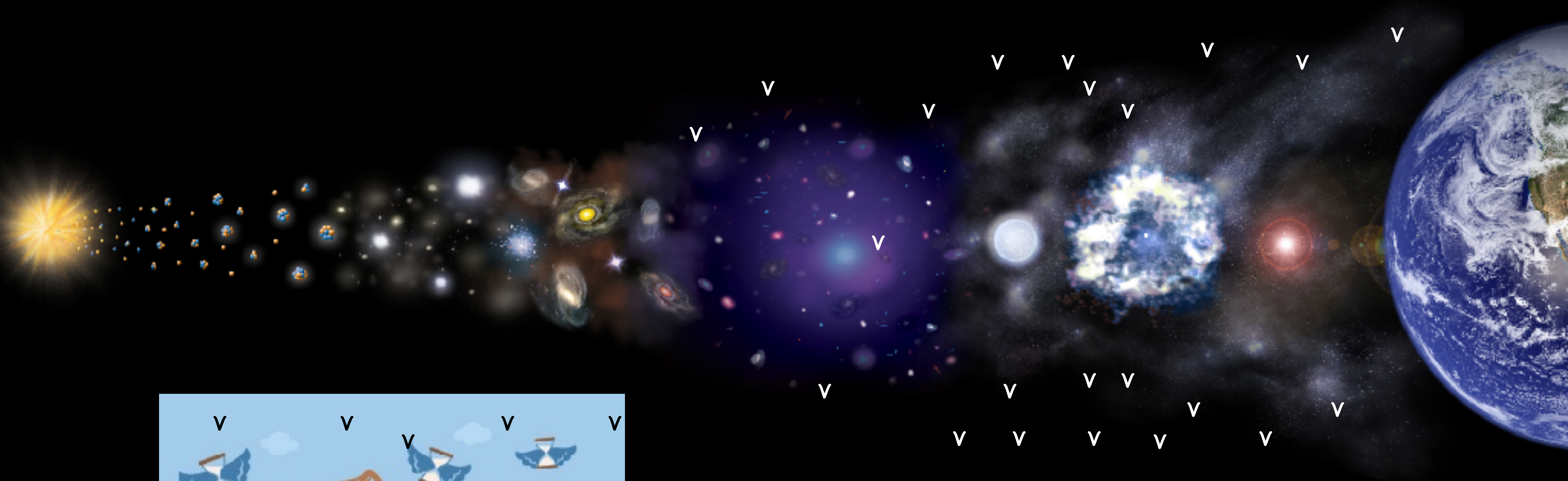
Neutrino masses: knowns and unknowns from Cosmology *et al*



Olga Mena

IFIC-CSIC/UV Valencia (Spain)

invisiblesPlus

elusives

neutrinos, dark matter & dark energy physics

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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VNIVERSITAT ID VALÈNCIA

EXCELENCIA SEVERO OCHOA

The knowns and the unknowns:

- What we know: Neutrino mass bounds from cosmology

- What we do not know (yet!) but we will probably know: Neutrino mass ordering from bounds on Σm_ν

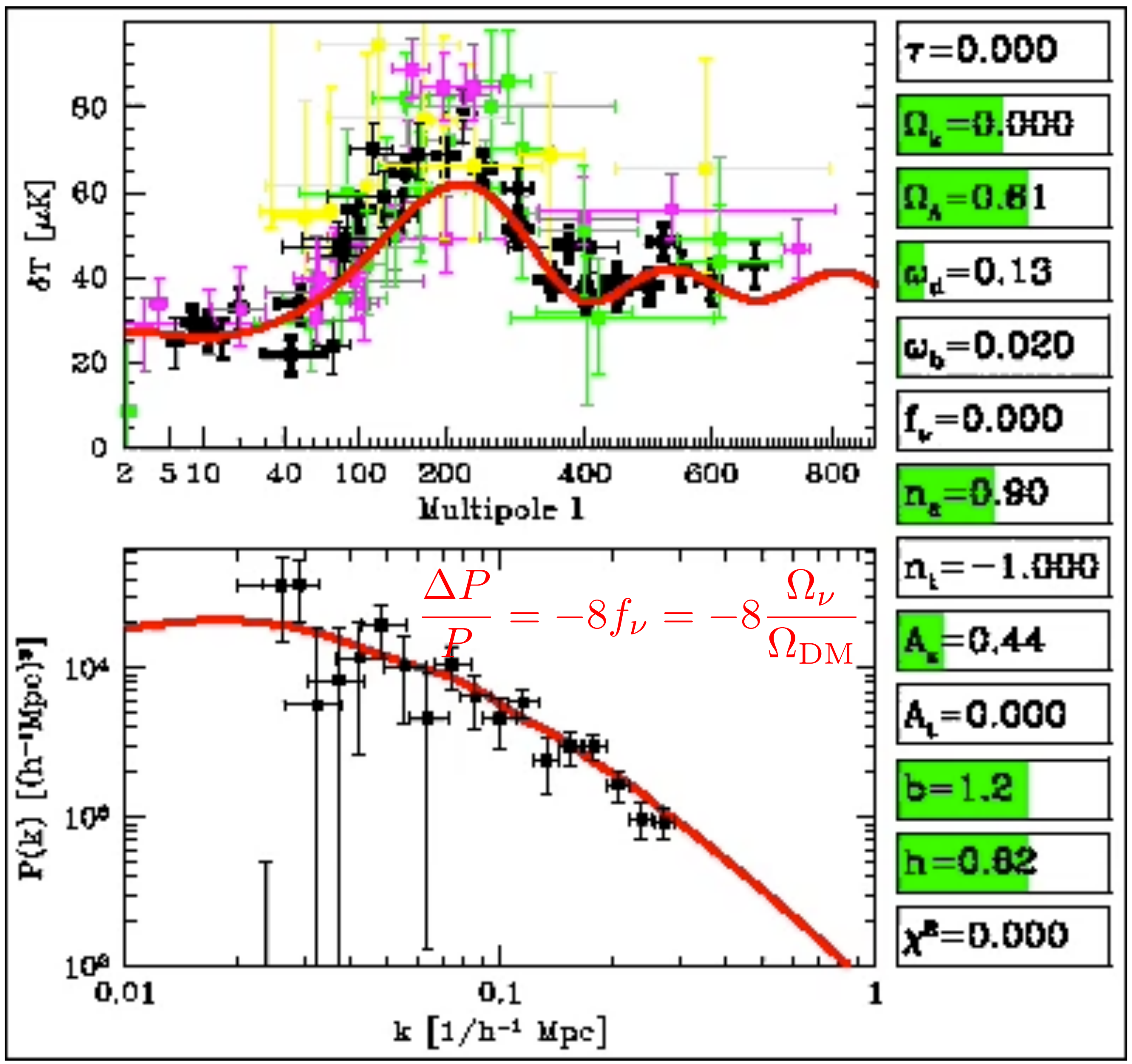
- What will be extremely hard to know: Neutrino mass ordering from individual m_i's

- The Dark Justice League game: Σm_ν versus $w(z)$

What we know: Massive neutrinos cosmological signatures

@ CMB: Early Integrated Sachs Wolfe effect. The transition to the non relativistic neutrino regime gets imprinted in the decays of the gravitational potentials near the recombination period (maximal around the first peak). CMB Lensing.

@LSS: Suppress structure formation on scales larger than the free streaming scale when they turn non relativistic. *(Bond et al PRL'80, Hu et al PRL'98)*



(M. Tegmark)

$$1 + z_{nr,\nu} \simeq 1890 \left(\frac{m_\nu}{1eV}\right)$$

At least two massive eigenstates became non-relativistic in the matter period

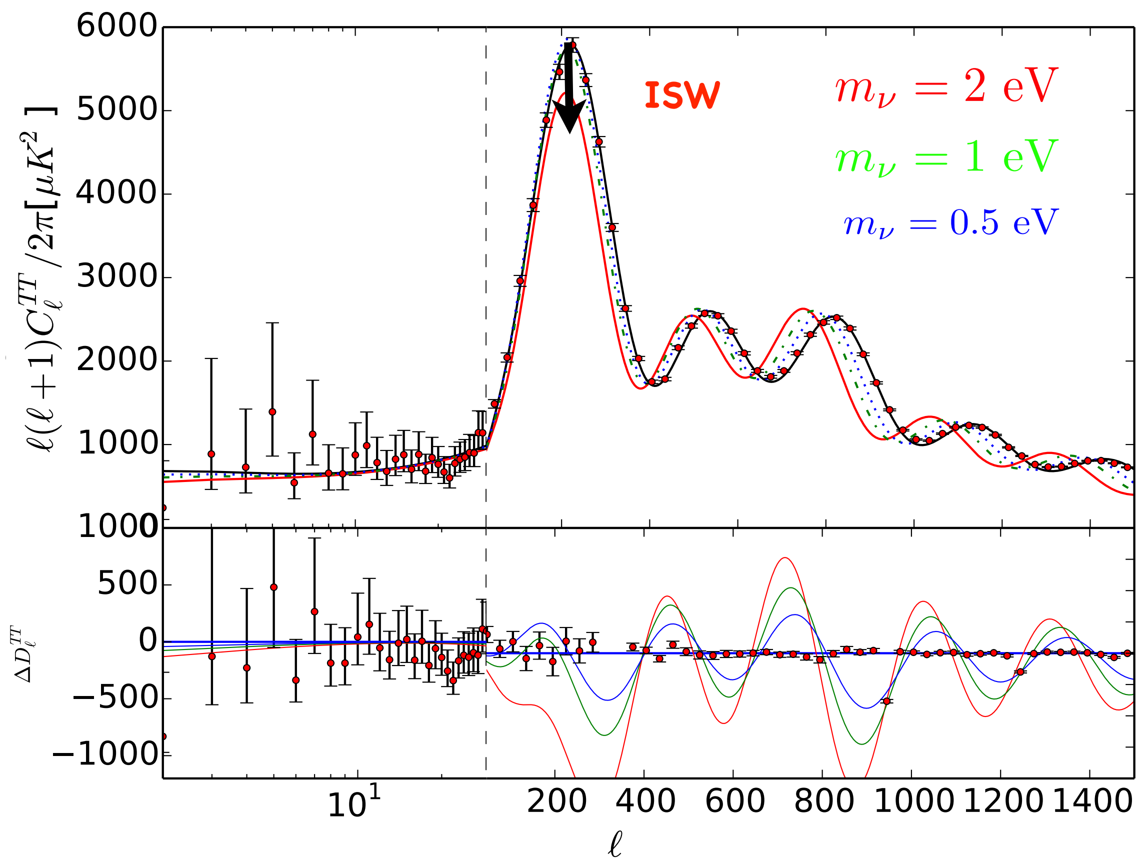
$$k_{fs,\nu}(z) \simeq 0.7 \left(\frac{m_\nu}{1eV}\right) \sqrt{\frac{\Omega_M}{1+z}}\ \mathbf{h\ Mpc^{-1}}$$

What we know: Massive neutrinos cosmological signatures

@ CMB: Early Integrated Sachs Wolfe effect (ISW)

$$\Theta(\hat{n}) = \frac{\delta T}{T}(\hat{n}) \simeq \Theta_0 + \Psi + \hat{n}(\hat{v}_e - v) + \int \dot{\Psi} + \dot{\Phi}\, d\eta$$

In matter domination, the gravitational potential is constant: NO ISW effect!
The transition from the relativistic to the non relativistic neutrino regime gets imprinted in the decays of the gravitational potentials near the recombination period, contributing to the ISW effect!



This early ISW effect leads to a depletion of:

$$\frac{\Delta C_\ell}{C_\ell} = -(\sum m_\nu/0.1\ \mathrm{eV})\%$$

on multipoles:

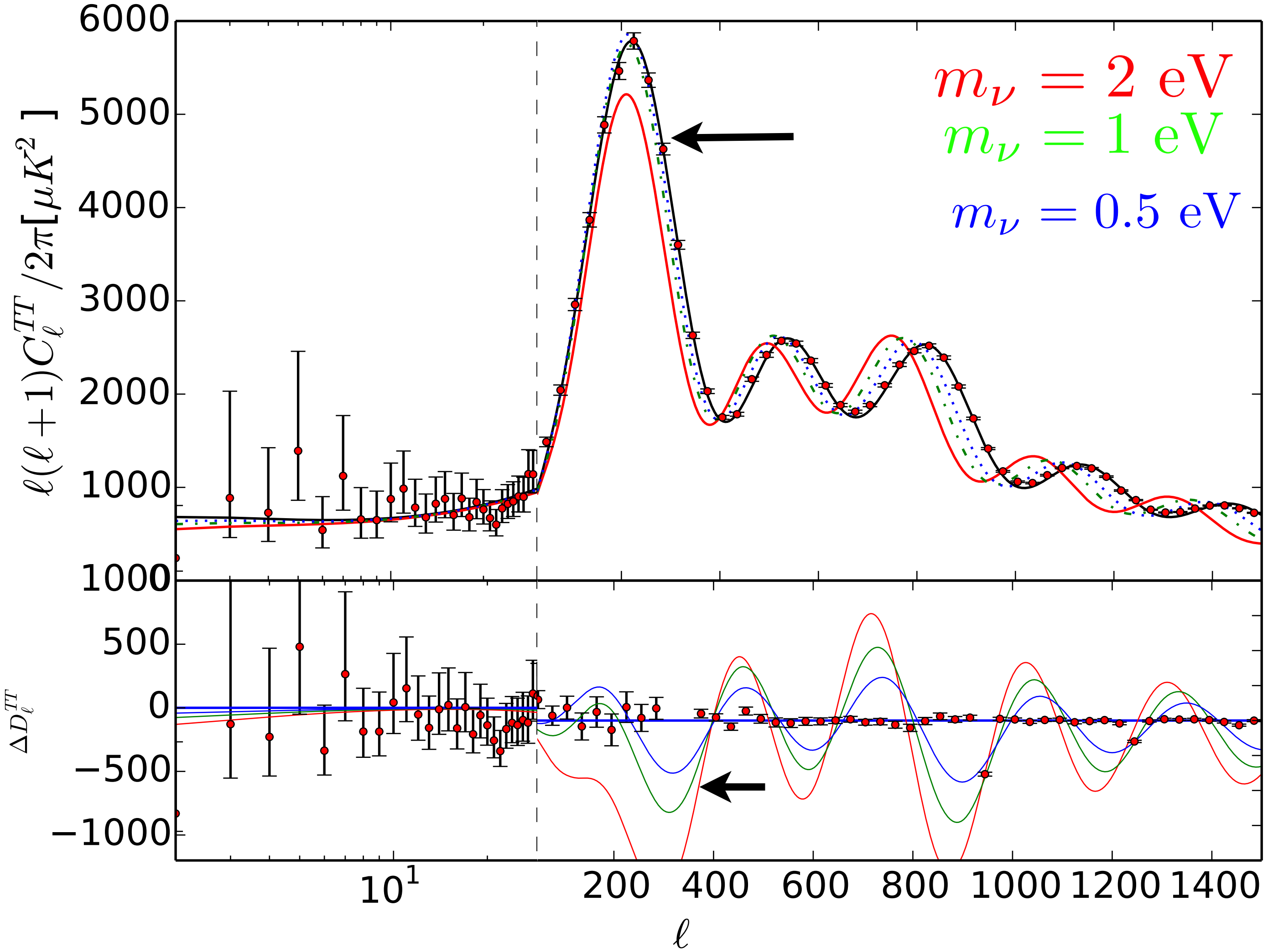
$$20 < \ell < 200$$

(Lesgourgues & Pastor, Phys.Rept'06)

What we know: Massive neutrinos cosmological signatures

@ CMB: Early Integrated Sachs Wolfe effect (ISW).

Shift in the angular position of the peaks.



$$\theta_s = \frac{r_s}{D_A}$$

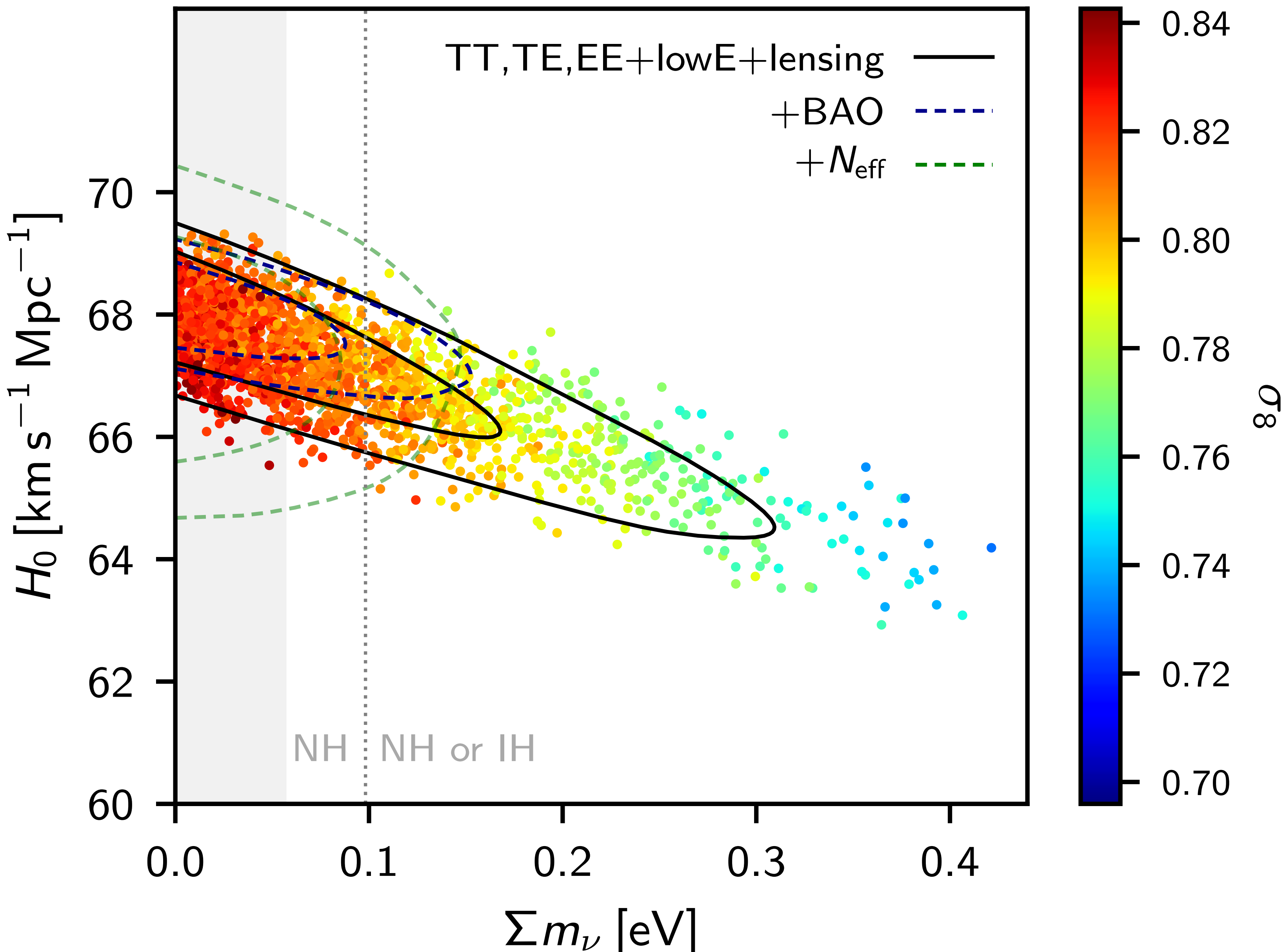
$$r_s = \int_0^{t(z_d)} c_s\,(1+z)dt = \frac{2}{3k_{eq}}\sqrt{\frac{6}{R_{eq}}}\ln\frac{\sqrt{1+R_d}+\sqrt{R_d+R_{eq}}}{1+\sqrt{R_{eq}}}$$

$$D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

The higher the neutrino mass, the lower the angular diameter distance. Peaks shift to lower multipoles. But this effect can be compensated with a lower Hubble constant:

Strong degeneracy between Σm_ν and the Hubble constant H_0!

What we know: Massive neutrinos cosmological signatures



Planck 2018 results, 1807.06209

Strong degeneracy between Σm_ν and the Hubble constant H_0!

What we know: Massive neutrinos cosmological signatures

@ CMB: Early Integrated Sachs Wolfe effect (ISW).

Shift in the angular position of the peaks.

What we know: Massive neutrinos cosmological signatures

@ CMB: Lensing remaps the CMB fluctuations: $\Theta_{\mathrm{lensed}}(\hat{n}) = \Theta(\hat{n} + \nabla\phi(\hat{n}))$

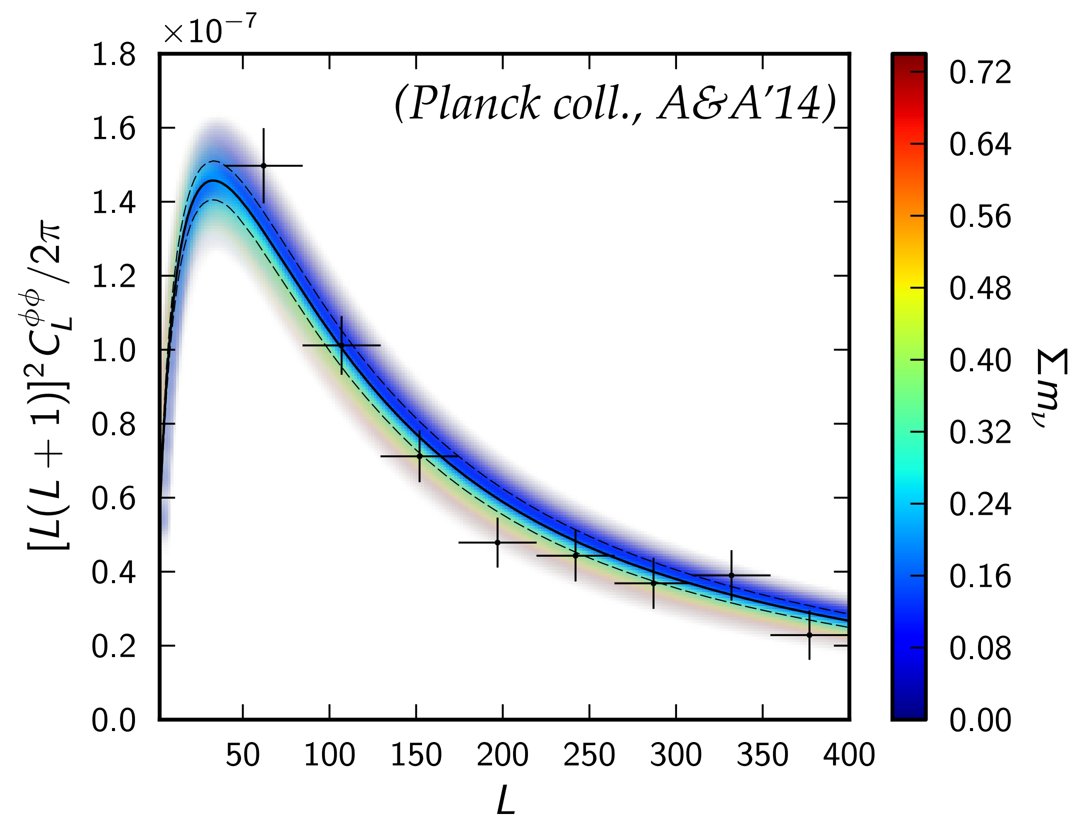
Lensing potential ϕ is a measure of the integrated mass distribution back to the last scattering surface

$$\phi(\hat{n}) = -2\int_0^{z_{rec}} \frac{dz}{H(z)} \Psi(z, D(z)\hat{n}) \left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)$$

Matter distribution ($\Psi(z, D(z)\hat{n})$) — **Geometry** ($\left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)$)

$$C_L^{\phi\phi} = \frac{8\pi^2}{L^3}\int_0^{z_{rec}} \frac{dz}{H(z)} D(z) \left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)^2 P_\Psi(z, k = L/D(z))$$

Neutrino free streaming affects the gravitational potential, changing the gravitational lensing of CMB photons as they traverse these potentials! *(Kaplinghat et al PRL'03, Lesgourgues et al, PRD'06)*



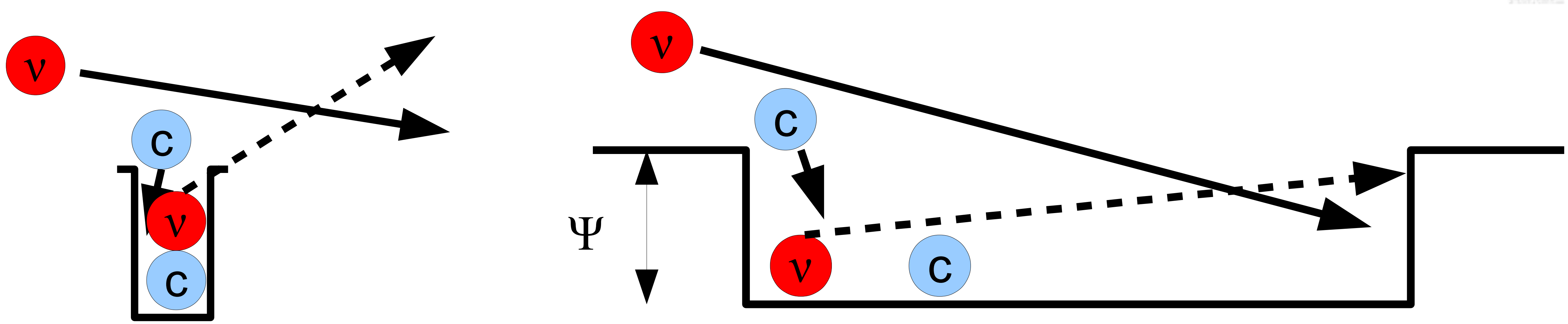
What we know: Massive neutrinos cosmological signatures

Neutrino masses suppress structure formation on scales larger than their free streaming scale when they turn non relativistic. *(Bond et al PRL'80)*

Neutrinos with eV masses are hot relics with large thermal velocities!

$$\langle v_{\rm thermal} \rangle \simeq 81(1+z)\left(\frac{\rm eV}{m_\nu}\right) \ {\rm km\ s^{-1}}$$

Cold dark matter instead has zero velocity and therefore it clusters at any scale!



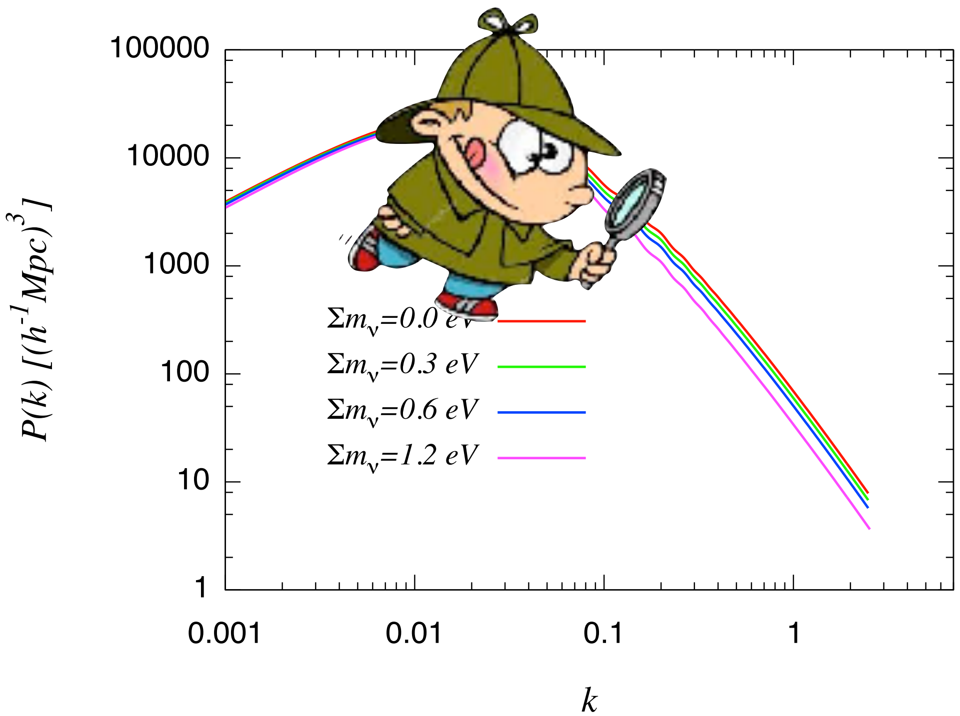
$\lambda \ll \lambda_{fs,\nu} \rightarrow k \gg k_{fs,\nu}$ $\lambda \gg \lambda_{fs,\nu} \rightarrow k \ll k_{fs,\nu}$

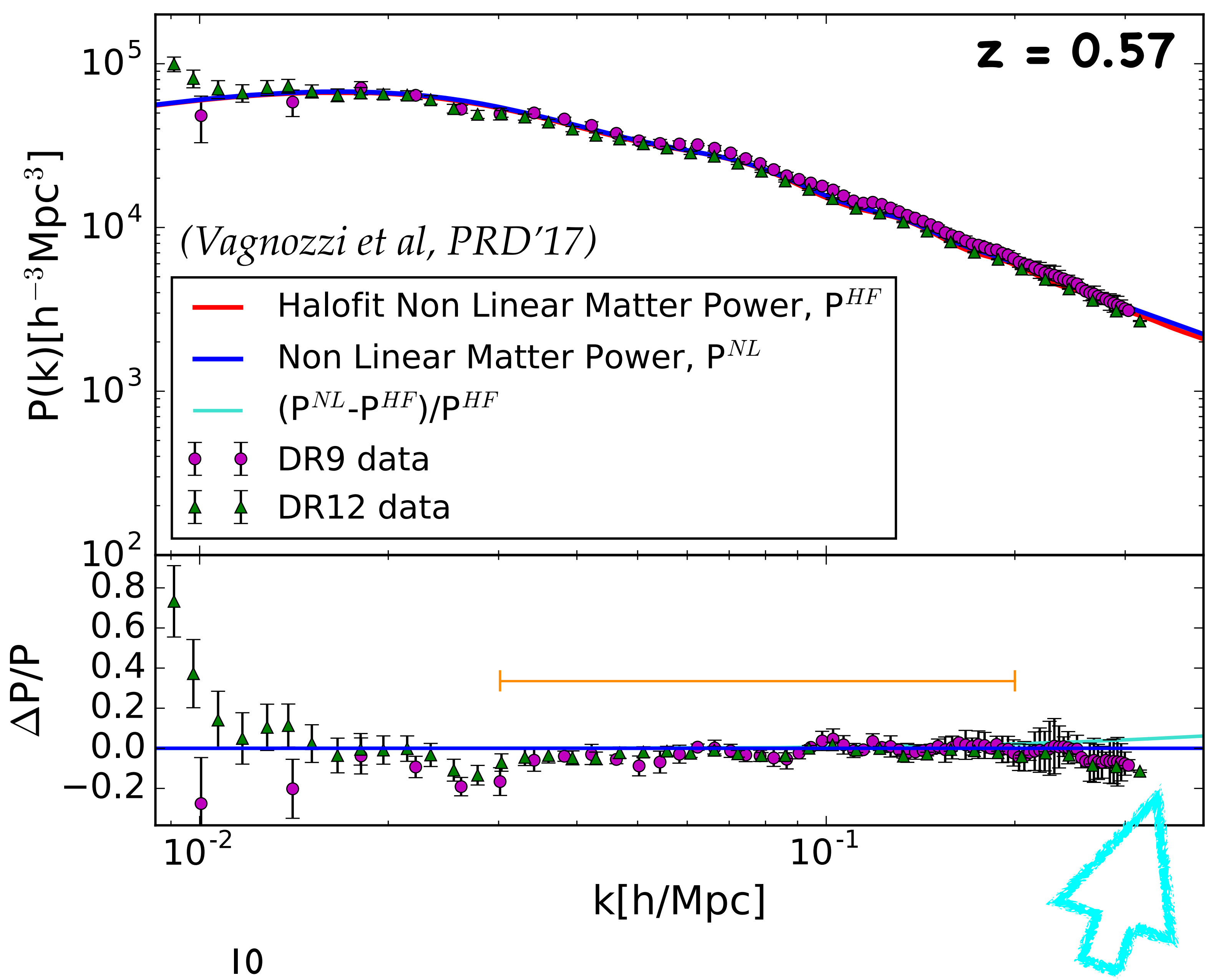
(From Y. Wong)

What we know: Massive neutrinos cosmological signatures

@LSS: Caveats, NON-LINEARITIES

Beyond a given scale k_{nl}, linear perturbation theory breaks down!





What we know: Massive neutrinos cosmological signatures

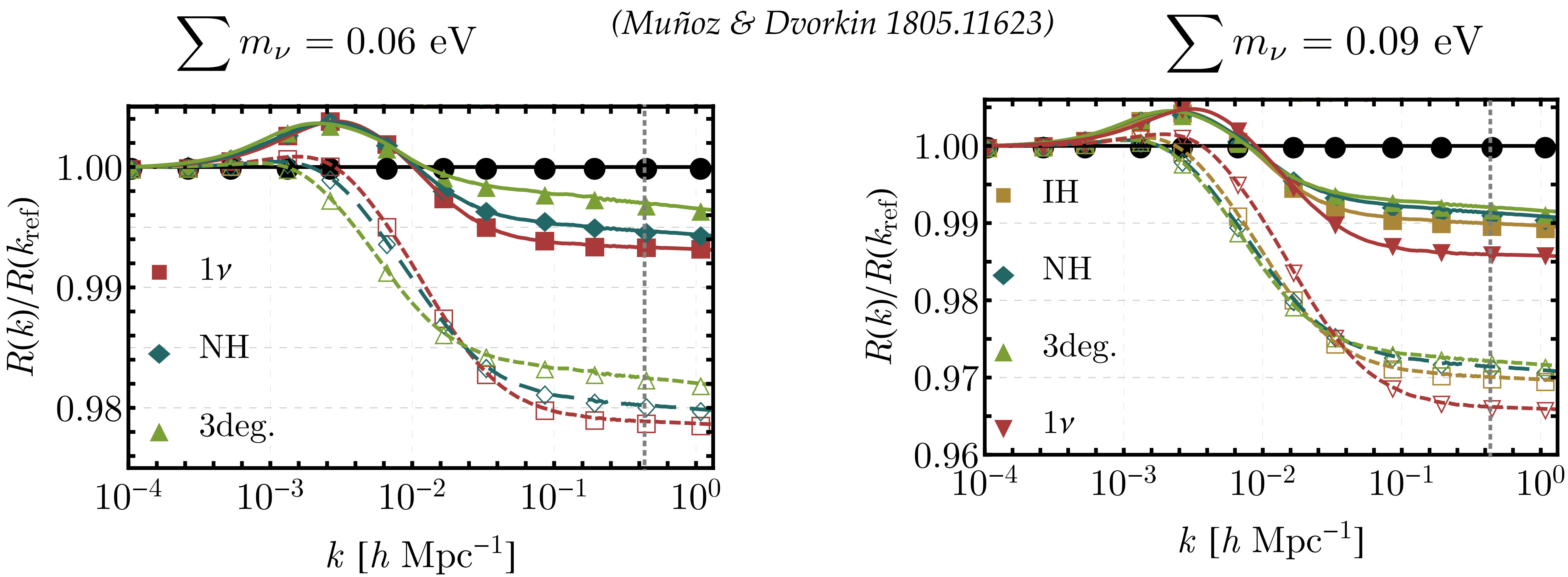
@LSS: Caveats, BIAS!

$$P_{gg}(k,z) = bias^2 P(k,z)$$

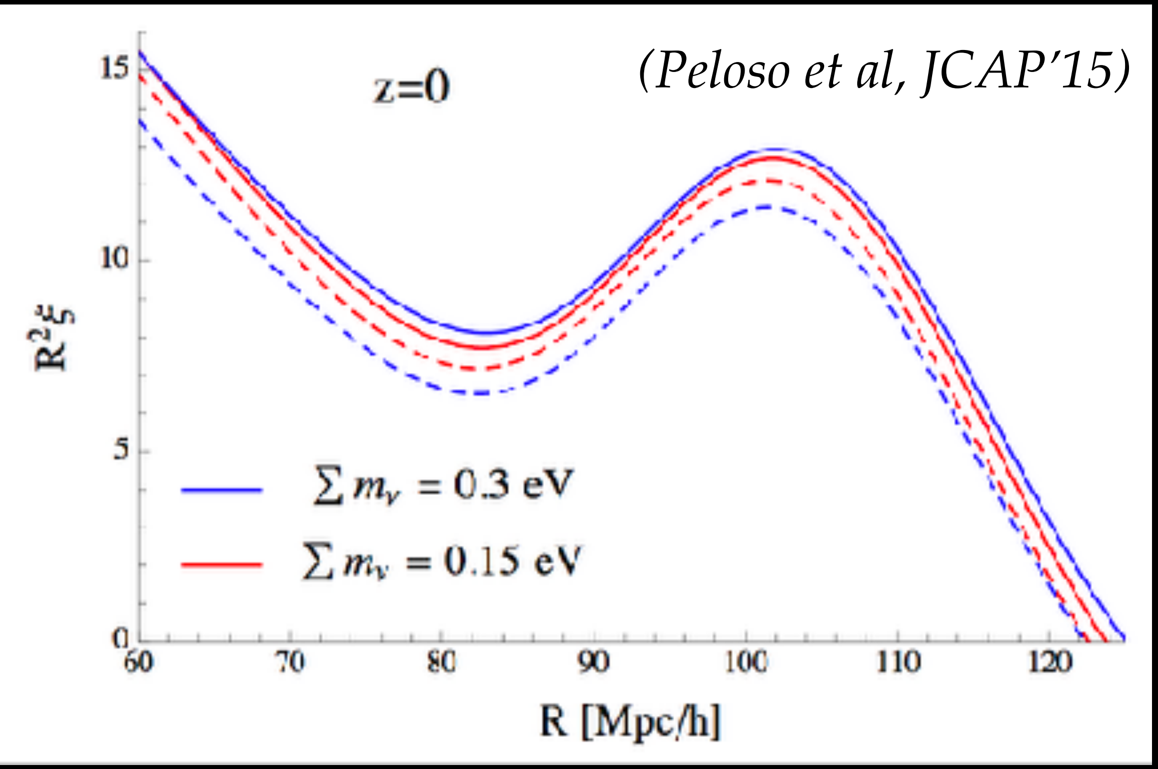
Galaxies are biased tracers of the underlying matter density field! *(Kaiser, APJ'84)*

Neutrinos themselves induce a scale-dependent bias *(LoVerde & Zaldarriaga; Castorina et al)*

(Muñoz & Dvorkin 1805.11623)



What we know: Massive neutrinos cosmological signatures

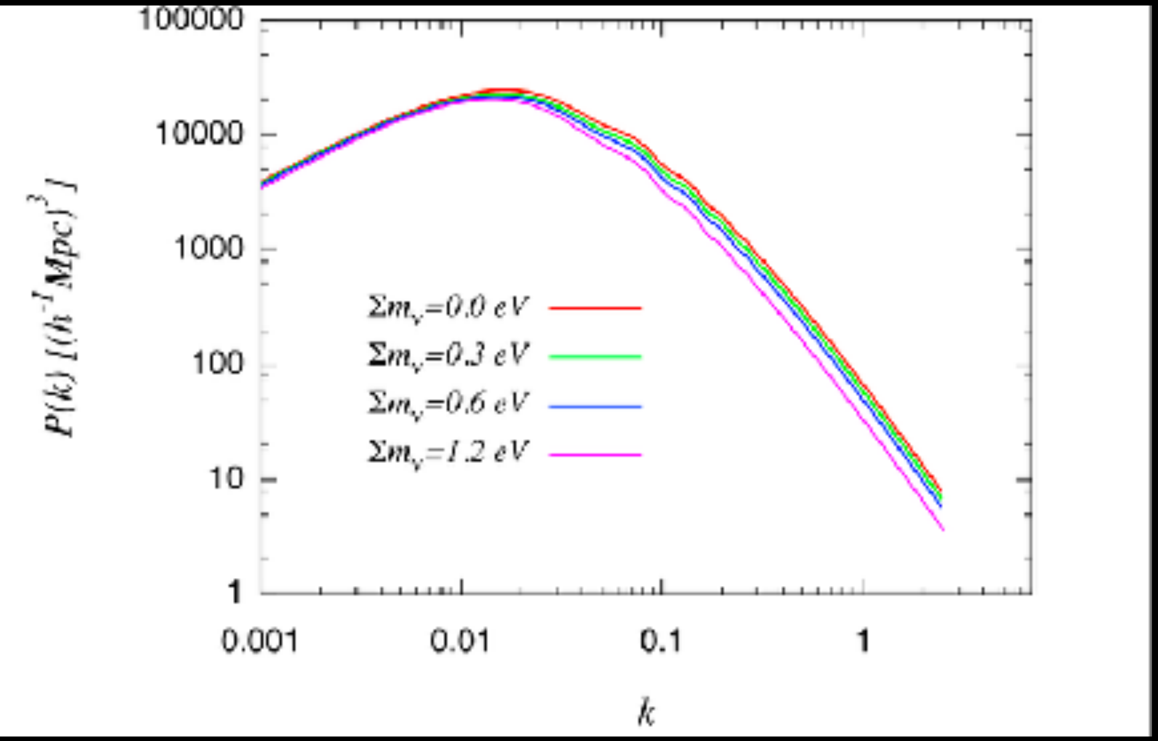


Large scale structure measurements can be interpreted either in the geometrical or shape forms

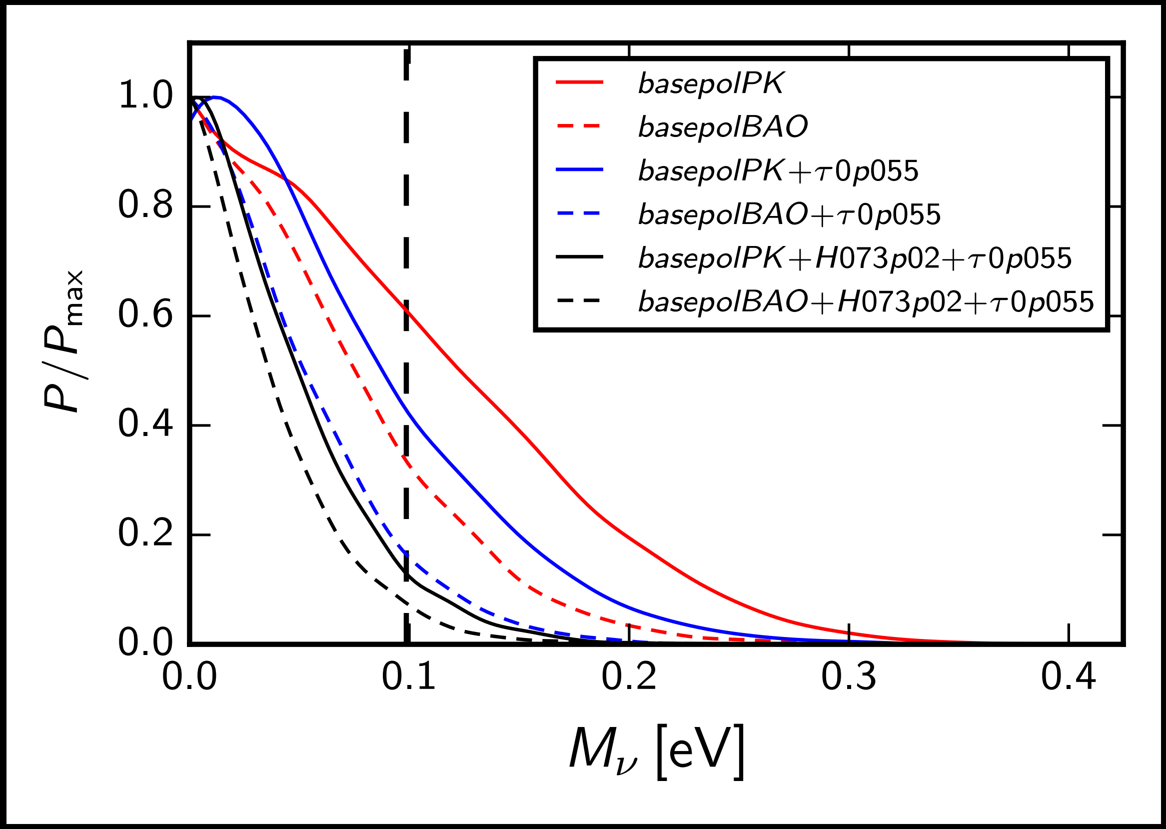
2 point correlation function

Fourier Transform

Matter power spectrum



BAO information more powerful



What we know

Planck 2018 results, 1807.06209

Planck TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

+ BAO

$$\sum m_\nu < 0.12 \text{ eV } 95\%\text{CL}$$

+ BAO + SNIa

$$\sum m_\nu < 0.11 \text{ eV } 95\%\text{CL}$$

+ BAO + SNIa + H_0=73.45 ±1.66 km/s/Mpc *Riess et al, APJ'18*

$$\sum m_\nu < 0.0970 \text{ eV } 95\%\text{CL}$$

What we know

Planck 2018 results, 1807.06209

Planck TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.26 \text{ eV} \qquad N_{\rm eff} = 2.90 \pm 0.37 \text{ } 95\%\text{CL}$$

+ BAO

$$\sum m_\nu < 0.12 \text{ eV} \qquad N_{\rm eff} = 2.96^{+0.34}_{-0.33} \text{ } 95\%\text{CL}$$

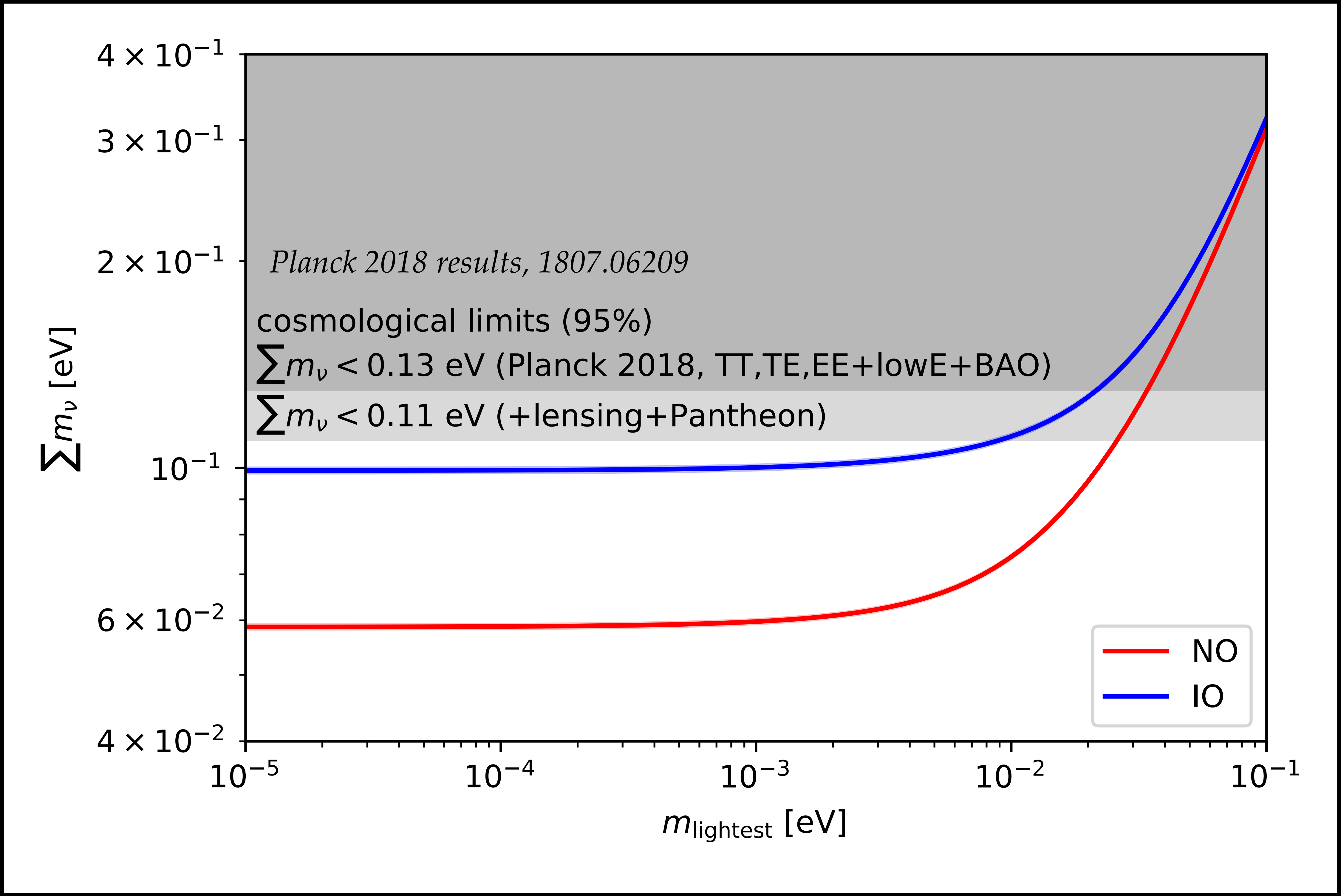
+ BAO + SNIa

$$\sum m_\nu < 0.11 \text{ eV} \qquad N_{\rm eff} = 2.98^{+0.35}_{-0.33} \text{ } 95\%\text{CL}$$

+ BAO + SNIa + H_0=73.45 ±1.66 km/s/Mpc + w + nrun

$$\sum m_\nu < 0.16\text{eV} \qquad N_{\rm eff} = 3.11^{+0.38}_{+0.38} \text{ } 95\%\text{CL}$$

What we know



Planck 2018 results, 1807.06209
cosmological limits (95%)
$\sum m_\nu < 0.13$ eV (Planck 2018, TT,TE,EE+lowE+BAO)
$\sum m_\nu < 0.11$ eV (+lensing+Pantheon)
$\sum m_\nu$ [eV]
4×10^{-1}
3×10^{-1}
2×10^{-1}
10^{-1}
6×10^{-2}
4×10^{-2}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
m_{lightest} [eV]
NO
IO

- What we do not know (yet!): Neutrino mass ordering

Cosmology IS CURRENTLY UNABLE to extract individually the mass of the neutrino eigenstates and the ordering of their mass spectrum:

All the limits on the neutrino mass ordering come from the bound on Σ m_ν.

Parameterizations:

(A) m_1, m_2, m_3

(B) $m_{\rm lightest}, \Delta m^2_{13}, \Delta m^2_{12}$ 

Priors:

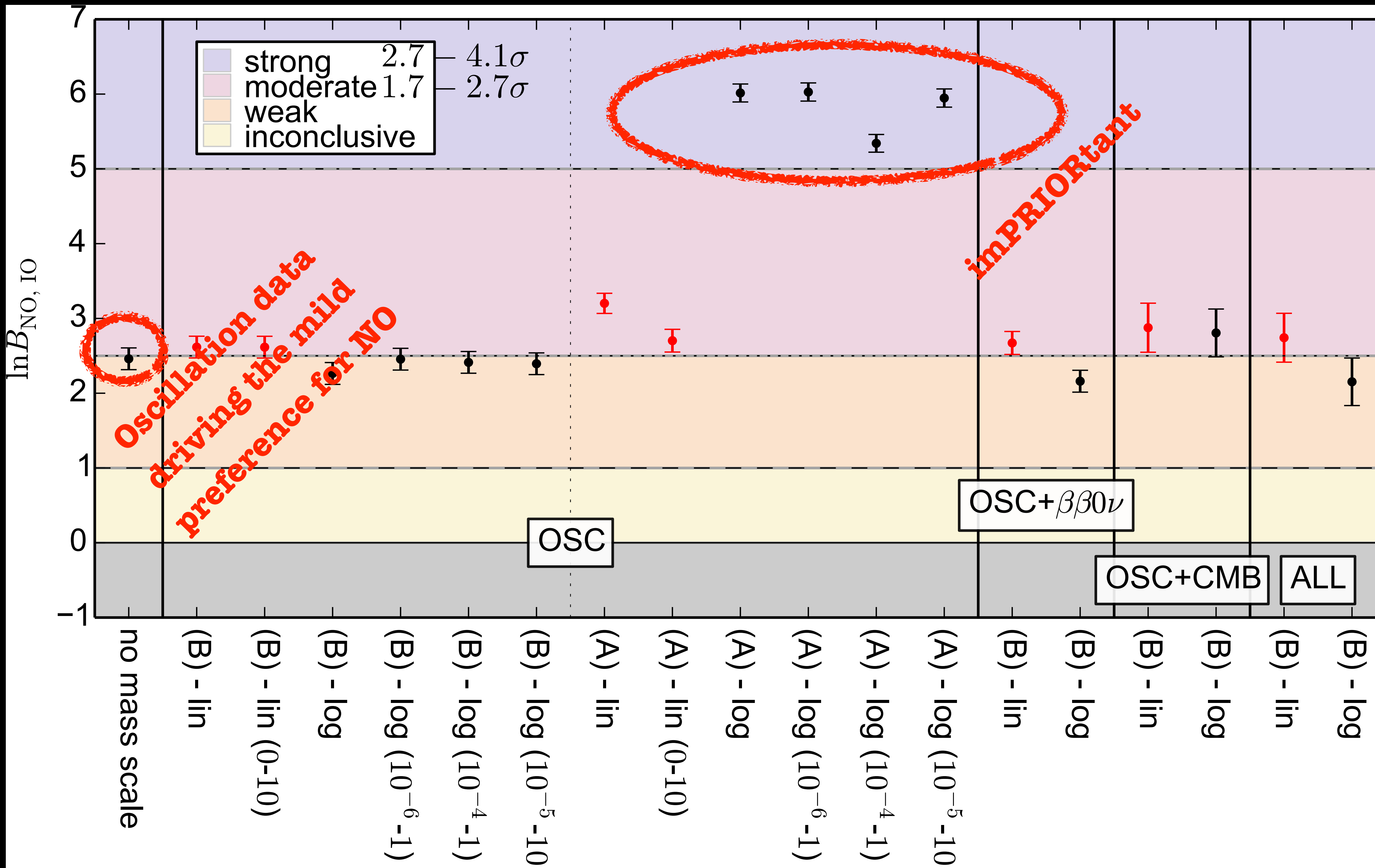
Linear

Logarithmic 

The most effective prior/parameterization is the one which minimizes the fraction of initial parameter space incompatible with data

- What we do not know (yet!): Neutrino mass ordering

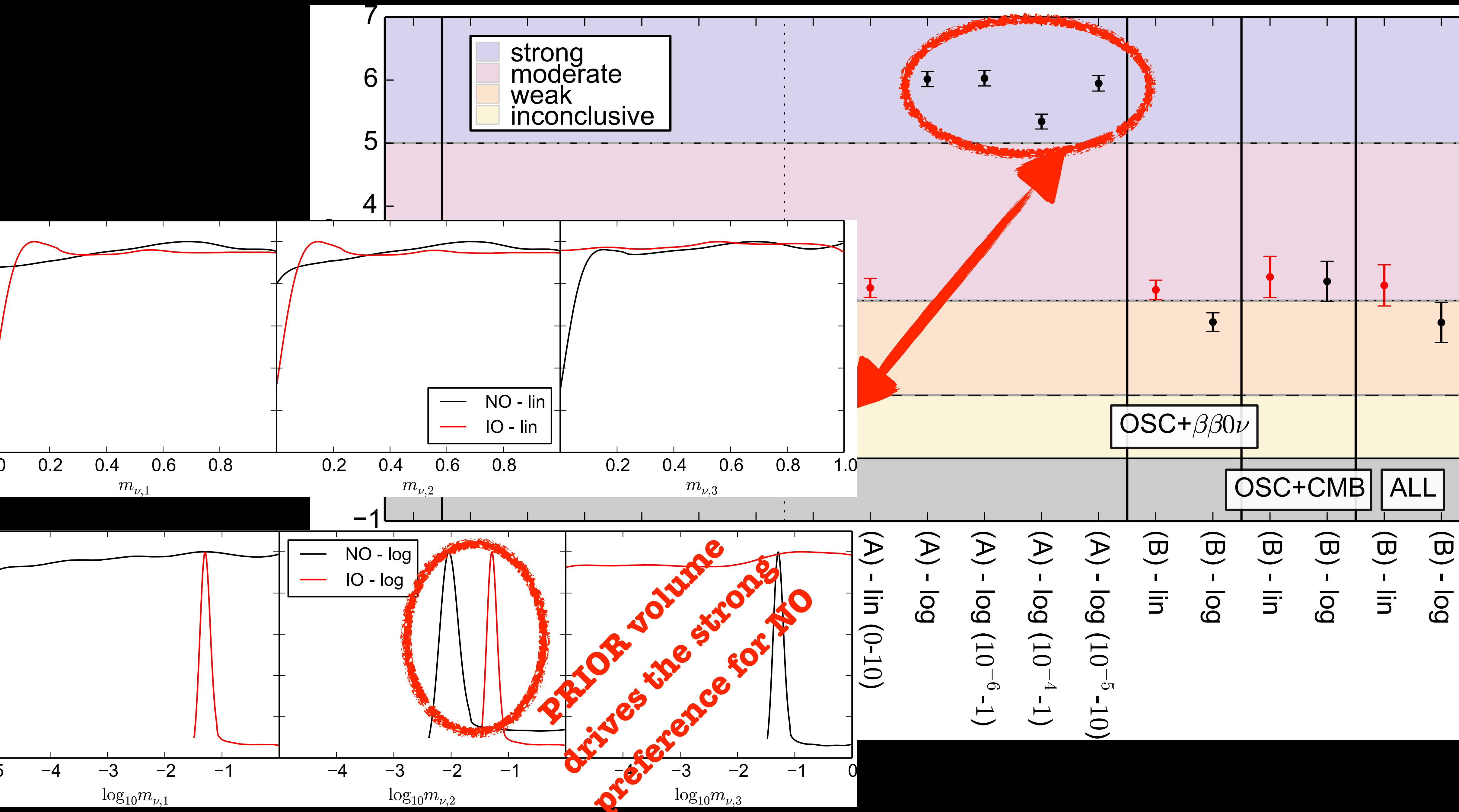
S. Gariazzo et al, JCAP'18



Agreement with previous analyses (Hannestad & Schwetz, JCAP' 16, Gerbino et al, PLB'17, Vagnozzi et al, PRD'17, Caldwell et al PRD'17, Capozzi et al PRD'17)

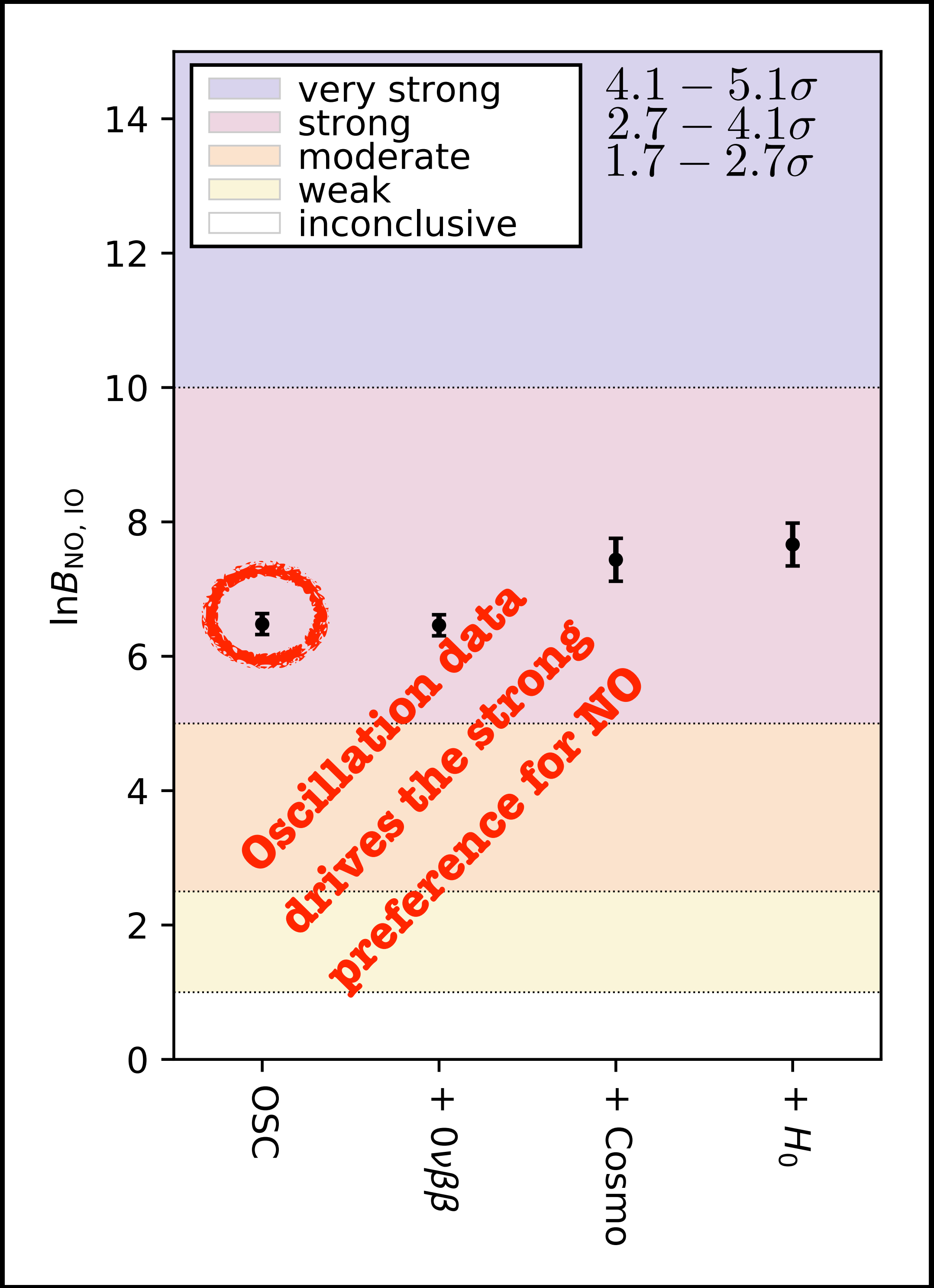
"The imPRIORtance":

If the PRIOR affects the posterior, the data (i.e. likelihoods) are NOT informative enough!



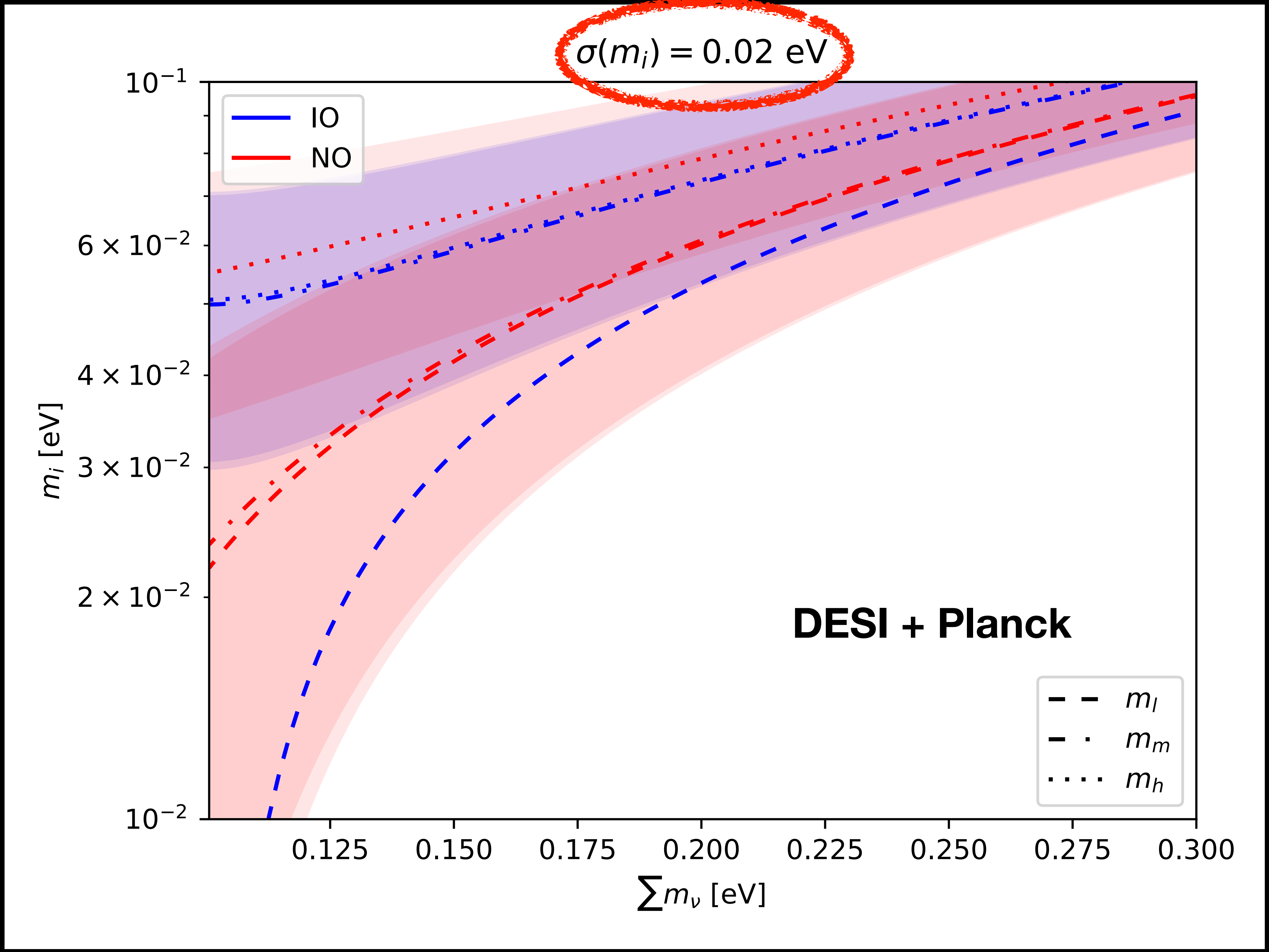
Gariazzo et al, JCAP'18

What we do not know but we'll probably (soon?) know.....



de Salas et al, 1806.11051

What will be extremely hard to know.....
Neutrino mass ordering from individual m_i's



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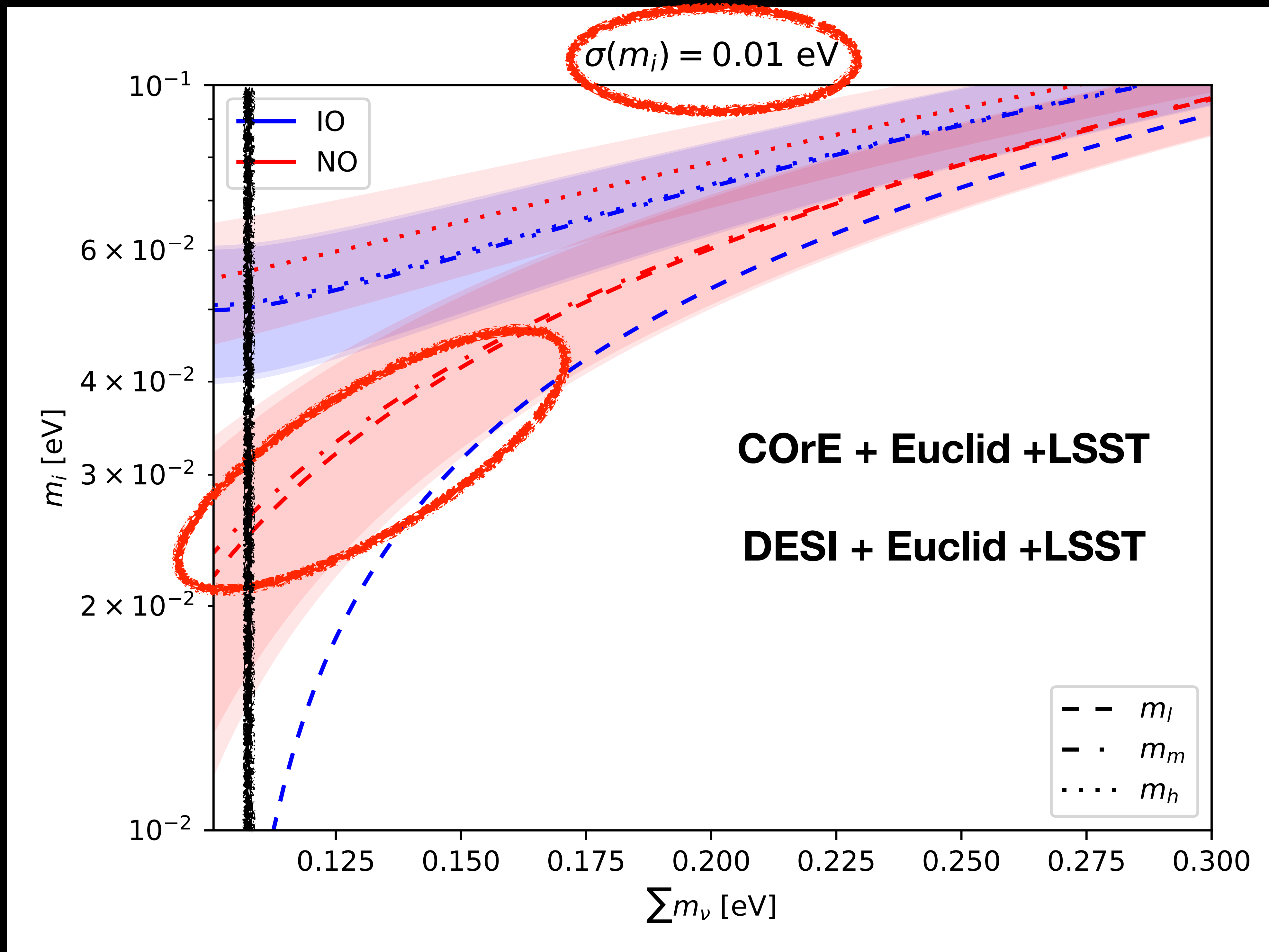

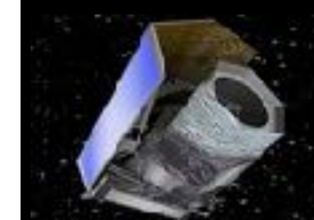

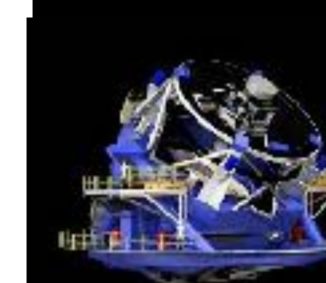

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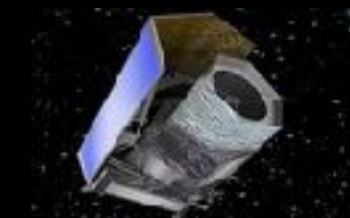
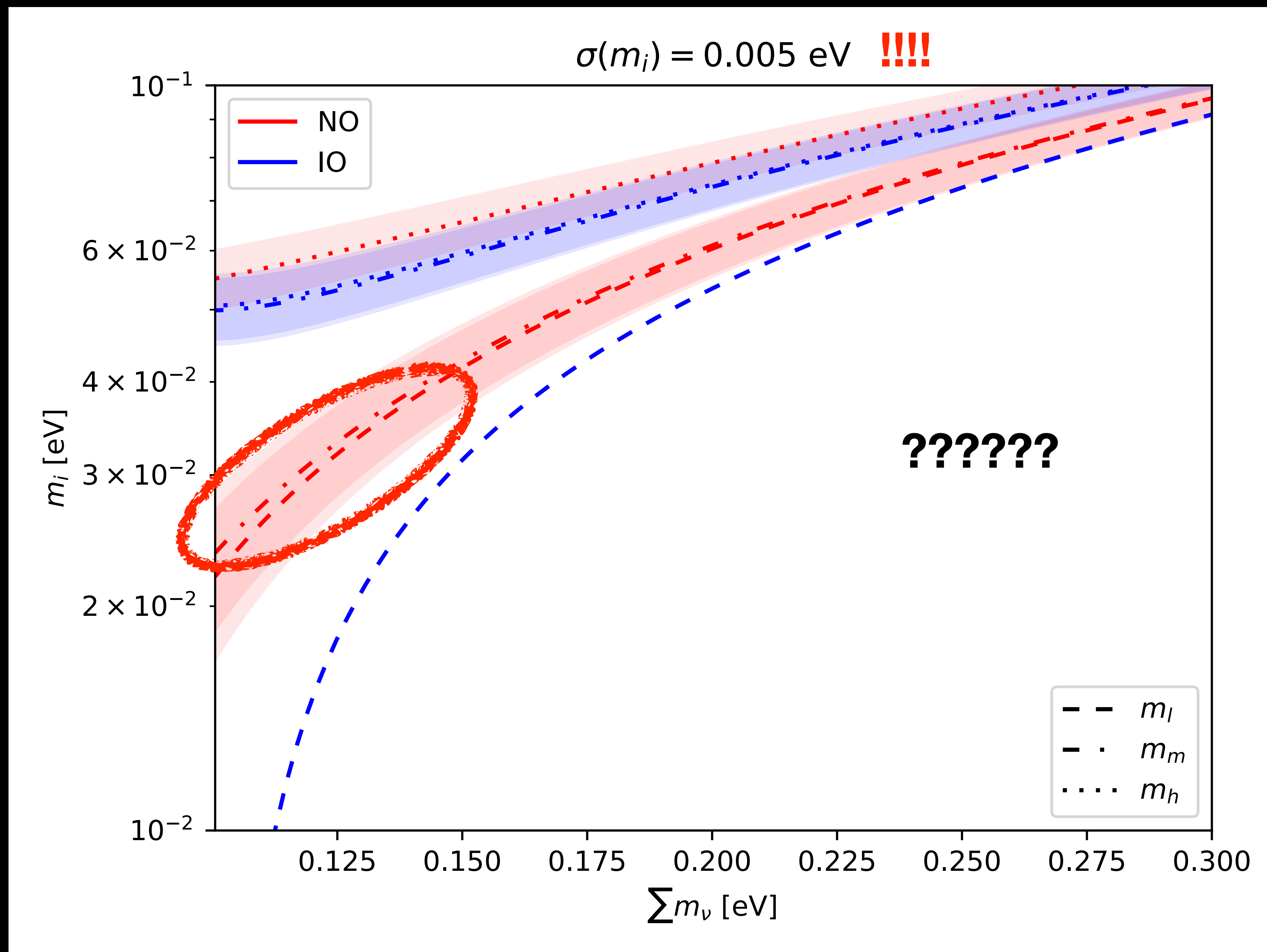
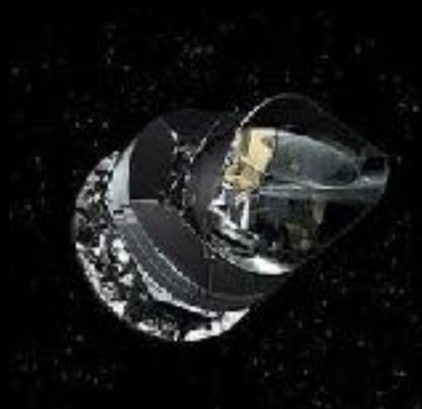
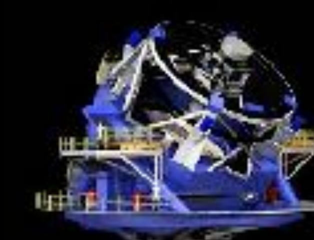




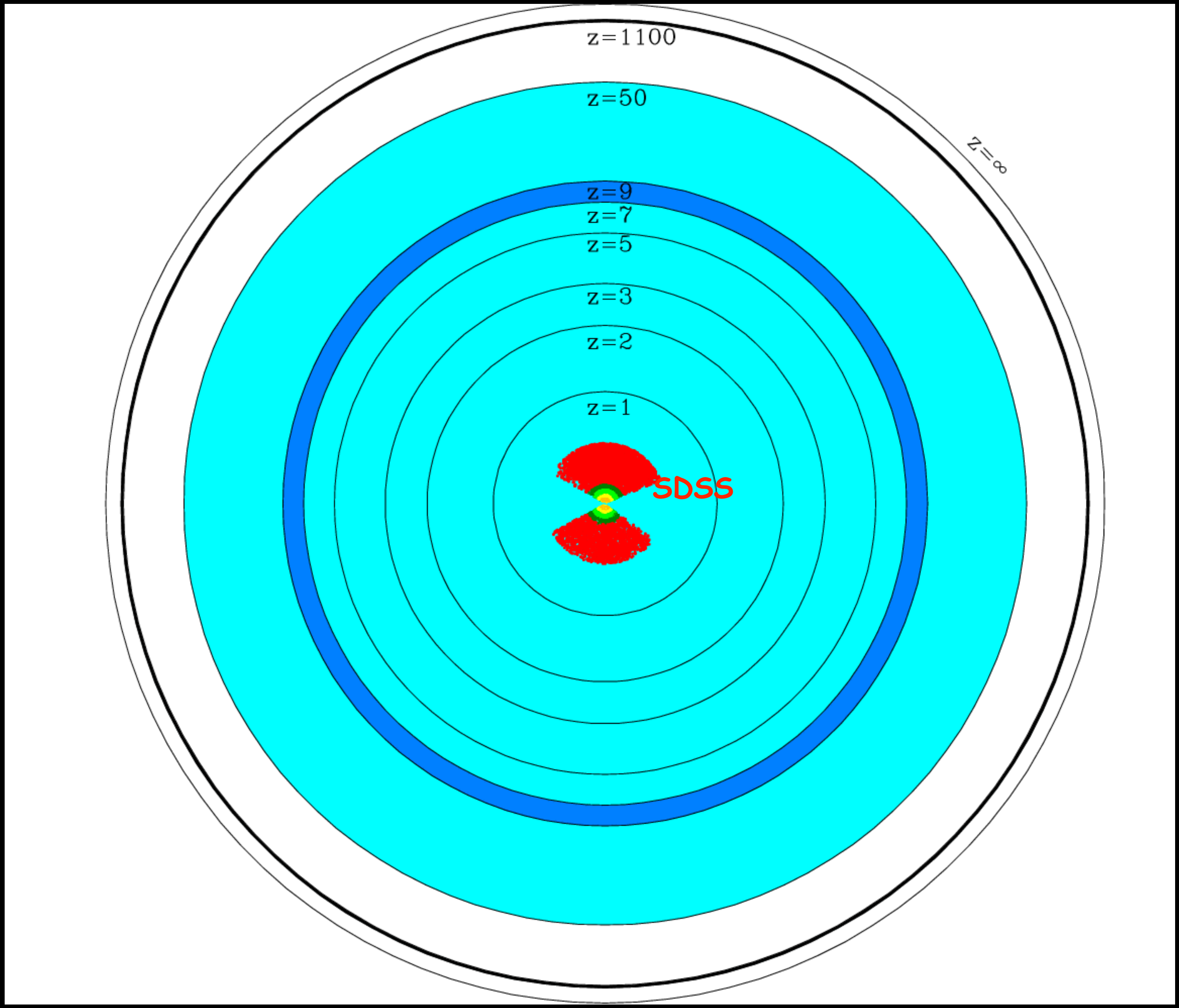




de Salas et al, 1806.11051

The 21 cm universe

21 cm cosmology could be able to map most of our observable universe, whereas the CMB probes mainly a thin shell at z≈1100 and large-scale structure maps only small volumes near the center so far.



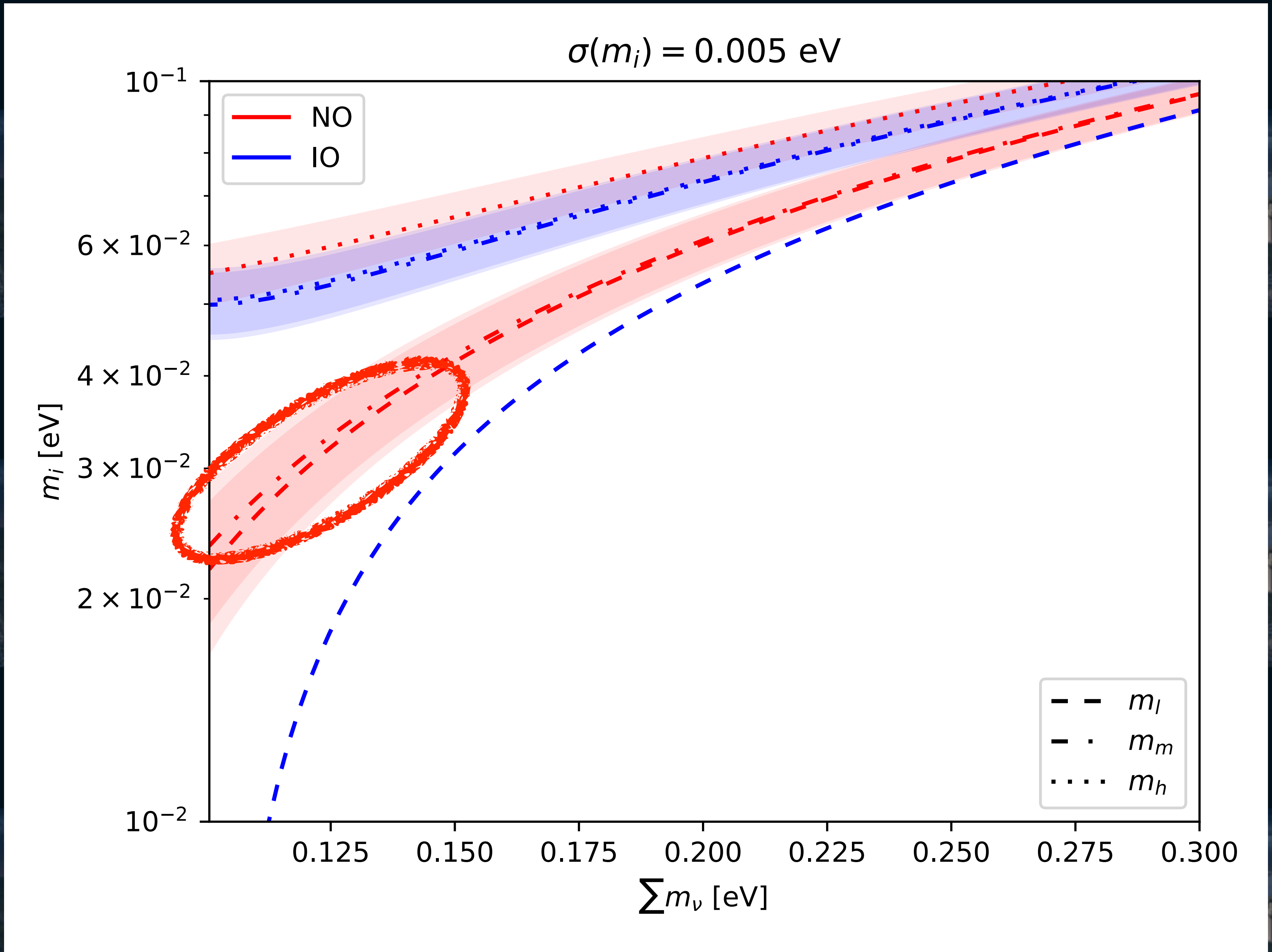
M. Tegmark and M. Zaldarriaga, PRD'09

The 21 cm universe: SKA

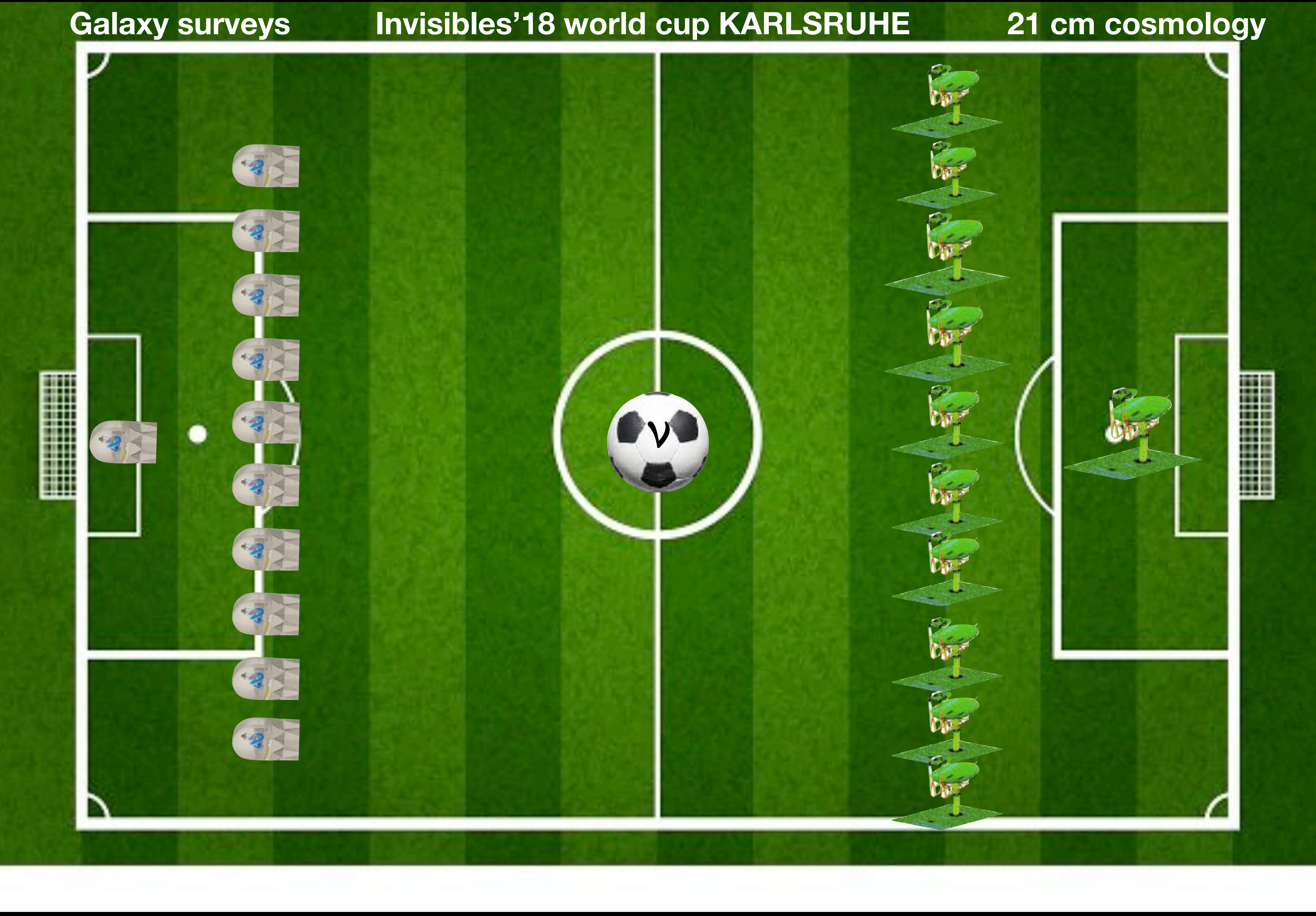
2000 high & mid frequency dishes plus a million low-frequency antennas:

Effective collecting area of one million m^2

An extremely futuristic and optimistic hope!



de Salas et al, 1806.11051


Galaxy surveys
Invisibles’18 world cup KARLSRUHE
21 cm cosmology
ν

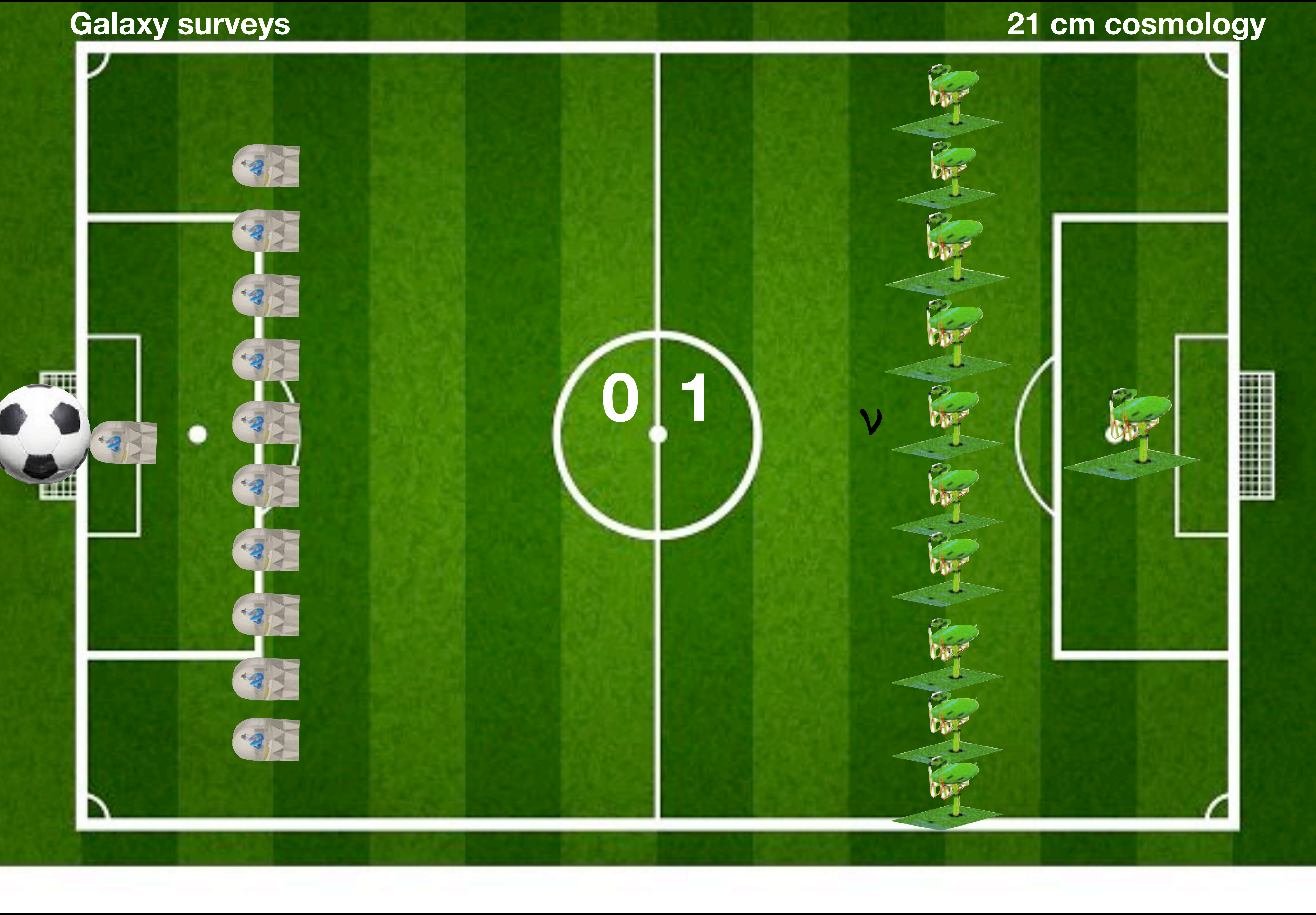
Galaxy clustering

Largest signal from relic neutrino masses and their ordering appears at scales which, at that redshifts, lie within the mildly non-linear regime.

One needs to rely on either N-body simulations or on analytical approximations!

21 cm cosmology

Epoch of Reionization 21 cm experiments will achieve the required scales to observe the neutrino signature within the linear regime, avoiding simulation problems and widely surpassing the constraints on neutrino and other relic masses from even very large galaxy surveys.


Galaxy surveys
21 cm cosmology
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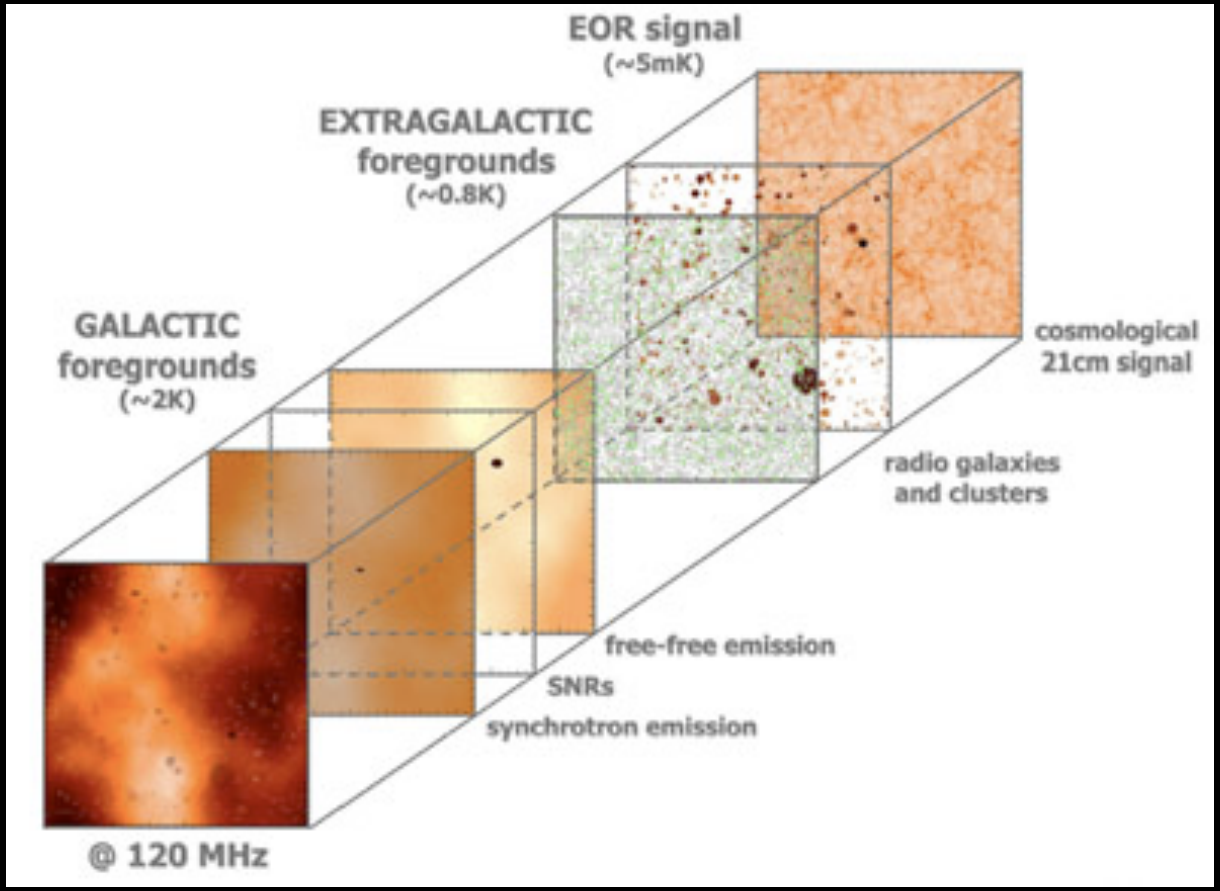
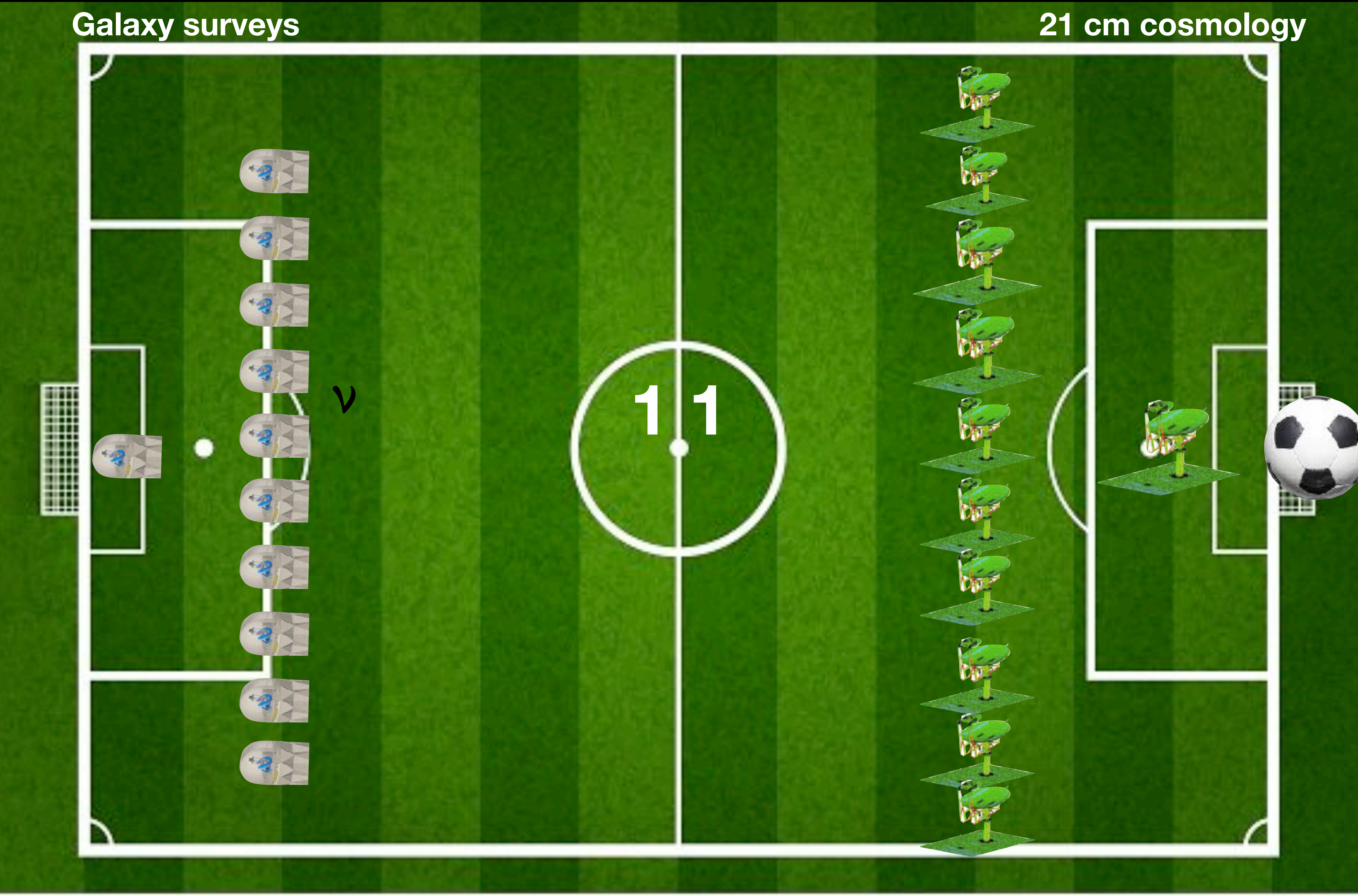
Galaxy clustering

21 cm cosmology

Foreground removal



(From S. Zaroubi)

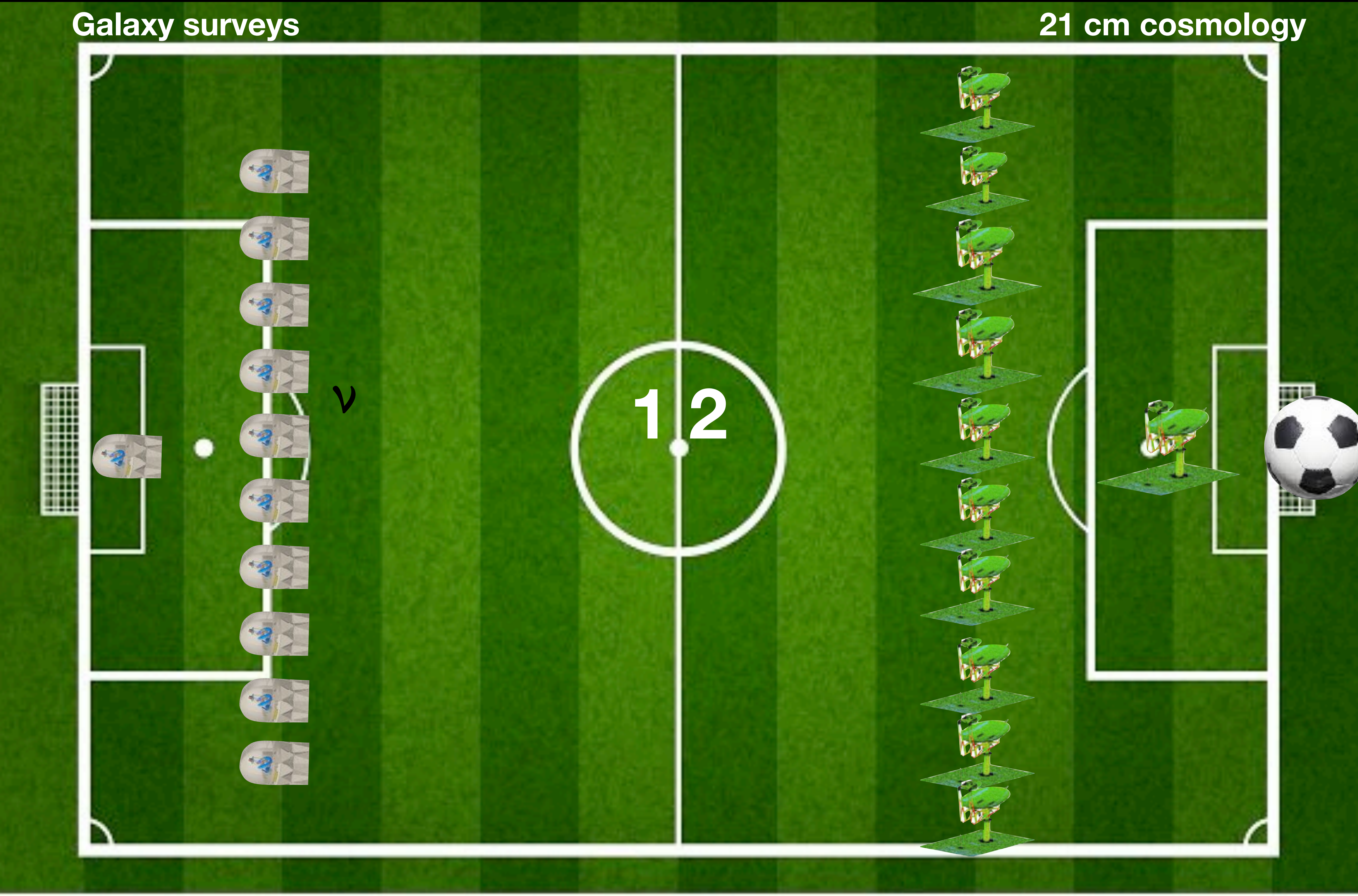

Galaxy surveys
21 cm cosmology
ν
1 1

Galaxy clustering

At redshifts $z<2$, the universe starts to be dominated by the dark energy fluid and the growth of matter perturbations is modified depending on the dark energy equation of state $w(z)$, whose precise time-evolution is unknown.
Consequently, for a given perturbation in the matter fluid, a suppression in its growth of structure could be due either to the presence of massive neutrinos or to a evolving dark energy fluid.

21 cm cosmology

Focusing at higher redshifts, the neutrino mass ordering constraints from 21 cm probes will be largely independent from the uncertainties in the dark energy fluid properties!


Galaxy surveys
21 cm cosmology
ν
1 2

The 3-Neutrino representative, Ω_ν

Madame Dark energy Ω_Λ

Mr Inflation

The radiation member, N_{eff}

Lady Cold Dark matter, Ω_{cdm}

The Dark JUSTICE GAME:

The 3-Neutrino representative Σm_ν

versus

the Dark energy equation of state w(z)

GAME RULES:

1. Choose your favourite cosmological model
2. Derive cosmological bounds on Σm_ν within that model, discarding neutrino oscillations (i.e. prior $\Sigma m_\nu > 0$)
3. Are cosmological bounds consistent with oscillation data?

YES!

GREAT! You just won the game!

Your model is not ruled out (yet!)

Go to 1.

NO!

(i.e. $\Sigma m_\nu < 0.06$ eV or $\Sigma m_\nu < 0.1$ eV)

Write a paper

GAME OVER….after referral process

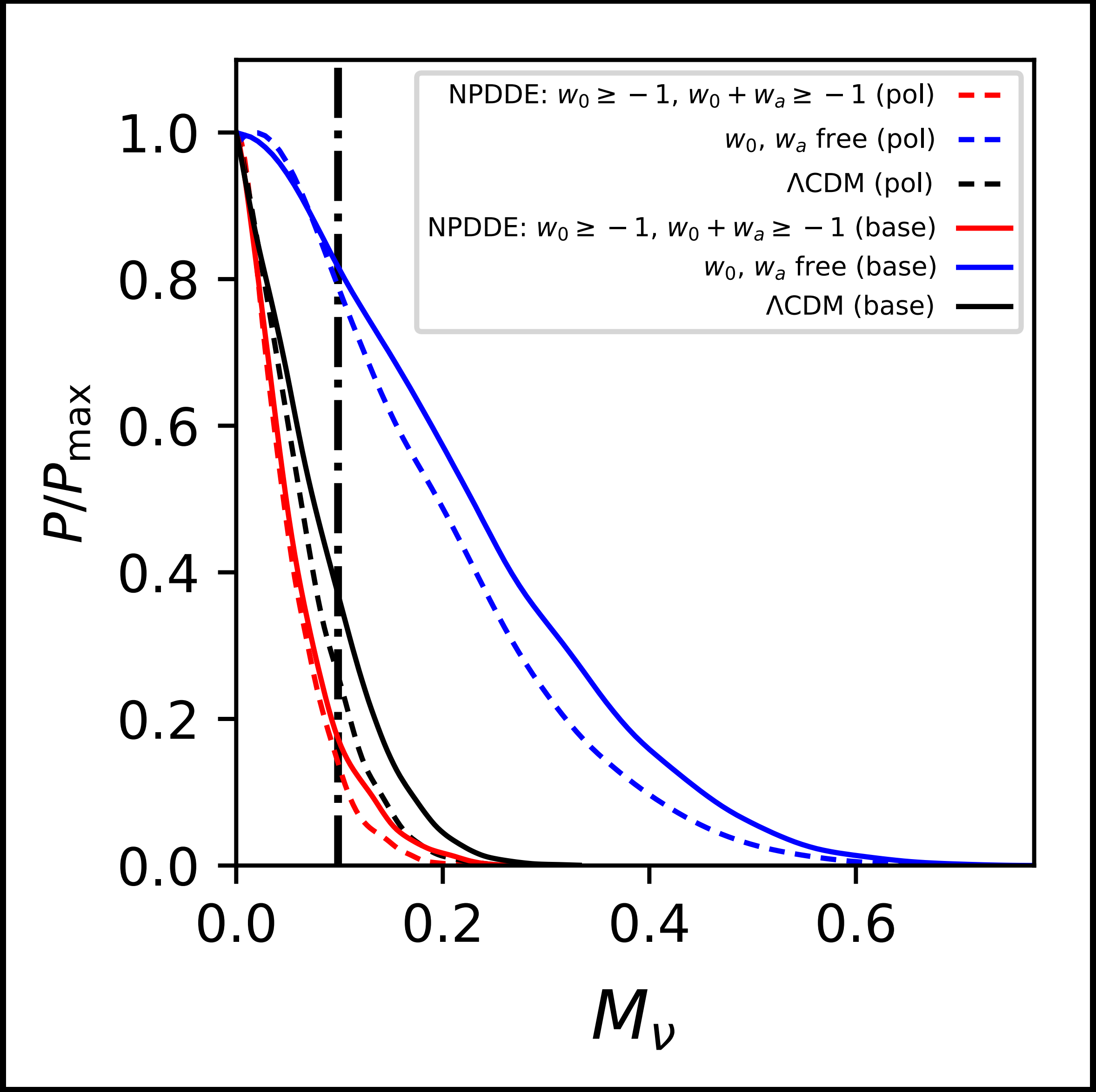
The Dark Justice Game

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

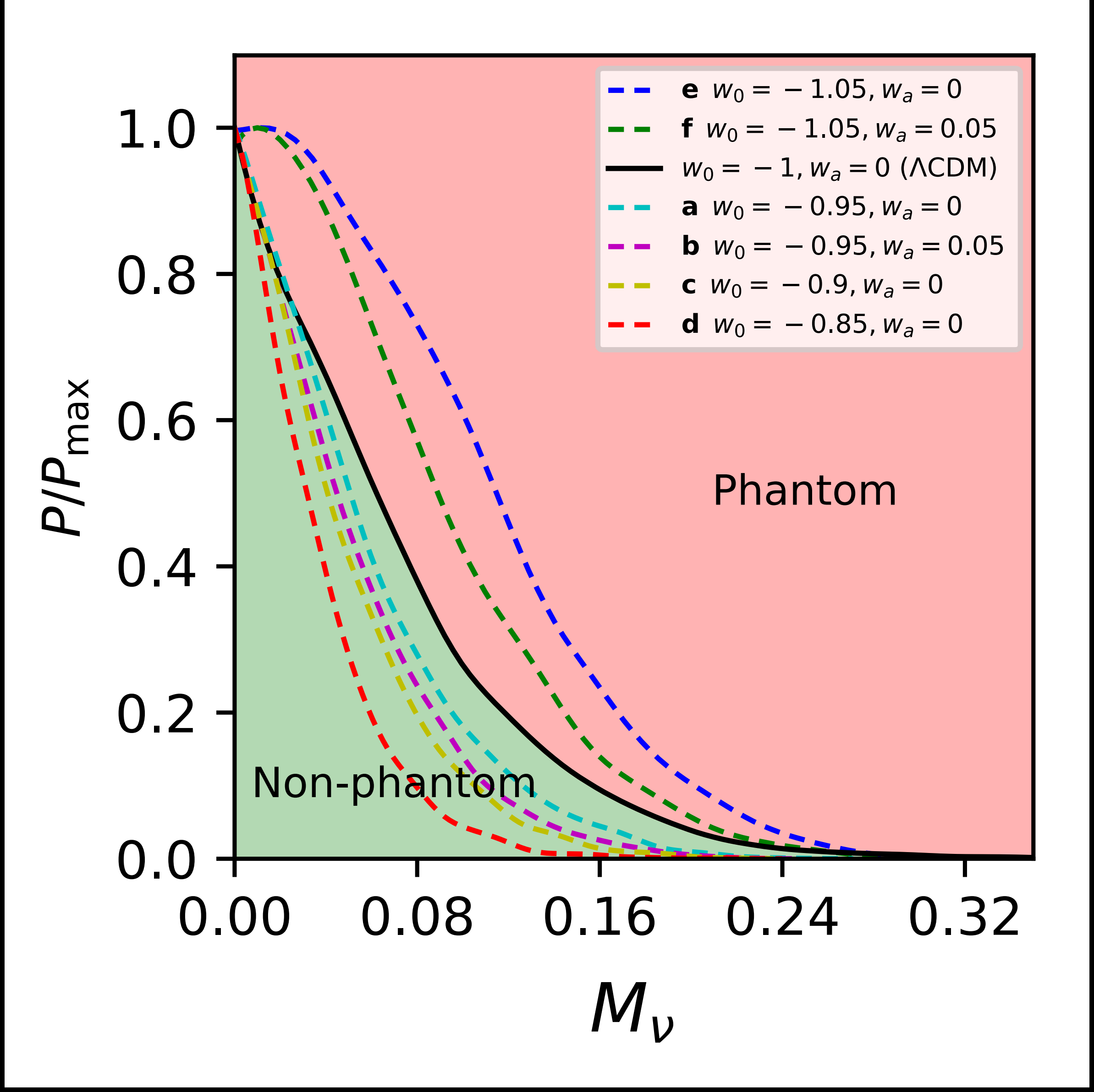
Chevalier & Polarsky'01 &Linder'03

$$w_0 \geq -1 \qquad w_0 + w_a \geq -1$$

NON-PHANTOM REGION



?



Vagnozzi et al'18


PHANTOM

The "Take Home" messages

- Neutrino masses leave key signatures in cosmological observables.
- NO hints so far for neutrino masses!
- Neutrino masses@CMB: Early ISW, lensing
- Neutrino masses@LSS: Free streaming
- Geometrical probes (BAO) more powerful than shape measurements
- Σm_ν<0.12 eV (95%CL) from 2018 Planck TTTEEE+lensing plus BAO data
- Strong evidence (3.5σ) for NO mostly FROM OSCILLATION MEASUREMENTS
- Very futuristic 21 cm cosmological probes could provide the individual m_i's
- For non-phantom (physical) dynamical dark energy, Σm_ν bounds get tighter!


ngiyabonga
danke
謝謝
teşekkür ederim
Баярлалаа
mersi
barka
welalin
tack
спасибо
faafetai lava
vinaka
dank je
misaotra
paldies
grazzi
kiitos
dankie
спасибі
blagodaram
matondo
thank you
gracias
хвала
dhanyavad
asante
manana
hvala
maururu
köszönöm
obrigada
enkosi
bedankt
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grazie
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sobodi
dĕkuji
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kop khun krap
taiku
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takk
dakujem
trugarez
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ありがとう
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najis tuke
didi madloba
terima kasih
rahmet
ευχαριστώ
diolch
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mercè
мерси
kam sah hamnida
rahmat
감사합니다
xièxie
merci