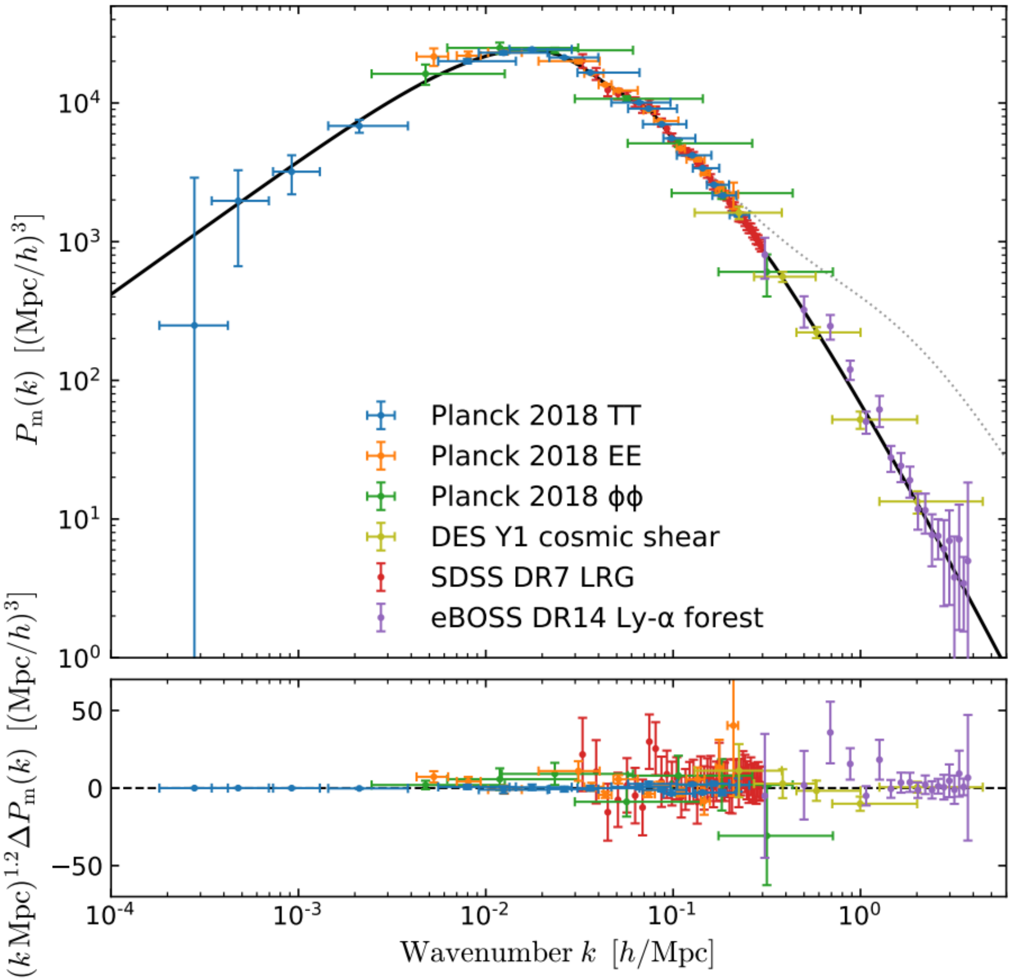
Cosmology and Neutrino Physics with the Ly-α forest

Constraints from Cosmological Simulations

Frédéric Bournaud
CEA/AIM Paris-Saclay

Based on a collaboration with
Solène Chabanier, Nathalie Palanque-Delabrouille, Yohan Dubois, et al….

The Ly-α forest as a cosmological probe

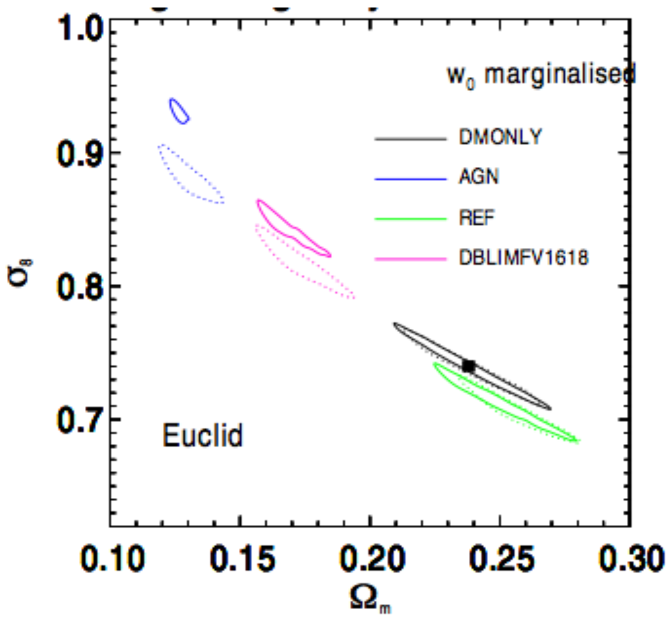


Smallest scales among cosmological probes :

- σ_8, n_S ...
- Sum of neutrino masses

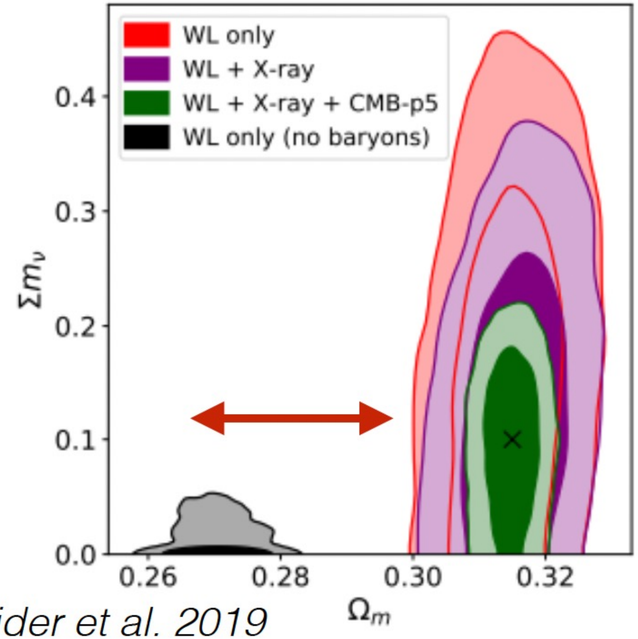
Chabanier, Millea & Palanque-Delabrouille 2019

Baryons as a source of systematics for cosmological probes



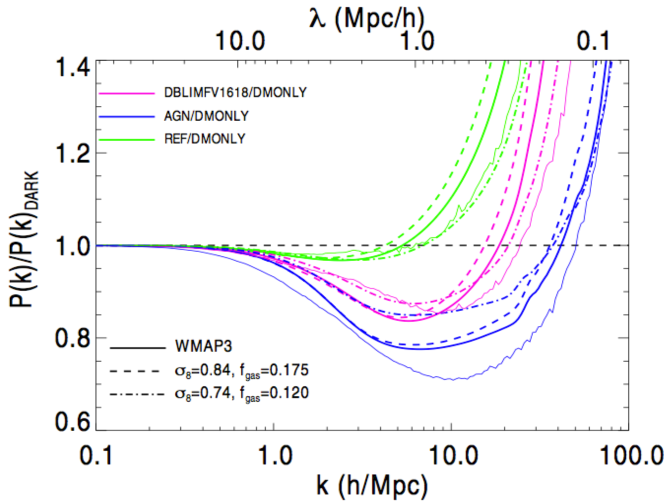
Semboloni, Hoekstra, Schaye 2013

Impact of AGN feedback on cosmological parameters with Weak Lensing



Schneider et al. 2019

Baryons as a source of systematics for the Ly-α forest



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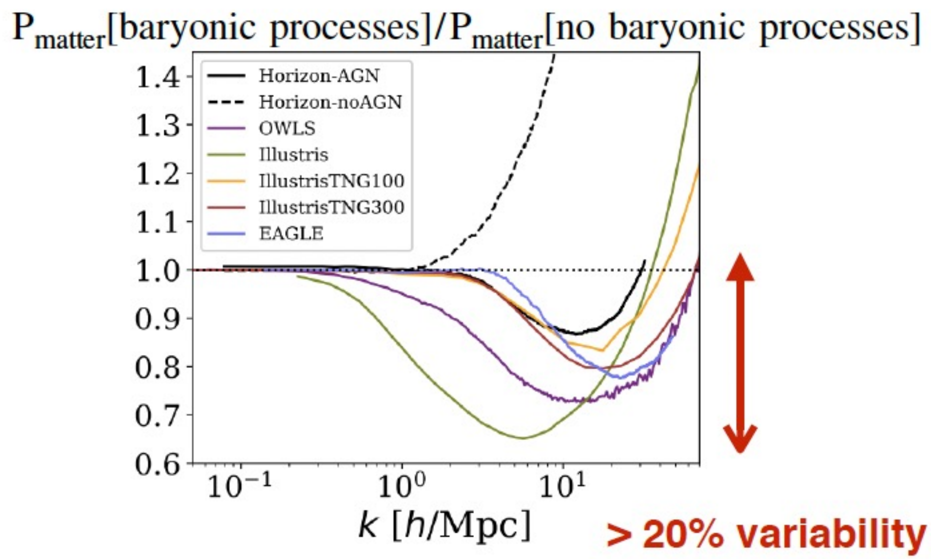

Chisari et al. 2018

- The Ly-α scale is highly sensitive to baryonic effects
- Target data precision < 1%

- No consensus from hydro simulations
- Key issue : feedback modelling (mostly AGN feedback, stellar/supernovae seems less crucial)
  => Where is the « true » AGN feedback effect ?

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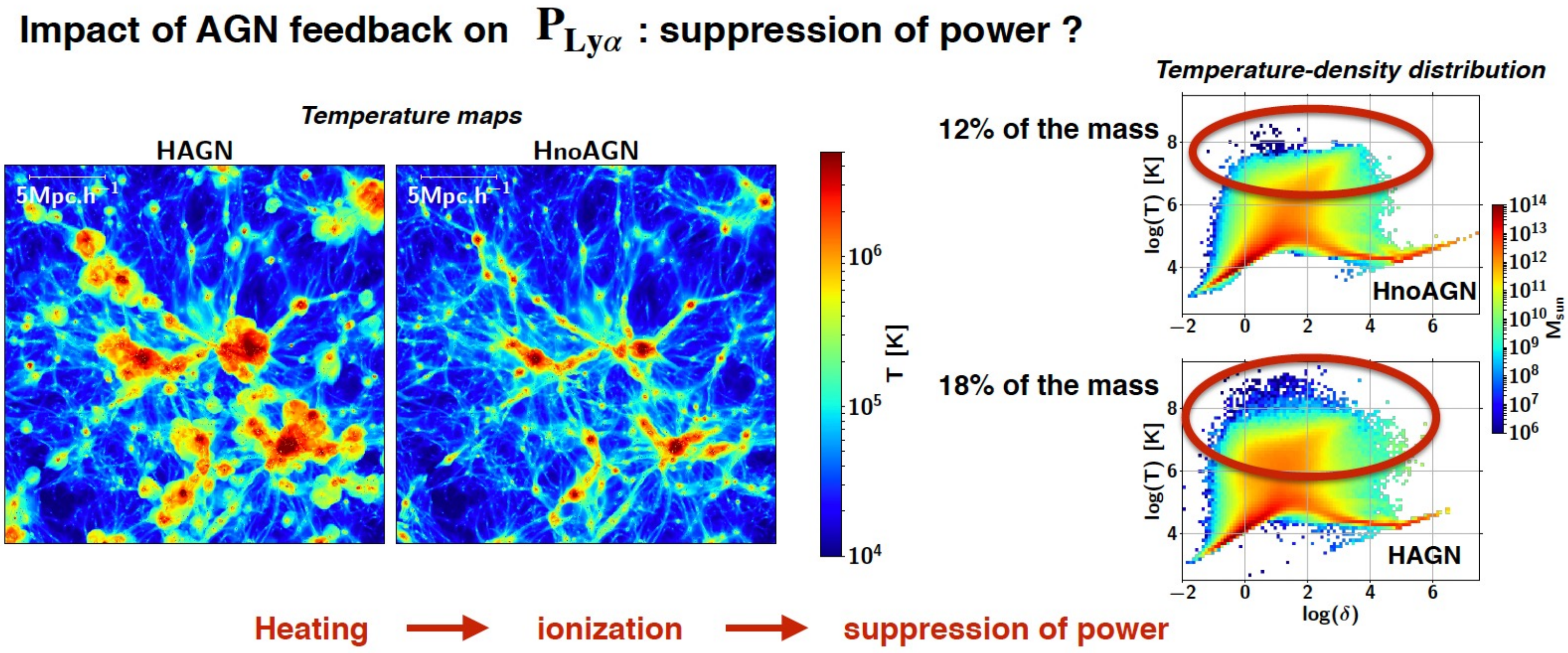

Dubois + 2016, Peirani + 2016

Bracketing AGN feedback effects

- Series of « Horizon-AGN-like » simulations. (Dubois+2016)
- Varying AGN feedback parameters to cover the whole plausible range

Variation of feeding and feedback parameters

→ chosen to span the observable uncertainties of galaxy properties

The mean fraction of gas in galaxies ↘ ***The Maggorian relation*** $M_{BH} - M_*$ ↙

		$\Delta\sigma_{f_{gas}}$	$\Delta\sigma_{M_{BH}-M_*}$
	HAGN	0	0
Stochasticity in the accretion rate	HAGN_clp10	$< \sigma_{f_{gas}}$	$\sigma_{M_{BH}-M_*}$
	HAGN_clp100	$\sigma_{f_{gas}}$	$\sigma_{M_{BH}-M_*}$
Radius of energy deposition	HAGN_R+	$3\sigma_{f_{gas}}$	$2\sigma_{M_{BH}-M_*}$
	HAGN_R-	$2.7\sigma_{f_{gas}}$	$3.3\sigma_{M_{BH}-M_*}$
Fraction of injected energy	HAGN_E+	$2.3\sigma_{f_{gas}}$	$3.5\sigma_{M_{BH}-M_*}$
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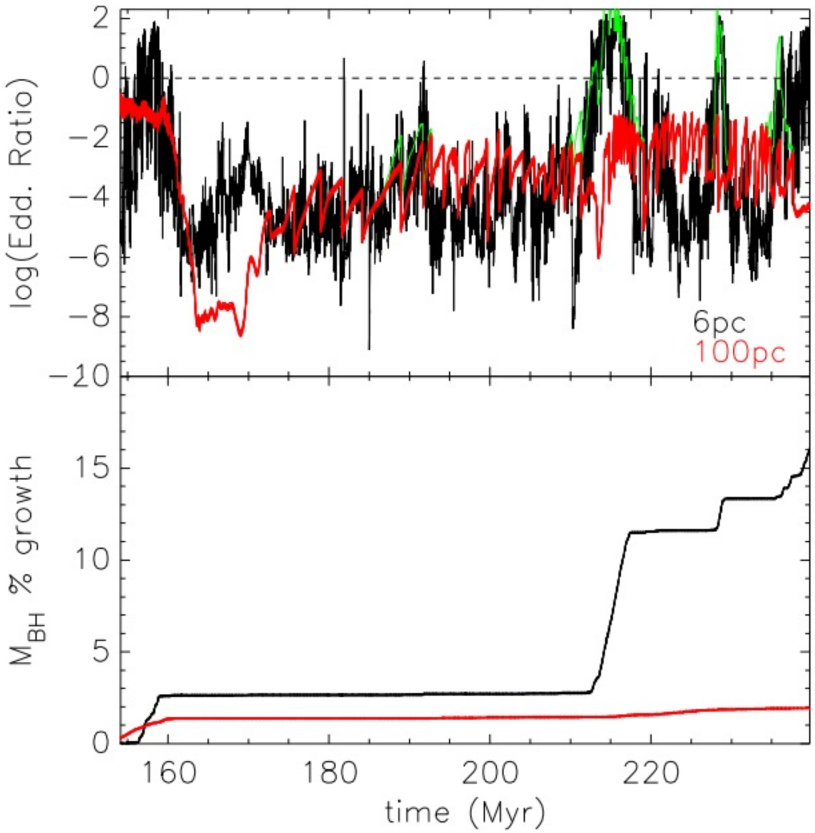
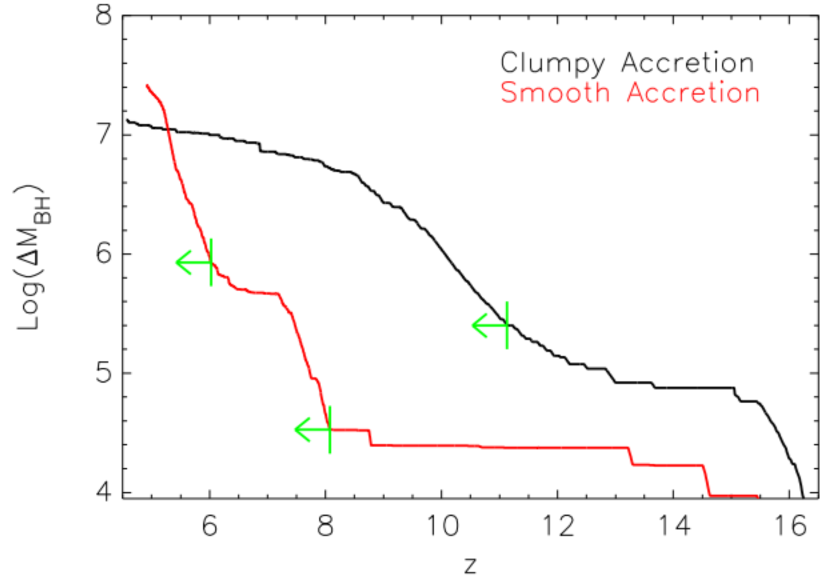
Shifts in galaxy-scale properties at redshift z=2

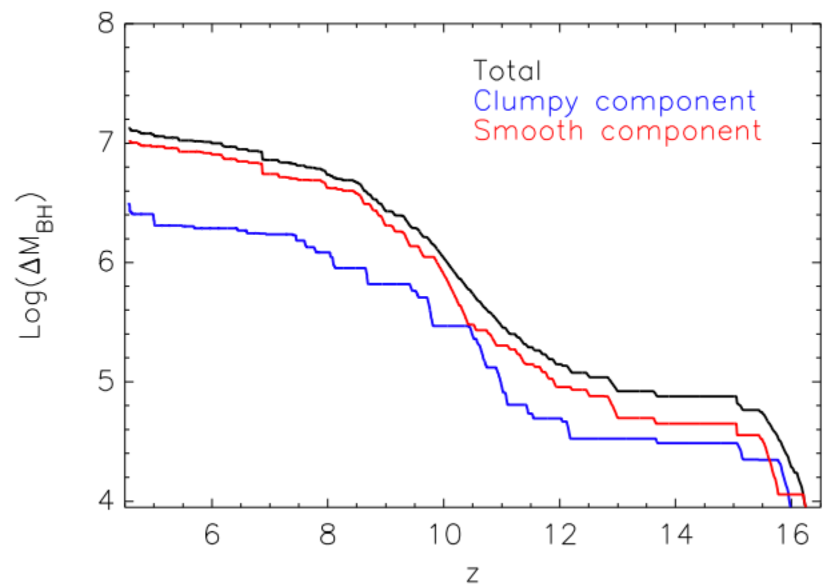
Range of feedback model covered is at the limit of realistic galaxy observables

Chabanier, Bournaud, Dubois et al. 2020

Clumy accretion onto SMBHs







DeGraf, Bournaud, Dekel + 2017

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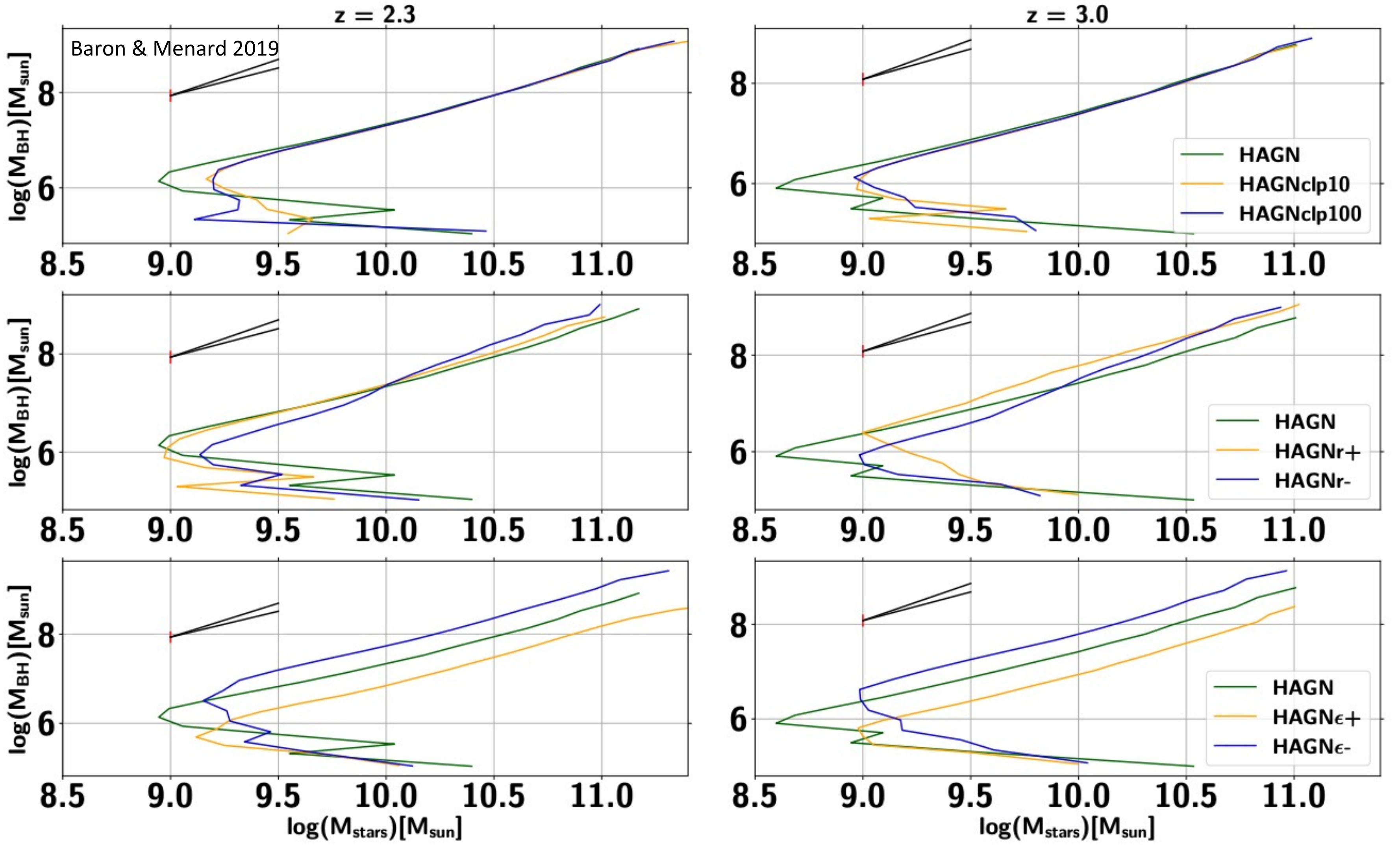

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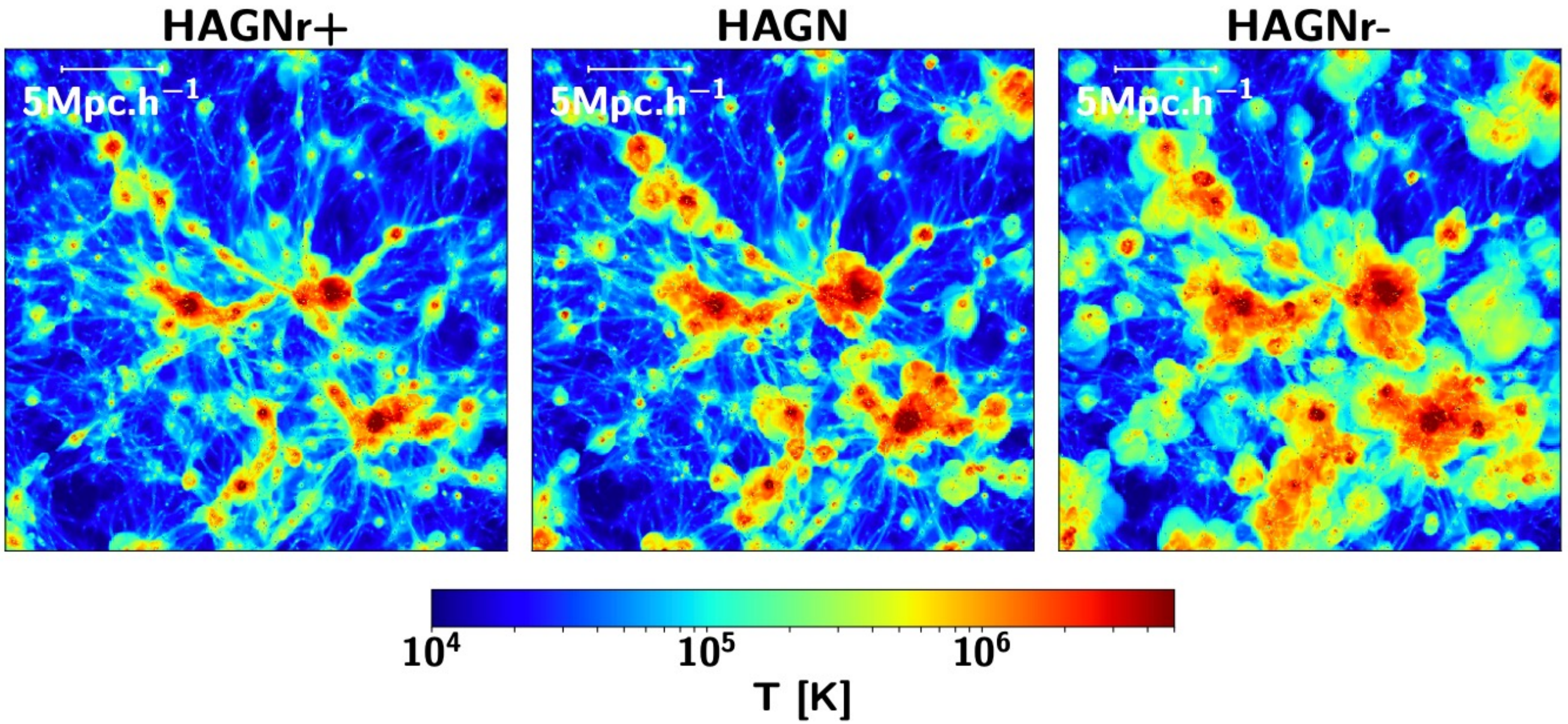

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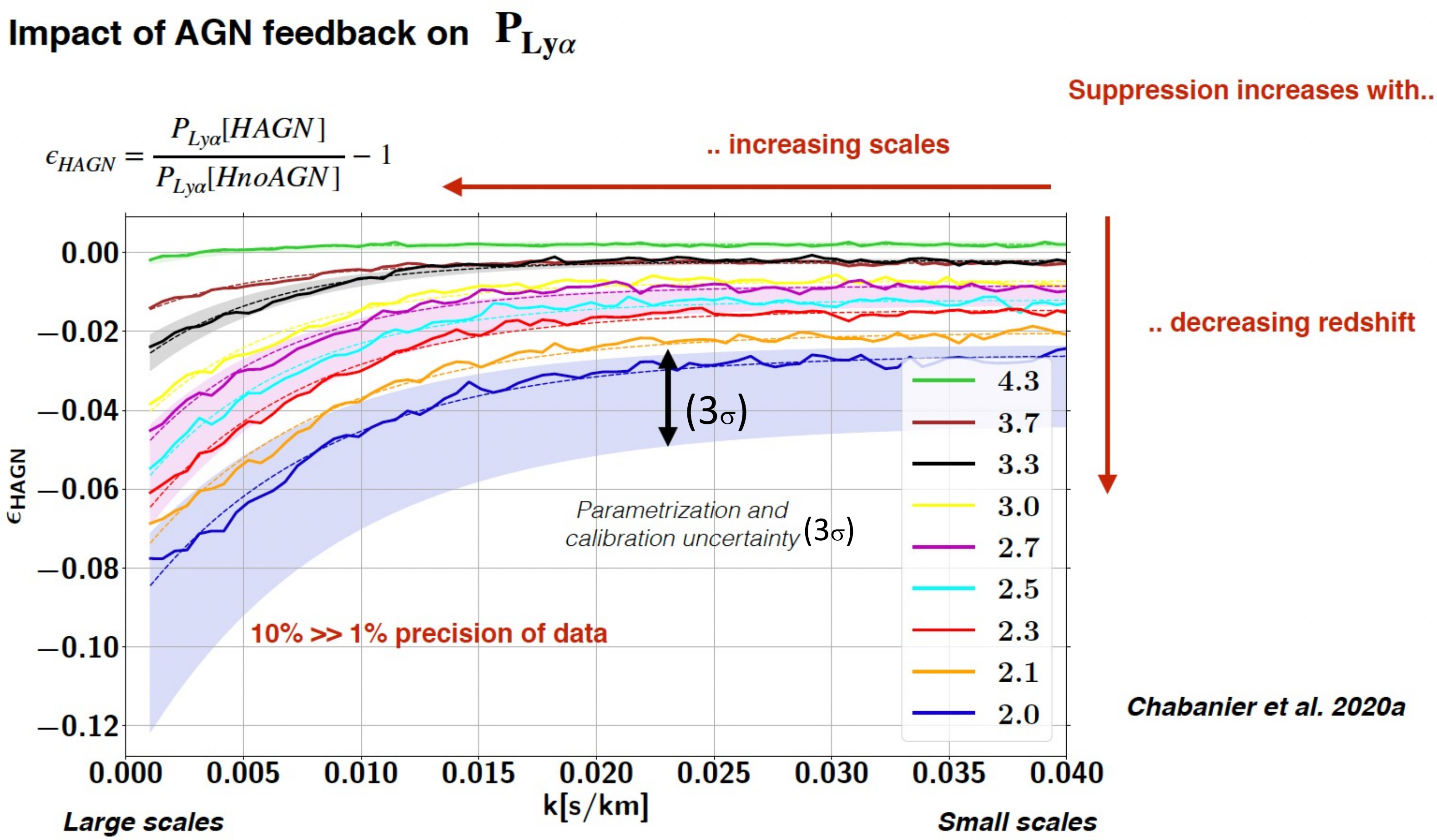
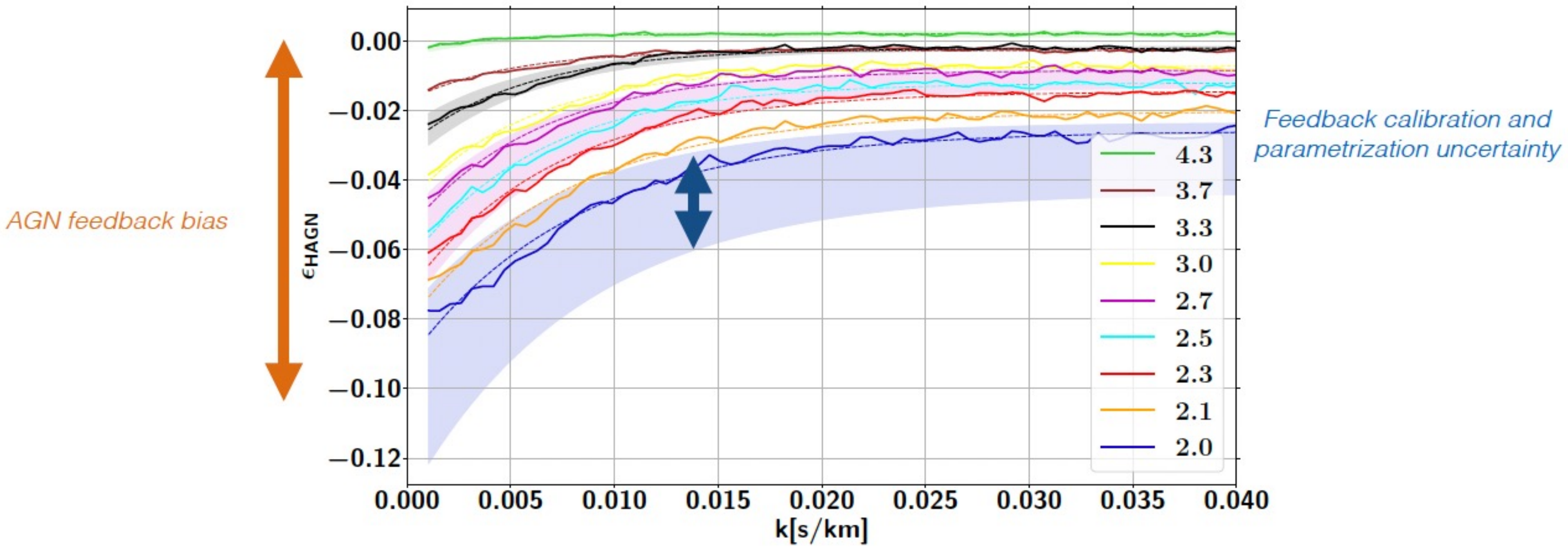
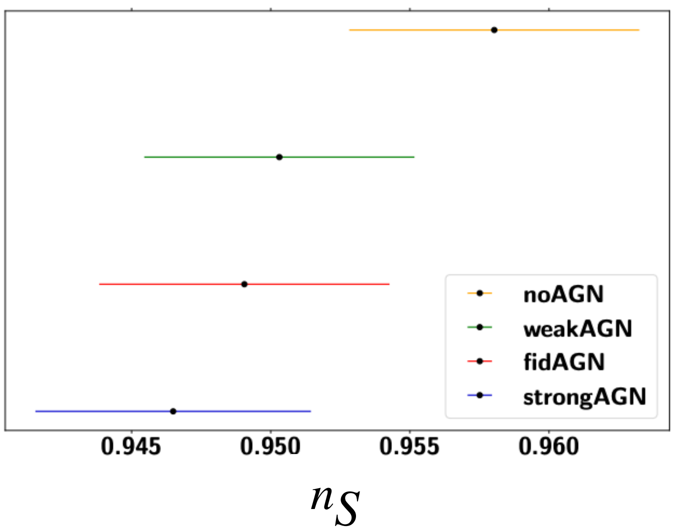


- AGN « correction » > eBOSS/DESI data accuracy (~1%)
- Similar work done for SN feedback : marginal effects

Chabanier, Bournaud, Dubois et al. 2020

eBOSS Ly-α forest analysis with baryonic (AGN) effects





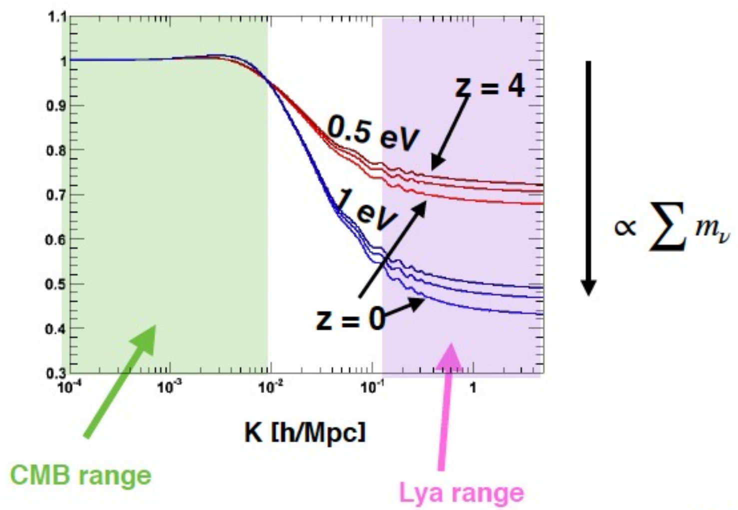
	noAGN	weakAGN	fidAGN	strongAGN
σ_8	0.82 ± 0.02	0.83 ± 0.02	0.83 ± 0.02	0.83 ± 0.02
n_s	0.958 ± 0.005	0.950 ± 0.005	0.949 ± 0.005	0.946 ± 0.005
Ω_m	0.268 ± 0.009	0.269 ± 0.009	0.270 ± 0.009	0.269 ± 0.009
$T_0(z=3)$ (10^3 K)	8.5 ± 2.0	8.6 ± 1.8	8.64 ± 1.9	8.7 ± 1.2
γ	0.92 ± 0.13	0.95 ± 0.12	0.93 ± 0.14	0.97 ± 0.15
A^τ (10^{-3})	2.33 ± 0.06	2.37 ± 0.06	2.38 ± 0.06	2.40 ± 0.06
η^τ	3.83 ± 0.03	3.83 ± 0.03	3.84 ± 0.03	3.84 ± 0.03

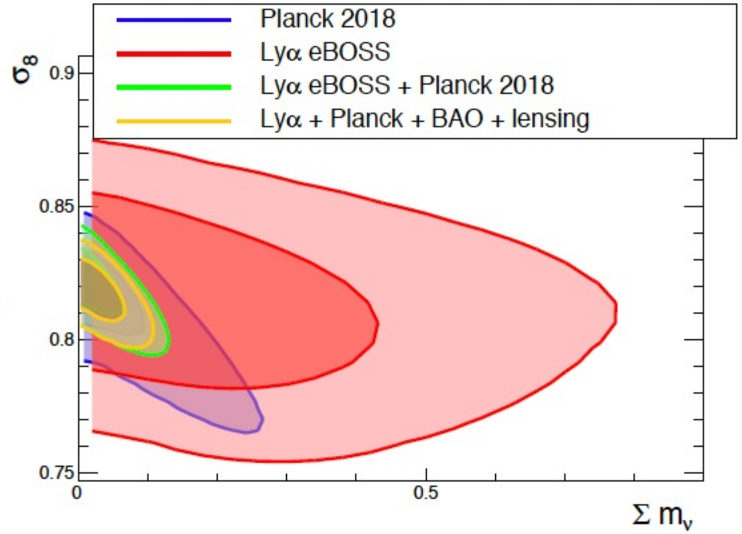
Chabanier + 2020, Palanque-Delabrouille + 2021

eBOSS Ly-α forest analysis with baryonic (AGN) effects

Sum of neutrino masses

$$P^{M_\nu}(k)\,/\,P^{M_\nu=0}(k)$$





- Lya alone: power suppression + z-dependence ⟶ $\sum m_\nu < 0.58$ eV @ 95% CL
  - ⟶ factor 2 improvement compared to BOSS

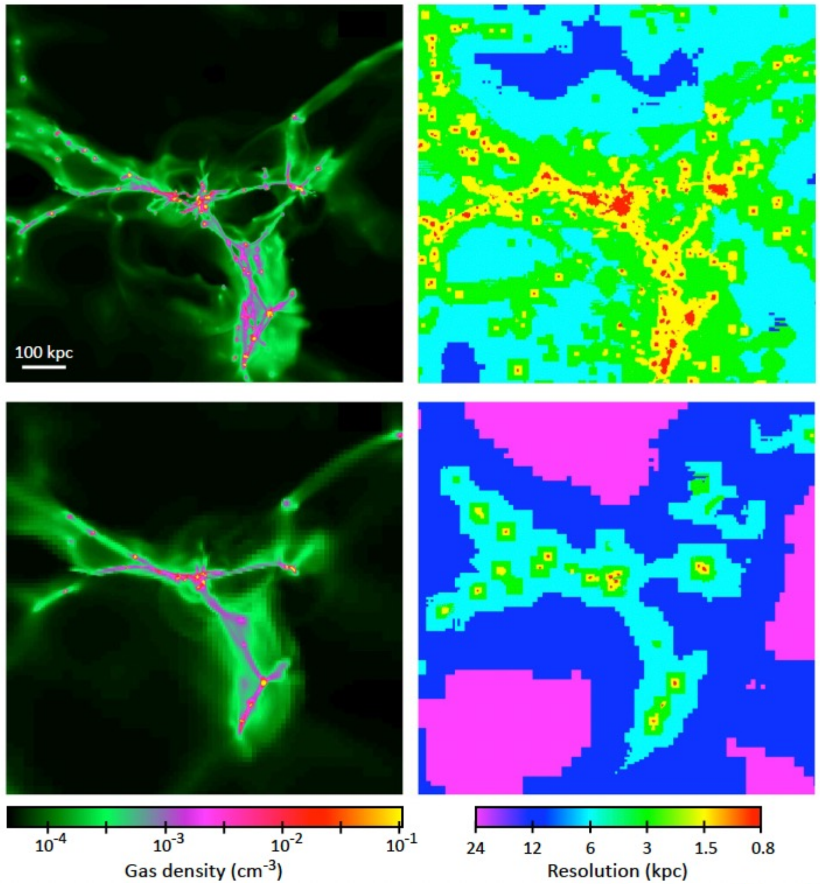
  but large degeneracy $\sigma_8 - \sum m_\nu$
- Lya + CMB: sensitive to amplitude suppression ⟶ $\sum m_\nu < 0.105$ eV @ 95% CL
  - ⟶ Combination breaks degeneracy and significantly tightens the constraint
- Lya + CMB + BAO + lensing: ⟶ $\sum m_\nu < 0.089$ eV @ 95% CL
  - ⟶ **Among the strongest constraints to date**
    marginal tensions on the inverted neutrino mass hierarchy $\left(\sum m_{\nu,min} = 0.095 \text{ eV}\right)$

Chabanier + 2020, Palanque-Delabrouille + 2021

Resolving inter-galactic gas in cosmological simulations

Extreme-Horizon z ~ 3

Horizon-AGN z ~ 3



Extreme-Horizon vs. Horizon-AGN

- Resolution in/near galaxies unchanged
- Improved in the IGM (x2-x4)

Minimal resolution HAGN

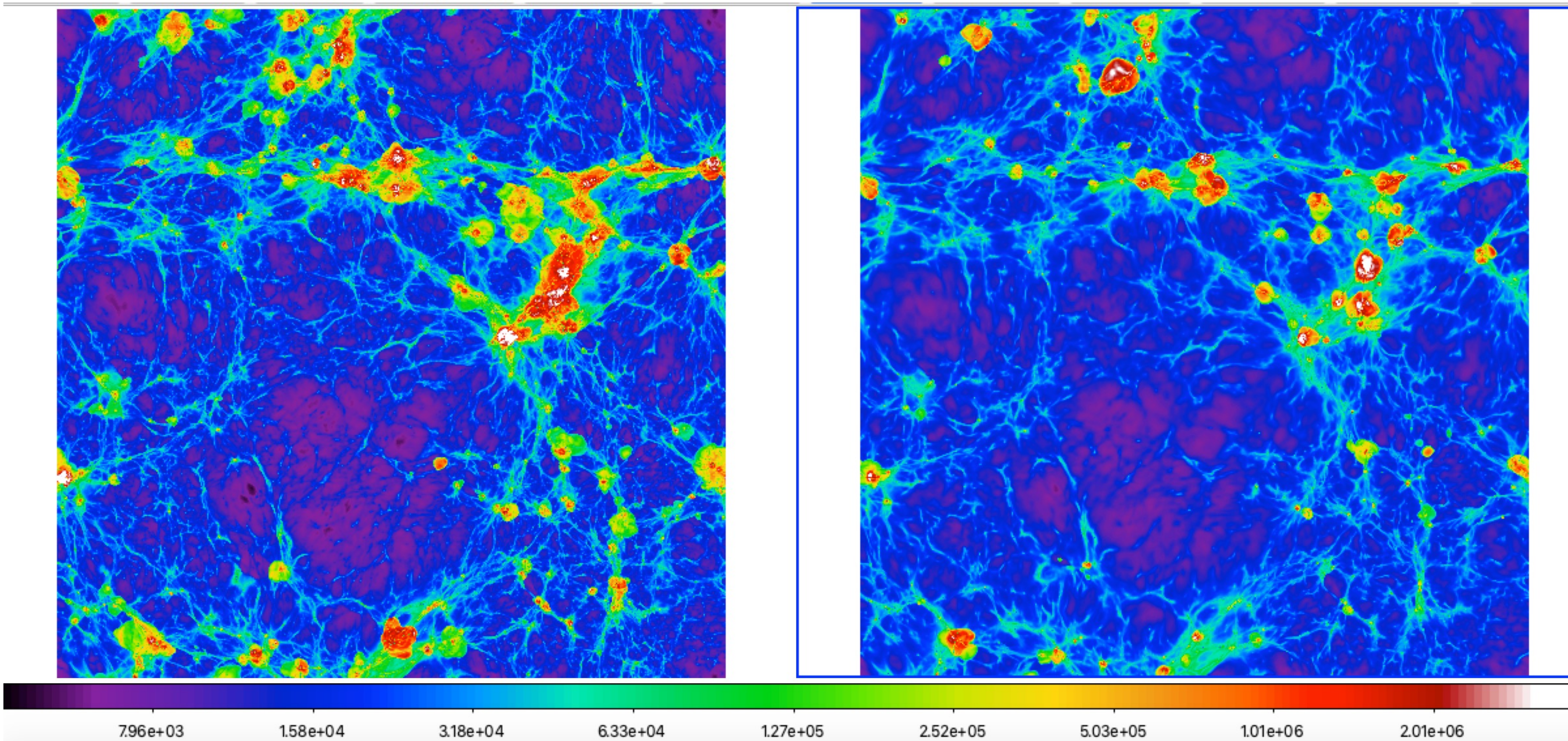
Minimal resolution EH

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 (HAGN) (z=2)	77%	19%	2%	0.2 %	0.01%	6×10^{-4}%	$z < 2$	$z < 2$

Chabanier, Bournaud, Dubois et al. 2020b

Resolving inter-galactic gas in cosmological simulations

EXTREME-HORIZON Same box, Horizon-AGN resolution



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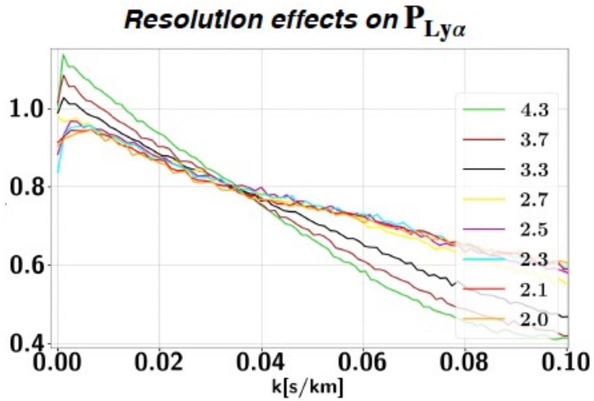
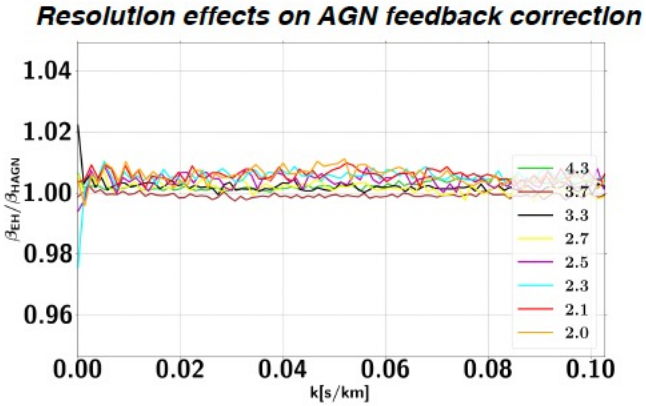


Large effects, especially at small scales
$P_{Ly\alpha}$ are not converged in absolute

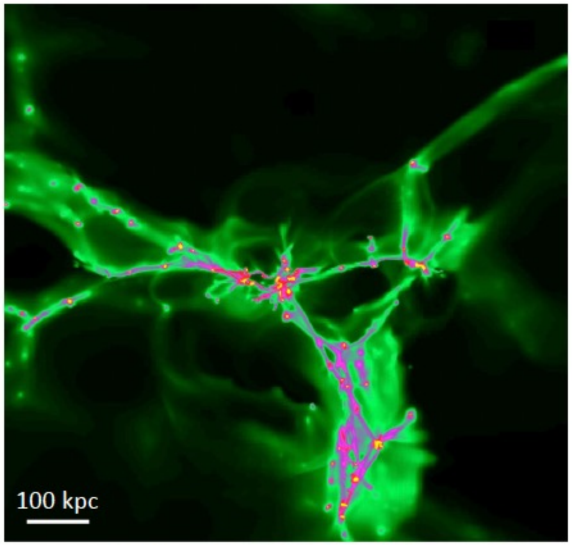


Differences well below the percent level
AGN feedback corrections are converged

Chabanier, Bournaud, Dubois et al. 2020b

Compact galaxy formation at high redshift

Extreme-Horizon z ~ 3

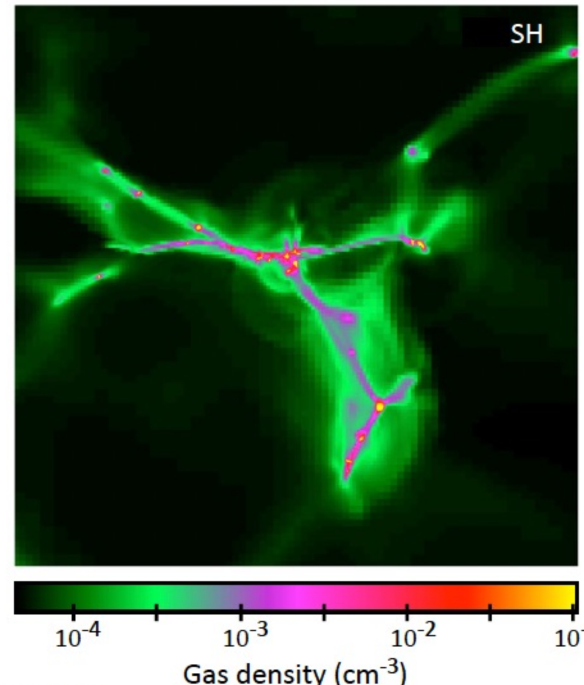


Chabanier at al. 2020b

Better resolution of cold-gas accretion onto galaxies

EH forms earlier low-mass galaxies

Horizon-AGN z ~ 3



Compact galaxies: loss of angular momentum

Ultra-compact galaxies: repeated major mergers of low-mass progenitors

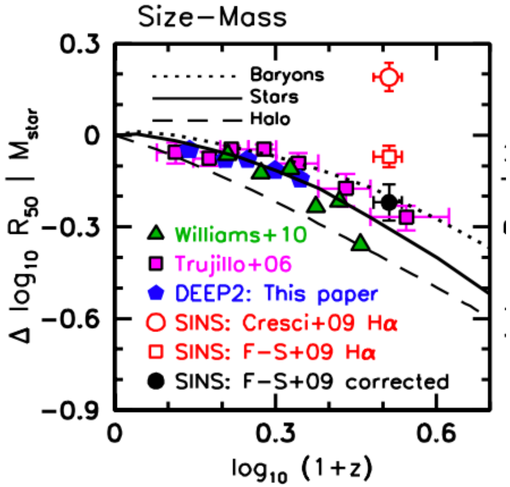
Chabanier, Bournaud, Dubois et al. 2020b

Compact galaxy formation at high redshift

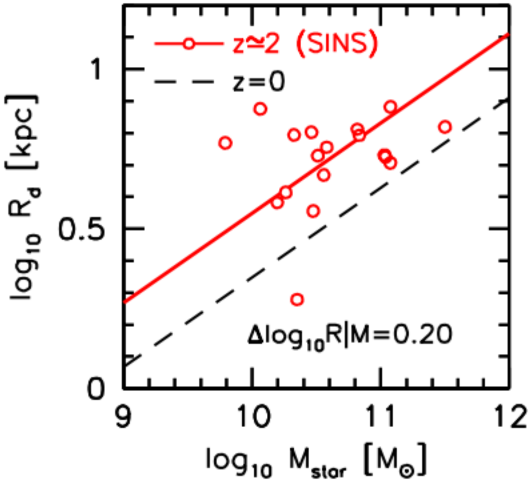
- Galaxies at z=1-3 are about twice more compact (at fiwed stellar or halo mass) than present-day galaxies, in their stellar component (not in gas)

- A population of ultra-compact outliers ($R_{1/2}$~1kpc for the MW mass) exists and comprises 5-10% of massive galaxies (<0.5% at z=0)

- Holds for star-forming, starbursting, and quenched galaxies (« red nuggets », « blue nuggets »…)

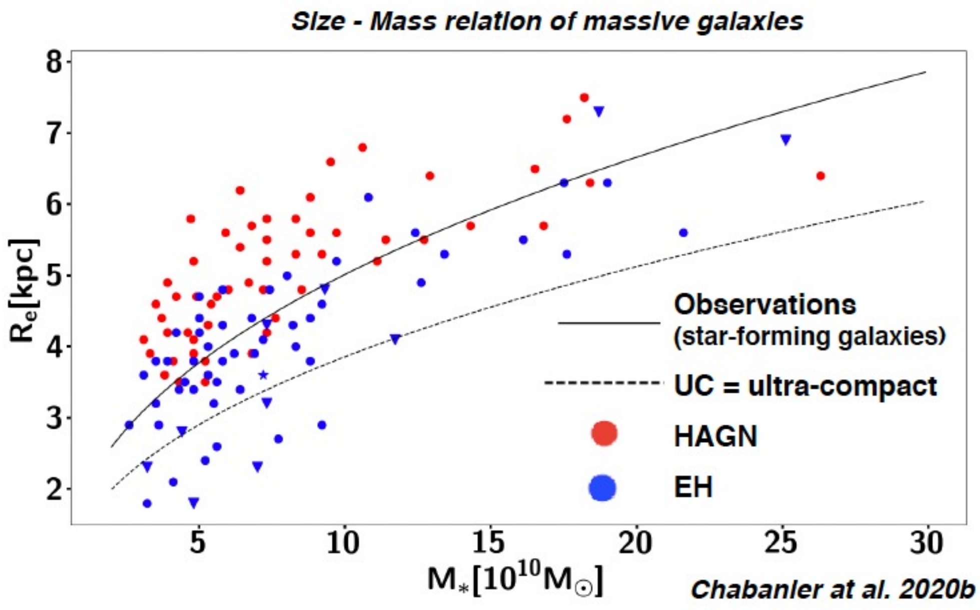


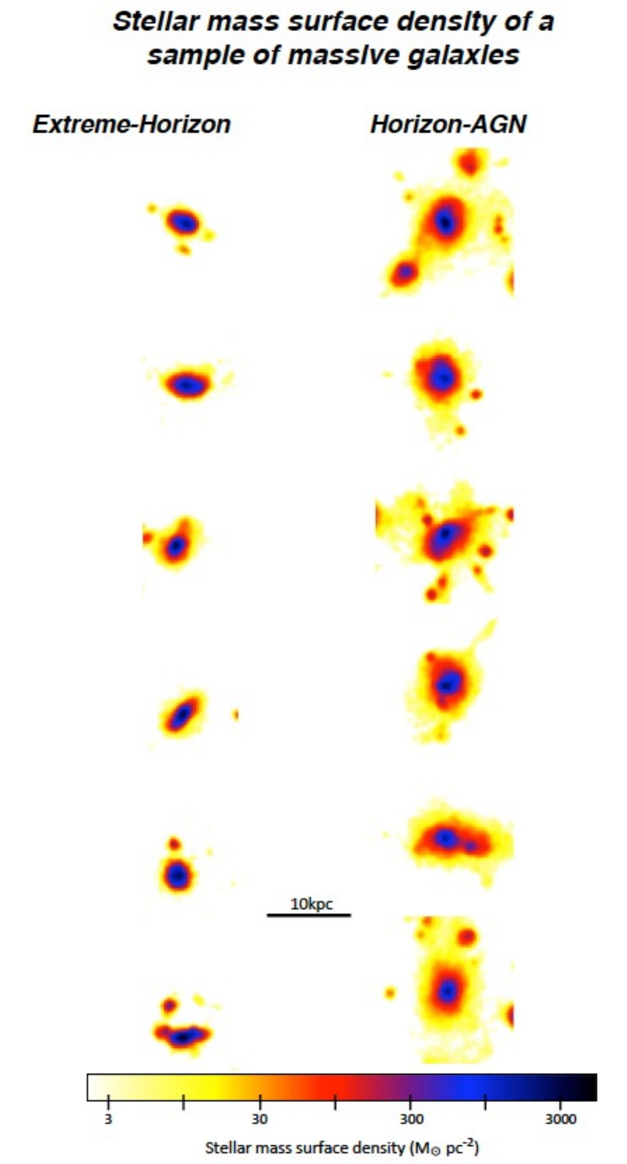
Dutton+2011



Forster-Schreiber+2013

Compact galaxy formation at high redshift





At z = 2 in the Extreme-Horizon simulation:

1) More compact massive galaxies

2) Population of ultra-compact galaxies

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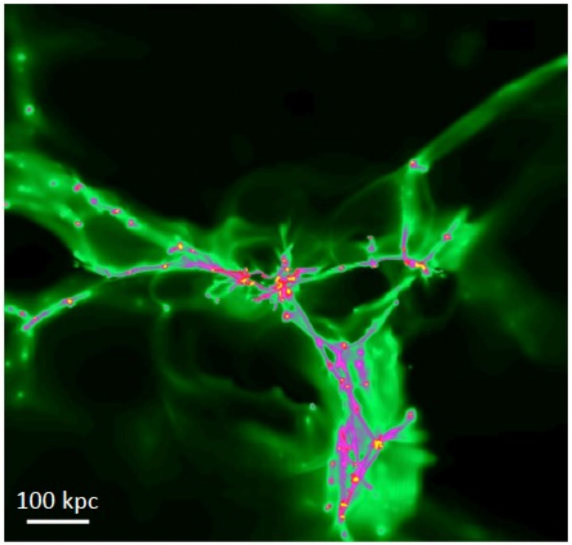

Chabanier at al. 2020b

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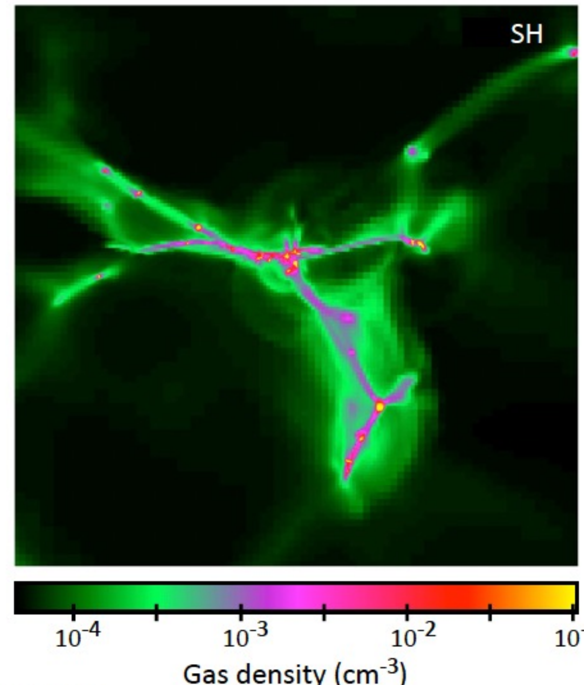

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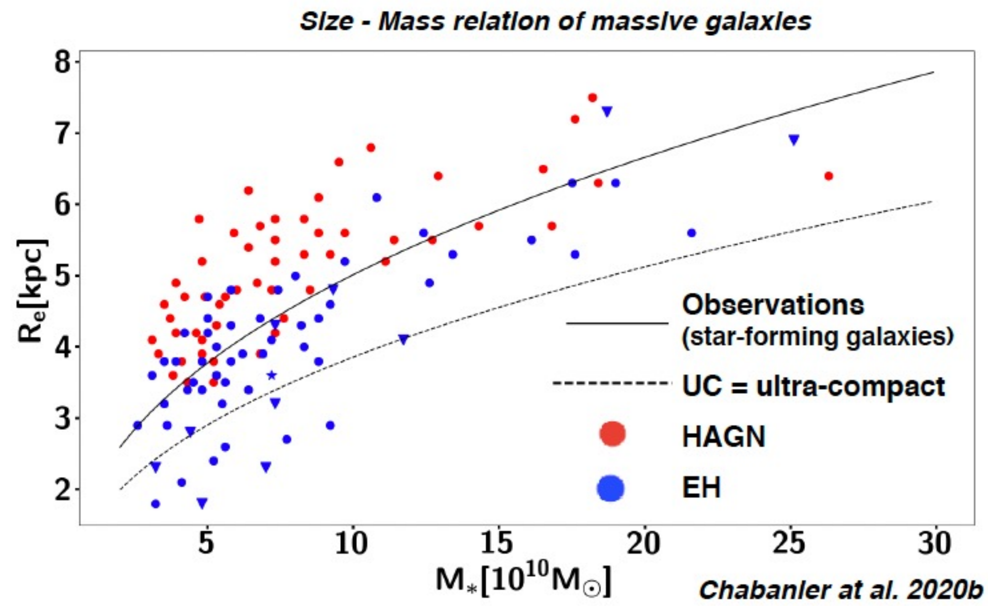

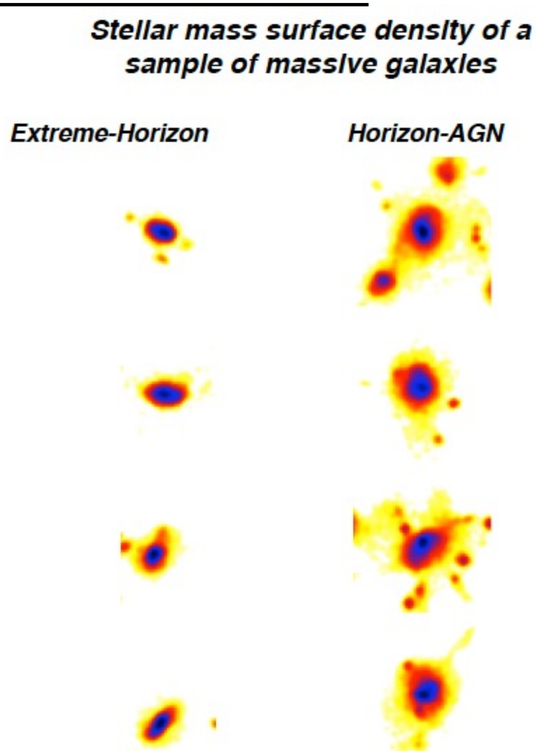

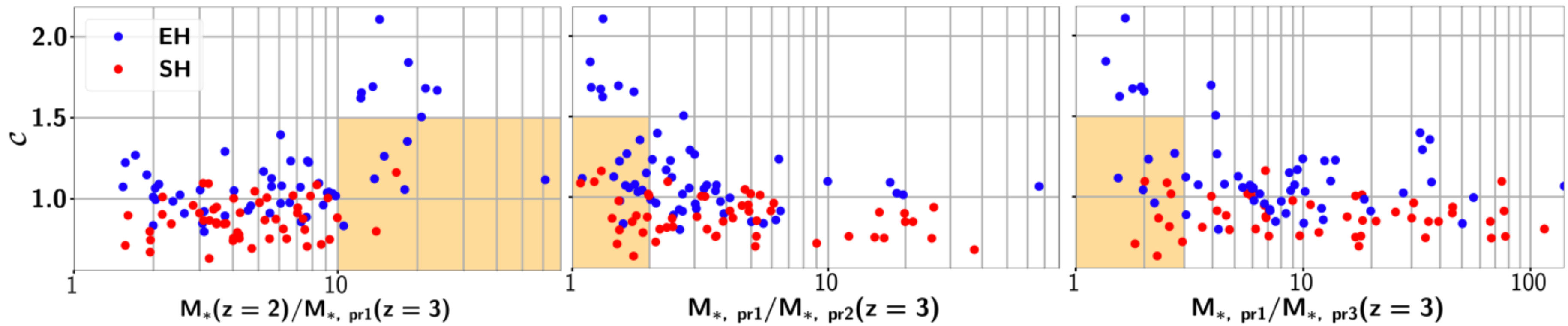

Chabanier, Bournaud, Dubois et al. 2020b

- Cosmological probes are affected by baryonic physics (cooling, feedback, etc)
- Systematics can be controlled owing to hydro simulations – exemplified here for Lyα
- Galaxy formation / large scale structure strongly depend on low-density regions/IGM
- Sub-grid baryonic physics can apparently be decently controlled
- Caveats :
  - No absolute convergence of hydro simulations.

  - Simulation boxes are (much) too small for full variance, densest and empties regions… or dark matter only.

  - Remains *very* expensive if one wants to probe the sub-grid calibration effects (IA…?)