and Toby

Do(n't) judge from the envelope



Simulations of **Massimo Cipressi**

Do(n't) judge from the envelope



(a) $\bar{\lambda} = 0.84\,,\ \gamma = 8.0$

Simulations of **Massimo Cipressi**

Where can NP hide?

Cosmological observables

Production + Dynamics + Collapse

Production	Dynamics	Collapse
$\delta_{\rm ini},\ z_{\rm NP},\ f_{\rm NL},\ \cdots$	$c_s^2,\ \Delta H,\ \Delta G_N,\ \cdots$	$\sigma,\ \lambda_{\rm dB},\ \cdots$

- Isocurvature
- Non-Gaussianities
- Late-time production of anisotropies
- ...

- Pressure
- Modified bkg
- New forces
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- Self-interactions
- Large De Broglie wavelength
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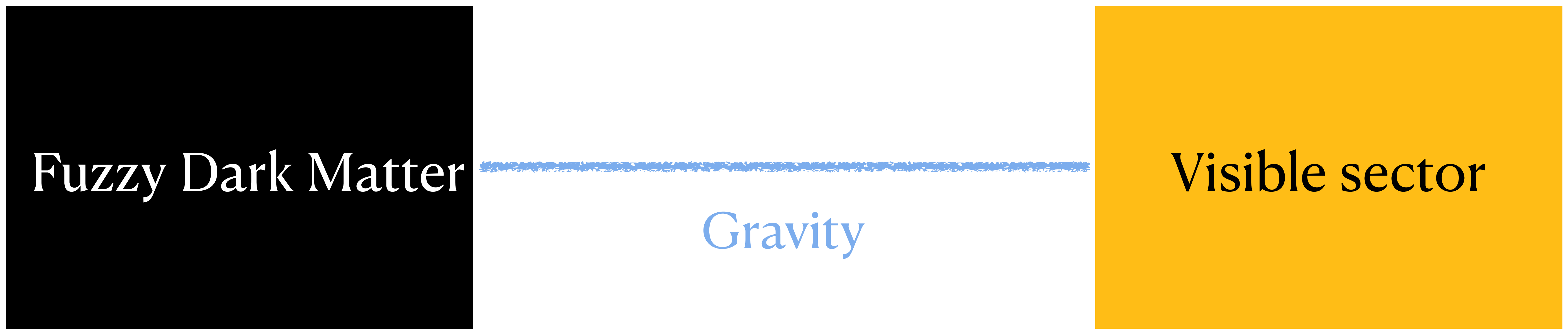
Can we see in the dark?



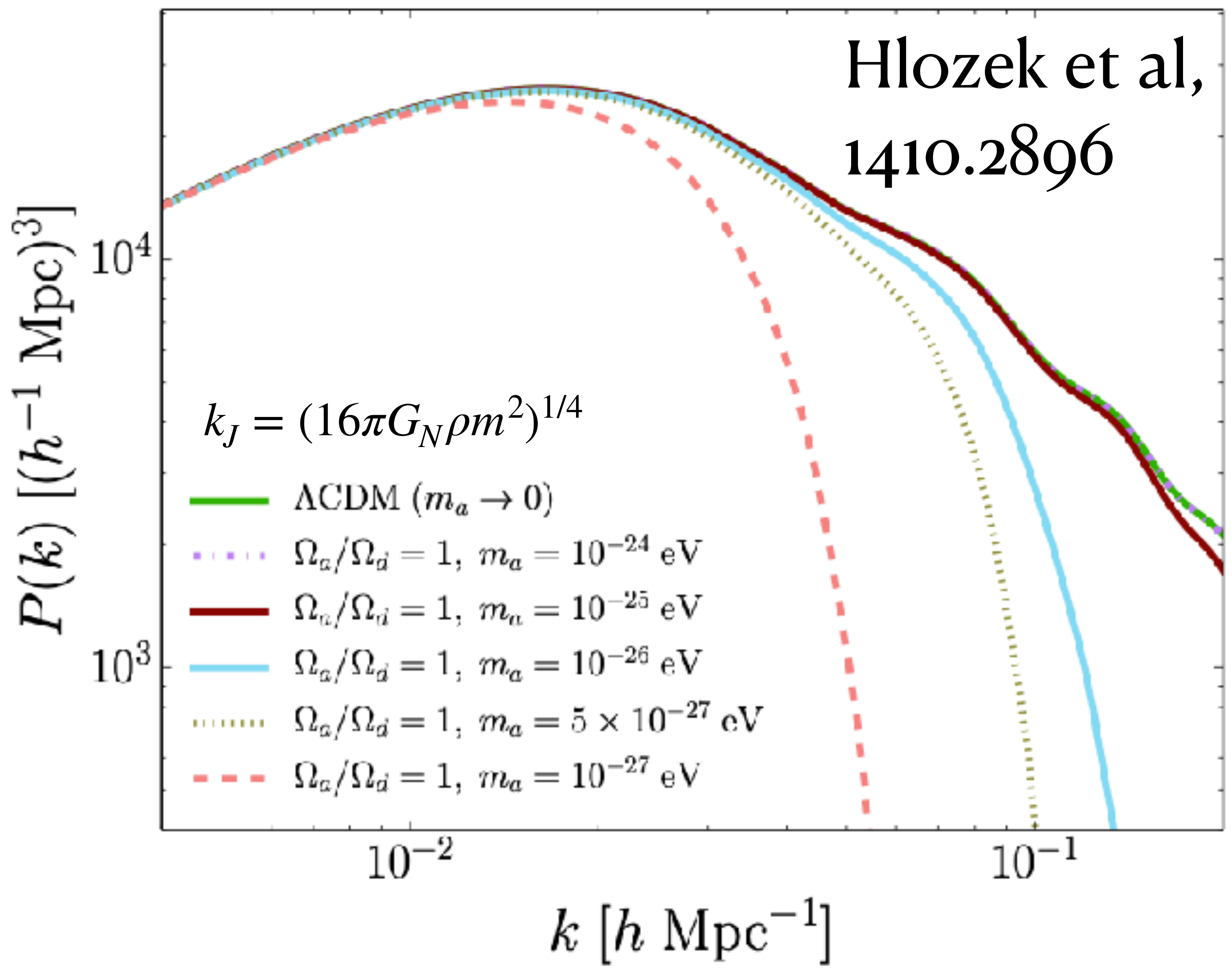
Why so fuzzy?

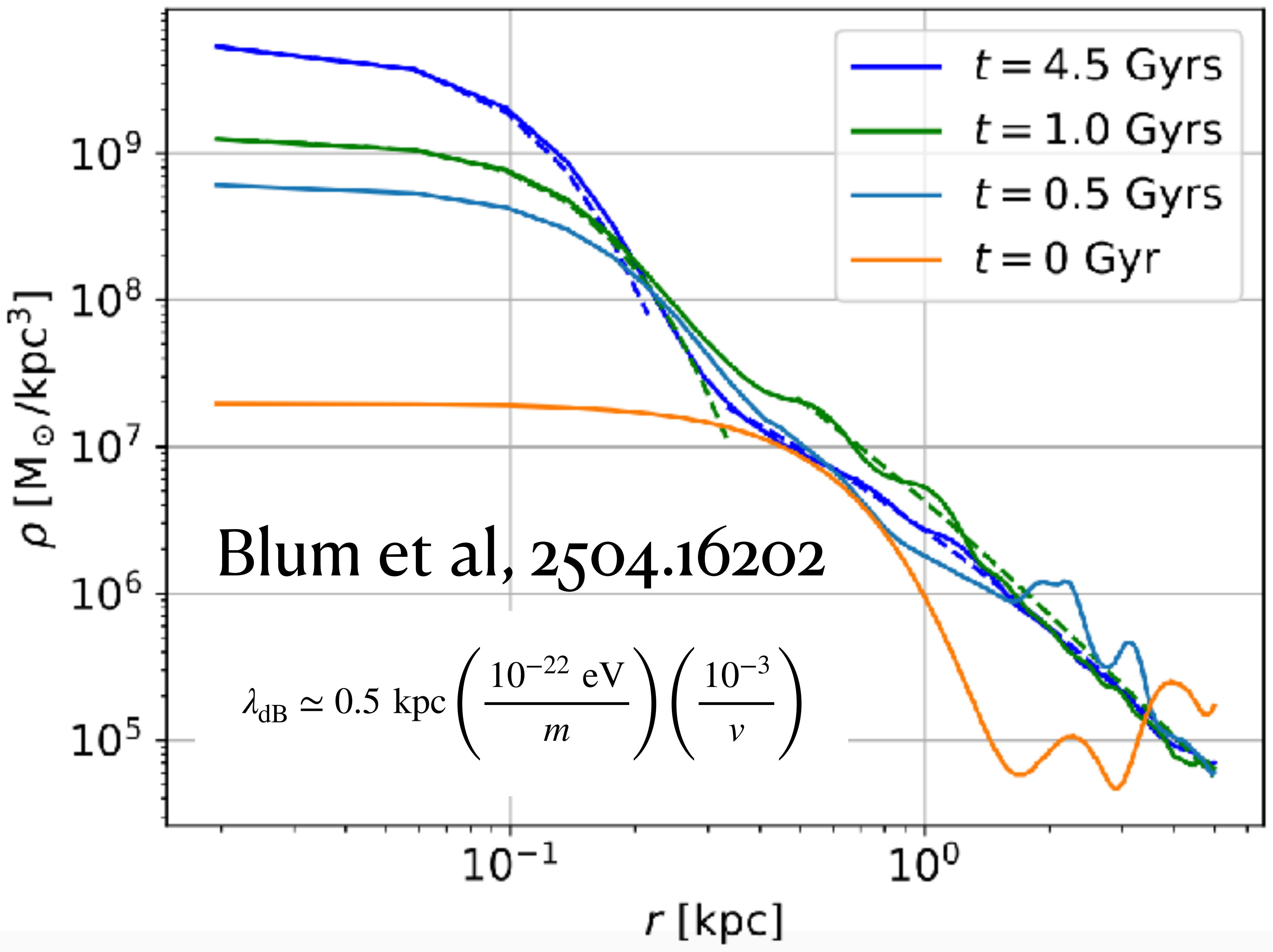
ΛCDM issues — Missing satellites → Macroscopic Jeans scale

Core vs cusp → Macroscopic dB wavelength

FDM solution:

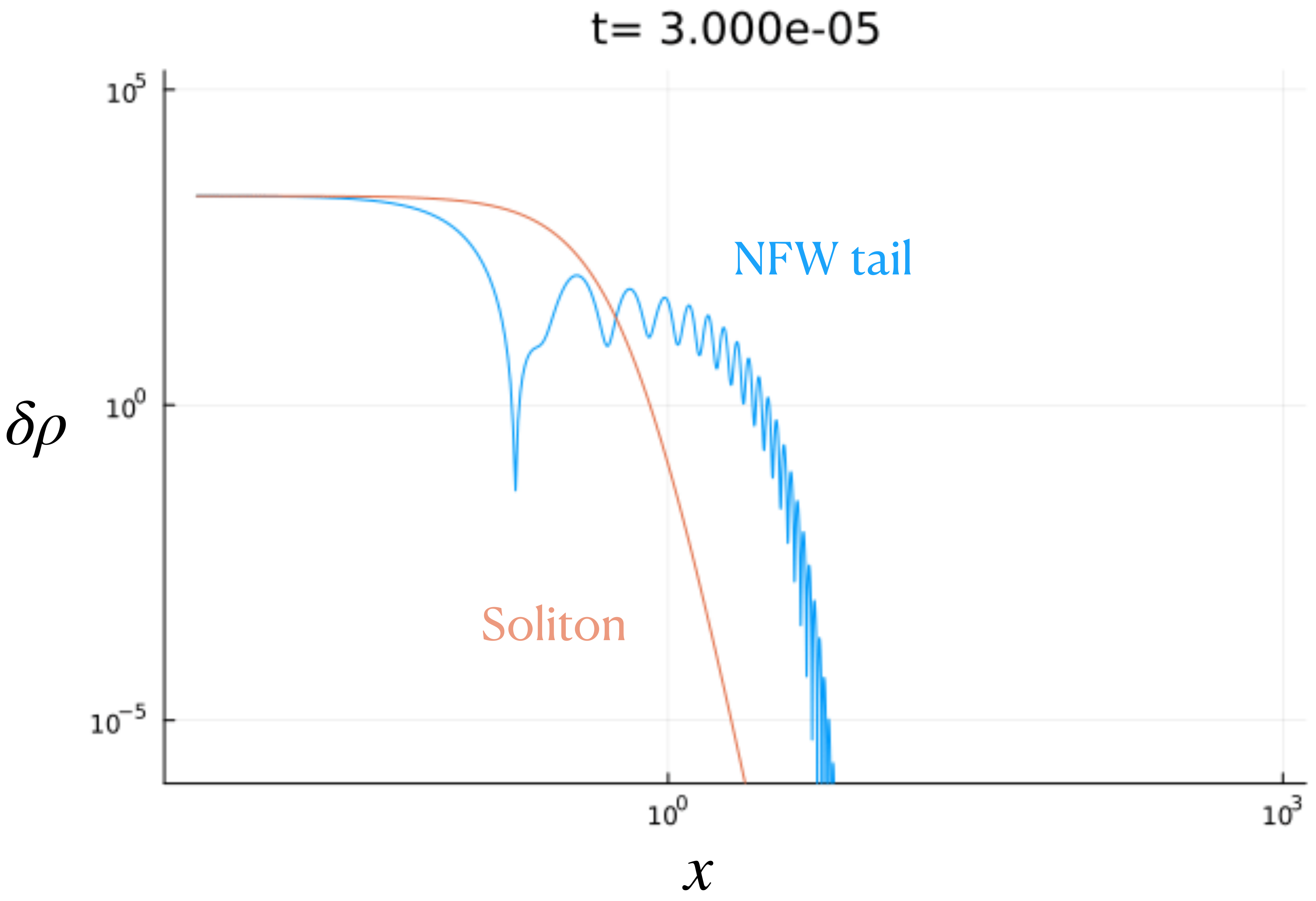
Ultralight DM

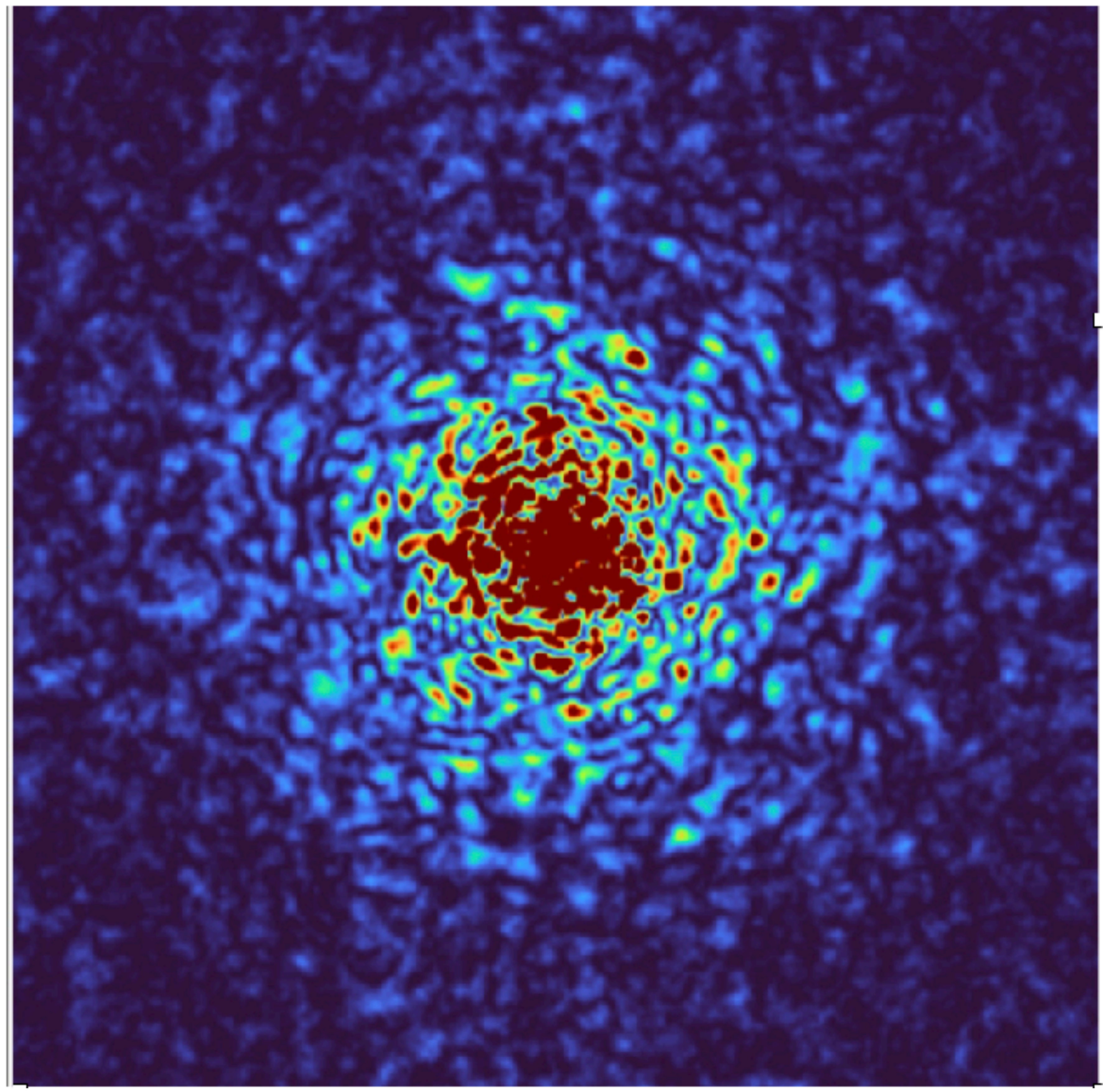




How do these features affect structures formation?

Modified dynamics of collapse

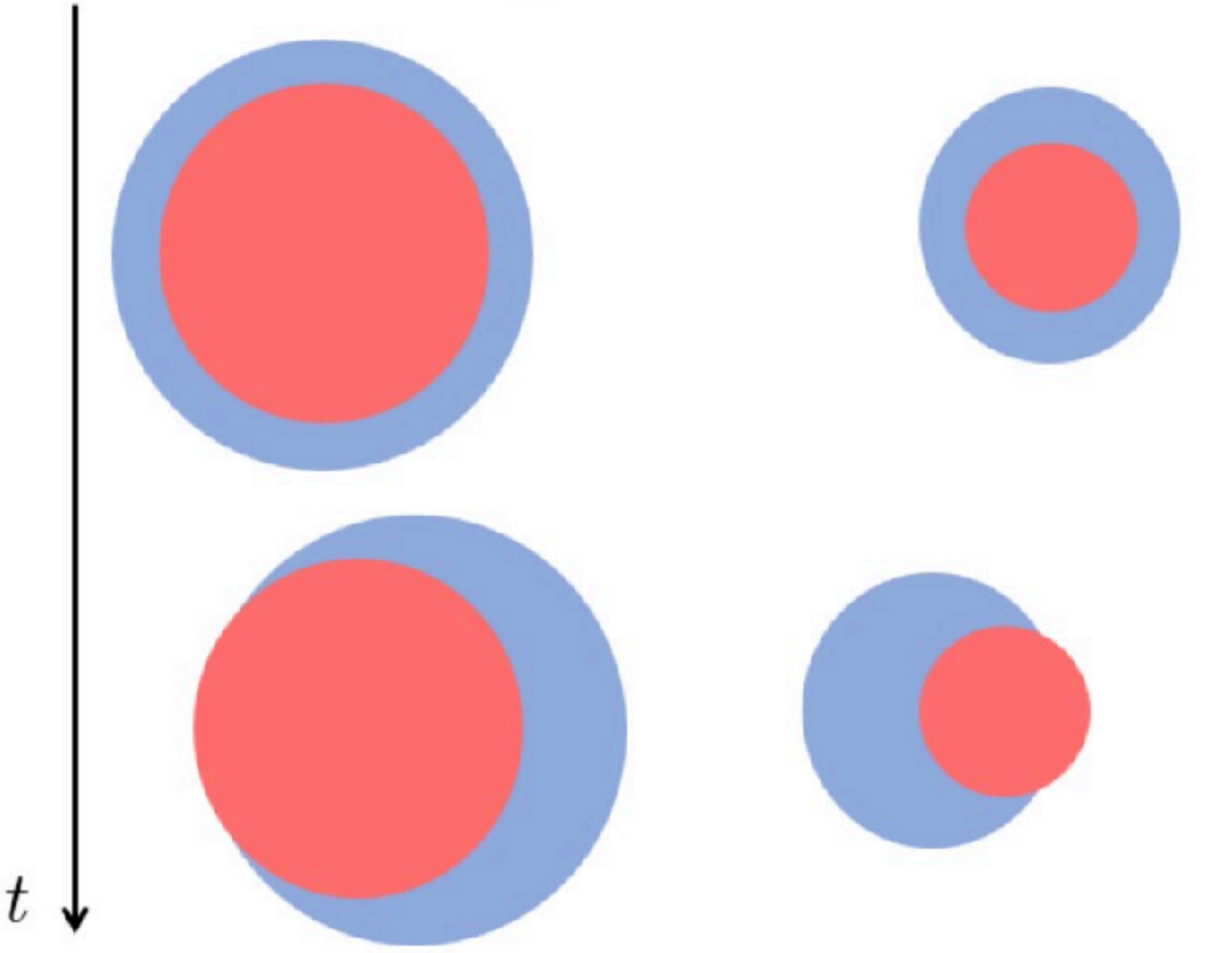


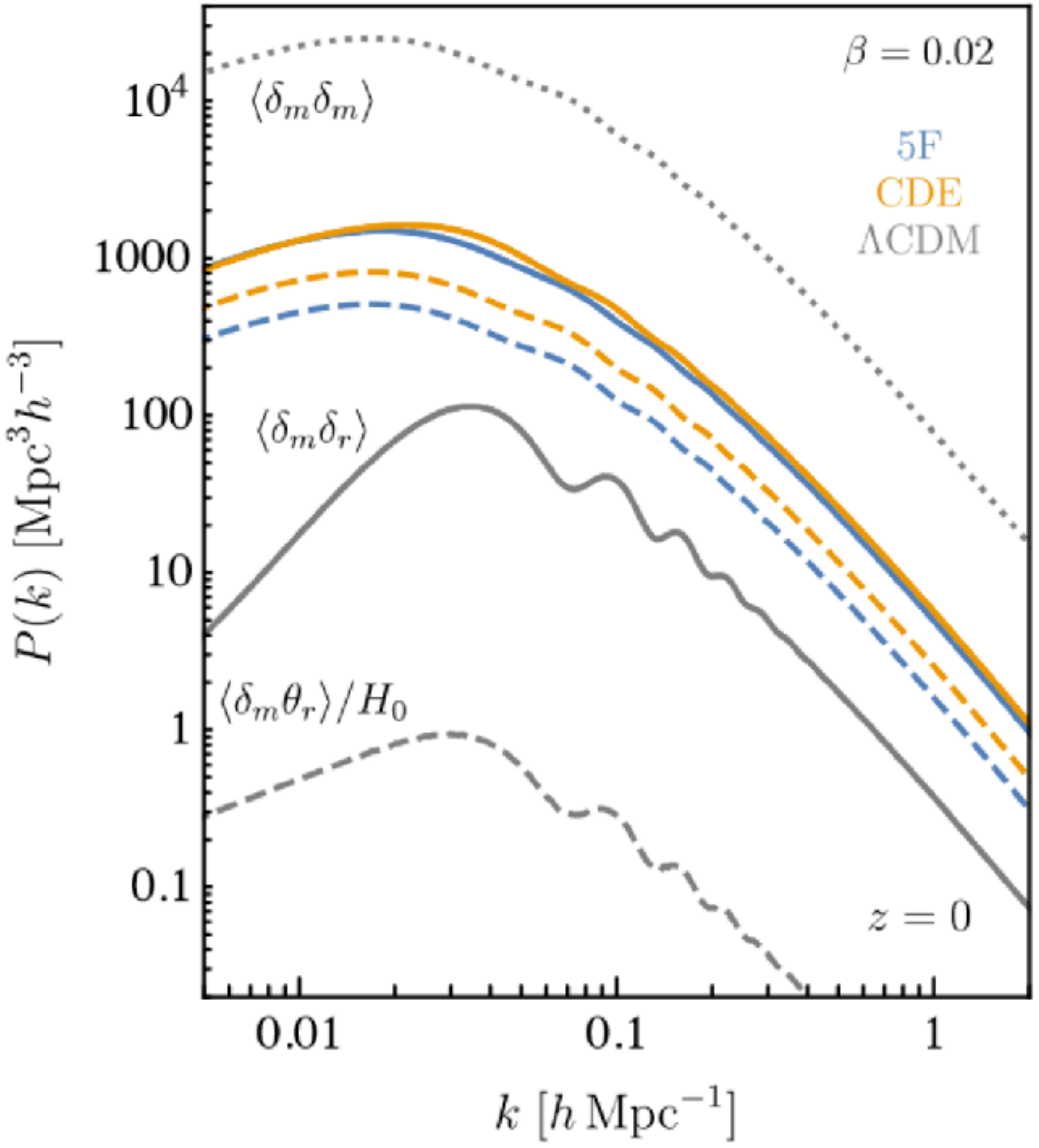


Credits: Giuseppe Rossi

Cultivating differences

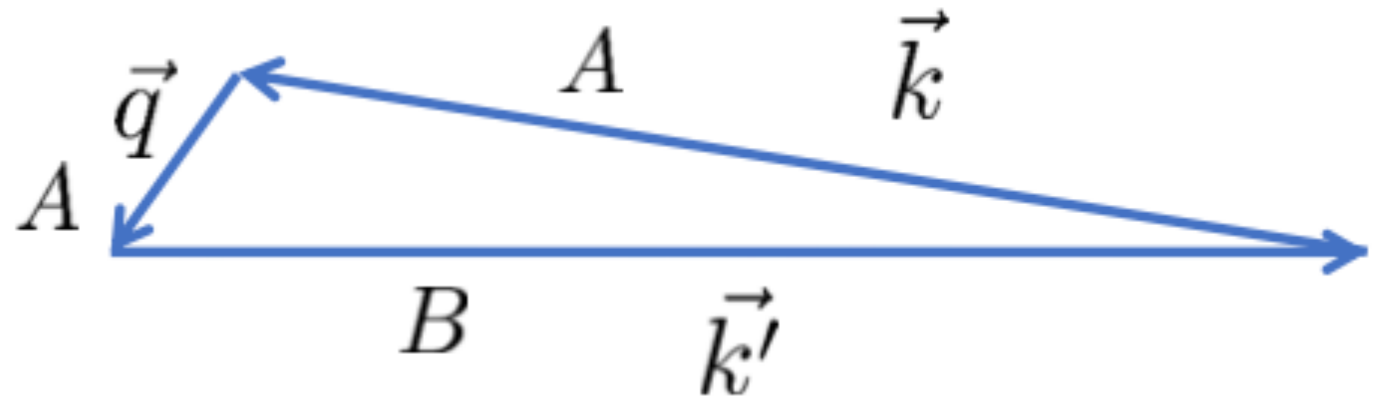
Relative fluctuations $\delta_r \equiv \delta_\chi - \delta_b$ ⟶ Violation of the equivalence principle





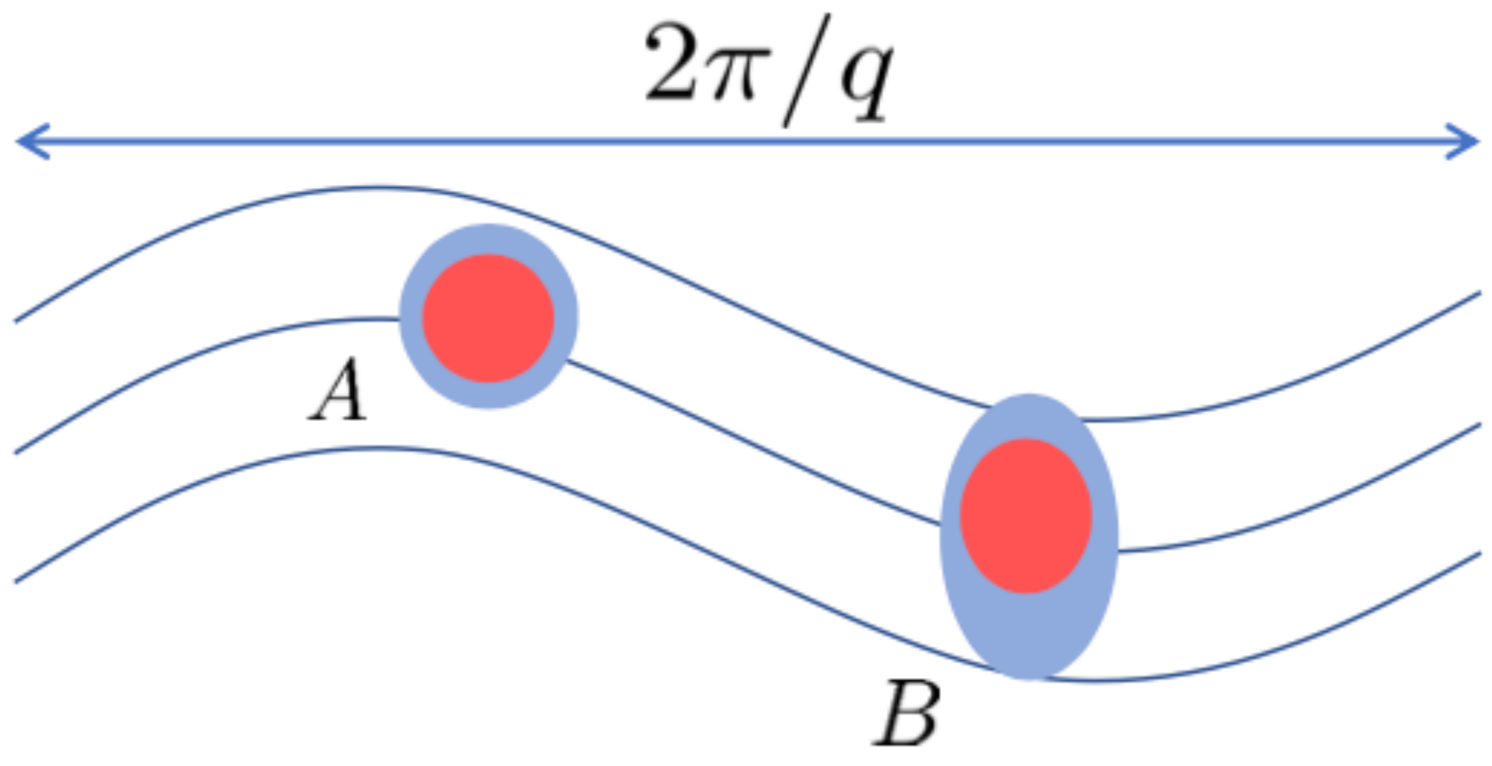
Smoking guns: Pole of the bispectrum

Pole emerging in the squeezed limit of the bispectrum for two different tracers



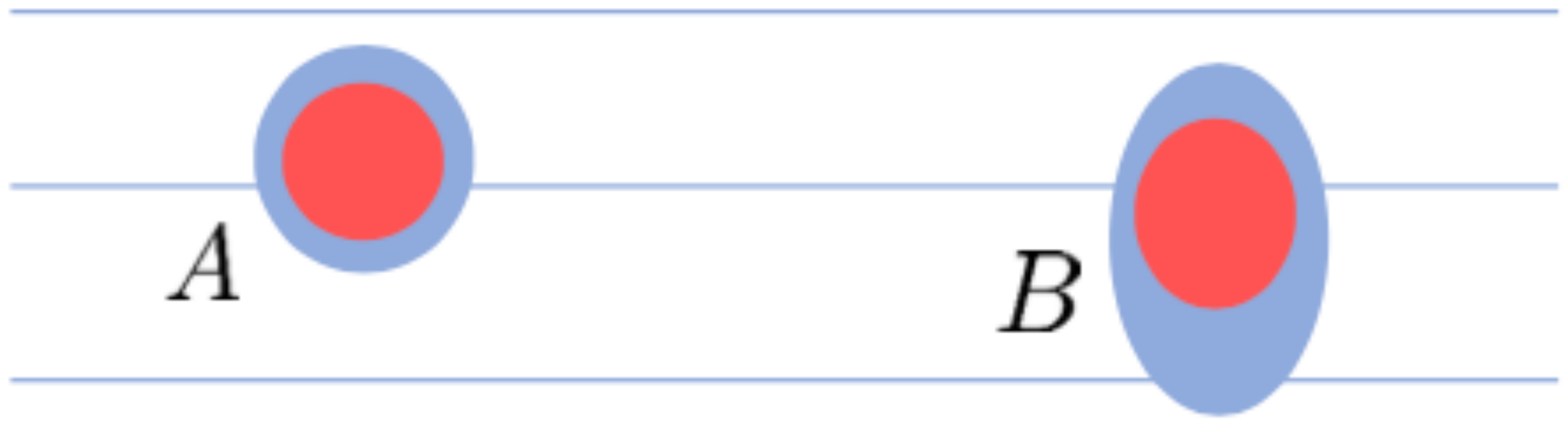
$$\lim_{q\to 0} \Delta B(q,k,k') \propto \Delta_{AB} \frac{\vec{q}\cdot\vec{k}}{q^2} P^{\rm lin}(k) P^{\rm lin}(q)$$

$$\Delta_{AB} = b_1^A (b_1^A b_r^B - b_1^B b_r^A)$$



Boost to free-fall system

Still feel a non-zero potential!



Smoking guns: Pole of the bispectrum