DESI and the Neutrino Frontier

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Outline & Primary References

1. Neutrino Cosmology: A Brief Introduction
2. **Neutrinos in DESI: Key Results**
3. Neutrino Physics: New Frontiers

- Synergies, Contributions, Outlook

PRIMARY REFERENCES

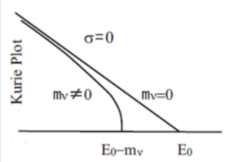
- DESI DR2 Results II (2025): arXiv:2503.14738
- DESI 2024 VI (2025), JCAP Vol. 2025, Issue 02

1. Neutrino Cosmology: A Brief Intro

Starting Point & Key History

1930 → PAULI

- Idea of neutrino to solve 'energy conservation crisis' in β-decay process
- $\beta^- \rightarrow \mathrm{n} \rightarrow \mathrm{p} + e^- + \bar{\nu}_e$
- $\beta^+ \rightarrow \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+ + \nu_e$

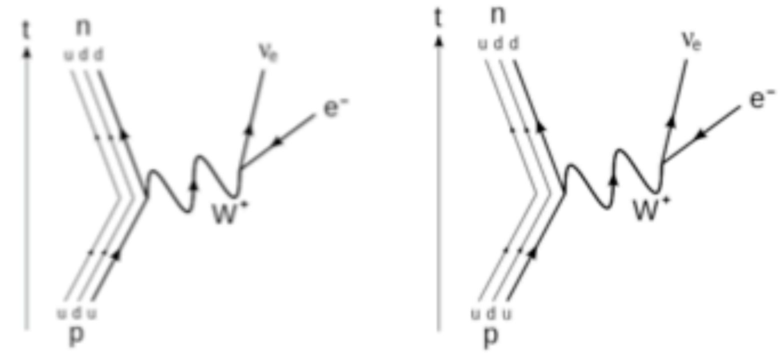


1934 → FERMI

- Theory of weak decay

1935 → BETHE

- Inverse β-decay → probability of detection
- $\nu + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-$
- $\bar{\nu} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$
- Cross section $\sigma_{\nu p} \sim 10^{-43}$ cm^2



β-decay – Feynman diagrams

1956 → REINES & COWAN

- Poltergeist experiment
- First neutrino indirect detection with coincidence signal (positron annihilation + neutron capture)

1957 → PONTECORVO

- Neutrino oscillations (mass-induced) & mixing
- Solved solar neutrino problem

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

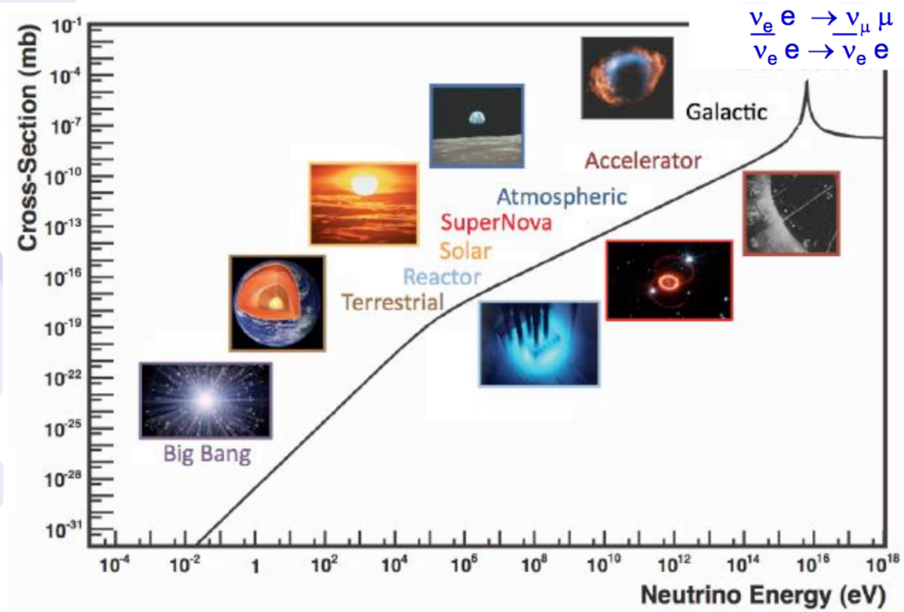
- Electron neutrinos
- Muon neutrinos
- Tau neutrinos

High number density → effects on cosmic structures

Neutrino Families

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

Courtesy A. Bravar



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** $\rightarrow$ squared effective electron neutrino mass

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

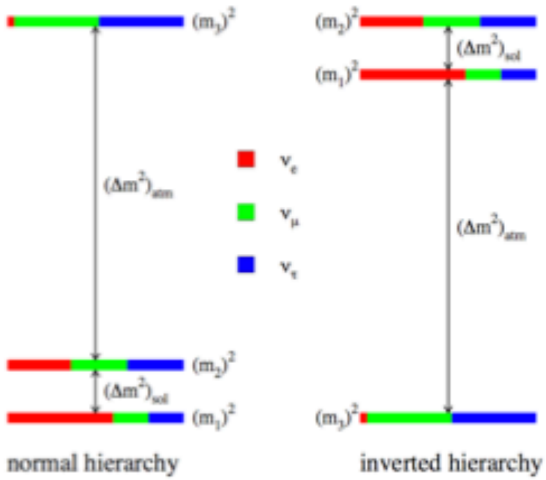
2. **Neutrinoless double β decay ($0\nu2\beta$)** $\rightarrow$ effective Majorana mass

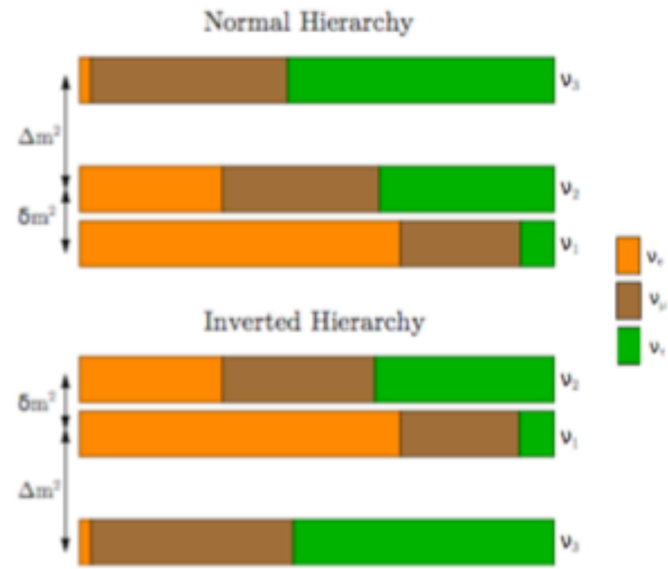
$$m_{\beta\beta} = |\sum_{\mathrm{i}} U_{\mathrm{ei}}^2 m_{\mathrm{i}}| = |\sum_{\mathrm{i}} \exp[i\Phi_{\mathrm{i}}]|U_{\mathrm{ei}}^2|m_{\mathrm{i}}|, \quad \Phi_2 = \xi, \Phi_3 = \zeta - 2\delta$$

3. **Cosmological observations** $\rightarrow$ 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**?

Neutrinos: Linear Evolution

Cosmological effects

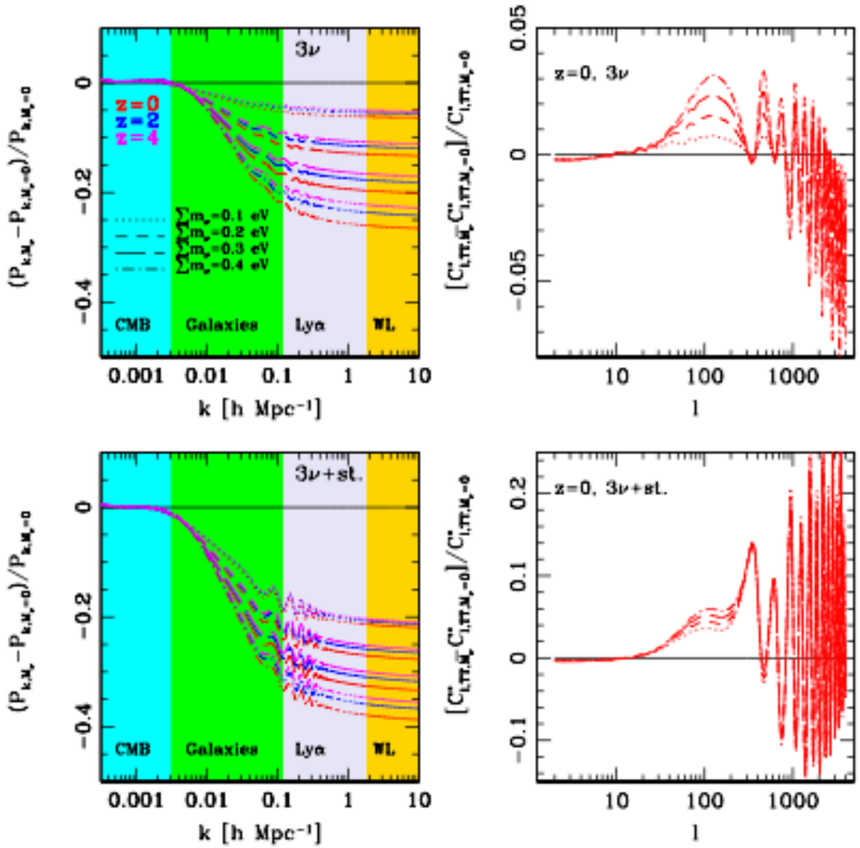
- Fix expansion rate at BBN
- Change background evolution → PS effects
- Slow down growth of structures

Neutrino free-streaming

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

Observables and Techniques

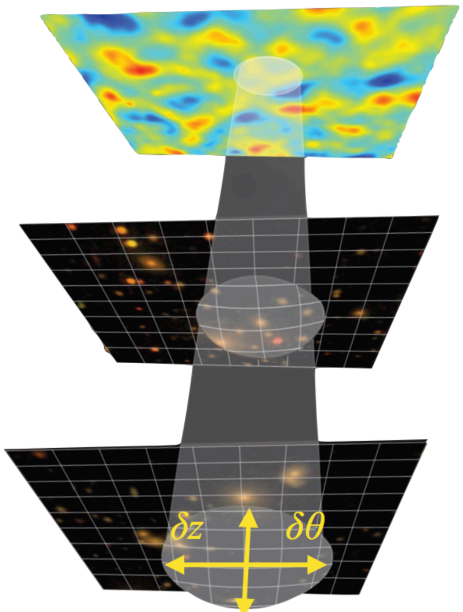
- CMB anisotropies → PS, lensing
- LSS probes
  - Galaxy PS
  - Cluster mass function
  - Galaxy weak lensing
  - **Ly-α forest**
  - 21-cm surveys



G. Rossi (2017, 2020)

Baryon Acoustic Oscillations (BAO)

Image Credit: Jiamin Hou



BAO measurements determine characteristic angular scale $\Delta\theta$ and redshift separation Δz in galaxy clustering → probe dimensionless ratio of characteristic length scale r_d at effective redshift z of galaxy/QSO sample

$\Delta\theta = r_d/D_M(z)$ → Late-time comoving angular diameter distance (across LoS)

$\Delta z = r_d/D_H(z)$ → Expansion time = c/H(z) (along LoS)

$r_d = r_s(z_d)$ sound horizon at baryon drag epoch $z_d \approx 1060$

$$r_s(z) = \int_z^\infty \frac{c_s(z')}{H(z')}\,dz'$$

BAO requires calibration of the ruler!

LATE-TIME BAO QUANTITIES

$$H(z) = H_0\, E(z)$$

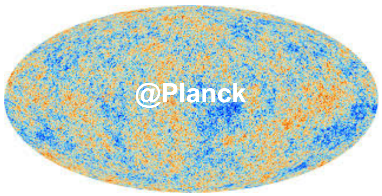
$$E(z) = f(\Omega_{cb}, \Omega_r, \Omega_K, \Omega_\nu, \Omega_\Lambda)$$

$$D_M(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{E(z')} \quad \text{flat FLRW}$$

At $z \ll z_{nr}$ → $\Omega_m = \Omega_{cb} + \Omega_\nu$ → Can only constrain Ω_m !

$$E(z) \approx \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

Additional Information: CMB, SNe, WL

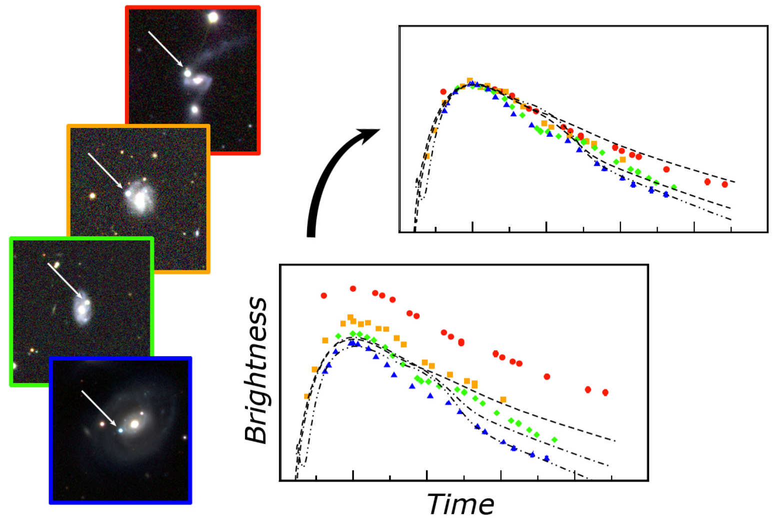


DATA: **LSS** (Galaxy, QSOs) + **CMB** (+ **SNe**, **WL**)

Cosmic Web | **Early Universe** | **Late Universe**

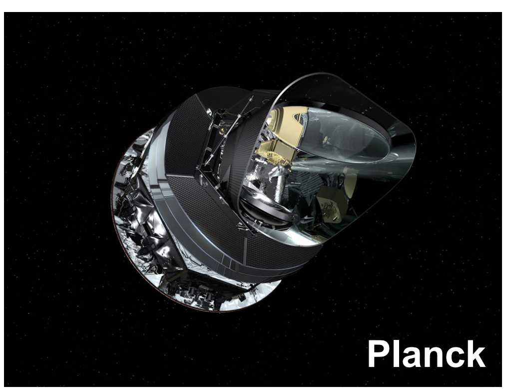
EXTERNAL DATA

- **BBN** → prior on $\Omega_b h^2$
- **CMB** → Planck, ACT, SPT
- **SNe** → Pantheon+, Union3, DESY5
- **WL** → DESY3 (3 x 2pt)



Type Ia supernovae as "standard candles **[Image Credit:** Berkeley Lab]

[Image Credit: NASA/ESA]



Gravitational lensing in the Abell 2218 galaxy cluster, imaged by Hubble Space Telescope **[Image Credit:** NASA/ESA]

Towards Neutrino Mass Hierarchy

Laboratory experiments

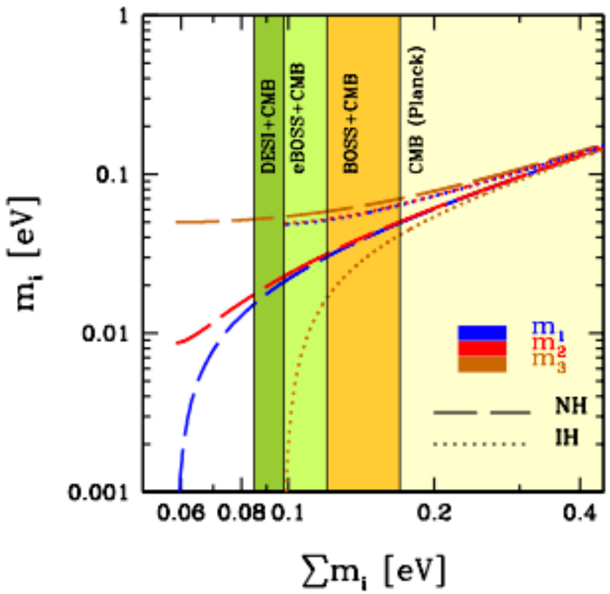
- Solar, atmospheric, reactors, accelerators $\rightarrow$ $M_\nu > 0.05$ eV
- β-decay $\rightarrow M_\nu < 2.2$ eV

Cosmology: Now (95% CL)

- Lyα $\rightarrow$ 0.900 eV
- Planck $\rightarrow$ 0.252 eV
- Planck + SN $\rightarrow$ 0.170 eV
- Planck + BAO + RSD + SN + DES (νwCDM) $\rightarrow$ 0.161 eV
- Planck + BAO + RSD + SN (νwCDM) $\rightarrow$ 0.139 eV
- Planck + BAO $\rightarrow$ 0.129 eV
- Planck + BAO + RSD + SN + DES$\rightarrow$ 0.111 eV
- Planck + BAO + RSD $\rightarrow$ 0.102 eV
- Planck + BAO + RSD + SN$\rightarrow$ 0.099 eV

Cosmology: Highlights

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



DESI DR1/DR2 → A game changer?

- **Rossi, G.** (2020), ApJS, 249, 19
- **Rossi, G.** (2017), ApJS, 233, 12
- **Rossi, G.** et al. (2015), PRD, 92, 063505
- **Rossi, G.** et al. (2014), A&A, 567, AA79

2. Neutrinos in DESI: Key Results

DESI DR1/DR2: Dark Energy

DESI DR1

- **DESI DR1 + CMB** → ΛCDM model disfavored at **2.6σ** to $w_0 w_a$CDM
- **DESI DR1 + CMB + DESY5** → ΛCDM model disfavored at **3.9σ** to $w_0 w_a$CDM

DESI DR2

- **DESI DR2 BAO results** → consistent with DESI DR1 and SDSS
- **DESI DR2 BAO** → well described by ΛCDM model!
- **DESI ΛCDM** parameters in **2.3σ tension** with **CMB** ← **New!**
- **DESI ΛCDM** parameters in **~2σ tension** with **SNe**
- **Results point to incompatibility between datasets within ΛCDM**

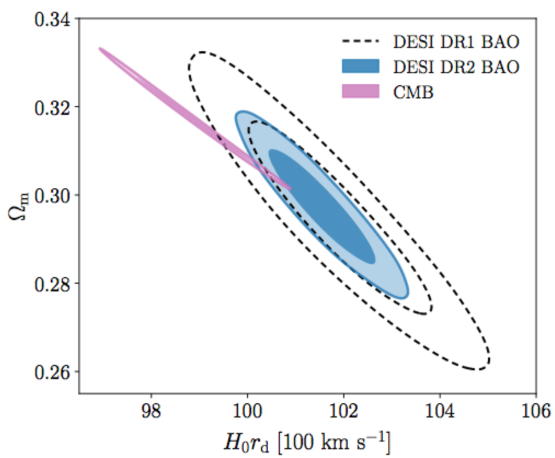
- **DESI DR2 BAO** → no strong preference for evolving DE (**1.7σ**)
- **DESI DR2 + CMB** → ΛCDM model disfavored at **3.1σ** to $w_0 w_a$CDM
- **DESI DR2 + CMB + SNe** → ΛCDM model disfavored up to **4.2σ** to $w_0 w_a$CDM

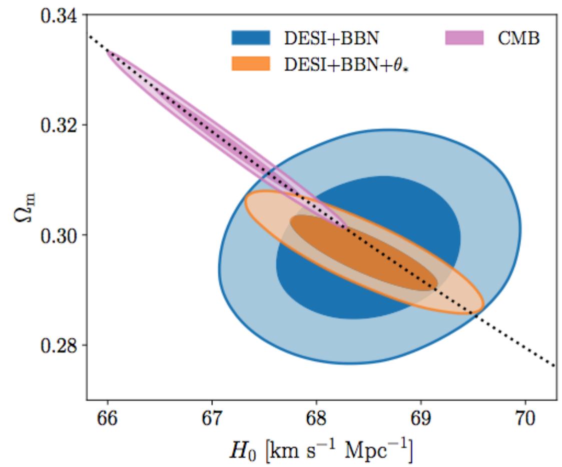
- ΛCDM challenged by DESI BAO + additional probes
- Dynamical DE possible solution ?

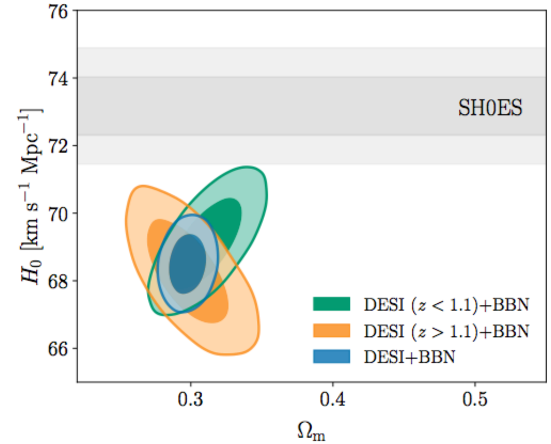
DESI DR2 Results II: arXiv:2503.14738

DESI DR2: Dark Energy

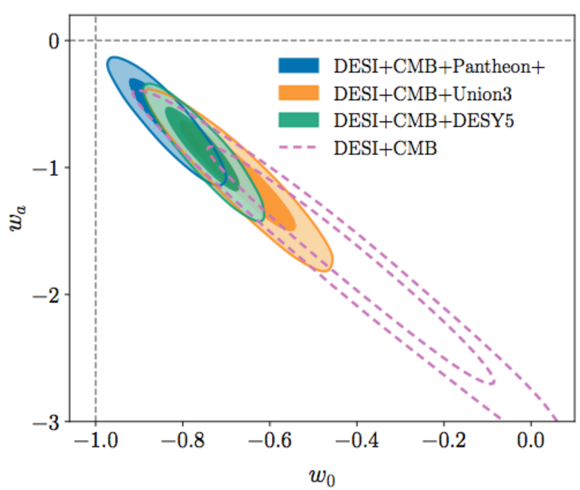
Flat ΛCDM

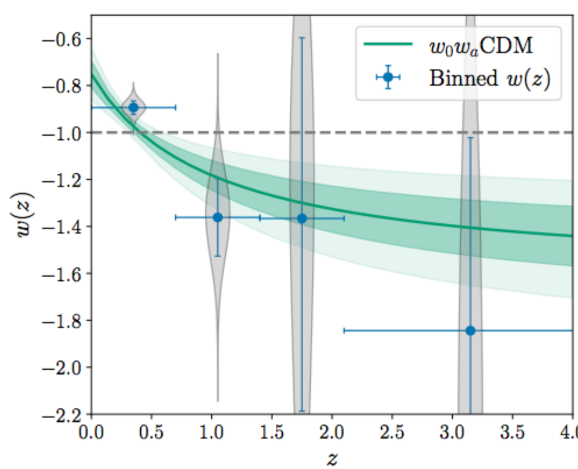






Flat w_0-w_aCDM





DESI DR2 Results II: arXiv:2503.14738

DESI DR1: Neutrino Mass Constraints

Flat ΛCDM + M_ν

With $M_\nu > 0$ eV prior & 3 degenerate neutrino mass states

- **DESI DR1 (FS+BAO) + BBN + $n_{s,10}$** → $M_\nu < 0.409$ eV (95%)
- **DESI DR1 (FS+BAO) + CMB (plik)** → $M_\nu < 0.072$ eV (95%)

Flat w_0-w_aCDM + M_ν

With $M_\nu > 0$ eV prior & 3 degenerate neutrino mass states

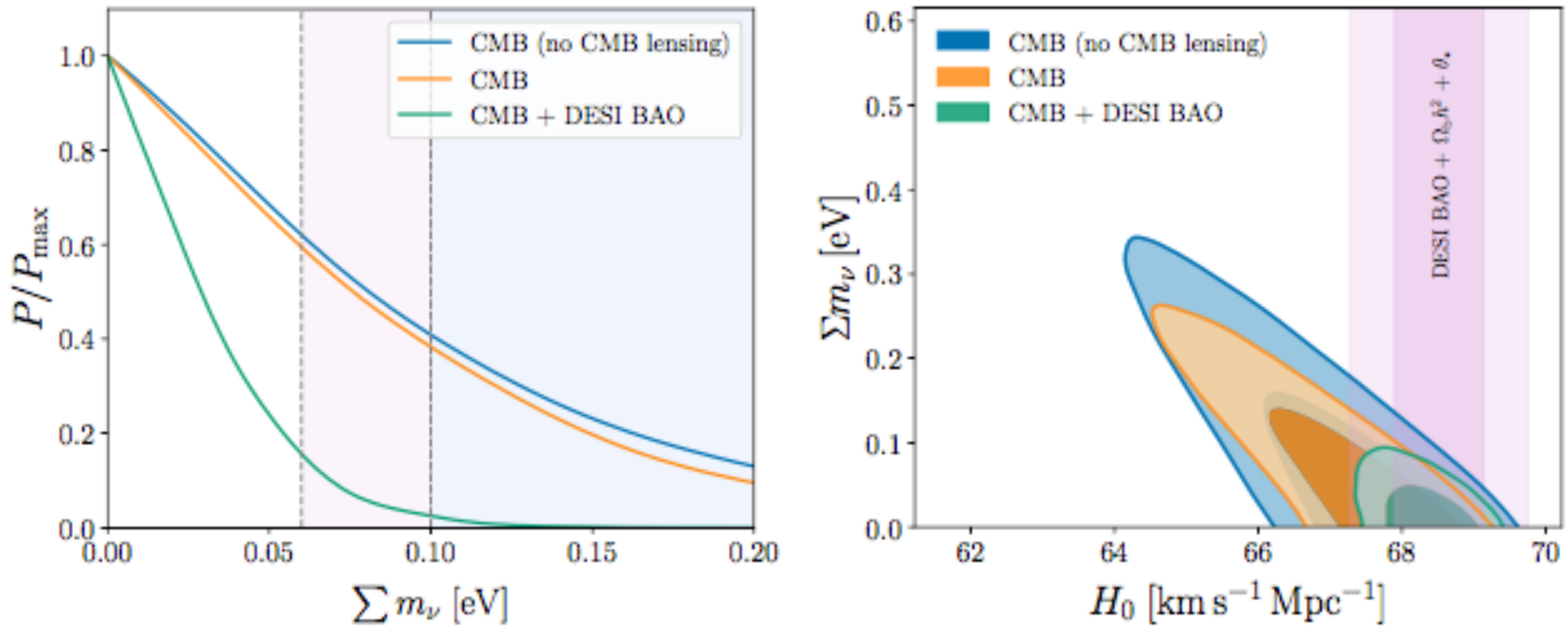
- **DESI DR1 (FS+BAO) + CMB + DESY5** → $M_\nu < 0.196$ eV (95%) (consistent with neutrino oscillations for NH or IH)

Puzzling aspects of DESI analysis (both BAO and FS)

DESI 2024 VI: JCAP Vol. 2025, Issue 02

- Strongest constraints in tension (~2σ) with neutrino oscillations
- Marginalized posterior distribution of M_ν peaks at lower edge of prior $M_\nu > 0$ eV → tail of distribution with central value in negative mass range & posterior away from its maximum likelihood value → `*prior weight effects*'

DESI DR1: Neutrinos



- $M_\nu < 0.072$ (0.113) eV at 95% confidence for a $M_\nu > 0$ ($M_\nu > 0.059$) eV prior

DESI 2024 VI:
JCAP Vol. 2025, Issue 02

DESI DR2: Neutrino Mass Constraints

With M_ν > 0 eV prior & 3 degenerate neutrino mass states

Flat ΛCDM + M_ν

20% reduction from DR1

DESI DR2 BAO + CMB (baseline) → $M_\nu < 0.0642$ eV (95%)

Flat wCDM + M_ν

DESI DR2 BAO + CMB (baseline) → $M_\nu < 0.0851$ eV (95%)

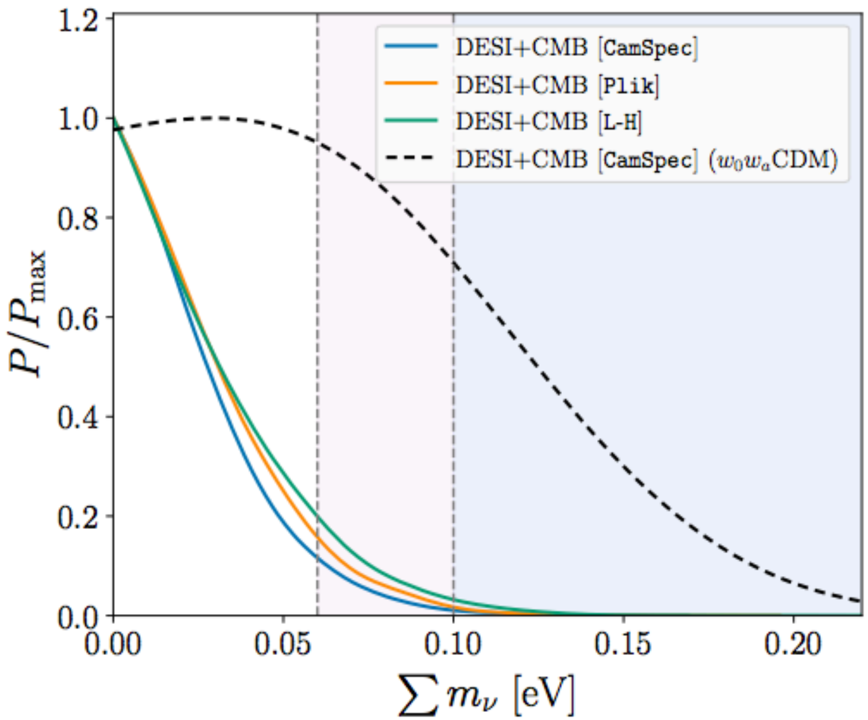
Flat w_0-w_aCDM + M_ν

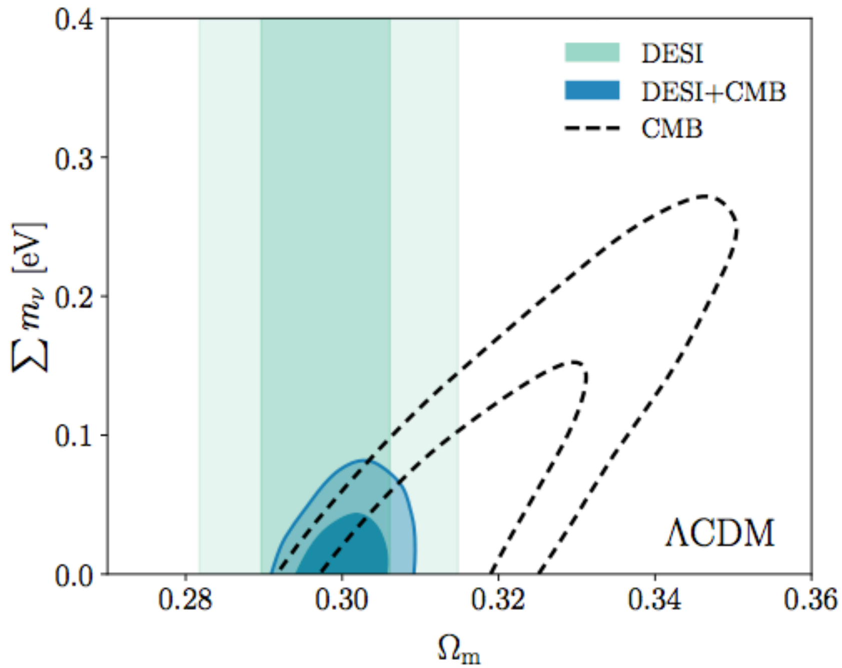
Significant relaxation of neutrino constraints

DESI DR2 BAO + CMB (baseline) → $M_\nu < 0.163$ eV (95%)

DESI DR2: Neutrino Mass Constraints

Flat ΛCDM



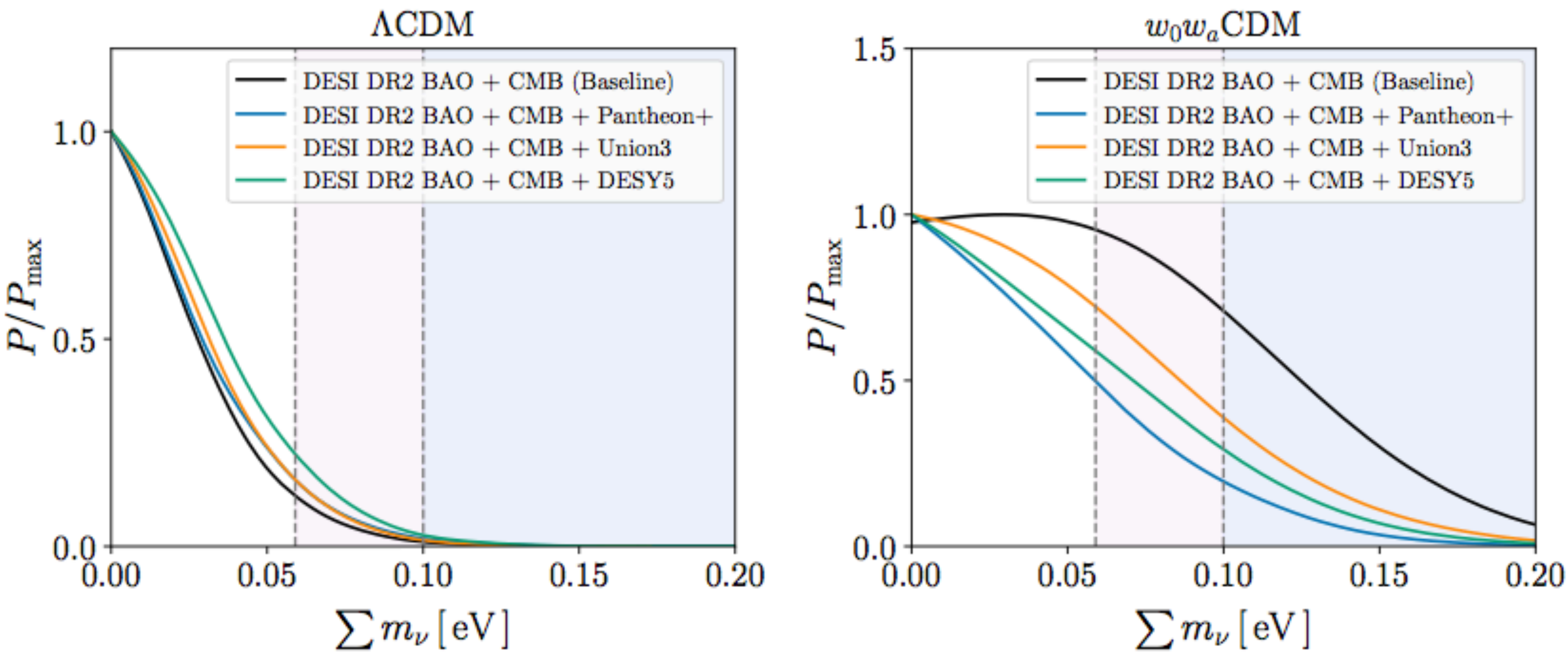


In a model with effective M_ν → peak of DESI+CMB likelihood <0 with **3σ tension** with terrestrial bounds

M_ν and Ω_m positively correlated → DESI preference for lower Ω_m than CMB drives small M_ν constraints!

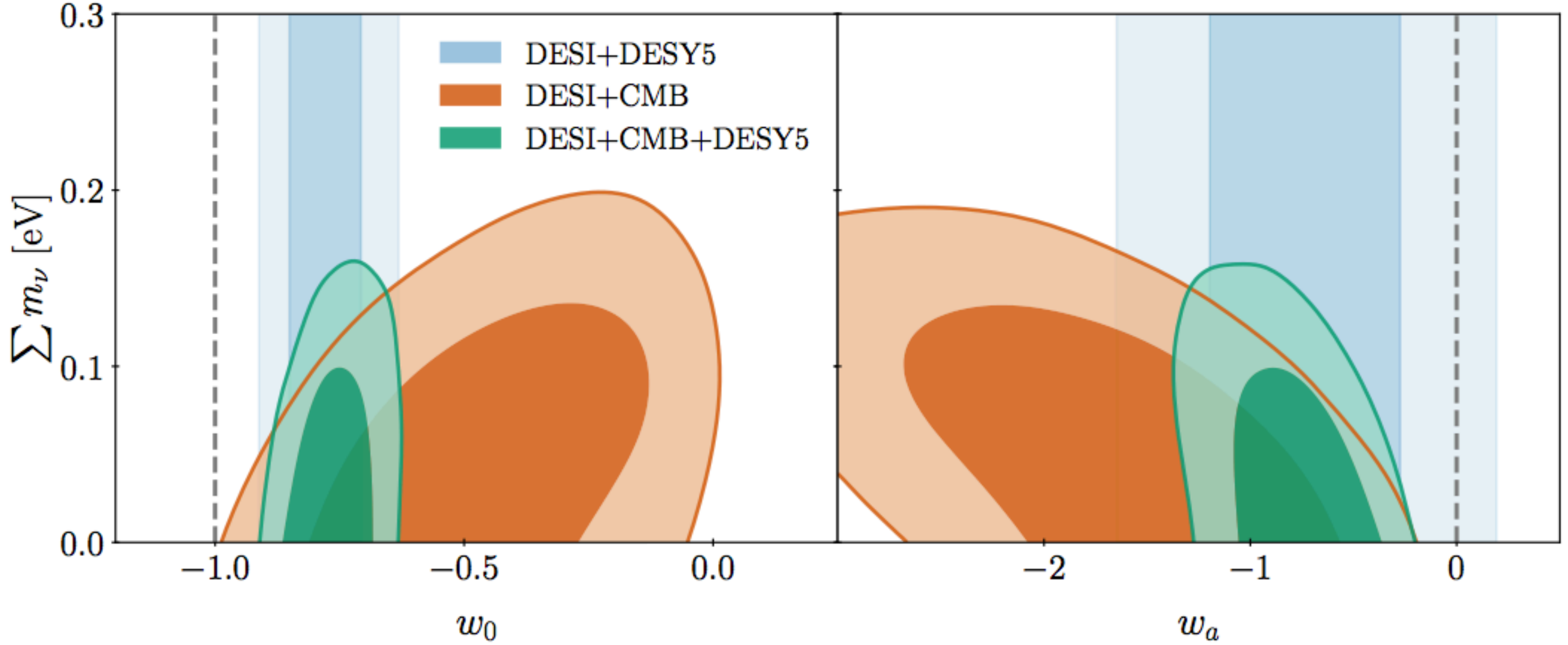
DESI DR2 Results II: arXiv:2503.14738

DESI DR2: Neutrino Mass Constraints



DESI DR2 Results II:
arXiv:2503.14738

DESI DR2: Neutrinos



Flat w_0-w_aCDM + M_ν

DESI DR2 Results II: arXiv:2503.14738

3. Neutrino Physics: New Frontiers

Primary Reference: **J. Moon, G. Rossi, H. Yu (2023), ApJS, 264, 1**

Negative Neutrino Mass ?

DESI results puzzling → i.e., `prior weight effects'

The Cosmological Preference for Negative Neutrino Mass

Daniel Green[1] and Joel Meyers[2]

[1]*Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA*
[2]*Department of Physics, Southern Methodist University, Dallas, TX 75275, USA*

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PUBLISHED: *September 17, 2024*

No νs is Good News

Nathaniel Craig[a,b] Daniel Green[c] Joel Meyers[d] and Surjeet Rajendran[e]

[a]*Department of Physics, University of California, Santa Barbara, CA 93106, U.S.A.*

Negative neutrino masses as a mirage of dark energy

Willem Elbers,[1,*] Carlos S. Frenk,[1] Adrian Jenkins,[1] Baojiu Li,[1] and Silvia Pascoli[2]

[1]*Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK*
[2]*Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, 40126 Bologna, Italy INFN, Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy*
(Dated: July 16, 2024)

- **Craig et al. (2024)** → model form CMB GL neutrino effect captured by $\sum\widetilde{m}_{\nu}$ that could be negative → negative values for that from DESI DR1+CMB → more lensing than accommodated by ΛCDM

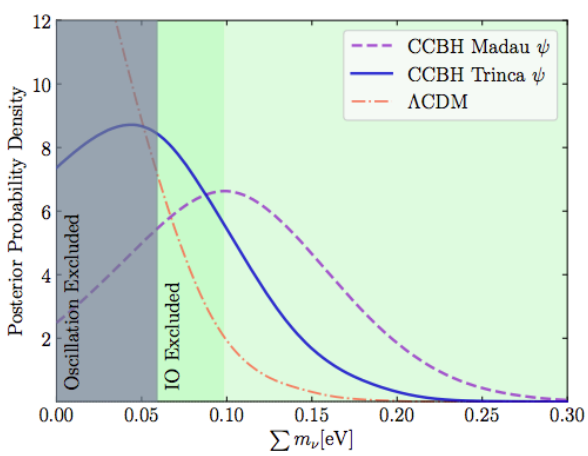
- **Elbers et al. (2024)** → introduce $\sum m_{\nu,\mathrm{eff}}$ allowing for negative energy densities, reducing to $M_{\nu}=\sum m_{\nu}$ for positive values. Assuming ΛCDM and wide uniform prior on $\sum m_{\nu,\mathrm{eff}}$ marginalized posterior peaks in negative sector + 2.8σ tension with NH oscillations & 3.3σ with IH but no tension if w_0-w_aCDM

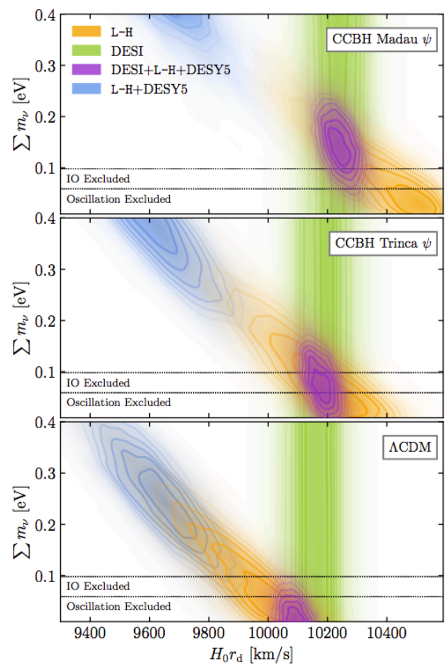
Necessity of **alternative techniques** beyond traditional methods → geometry & shape of density PS besides expansion rate

Matter Conversion to DE

Positive neutrino masses with DESI DR2 via matter conversion to dark energy

S. P. Ahlen,[1] A. Aviles,[2,3] B. Cartwright,[4] K. S. Croker,[4,5] W. Elbers,[6] D. Farrah,[5,7] N. Fernandez,[8] G. Niz,[9,3] J. W. Rohlf,[1] G. Tarlé,[10,*] R. A. Windhorst,[4] J. Aguilar,[11] U. Andrade,[12,10] D. Bianchi,[13,14] D. Brooks,[15] T. Claybaugh,[11] A. de la Macorra,[16] A. de Mattia,[17] B. Dey,[18,19] P. Doel,[15] J. E. Forero-Romero,[20,21] E. Gaztañaga,[22,23,24] S. Gontcho A Gontcho,[11] G. Gutierrez,[25] D. Huterer,[10] M. Ishak,[26] R. Kehoe,[27] D. Kirkby,[28] A. Kremin,[11] M. Ishak,[26] R. Kehoe,[27] D. Kirkby,[28] A. Kremin,[11] O. Lahav,[15] C. Lamman,[29] M. Landriau,[11] L. Le Guillou,[30] M. E. Levi,[11] M. Manera,[31,32] R. Miquel,[33,32] J. Moustakas,[34] I. Pérez-Ràfols,[35] F. Prada,[36] G. Rossi,[37] E. Sanchez,[38] M. Schubnell,[10] H. Seo,[39] J. Silber,[11] D. Sprayberry,[40] M. Walther,[41,42] B. A. Weaver,[40] R. H. Wechsler,[43,44,45] and H. Zou[46]
(DESI Collaboration)





arXiv:2504.20338

First DESI PRL!

See talk on Thursday by K. Croker

Suppressed Growth Rate

Neutrino mass tension or suppressed growth rate of matter perturbations?

William Giarè [1,*] Olga Mena [2,†] Enrico Specogna [1,‡] and Eleonora Di Valentino [1,§]

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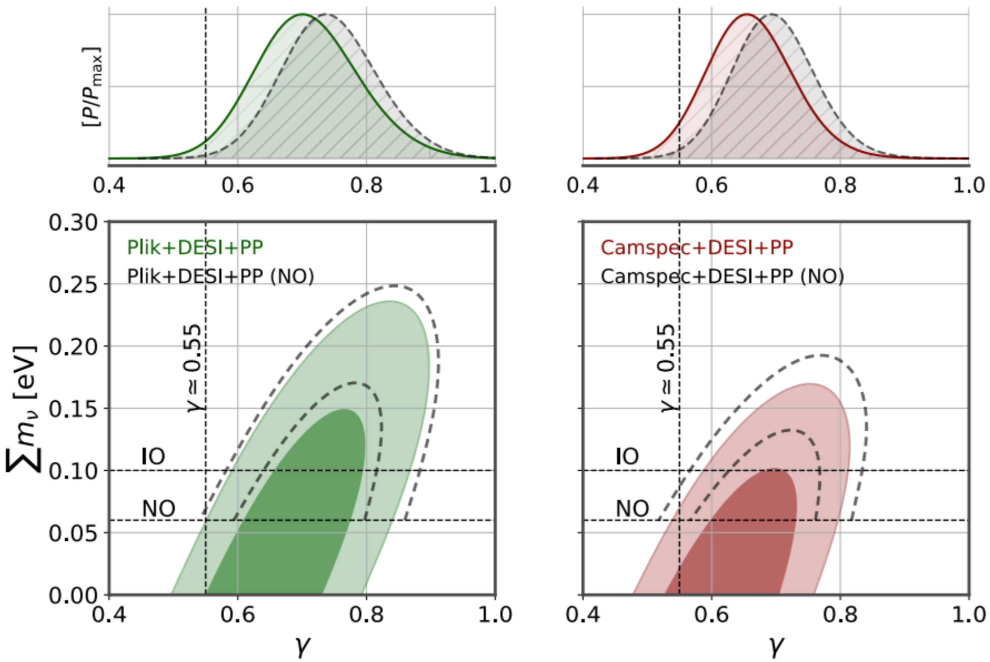
[2] *Instituto de Física Corpuscular (IFIC), University of Valencia-CSIC, Parc Científic UV, c/ Catedrático José Beltrán 2, E-46980 Paterna, Spain*

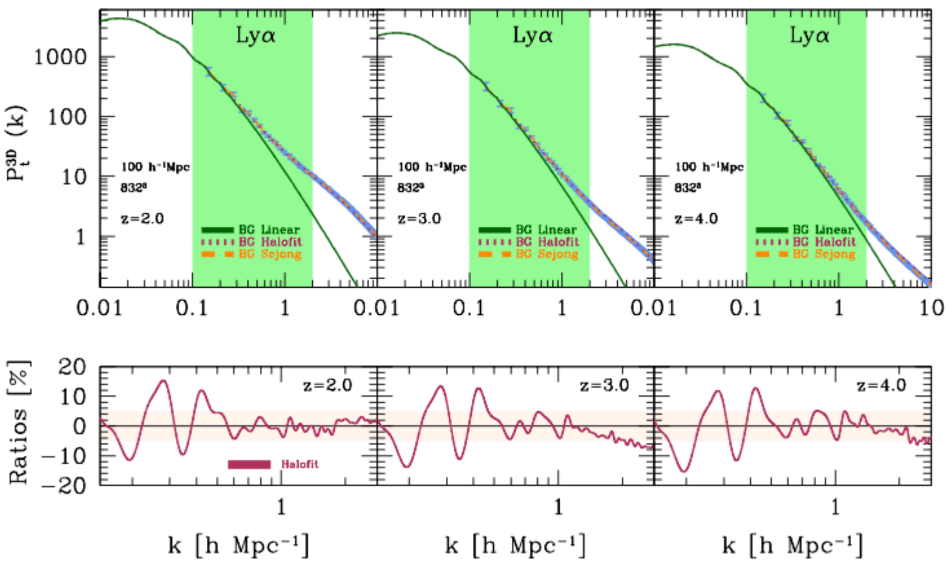


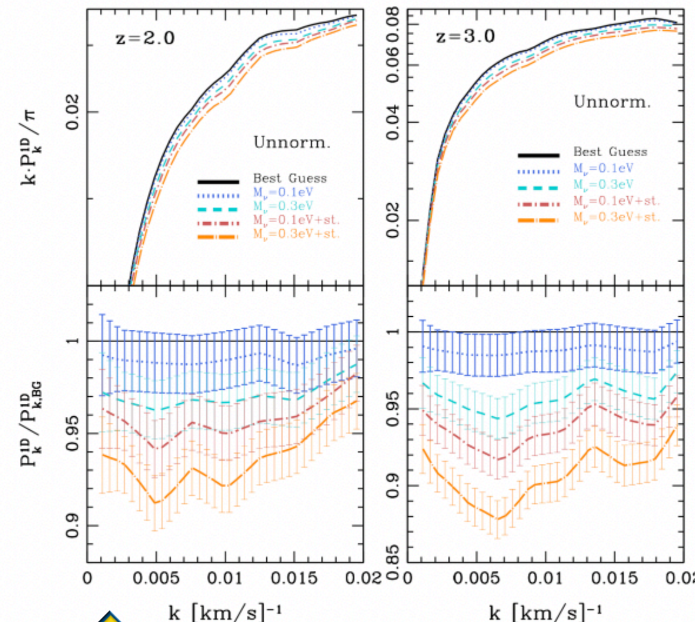
arXiv:2507.01848

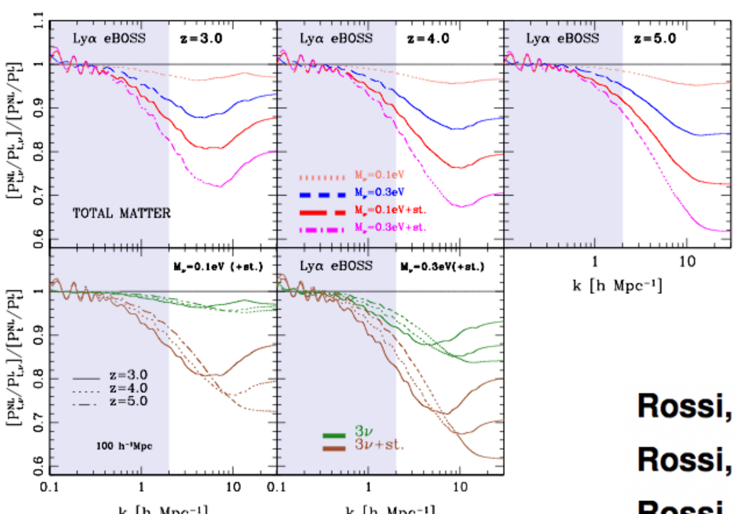
`Perturbation-level flexibility, especially in structure growth, can mitigate tensions that appear under stricter assumptions'

?

Neutrinos: `Traditional' Methods



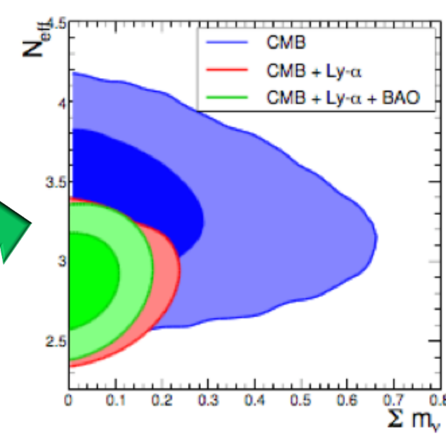




Flux Power Spectrum

Matter Power Spectrum

Constraints

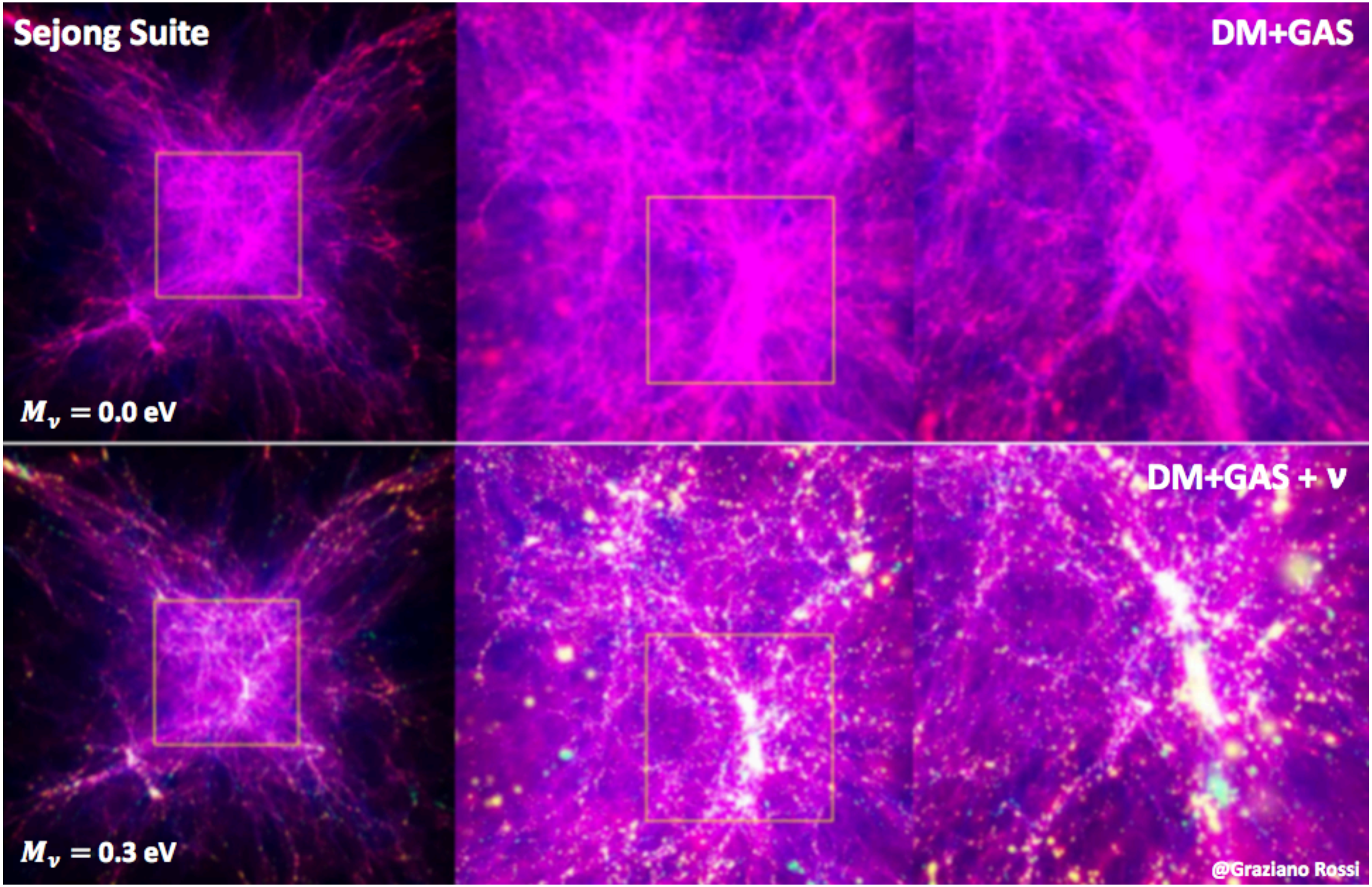


Rossi, G. (2020), ApJS, 249, 19

Rossi, G. (2017), ApJS, 233, 12

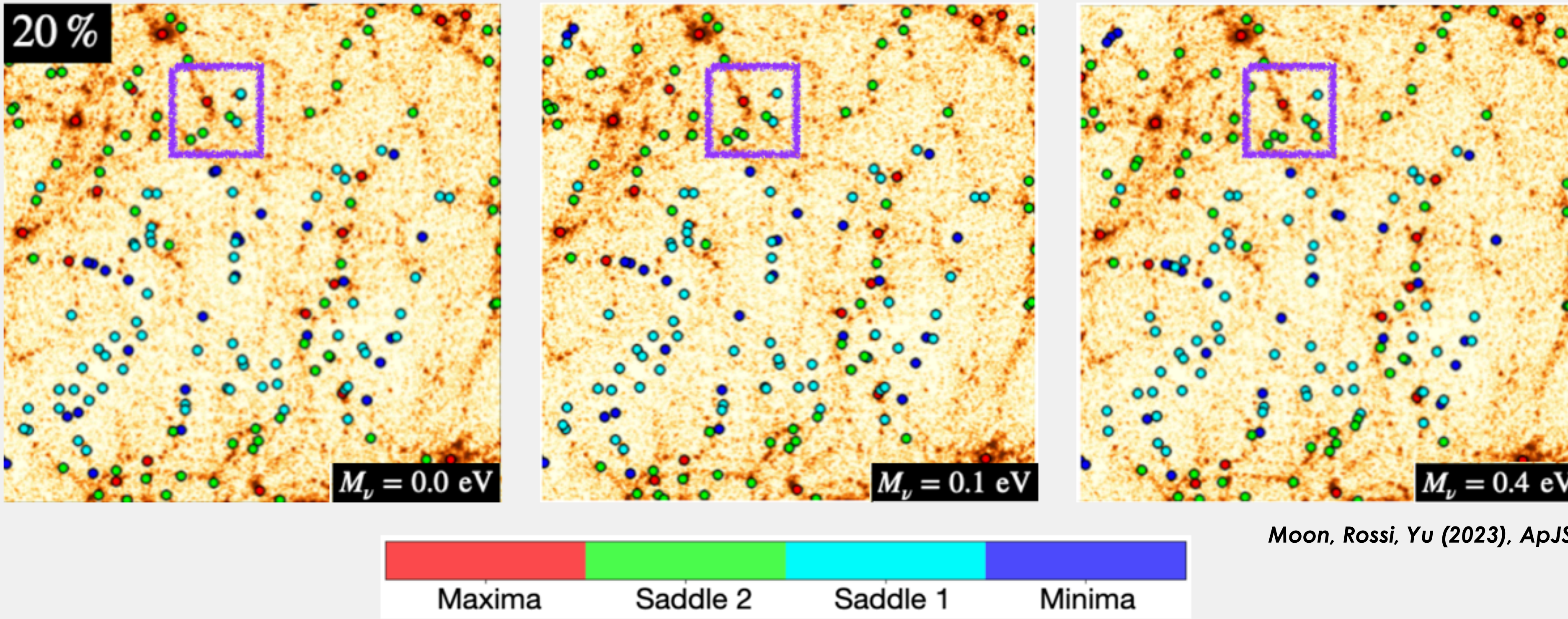
Rossi, G. et al. (2015), PRD, 92, 063505

The *Sejong Suite*: Visualizations



G. Rossi (2020), ApJS, 249, 19

Critical Points: Definition

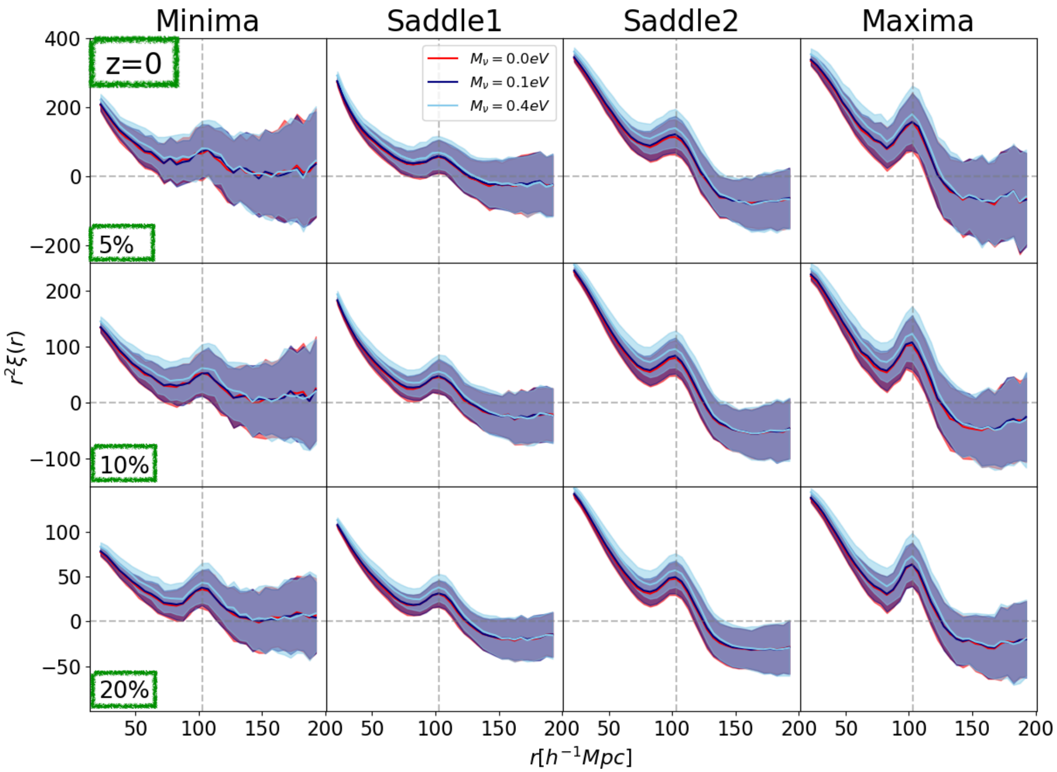


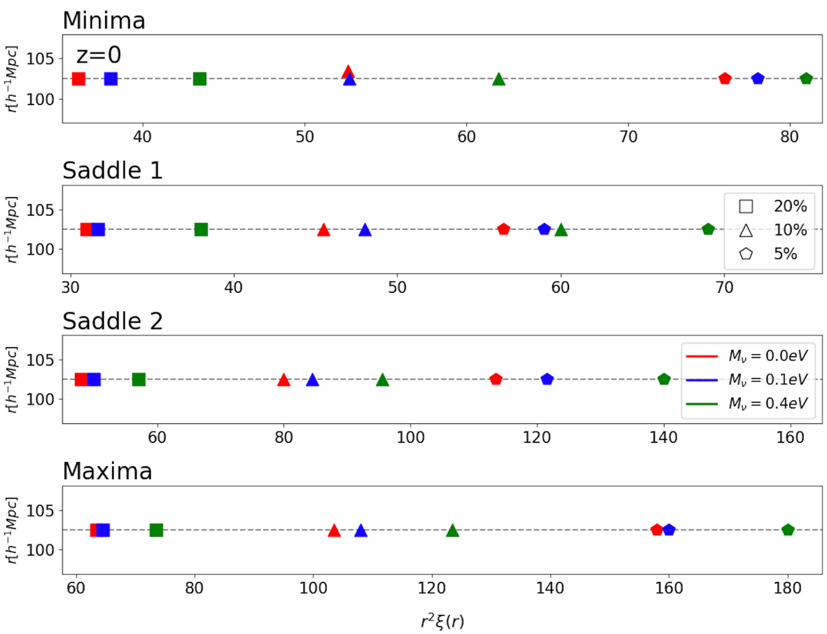
Moon, Rossi, Yu (2023), ApJS

Special points where spatial gradient of density field vanishes.
Faithful tracers of cosmological structures.

Auto-CFs of Critical Points: BAO

Moon, Rossi, Yu (2023), ApJS



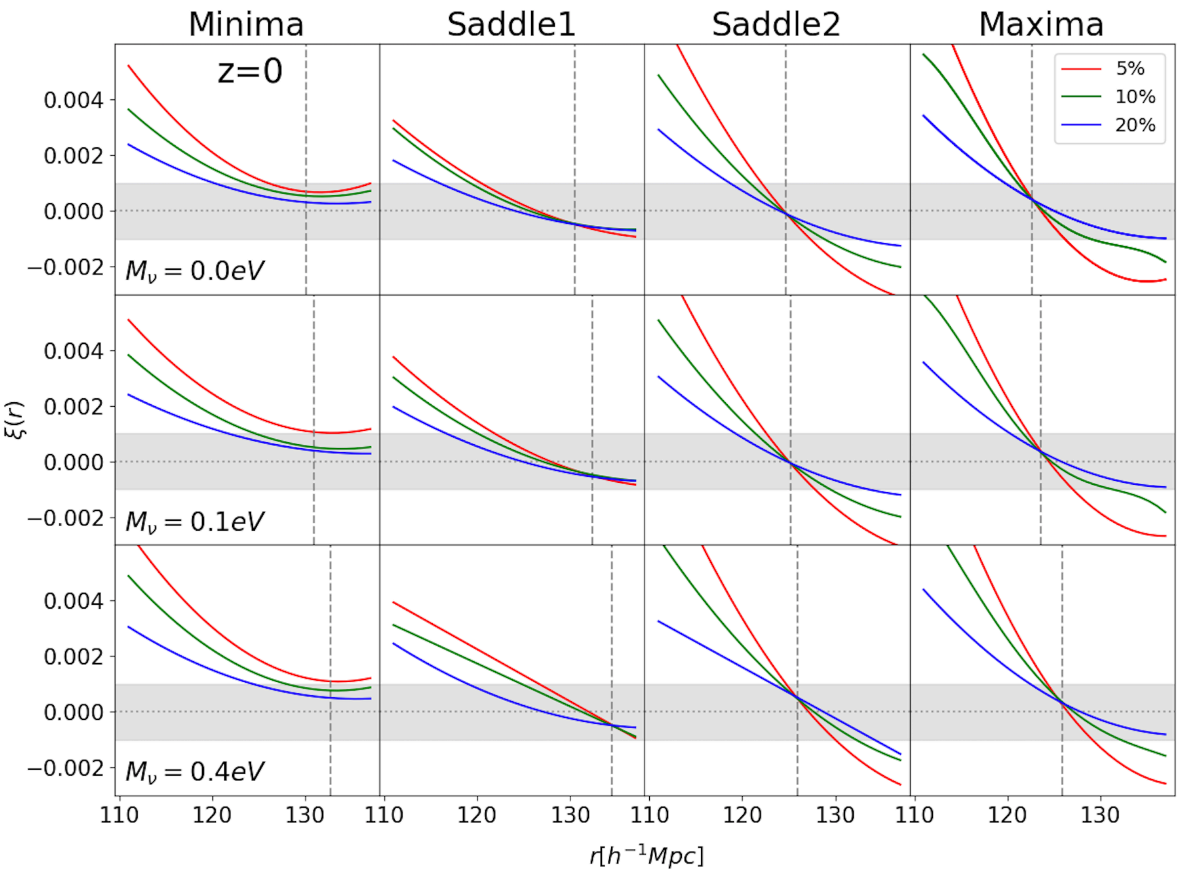


Relevant Highlights

- BAO scales always at $102.5h^{-1}\mathrm{Mpc}$
- Massive neutrinos enhance $\xi^{\mathrm{cp}}_{\mathrm{auto}}$ BAO amplitudes
- BAO peaks in autocorrelations amplified with decreasing $\mathcal{R}$

up to **7%** effect at $z = 0$ for $M_\nu = 0.1\mathrm{eV}$ in $\xi^{\mathrm{cp}}_{\mathrm{auto}}$

Auto-CFs of Critical Points: Inflection



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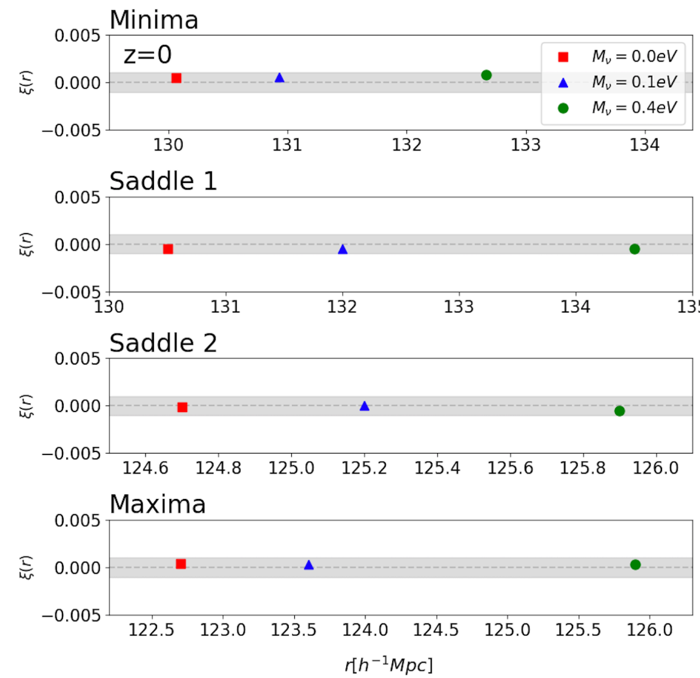
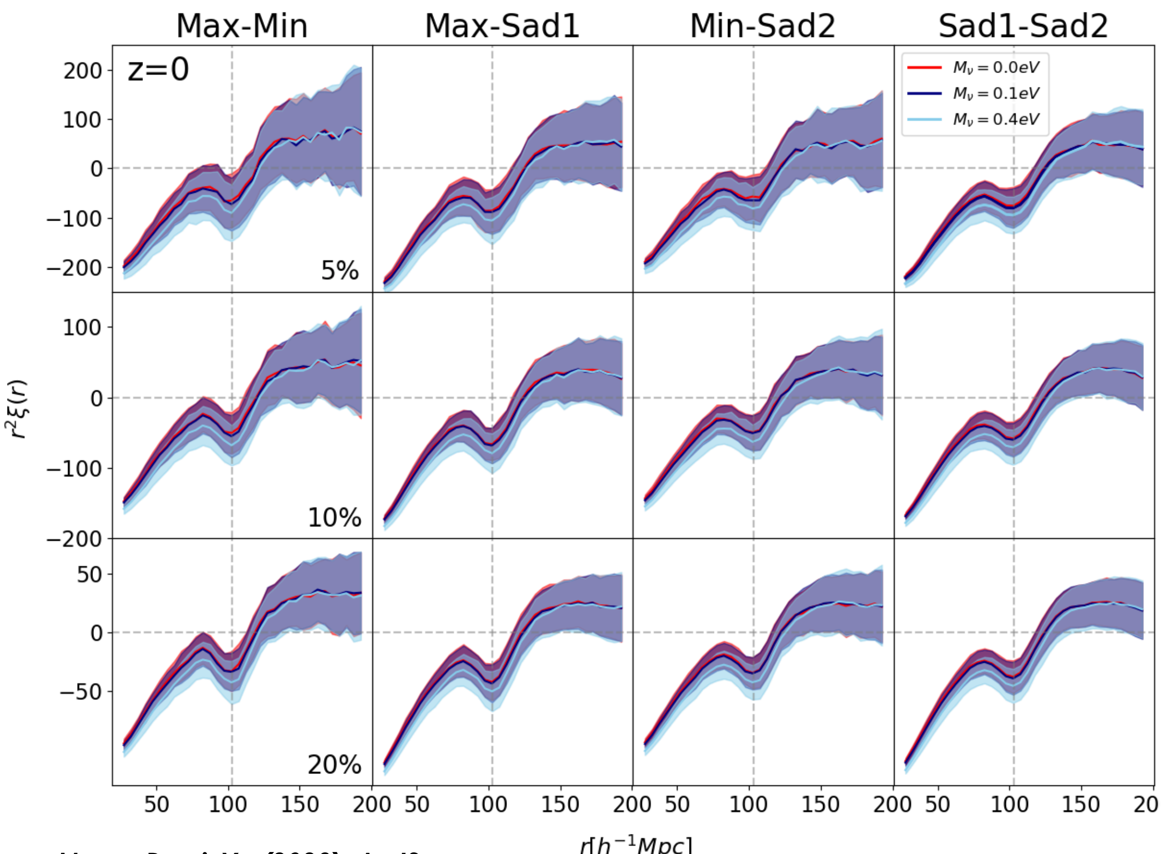


Inflection points quite sensitive to massive neutrinos

Inflection Scale

- Spatial position where ξ's computed at $\neq \mathcal{R}$ intersect (or are minimally distant)
- Equivalent to $\xi = 0$ (zero-crossing) scale within error bars
- Affected by M_ν, as well as BAO amplitudes

Cross-CFs of Critical Points: BAO



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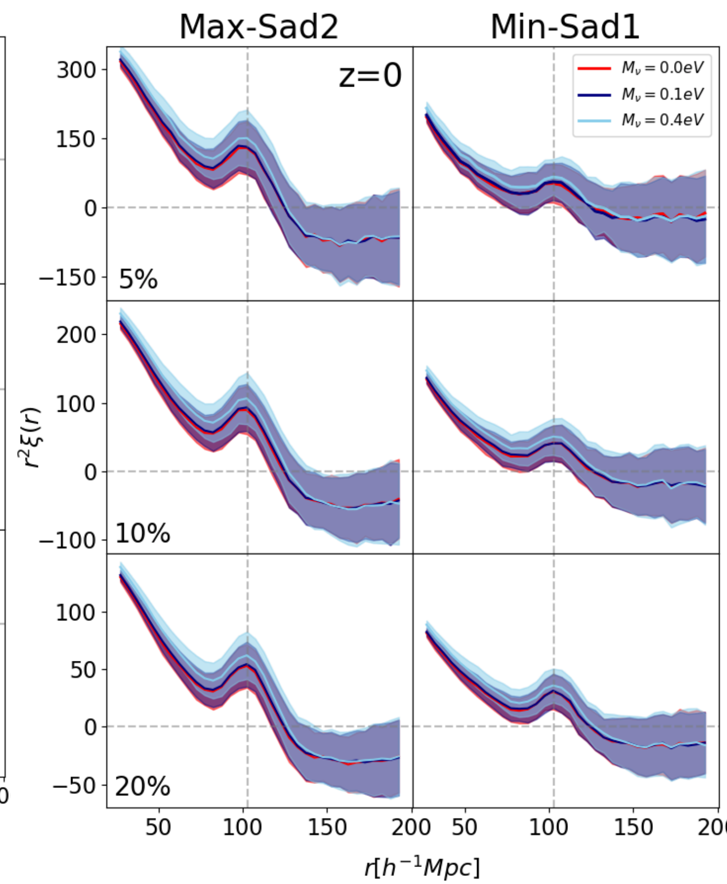
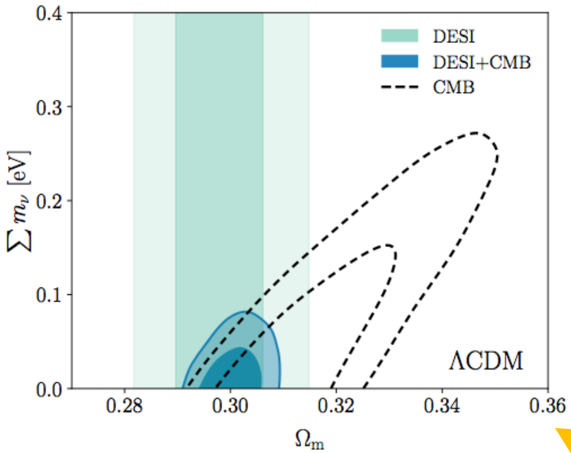


- Spatial positions of BAO dips/peaks in cross-correlations also robustly defined at $r = 102.5h^{-1}\mathrm{Mpc}$
- Independence of critical point type pair, neutrino mass, rarity
- BAO features 'reversed' $\rightarrow$ dips for oppositely biased tracers

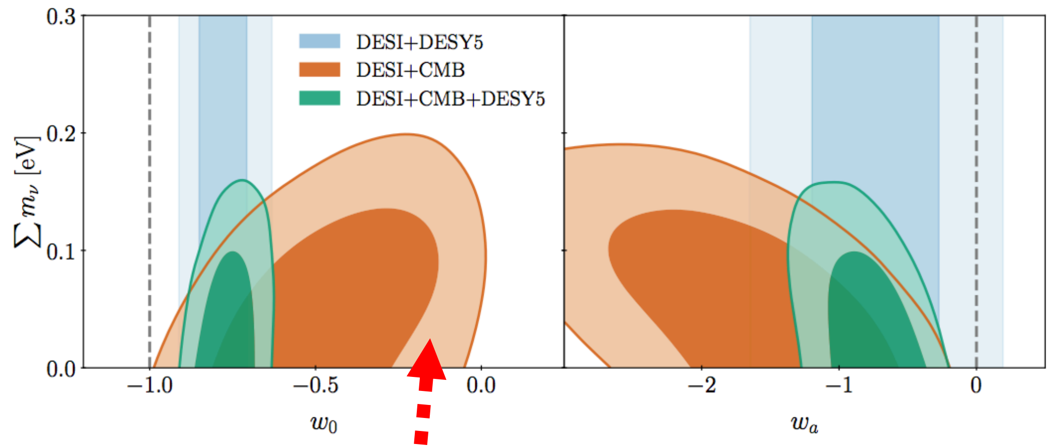
Synergies, Contributions, Outlook

Key Results & Main Messages: Neutrinos

Flat ΛCDM



Flat w_0-w_aCDM



DESI DR2 Results II:
arXiv:2503.14738

- Give up ΛCDM? Negative neutrino mass?
- Moderate tension with lower limits from neutrino oscillations (Ω_m-driven)
- Beyond traditional methods

?

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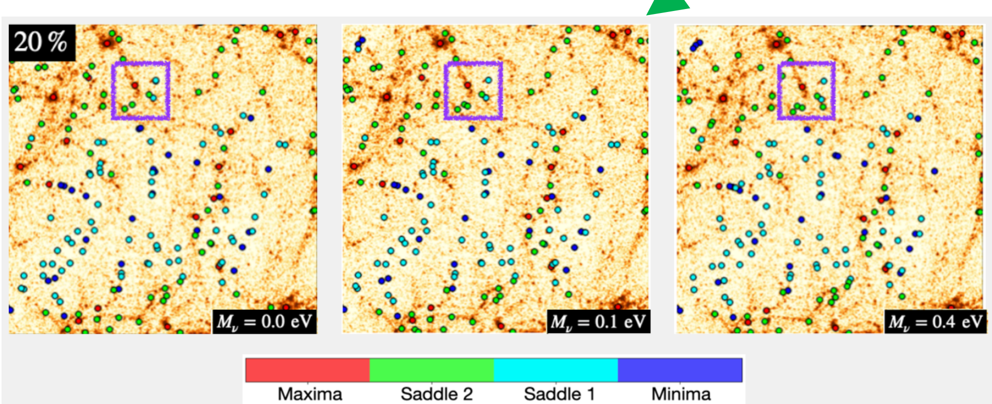

The Cosmological Preference for Negative Neutrino Mass

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