# CAN WE DETECT THE COSMIC NEUTRINO BACKGROUND?

$^3$He

$\nu$

$^3$H

$e^{\pm}$

Related to 2111.12726 (JCAP) and 2111.14870 (PRD)
**Collaborators:** Nash Sabti, Miguel Escudero, Thomas Schwetz

**James Alvey**
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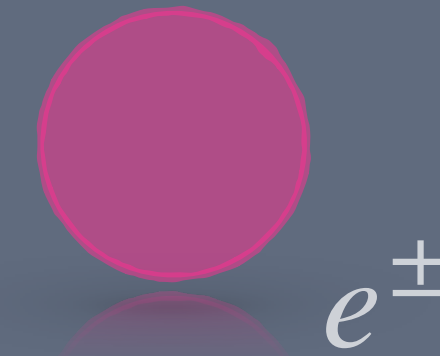j.b.g.alvey@uva.nl

# MOTIVATION: WHY IS THE CνB INTERESTING?

$e^{\pm}$

**Test of Standard Model:** Relic neutrino production in the early Universe is a clear prediction of the standard cosmological model

$^{3}\mathrm{He}$

$\nu$

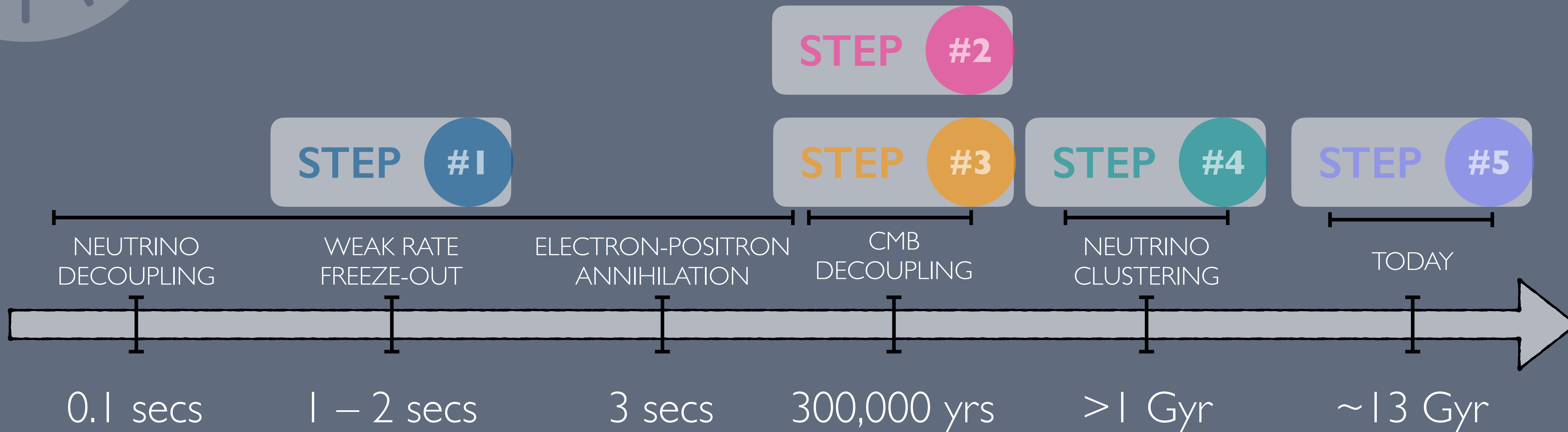**Conditions in Early Universe:** Specific features highly sensitive to physics around the time of neutrino decoupling ($t \sim 1\,\mathrm{s}$)

$^{3}\mathrm{H}$

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# OUTLINE: STEPS TOWARDS A CνB DETECTION

**STEP** **#1** THE ROLE OF BBN

**STEP** **#2** PHYSICS OF THE CMB

**STEP** **#3** MEASURING NEUTRINO PROPERTIES IN COSMOLOGY

**STEP** **#4** NEUTRINO CLUSTERING

**STEP** **#5** DETECTION (AT PTOLEMY)

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# NEUTRINOS IN BBN

| | NEUTRINO DECOUPLING | WEAK RATE FREEZE-OUT | ELECTRON-POSITRON ANNIHILATION | PROTON TO NEUTRON FREEZE-OUT | DEUTERIUM BOTTLENECK OVERCOME | END OF NUCLEOSYNTHESIS |
|---|---|---|---|---|---|---|
| $T$ | 2 MeV $2 \times 10^{10}$ K | $0.7 - 0.8$ MeV $8 - 9 \times 10^9$ K | 0.5 MeV $6 \times 10^9$ K | 0.28 MeV $3 \times 10^9$ K | 0.078 MeV $9 \times 10^8$ K | 0.066 MeV $8 \times 10^8$ K |
| $t$ | 0.1 secs | $1 - 2$ secs | 3 secs | 10 secs | 200 secs | 300 secs |

$\nu$

$\nu$

$e^{\pm}$

$e^{\pm}$

$$\Gamma_{\nu\nu \to ee} \sim G_{\mathrm{F}}^2 T^5 \sim H$$

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# NEUTRINOS IN BBN



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$e^{\pm}$

$e^{\pm}$

$\gamma$

$\gamma$

Equilibrium
far to right

**Result:** $T_\nu < T_\gamma$ and $N_{\text{eff}} \simeq 3$

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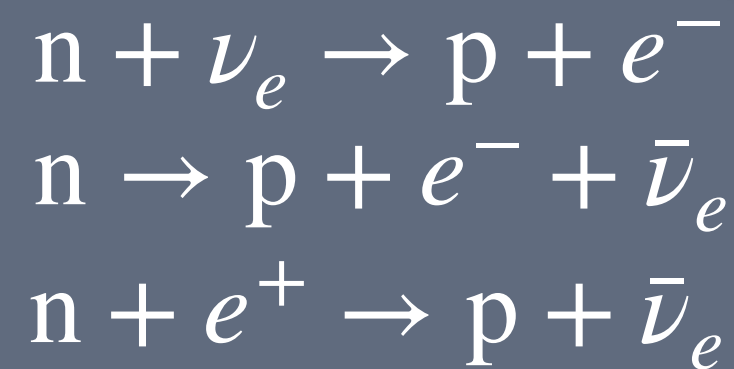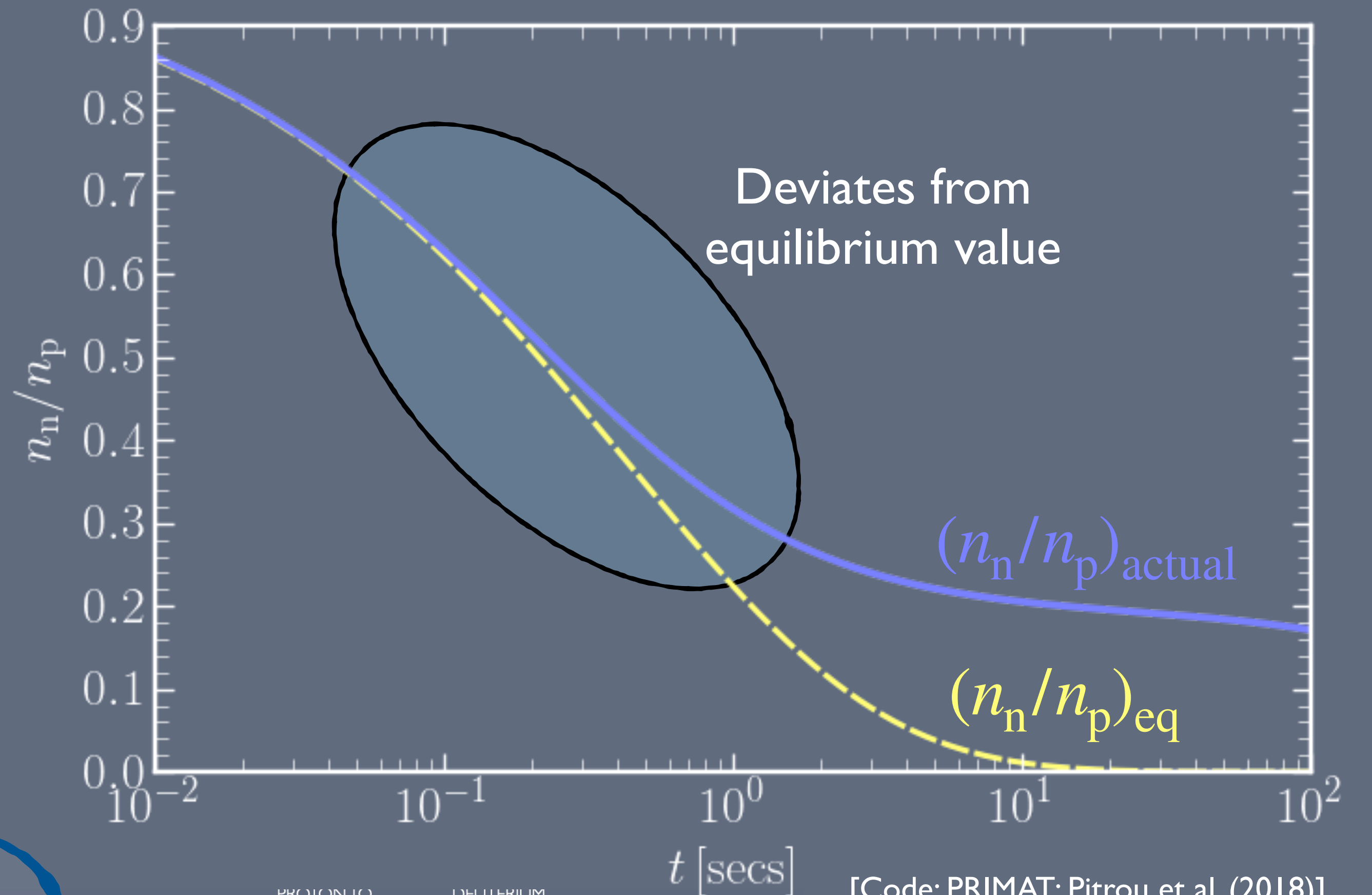j.b.g.alvey@uva.nl

BBN

$T \simeq 0.8\,\mathrm{MeV}$
$t \sim 1\,\mathrm{sec}$

# PROTONS AND NEUTRONS:
## WEAK FREEZE-OUT

Kept in **equilibrium**
by the reactions

n

$n + \nu_e \to p + e^-$
$n \to p + e^- + \bar{\nu}_e$
$n + e^+ \to p + \bar{\nu}_e$

p

…until around 0.8 MeV

Deviates from
equilibrium value

$(n_\mathrm{n}/n_\mathrm{p})_\mathrm{actual}$

$(n_\mathrm{n}/n_\mathrm{p})_\mathrm{eq}$
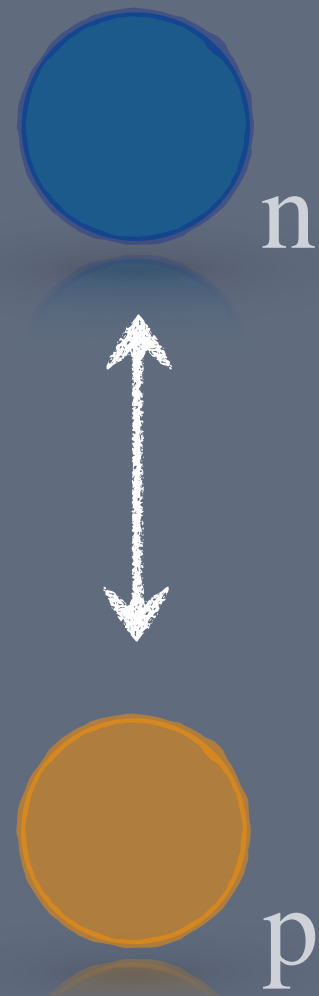
[Code: PRIMAT; Pitrou et al. (2018)]
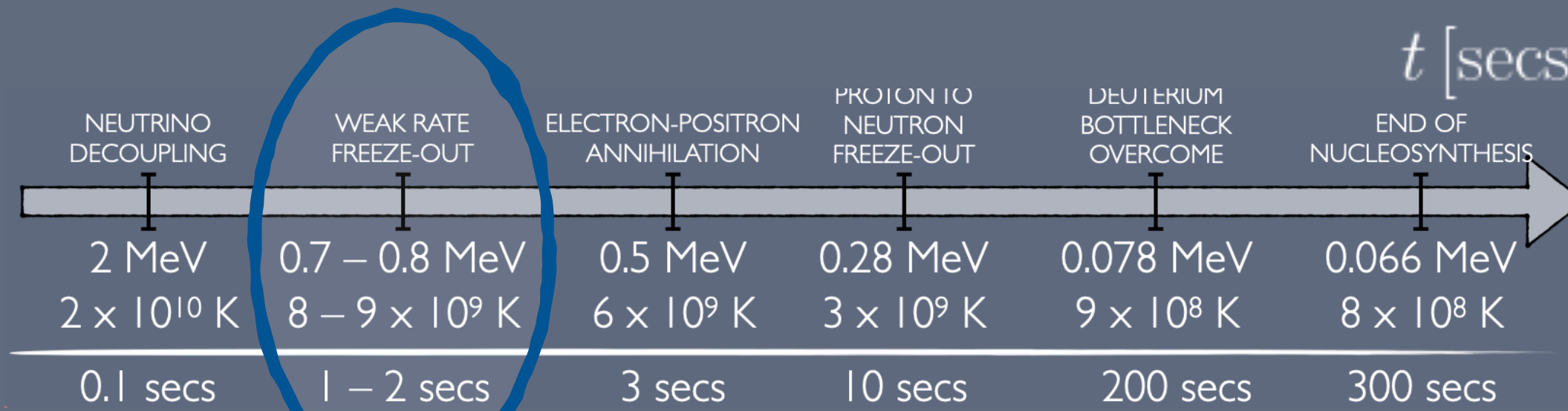
| | NEUTRINO DECOUPLING | WEAK RATE FREEZE-OUT | ELECTRON-POSITRON ANNIHILATION | PROTON TO NEUTRON FREEZE-OUT | DEUTERIUM BOTTLENECK OVERCOME | END OF NUCLEOSYNTHESIS |
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BBN

STEP #1 THE ROLE OF BBN

STEP #2 PHYSICS OF THE CMB

STEP #3 MEASURING NEUTRINO PROPERTIES IN COSMOLOGY

STEP #4 NEUTRINO CLUSTERING

STEP #5 DETECTION (AT PTOLEMY)

**Question:** How do neutrinos affect the CMB?

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CMB PHYSICS

# NEUTRINOS AND THE CMB

**Hubble Rate:** In the SM, neutrinos are fully decoupled species as far as the CMB is concerned, so their impact is **purely gravitational**

$$H(z) = \sqrt{\frac{8\pi G}{3} \left( \rho_\nu(z) + \cdots \right)^{1/2}}$$

Photons, baryons, dark matter etc.
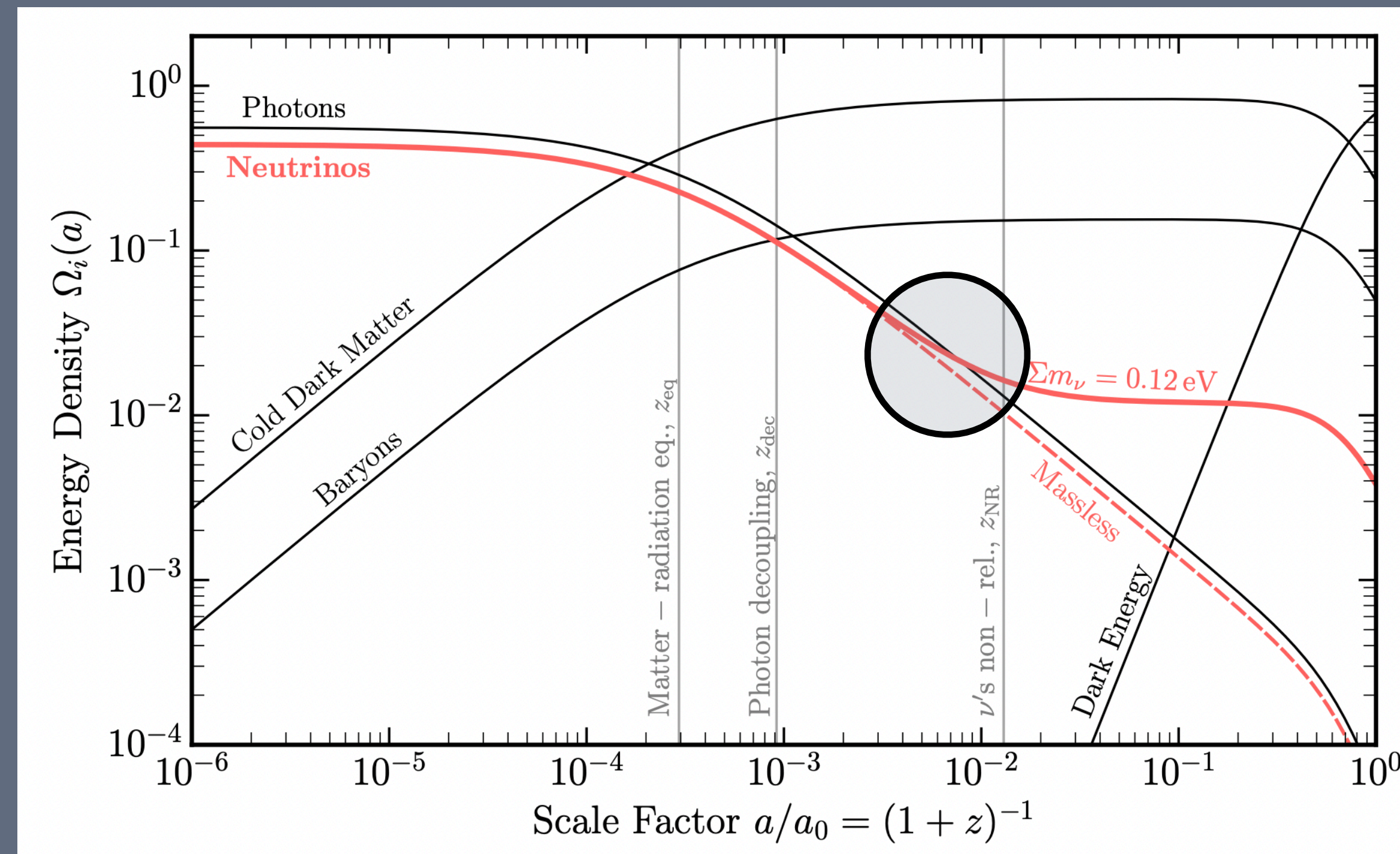
**Question:** What does $\rho_\nu(z)$ look like?

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# NEUTRINO EQ. OF STATE

## Early Universe

$$\rho_\nu(z) \sim \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\ \rho_\gamma(z)$$

- Relativistic species
- Contributes as radiation
- Lower temperature than photons



## Late Universe

$$\rho_\nu(z) \sim m_\nu n_{\nu,0}(1+z)^3$$

- Non-relativistic species
- Contributes as matter
- Characterised by the product $\rho_{\nu,0} \equiv m_\nu n_{\nu,0}$

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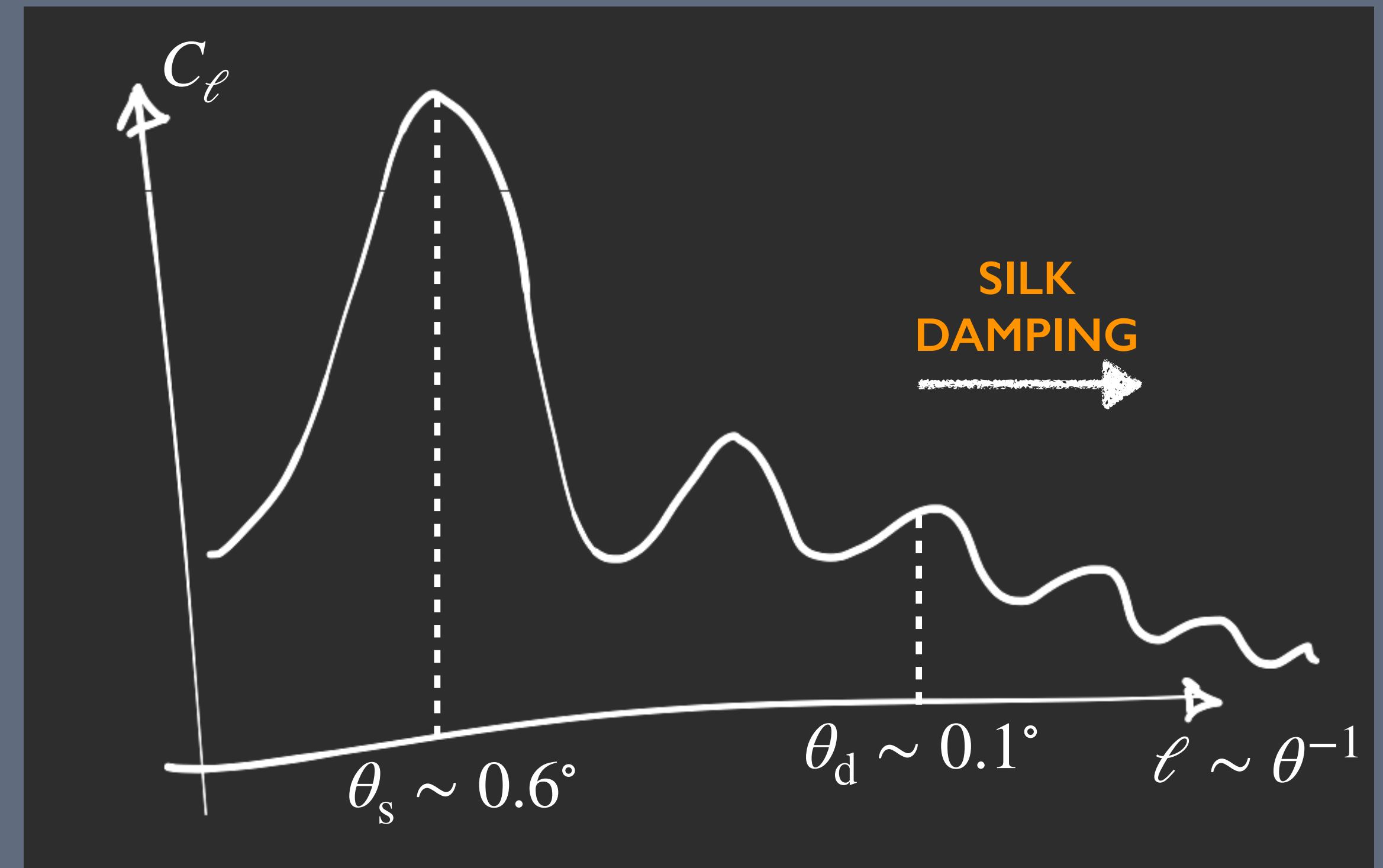j.b.g.alvey@uva.nl

CMB PHYSICS

# KEY SCALES IN THE CMB

**CMB Measurements:** Simply put, CMB data is a collection of measurements (of perturbations) made at different angular scales

**Two key scales:** For neutrino physics, there are two key scales:

A) The <u>sound horizon</u> $\theta_s = r_s/D_A$

B) The <u>damping scale</u> $\theta_d = r_d/D_A$



$$C_\ell$$

SILK DAMPING

$$\theta_s \sim 0.6°$$

$$\theta_d \sim 0.1°$$

$$\ell \sim \theta^{-1}$$

$$N_{\mathrm{eff}}$$

$$r_d \sim \left( \frac{1}{H(z \sim 1100)} \right)^{1/2} \qquad r_s \sim \frac{1}{H(z > 1100)}$$

$$\rho_{\nu,0}^{\mathrm{NR}}$$

$$D_A \sim \frac{1}{H(z < 1100)}$$

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# CASE STUDY: MEASURING $N_{\rm eff}$

Directly sensitive to $N_{\rm eff}$

$$r_{\rm d} \sim \left( \frac{1}{H(z \sim 1100)} \right)^{1/2} \qquad r_{\rm s} \sim \frac{1}{H(z > 1100)}$$

Directly sensitive to $\rho_\nu^{\rm NR}$

$$D_{\rm A} \sim \frac{1}{H(z < 1100)}$$
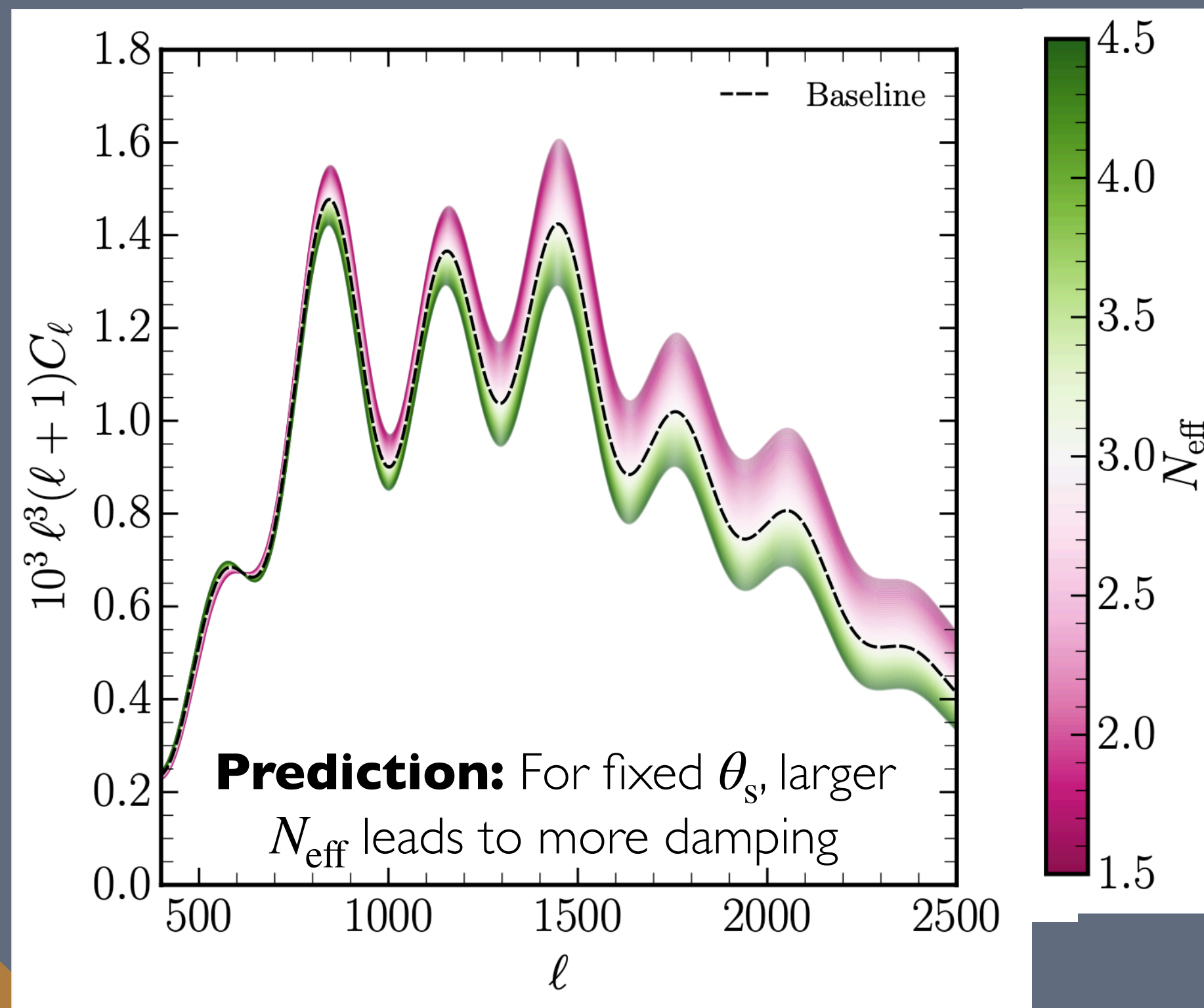
ACTS AS A PROJECTION EFFECT

**Combining scales:** To overcome the projection effect, need to *combine* measurements at different angular scales, here we can measure:

$$\theta_{\rm s}/\theta_{\rm d} \sim \; H(z \geq 1100)^{-1/2} \sim N_{\rm eff}^{-1/4}$$



**Prediction:** For fixed $\theta_{\rm s}$, larger $N_{\rm eff}$ leads to more damping

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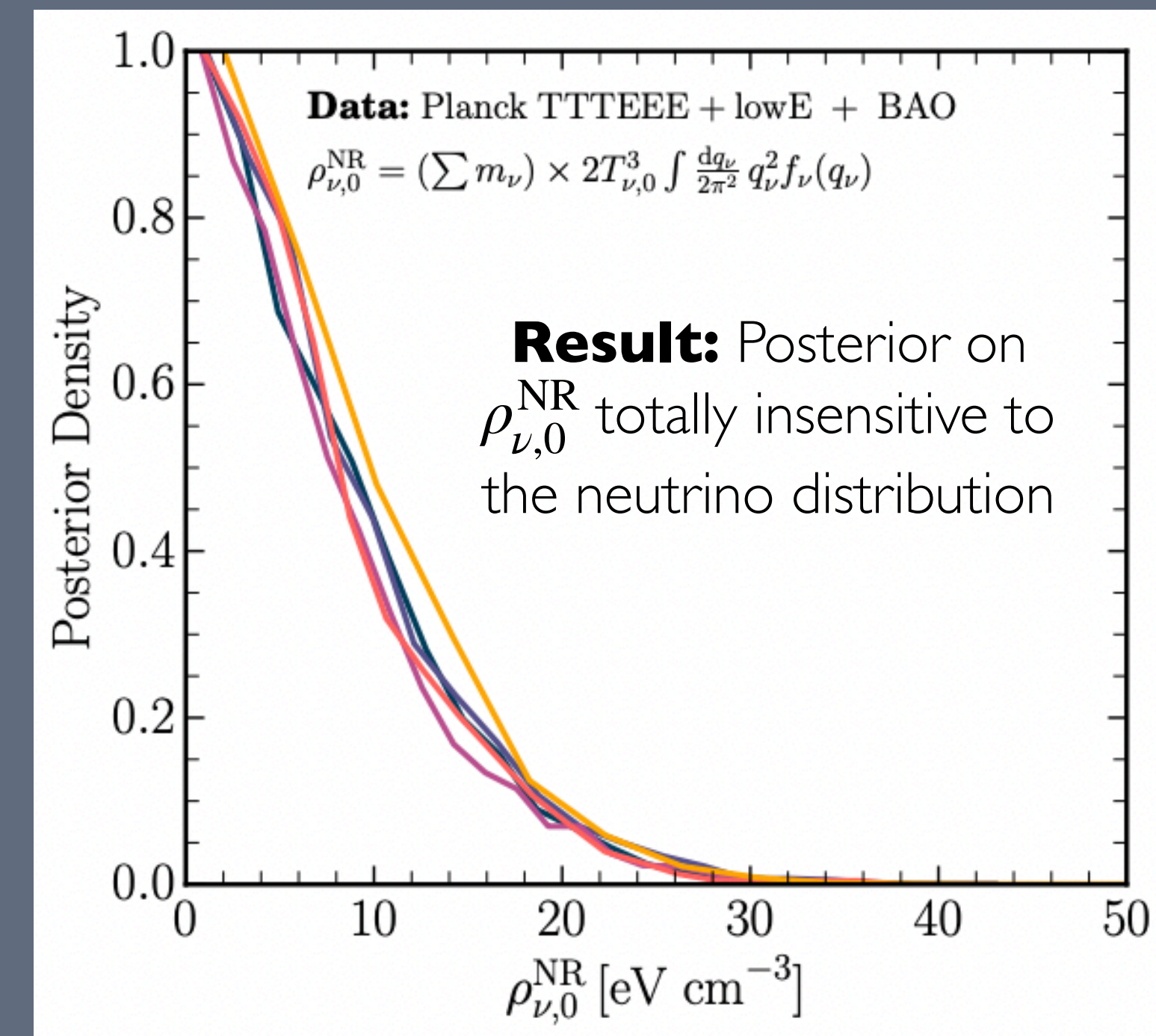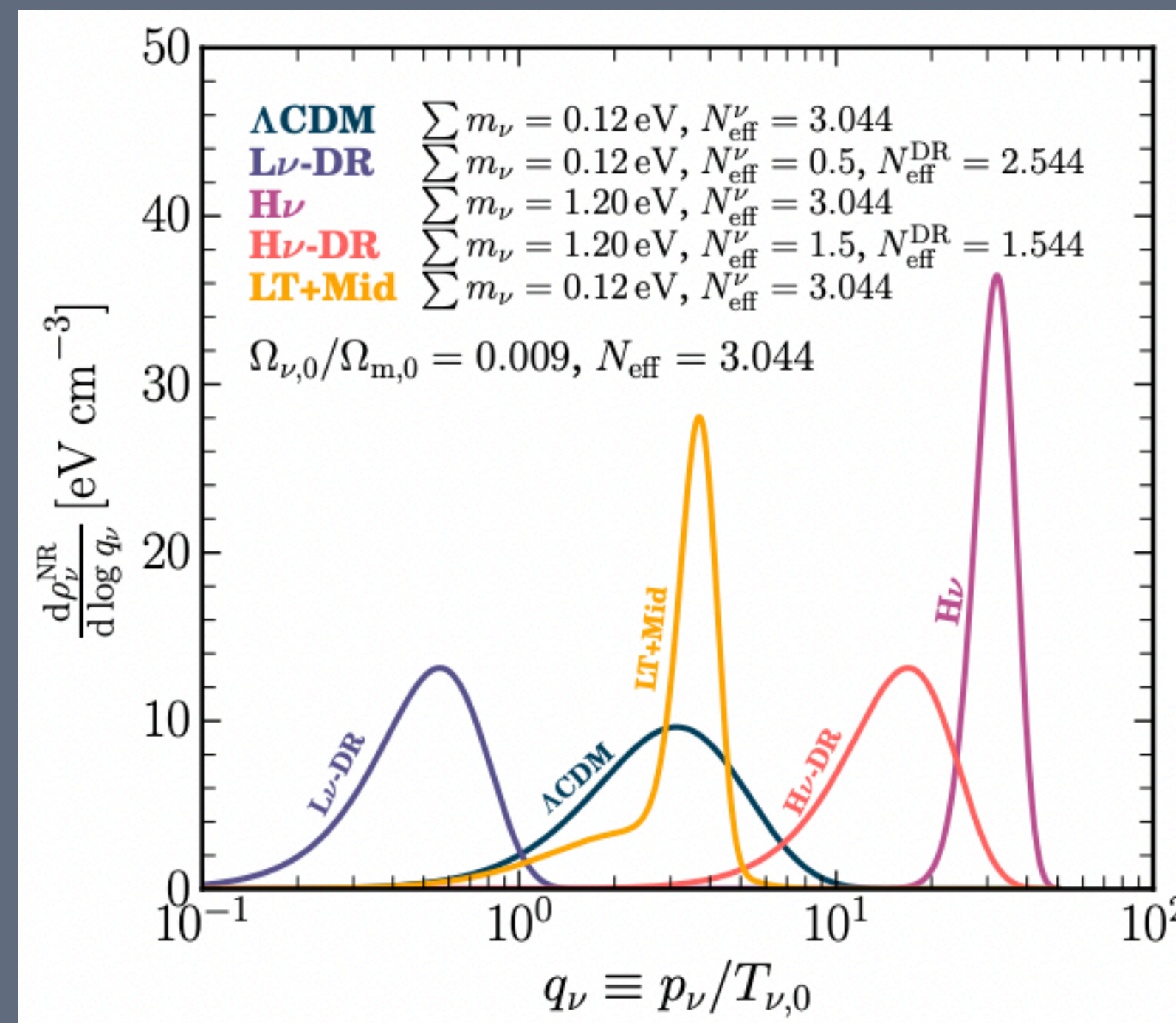j.b.g.alvey@uva.nl

CMB LIMITS

# DIRECT MEASUREMENTS OF $\rho_{\nu,0}^{\mathrm{NR}}$?

**Key Idea:** We want to test the claim that you can only directly measure the combination $\rho_{\nu,0}^{\mathrm{NR}} = m_\nu n_{\nu,0}$ from the CMB

## Method

- Modify the neutrino distribution function - equivalent to varying the number density
- Tune the mass so that there is the same non-relativistic energy density
- Tune additional contributions to $N_{\mathrm{eff}}$ to maintain $N_{\mathrm{eff}} \sim 3$



**Result:** Posterior on $\rho_{\nu,0}^{\mathrm{NR}}$ totally insensitive to the neutrino distribution

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**Answer:** In the most model-independent sense, we can only measure the relativistic ($N_{\mathrm{eff}}$) and non-relativistic ($\rho_\nu^{\mathrm{NR}}$) energy densities

$$N_{\mathrm{eff}} \simeq 3.0 \pm 0.4, \quad \rho_{\nu,0}^{\mathrm{NR}} < 14\,\mathrm{eV\,cm^{-3}}$$

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CMB LIMITS

**Question:** What happens to neutrinos in and around galactic halos?

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IV CLUSTERING

# TRAPPING NEUTRINOS IN HALOS

Relic neutrino

$\nu$

$v_\nu(z)$

(set by cosmology)
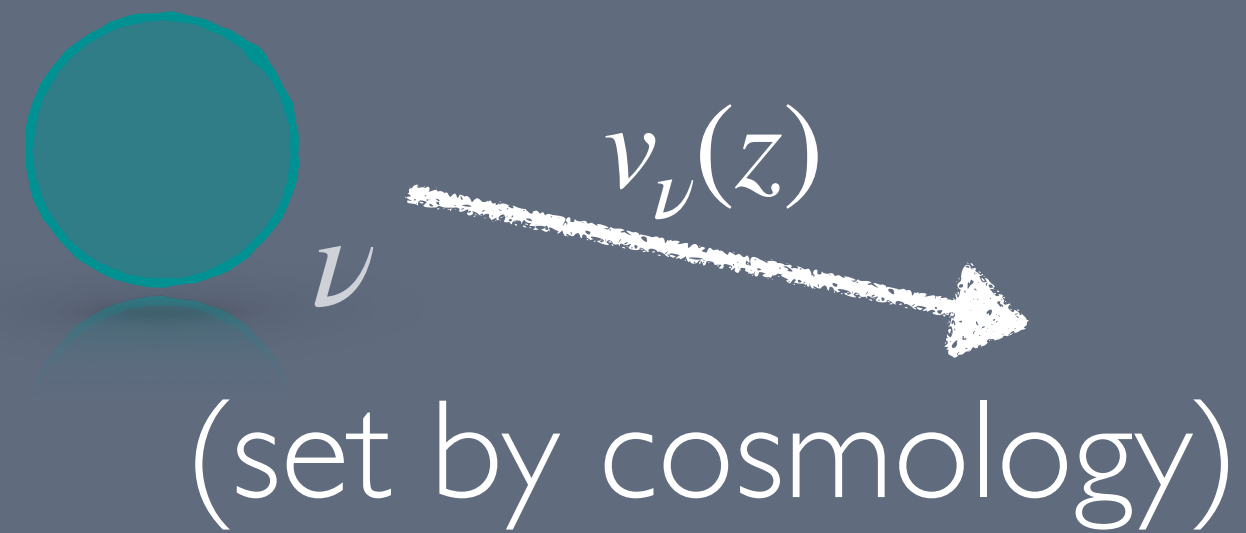
Escape Velocity $v_{\mathrm{esc}}$

**Neutrino Clustering:**
Neutrinos can cluster onto the Milky Way halo if their average velocity is less than the escape velocity of the halo $v_{\mathrm{esc}} > v_\nu(z)$

**Result:** Potentially generates a local overdensity of neutrinos compared to the cosmological relic density $n_\nu^{\mathrm{loc.}} = n_{\nu,0}(1+\delta)$

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IV    CLUSTERING

**Answer:** If the average neutrino velocity is smaller than the escape velocity of the halo, they can be gravitationally captured, boosting their number density

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IV   CLUSTERING

**Question:** How do we detect relic neutrinos and what is the current outlook?

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# PTOLEMY DETECTION STRATEGY

**Inverse $\beta$ Capture:** The current PTOLEMY proposal aims to detect relic neutrinos using inverse $\beta$ capture onto unstable nuclei, such as tritium

## Desirable Characteristics

- Unstable, but long-lived nuclei
- High-resolution detector capabilities for electron energy
- Large capture cross section
- Stable daughter nucleus
- Reliable chemical properties
- Precise nuclear calculations

$\nu$

$^3\mathrm{He}$

$^3\mathrm{H}$

$e^{\pm}$
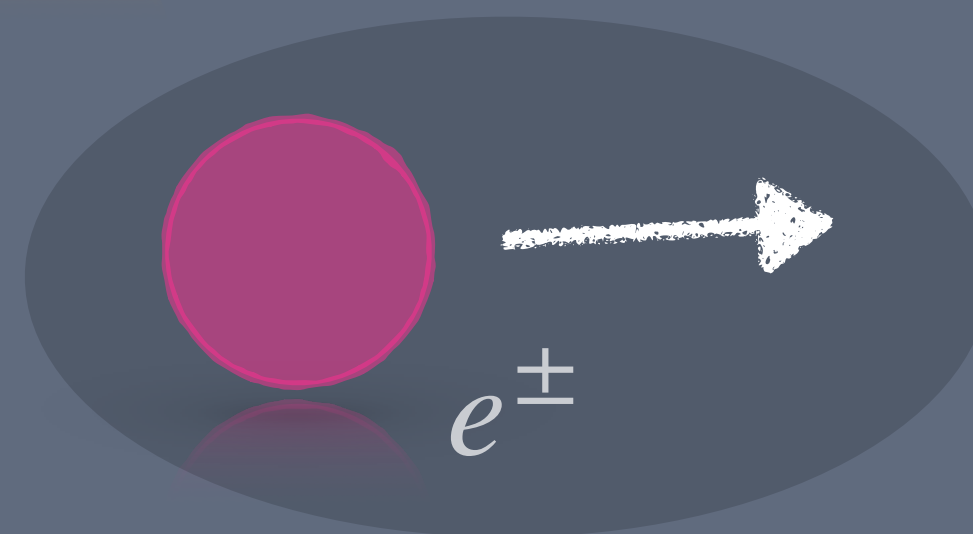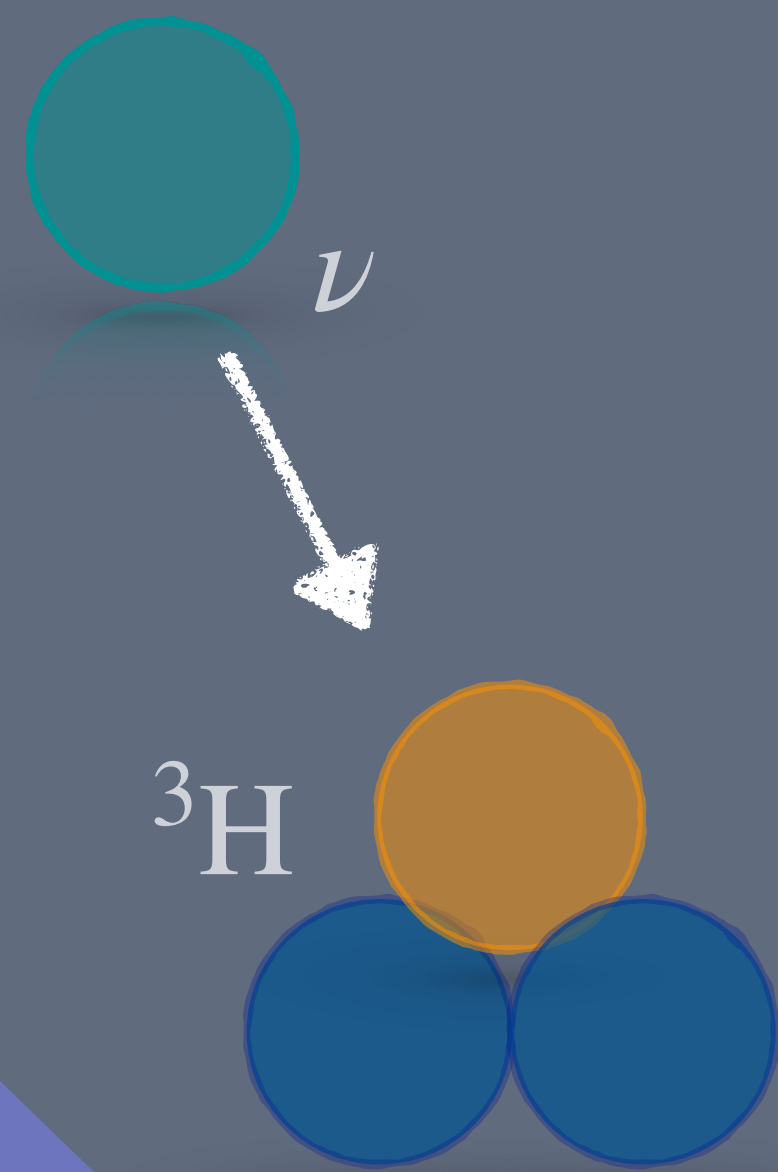
Monochromatic
$$E_e = E_{\mathrm{end},0} + m_\nu$$

Aim to detect this electron

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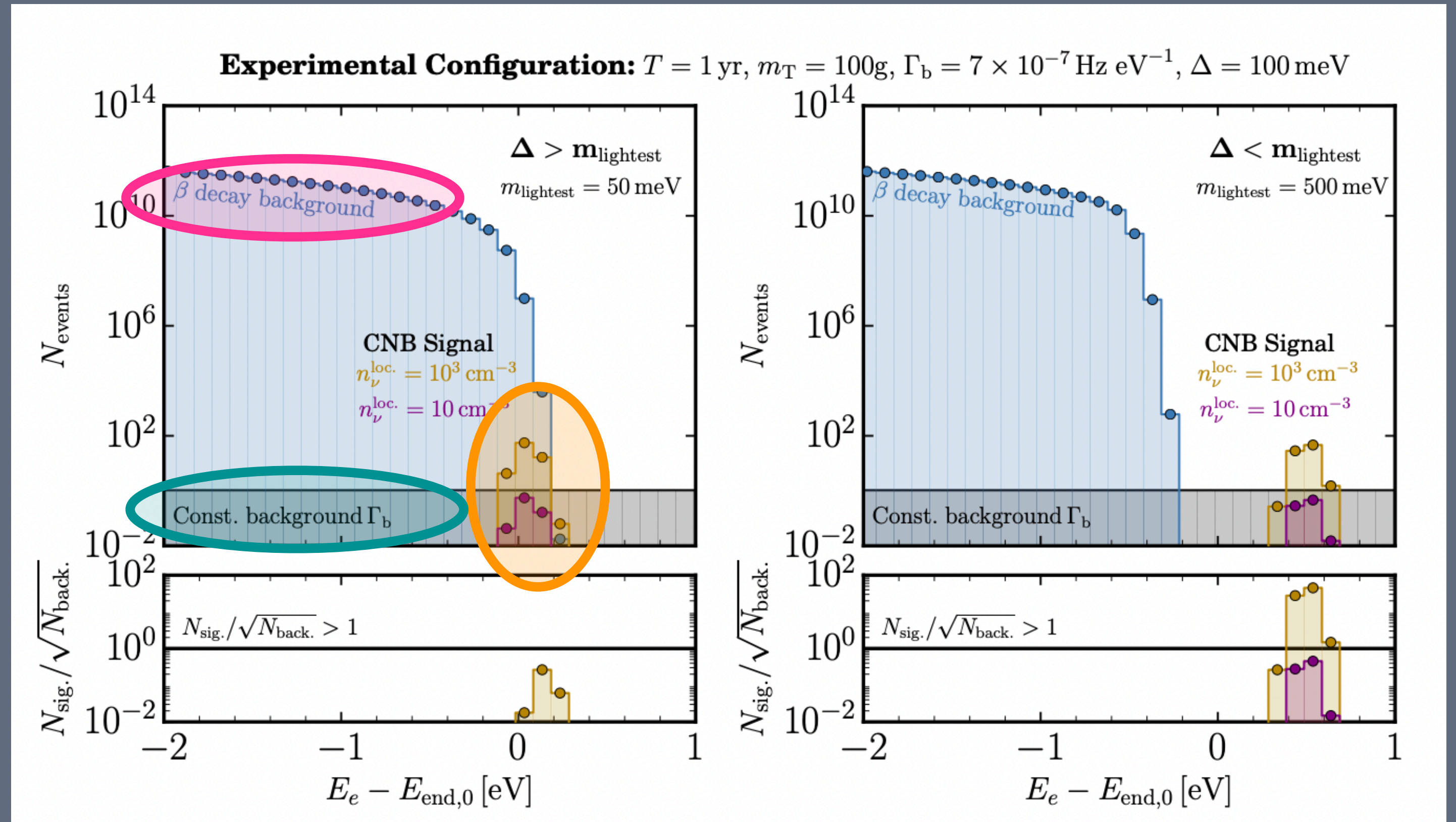$\nu$ DETECTION

# TYPES OF EVENTS AT PTOLEMY

- **Signal Events:** Genuine CNB capture events, $\Gamma_{\mathrm{CNB}} \propto n_\nu^{\mathrm{loc.}} N_T \langle \sigma_{\mathrm{cap.}} v_\nu \rangle$
- **Beta Decay:** Any nuclei that can be used for $\beta$-capture can also beta decay, leads to a very large background
- **Other Sources:** Outside of beta decay range, there may be other backgrounds which should be at the level of $10^{-5}\,\mathrm{Hz}$ (1 or 2 events a year)



**Experimental Configuration:** $T = 1\,\mathrm{yr}$, $m_{\mathrm{T}} = 100\mathrm{g}$, $\Gamma_{\mathrm{b}} = 7 \times 10^{-7}\,\mathrm{Hz\,eV^{-1}}$, $\Delta = 100\,\mathrm{meV}$
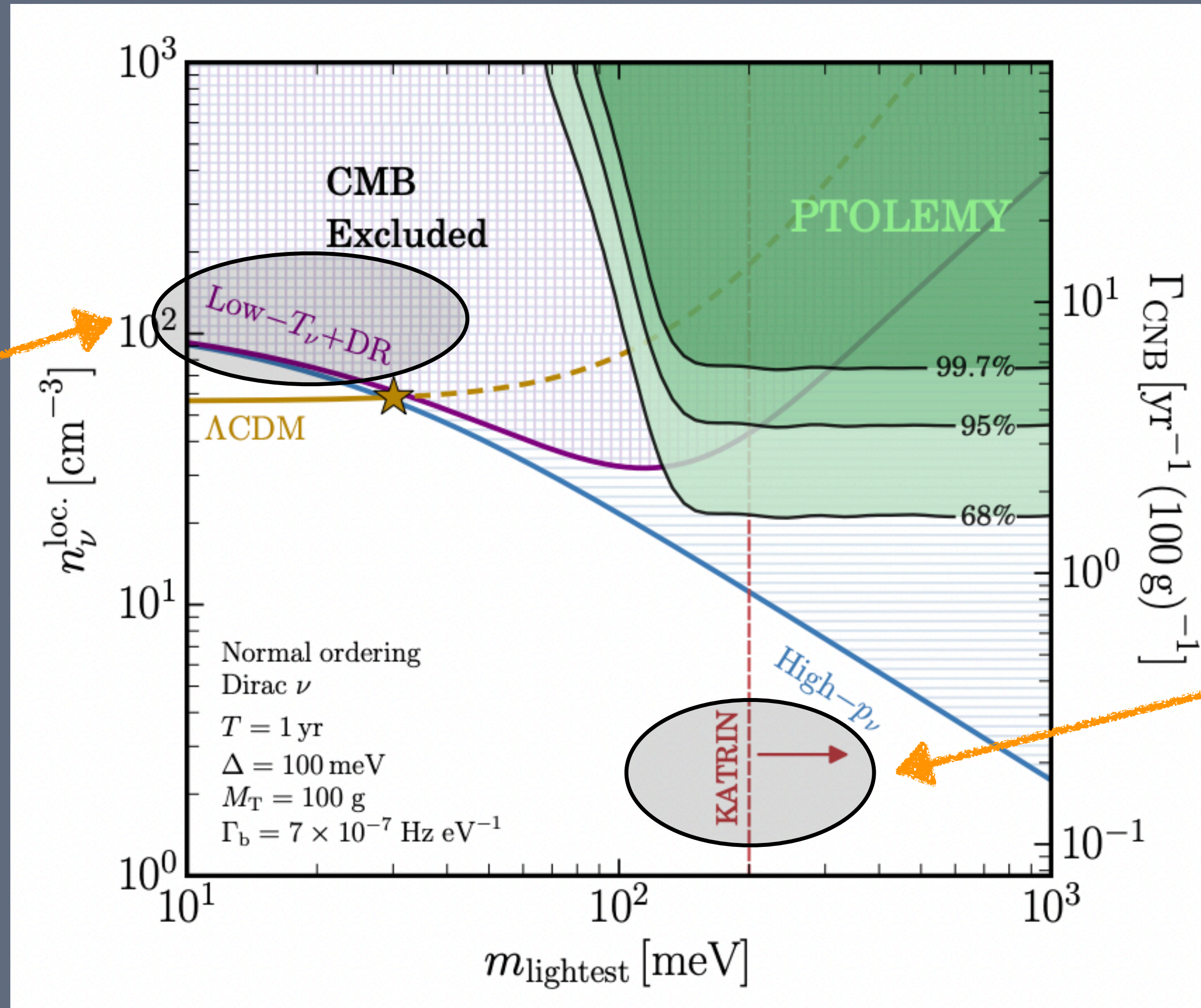
**Sensitivity:** The reach of PTOLEMY is controlled by the detector resolution $\Delta$ and the overall signal to background rate $\Gamma_{\mathrm{CNB}}/\Gamma_{\mathrm{b}}$

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DETECTION

# PTOLEMY SENSITIVITY



**Question:** Is the signal separate from the background?

**Question:** Is the signal larger than the background?

**Cosmo. scenario:** Affects the local number density and the range of allowed masses

**Expt. Landscape:** How would a detection in a CNB experiment be compatible with other probes?

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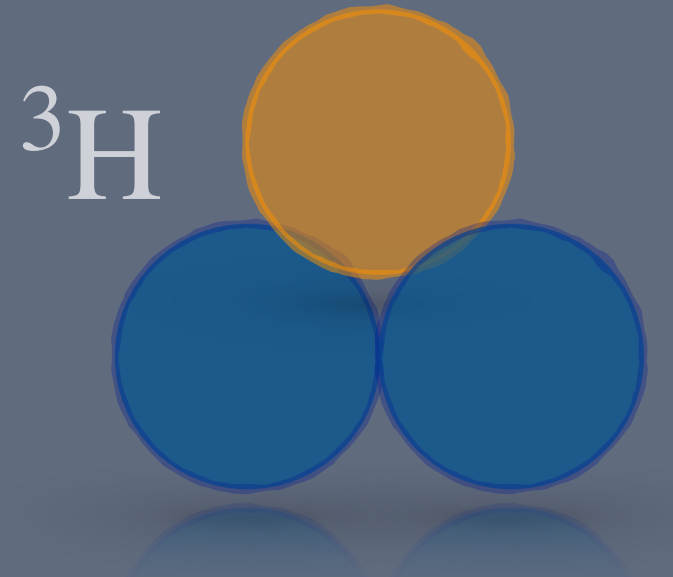
DETECTION

**Answer:** The detection prospects at a PTOLEMY-like experiment depend on the cosmological model and are highly complementary with other experimental probes such as DESI/Euclid, $0\nu\beta\beta$ experiments and KATRIN

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IV DETECTION

# OUTLOOK: WHAT DOES THE FUTURE HOLD? $^3\mathrm{H}$

**Experimental Design:** Recently, issues around the possible detector resolution have been raised, and alternatives such as heavy nuclei ($^{171}\mathrm{Tm}$ etc.) or adsorption on graphene are being actively explored

**Model Development:** So far the literature surrounding possible mechanism for modifying the neutrino distribution function in this way is relatively limited, would be very interesting to develop new models that could be tested by cosmology and terrestrial detectors

**Future Data:** Current and future experiments such as DESI/Euclid or $0\nu\beta\beta$ facilities will provide complementary information to the CMB, KATRIN and a PTOLEMY-like expt.

$\nu$

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OUTLOOK

# SUMMARY: CAN WE DETECT THE CνB?

**STEP** **#1** THE ROLE OF BBN

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**STEP** **#5** DETECTION (AT PTOLEMY)

- **<u>Detection of the CνB</u>** would represent a huge milestone in neutrino physics
- It plays an important role in the **<u>evolution of the early Universe</u>**, particularly during BBN and the CMB. In the latter case, precise measurements of CMB anisotropies place stringent constraints on the properties of neutrinos in cosmology ($N_{\mathrm{eff}}, \rho_{\nu,0}^{\mathrm{NR}}$)
- Considering the **<u>wider experimental landscape</u>**, something like PTOLEMY has the potential to uncover nteresting cosmological scenarios, or confirm another pivotal aspect of the standard model

**Thank you!**

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OUTLOOK

# BACKUP SLIDES

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BACKUP

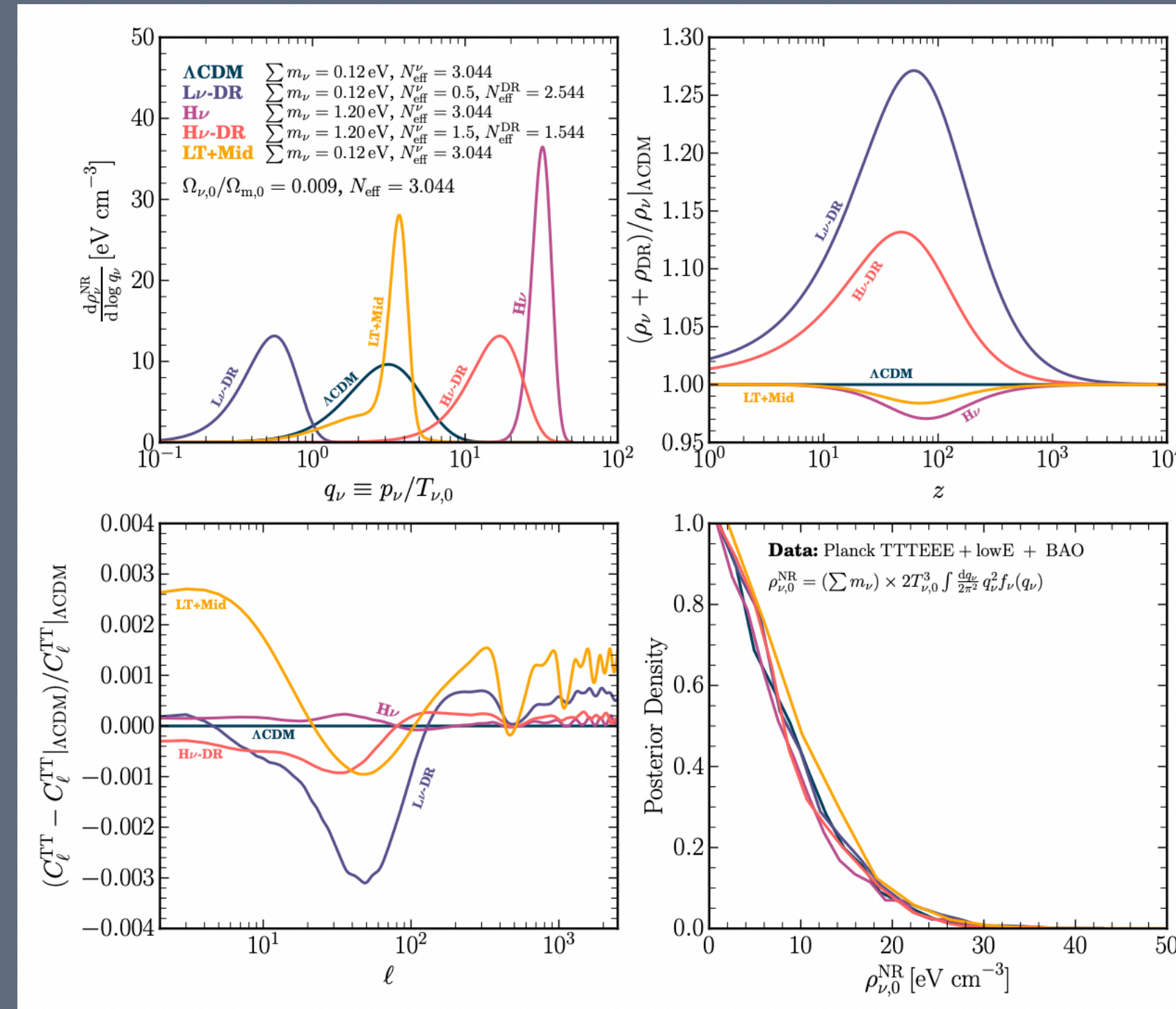$$\textbf{Fermi}-\textbf{Dirac} = \left\{ f_\nu(q_\nu) = (e^{q_\nu} + 1)^{-1}, \right.$$

$$\textbf{Gaussian} = \left\{ \begin{array}{l} f_\nu(q_\nu | N_{\rm eff}^\nu, y_*, \sigma_*) = \\ A(N_{\rm eff}^\nu, y_*, \sigma_*) \exp\left(-\frac{(q_\nu - y_*)^2}{2\sigma_*^2}\right), \end{array} \right.$$

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\gamma}\right)$$

$$1 + z_{\rm NR} = \frac{8}{21}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{\nu,0}^{\rm NR}}{N_{\rm eff}^\nu \rho_{\gamma,0}},$$

$$N_{\rm eff}^\nu = \frac{360}{7\pi^4}\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4 \int_0^\infty dq_\nu\, q_\nu^3 f_\nu(q_\nu)$$

$$\frac{n_\nu}{n_\nu^{\rm FD}} = \frac{2}{3\zeta(3)} \int_0^\infty dq_\nu\, q_\nu^2 f_\nu(q_\nu)$$

- **ΛCDM** The SM case, where neutrinos have a Fermi-Dirac distribution with temperature $T_\nu = T_\gamma/1.39578$. This gives $N_{\rm eff} = N_{\rm eff}^\nu = 3.044$.

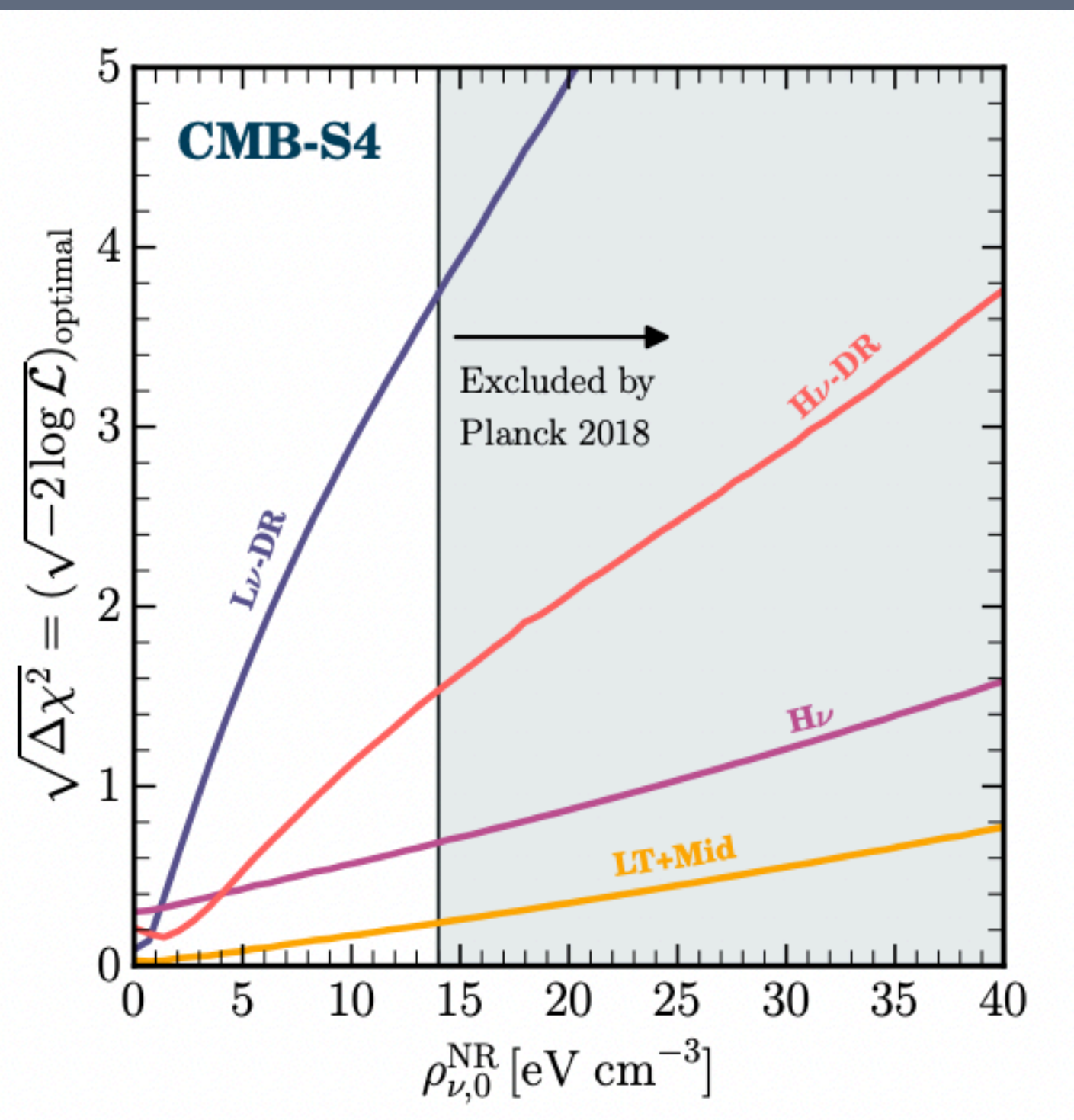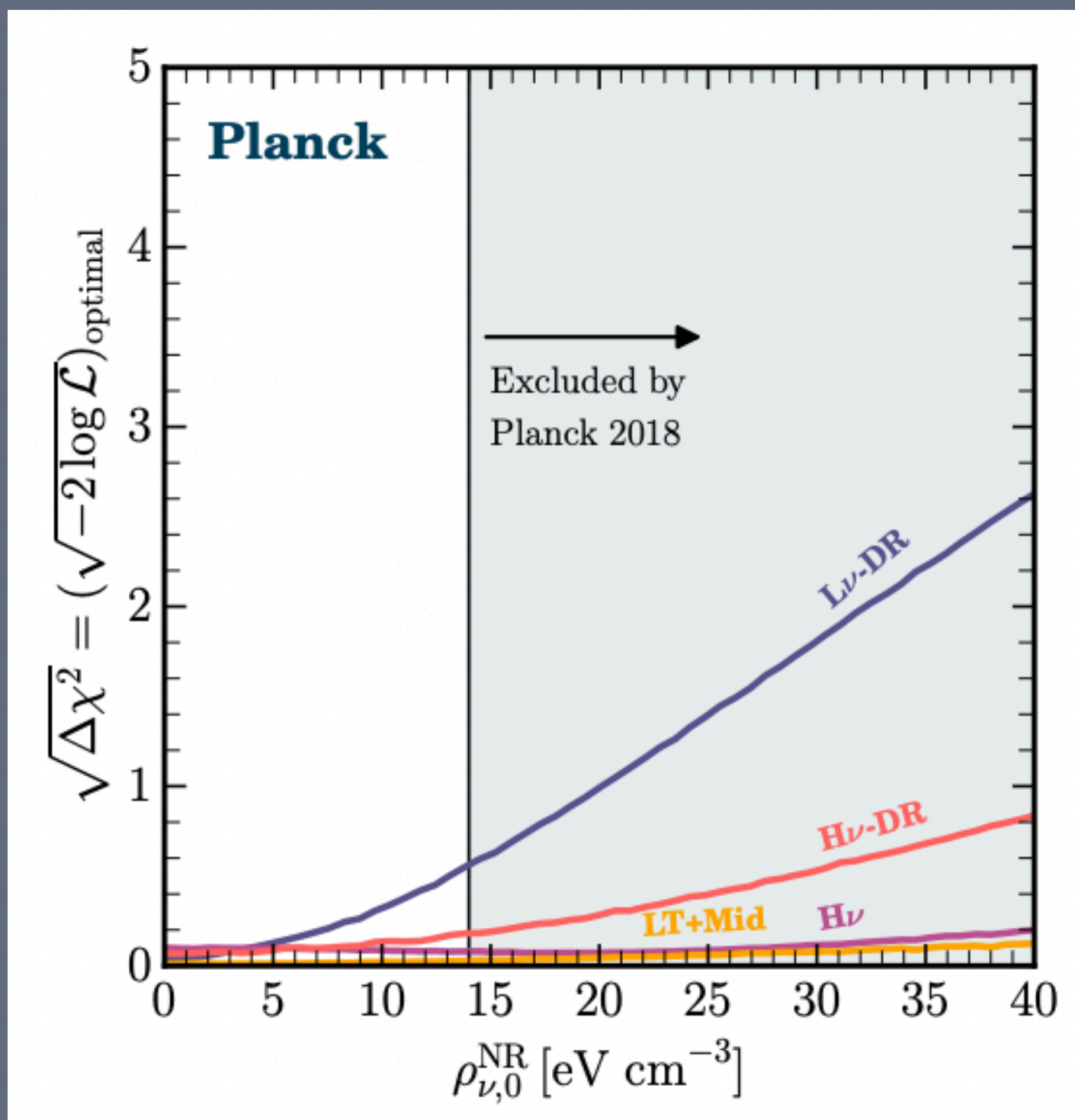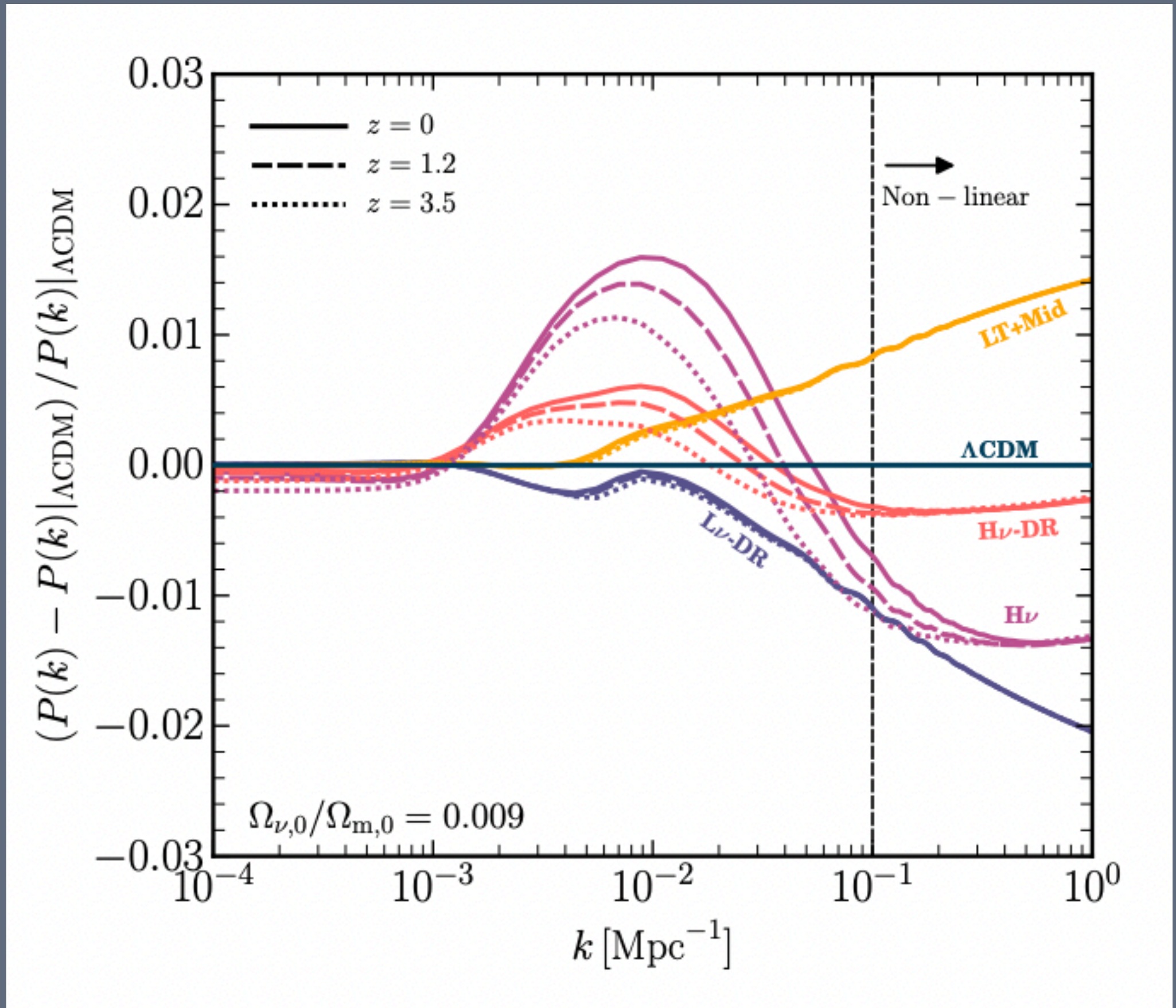- **Lν-DR** A low-energy neutrino population with a Gaussian distribution (where $N_{\rm eff}^\nu = 0.5$, $y_* = 0.1$ and $\sigma_* = 0.294218$), complemented with massless dark radiation (DR) to give a total $N_{\rm eff} = N_{\rm eff}^\nu + N_{\rm eff}^{\rm DR} = 3.044$.

- **Hν** A high-energy neutrino population with a Gaussian distribution, where $N_{\rm eff}^\nu = 3.044$, $y_* = 30$ and $\sigma_* = 4.82113$.
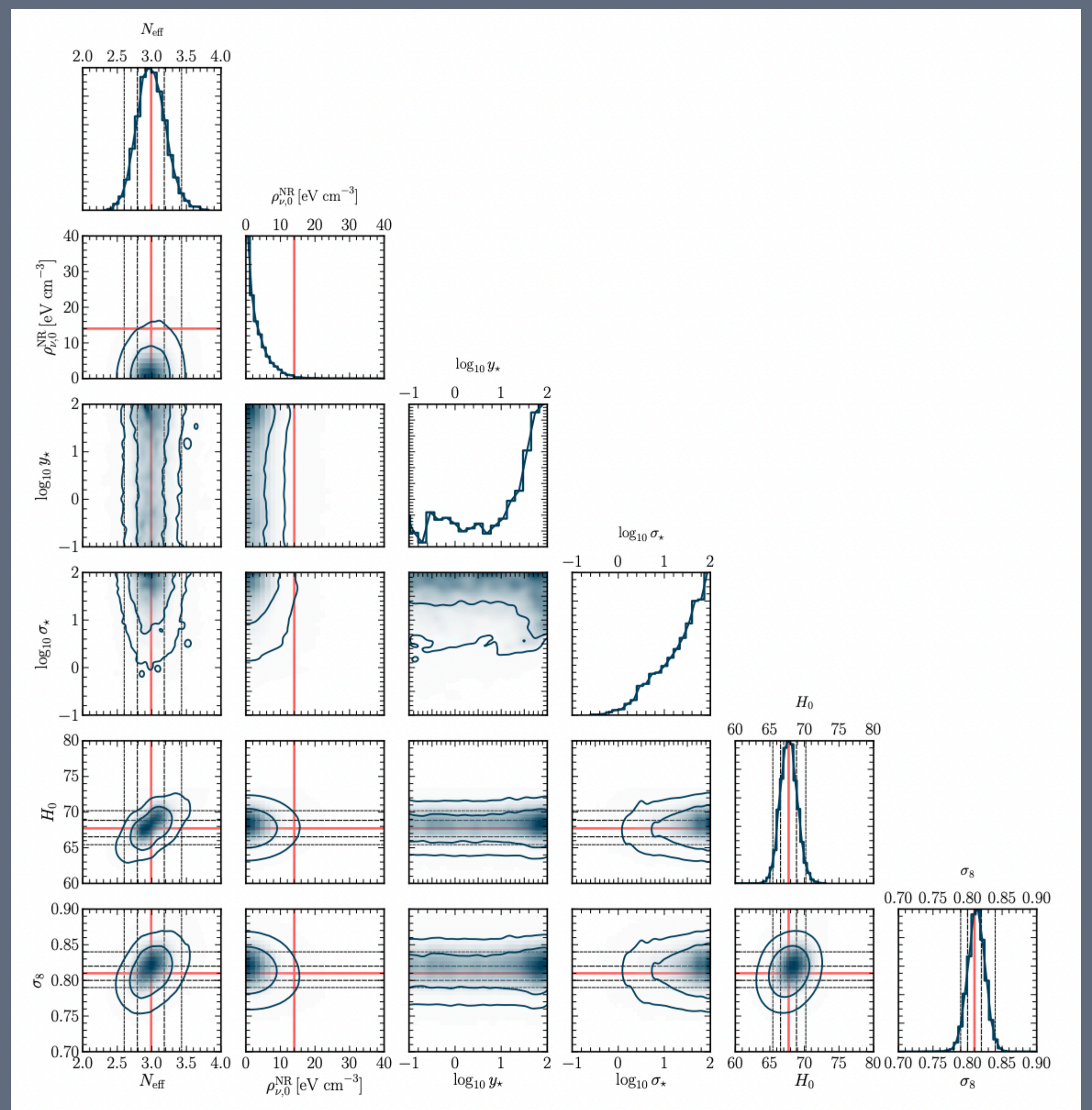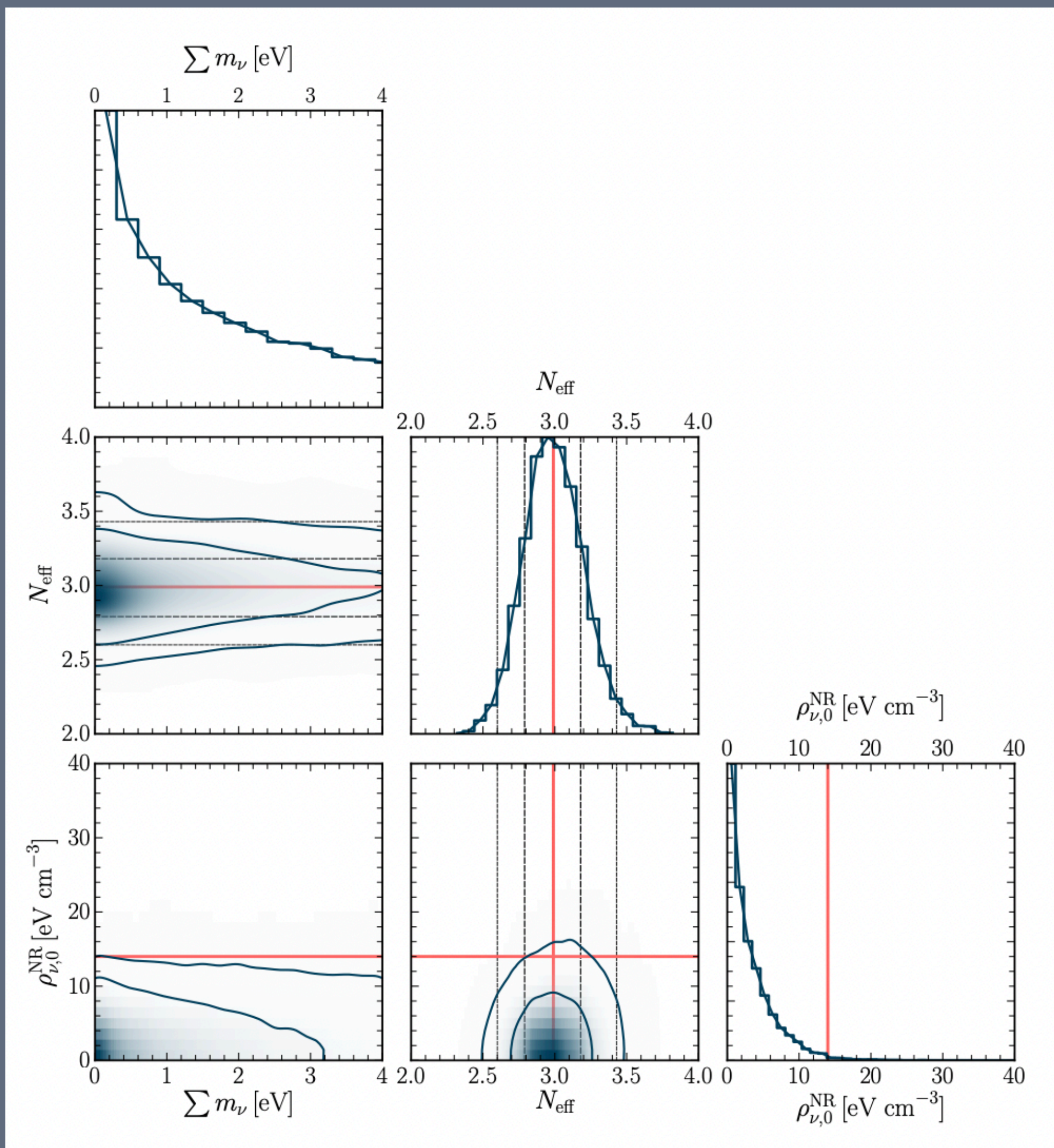
- **Hν-DR** A high-energy neutrino population with a Gaussian distribution (where $N_{\rm eff}^\nu = 1.5$, $y_* = 3$ and $\sigma_* = 8.82654$), complemented with massless dark radiation.

- **LT+Mid** A mid-energy neutrino population with a Gaussian distribution (where $N_{\rm eff}^\nu = 2.3139$, $y_* = 3.5$ and $\sigma_* = 0.508274$), together with a low-temperature population that has a Fermi-Dirac distribution with $T_\nu = T_\gamma/2$.

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BACKUP

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BACKUP

BACKUP

$$v_\nu(z) = 4000(1+z)\left[\frac{0.04\,\text{eV}}{m_\nu}\right]\,\text{km\,s}^{-1} \qquad [\Lambda\text{CDM}], \quad (18)$$

$$v_\nu(z) = 4000\,(1+z)\left[\frac{0.04\,\text{eV}}{m_\nu}\right]^{4/3}\,\text{km\,s}^{-1}\,[\textbf{Low-}\boldsymbol{T_\nu}\textbf{+DR}], \quad (19)$$

$$v_\nu(z) = 4000\,(1+z)\,\text{km\,s}^{-1} \qquad\qquad\qquad [\textbf{High-}\boldsymbol{p_\nu}], (20)$$

$$f_{\rm c} \simeq 77\,(m_\nu/\text{eV})^{2.2} \qquad\qquad\qquad [\Lambda\text{CDM}]\,,$$

$$f_{\rm c} \simeq 96\,(m_\nu/\text{eV})^{2.0} \qquad\qquad [\textbf{Low-}\boldsymbol{T_\nu}\textbf{+DR}]\,,$$

$$f_{\rm c} \simeq 0 \qquad\qquad\qquad\qquad [\textbf{High-}\boldsymbol{p_\nu}]\,,$$

$$E_{\rm end}^{m_\nu=0} = \frac{m_{^3\text{H}}^2 + m_e^2 - m_{^3\text{He}}^2}{2m_{^3\text{H}}}$$

$$n_{\nu,0} < 56\,\text{cm}^{-3}\frac{0.12\,\text{eV}}{\sum m_\nu}$$

$$\lambda(\boldsymbol{\theta};\hat{\boldsymbol{\theta}}) = 2\ln\frac{\mathcal{L}(\hat{\boldsymbol{\theta}})}{\mathcal{L}(\boldsymbol{\theta})}$$

$$= 2\sum_k\left[N^k(\boldsymbol{\theta}) - N^k(\hat{\boldsymbol{\theta}}) + N^k(\hat{\boldsymbol{\theta}})\ln\frac{N^k(\hat{\boldsymbol{\theta}})}{N^k(\boldsymbol{\theta})}\right]$$

$$\sum m_\nu < 0.12\,\text{eV}\left[\frac{T_\nu^{\rm SM}}{T_\nu}\right]^3$$

$$\sum m_\nu < 0.12\,\text{eV}\,\frac{\langle p_\nu\rangle}{3.15\,T_\nu^{\rm SM}}$$

$$\frac{\text{d}\widetilde{\Gamma}_\beta}{\text{d}E_e} = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8\ln 2})}\int \text{d}E'\frac{\text{d}\Gamma_\beta}{\text{d}E'}\times$$

$$\times\exp\left[-\frac{(E_e - E')^2}{2(\Delta/\sqrt{8\ln 2})^2}\right],$$

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BACKUP

$$\frac{\mathrm{d}\widetilde{\Gamma}_{\mathrm{CNB}}}{\mathrm{d}E_e} = \frac{c_{\mathrm{D/M}}}{\sqrt{2\pi}(\Delta/\sqrt{8\ln(2)})}$$

$$\times \sum_i \Gamma_i \exp\left\{-\frac{\left[E_e - (E_{\mathrm{end}}^{m_\nu=0} + m_i)\right]^2}{2\left(\Delta/\sqrt{8\ln(2)}\right)^2}\right\},$$
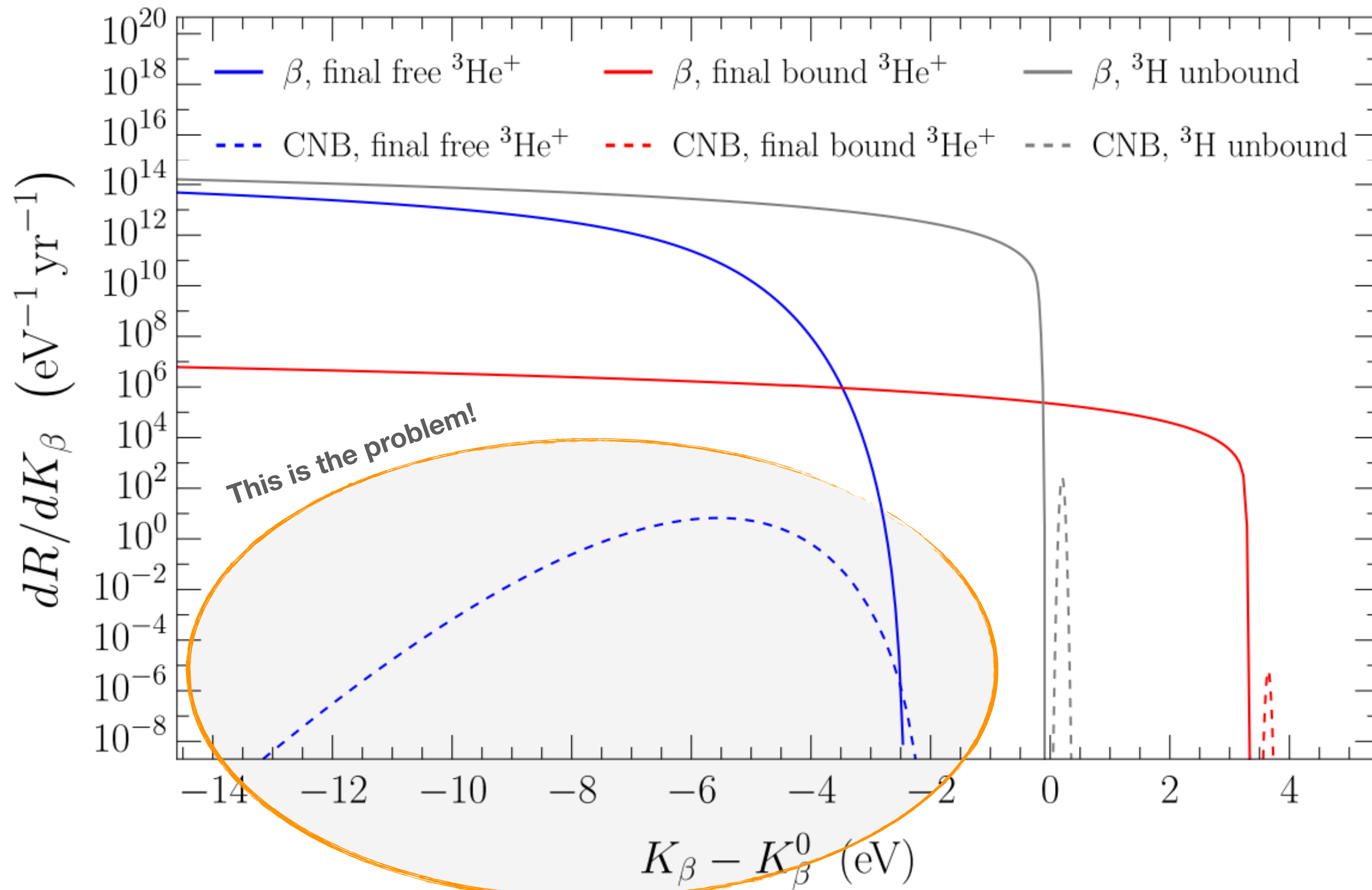
$$N_\beta^k = T \int_{E_k-\Delta/2}^{E_k+\Delta/2} \frac{d\widetilde{\Gamma}_\beta}{dE_e} dE_e$$

$$N_{\mathrm{CNB}}^k = T \int_{E_k-\Delta/2}^{E_k+\Delta/2} \frac{d\widetilde{\Gamma}_{\mathrm{CNB}}}{dE_e} dE_e,$$

$$\frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E_e} = \frac{\overline{\sigma}}{\pi^2} N_{\mathrm{T}} \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i)$$
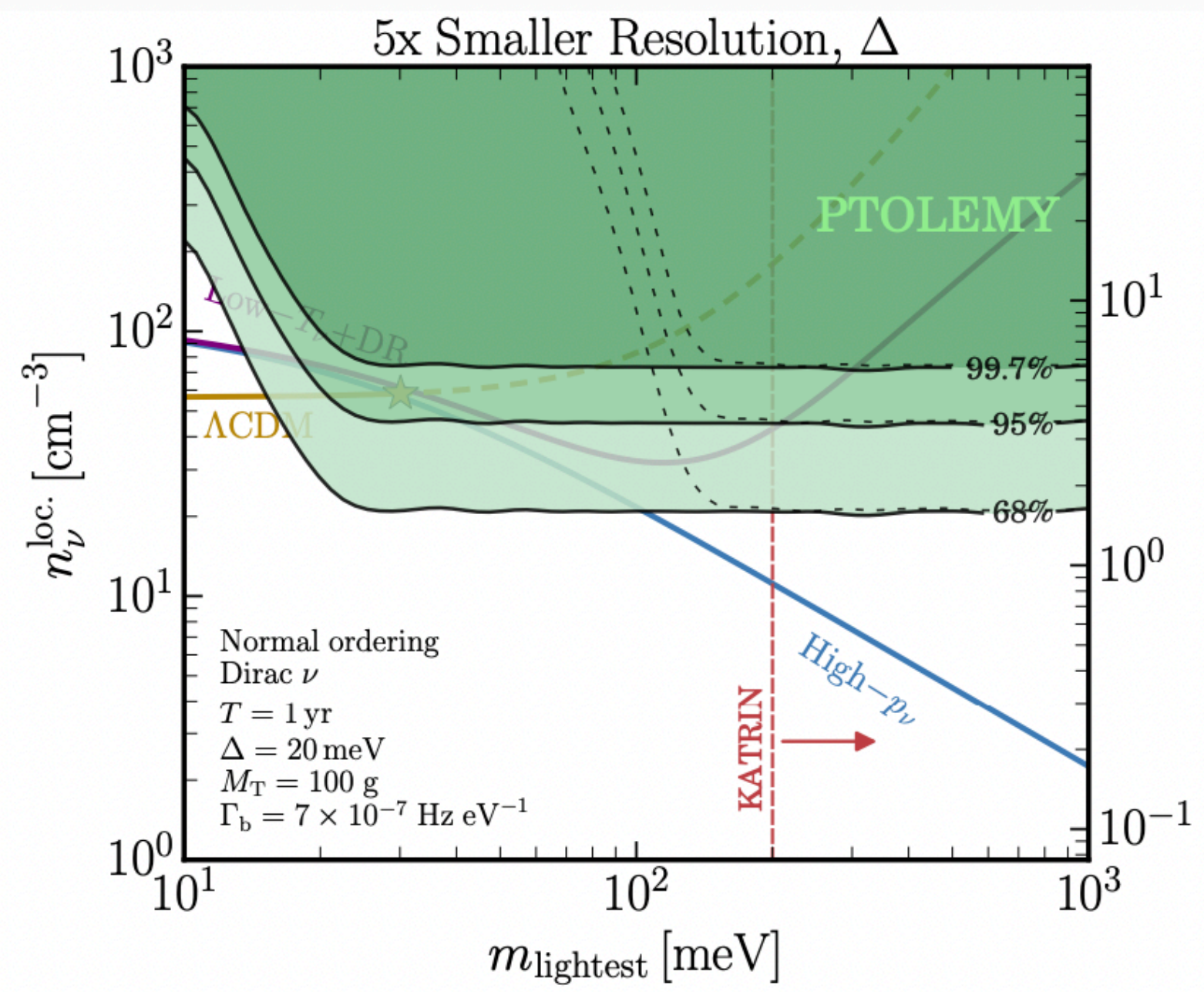
$$N^k(\boldsymbol{\theta}) = T \Delta \Gamma_{\mathrm{b}}$$
$$+ A_\beta N_\beta^k(T, \Delta, M_{\mathrm{T}}, m_{\mathrm{lightest}}, \delta E_{\mathrm{end}})$$
$$+ A_{\mathrm{CNB}} N_{\mathrm{CNB}}^k(T, \Delta, M_{\mathrm{T}}, n_\nu^{\mathrm{loc}}, m_{\mathrm{lightest}}, \delta E_{\mathrm{end}}),$$

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Taken from 2203.11228 (PTOLEMY collab.)

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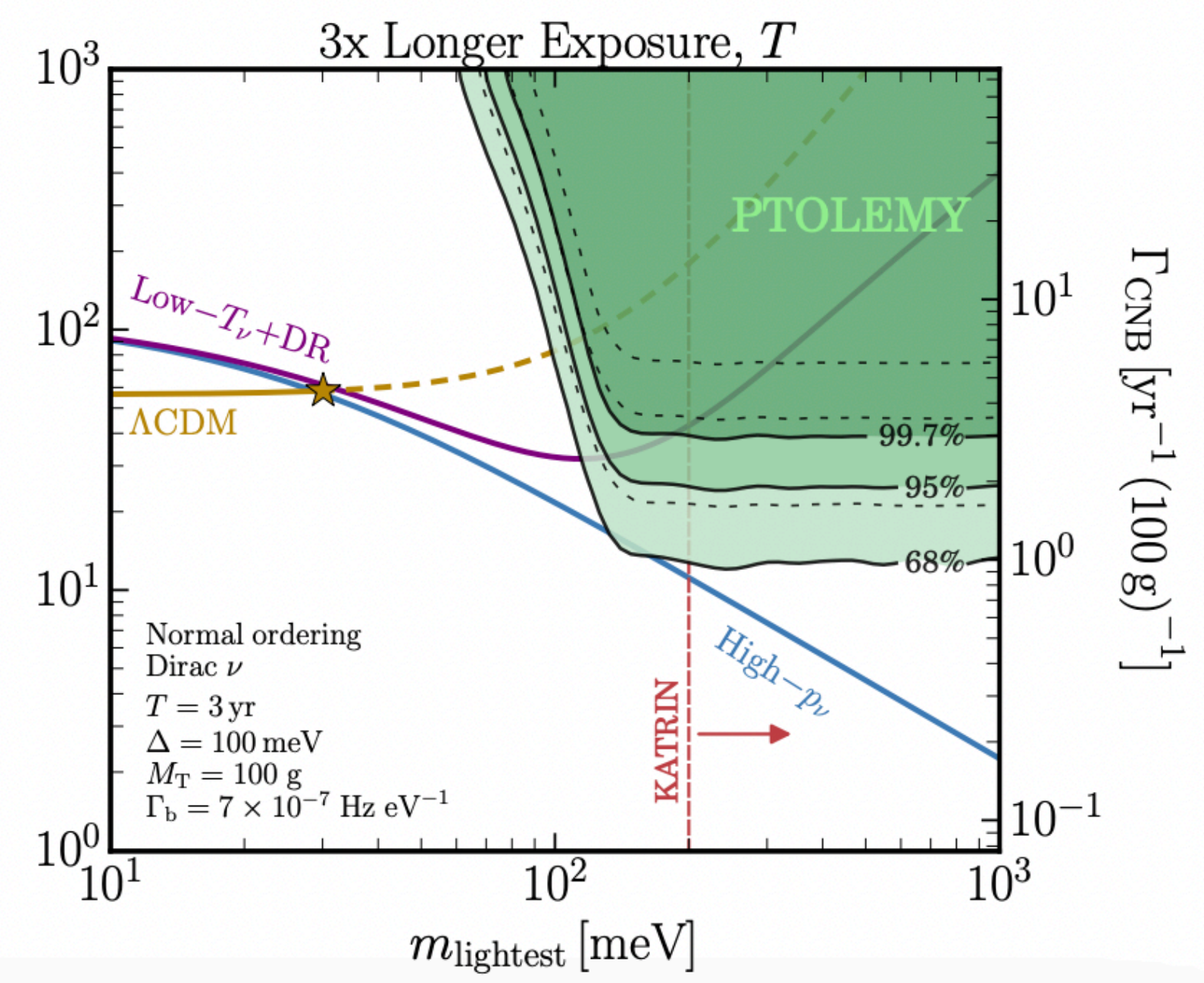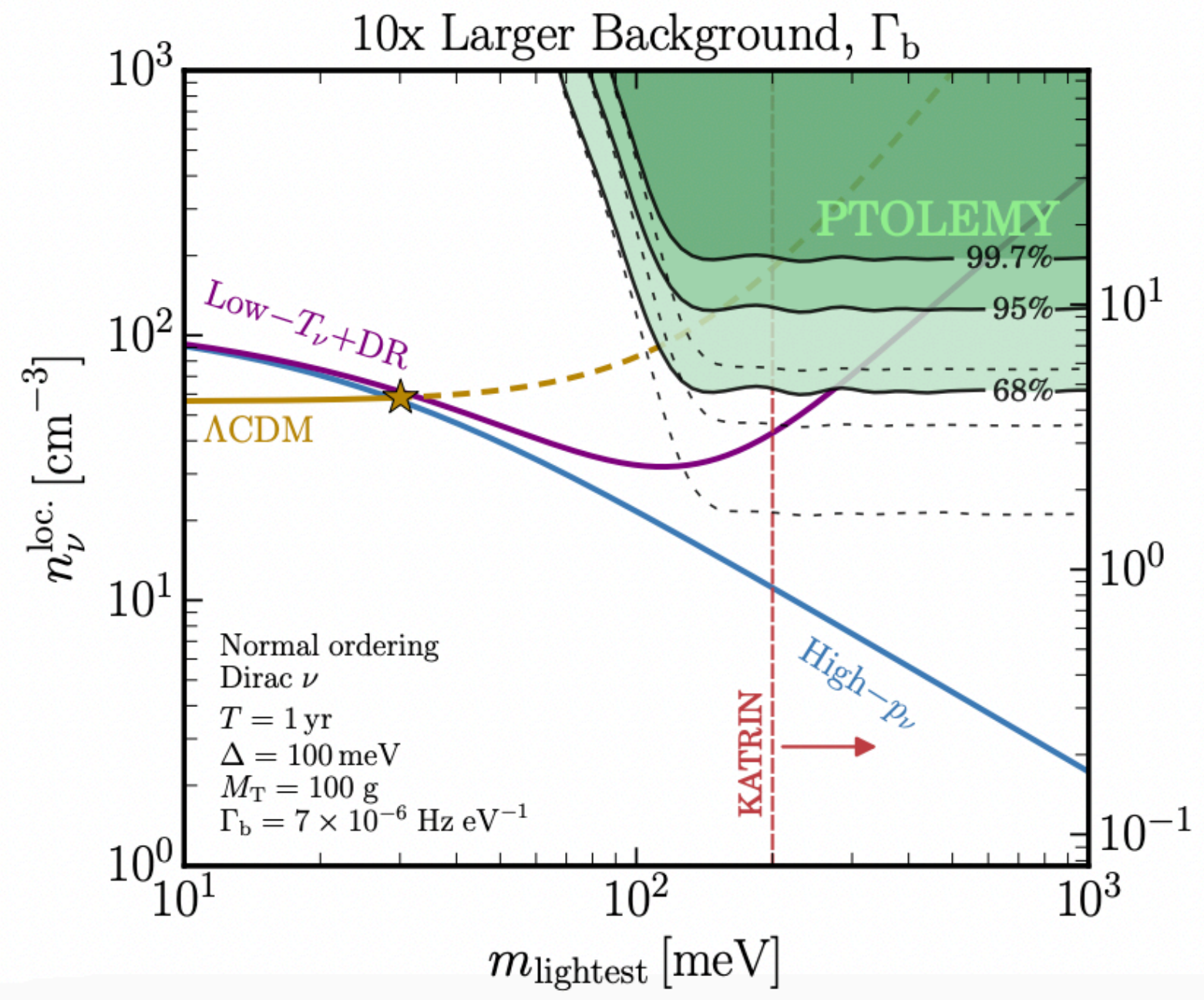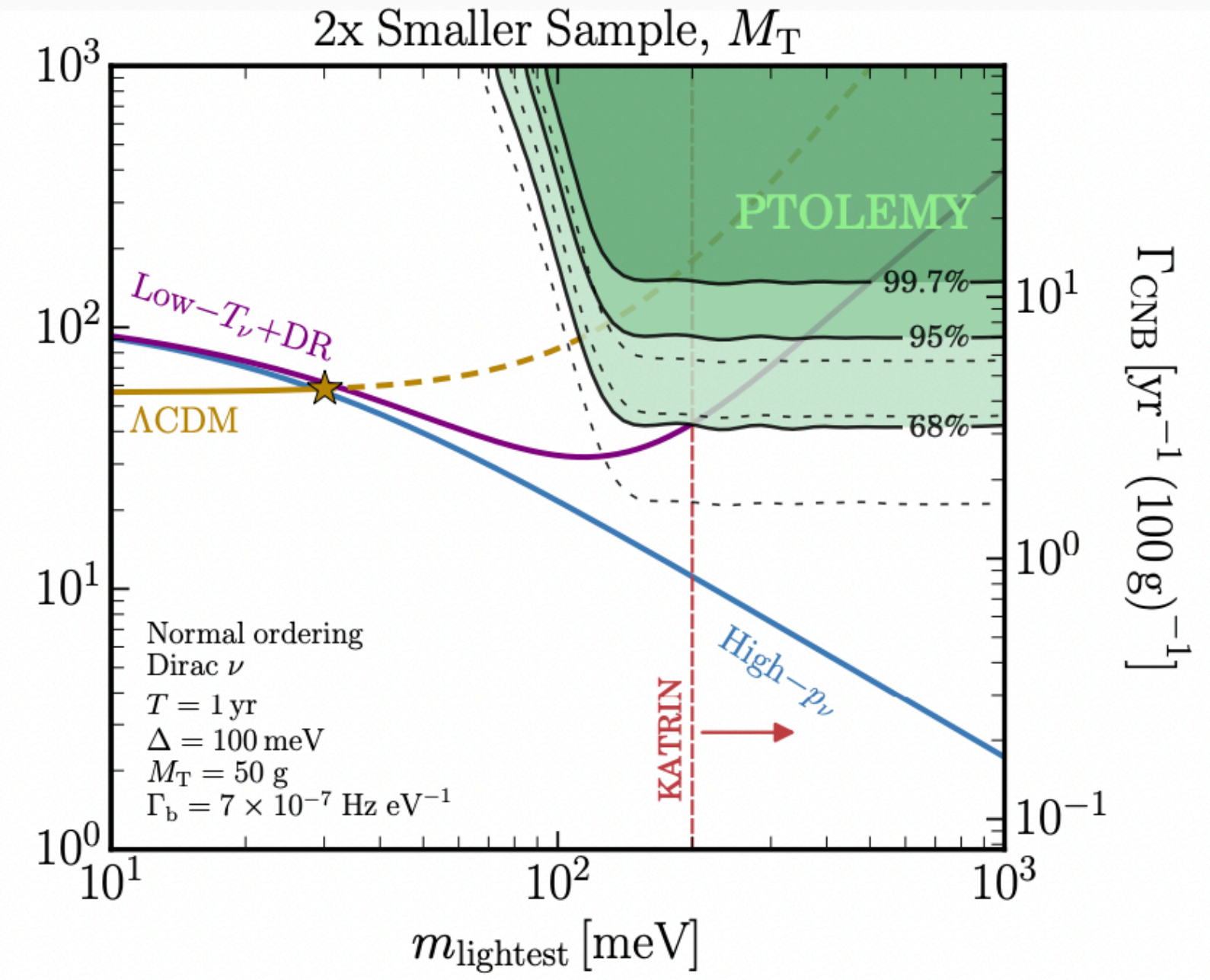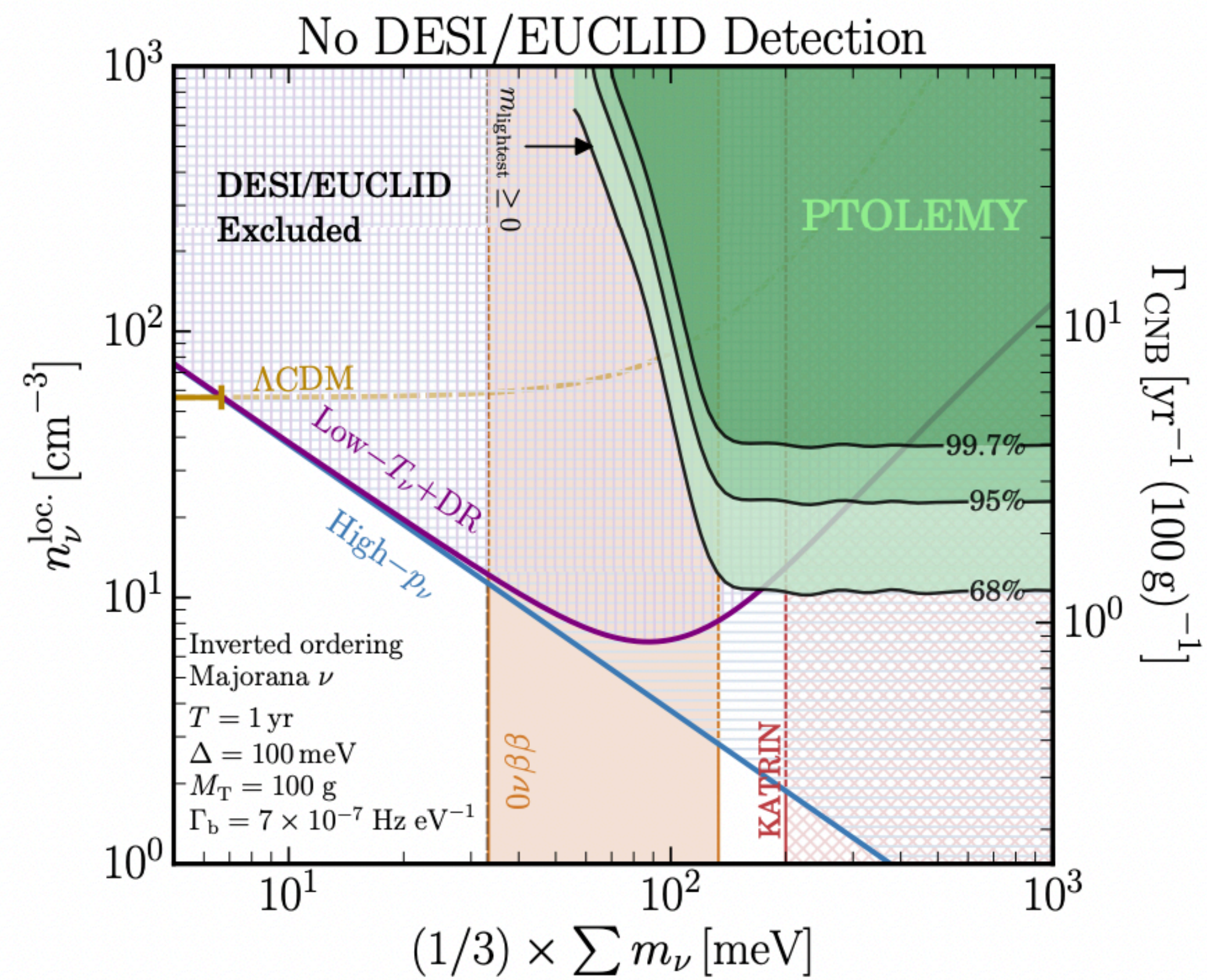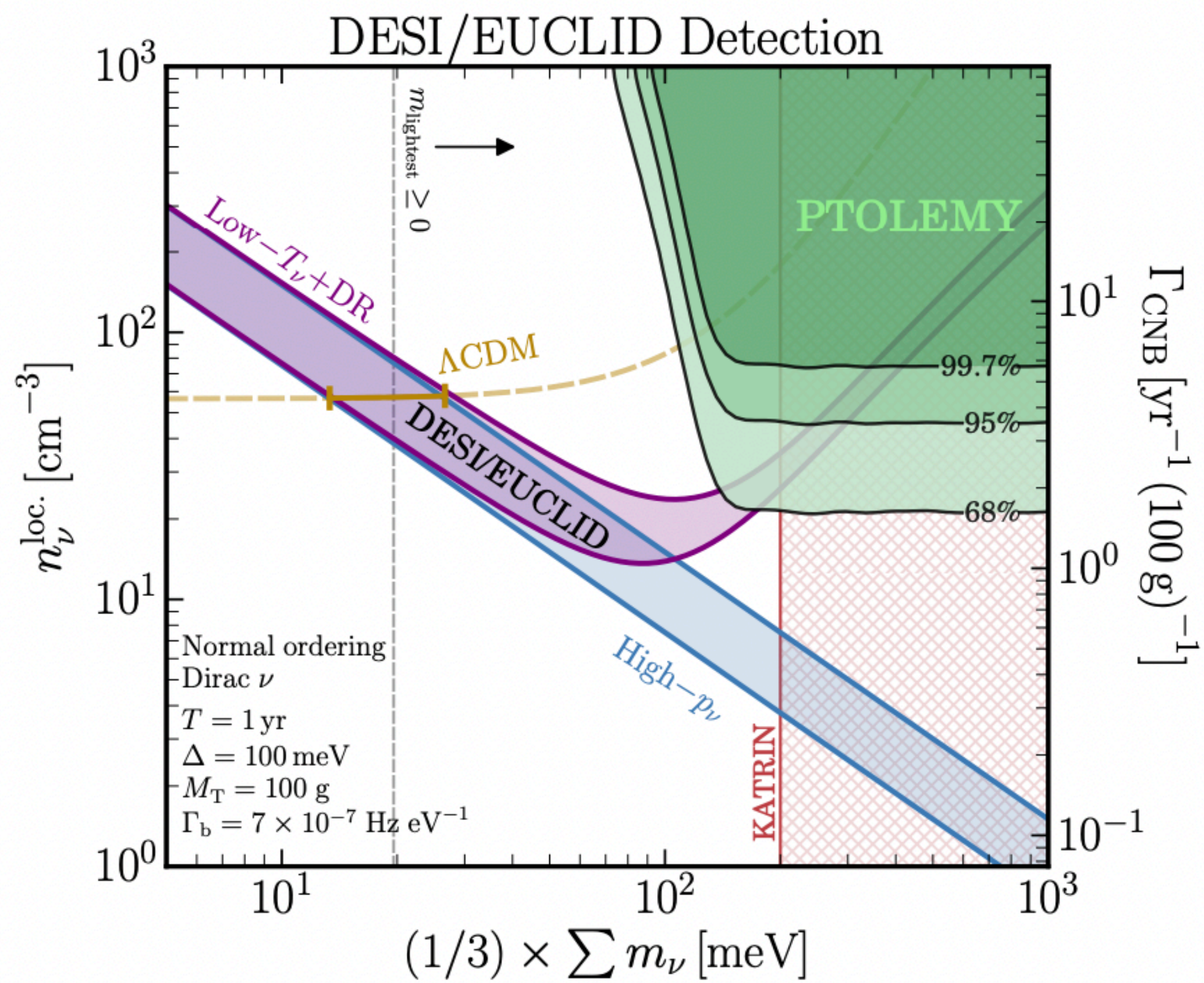
| Cosmological Scenario | CNB Detection? | Comments |
|---|---|---|
| $\Lambda$CDM | Very challenging, see Figs. 2, 3 and 4 | Similar considerations apply to cosmologies where neutrino properties are not drastically altered. |
| Low-$T_\nu$+DR [50, 51] (see Sec. II) | Good, see magenta lines in Figs. 2−4 | The detection prospects depend upon $T_\nu$ and $m_\nu$. |
| High-$p_\nu$ [40] (see Sec. II) | Unlikely, see blue lines in Figs. 2−4 | There are very few neutrinos on Earth. |
| Neutrino Decays, $\nu_i \rightarrow \nu_4 \, \phi$ [41, 42, 45] | No | No relic active neutrino background today. |
| Neutrino Decays, $\nu_i \rightarrow \nu_j \, \phi$ [42, 44, 54] | Yes, but only if $\Delta \lesssim 50\,\mathrm{meV}^\star$ | Only cosmologically viable for $\sum m_\nu \lesssim 0.17\,\mathrm{eV}$ [42]. |
| Long range $\nu$ interactions [49] | Potentially yes, with $\Delta \lesssim m_\nu$ | The CNB would be made out of dense neutrino nuggets, |
| Growing Neutrino Quintessence [64–66] | Potentially yes, with $\Delta \lesssim m_\nu$ | but their distribution in the Universe is unknown [55, 56]. |
| Neutrino masses from the $\theta$ term [46] | No | No relic neutrino background today. |
| Neutrino masses from a late PT [47, 48] | Yes, provided that $\Delta \lesssim m_\nu$ | Only cosmologically viable for $\sum m_\nu < 1.41\,\mathrm{eV}$ [48]. |

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