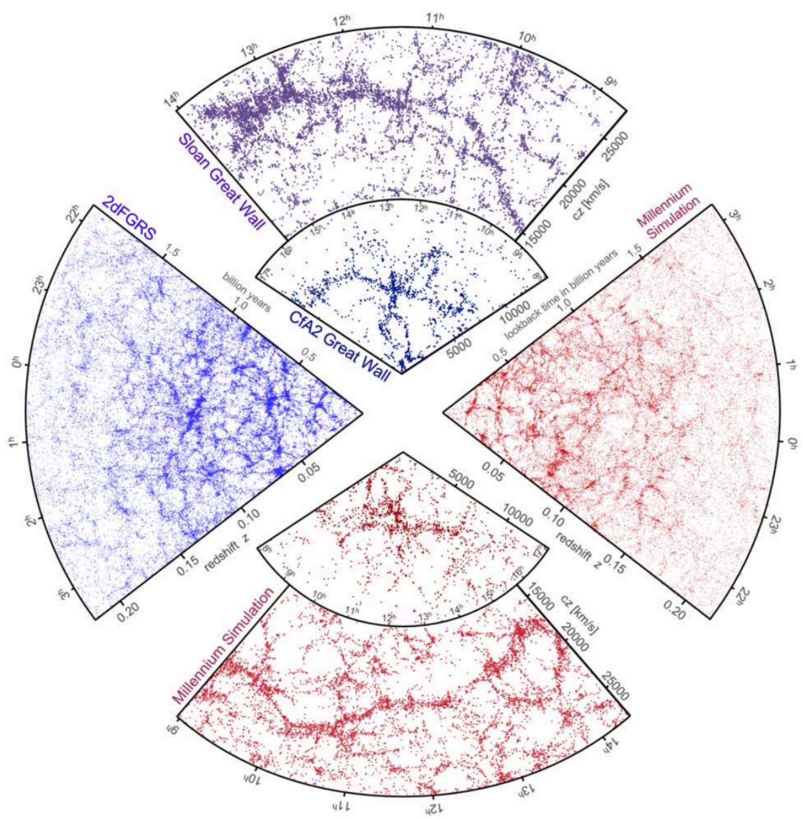
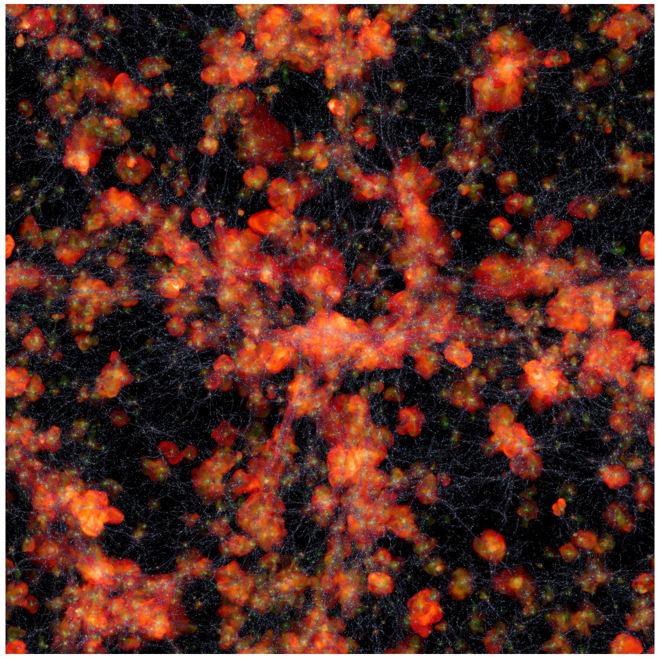
The dark universe under the light of numerical simulations





Solène Chabanier

Nathalie Palanque-Delabrouille, Frédéric Bournaud,
Christophe Yèche, Yohan Dubois, Zarija Lukic …

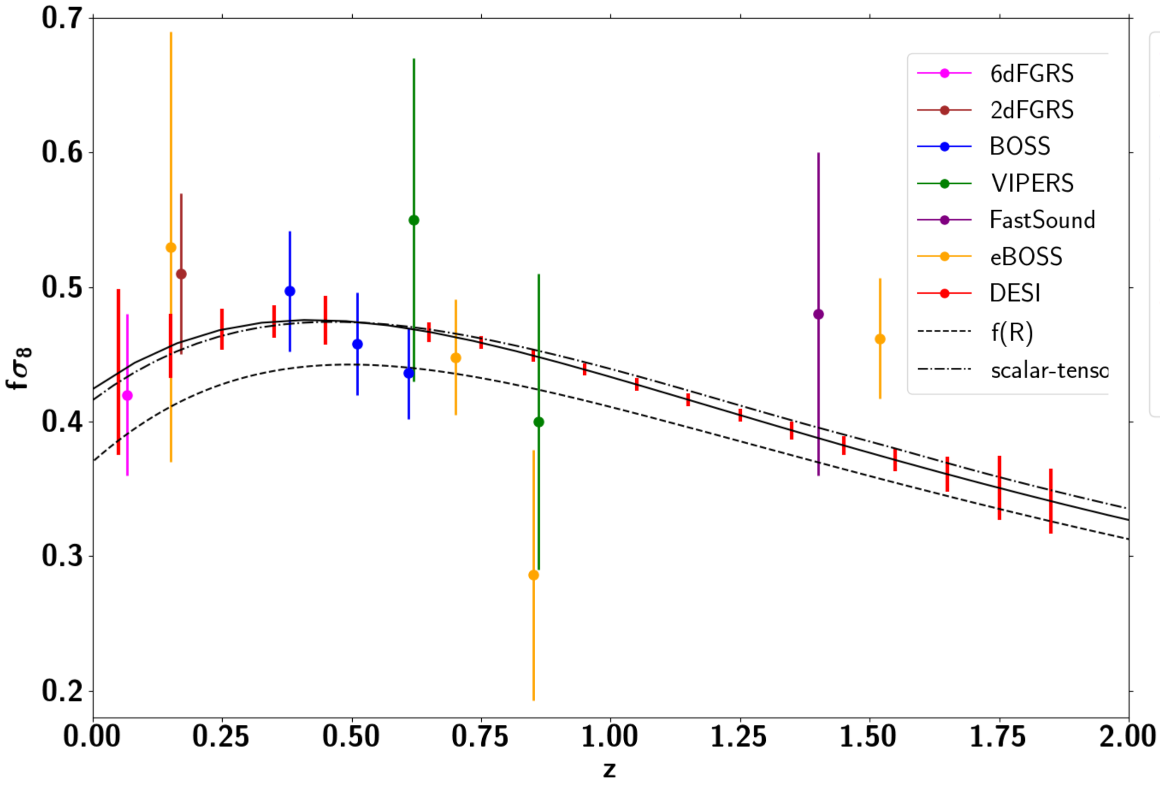
The era of precision cosmology

- Precision of on-going and future surveys close to 1%

→ *Increasing statistics, probing more redshift and pushing analysis to* ***smaller scales***

$$\sigma\left(\sum m_\nu\right)_{eBOSS} = 0.08\mathrm{eV} \longrightarrow \sigma\left(\sum m_\nu\right)_{DESI} = 0.02\mathrm{eV}$$

$$\sigma(f\sigma_8)_{eBOSS} = 3\,\% \longrightarrow \sigma(f\sigma_8)_{DESI} = 0.38\,\%$$



- Measurements will be systematics dominated

→ *Modeling (non-linear scales, prediction of exotic models..)*

→ *Observational (selection effect, methodology..)*

What do numerical simulations bring to observational cosmology ?

The dark universe under the light of numerical simulations

1- Context

Precision cosmology, next generation cosmological surveys

2- High-precision theoretical predictions

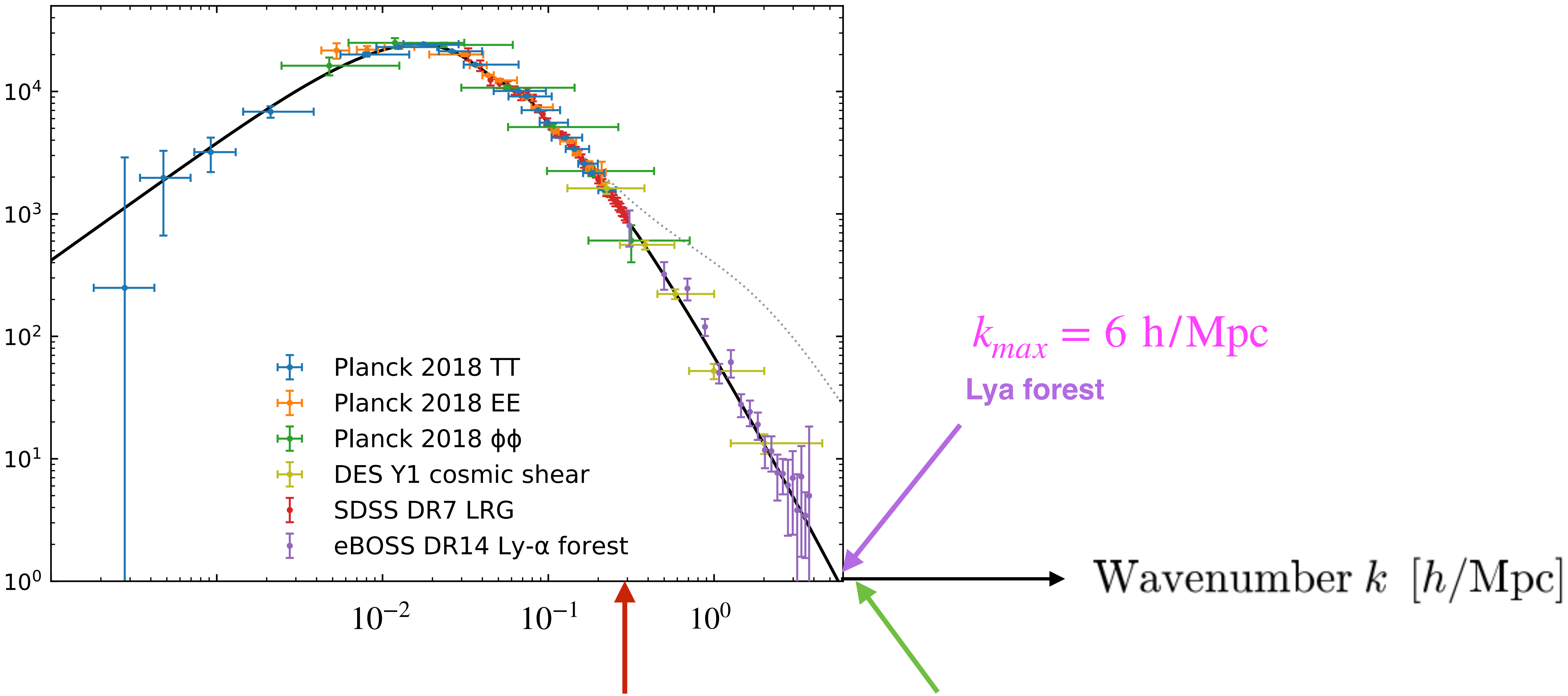
N-body simulations, non-linear regime, numerical laboratories

3- Impact of baryons on cosmology

Biased tracers, actors of matter distribution, AGN feedback

Probing non-linear scales

Chabanier et al. 2019b



$k_{max} = 6$ h/Mpc

Lya forest

$k_{max} = 0.3$ h/Mpc

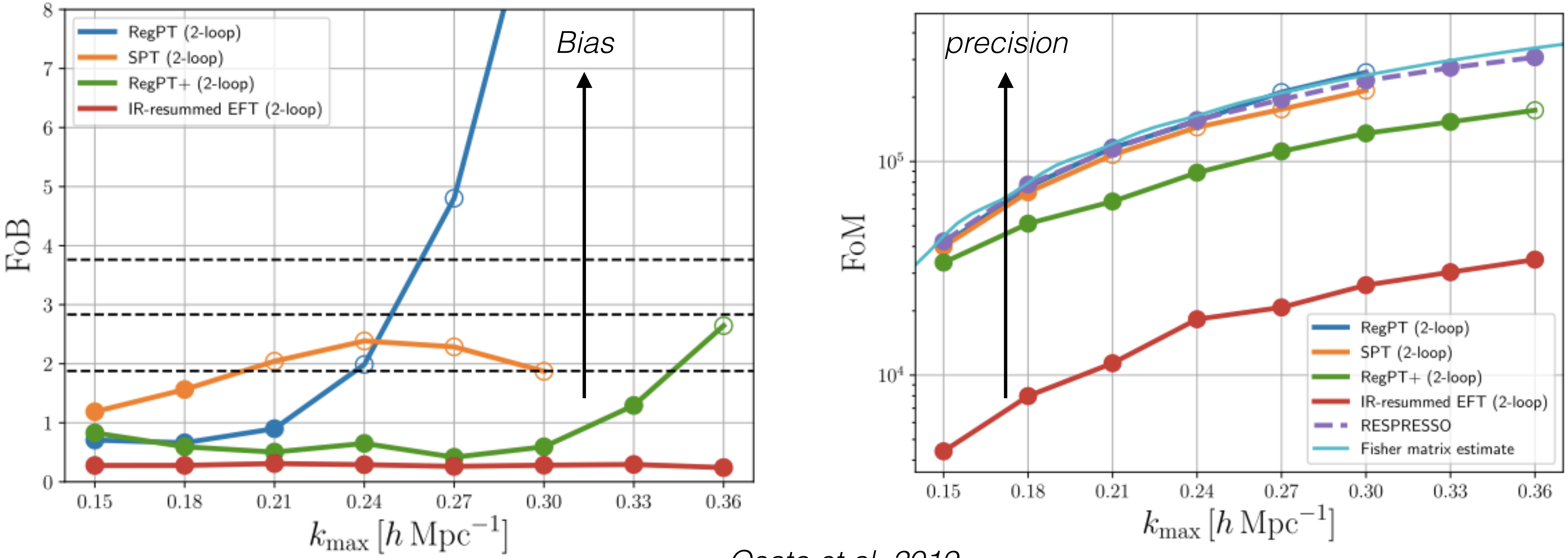
Galaxy spectroscopic surveys

$k_{max} = 7$ h/Mpc

Weak-lensing (Euclid)

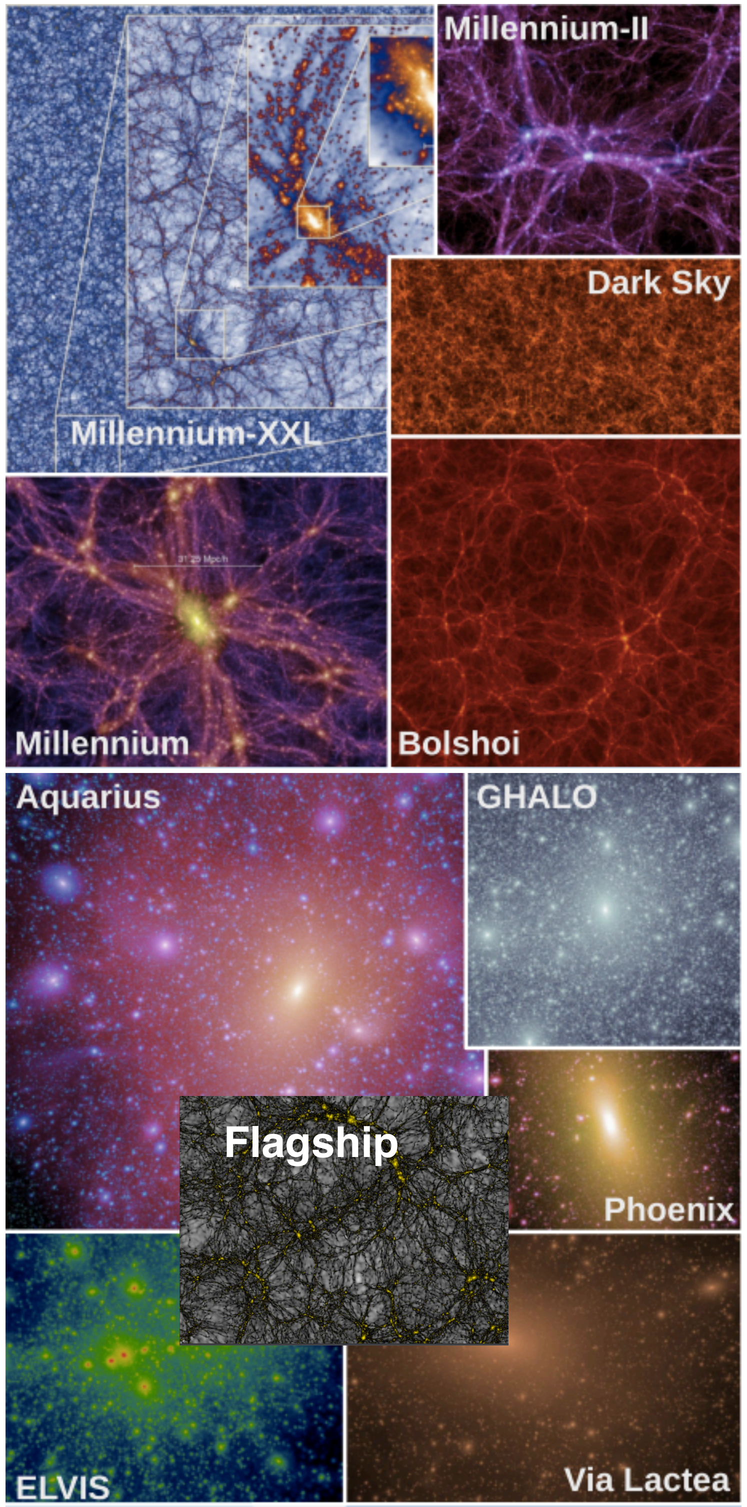
Numerical vs analytical predictions

Analytical predictions:
Compromise between accuracy and precision

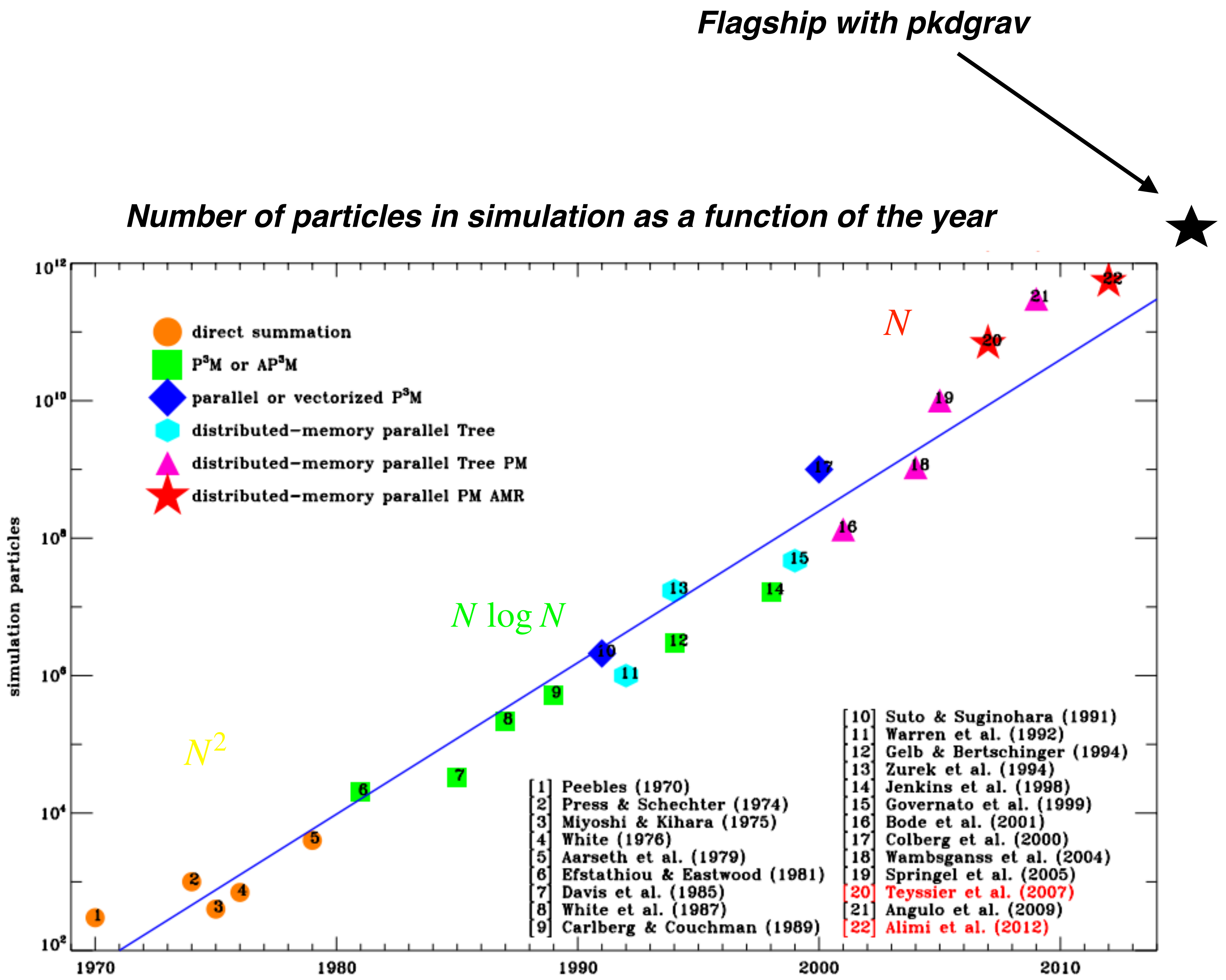


Osato et al. 2019

N-body simulations



Adapted from Vogelsberger et al. 2019



Flagship with pkdgrav

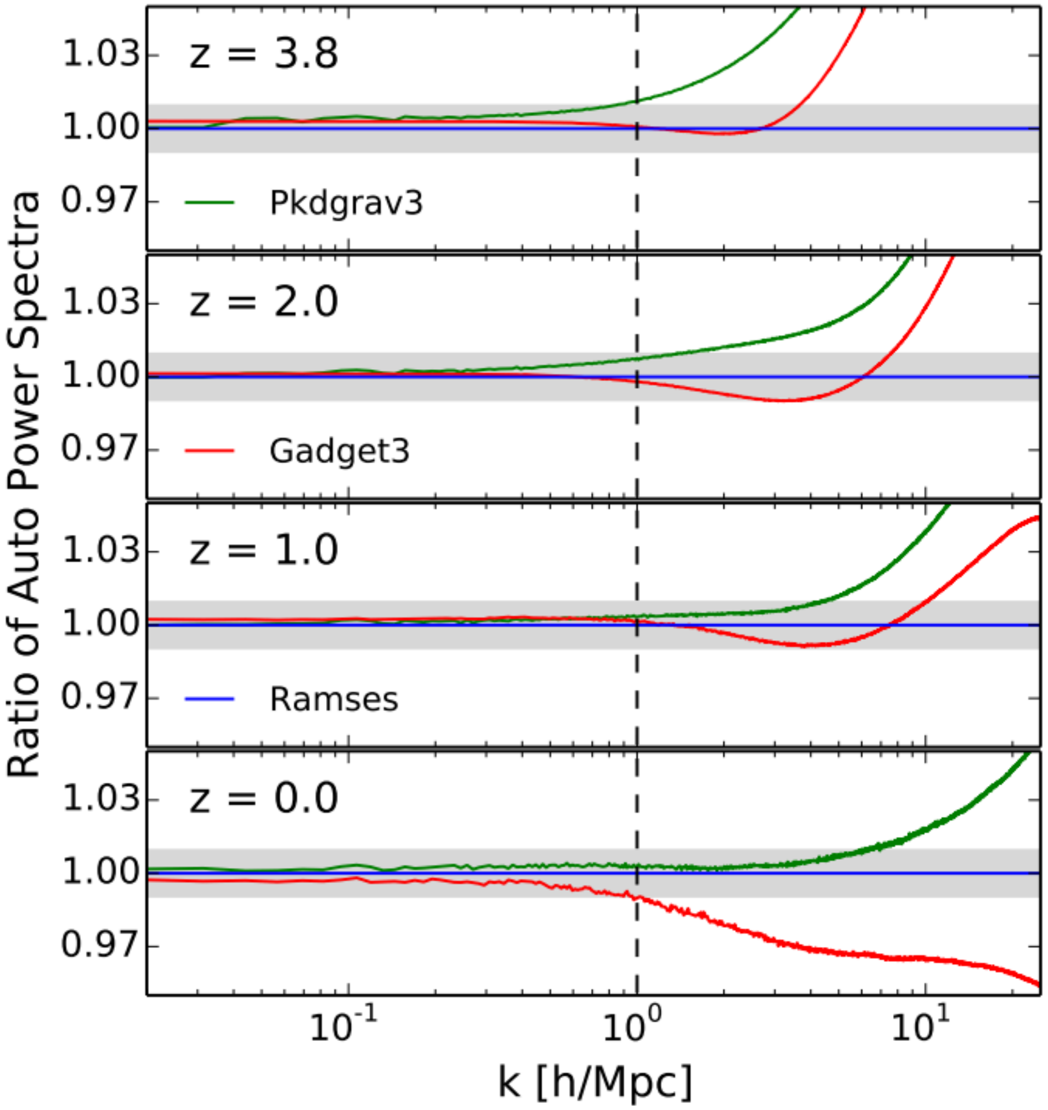
Number of particles in simulation as a function of the year

(1) Are N-body codes converged ?

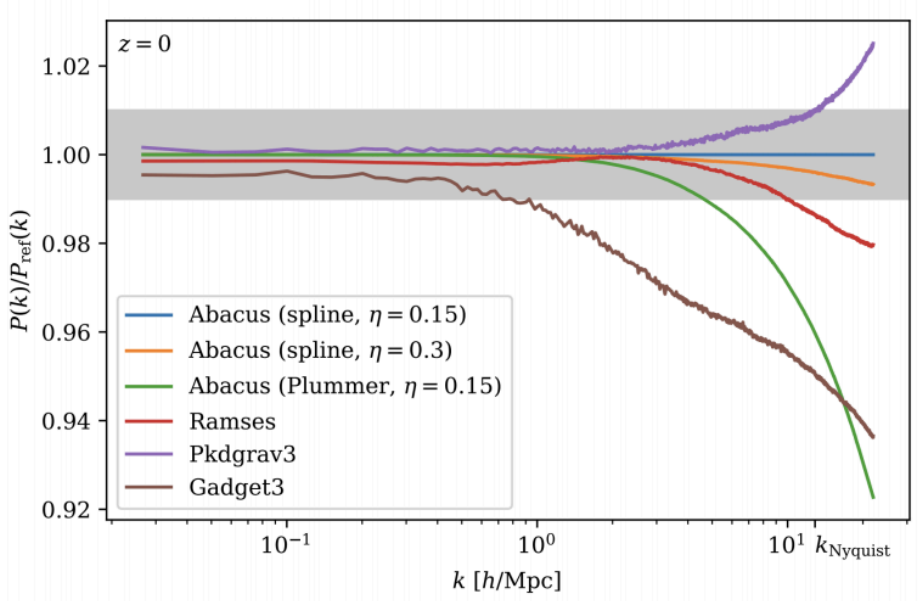
(2) Can we realistically used them to do cosmological inferences ?

Convergence of N-body simulations

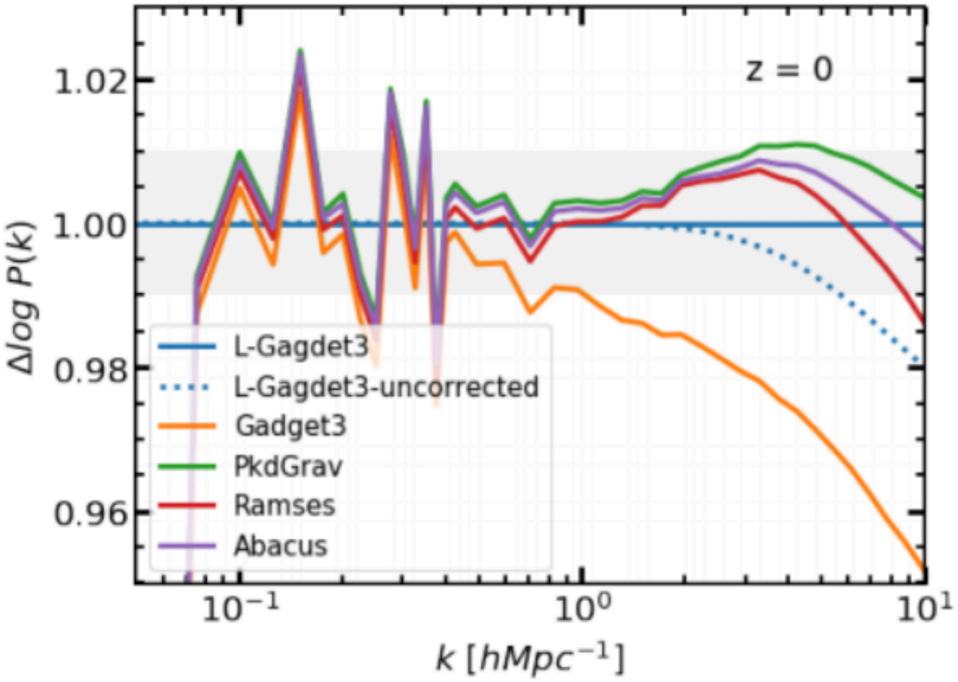
Schneider et al. 2016



Garrison et al. 2018



Angulo et al. 2020



→ **N-body codes have converged below 1% for k < 10 h/Mpc**

Suites of N-body sims: emulation

- Intractable to perform simulation for every cosmological models

→ *emulation of theoretical predictions in the cosmological parameter space*

- Realization of grid of N-body simulations sampling the parameter space

→ *different exploration techniques: monte carlo, latin hypercube, optimized latin hypercube*

- Some recent realizations:

- The Abacus cosmos suite: specifically designed for DESI → 200k CPU hours

40 cosmologies in $(H_0, \Omega_{DE}, \Omega_m, n_s, \sigma_8, w_0)$

$L_{box} = 1.1\ \mathrm{Gpc/h}$ and $L_{box} = 720\ \mathrm{Mpc/h}$

Garrison et al. 2018

$M_{reso} = 1 \cdot 10^{10} M_\odot/\mathrm{h}$ and $M_{reso} = 4 \cdot 10^{10} M_\odot/\mathrm{h}$

- The Euclid emulator suite *(pkdgrav)*: specifically designed for Euclid → 4M CPU hours

100 cosmologies in $(\omega_b, \omega_m, n_s, h, \omega_0, \sigma_8)$

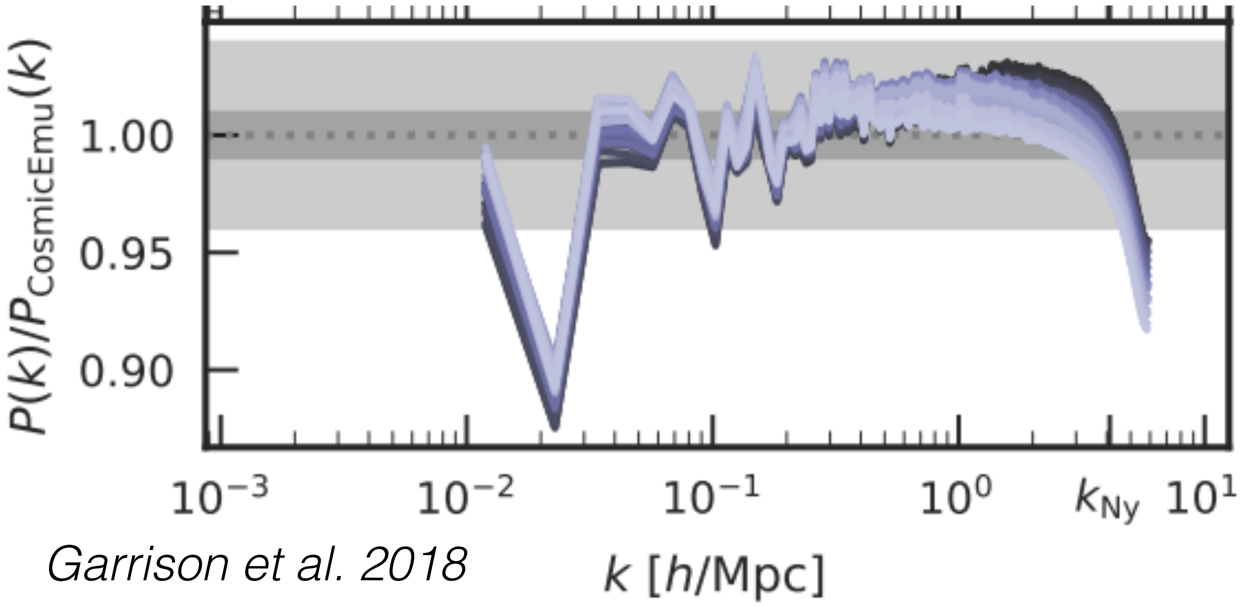
$L_{box} = 1.25\ \mathrm{Gpc/h}$

Knabenhans et al. 2019

$M_{reso} = 2 \cdot 10^{10} M_\odot/\mathrm{h}$

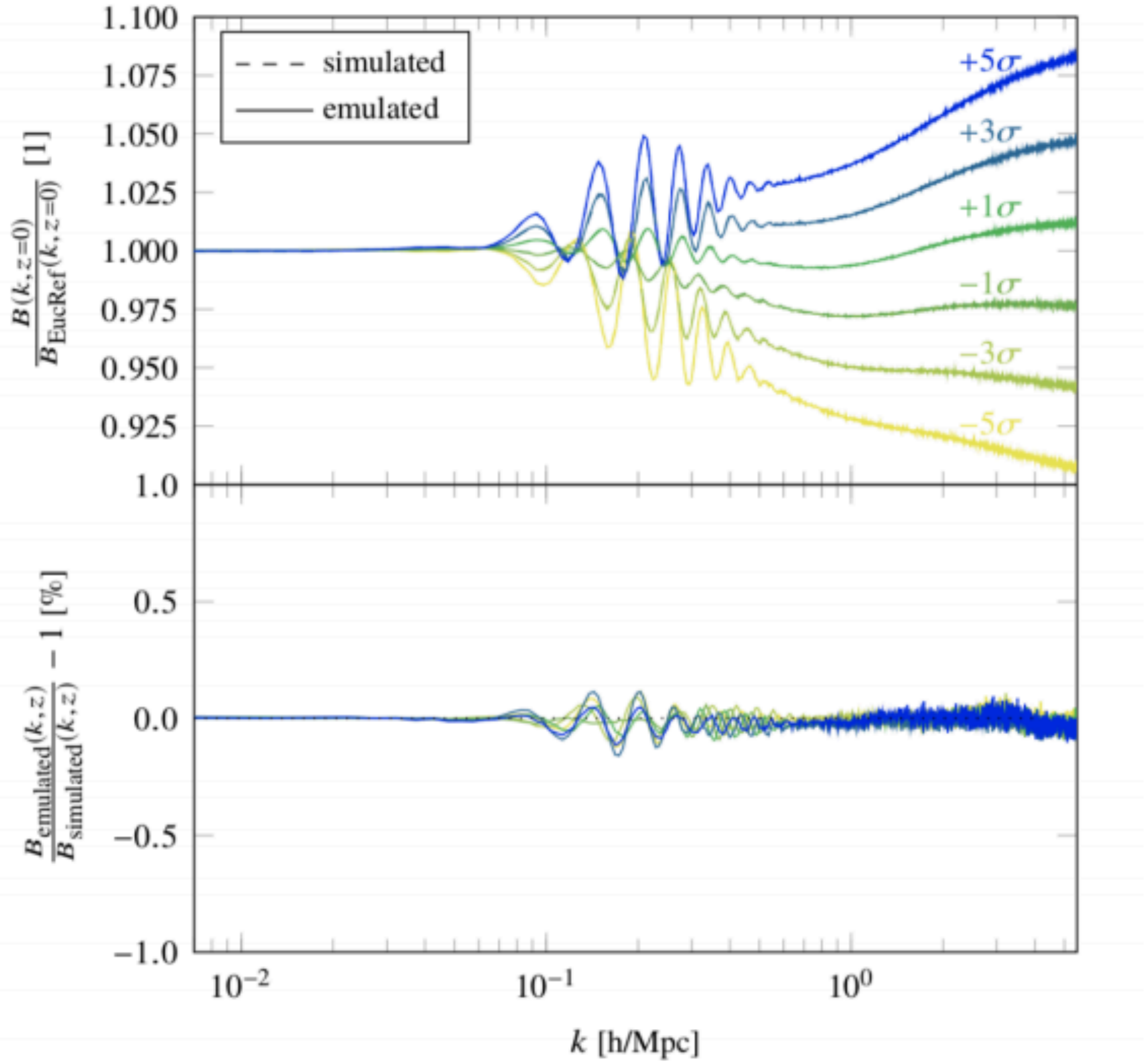
Suites of N-body sims: emulation

CosmicEmu with the Abacus suite



Garrison et al. 2018

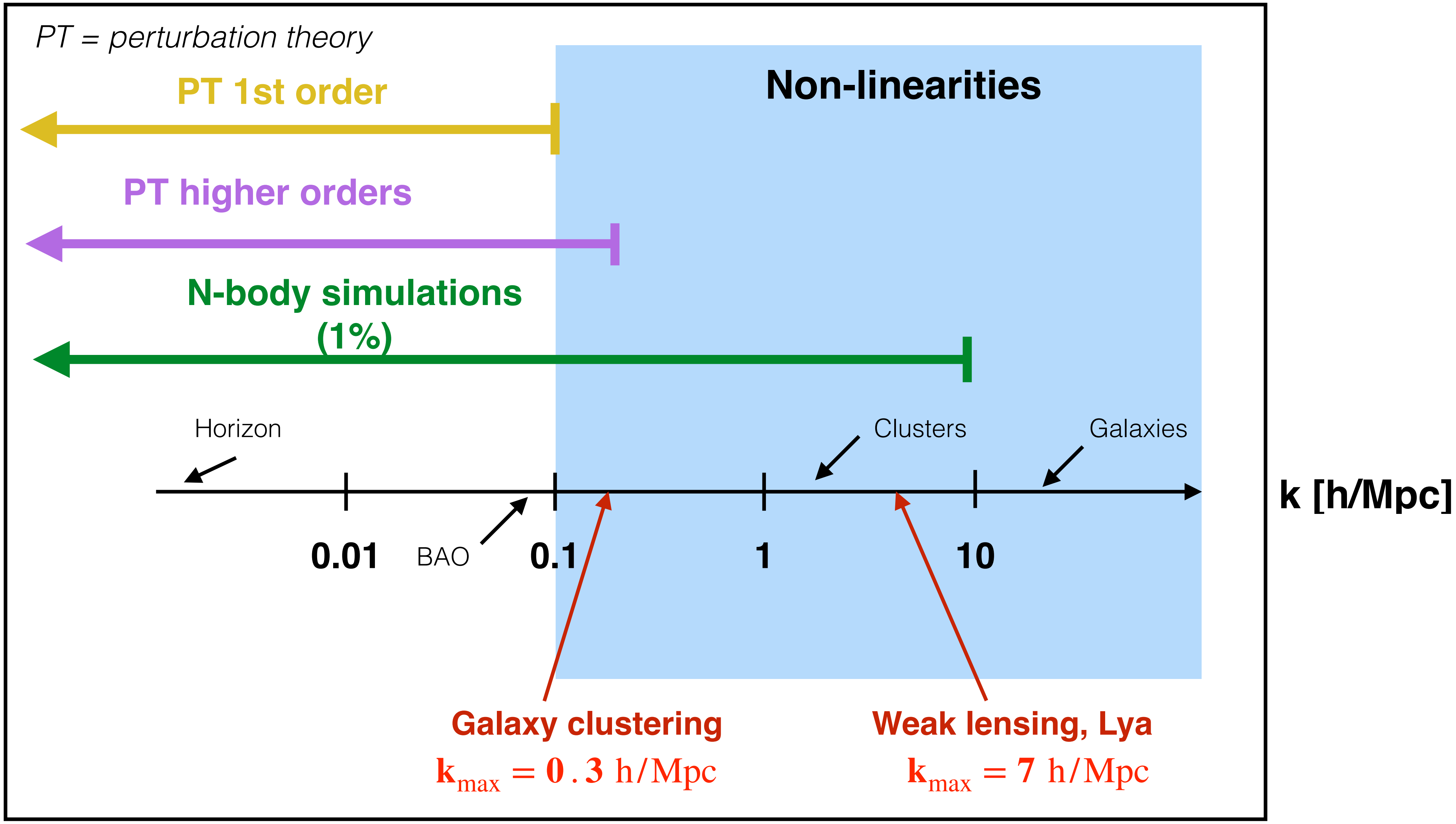
The EuclidEmulator



Knabenhans et al. 2019

→ **Emulation errors can be as low as 0.2%**

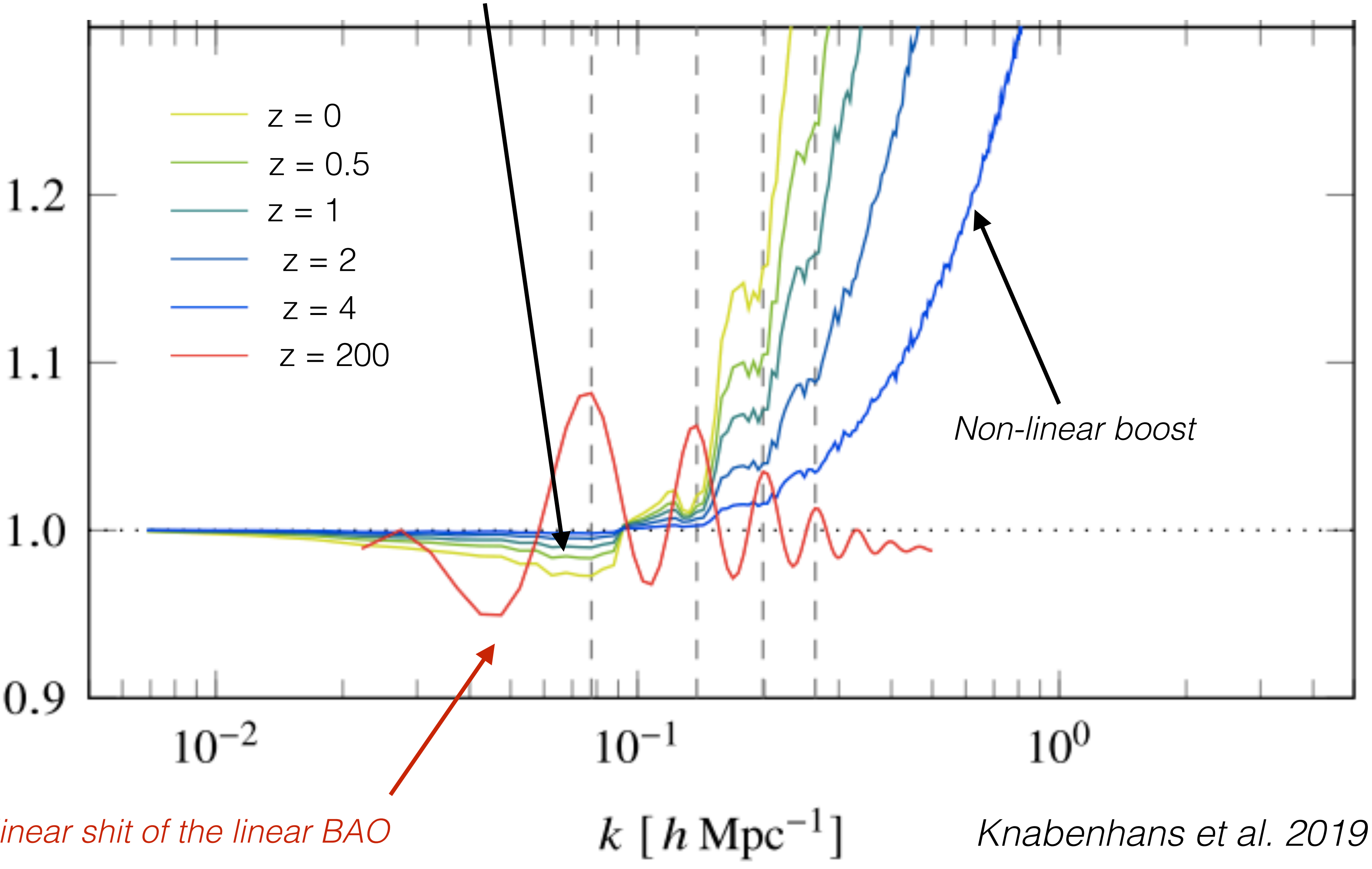
Numerical vs analytical predictions



Non-linear effects

Non-linear corrections to the matter power spectrum

Non-linear suppression of power induced by pre-virialization



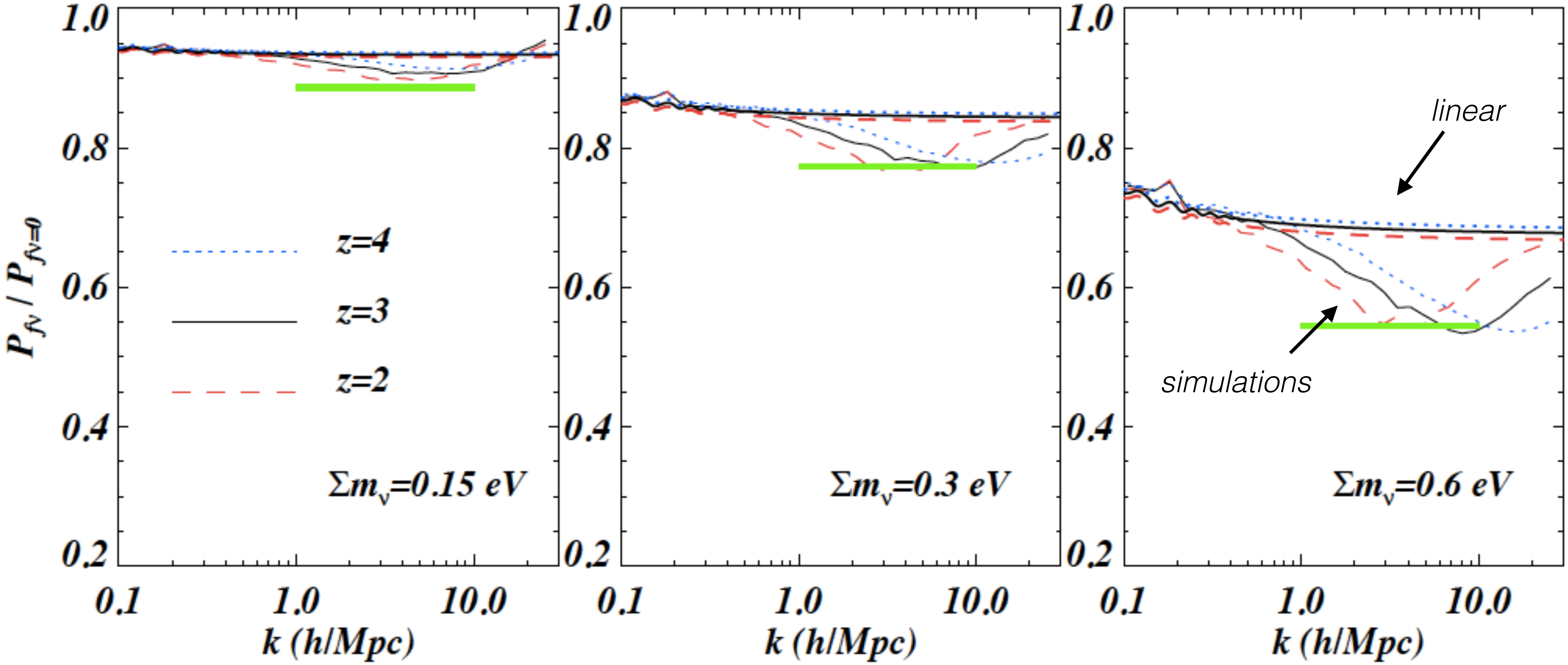
Non-linear boost

Non-linear shit of the linear BAO

Knabenhans et al. 2019

Non-linear effects

Probing neutrino masses with the non-linear matter power spectrum



Viel et al. 2010

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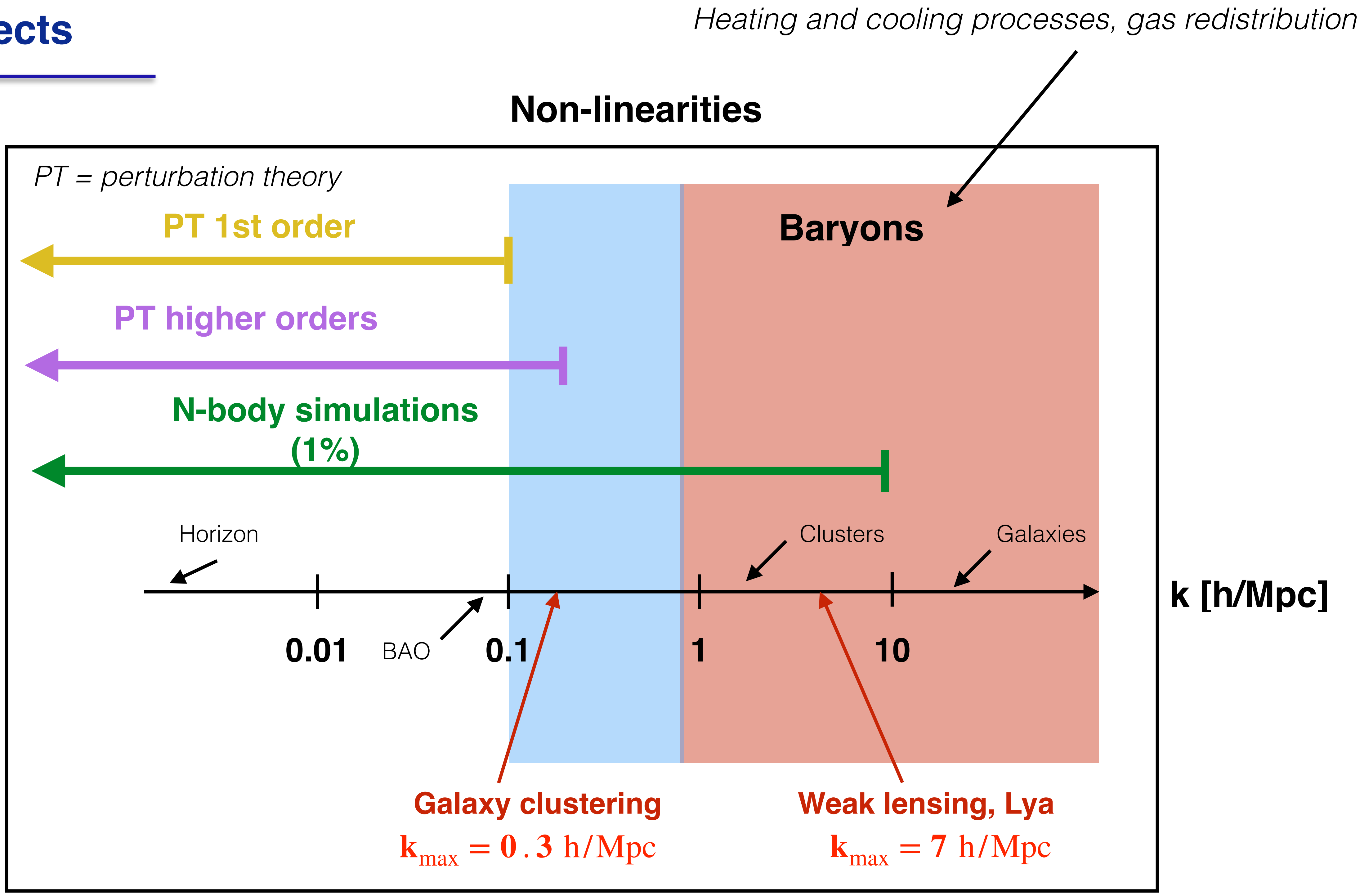
Baryonic effects



Recent cosmological hydrodynamical simulations:

- box large enough → sufficient statistics *(tens of thousands of galaxies)*
- reasonable resolution → galaxy formation modeling

Hydrodynamical simulations

- Solving Euler equations of an inviscid ideal gas

Mass conservation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum conservation $$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}^2\right) + \nabla p = \rho \nabla \Phi$$

+ gravity via Poisson equation

Energy conservation $$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + p)\mathbf{v}] = \rho \mathbf{v} \cdot \nabla \Phi$$

→ ***More memory consuming****: gas pressure, density, position*3, velocity*3, metallicity*

- General approaches:

Lagrangian particle-based *(Gadget)*

Inability to control resolution, numerical diffusion of shocks and mixing processes

Eulerian grid-based *(Ramses)*

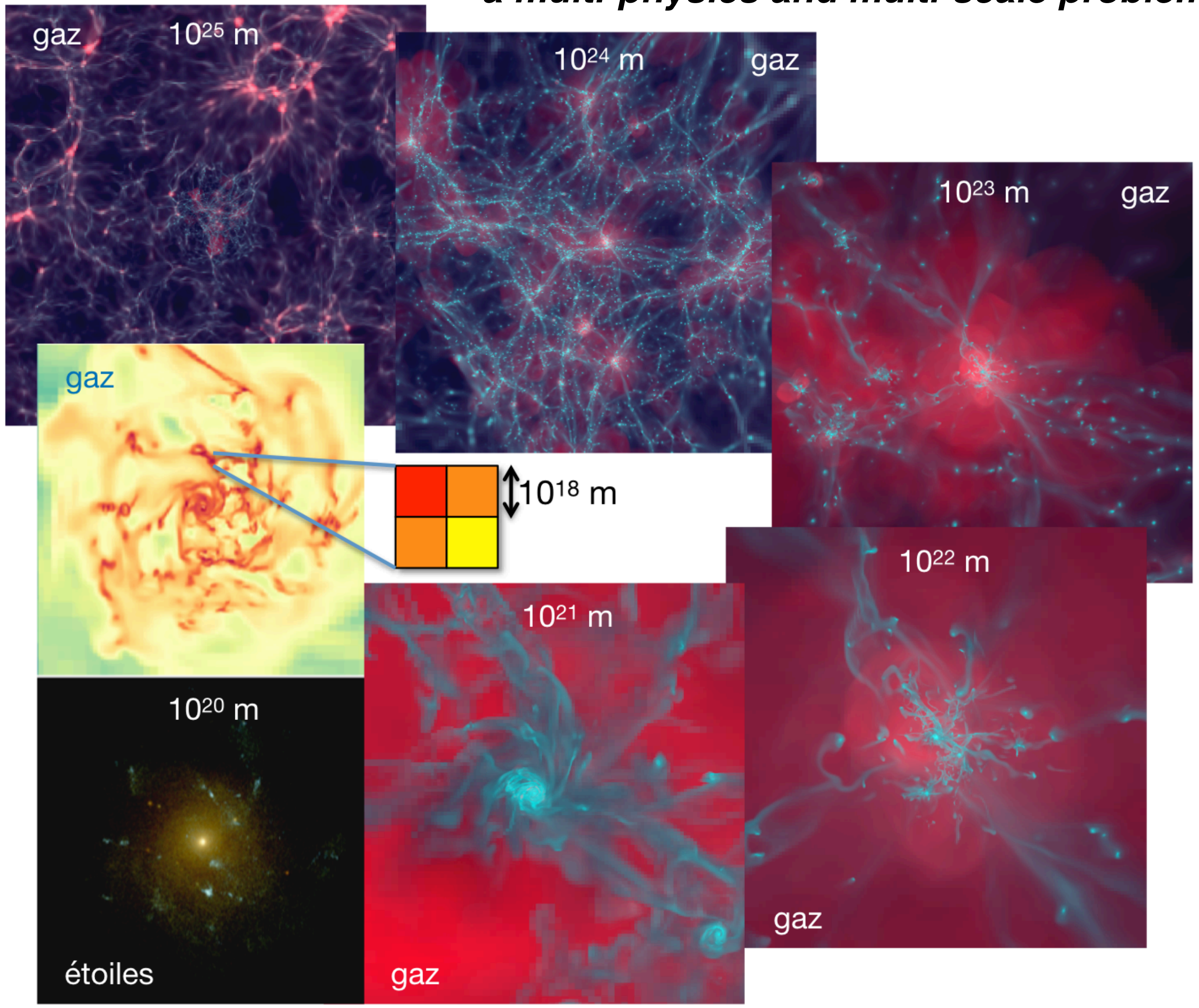
Numerical diffusion, violation of Galilean invariance, privileged directions along the axes

Moving mesh *(AREPO)*

→ **Convergence of hydrodynamical solvers depends on the problem at hand**

Hydrodynamical simulations

Galaxy evolution in a cosmological context:
a multi-physics and multi-scale problem



- Approximate resolution of state-of the-art cosmological simulation: ~1 kpc >> *1pc BH radius*

→ We have to rely on **sub-grid models** = effective description of physical processes

Implies calibration of sub grid parameters upon galaxy observables

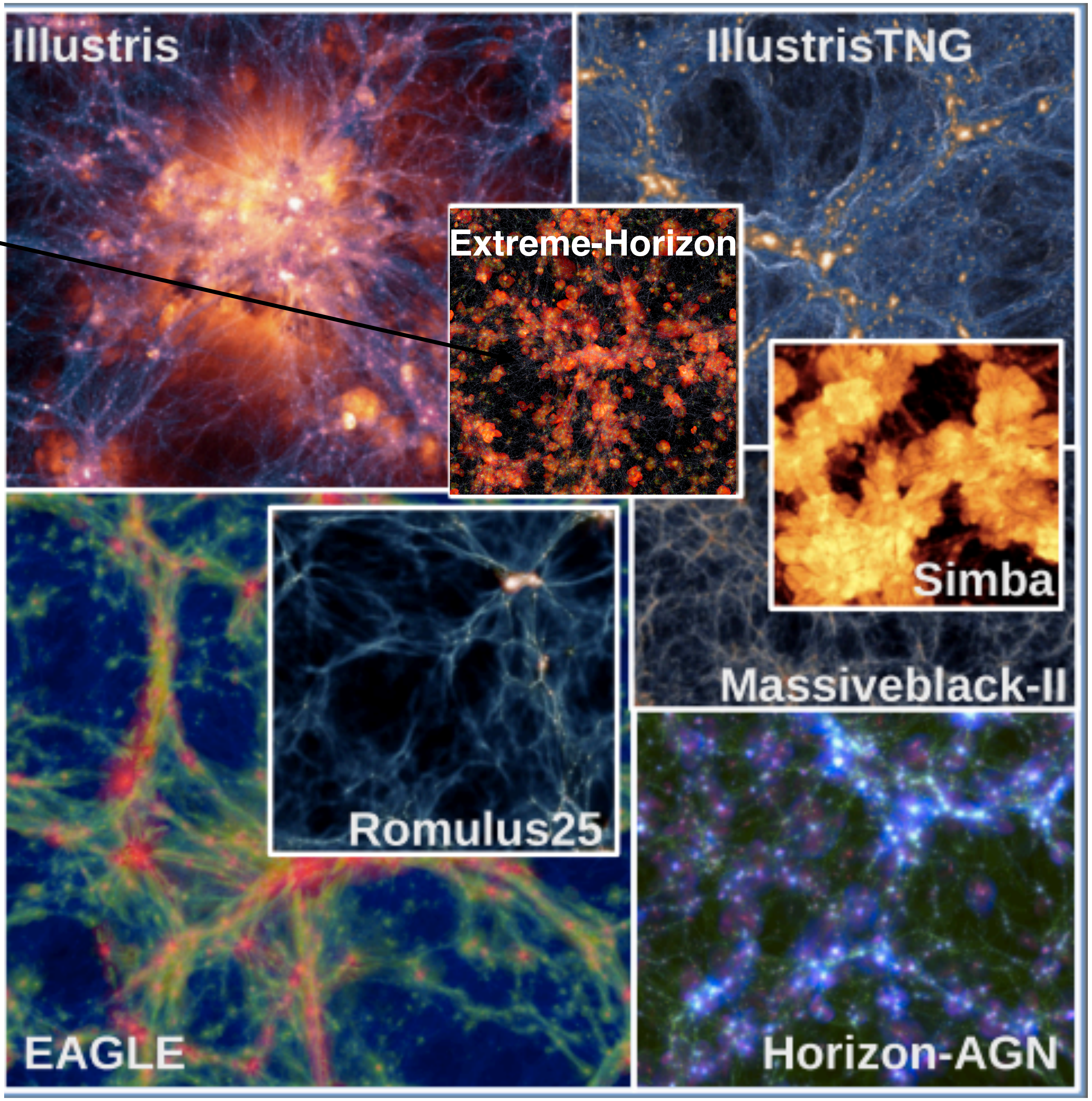
- Energy injection models *(stellar and AGN feedbacks)* considerably increase computing time ~ **x10 with AGN feedback**

Hydrodynamical simulations

18 millions CPU hours
moving-mesh

55 millions CPU hours
grid-based

3.5 millions CPU hours
particle-based



Adapted from Vogelsberger et al. 2019

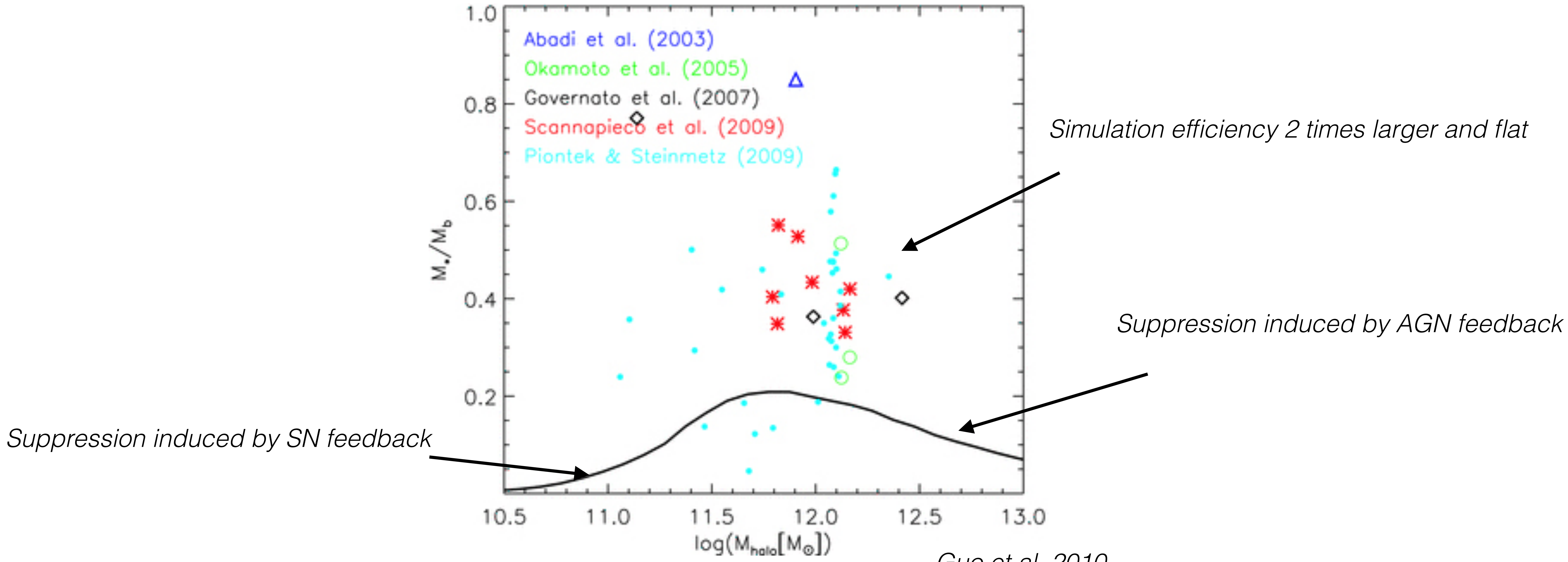
Open issues in hydrodynamical simulations

- To faithfully model LSS and validate sub grid models we need to simulate realistic galaxies

→ *Sims fail at reproducing simultaneously different observational results in all redshift and mass ranges*

- Overcooling: **too much baryons are locked into stars**

Galaxy formation efficiency as a function of halo mass



Simulation efficiency 2 times larger and flat

Suppression induced by AGN feedback

Suppression induced by SN feedback

Guo et al. 2010

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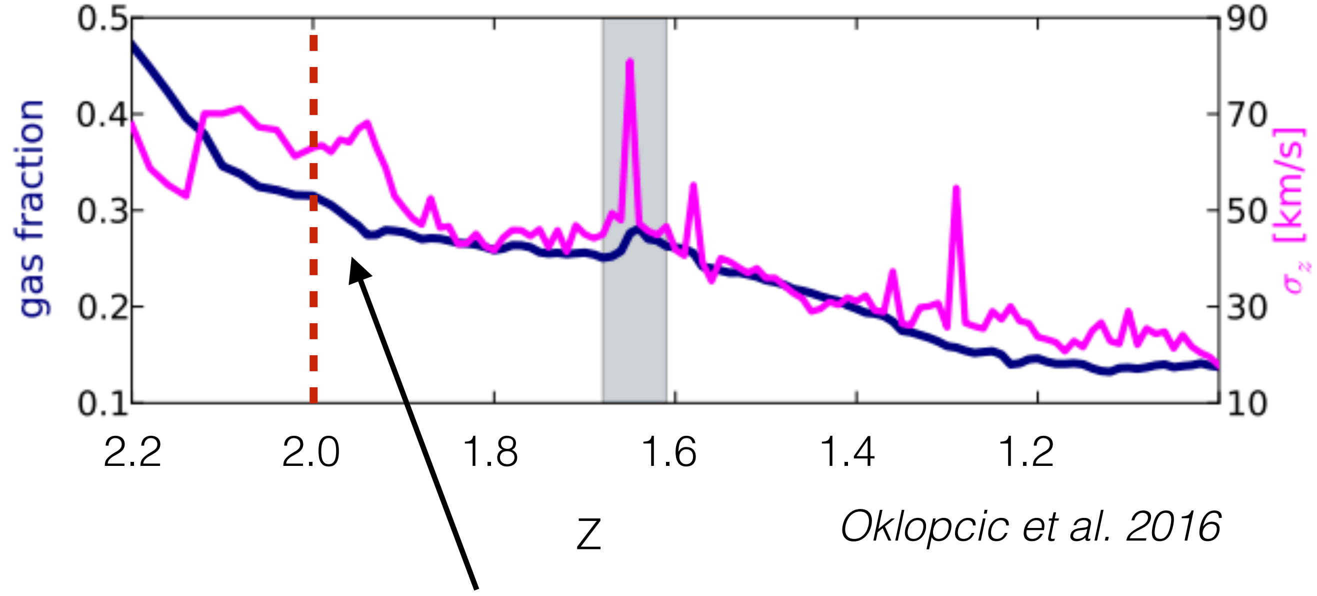
- Not only an issue with feedback model

→ *Most of sims **lack gas in the crucial era of z~2:** 10-20% in sims vs 50% in observations*

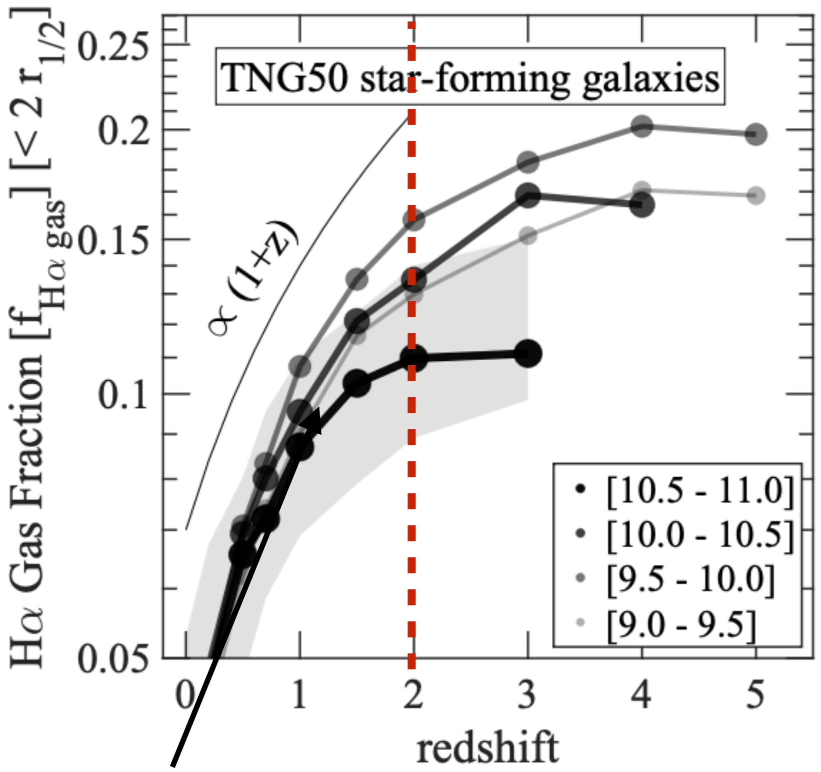
Gas fraction in Fire



Oklopcic et al. 2016

~ 25% of gas at z = 2
(in 25 kpc sphere when MW is 10 kpc radius at z = 0)

TNG50 galaxies: stellar and gaseous disks



~ 12% of gas at z = 2

Pillepich et al. 2019

Open issues in hydrodynamical simulations

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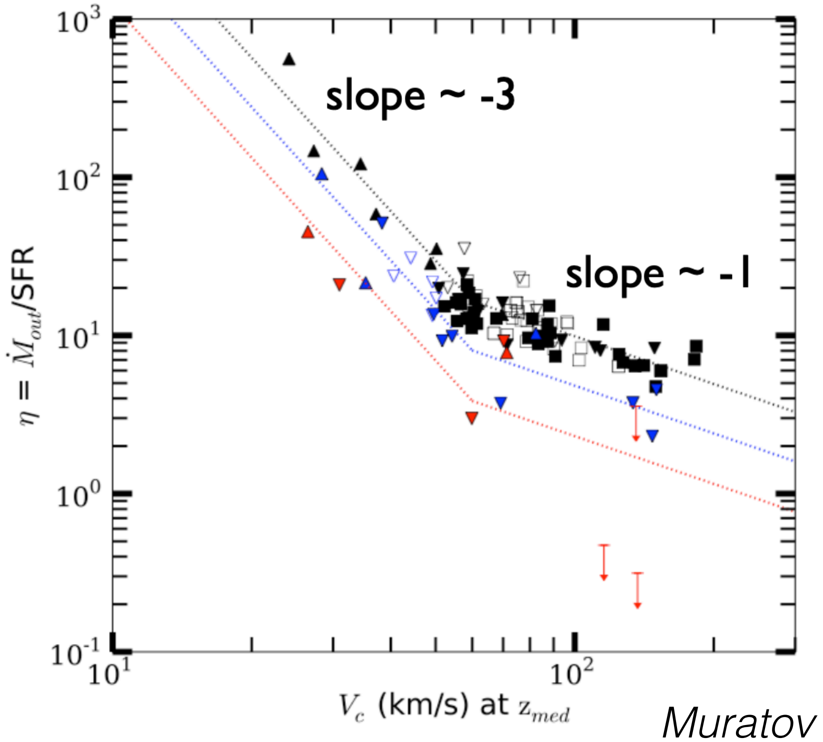
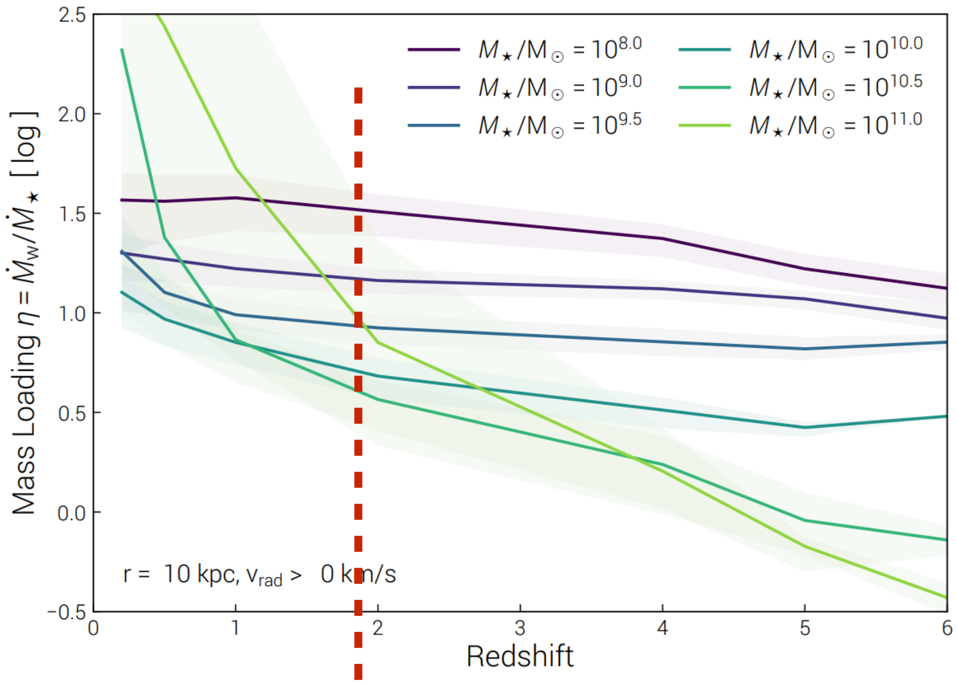
  - → *Sims fail at reproducing simultaneously different observational results in all redshift and mass ranges*
- Overcooling: too much baryons are locked into stars
- Not only an issue with feedback model
  - → *Most of sims lack gas in the crucial era of z~2: 10-20% in sims vs 50% in observations*
  - → *Results from* ***too strong SN/AGN feedback*** *and excessive galactic winds: loading factors 10-30 in sims vs 0.5-1 in observations*

Mass loading factor in Fire



Muratov et al. 2015

Mass loading factor in Illustris-TNG50



Nelson et al. 2019

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Lowering feedbacks *would induce a too rapid gas-to-star conversion* → ***More tension on stellar mass !***

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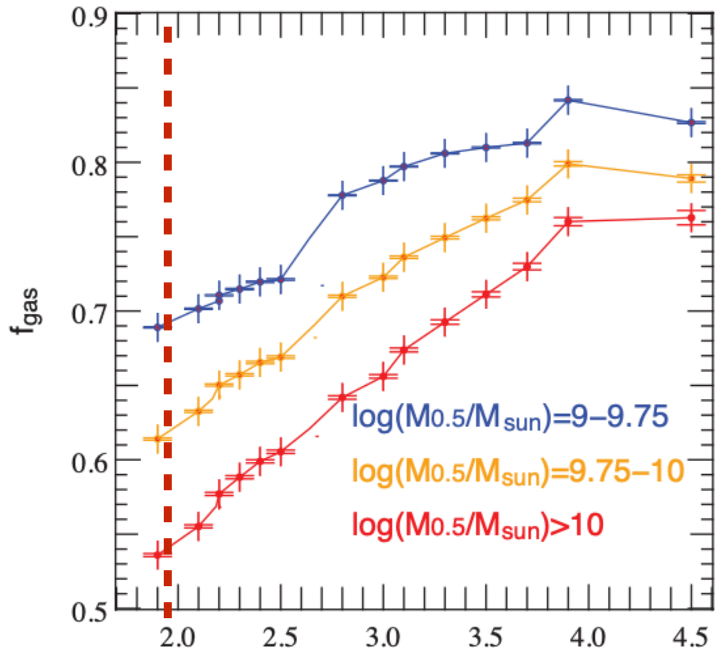
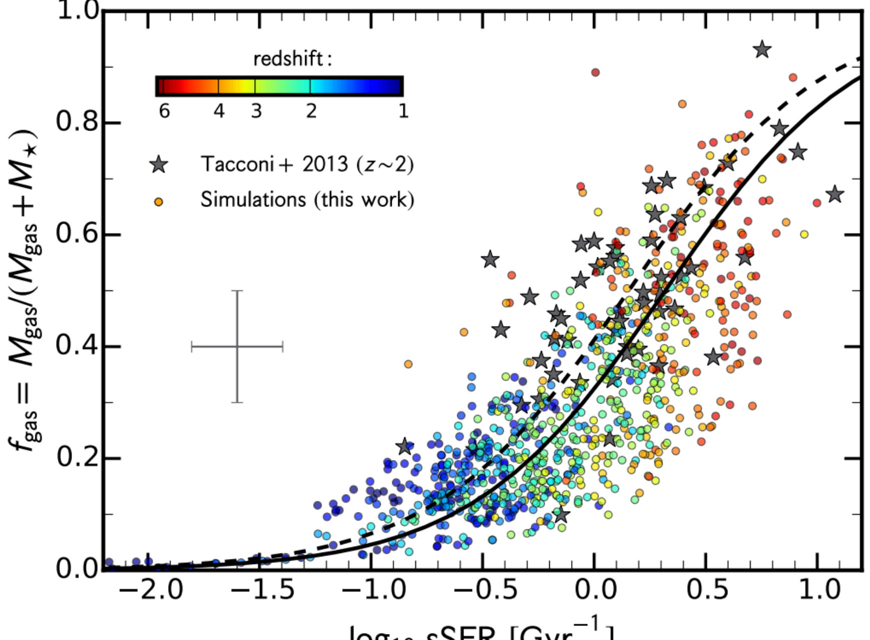
Some exceptions to stay optimistic

Gas fraction in Horizon-AGN



Welker et al. 2017

Gas fraction in VELA



Ceverino et al. 2018

Open issues in hydrodynamical simulations

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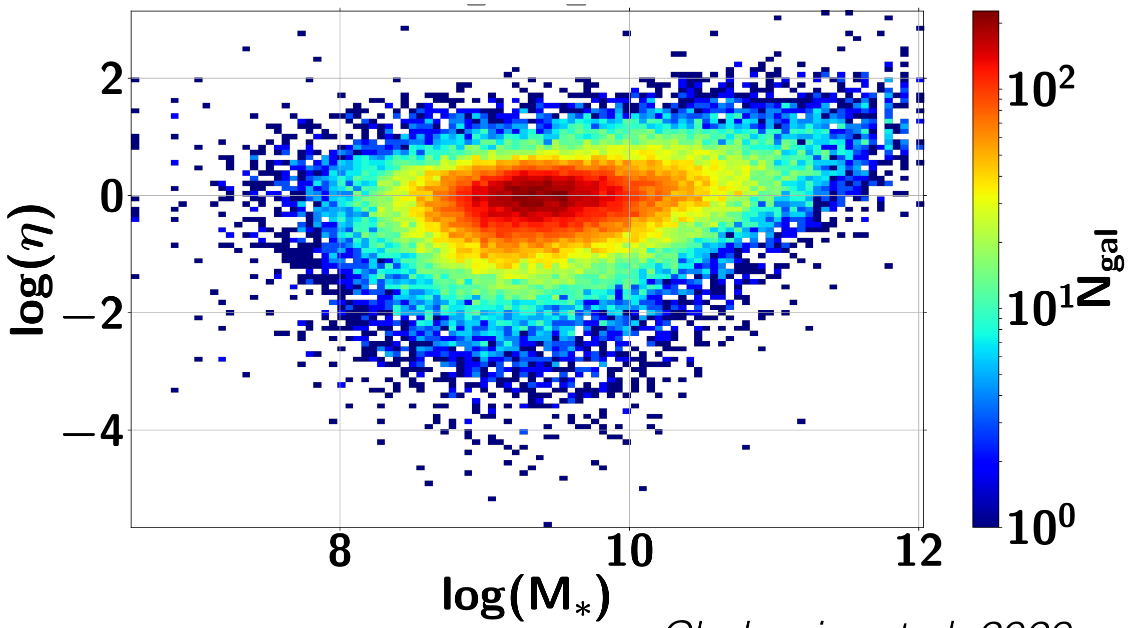
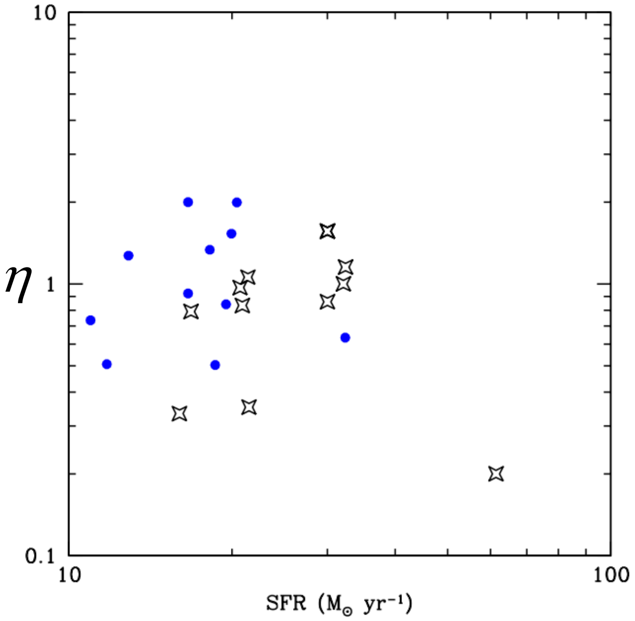
Some exceptions to stay optimistic

Mass loading factors in Horizon-AGN



Chabanier et al. 2020a

Mass loading factor in VELA



Ceverino et al. 2018

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Lowering feedbacks *would induce a too rapid gas-to-star conversion* → ***More tension on stellar mass !***

- Adhoc calibration of sub grid models:

(1) induces large variations if different implementation/calibration

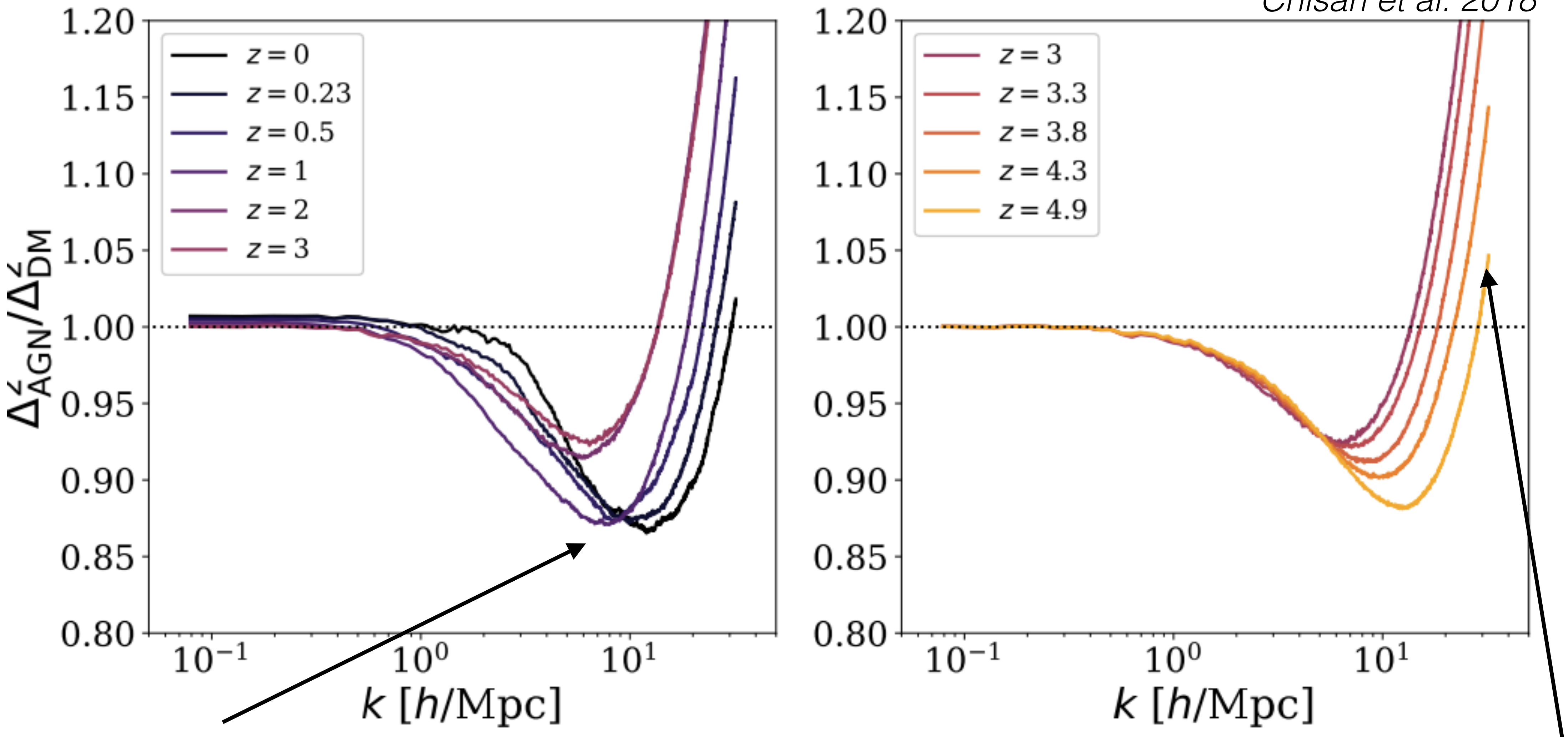
(2) makes it difficult to reproduce at the same time all galaxy properties

galaxy formation efficiency, star formation history, galaxy morphology

Baryonic effects

Impact of baryonic physics on the total matter clustering with HAGN
Matter Power Spectrum: P[baryons] / P[DM-only]

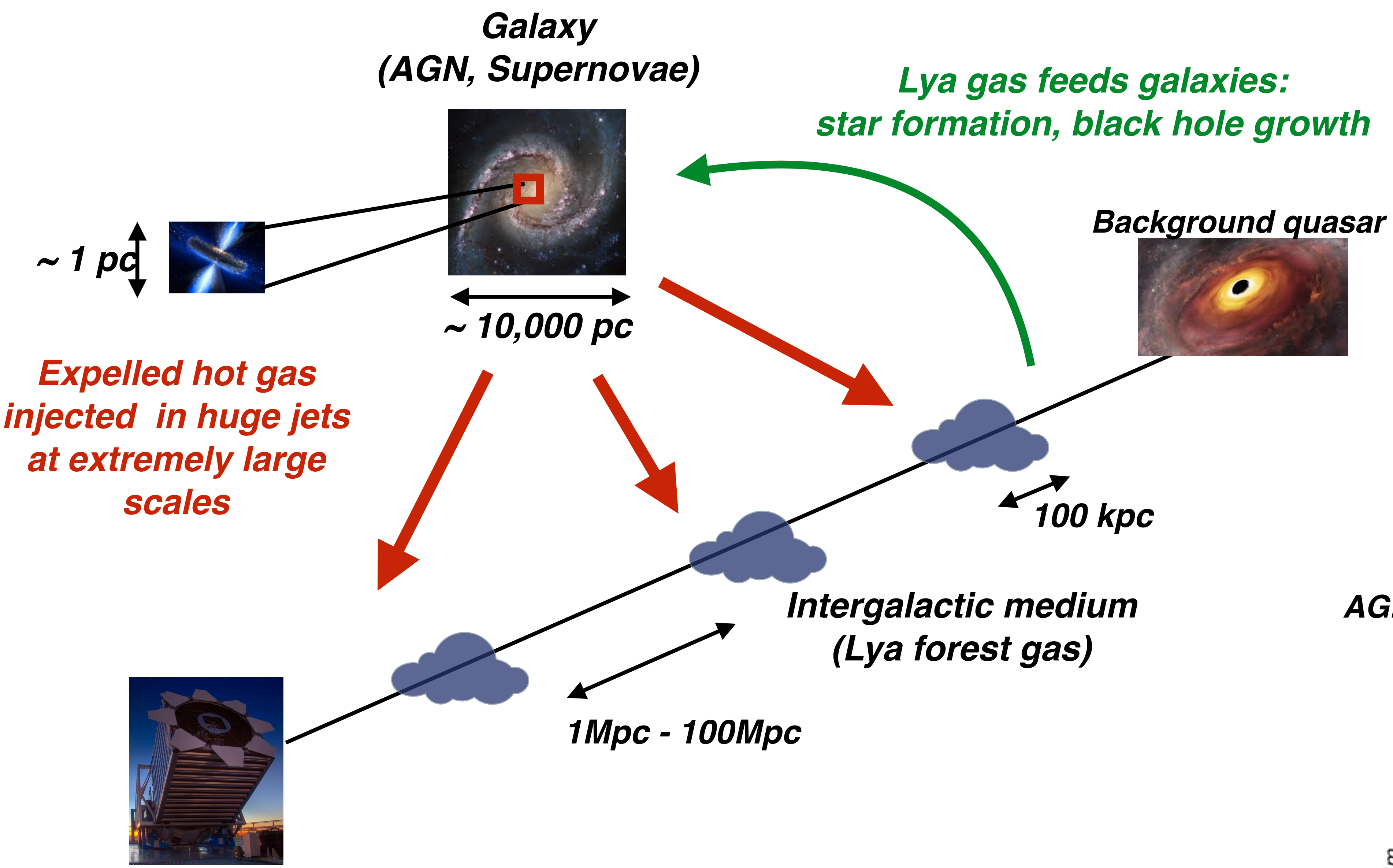
Chisari et al. 2018



Suppression:
baryon pressure delays collapse of DM halos

Small-scale boost:
gas cooling leads to an adiabatic contraction

AGN feedback on the Lya forest



Galaxy (AGN, Supernovae)

~ 1 pc

~ 10,000 pc

Lya gas feeds galaxies: star formation, black hole growth

Background quasar

Expelled hot gas injected in huge jets at extremely large scales

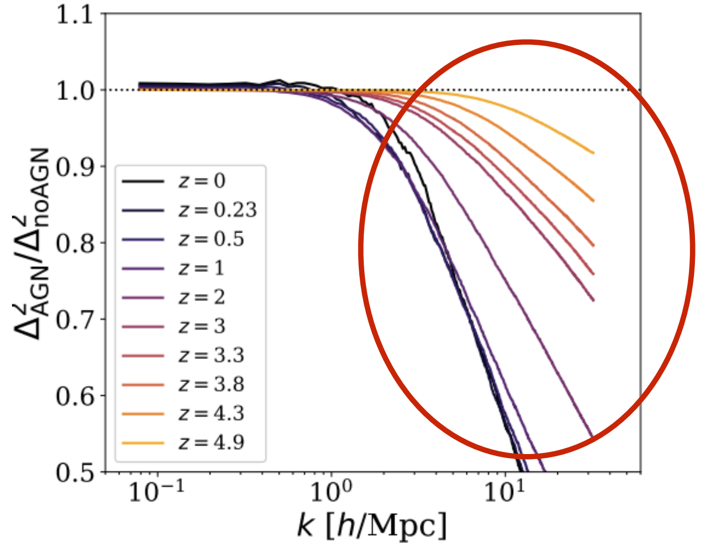
100 kpc

Intergalactic medium (Lya forest gas)

1Mpc - 100Mpc

Impact of AGN feedbacks

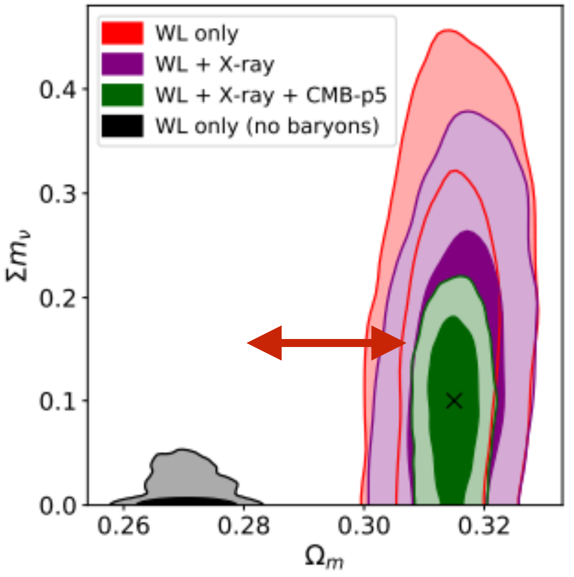
Matter Power Spectrum: P[AGN] / P[noAGN]



Chisari et al. 2018

AGN feedback impact with Weak Lensing:

Neutrino masses / matter density



Schneider et al. 2019

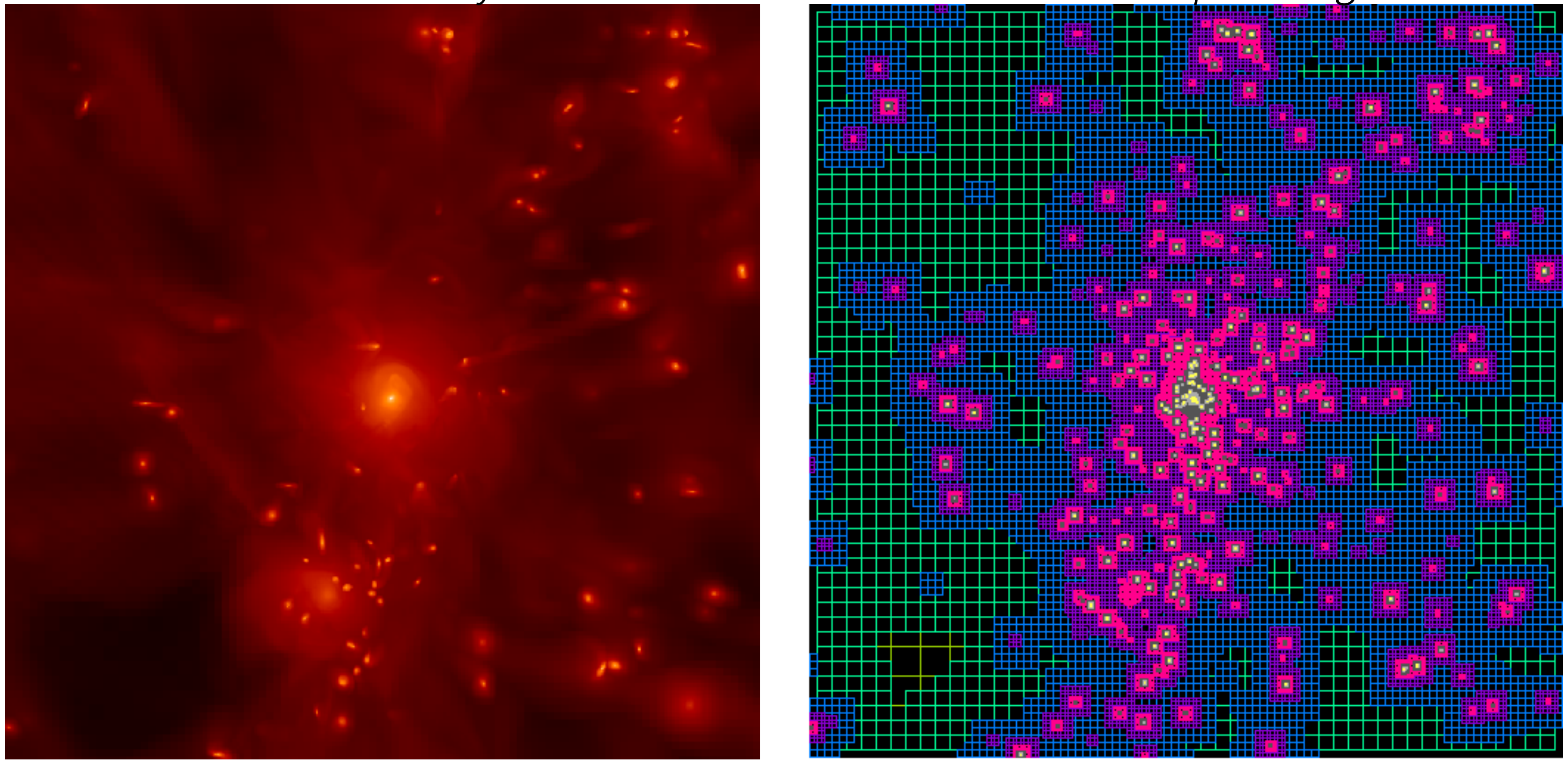
AGN feedback on the Lya forest

The fiducial Horizon-AGN simulation

Dubois et al. 2014

- Cosmological hydrodynamical simulation run with the Adaptative Mesh Refinement (AMR) code RAMSES

Teyssier 2002



Adaptative grid following matter density

Matter density *Adaptative grid*

Teyssier 2002

→ Particularly useful for Lya studies since we can:

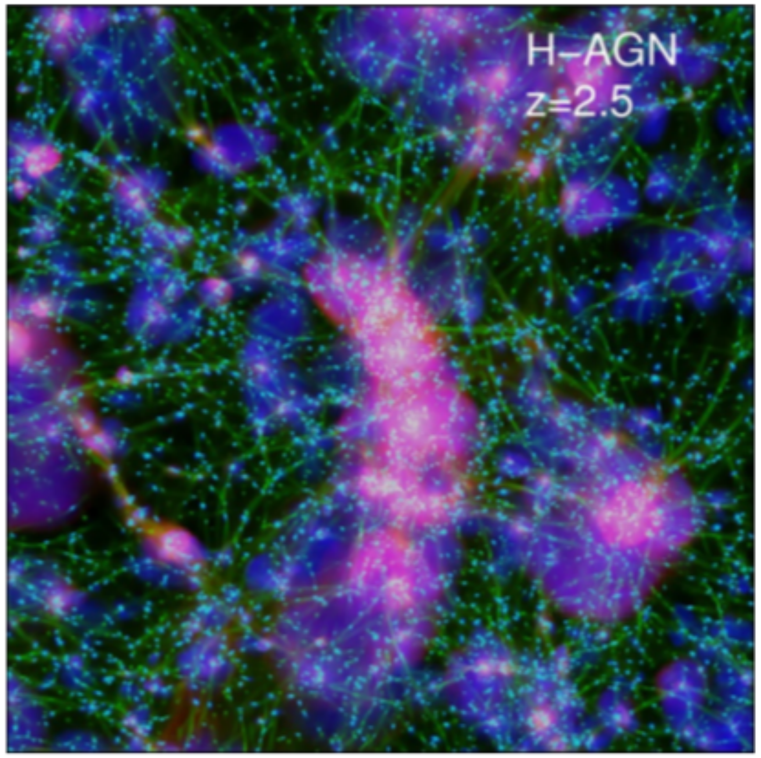
- **enforce the minimal size** of the grid (~100 kpc): 90% of the volume
- model galaxies and feedback (~ 1 pc): 1% of the volume

AGN feedback on the Lya forest

The fiducial Horizon-AGN simulation *Dubois et al. 2014*

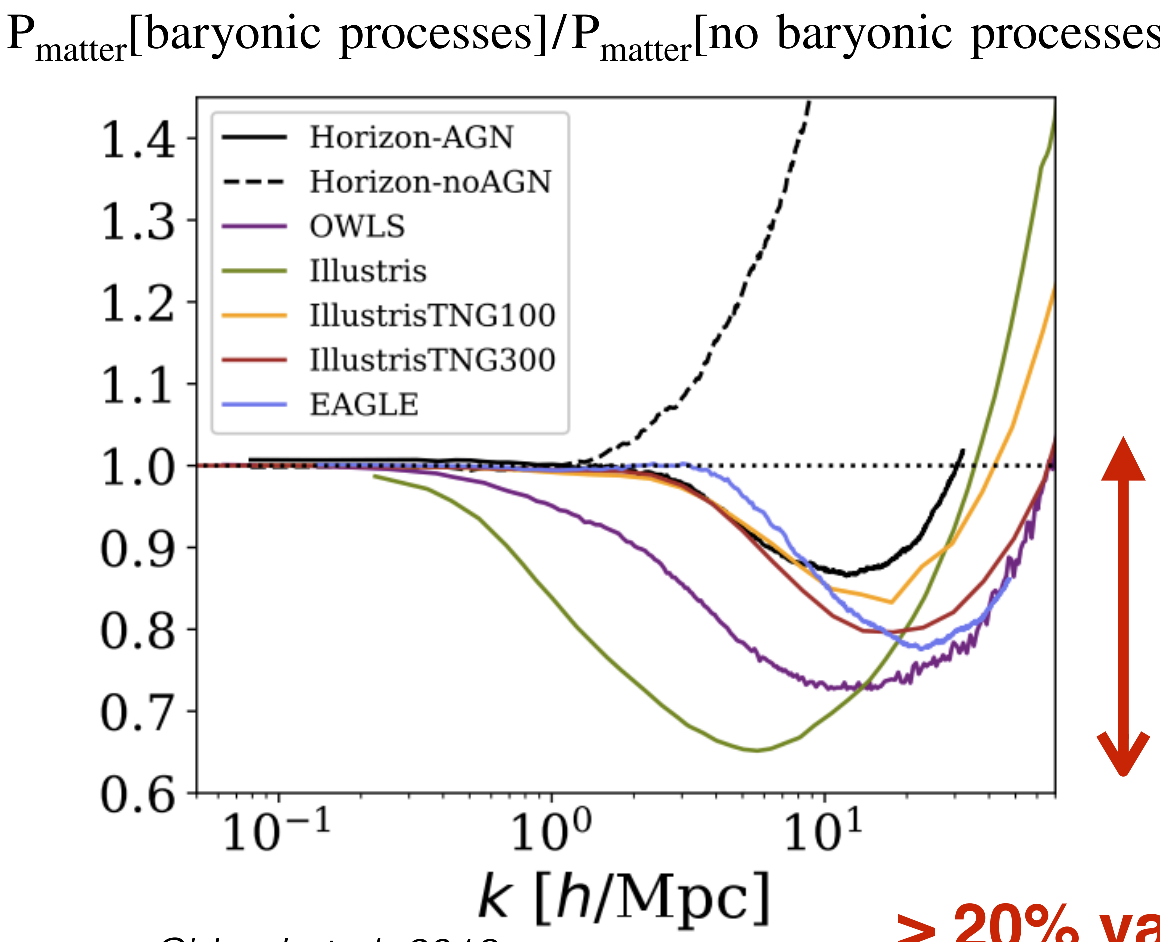
- Cosmological hydrodynamical simulation run with the Adaptative Mesh Refinement (AMR) code RAMSES
  Teyssier 2002
- Box size: $L_{box} = 100\ Mpc/h$
- Cell size: from $100\ \mathrm{kpc/h}$ to $1\ \mathrm{kpc/h}$
- Included physics: - Gas cooling with contribution from metals
  - Heating from a uniform UV background
  - Stellar formation
  - Stellar feedback: release mass, energy and metals
  - AGN feedback
- Companion simulation Horizon-noAGN

gas density
temperature
gas metallicity



AGN feedback and cosmology

Impact of baryonic processes on matter clustering with different hydrodynamical simulations



Chisari et al. 2018

> 20% variability
>>1% targeted precision

→ **Parametrization and calibration of sub-grid models induce a large variability in hydrodynamical simulation predictions**

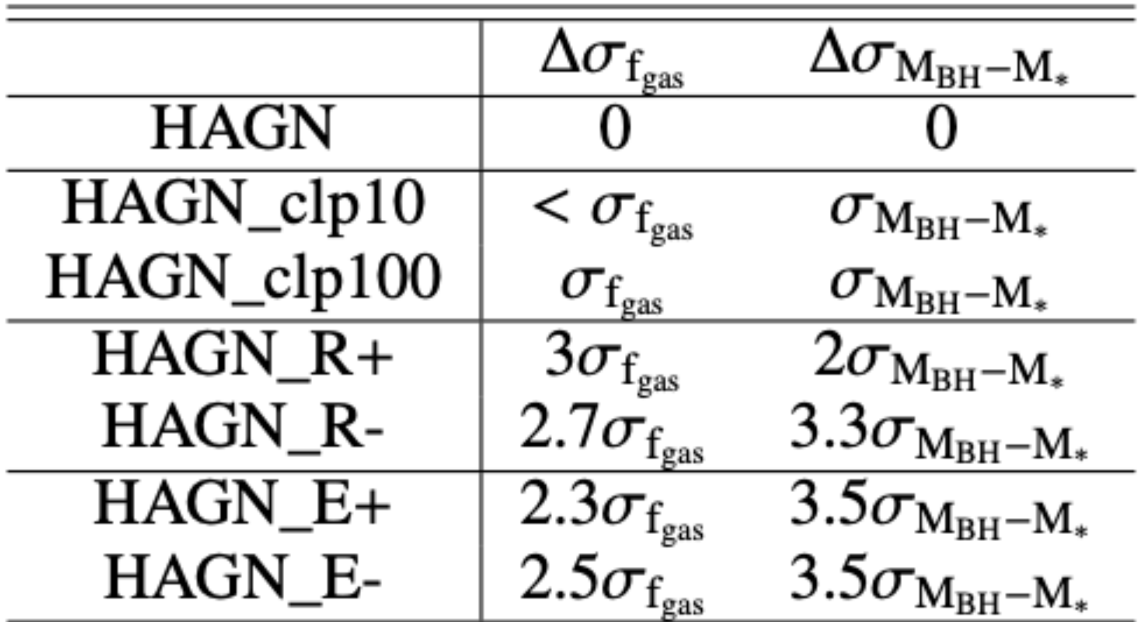
AGN feedback on the Lya forest

- Construction of a set of simulations exploring a large range plausible range of feedback models
- Starting from Horizon-AGN, then variation of feeding and feedback parameters

→ chosen to **span the observable uncertainties of galaxy properties**

The mean fraction of gas in galaxies
How much gas is ejected by feedbacks

The Maggorian relation $\mathrm{M_{BH} - M_*}$
Coupling between galaxy and BH growths



	$\Delta\sigma_{\mathrm{f_{gas}}}$	$\Delta\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN	0	0
HAGN_clp10	$< \sigma_{\mathrm{f_{gas}}}$	$\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_clp100	$\sigma_{\mathrm{f_{gas}}}$	$\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_R+	$3\sigma_{\mathrm{f_{gas}}}$	$2\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_R-	$2.7\sigma_{\mathrm{f_{gas}}}$	$3.3\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_E+	$2.3\sigma_{\mathrm{f_{gas}}}$	$3.5\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_E-	$2.5\sigma_{\mathrm{f_{gas}}}$	$3.5\sigma_{\mathrm{M_{BH}-M_*}}$

Range of feedback model covered is at the limit of realistic galaxy observables

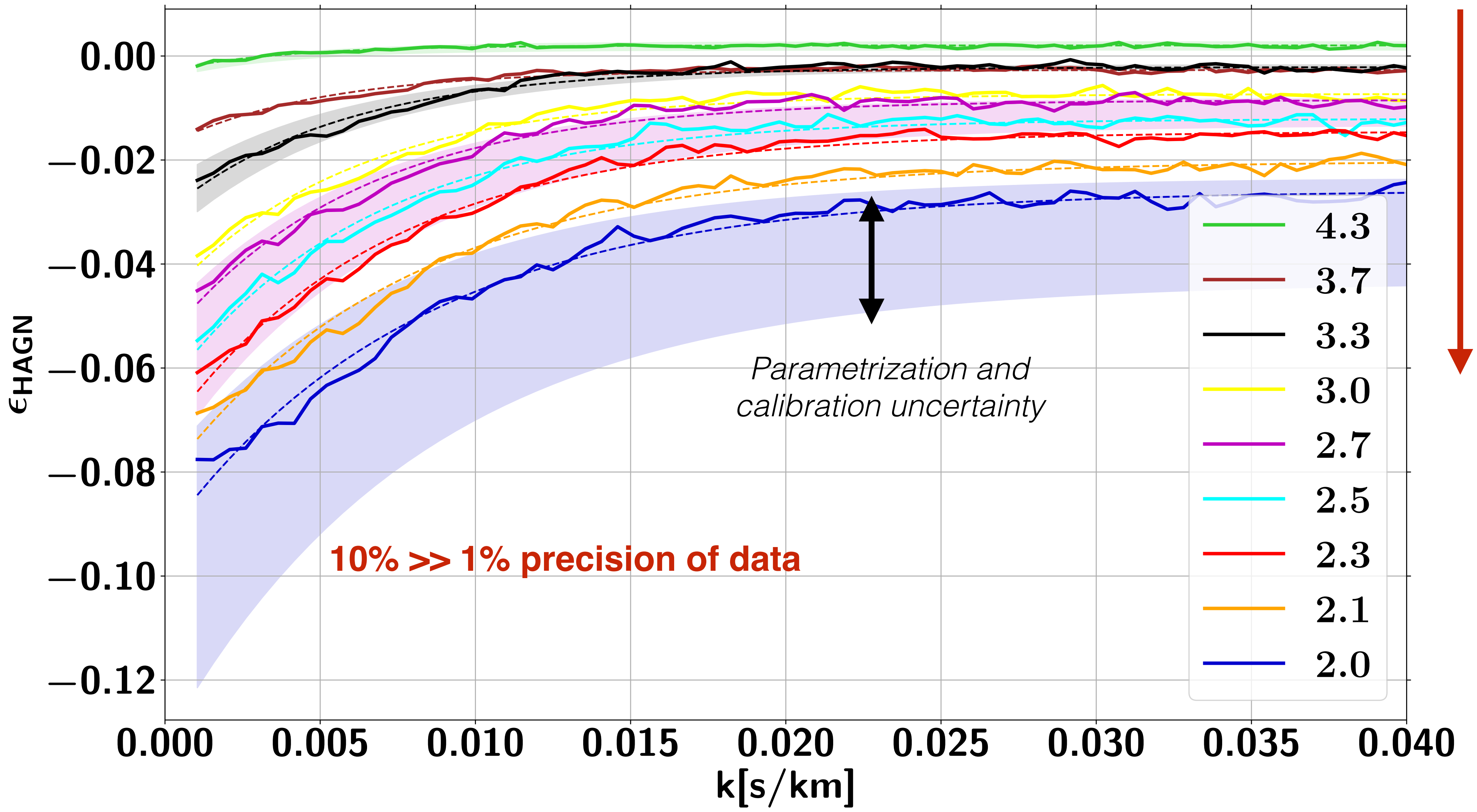
AGN feedback on the Lya forest

Suppression increases with..

$$\epsilon_{HAGN} = \frac{P_{Ly\alpha}[HAGN]}{P_{Ly\alpha}[HnoAGN]} - 1$$

.. increasing scales

.. decreasing redshift



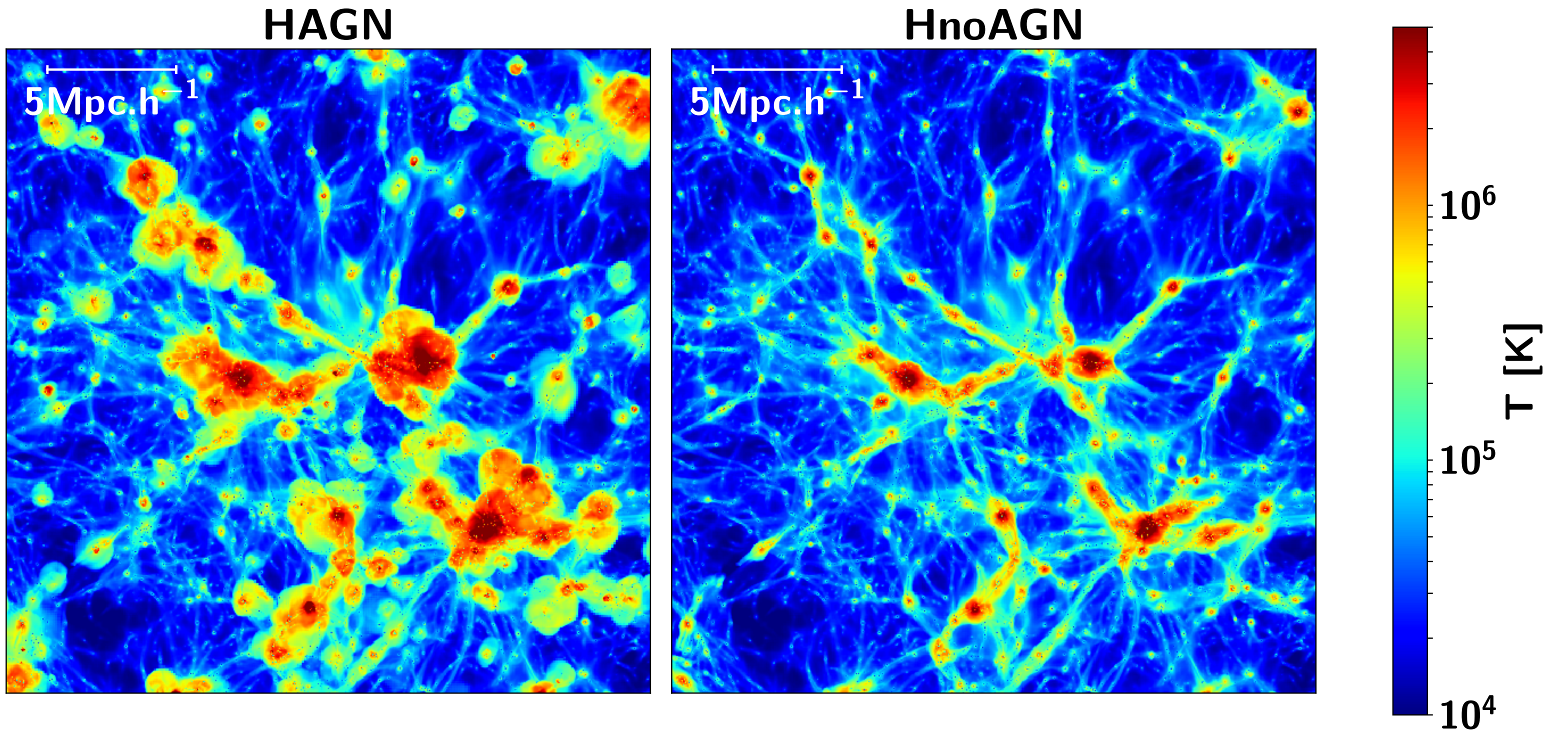
Parametrization and calibration uncertainty

10% >> 1% precision of data

Chabanier et al. 2020a

AGN feedback on the Lya forest

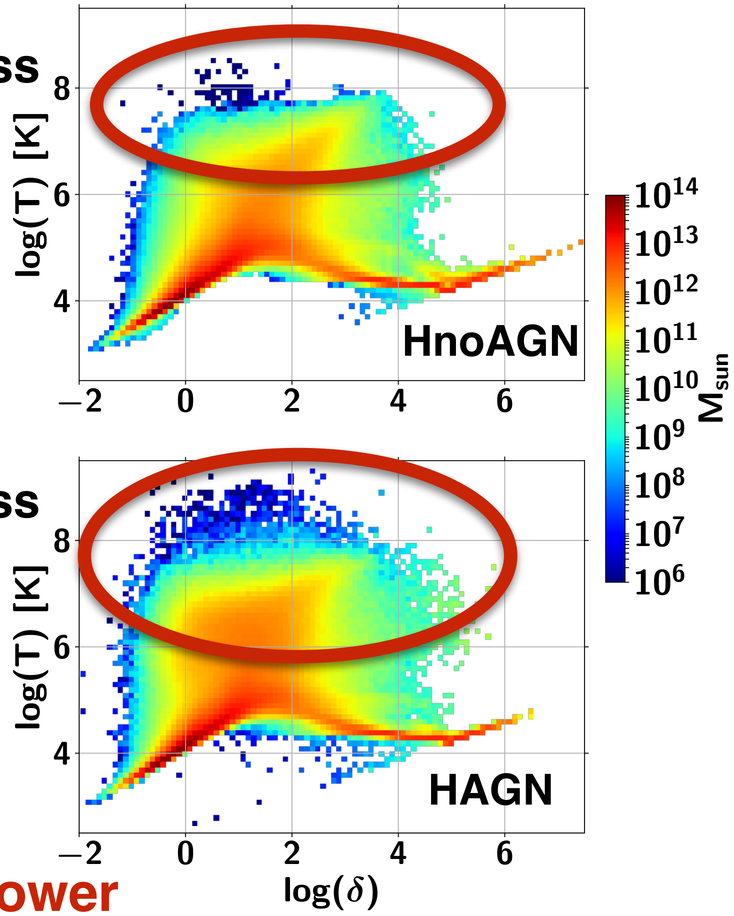
Temperature maps



Temperature-density distribution

12% of the mass

18% of the mass



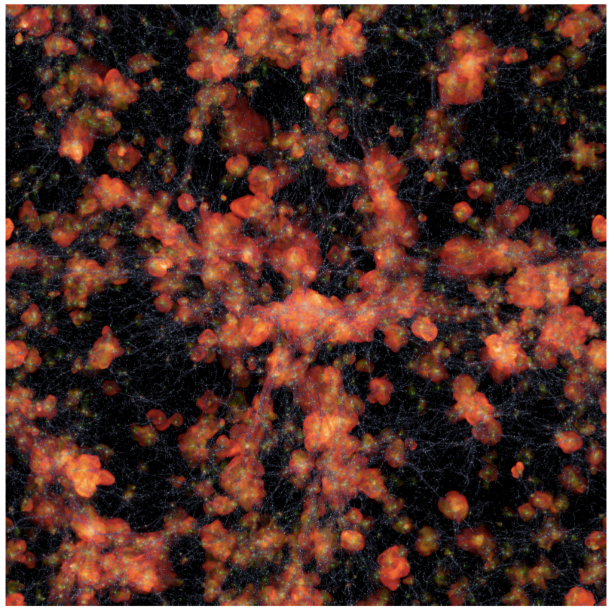
Heating → ionization → suppression of power

Resolution dependent

Thermal effects dominate over gas re-distribution effects

→ **Coupling between IGM resolution and AGN feedback correction ?**

AGN feedback on the Lya forest



The Extreme-Horizon simulation

- **Goal**: push resolution in the diffuse IGM (~90% of the simulation volume)
  test systematic effects on the AGN feedback correction

- Co-PIs: Chabanier and Dubois, on the brand new AMD partition of TGCC/Joliot-Curie

Horizon-AGN simulation
L = 100 Mpc/h
Number of resolution elements: ~ **4 billion**
4,096 CPUs
4 Mh

→

Doubling resolution everywhere
except inside galaxies where the resolution is kept unchanged

Extreme-Horizon simulation
L = 50 Mpc/h
Number of resolution elements: ~ **18 billion**
25,000 CPUs
50 Mh

- Control simulation Standard-Horizon: at the standard resolution of cosmo sims

Minimal resolution SH/HAGN

Minimal resolution EH

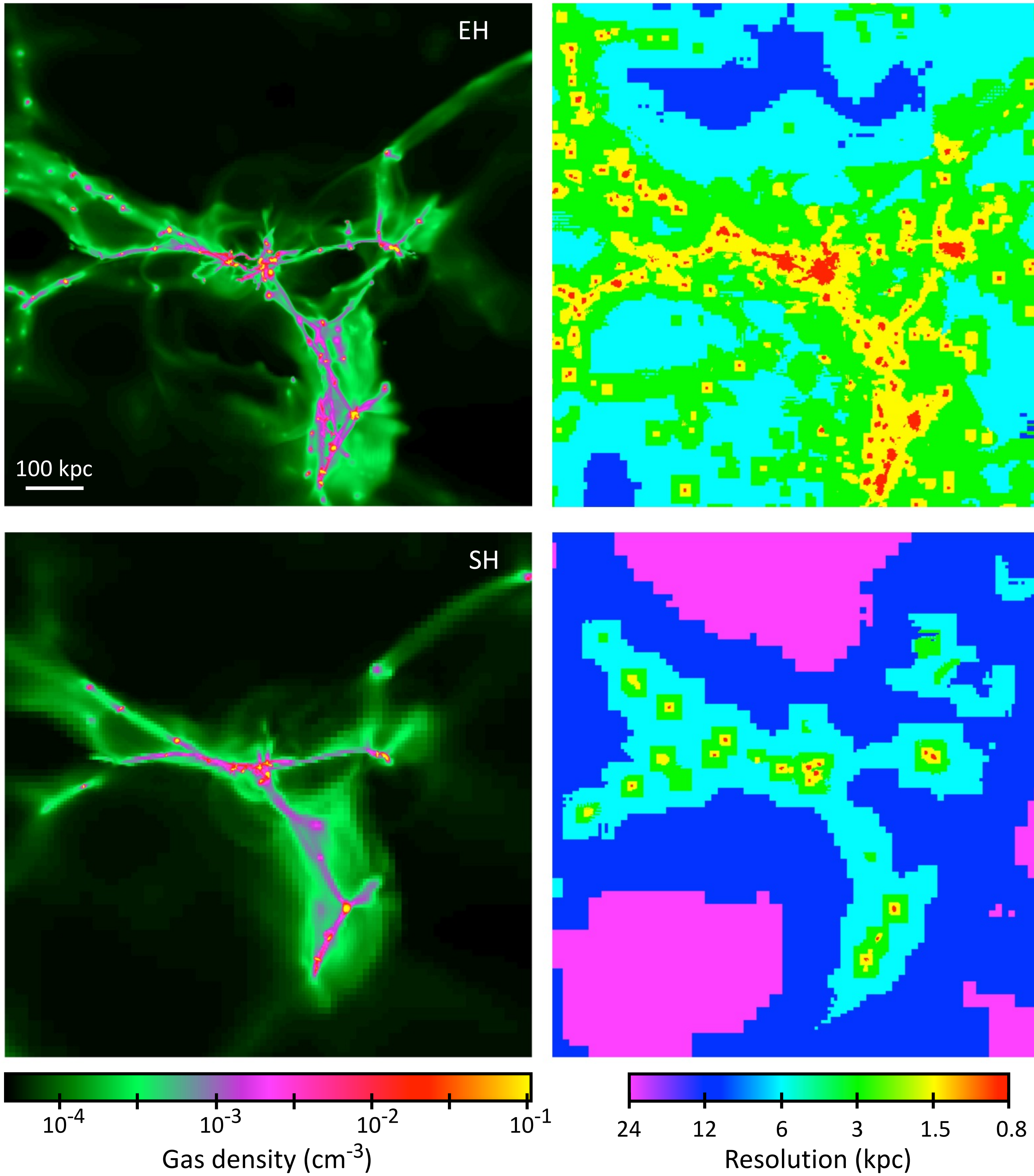
comoving grid resolution [kpc/h]	97.6	48.8	24.4	12.2	6.1	3.05	1.52	0.76
physical grid resolution [kpc]	47	23.5	11.7	5.8	2.9	1.5	0.7	0.3
volume fraction (EH) (z = 2)	–	45%	43%	10%	1%	0.04%	$z < 2$	$z < 2$
volume fraction (SH) (z = 2)	80%	17%	2%	0.17 %	0.013%	5×10^{-4}%	$z < 2$	$z < 2$
volume fraction (HAGN) (z = 2)	77%	19%	2%	0.2 %	0.01%	6×10^{-4}%	$z < 2$	$z < 2$

AGN feedback on the Lya forest

Chabanier et al. 2020b

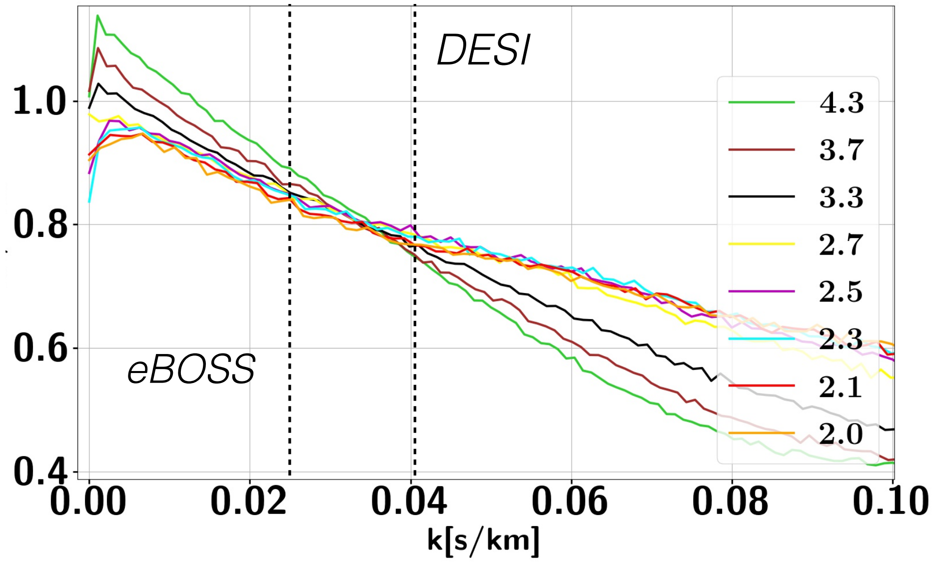
Extreme-Horizon z ~ 3

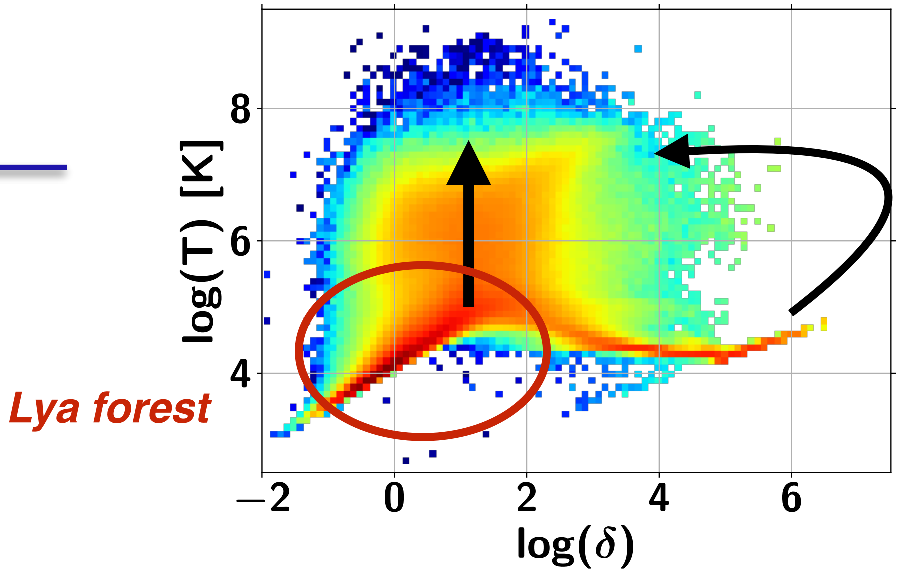
Standard-Horizon z ~ 3



AGN feedback on the Lya forest

Resolution effects on $\mathbf{P_{Ly\alpha}}$



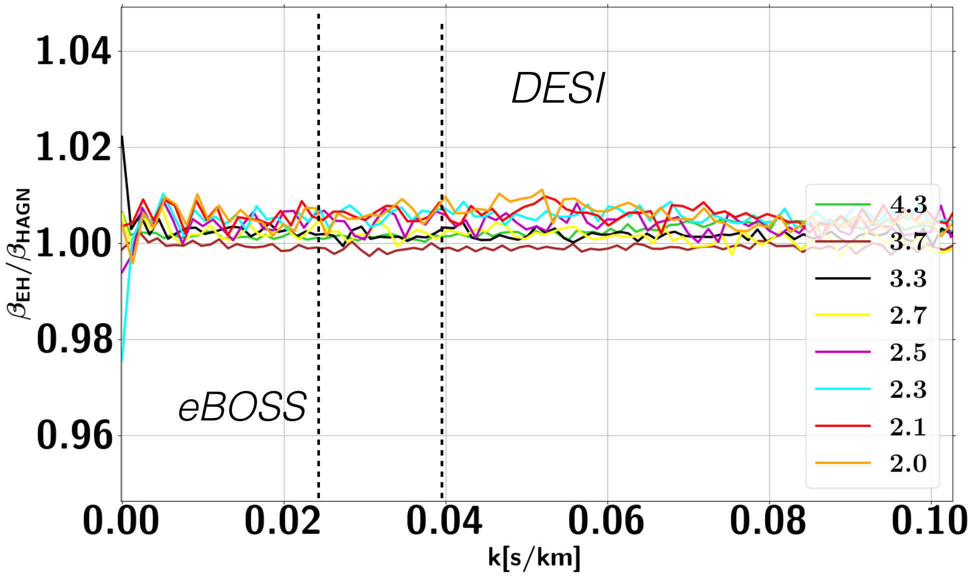


feedbacks=
Heating + redistribution

→ Large effects, especially at small scales
$P_{Ly\alpha}$ are not converged in absolute

Sensitive to cooling of « cold » gas (T $\sim 10^4$ *K)*

Resolution effects on AGN feedback correction



Differences well below the percent level
→ **AGN feedback corrections are converged**

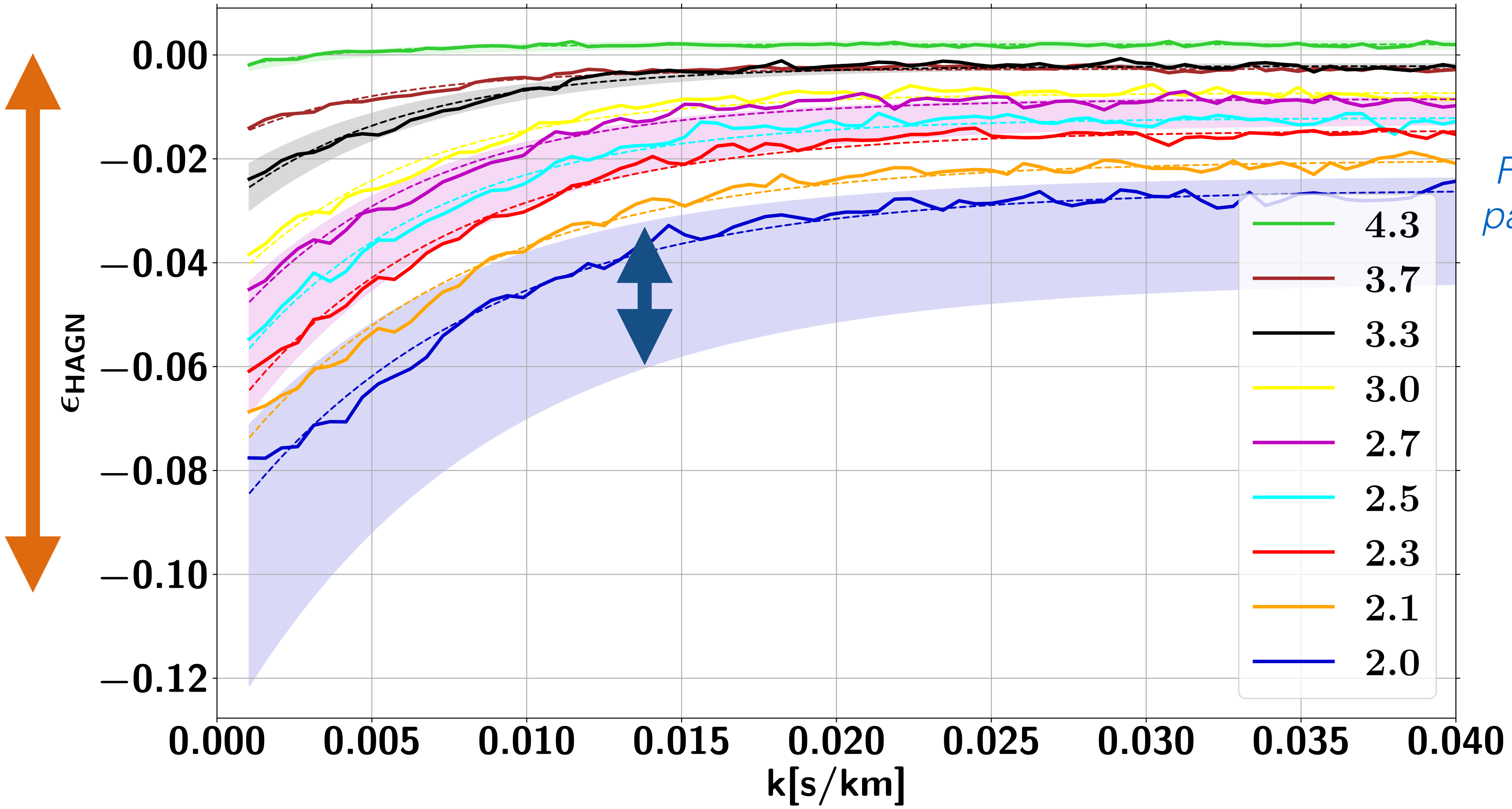
Sensitive to cooling of « hot » gas (T $> 10^6$ *K), lost anyway with* $P_{Ly\alpha}$

Important outcome: major improvements of galaxy properties (compactness) without calling upon novel sub grid models

Chabanier et al. 2020b

AGN feedback on the Lya forest

AGN feedback bias



Feedback calibration and parametrization uncertainty

$$\frac{\Delta n_s}{n_s} \sim 2\sigma_{n_s,eBOSS} \pm 0.8\sigma_{n_s,eBOSS}$$

$$\frac{\Delta\sigma_8}{\sigma_8} = 1\sigma_{\sigma_8,eBOSS} \pm 0.25\sigma_{\sigma_8,eBOSS}$$

AGN feedback are not negligible given the level of precision reached by Lya data

$$\sigma_{DESI} \ll \sigma_{eBOSS}$$

Conclusions

- Next-generation surveys target the 1% precision on measurements

  → *Small-scale non linearities must be precisely taken into account*

- N-body numerical simulations are ideal tools to make robust theoretical predictions

  → *N-body codes have now reached the 1% convergence up to k = 10 h/Mpc*

  → *Emulation techniques allow precise interpolation for a small number of simulations*

- Hydrodynamical simulations have reached:

  - large volumes *(enough statistics)*

  - reasonable resolution *(model galaxy formation)*

- Divergences induced by implementation and calibration of subgrid models are **not a fatality**

  → *Grid of simulations to explore wide range of realistic subgrid models*

  → *Numerical laboratories to parametrize baryonic effects*