Neutrinos, Dark Sector Cosmology, and the Lyman-α Forest

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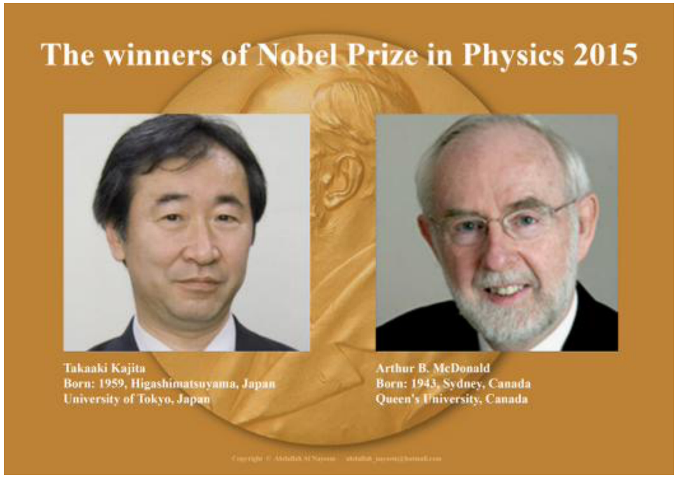
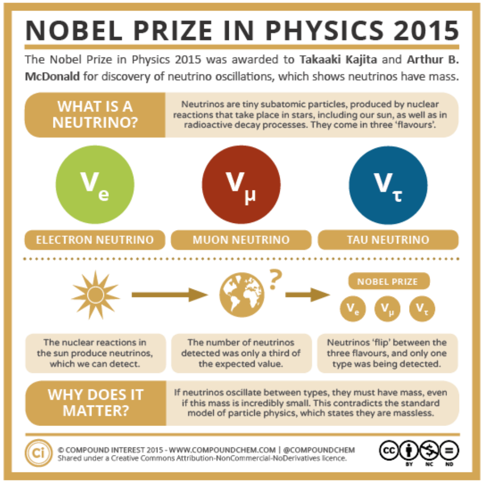
Focus: Neutrinos, Dark Radiation, WDM

> *'Neutrinos win the minimalist contest: zero charge, zero radius, and very probably zero mass.'*
>
> – Leon M. Lederman
>
> In *Leon Lederman and Dick Teresi*, 'The God Particle: If the Universe is the Answer, What is the Question' (1993, 2006)

Instead, neutrinos are massive particles!

Neutrino cosmology → beautiful example of complementarity with particle physics





NOBEL PRIZE IN PHYSICS 2015

The Nobel Prize in Physics 2015 was awarded to **Takaaki Kajita** and **Arthur B. McDonald** for discovery of neutrino oscillations, which shows neutrinos have mass.

WHAT IS A NEUTRINO? Neutrinos are tiny subatomic particles, produced by nuclear reactions that take place in stars, including our sun, as well as in radioactive decay processes. They come in three 'flavours'.

The nuclear reactions in the sun produce neutrinos, which we can detect.

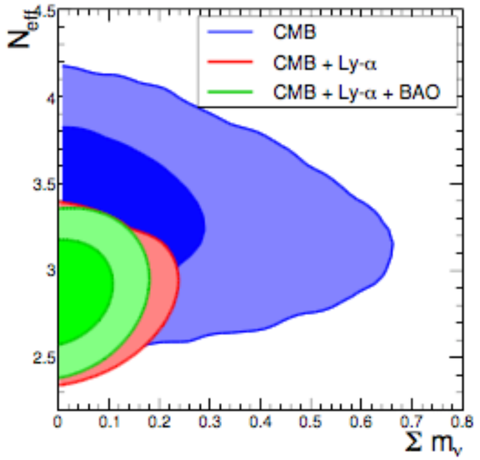
The number of neutrinos detected was only a third of the expected value.

Neutrinos 'flip' between the three flavours, and only one type was being detected.

WHY DOES IT MATTER? If neutrinos oscillate between types, they must have mass, even if this mass is incredibly small. This contradicts the standard model of particle physics, which states they are massless.

Main Highlights

MOTIVATION: ROBUST COSMOLOGICAL BOUNDS



Rossi et al. (2015)

- Numerical & modeling uncertainties
- Instrumental resolution & noise
- IGM thermal history, UV fluctuations, ...
- Degeneracies & systematics
- Details of statistical analysis

Massless sterile neutrino (thermalized) ruled out at $> 5\sigma$

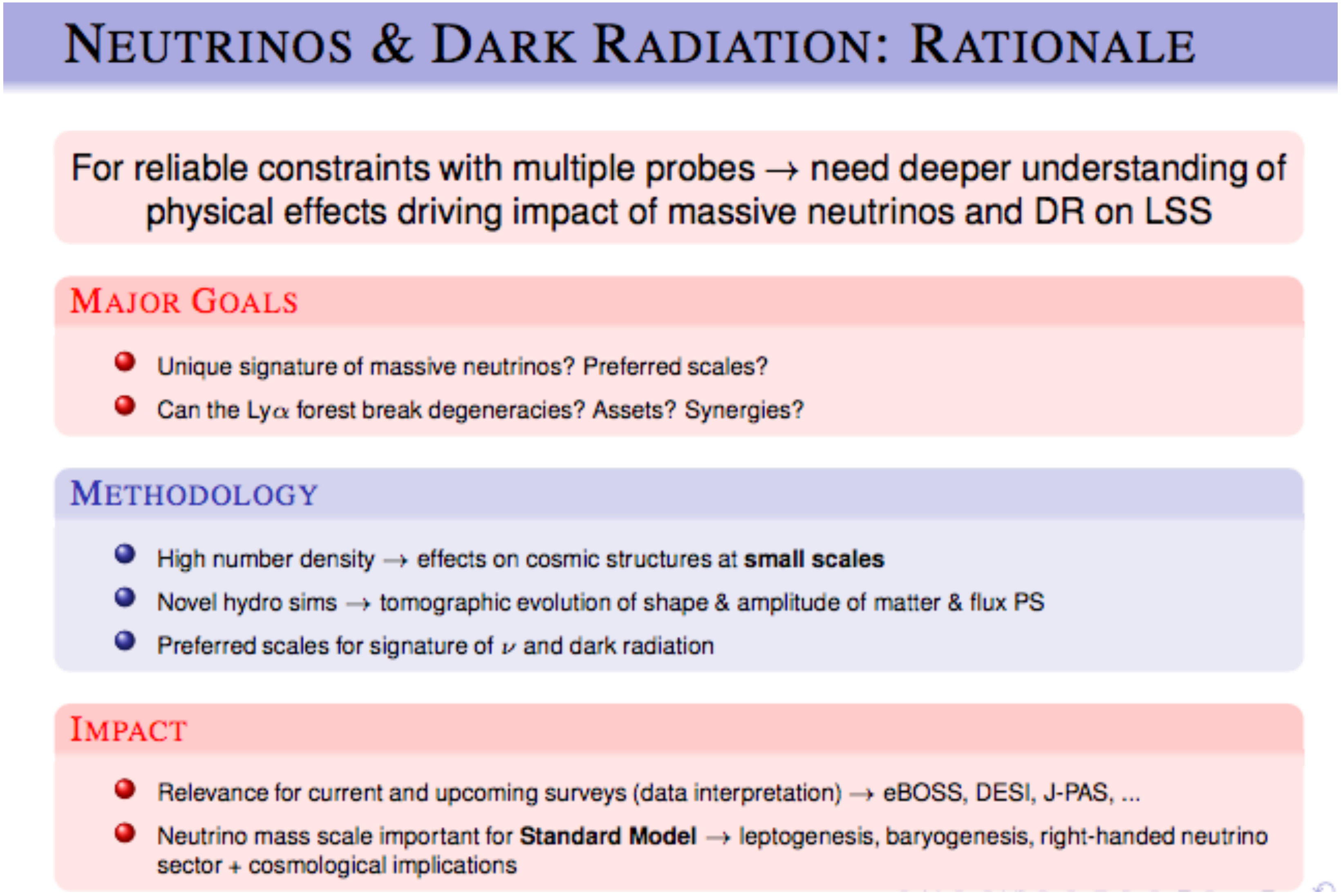
INDIVIDUAL CONSTRAINTS ON $\sum m_\nu$ (95% CL)

$$\sum \mathbf{m}_\nu < \mathbf{0.12\ eV} \rightarrow \text{CMB + Lyman-}\alpha\text{ + BAO}$$

JOINT CONSTRAINTS ON $N_{\rm eff}$ AND $\sum m_\nu$ (95% CL)

$$\mathbf{N}_{\rm eff} = \mathbf{2.88}^{+0.20}_{-0.20}\ \&\ \sum \mathbf{m}_\nu < \mathbf{0.14\ eV} \rightarrow \text{CMB + Lyman-}\alpha\text{ + BAO}$$

Overall Strategy



NEUTRINOS & DARK RADIATION: RATIONALE

For reliable constraints with multiple probes → need deeper understanding of physical effects driving impact of massive neutrinos and DR on LSS

MAJOR GOALS

- Unique signature of massive neutrinos? Preferred scales?
- Can the Lyα forest break degeneracies? Assets? Synergies?

METHODOLOGY

- High number density → effects on cosmic structures at **small scales**
- Novel hydro sims → tomographic evolution of shape & amplitude of matter & flux PS
- Preferred scales for signature of ν and dark radiation

IMPACT

- Relevance for current and upcoming surveys (data interpretation) → eBOSS, DESI, J-PAS, ...
- Neutrino mass scale important for **Standard Model** → leptogenesis, baryogenesis, right-handed neutrino sector + cosmological implications

Outline

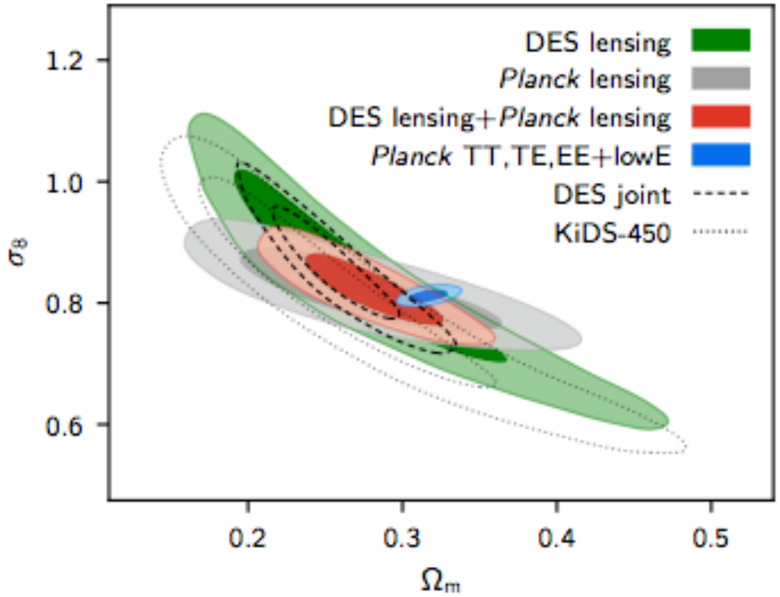
- Neutrino Cosmology in a Nutshell
- Novel Hydro Simulations
- Neutrinos, High-z Web, Lyα Forest
- Dark Sector: Constraints & Potential
- Summary & Outlook

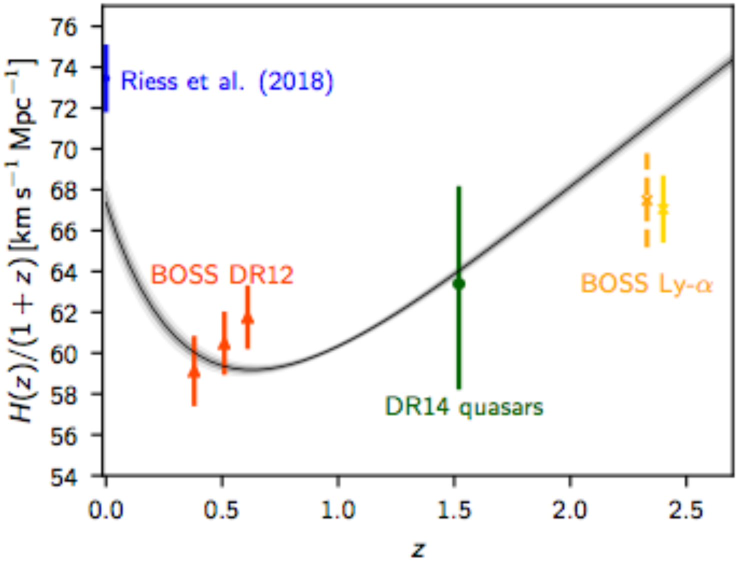
KEY REFERENCES

- **Rossi, G.** (2019), to appear
- Ata, Baumgarten, Bautista (+ **Rossi, G.**) et al. (2018), MNRAS, 473, 4773
- **Rossi, G.** (2017), ApJS, 233, 12
- **Rossi, G.**, Yèche, C., Palanque-Delabrouille, N., & Lesgourgues, J. (2015), PRD, 92, 063505
- Palanque-Delabrouille, N., Yèche, C., Baur, J., (+ **Rossi, G.**) et al. (2015), JCAP, 11, 011
- Palanque-Delabrouille, N., Yèche, C., Lesgourgues, J., **Rossi, G.**, et al. (2015), JCAP, 2, 045
- **Rossi, G.**, Palanque-Delabrouille, N., Borde, A., et al. (2014), A&A, 567, AA79

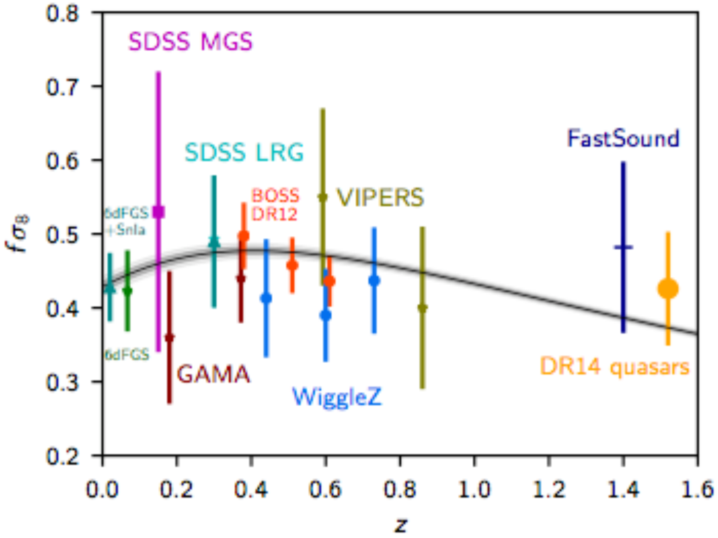
NEUTRINO COSMOLOGY IN A NUTSHELL

LCDM Still Holds but …



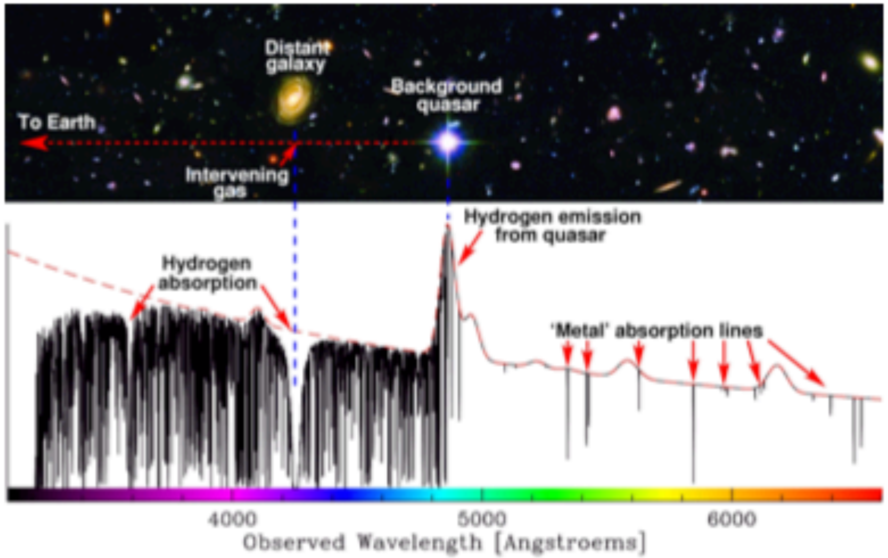


PLANCK 2018
(**Planck Coll. 2018 - VI**)



Still Tensions ….
Massive Neutrinos ?
Beyond the Standard Model

Lyman-α Forest Asset



LY-α: IMPORTANCE

- Probes the intergalactic medium at high-z
- Maps the primordial density fluctuations
- Synergy with other LSS probes

LYA: DIFFICULTIES

- Need numerical simulations with full hydro
- Complex IGM thermal history
- Star formation uncertain
- Non-trivial frequency dependence
- Systematics and other technical issues

LYA: ADVANTAGES

- Mildly nonlinear scales
  i.e. $\rightarrow$ k [0.1 – 2] h/Mpc, [0.002 – 0.02] s/km
- High redshift ($2 \lesssim z \lesssim 5$)
- Complementary and orthogonal to other probes
- Special role in probing free-streaming of neutrinos on matter PS
- Evolution of $\nu \rightarrow$ signature with z (scale-dependent suppression)

Neutrinos: Peculiar Leptons, Everywhere

NEUTRINOS: BASIC PROPERTIES

- Peculiar particle → weakest interactions, smallest possibly non-vanishing mass
- Important because second most abundant particle in the universe (after photons)
- Total number density (all flavors) → $\sim 340/\mathrm{cm}^3$ (for baryonic matter $n_b \sim 2.5 \times 10^{-7}/\mathrm{cm}^3$)
- 3-flavor paradigm (3 flavor & mass eigenstates)
- Leptons but special particles
- Massless in standard model
- Only weak + gravity force, so very weak effects on matter
- Average energy of cosmic neutrinos very low → $6.1K \sim 5 \times 10^{-4}$ eV

NEUTRINO → LEPTON

- Electrically neutral
- Weakly interacting
- Half-integer spin

NEUTRINO FLAVORS

- Electron neutrinos
- Muon neutrinos
- Tau neutrinos

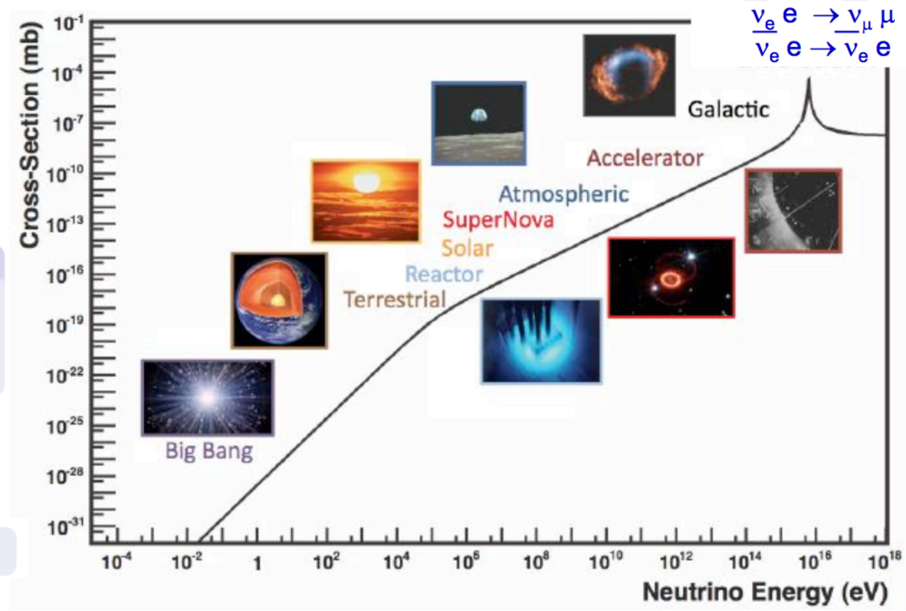
Focus here → **Cosmological Neutrinos**

High number density → effects on cosmic structures

NEUTRINO FAMILIES

- Cosmological neutrinos
- Astrophysical neutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Terrestrial (laboratory) neutrinos

Courtesy A. Bravar



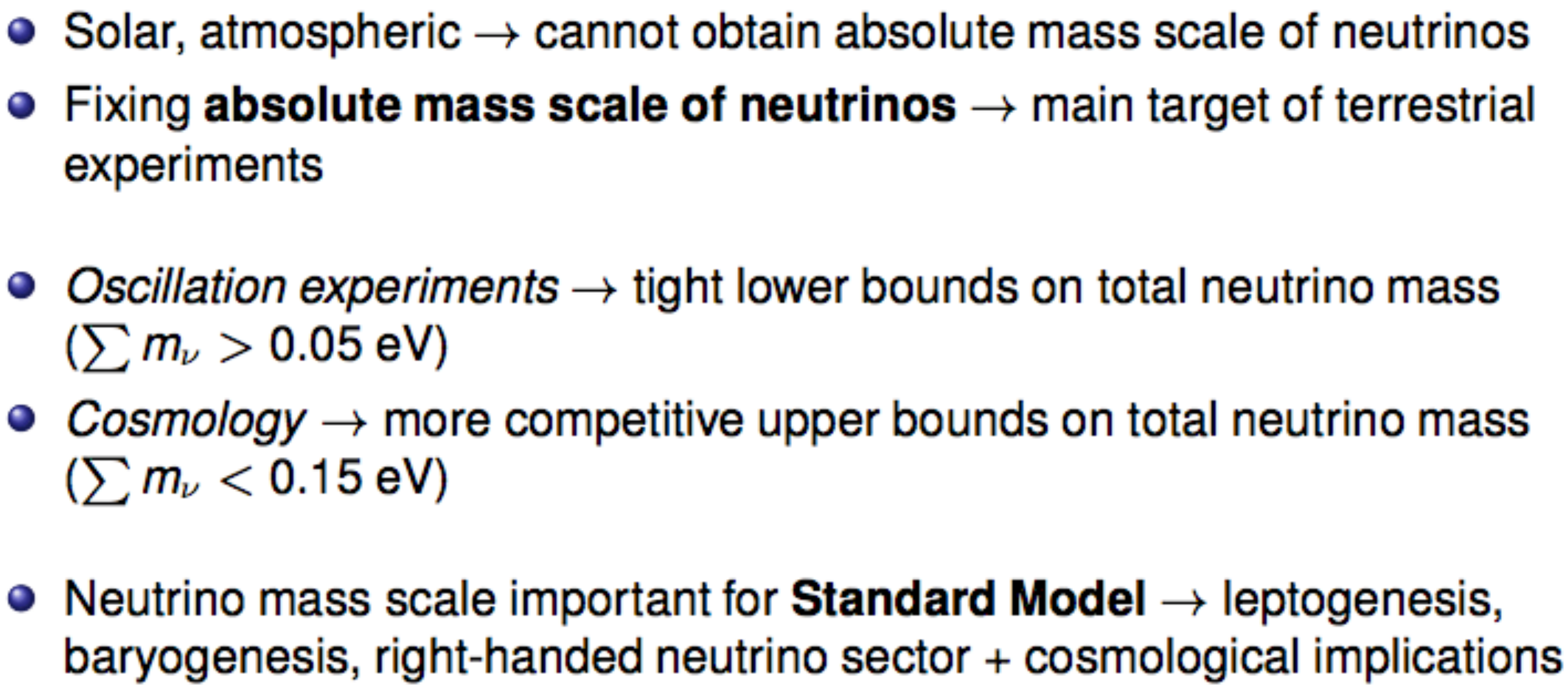
Neutrinos: Formalism

- ν_α $(\alpha = e, \mu, \tau) \rightarrow$ neutrino flavor eigenstates
- $\nu_{\rm i}$ $({\rm i} = 1, 2, 3) \rightarrow$ neutrino mass eigenstates
- $m_{\rm i}$ $({\rm i} = 1, 2, 3) \rightarrow$ neutrino individual masses
- $m_2 > m_1$, $m_2 \simeq m_1$
- $\Delta m^2_{21} \equiv \Delta m^2_{\rm solar} \equiv \delta m^2 = m^2_2 - m^2_1 > 0 \rightarrow$ solar mass splitting
- $|\Delta m^2_{31}| \equiv |\Delta m^2_{\rm atm}| = |m^2_3 - m^2_1| \rightarrow$ atmospheric mass splitting
- $\Delta m^2_{31} > 0 \rightarrow$ normal hierarchy (NH)
- $\Delta m^2_{31} < 0 \rightarrow$ inverted hierarchy (IH)
- Relation flavor-mass eigenstates $\rightarrow$

$$|\nu_\alpha> = \sum_{\rm i} U_{\alpha {\rm i}} \, |\nu_{\rm i}>$$

- $U_{\alpha{\rm i}} \rightarrow$ mixing matrix, elements parameterized by $(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \xi, \zeta)$

Massive Neutrinos & Cosmology



- Solar, atmospheric → cannot obtain absolute mass scale of neutrinos
- Fixing **absolute mass scale of neutrinos** → main target of terrestrial experiments

- *Oscillation experiments* → tight lower bounds on total neutrino mass ($\sum m_\nu > 0.05$ eV)
- *Cosmology* → more competitive upper bounds on total neutrino mass ($\sum m_\nu < 0.15$ eV)

- Neutrino mass scale important for **Standard Model** → leptogenesis, baryogenesis, right-handed neutrino sector + cosmological implications

Absolute Neutrino Mass

PROBING THE NEUTRINO MASS SCALE

1. Direct measurements through β decay kinematics
2. Neutrinoless double β decay ($0\nu2\beta$)
3. Cosmological observations

① **Direct β decay** → squared effective electron neutrino mass

$$m_\beta^2 = \sum_{\mathrm{i}} |U_{\mathrm{ei}}|^2 m_{\mathrm{i}}^2$$

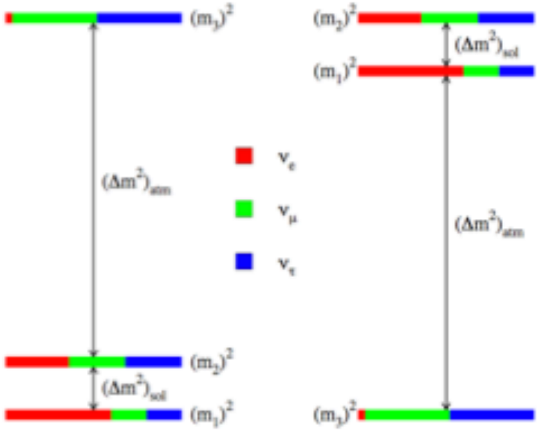
② **Neutrinoless double β decay ($0\nu2\beta$)** → effective Majorana mass

$$m_{\beta\beta} = |\sum_{\mathrm{i}} U_{\mathrm{ei}}^2 m_{\mathrm{i}}| = |\sum_{\mathrm{i}} \exp[i\Phi_{\mathrm{i}}]|U_{\mathrm{ei}}^2|m_{\mathrm{i}}|, \quad \Phi_2 = \xi, \Phi_3 = \zeta - 2\delta$$

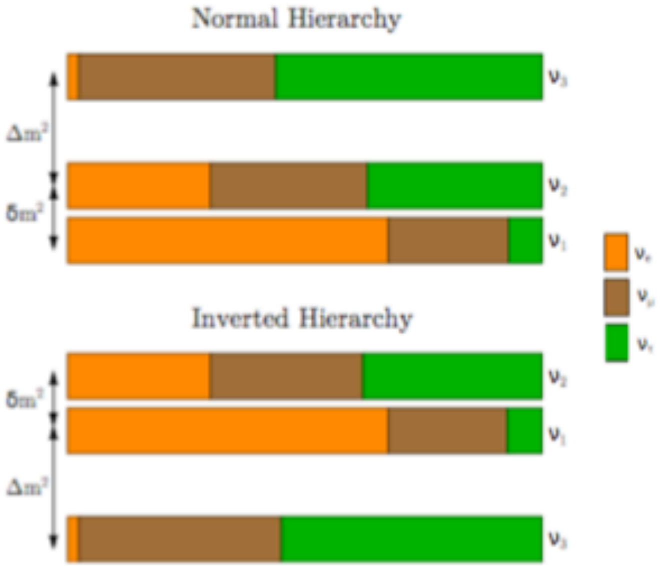
③ **Cosmological observations** → total neutrino mass

$$M_\nu = \sum_{\mathrm{i}} m_{\mathrm{i}} = m_1 + m_2 + m_3$$

Neutrino Mass Hierarchy



normal hierarchy inverted hierarchy



- $\Delta m^2_{21} \equiv \Delta m^2_{\rm solar} \equiv \delta m^2 = m^2_2 - m^2_1 > 0 \rightarrow$ solar mass splitting
- $|\Delta m^2_{31}| \equiv |\Delta m^2_{\rm atm}| = |m^2_3 - m^2_1| \rightarrow$ atmospheric mass splitting
- $\Delta m^2_{31} > 0 \rightarrow$ NH; $\Delta m^2_{31} < 0 \rightarrow$ IH

- $\delta m^2 \equiv \Delta m^2_{21} = m^2_2 - m^2_1 > 0 \rightarrow$ solar mass splitting
- $\Delta m^2 = m^2_3 - \frac{m^2_1 + m^2_2}{2}$

3 active relativistic relic neutrinos in standard model

What about **sterile neutrinos**?

Current Bounds

LABORATORY EXPERIMENTS

- Solar, atmospheric, reactors, accelerators → $M_\nu > 0.05$ eV
- β-decay → $M_\nu < 2.2$ eV

COSMOLOGY: NEAR FUTURE

- eBOSS LyA + CMB → $M_\nu \sim 0.1$ eV
- ACTPol + Planck → $M_\nu \sim 0.07$ eV
- Planck + eBOSS, LSST, DES → $M_\nu \sim 0.06$ eV
- Surveys in 2020 (DESI) → $M_\nu \sim 0.03$ eV

COSMOLOGY: NOW (95% CL)

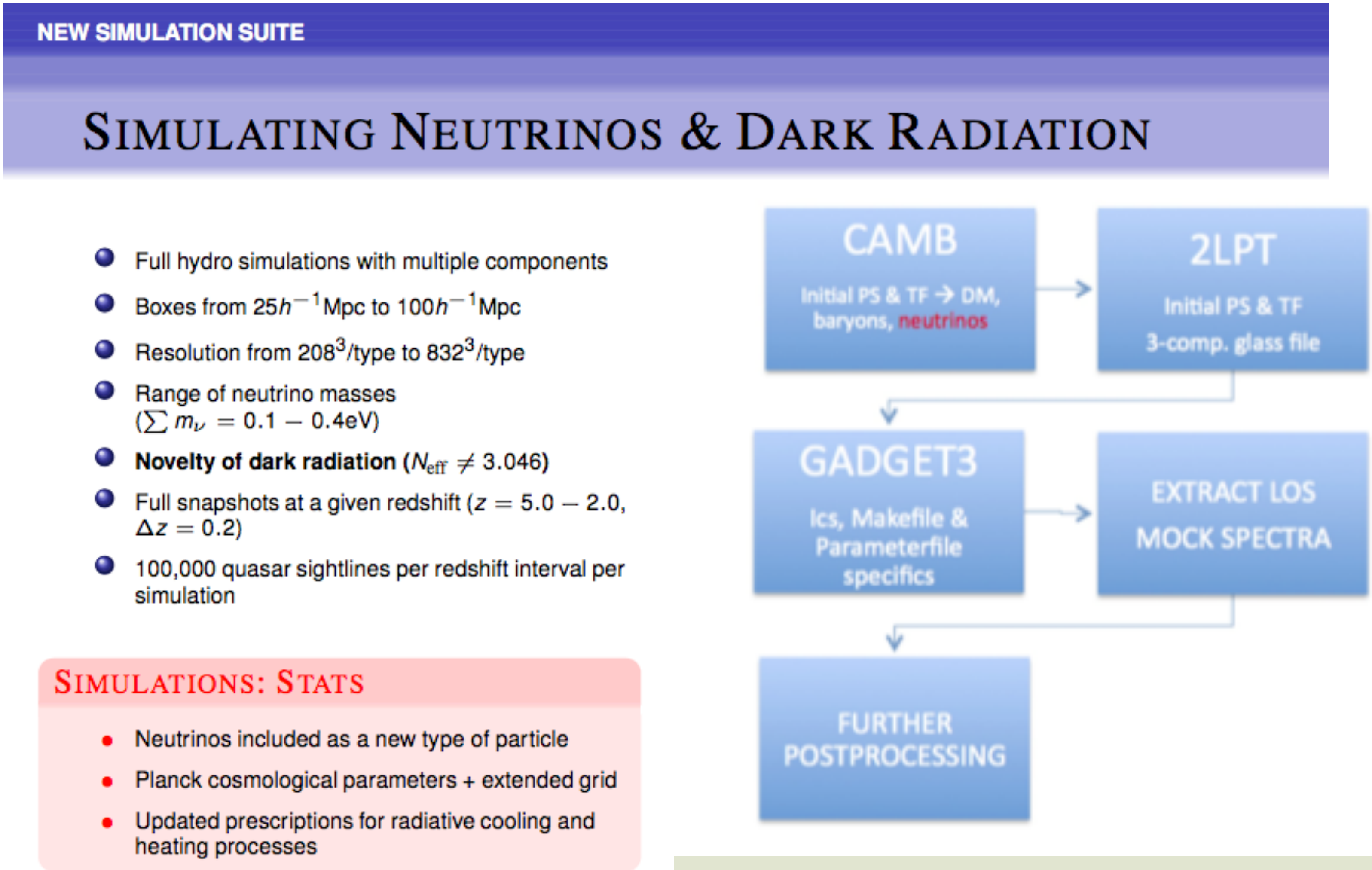
- LyA → $M_\nu < 0.9$ eV
- WMAP9 → $M_\nu < 0.44$ eV
- WMAP7+LRG+H_0 → $M_\nu < 0.44$ eV
- WMAP7+ACT+BAO+H_0 → $M_\nu < 0.39$ eV
- WMAP7+WiggleZ+BAO+H_0 → $M_\nu < 0.29$ eV
- WMAP7+MegaZ+BAO+SNIa+H_0 → $M_\nu < 0.281$ eV
- Planck+WP+highL+BAO → $M_\nu < 0.23$ eV
- Planck+WiggleZ+BAO → $M_\nu < 0.18$ eV
- Latest claims → $M_\nu < 0.11$ eV → 0.13 eV

WARNING

Systematic offset between estimates of the matter PS obtained with different methods!

NOVEL HYDRO SIMULATIONS

Upgraded Simulation Suite



NEW SIMULATION SUITE

SIMULATING NEUTRINOS & DARK RADIATION

- Full hydro simulations with multiple components
- Boxes from $25h^{-1}$Mpc to $100h^{-1}$Mpc
- Resolution from 208^3/type to 832^3/type
- Range of neutrino masses ($\sum m_\nu = 0.1 - 0.4$eV)
- **Novelty of dark radiation** ($N_{\rm eff} \neq 3.046$)
- Full snapshots at a given redshift ($z = 5.0 - 2.0$, $\Delta z = 0.2$)
- 100,000 quasar sightlines per redshift interval per simulation

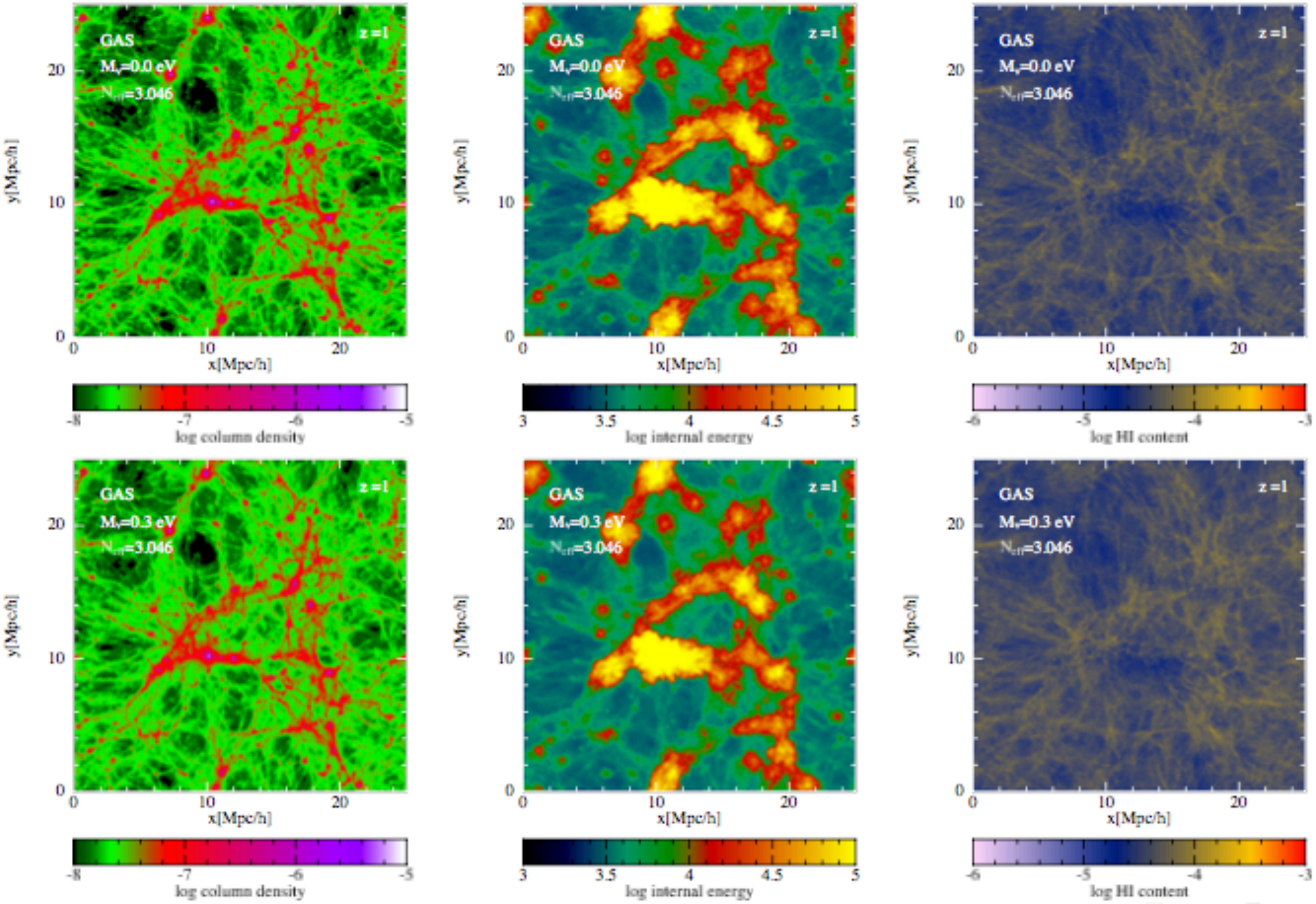
SIMULATIONS: STATS

- Neutrinos included as a new type of particle
- Planck cosmological parameters + extended grid
- Updated prescriptions for radiative cooling and heating processes

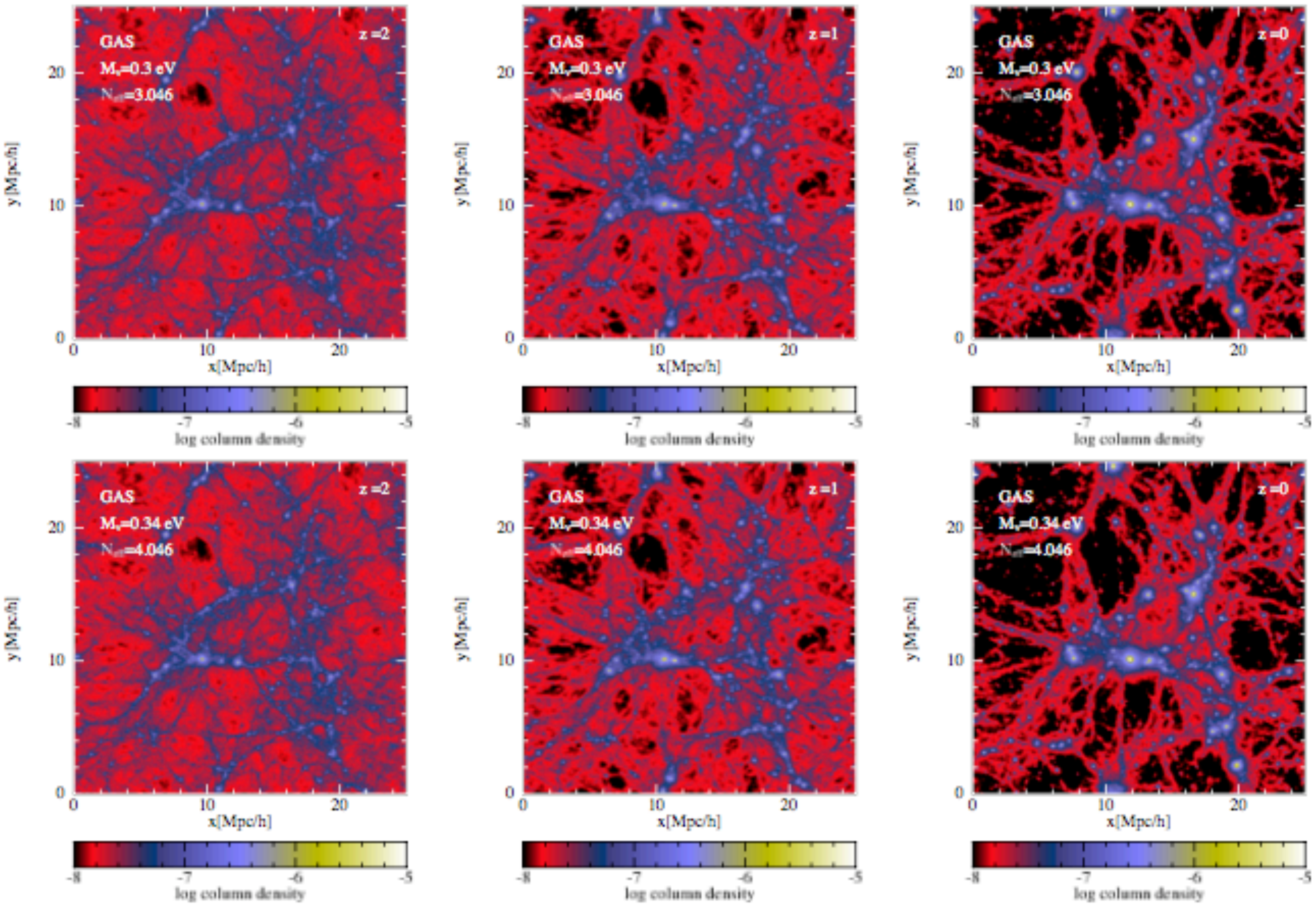
Products
(1) Full cubes at o.2 snapshots in z, from z=5.0 to z=2.0 in intervals of 0.2
(2) LyA skewers → 288 million, for the same z, 100,000 LOS per sims
(3) Particle samples over the same redshifts and cosmologies

Visualization: Gas Properties

G. Rossi (2018, 2019)

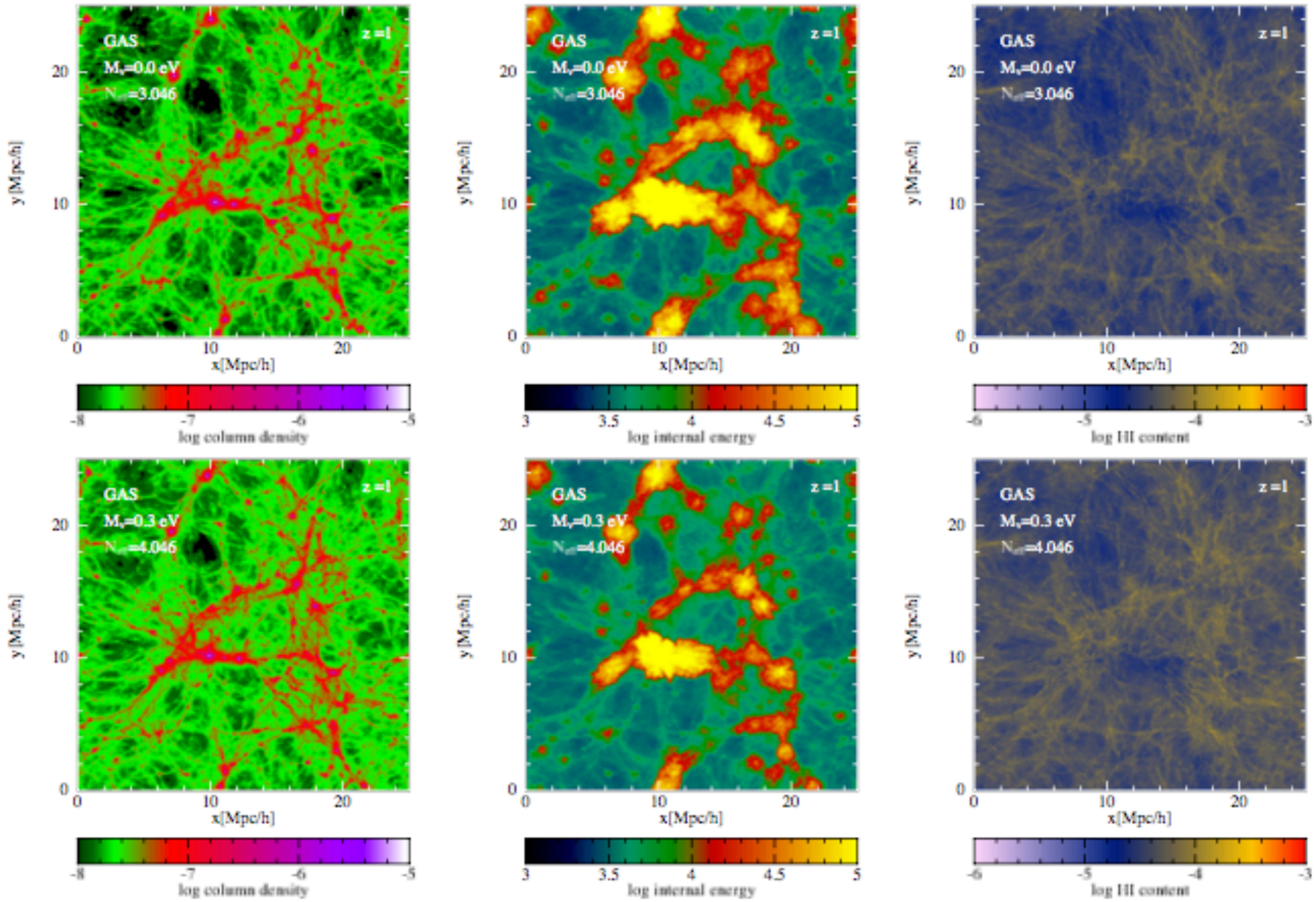


Simulations with Dark Radiation (1)



Rossi et al. (2015)

Simulations with Dark Radiation (2)

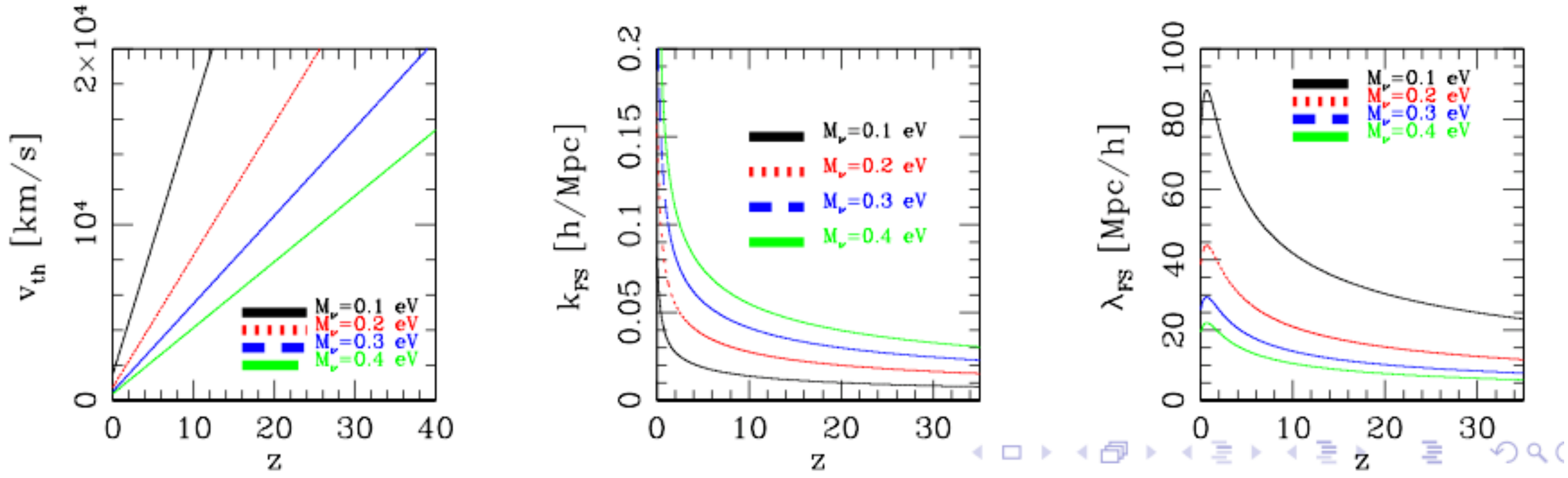


Rossi (2018, 2019)

NEUTRINOS, HIGH-z WEB, Lyα FOREST

Characteristic Linear Scales

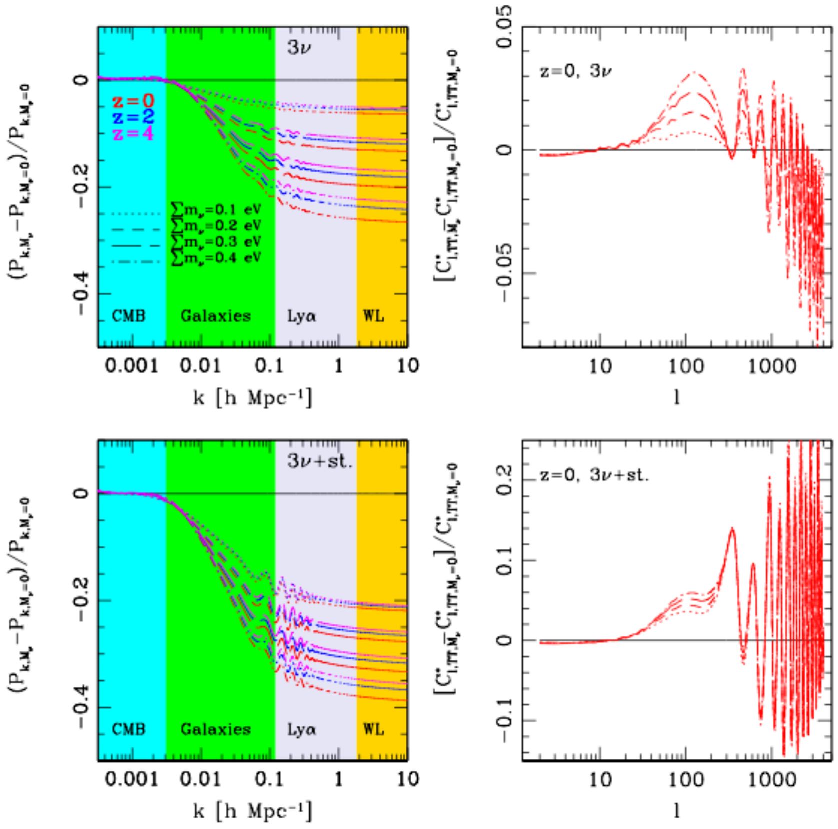
- **Time $z_{\rm NR}$ or wavenumber $k_{\rm NR}$ at which neutrinos become non-relativistic**
- **Comoving free-streaming length $\lambda_{\rm FS}$ (or wavenumber $k_{\rm FS}$)**
- $z_{\rm NR} \sim 2000(m_\nu/{\rm eV})$
- Average thermal velocity $v_{\rm th} \simeq 150(1+z)(1{\rm eV}/m_\nu)$ km/s
- Typical assumption for LSS effects → all models share same $\omega_{\rm m} = \Omega_{\rm m} h^2$, $\omega_{\rm b} = \Omega_{\rm b} h^2$, Ω_Λ, $A_{\rm s}$, $n_{\rm s}$, τ
- When ν included → $\omega_\nu = \Omega_\nu h^2$ and $\omega_{\rm c} = \Omega_{\rm c} h^2$, with $\omega_{\rm c} = \omega_{\rm m} - \omega_{\rm b} - \omega_\nu$
- $k_{\rm NR} \simeq 0.018\,\Omega_{\rm m}^{1/2}(m_\nu/{\rm eV})^{1/2} h{\rm Mpc}^{-1}$
- $k_{\rm FS}(z) = \sqrt{\dfrac{4\pi G\bar{\rho}(z)a^2(z)}{v_{\rm th}^2(z)}} \sim 0.82\,\dfrac{\sqrt{\Omega_\Lambda+\Omega_{\rm m}(1+z)^3}}{(1+z)^2}\left(\dfrac{m_\nu}{1{\rm eV}}\right) h{\rm Mpc}^{-1}$



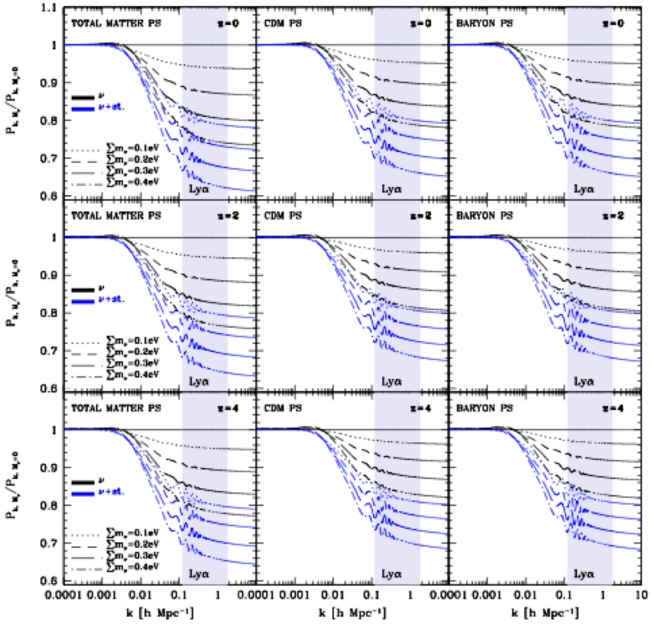
G. Rossi (2018)

Linear Evolution

- Effects on C_ℓ less intuitive → mainly related to pre-recombination physics
- ν still ultrarelativistic, so repercussions only at bkgd level
- Later equality → higher CMB peaks (1st & 3th)
- Increase size of sound horizon at recombination → dependence on $a_{\rm eq}$ and $\rho_{\rm b}$
- Effects on BAO scale
- Addition of sterile neutrino → suppress first peak and enhance others

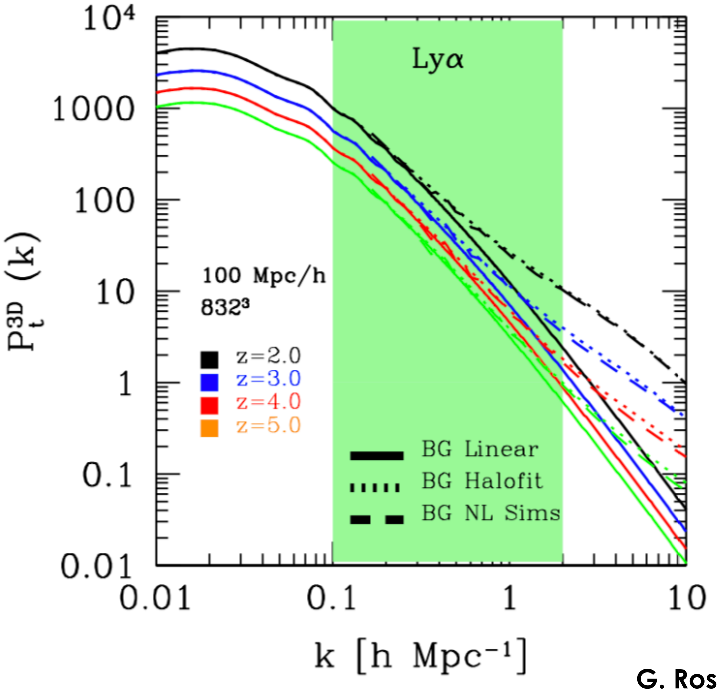


G. Rossi (2017)

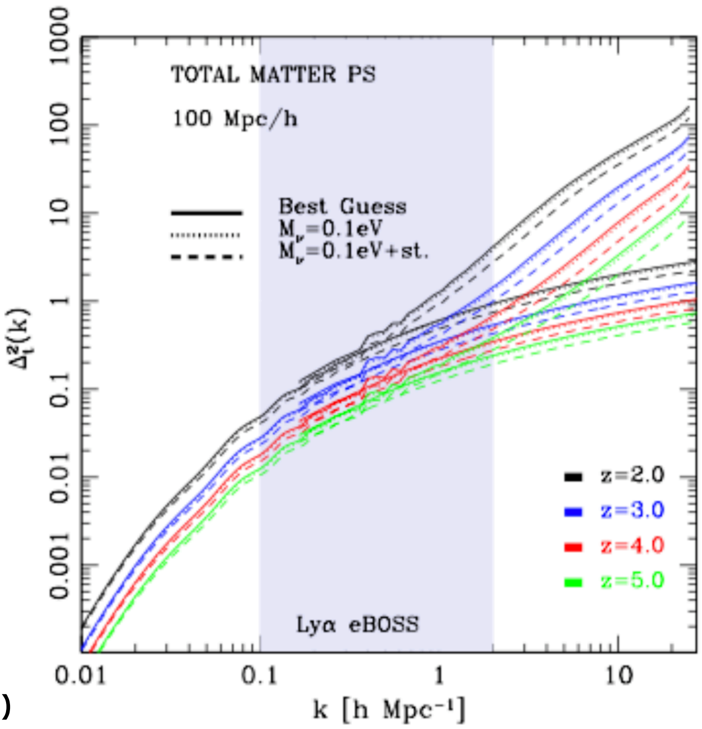


Linear evolution per component

Neutrinos & NL 3D Total Matter PS



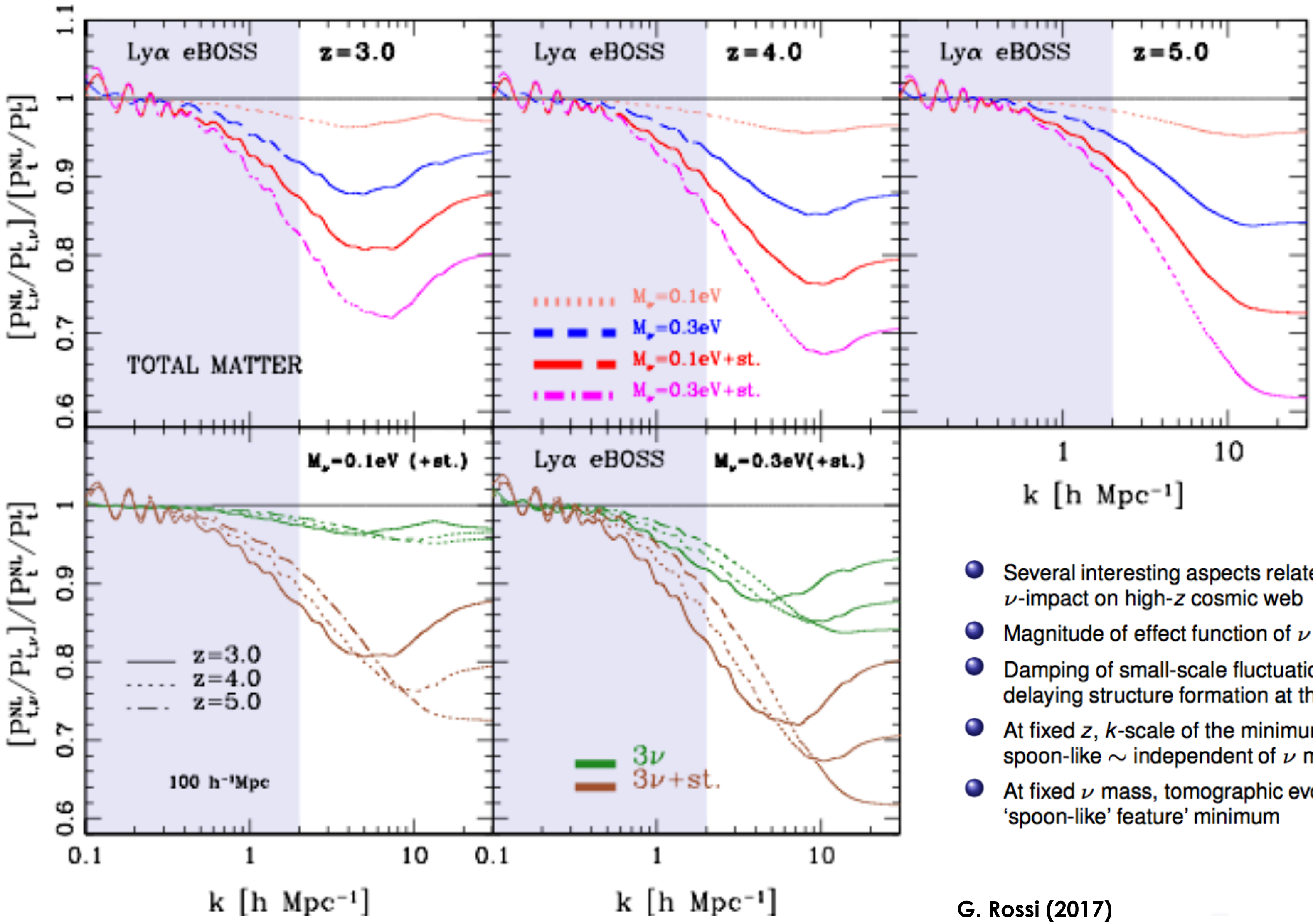
G. Rossi (2017, 2019)



- Linear theory unable to capture several key aspects of small-scale evolution
- Role of baryons critical
- Baryonic effects can mimic neutrino- or dark-radiation- induced suppressions

- Linear level → if no ν, matter fluctuations obey scale-independent eqn.
- Massive neutrinos induce scale-dependent distortion of power spectrum shape & combined evolution in $P(k, z)$ amplitude

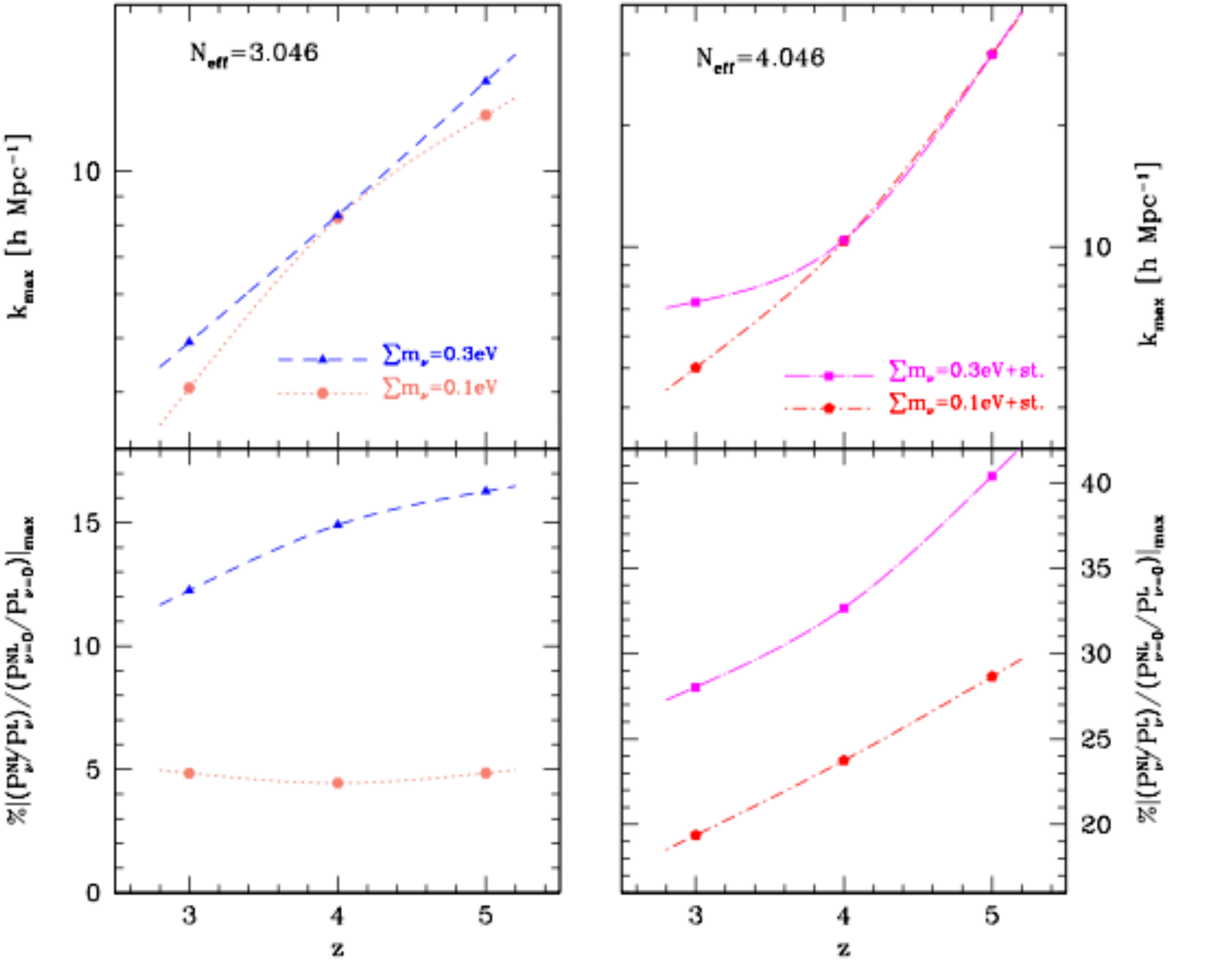
Spoon-Like Effect on NL 3D Matter PS



- Several interesting aspects related to ν-impact on high-z cosmic web
- Magnitude of effect function of ν mass
- Damping of small-scale fluctuations & delaying structure formation at those scales
- At fixed z, k-scale of the minimum of the spoon-like $\sim$ independent of ν mass
- At fixed ν mass, tomographic evolution of 'spoon-like' feature' minimum

G. Rossi (2017)

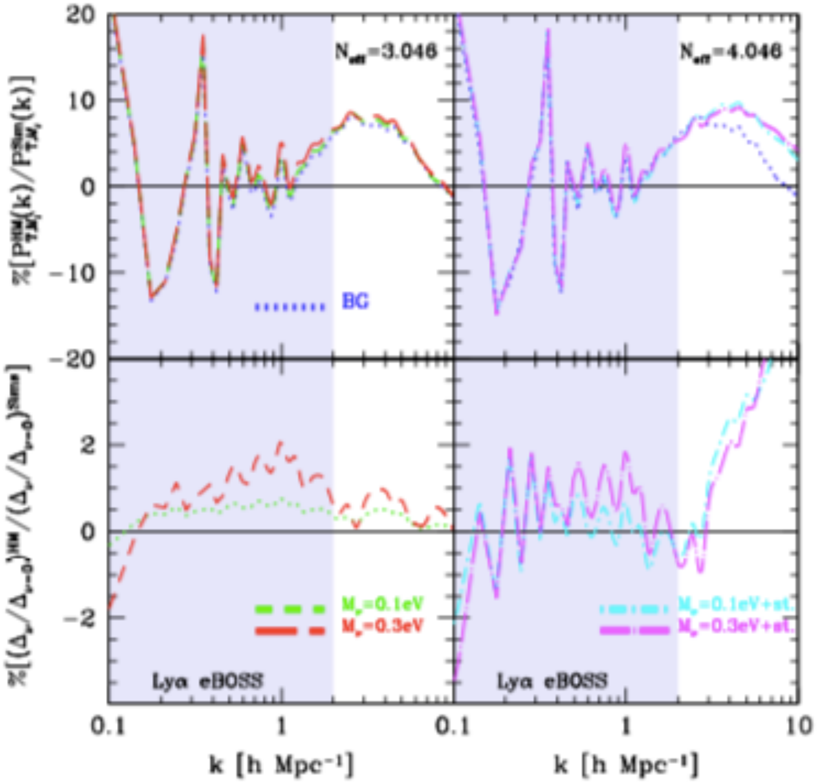
Massive Neutrinos: Relevant NL Scales



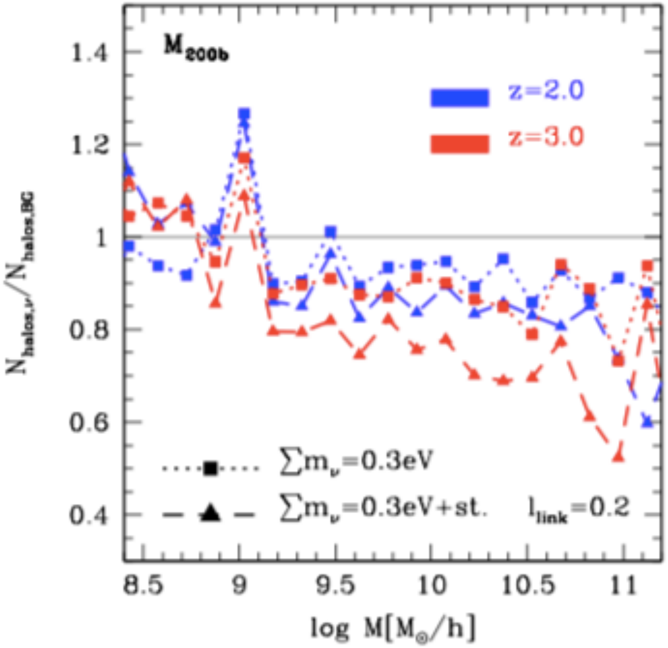
G. Rossi (2017)

- NL scale based on 'spoon-like'-feature
- Close relation with halo formation times
- Close relation with building of halo mass function in ν-cosmologies
- Combine *k*-max of spoon-like minimum & amplitude of its effect across *z*

Halo Model Interpretations

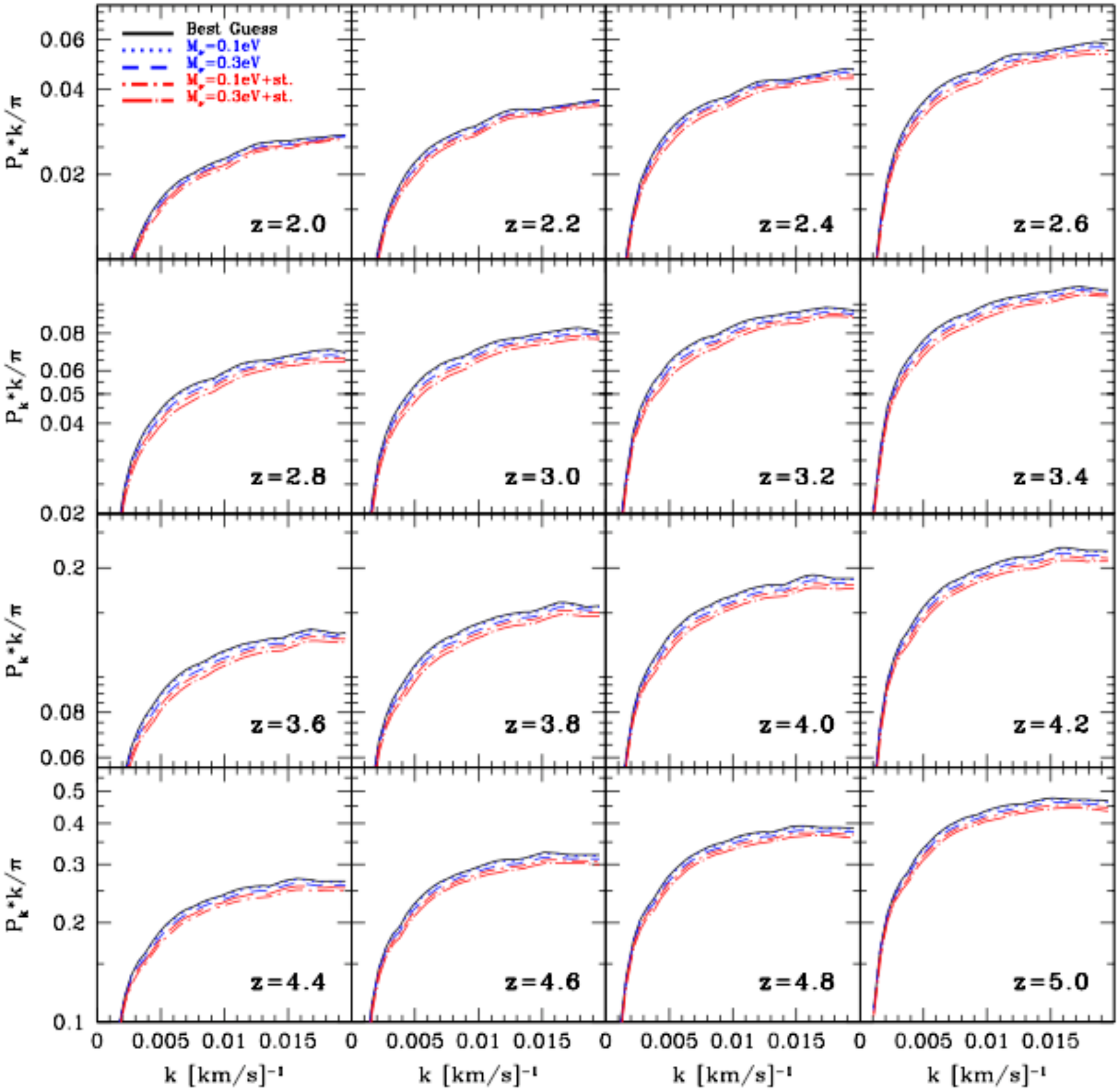


G. Rossi (2017)



- Halo model predictions → up to 20% discrepancies
- Better in terms of ratios
- Relevance of one-halo term
- Effects on halo mass function

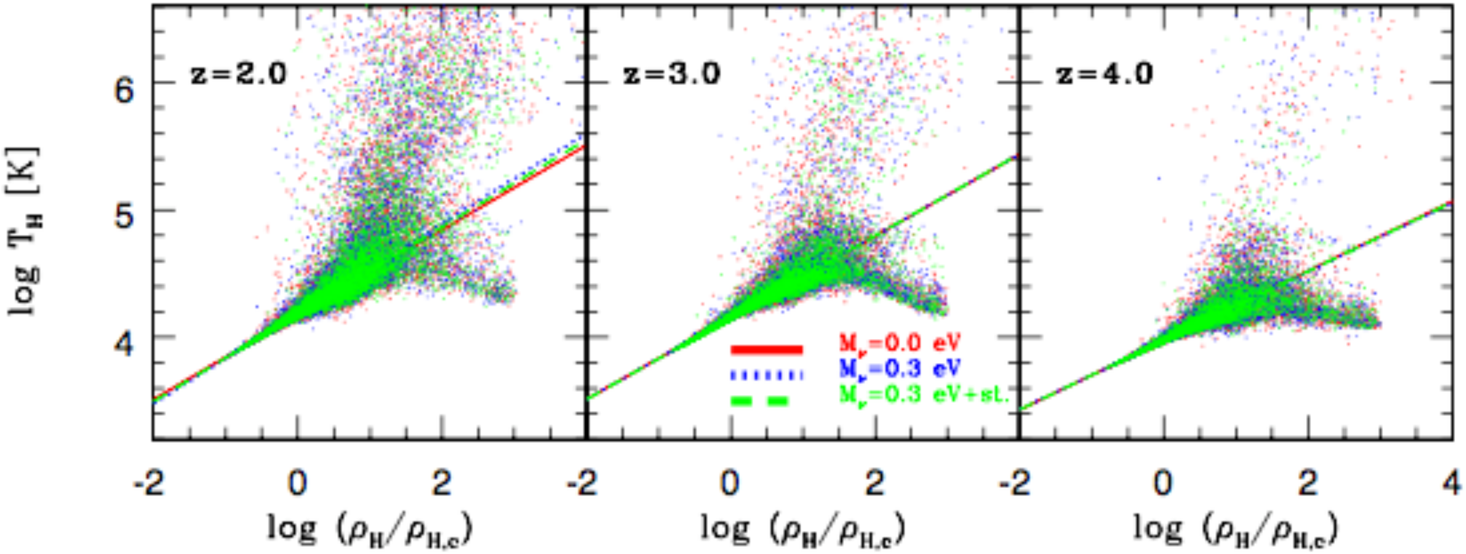
Flux Statistics



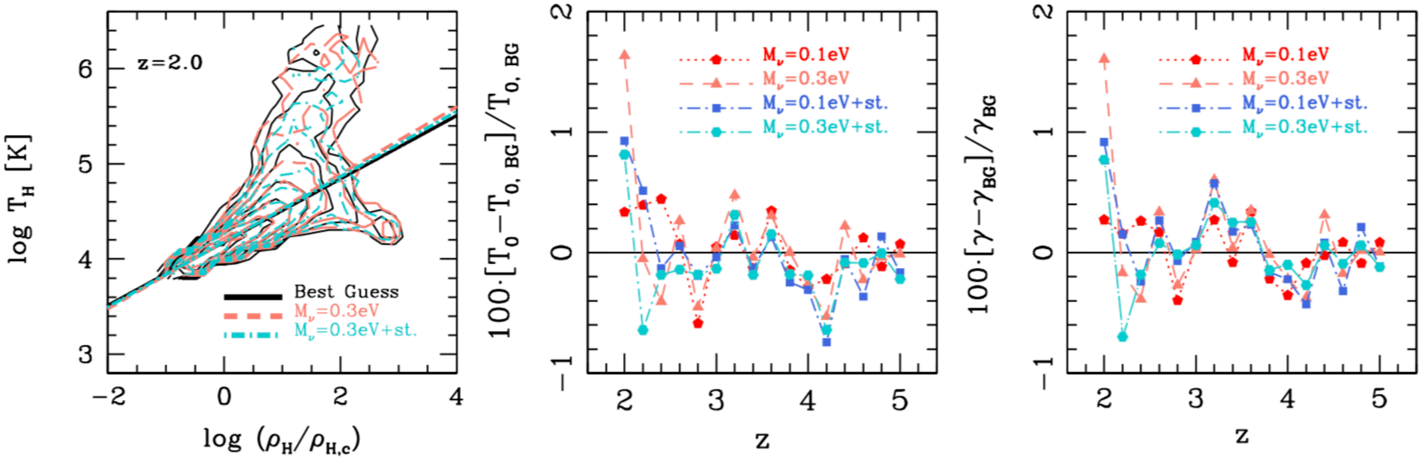
- Tomographic evolution of 1D PS shape & amplitude
- $z = 2.0 - 5.0$, $\Delta z = 0.2$
- Averaged over 10,000 mock absorption spectra per *z*-interval
- Propagation of 'spoon-like' feature to flux PS

G. Rossi (2017, 2019)

IGM Physics: Impact

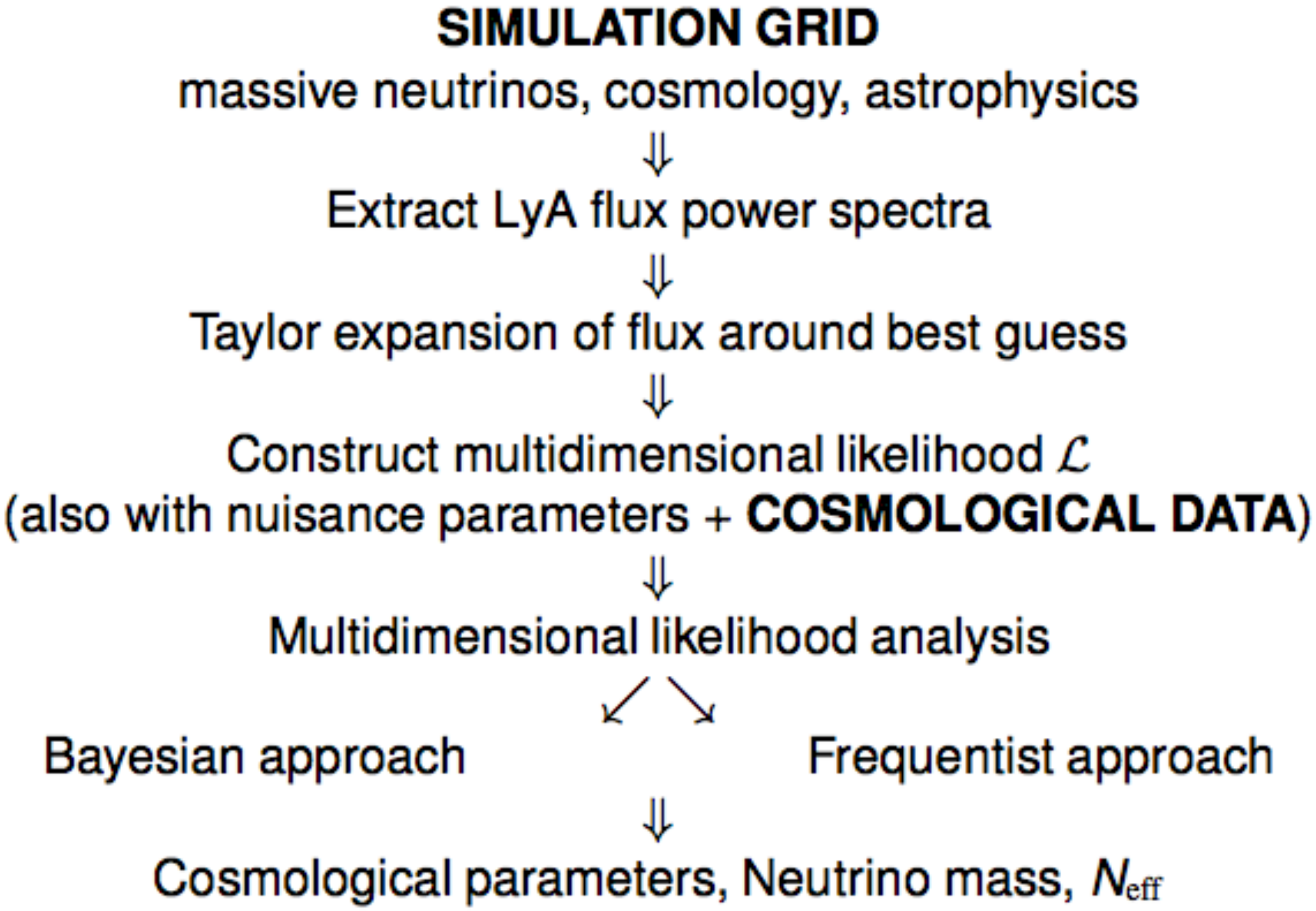


G. Rossi (2017, 2019)



DARK SECTOR: CONSTRAINTS & POTENTIAL

Constraints: General Strategy



SIMULATION GRID

massive neutrinos, cosmology, astrophysics

⇓

Extract LyA flux power spectra

⇓

Taylor expansion of flux around best guess

⇓

Construct multidimensional likelihood $\mathcal{L}$

(also with nuisance parameters + **COSMOLOGICAL DATA**)

⇓

Multidimensional likelihood analysis

↙ ↘

Bayesian approach Frequentist approach

⇓

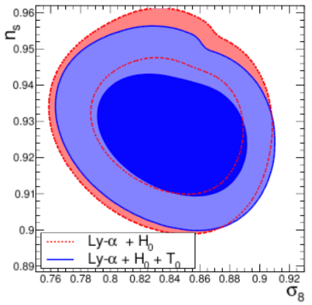
Cosmological parameters, Neutrino mass, $N_{\rm eff}$

Lyα Likelihood Construction

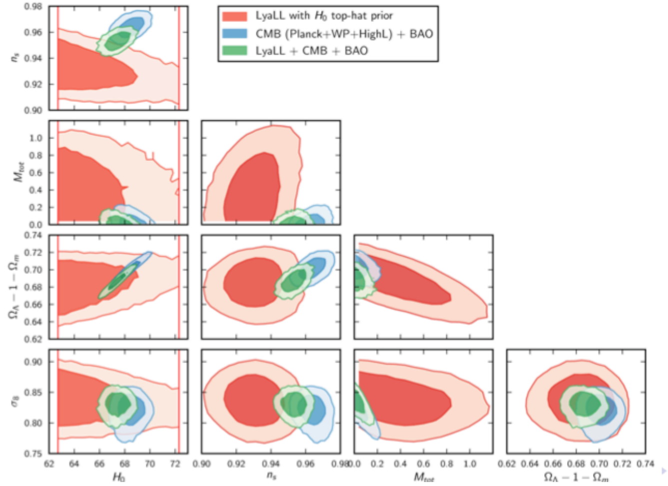
- Model $\mathcal{M}$ defined by three categories of parameters – **cosmological** ($\boldsymbol{\alpha}$), **astrophysical** ($\boldsymbol{\beta}$), **nuisance** ($\boldsymbol{\gamma}$) – globally indicated with $\boldsymbol{\Theta} = (\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma})$
- $N_{\rm k} \times N_{\rm z}$ dataset $\boldsymbol{X}$ of power spectra $P(k_{\rm i}, z_{\rm j})$ measured in $N_{\rm k}$ bins in k and $N_{\rm z}$ bins in redshift with experimental Gaussian errors $\sigma_{\rm i,j}$, with $\boldsymbol{\sigma} = \{\sigma_{\rm i,j}\}$, $i = 1, N_{\rm k}$ and $j = 1, N_{\rm z}$
- $$\mathcal{L}^{Ly\alpha}(\boldsymbol{X}, \boldsymbol{\sigma}|\boldsymbol{\Theta}) = \frac{\exp[-(\Delta^{\rm T} C^{-1} \Delta)/2]}{(2\pi)^{\frac{N_{\rm k} N_{\rm z}}{2}} \sqrt{|C|}} \, \mathcal{L}^{Ly\alpha}_{\rm prior}(\boldsymbol{\gamma})$$
- Δ is a $N_{\rm k} \times N_{\rm z}$ matrix with elements $\Delta(k_{\rm i}, z_{\rm j}) = P(k_{\rm i}, z_{\rm j}) - P^{\rm th}(k_{\rm i}, z_{\rm j})$
- $P^{\rm th}(k_{\rm i}, z_{\rm j})$ predicted theoretical value of the power spectrum for the bin $k_{\rm i}$ and redshift $z_{\rm j}$ given the parameters $(\boldsymbol{\alpha}, \boldsymbol{\beta})$ and computed from simulations
- C is the sum of the data and simulation covariance matrices
- $\mathcal{L}^{Ly\alpha}_{\rm prior}(\boldsymbol{\gamma})$ accounts for the nuisance parameters, a subset of the parameters $\boldsymbol{\Theta}$

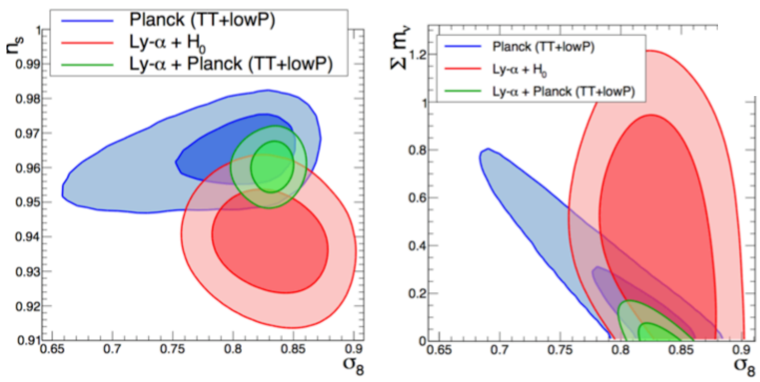
Constraints: Examples

Palanque-Delabrouille et al. (2015a)

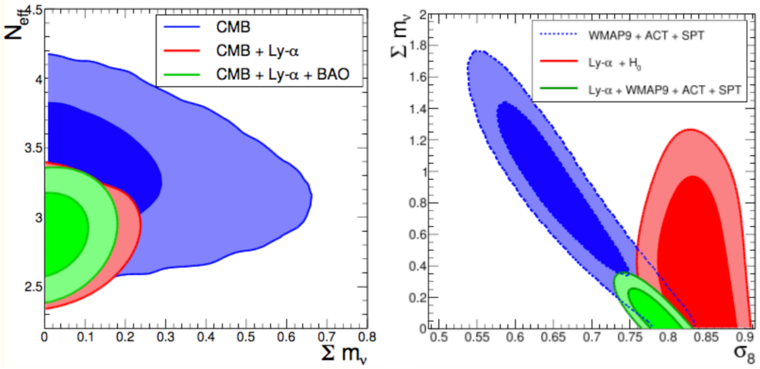


Palanque-Delabrouille et al. (2015a)





Rossi et al. (2015)



$\sum m_\nu < 0.12$ eV → CMB + Lyman-α + BAO

$N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ and $\sum m_\nu < 0.15$ eV (all at 95% CL) → CMB + Lyman-α

Ongoing: eBOSS Applications

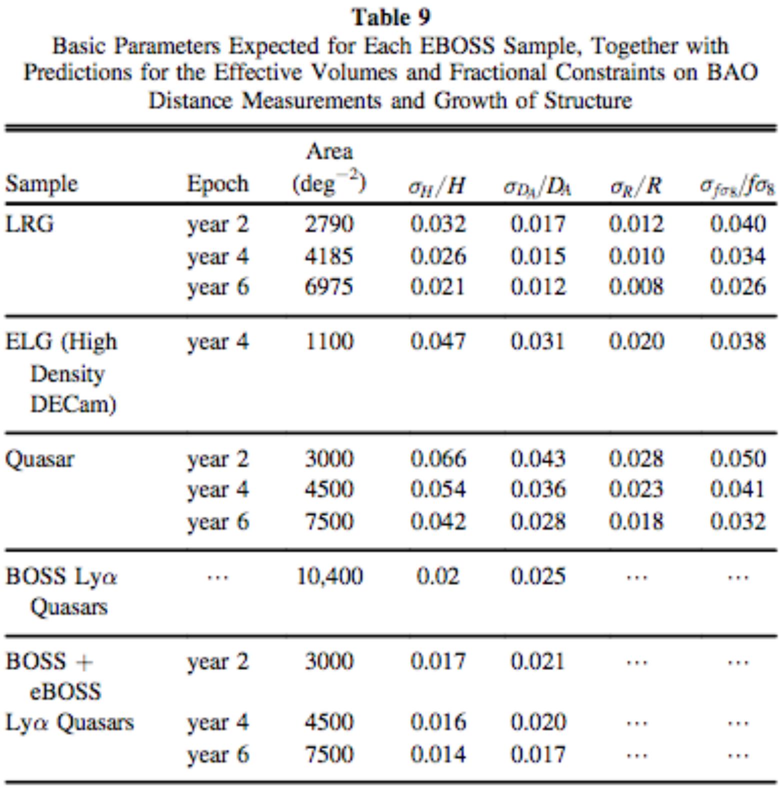


Table 9

Basic Parameters Expected for Each EBOSS Sample, Together with Predictions for the Effective Volumes and Fractional Constraints on BAO Distance Measurements and Growth of Structure

Sample	Epoch	Area (deg^{-2})	σ_H/H	σ_{D_A}/D_A	σ_R/R	$\sigma_{f\sigma_8}/f\sigma_8$
LRG	year 2	2790	0.032	0.017	0.012	0.040
	year 4	4185	0.026	0.015	0.010	0.034
	year 6	6975	0.021	0.012	0.008	0.026
ELG (High Density DECam)	year 4	1100	0.047	0.031	0.020	0.038
Quasar	year 2	3000	0.066	0.043	0.028	0.050
	year 4	4500	0.054	0.036	0.023	0.041
	year 6	7500	0.042	0.028	0.018	0.032
BOSS Lyα Quasars	⋯	10,400	0.02	0.025	⋯	⋯
BOSS + eBOSS Lyα Quasars	year 2	3000	0.017	0.021	⋯	⋯
	year 4	4500	0.016	0.020	⋯	⋯
	year 6	7500	0.014	0.017	⋯	⋯

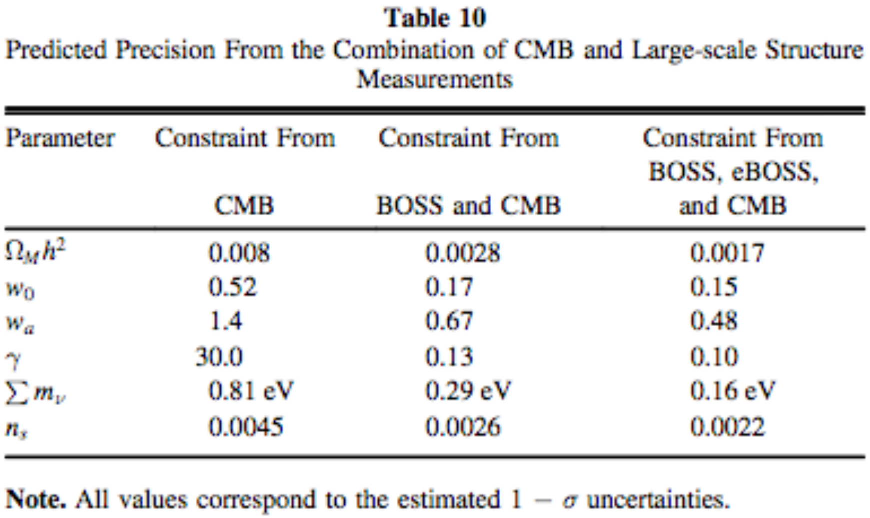
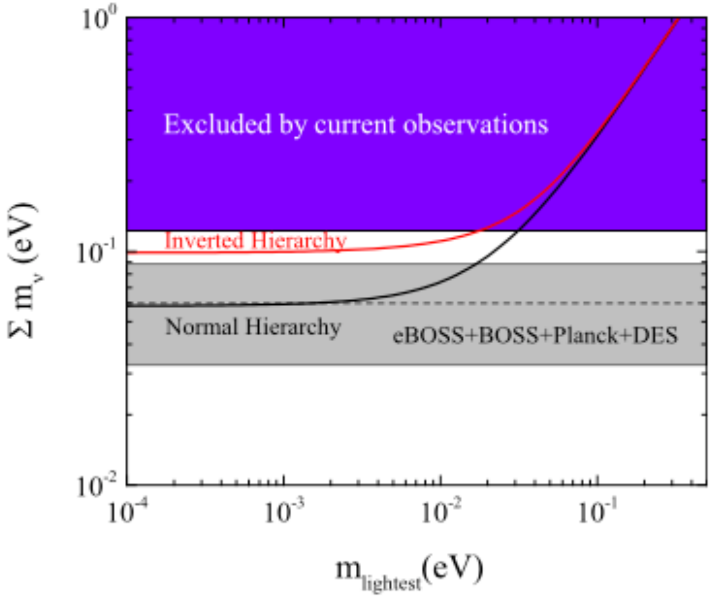


Table 10

Predicted Precision From the Combination of CMB and Large-scale Structure Measurements

Parameter	Constraint From CMB	Constraint From BOSS and CMB	Constraint From BOSS, eBOSS, and CMB
$\Omega_M h^2$	0.008	0.0028	0.0017
w_0	0.52	0.17	0.15
w_a	1.4	0.67	0.48
γ	30.0	0.13	0.10
$\sum m_\nu$	0.81 eV	0.29 eV	0.16 eV
n_s	0.0045	0.0026	0.0022

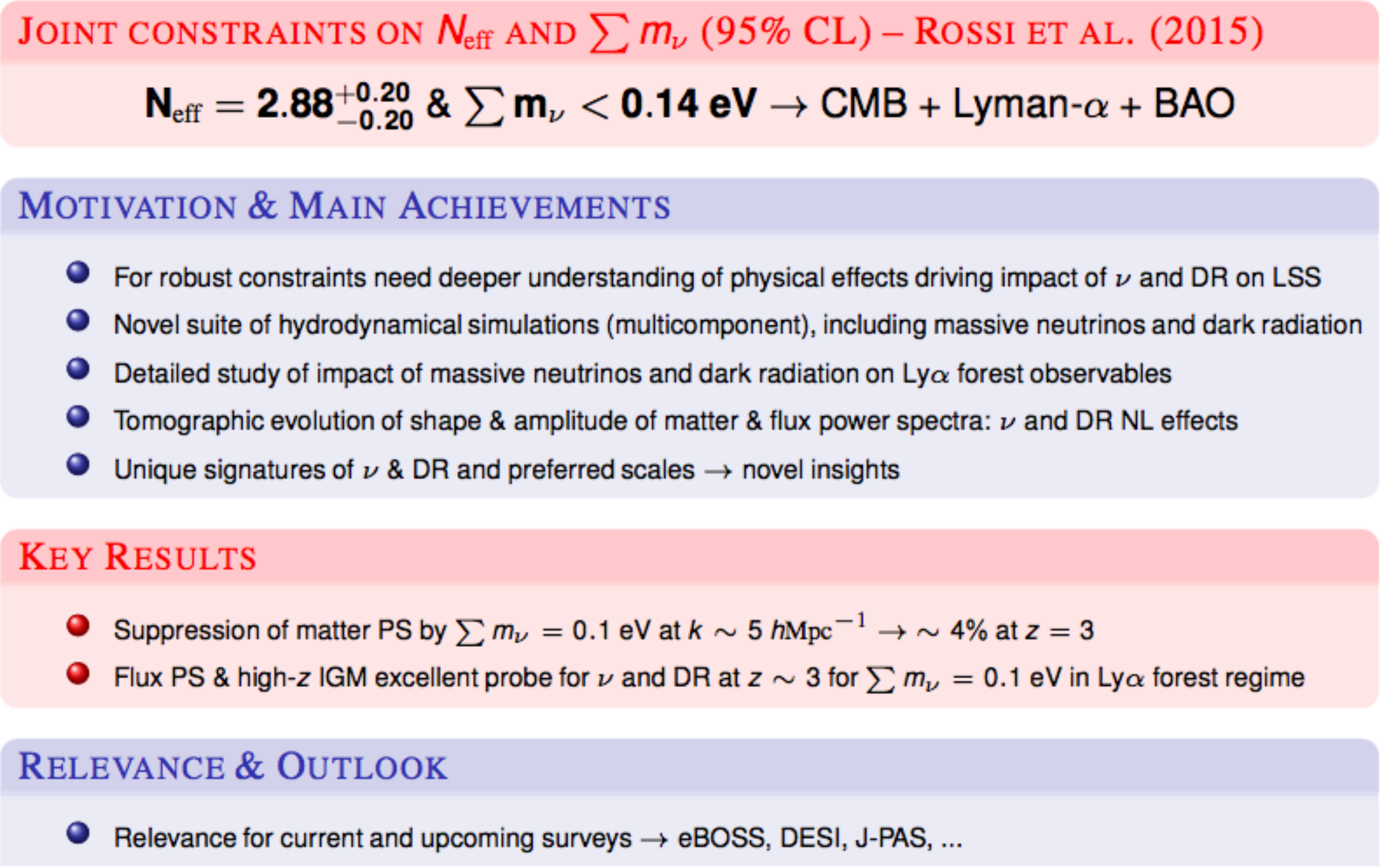
Note. All values correspond to the estimated $1-\sigma$ uncertainties.



Zhao et al. (2016)
Dawson et al. (2016)

SUMMARY & OUTLOOK

Key Results & Outlook



JOINT CONSTRAINTS ON $N_{\rm eff}$ AND $\sum m_\nu$ (95% CL) – ROSSI ET AL. (2015)

$$\mathbf{N_{eff} = 2.88^{+0.20}_{-0.20}} \ \& \ \sum \mathbf{m_\nu < 0.14\ eV} \rightarrow \text{CMB + Lyman-}\alpha\text{ + BAO}$$

MOTIVATION & MAIN ACHIEVEMENTS

- For robust constraints need deeper understanding of physical effects driving impact of ν and DR on LSS
- Novel suite of hydrodynamical simulations (multicomponent), including massive neutrinos and dark radiation
- Detailed study of impact of massive neutrinos and dark radiation on Lyα forest observables
- Tomographic evolution of shape & amplitude of matter & flux power spectra: ν and DR NL effects
- Unique signatures of ν & DR and preferred scales $\rightarrow$ novel insights

KEY RESULTS

- Suppression of matter PS by $\sum m_\nu = 0.1$ eV at $k \sim 5\ h\mathrm{Mpc}^{-1} \rightarrow \sim 4\%$ at $z = 3$
- Flux PS & high-z IGM excellent probe for ν and DR at $z \sim 3$ for $\sum m_\nu = 0.1$ eV in Lyα forest regime

RELEVANCE & OUTLOOK

- Relevance for current and upcoming surveys $\rightarrow$ eBOSS, DESI, J-PAS, ...