Neutrinos and impact on cosmology

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What cosmology can tell us about neutrinos

✗

- Mixing angles
- Phases
- Dirac vs Majorana

✓

- Absolute neutrino mass scale
- Number of neutrinos

- Hierarchy (?)

A short cosmic history

	Inflation	Neutrinos decouple Formation of light elements (BBN)	Photons decouple and propagate (CMB)	Dark ages	Cosmic dawn	The present Universe
Temperature		1 MeV	1 eV			2.7 K
Redshifts (z)		10^8	1080			0

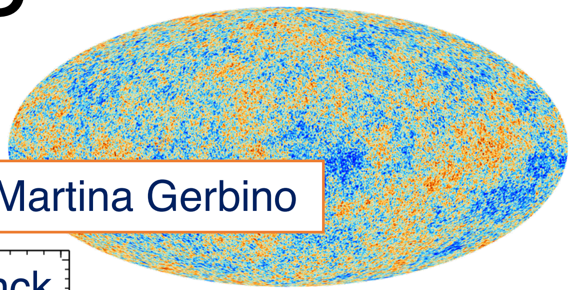
(KATRIN $m_\beta < 0.8$ eV 90% CL)

$$z_{\mathrm{nr},i} \sim \frac{m_{\nu,i}}{0.5\,\mathrm{meV}}$$

Neutrino non-rel.

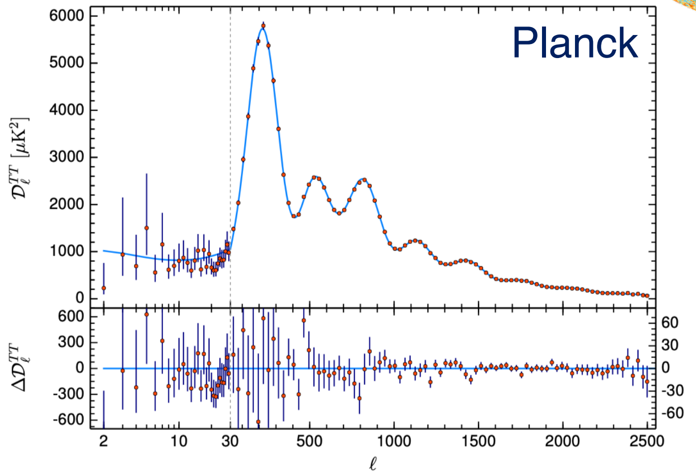
Cosmological observables

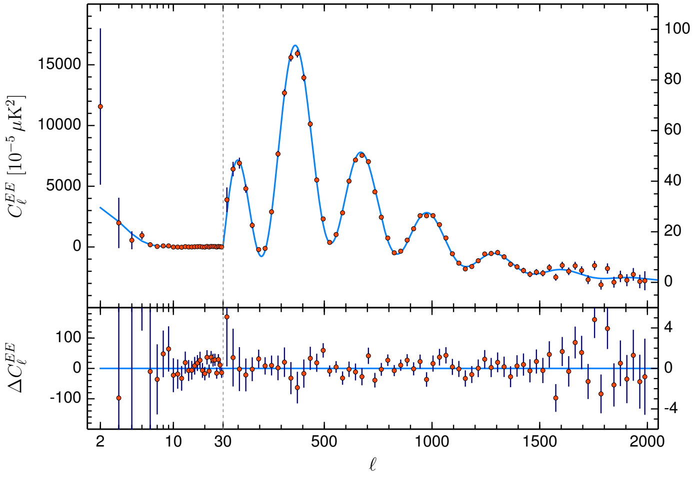
Early Universe



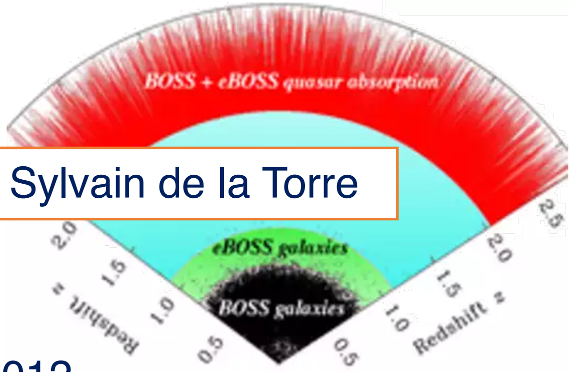
CMB

Talk by Martina Gerbino





Late Universe

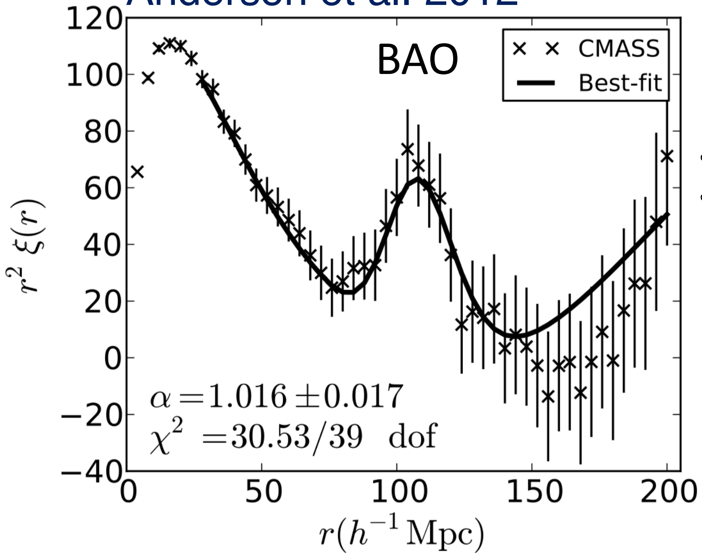


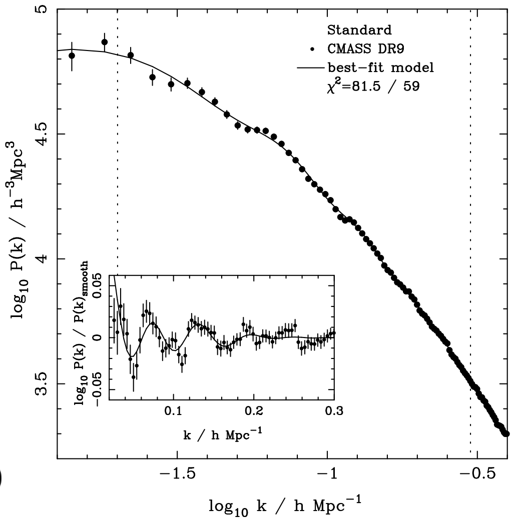
LSS

Talk by Sylvain de la Torre

Galaxy positions and weak lensing

Anderson et al. 2012



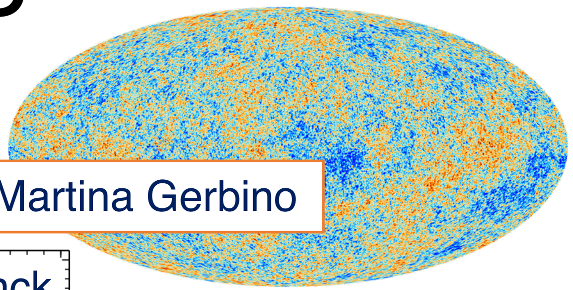


$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}) \rangle$$

$$P(k) = \int \xi(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} d^3x$$

Cosmological observables

Early Universe



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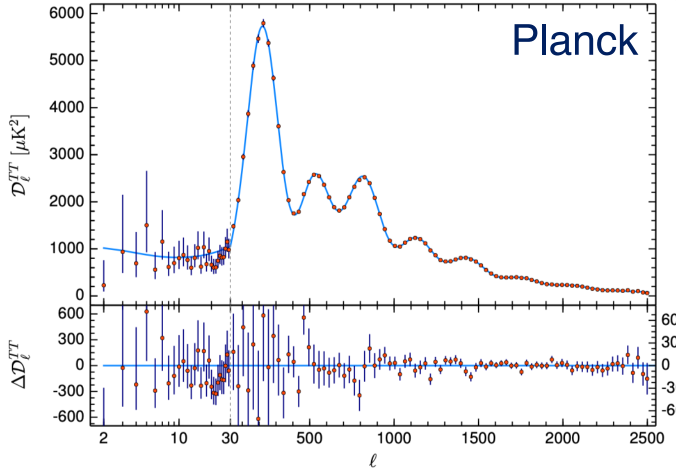
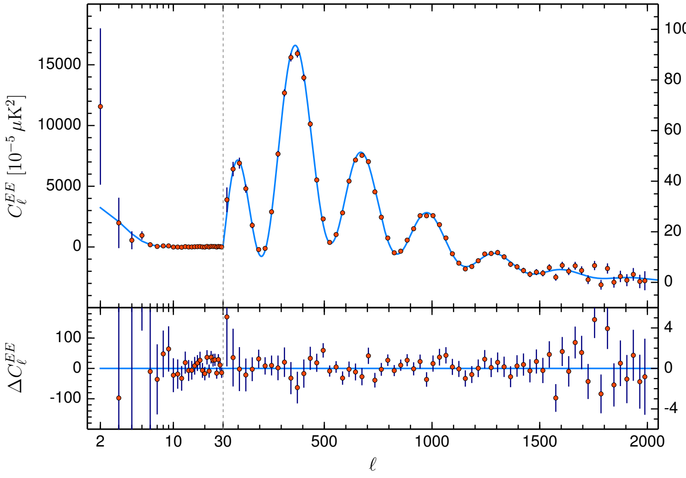
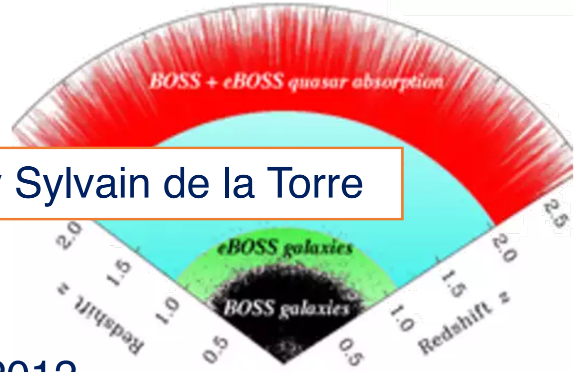




Late Universe



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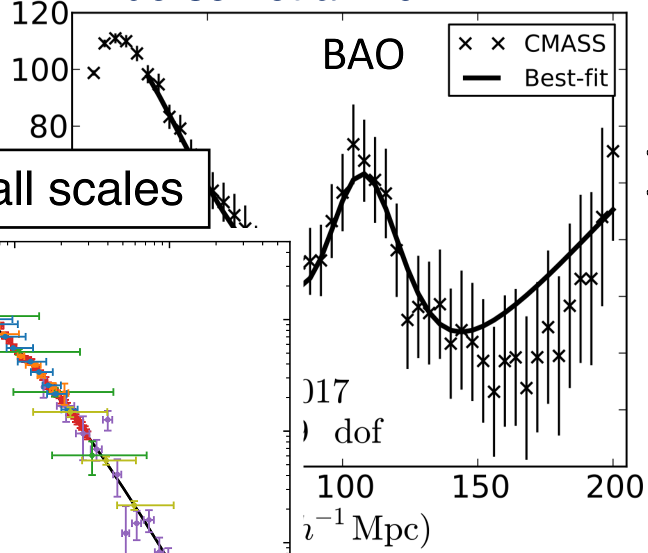
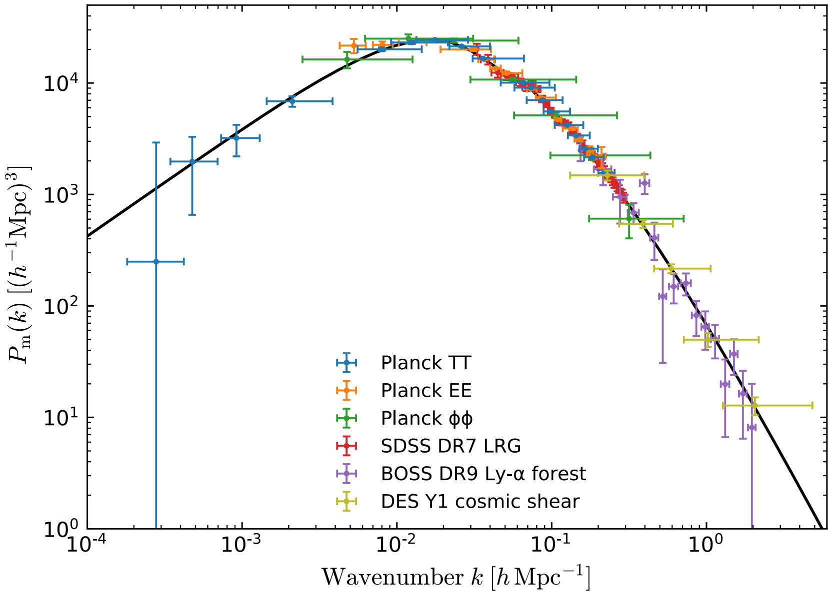
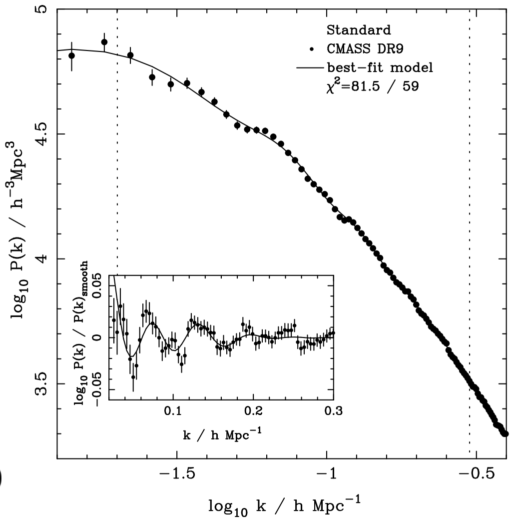


Large scales - small scales

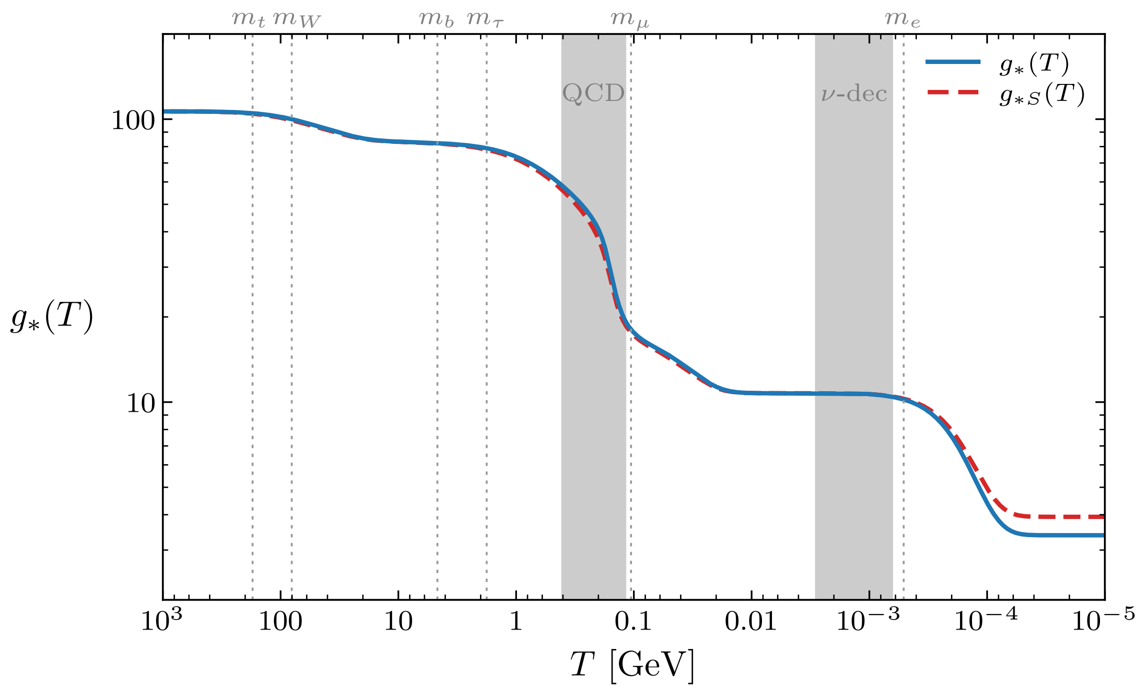




$\delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle$

$$P(k) = \int \xi(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} d^3x$$

Cosmic neutrino background (CνB)



$$\Gamma_{\text{weak}} \sim H \text{ at } T \sim 1 \text{ MeV}$$

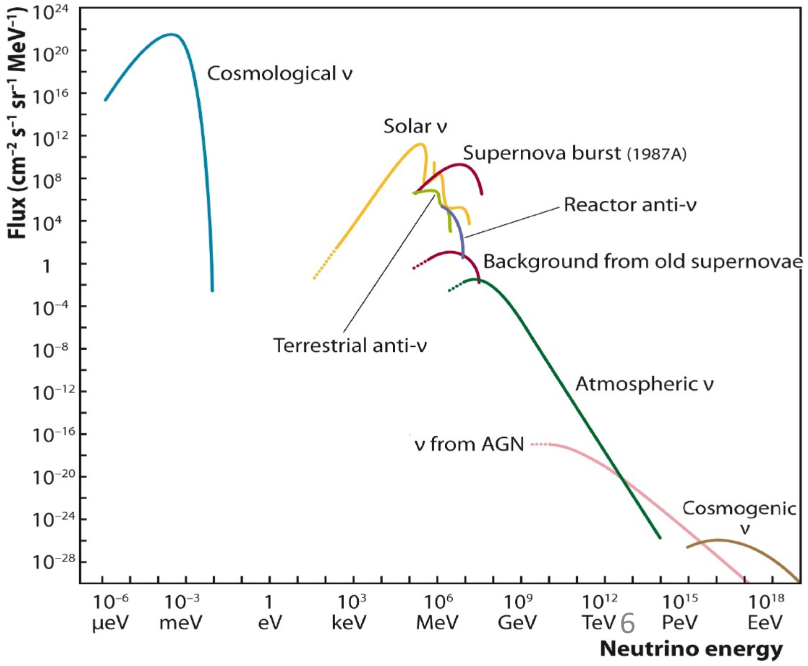
$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3}$$

Indirect probes from cosmology

Today:

$T_\nu \sim 1.9$ K

$n_\nu \sim 300$ cm^{-3}



Cosmic neutrino background (CνB)

- Neutrino number N_{eff} = $\frac{\text{(energy density of neutrinos + BSM light particles)}}{\text{(energy density of one neutrino species)}}$

  $N_{eff}^{SM} = 3.044 \pm 0.001$ [Mangano et al. 2002, Froustey et al. 2020, Escudero 2020]

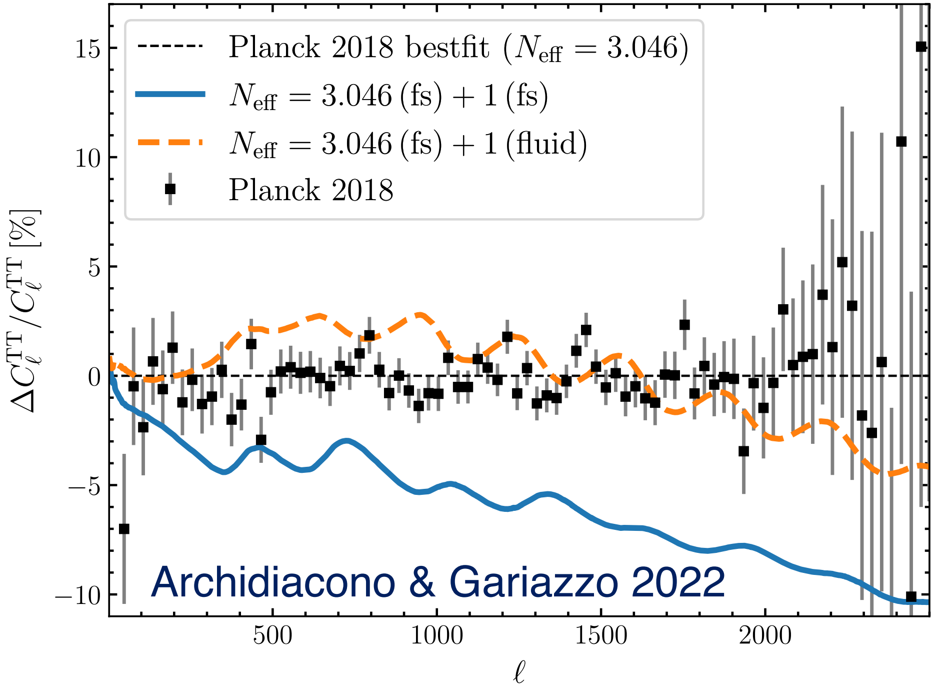
- Neutrino mass $\Omega_\nu h^2 = \frac{\sum m_{\nu,i}}{93.12\text{eV}} \sim 0.5\%$ [Mangano et al. 2005, Froustey et al. 2020]

  not individual masses [Archidiacono et al. 2020]

Indirect probes of CνB

- Impact on CMB [Bashinsky & Seljak 2004, Lesgourgues & Pastor 2006, Gerbino & Lattanzi 2018]

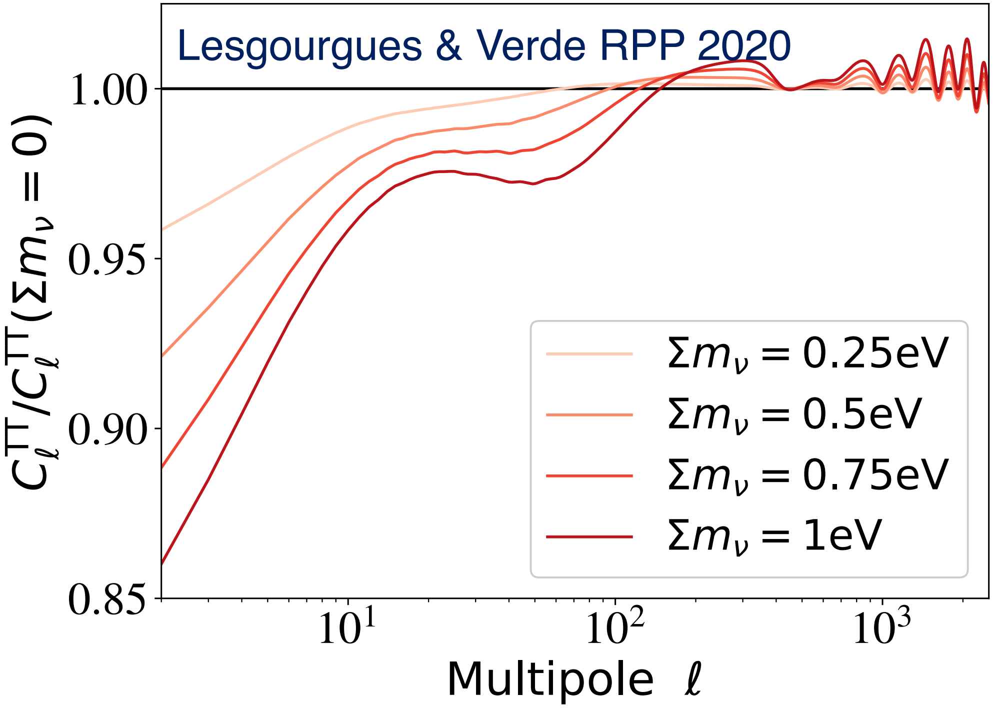
N_{eff}



Planck TT,TE,EE + lowE

$N_{eff} = 2.92 \pm 0.36$ (95%cl)

Σm_ν



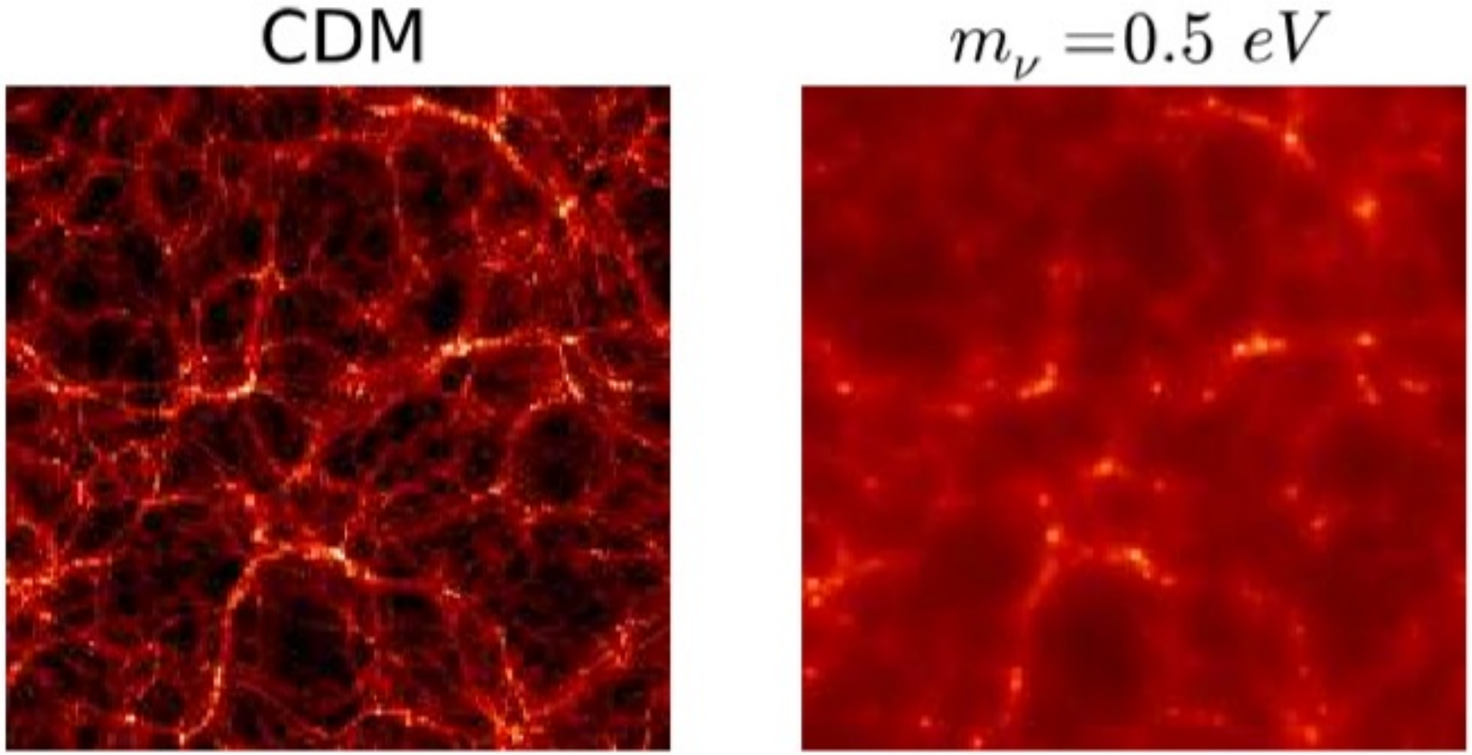
Planck TT,TE,EE + lowE

$\Sigma m_\nu < 0.26$ eV (95%cl)

…+BBN $N_{eff} = 2.78 \pm 0.28$ (68%cl) [Pisanti et al. 2021]

Indirect probes of CνB

- Impact on structure formation: Free-Streaming $d_{\mathrm{FS},i} \sim 1\,\mathrm{Gpc}\frac{eV}{m_{\nu,i}}$



Maria Archidiacono – University of Milan

Indirect probes of CνB

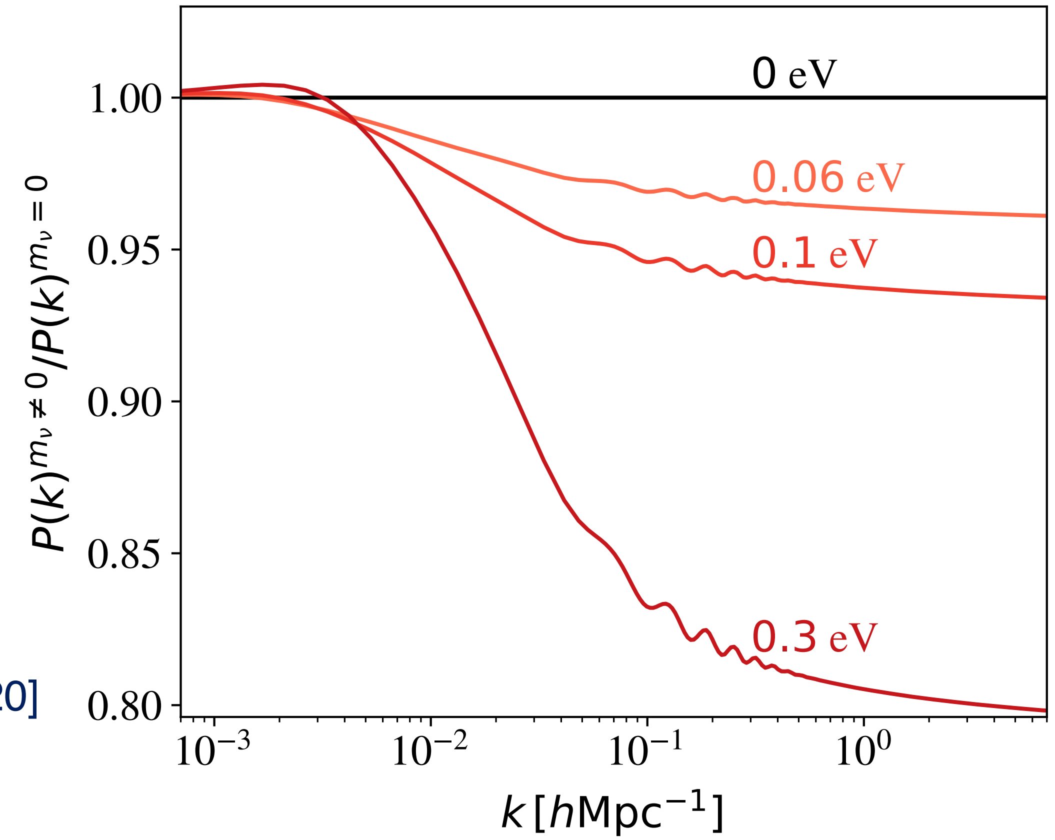
- Impact on power spectrum of matter density fluctuations

$$\delta_{\rm cdm}^{m_\nu=0} \propto a$$

$$\delta_{\rm cdm}^{m_\nu\neq0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$$

Planck TT,TE,EE + low E + lensing + BAO
$\Sigma m_\nu < 0.12$ eV (95%cl)

Planck TT,TE,EE + low E + lensing + BAO
+Lyman-α
$\Sigma m_\nu < 0.09$ eV (95%cl) [Palanque-Delabrouille et al. 2020]



Neutrino mass constraints: recent history

Data	Σm_ν
Planck TTTEEE	< 0.26 eV (95% cl)[1]
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Planck TTTEEE + lensing + BAO	< 0.12 eV (95% cl)[1]
Planck TTTEEE + lensing + BAO + Ly-α	< 0.09 eV (95% cl)[2]

[1] Planck Collaboration 2018

[2] Palanque-Delabrouille et al. 2020

Neutrino mass constraints: near future

Data	Σm_ν
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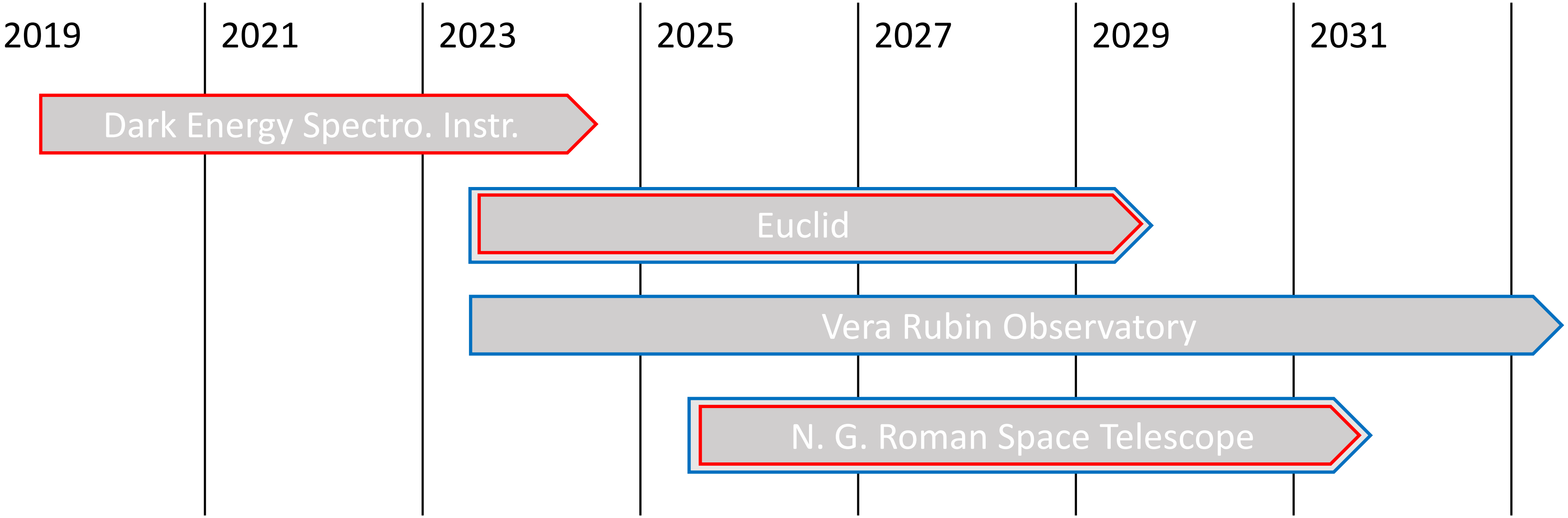
CMB-SO	90-110 meV[3]

[3] The Simons Observatory 2019

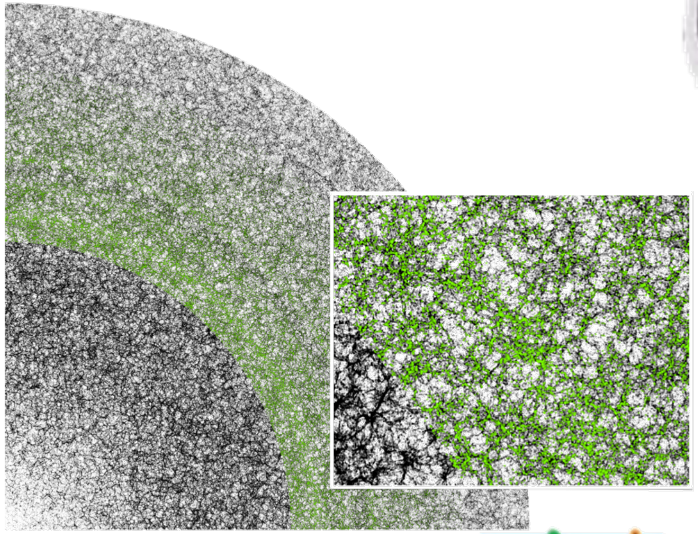
Stage IV Large Scale Surveys



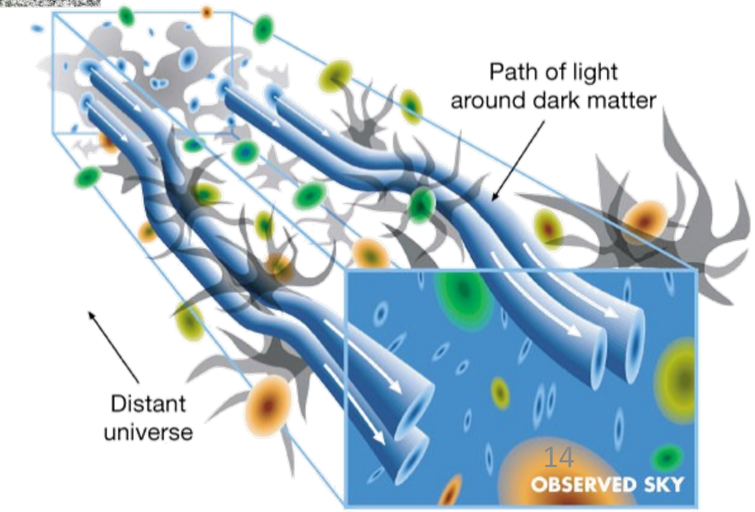
Spectroscopy
Imaging

Euclid in a nutshell

See talks by Sylvain de la Torre, Chiara Sirignano, Louis Pierre Marie Gabarra, Francesca Passalacqua, Bianca De Caro, Giovanni Verza



- **ESA** M2 space mission in the framework of the Cosmic Vision program
- Launch scheduled for **2023**. Duration **> 6 years**
- 1.2m telescope with two instruments: Visible Imager (**VIS**) and Near Infrared Spectrometer and Photometer (**NISP**)
- Wide survey (**15.000 deg^2**) and deep survey (40 deg^2 in 3 different fields)
- Measurements of over **1 billion images** and more than **10 millions spectra** of galaxies out to z>2
- Main scientific objectives: **Dark Energy**, **Dark Matter**, and **General Relativity**
- Primary probes: **Galaxy Clustering** and **Weak Lensing** (1% accuracy)



Indirect probes of CνB

- Impact on power spectrum of matter density fluctuations

$$\delta_{\rm cdm}^{m_\nu=0} \propto a$$

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Planck TT,TE,EE + low E + lensing + BAO
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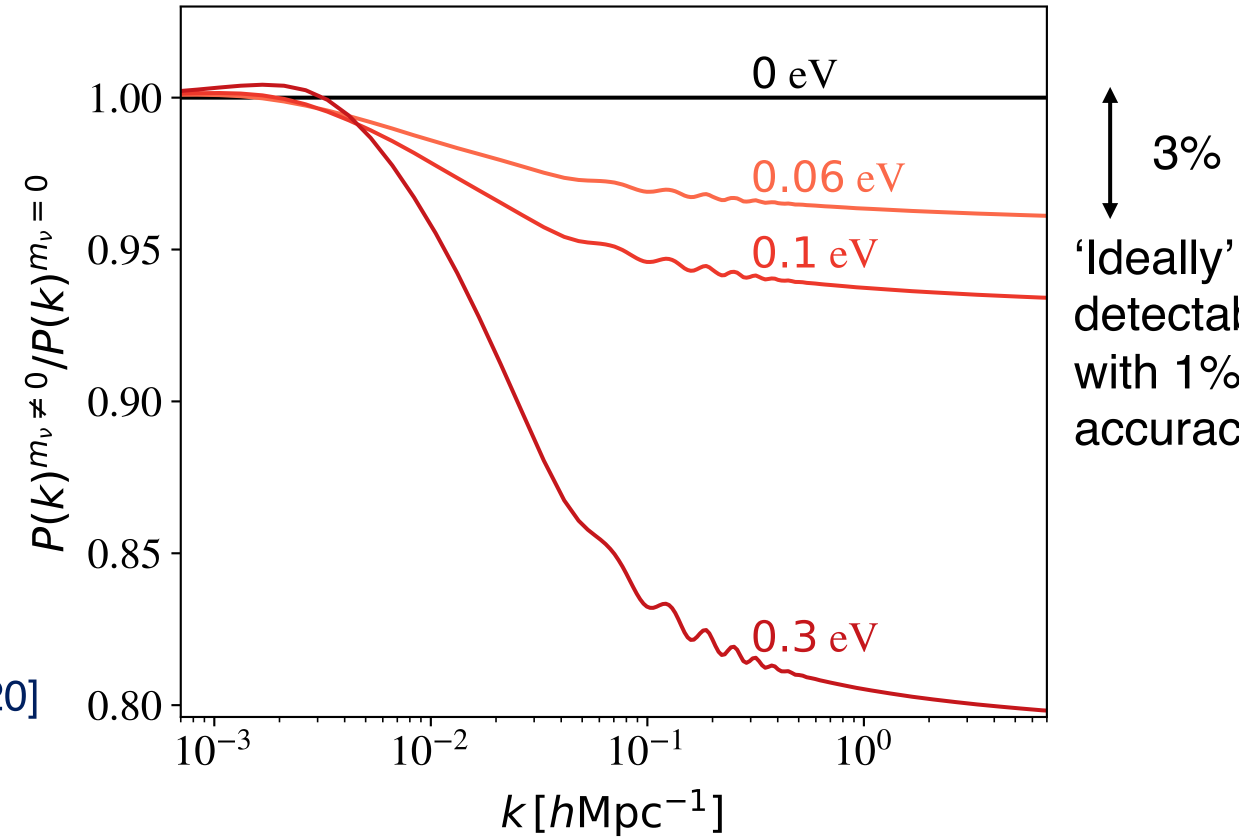
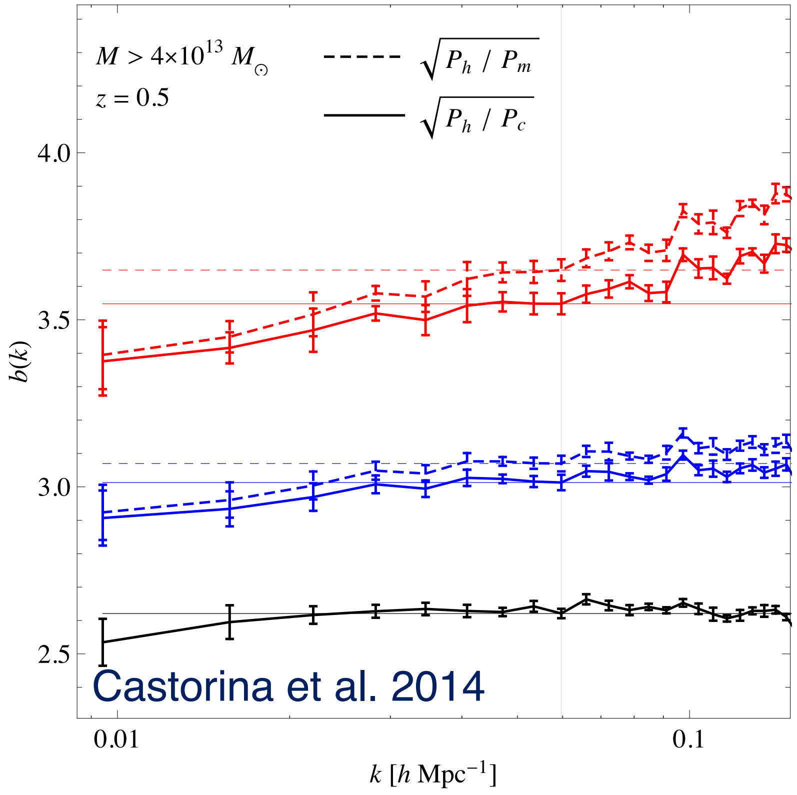


'Ideally' detectable with 1% accuracy

Known unknowns (systematics, etc.)

1. Galaxy bias $P_{galaxy} = b^2 P_{matter} + N$
   [Castorina et al. 2014, Vagnozzi, Brinckmann, MA et al. 2018]



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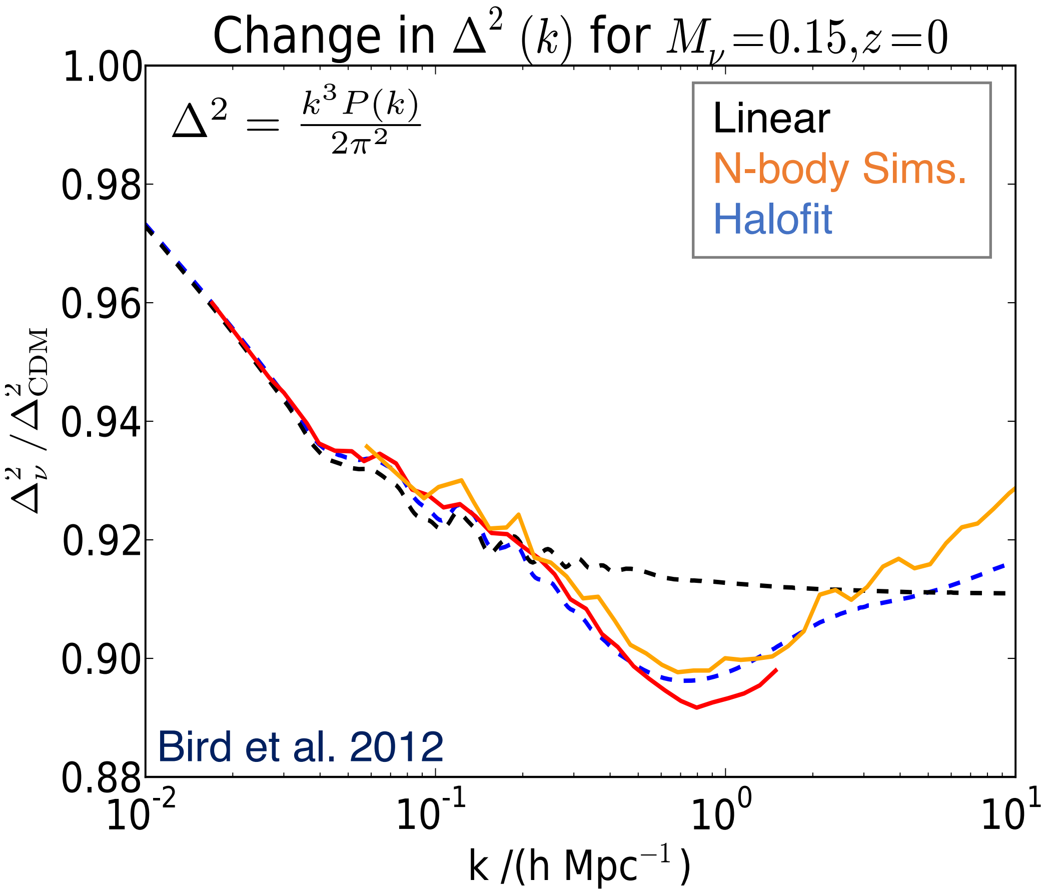

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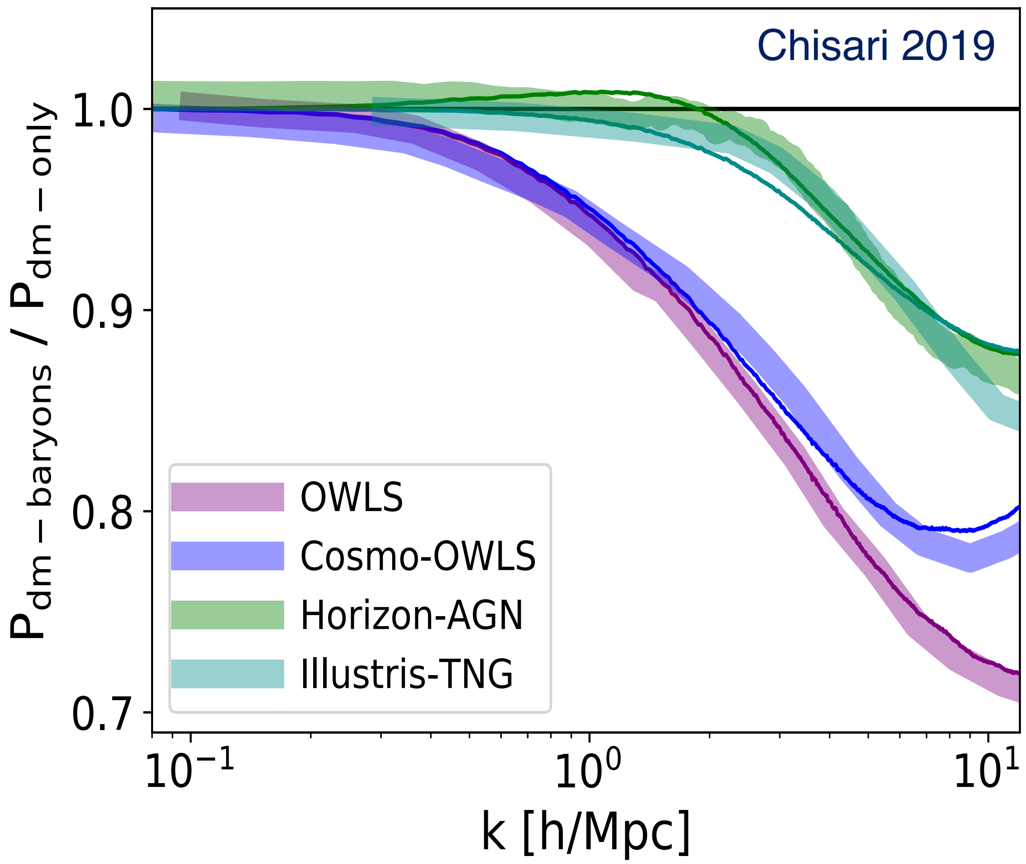
3. Baryonic feedback [Chisari 2019]



Neutrino mass constraints: near future

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Data	$\sigma(\Sigma m_\nu)$
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Planck + Euclid	20 meV[4]
Planck + Euclid + SKA	15 meV[4]
LiteBIRD + CMB-S4 + Euclid	12 meV[5]

[3] The Simons Observatory 2019
[4] Sprenger, MA et al. 2019
[5] Brinckmann, Hooper, MA et al. 2019

Neutrino mass constraints: near future

ΛCDM

Data	Σm_ν
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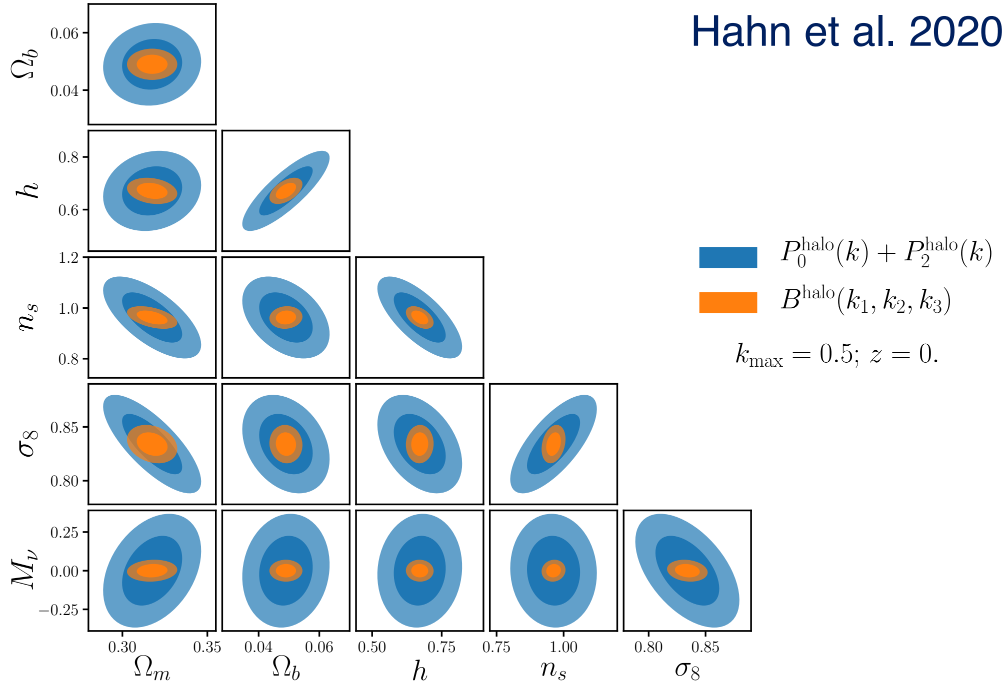
[5] Brinckmann, Hooper, MA et al. 2019

w0wa

Planck + Euclid	30 meV[4]

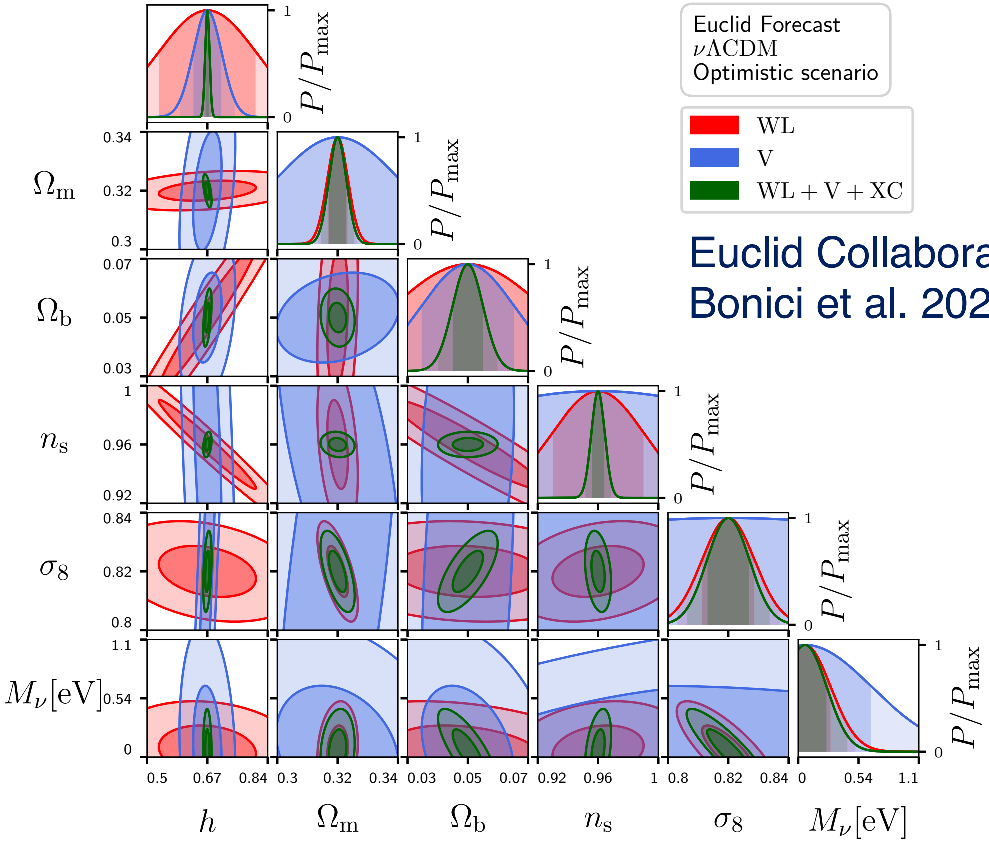
Breaking degeneracies

Hahn et al. 2020



The bispectrum improves $\sigma(\Sigma m_\nu)$ over a factor 5 wrt the power spectrum

[see also Chudaykin et al. 2019]



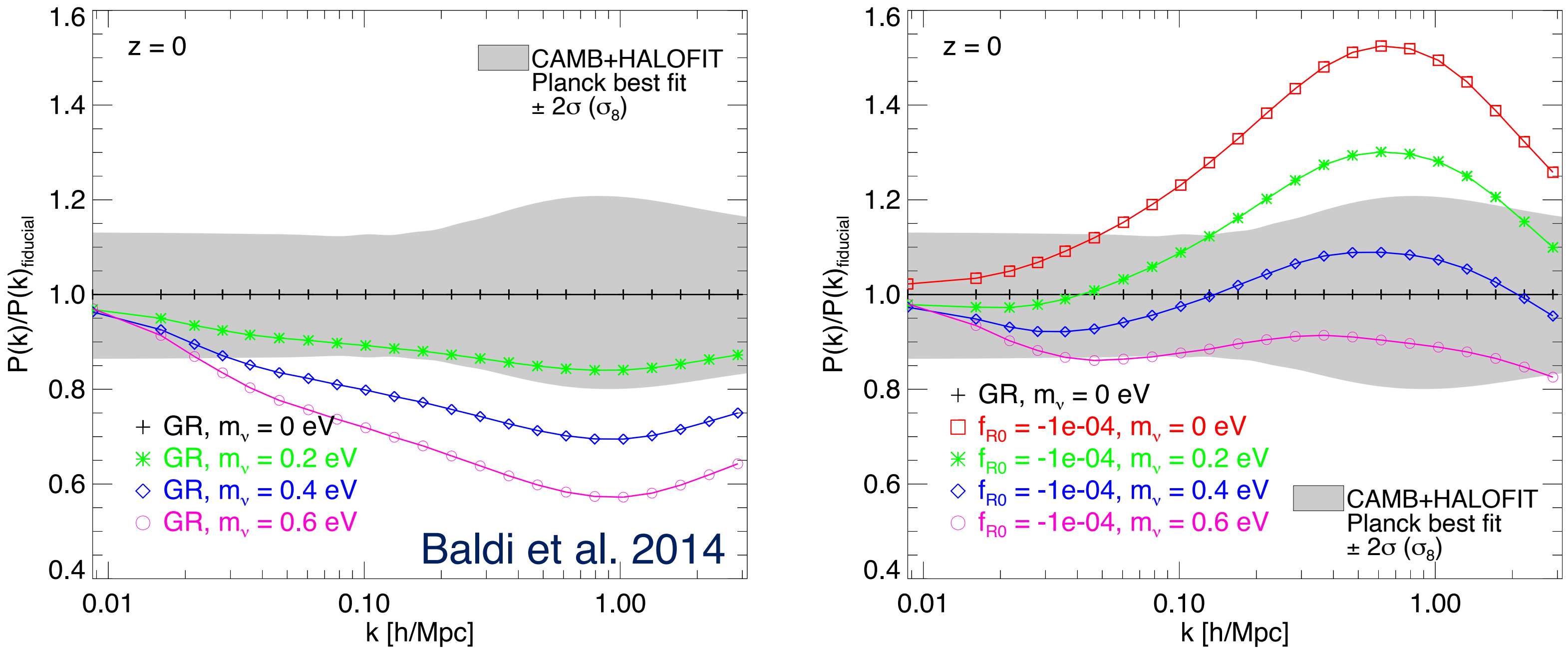
Euclid Collaboration Bonici et al. 2020

See talk by Giovanni Verza

The nightmare scenario

What if cosmology prefers $\Sigma m_\nu < 0.06$ eV (= minimum of neutrino oscillations)?

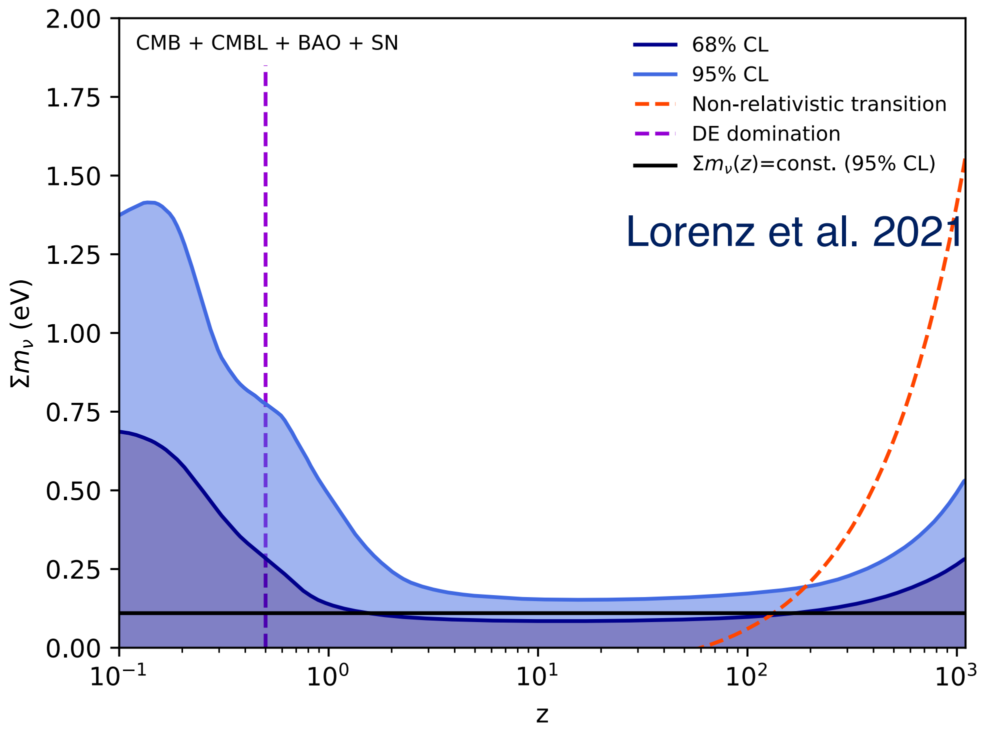
- Extended cosmological models (beyond ΛCDM)
    - Modified gravity [Starobinsky 1980, Hu & Sawicki 2007, Baldi et al. 2014]



The nightmare scenario

What if cosmology prefers $\Sigma m_\nu < 0.06$ eV (= minimum of neutrino oscillations)?

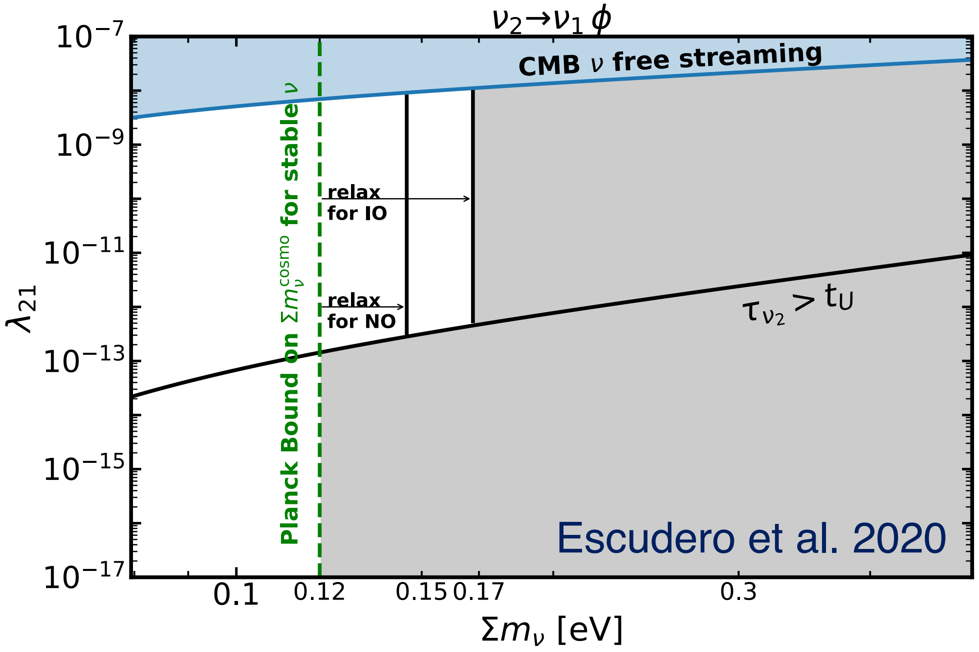
- Extended particle physics models (beyond SM)
  - Time varying neutrino masses [Lorenz et al. 2021, Huang et al. 2022]



The nightmare scenario

What if cosmology prefers $\Sigma m_\nu < 0.06$ eV (= minimum of neutrino oscillations)?

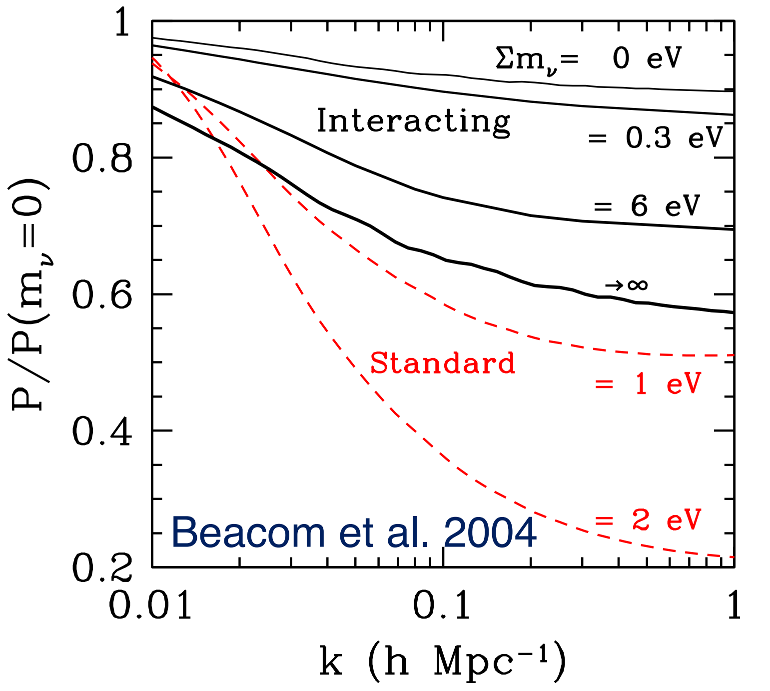
- Extended particle physics models (beyond SM)
    - Invisible neutrino decay into BSM particles, e.g. lighter (sterile) neutrinos plus a massless (pseudo)scalar particle [Barenboim et al. 2021, Escudero et al. 2020]



The nightmare scenario

What if cosmology prefers $\Sigma m_\nu < 0.06$ eV (= minimum of neutrino oscillations)?

- Extended particle physics models (beyond SM)
  - Neutrino self-interactions and annihilation [“Neutrinoless Universe” Beacom et al. 2004, Esteban et al. 2021, Blinov et al. 2020, Kreisch et al. 2020, Archidiacono et al. 2020]



Hierarchy?

The debate over the hierarchy

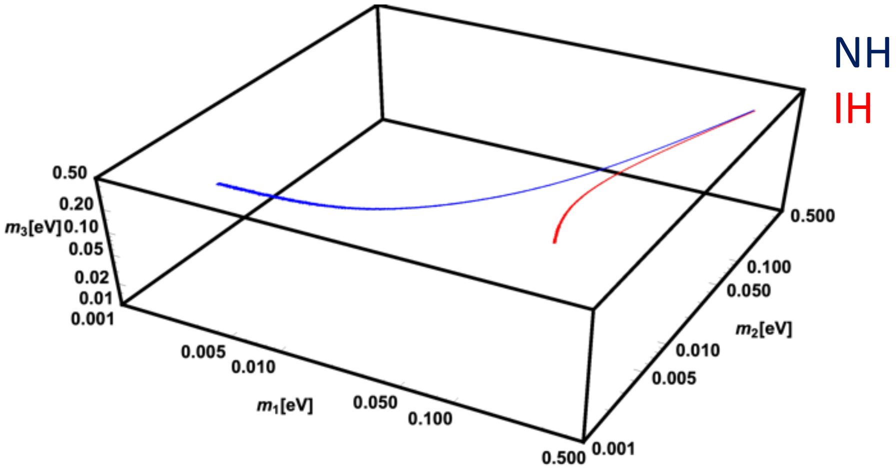
Degenerate hierarchy (DH) approximation: $m_1 = m_2 = m_3$

The debate over the hierarchy

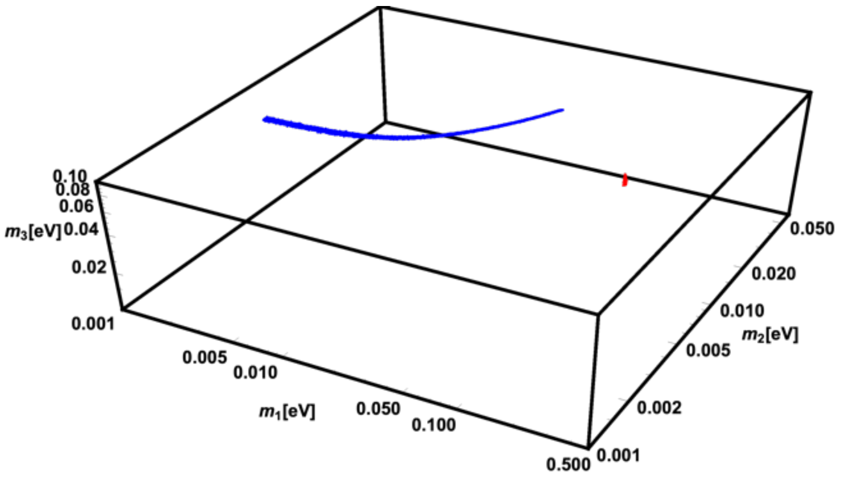
Degenerate hierarchy (DH) approximation: $m_1 = m_2 = m_3$

«Decisive evidence for the normal hierarchy» Jimenez et al. 2022

Neutrino oscillation data



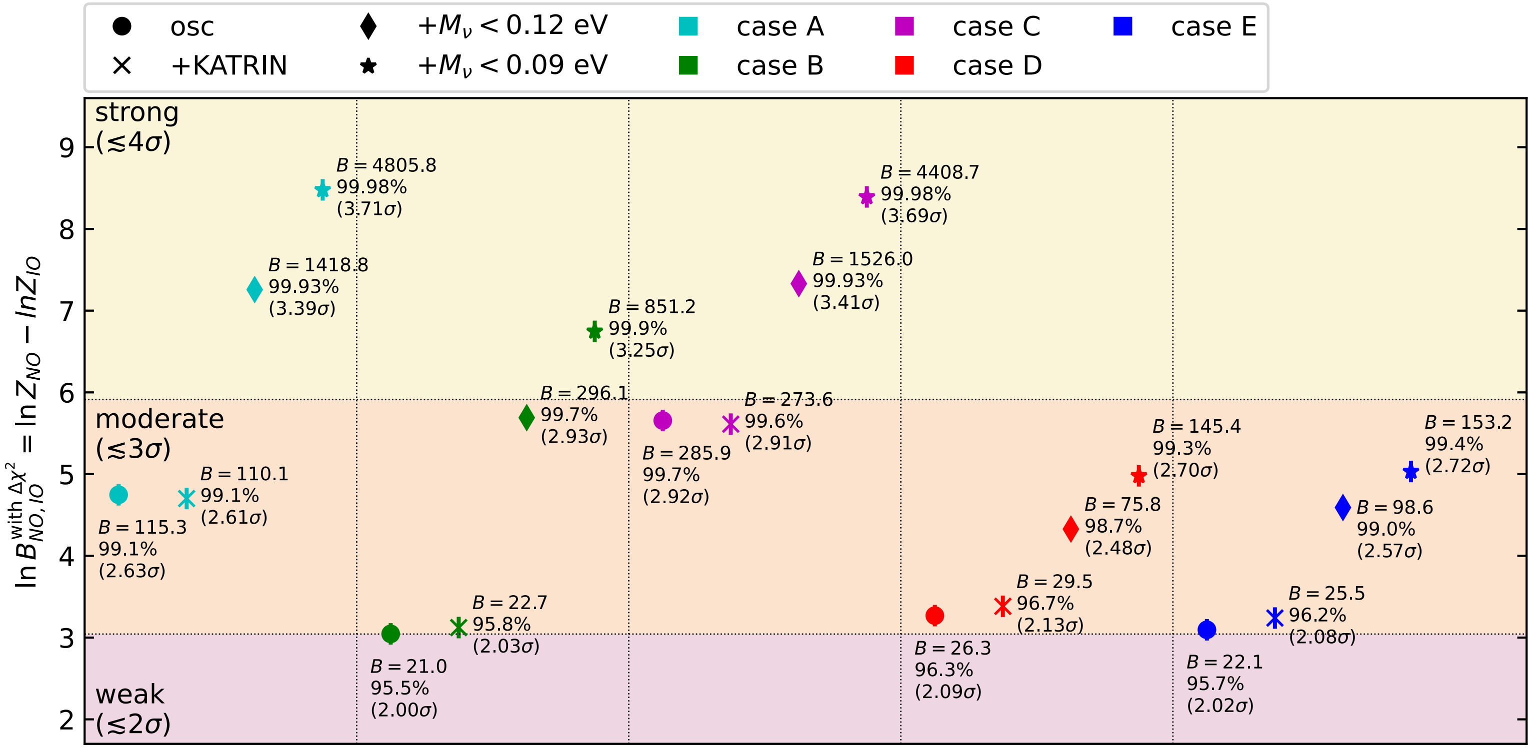
+ Cosmological bound on Σm_ν



The debate over the hierarchy

Degenerate hierarchy (DH) approximation: $m_1 = m_2 = m_3$

«Moderate evidence, mostly driven by neutrino oscillation data» Gariazzo et al. 2022 (see also Hergt et al. 2021)

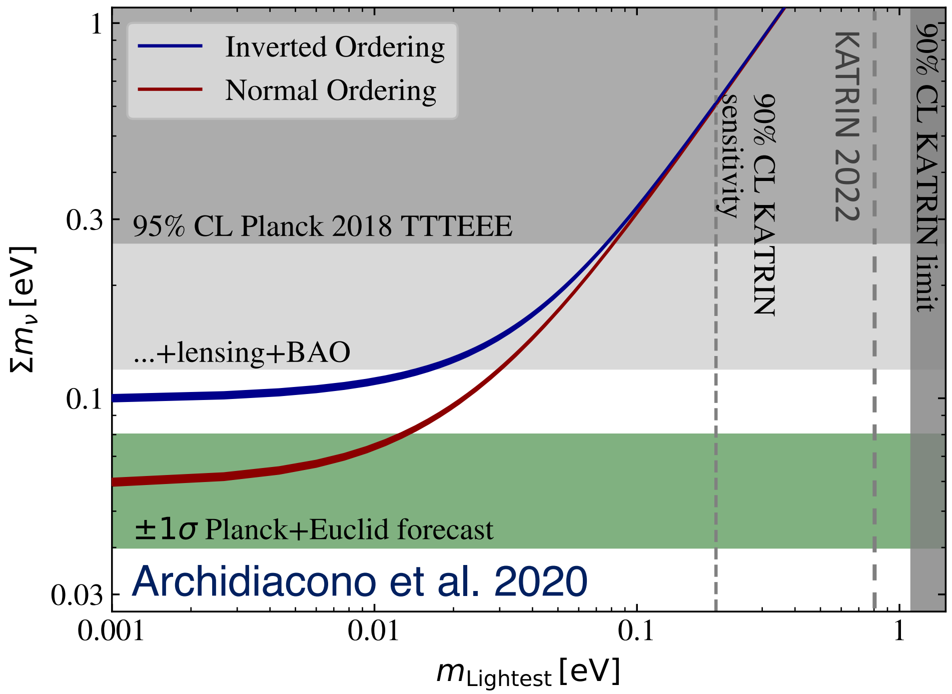


<u>case A</u> is based on Jimenez et al.: a Gaussian prior on the logarithm of the three neutrino mass eigenstates

"The significance of the preference in favor of NO changes significantly when we consider different parameterizations."

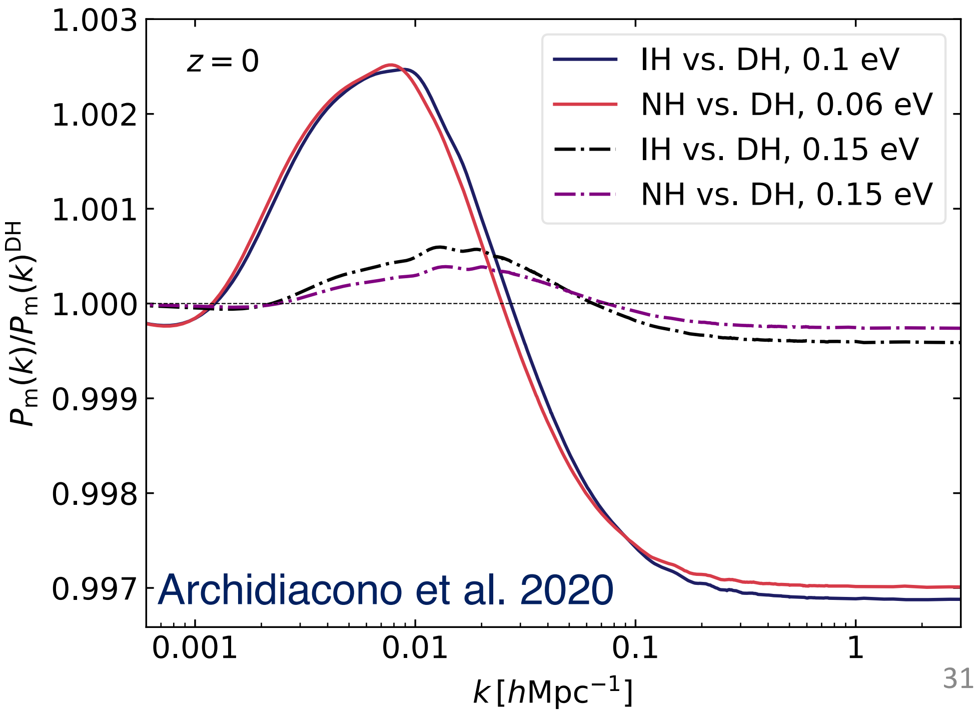
For a different approach, Long et al. 2018, and Heavens & Sellentin 2018

The debate over the hierarchy



Future (current?) cosmological data can potentially disfavour IH

Cosmology is not sensitive to individual masses

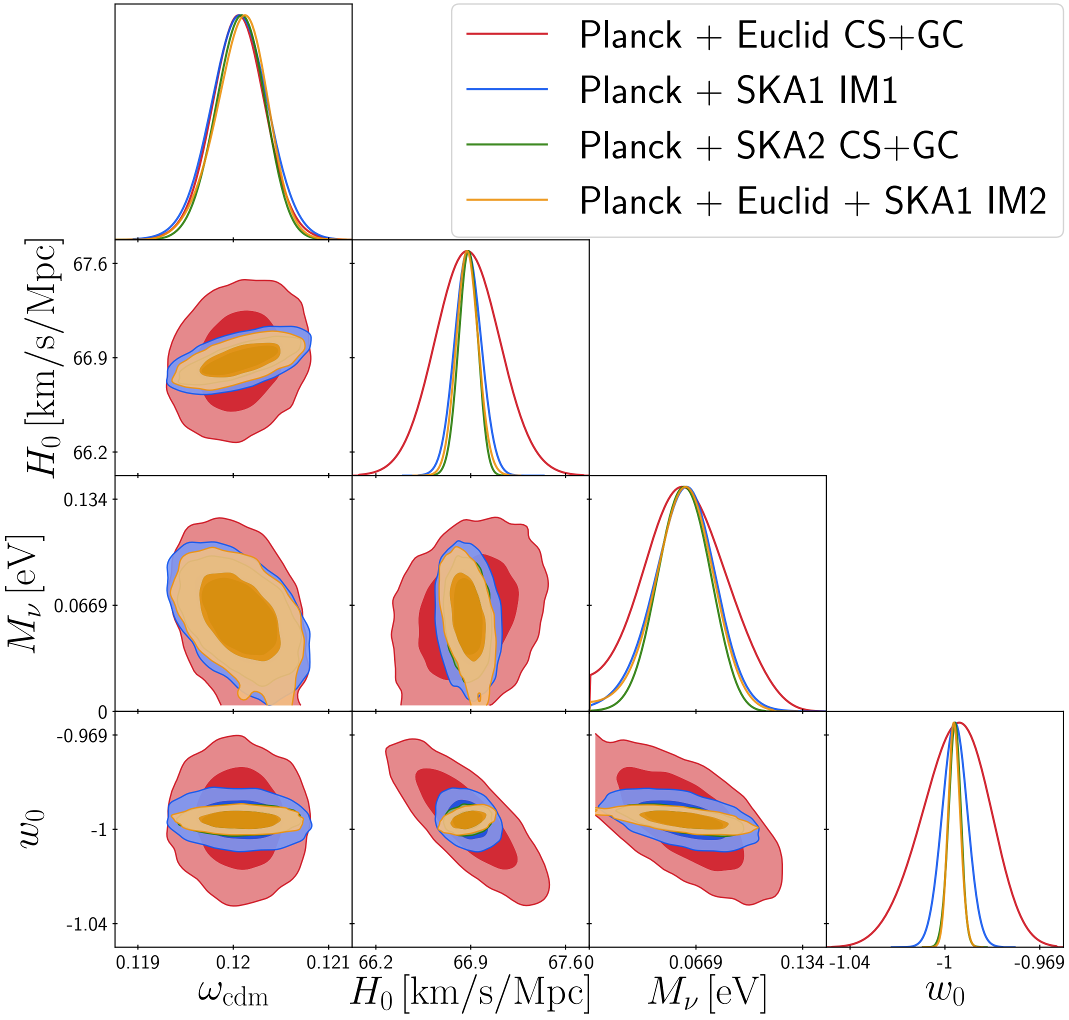


Conclusions

- Current cosmological bounds $\Sigma m_\nu < 0.12$ - 0.09 eV (95%cl)
- Future LSS and CMB surveys can provide a 2 to 4σ evidence for a non-zero neutrino mass sum
- Caveat:
  - Systematic effects
  - Model dependence
- A «Neutrinoless Universe» (or a mismatch with direct experiments) will require to rethink the ΛCDM paradigm

Backup

Degeneracies and model dependence

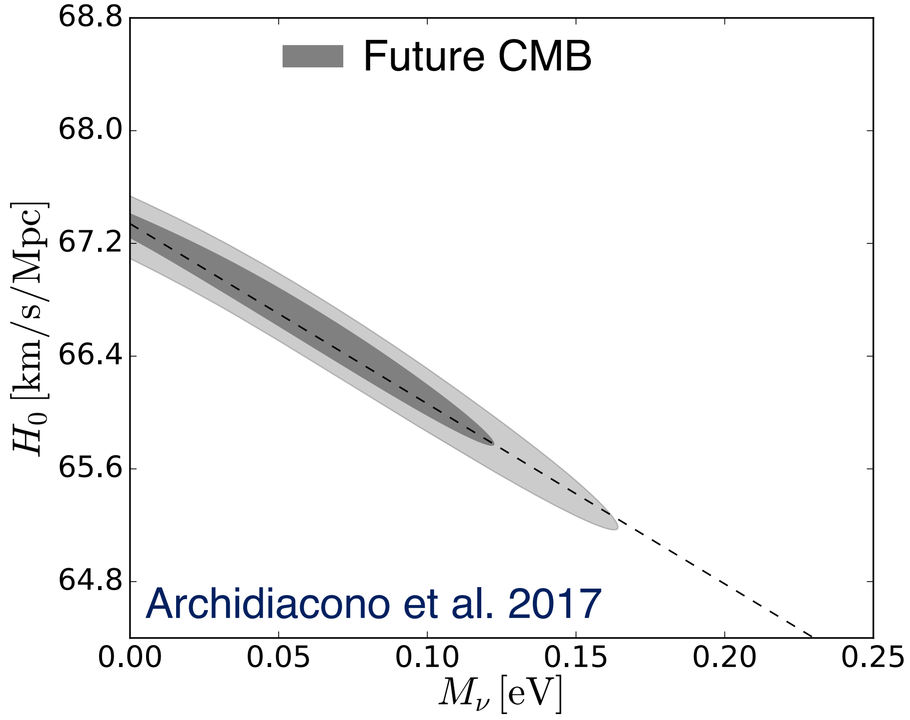


Sprenger, MA et al. 2018

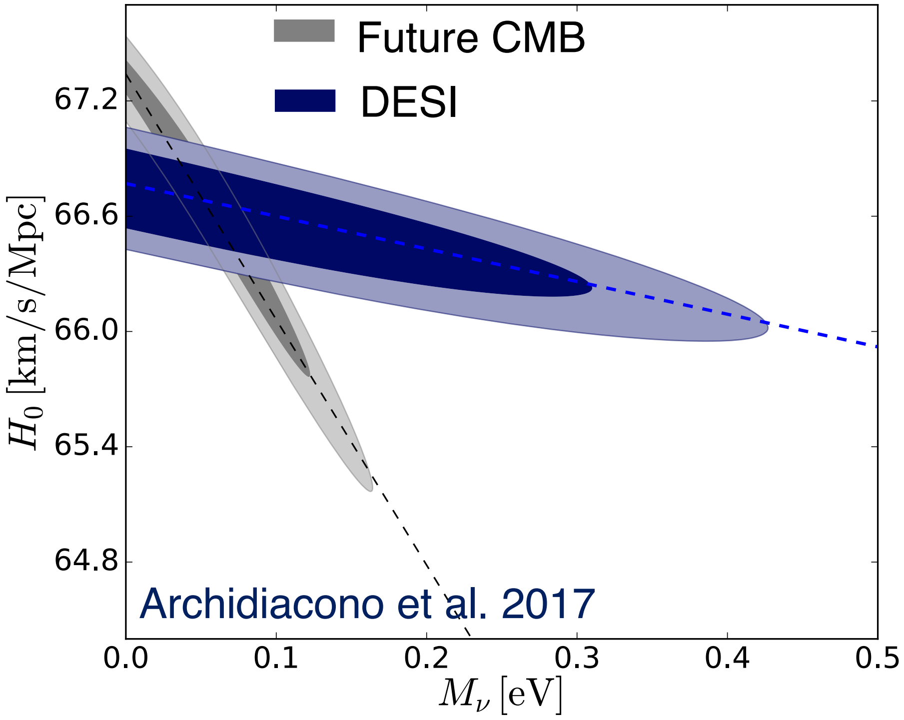
Current bounds and future constraints are model dependent, i.e. they can be relaxed in extended models (beyond ΛCDM)

Higher order statistics can break degeneracies in extended models [Chudaykin et al. 2019, Hahn et al. 2020, Ajani et al. 2020]

Degeneracies and model dependence



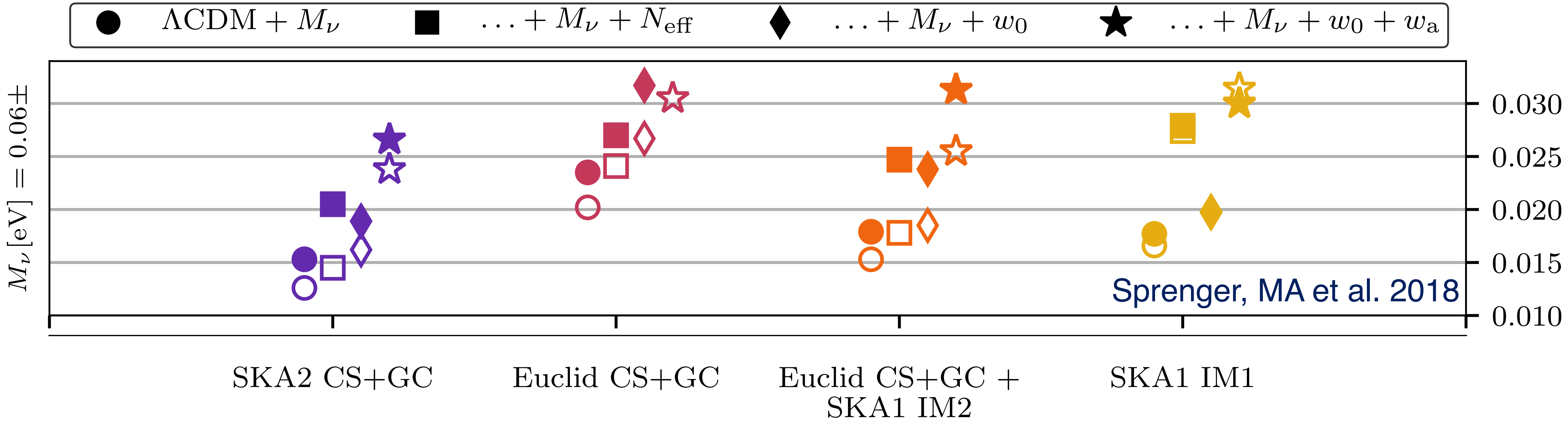
The ability of parameter A to mimic the effect of parameter B leading to the same observables



Joint analysis of independent observables can break parameter degeneracy

Degeneracies and model dependence

Current bounds and future constraints are model dependent, i.e. they can be relaxed in extended models (beyond ΛCDM)



Higher order statistics can break degeneracies in extended models [Chudaykin et al. 2019, Hahn et al. 2020, Ajani et al. 2020]