CONSTRAINING THE MASS OF COSMOLOGICAL NEUTRINOS: TECHNIQUES FOR BOSS, eBOSS, AND DESI

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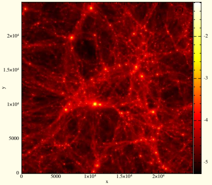
KEY POINTS

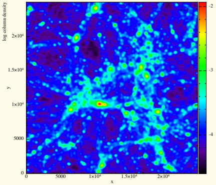
1. Peculiarity of the Lyman-α forest in constraining the mass of cosmological neutrinos

2. Novel suite of hydrodynamical simulations for the Lyman-α forest with massive neutrinos

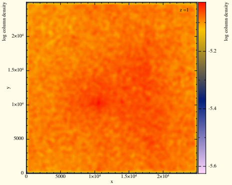
3. Competitive constraints on neutrino mass and cosmological parameters from current and future data (BOSS, eBOSS, DESI)



Gas



Dark Matter



Neutrinos

Outline

1. Neutrino science
   - Massive neutrinos in cosmology
   - Linear evolution
   - Power of Lyman-α forest
2. Neutrino simulations
   - General technique
   - Pipeline, post-processing, products
3. Results and prospects
   - Visualizations
   - Matter power spectra and flux statistics
   - Ongoing work with BOSS data
   - Prospects for eBOSS and DESI

MAIN REFERENCES

- **G. Rossi** et al. (2014), A&A, arXiv: 1401.6464
- Palanque-Delabrouille et al. (2013), A&A, 559, A85

Bounds on neutrino masses

Laboratory experiments

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

Cosmology: Now (examples, 95% CL)

- LyA $\to M_\nu < 0.9$ eV
- WMAP9 $\to M_\nu < 0.44$ eV
- WMAP7+LRG+H_0 $\to M_\nu < 0.44$ eV
- WMAP7+ACT+BAO+H_0 $\to M_\nu < 0.39$ eV
- WMAP7+WiggleZ+BAO+H_0 $\to M_\nu < 0.29$ eV
- WMAP7+MegaZ+BAO+SNIa+H_0 $\to M_\nu < 0.281$ eV
- Planck+WP+highL+BAO $\to M_\nu < 0.23$ eV
- WMAP3+SNe+GC+LyA $\to M_\nu < 0.17$ eV
- Planck+WiggleZ+BAO $\to M_\nu < 0.15 \to 0.18$ eV ?

Cosmology: Future

- BOSS LyA + other probes $\to$ $M_\nu \sim 0.1$ eV
- ACTPol + Planck $\to M_\nu \sim 0.07$ eV
- Planck + BOSS, LSST, DES $\to$ $M_\nu \sim 0.06$ eV
- Surveys in 2020 $\to M_\nu \sim 0.03$ eV

Warning

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

Effects of neutrino masses on cosmology

Cosmological effects

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

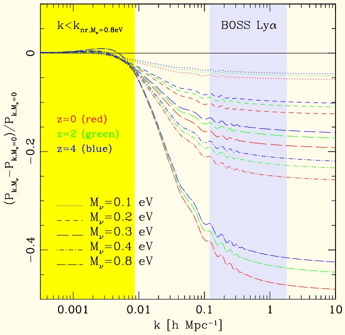
Neutrino free-streaming

- After thermal decoupling $\rightarrow$ ν as a collisionless fluid
- Minimum free-steaming wavenumber k_{nr}

Observables and techniques

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

Rossi et al. (2014)



Linear matter power spectra (ratios) with 3 degenerate species of massive neutrinos

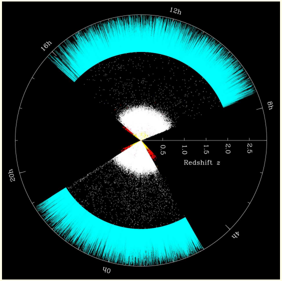
WHY THE LYA FOREST?

LYA: ADVANTAGES

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

LYA: DIFFICULTIES

- Need numerical simulations with full hydro
- Complicated thermodynamical evolution if IGM
- Star formation uncertain
- Non-trivial frequency dependence
- Systematics and other technical issues



LY-α: IMPORTANCE

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

NEUTRINO SCIENCE
NEUTRINO SIMULATIONS
RESULTS & PROSPECTS

METHODS, OBJECTIVES, IMPROVEMENTS

MAIN GOAL $\rightarrow$ IMPROVING ON VIEL ET AL. (2010)

"Reaching an accuracy below 1% level at scales relevant for the Lyα forest or weak lensing data will be challenging, but should be doable and will be an important step in turning the exciting prospect of an actual measurement of neutrino masses into reality"

SIMULATING MASSIVE NEUTRINOS

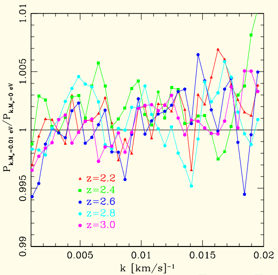
- Neutrinos included as a new type of particle
- Short-range gravitational tree force for neutrinos not computed

NOVEL FEATURES

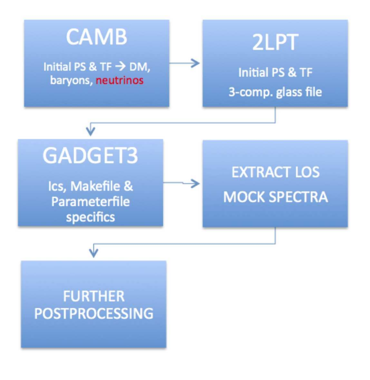
- 2LPT ICs + CAMB
- Planck cosmological parameters
- Splicing technique $\rightarrow$ higher resolution
- Updated prescriptions for radiative cooling and heating processes

SANITY CHECKS

- Convergence and resolution tests
- Best-guess vs. $M_\nu = 0.01$ eV



Pipeline and Post-processing



Technical Details

- Curie thin node architecture
- 5040 B510 bullx nodes
- For each node → 2 eight-core Intel processors Sandy Bridge EP (E5-2680) 2.7 GHz, 64 GB
- 10080 eight-core processors, Intel Xeon Next Generation, total of 80640 cores
- 768^3 particles, $25 - 100\ h^{-1}$Mpc, 80 khrs
- Extraction of 100,000 LOS/snapshot/sim.

Simulations shown here

- DM+GAS+NEUTRINOS
- 192^3 particles per type
- $25\ h^{-1}$Mpc, $M_\nu = 0.1, 0.4, 0.8$ eV
- ICs → 2LPT at $z = 30$

PRODUCTS

A suite of 48 hydrodynamical simulations with massive neutrinos

- Typical set (3 sims.) $\rightarrow$ (a) 100 h^{-1}Mpc$/768^3$, (b) 25 h^{-1}Mpc$/768^3$, (c) 25 h^{-1}Mpc$/192^3$
- With splicing technique $\rightarrow$ equivalent of 100 h^{-1}Mpc$/3072^3$
- Full snapshots at a given redshift ($z = 4.6 - 2.2$, $\Delta z = 0.2$)
- 100,000 quasar sightlines per redshift interval per simulation

Group I

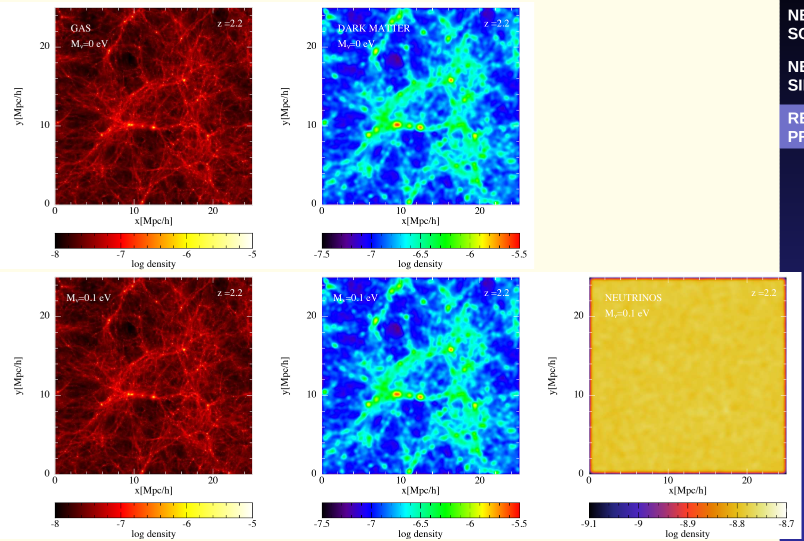
Simulation Set	M_ν [eV]
BG a/b/c	0
NUBG a/b/c	0.01
NU01 a/b/c	0.1
NU01-norm a/b/c	0.1
NU02 a/b/c	0.2
NU03 a/b/c	0.3
NU04 a/b/c	0.4
NU04-norm a/b/c	0.4
NU08 a/b/c	0.8
NU08-norm a/b/c	0.8

Group II

Simulation Set	M_ν [eV]
γ+NU08 a/b/c	0.8
H_0+NU08 a/b/c	0.8
n_s+NU08 a/b/c	0.8
Ω_m+NU08 a/b/c	0.8
σ_8+NU08 a/b/c	0.8
T_0+NU08 a/b/c	0.8

- **Group I** $\rightarrow$ Best-guess and neutrino runs
- **Group II** $\rightarrow$ Cross-terms

VISUALIZATIONS: GAS, DM, NEUTRINOS



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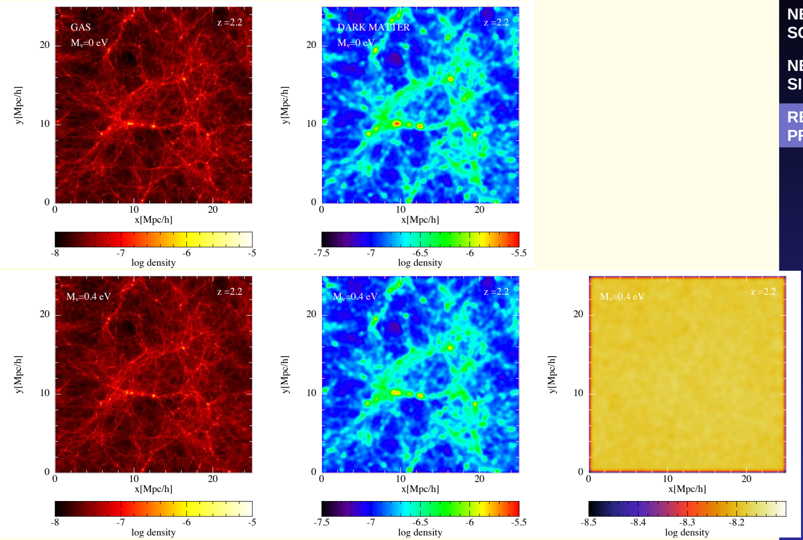

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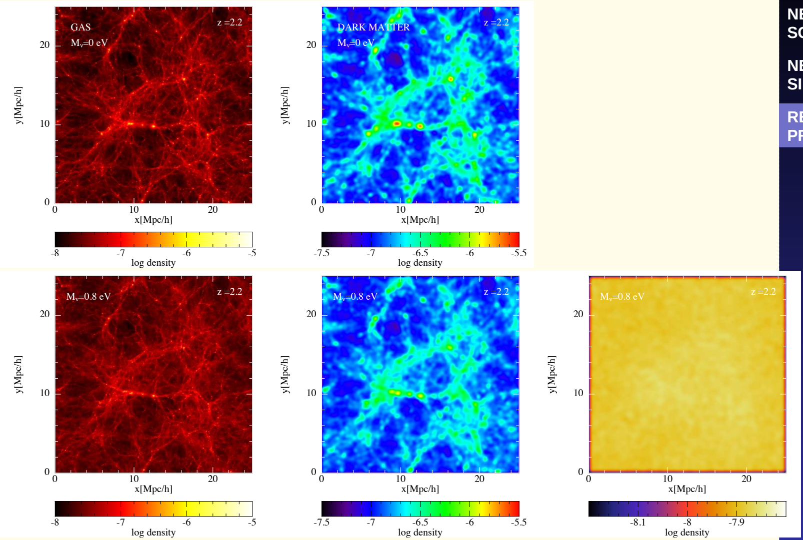

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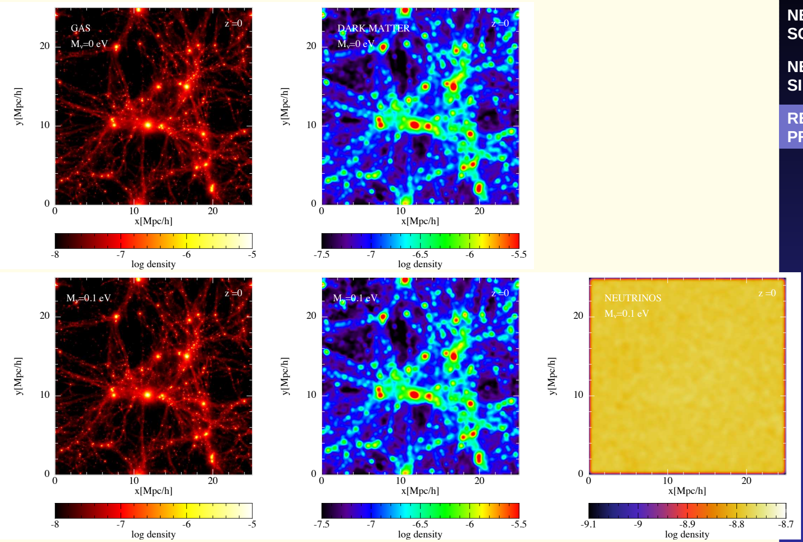
NEUTRINO SIMULATIONS
RESULTS & PROSPECTS

VISUALIZATIONS: GAS, DM, NEUTRINOS



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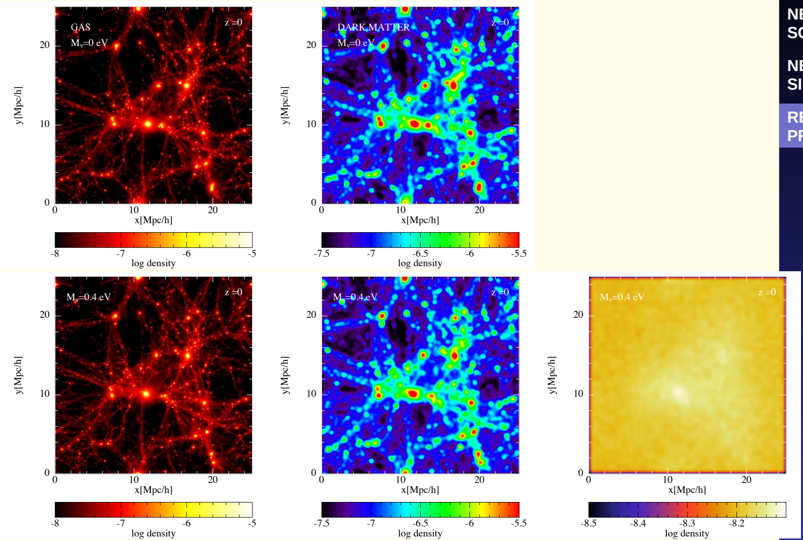

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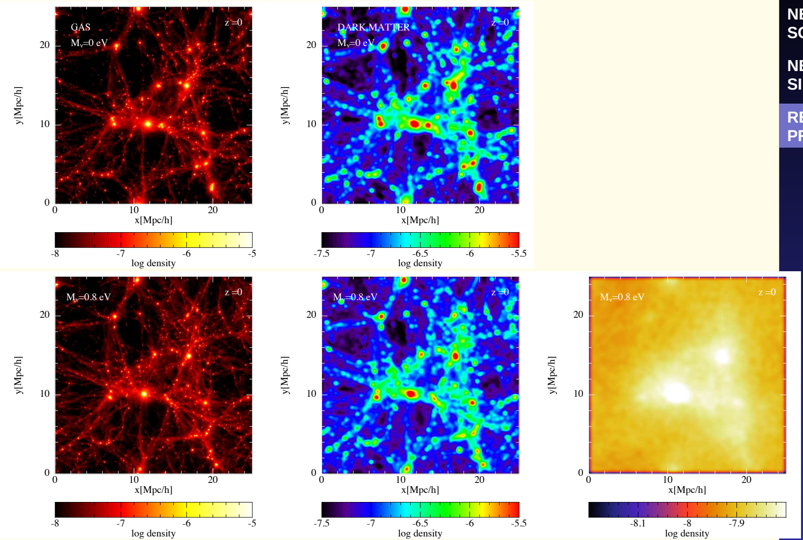
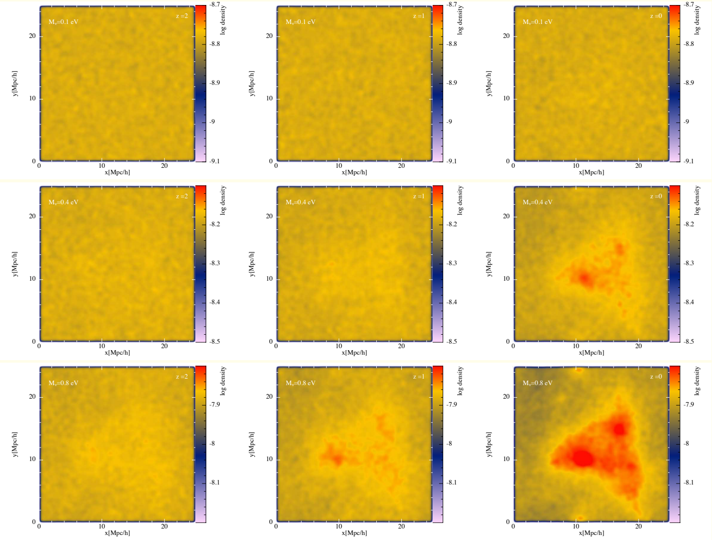
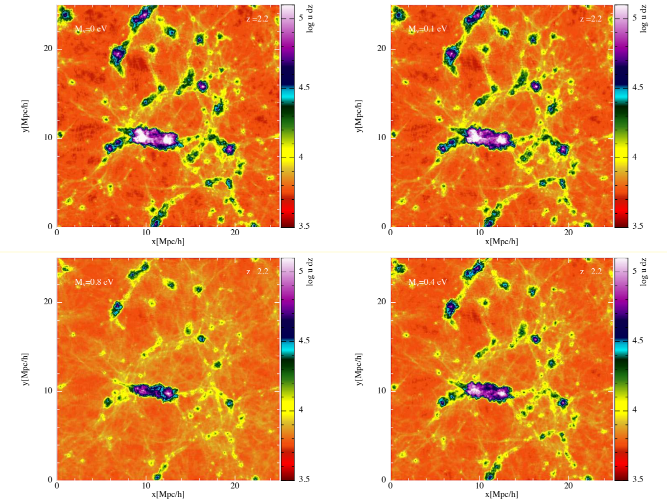


VISUALIZATIONS: NEUTRINO EVOLUTION



VISUALIZATIONS: GAS PROPERTIES



Internal Energy

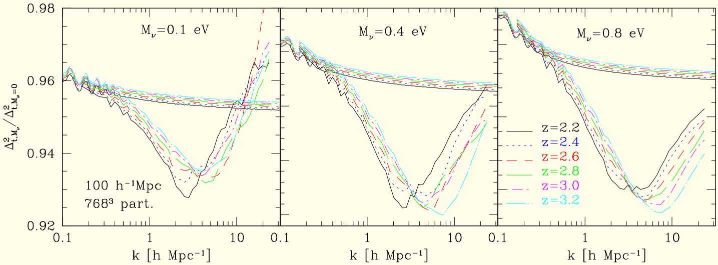
Rossi et al. (2014)

3D Matter Power Spectrum

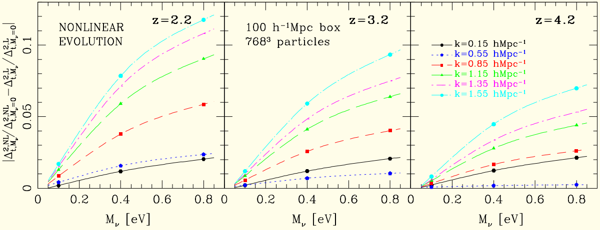
Impact on matter PS ($k > k_{nr}$)

1. Massive neutrinos do not cluster
2. z_{eq} or baryon-to-CDM ratio affected
3. Growth rate of CDM perturbations reduced

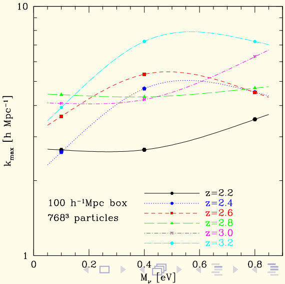
Rossi et al. (2014), see also Bird et al. (2012) and Viel et al. (2010)



3D Matter Power Spectrum



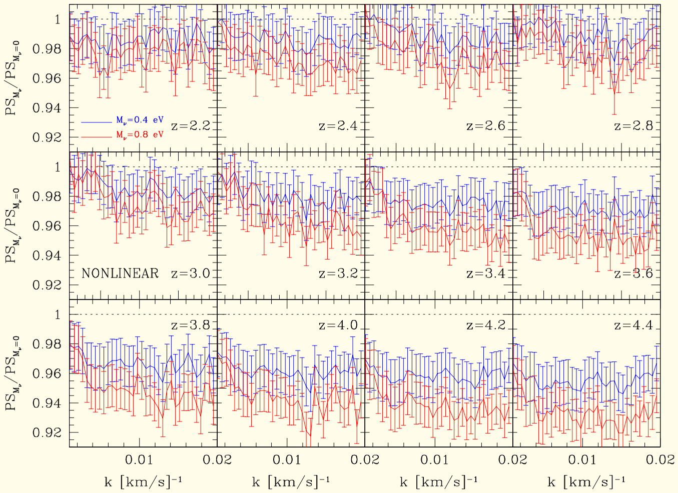
Rossi et al. (2014)



Relevant scales for ν

1. Scales where PS suppression is maximized (BOSS Lyα) $\uparrow$
2. Scales where PS suppression is maximized (general) $\rightarrow$

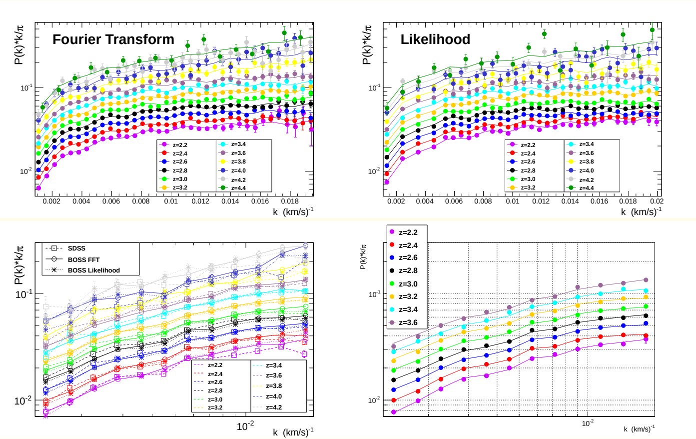
Flux Statistics



Rossi et al. (2014)

1D Power Spectrum: methods and fits

N. Palanque-Delabrouille et al. (2013)



ONGOING WORK: BOSS APPLICATIONS

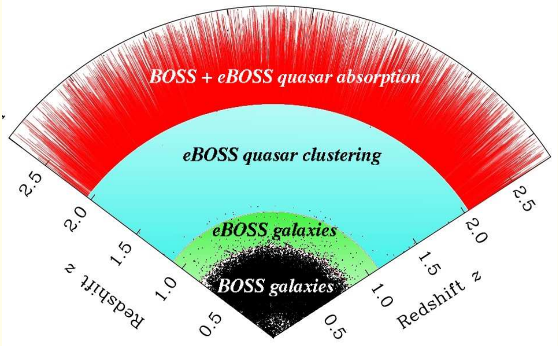
CONSTRAINING THE NEUTRINO MASS WITH THE LYα FOREST

- Modeling of the 1D PS with massive neutrinos required to constrain ν-mass and cosmological parameters
- Combine this modeling with measurements from BOSS
- Combine this modeling with other probes (CMB, LSS)
- Multidimensional likelihood analysis (as in Viel et al. 2006, 2010)
- Uncertainties estimates from simulations
- Orthogonality of the Lyα forest

BROADER APPLICATIONS

- 3D modeling of the Lyα forest
- Cross-correlations between different probes
- Particle physics related topics

Prospects for eBOSS and DESI



eBOSS

1. Range of redshifts currently left unexplored by other 3D maps of LSS
2. Largest volume survey of the Universe to date
3. Combination with SPIDERS X-ray selected sample of quasars, and TDSS

DESI, Euclid, WFIRST, HETDEX

1. Font-Ribera et al. (2013) $\rightarrow$ DESI Fisher matrix projections $\rightarrow \sum m_\nu$ at 0.02 eV level
2. Levi et al. (2013) $\rightarrow$ DESI 1% level measurements of distance scale in 35 z-bins $\rightarrow$ unprecedented constraints on cosmological models

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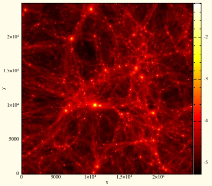
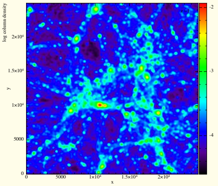
Main Messages & Ongoing Work

1. Peculiarity of the Lyman-α forest in constraining neutrino mass
2. Novel suite of hydrodynamical simulations
3. BOSS applications and potential for future surveys

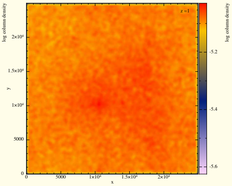
- Stringent constraints on the neutrino mass and on cosmological parameters (upcoming)
- Great potential, especially for Lyα forest science



Gas



Dark Matter



Neutrinos

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