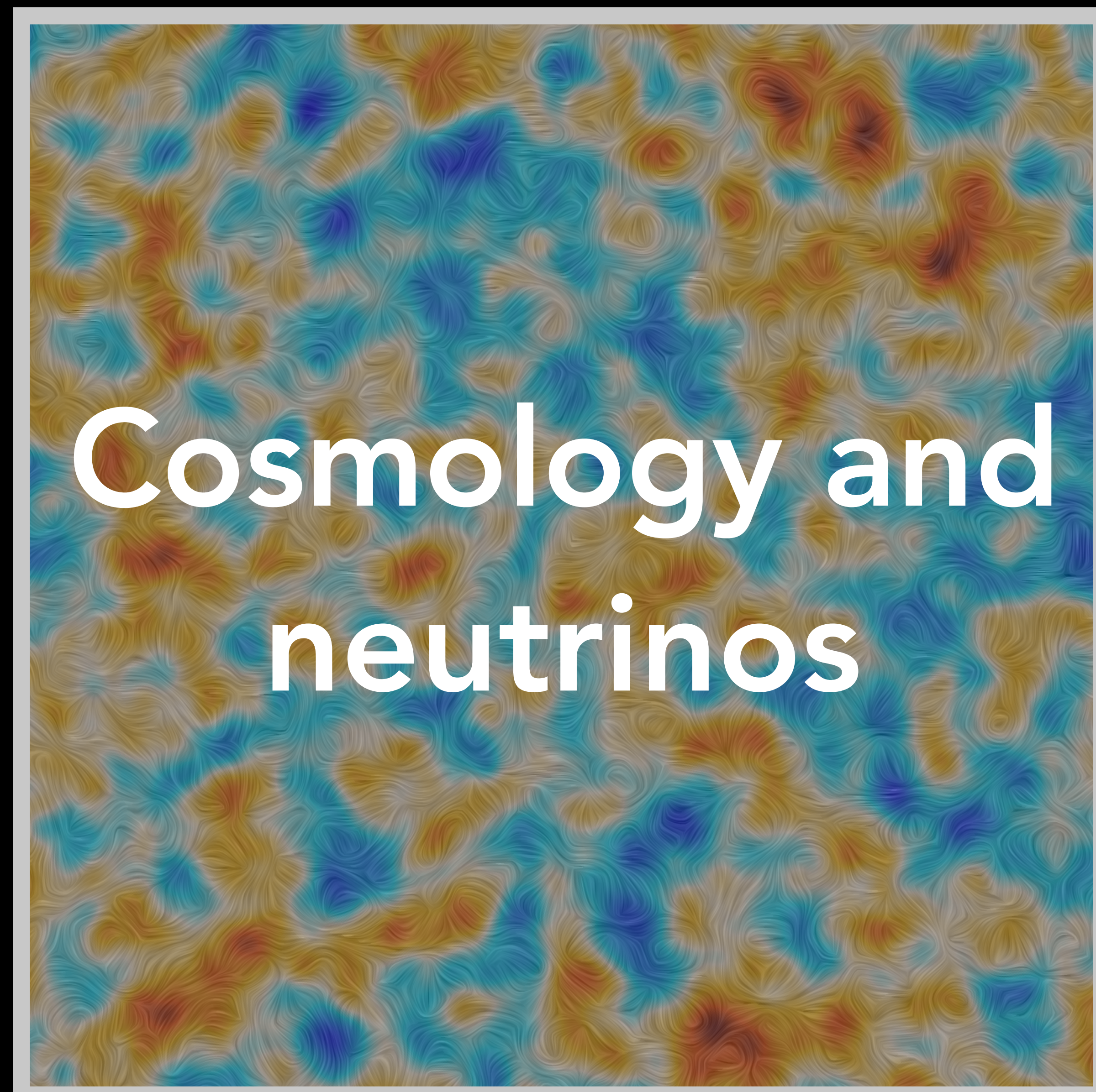
CERN, 29.03.2017



# Cosmology and neutrinos

Julien Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

## CERN, 29.03.2017

1. status of cosmological data and of the cosmological standard model
2. potential neutrino effects
3. summed active $\nu$ mass
4. light sterile neutrinos
5. heavy sterile $\nu$'s (WDM)


Julien Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

# Which observables are we talking about?

| Observables derived from first principles<br>GR+QED, Integration of linearised Einstein + Boltzmann | Observables derived from modelling of complex phenomena<br>non-linear simulations, phenomenological fits & scaling laws |
|---|---|



Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

# Which observables are we talking about?

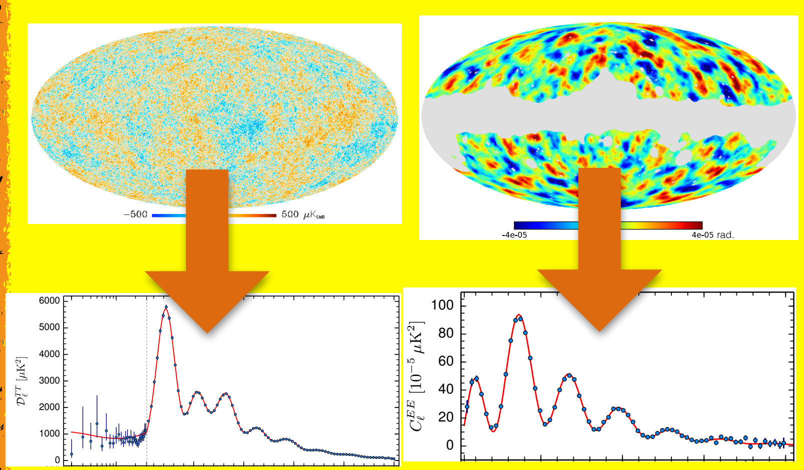
## Observables derived from first principles

GR+QED, Integration of linearised Einstein + Boltzmann

## Observables derived from modelling of complex phenomena

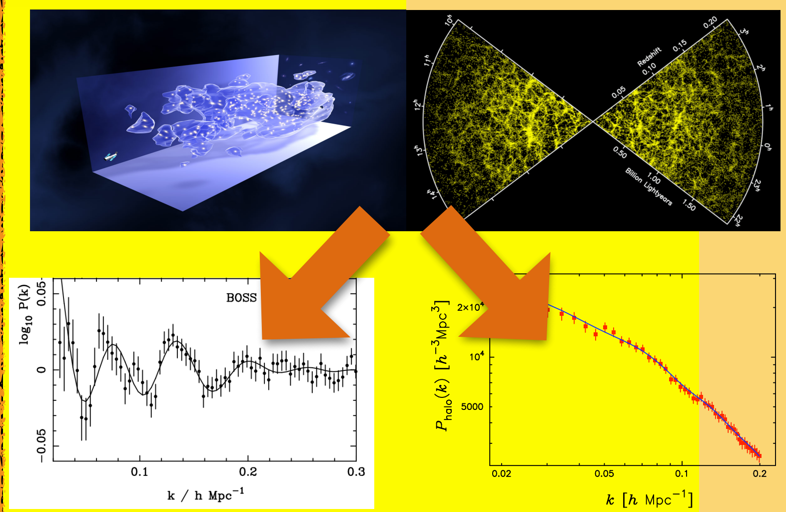
non-linear simulations, phenomenological fits & scaling laws

### CMB



temperature/polarisation/ lensing power spectrum

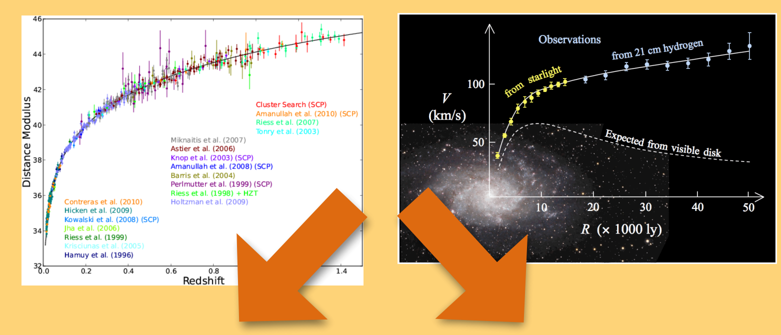
### Large Scale Structure




BAO scale

matter power spectrum

### Supernovae, Cepheids, small-scale structures, light element abundances




Hubble rate, acceleration of expansion, satellite galaxies count…

# Which observables are we talking about?

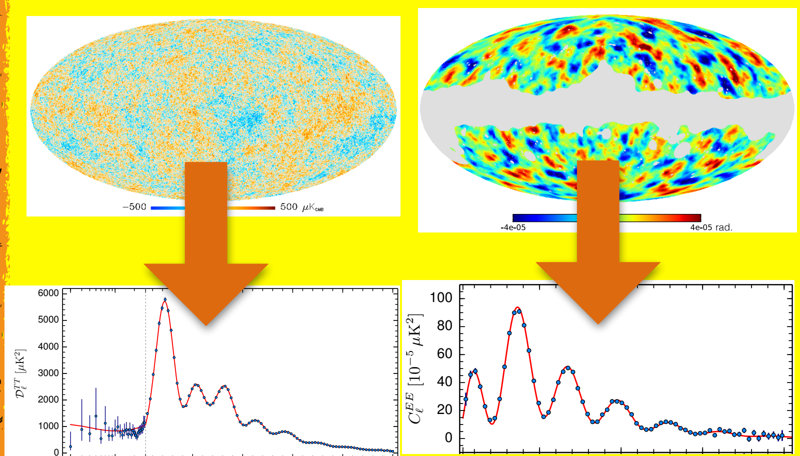
## Observables derived from first principles

GR+QED, Integration of linearised Einstein + Boltzmann

## Observables derived from modelling of complex phenomena

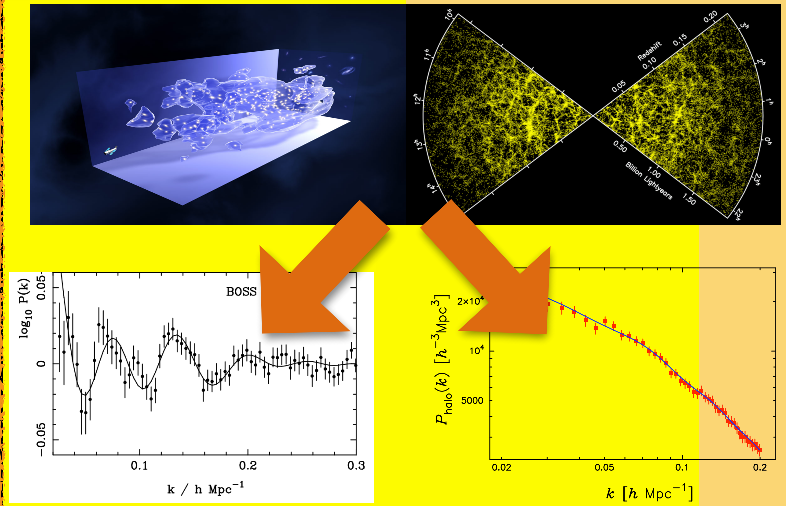
non-linear simulations, phenomenological fits & scaling laws

### CMB



temperature/polarisation/
lensing power spectrum

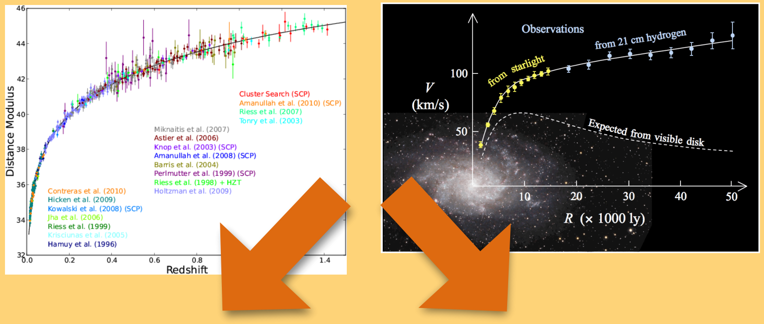
### Large Scale Structure



BAO scale

matter power spectrum

### Supernovae, Cepheids, small-scale structures, light element abundances



Hubble rate,
acceleration of expansion,
satellite galaxies count…

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

for binned TT data, $\chi 2$/dof=1.004 for 731 d.o.f.

most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

(w.r.t. Planck 2016 TT+SIMlow)

## H0 tension (direct measurement versus inferred model-dependent CMB value)

?

n

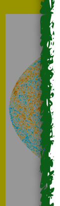
nena

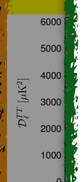
ling laws

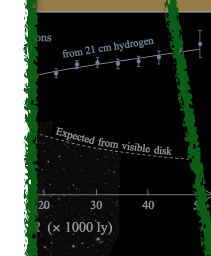
eids,

res,

ances








sion,

satellite galaxies count…

lensing power spectrum

scale

spectrum

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

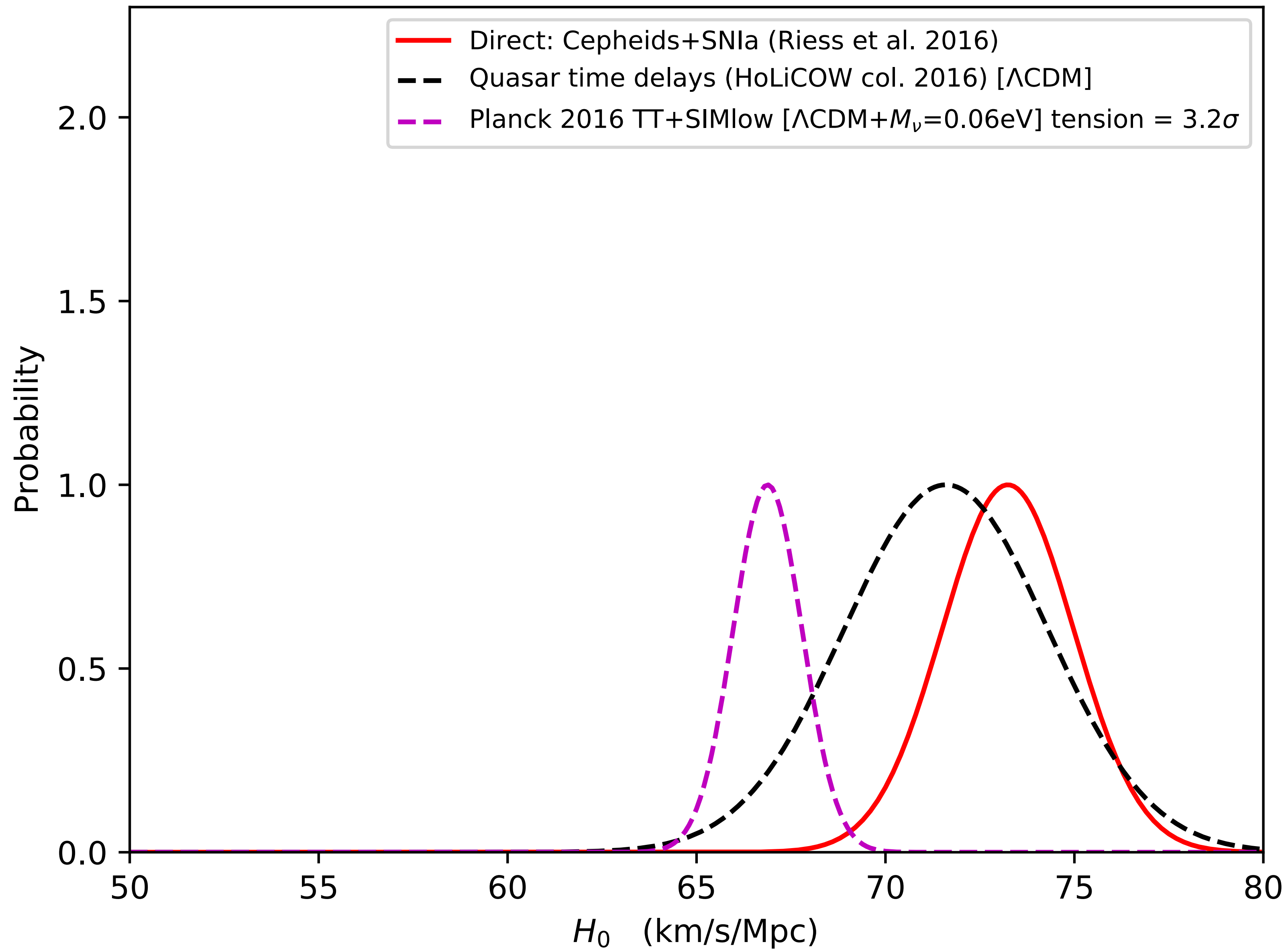
for binned TT data, χ2/dof=1.004 for 731 d.o.f.

most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

(w.r.t. Planck 2016 TT+SIMlow)

## H0 tension (direct measurement versus inferred model-dependent CMB value)




?

nena

ling laws

eids,

res,

ances

lensing power spectrum

scale

spectrum

sion,

satellite galaxies count…

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

for binned TT data, χ2/dof=1.004 for 731 d.o.f.

most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

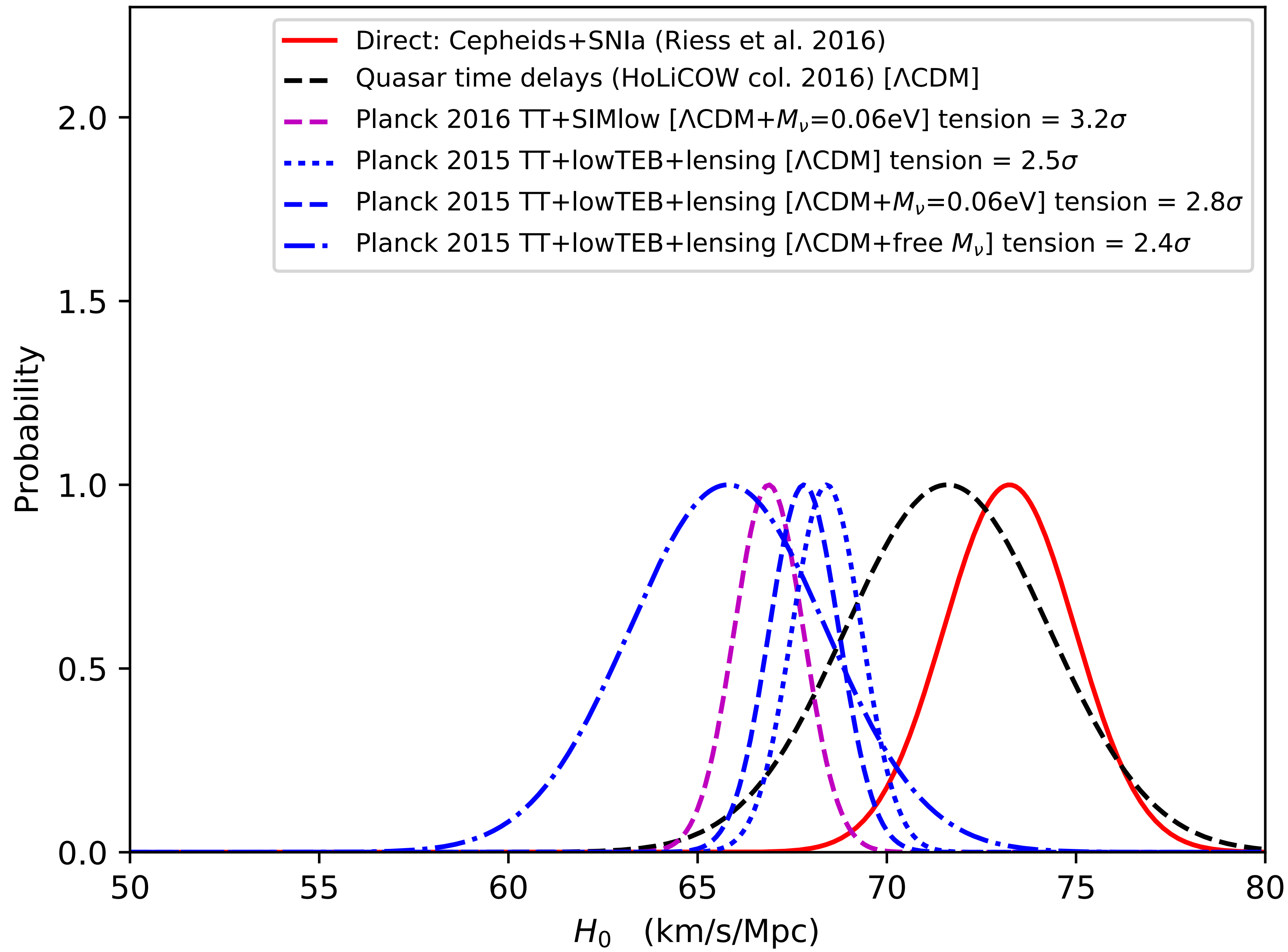
(w.r.t. Planck 2016 TT+SIMlow)



Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

## H0 tension (direct measurement versus inferred model-dependent CMB value)




?

nena

ling laws

eids,

res,

ances

lensing power spectrum

scale

spectrum

sion,

satellite galaxies count…

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

for binned TT data, χ2/dof=1.004 for 731 d.o.f.

most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

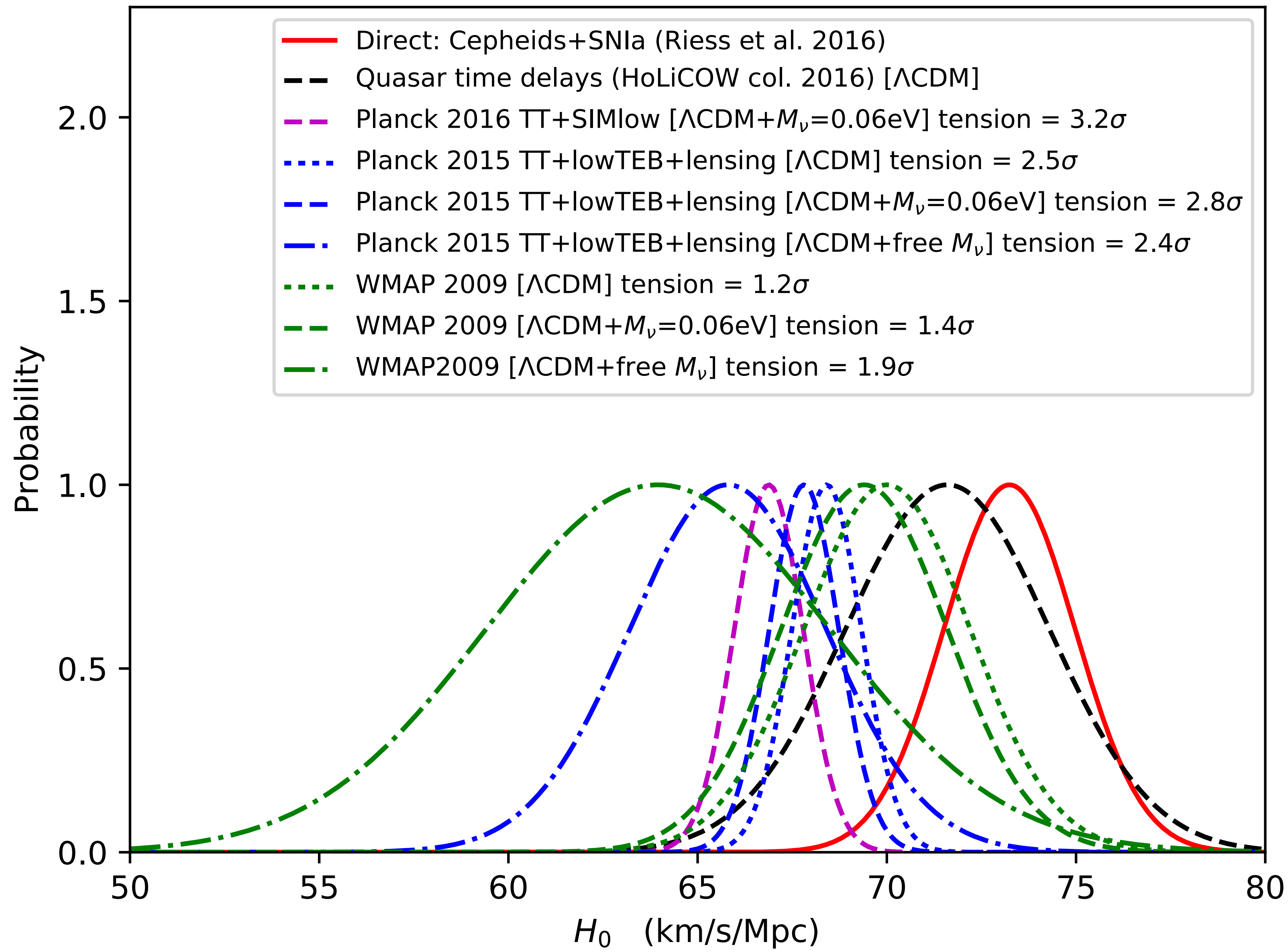
(w.r.t. Planck 2016 TT+SIMlow)



Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

## H0 tension (direct measurement versus inferred model-dependent CMB value)




?

ena

ling laws

eids,

res,

ances

lensing power spectrum

scale

spectrum

sion,

satellite galaxies count…

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

for binned TT data, χ2/dof=1.004 for 731 d.o.f.

most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

(w.r.t. Planck 2016 TT+SIMlow)



TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

?

**If tension was confirmed,** most obvious extensions of ΛCDM would not help …

- $N_{eff}>3$: shift in matter-radiation equality degenerate with $H_0$ + several other effects not degenerate with it (baryon drag, ….). CMB alone: $N_{eff} = 3.13^{+0.29}_{-0.34}$ (68%, Planck 2015 TT+lowTEB+lensing) leaves little freedom for accommodating large $H_0$ (and raises additional tensions)
- same with combinations of $N_{eff}$ / neutrino masses / $w_{DE}$ / curvature / GWs …

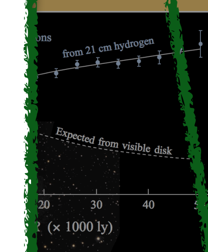
ena

ling laws

eids,

es,

ances




sion,

lensing power spectrum

scale

spectrum

satellite galaxies count…

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

for binned TT data, χ2/dof=1.004 for 731 d.o.f.

most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

(w.r.t. Planck 2016 TT+SIMlow)

**If tension was confirmed,** most obvious extensions of ΛCDM would not help …

- $N_{eff}>3$: shift in matter-radiation equality degenerate with $H_0$ + several other effects not degenerate with it (baryon drag, ….). CMB alone: $N_{eff} = 3.13^{+0.29}_{-0.34}$ (68%, Planck 2015 TT+lowTEB+lensing) leaves little freedom for accommodating large $H_0$ (and raises additional tensions)
- same with combinations of $N_{eff}$ / neutrino masses / $w_{DE}$ / curvature / GWs …

… we would need to pay a higher price, e.g.:

- Sterile neutrinos + NSI (will see later in context of neutrino osc. anomalies; Archidiacono et al. 2016)
- DM-DR interactions (JL, Marques-Tavares, Schmaltz 2016)
- local $H_0$ versus average expansion: does not work unless we live in a local void so underdense that it would contradict ΛCDM and observations

Then following bounds could change; although bounds on active neutrino masses turn out to be rather stable ungainst these models

lensing power spectrum

scale

spectrum

sion,
satellite galaxies count…

~1500 (Planck) + ~10 *independent* data points

minimal 6-parameter model: excellent fit

for binned TT data, χ2/dof=1.004 for 731 d.o.f.

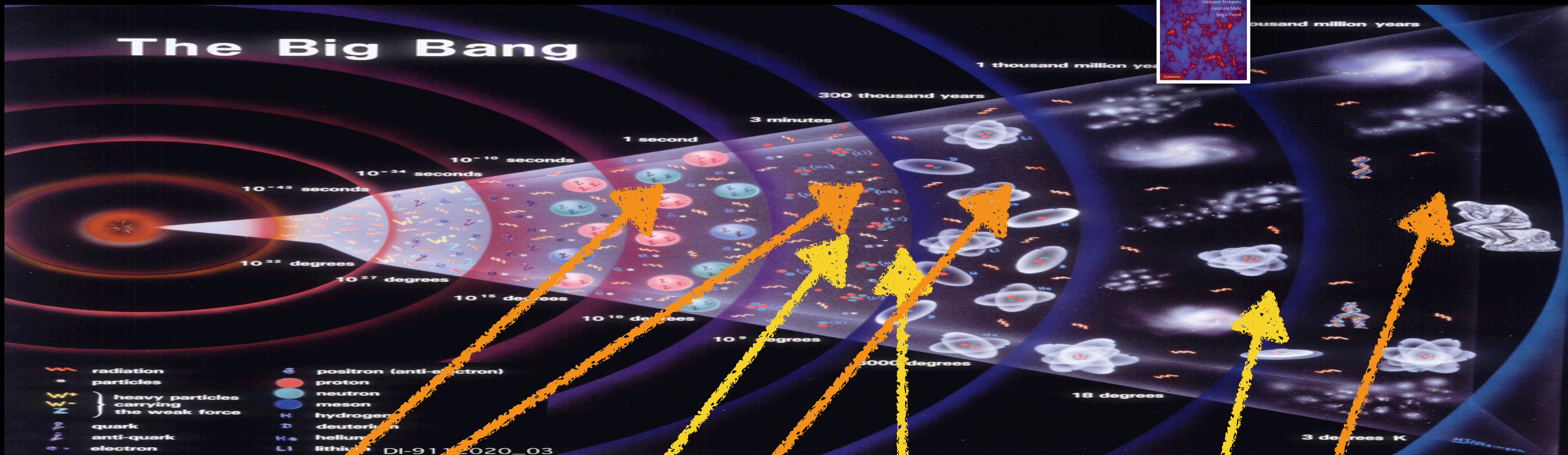
most recent $H_0$ measurement *(Riess et al.)*

1 point in tension at 3.2σ

(w.r.t. Planck 2016 TT+SIMlow)

# What neutrino effects are we testing?

Lesgourgues & Pastor Pys. Rep. 2016; Lesgourgues et al. “Neutrino Cosmology” CUP ; Drewes et al. 1602.04816




relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

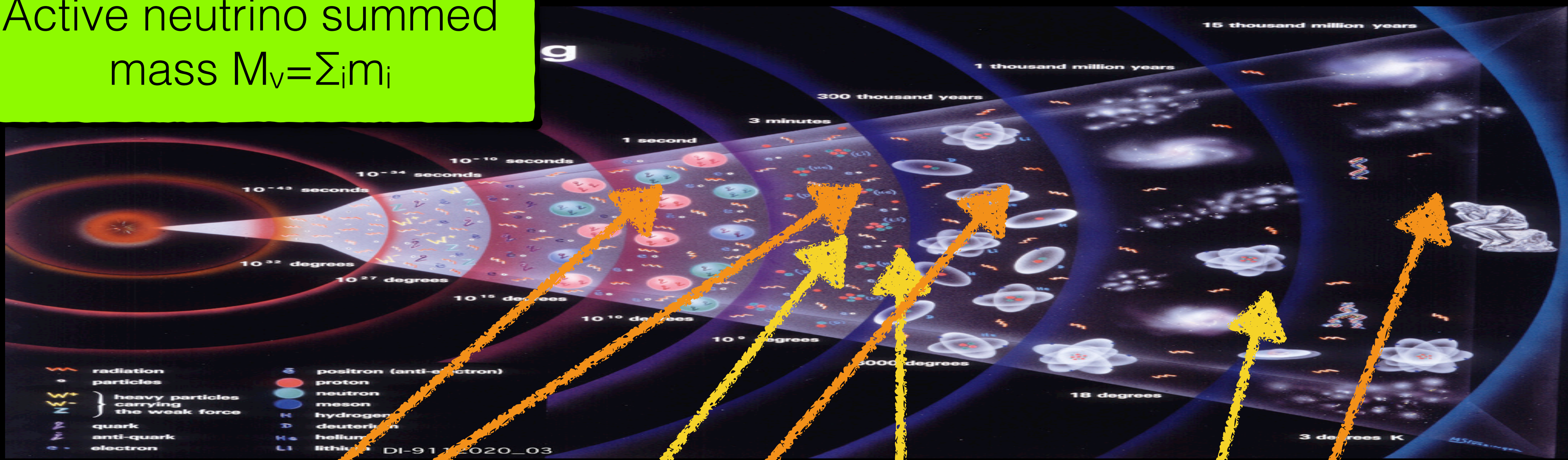
**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering

# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu = \Sigma_i m_i$




relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering

# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu = \Sigma_i m_i$


Model parameters / magnitude of effects on observables:

- masses of 3 mass eigenstates: $m_1$, $m_2$, $m_3$
- basis { $m_1+m_2+m_3$, $m_3-m_1$, $m_3-m_2$ }

| $m_1+m_2+m_3$ | $m_3-m_1$, $m_3-m_2$ |
| --- | --- |
| ($\rho_\nu$ in recent universe). | (individual free-streaming scales) |
| ~5% (0.06eV)<br>~50% (0.6eV) | ~0.1%<br>between deg/NH/IH |

… actual bounds only on $M_\nu = m_1+m_2+m_3$

relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering



Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu = \Sigma_i m_i$


In standard picture (no NSI, no large ν/anti-ν asymmetry, …) bounds on $M_\nu = m_1+m_2+m_3$ independent on:

- Flavour oscillations, mixing angles

(because 3 p.s.d.'s nearly identical in mass/interaction basis)

- Dirac/Majorana
- CP violating phase

relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

**neutrino** slow down early dark matter clustering

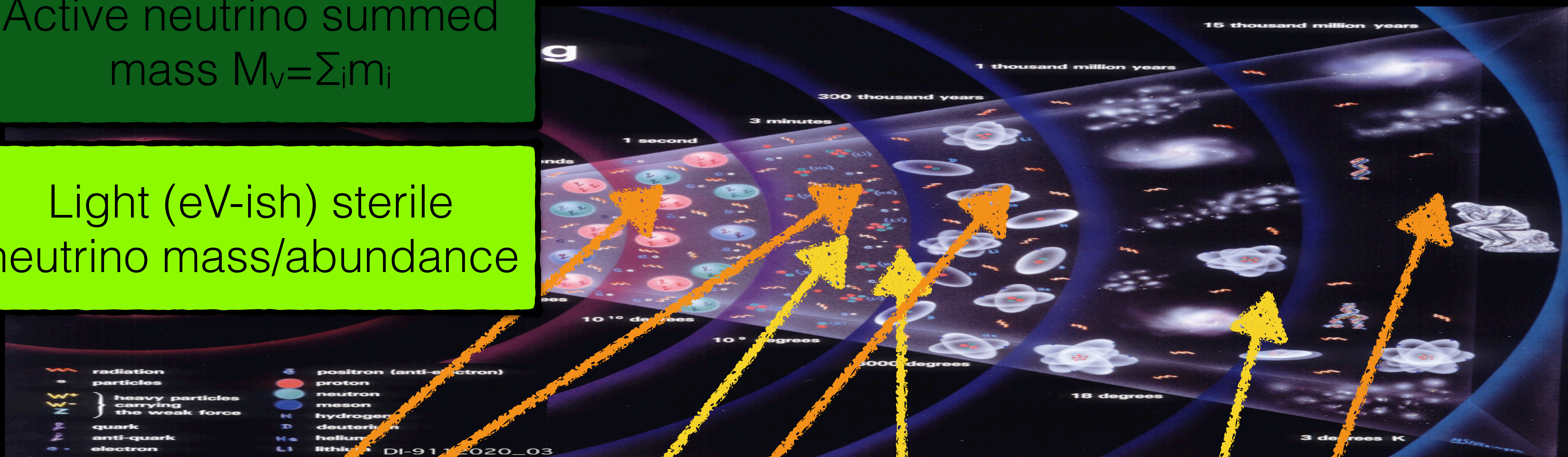
**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering

# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu = \Sigma_i m_i$

Light (eV-ish) sterile neutrino mass/abundance




relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering


TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu = \Sigma_i m_i$

Light (eV-ish) sterile neutrino mass/abundance


Theoretical model features 4 mass eigenstates…

Model-dependent bounds, depending on phase-space distribution (psd) of sterile neutrino at T<1keV, expressed on two *additional* parameters *related* to:

- psd of $\nu_4$ —> more precisely $\Delta N_{eff}$
- $m_4$ —> more precisely some $m_4^{eff}$ derived from $\Delta\rho_{\nu 4}$

relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

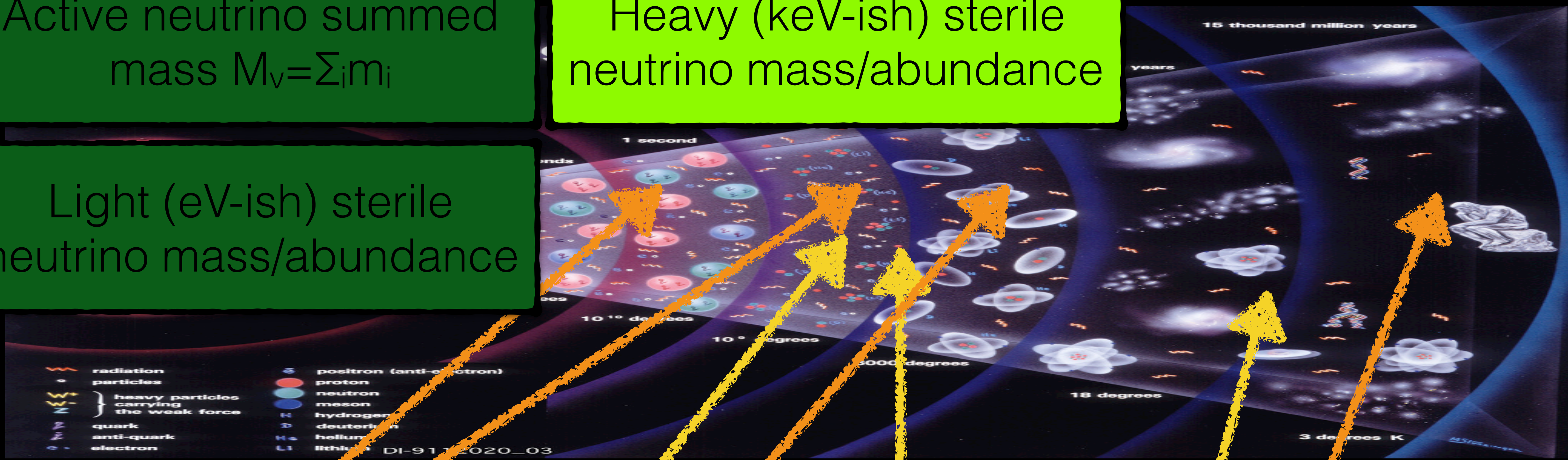
**neutrino** slow down late ordinary/dark matter clustering

# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu = \Sigma_i m_i$

Heavy (keV-ish) sterile neutrino mass/abundance

Light (eV-ish) sterile neutrino mass/abundance




relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering



Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

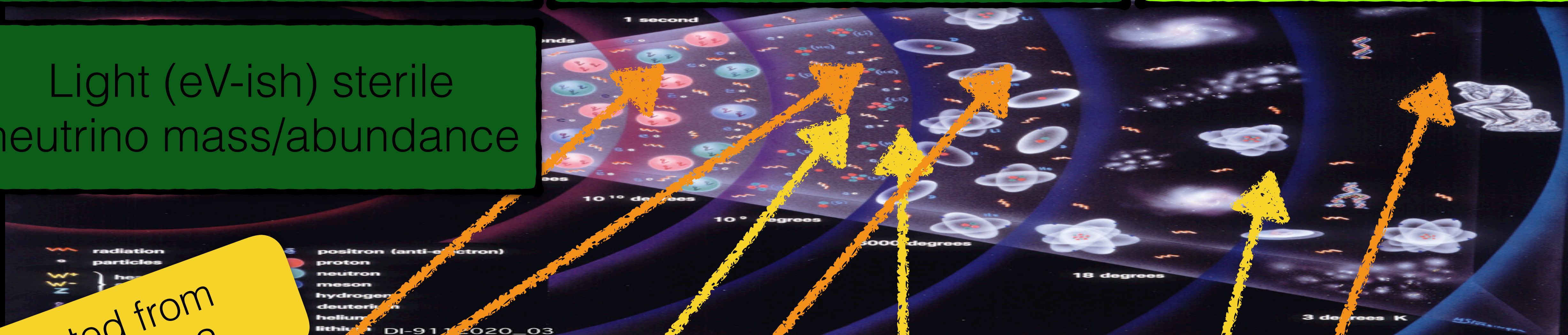
# What neutrino effects are we testing?

Active neutrino summed mass $M_\nu=\Sigma_i m_i$

Heavy (keV-ish) sterile neutrino mass/abundance

Active neutrino non-standard interactions

Light (eV-ish) sterile neutrino mass/abundance



$\nu$ prevented from thermalisation ?

relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular sc

$\nu$ decay ?

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering

$\nu$ scatter on DM

$\nu$ recouple like fluid ?

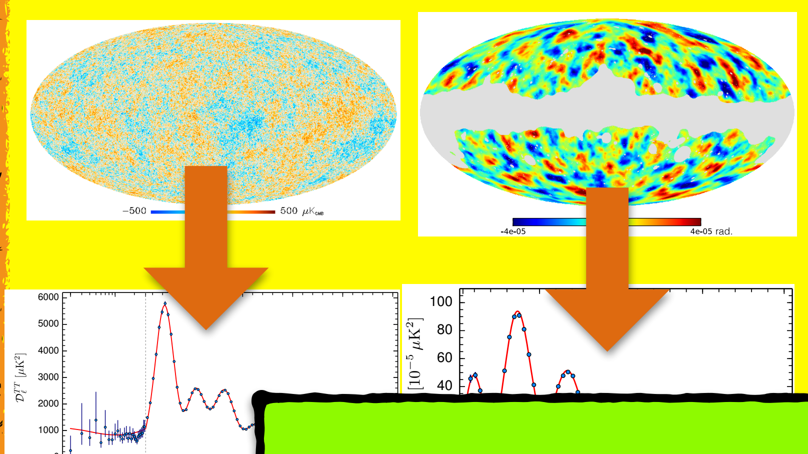
$\nu$ scatter on DM

# Which observables are we talking about?

**Observables derived from first principles**
GR+QED, Integration of linearised Einstein + Boltzmann

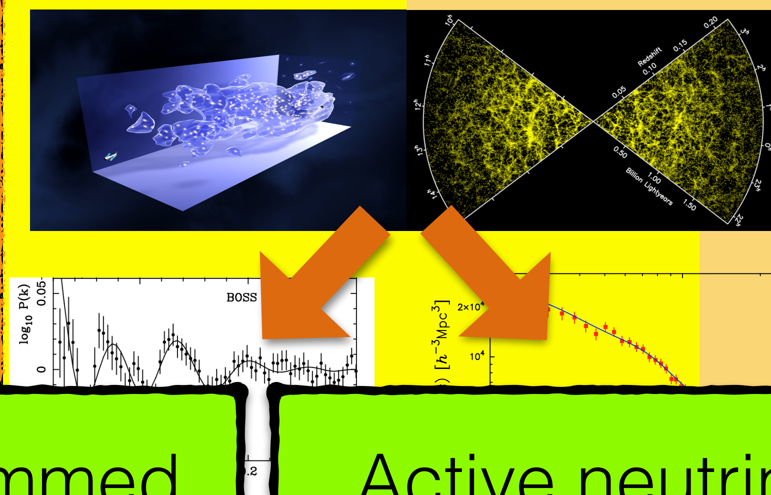
**Observables derived from modelling of complex phenomena**
non-linear simulations, phenomenological fits & scaling laws

## CMB

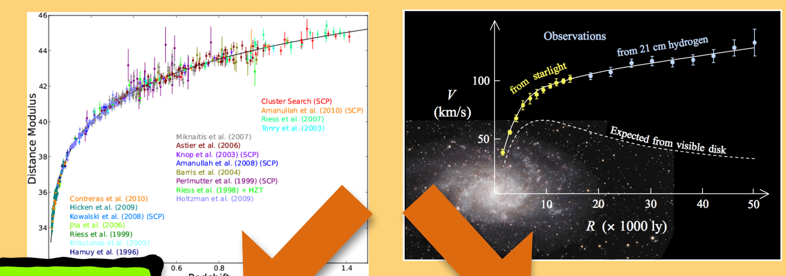


tempe
lensin

## Large Scale Structure



## Supernovae, Cepheids, small-scale structures, light element abundances



Hubble rate,
eleration of expansion,
ellite galaxies count…

**Active neutrino summed mass $M_\nu=\Sigma_i m_i$**

**Active neutrino non-standard interactions**

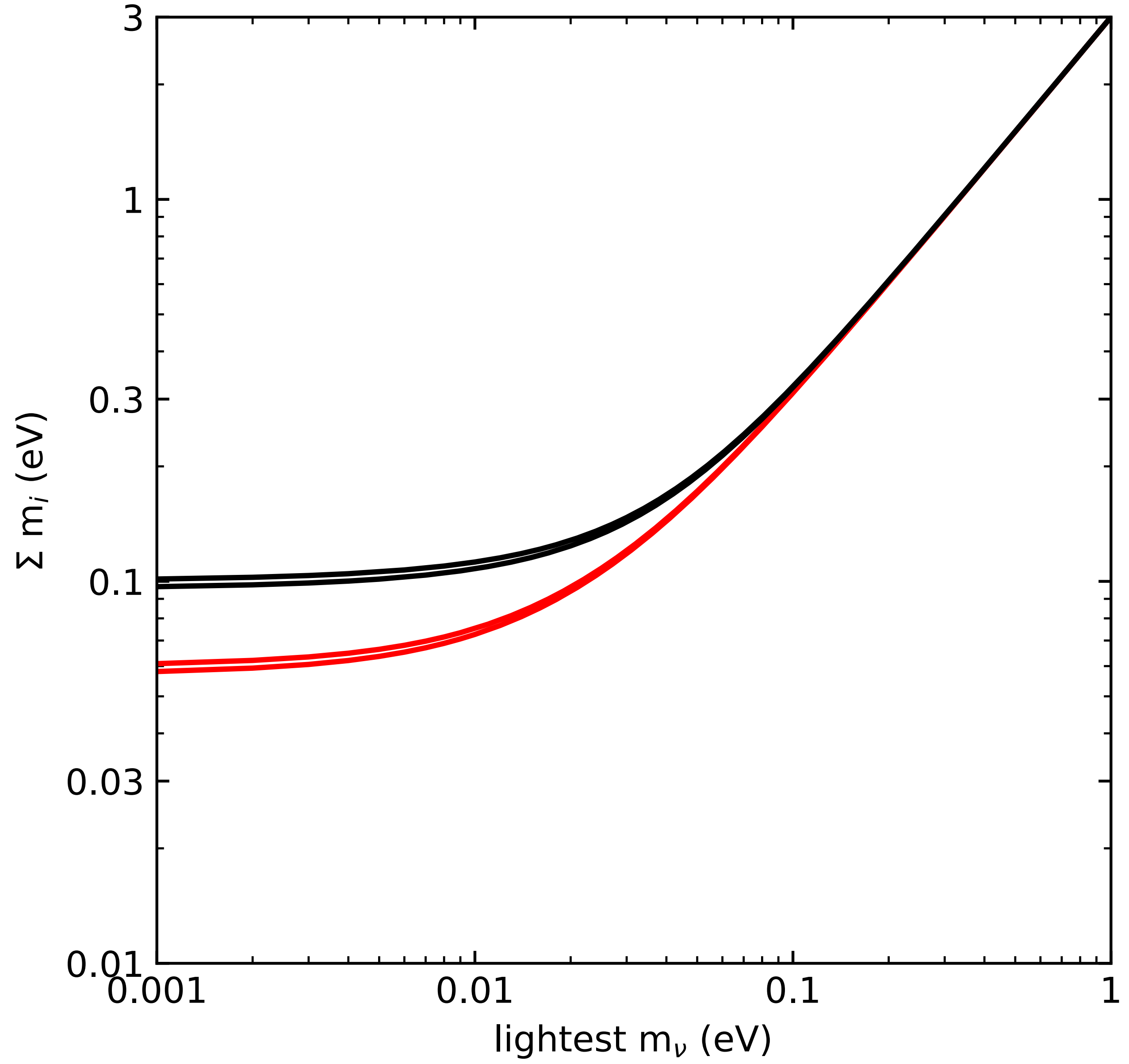
**Light (eV-ish) sterile neutrino mass/abundance**

**Heavy (keV-ish) sterile neutrino mass/abundance**

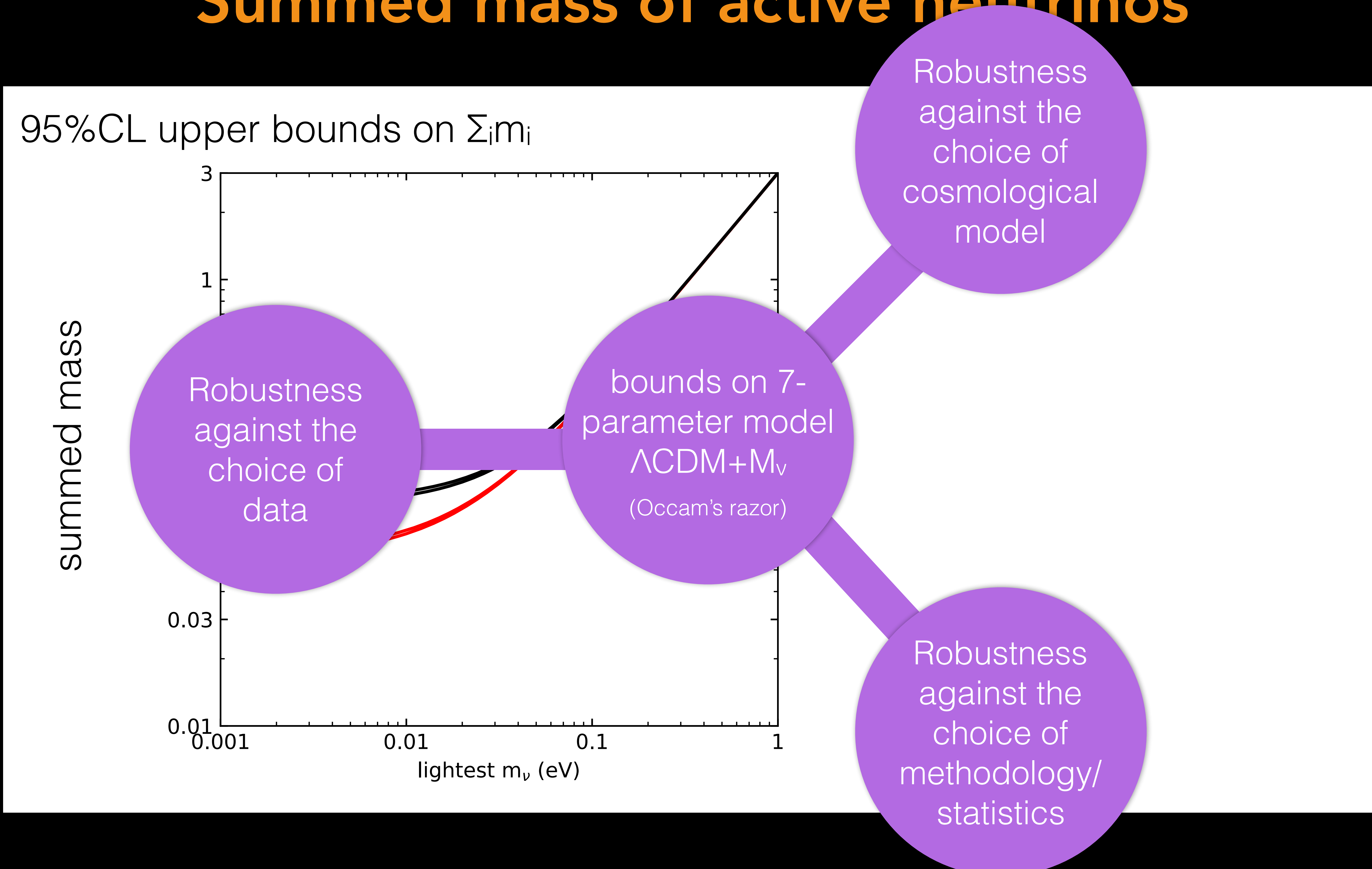
# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$

summed mass

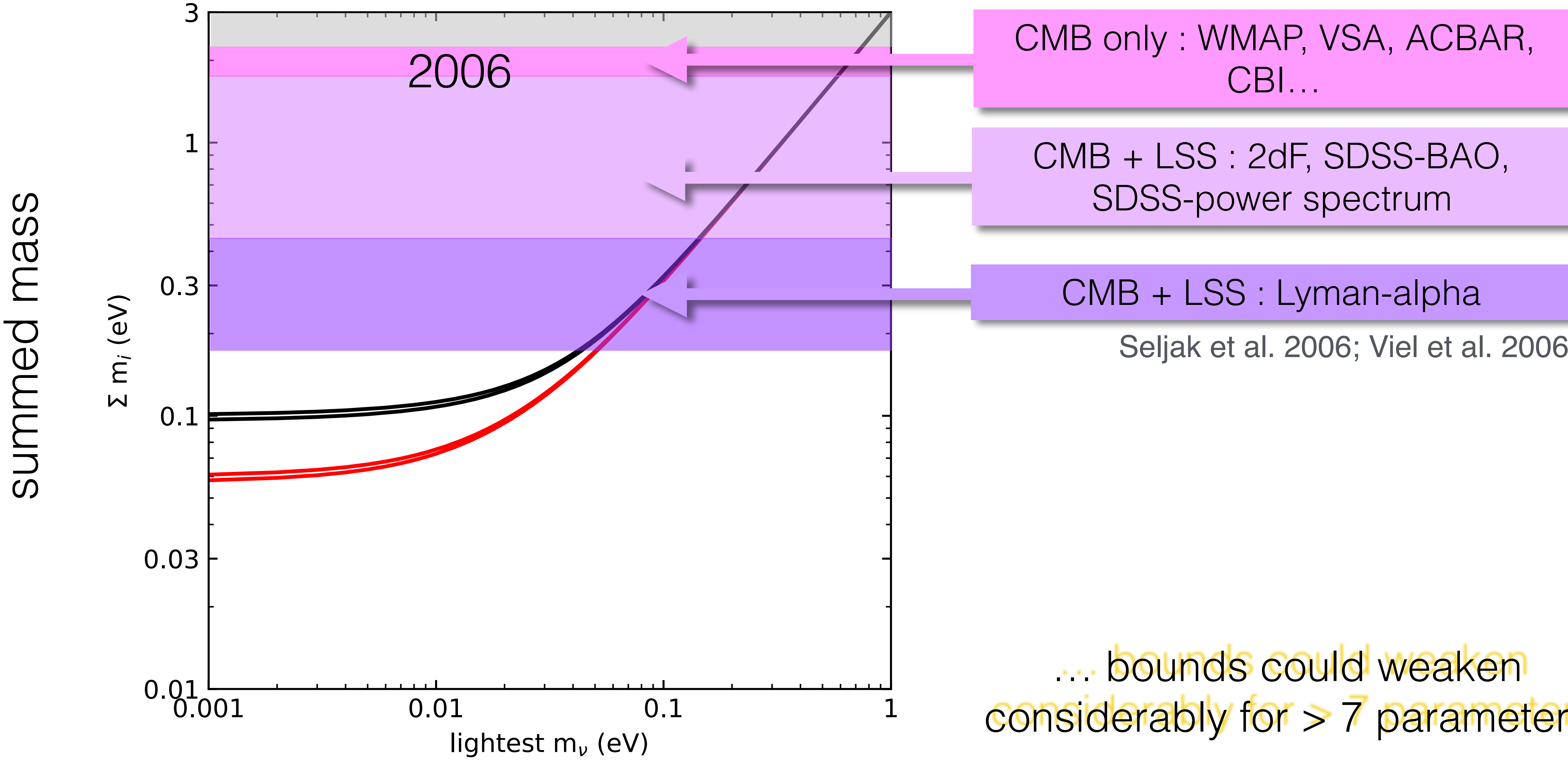


# Summed mass of active neutrinos



# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



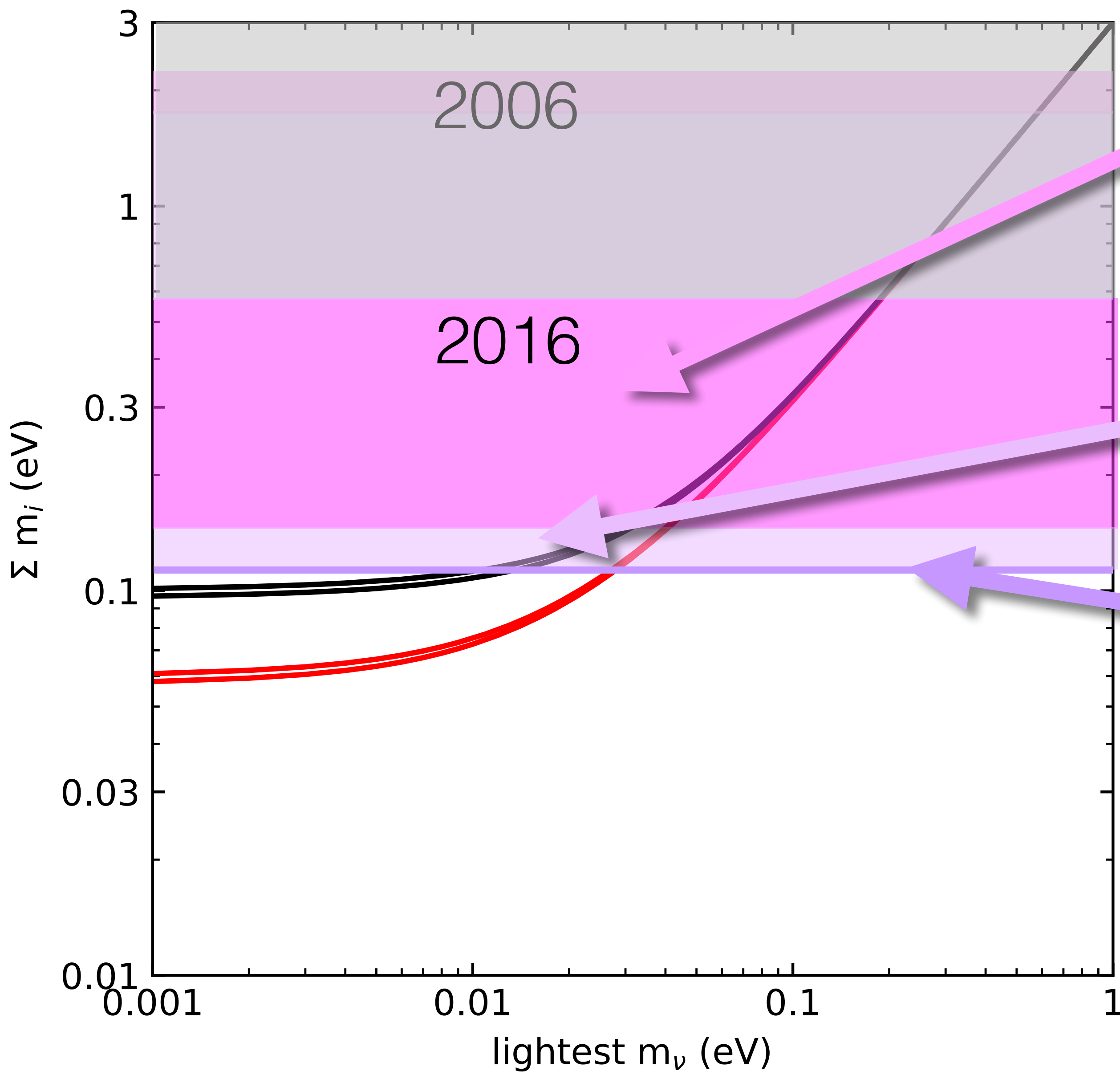

Seljak et al. 2006; Viel et al. 2006

… bounds could weaken considerably for > 7 parameters

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters

summed mass




CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

CMB + LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO: $\Sigma_i m_i$ < **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO: $\Sigma_i m_i$ < **120 meV** (95%CL)

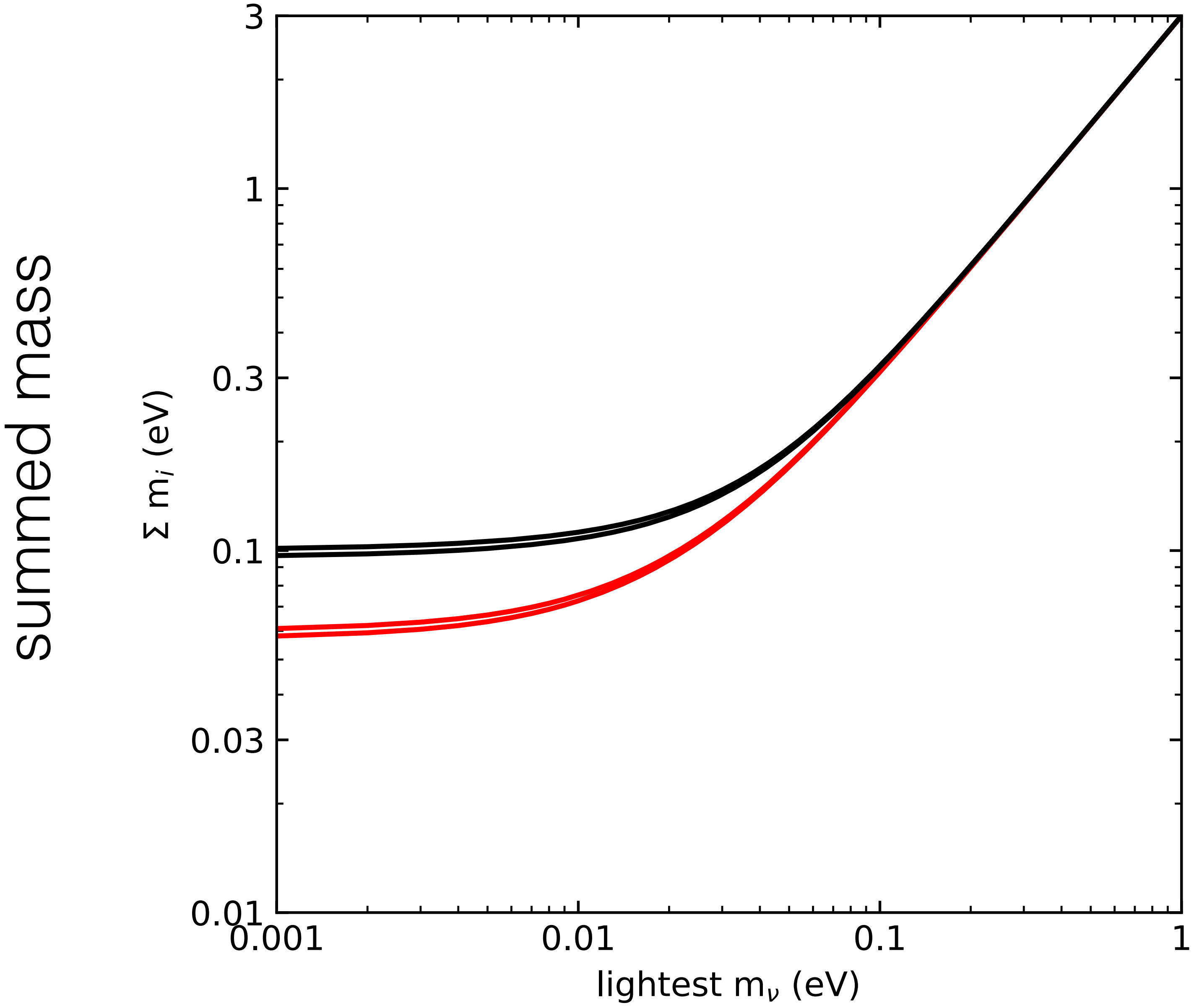
- Planck 2015 + Lyman-α: $\Sigma_i m_i$ < **120 meV** (95%CL)

[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzy et al. 1701.08172

… harder to avoid bounds with simple cosmological model extensions

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters




Usual suspects:

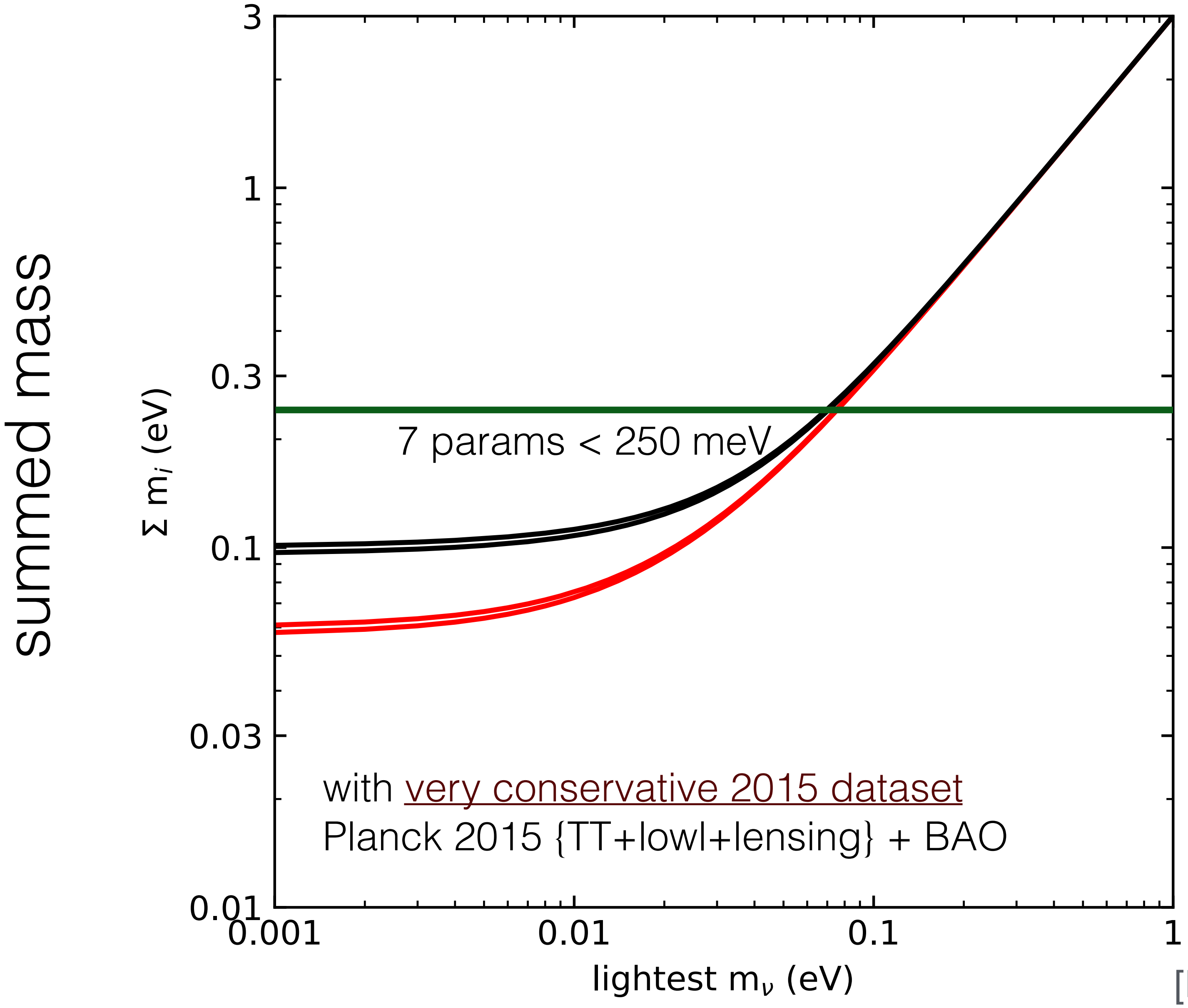
- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- primordial perturbations

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters




Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

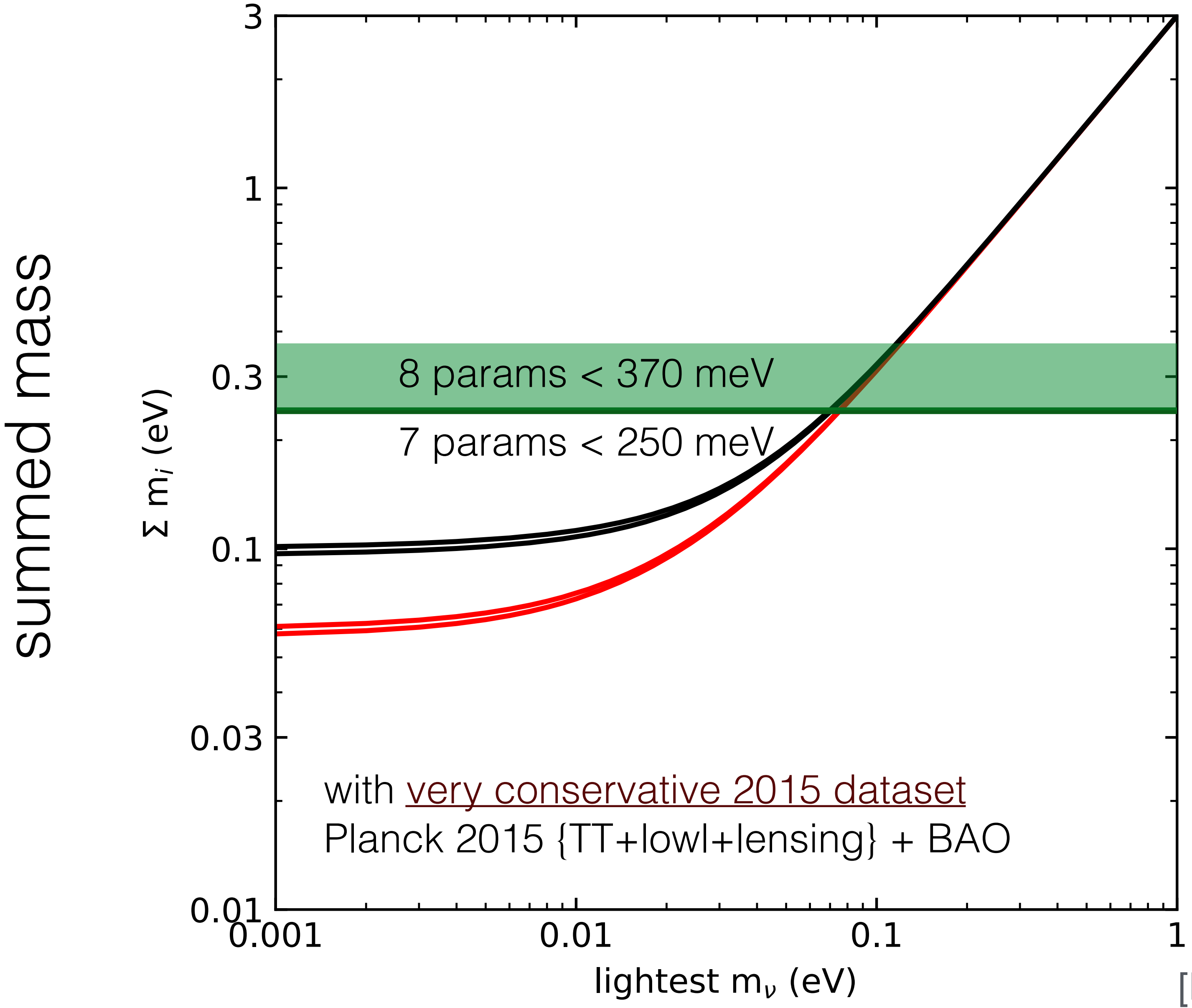
Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- primordial perturbations

[Planck col.] 1502.01589;

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters




Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

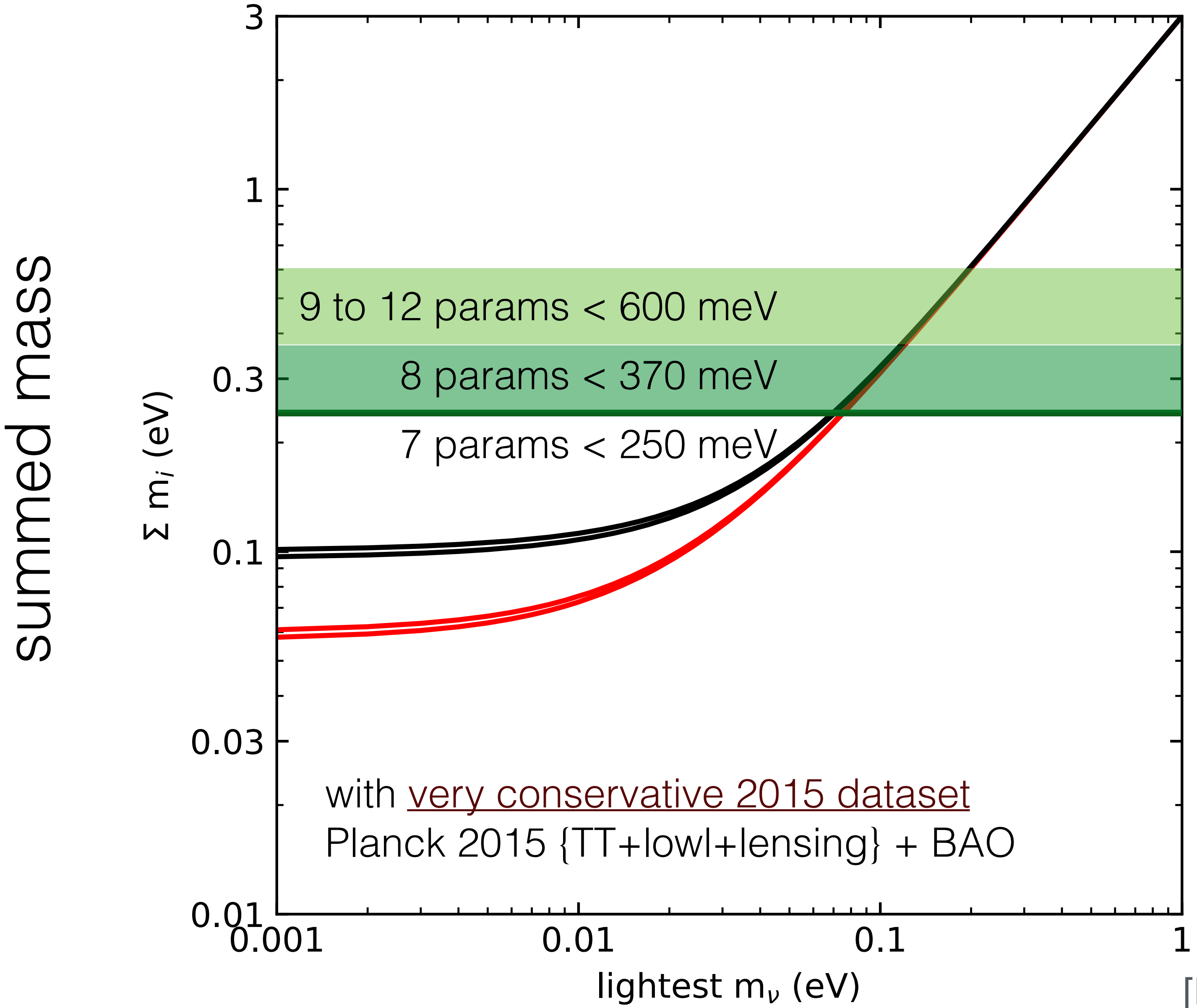
Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- primordial perturbations

[Planck col.] 1502.01589;

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters




Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

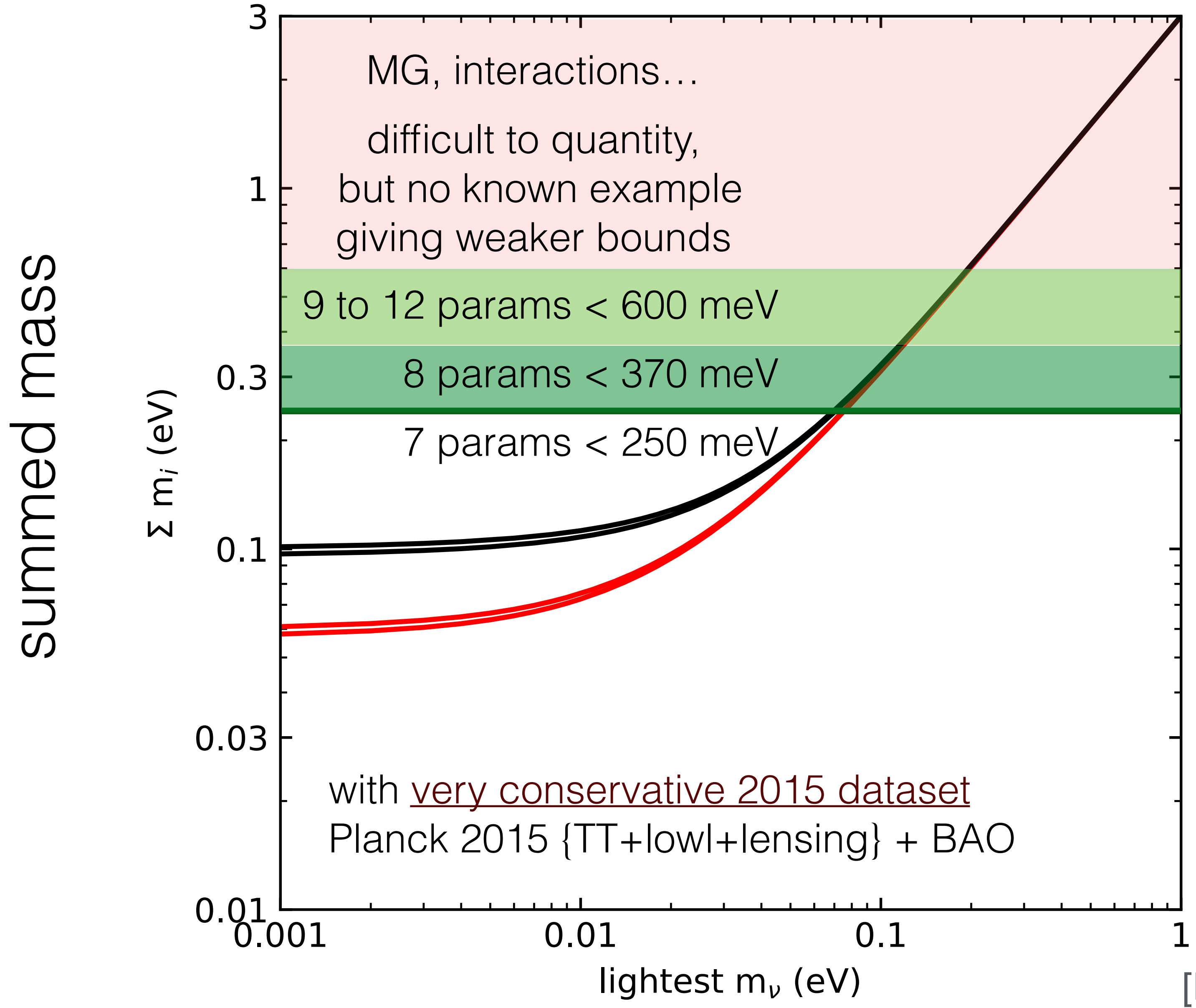
Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- primordial perturbations

[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters




Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

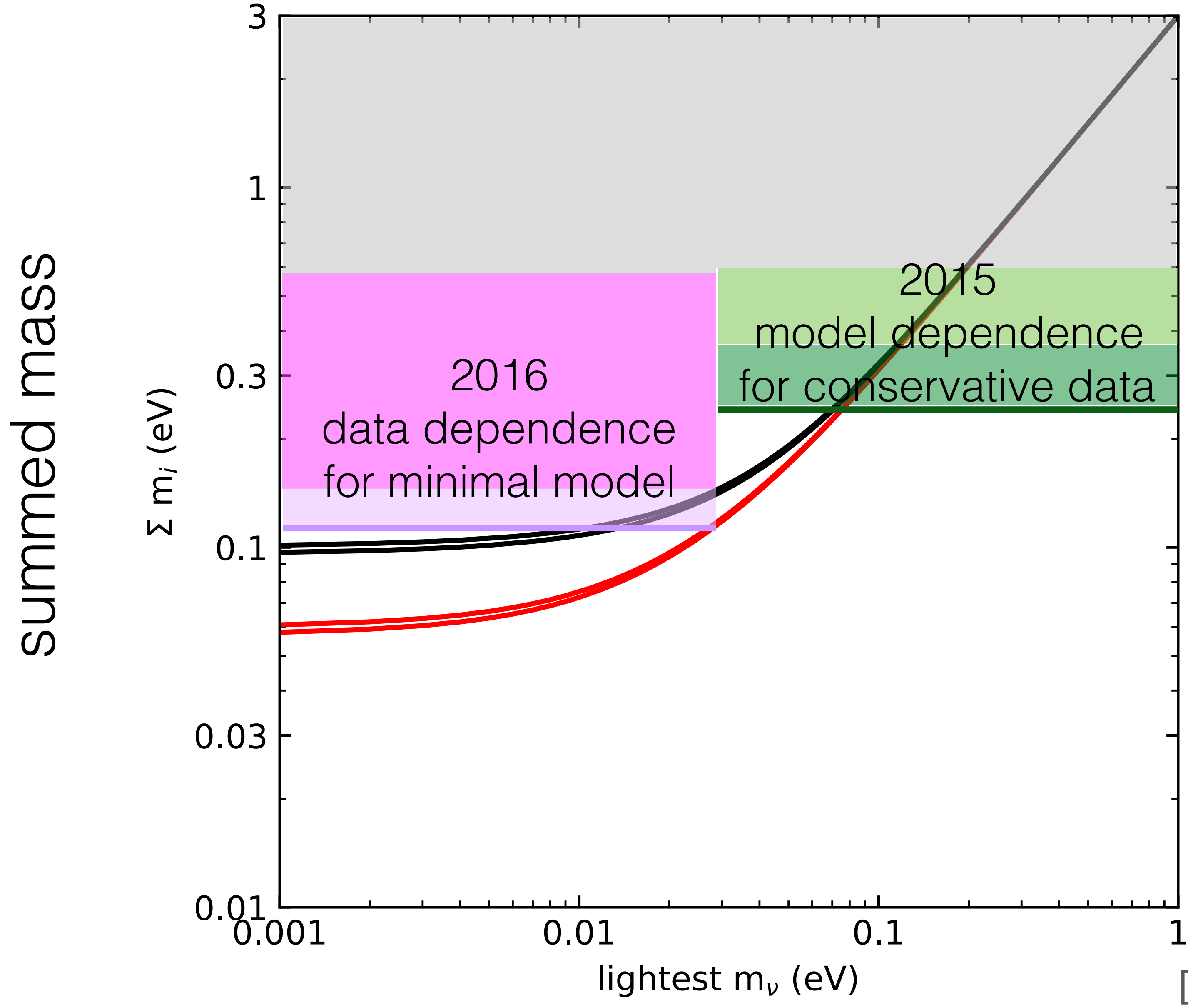
Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- ~~primordial perturbations~~

[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

# Summed mass of active neutrinos

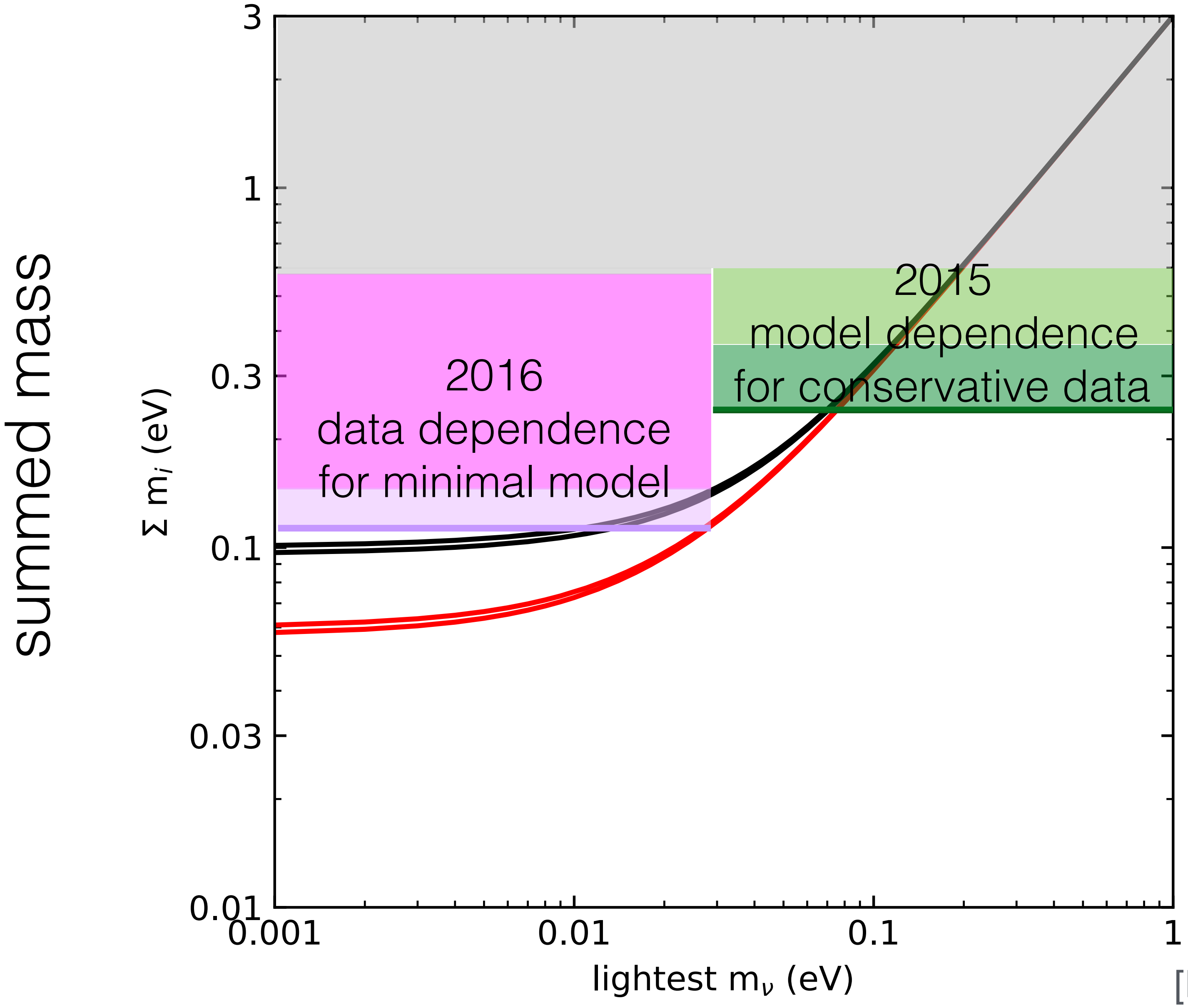
95%CL upper bounds on $\Sigma_i m_i$




[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$



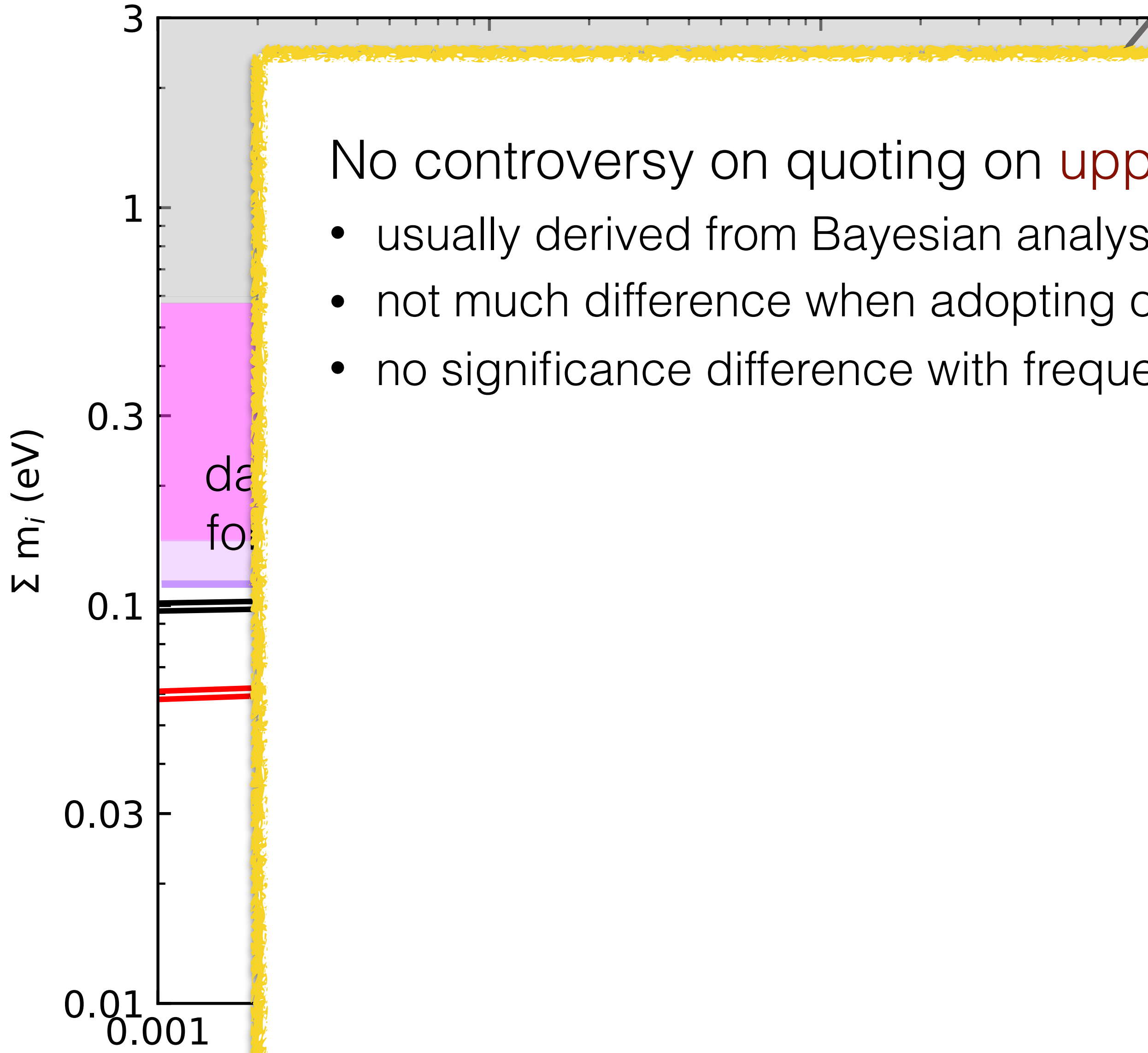

What about dependence on methodology/statistics ?

[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$

summed mass




What about dependence on methodology/statistics ?

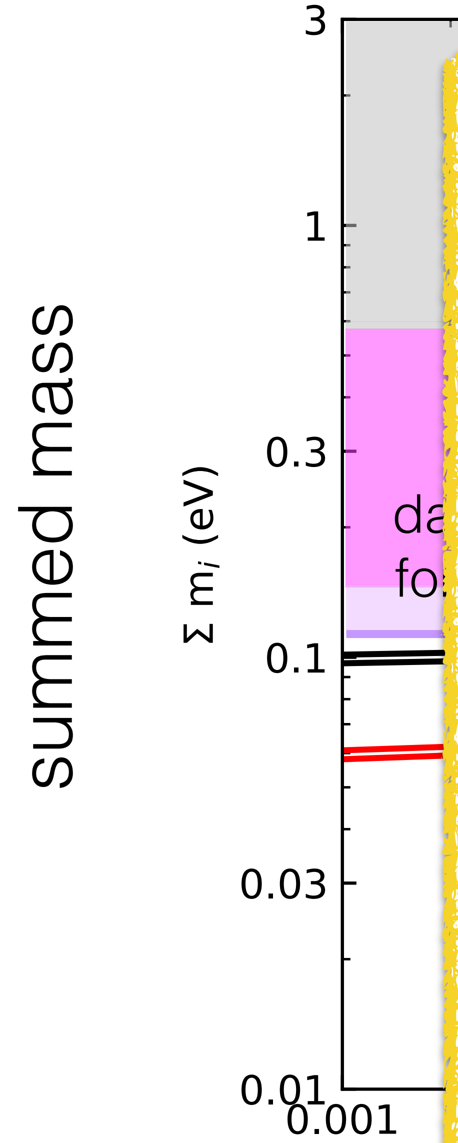
No controversy on quoting on upper cosmological bounds on $\Sigma_i m_i$:

- usually derived from Bayesian analysis with flat prior on $\Sigma_i m_i > 0$
- not much difference when adopting other priors (e.g. flat > 0.06eV or 0.11eV)
- no significance difference with frequentist bounds

646

# Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$




What about dependence on methodology/statistics ?

No controversy on quoting on upper cosmological bounds on $\Sigma_i m_i$:

- usually derived from Bayesian analysis with flat prior on $\Sigma_i m_i > 0$
- not much difference when adopting other priors (e.g. flat > 0.06eV or 0.11eV)
- no significance difference with frequentist bounds

Recent controversy on goodness of fit of NH versus IH with joint cosmo+laboratory bounds:

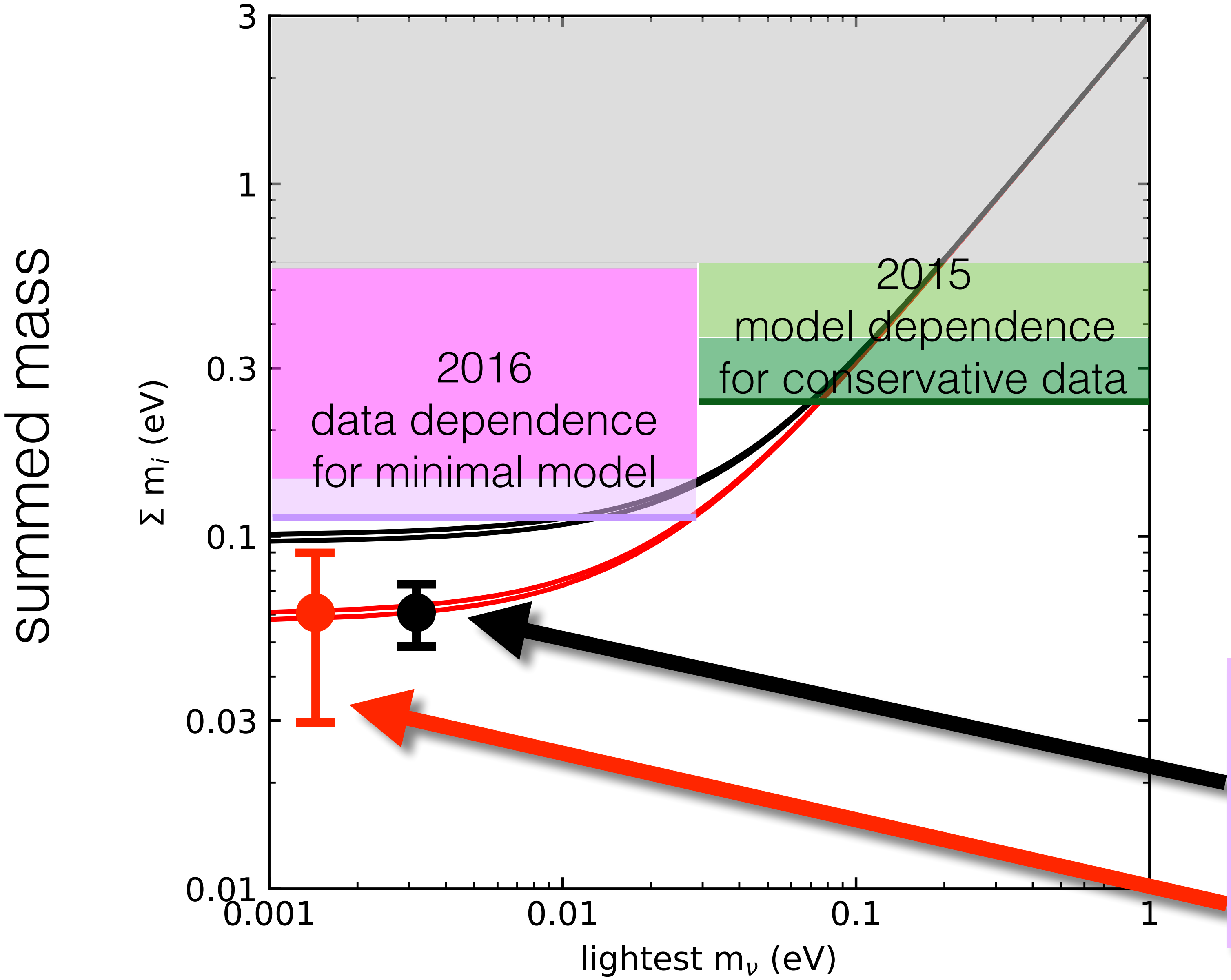
- Bayesian evidence ratio : role of priors is important; depending on methodology:
  - from weak: odds of 2 to 1 (Hannestad & Schwetz 1606.04691)
  - to strong: odds of 50 to 1 (Simpson et al. 1703.03425)
- Frequentist ($\Delta\chi^2$): 2σ preference for NH (Capozzi et al. 1703.04471)

Premature discussion —> depends too much on underlying cosmology & datasets (e.g. <0.120meV vs. <0.170meV makes crucial difference)

646

# Summed mass of active neutrinos

**FUTURE LSS:** 1σ forecast errors on $\Sigma_i m_i$




| | | |
|---|---|---|
| DES | 2013-2018 | Ground |
| eBOSS | 2014-2020 | Ground |
| DESI | 2018-2022 | Ground |
| Euclid | 2019-… | Space |
| wFIRST | 2020-… | Space |
| LSST | 2023-… | Ground |
| SKA | 1:2018-2023<br>2:2023-2030 | Ground |

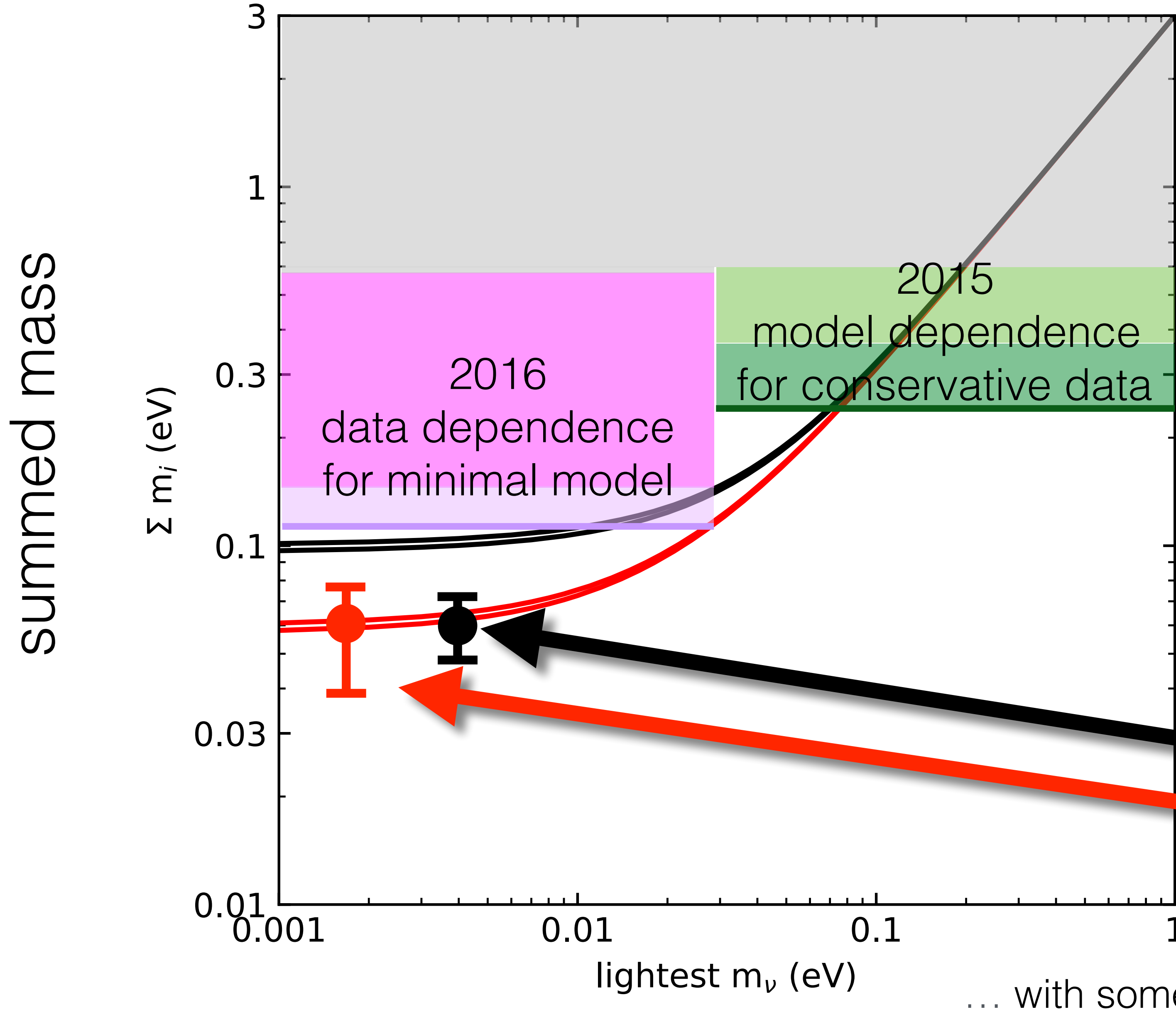
Planck + next generation LSS :
DES, DESI, Euclid, LSST, wFIRST, SKA

σ ~ { **60 -> 14 meV (7 params)**
up to 4x worse (complicated models) }

e.g. Font-Ribera et al. 1308.4164

# Summed mass of active neutrinos

**FUTURE CMB:** 1σ forecast errors on $\Sigma_i m_i$




CMB-Stage III, IV : no better numbers but gain in robustness
(e.g. σ ~ 15meV from S-IV+DESI only)
Need large angles (τ degeneracy)…

CORE + next generation LSS :
DES, DESI, Euclid, LSST, wFIRST, SKA

**σ** { **40 -> 12 meV (7 params + …)**
up to 2x worse (complicated models)

e.g. Brinckmann et al. 1612.00021

… with some uncertainty on optical depth determination by SKA

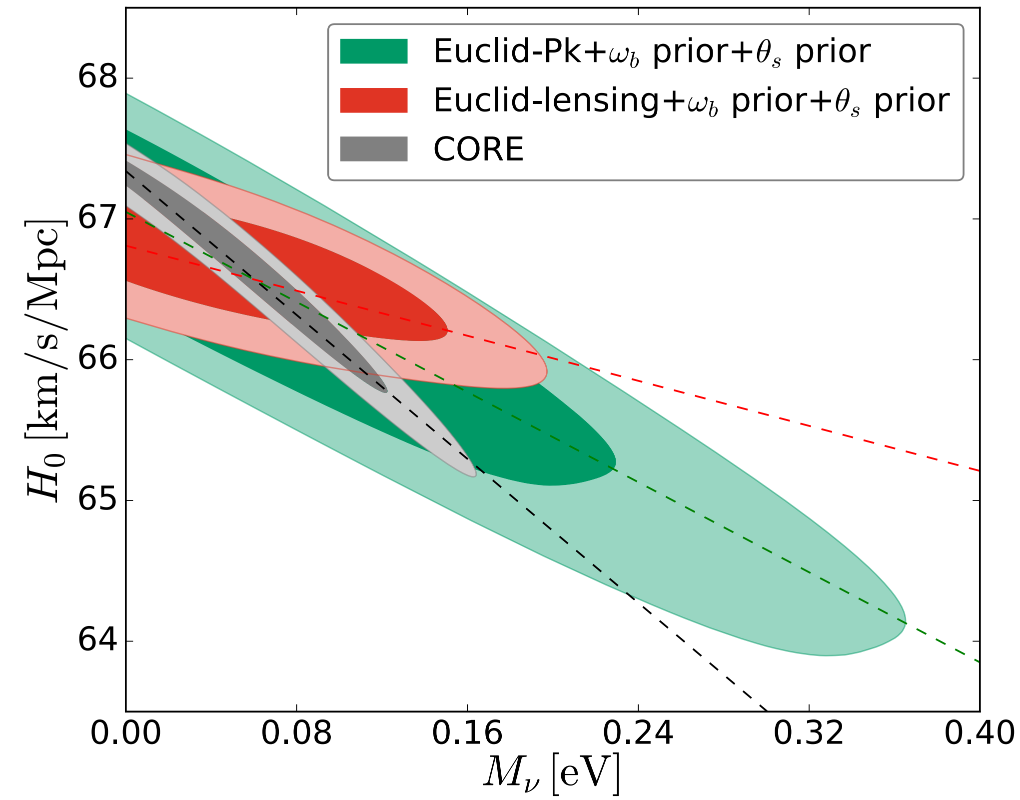


Institute for Theoretical Particle Physics and Cosmology RWTH AACHEN UNIVERSITY

# ve neutrinos

**FU**

Combination of CMB and various LSS probes remove degeneracies




Full-sky CMB experiment and SKA 21cm survey crucial to avoid degeneracy with optical depth

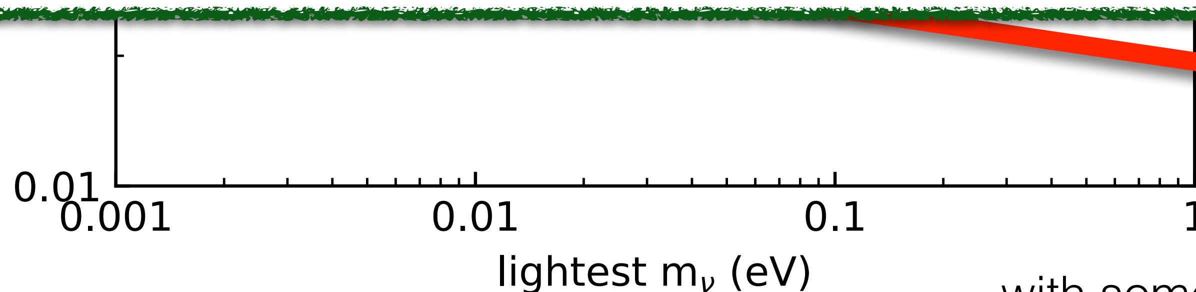
Archidiacono, Brinckmann, JL, Poulin 2016

CMB-Stage III, IV : no better numbers but gain in robustness (e.g. σ ~ 15meV from S-IV+DESI only) Need large angles (τ degeneracy)…

CORE + next generation LSS : DES, DESI, Euclid, LSST, wFIRST, SKA

σ { **40 -> 12 meV (7 params + …)**
up to 2x worse (complicated models)

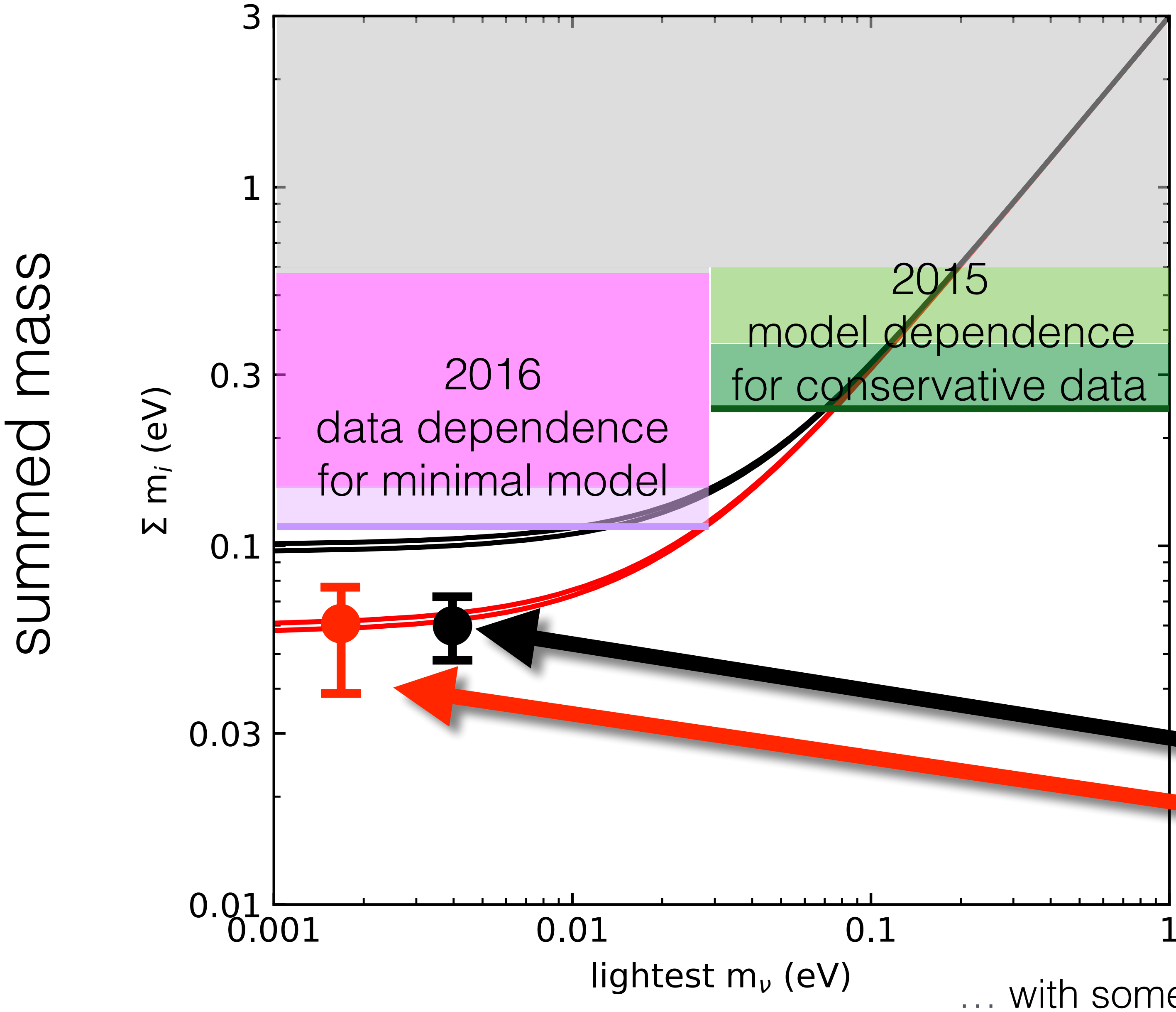
e.g. Brinckmann et al. 1612.00021




… with some uncertainty on optical depth determination by SKA

# Summed mass of active neutrinos

**FUTURE CMB:** 1σ forecast errors on $\Sigma_i m_i$




**5σ detection of $M_\nu$ possible even if $M_\nu$ = 60 meV, but only for minimal ΛCDM+$M_\nu$ model**

CMB-Stage III ... better numbers
but gain i... bustness
(e.g. σ ~ 15meV f... S-IV+DESI only)
Need large angle... τ degeneracy)…

CORE + next generation LSS :
DES, DESI, Euclid, LSST, wFIRST, SKA

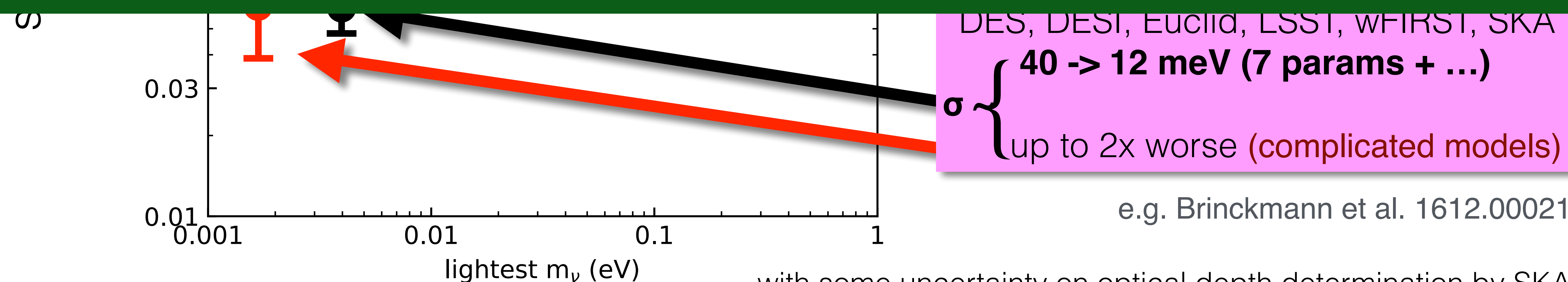
σ { **40 -> 12 meV (7 params + …)**
up to 2x worse (complicated models)

e.g. Brinckmann et al. 1612.00021

… with some uncertainty on optical depth determination by SKA

# Summed mass of active neutrinos

- at first sight much more sensitive than many β- and double-β- decay (KATRIN, GERDA, …), but indirect probe of a different parameter with several assumptions
- cannot be disappointing: given exquisite sensitivities, non-detection or discrepancy with β- decay would require major change of paradigm on the late time behaviour of the cosmological model (new physics to describe structure formation: MG, non-standard particle interactions) or on neutrino physics (decaying neutrinos, mass from coupling with varying scalar, NSI, etc.)



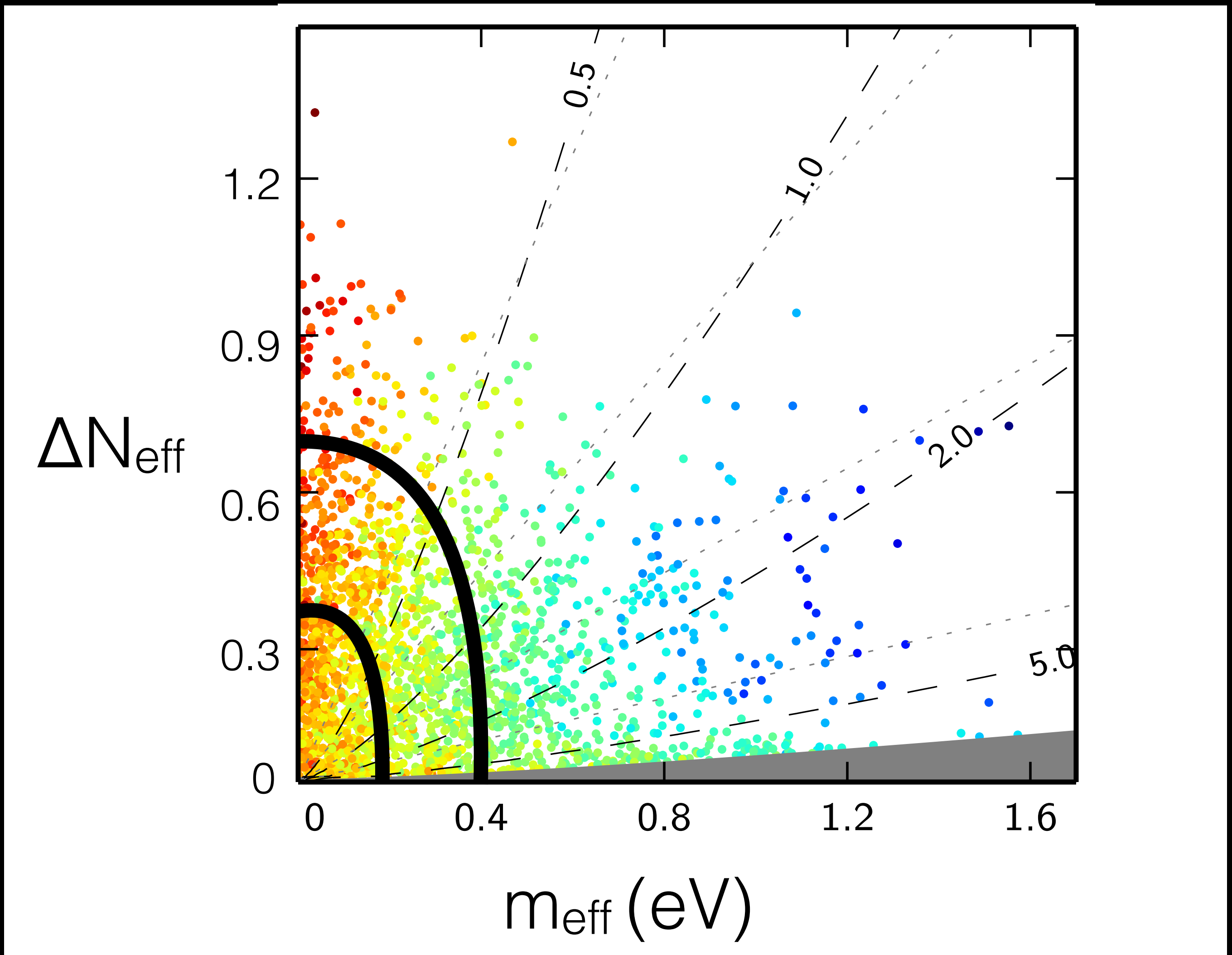

e.g. Brinckmann et al. 1612.00021

… with some uncertainty on optical depth determination by SKA

# Extra relics (small mass case)

**Current an future bounds** on one early-decoupled or non-thermalized extra light species (e.g. $\nu_4$ of 3+1 scenario, abusively called "sterile neutrino")

| Effective density parameters | Planck 2015 (TT+lowP+lensing) + BAO |
|---|---|
| $\Delta N_{eff}$ (extra contribution to density *before* NR transition) | <0.7 (95%CL) |
| $m_{eff}$ (extra contribution to density *after* NR transition) | < 400 meV (95%CL) |

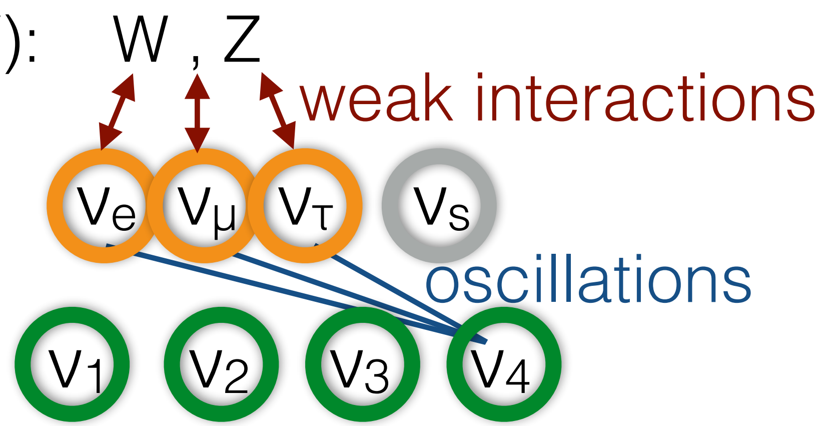



For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

# Extra relics (small mass case)

Connection with neutrino reactor/SBL oscillation anomaly: 3+1 scenario:

- before active ν decoupling (T~1MeV):
- weak interaction basis:
- mass basis :

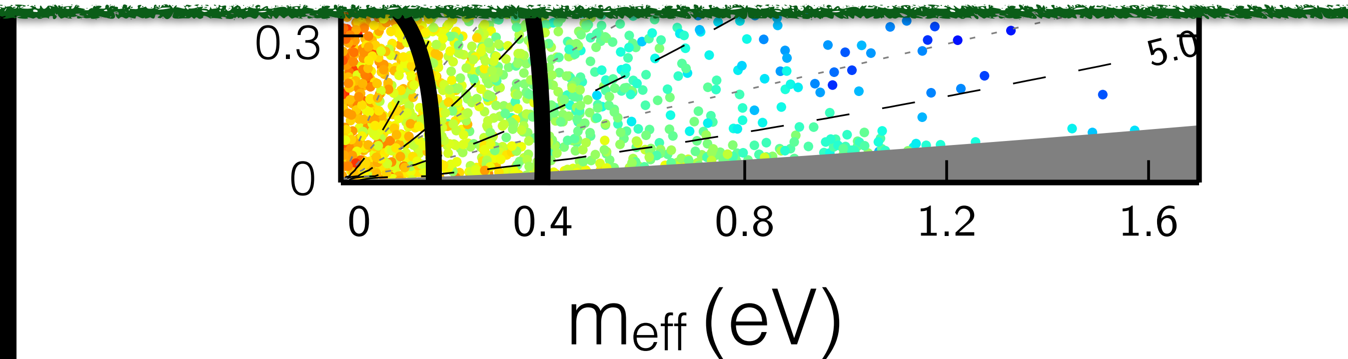



- $\sin^2 2\theta \sim 0.05$ ——> thermalisation: ~ same p.s.d for $\nu_1$ , $\nu_2$ , $\nu_3$ , $\nu_4$
  e.g. Hannestad, Tambora & Tram 2012; Bridle et al. 1607.00032

Cosmological model:

- ΛCDM with 4 light thermalised species with $\Delta N_{eff}=1$, $m_{eff} = m_4$
- Data probes $[m_1+m_2+m_3+m_4]$, but bounds on $m_{eff}$ can be reported:

| | |
|---|---|
| $m_{eff}$ (extra contribution to density *after* NR transition) | < 400 meV (95%CL) |

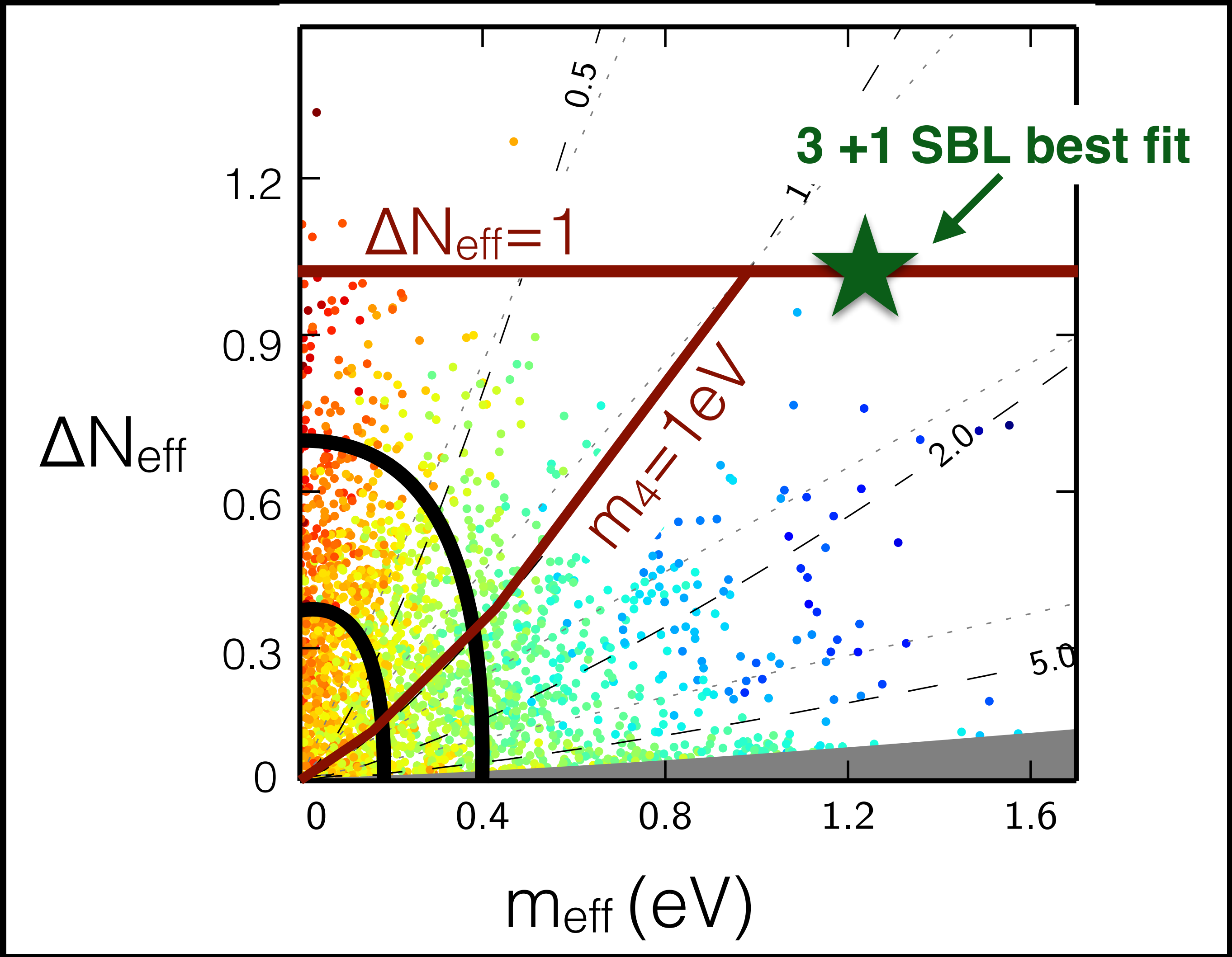



For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

# Extra relics (small mass case)

**Current an future bounds on one early-decoupled or non-thermalized extra light species (e.g. $\nu_4$ of 3+1 scenario, abusively called "sterile neutrino")**

| Effective density parameters | Planck 2015 (TT+lowP+lensing) + BAO |
|---|---|
| $\Delta N_{eff}$ (extra contribution to density *before* NR transition) | <0.7 (95%CL) |
| $m_{eff}$ (extra contribution to density *after* NR transition) | < 400 meV (95%CL) |




For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

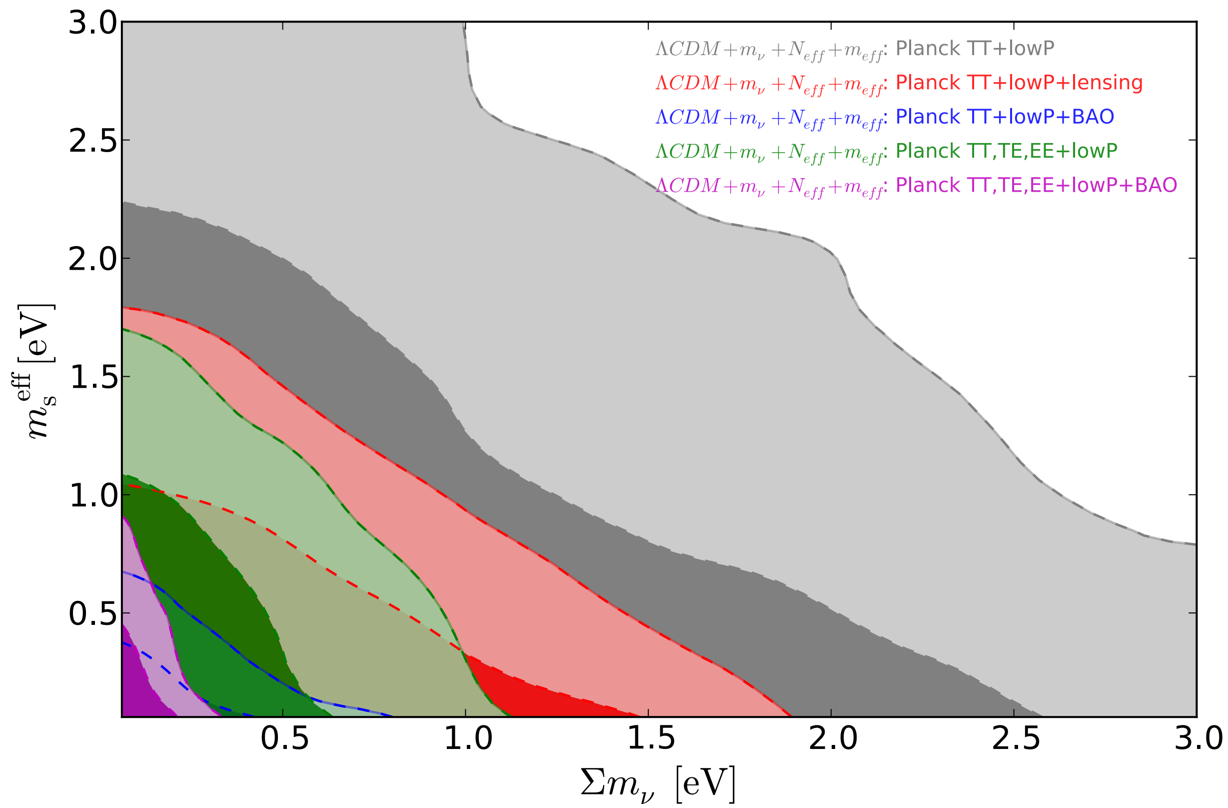
# Extra relics (small mass case)

**Can we tweak cosmological model and accommodate $\Delta N_{eff}$~1 and $m_s$~1eV?**

- Sounds very difficult
- not even with full freedom in primordial spectrum:

Di Valentino et al. 1601.0755

After marginalisation over 12 free parameters for binned primordial spectrum:




$m_s$ =1eV

- excluded at >4σ with Planck 2015 TT+lowP + BAO

+ $N_{eff}$ =4:

- compatible at 2σ without Planck 2015 TTTEEE,
- excluded at >2σ with Planck 2015 TTTEEE

**For Dodelson-Widrow neutrinos, physical mass m = $m_{eff}/\Delta N_{eff}$**

# Extra relics (small mass case)

**How to suppress the $\nu_4$ density in both relativistic and non-relativistic regimes?**

**talk by N. Saviano on Monday**

- Low-temperature reheating

  Gelmini et al. 2014, de Salas et al. 2015

- Leptonic asymmetry and resonant oscillations… *issues with BBN* ($\mu_e$)

  Di Bari et al. 2001; …; Hannestad, Tambora & Tram 2012; Mirizzi et al. 2012; Saviano et al. 2013

- NSI (need to pass bounds on fifth force and SN energy loss…)
  - $\nu_4$ interacts with (dark) gauge boson

    Dasgupta, Kopp 2015 ; Saviano et al. 2014; Mirizzi et al. 2014; Chu, Dasgupta, Kopp 2015

  - $\nu_4$ interacts with (dark) pseudoscalar

    Hannestad et al. 2013; Saviano et al. 2014; Archidiacono et al. 2016

    - $\nu_4$ production is suppressed, $\phi$-$\nu_s$ recouple —> neutrinos as relativistic fluid *(potential issue for fitting CMB data)*, $\nu_4$ annihilate into $\phi$ at late times…
    - if $N_{eff}$>3 detected: possible tests, but there is a range compatible with SN and with negligible $\Delta N_{eff}$ : how can we test this model?

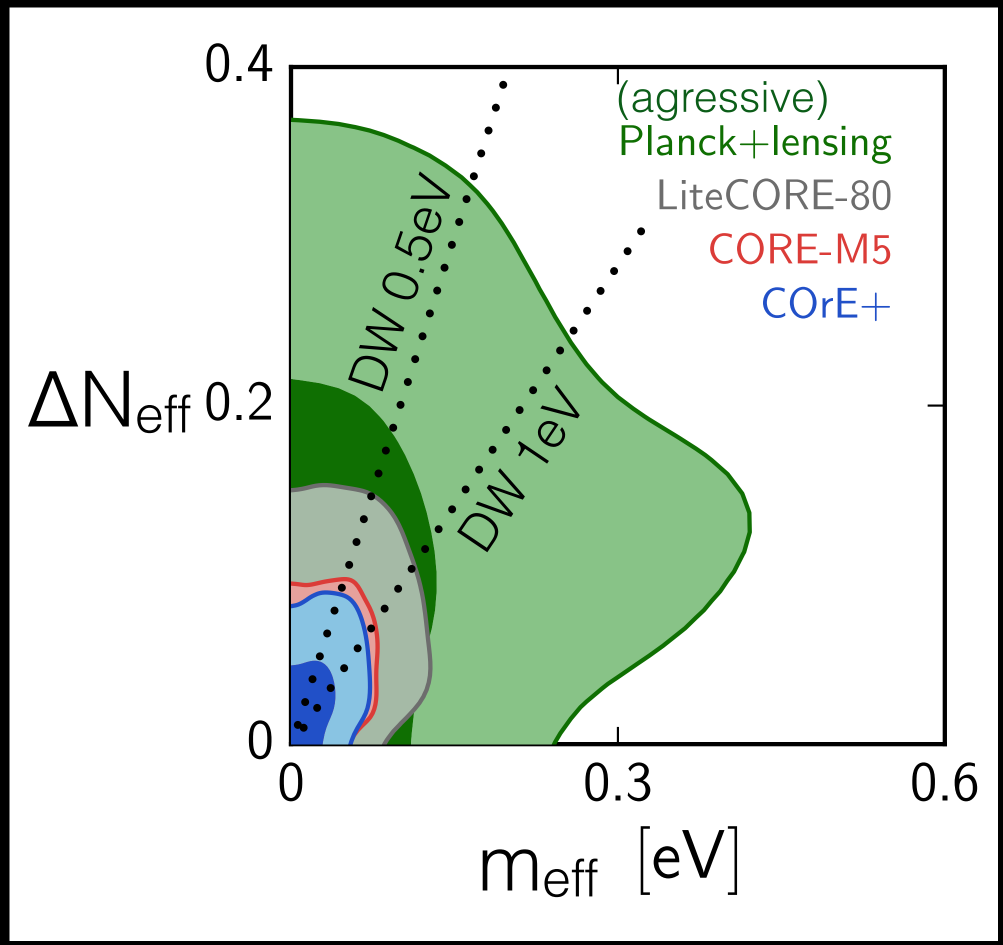
**For Dodelson-Widrow neutrinos, physical mass m = $m_{eff}/\Delta N_{eff}$**

# Extra relics (small mass case)

**Current an future bounds on one early-decoupled or non-thermalized extra light species (e.g. sterile neutrino)**

| Effective density parameters | Planck 2015 (TT+lowP+lensing) + BAO | CORE + DESI + Euclid CORE collaboration [1612.00021] |
|---|---|---|
| $\Delta N_{eff}$ (extra contribution to density *before* NR transition) | <0.7 (95%CL) | $2\sigma$ ~ 0.10 |
| $m_{eff}$ (extra contribution to density *after* NR transition) | < 400 meV (95%CL) | $2\sigma$ ~ 66 meV |

For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$




CORE et al. 1612.00021

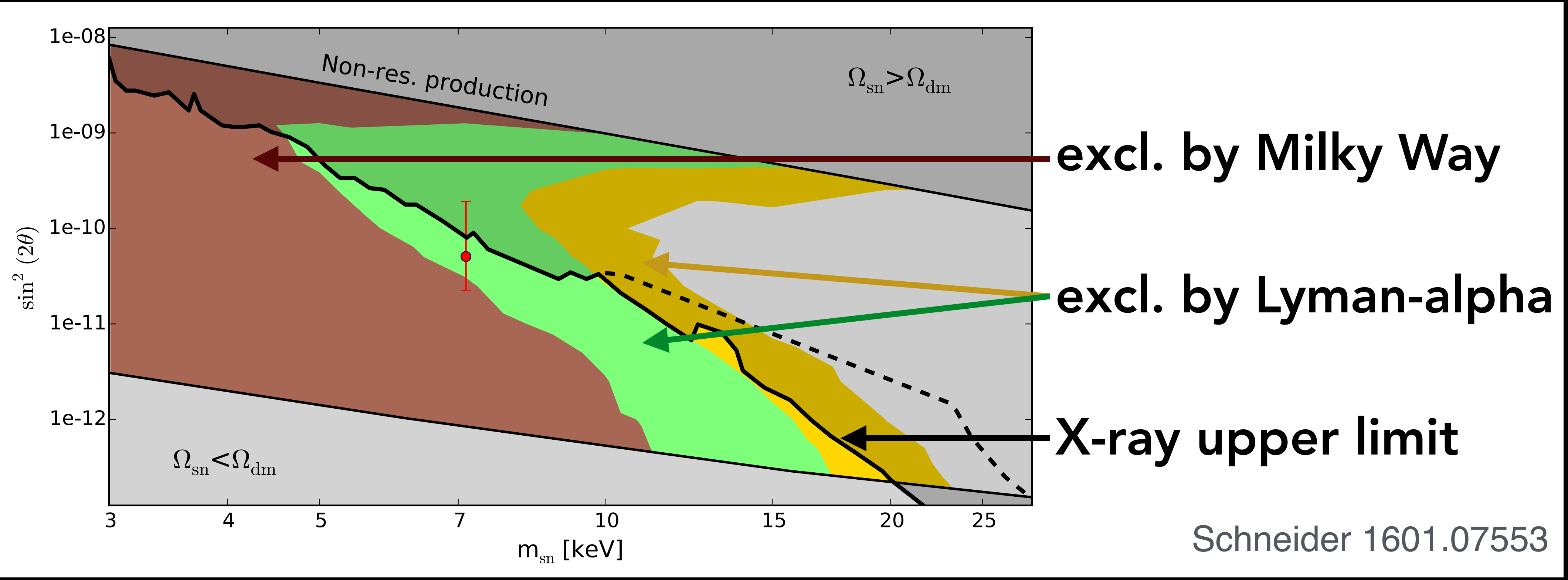
(forecasted errors obtained while simultaneously varying — and measuring — active neutrino mass scale)



Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

# KeV sterile neutrino

- Non-resonantly produced (leptonic asymmetry << $10^{-6}$): ``pure Warm Dark Matter": EXCLUDED
- Resonantly produced (leptonic asymmetry ~ $10^{-6}$): ``Cold+Warm Dark Matter": PROBABLY EXCLUDED (effect of $T_{IGM}(z)$ ? Garzilli et al.2015)

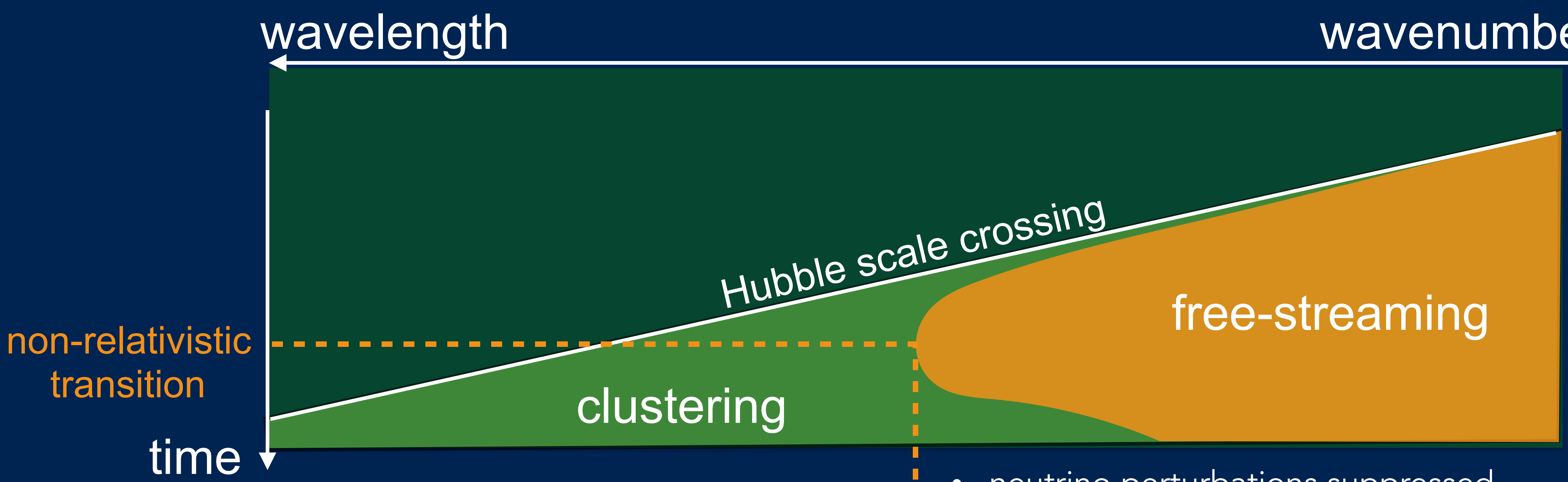



Schneider 1601.07553

- As a fraction of DM only: future improvement on both sides (X-ray -despite Hitomi failure- , Lyman-alpha)

# END

# What neutrino effects are we testing?




impact on LSS (matter power spectrum, galaxy lensing)
and
CMB (integrated Sachs-Wolfe, CMB lensing)

- neutrino perturbations suppressed
- cdm perturbations too (different balance gravity/expansion)
- evolution of metric perturbation modified

.04816

trino
pansion
r scale)

**neutrino** slow down early dark matter clustering

**neutrino** propagation and dispersion velocity

**neutrino** slow down late ordinary/dark matter clustering