Three Neutrinos in Cosmology (to Say Nothing of the Laboratory)

Martina Gerbino
Oskar Klein Centre
for Cosmoparticle Physics, Stockholm, SE

INPA seminar, LBNL, 3 March 2017

Based on Vagnozzi+(incl.MG) arXiv:1701.08172, Gerbino+ arXiv:1611.07847, Gerbino+ PRD952017, Gerbino+ PRD93 2016

Oskar Klein centre

Stockholms universitet

SUMMARY

- Massive neutrino cosmology in a nutshell
- Neutrino numbers: why do we care, how much can we trust
- Complementarity with laboratory searches

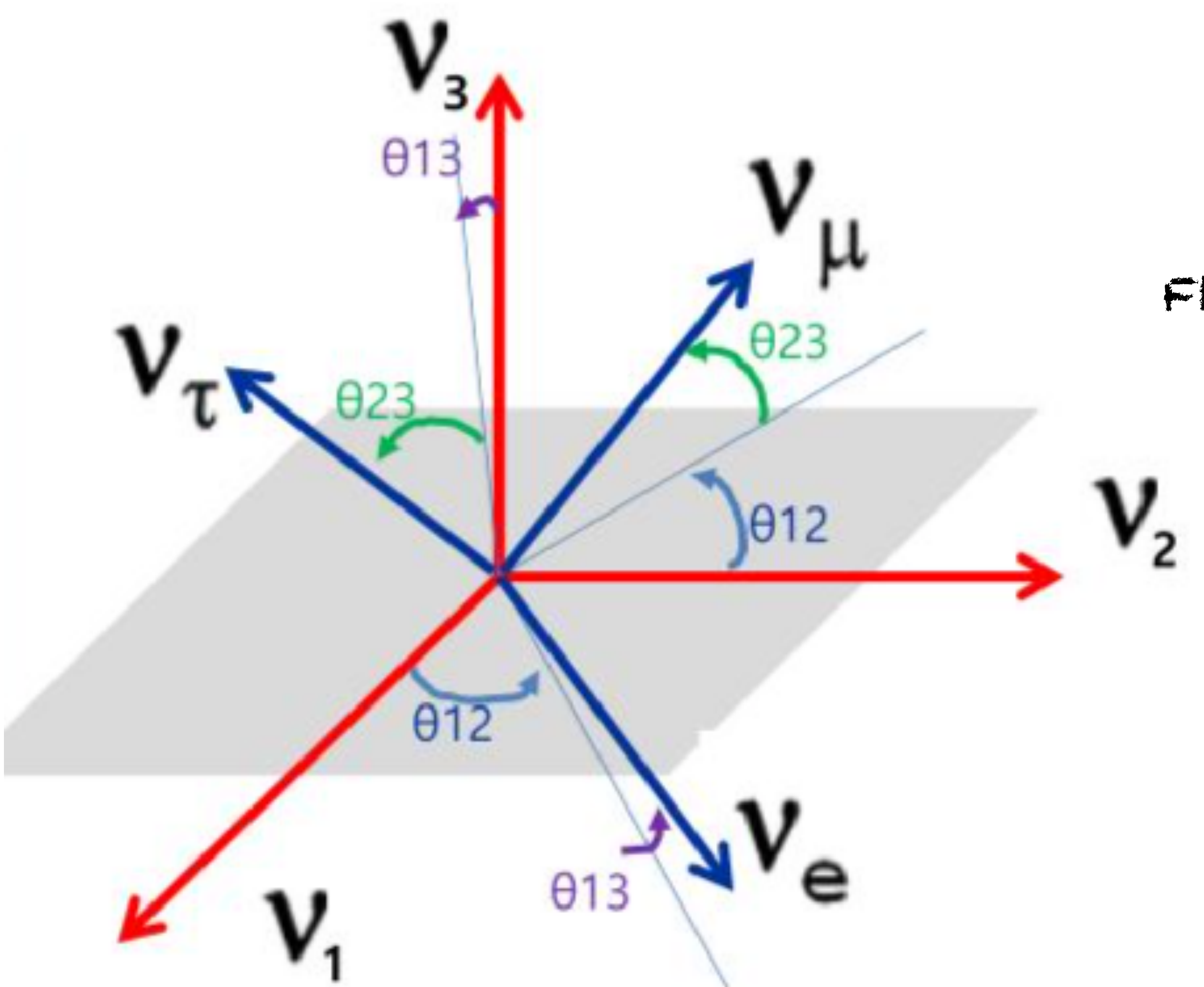
Of course we care, because...

- Neutrinos are the only SM particles of unknown mass
- Neutrino mass sets the seesaw scale (mass generation model, we presume...)
- Neutrino mass can act as a 'nuisance' parameter
- Measuring the neutrino mass could be a step forward unveiling other neutrino properties (hierarchy, nature, ...)

What we know, from the outside

How do they behave?

Neutrinos oscillate



Flavour eigenstate — Mass eigenstate

$$|\nu_\alpha>= U_{\alpha,i}\, e^{-iH_i t}|\nu_i>$$

Mixing matrix

$$1 - |<\nu_i|\nu_\alpha>|^2 \neq 0$$

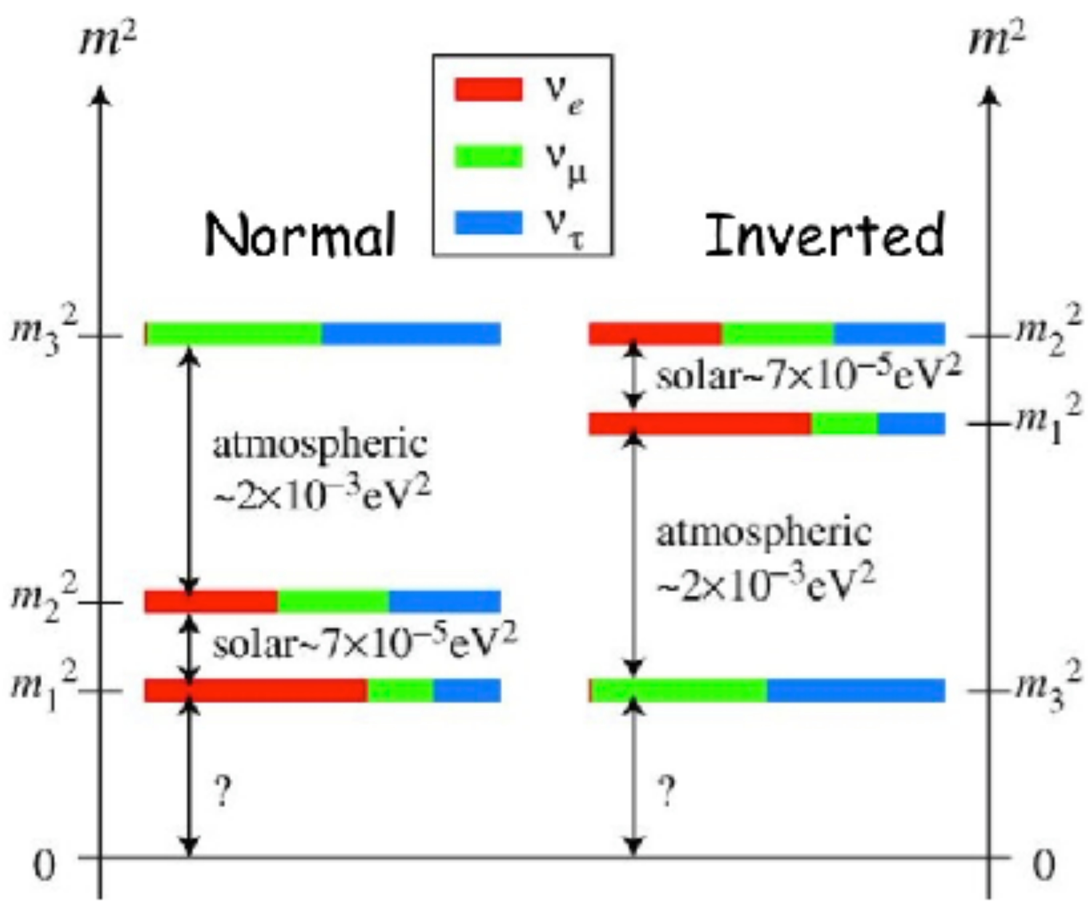
Probability to observe a flavour different from that emitted

What we know, from the outside

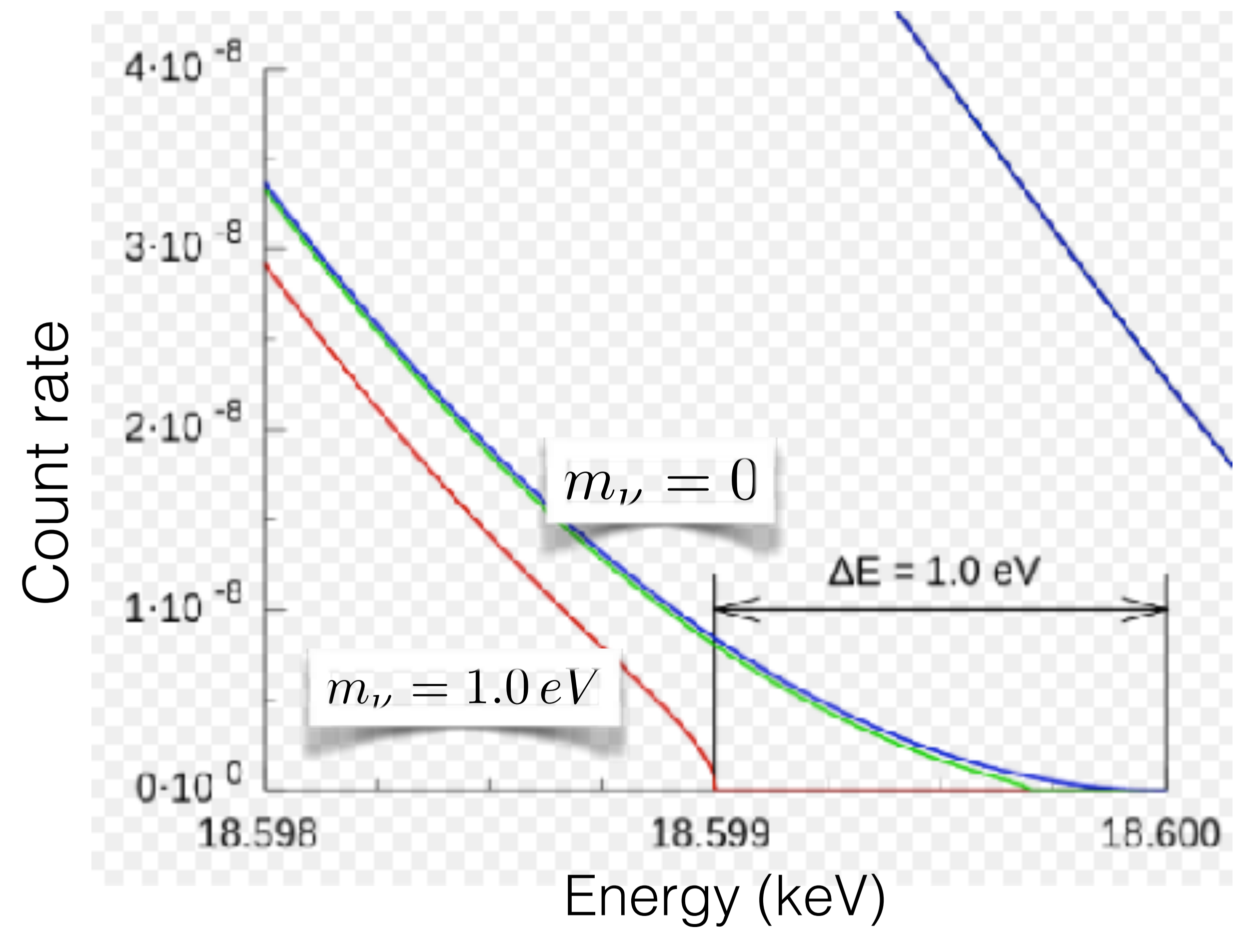
How do they behave?

Neutrinos oscillate, so they are massive

$$0.06\,\mathrm{eV} \leq M_\nu \leq 6\,\mathrm{eV}$$



Lower bound
from oscillation experiments

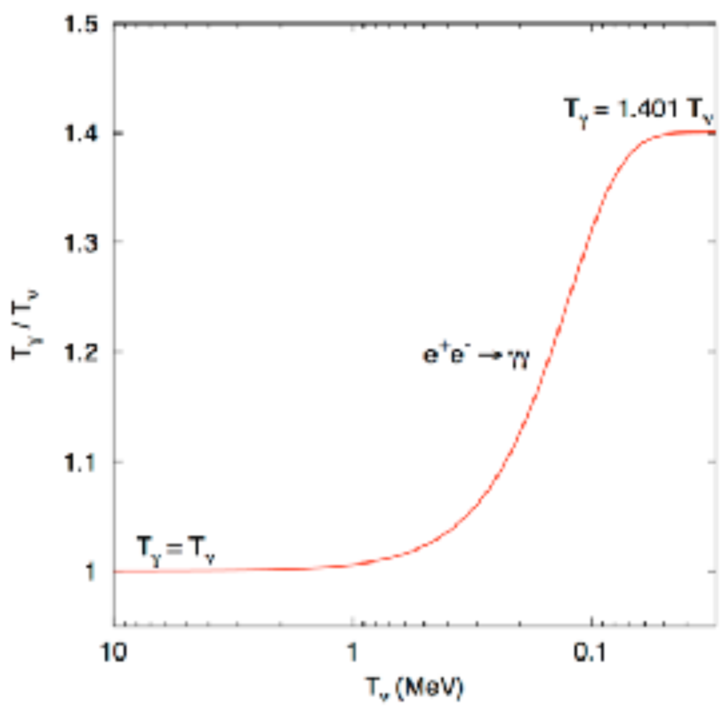


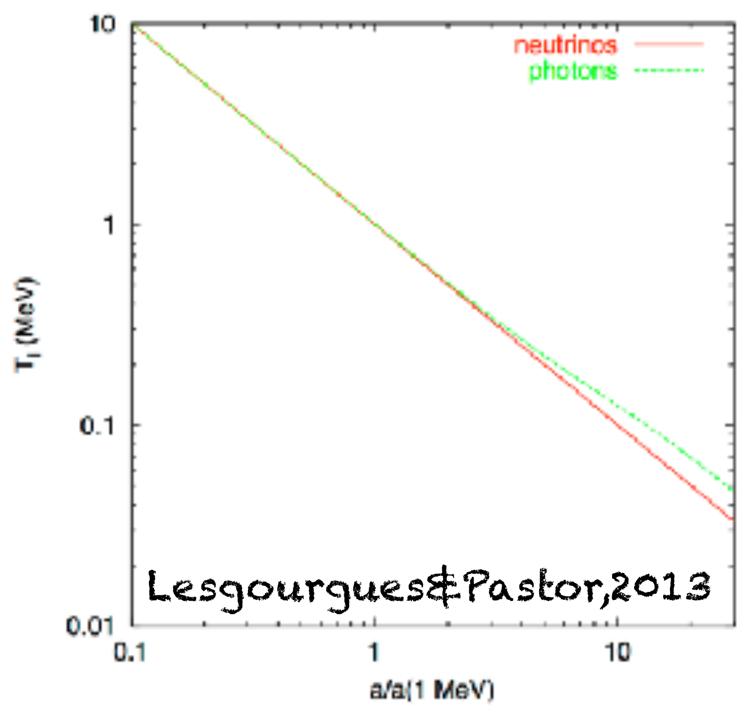
Upper bound
from kinematic measurements

Some basic facts

- Standard cosmological model predicts the existence of a background of relic neutrinos (CνB)
- $\Gamma_w > H$ (T>1MeV) -> Thermal equilibrium with primordial plasma (T_ν=T)
- T < 1 MeV -> neutrino free stream keeping an equilibrium spectrum ($T_\nu \neq T$, $T_\nu \propto 1/a$):

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$





- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

Neutrino phenomenology

Neutrinos were relativistic in the early Universe

$$\rho_\nu = g_\nu \int p f(p) d^3p \propto g_\nu T_\nu^4$$

so they contributed to the radiation density

$$\rho_{rad} = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

with $\rho_x \propto g_x T_x^4$, $T_\nu/T_\gamma = (4/11)^{1/3}$

$$N_{\rm eff} = \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm st}} = 3.046$$

Mangano+,2005
deSalas&Pastor,2016

Neff could account for any 'extra' radiation component

Neutrino phenomenology

Neutrinos are non-relativistic today

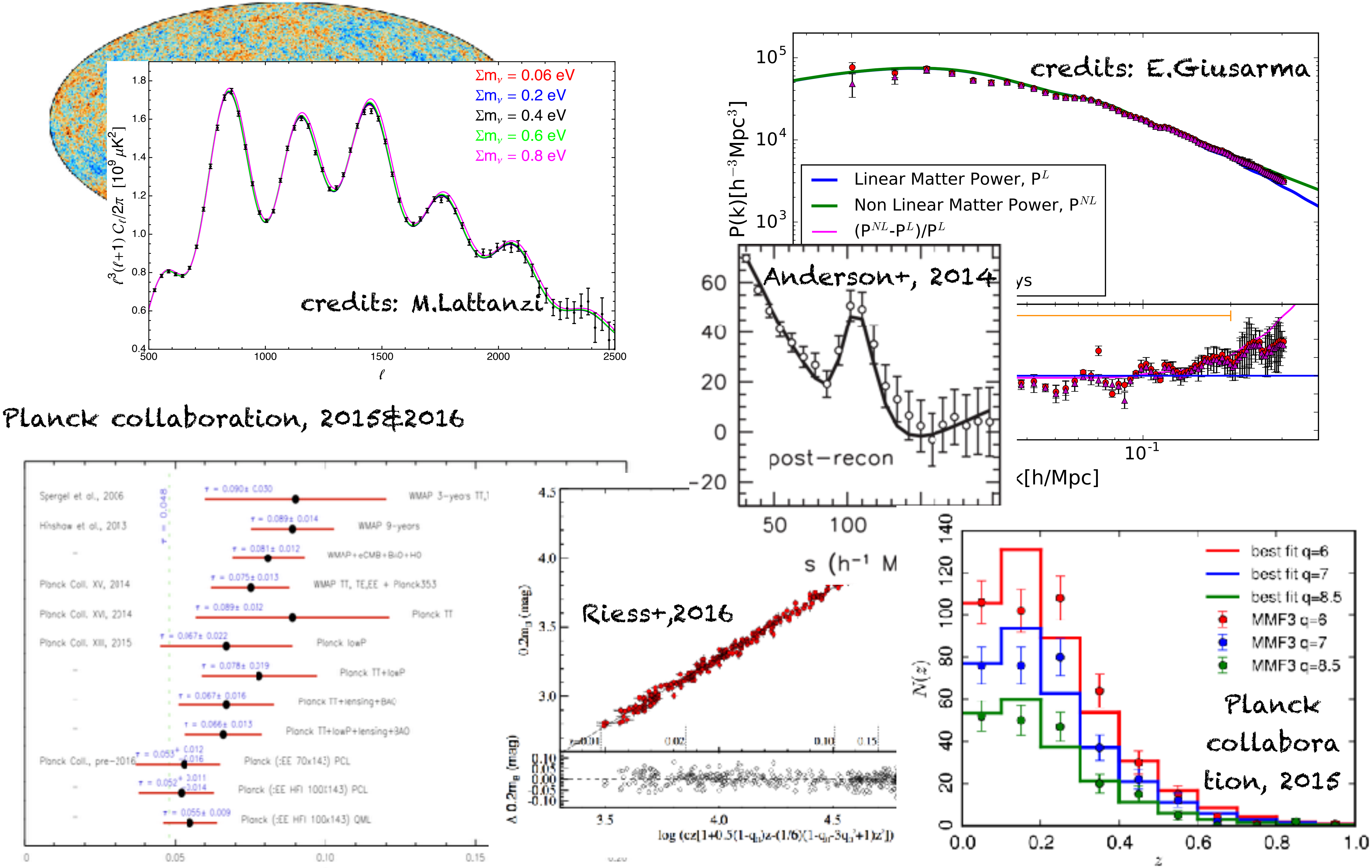
$$\rho_\nu = m_\nu n_\nu = m_\nu g_\nu \int f(p) d^3p \propto m_\nu g_\nu T_\nu^3$$

so they contribute to the matter content

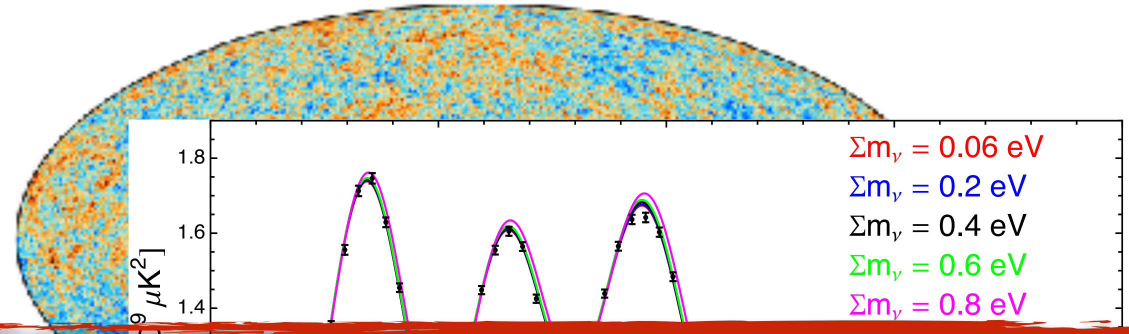
$$\Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2 \text{ eV}} \qquad \rho_c = \frac{3H^2}{8\pi G}$$

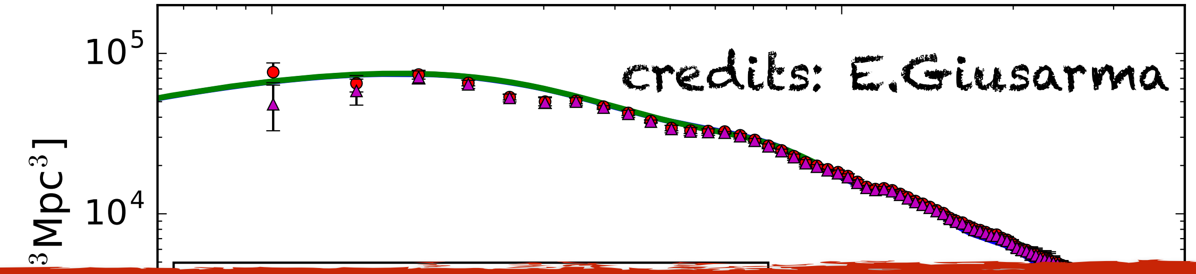
- Background: matter-radiation equality shifted, cosmological distances modified
- Perturbations: early ISW at intermediate scales, power suppression at small scales, structure growth modified, scale-dependent bias induced

Jigsaw puzzle

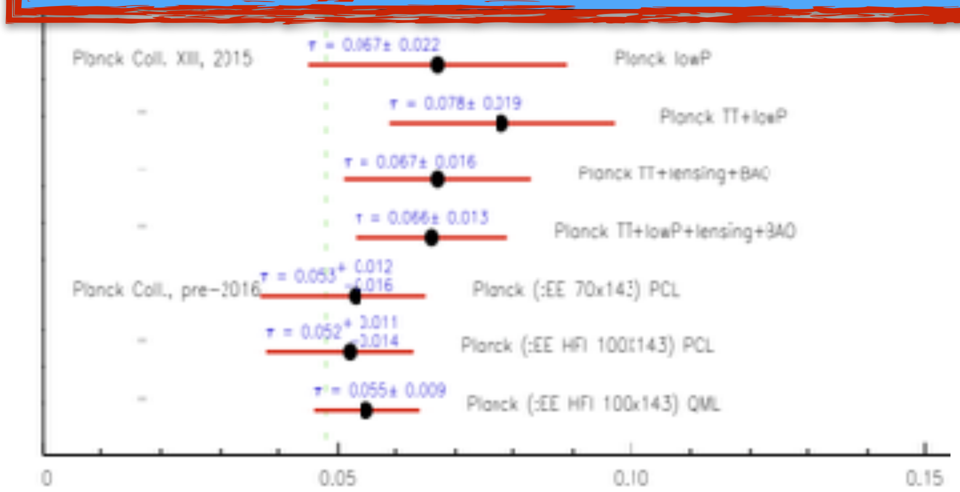


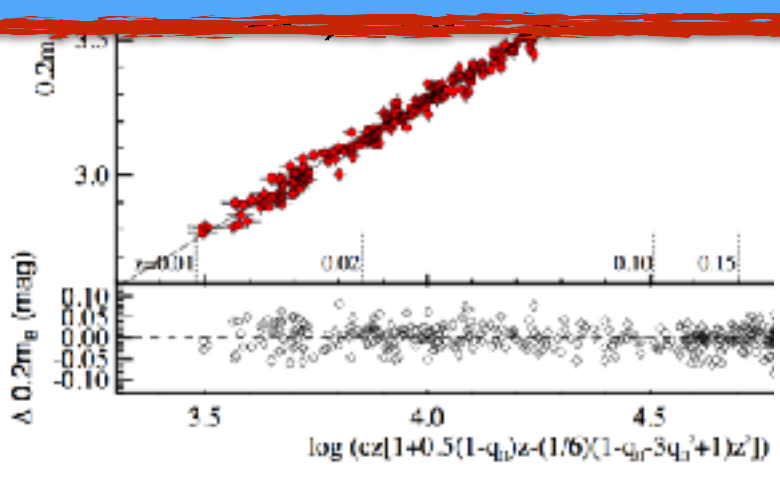
Jigsaw puzzle

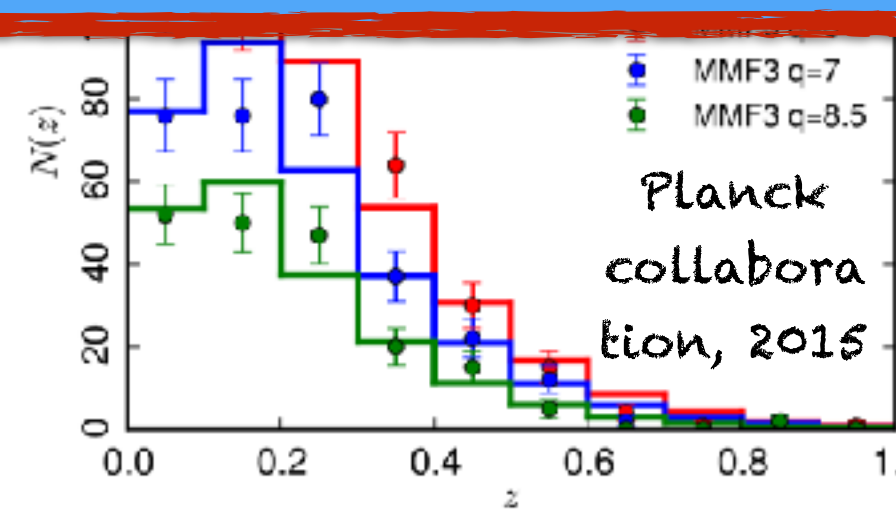




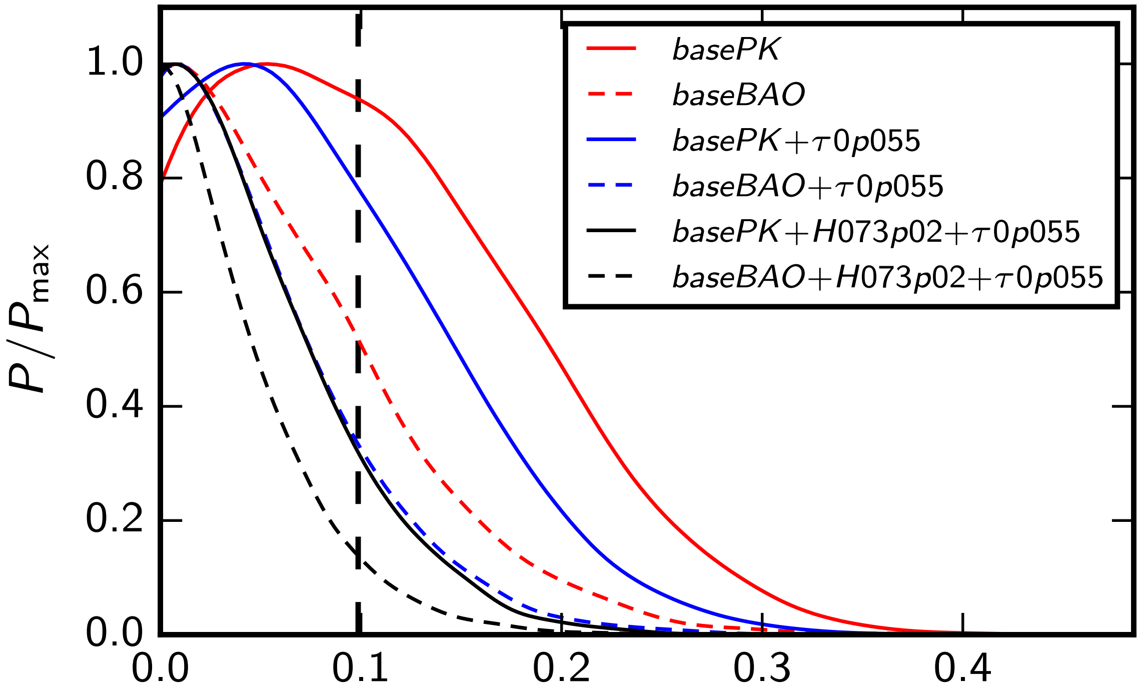
Great complementarity, increased sensitivity, a lot of information can be extracted



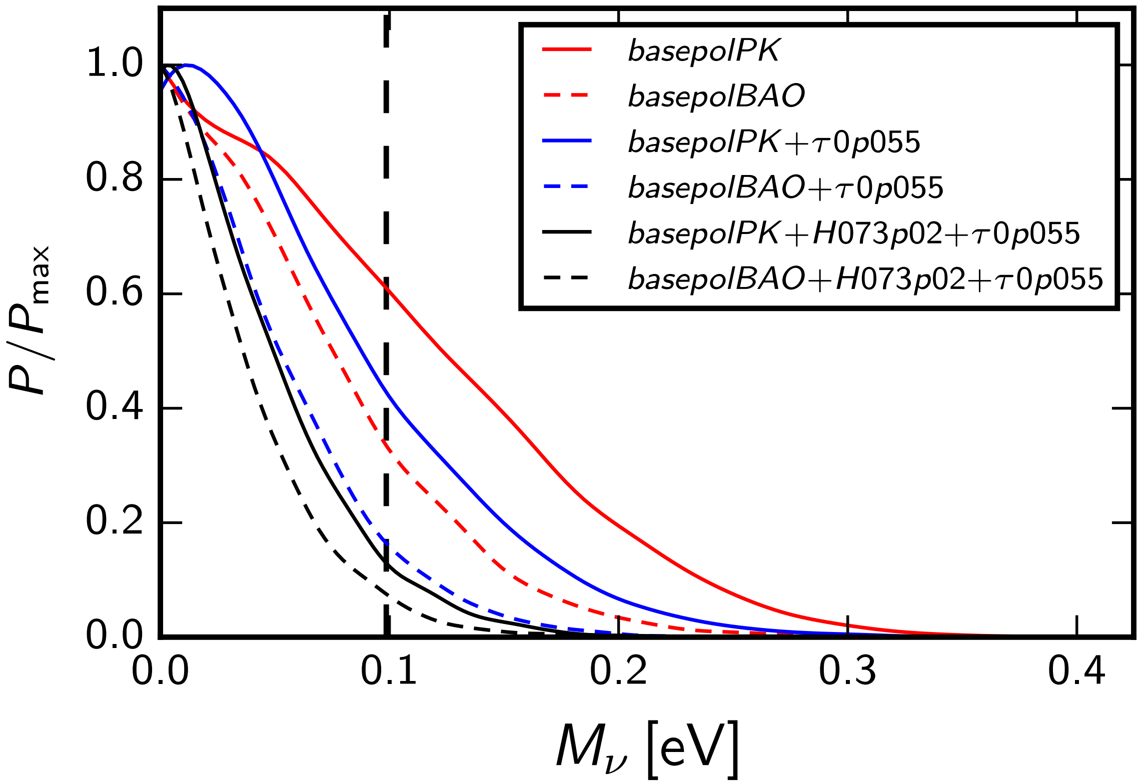




Joint constraints on neutrino mass



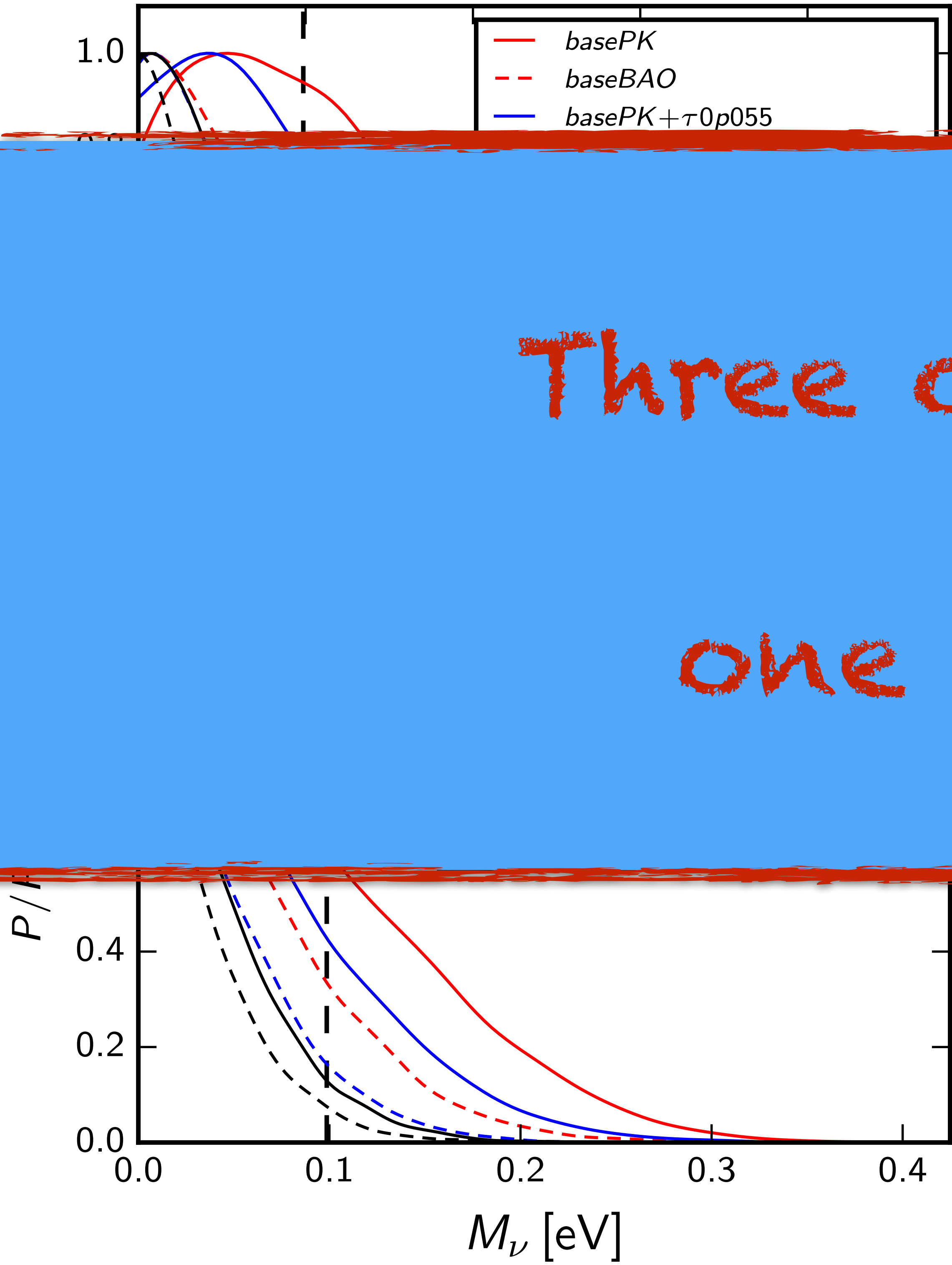
Dataset	3deg
	M_ν (95% C.L.)
$base \equiv Planck\ TT{+}lowP$	< 0.716 eV
$base{+}P(k)$	< 0.299 eV
$basePK \equiv base{+}P(k){+}BAO$	< 0.246 eV
$basePK{+}\tau0p055$	< 0.205 eV
$basePK{+}SZ$	< 0.239 eV
$basePK{+}H073p02$	< 0.164 eV
$basePK{+}H070p6$	< 0.219 eV
$basePK{+}H073p02{+}\tau0p055$	< 0.140 eV
$basePK{+}H073p02{+}\tau0p055{+}SZ$	< 0.136 eV



Dataset	3deg
	M_ν (95% C.L.)
$baseBAO \equiv PlanckTT{+}lowP{+}BAOFULL$	< 0.186 eV
$baseBAO{+}\tau0p055$	< 0.151 eV
$baseBAO{+}H073p02$	< 0.148 eV
$baseBAO{+}H073p02{+}\tau0p055$	< 0.115 eV
$baseBAO{+}H073p02{+}\tau0p055{+}SZ$	< 0.114 eV

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass

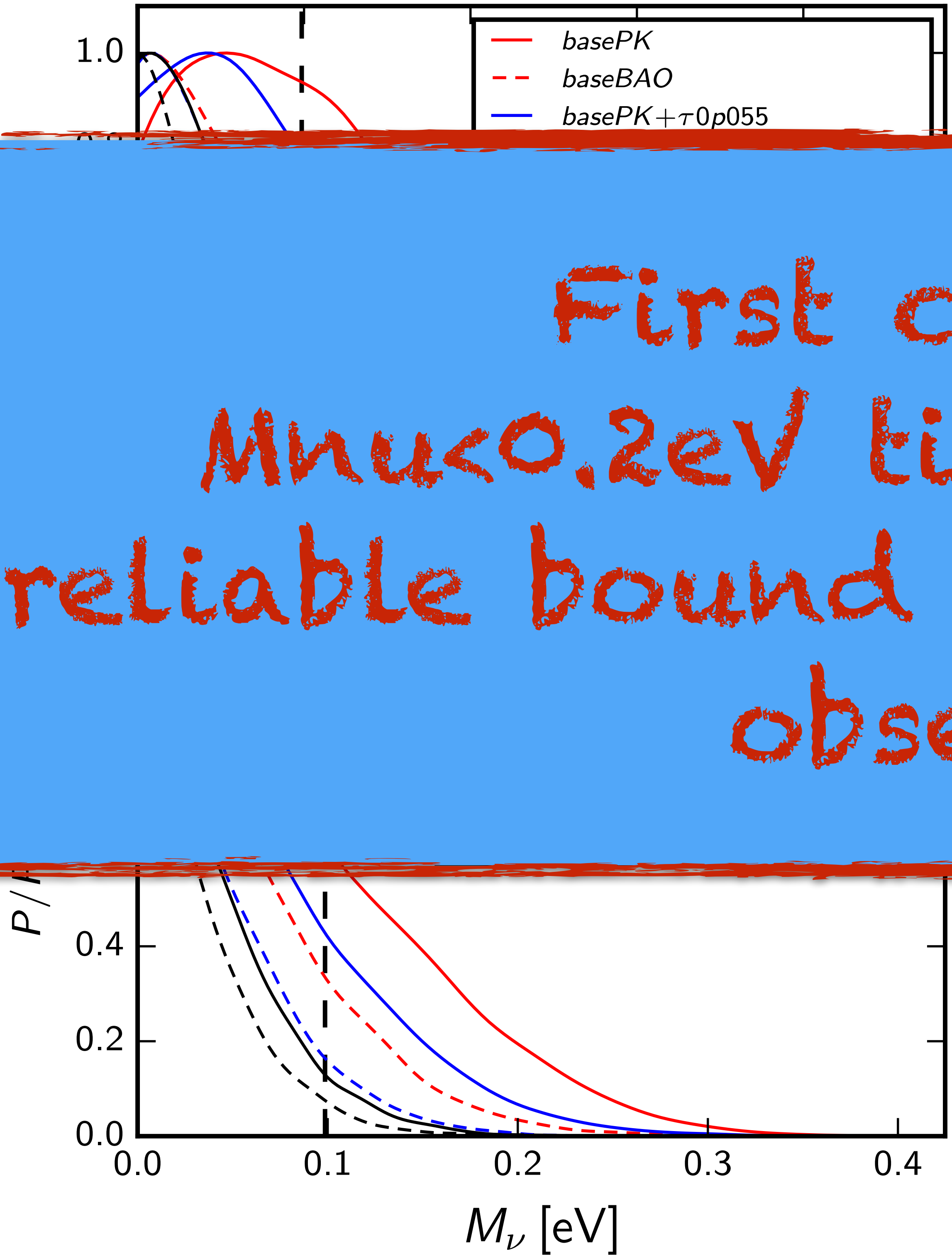


Dataset	*3deg*
	M_ν (95% C.L.)
baseBAO+τ0p055	< 0.151 eV
baseBAO+H073p02	< 0.148 eV
baseBAO+H073p02+τ0p055	< 0.115 eV
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV

Three conclusions and one question

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass

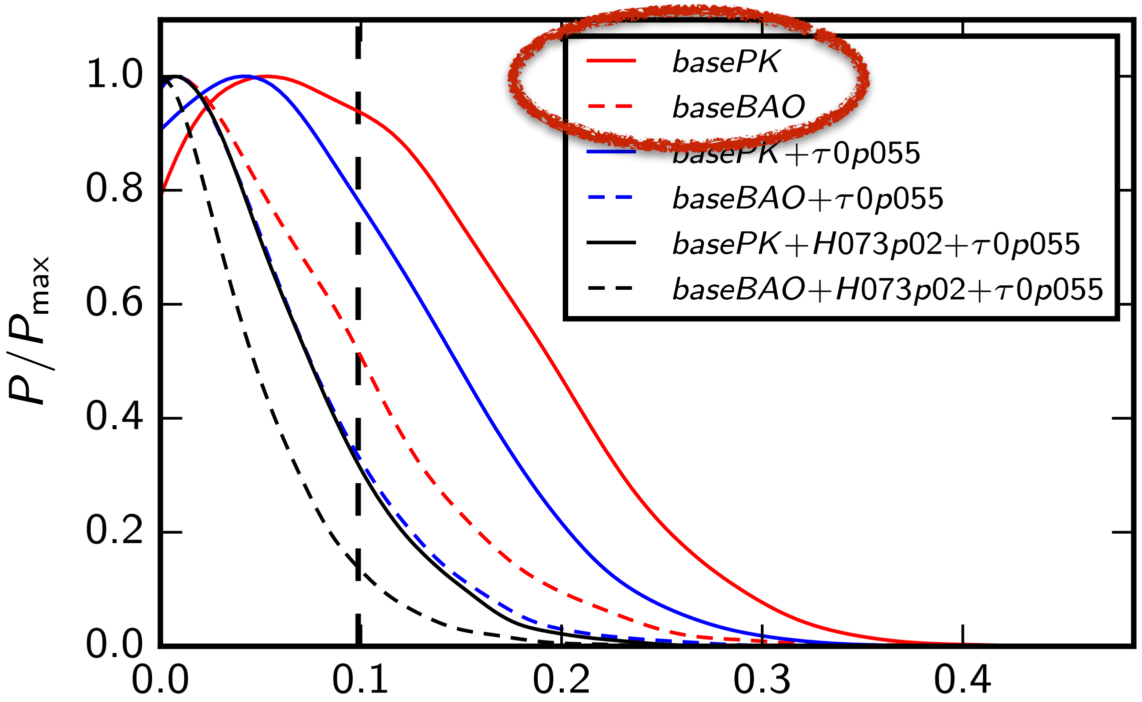


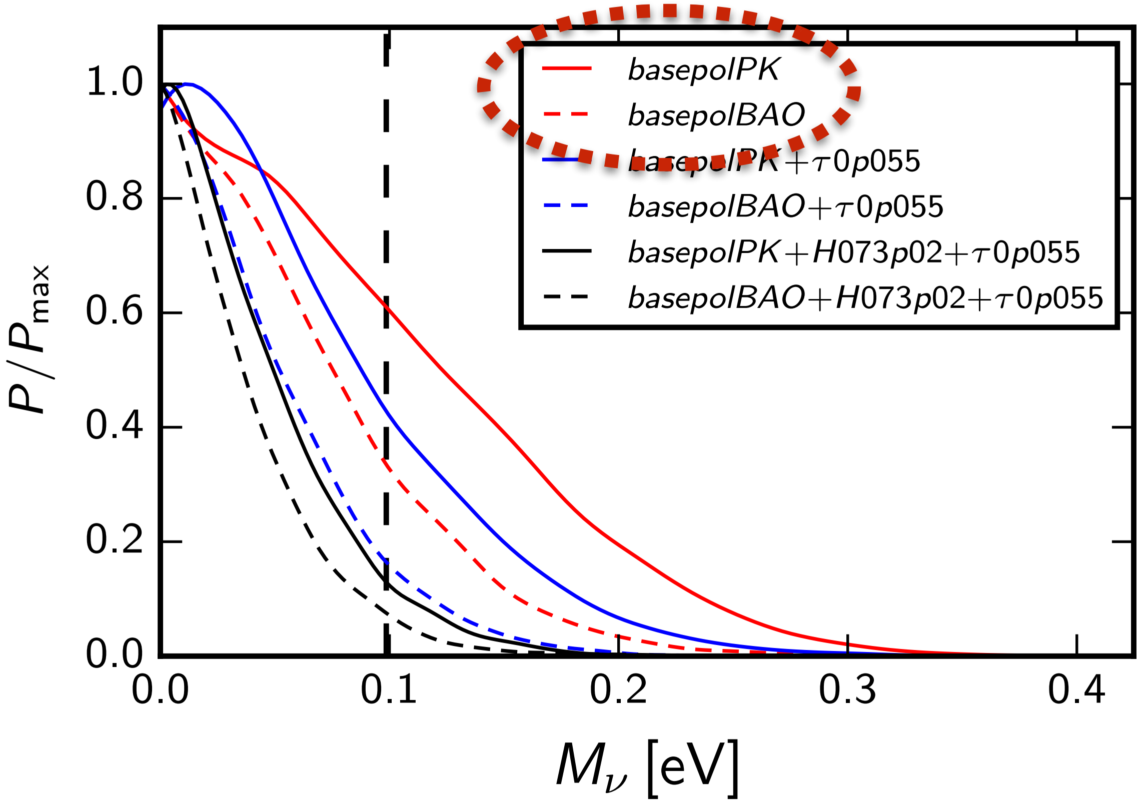
Dataset	3deg
	M_ν (95% C.L.)
baseBAO+H073p02	< 0.148 eV
baseBAO+H073p02+τ0p055	< 0.115 eV
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV

First conclusion:
Mnu<0.2eV tightest AND most reliable bound from cosmological observables

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass



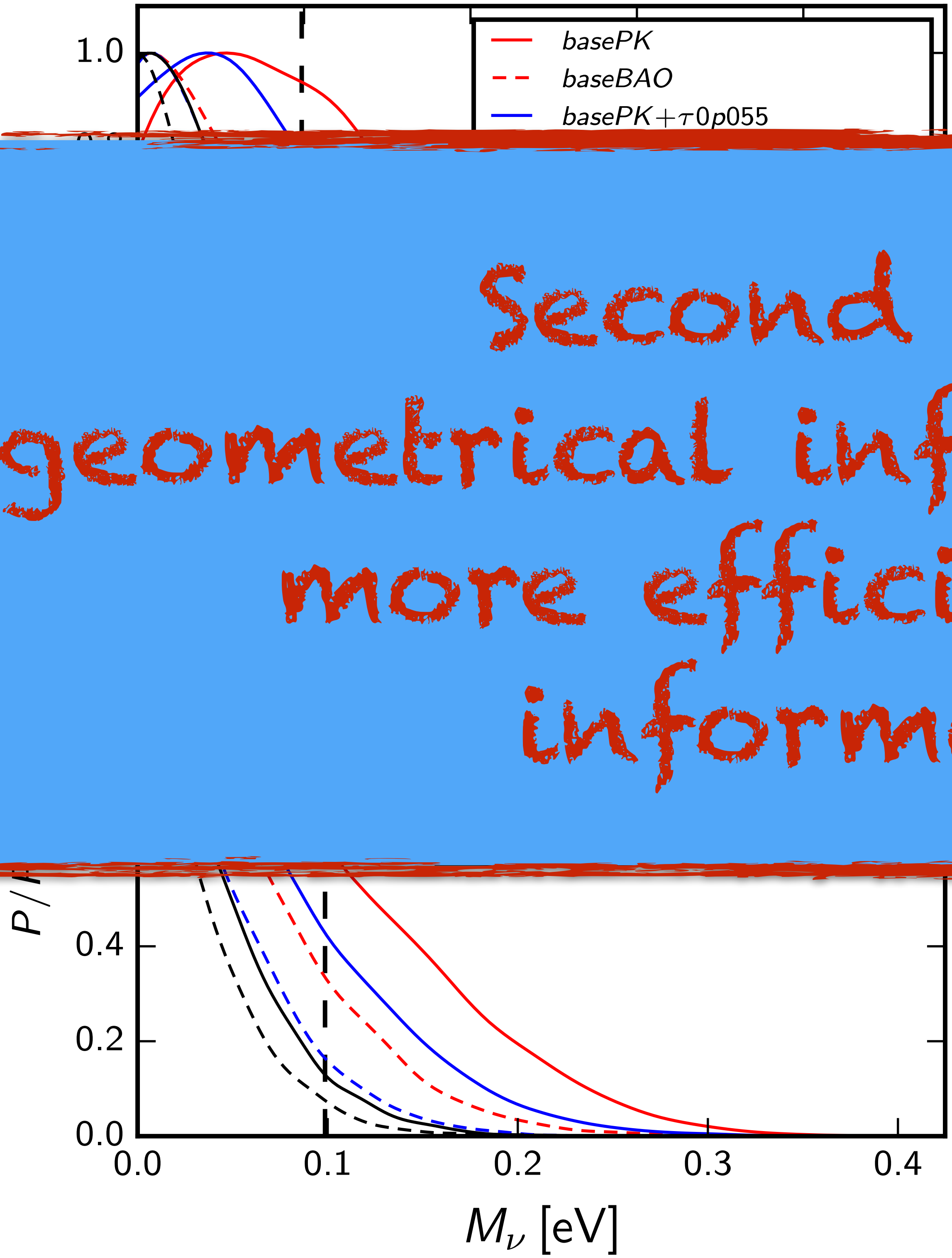


Dataset	3deg
	M_ν (95% C.L.)
$base \equiv Planck\ TT+lowP$	< 0.716 eV
$base+P(k)$	< 0.299 eV
$basePK \equiv base+P(k)+BAO$	< 0.246 eV
$basePK+\tau0p055$	< 0.205 eV
$basePK+SZ$	< 0.239 eV
$basePK+H073p02$	< 0.164 eV
$basePK+H070p6$	< 0.219 eV
$basePK+H073p02+\tau0p055$	< 0.140 eV
$basePK+H073p02+\tau0p055+SZ$	< 0.136 eV

Dataset	3deg
	M_ν (95% C.L.)
$baseBAO \equiv PlanckTT+lowP+BAOFULL$	< 0.186 eV
$baseBAO+\tau0p055$	< 0.151 eV
$baseBAO+H073p02$	< 0.148 eV
$baseBAO+H073p02+\tau0p055$	< 0.115 eV
$baseBAO+H073p02+\tau0p055+SZ$	< 0.114 eV

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass

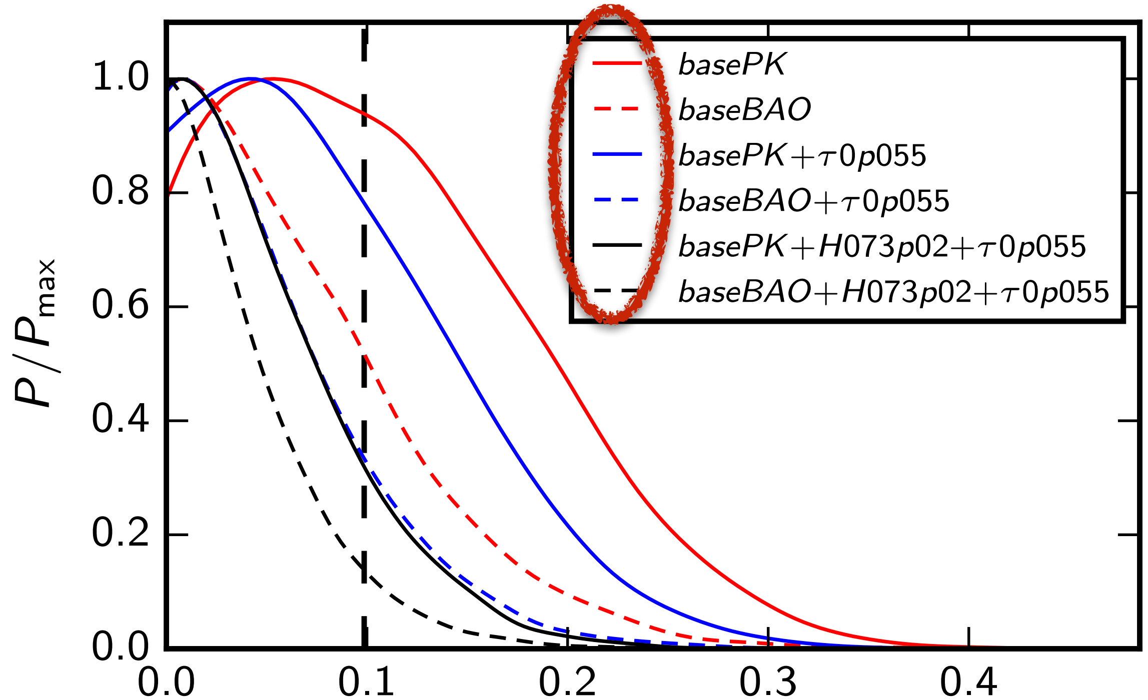


Dataset	*3deg*
	M_ν (95% C.L.)
baseBAO+H073p02	< 0.148 eV
baseBAO+H073p02+τ0p055	< 0.115 eV
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV

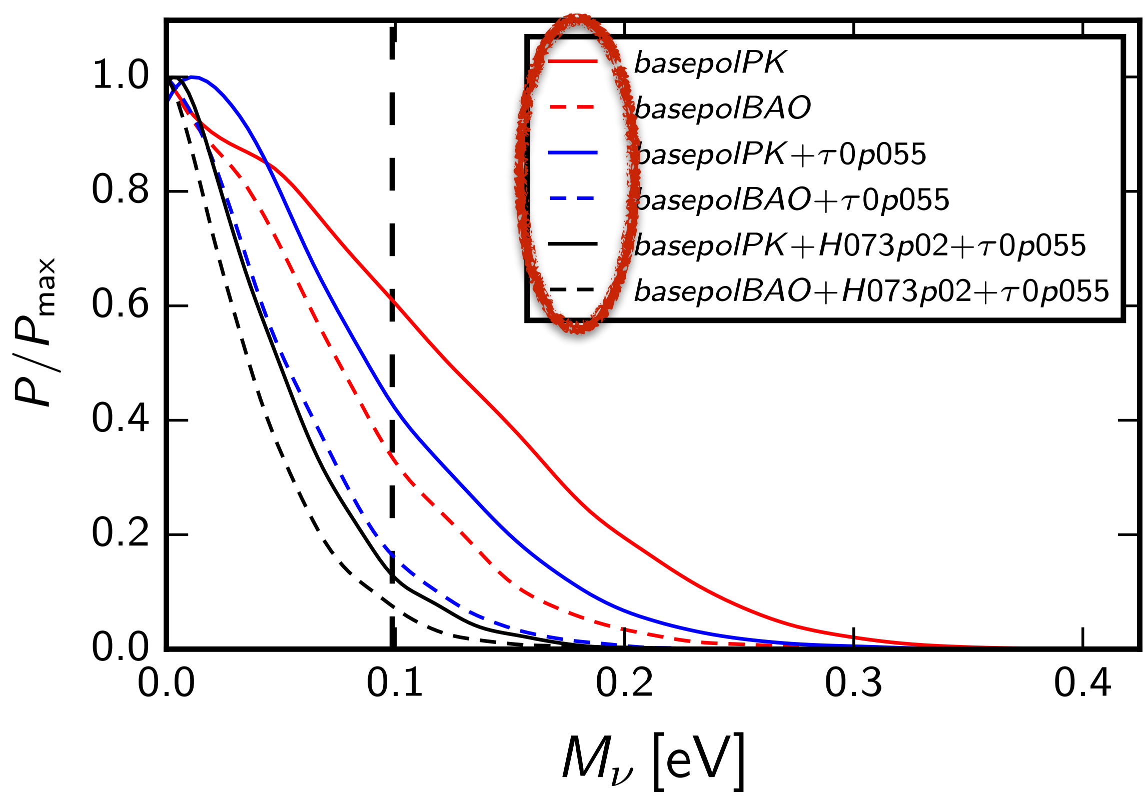
Second conclusion: geometrical information (BAO) are more efficient than shape information (MPS)

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass



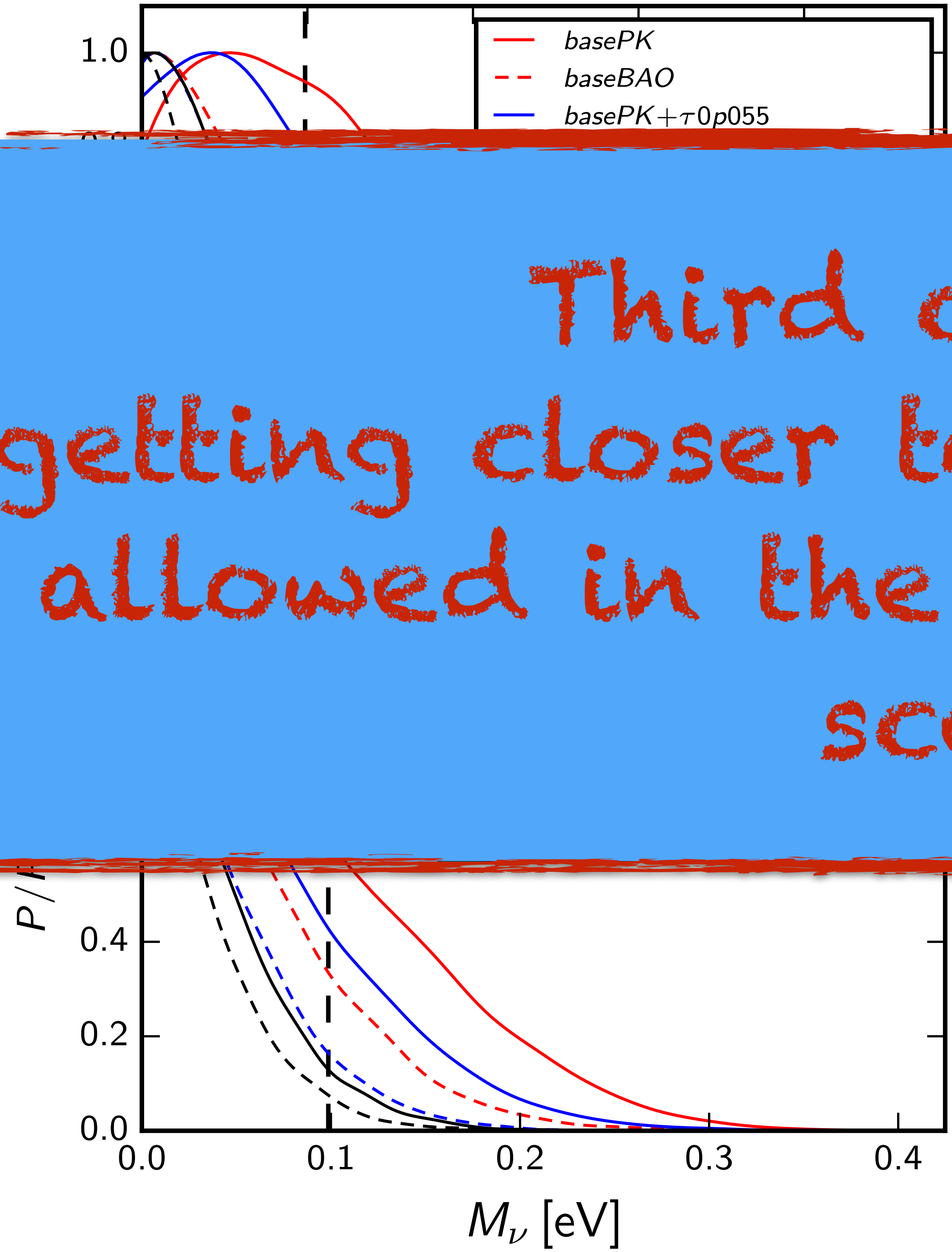
Dataset	3deg
	M_ν (95% C.L.)
base ≡ *Planck TT+lowP*	< 0.716 eV
base+P(k)	< 0.299 eV
basePK ≡ *base+P(k)+BAO*	< 0.246 eV
basePK+τ0p055	< 0.205 eV
basePK+SZ	< 0.239 eV
basePK+H073p02	< 0.164 eV
basePK+H070p6	< 0.219 eV
basePK+H073p02+τ0p055	< 0.140 eV
basePK+H073p02+τ0p055+SZ	< 0.136 eV



Dataset	3deg
	M_ν (95% C.L.)
baseBAO ≡ *PlanckTT+lowP+BAOFULL*	< 0.186 eV
baseBAO+τ0p055	< 0.151 eV
baseBAO+H073p02	< 0.148 eV
baseBAO+H073p02+τ0p055	< 0.115 eV
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass

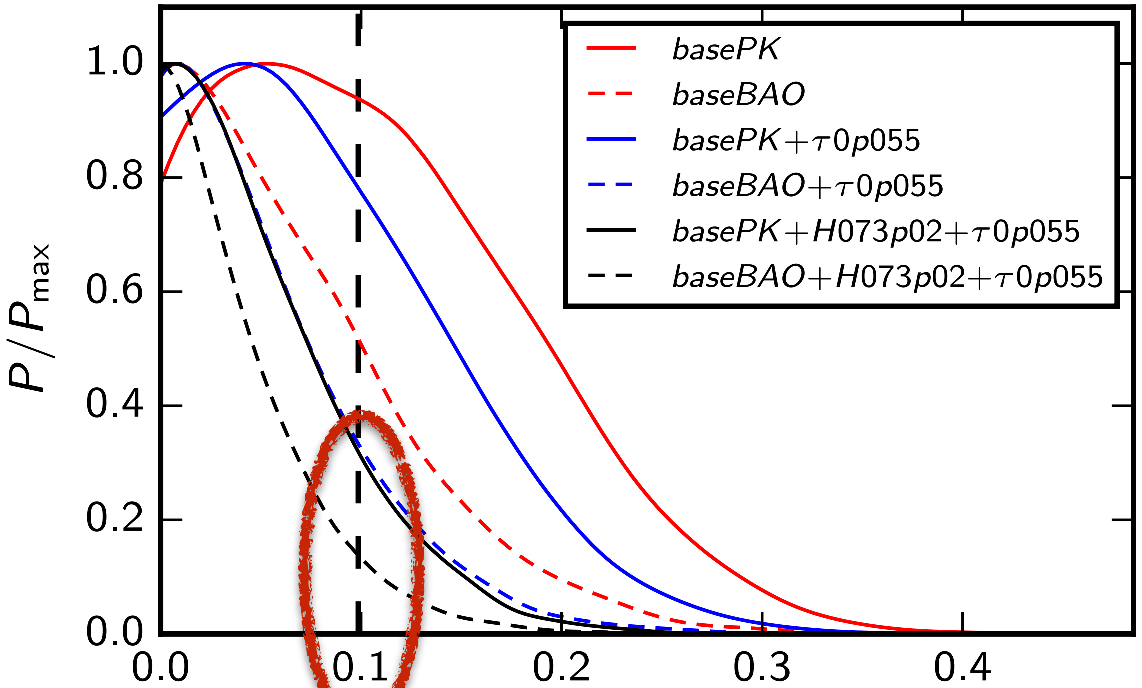


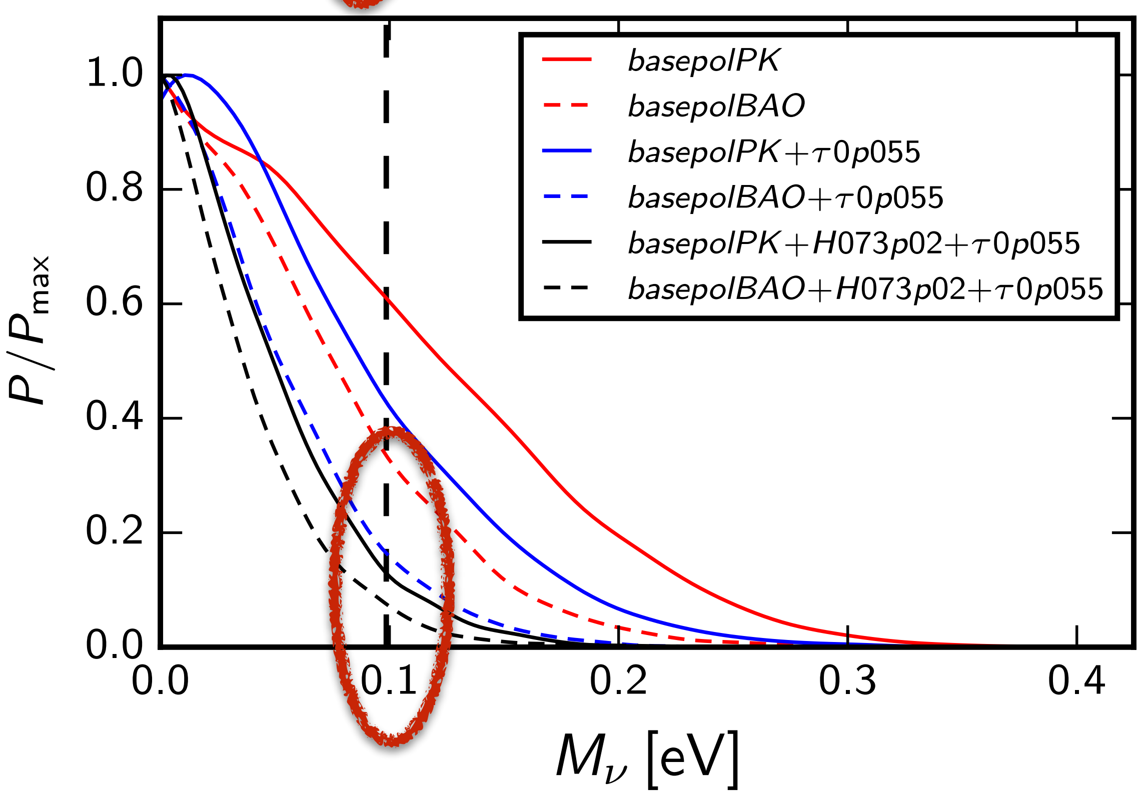
Dataset	3deg
	M_ν (95% C.L.)
baseBAO+τ0p055	< 0.151 eV
baseBAO+H073p02	< 0.148 eV
baseBAO+H073p02+τ0p055	< 0.115 eV
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV

Third conclusion:
getting closer to the minimal mass allowed in the inverted hierarchy scenario

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass





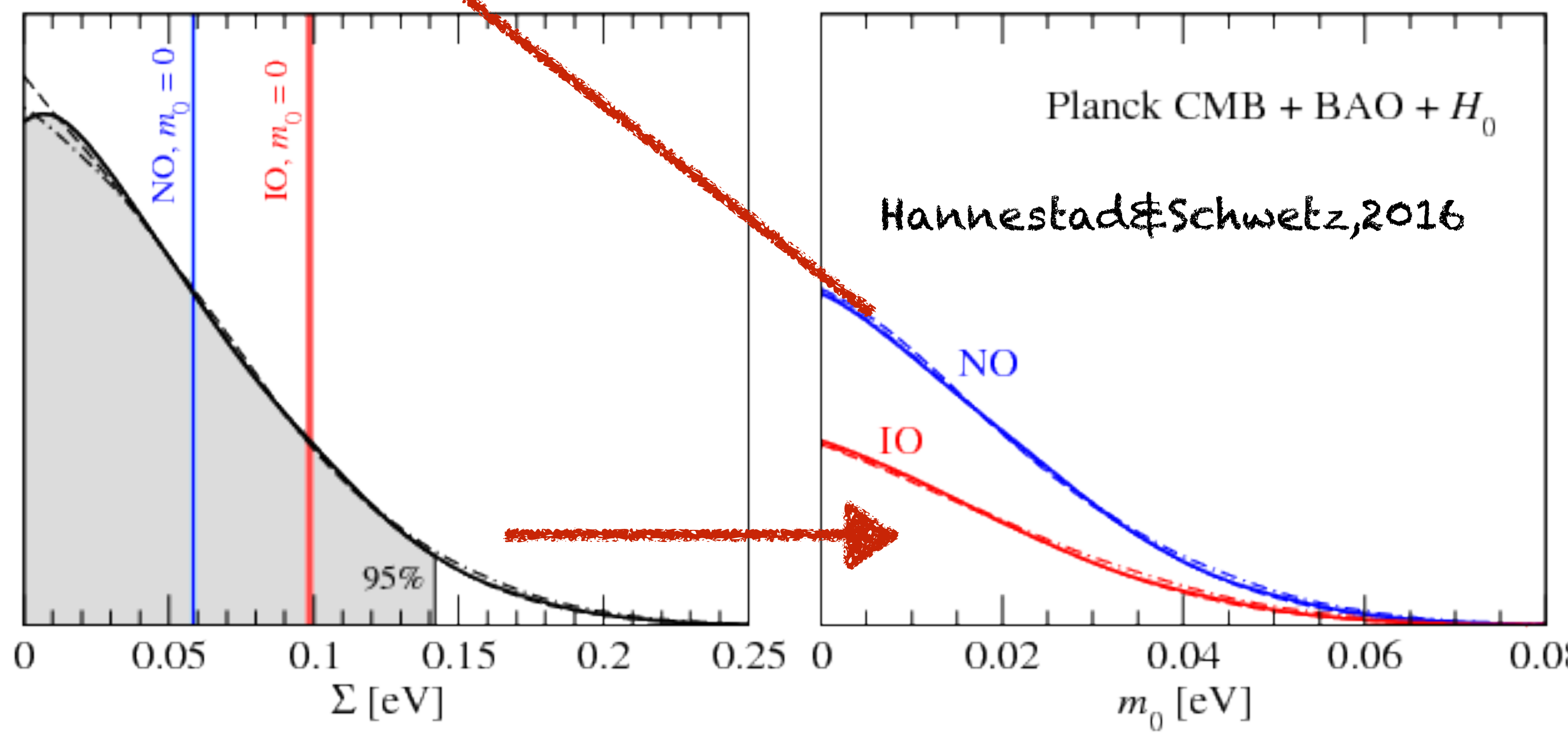
Dataset	*3deg*
	M_ν (95% C.L.)
base ≡ *Planck TT+lowP*	$<$ 0.716 eV
base+P(k)	$<$ 0.299 eV
basePK ≡ *base+P(k)+BAO*	$<$ 0.246 eV
basePK+τ0p055	$<$ 0.205 eV
basePK+SZ	$<$ 0.239 eV
basePK+H073p02	$<$ 0.164 eV
basePK+H070p6	$<$ 0.219 eV
basePK+H073p02+τ0p055	$<$ 0.140 eV
basePK+H073p02+τ0p055+SZ	$<$ 0.136 eV

Dataset	*3deg*
	M_ν (95% C.L.)
baseBAO ≡ *PlanckTT+lowP+BAOFULL*	$<$ 0.186 eV
baseBAO+τ0p055	$<$ 0.151 eV
baseBAO+H073p02	$<$ 0.148 eV
baseBAO+H073p02+τ0p055	$<$ 0.115 eV
baseBAO+H073p02+τ0p055+SZ	$<$ 0.114 eV

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass

$$p_H = \frac{p(H)\int_0^\infty dm_0\ \mathcal{L}(D|m_0,H)}{p(N)\int_0^\infty dm_0\ \mathcal{L}(D|m_0,N) + p(I)\int_0^\infty dm_0\ \mathcal{L}(D|m_0,I)}$$

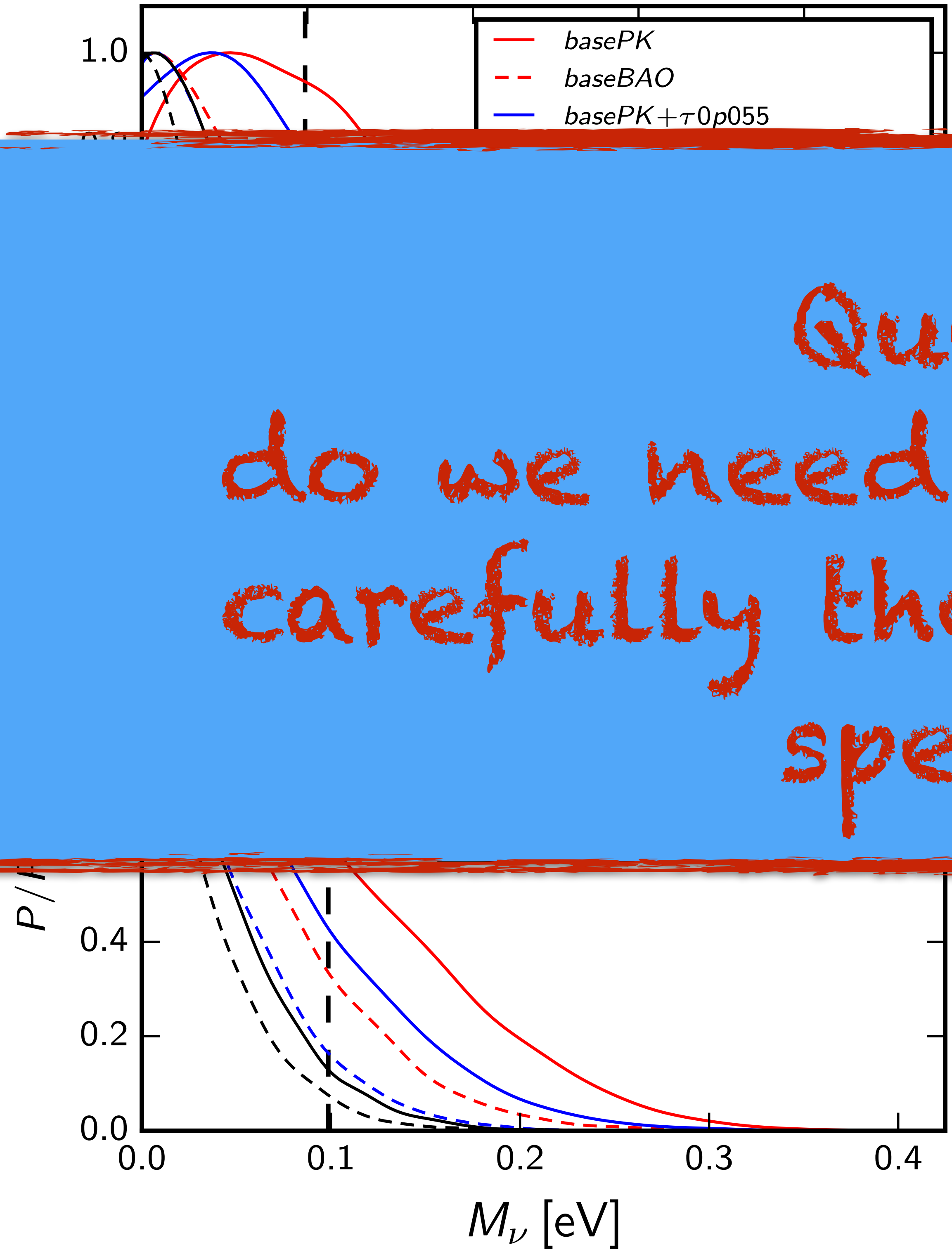


Dataset	M_ν (95% C.L., *3deg*)	$\mathrm{CL}_{\mathrm{IH}}$	p_N/p_I
basepolPK+H073p02+τ0p055	< 0.109 eV	74%	2.8 : 1
basepolPK+H073p02+τ0p055+SZ	< 0.117 eV	71%	2.4 : 1
baseBAO+H073p02+τ0p055	< 0.115 eV	72%	2.6 : 1
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV	72%	2.6 : 1
basepolBAO+τ0p055	< 0.118 eV	71%	2.4 : 1
basepolBAO+H073p02	< 0.113 eV	72%	2.6 : 1
basepolBAO+H073p02+τ0p055	< 0.094 eV	77%	3.3 : 1
basepolBAO+H073p02+τ0p055+SZ	< 0.093 eV	77%	3.3 : 1

~3:1 preference for NH vs IH

Vagnozzi+ (incl. MG), 2017

Joint constraints on neutrino mass



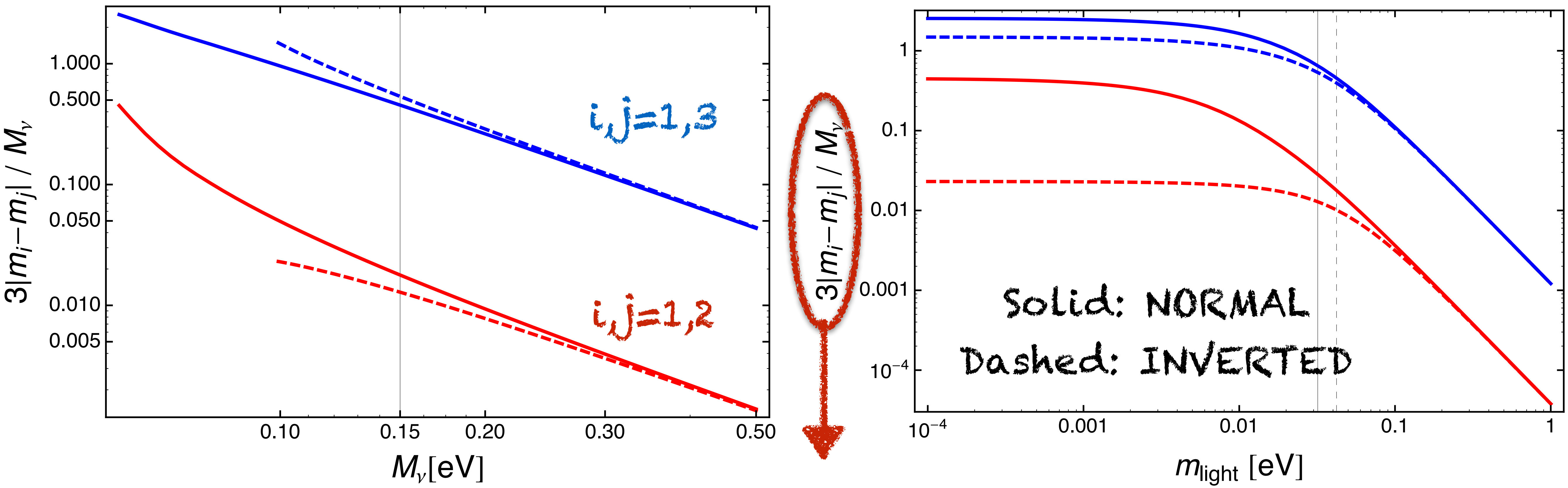
Dataset	*3deg*
	M_ν (95% C.L.)
baseBAO+τ0p055	< 0.151 eV
baseBAO+H073p02	< 0.148 eV
baseBAO+H073p02+τ0p055	< 0.115 eV
baseBAO+H073p02+τ0p055+SZ	< 0.114 eV

Question:
do we need to model more carefully the neutrino mass spectrum?

Vagnozzi+ (incl. MG), 2017

On the validity of 3deg approx

Vagnozzi+ (incl. MG), 2017



FoM: how much the mass difference is relevant wrt the 3deg approx as a function of the total mass (or the lightest mass)

Mathematically poor approximation

Physically: is cosmology sensitive to difference in neutrino mass spectrum?

Quantifying the sensitivity

Bayesian hierarchical analysis can help

$$\mathcal{P} = \mathcal{P}(\vec{\theta}, h) \quad h = NH, IH$$

Advantages:

- neutrinos modelled with exact mass spectrum

NORMAL HIERARCHY

$$m_{\nu,1} = m_{\rm light}$$

$$m_{\nu,2} = \sqrt{m_1^2 + \Delta m_{12}^2}$$

$$m_{\nu,3} = \sqrt{m_1^2 + \Delta m_{13}^2}$$

INVERTED HIERARCHY

$$m_{\nu,3} = m_{\rm light}$$

$$m_{\nu,1} = \sqrt{m_3^2 + \Delta m_{13}^2}$$

$$m_{\nu,2} = \sqrt{m_1^2 + \Delta m_{12}^2}$$

- information from oscillations taken into account
- takes into account uncertainties related to the hierarchy

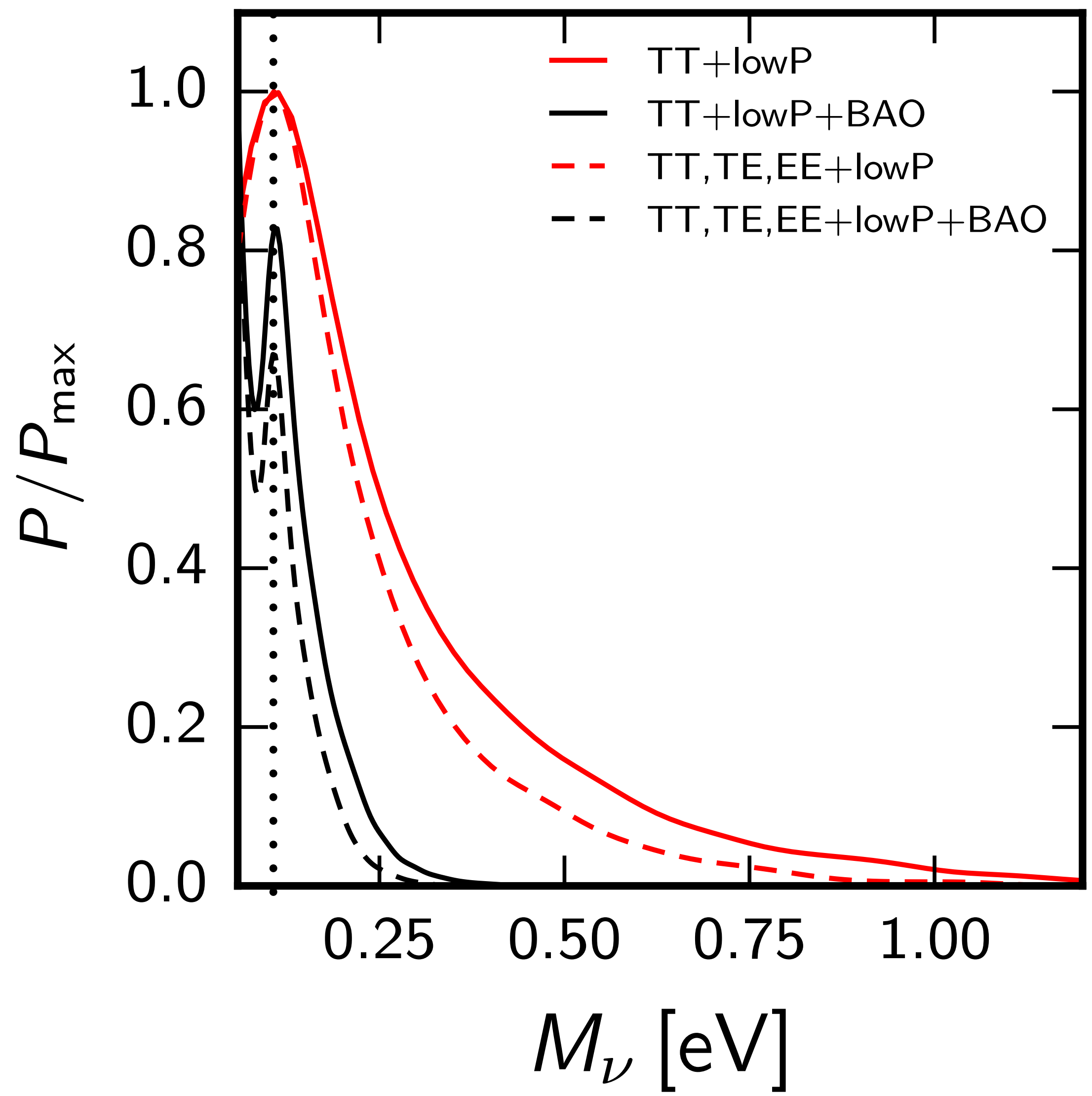
$$\mathcal{P}_{\vec{\theta}} = \int \mathcal{P}(\vec{\theta}, h)\, dh$$

- quantifies sensitivity to the hierarchy

$$\mathcal{P}_{\rm NH} \equiv p(h_{\rm type} = {\rm NH}\,|\,\vec{d}) = \int \mathcal{P}\left(\vec{\theta},\, h_{\rm type} = {\rm NH}\right) d\vec{\theta}$$

Gerbino+, 2016

With current data



$$M_\nu^{\rm min} \leq M_\nu \leq 0.740\,{\rm eV}$$

$$M_\nu^{\rm min} \leq M_\nu \leq 0.232\,{\rm eV}$$

$$M_\nu^{\rm min} \leq M_\nu \leq 0.558\,{\rm eV}$$

$$M_\nu^{\rm min} \leq M_\nu \leq 0.199\,{\rm eV}$$

$$M_\nu^{\rm min} = 0.059\,{\rm eV}$$

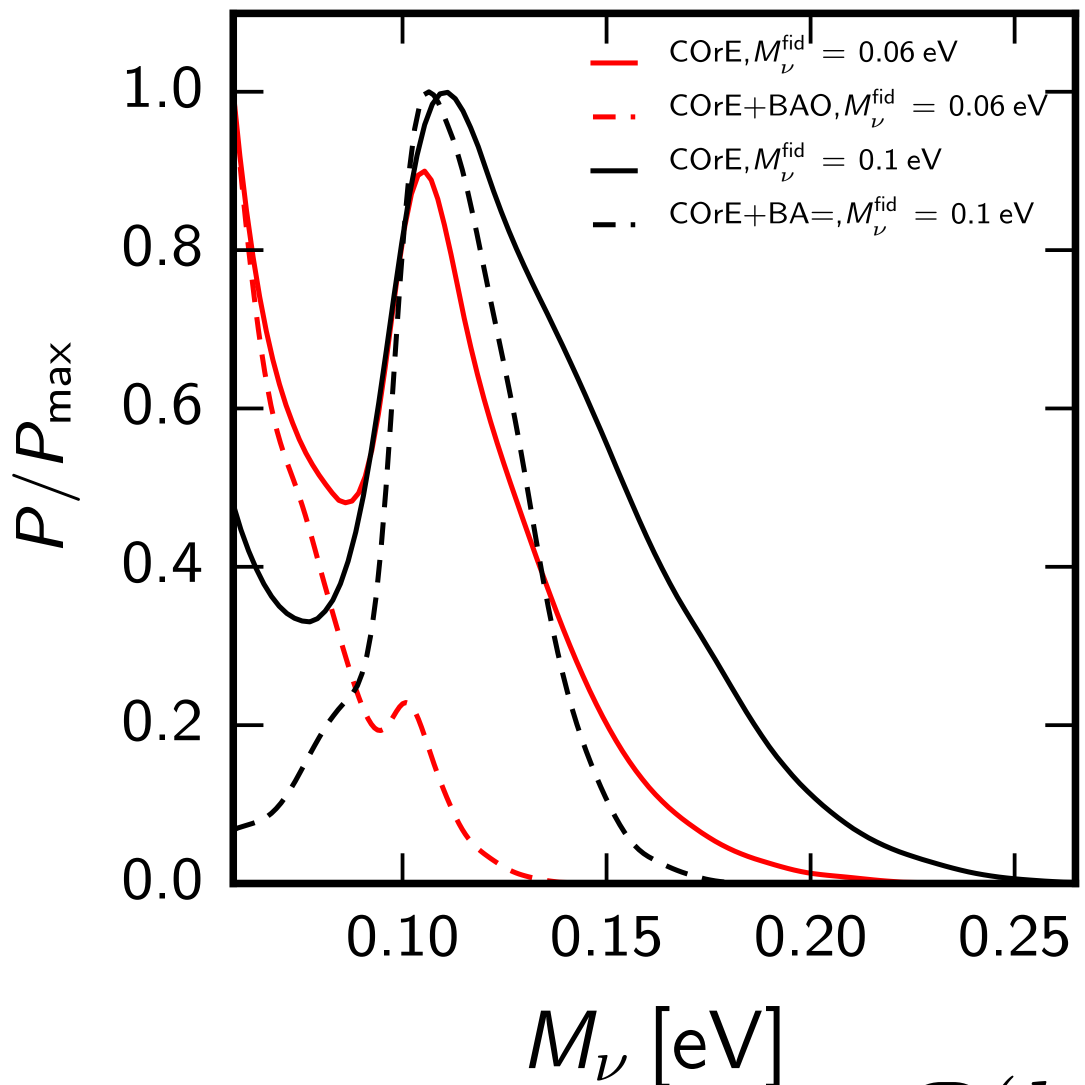
$$\mathcal{P}(h = NH) : \mathcal{P}(h = IH)$$

3:2

Planck TT,TE,EE+lowP+BAO

Gerbino+, 2016

With forecasted data



$$M_\nu^{\rm min} \leq M_\nu \leq 0.109\,{\rm eV}$$

$$M_\nu = 0.112^{+0.037}_{-0.040}\,{\rm eV}$$

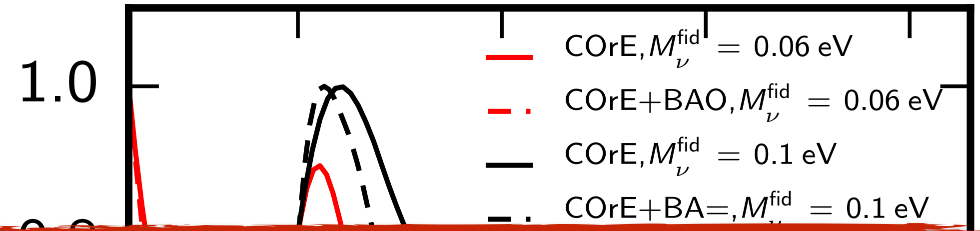
$$\mathcal{P}(h = NH) : \mathcal{P}(h = IH)$$

9:1 Supercool!!!

1:1 Nothing to declare...

Gerbino+, 2016

With forecasted data



Probably not:
What really matters is the total neutrino mass
3deg still physically motivated

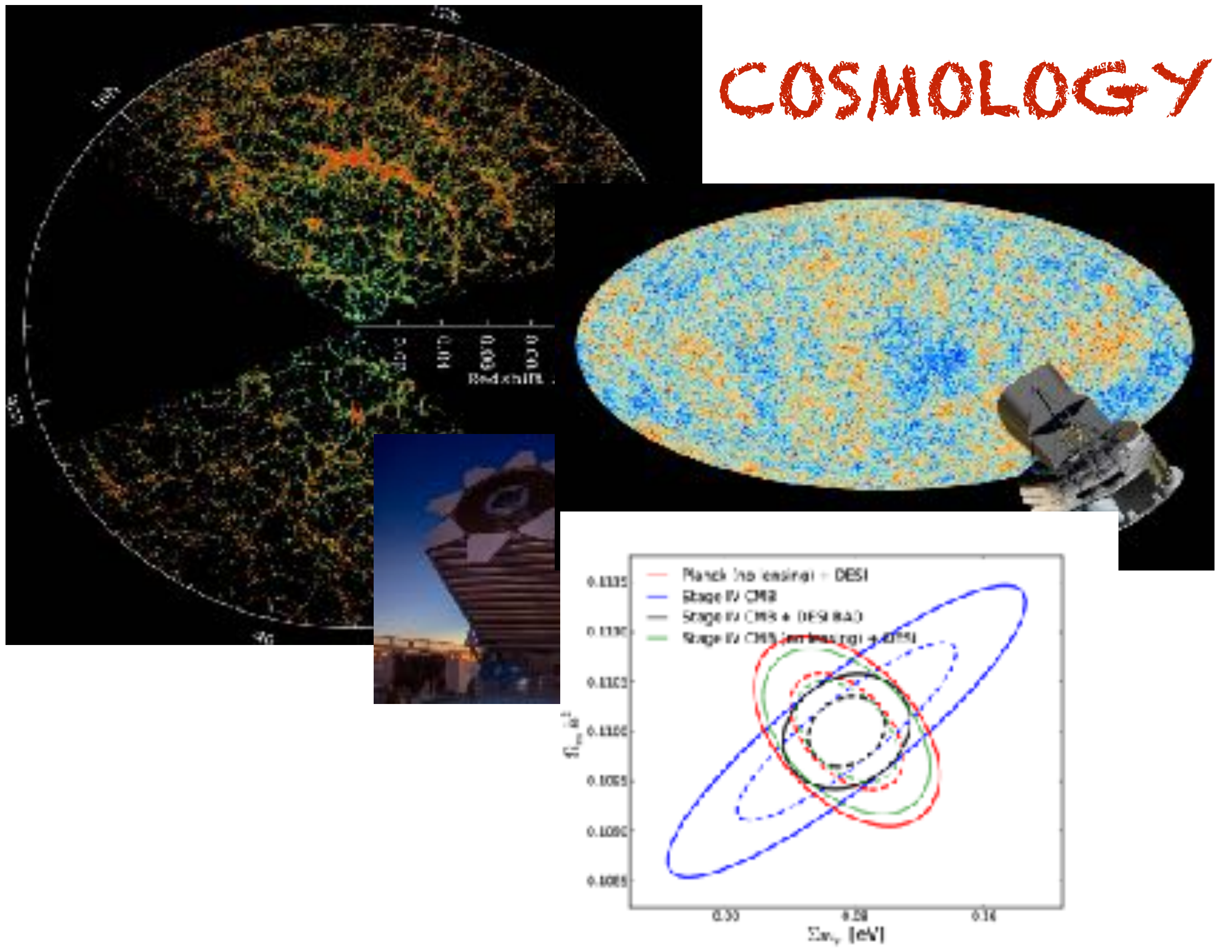
$P(h = NH) : P(h = IH)$

9:1 Supercool!!!

1:1 Nothing to declare...

Gerbino+, 2016

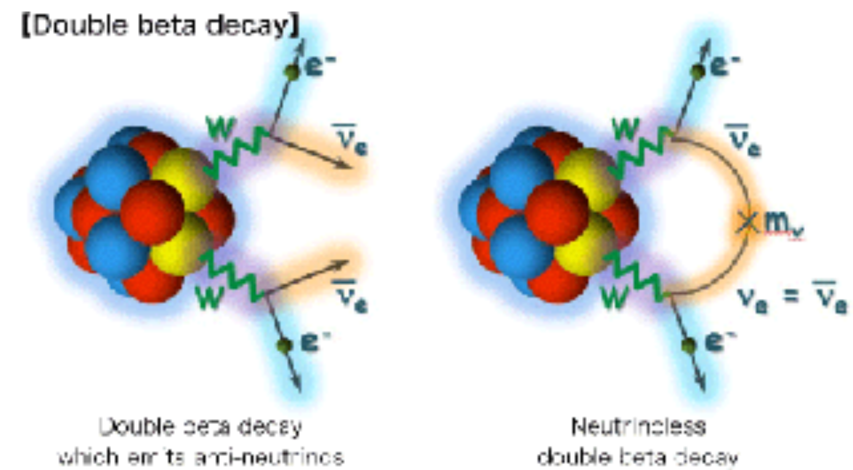
Look around you!

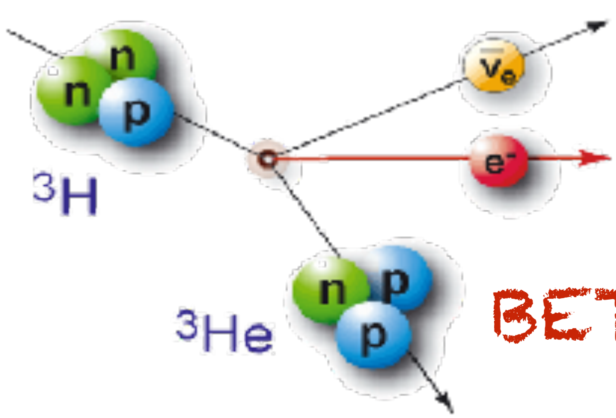


COSMOLOGY M_ν

OSCILLATIONS Δm^2_{ij}

DOUBLE BETA DECAY



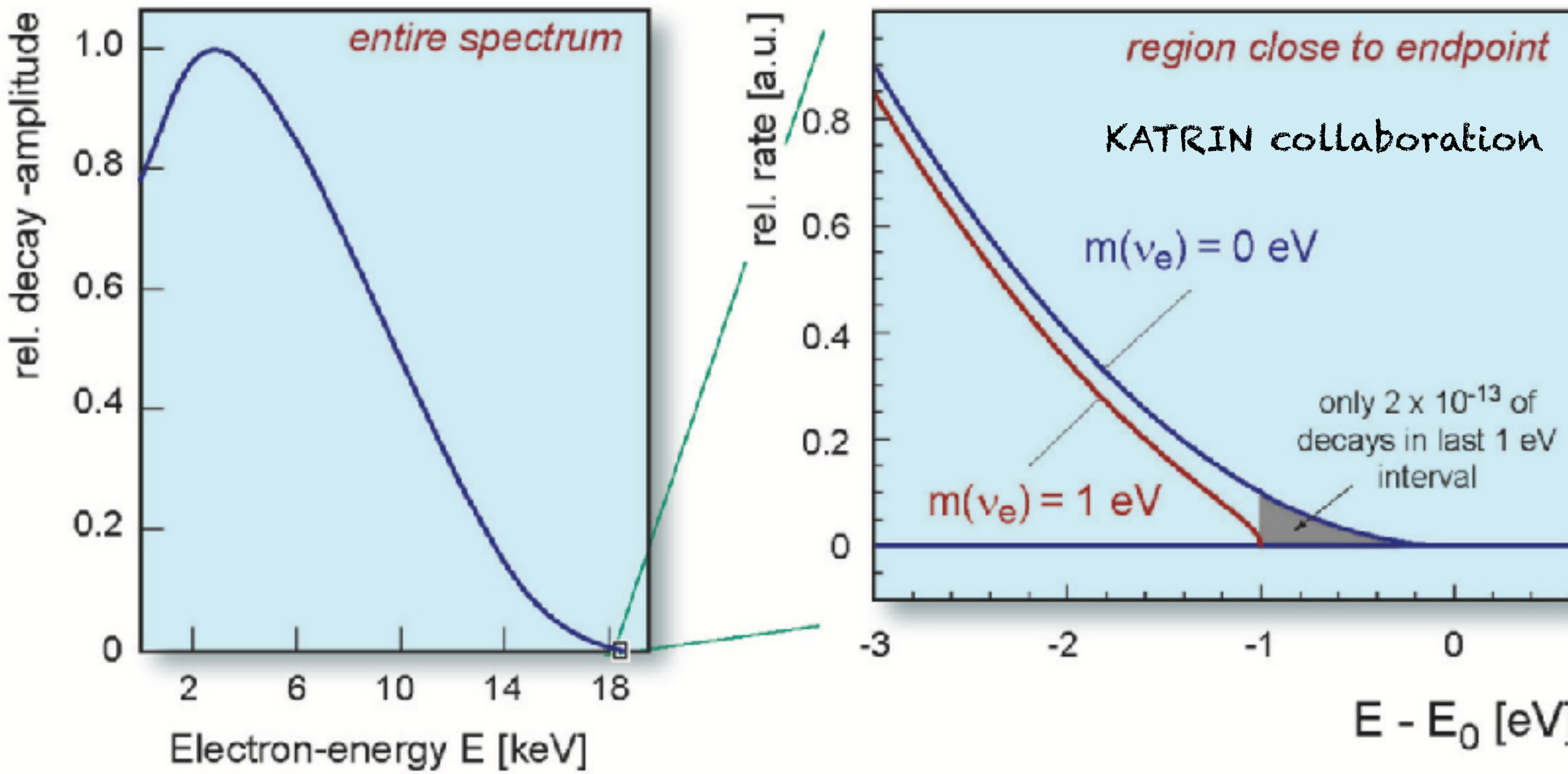


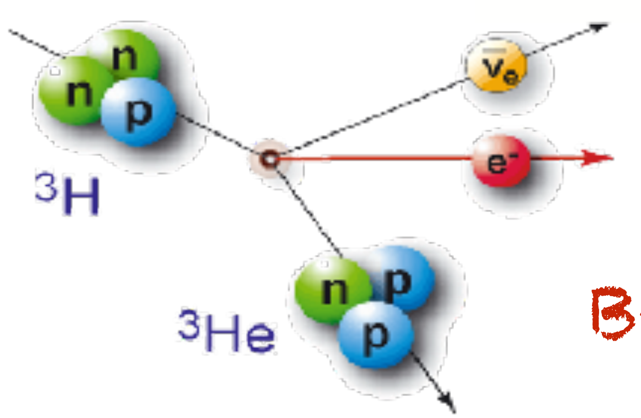
BETA DECAY

$$m^2_\beta = \Sigma_j U^2_{ij} m^2_j$$

$$m_{\beta\beta} = |\Sigma_j U^2_{ij} m_j|$$

Look around you!





BETA DECAY

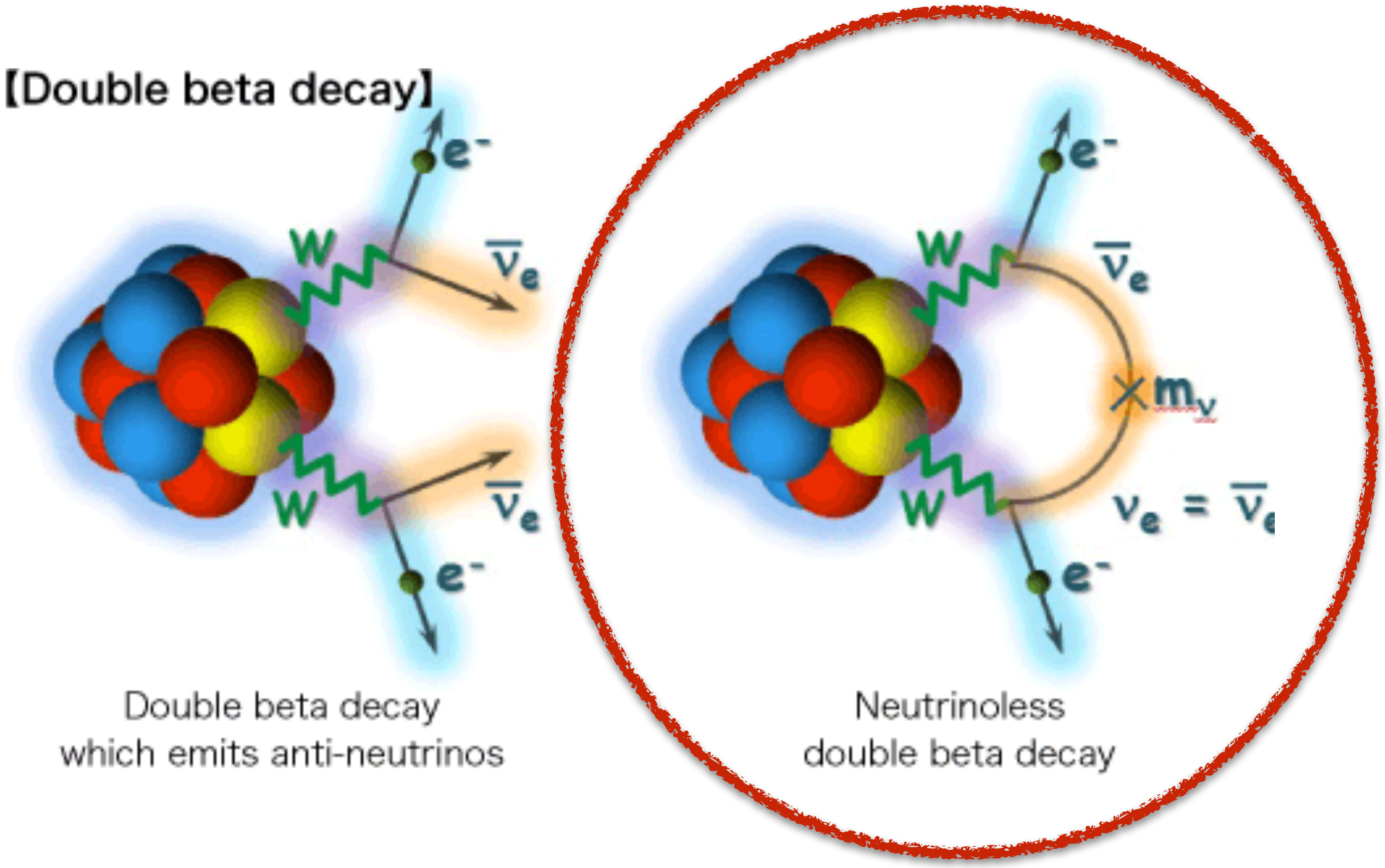
$$m_\beta < 2.2\,\mathrm{eV}$$

$$m_\beta^2 = \Sigma_j U_{ij}^2 m_j^2$$

Pro: robust, model independent

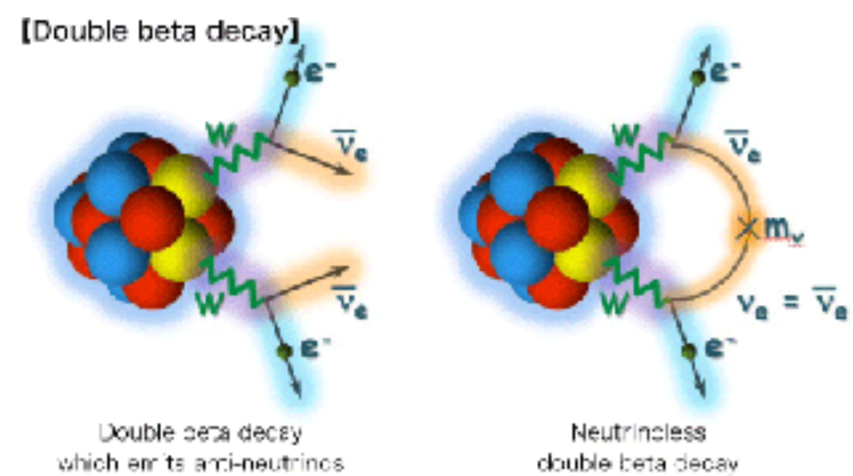
Cons: broadest constraints

Look around you!



$$m_{\beta\beta} < 0.2\,\mathrm{eV}$$

DOUBLE BETA DECAY

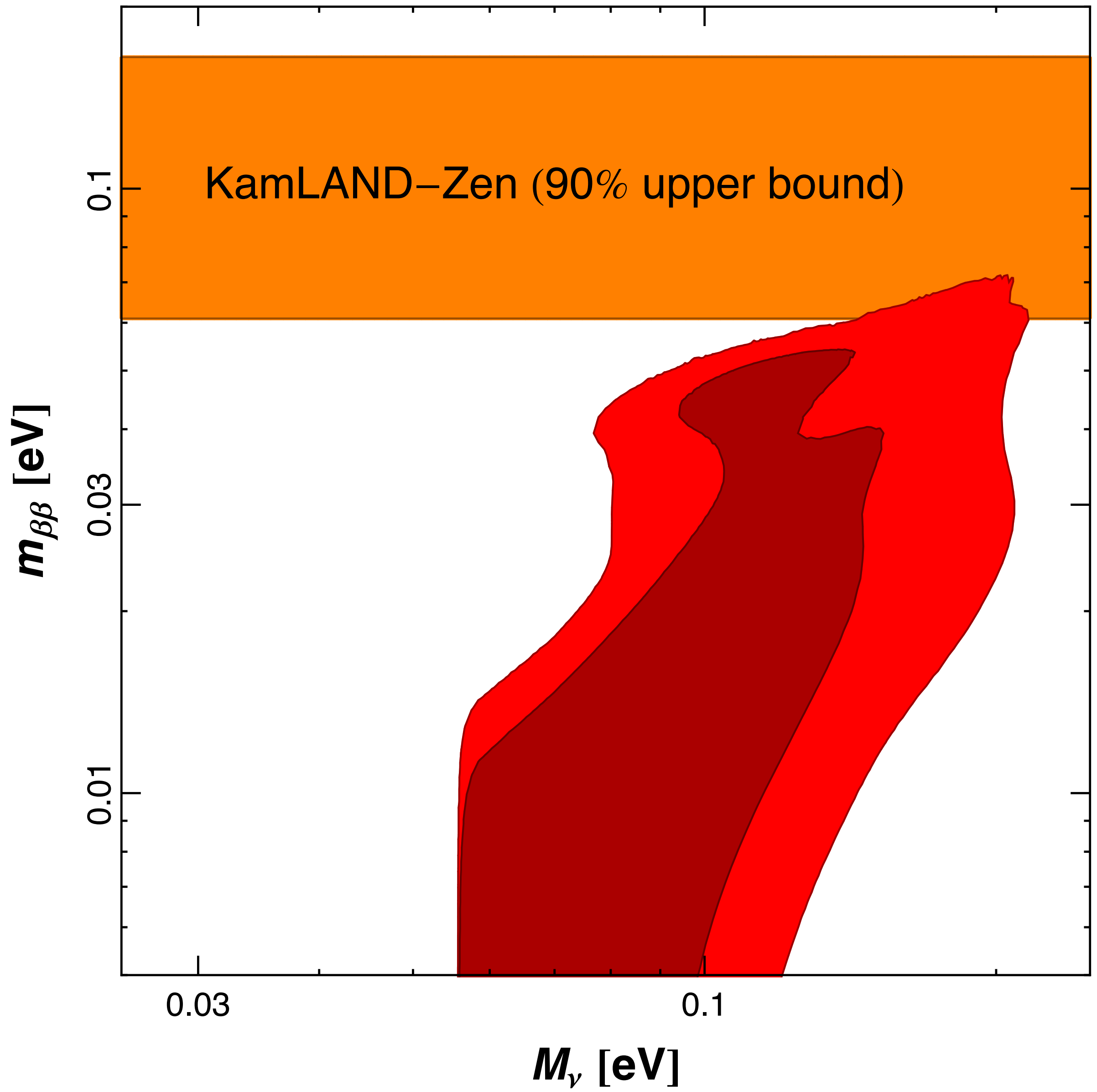


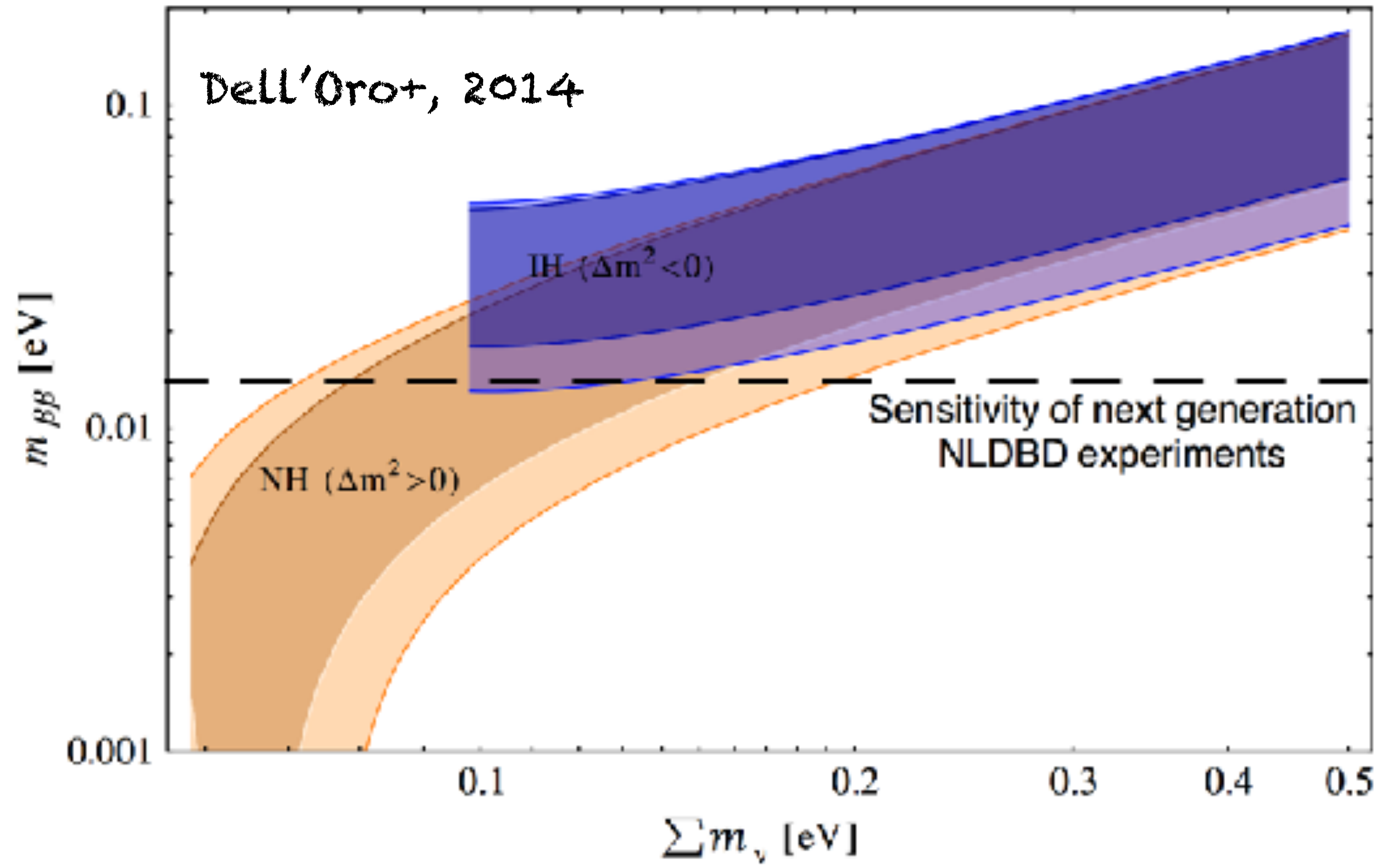
Pro: if signal observed, neutrinos are Majorana!

Cons: model dependent, disruptive interference

$$m_{\beta\beta} = |\Sigma_j U_{ij}^2 m_j|$$

Shake it up!

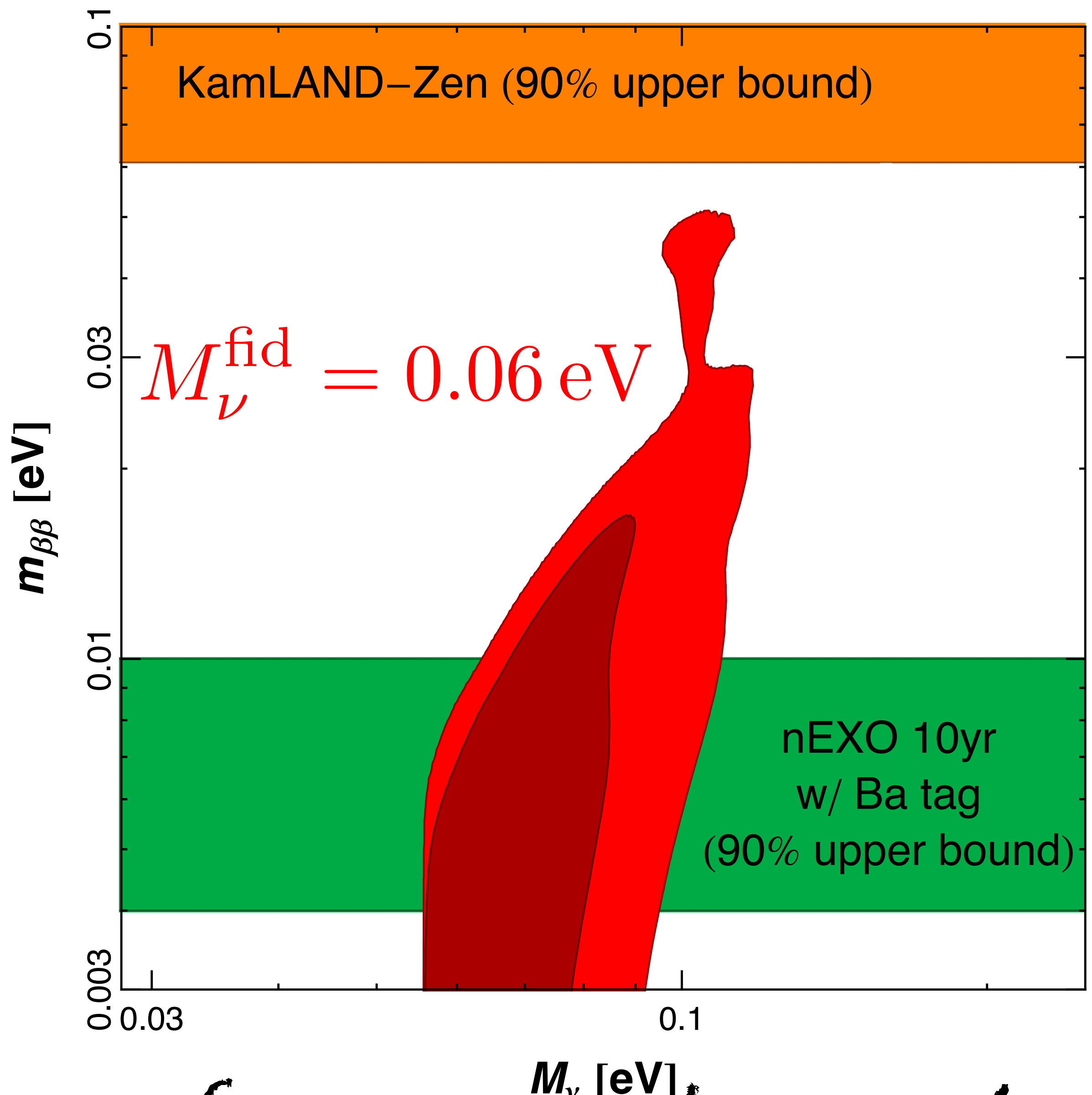


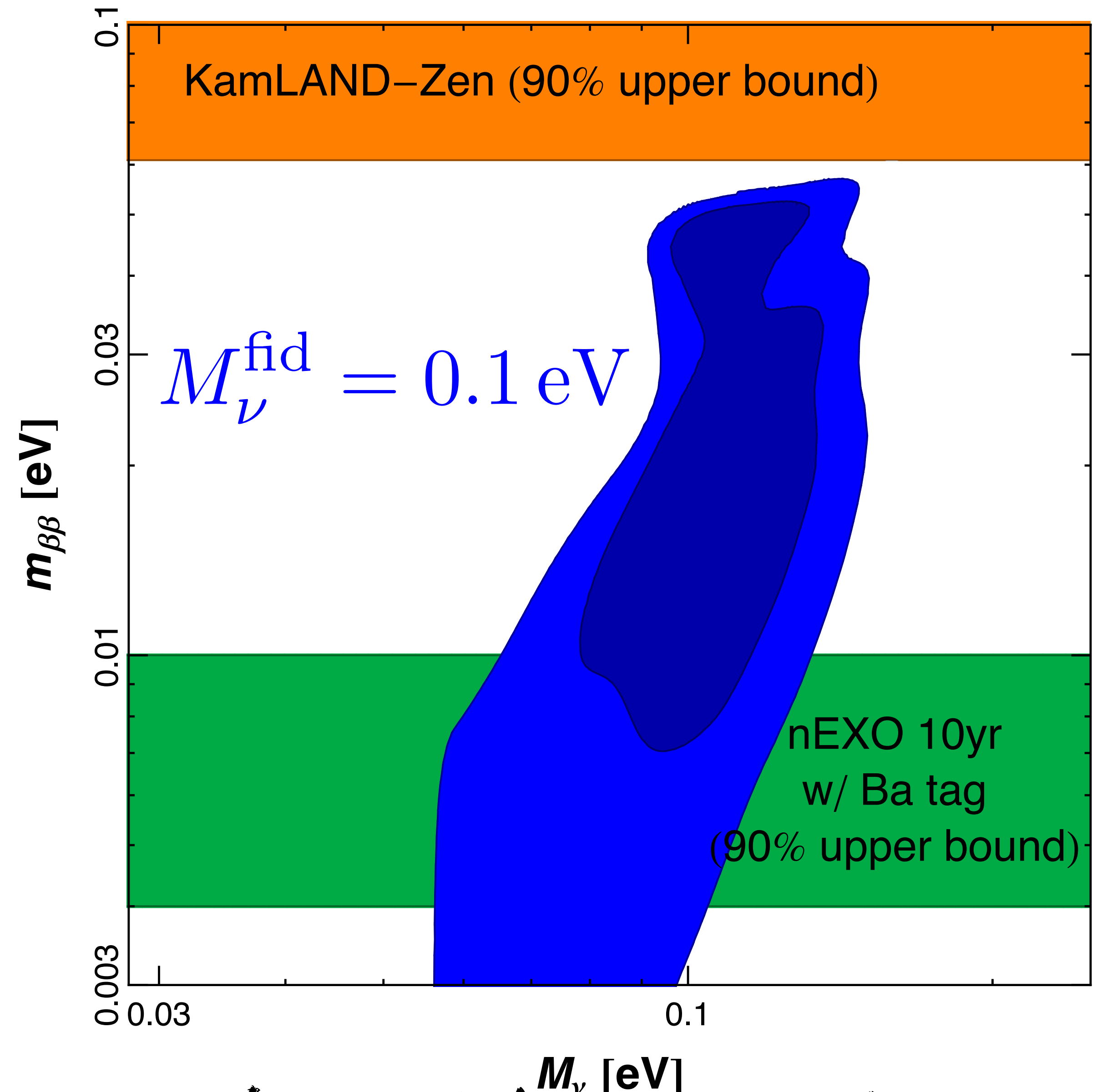


Cosmology and lab are complementary
and start to be equally sensitive

Gerbino+, 2016

Shake it up (in the future)!



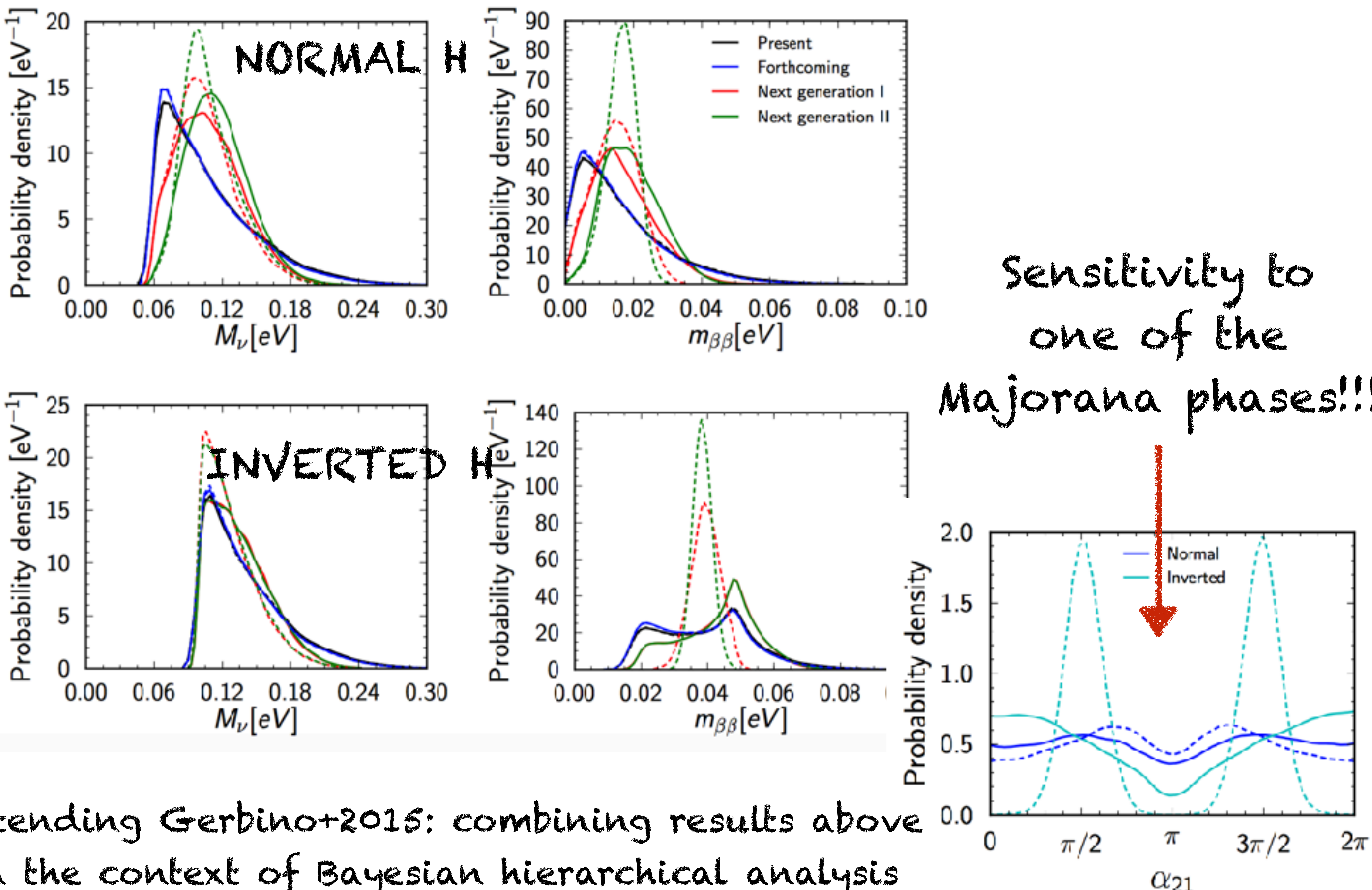


If Mnu=0.1eV, sigma(mbb)~10meV could guarantee 0n2b measurement

0n2b could in turn helps unravel the hierarchy (wip, extending the results in Gerbino+2015 in the hierarchical bayesian context)

Gerbino+, 2016

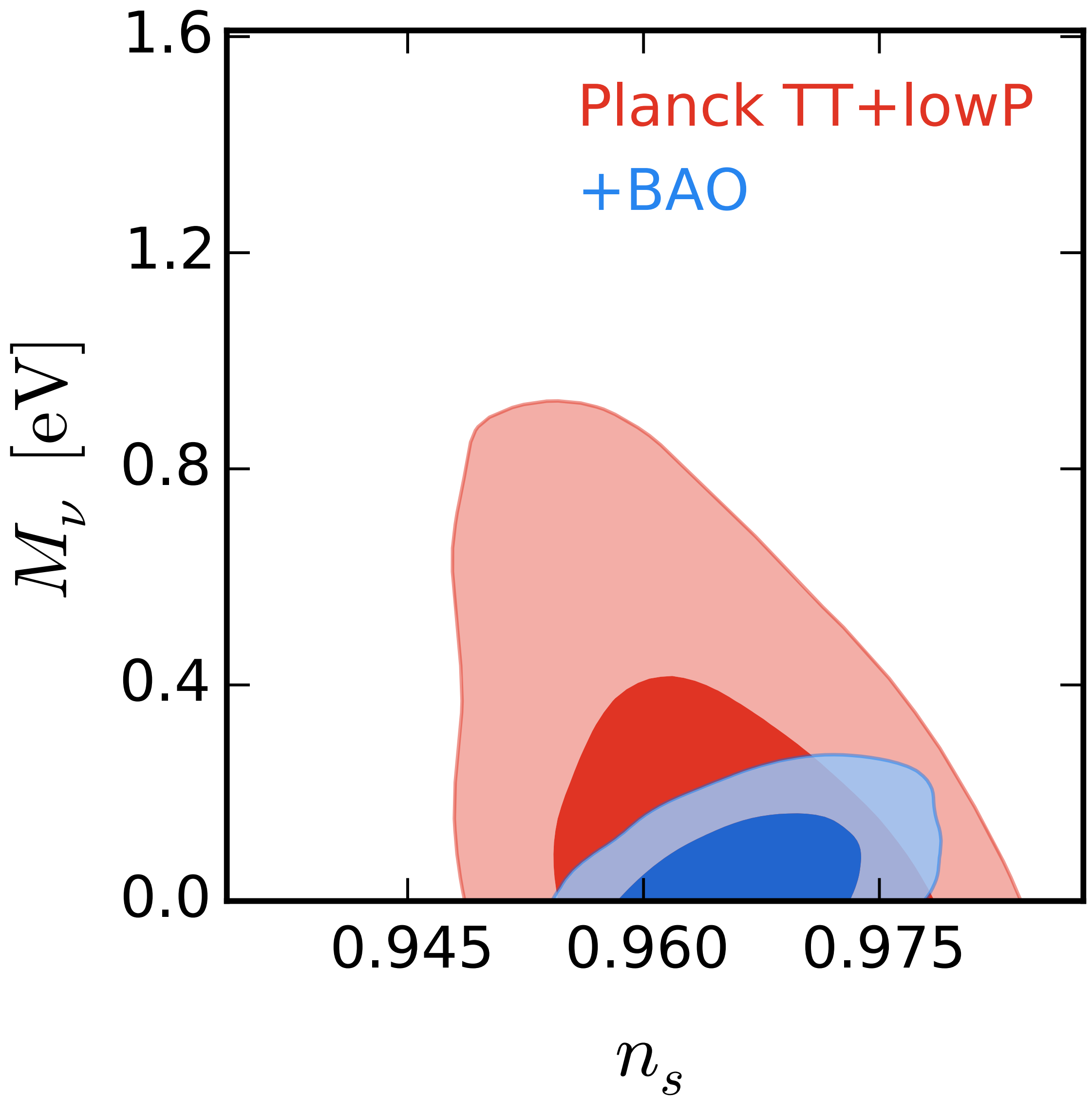
Work in progress

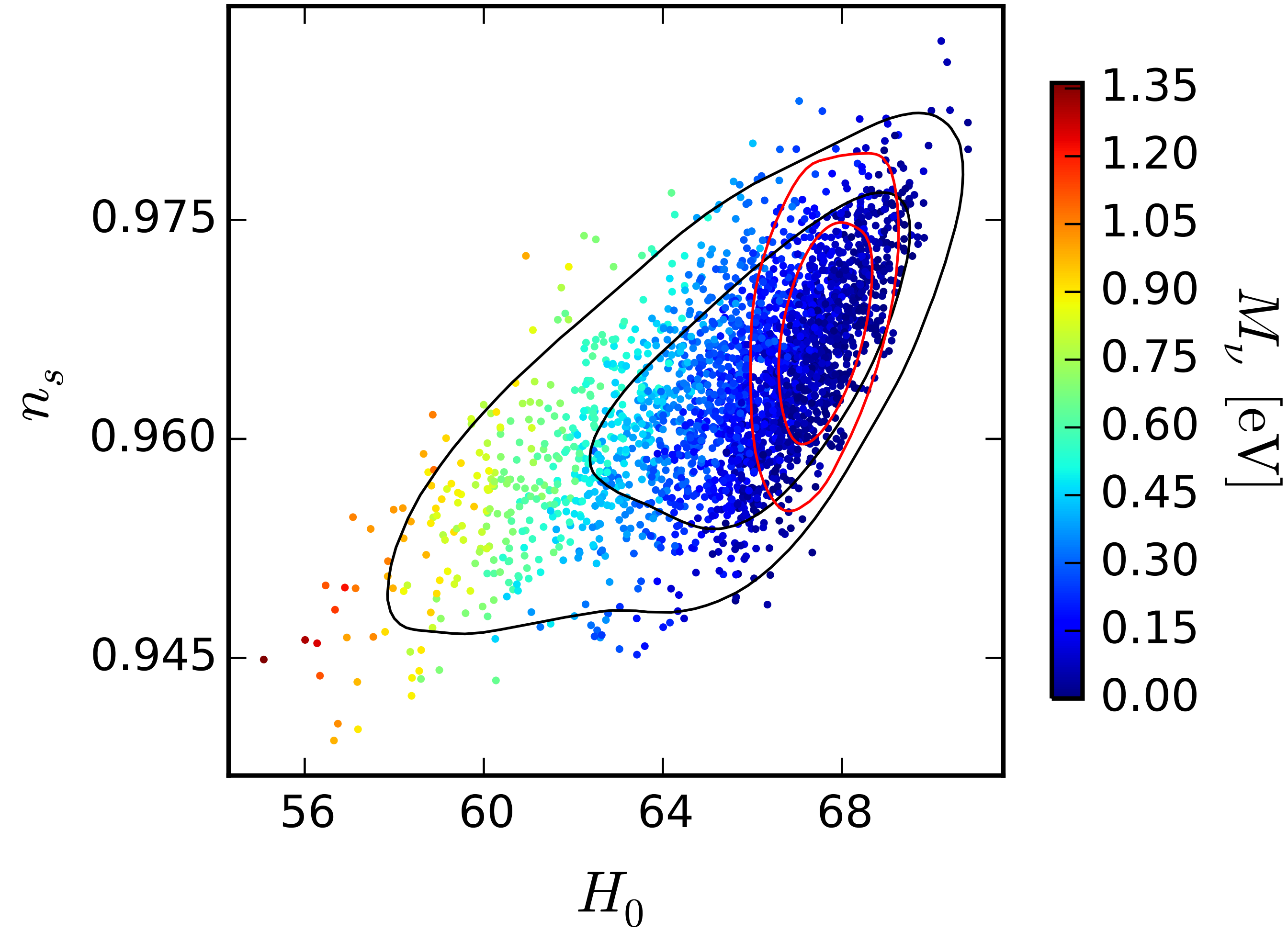


Sensitivity to one of the Majorana phases!!!

Extending Gerbino+2015: combining results above in the context of Bayesian hierarchical analysis

Neutrino masses as nuisance





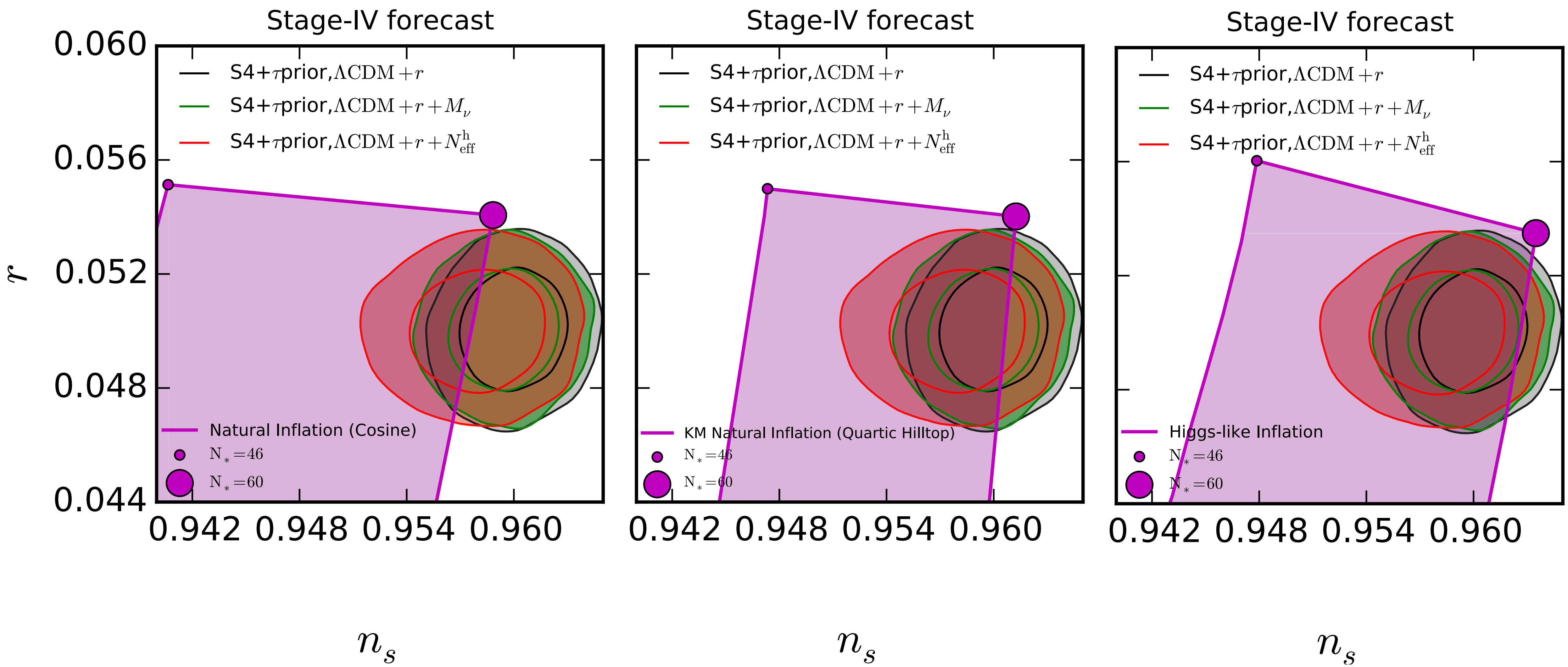
		$\Lambda\mathrm{CDM}+r$	$\Lambda\mathrm{CDM}+r+M_\nu$
Planck TT+lowP	NH	0.9666 ± 0.0062	$0.9640^{+0.0075}_{-0.0066}$
	approx	0.9664 ± 0.0063	$0.9642^{+0.0073}_{-0.0066}$
+BK14	NH	0.9656 ± 0.0062	0.9641 ± 0.0064
	approx	0.9654 ± 0.0062	0.9640 ± 0.0066
+BAO	NH	0.9676 ± 0.0045	0.9677 ± 0.0046
	approx	0.9675 ± 0.0045	0.9679 ± 0.0046

Negligible shifts wrt the splitting

Fractional shifts wrt to the mass

Gerbino+, 2016

Neutrino masses as nuisance



	COrE	S4
ΛCDM $+ r$	0.9601 ± 0.0014	0.9599 ± 0.0019
ΛCDM $+ r + M_\nu$	0.9593 ± 0.0016	0.9595 ± 0.0020

The exact splitting is relevant as far as it sets the minimum mass value when marginalising over Mnu

Gerbino+, 2016

CONCLUSIONS

- Cosmology provides robust and tight limits on Mnu, with Mnu<0.2eV @95% highly reliable
- We are close to scratching the IH minimum mass value
- We start to care about how precisely we model neutrino masses and how sensitive we are to the choice of the neutrino hierarchy
- Valuable information can be gathered from lab
- We care because we want to know more about neutrinos AND because we want to nail down the sensitivity to the other parameters