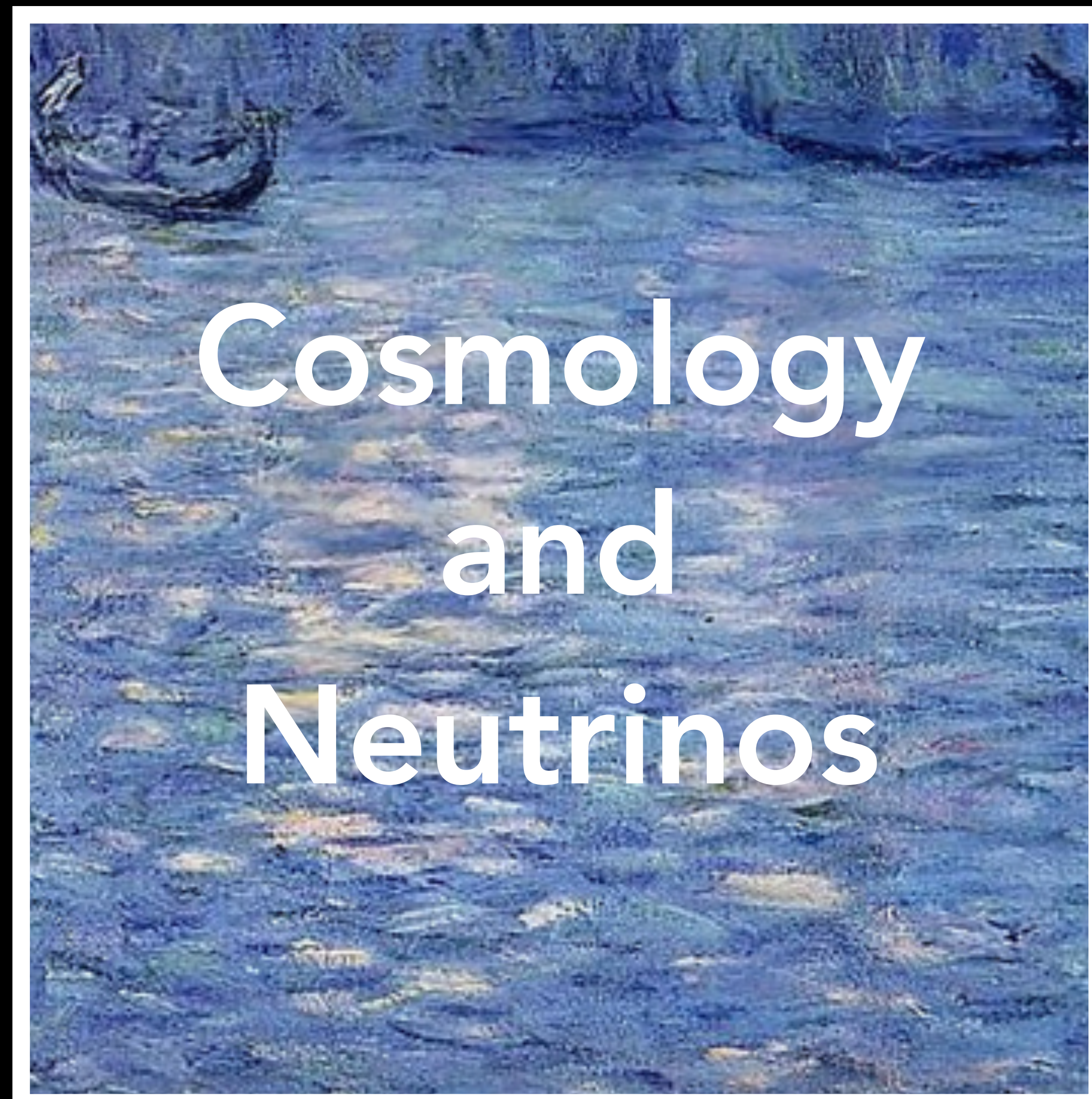
XVII International Workshop on Neutrino Telescope
Venezia, 16.03.2017



Julien Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), 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

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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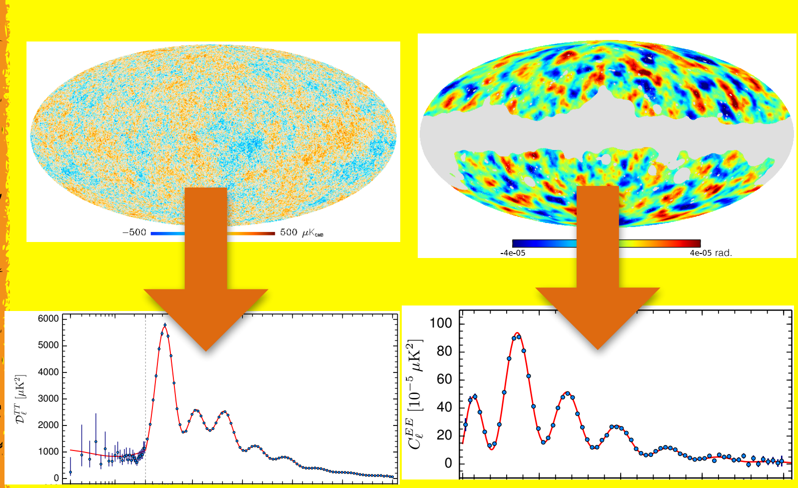
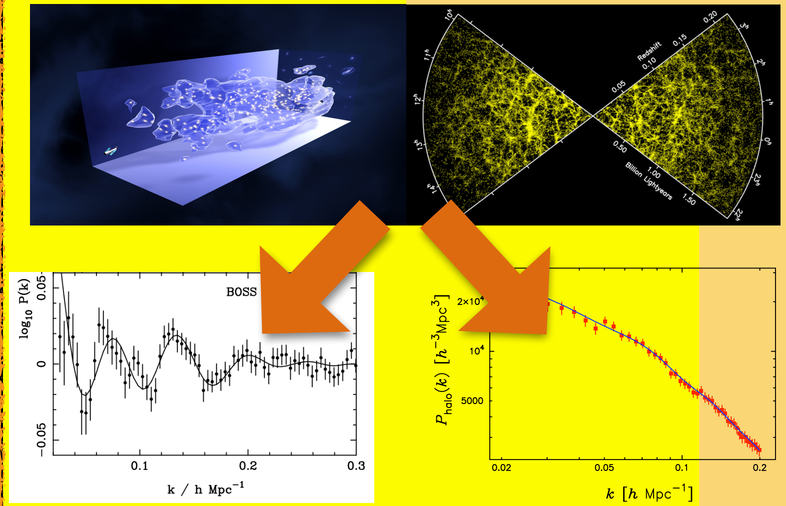


temperature/polarisation/
lensing power spectrum

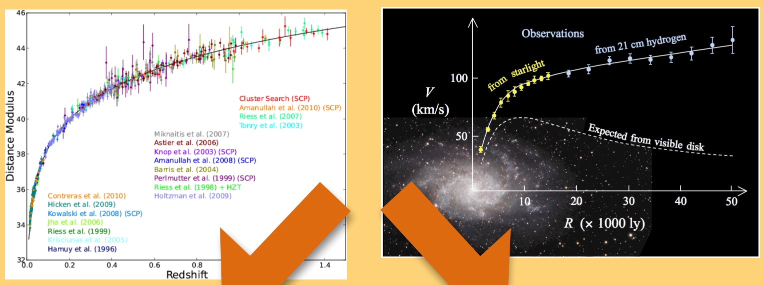
Large Scale Structure



BAO
scale

matter power
spectrum

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



Hubble rate,
acceleration of expansion,
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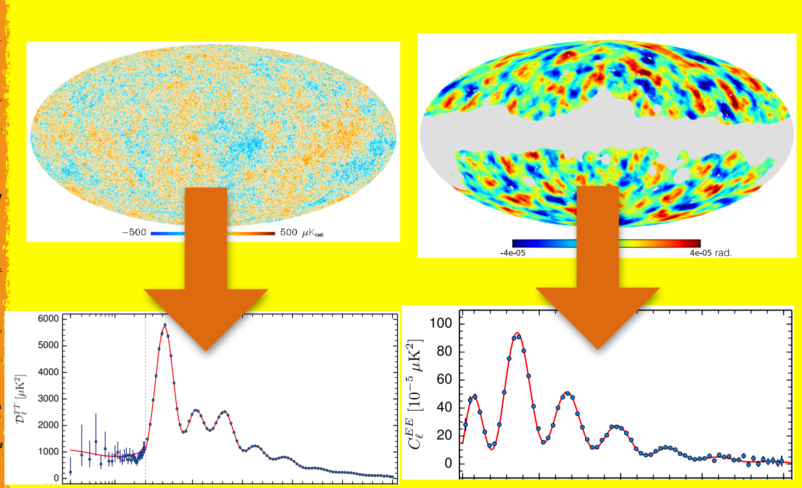

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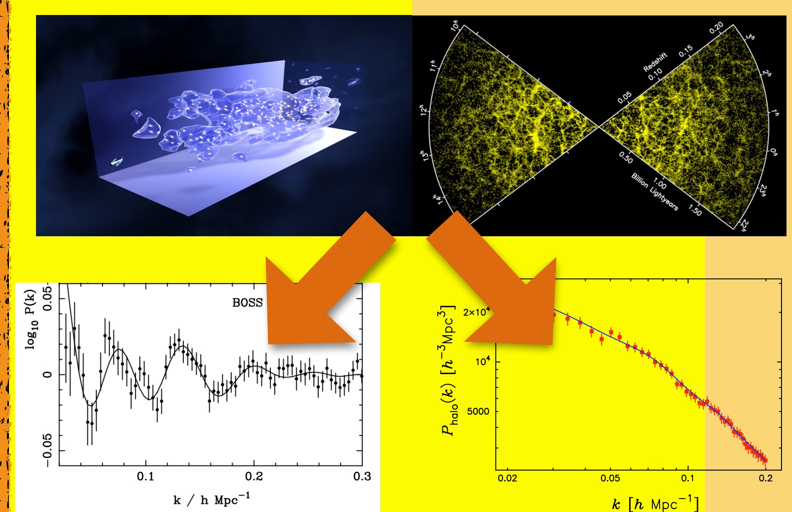

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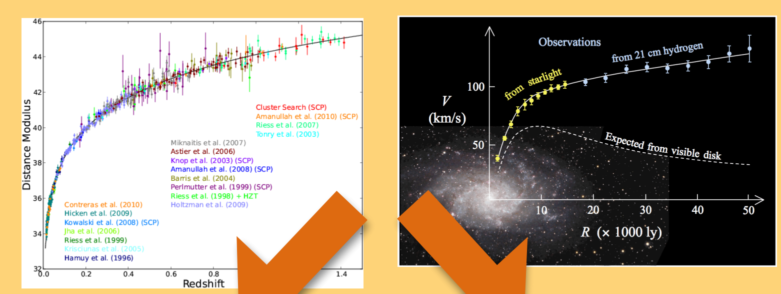


Hubble rate, acceleration of expansion, satellite galaxies count…

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

minimal 6-parameter model: excellent fit

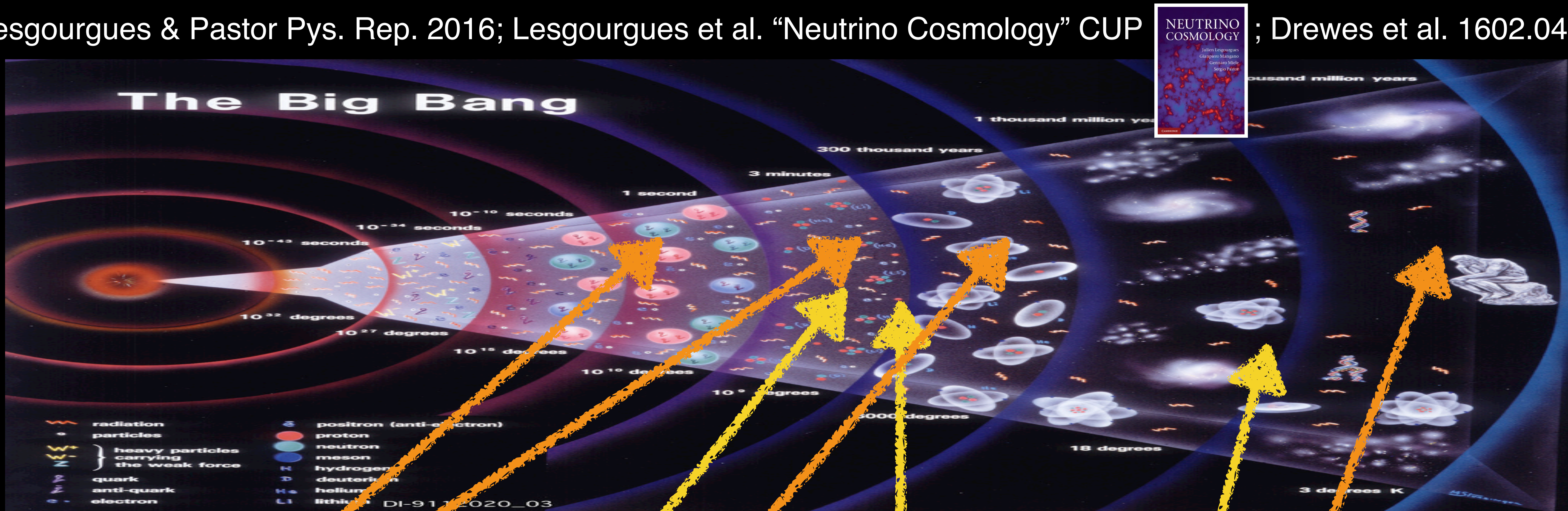
for binned TT data, $\chi 2$/dof=1.004 for 731 d.o.f.

most recent H_0 measurement *(Riess et al.)* :1 point in tension at 2.7σ

(73.24-66.93)/(1.74+0.62)=2.67

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

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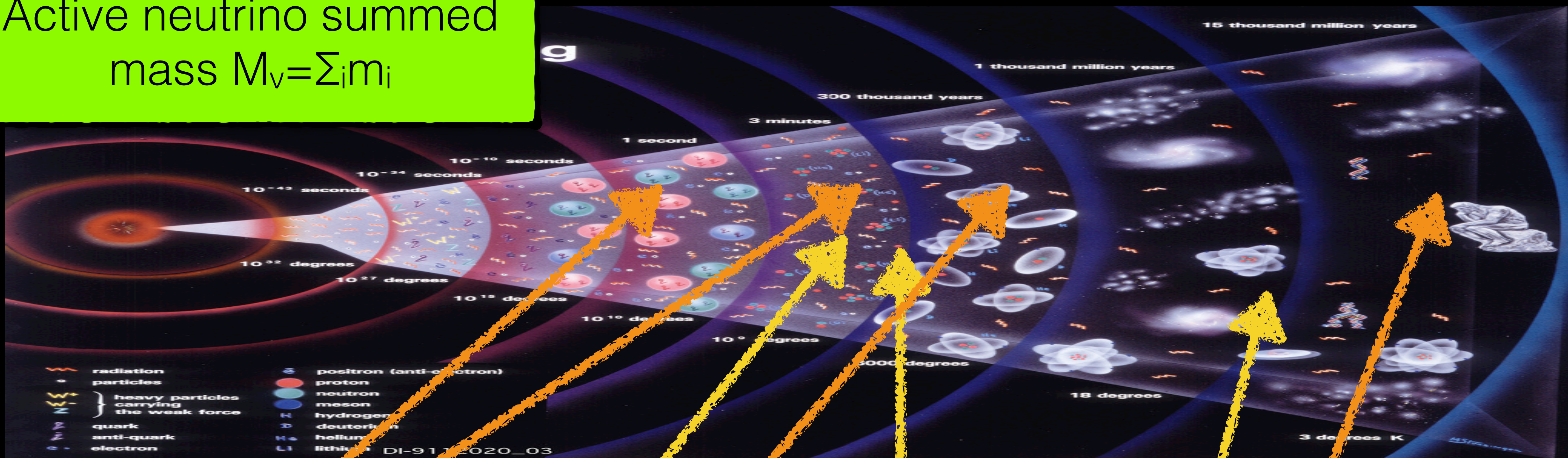

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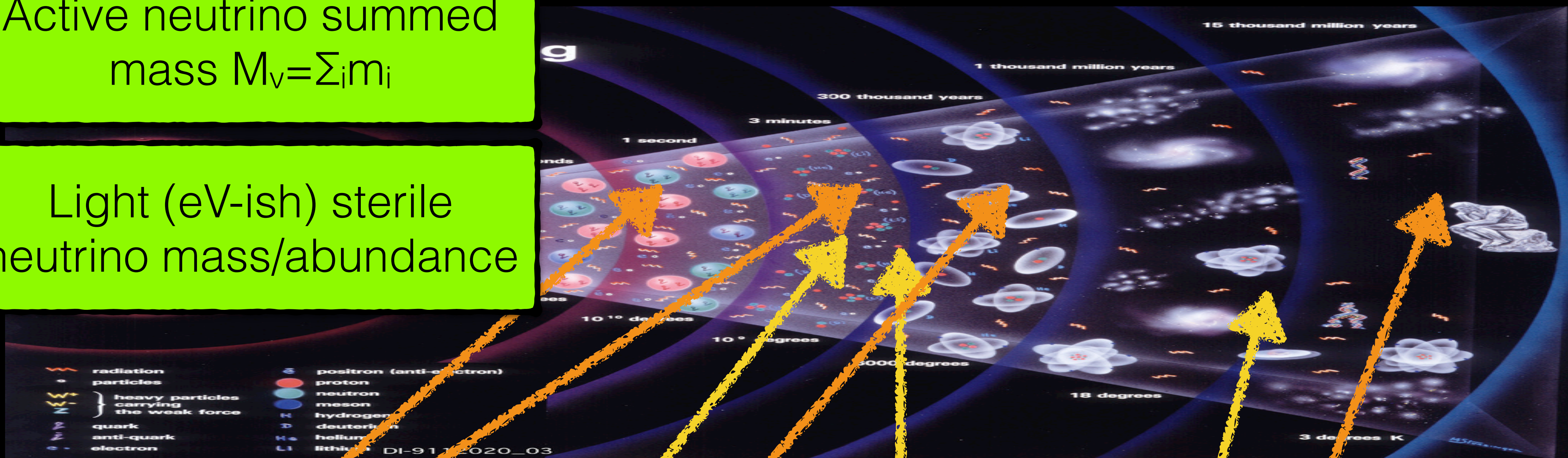

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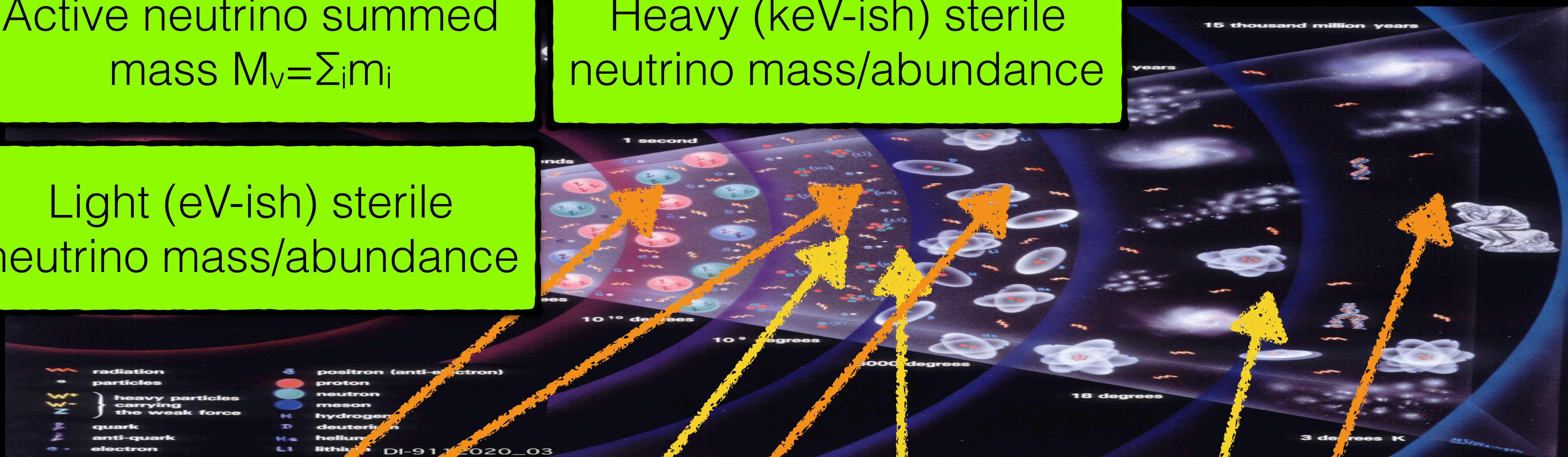

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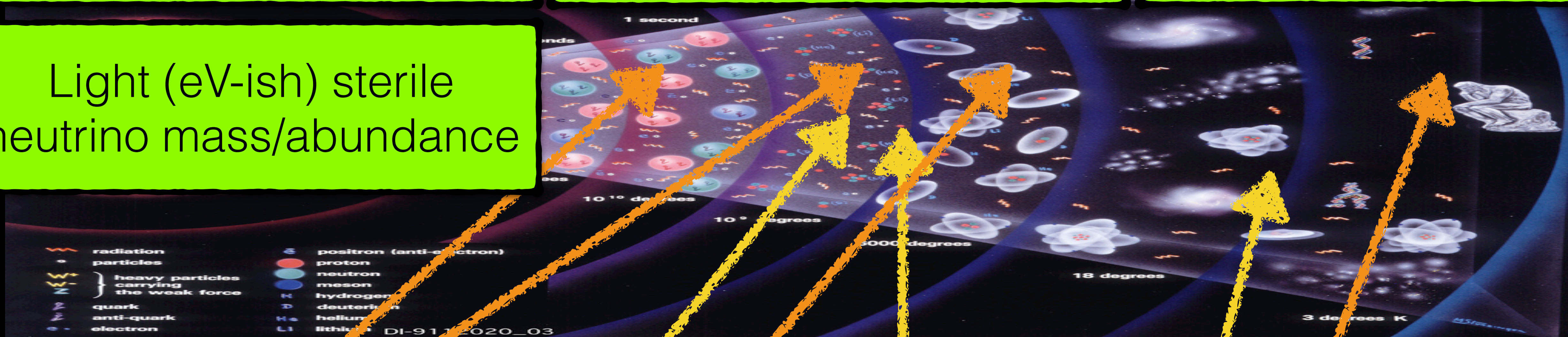

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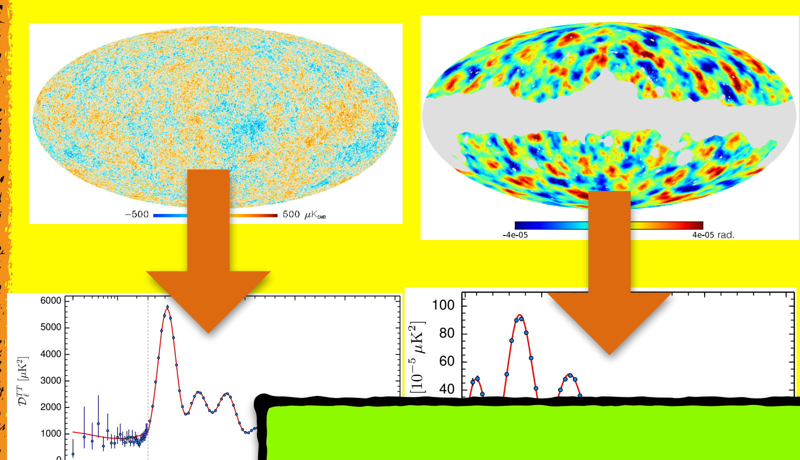

tempe
lensin

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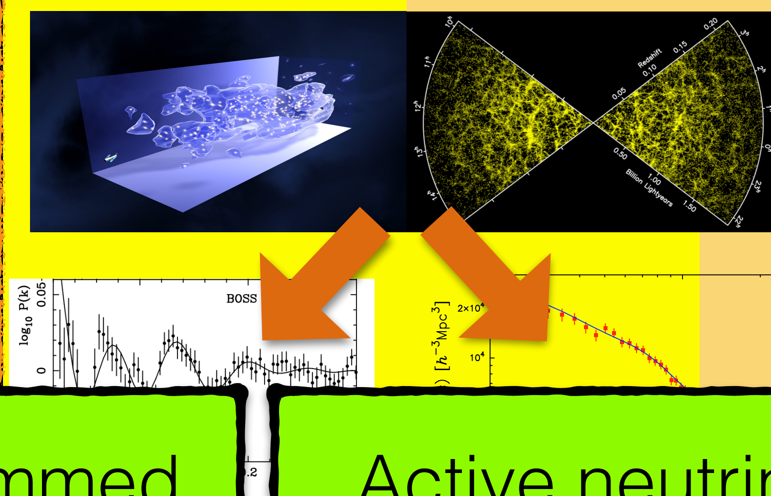

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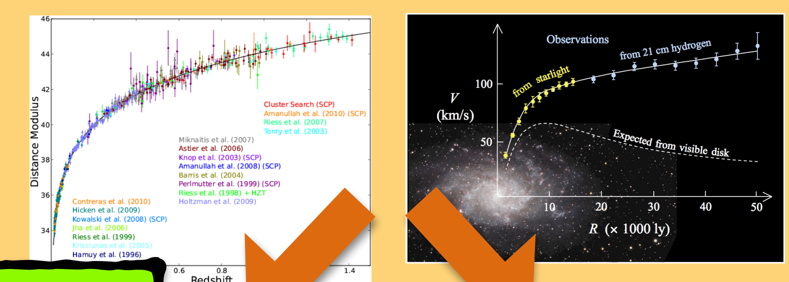

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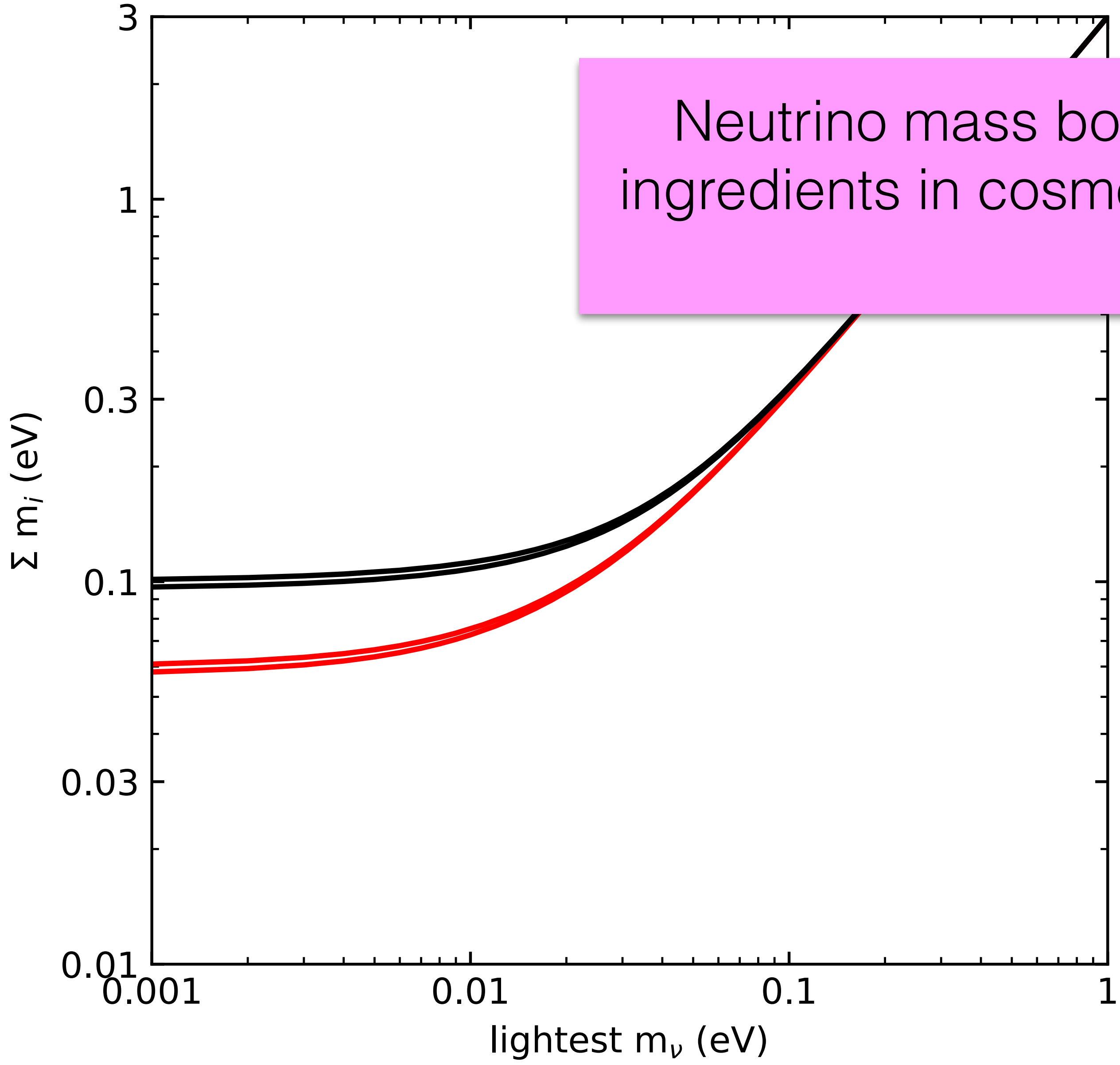
95%CL upper bounds on $\Sigma_i m_i$

summed mass



Neutrino mass bounds depend on number of new ingredients in cosmological model beyond minimal (6-param) model

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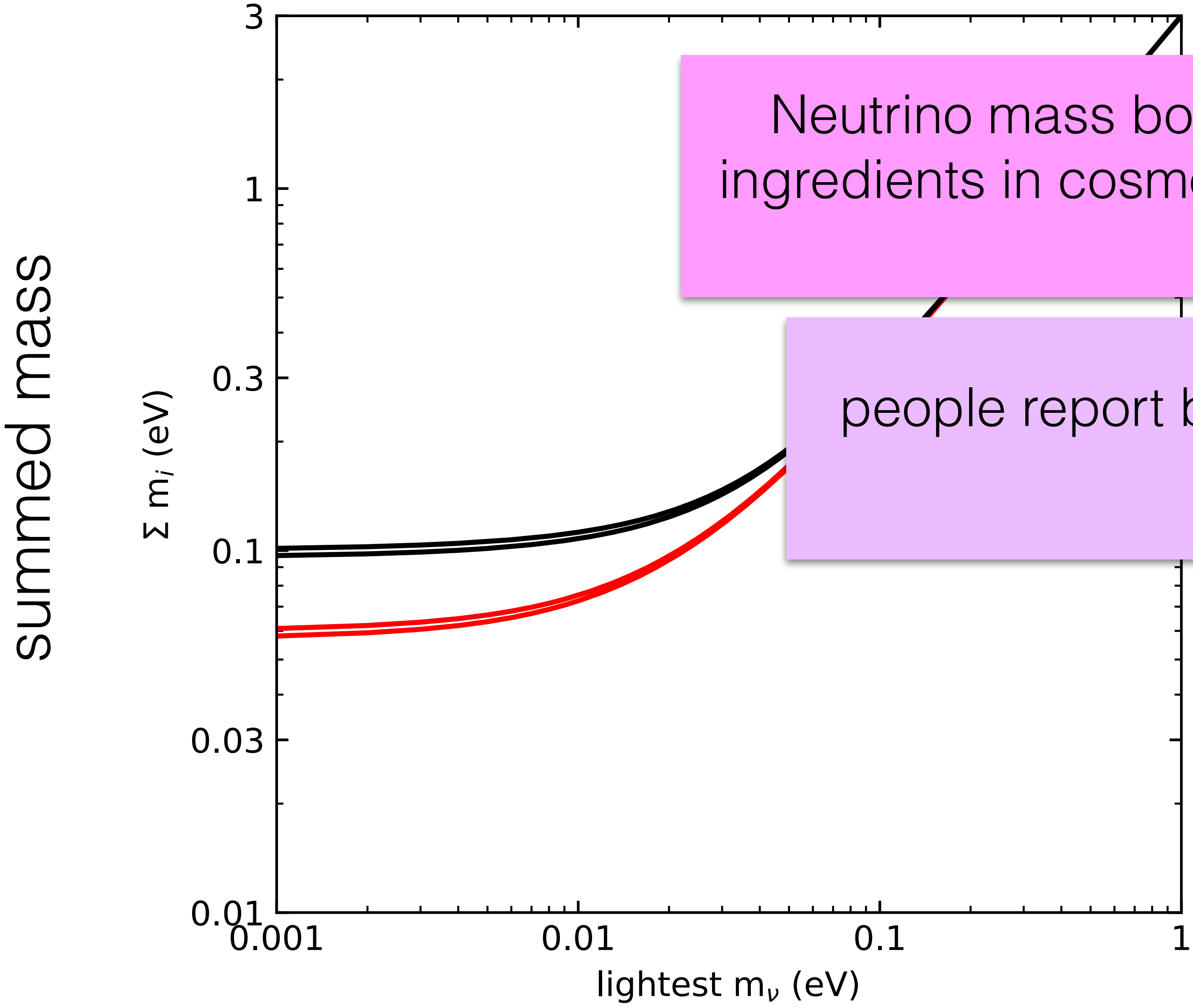

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people report bounds on 7-param model and on extended model

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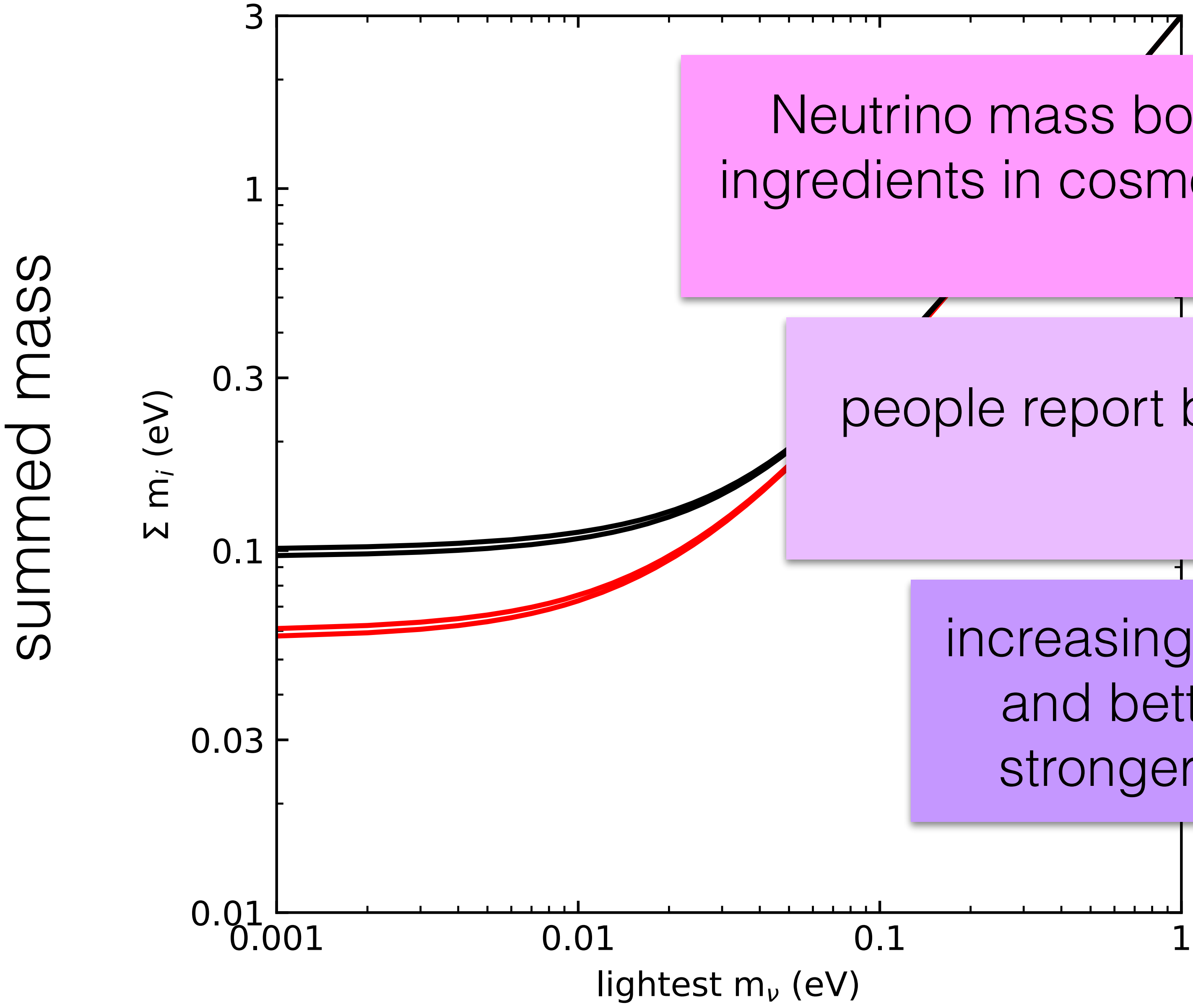

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increasing amount of data with smaller errors and better complementarity: bounds get stronger, but also less model-dependent

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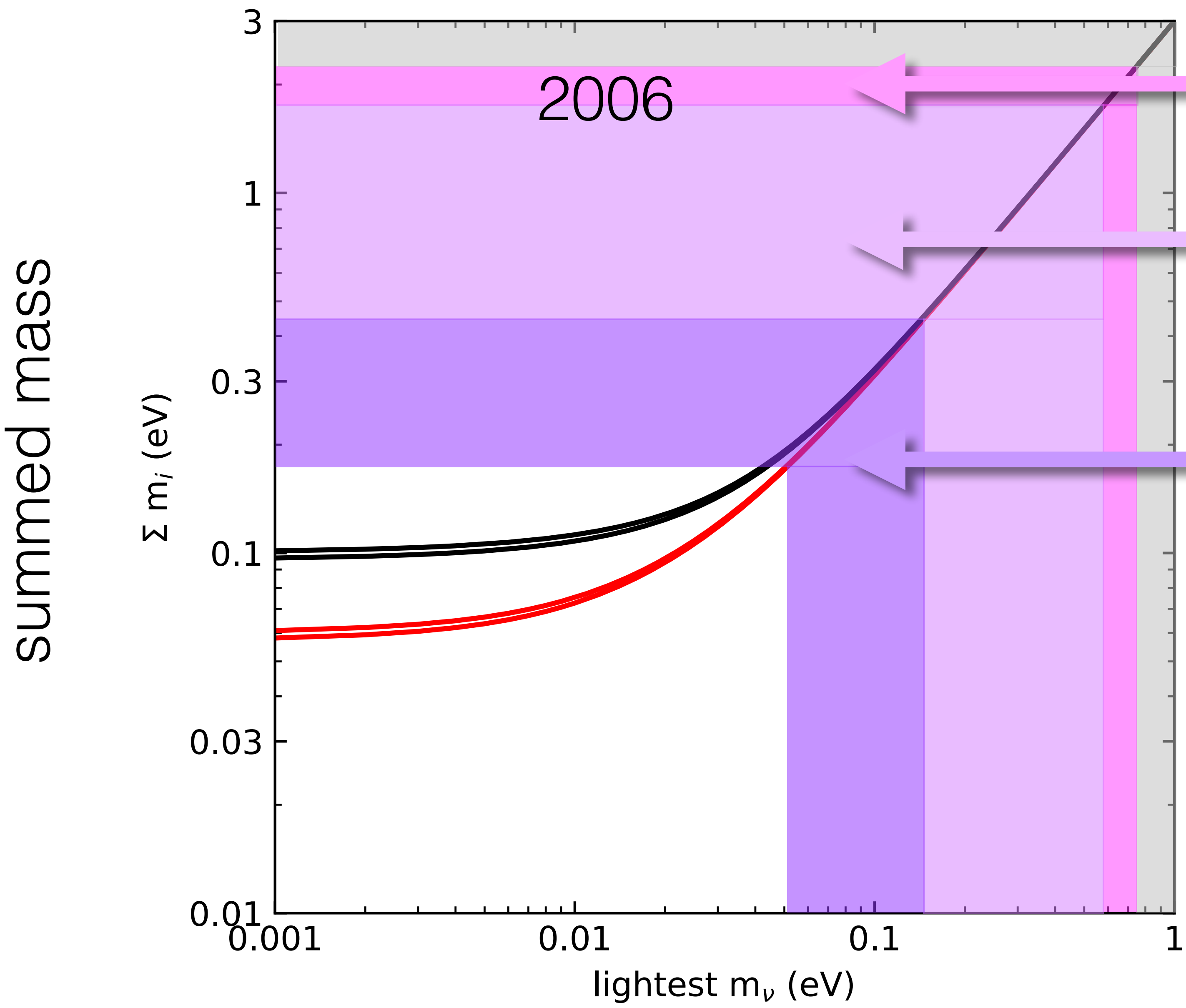

CMB only : WMAP, VSA, ACBAR, CBI…

CMB + LSS : 2dF, SDSS-BAO, SDSS-power spectrum

CMB + LSS : Lyman-alpha

Seljak et al. 2006; Viel et al. 2006

Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$

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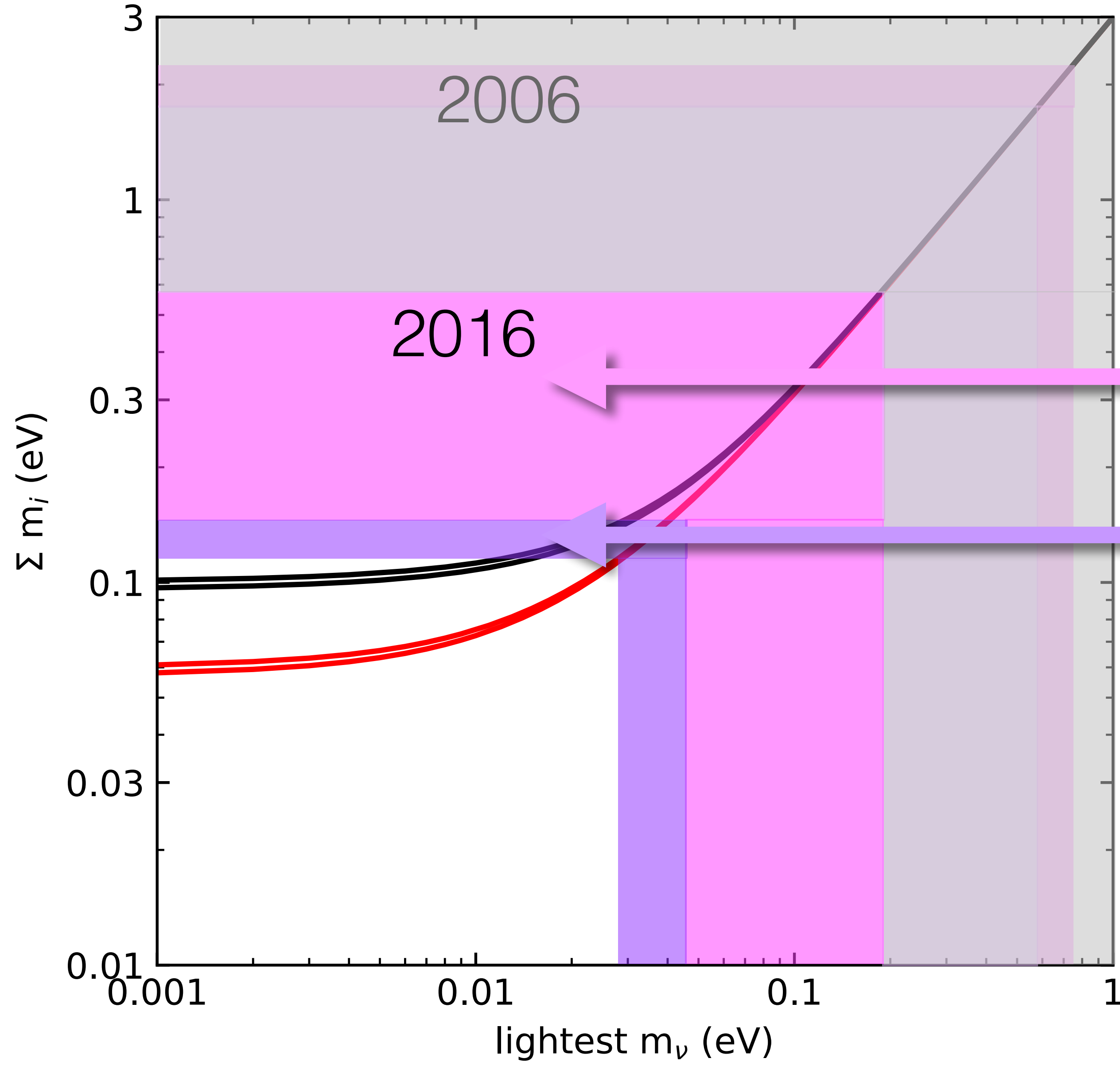


CMB only: Planck,
w/o polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

[Planck col.] 1605.02985

CMB + LSS :

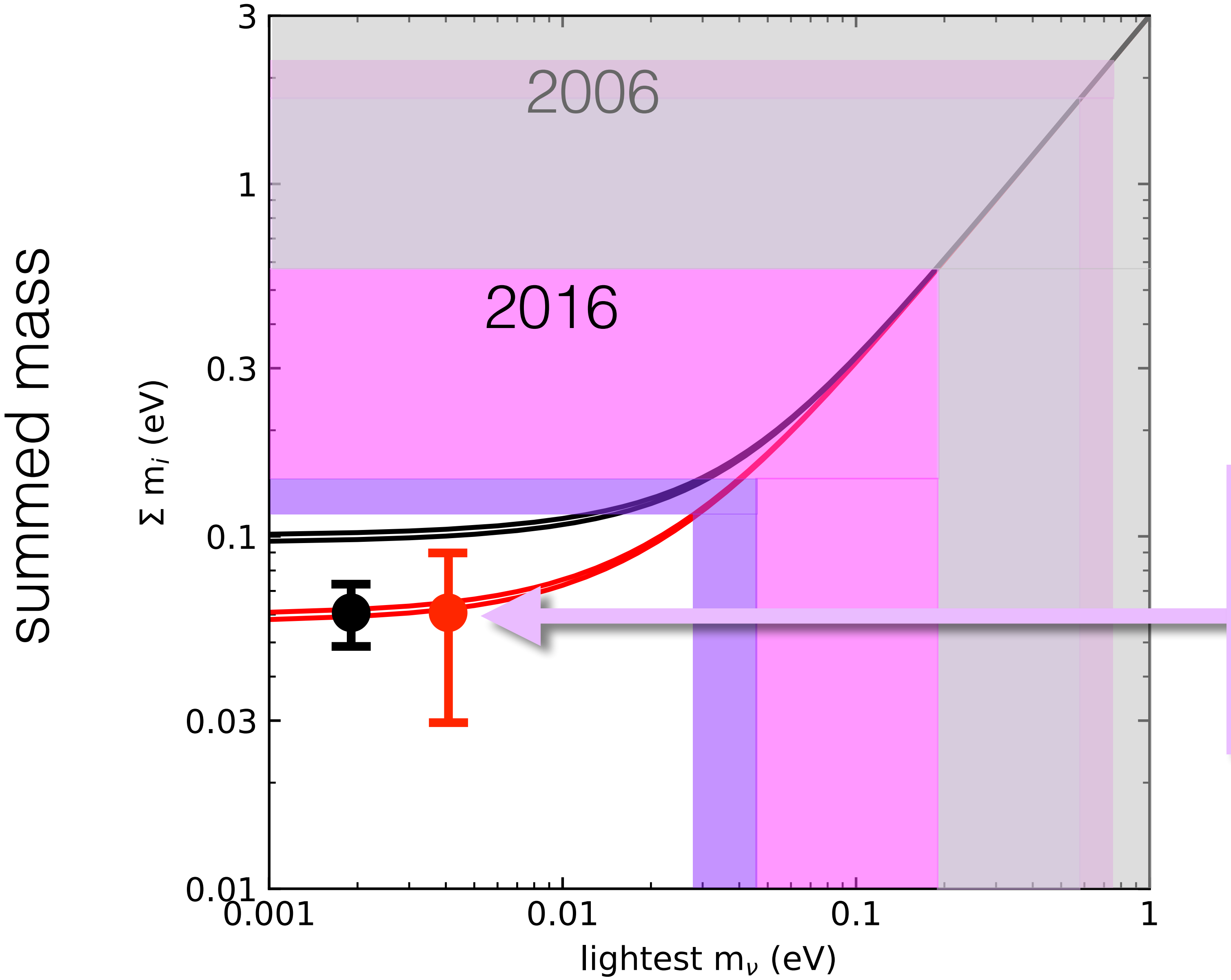
- with galaxies: $\Sigma_i m_i$ < 130 meV (95%CL)
- with Lyman-α: $\Sigma_i m_i$ < 120 meV (95%CL)
- with BAOs: $\Sigma_i m_i$ < 118 meV (95%CL)

Cuesta et al. 1511.05983; Palanque-Delabrouille et al. 1506.05976; Vagnozzy et al. 1701.08172

NH already favoured by cosmo. + labo. bounds (Simpson et al. 1703.03425; Capozzi et al. 1703.04471)

Summed mass of active neutrinos

95%CL upper bounds / 1σ forecast errors on $\Sigma_i m_i$



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

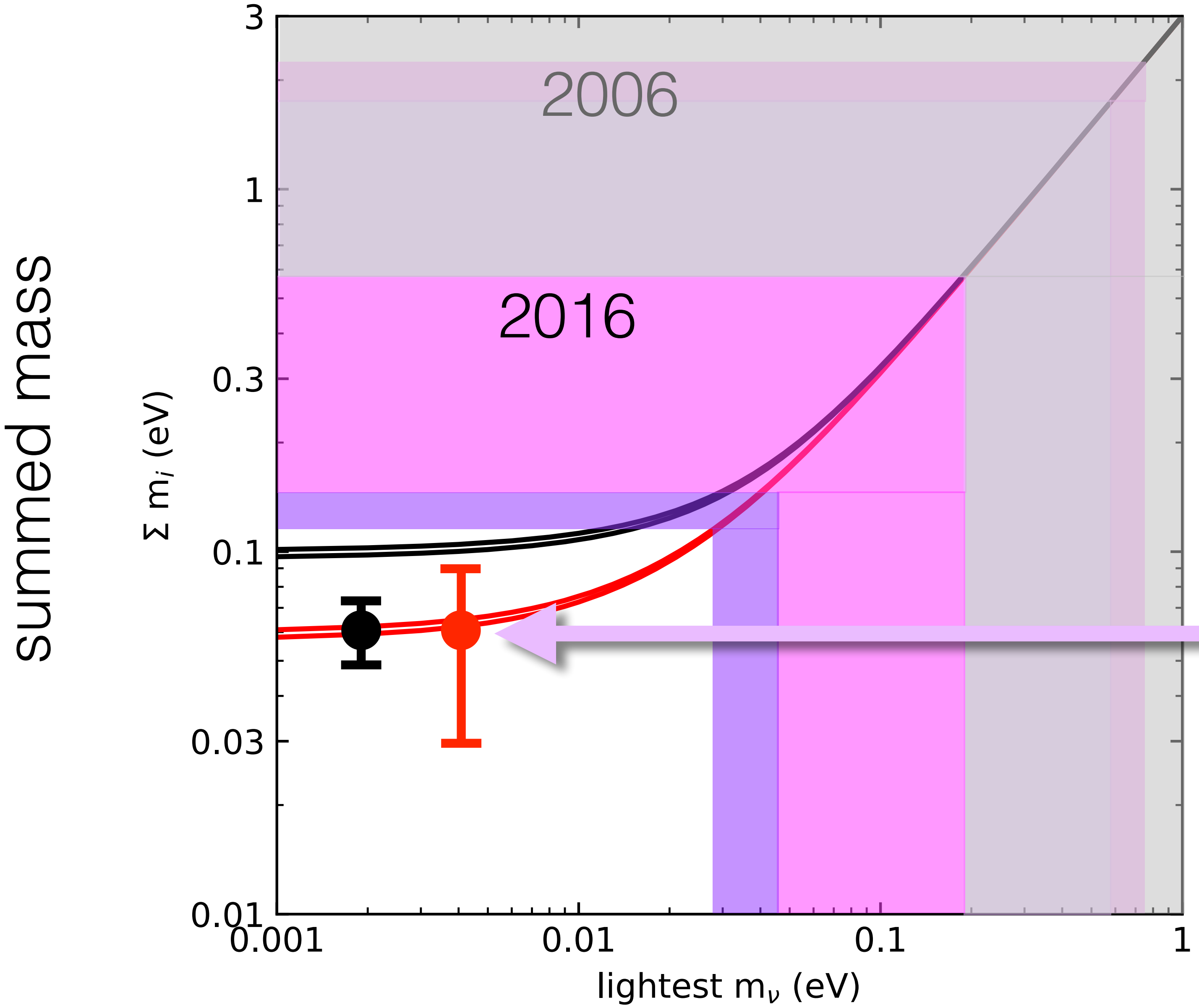
σ ~ { **40 -> 12 meV (7 params + …)**
60 -> 30 meV (complicated DE)
60 -> 40 meV (complicated MG)

e.g. Font-Ribera et al. 1308.4164

… with conservative use of SKA; 21cm?

Summed mass of active neutrinos

95%CL upper bounds / 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 2:2023-2030	Ground

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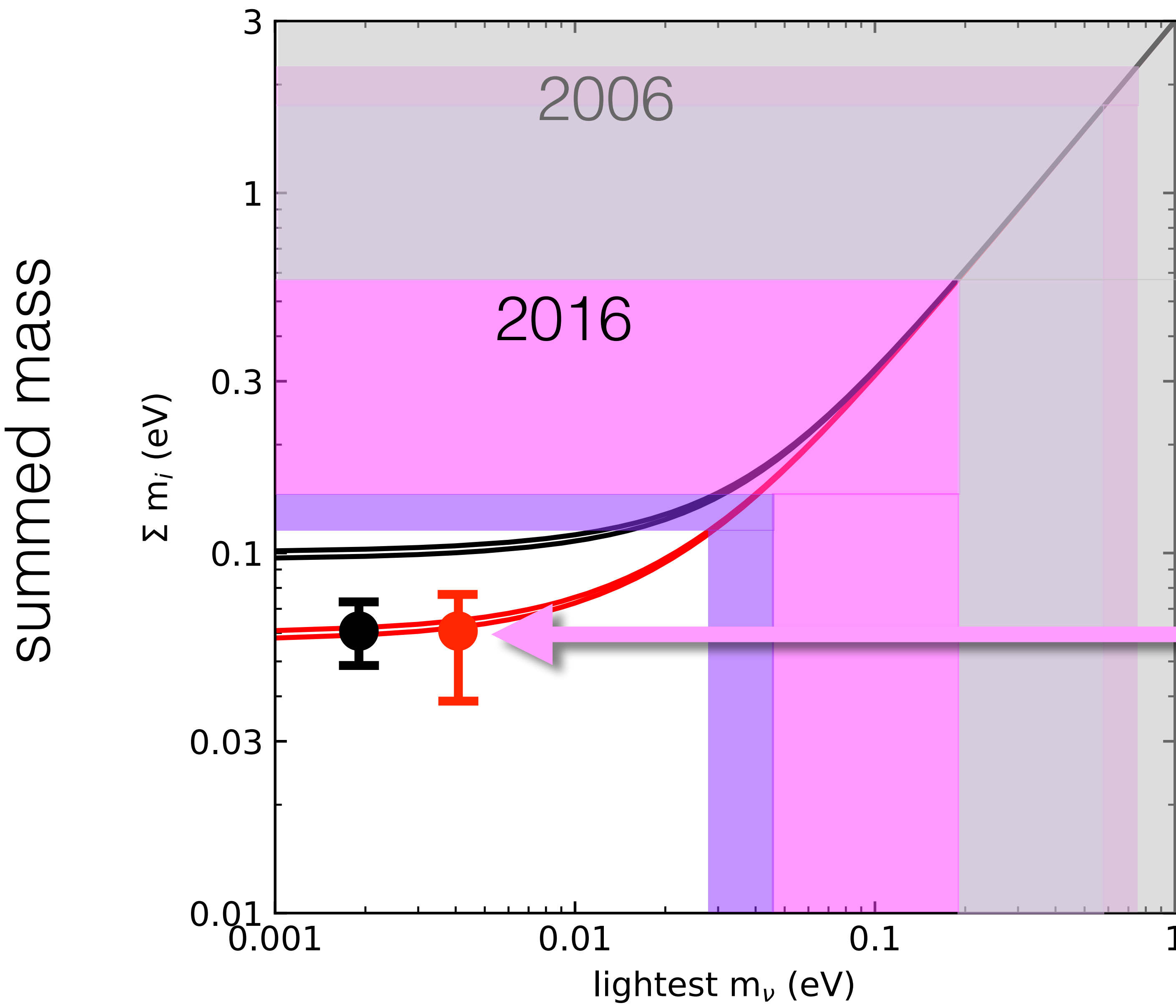

CMB-Stage III, IV : no better numbers but gain in robustness (e.g. σ ~ 15meV from S-IV+DESI only) Need large angles…

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

σ ~ {
- **40 -> 10 meV (7 params + …)**
- 60 -> 20 meV (complicated DE)
- …. (complicated MG)

e.g. Brinckmann et al. 1612.00021

… with conservative use of SKA; 21cm?

Neutrino masses

Conclusions:

- 5σ detection of M_ν possible even if M_ν = 60 meV, M_ν = safest discovery opportunity for cosmologists
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- No direct significant test of NH versus IH like PINGU, ORCA, JUNO; but if measured mass is close to 60 meV, IH could be excluded at 2σ (Planck+Euclid, ~2022) and later up to 4 to 5σ… (see e.g. Hannestad and Schwetz 2016; Simpson et al. 2017)

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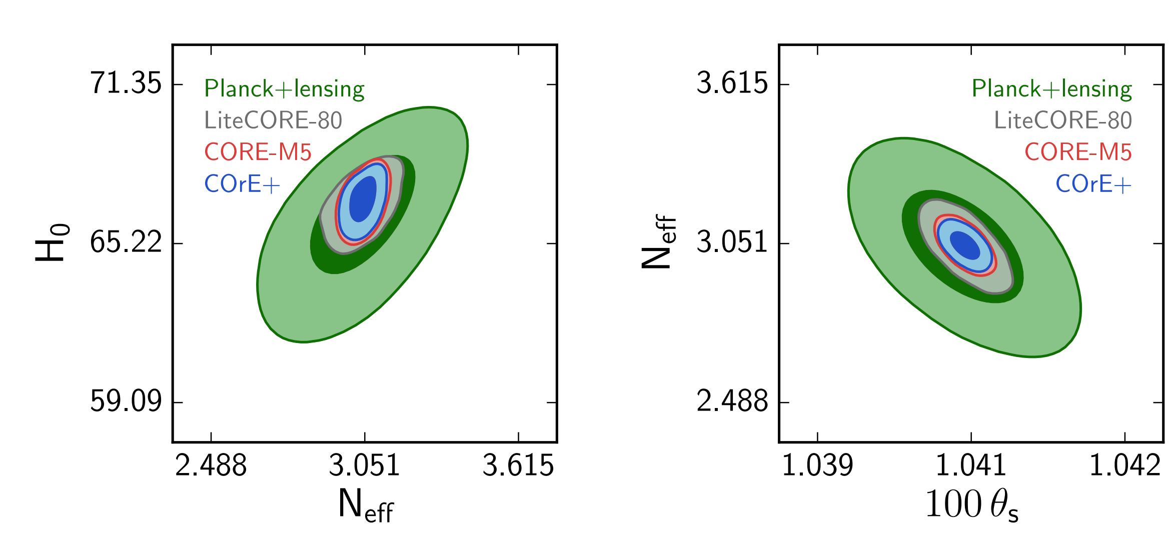
- Non-detection would require major change of paradigm on the late time behaviour of the cosmological model (new physics to describe structure formation: MG, non-standard particle interactions) or on neutrino physics (cosmological neutrinos decay, mass from coupling with varying scalar, etc.)

Extra relics (massless case)

Current an future bounds on density of relativistic relics beyond photons (standard model: $N_{eff} = 3.046$)

CORE / S-IV would resolve degeneracy with H_0 (redshift of equality) and is limited by determination of peak scale angle (neutrino drag effect)

Planck 2015 (TT,TE,EE + lowP + lensing)	CORE alone CORE collaboration [1612.00021]
$N_{eff} = 3.04 \pm 0.18$ (68%CL)	$\sigma(N_{eff}) = 0.041$



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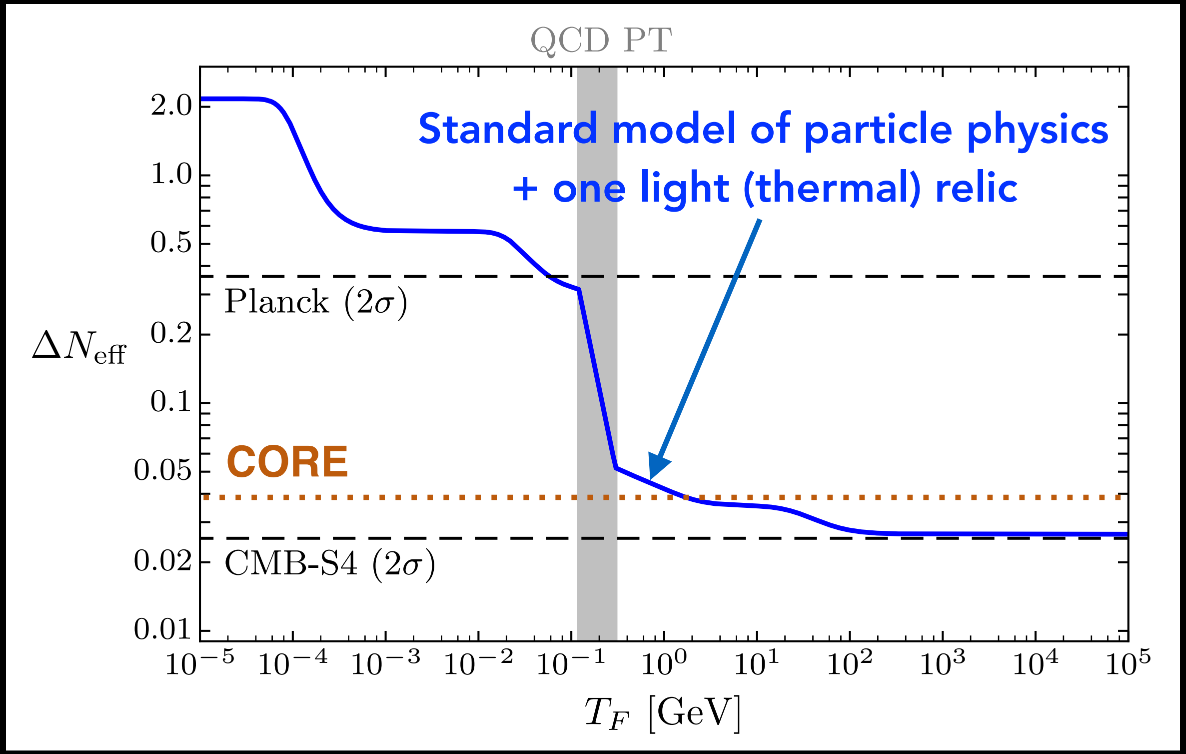
Test of non-thermal or early decoupled thermal relics (Axion-Like Particles, …), low-temperature reheating models, **neutrino non-standard interactions, light sterile neutrinos**

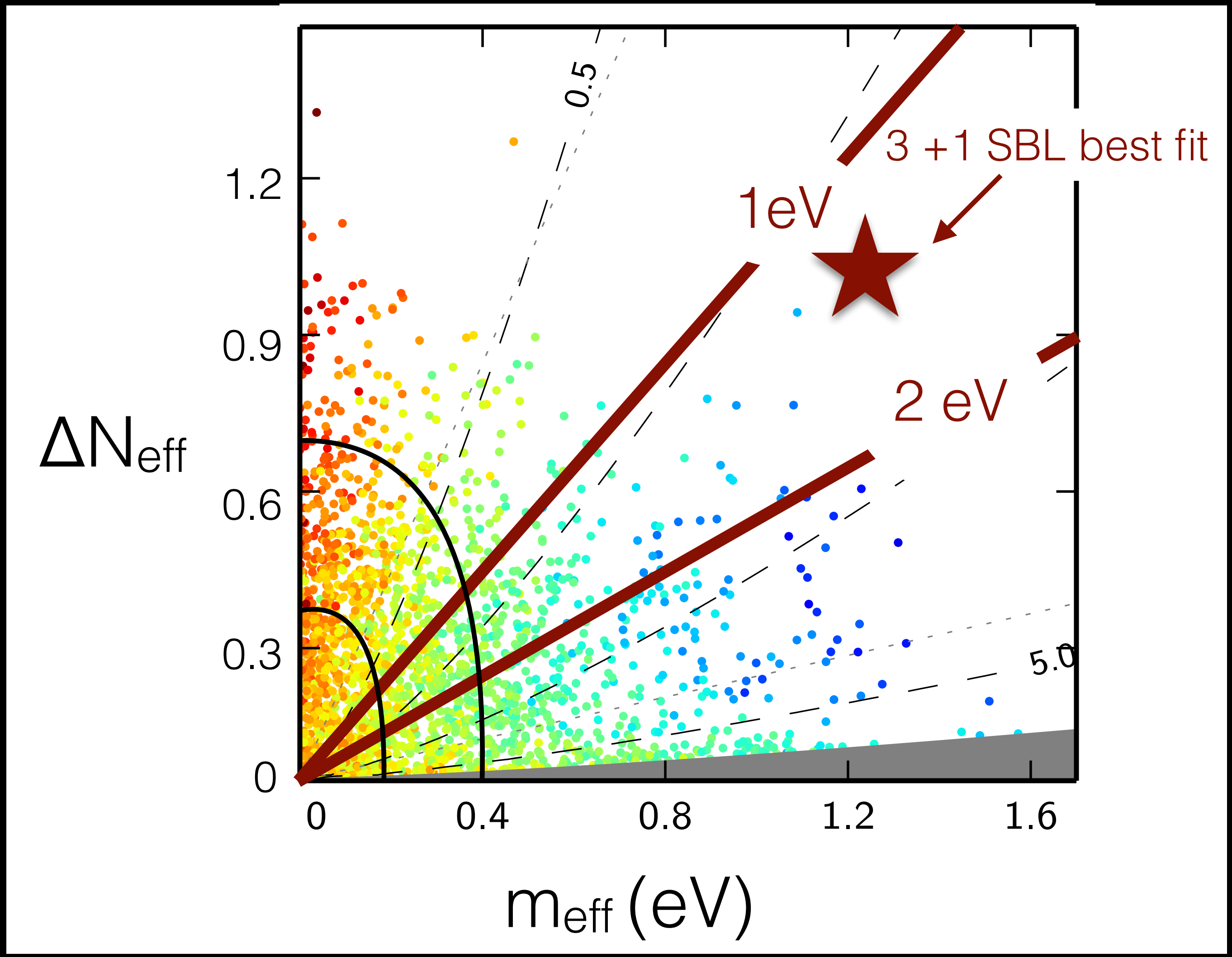


Bauman et al. 1604.08614

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
ΔN_{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 $m = m_{eff}/\Delta N_{eff}$

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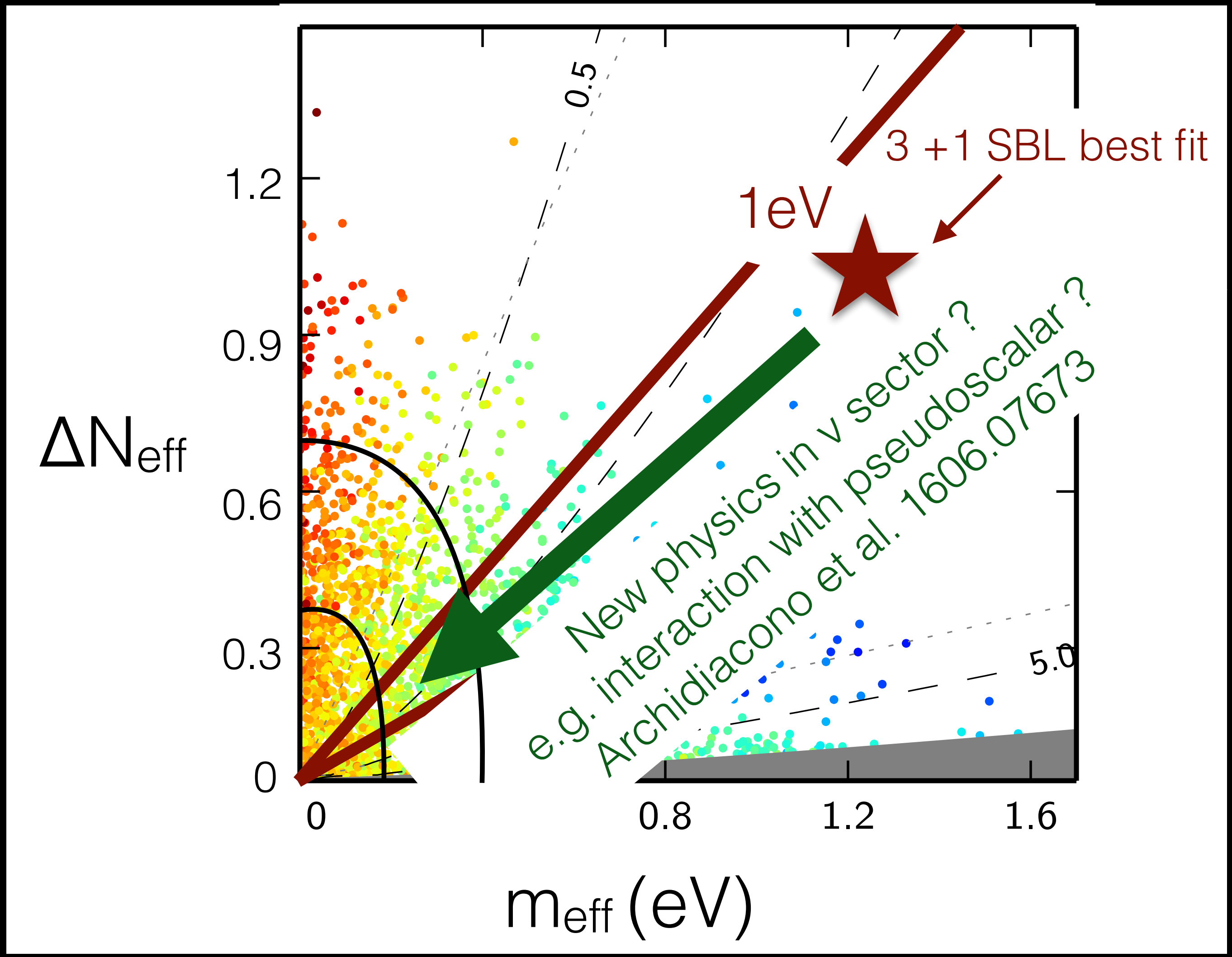

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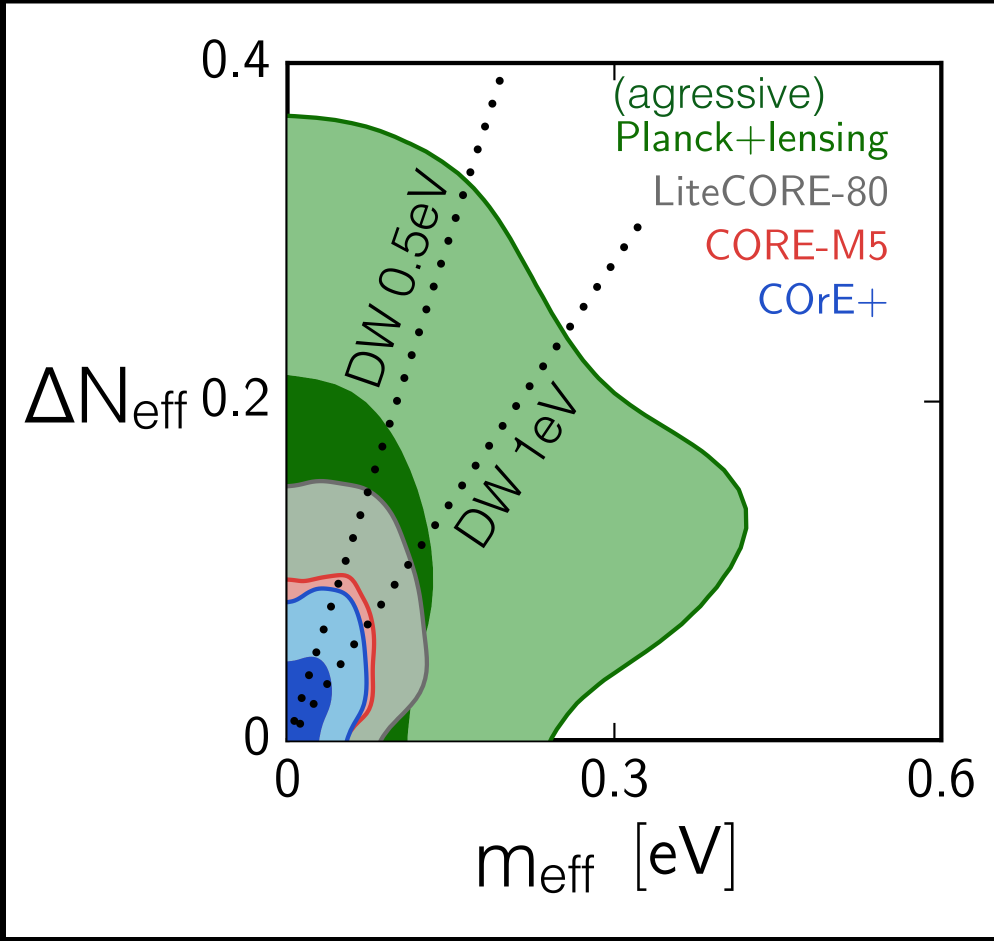
ΔN_{eff} (extra contribution to density *before* NR transition)	<0.7 (95%CL)	2σ ~ 0.10
m_{eff} (extra contribution to density *after* NR transition)	< 400 meV (95%CL)	2σ ~ 66 meV

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

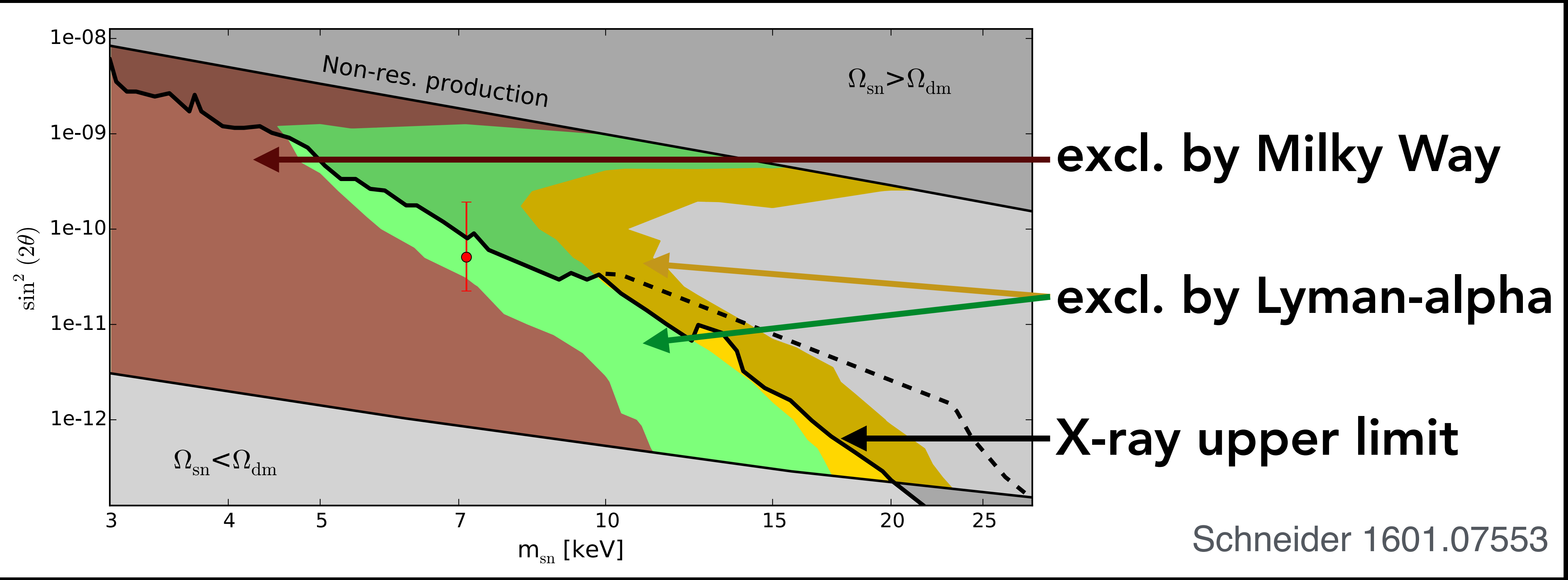


CORE et al. 1612.00021

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

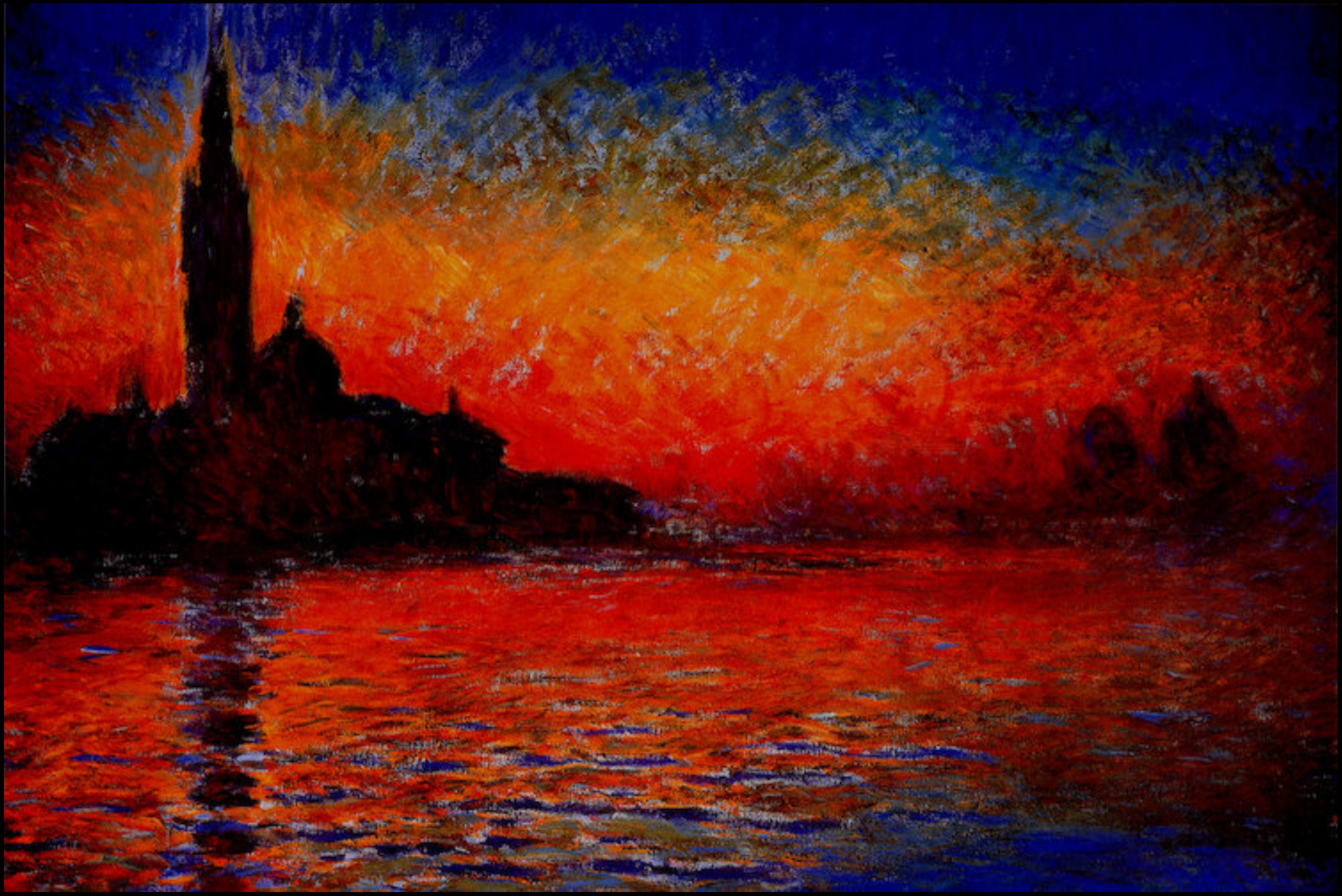
KeV sterile neutrino

- 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)



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

END



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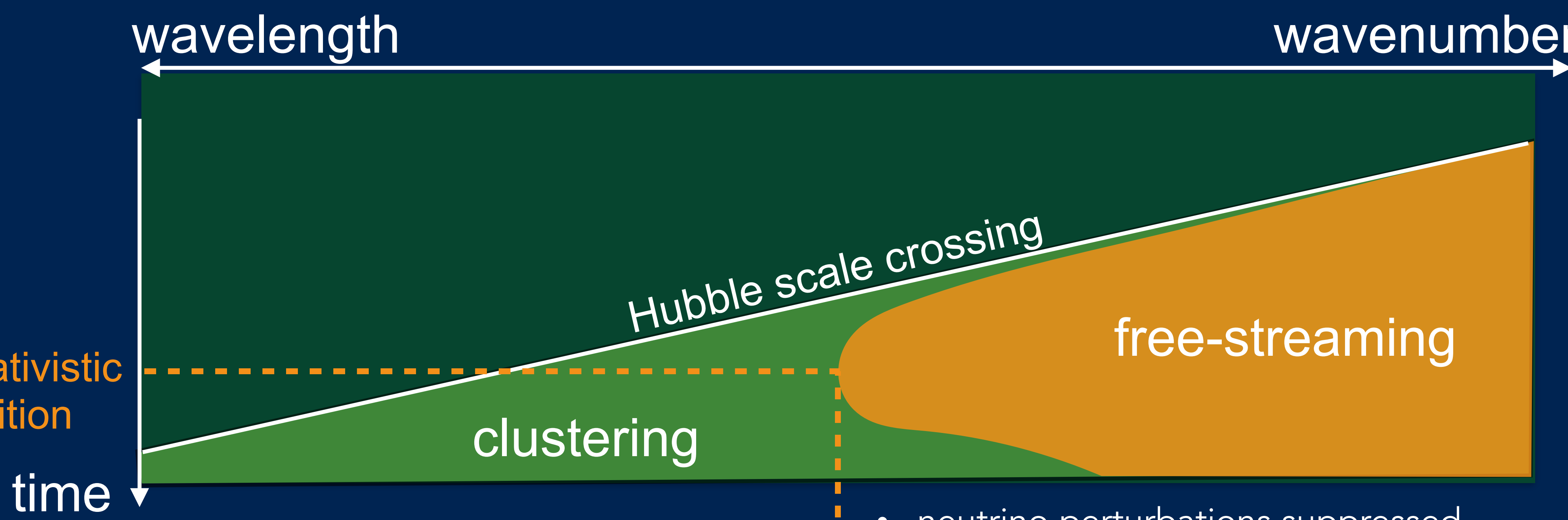

- neutrino perturbations suppressed
- cdm perturbations too (different balance gravity/expansion)
- evolution of metric perturbation modified

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

neutrino slow down early dark matter clustering

neutrino propagation and dispersion velocity

neutrino slow down late ordinary/dark matter clustering