The Impact of Primordial Magnetic Fields on High Redshift Structures

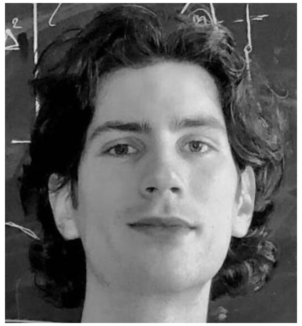
Matteo Viel - SISSA (Trieste, Italy)

IFPU focus week - PMFs

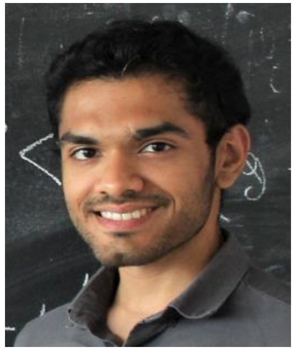
14/02/25

Plan

- The "real" cosmic web
- Impact on structure formation at linear level
- Impact on structure formation at non-linear level
- Focus on JWST
- Constraints from the Lyα-forest



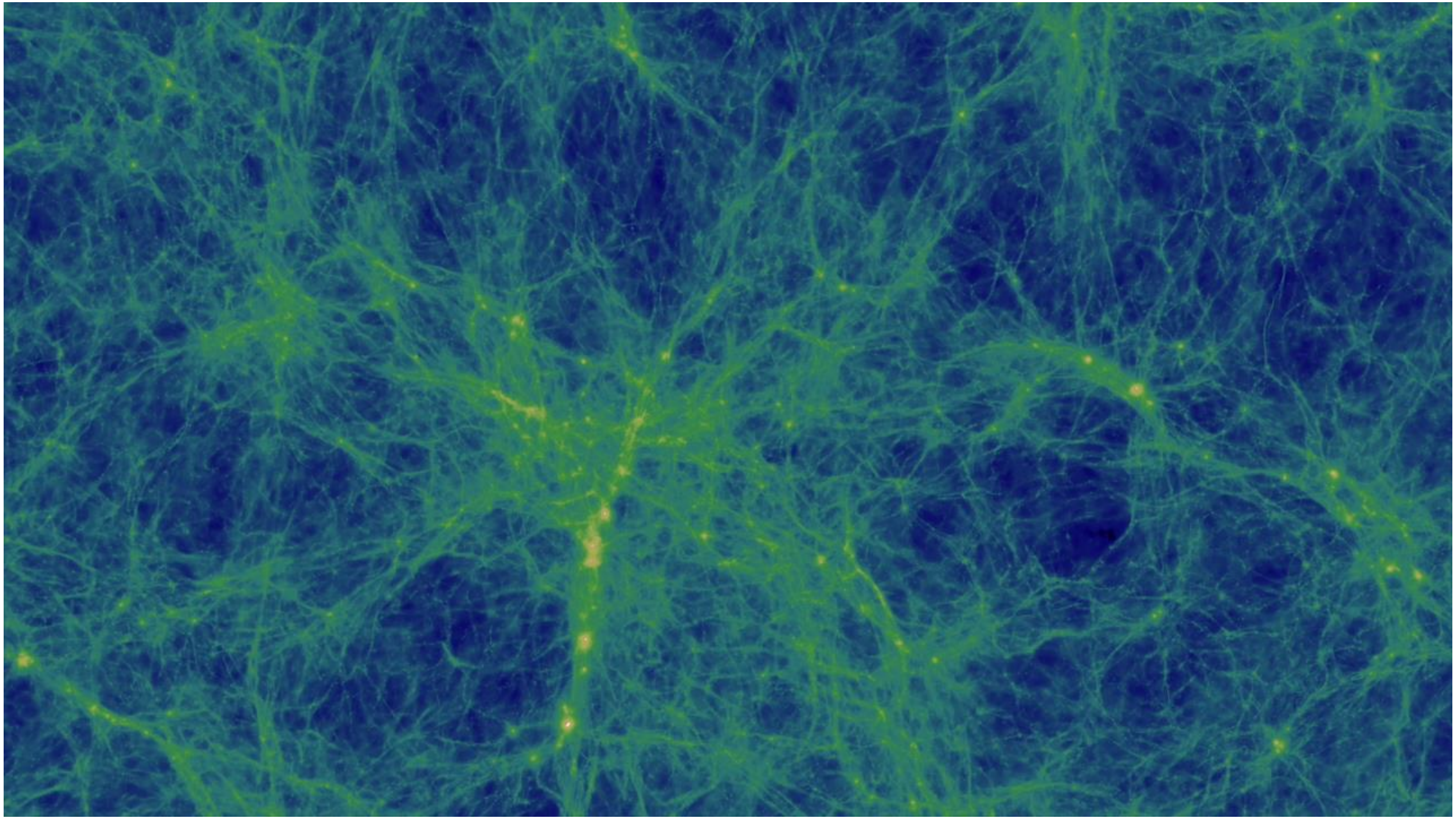
Mak Pavicevic



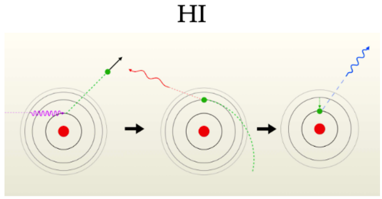
Pranjal Ralegankar

Ralegankar, Pavicevic, Viel, JCAP, 2024, 07, 27
Ralegankar, Garaldi, Viel arXiv:2410.02676
Pavicevic, Irsic, Viel, Bolton, Haehnelt, Martin-Alvarez, Puchwein, Ralegankar arXiv:2501.06299

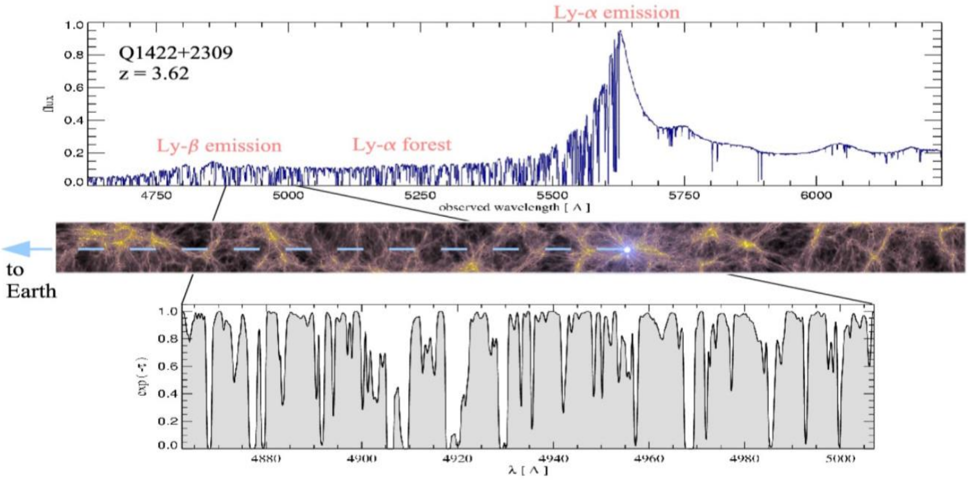
The cosmic web: intergalactic medium

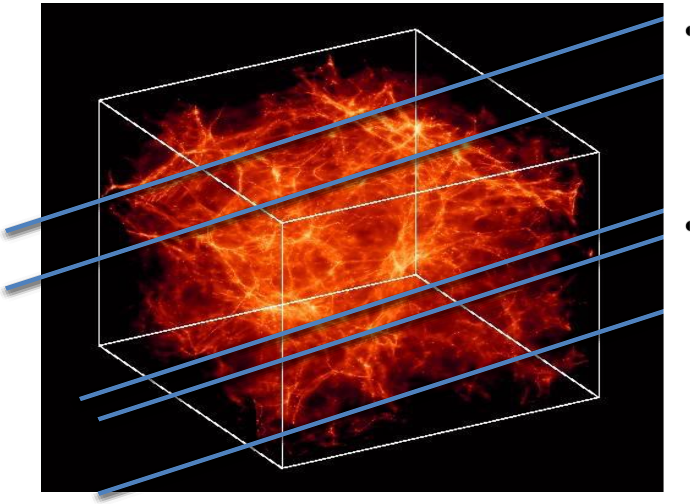


The Lyman-alpha forest



$$\lambda = \lambda_0(1+z)$$
$$\lambda_0 = 1215.67\,\text{Å}$$





- **Intergalactic medium:** filaments at low density (outside galaxies) - distances spanned 0.1-100 Mpc/h
- Lyman-alpha forest its the main manifestation of the IGM
- High redshift observable, 1D projected power (but also 3D)

The cosmic web: intergalactic medium

- High redshift counterpart of Vazza's cosmic web you saw on Wednesday
- Probes densities around the mean
- Traces the large/small/medium scales of matter fluctuations
- Volume filling factor of galaxies is negligible
- Not sensitive to baryonic feedback
- No room for turbulence
- Astrophysical nuisances: mainly gas thermal state

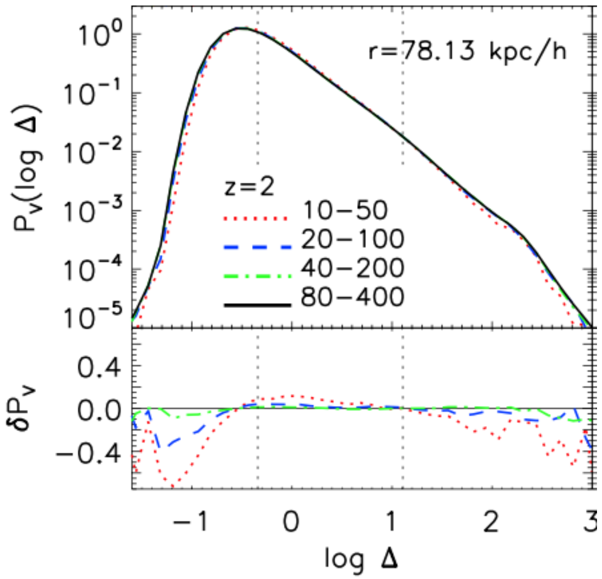
IGM - II

- Diffuse IGM: prediction of standard (and sometimes non standard) cosmological models of structure formation

- Strongly evolving in redshift. Fills most of the volume. Fitted by a lognormal distribution.

- Till about 10 years ago, semi-analytical models were enough, now not any more.

Bolton & Becker 2008



Intergalactic Medium

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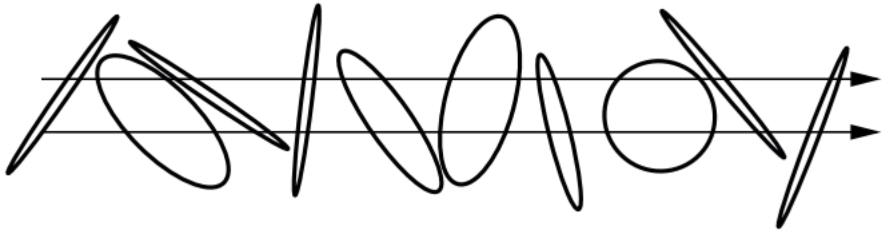
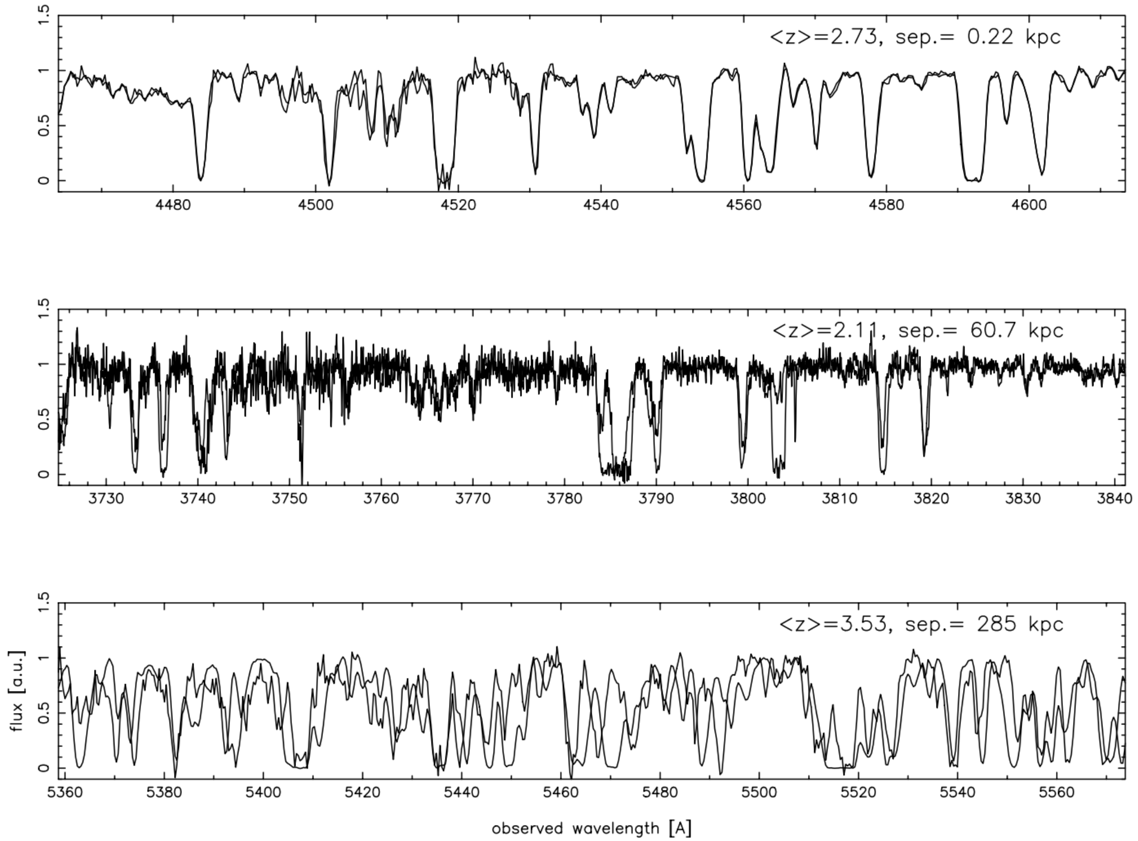
- Large scale motions dominated by the Hubble flow
- Majority of "clouds" even exands with super-Hubble velocity
- At low redshift clouds detach from cosmic expansion and go through gravitational instability
- More recent studies: ultrastable spectrographs can go down to 1 km/s "shifts" setting limits to turbulent motions below the kpc scale





Rauch, Becker, MV+ 2005

Setting the stage

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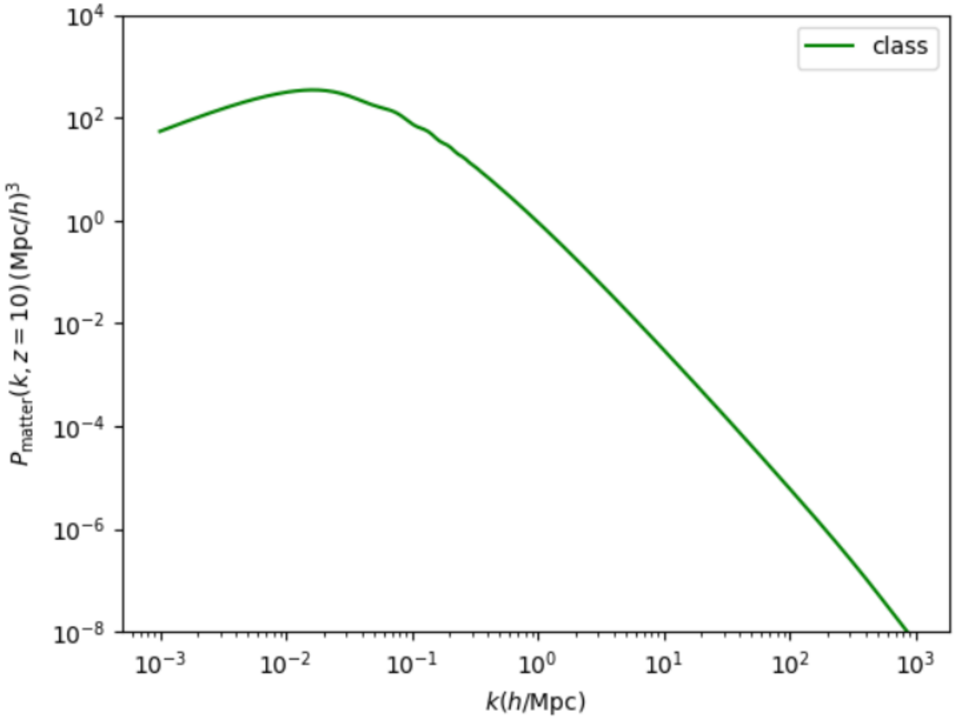
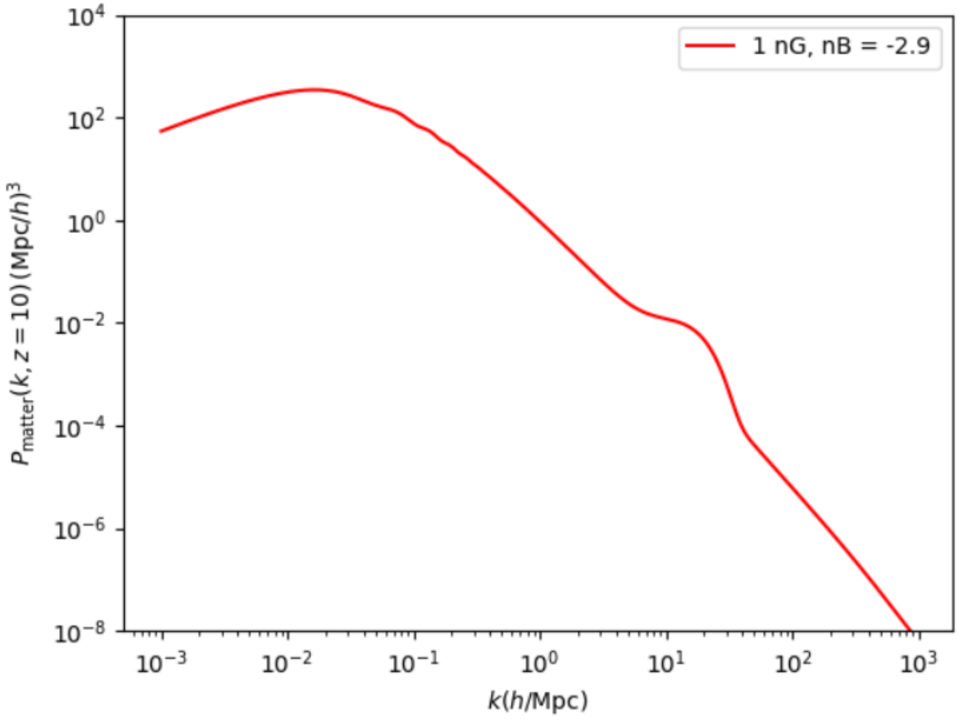
$$\langle B_i(k) B_j^*(k') \rangle = (2\pi)^3 \delta^3(k - k') \left(\delta_{ij} - \frac{k_i k_j}{k^2} \right) \frac{P_B(k)}{2}$$

$$P_B(k) \propto B_{1\mathrm{Mpc}}^2 k^{n_B}$$

$$P_{\Lambda CDM}$$



$$P_{\Lambda CDM} + P_{PMF}$$



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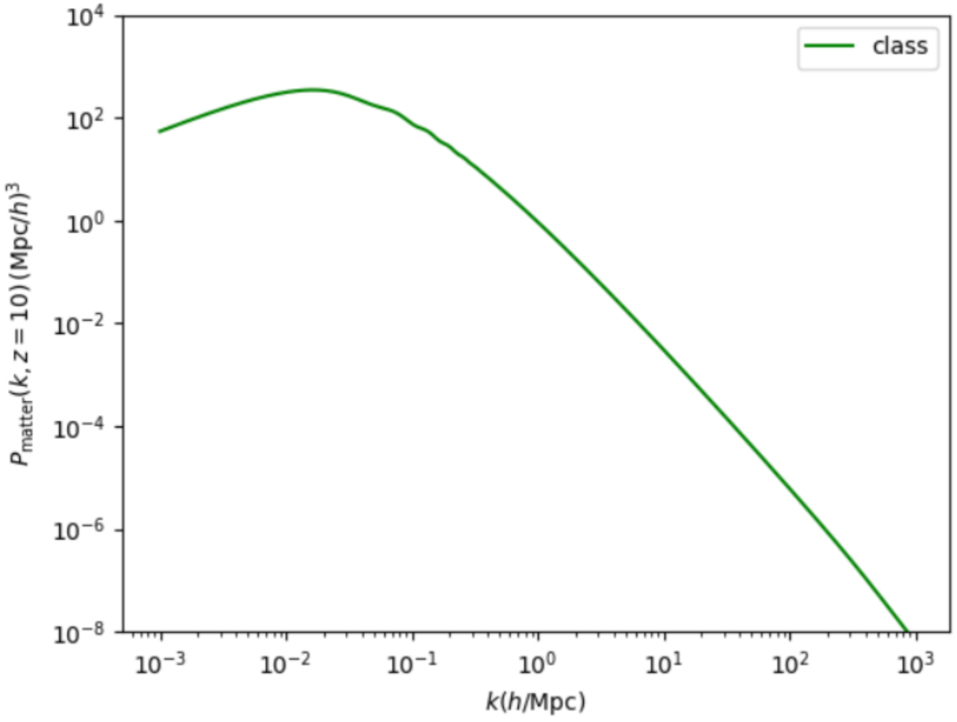

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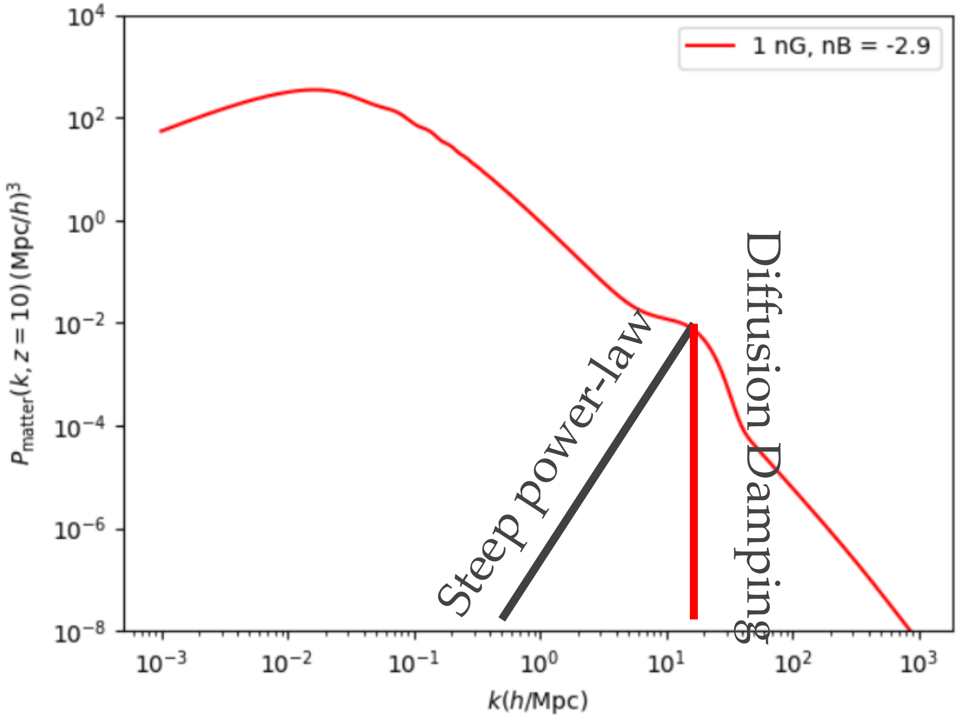

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Matteo Viel

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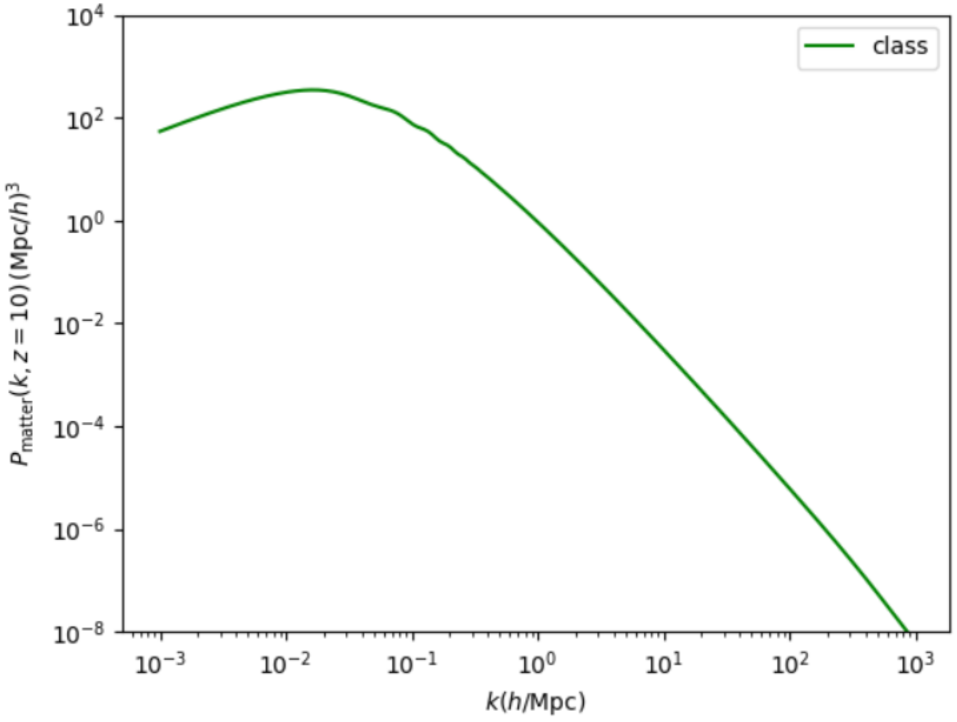

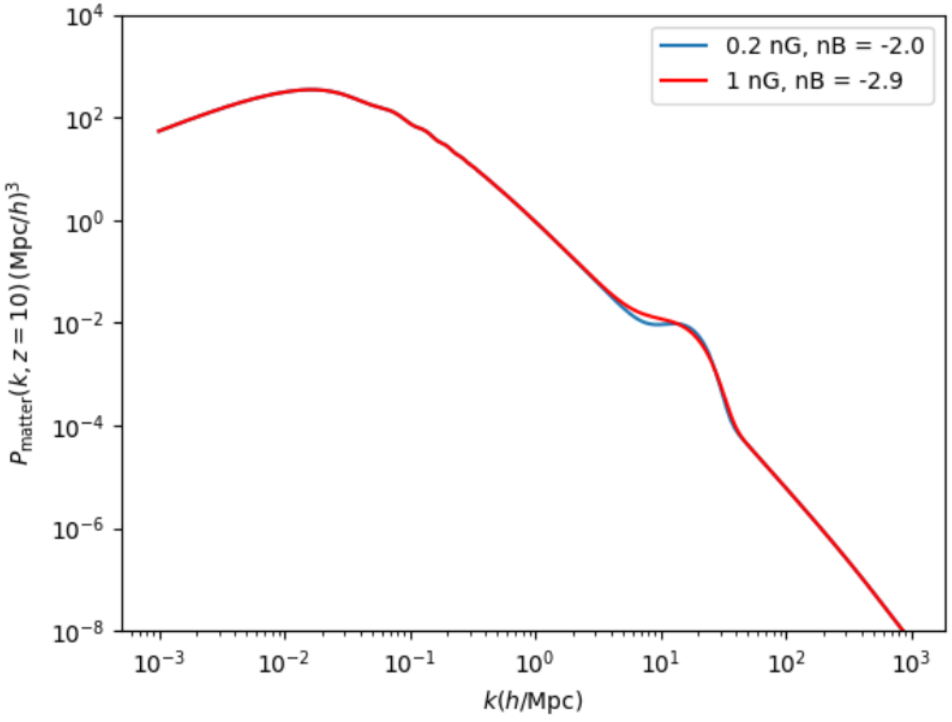

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Matteo Viel

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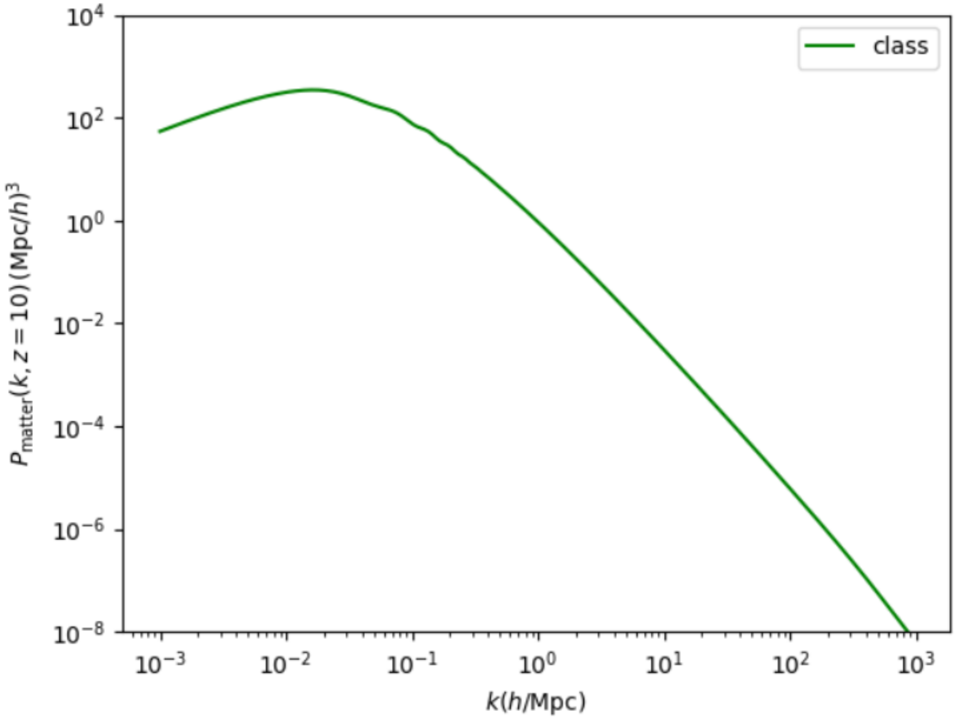

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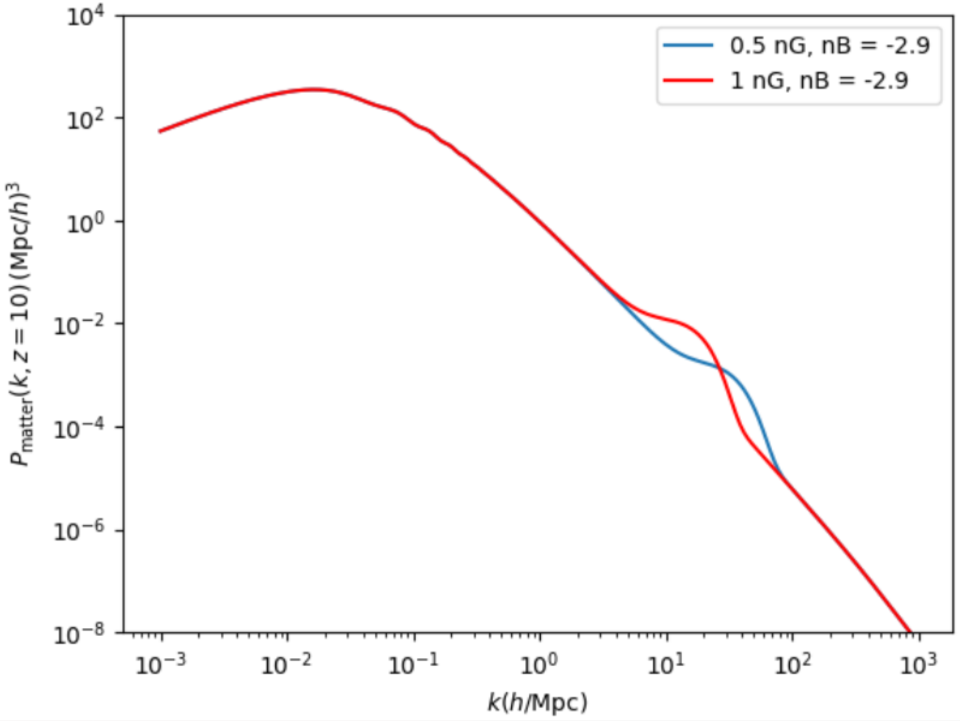

Ideal MHD in the postrecombination Universe

$$\frac{\partial\,(\vec{B})}{\partial t} = \frac{\nabla\times(\vec{v}_b\times\vec{B})}{a}$$

$$\frac{\partial\vec{v}_b}{\partial t} + H\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{\left(\nabla\times\vec{B}\right)\times\vec{B}}{4\pi a^5\rho_b} - \frac{c_b^2\nabla\delta_b}{a} - \frac{\nabla\phi}{a}$$

$$\frac{\partial\delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b\vec{v}_b)}{a}$$

$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2\delta_{DM}}{\partial a^2} + \left[\frac{\partial\ln(a^2H)}{\partial\ln a} + 1\right]\frac{\partial\delta_{DM}}{a\partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

Ralegankar, Pavicevic, Viel, 2024, JCAP, 07, 027 (Kim+96, Adi+24)

Ideal MHD in the postrecombination Universe

Matteo Viel

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At large scales
$\delta \ll 1$
$v_b \ll aH$

Velocity field is generated

$$\partial_t v_b \propto (\nabla\times B)\times B$$

Ideal MHD in the postrecombination Universe

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$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

Comoving Magnetic field is conserved

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a\partial a} = -\frac{\nabla\cdot(\nabla\times\vec{B})\times\vec{B}}{(4\pi a^3\rho_b)a^5H^2} + \frac{\nabla^2\phi}{(a^2H)^2}$$

Baryon perturbations driven by magnetic field and gravity

$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a\partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

Gravity has the usual form

Ideal MHD in the postrecombination Universe

Matteo Viel

$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

S_0/a^3H^2

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a\partial a} = -\frac{\nabla\cdot(\nabla\times\vec{B})\times\vec{B}}{(4\pi a^3\rho_b)a^5H^2} + \frac{\nabla^2\phi}{(a^2H)^2}$$

$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a\partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

$$S_0 = \frac{\nabla\cdot[(\nabla\times\vec{B})\times\vec{B}]}{4\pi a^3\rho_{\rm b}}$$

Key ingredient is the S_0 source term

Ideal MHD in the postrecombination Universe

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$$a^2\frac{\partial^2\delta_b}{\partial a^2}+a\frac{3}{2}\frac{\partial\delta_b}{\partial a}-\frac{3}{2}\frac{\Omega_b}{\Omega_m(1+a_{eq}/a)}\delta_b=-\frac{S_0}{a^3H^2}+\frac{3}{2}\frac{\Omega_{DM}}{\Omega_m(1+a_{eq}/a)}\delta_{DM}$$

$$a^2\frac{\partial^2\delta_{DM}}{\partial a^2}+a\frac{3}{2}\frac{\partial\delta_{DM}}{\partial a}-\frac{3}{2}\frac{\Omega_{DM}}{\Omega_m(1+a_{eq}/a)}\delta_{DM}=\frac{3}{2}\frac{\Omega_b}{\Omega_m(1+a_{eq}/a)}\delta_b.$$

DM

baryons

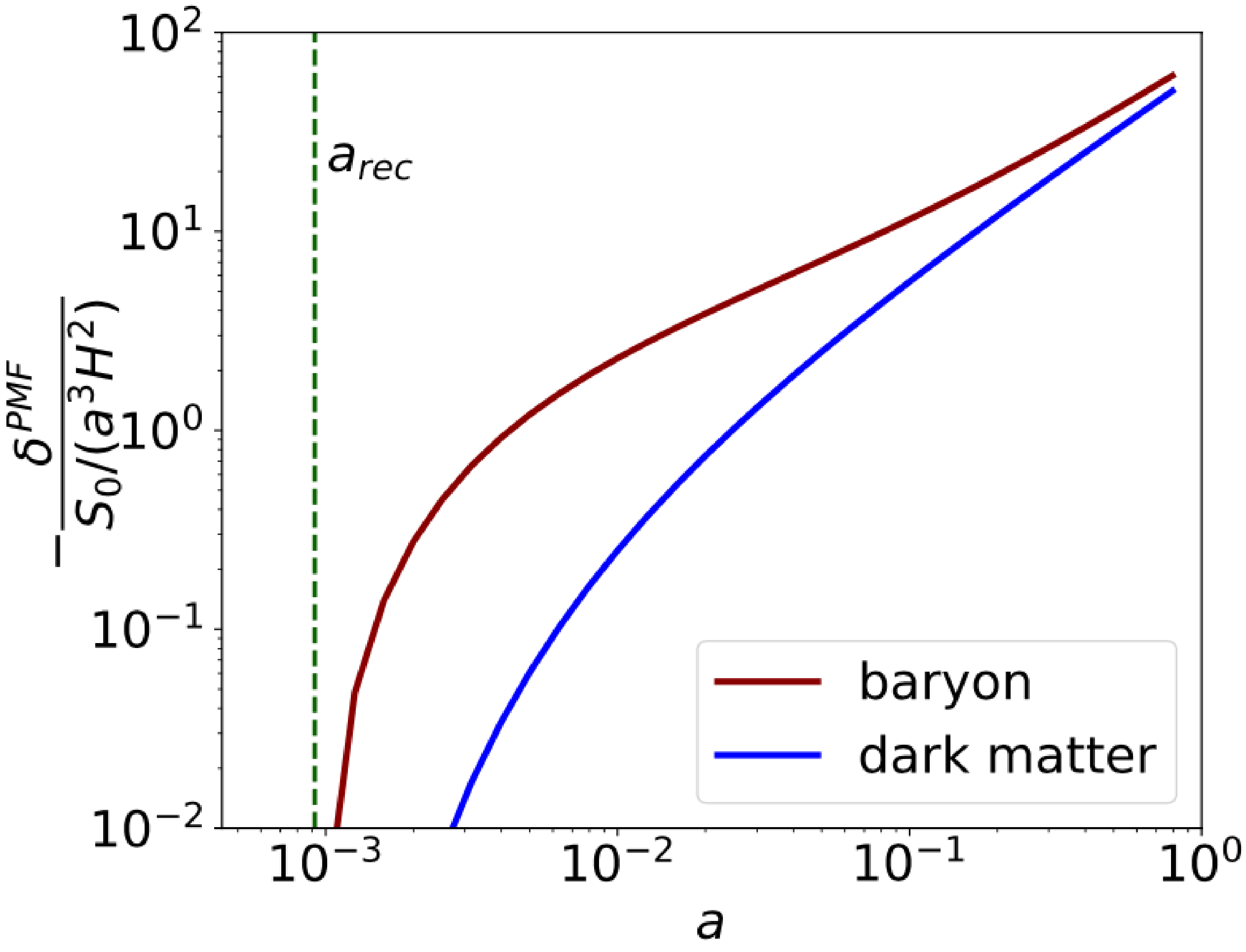
Coupled differential equations

$$\delta_b^{PMF}=-\xi_b(a)\frac{S_0}{a^3H^2}\qquad \delta_{DM}^{PMF}=-\xi_{DM}(a)\frac{S_0}{a^3H^2}.$$

$$P_b^{PMF}\propto P_{S0}$$

Power spectrum of Lorentz force
For n_B~ -3 (scale invariant) this returns
P_{matter} ~ k

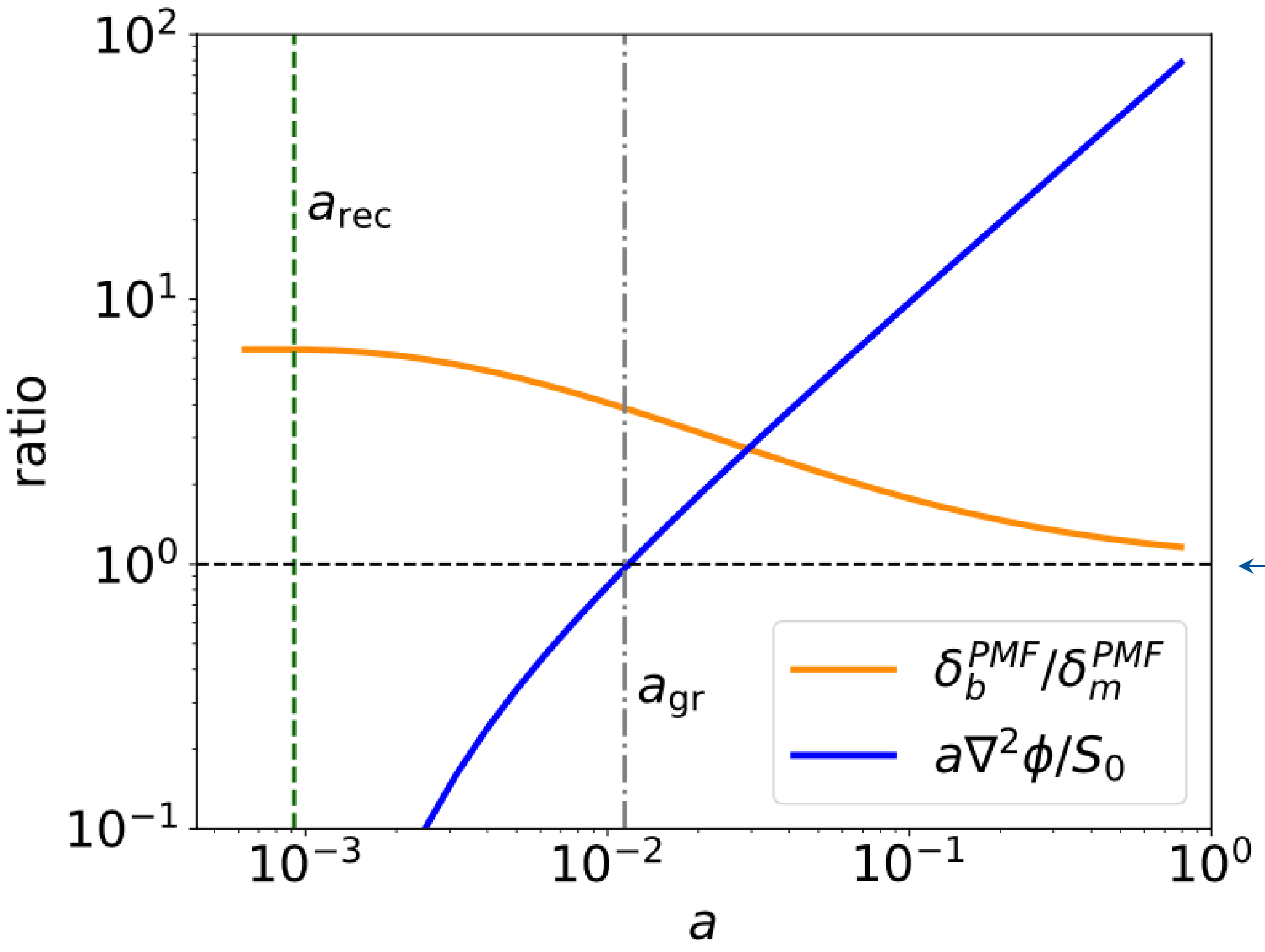
Ideal MHD in the postrecombination Universe



- Time evolution of perturbations (scale dependence is hidden in S0)
- Baryons are primarily enhanced
- DM is lagging behind and eventually catches up at z~0

Raleganckar, Pavicevic, Viel, 2024, JCAP, 07, 027

Ideal MHD in the postrecombination Universe



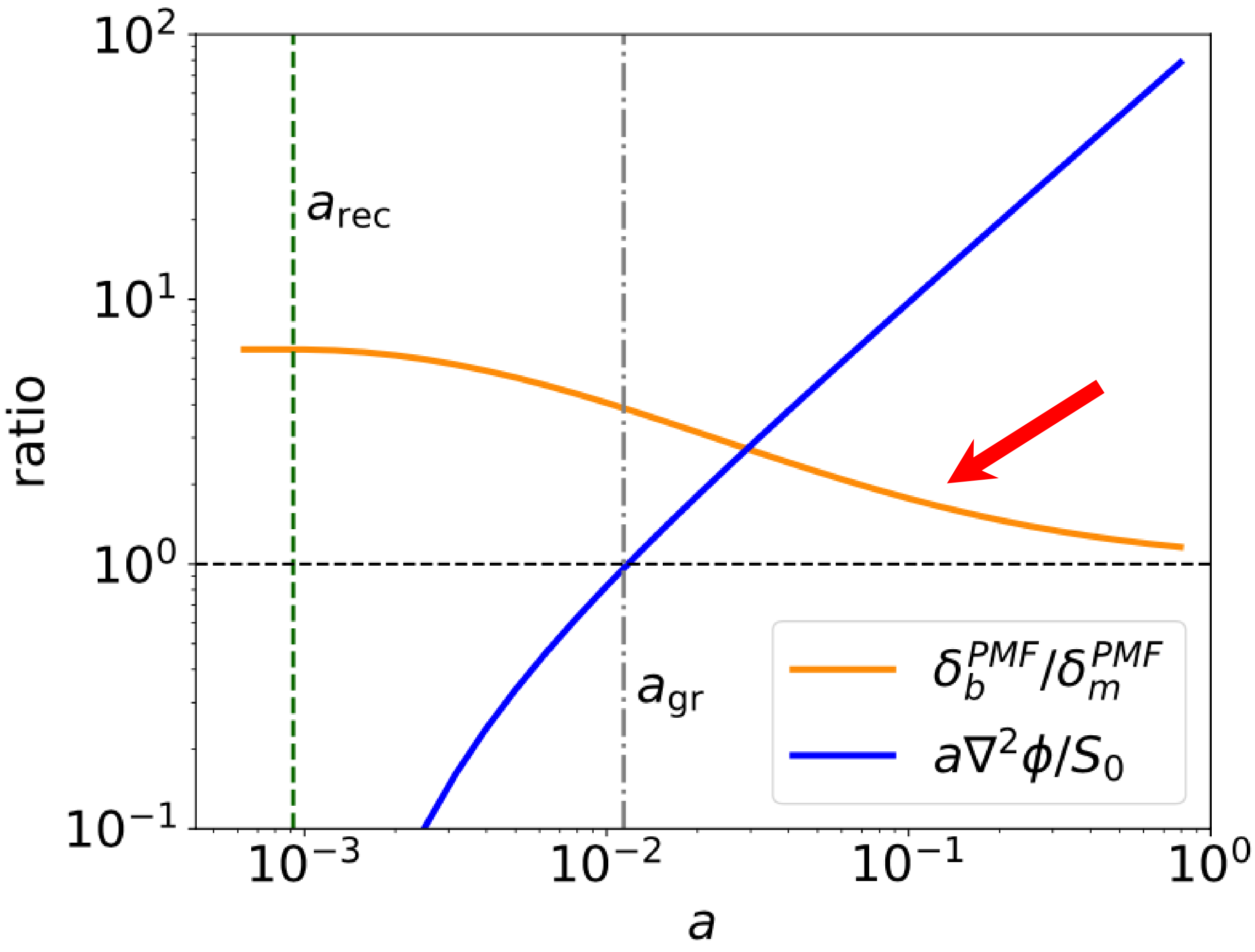
- Ratio of perturbations is equivalent to baryon fraction and starts very high and only now reaches the cosmic mean 0.17 value

← Cosmic mean

Raleganka, Pavicevic, Viel, 2024, JCAP, 07, 027

Ideal MHD in the postrecombination Universe

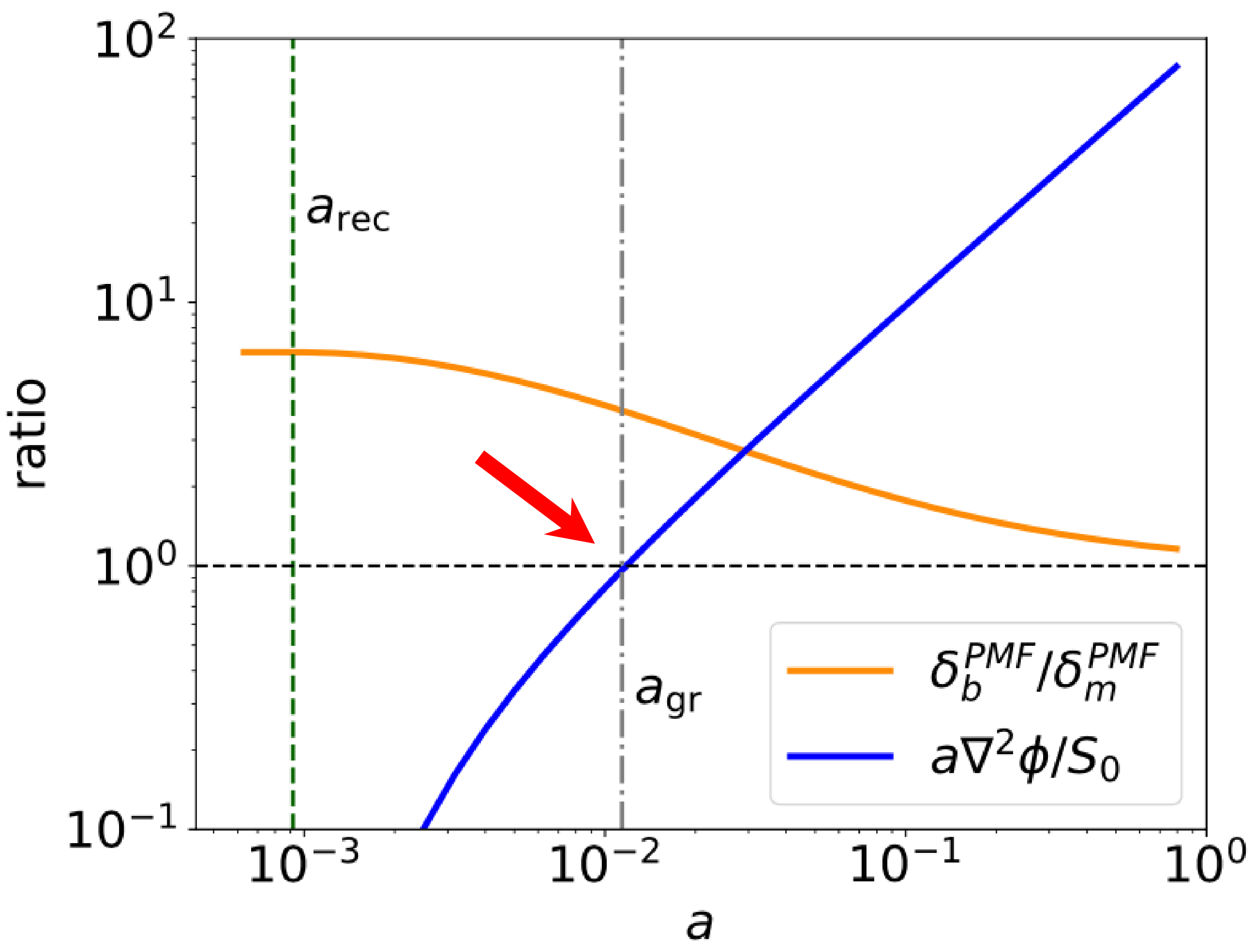
Matteo Viel



- Ratio of perturbations is equivalent to baryon fraction starts very high and only now reaches the cosmic mean 0.17 value

- At z=10 baryon fraction is 2 times the cosmic mean

Ideal MHD in the postrecombination Universe



- Ratio of perturbations is equivalent to baryon fraction starts very high and only now reaches the cosmic mean 0.17 value
- At z=10 baryon fraction is 2 times the cosmic mean
- At z=100 gravity overcomes Lorentz force (this is independent of B and at all scales)

Magnetic Damping Scale

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$$v_{\rm b} \sim \frac{1}{aH\lambda_{\rm D}} \frac{\vec{B}^2_{\rm phys}}{4\pi\rho_{\rm b}}.$$

Baryon flow velocity from Euler Equation (Lorentz force)

$$v_{\rm b}/\lambda_{\rm D} \sim aH$$

Breaking of linearity

$$v_{\rm A}^2 \equiv \frac{\langle \vec{\rm B}^2_{\rm phys} \rangle}{4\pi\rho_{\rm b}}$$

Alfven velocity def.

$$\lambda_{\rm D} \sim \frac{v_{\rm A}}{aH}$$

$$\lambda_{\rm D} \sim 0.1{\rm Mpc} \left(\frac{B}{\rm nG}\right) \qquad k_D \sim 3(nG/B_0){\rm Mpc}^{-1}$$

- Linear perturbation theory does not work at small scales
- Density perturbations backreact on the magnetic field
- MHD Turbulence suppresses perturbations

The baryon PMF induced power spectrum

Matteo Viel

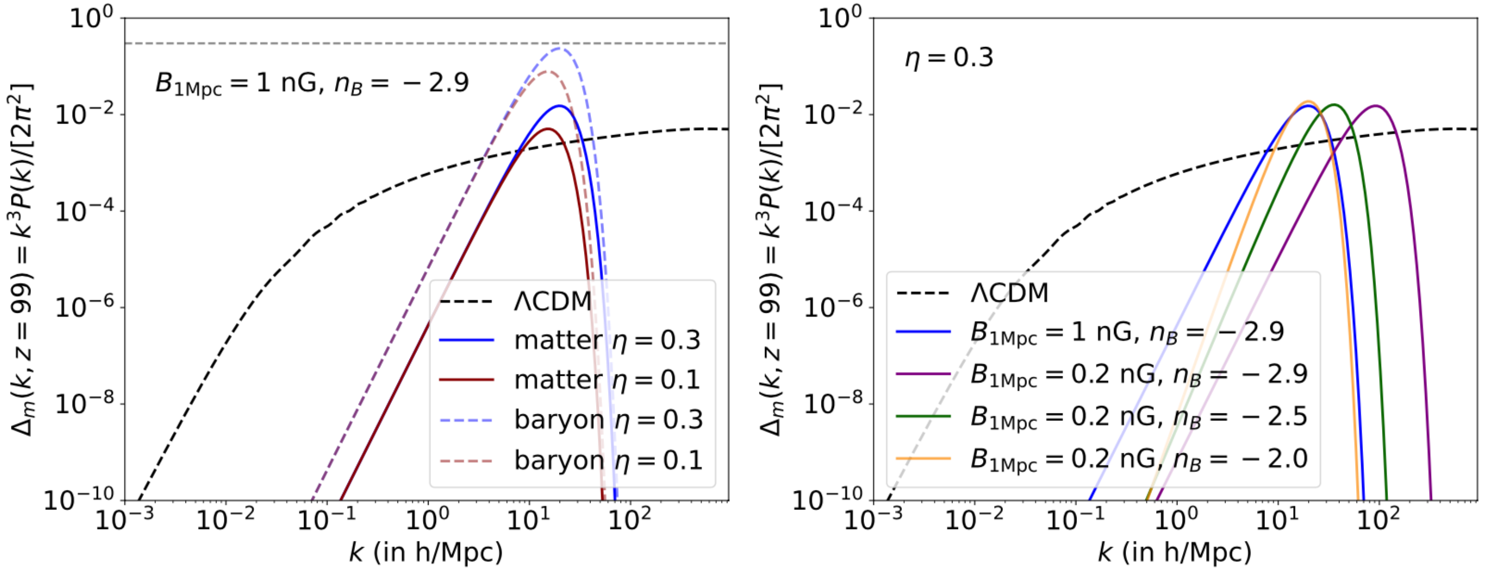
$$P_{\rm B}(k) = A k^{n_{\rm B}} e^{-k^2\lambda_{\rm D}^2} \qquad B_{\rm 1Mpc}^2 \equiv \int \frac{d^3k}{(2\pi)^3} P_{\rm B}(k) e^{-k^2\lambda_{\rm Mpc}^2} = \frac{A\lambda_{\rm Mpc}^{-(3+n_{\rm B})}}{4\pi^2}\Gamma([n_{\rm B}+3]/2)$$

$$P_{\rm b}^{\rm PMF}(k) = \xi_{\rm b}^2(a)\frac{k^4}{8(4\pi a^3\rho_{\rm b}[a^3H^2])^2}\int \frac{d^3q}{(2\pi)^3}\frac{P_B(q)P_{\rm B}(k-q)}{(k-q)^2}\left[k^2+2q^2+4\frac{(q\cdot k)^4}{k^4q^2} - 4\frac{(q\cdot k)^2}{k^2} - 4\frac{(q\cdot k)^3}{k^2q^2} + \frac{(q\cdot k)^2}{q^2}\right]$$

$$\Delta_{\rm b}^{\rm PMF}(k) \equiv \frac{k^3 P_{\rm b}^{\rm PMF}(k)}{2\pi^2} = 10^{-4}\xi_{\rm b}^2(a)\left(\frac{k}{{\rm Mpc}^{-1}}\right)^{2n_{\rm B}+10}\left(\frac{B_{\rm 1Mpc}}{\rm nG}\right)^4 G_{n_{\rm B}} e^{-2k^2\lambda_{\rm D}^2}, \qquad (2.2$$

where $G_{n_{\rm B}}$ is a dimensionless number determined by

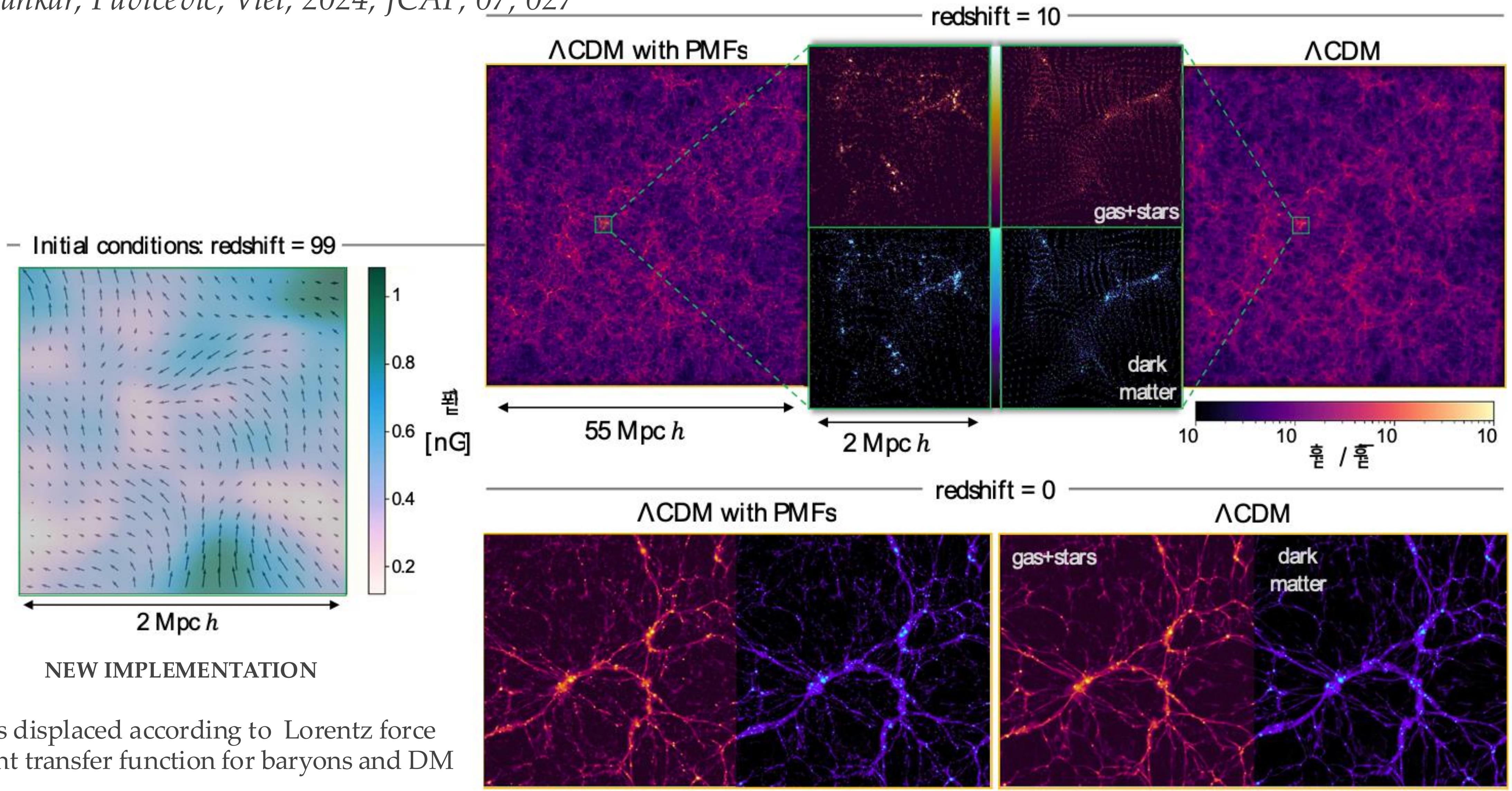
$$G_{n_{\rm B}} = \int_0^\infty dx \int_{-1}^1 \frac{dy}{2} x^{n_{\rm B}+2}(1+x^2-2xy)^{n_{\rm B}/2-1}\frac{[1+2x^2+4y^4x^2-4y^2x^2-4y^3x+y^2]}{\Gamma^2([n_{\rm B}+3]/2)}$$



Raleganker, Pavicevic, Viel 2024
Adi, Cruz, Kamionkowski 2024

Hydro sims

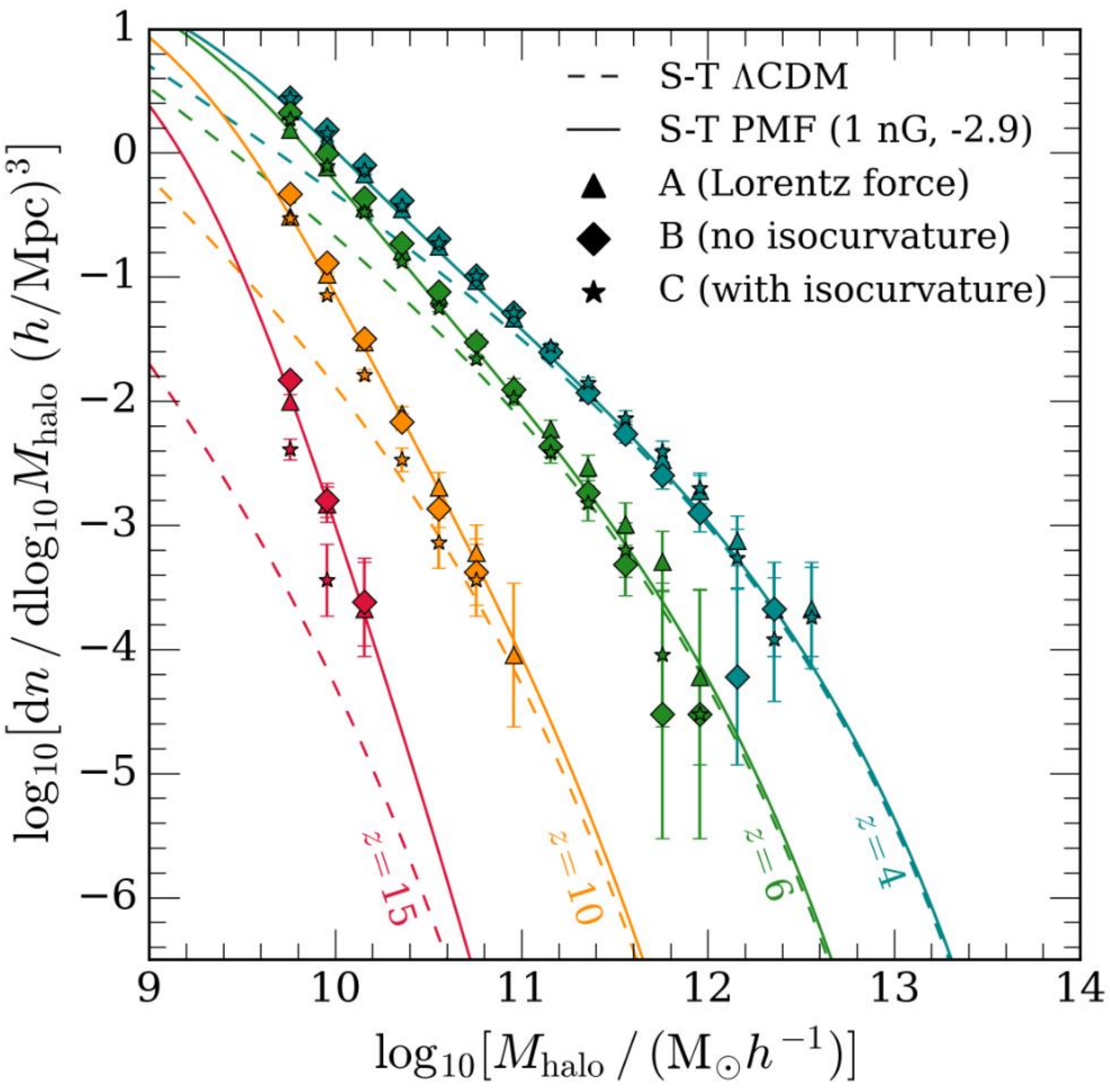
Raleganka, Pavicevic, Viel, 2024, JCAP, 07, 027



NEW IMPLEMENTATION

1) Baryons displaced according to Lorentz force
2) Different transfer function for baryons and DM

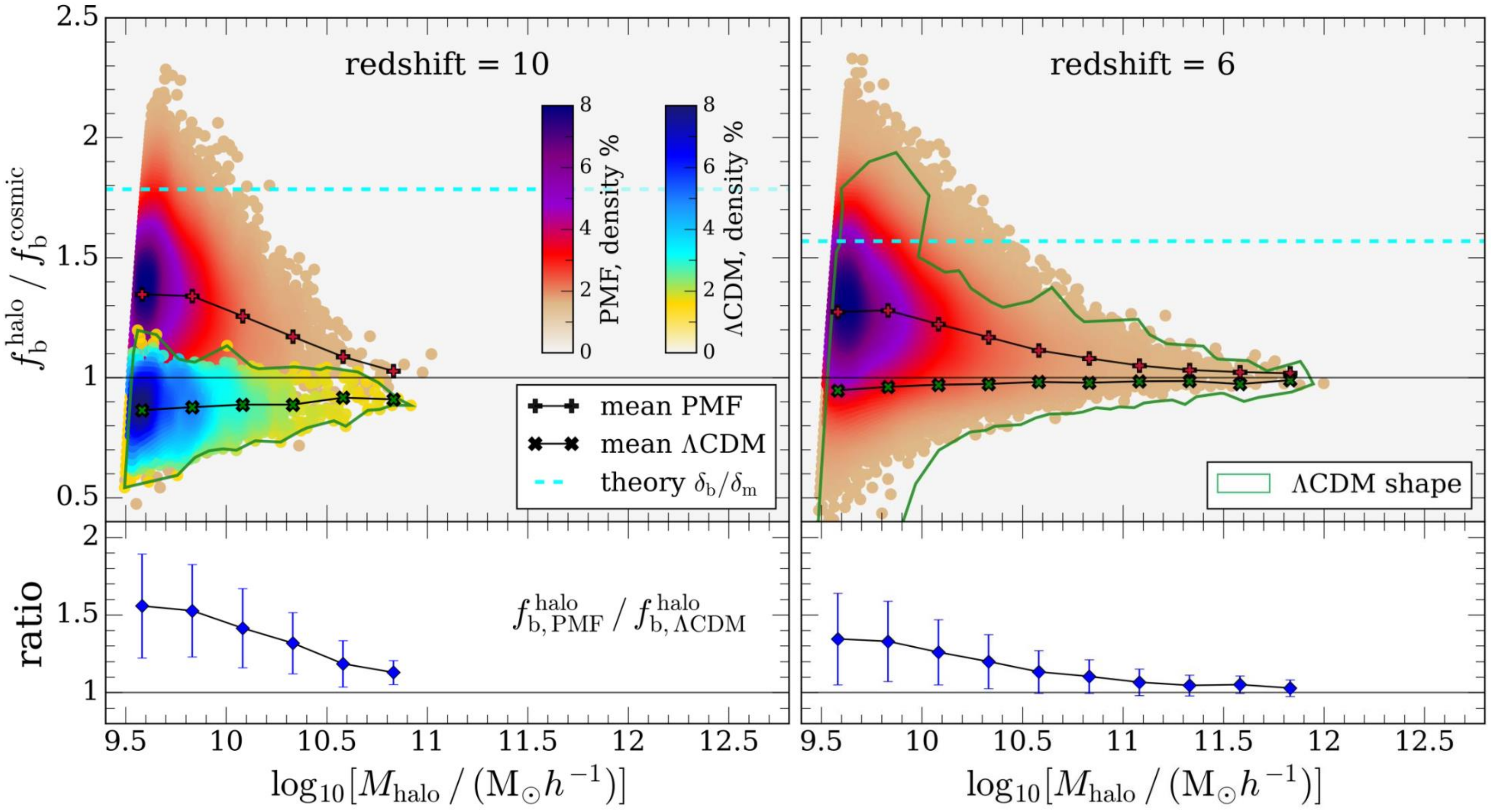
Halo Mass Function



- Extra PMFs power produces more haloes, at "low" mass
- With lower B values (< 1 nG) the enhancement will move to lower masess
- Below 0.05 nG effect is probably too small at any scale

Ralegankar, Pavicevic, Viel, 2024, JCAP, 07, 027

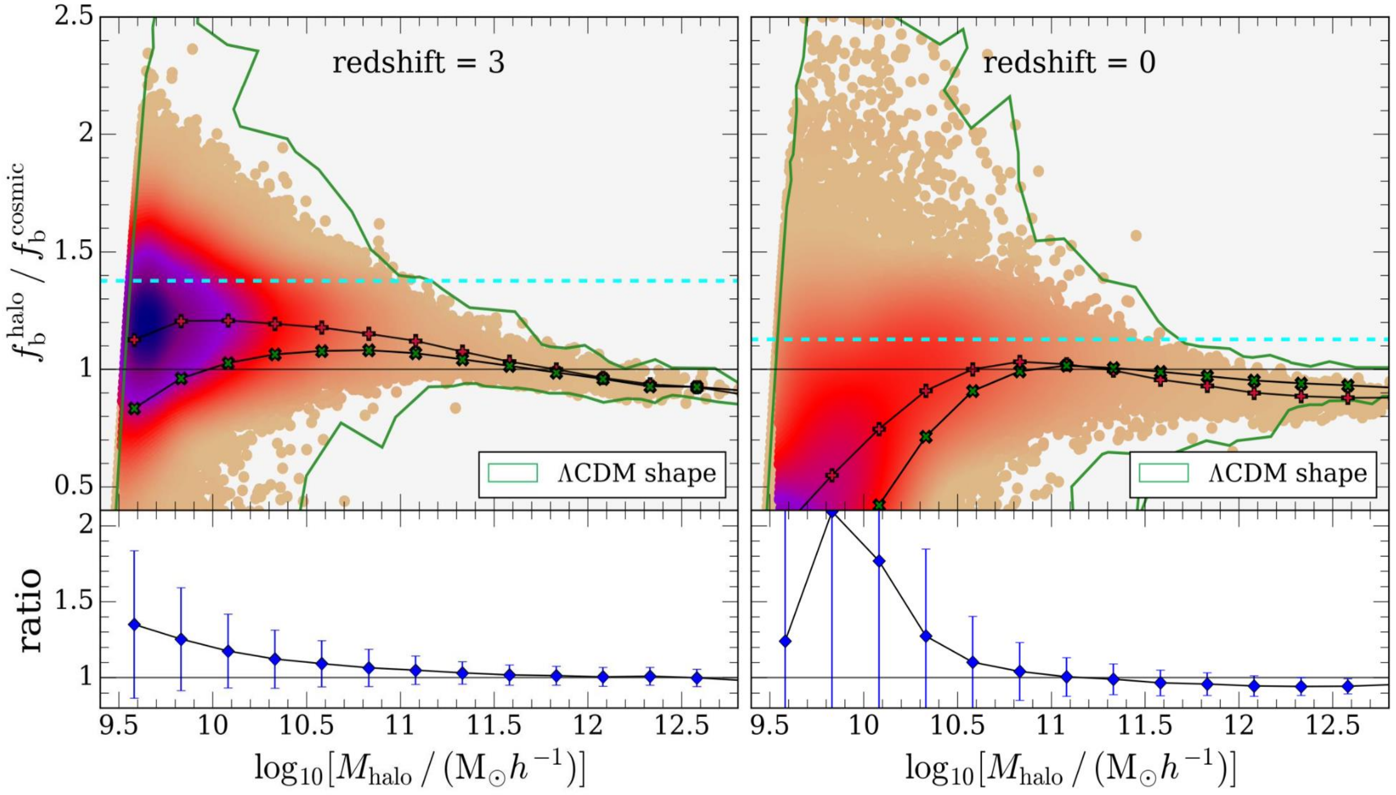
Halo Baryon Fractions at high redshift



- Larger baryon fraction in haloes also shown in hydro sims
- At large masses (scales) cosmic values is recovered
- More scatter in PMF models

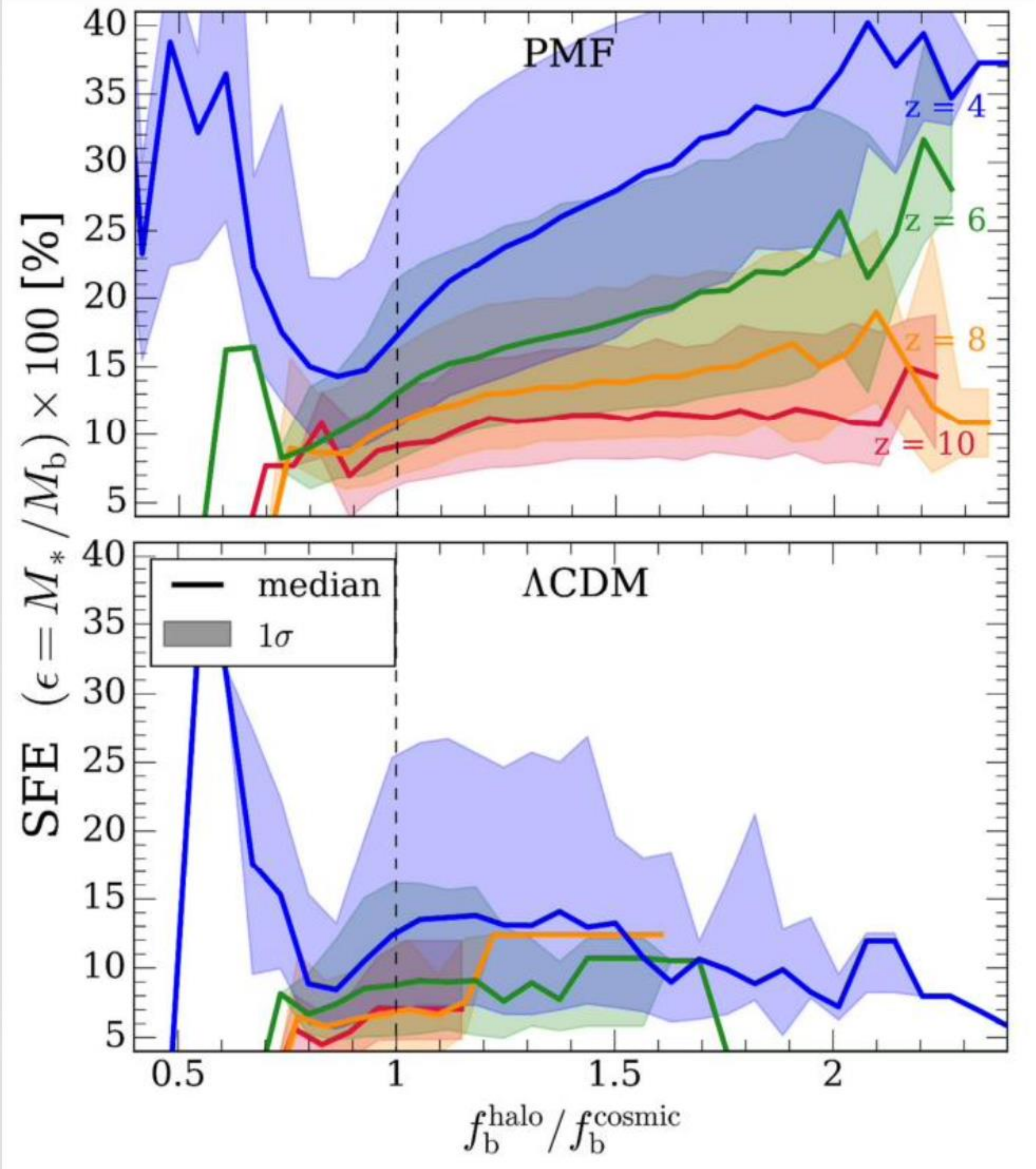
Ralegankar, Pavicevic, Viel, 2024, JCAP, 07, 027

Halo Baryon fraction at lower redshift



- At low (z<3) redshift the effect vanishes

Star formation



- Star formation efficiency vs baryon fraction is very redshift dependent in PMF models
- IMPORTANT: no feedback for these simulations.
- IMPORTANT: no MHD for these simulations! Purely gravitational interactions

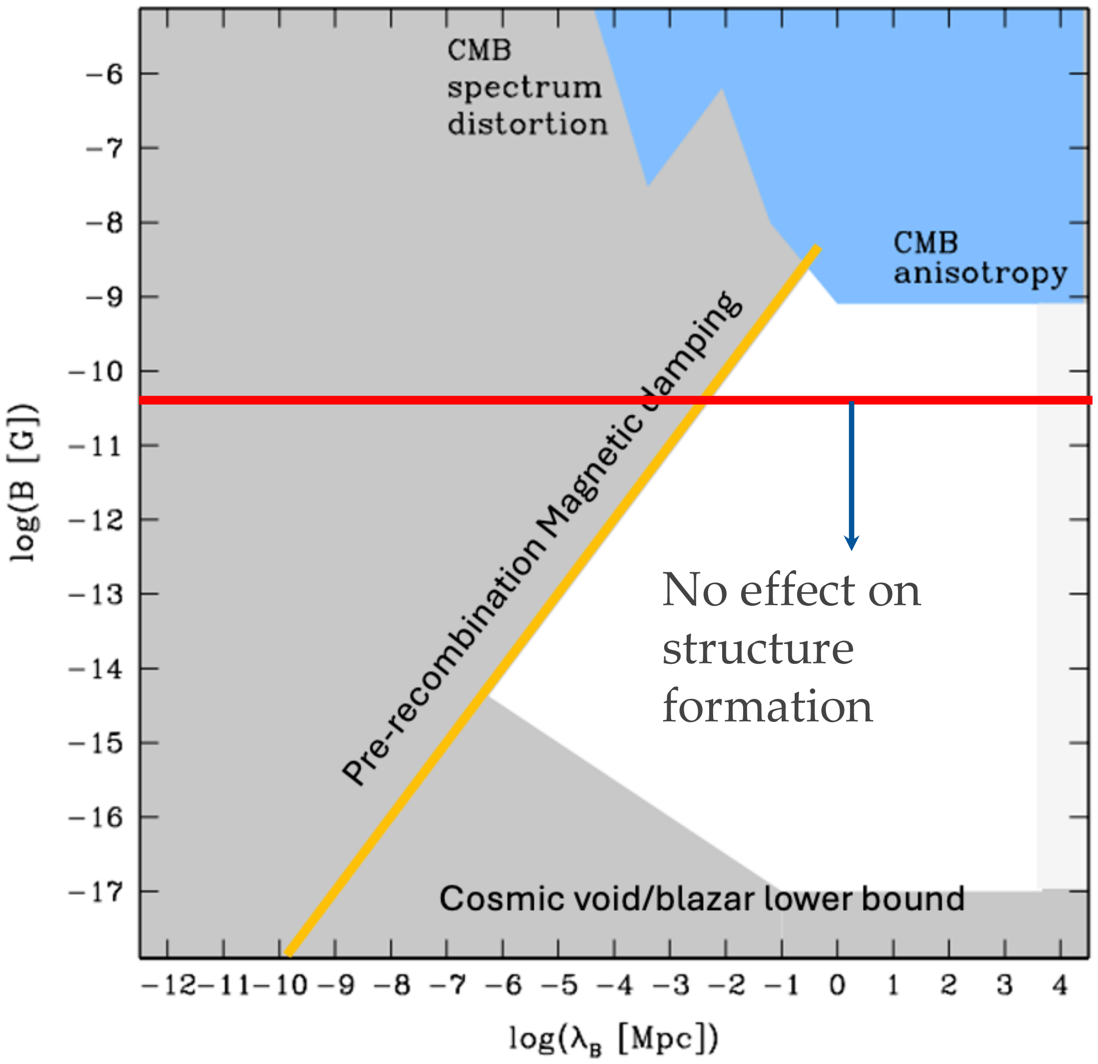
Back on the constraint plot

- Linear theory simple analytical predictions:
More small mass haloes
With large baryon fractions

- Hydro sims with no feeback confirm this and quantify the amount of star formation efficiency and its scatter

- Below 0.05nG the effect is likely to vanish

- Can we do something more?

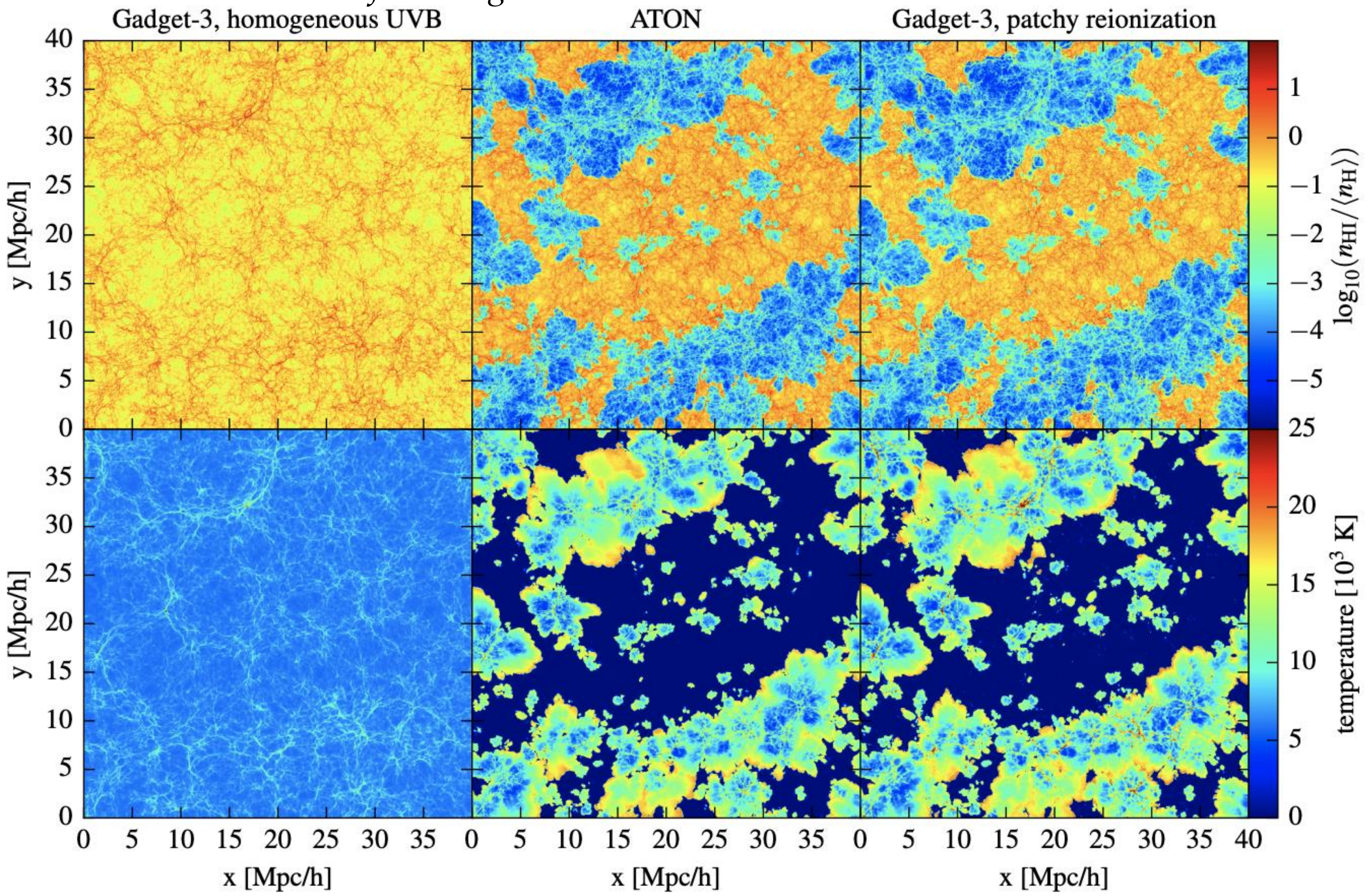


Simulations of IGM structures

Matteo Viel

https://www.nottingham.ac.uk/astronomy/sherwood/

z=7 (with reionization finishing at z=5.3)



Bolton+17
Puchwein, Bolton+23

J. Bolton *E. Puchwein*

- **Sherwood-Relics suite** (>200 simulations: boxes 5-160 cMpc/h; M_{gas}=3.7e3-6.4e6 $M_{\odot}$) – about 75 Million CPU hrs (2017-now)
- G3 code + ATON to perform radiative transfer for patchy reionization
- Focus (and model calibration) on the high-z (z>4) forest

The simulations: patchy reionization effects on 1D flux power

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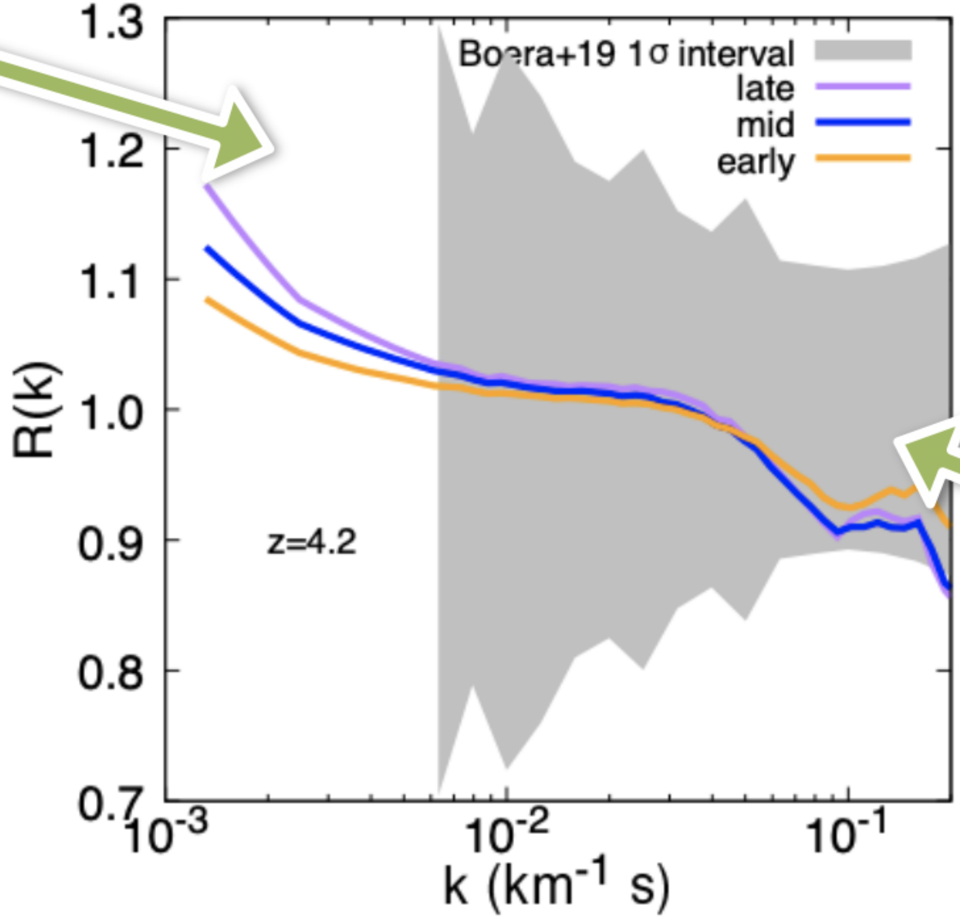
Boost
due to variation
in neutral fraction
from large scale
temperature fluctuations



Molaro+23
“Detected” this
increase of power at 2.7σ
from KODIAQ, SQUAD,
XQ100 sample of 538 QSOs

Suppression
due to thermal broadening
of recently ionised regions

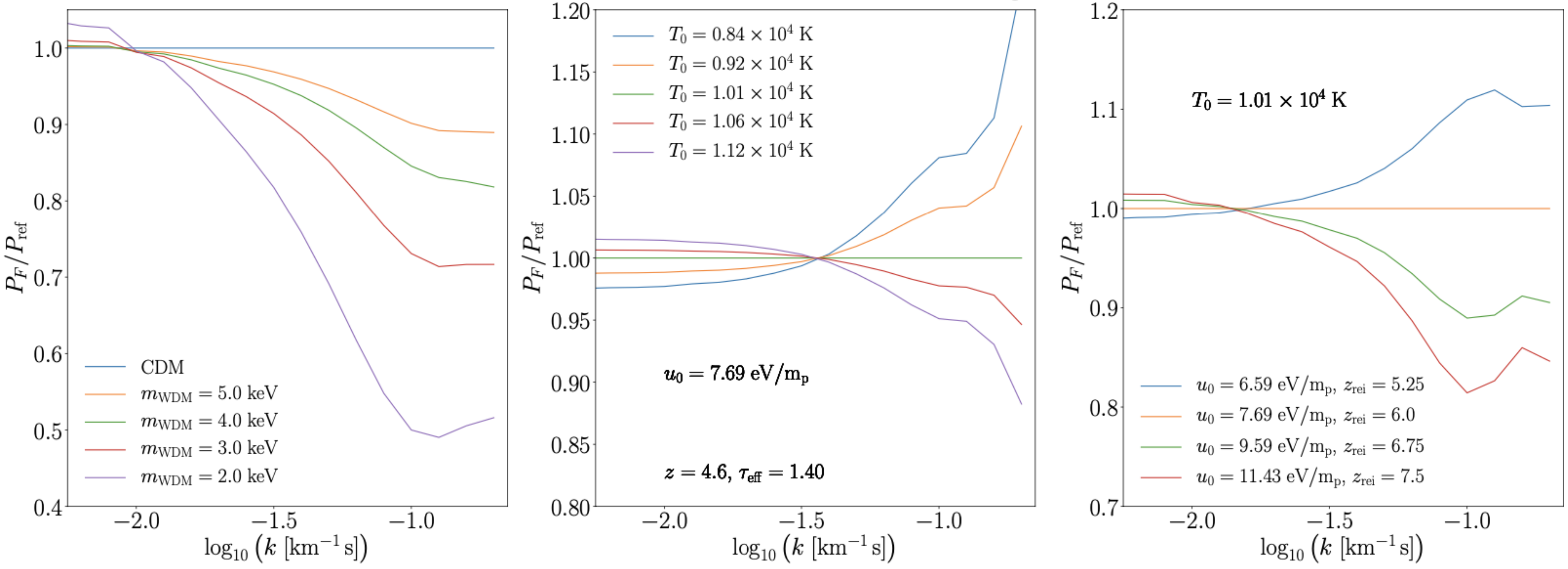
Molaro, Bolton, Irsic,… MV 2021&2023

Physical scales involved

Unveiling Dark Matter free-streaming at the smallest scales with high redshift Lyman-alpha forest

Vid Iršič[1,2], Matteo Viel[3,4,5,6,7], Martin G. Haehnelt[1,8], James S. Bolton[9], Margherita Molaro[9], Ewald Puchwein[10], Elisa Boera[5,6], George D. Becker[11], Prakash Gaikwad[12], Laura C. Keating[13], Girish Kulkarni[14]
[1]Kavli Institute for Cosmology, University of Cambridge

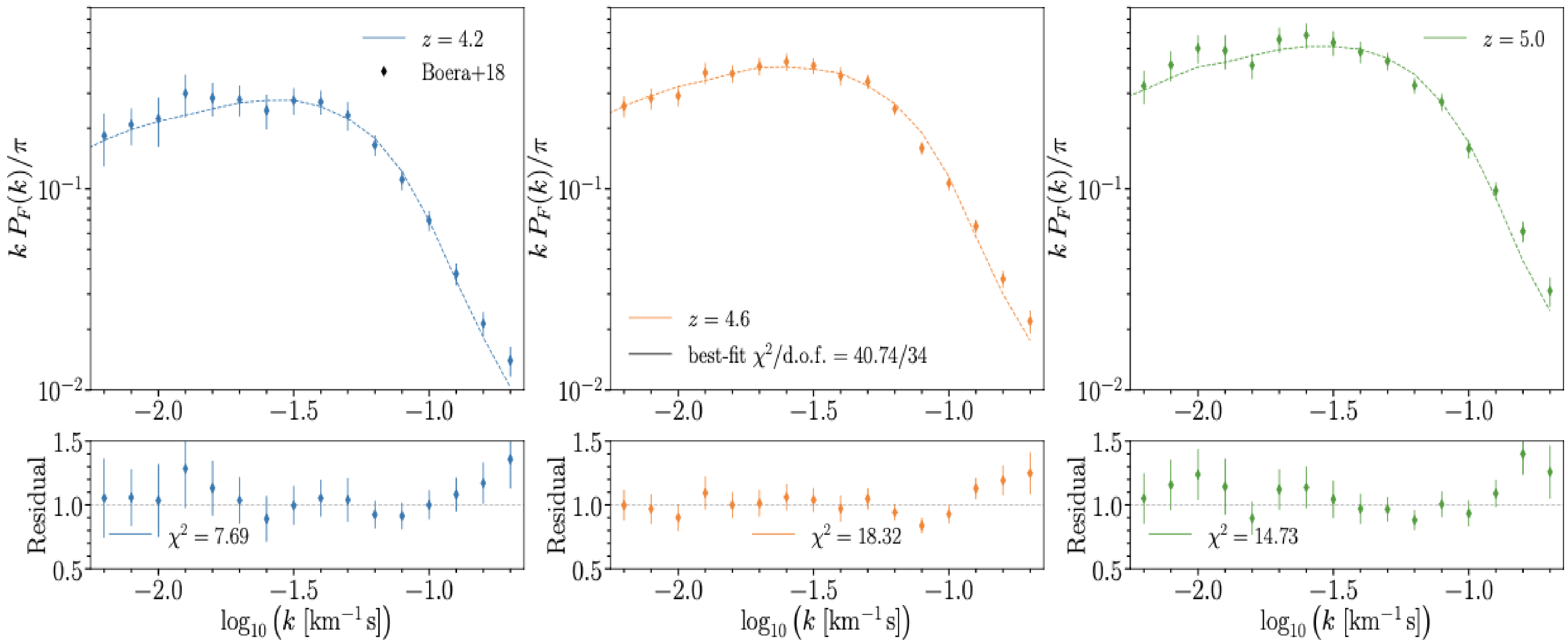
WDM free streaming | Thermal broadening | Gas pressure



$$u_0(t) = \int_0^t dt \frac{\mathcal{H}}{\bar{\rho}_m} \frac{3k_B}{2\mu}$$ H is heating rate

1D Lyman-α flux power and LCDM best-fit

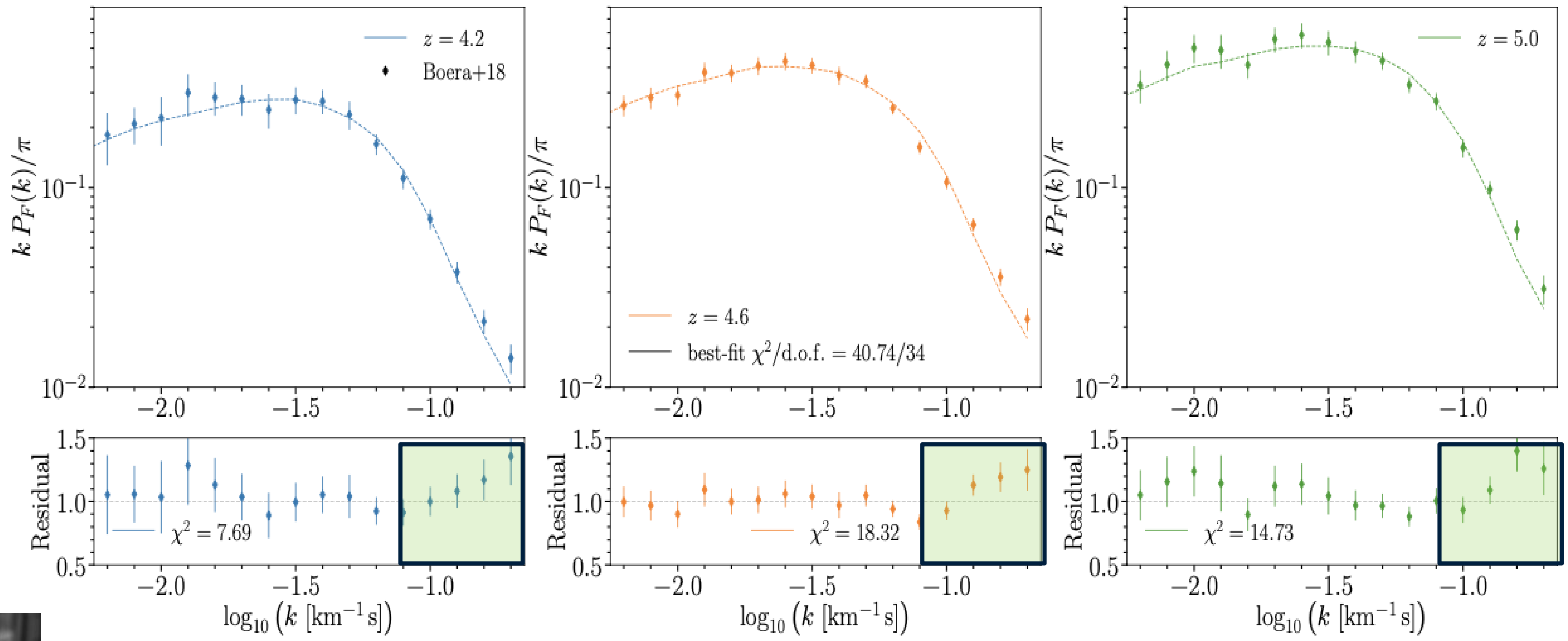
Matteo Viel



Boera+19, Irsic+24

1D Lyman-α flux power and LCDM best-fit

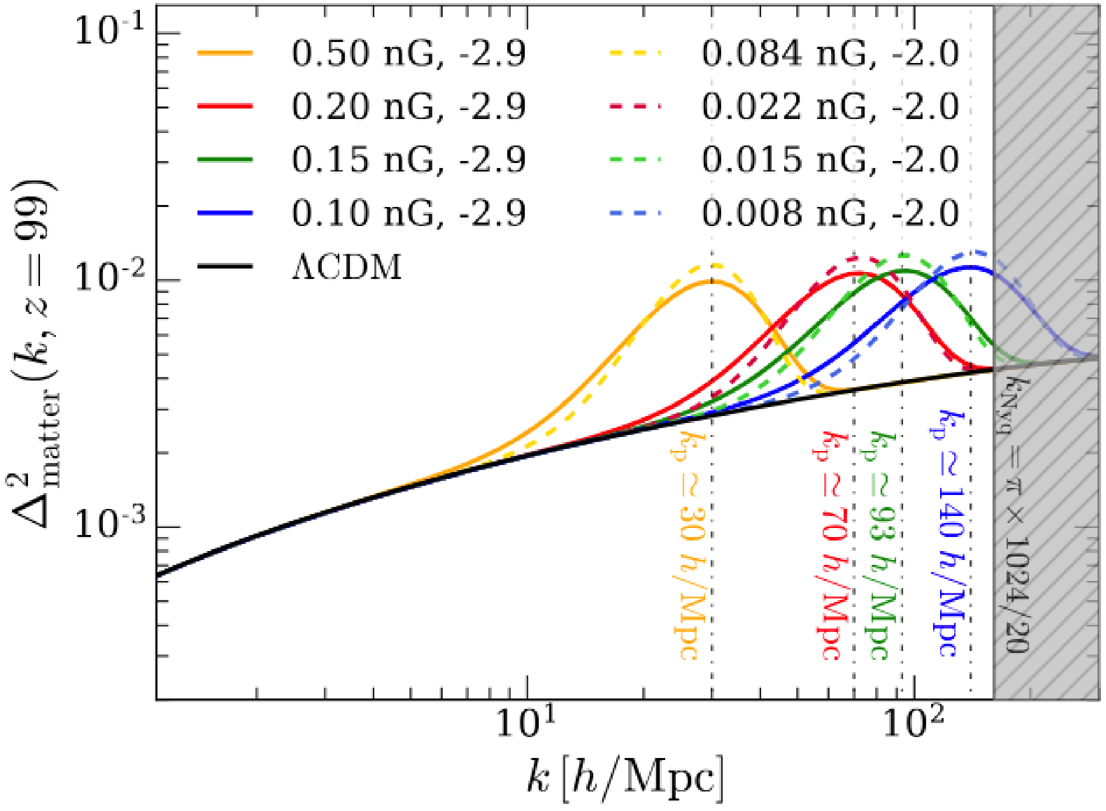
Matteo Viel



$$m_{\rm WDM} > 5.7\,{\rm keV}$$

Boera+19, Irsic+23

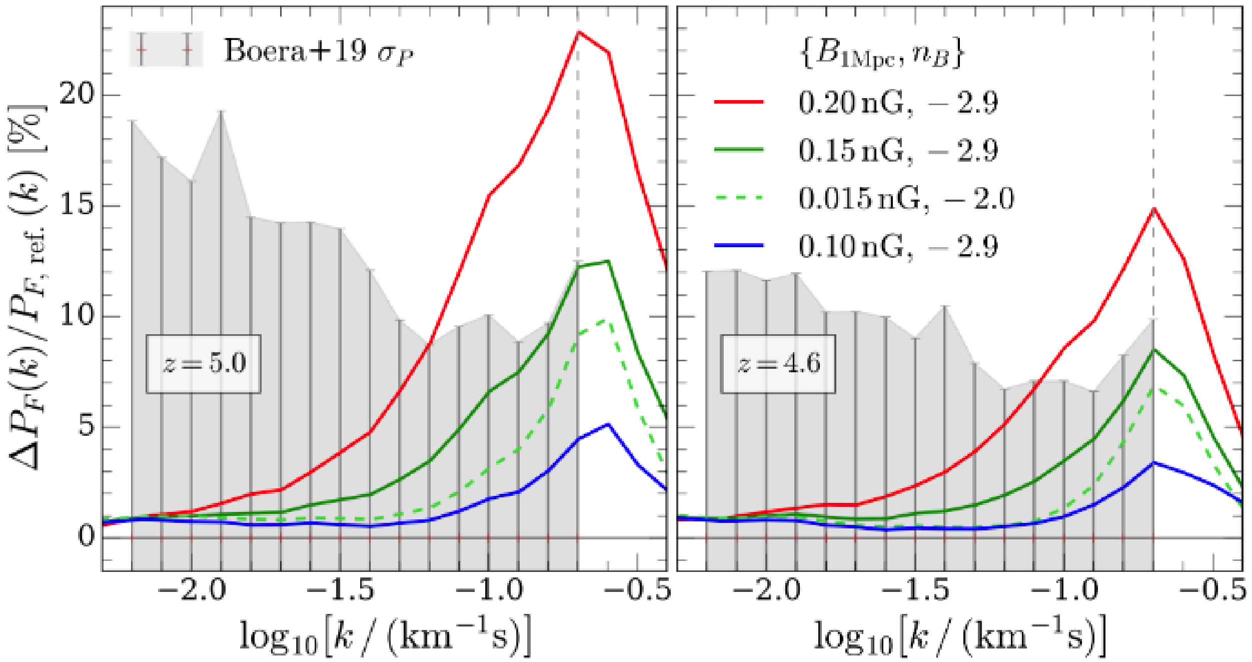
PMF models



- 4 different PMF models at fixed nB=-2.9, 1 model with nB=-2
- Effect on matter power parameterized by kpeak
- For each PMF we simulate 12 thermal histories and build a likelihood in the CDM+PMF space with >0.5 million flux models

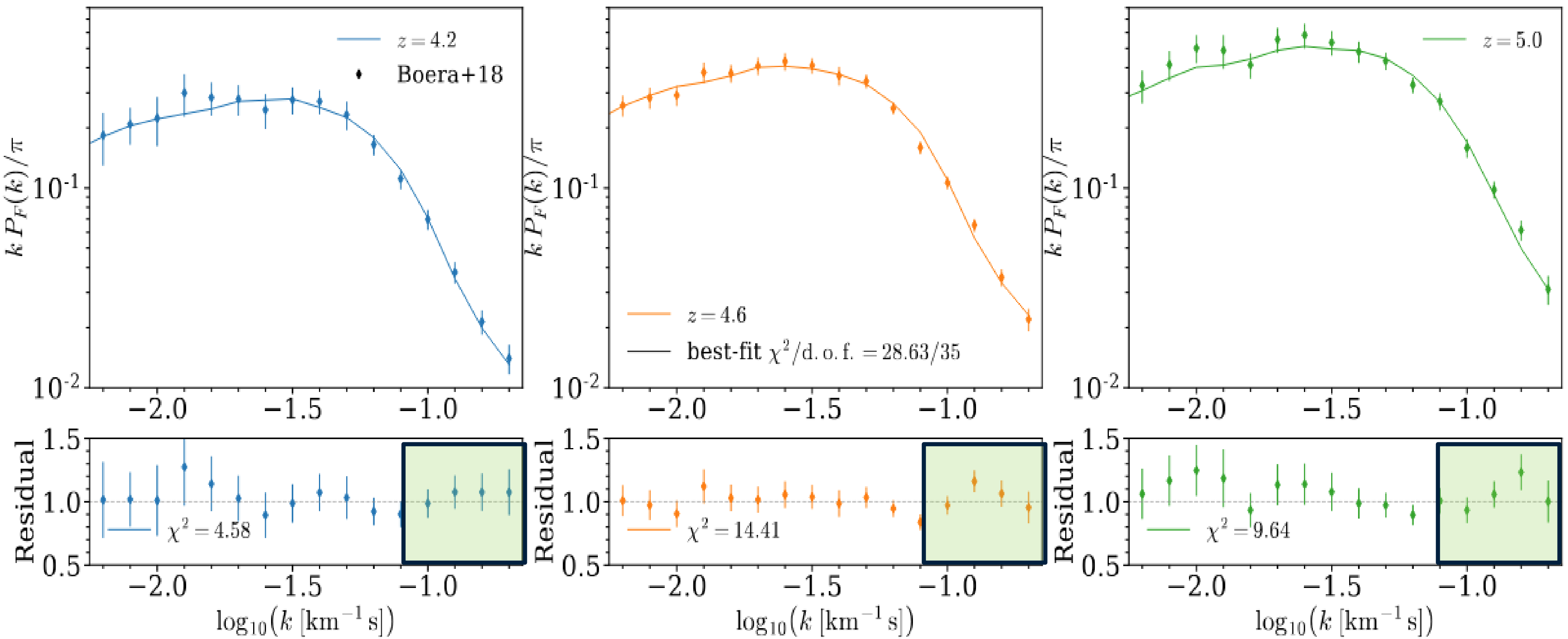
Pavicevic, Irsic, Viel, et al. 2025, arXiv:2501.06299

Impact on flux power



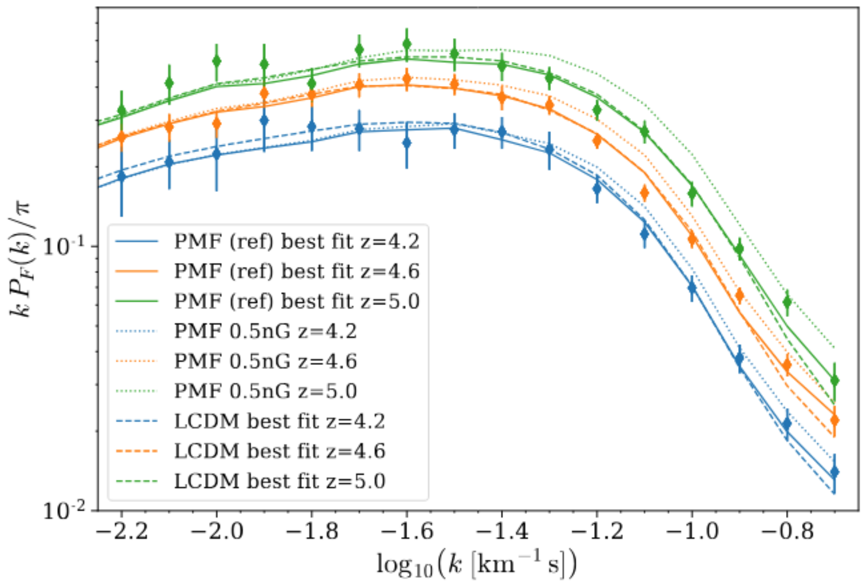
- ➢ Strong scale/z dependent increase of power

Best fit PMF models

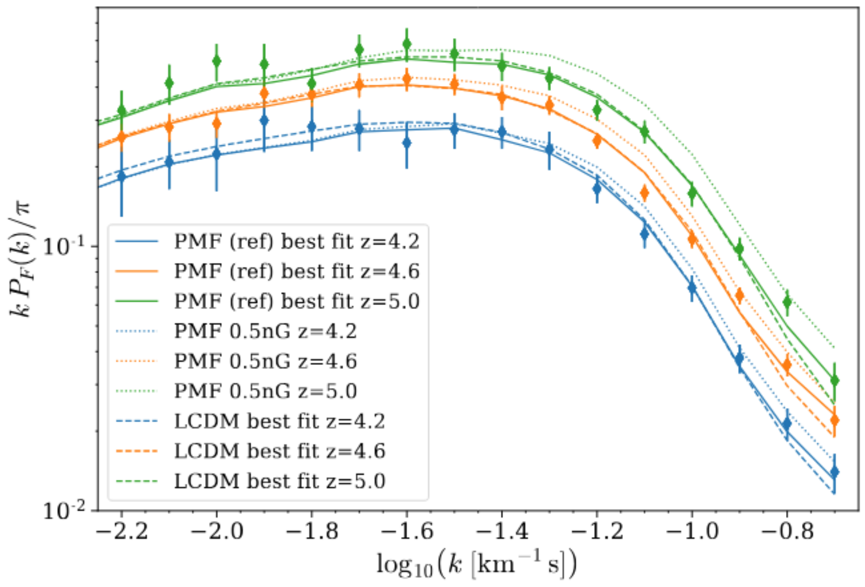


$$\chi^2_{\Lambda\mathrm{CDM}} = 40.8 \ \text{ for } \ 36 \ \text{ d.o.f.} \qquad \chi^2_{\mathrm{PMF}} = 28.63 \ \text{ for } \ 35 \ \text{ d.o.f.}$$

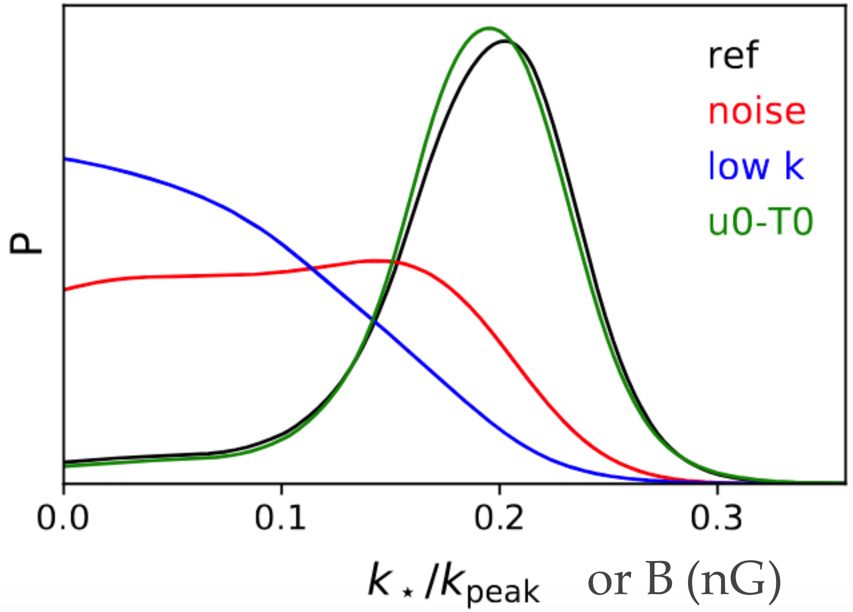
Constraints on peak position



Constraints on peak position



$$k_{\mathrm{peak}} = \lambda_{\mathrm{D}}^{-1}\sqrt{\frac{n_{\mathrm{B}}+5}{2}}\ \mathrm{Mpc}^{-1} \qquad k_\star = 10\,\mathrm{Mpc}^{-1}$$



Detection → B=0.2 ± 0.05 nG (1σ)
Upper limit → B=0.3 nG (3σ)

PMFs: interplay with baryonic corrections

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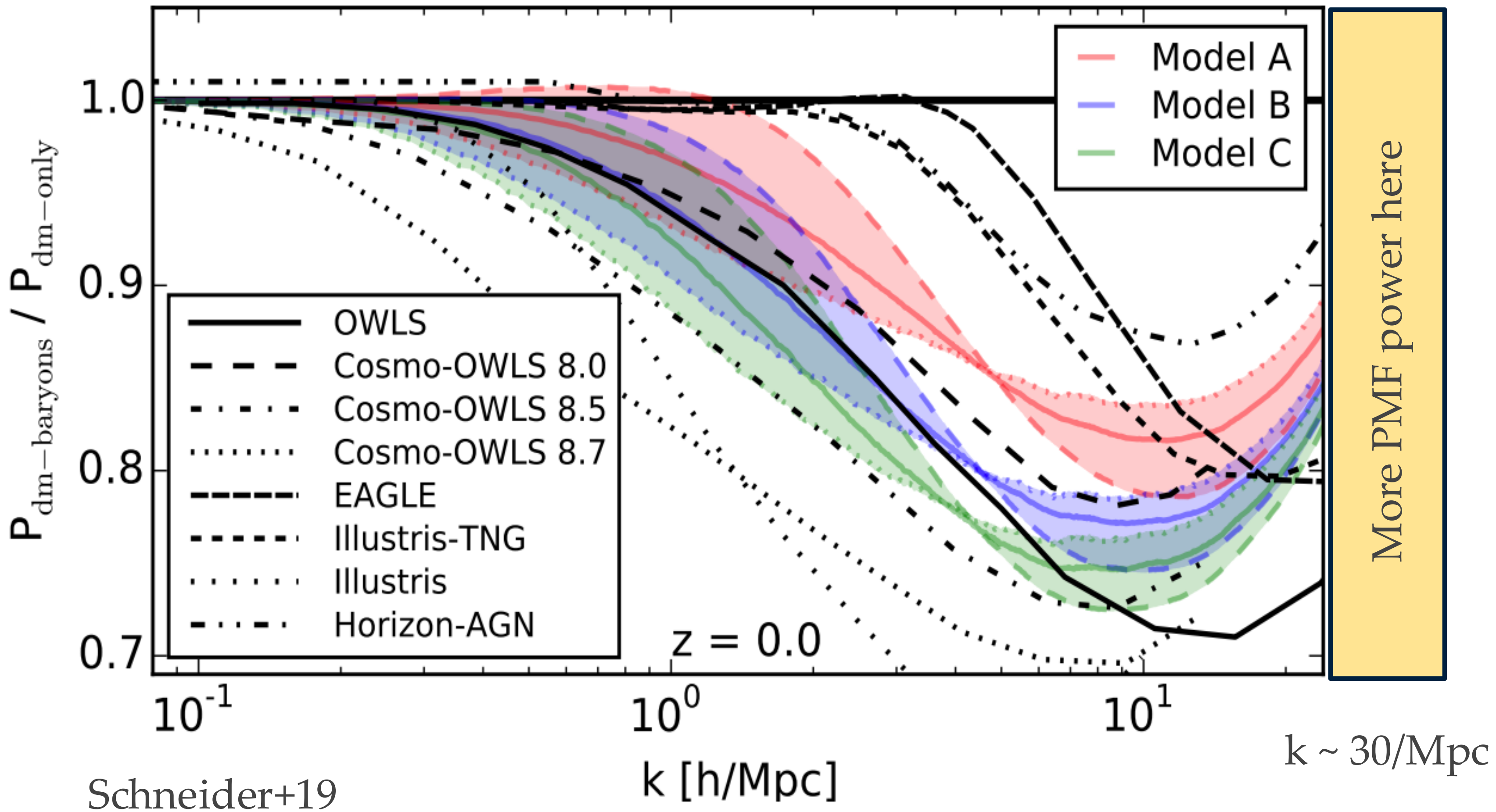


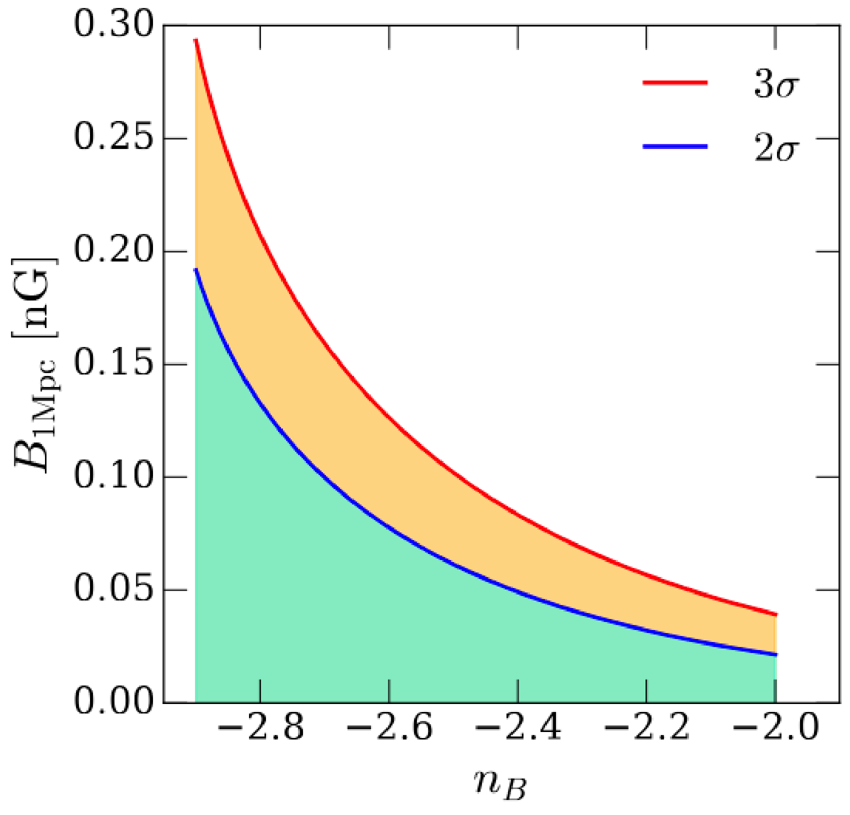
Schneider+19

Summary

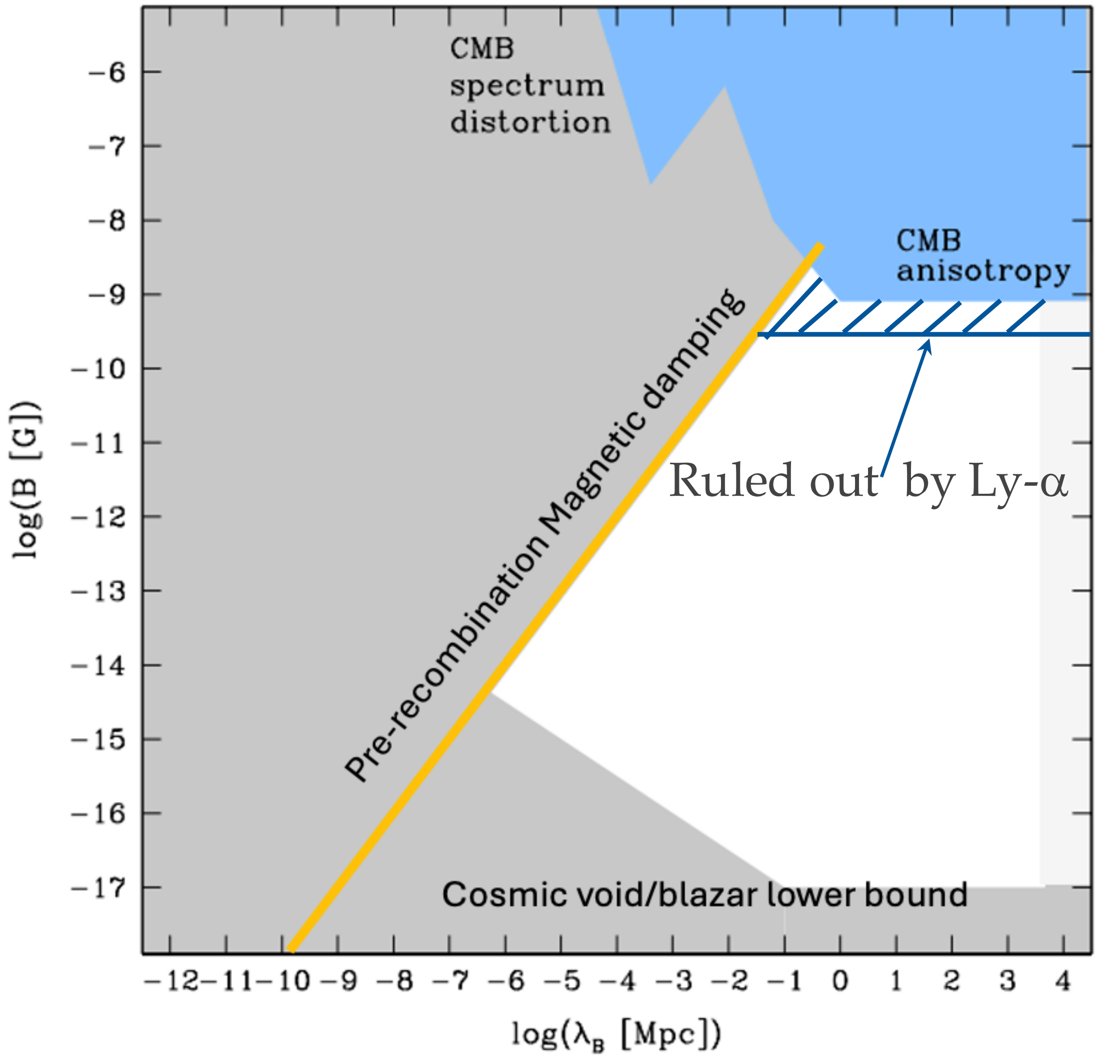
- PMFs can enhance baryon fraction apart from enhancing matter power spectrum
- Can affect **star formation/important for JWST**
- Observing **high baryon fraction** at high redshift will be smoking gun signal for PMFs
- **Lyα forest ideal probe** of PMFs, since it samples low density environments far from galaxies
- Constraints from Lyα forest point to **a detection at 0.2 nG** or more conservatively a tight 3σ **upper limit of 0.3 nG**

Constraints on peak position

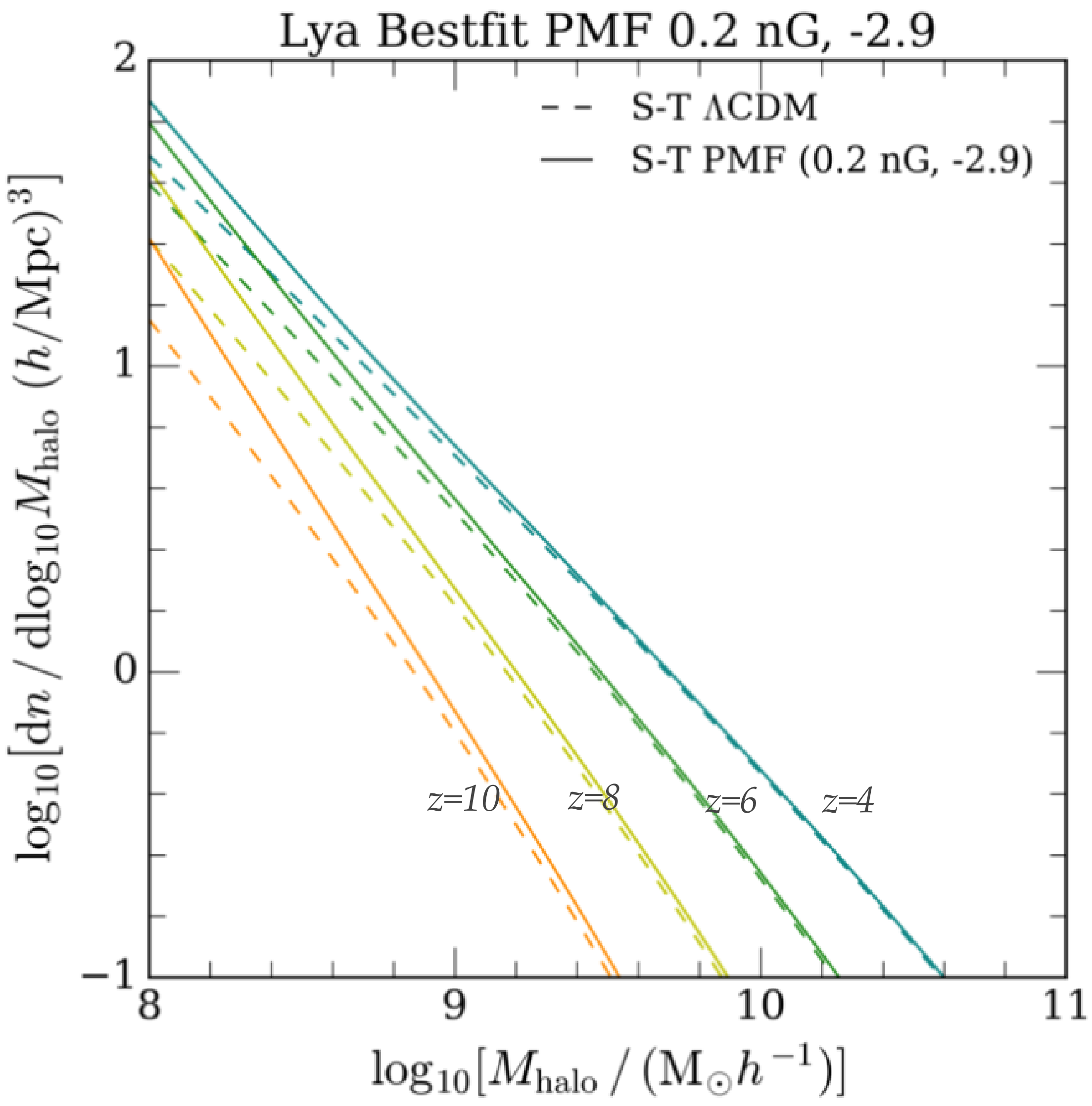
Matteo Viel



Extending to other n_B values

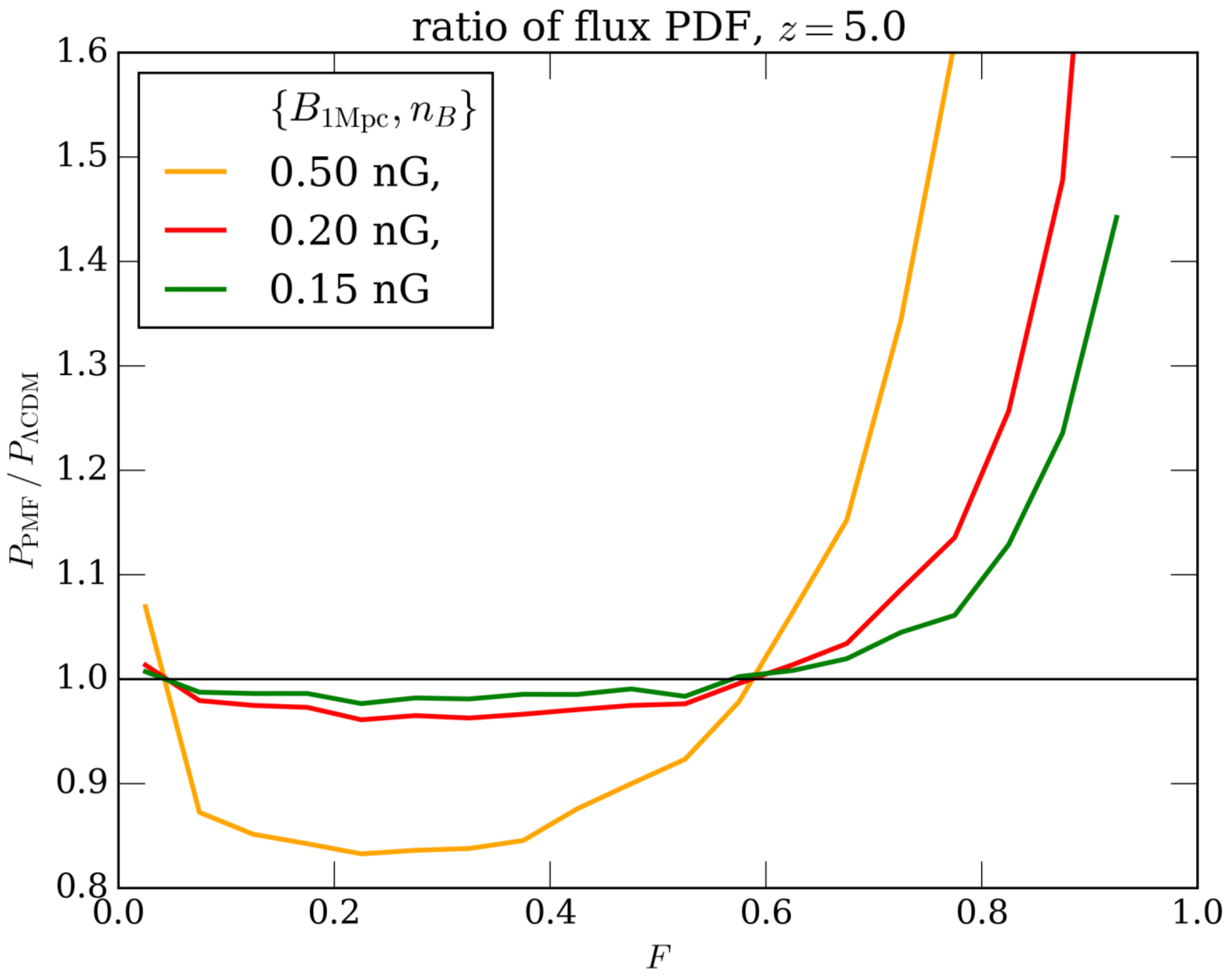


Implications for the detection

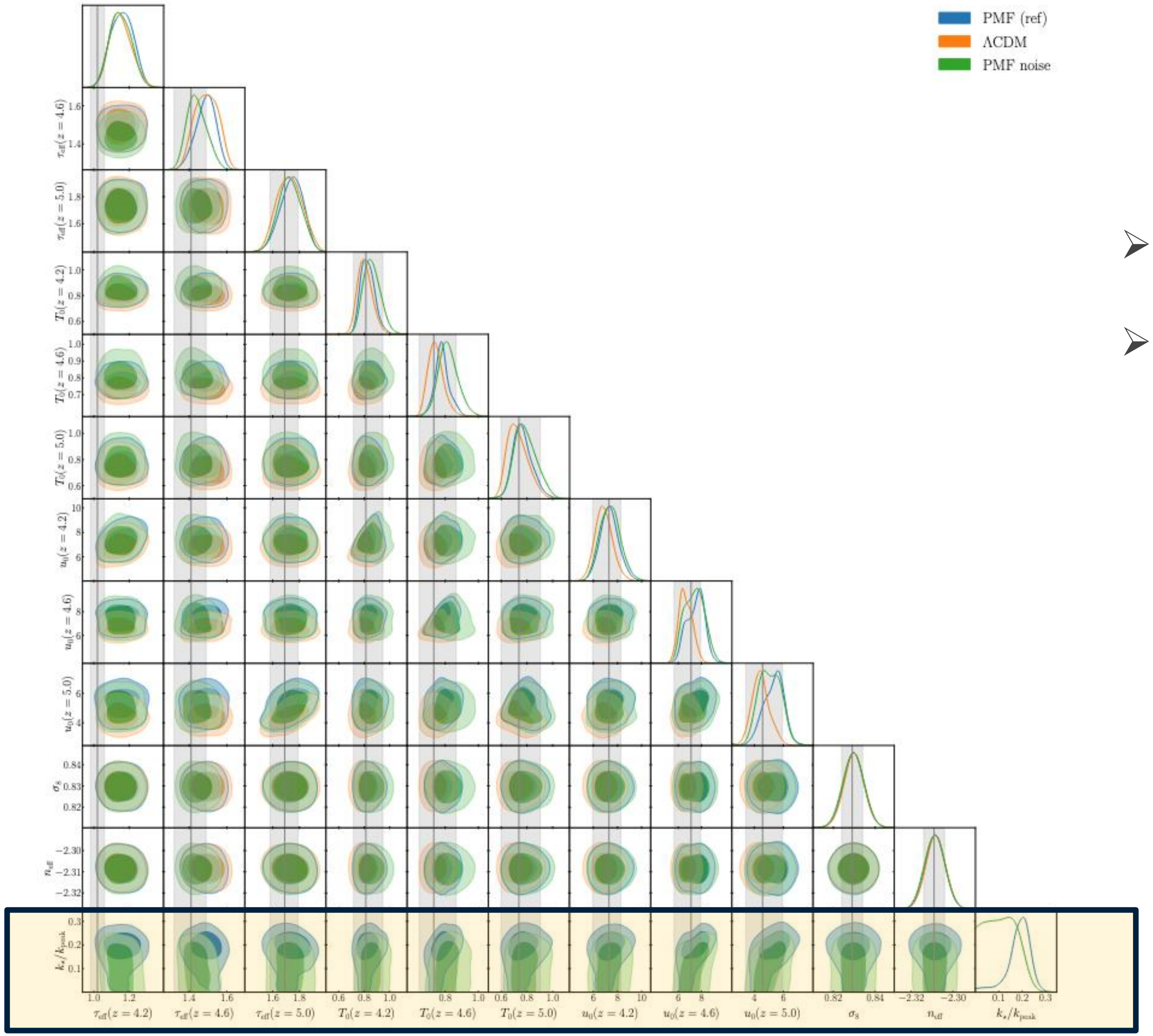


- MF is boosted at $M_{halo}<10^9\ M_\odot/h$
- ~2 more $10^8\ M_\odot/h$ haloes at z=10 expected compared to ΛCDM

PMFs: flux pdf

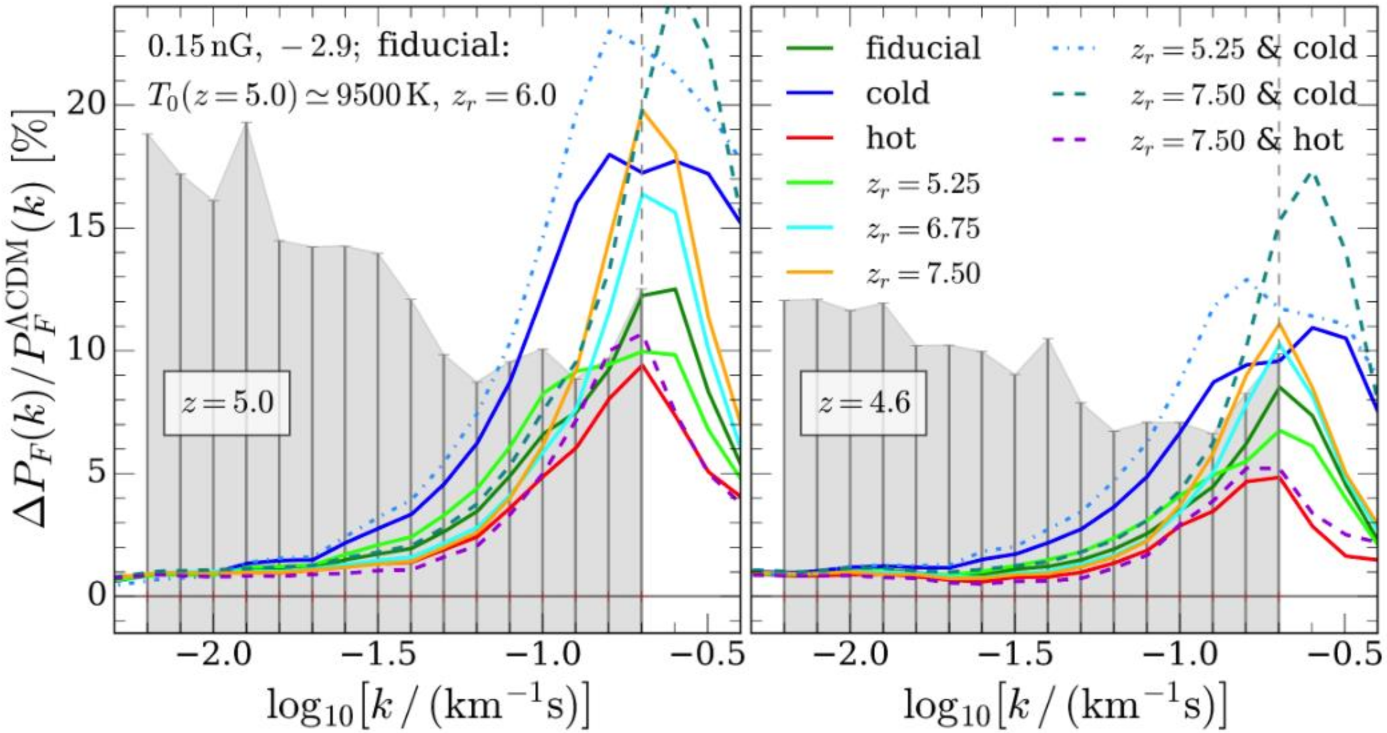


Extra slides: triangle plot



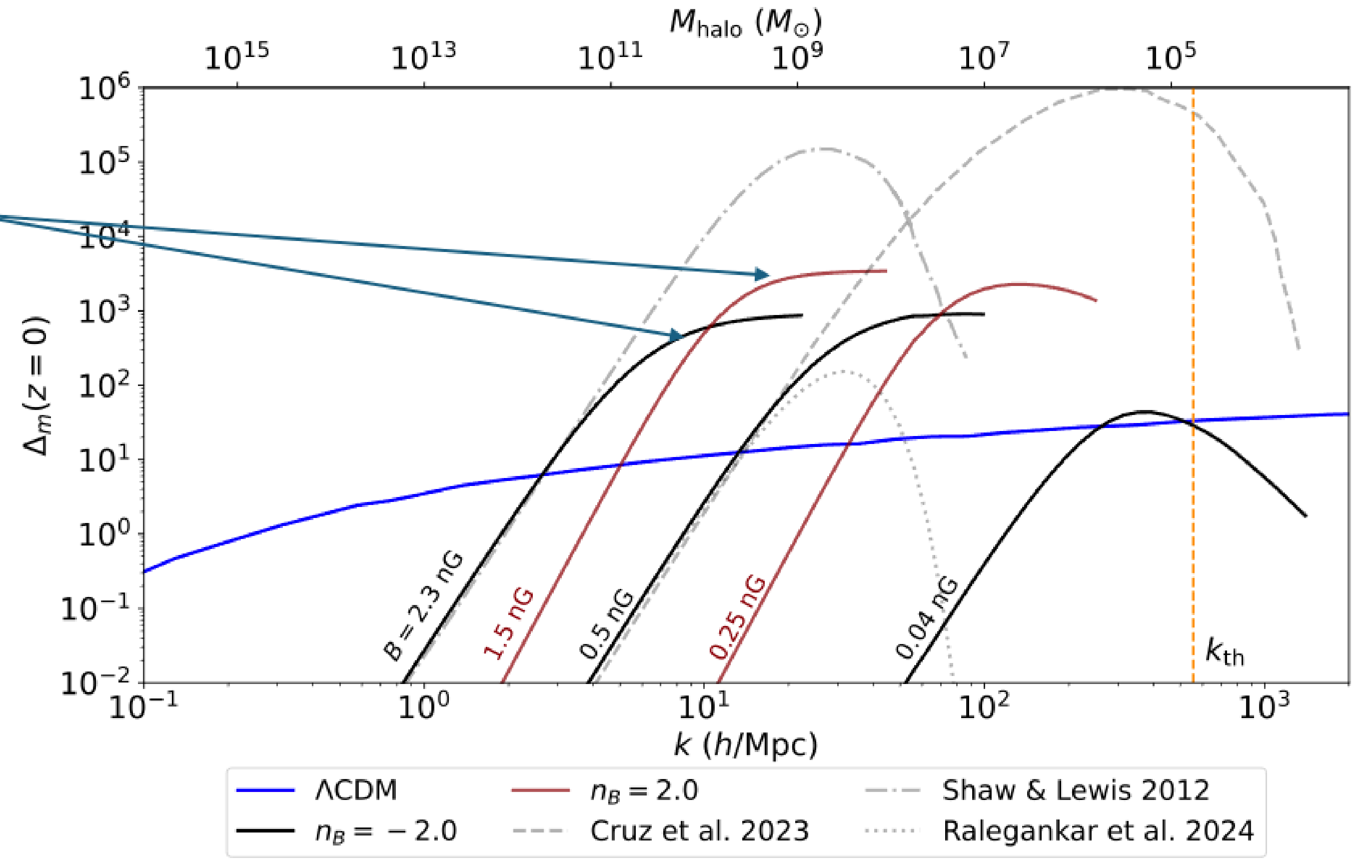
- Not strong degeneracies present
- Weak degeneracies with injected heat and noise modelling

Extra slides: PMFs vs thermal parameters



Non-linear scales with MHD

Magnetic Jeans scale/ non-linear regime



Ralegankar, Garaldi, Viel, 2024, arXiv:2410.02676