Neutrinos & High-Redshift Cosmic Web with the **Lyman-α** Forest

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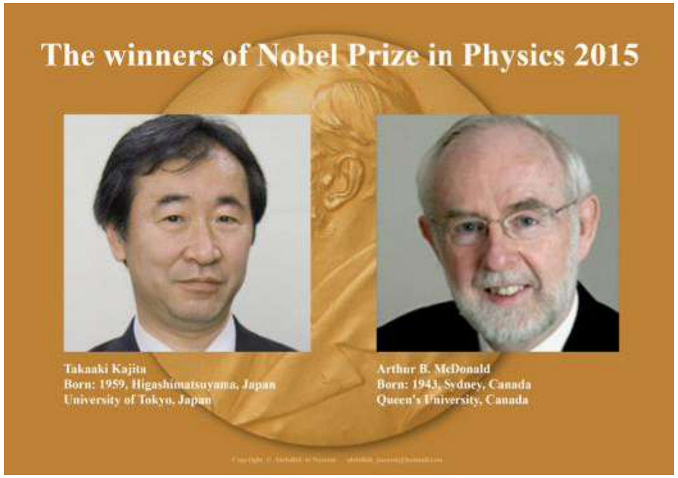
Focus: Neutrinos, Dark Radiation, WDM

> *‘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!

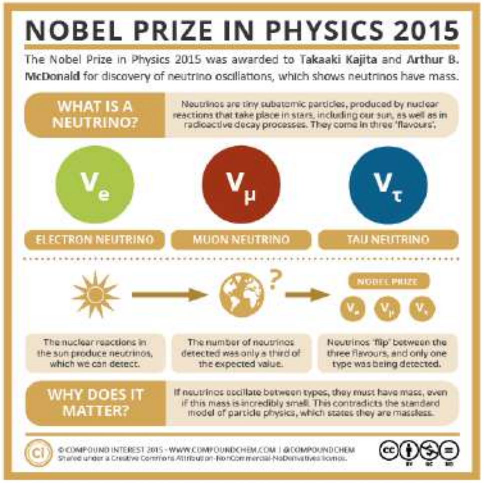
Neutrino cosmology → beautiful example of complementarity with particle physics



The winners of Nobel Prize in Physics 2015

Takaaki Kajita
Born: 1959, Higashimatsuyama, Japan
University of Tokyo, Japan

Arthur B. McDonald
Born: 1943, Sydney, Canada
Queen's University, Canada



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.

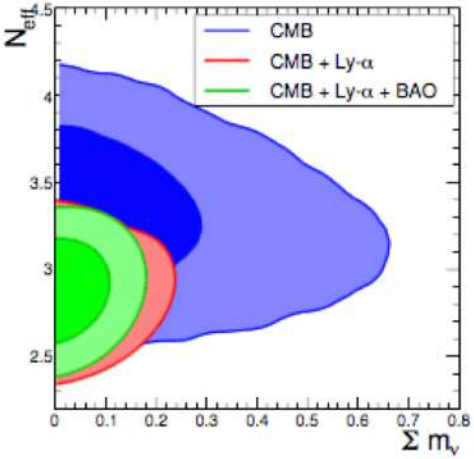
The number of neutrinos detected was only a third of the expected value.

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 $> 5\sigma$

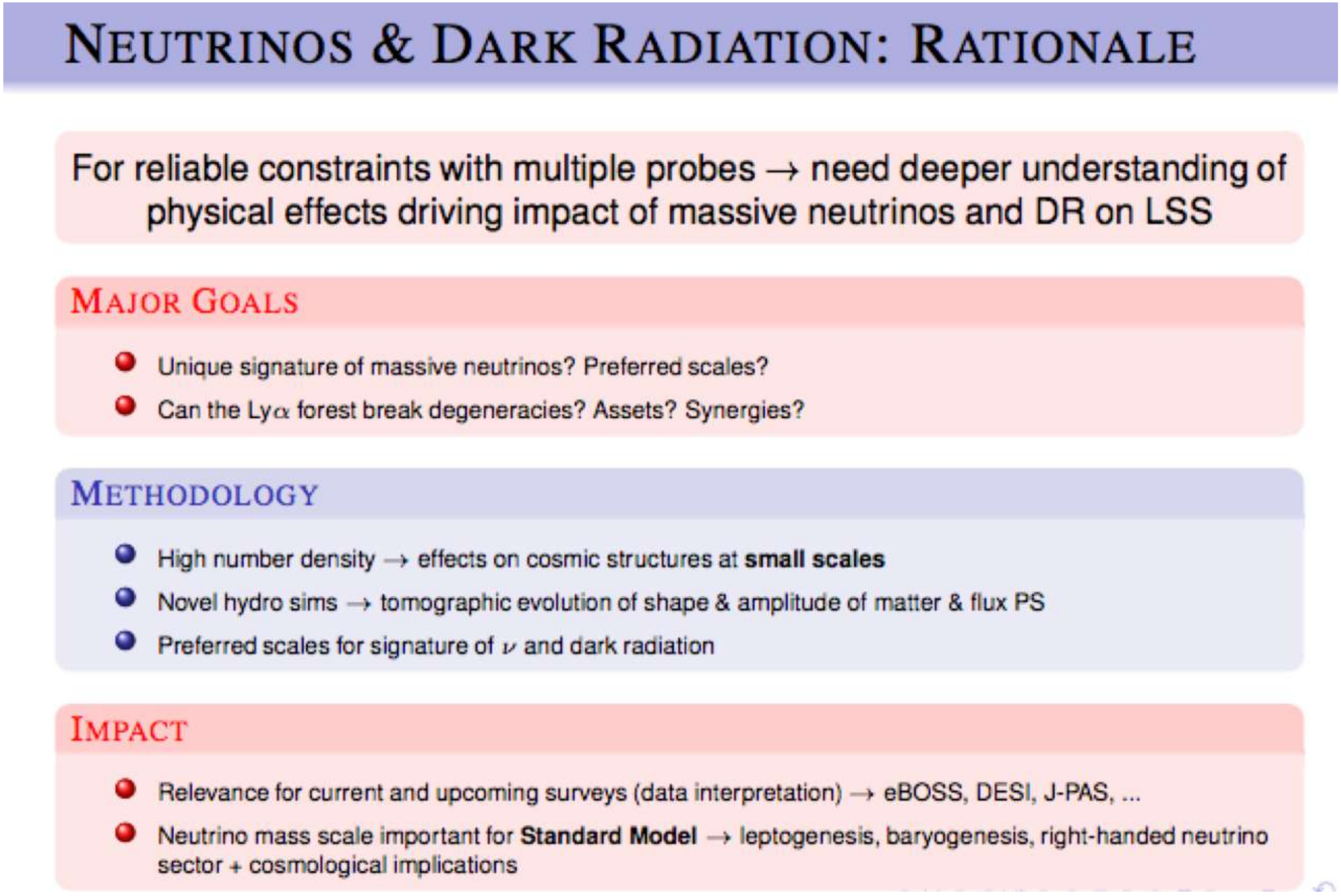
INDIVIDUAL CONSTRAINTS ON $\sum m_\nu$ (95% CL)

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

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

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

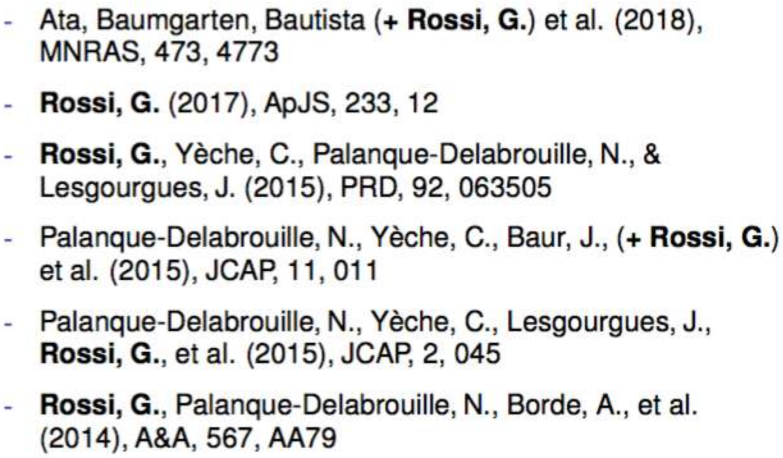
IMPACT

- 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

- Introductory Background
- Novel Hydro Simulations
- Neutrinos, High-z Web, Lyα Forest
- Techniques for Neutrino Constraints
- SDSS Constraints & Potential
- Summary & Outlook

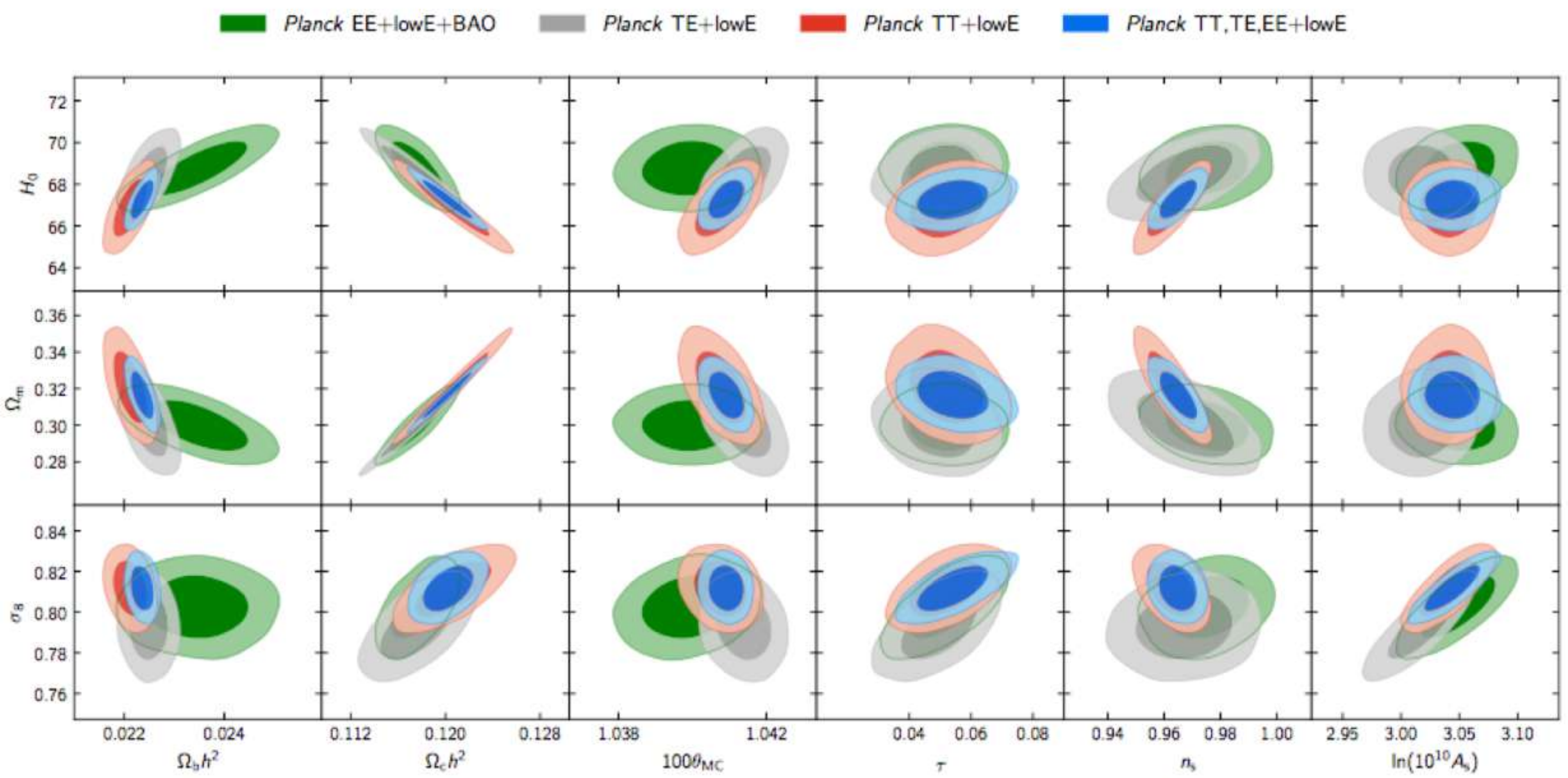
KEY REFERENCES

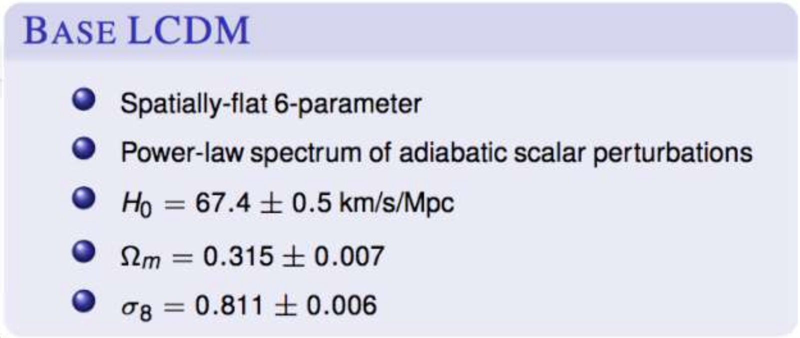


- Ata, Baumgarten, Bautista (+ **Rossi, G.**) et al. (2018), MNRAS, 473, 4773
- **Rossi, G.** (2017), ApJS, 233, 12
- **Rossi, G.**, Yèche, C., Palanque-Delabrouille, N., & Lesgourgues, J. (2015), PRD, 92, 063505
- Palanque-Delabrouille, N., Yèche, C., Baur, J., (+ **Rossi, G.**) et al. (2015), JCAP, 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

INTRODUCTORY BACKGROUND

Base LCDM

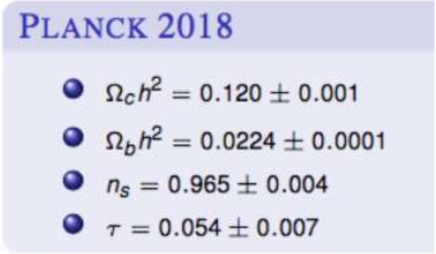




BASE LCDM

- Spatially-flat 6-parameter
- Power-law spectrum of adiabatic scalar perturbations
- $H_0 = 67.4 \pm 0.5$ km/s/Mpc
- $\Omega_m = 0.315 \pm 0.007$
- $\sigma_8 = 0.811 \pm 0.006$

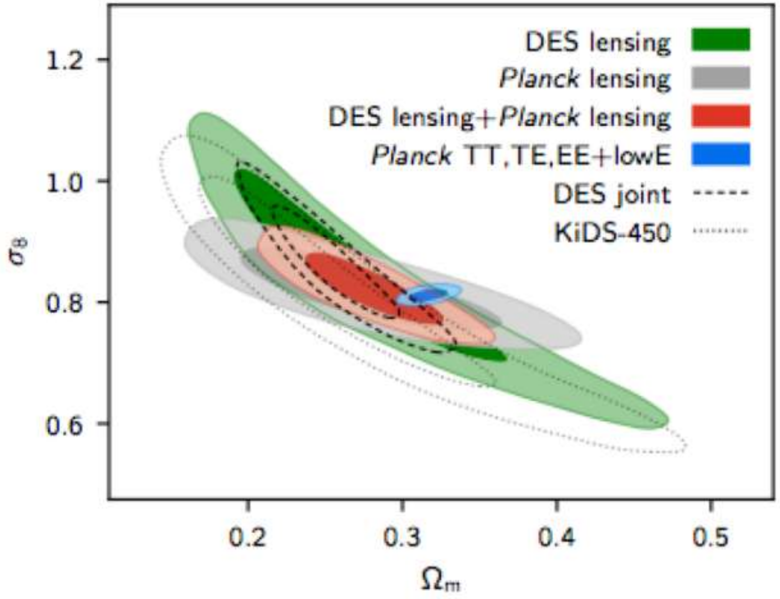
PLANCK 2018
(**Planck Coll. 2018 - VI**)



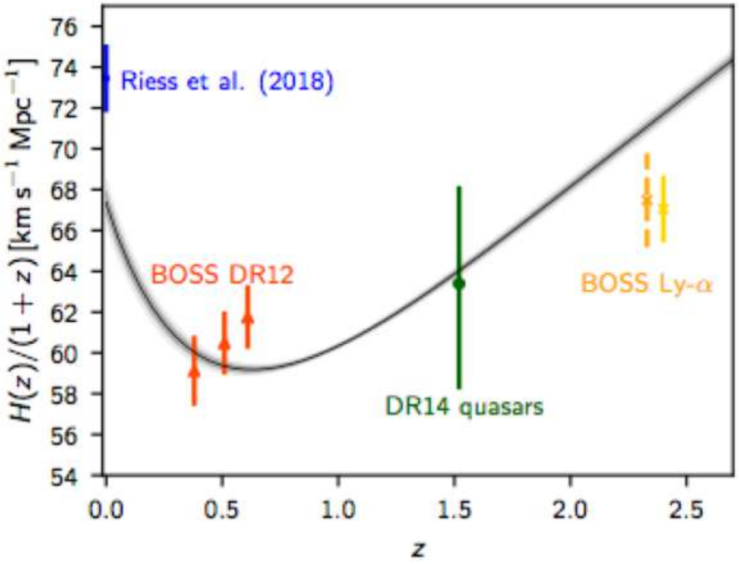
PLANCK 2018

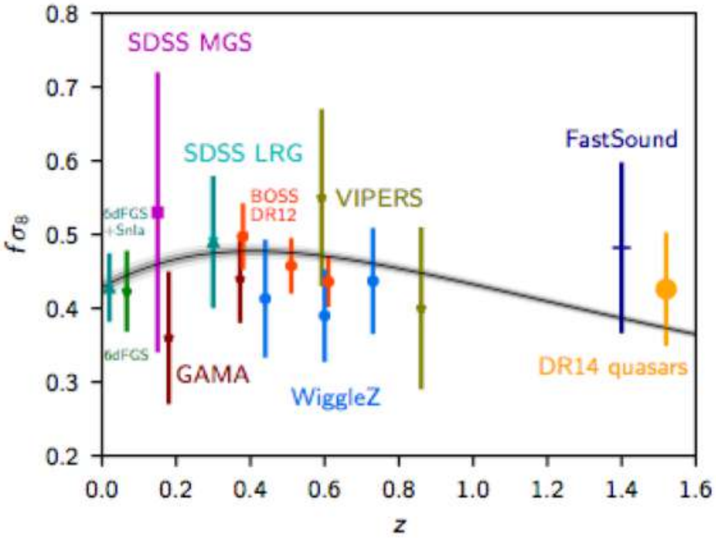
- $\Omega_c h^2 = 0.120 \pm 0.001$
- $\Omega_b h^2 = 0.0224 \pm 0.0001$
- $n_s = 0.965 \pm 0.004$
- $\tau = 0.054 \pm 0.007$

LCDM Still Holds but …



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





Still Tensions ….
and … Massive Neutrinos ?

Large-Scale Computing

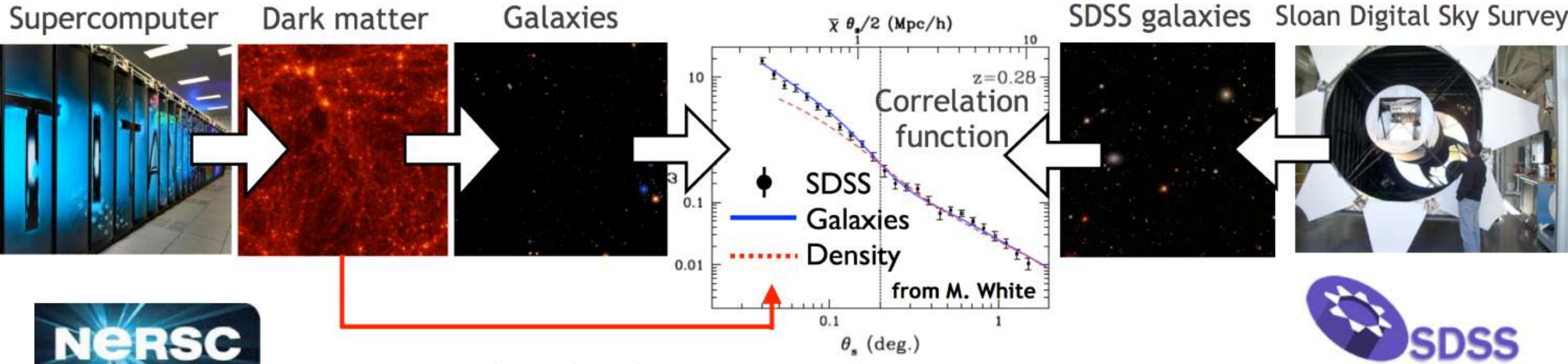
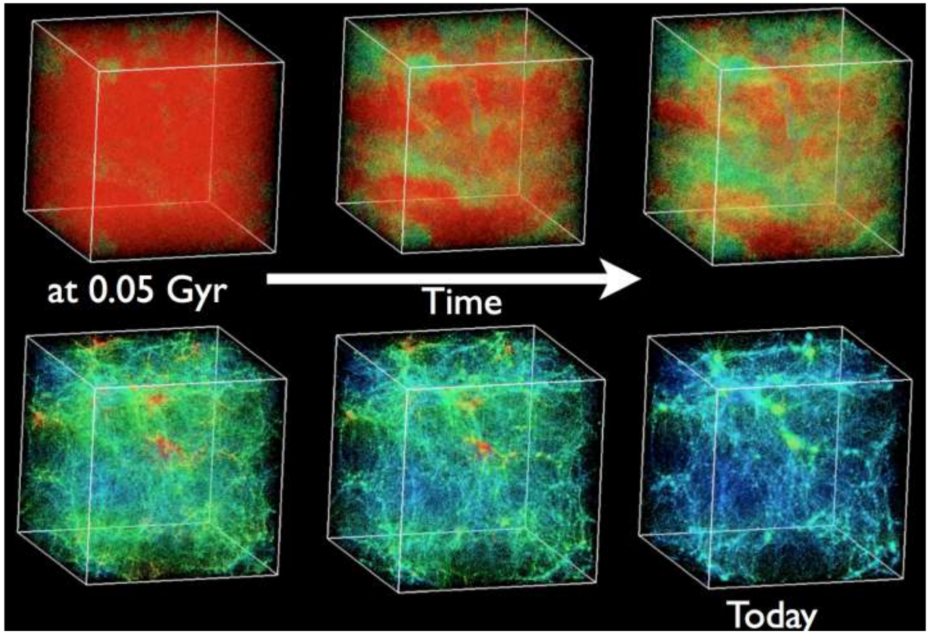
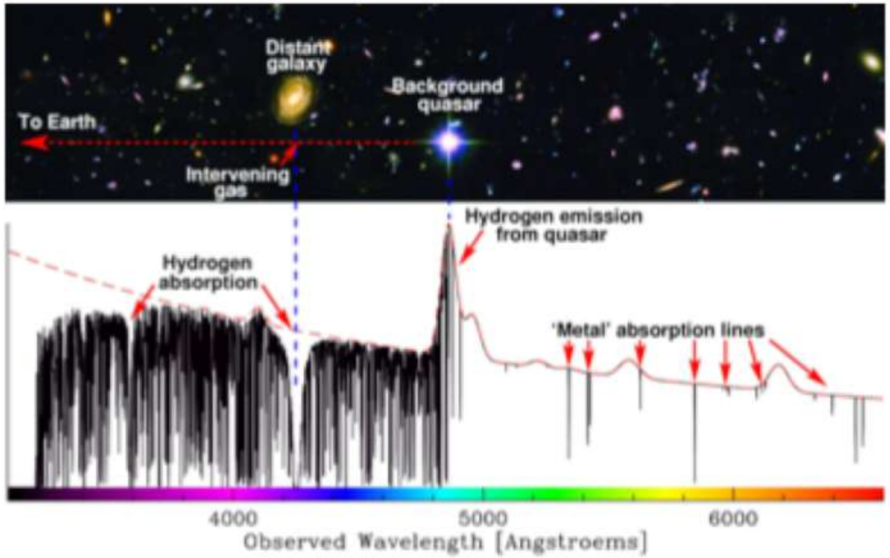


Image Credit: Katrin Heitmann

- Data interpretation driven by simulations
- Simulations driven by underlying **science goals**
- No cosmology without large-scale computing
- **Challenges:** larger volumes, higher resolution, big data
- Simulating tracers: `*an art*’



Lyman-α Forest Asset



LY-α: IMPORTANCE

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

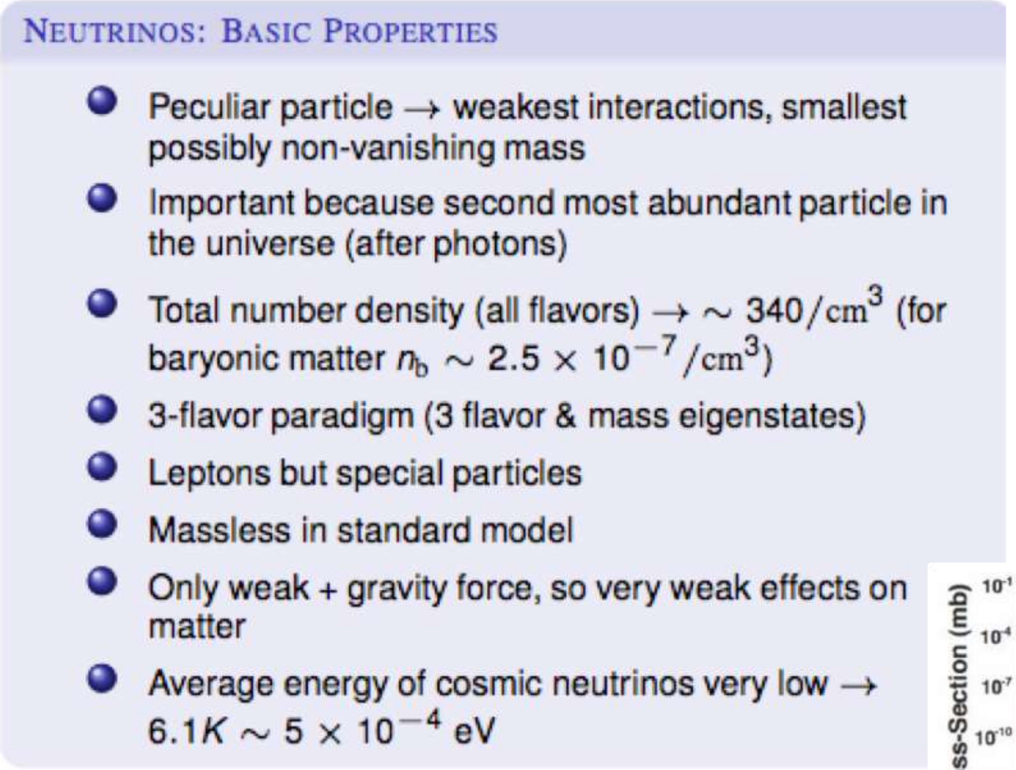
LYA: DIFFICULTIES

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

LYA: ADVANTAGES

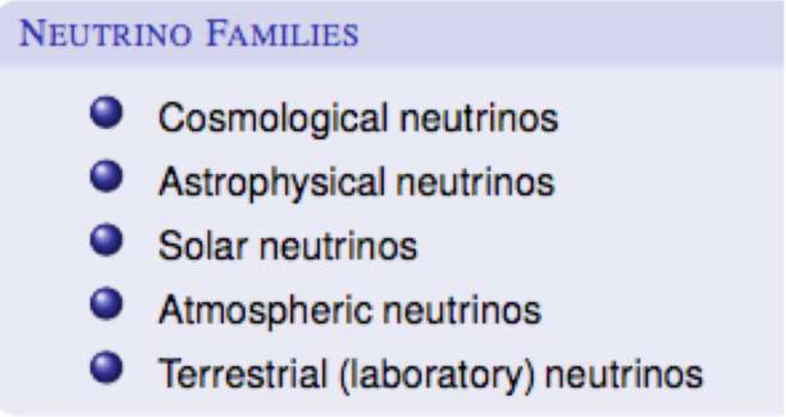
- Mildly nonlinear scales
  i.e. $\rightarrow$ k [0.1 – 2] h/Mpc, [0.002 – 0.02] s/km
- High redshift ($2 \leq z \leq 5$)
- Complementary and orthogonal to other probes
- Special role in probing free-streaming of neutrinos on matter PS
- Evolution of $\nu \rightarrow$ signature with *z* (scale-dependent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

Neutrinos: Peculiar Leptons, Everywhere



NEUTRINOS: BASIC PROPERTIES

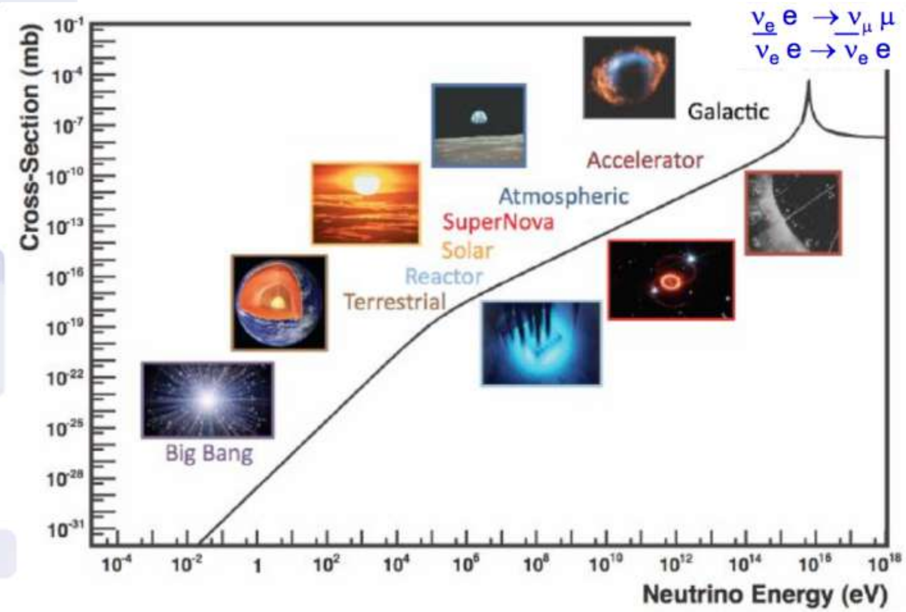
- Peculiar particle → weakest interactions, smallest possibly non-vanishing mass
- Important because second most abundant particle in the universe (after photons)
- Total number density (all flavors) → $\sim 340/\mathrm{cm}^3$ (for baryonic matter $n_b \sim 2.5 \times 10^{-7}/\mathrm{cm}^3$)
- 3-flavor 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

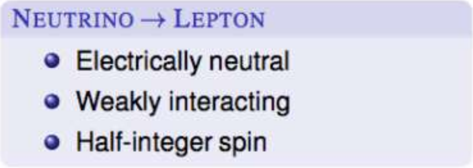


NEUTRINO FAMILIES

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

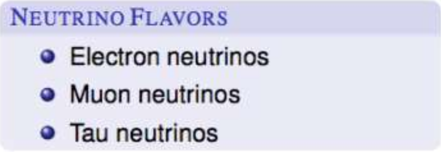
Courtesy A. Bravar





NEUTRINO → LEPTON

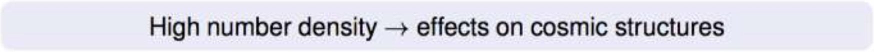
- Electrically neutral
- Weakly interacting
- Half-integer spin



NEUTRINO FLAVORS

- Electron neutrinos
- Muon neutrinos
- Tau neutrinos

Focus here → **Cosmological Neutrinos**



High number density → effects on cosmic structures

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 $(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \xi, \zeta)$

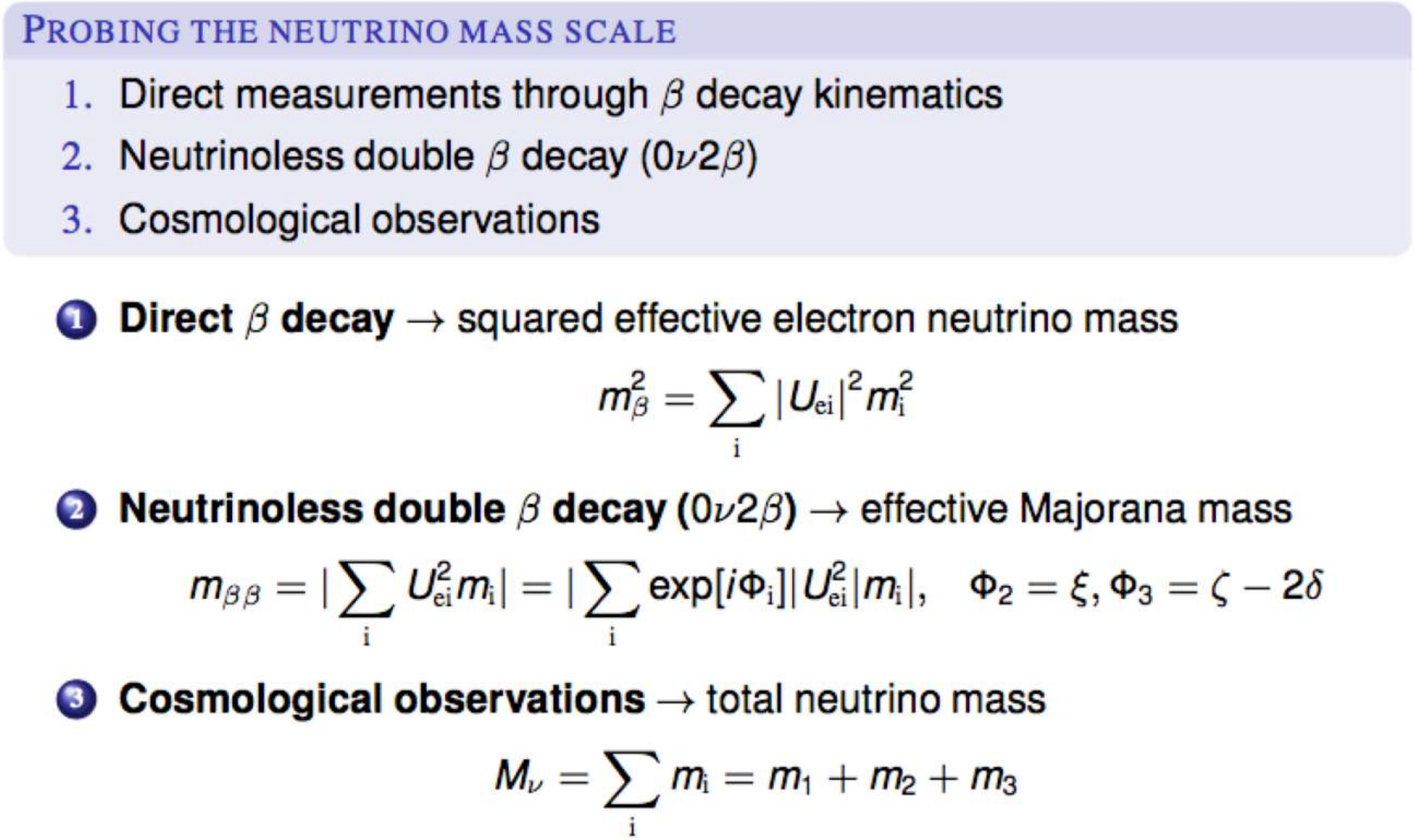
Massive Neutrinos & Cosmology

- 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

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

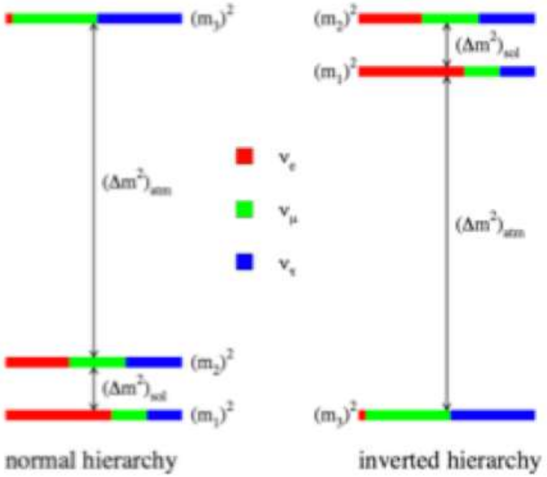
② **Neutrinoless double β decay ($0\nu2\beta$)** → effective Majorana mass

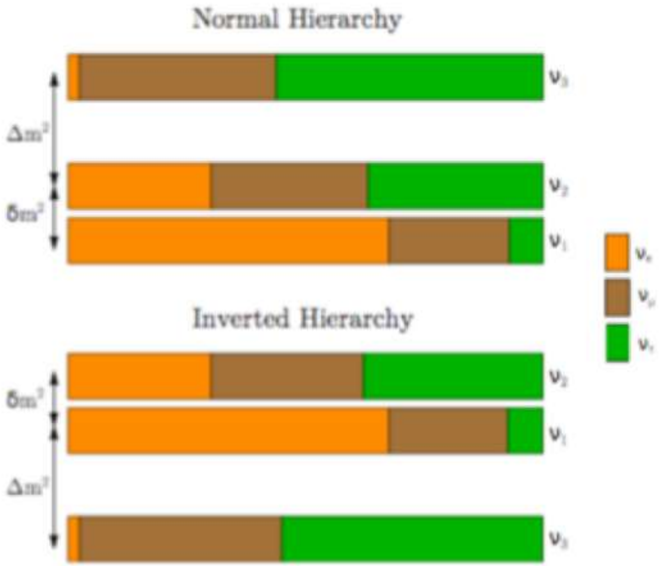
$$m_{\beta\beta} = |\sum_{\mathrm{i}} U_{\mathrm{ei}}^2 m_{\mathrm{i}}| = |\sum_{\mathrm{i}} \exp[i\Phi_{\mathrm{i}}]|U_{\mathrm{ei}}^2| m_{\mathrm{i}}|, \quad \Phi_2 = \xi, \Phi_3 = \zeta - 2\delta$$

③ **Cosmological observations** → total neutrino mass

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

Neutrino Mass Hierarchy





- $\Delta m^2_{21} \equiv \Delta m^2_{\rm solar} \equiv \delta m^2 = m_2^2 - m_1^2 > 0 \rightarrow$ solar mass splitting
- $|\Delta m^2_{31}| \equiv |\Delta m^2_{\rm atm}| = |m_3^2 - m_1^2| \rightarrow$ atmospheric mass splitting
- $\Delta m^2_{31} > 0 \rightarrow$ NH; $\Delta m^2_{31} < 0 \rightarrow$ IH

- $\delta m^2 \equiv \Delta m^2_{21} = m_2^2 - m_1^2 > 0 \rightarrow$ solar mass splitting
- $\Delta m^2 = m_3^2 - \frac{m_1^2 + m_2^2}{2}$

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)

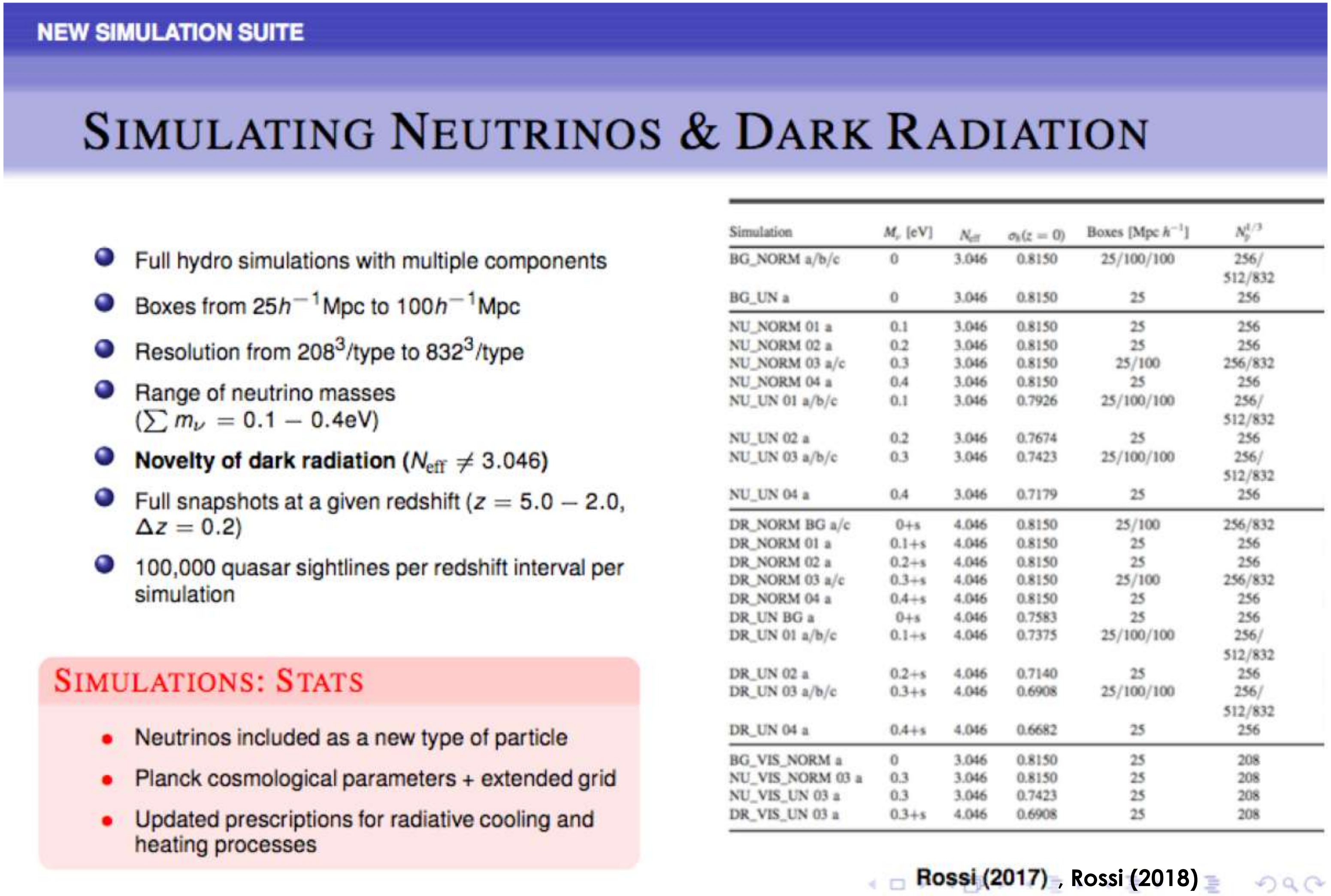
- LyA → $M_\nu < 0.9$ eV
- WMAP9 → $M_\nu < 0.44$ eV
- WMAP7+LRG+H_0 → $M_\nu < 0.44$ eV
- WMAP7+ACT+BAO+H_0 → $M_\nu < 0.39$ eV
- WMAP7+WiggleZ+BAO+H_0 → $M_\nu < 0.29$ eV
- WMAP7+MegaZ+BAO+SNIa+H_0 → $M_\nu < 0.281$ eV
- Planck+WP+highL+BAO → $M_\nu < 0.23$ eV
- Planck+WiggleZ+BAO → $M_\nu < 0.18$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

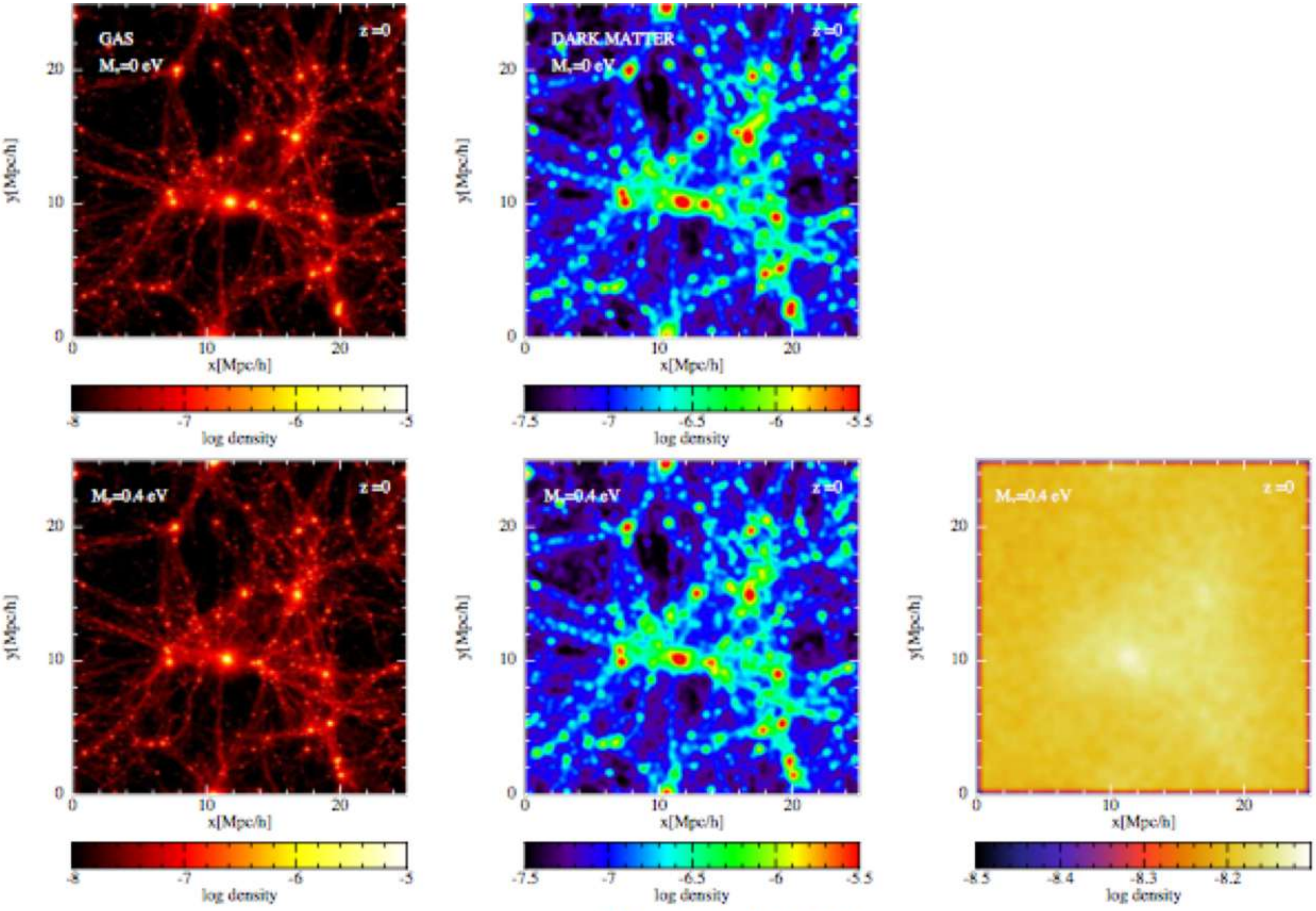
SIMULATIONS: STATS

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

Simulation	M_ν [eV]	$N_{\rm eff}$	$\sigma_8(z=0)$	Boxes [Mpc h^{-1}]	$N_p^{1/3}$
BG_NORM a/b/c	0	3.046	0.8150	25/100/100	256/512/832
BG_UN a	0	3.046	0.8150	25	256
NU_NORM 01 a	0.1	3.046	0.8150	25	256
NU_NORM 02 a	0.2	3.046	0.8150	25	256
NU_NORM 03 a/c	0.3	3.046	0.8150	25/100	256/832
NU_NORM 04 a	0.4	3.046	0.8150	25	256
NU_UN 01 a/b/c	0.1	3.046	0.7926	25/100/100	256/512/832
NU_UN 02 a	0.2	3.046	0.7674	25	256
NU_UN 03 a/b/c	0.3	3.046	0.7423	25/100/100	256/512/832
NU_UN 04 a	0.4	3.046	0.7179	25	256
DR_NORM BG a/c	0+s	4.046	0.8150	25/100	256/832
DR_NORM 01 a	0.1+s	4.046	0.8150	25	256
DR_NORM 02 a	0.2+s	4.046	0.8150	25	256
DR_NORM 03 a/c	0.3+s	4.046	0.8150	25/100	256/832
DR_NORM 04 a	0.4+s	4.046	0.8150	25	256
DR_UN BG a	0+s	4.046	0.7583	25	256
DR_UN 01 a/b/c	0.1+s	4.046	0.7375	25/100/100	256/512/832
DR_UN 02 a	0.2+s	4.046	0.7140	25	256
DR_UN 03 a/b/c	0.3+s	4.046	0.6908	25/100/100	256/512/832
DR_UN 04 a	0.4+s	4.046	0.6682	25	256
BG_VIS_NORM a	0	3.046	0.8150	25	208
NU_VIS_NORM 03 a	0.3	3.046	0.8150	25	208
NU_VIS_UN 03 a	0.3	3.046	0.7423	25	208
DR_VIS_UN 03 a	0.3+s	4.046	0.6908	25	208

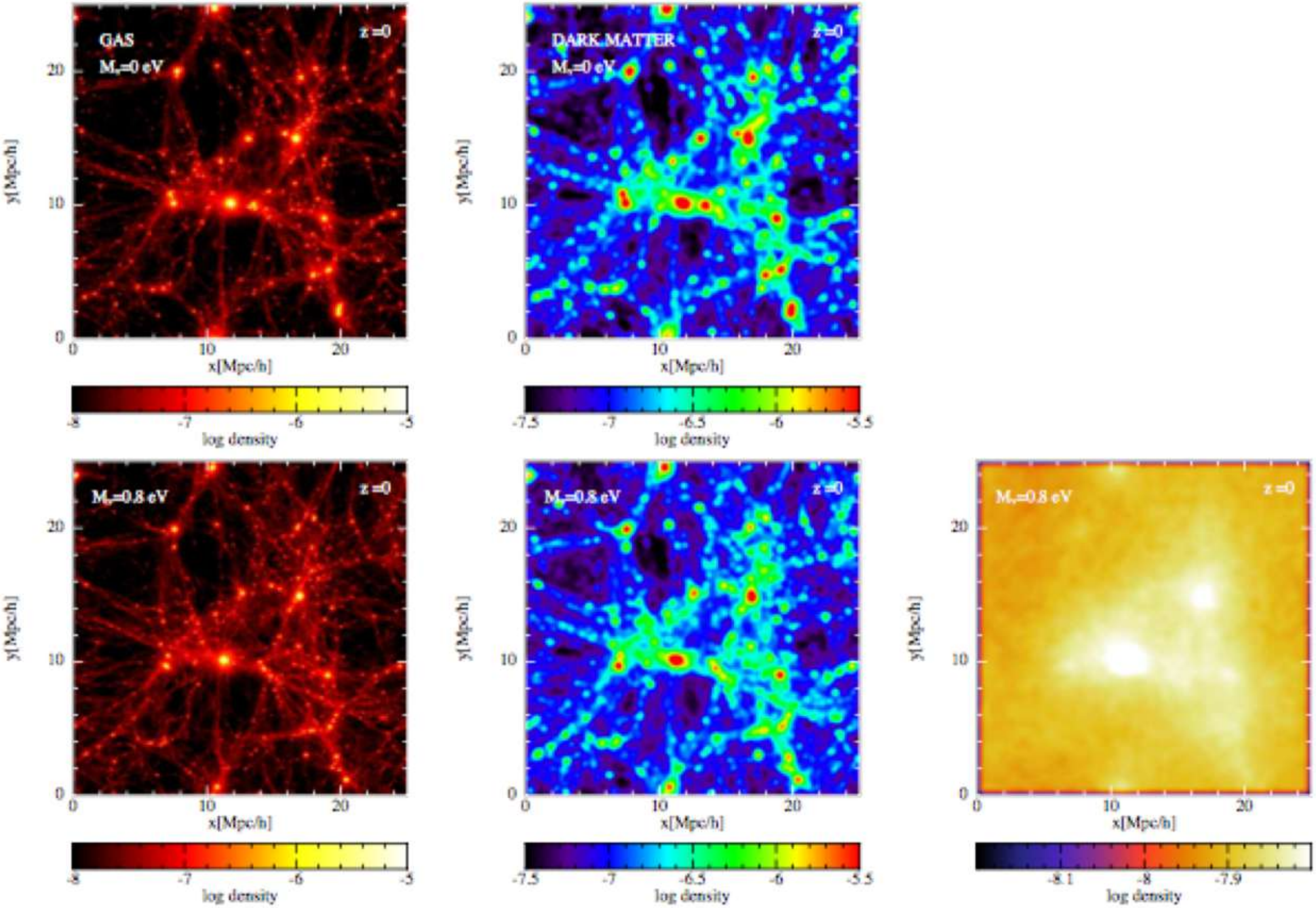
Rossi (2017) , Rossi (2018)

Cosmologies with Massive Neutrinos (1)



Rossi et al. (2014)

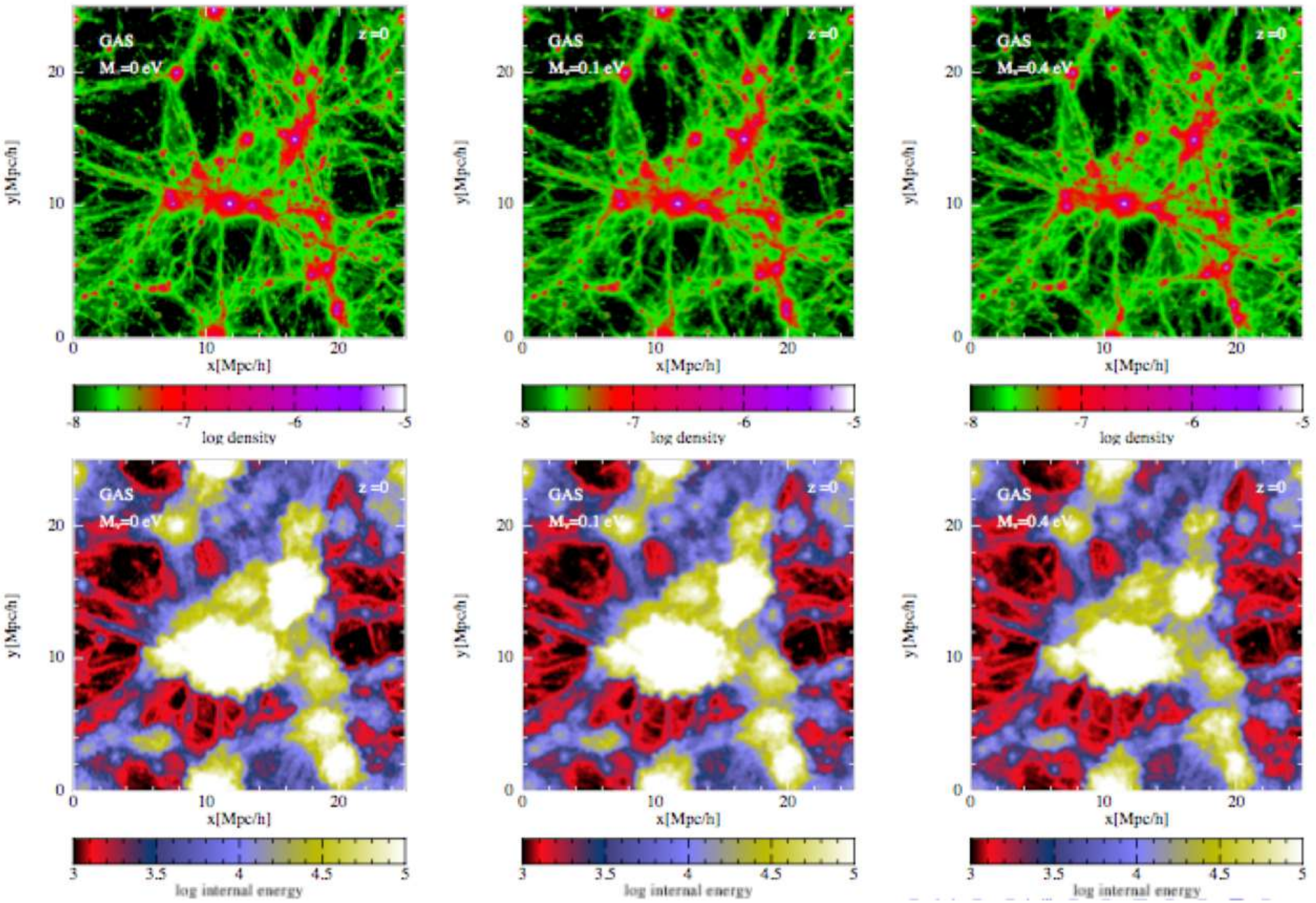
Cosmologies with Massive Neutrinos (2)



Rossi et al. (2014)

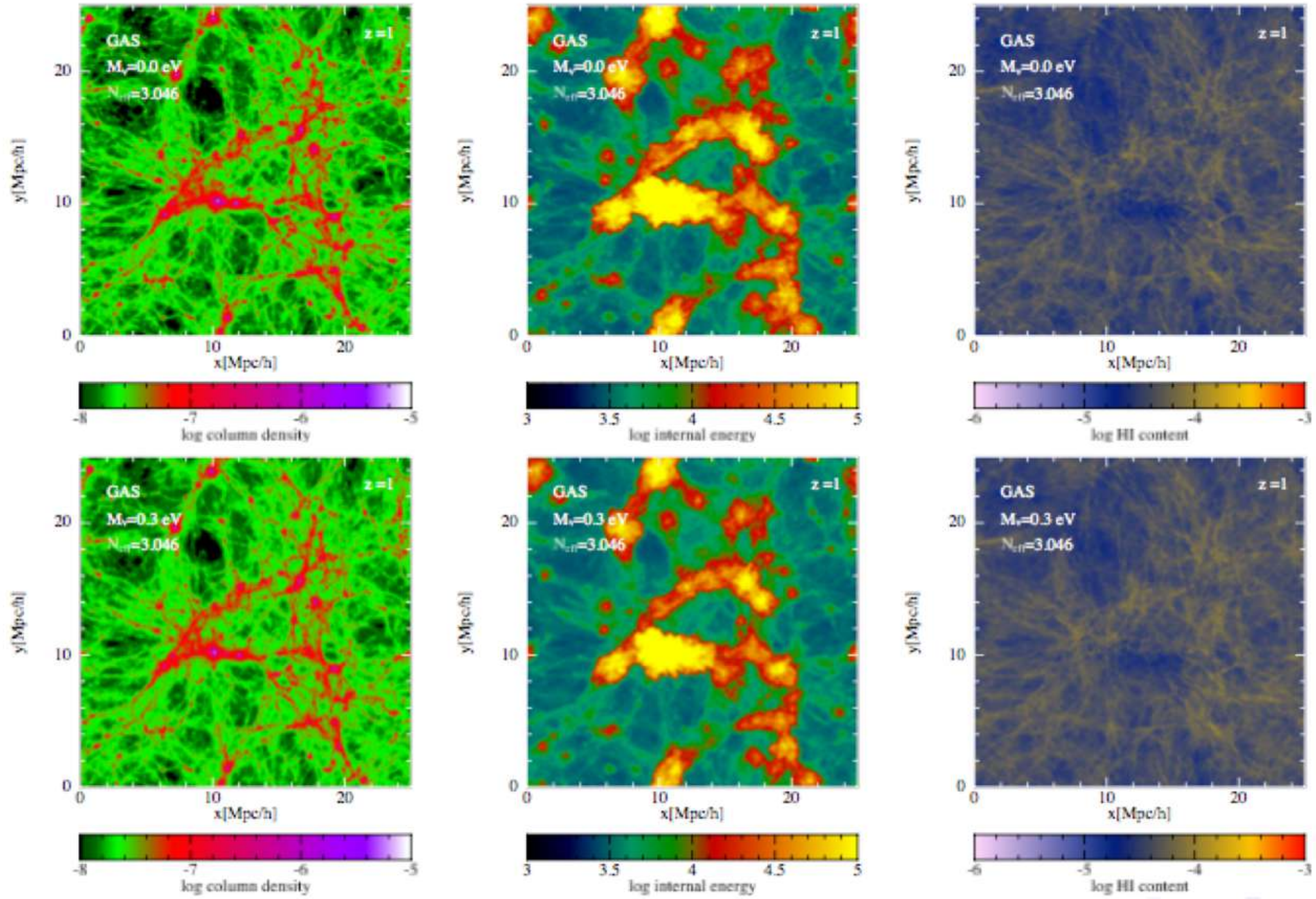
Gas Properties (1)

G. Rossi (2017)

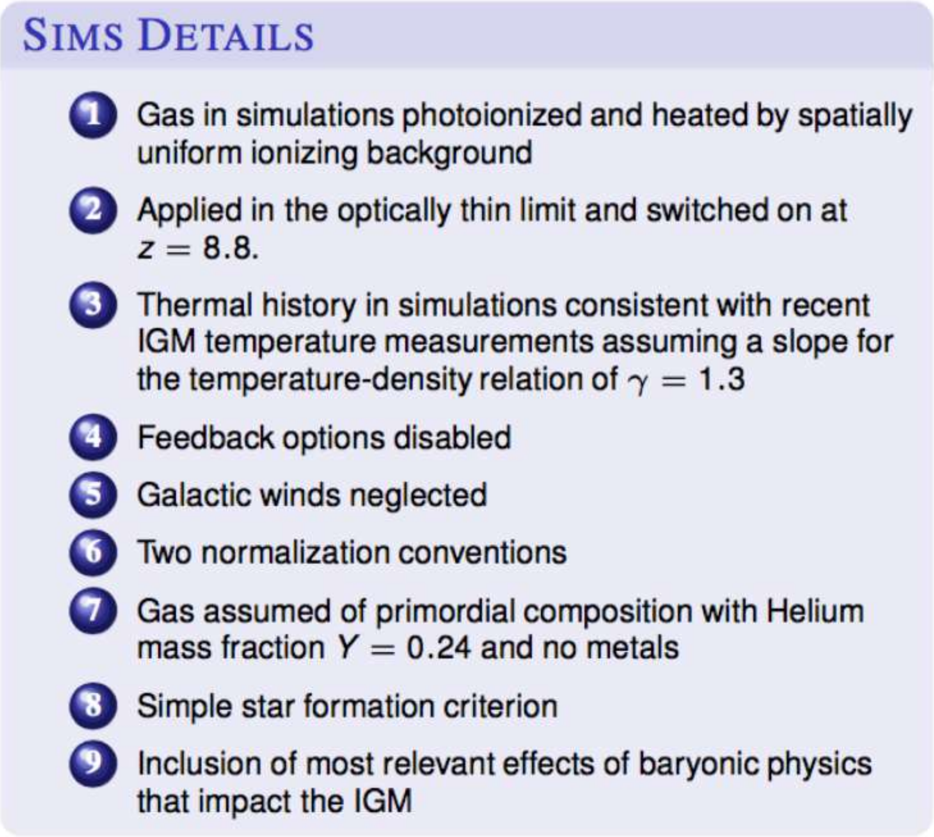


Gas Properties (2)

G. Rossi (2018)

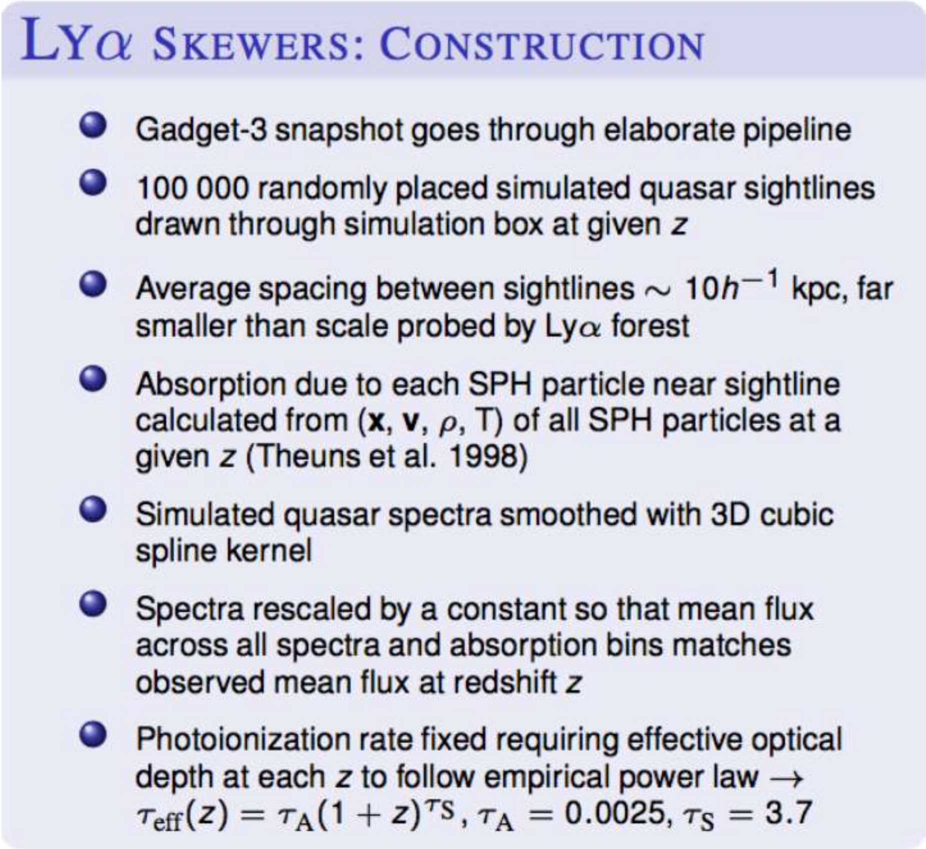


Constructing Lyα Skewers



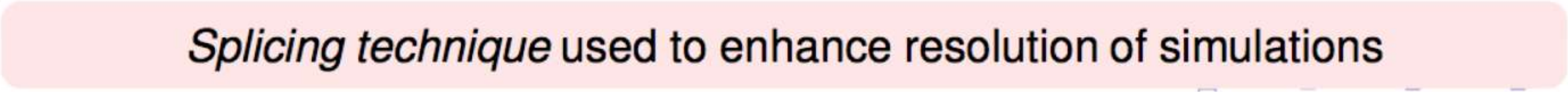
SIMS DETAILS

1. Gas in simulations photoionized and heated by spatially uniform ionizing background
2. Applied in the optically thin limit and switched on at $z = 8.8$.
3. Thermal history in simulations consistent with recent IGM temperature measurements assuming a slope for the temperature-density relation of $\gamma = 1.3$
4. Feedback options disabled
5. Galactic winds neglected
6. Two normalization conventions
7. Gas assumed of primordial composition with Helium mass fraction $Y = 0.24$ and no metals
8. Simple star formation criterion
9. Inclusion of most relevant effects of baryonic physics that impact the IGM



LYα SKEWERS: CONSTRUCTION

- Gadget-3 snapshot goes through elaborate pipeline
- 100 000 randomly placed simulated quasar sightlines drawn through simulation box at given z
- Average spacing between sightlines $\sim 10h^{-1}$ kpc, far smaller than scale probed by Lyα forest
- Absorption due to each SPH particle near sightline calculated from ($\mathbf{x}$, $\mathbf{v}$, ρ, T) of all SPH particles at a given z (Theuns et al. 1998)
- Simulated quasar spectra smoothed with 3D cubic spline kernel
- Spectra rescaled by a constant so that mean flux across all spectra and absorption bins matches observed mean flux at redshift z
- Photoionization rate fixed requiring effective optical depth at each z to follow empirical power law → $\tau_{\rm eff}(z) = \tau_{\rm A}(1+z)^{\tau_{\rm S}}$, $\tau_{\rm A} = 0.0025$, $\tau_{\rm S} = 3.7$



Splicing technique used to enhance resolution of simulations

NEUTRINOS, HIGH-z WEB, Lyα Forest

Linear Evolution (1)

COSMOLOGICAL EFFECTS

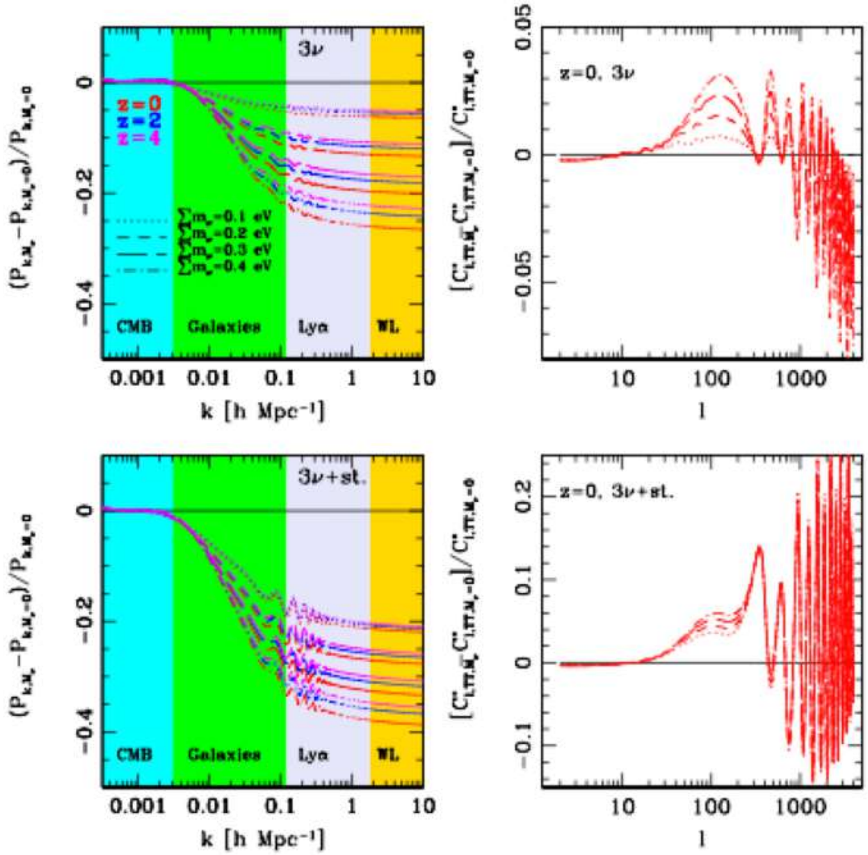
- Fix expansion rate at BBN
- Change background evolution → PS effects
- Slow down growth of structures

NEUTRINO FREE-STREAMING

- After thermal decoupling → ν collisionless fluid
- Minimum free-steaming wavenumber $k_{\rm nr}$

OBSERVABLES AND TECHNIQUES

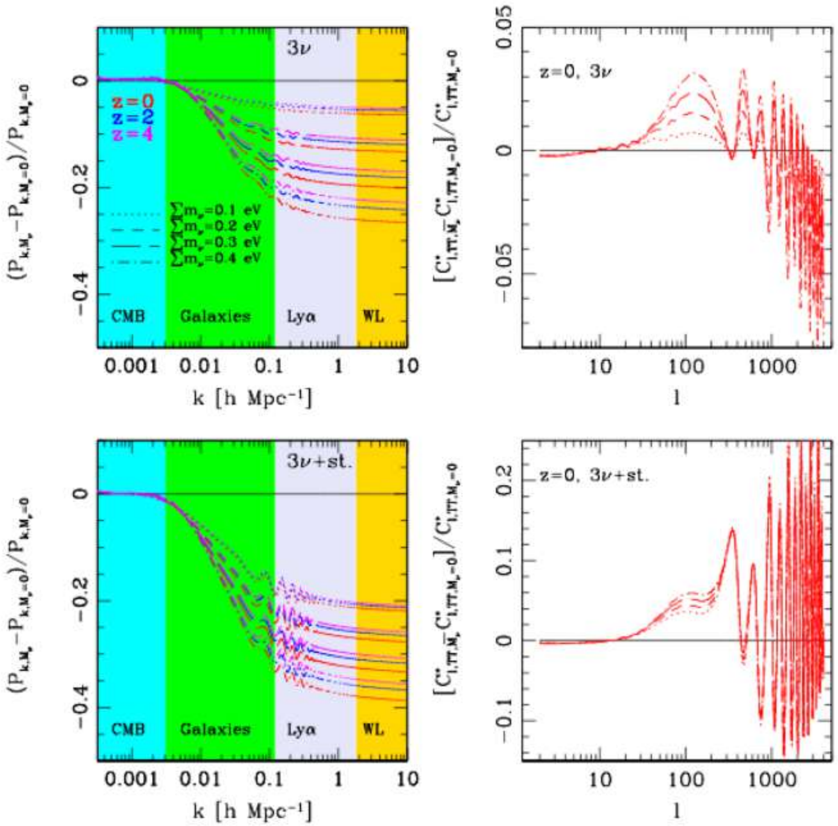
- CMB anisotropies → PS, lensing
- LSS probes
  - Galaxy PS
  - Cluster mass function
  - Galaxy weak lensing
  - **Ly-α forest**
  - 21-cm surveys



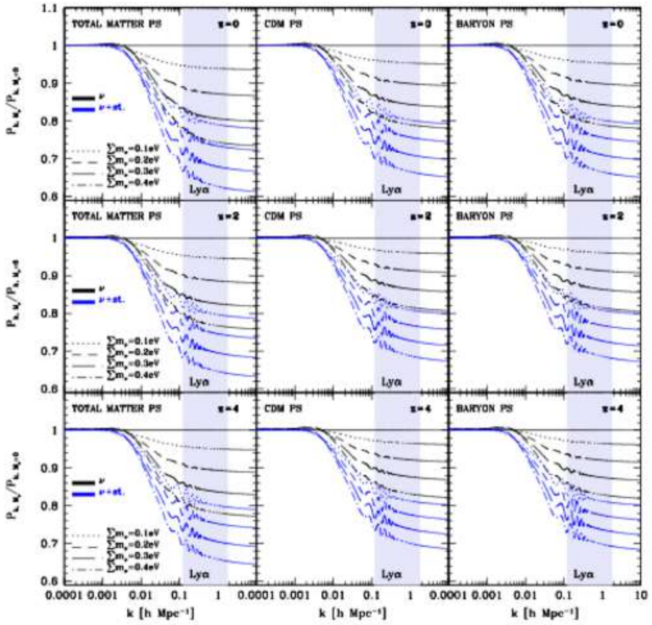
G. Rossi (2017)

Linear Evolution (2)

- 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



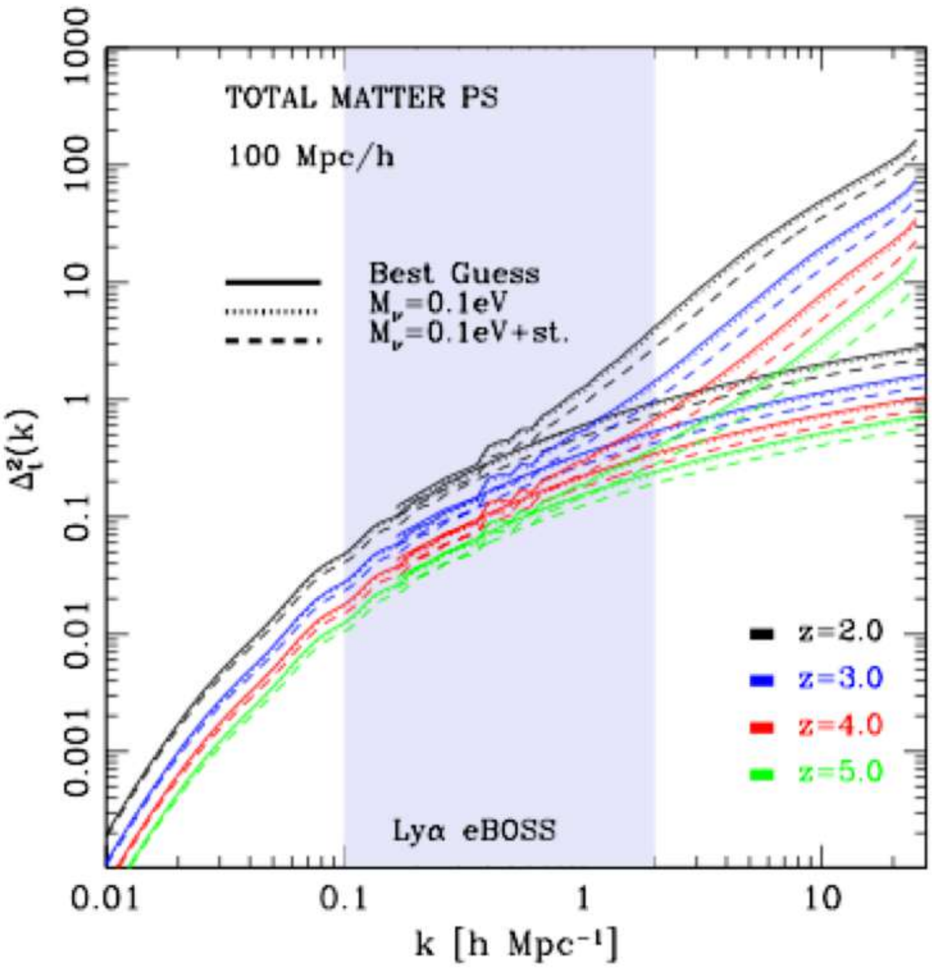
G. Rossi (2017)



Linear evolution per component

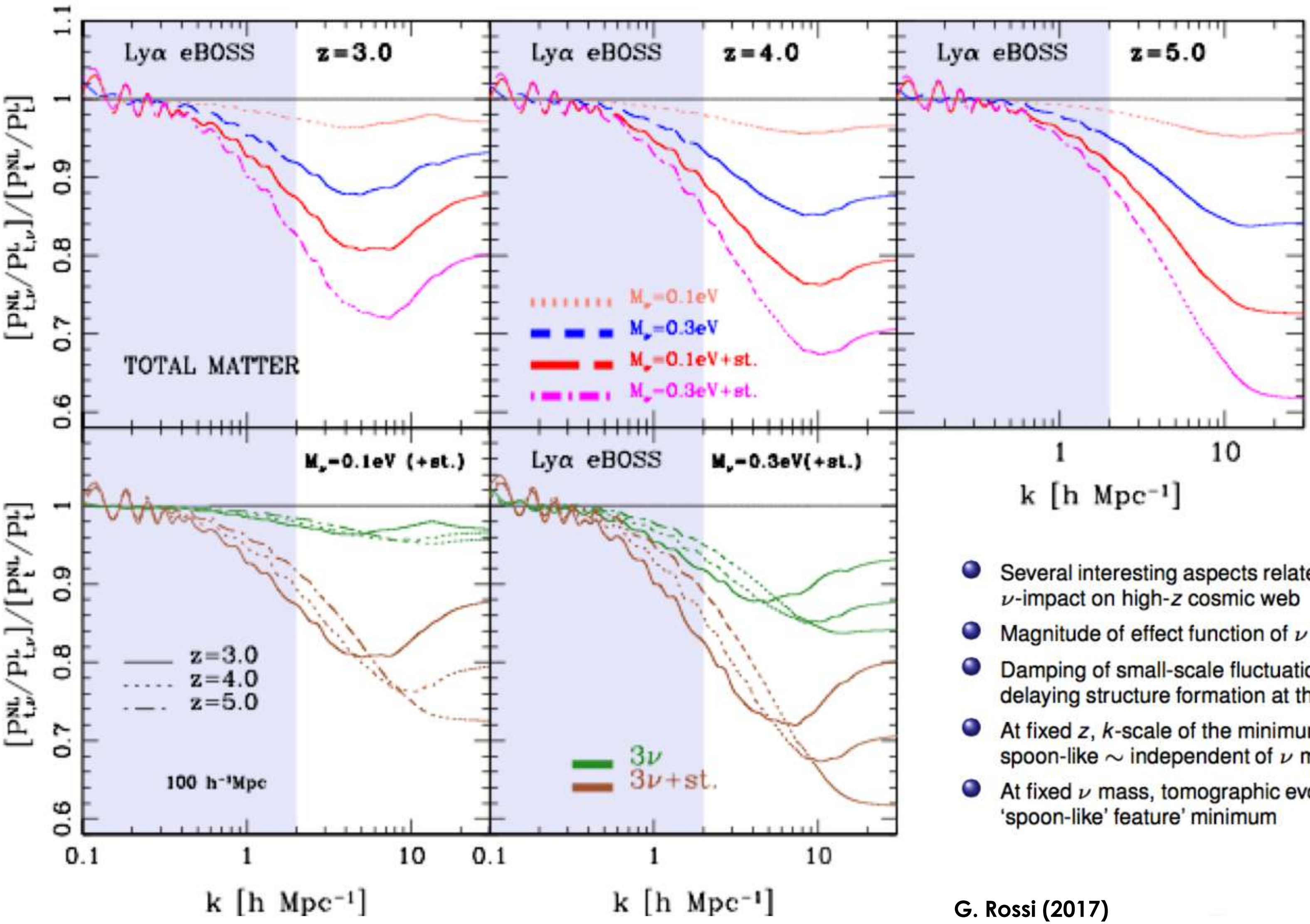
Neutrinos & NL 3D Total Matter PS

G. Rossi (2017)



- 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

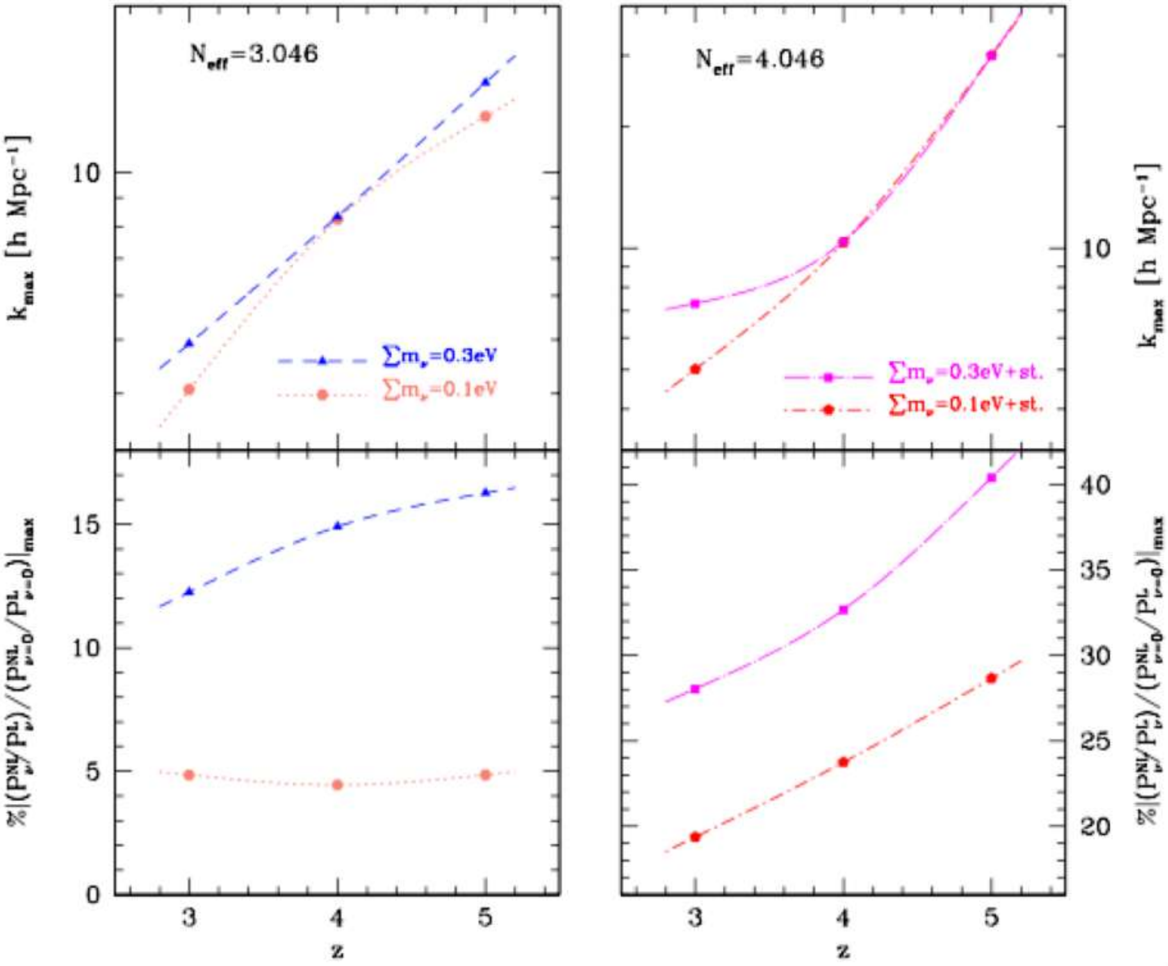
Spoon-Like Effect on NL 3D Matter PS



- 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 ~ independent of ν mass
- At fixed ν mass, tomographic evolution of 'spoon-like' feature' minimum

G. Rossi (2017)

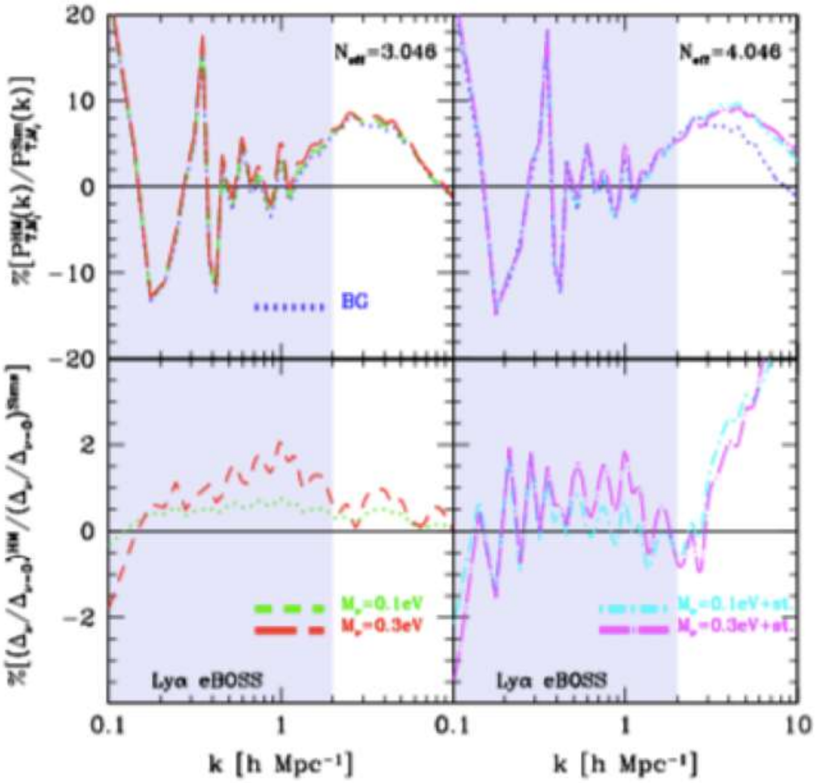
Massive Neutrinos: Relevant NL Scales



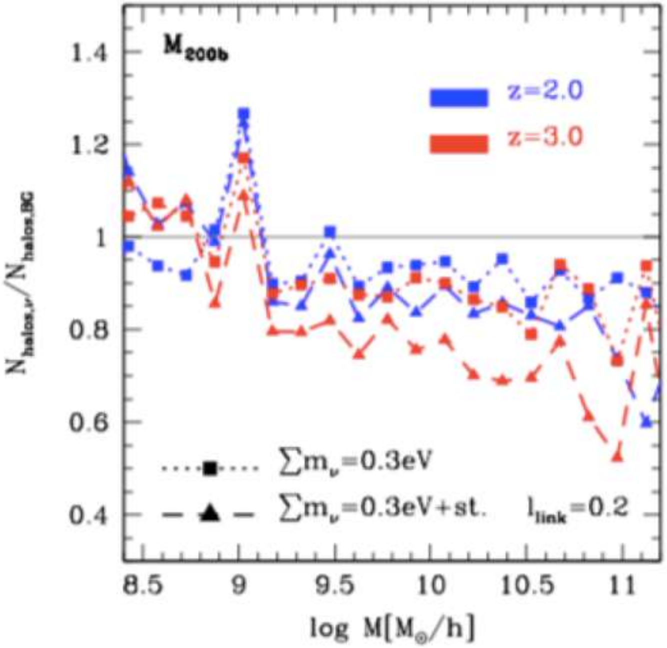
G. Rossi (2017)

- 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

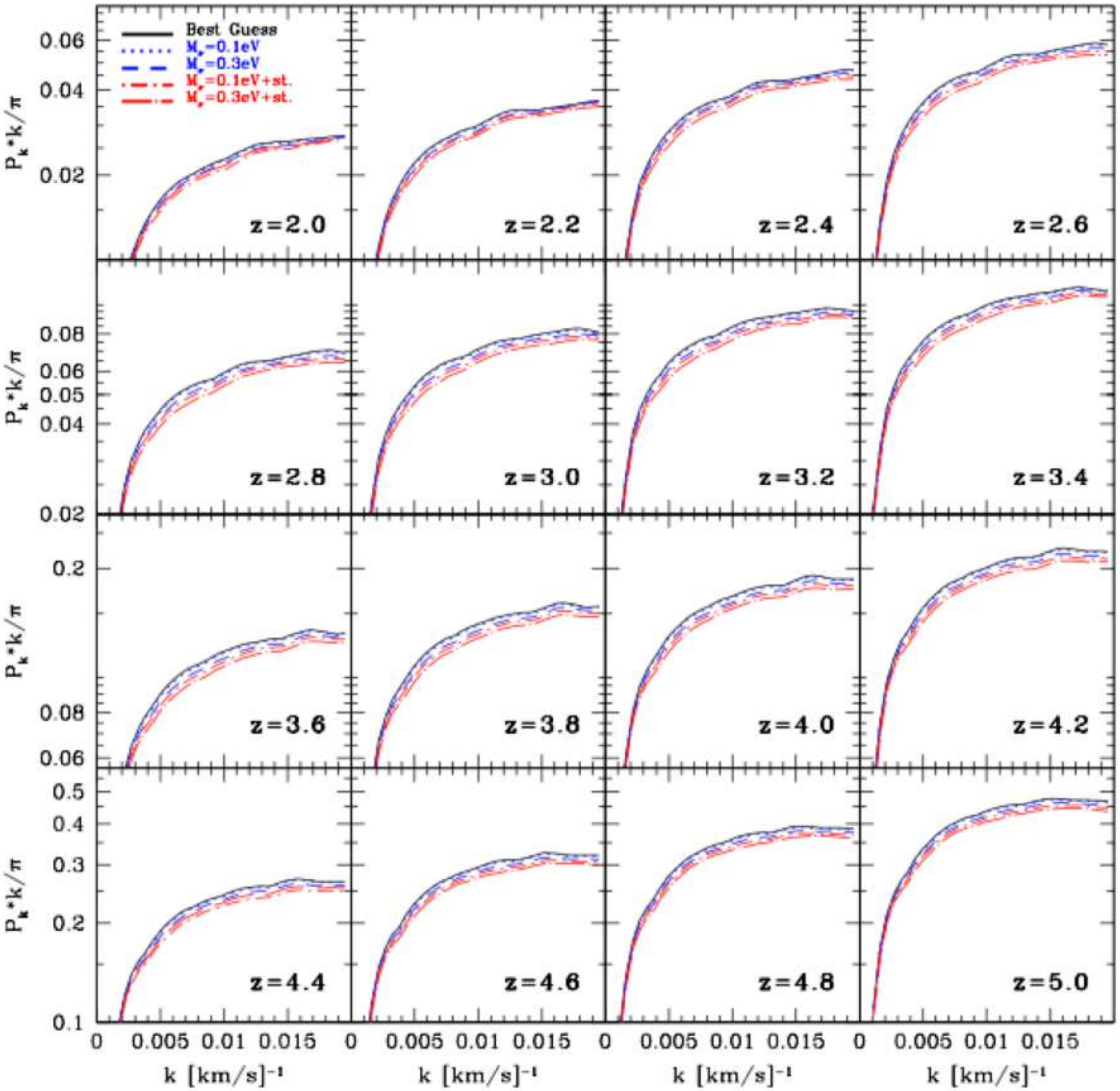


G. Rossi (2017)



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

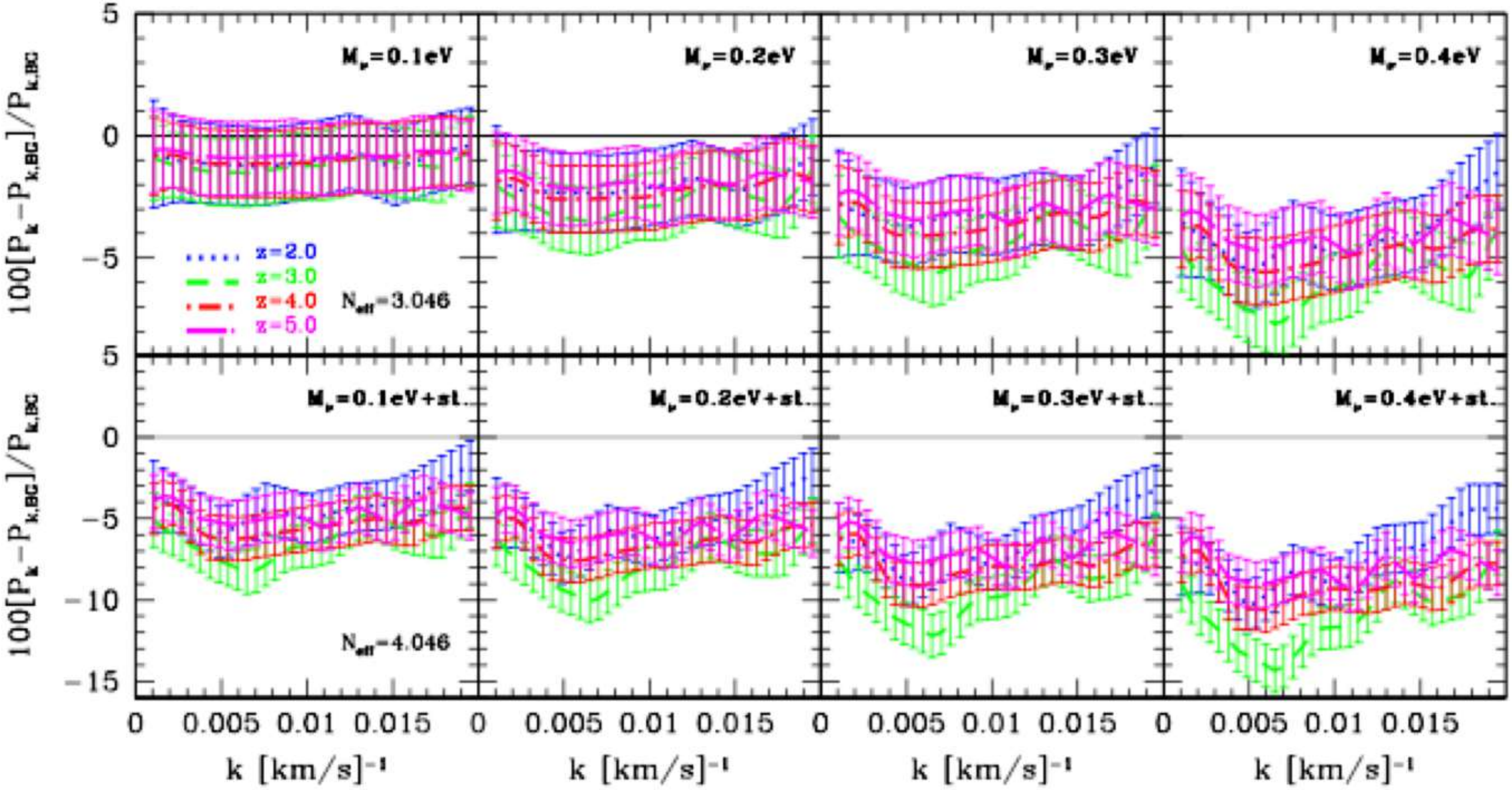
Flux Statistics (1)



G. Rossi (2017)

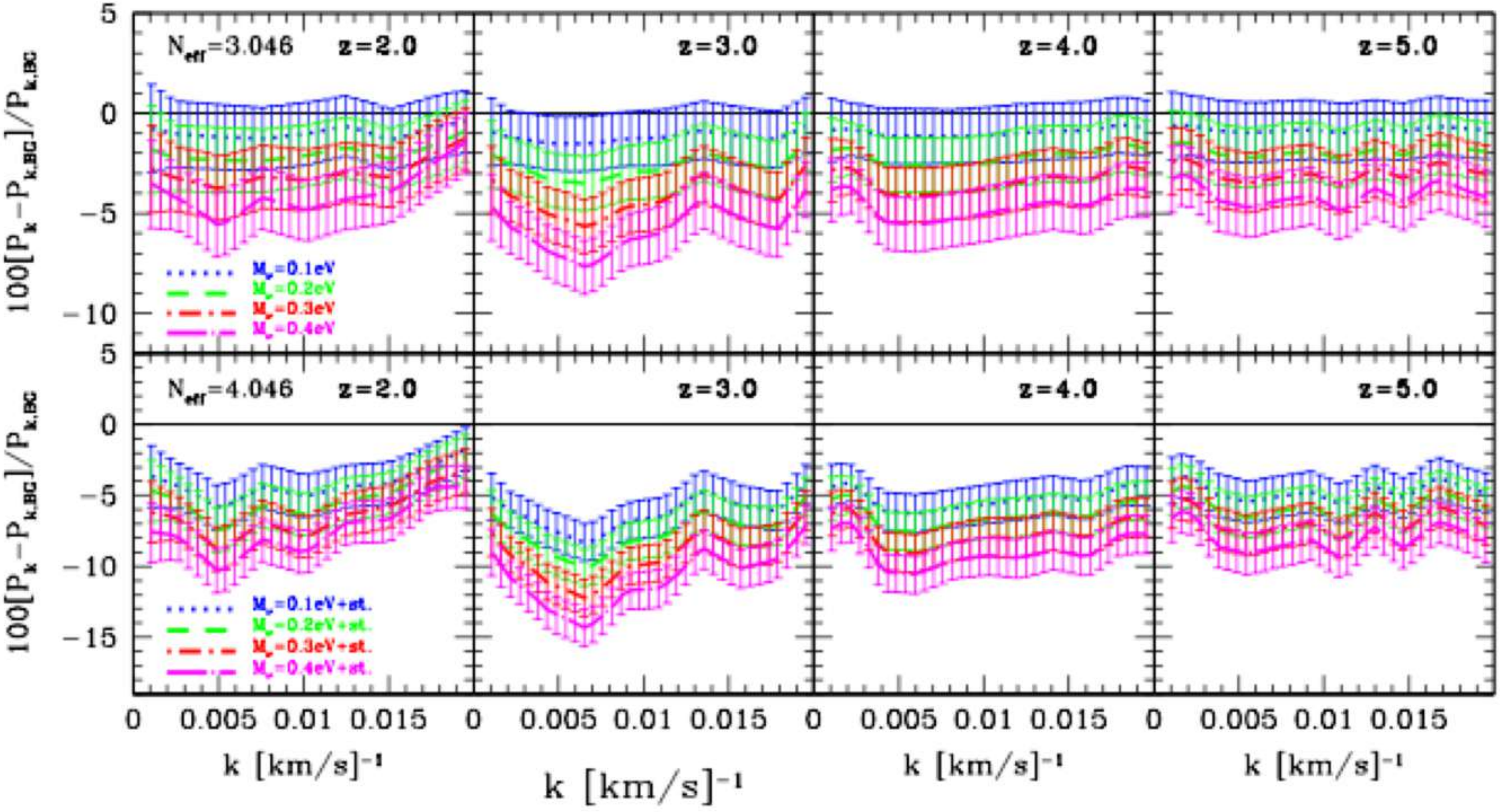
- Tomographic evolution of 1D PS shape & amplitude
- $z = 2.0 - 5.0$, $\Delta z = 0.2$
- Averaged over 10,000 mock absorption spectra per z-interval
- Propagation of 'spoon-like' feature to flux PS

Flux Statistics (2)



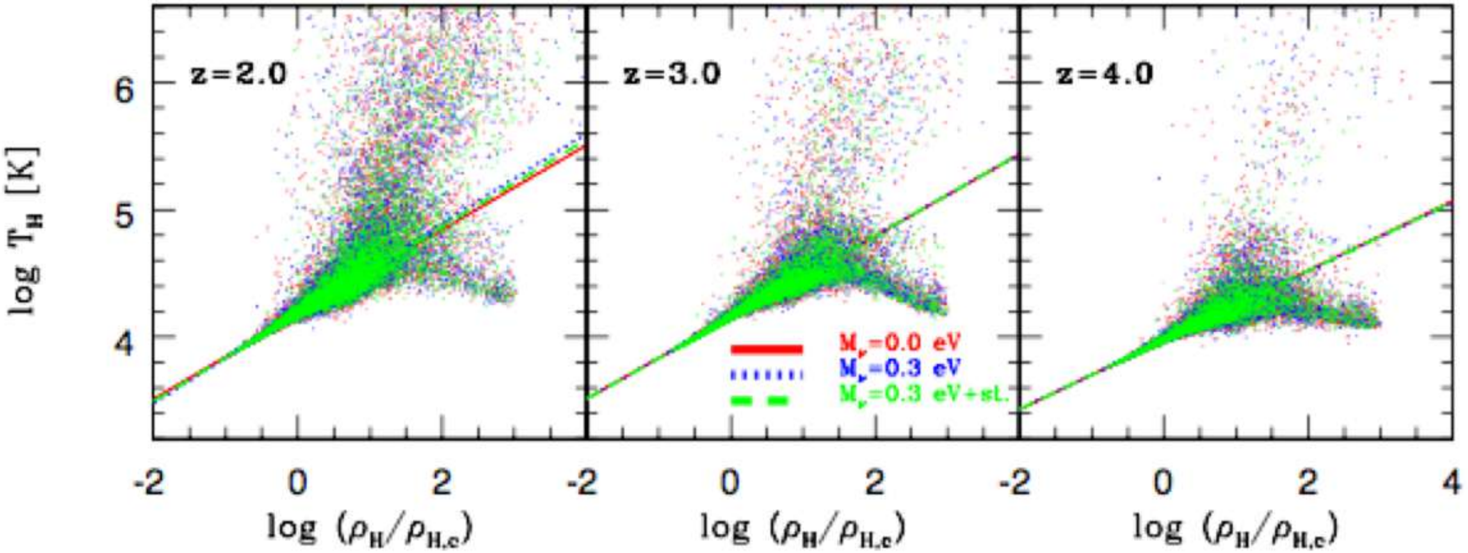
G. Rossi (2017)

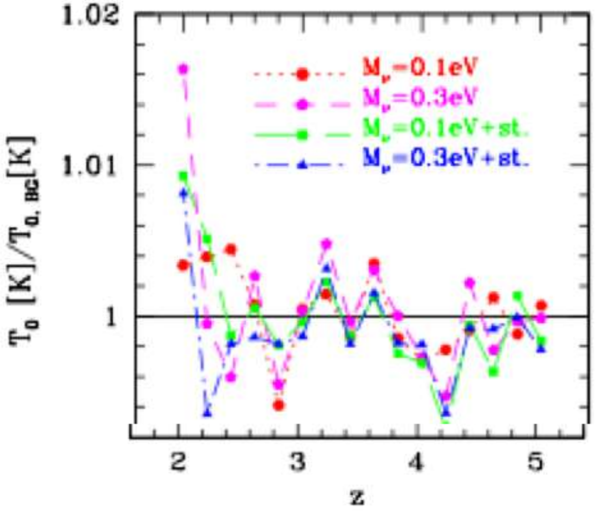
Flux Statistics (3)

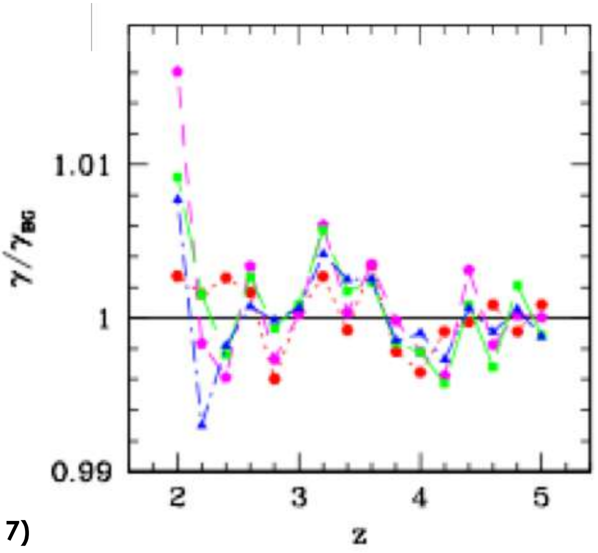


G. Rossi (2017)

IGM Physics: Impact



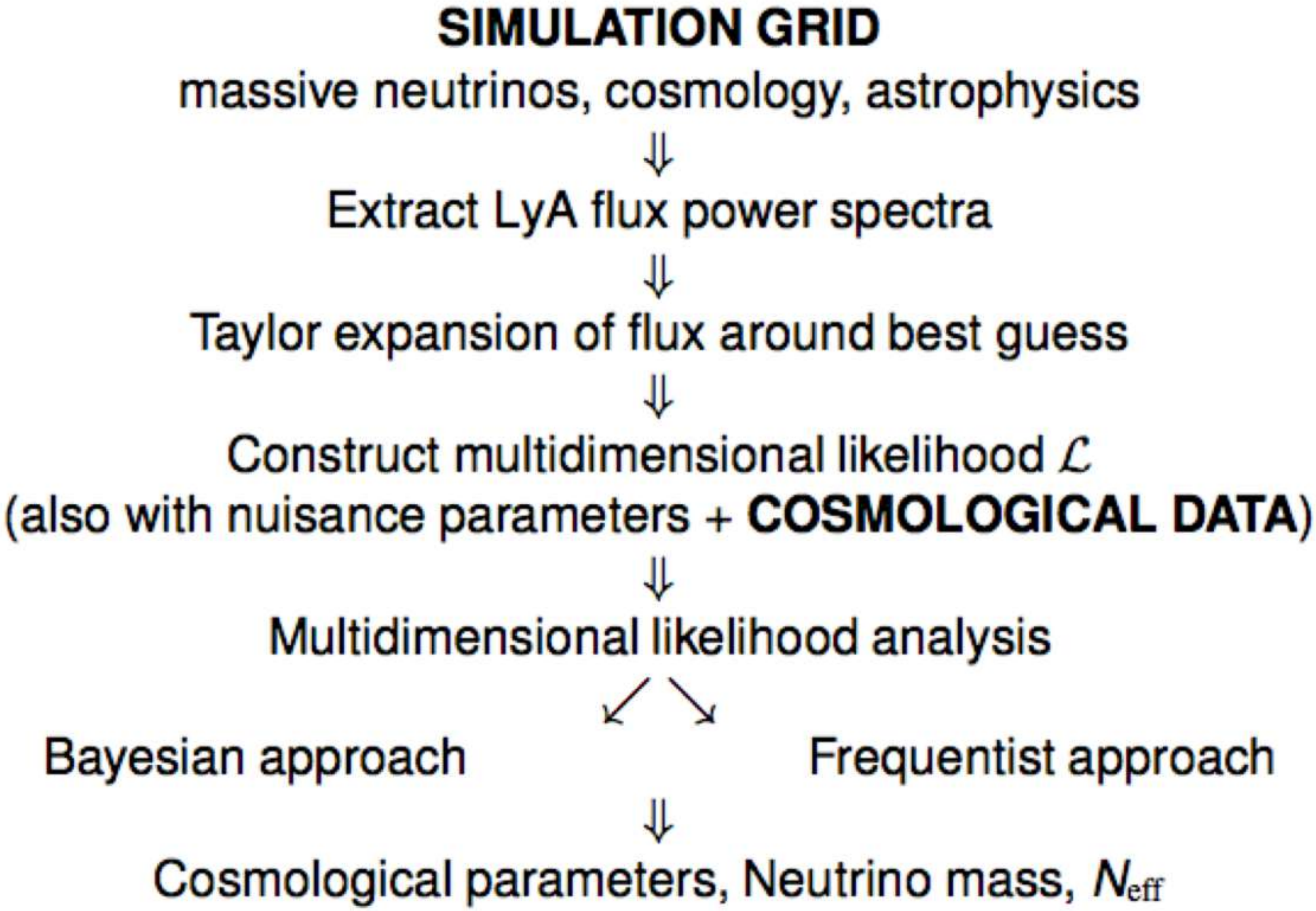




G. Rossi (2017)

TECHNIQUES FOR NEUTRINO CONSTRAINTS

Constraints: General Strategy



SIMULATION GRID

massive neutrinos, cosmology, astrophysics

$\Downarrow$

Extract LyA flux power spectra

$\Downarrow$

Taylor expansion of flux around best guess

$\Downarrow$

Construct multidimensional likelihood $\mathcal{L}$

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

$\Downarrow$

Multidimensional likelihood analysis

$\swarrow \quad \searrow$

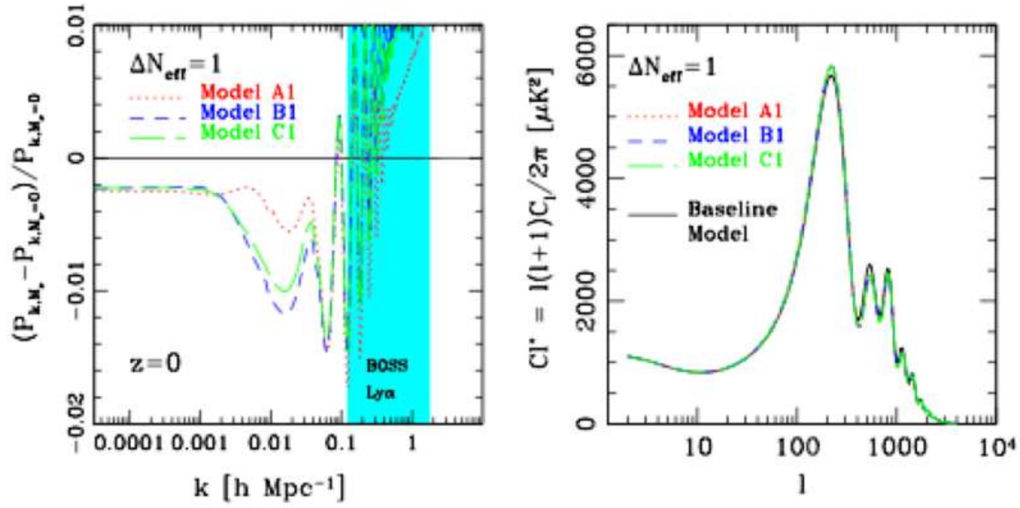
Bayesian approach — Frequentist approach

$\Downarrow$

Cosmological parameters, Neutrino mass, N_{eff}

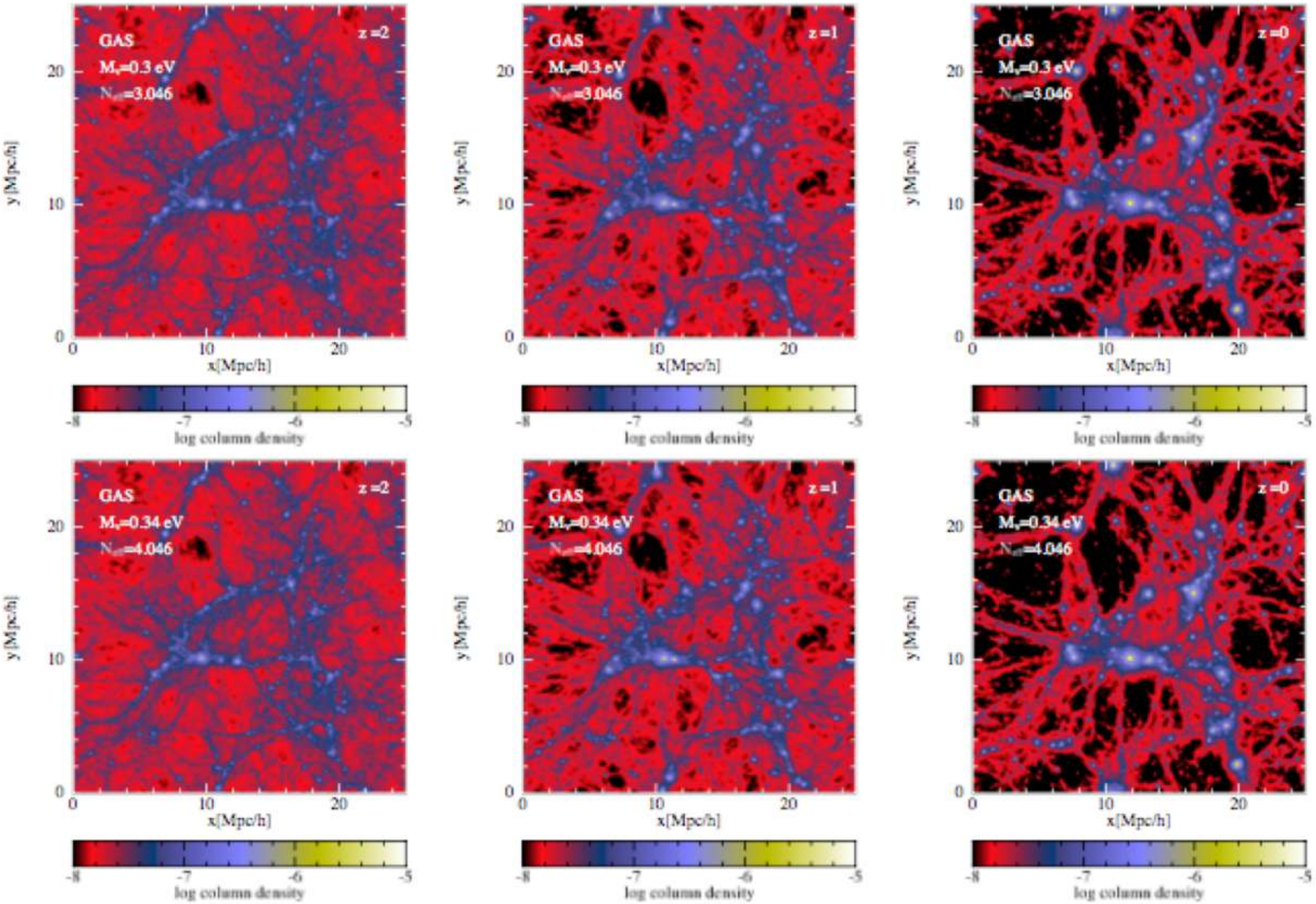
DR: Proxy for Lyα Forest

- Technique of Palanque-Delabrouille et al. (2015) extended with analytic proxy for dark radiation models in Lyα likelihood
- **Trick** → *If two models have same linear matter PS → nearly identical NL matter and flux PS*
- Simulations with non-standard $N_{\rm eff}$ to confirm analytic proxy



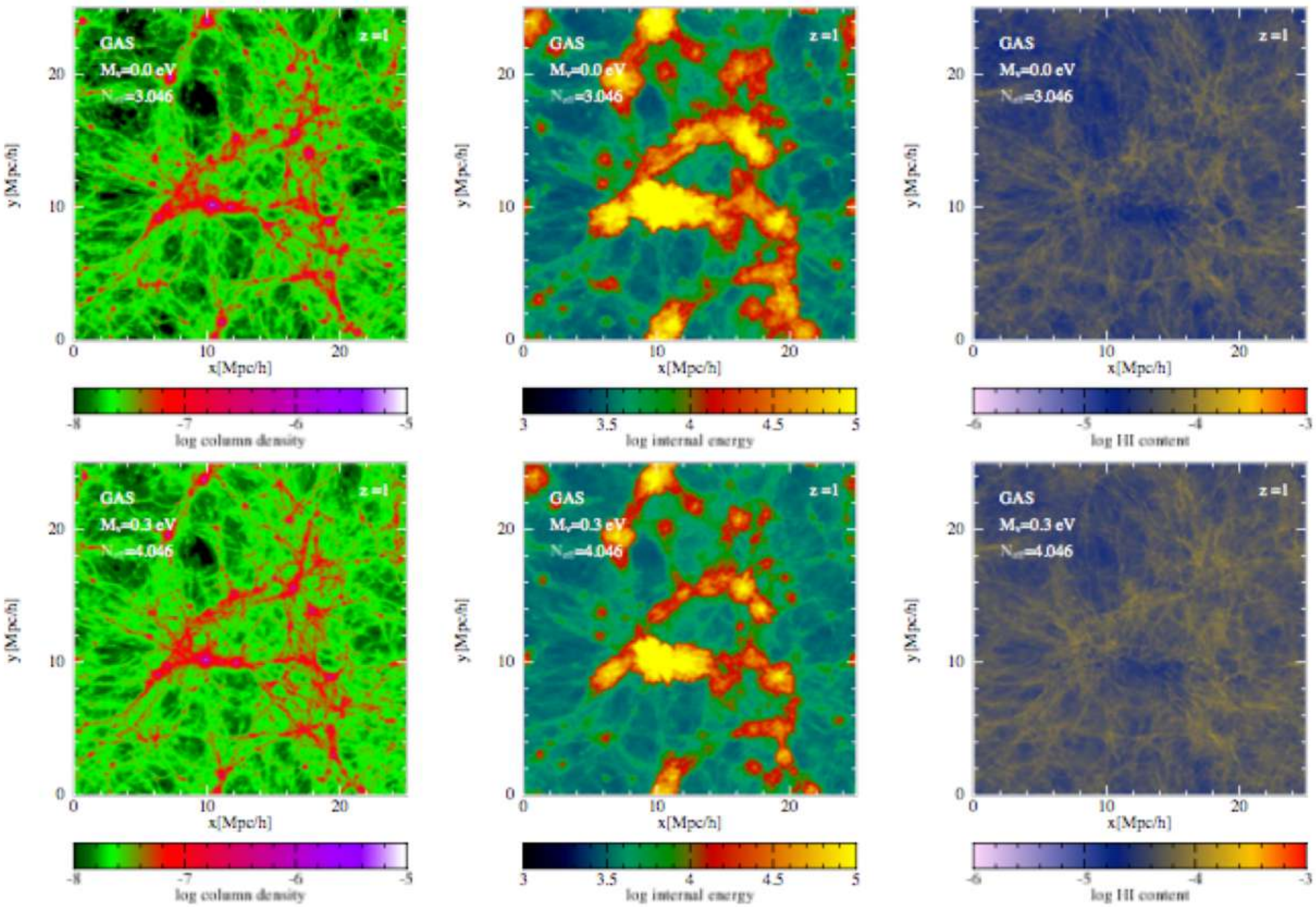
Rossi et al. (2015)

Simulations with Dark Radiation (1)



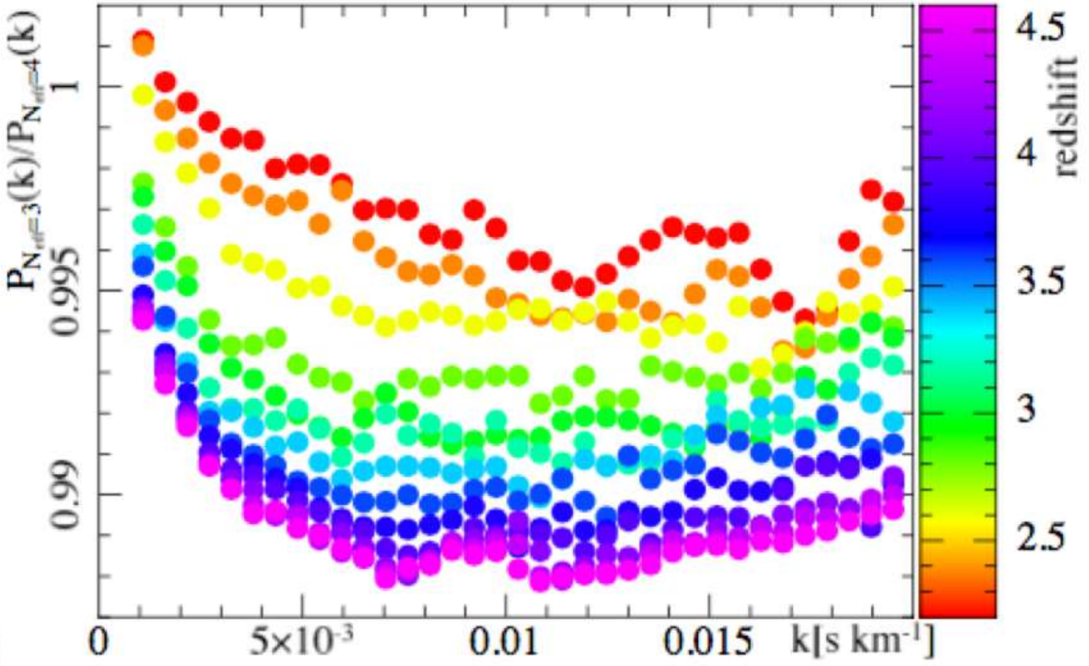
Rossi et al. (2015)

Simulations with Dark Radiation (2)



Rossi (2018)

Sensitivity to N_{eff}



Rossi et al. (2015)

- Deviations in flux PS all within 1% of baseline model
- Analytic proxy for LyA likelihood fully validated in NL regime

Analysis Techniques

ANALYSIS STRATEGIES

- Bayesian Approach
- Frequentist Approach

FREQUENTIST APPROACH: INSIGHTS

- Minimize $\chi^2(\boldsymbol{X}, \boldsymbol{\sigma}|\Theta) = -2\ln[\mathcal{L}(\boldsymbol{X}, \boldsymbol{\sigma}|\Theta)]$
- Compute the global minimum χ^2_0, leaving all the *N* cosmological parameters free
- Set confidence levels (CL) on a chosen parameter $\alpha_{\rm i}$ by performing the minimization for a series of fixed values of $\alpha_{\rm i}$ – thus with $N-1$ degrees of freedom
- Difference between χ^2_0 and the new minimum allows us to compute the CL on $\alpha_{\rm i}$

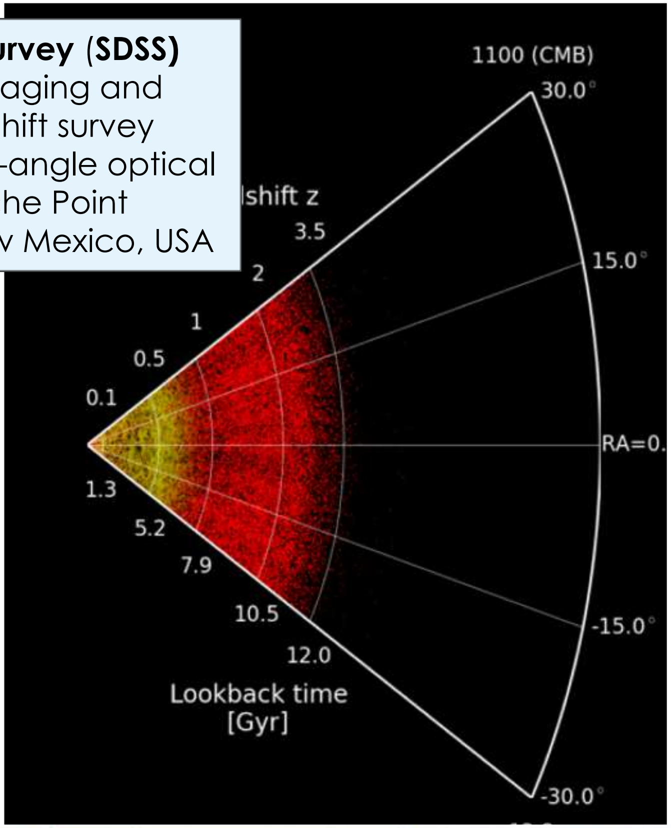
SDSS CONSTRAINTS & POTENTIAL

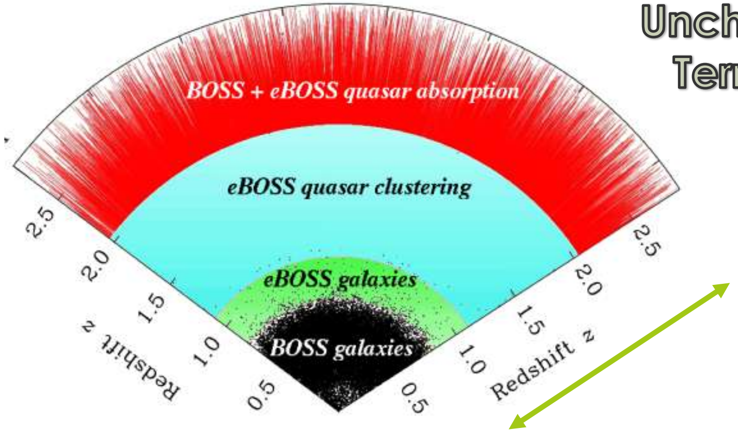
SDSS-IV: eBOSS DR14 QSOs

ASTRONOMERS MAKE THE LARGEST MAP OF THE UNIVERSE YET

Astronomers with the Sloan Digital Sky Survey (SDSS) have created the first map of the Universe based entirely on quasars, the incredibly bright and distant points of light powered by supermassive black holes.

Sloan Digital Sky Survey (SDSS) major multi-filter imaging and spectroscopic redshift survey using a 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, USA





Uncharted Territory

DR14 QSOs Results

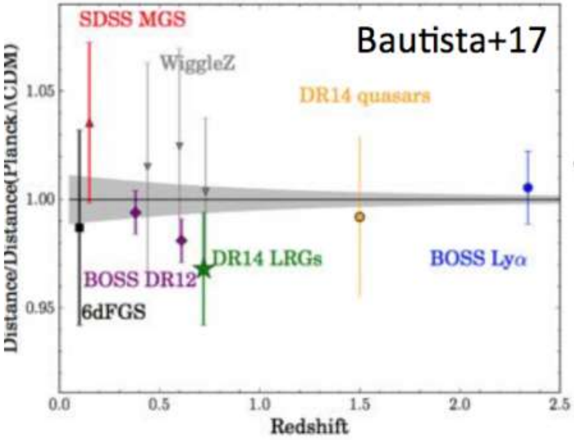
eBOSS BAO from DR14

Next Nov: final results

Laurent et al. (2018)
Rodriguez-Torres et al. (2018)
Ata et al. (2018)
Gil-Marin et al. (2018)
Zarrouk et al. (2018)

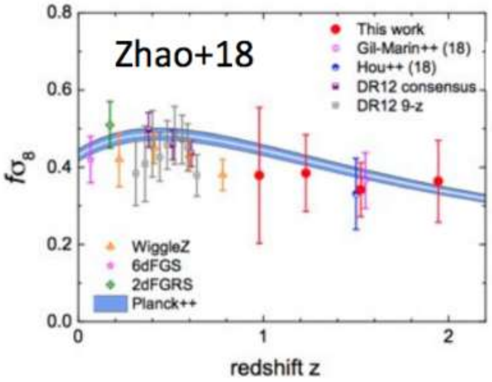
Zhao et al. (2018)
Wang et al. (2018)
Ruggeri et al. (2018)
Hou et al. (2018)
Zhu et al. (2018)

Distances: 80k LRGs, 2.6% distance
147k QSOs, 4.4% distance



Quasars: Ata+17, Zhu+18, Wang+18
LRGs: Bautista+17

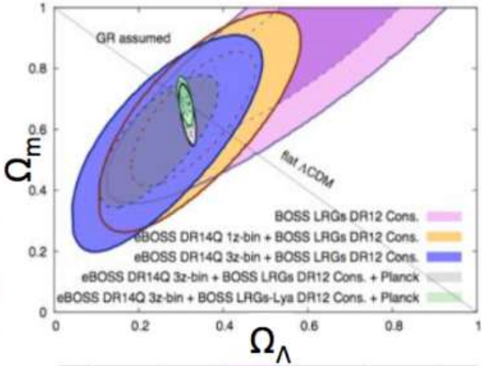
Structure growth from quasars:

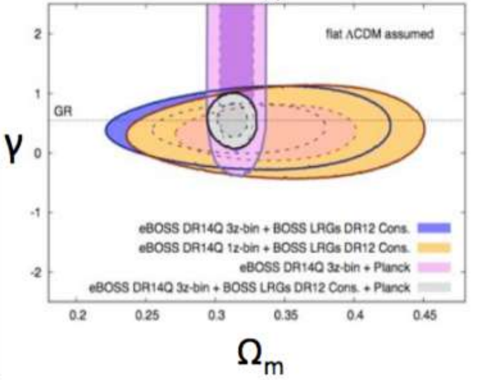


$$f(z) \equiv \frac{\mathrm{dlog}\delta}{\mathrm{dlog}a} = [\Omega_M(z)]^{\gamma}$$

δ is over-density
σ_8 goes as D(z)

Gil-Marín+18



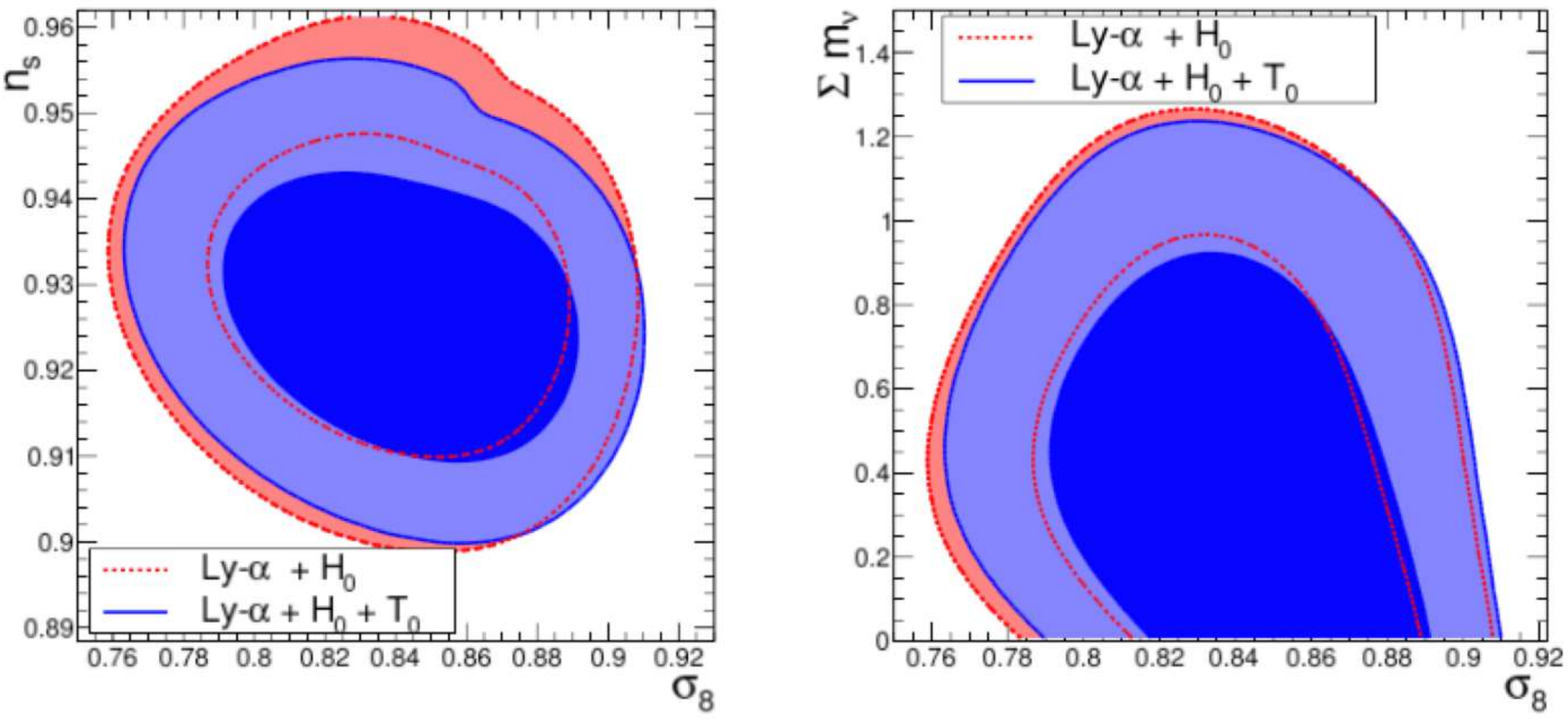


Zarrouck+18
Hou+18

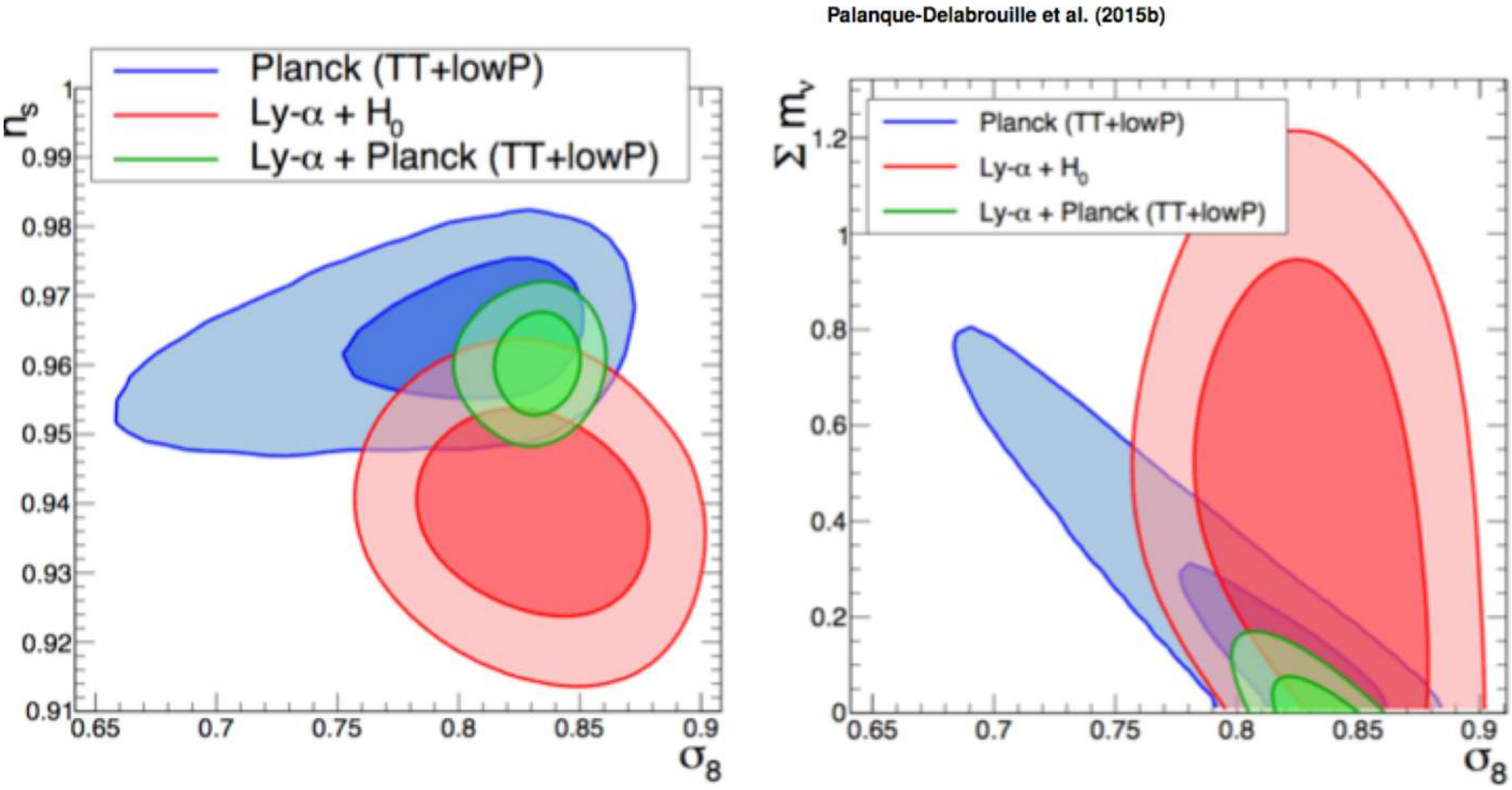
SDSS

Lyα Alone

Palanque-Delabrouille et al. (2015a)

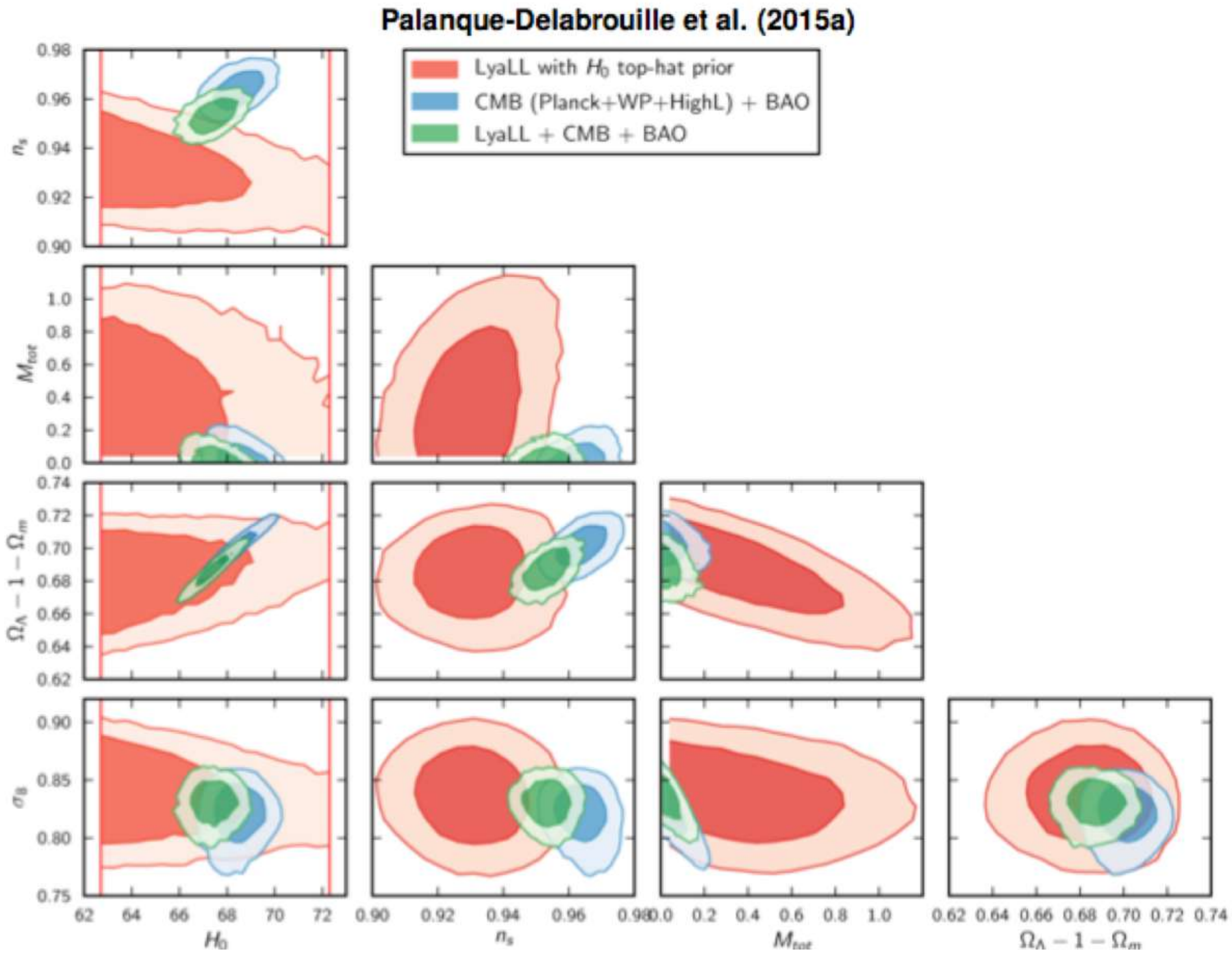


Combinations (Frequentist)

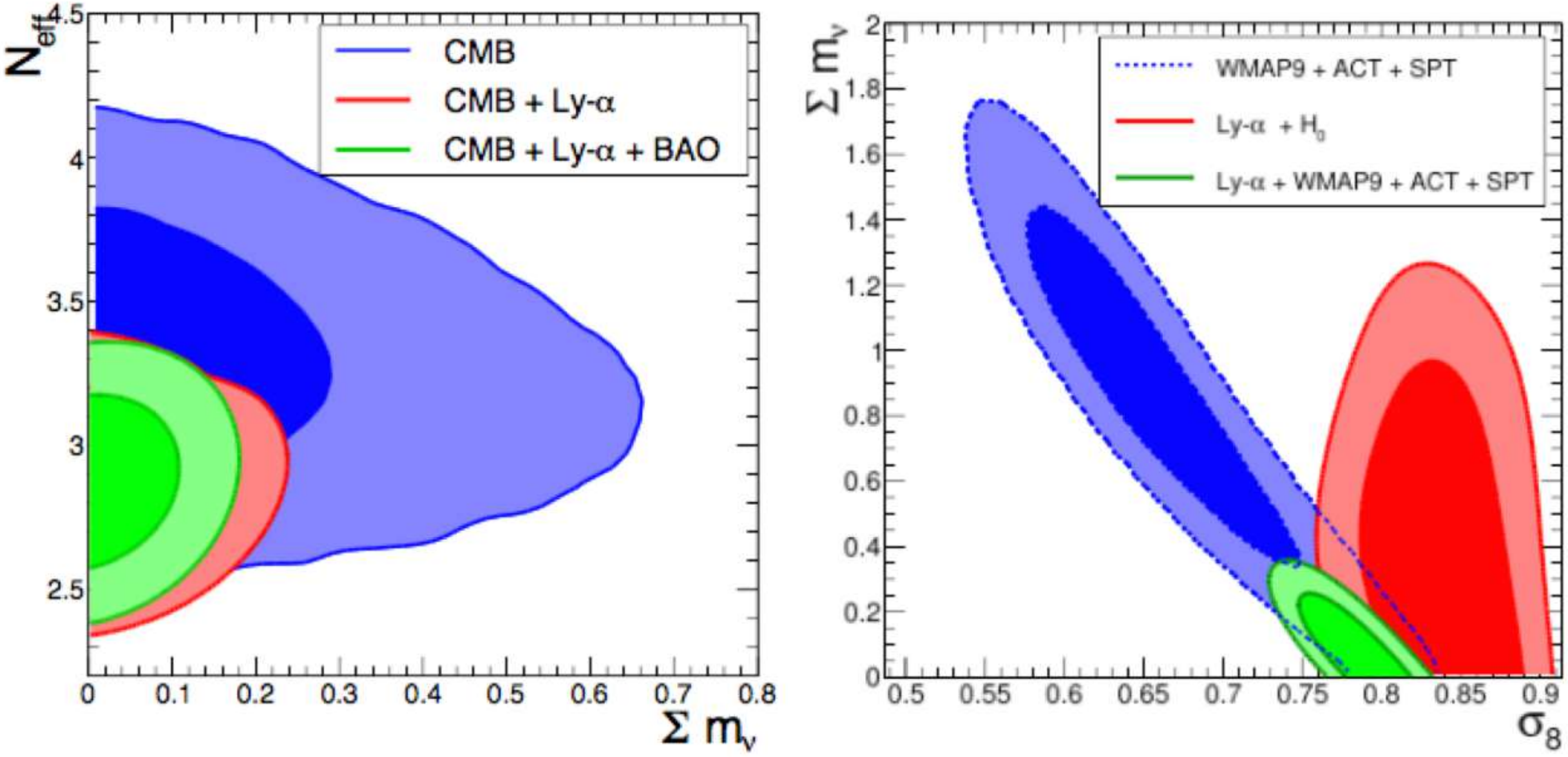


$$\sum m_\nu < 0.12 \text{ eV} \rightarrow \text{CMB + Lyman-}\alpha\text{ + BAO}$$

Combinations (Bayesian)



Final Joint Constraints



Rossi et al. (2015)

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

eBOSS Forecasts: Examples

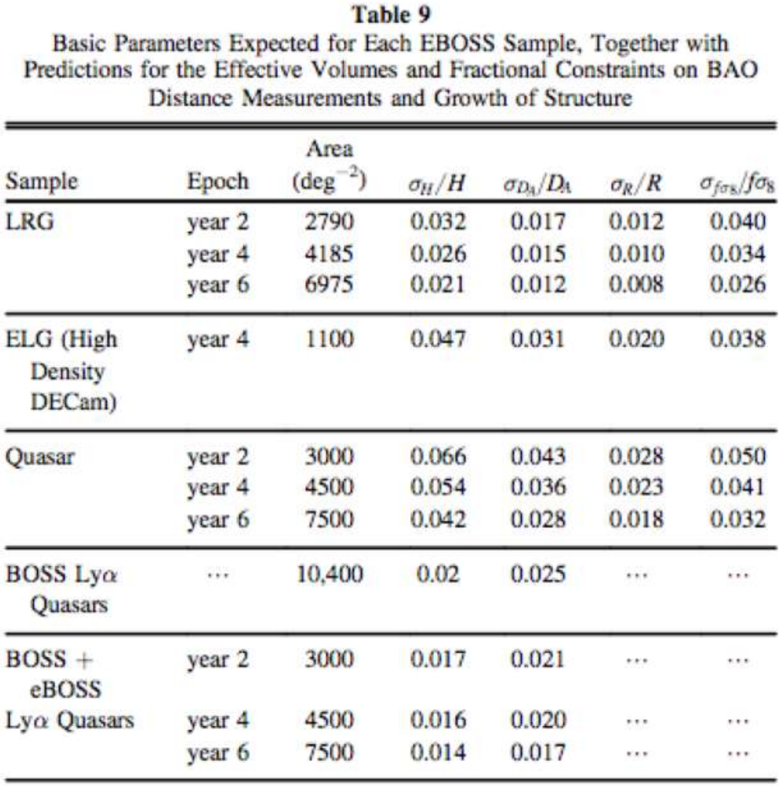


Table 9

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	⋯	⋯

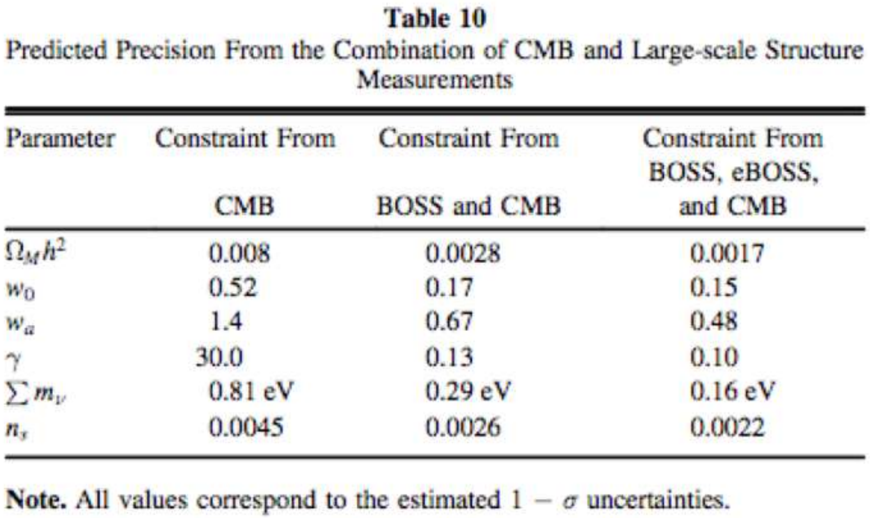
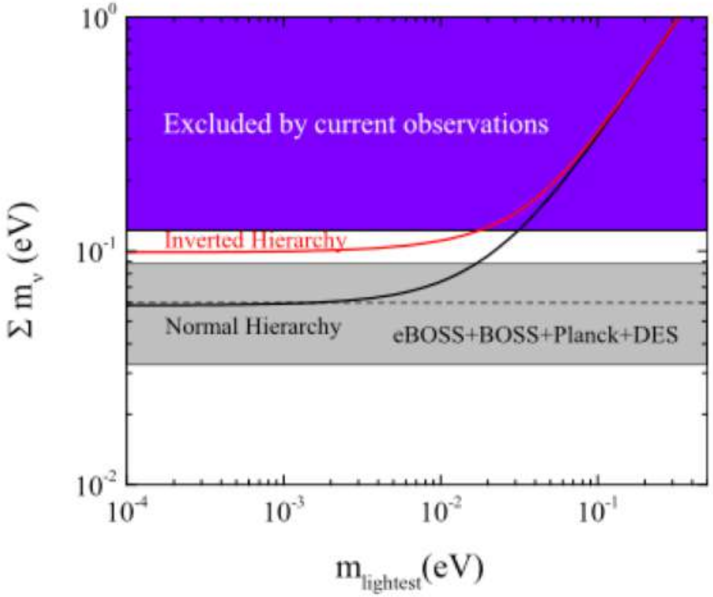


Table 10

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)

Lyα Forest Cosmology @ Sejong

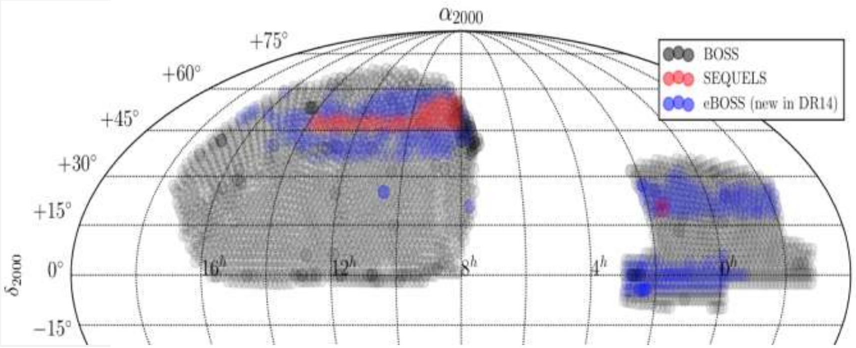
Main Goals

- Measure 1D PS from latest SDSS data

Young Bae Lee – Master Thesis

DR14 & DR14 QSO CATALOG

- Cumulative and re-release of all previous data
- First data release from eBOSS
- 500 eBOSS new plates cover $\sim 2480\,\mathrm{deg}^2$
- DR14 catalog contains 526,356 QSOs
- including 144,046 new discoveries
- Over 500,000 QSOs in the range 0.9 < z < 2.2
- Over 50,000 new Lyα forest QSOs at z > 2.1



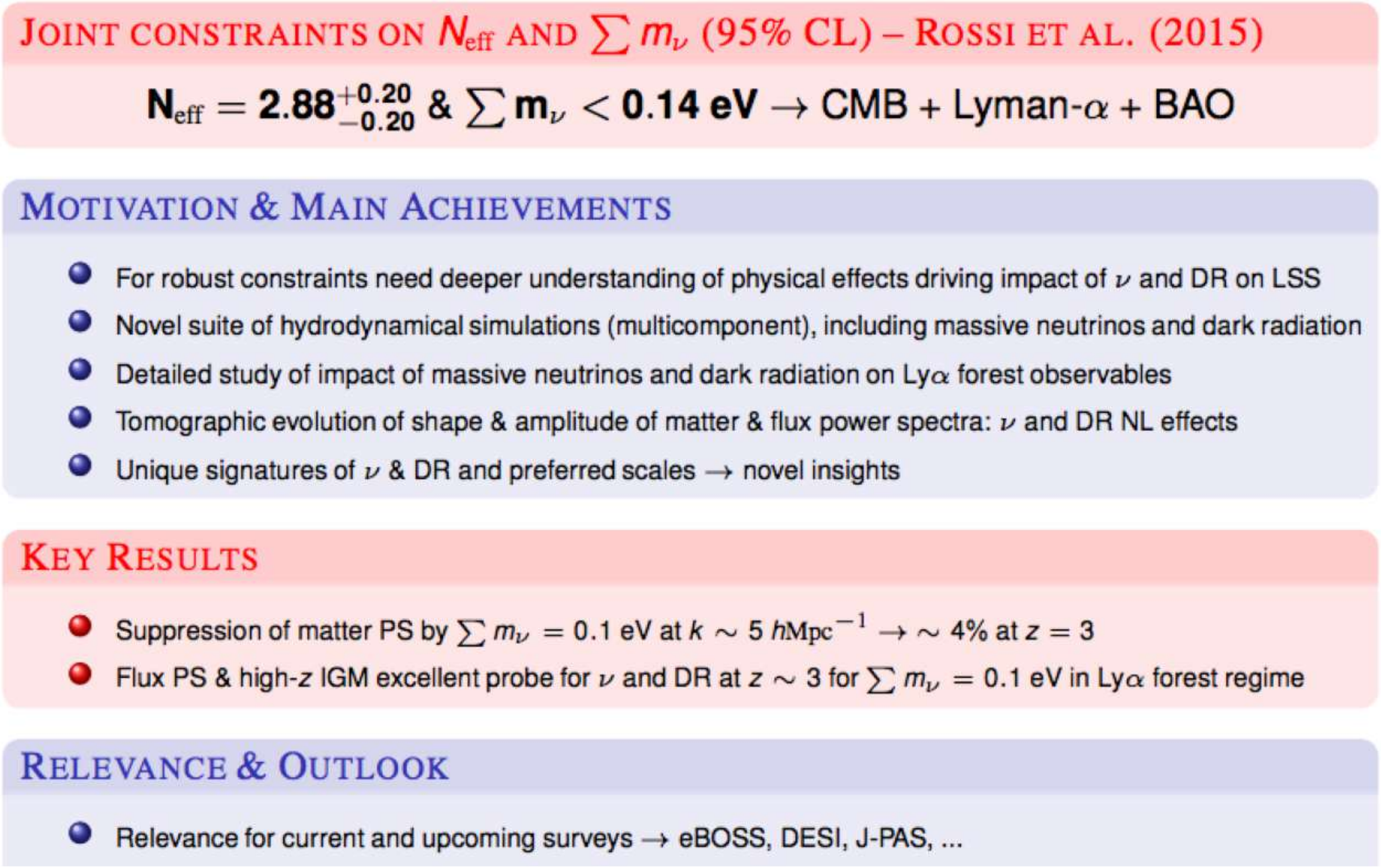
Abolfathi et al. 2018

DATA SELECTION

- From DR14Q, we select Lyα forest QSOs based on redshift & quality
- Apply quality cuts to the spectra $- \mathrm{R} < 85\ \mathrm{km/s}\ \ \&\ \ \mathrm{S/N} > 3, 4, 6, 8$
- Define Lyα forest range $1050 < \lambda_{RF} < 1180\text{Å}$
- Lyα forest spans a redshift range $\Delta \mathrm{z} \sim 0.4$ to 0.6
- Split forest into subregions to improve redshift resolution $\Delta \mathrm{z} < 0.2,\ \boldsymbol{'z\text{–}sectors'}$

Future & Outlook

Key Results & Outlook



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

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

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 → novel insights

KEY RESULTS

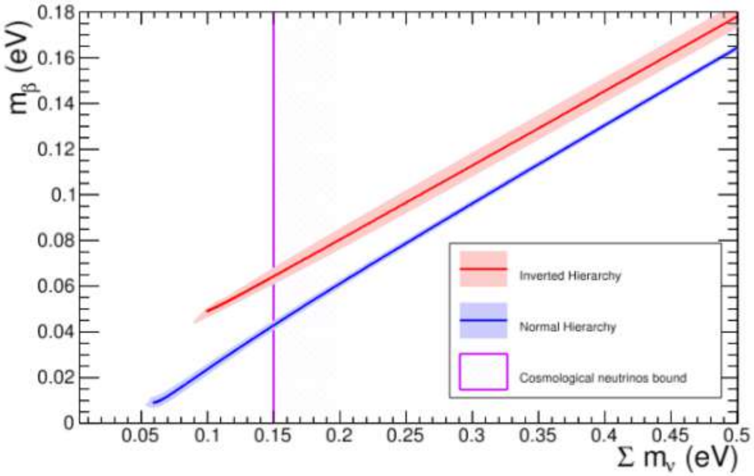
- Suppression of matter PS by $\sum m_\nu = 0.1$ eV at $k \sim 5\ h\text{Mpc}^{-1} \rightarrow \sim 4\%$ at $z = 3$
- Flux PS & high-z IGM excellent probe for ν and DR at $z \sim 3$ for $\sum m_\nu = 0.1$ eV in Lyα forest regime

RELEVANCE & OUTLOOK

- Relevance for current and upcoming surveys → eBOSS, DESI, J-PAS, ...

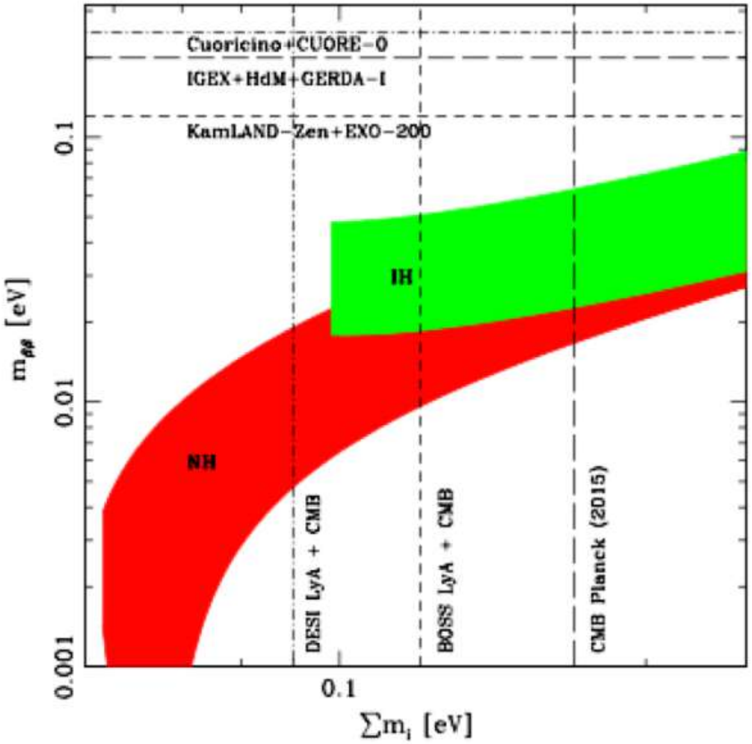
Particle Physics Implications

Palanque-Delabrouille et al. (2015a)



$\sum m_\nu < 0.15$ eV $\rightarrow m_\beta < 0.04$ eV $\rightarrow$ If KATRIN detects $m_\beta > 0.2$ eV the 3-neutrino model is in trouble!

Signal out of reach for next generation experiments?



G. Rossi (2018)

CAUTIONARY WARNINGS

Lyα forest alone very weak, combination with CMB nontrivial (i.e., $A_{\rm lens} = 1$?), lower n_s, running of spectral index + much more to be understood ...