# Fundamental physics with ANDES

ANDES

Matteo Viel - SISSA (Trieste, Italy)

Meeting della strumentazione ELT a guida italiana

Napoli 14/5/26

# WG-4 activities



| | |
|---|---|
| Variation of fine structure constants | Talk by Dinko Milakovic |
| Redshift drift | Talk by Luca Pasquini |
| Measuring matter properties at small scales | **This talk** |

# WG-4 activities



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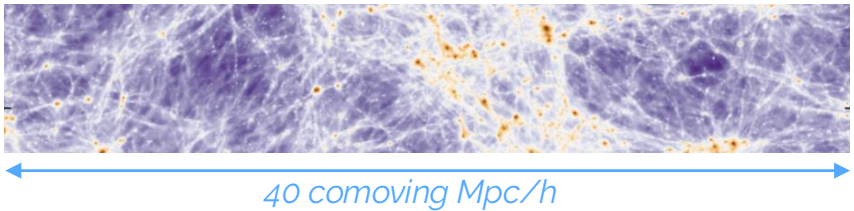


Structures at the kpc-Mpc scale, intergalactic matter

# Cosmology with a small field of view

Matteo Viel

- High-resolution, few targets, small statistical samples might seem not the ideal way to perform cosmological investigations. Sample variance needs to be estimated/modelled.
- However, even from a few targets (i.e. QSO spectra), it is possible to get lots of small-scale information (modes).
- Tricky bit is to interpret small scale information (i.e. non-linearities).
- Non-linearities couple scales, and couple astro/gravitational effects and typically erase primordial information

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Turning this into:

**Small-scale Cosmology with the (right) field of view**

# The landscape of spectroscopic surveys

Matteo Viel

*Spec5 white paper*

**Table 1.** Yield of Stellar and Galaxy Velocities from Recent, Current and Planned Surveys

| Instrument | Telescope | Nights / year | Star RVs | Galaxy Redshifts ($z < 2.1$) | Galaxy Redshifts ($z > 2.1$) | Area [deg$^2$] | Operation [years] | Ref |
|---|---|---|---|---|---|---|---|---|
| SDSS/BOSS/eBOSS | Sloan 2.5m | all | 1.0M | 3.5M | 0.34M | 10,000 | 1999-2019 | (Abdurro'uf et al. 2022) |
| SDSS/APOGEE | Sloan 2.5m **(a)** | all | 0.73M | – | – | all-sky | 2011-2019 | (Abdurro'uf et al. 2022) |
| SDSS-V | Sloan 2.5m **(a)** | all | 6.0M | 0.4M | | all-sky | 2020-2027 | (Kollmeier et al. 2017) |
| LAMOST | 3.6-4.9m | all | 11.1M | 0.27M | 0.02M | 15,000 | 2012- | (Yan et al. 2022; Jin et al. 2023) |
| Gaia | 0.72m$^2$ space | all | 7.2M | – | – | all-sky | 2014-16 | (Gaia Collaboration et al. 2018) **(b)** |
| HETDEX | HET 9.2m | 60 | – | – | 1M | 540 | 2014- | (Gebhardt et al. 2021) |
| DESI | Mayall 4m | all | 20M | 40M | 0.8M | 14,000 | 2021-26 | (DESI Collaboration et al. 2016) |
| Euclid | 1.2m space | all | – | 35M | – | 15,000 | 2024- | (Laureijs et al. 2011) |
| Sumire/PFS | Subaru 8.2m | 20 | 1M | 3.5M | 0.5M | 800/1400 | 2025- | (Takada et al. 2014) |
| 4MOST | VISTA 4m | all | 16M | 12.3M | 0.1M | 15,000 | 2025- | (Guiglion et al. 2019) **(c)** |
| Roman | 2.4m space | all | – | 12M | 1M | 2,000 | 2027- | (Wang et al. 2022) |
| DESI-ext | Mayall 4m | all | | 20M | 0.2M | 17,000 | 2025-28 | |
| MUST | New 6.5m | all | – | 126M | 40M | 11,000 | 2030's | (Zhao et al. 2024) |
| MSE | New 11.25m | all | 10M | 7M | 0.6M | 3200/80 | 2030's | (The MSE Science Team et al. 2019)**(d)** |
| WST | New 12m | all | 25M | 250M | | 18,000 | 2030's | (Bacon et al. 2024) **(e)** |
| MegaMapper | New 6.5m | all | 150M | 76M | 112M | 18,000 | 2030's | (Schlegel et al. 2022d,c) **(f)** |
| **Spec-S5** | **2 x 6m** | **all** | **150M** | **76M** | **112M** | **all-sky** | **2036-** | **(g)** |

Stage V

ANDES spectrograph is likely to "fight" against cosmological surveys

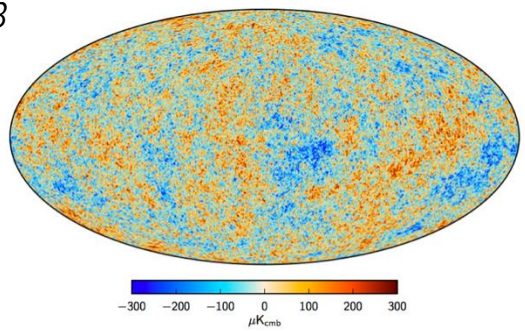
# Why small scales are interesting

Matteo Viel

- Cosmic Microwave Background or galaxy clustering do not tell us anything about microphysics of dark matter particles
- And very little about how structure formation proceeds, since in LCDM small haloes are supposed to form first
- They are effectively probing the structure formation paradigm in a regime which is either at z=1100 and or relatively large scales.

*Planck CMB*

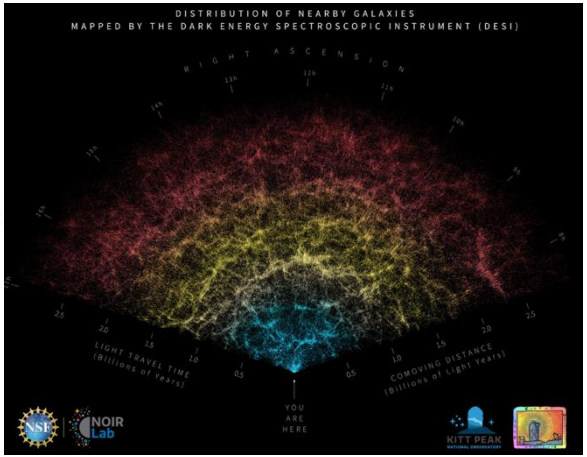
Initial Conditions




13 Gyrs later

Under the influence of gravity and astrophysical processes....

Non-linear Universe

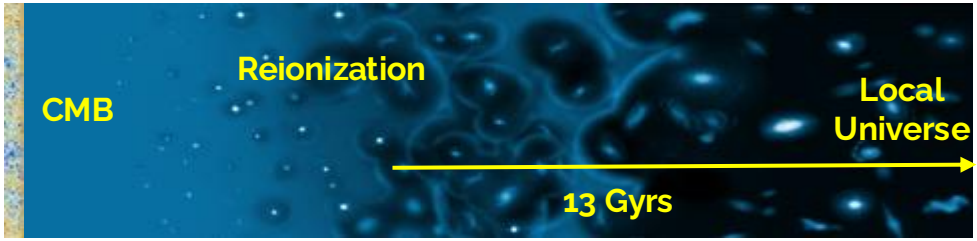



*DESI galaxies*

# The promises of the post-reionization Universe

Matteo Viel

## The **post-reionization** Universe




- **Complementary** to Cosmic Microwave Background and local Universe
- **More linear** Universe (simpler?)
- Full of **cold gas**-dominated galaxies
- Large **uncharted volume**: JWST, DESI, LSST, Euclid, Intensity Mapping, etc.

Spectroscopic investigation of a large volume with the Ly$\alpha$ forest Using 3D and 1D flux power

DESI results have elevated 3D power to a full geometrical cosmological probe (BAO)

1D power is a dynamical probe

Very soon also 3D power will be used to address structure formation (i.e. clustering)

# Physical scales

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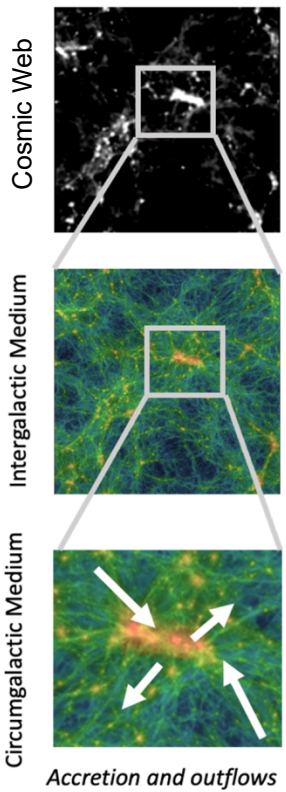


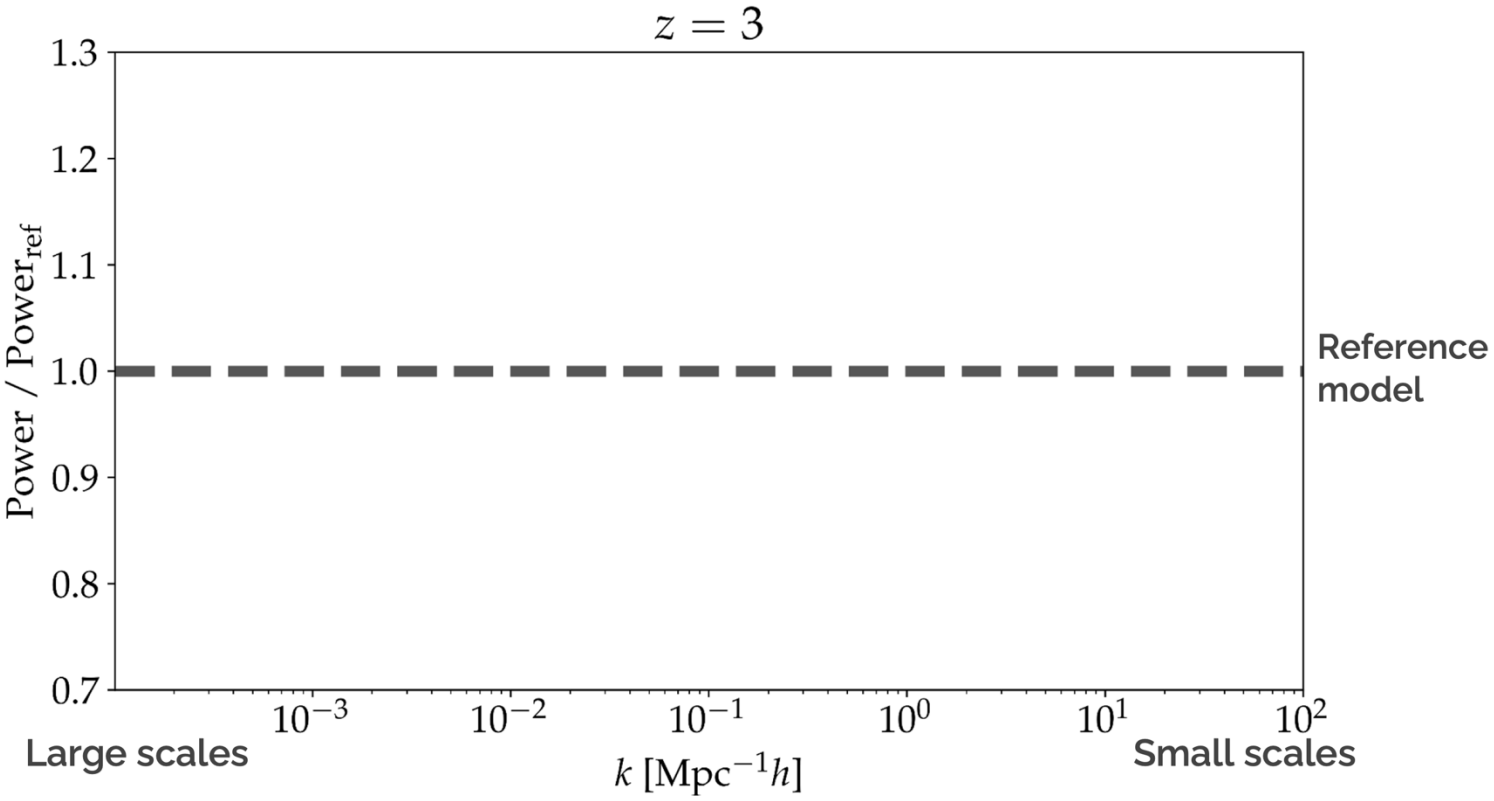

# Physical scales

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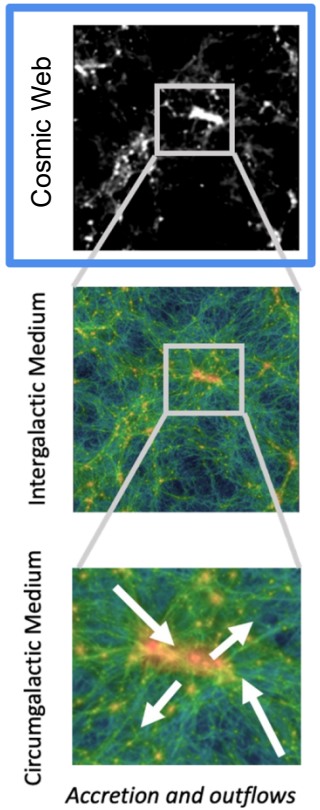


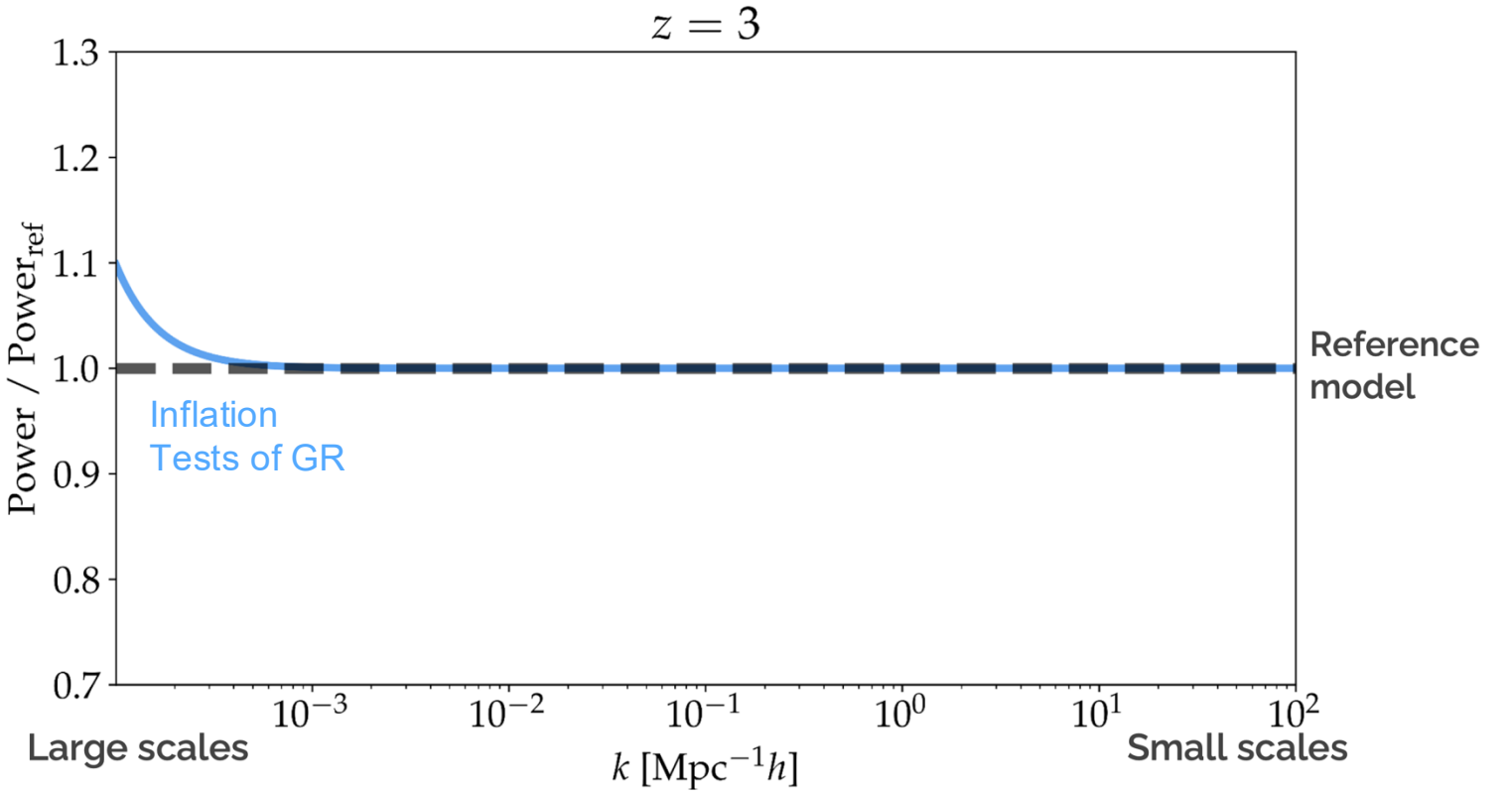

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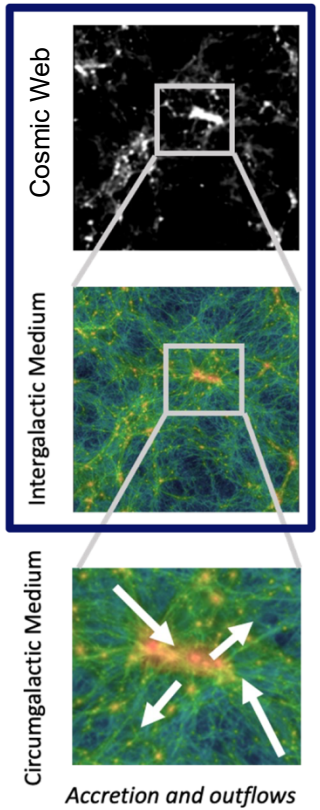


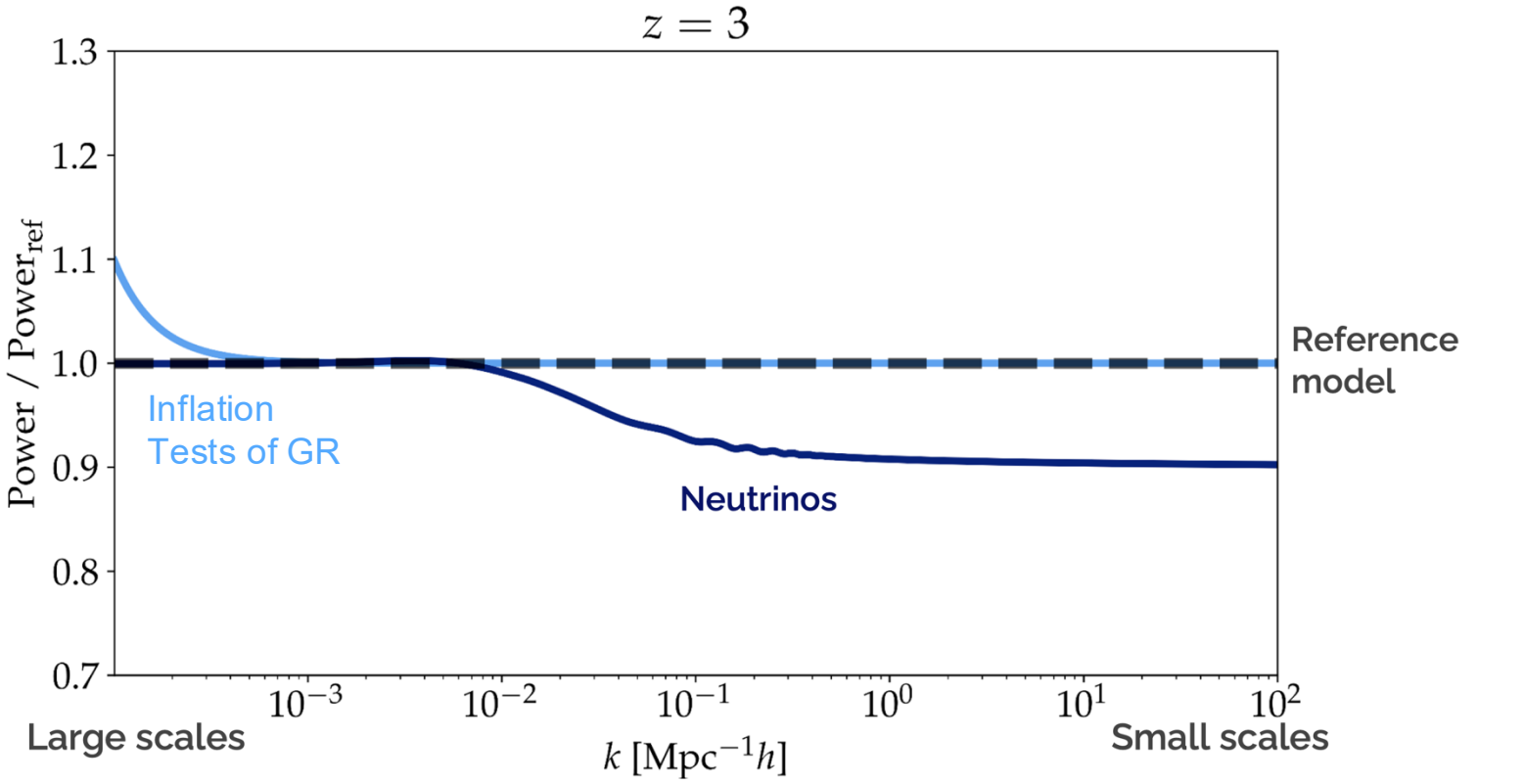

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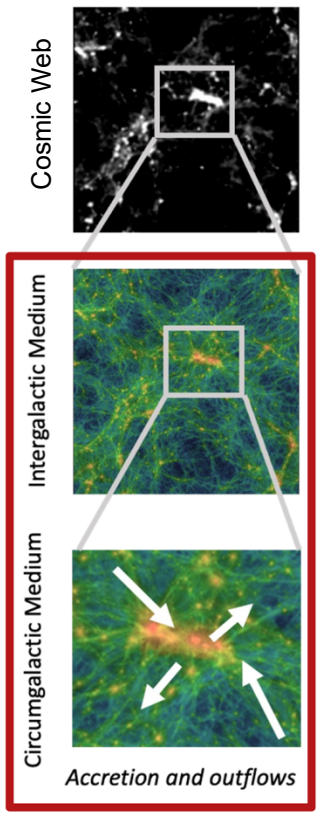


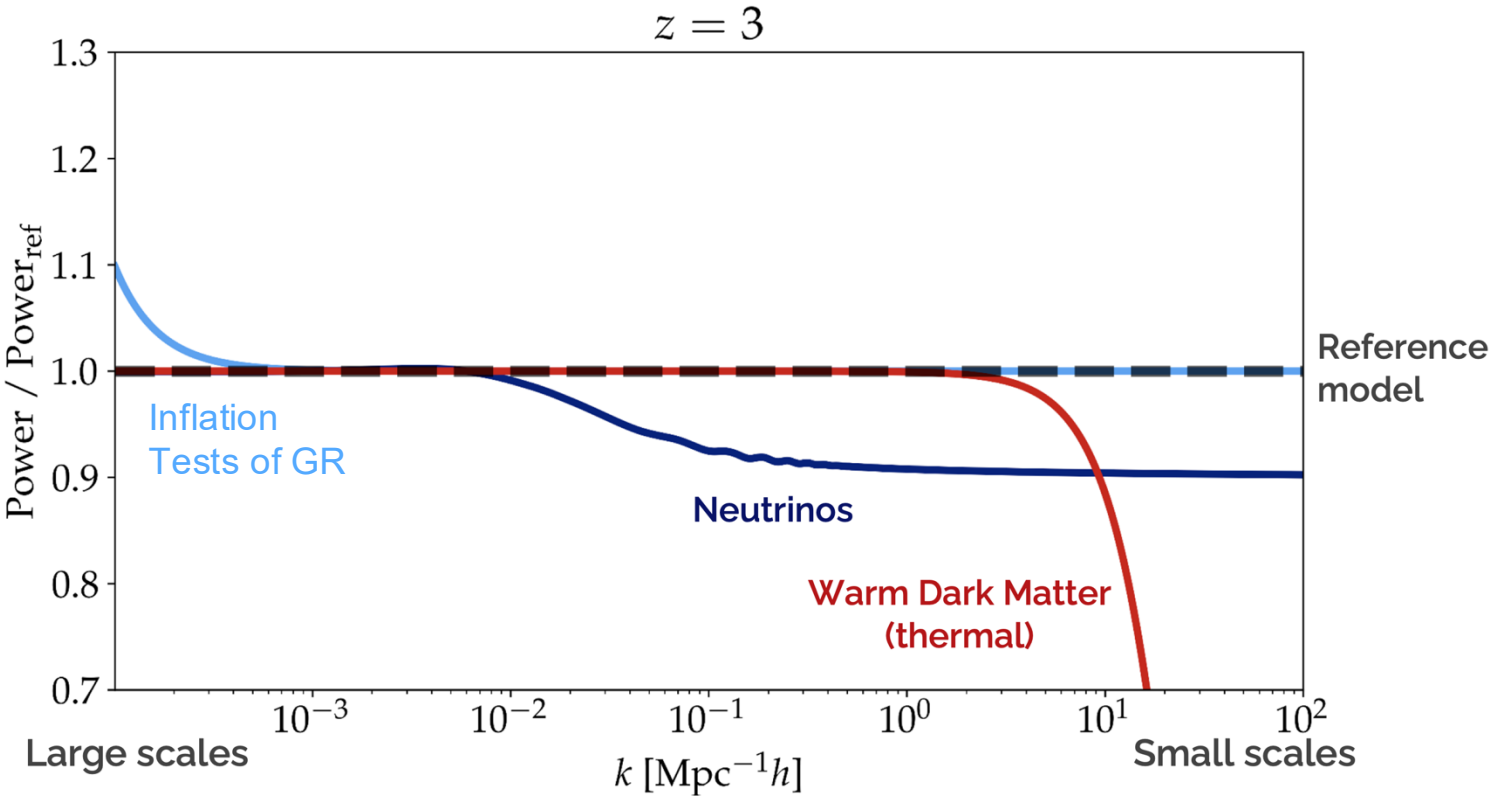

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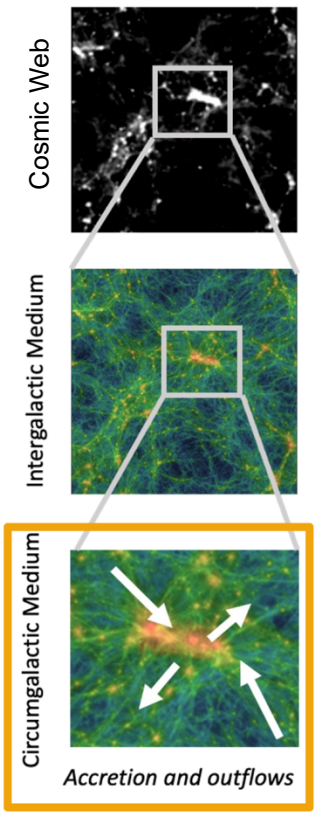


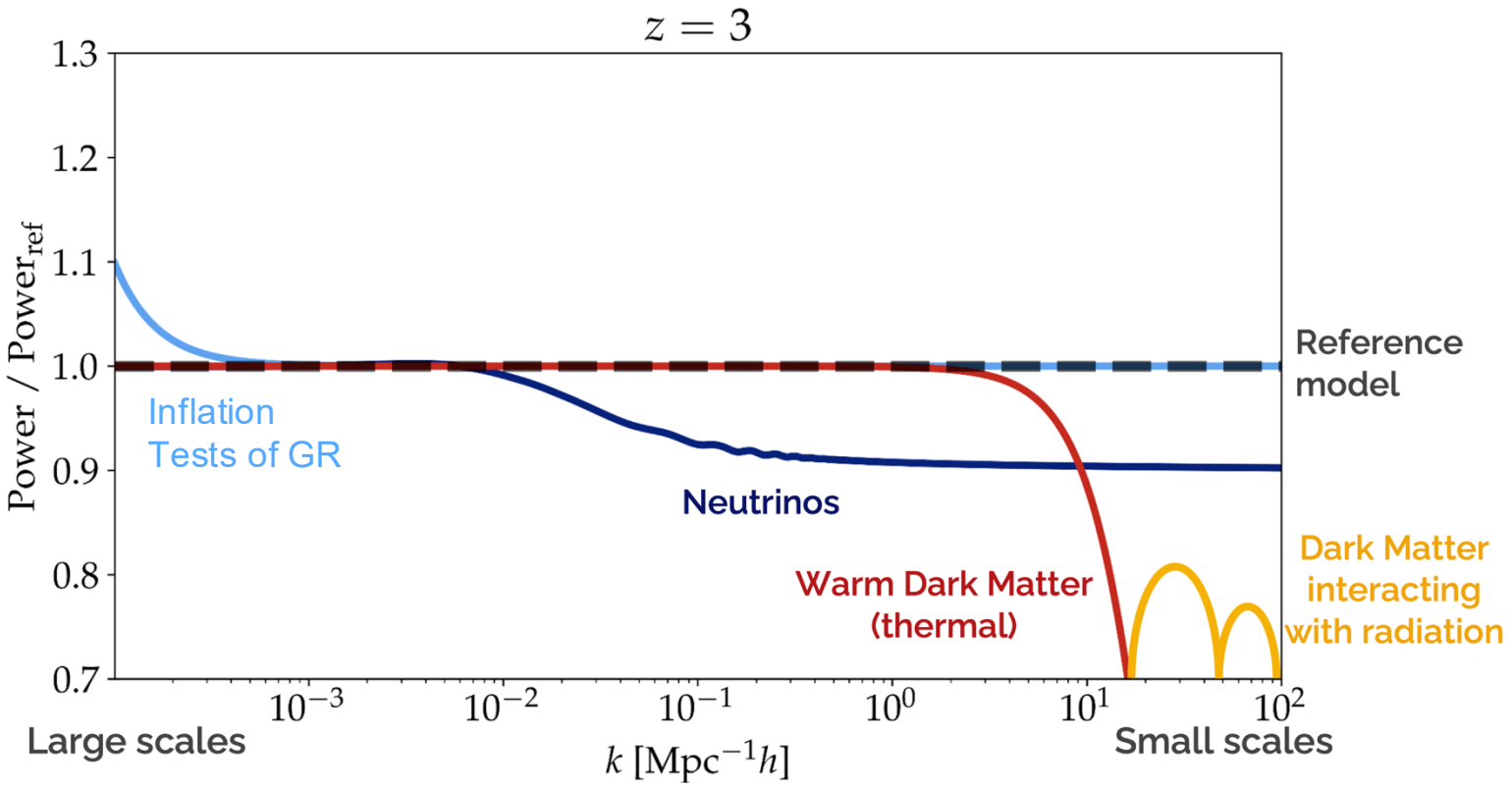

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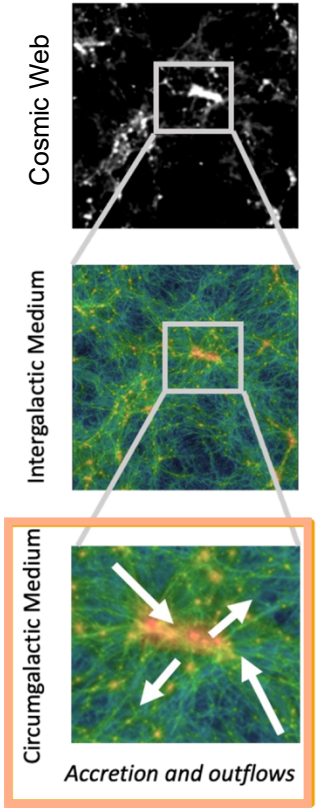


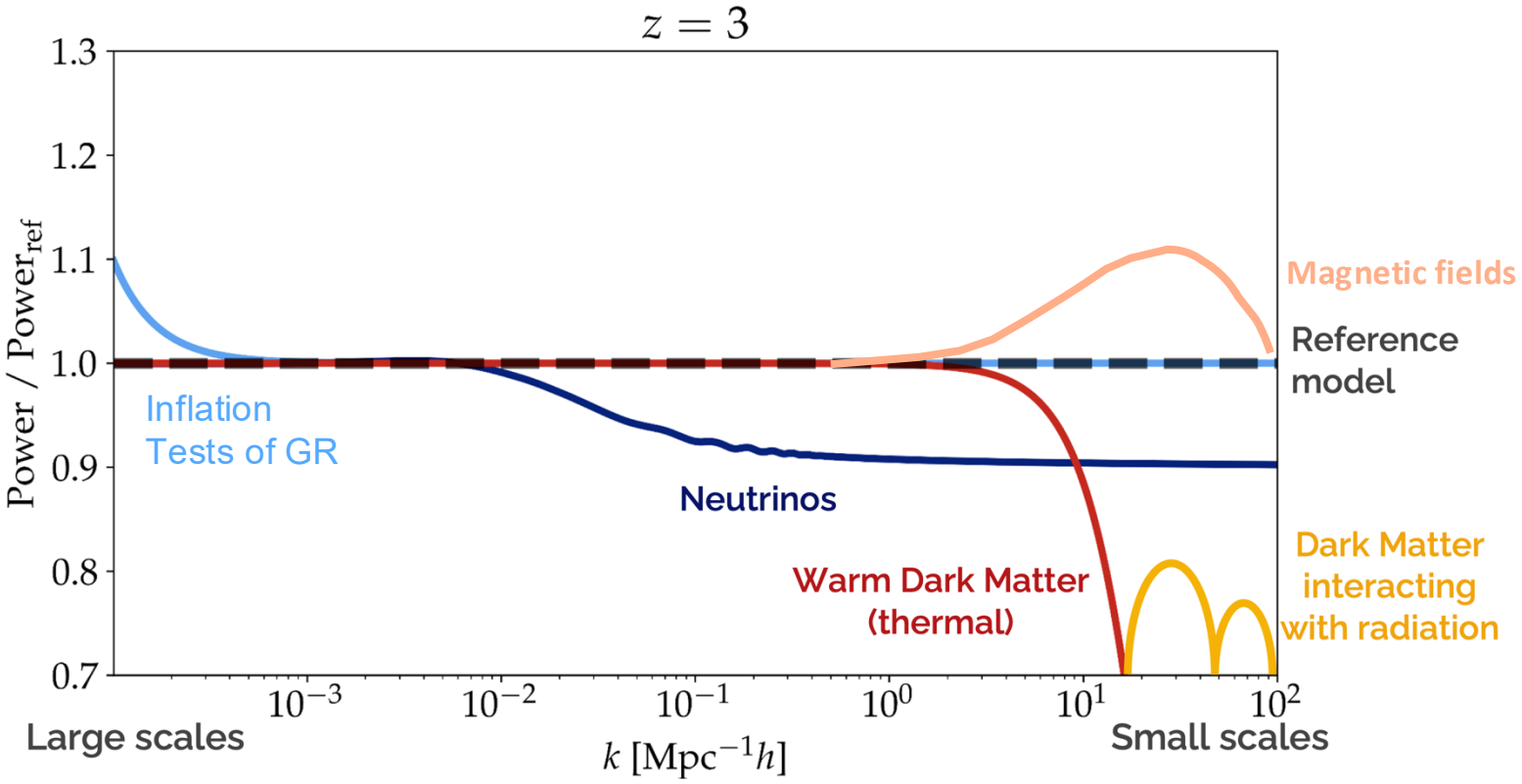

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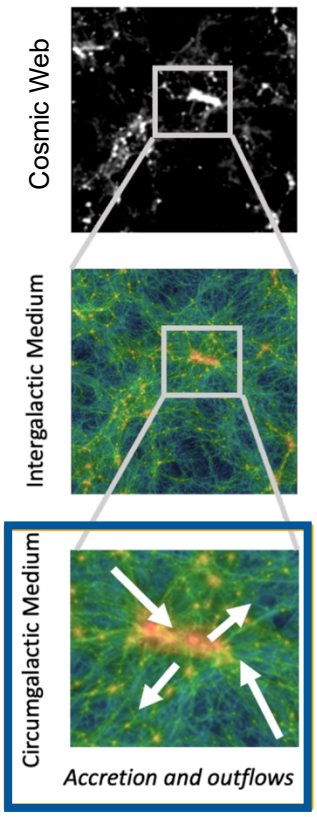


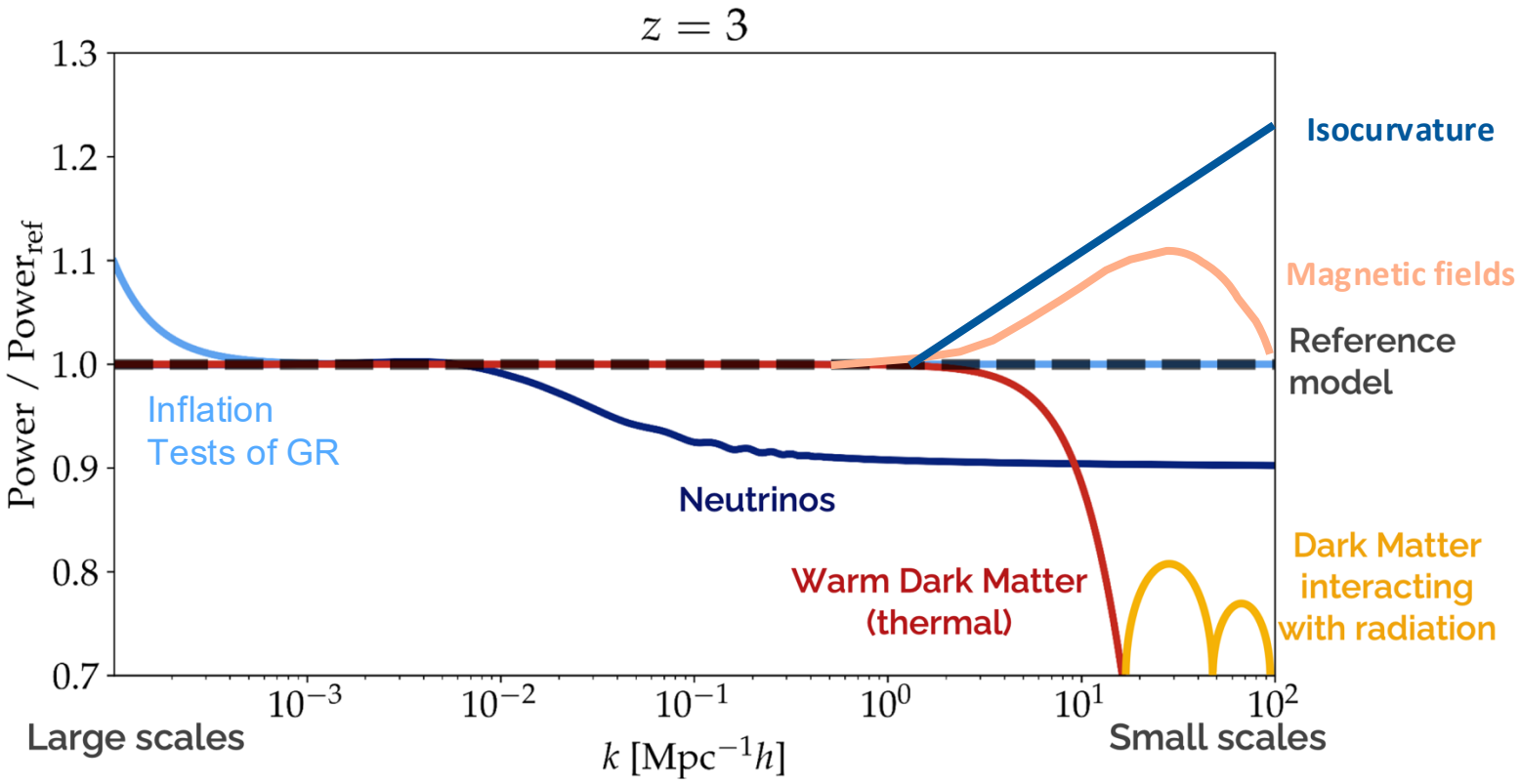

# Physical scales

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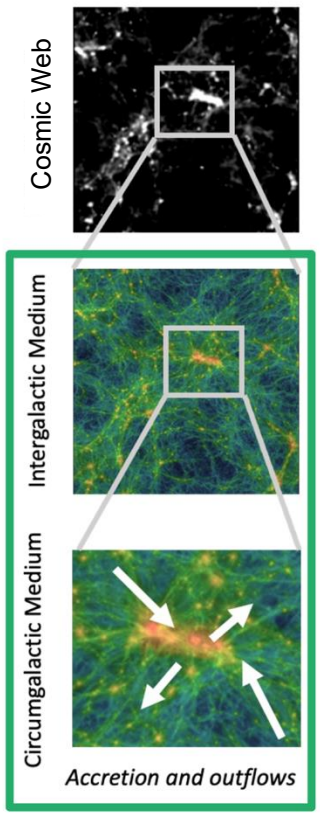


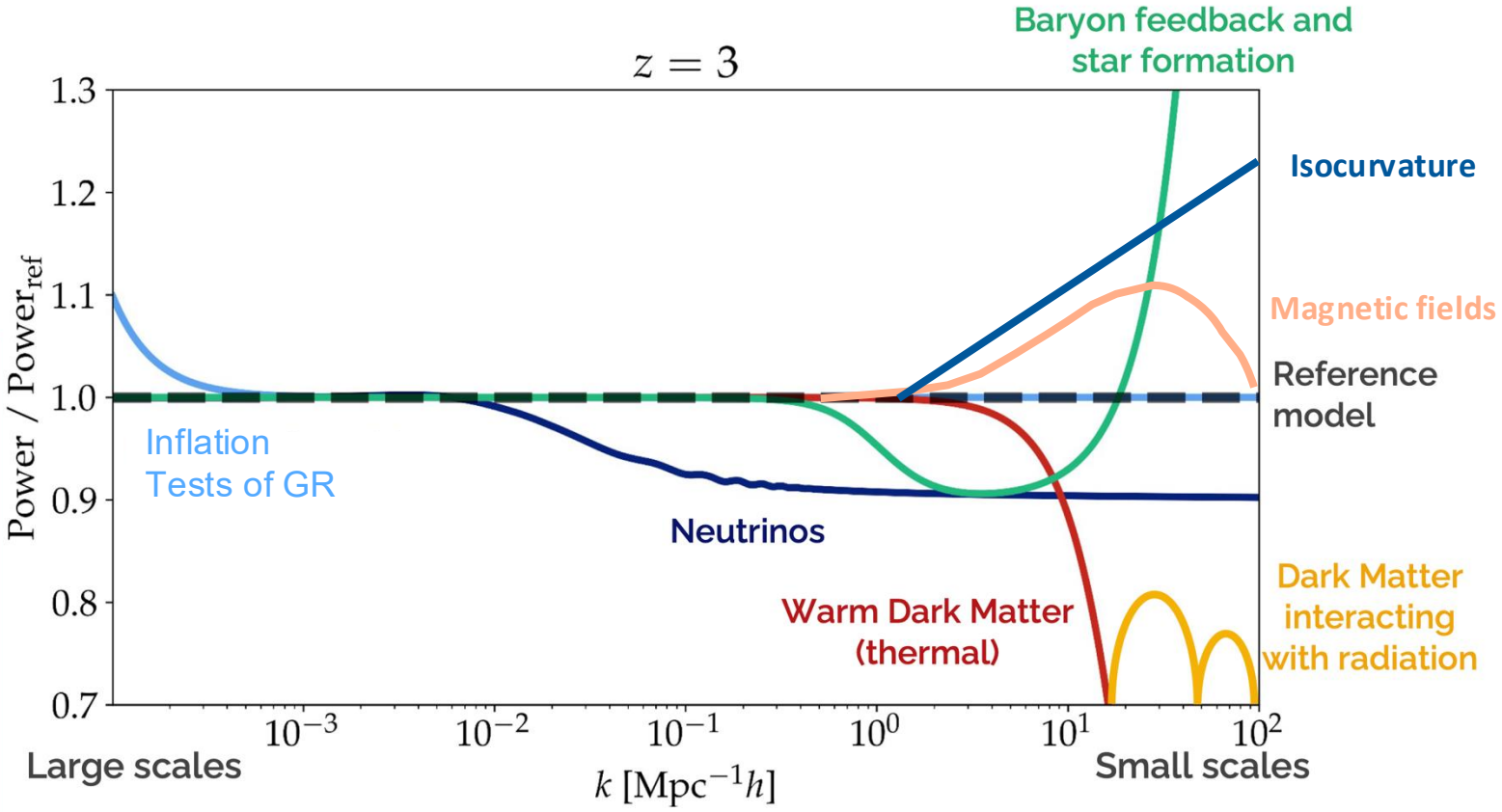

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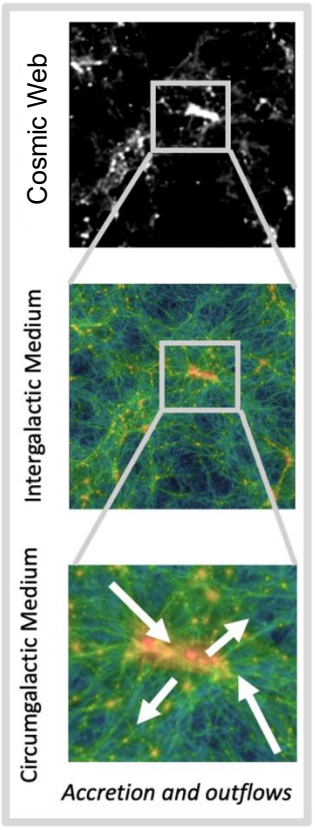


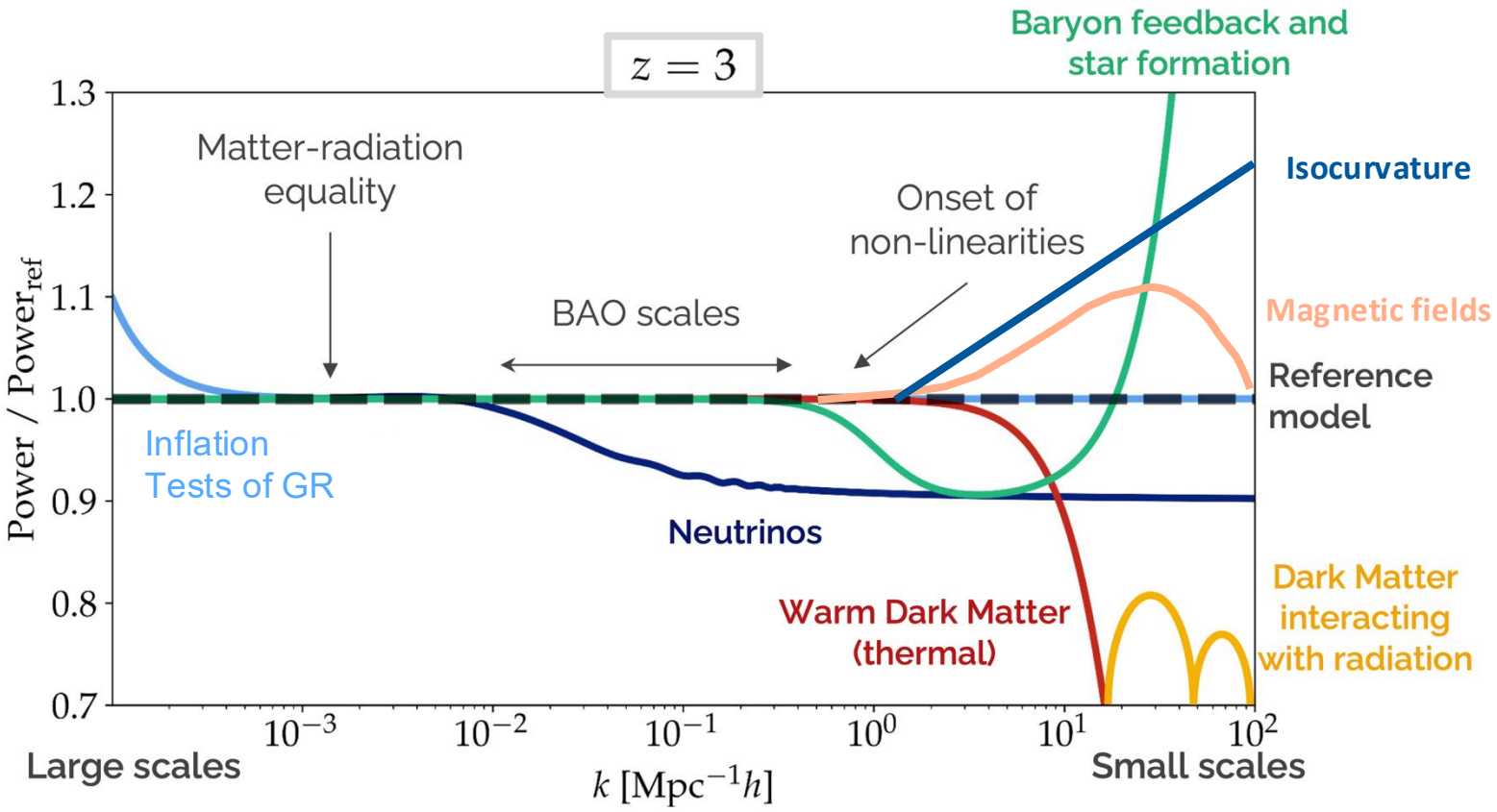


HI measures density perturbations in a matter dominated regime!

# UVES/Keck and the forest 1D flux power

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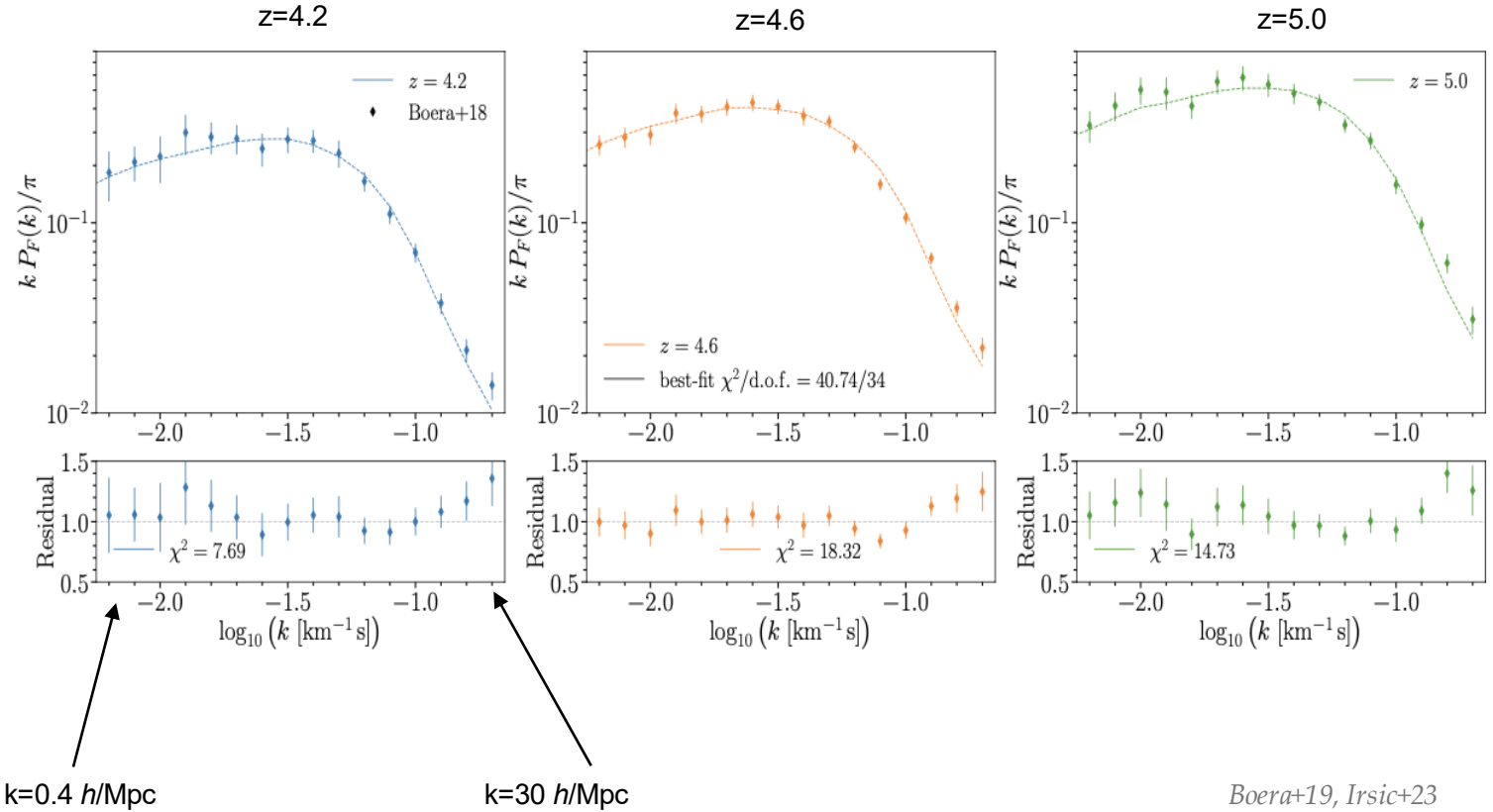
1D FLUX POWER




*Boera+19, Irsic+23*

# UVES/Keck and the forest 1D flux power

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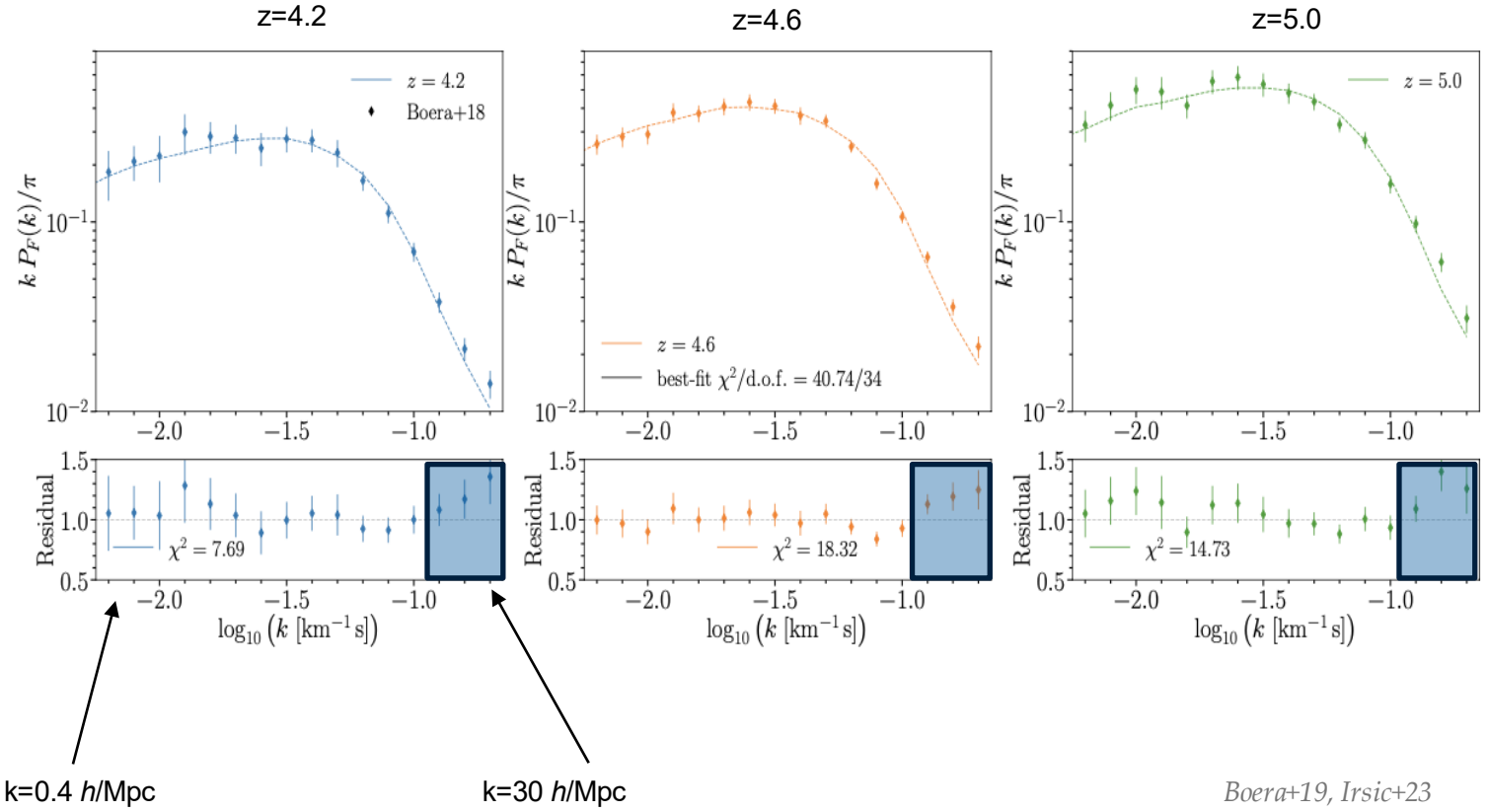
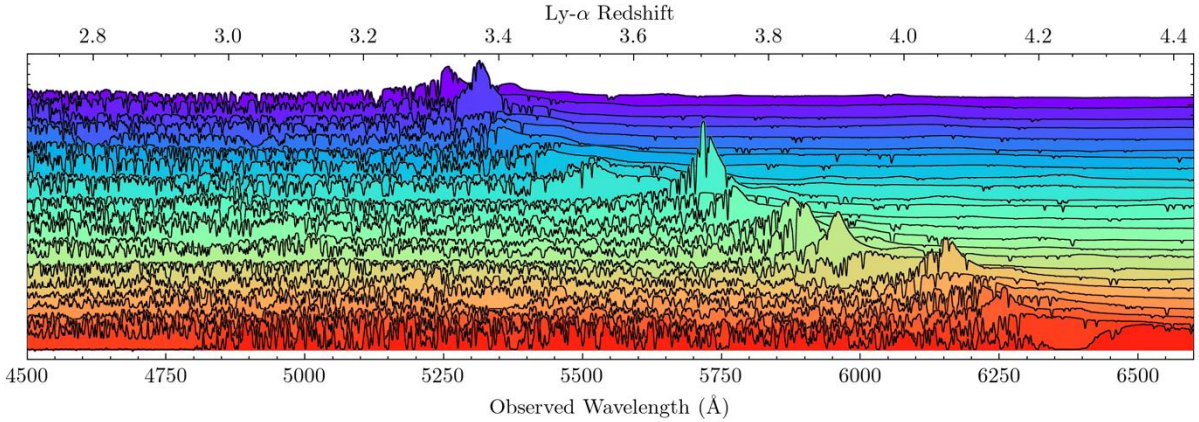



*Boera+19, Irsic+23*

# ESPRESSO and the forest

Matteo Viel




Andrea Trost

- The EQUALS sample (PI. Berg): 23 bright quasars; $3.3 < z < 4.3$
- Including Noise and Resolution correction the Flux Power spectrum is defined to much smaller scales w.r.t. literature analyses (i.e. HIRES/UVES data)
- Greater sensitivity to small scale physics (thermal state of the IGM too)

# ESPRESSO and the forest

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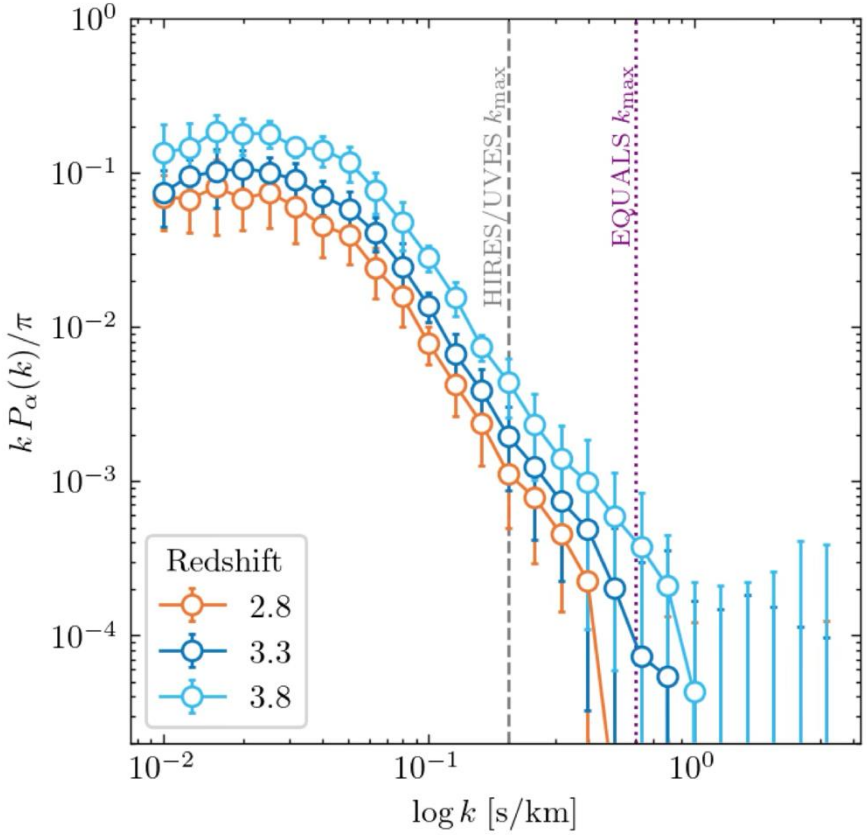


0.2 s/km → 8 kpc/h [physical]

0.8 s/km → 2 kpc/h [physical]

Noise

$$P_\alpha = \frac{P_{\rm raw} - P_N}{W_R^2(k)}$$

Resolution

# ESPRESSO and the forest: resolution

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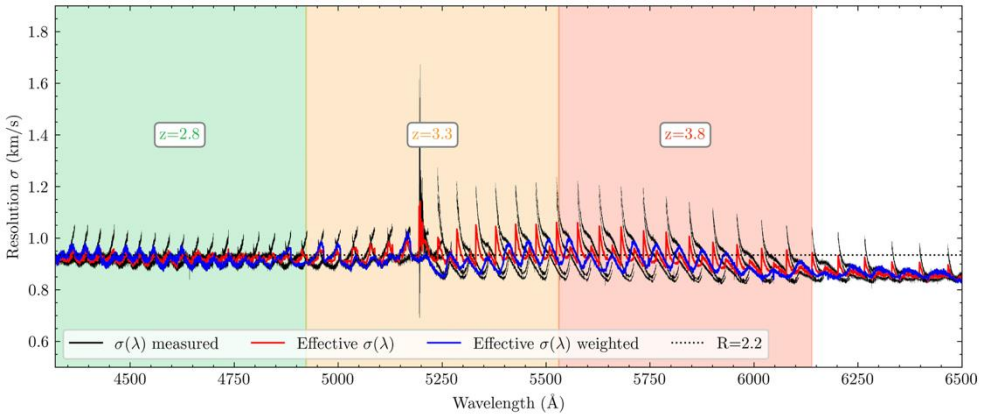
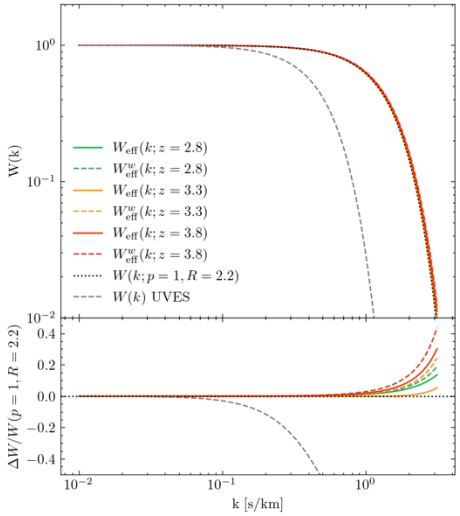



- The resolution of ESPRESSO is measured with very high precision by fitting the lines of the LFC calibration frames
- Resolution varies across each order and among slices when combining orders resolution is a mixture of gaussians R is not constant ($R_{ESP}$~2.2 km/s; $R_{UVES/HIRES}$~6 km/s)
- Precise determination of LSF is critical for resolution correction and small-scale analysis
- Small variations in R can have up to 50% differences in W at k~1 s/km

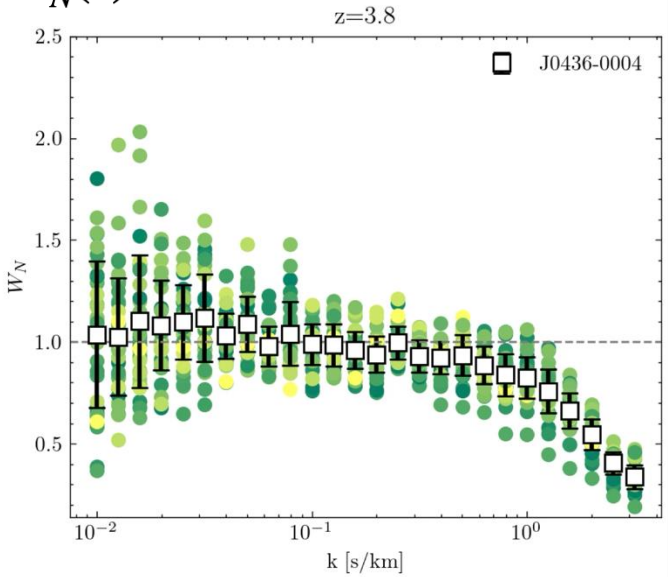
# ESPRESSO and the forest: noise

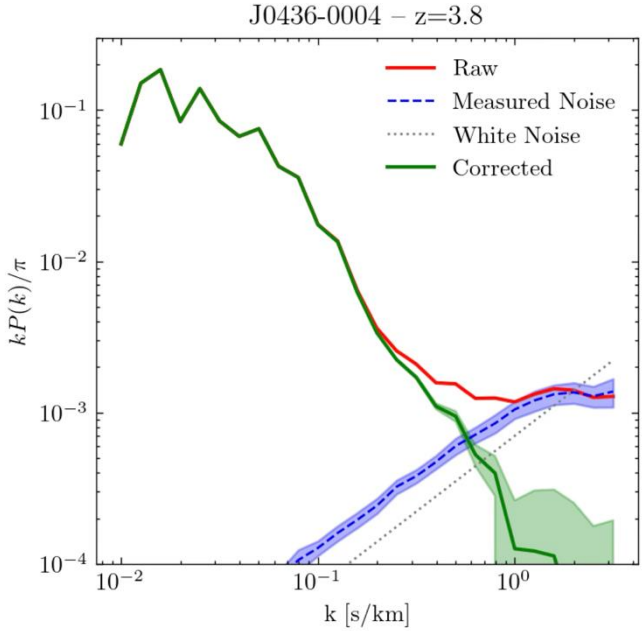
Matteo Viel

- Shot noise dominates the small scales of the flux power spectrum. If modelled correctly, can be removed to get a clean astrophysical signal

- For purely white/uncorrelated noise constant but real noise is correlated across (nearby) pixels and across echelle orders

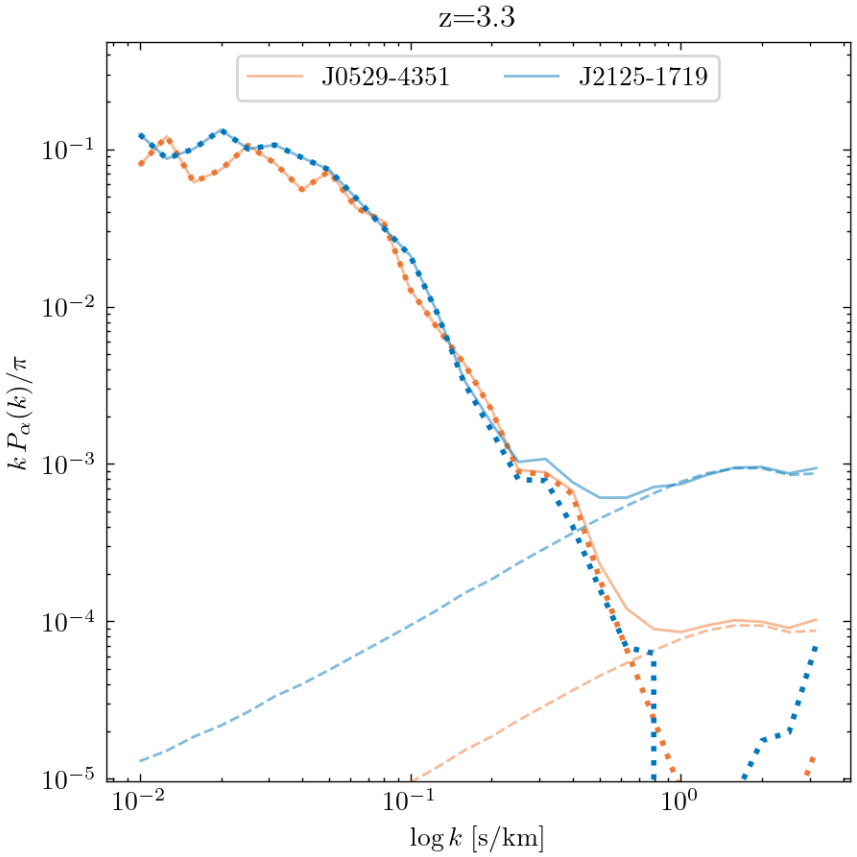
$$P_N = A\, W_N(k)$$



# ESPRESSO and the forest: the role of bright QSOs

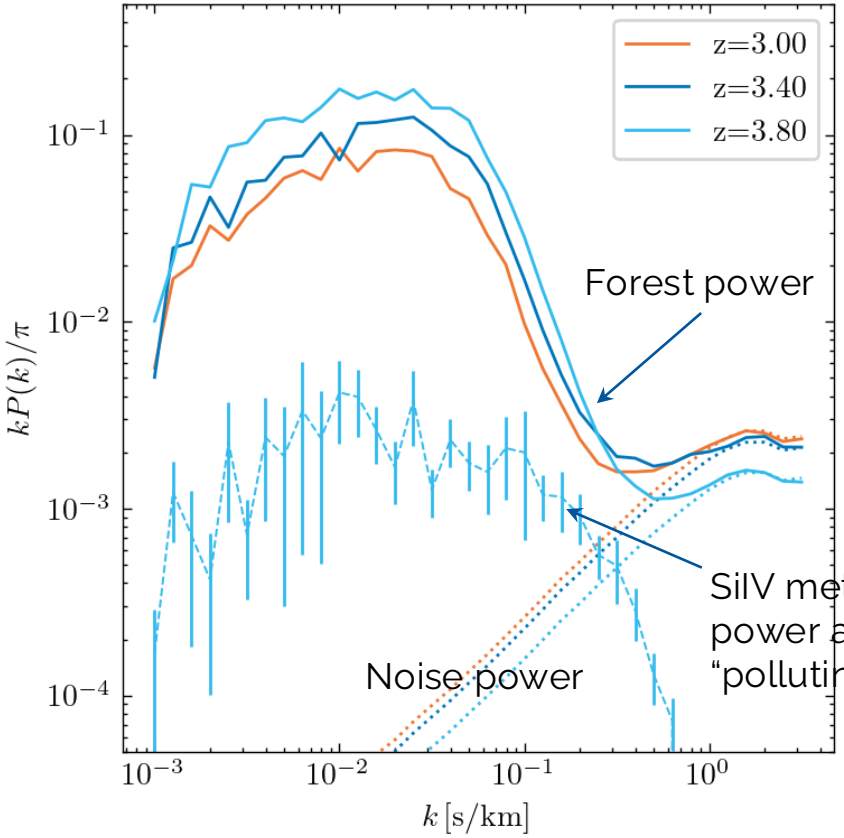
Matteo Viel




- In principle, a good determination of small-scale power could be determined by 1 bright or super bright QSO

# ESPRESSO and the forest: metal enrichment

Matteo Viel

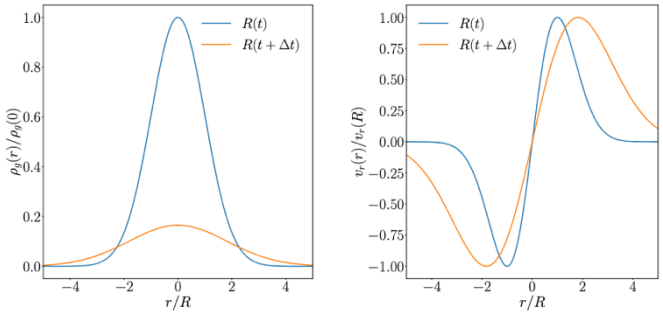


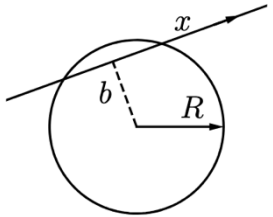

- Metal power falls off less abruptly than forest power due to different thermal broadening
- Metal power subdominant compared to noise at k>0.3 s/km
- Once noise is removed metal power at k~1 s/km is likely to be similar to forest power.

# The role of peculiar velocities

Matteo Viel

A simple “expanding bubble” toy model Gaussian density profile, expansion dominated by the gas pressure



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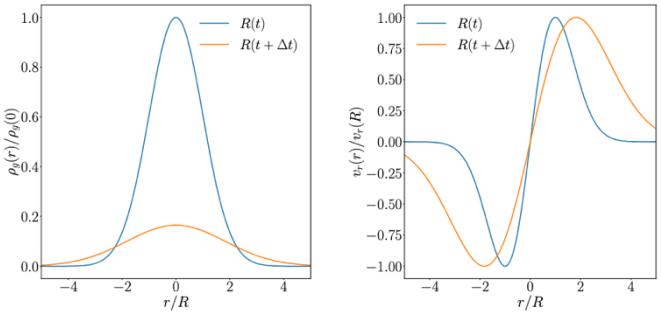
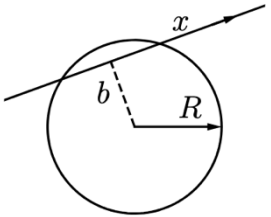
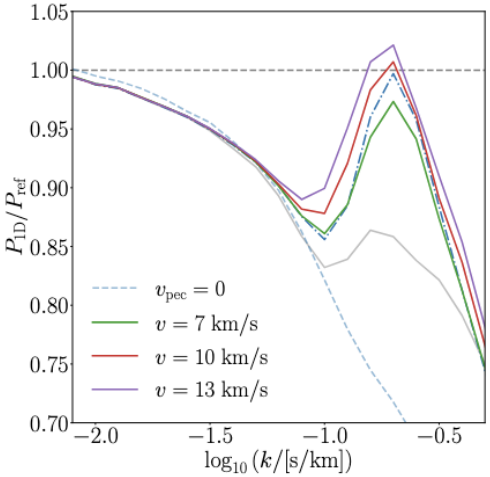
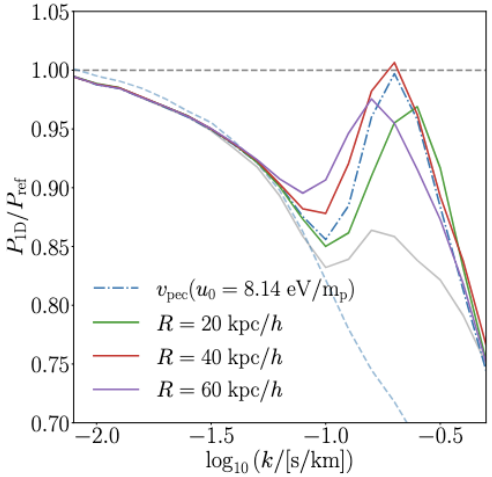



Peak’s position is determined solely by the size of the expanding bubbles at the time observation

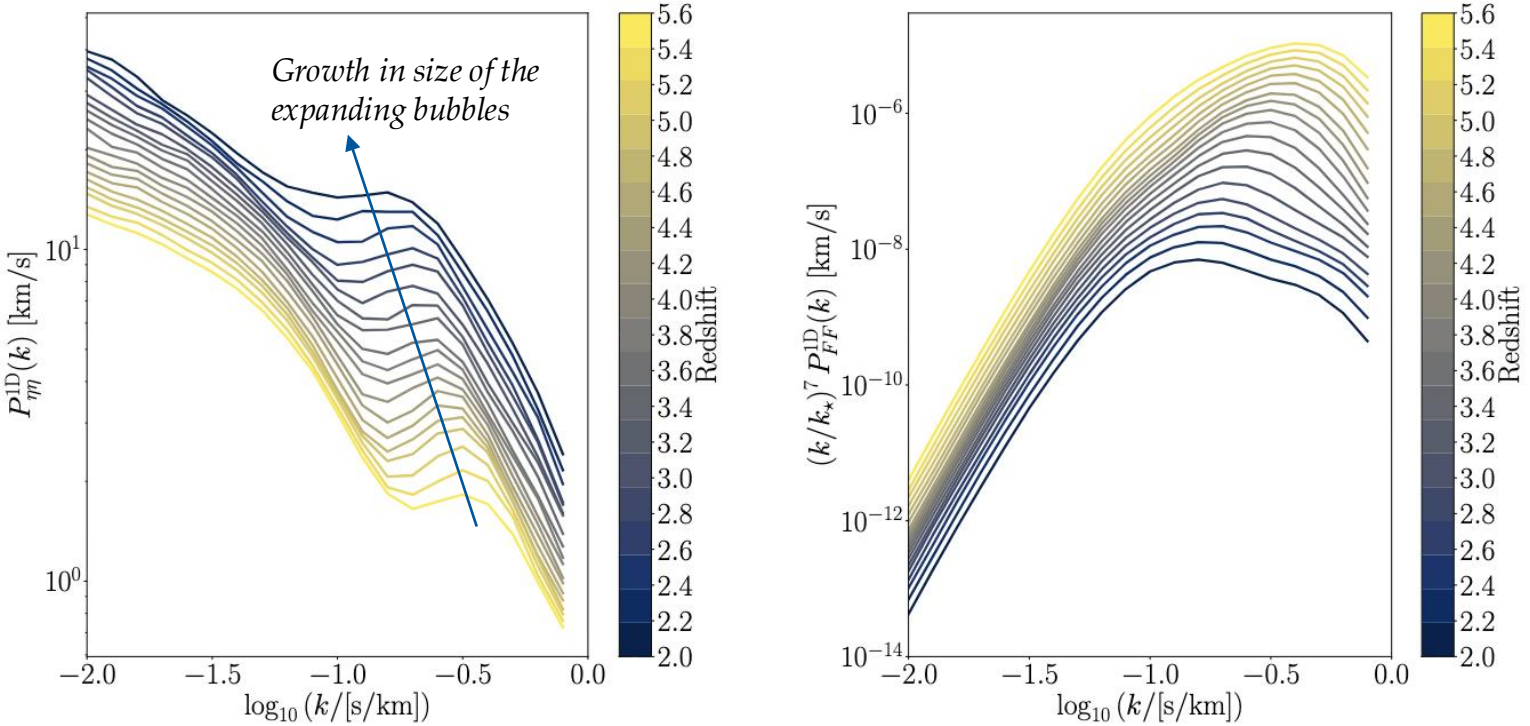


# Measuring the gas filtering scale (i.e. pressure)

Matteo Viel

Redshift evolution of the peak from hydrodynamic simulations



# Measuring the gas filtering scale

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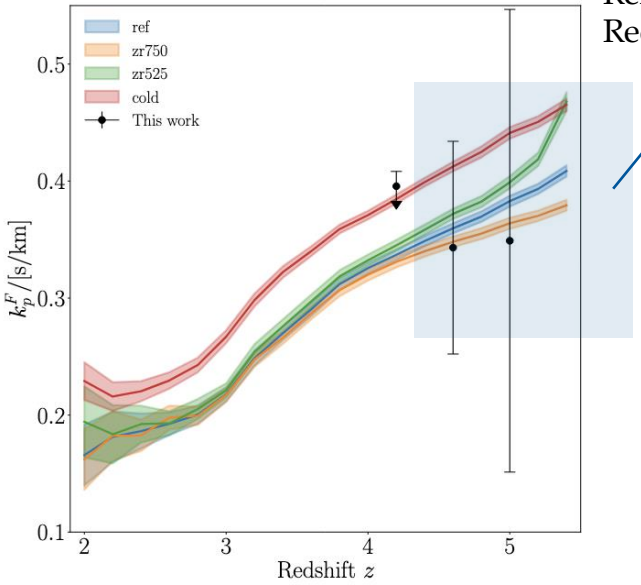
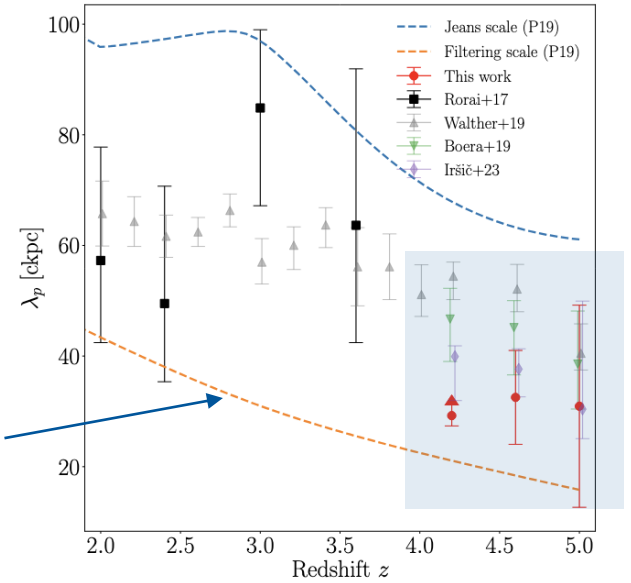
Position of the peak




Sensitive to Reionization Redshift?

Measuring the filtering scale




Reference Calculation With $z_{reio}$=6

*Irsic, MV + in prep.*

# Conclusions



- Stage-V will be a curse and a blessing but we can turn ANDES to be a small-scale spectroscopic calibrator of Stage-V experiments. This is particularly relevant for the forest.

- Systematic errors must be at the level of statistical errors. This is challenging but we are learning a lot from ESPRESSO.

- Sinergies with other instruments will be strong, most likely radio experiments (e.g. intensity mapping at 21cm – intrinsically a low angular resolution observation) will offer breakthroughs: foreground removal, signal detected in cross-correlation, exquisite radial resolution, learning the physics of galaxies' HI content.

# Moving closer to galaxies

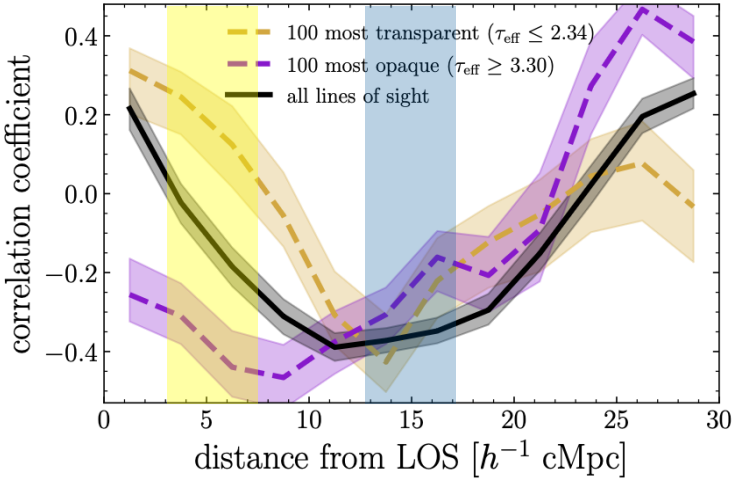
Matteo Viel

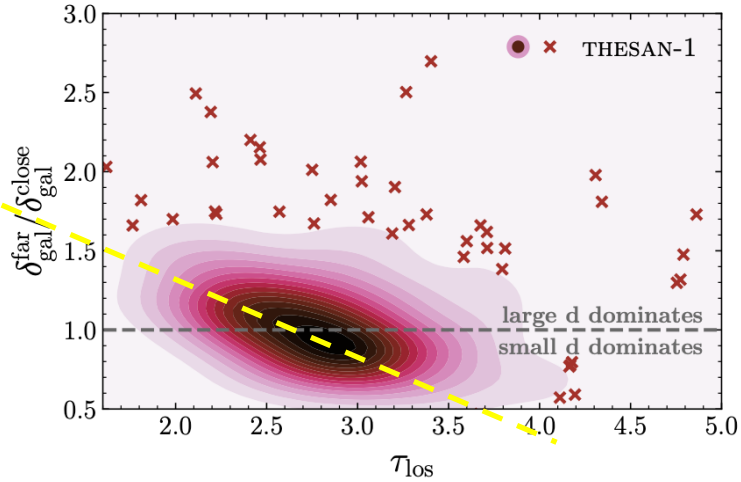
*Garaldi+25 THESAN simulation*

Galaxy density and optical depth

z=5.7

Environmental anti-correlation




- ✓ The LOS effective optical depth ($\tau_{\rm los}$) shows the strongest (anti-) correlation with the abundance of galaxies at distances $d$~15 Mpc/$h$. This is reduced to $d$~7 Mpc/$h$ for the most opaque sightlines (reionization is less developed around them and the highly-ionized bubbles are smaller)

- ✓ The scale ~10-15 Mpc/h seems pretty robust to variation of the physics. Average size of a galaxy void is 15 Mpc/h at this redshift