CAN WE DETECT THE COSMIC NEUTRINO BACKGROUND?

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

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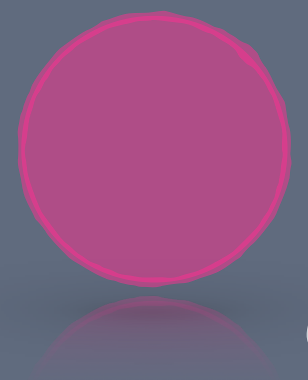
MOTIVATION: WHY IS THE CνB INTERESTING?

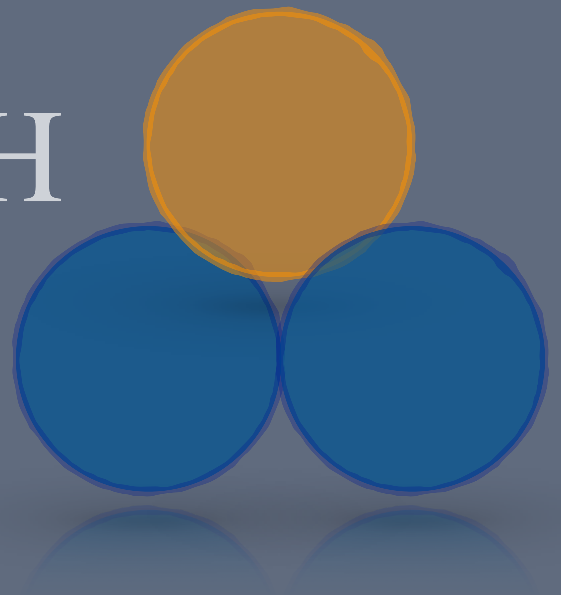

$e^{\pm}$

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


ν

$^{3}\mathrm{He}$


Conditions in Early Universe: Specific features highly sensitive to physics around the time of neutrino decoupling ($t \sim 1$ 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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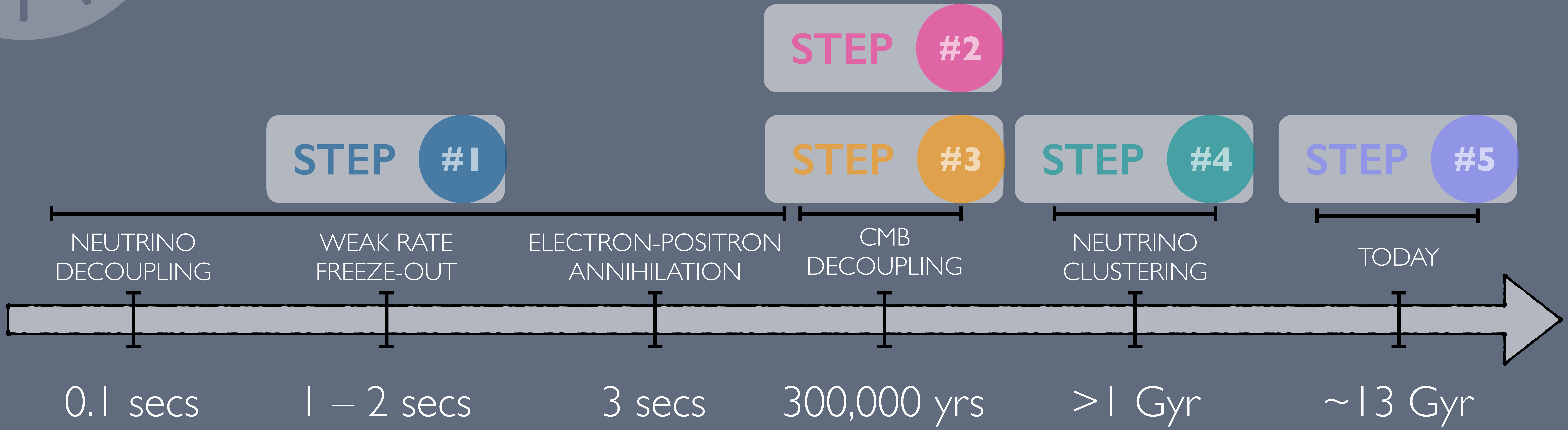
TIMELINE OF THE CνB



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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: What constraints does the physics of BBN place on the relic neutrino background?

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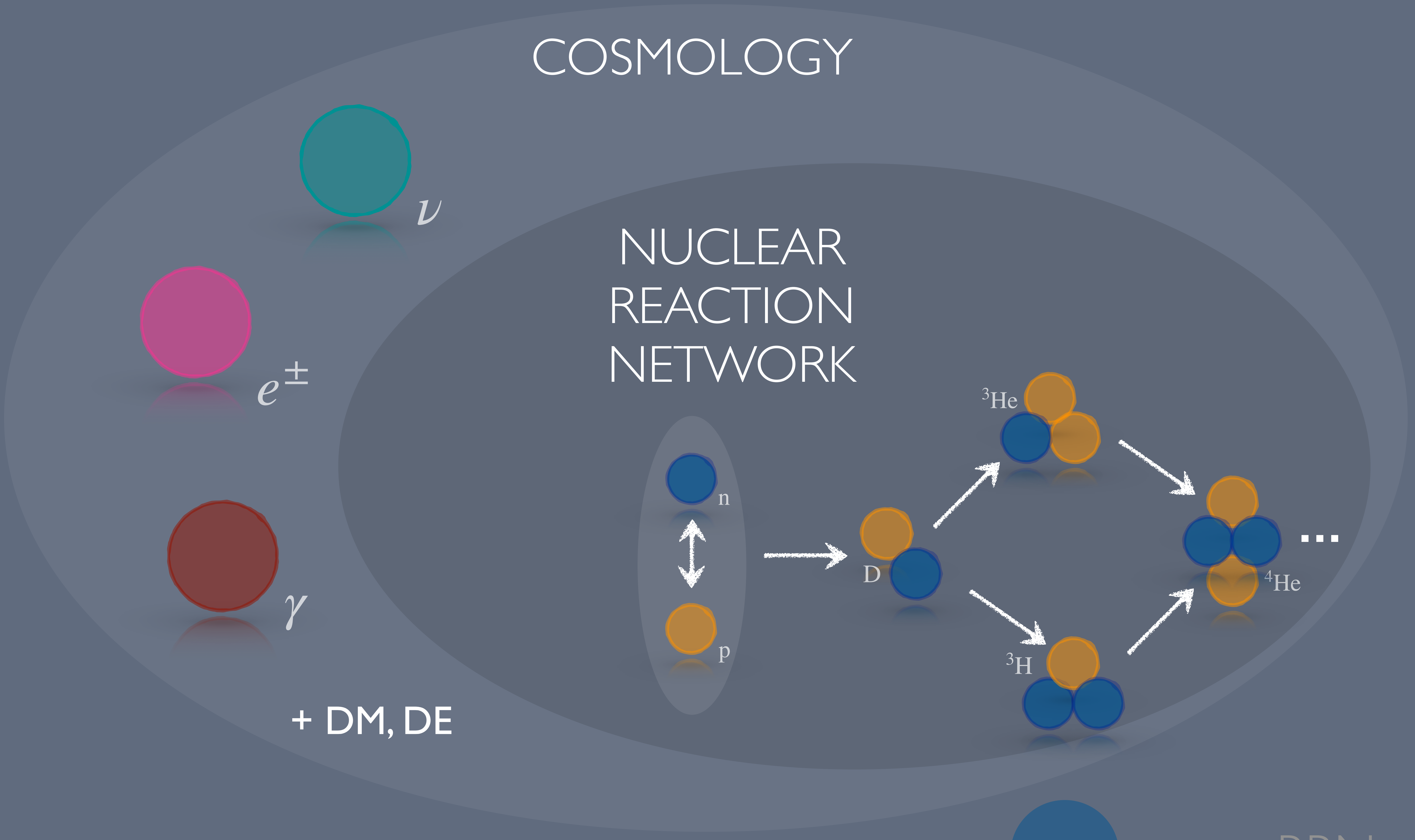
PHYSICS OF BBN



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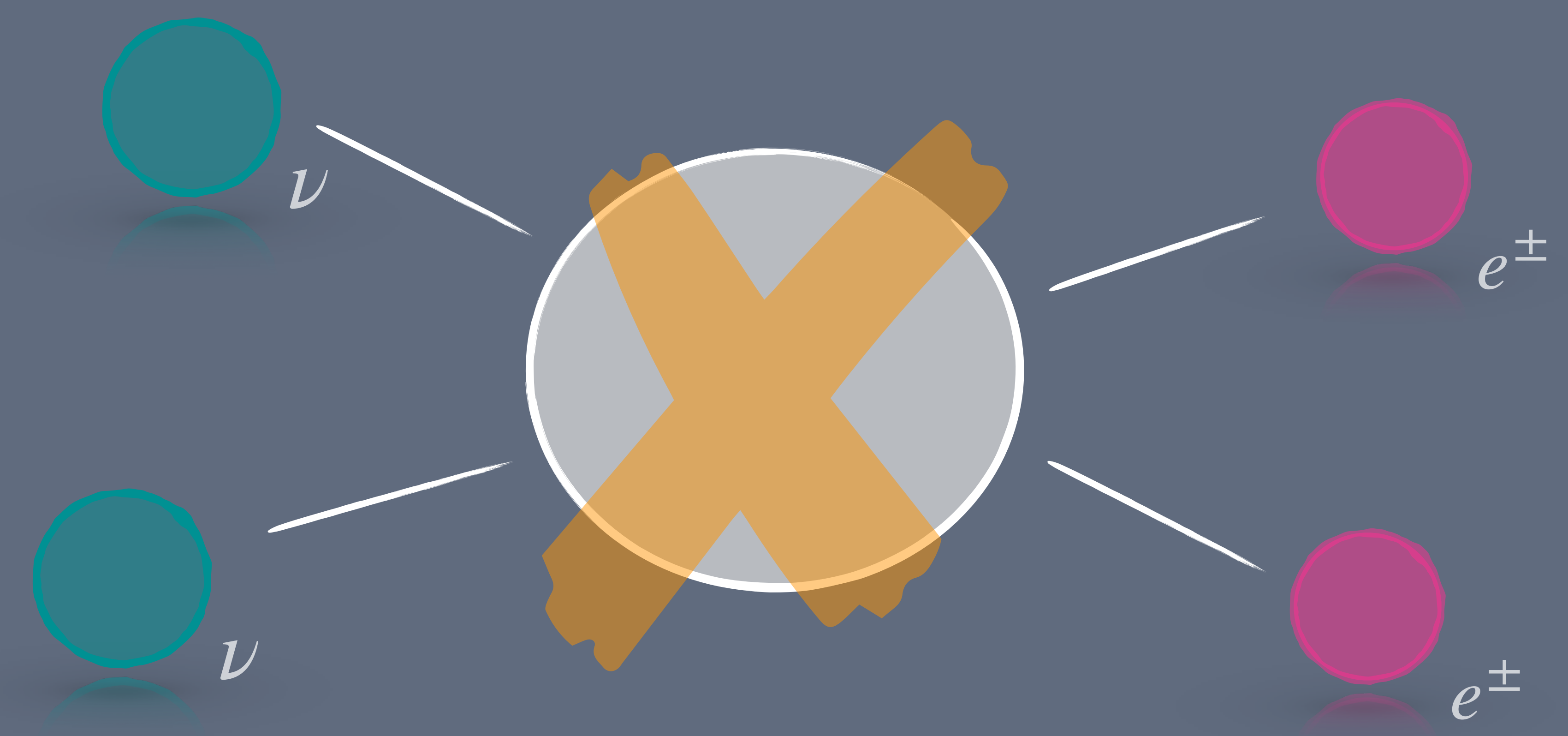
NEUTRINOS IN BBN

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



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

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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
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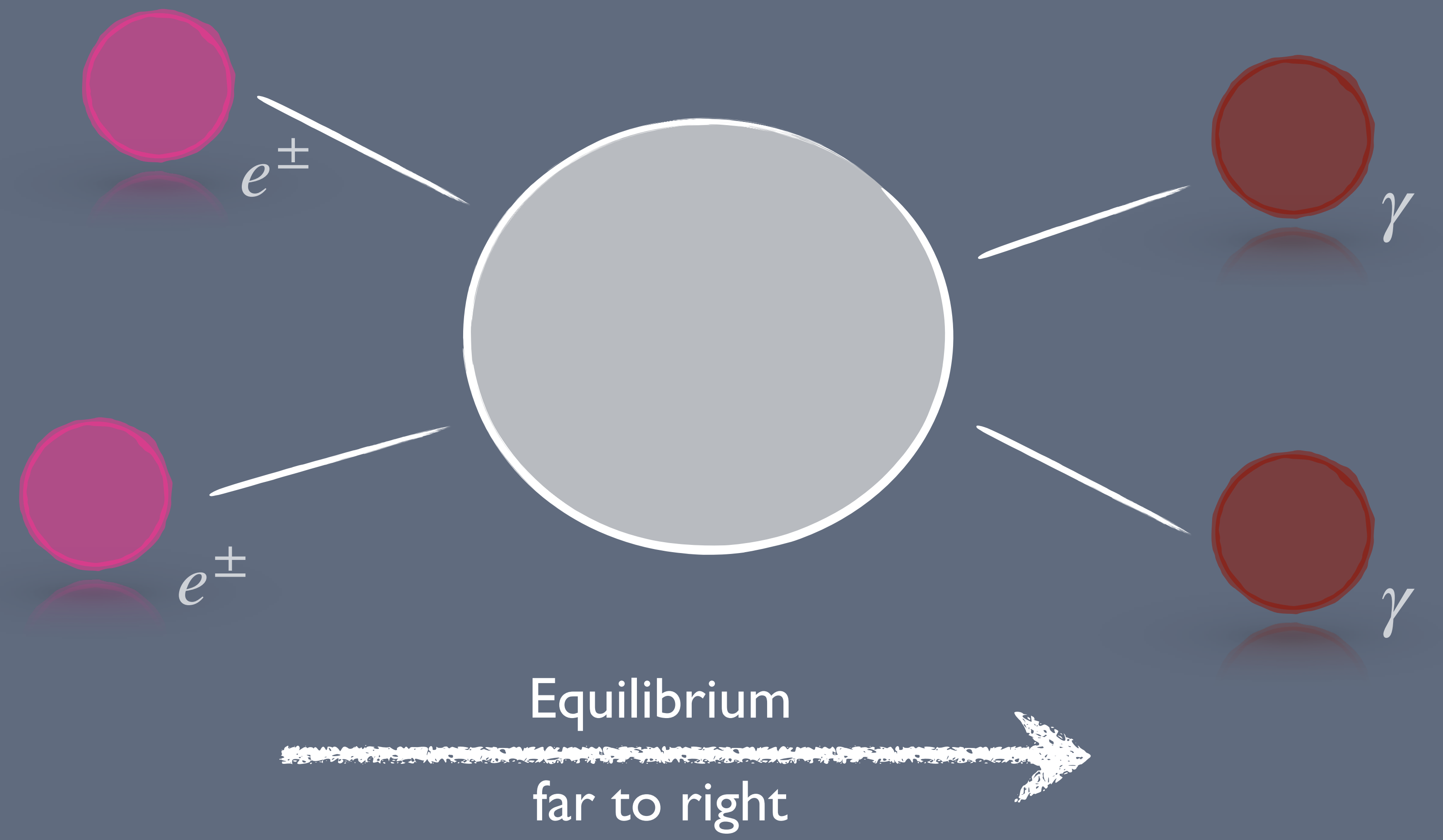

Result: $T_\nu < T_\gamma$ and $N_{\text{eff}} \simeq 3$

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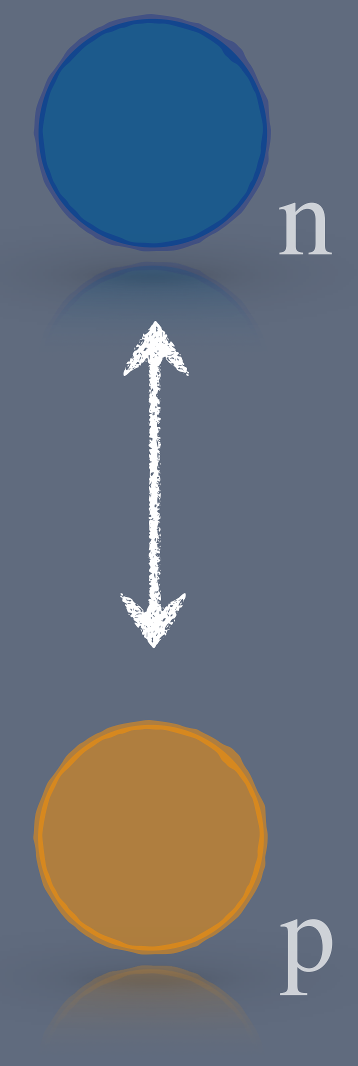
$T \simeq 0.8\,\text{MeV}$
$t \sim 1\,\text{sec}$

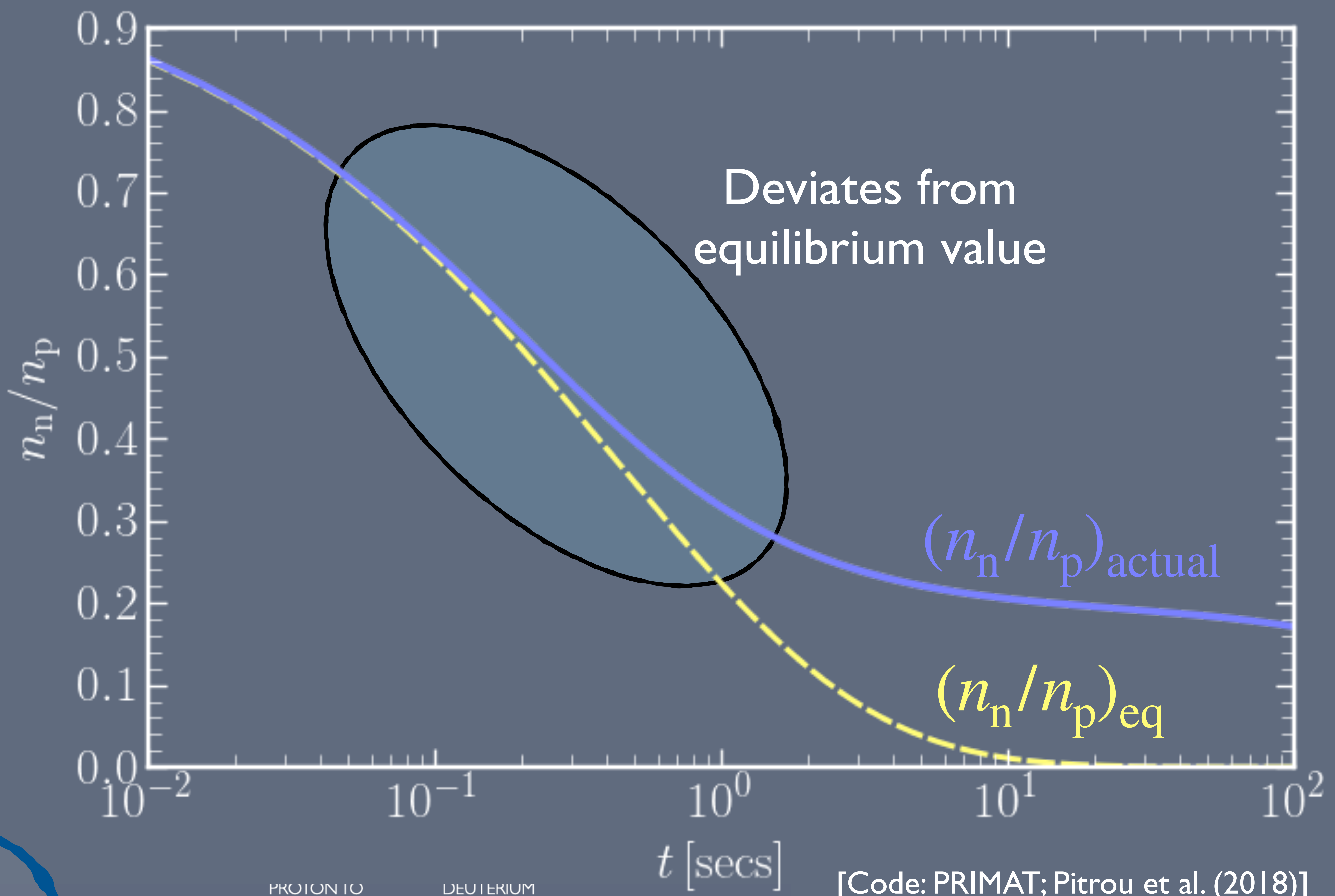
PROTONS AND NEUTRONS:
WEAK FREEZE-OUT

Kept in **equilibrium** by the reactions

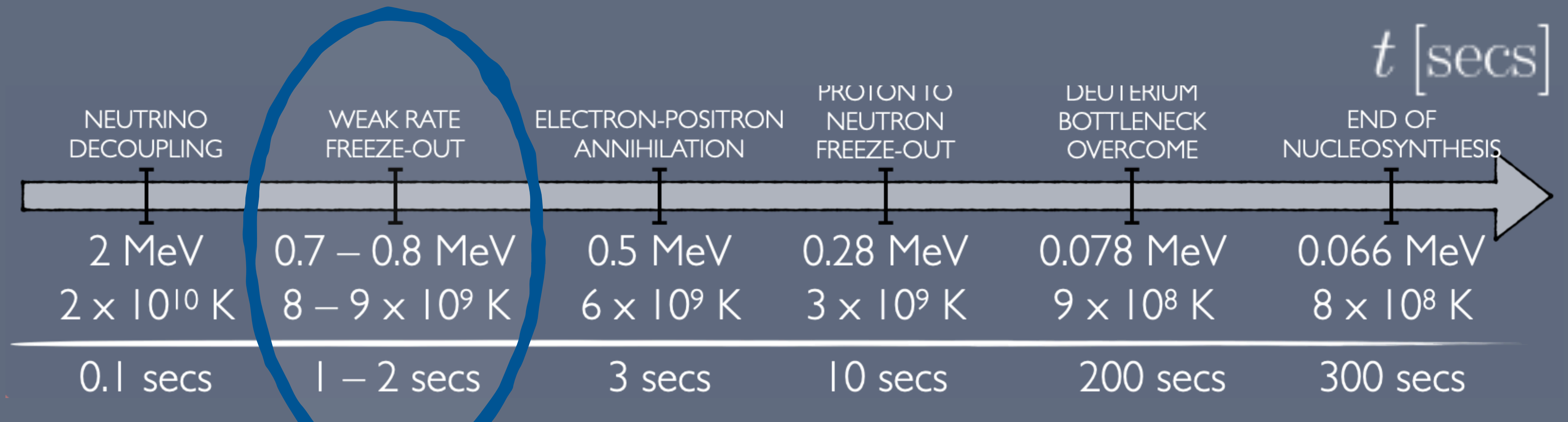
$$n + \nu_e \to p + e^-$$
$$n \to p + e^- + \bar{\nu}_e$$
$$n + e^+ \to p + \bar{\nu}_e$$



…until around 0.8 MeV



[Code: PRIMAT; Pitrou et al. (2018)]



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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)

Answer: BBN is a crucial checkpoint for the CνB, with the key processes of neutrino decoupling, electron-positron annihilation and weak freeze-out delicately controlling the final primordial nuclear abundances

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Question: How do neutrinos affect the CMB?

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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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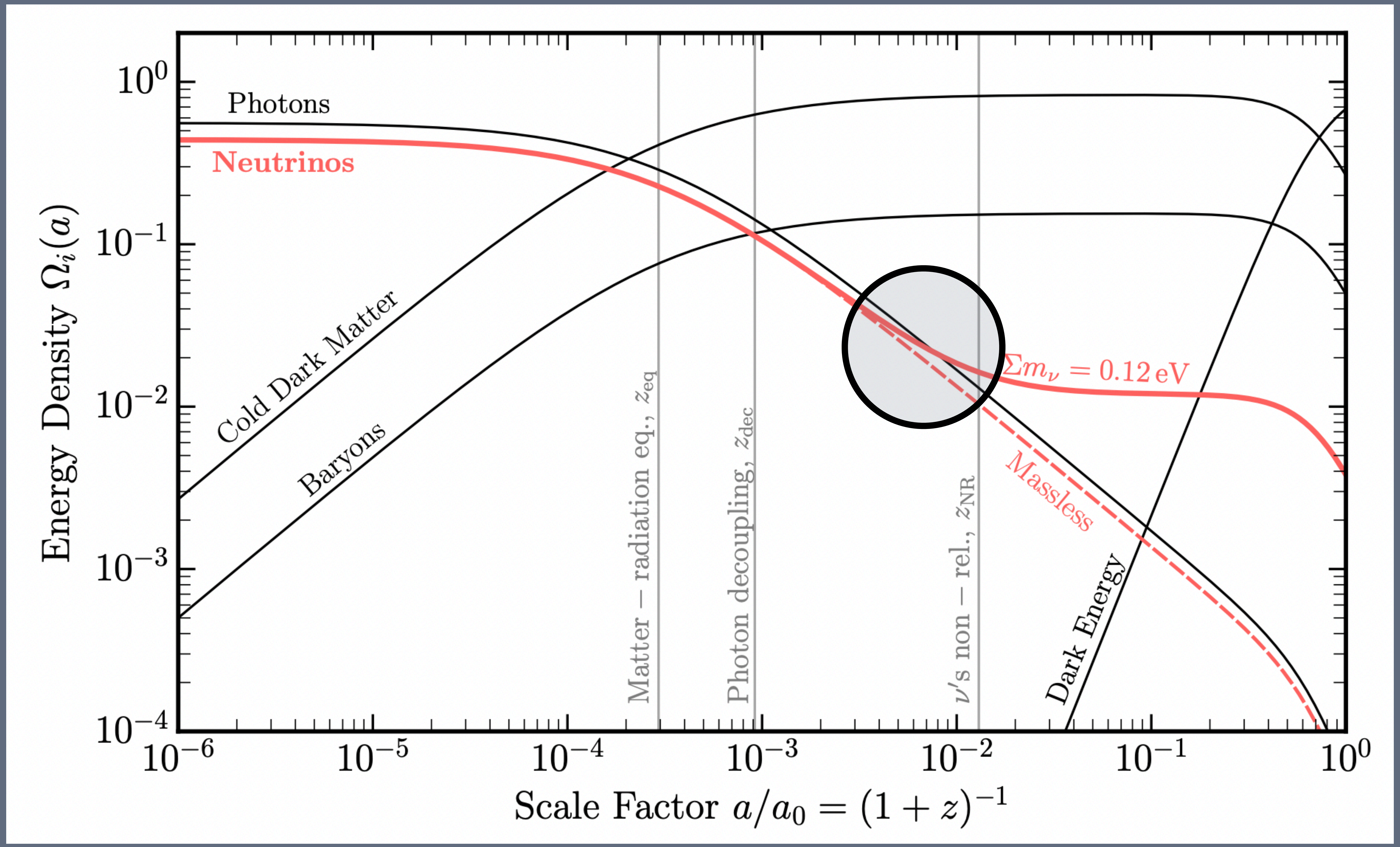
NEUTRINO EQ. OF STATE

Early Universe

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

- 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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Answer: The effect of neutrinos on the CMB is almost purely gravitational, and depends on their behaviour as both a relativistic and non-relativistic species (at late times)

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Question: What properties of neutrinos can we measure from the CMB?

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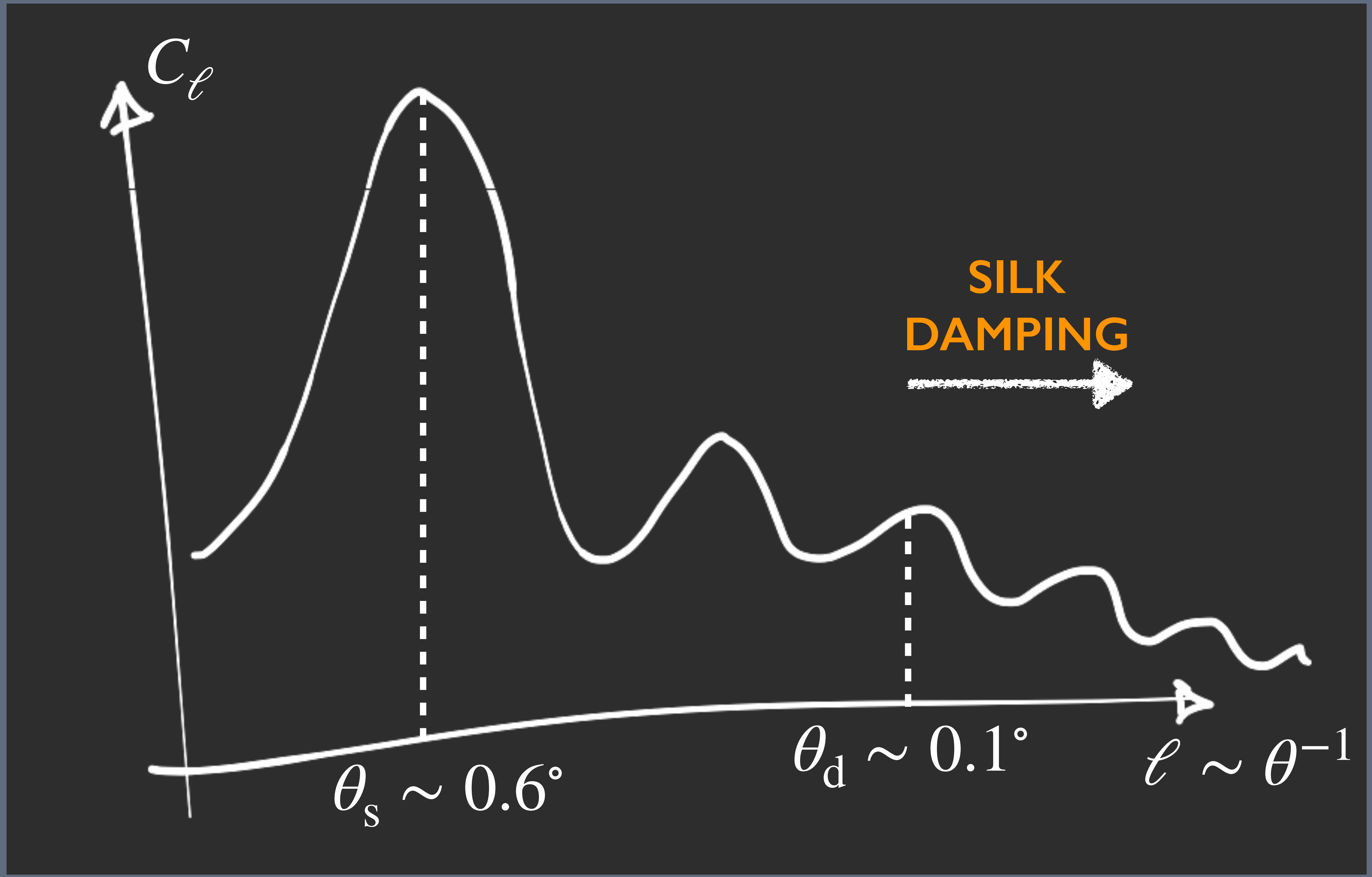
KEY SCALES IN THE CMB

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 sound horizon $\theta_\mathrm{s} = r_\mathrm{s}/D_\mathrm{A}$

B) The damping scale $\theta_\mathrm{d} = r_\mathrm{d}/D_\mathrm{A}$



N_eff

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

$$D_\mathrm{A} \sim \frac{1}{H(z < 1100)}$$

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

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

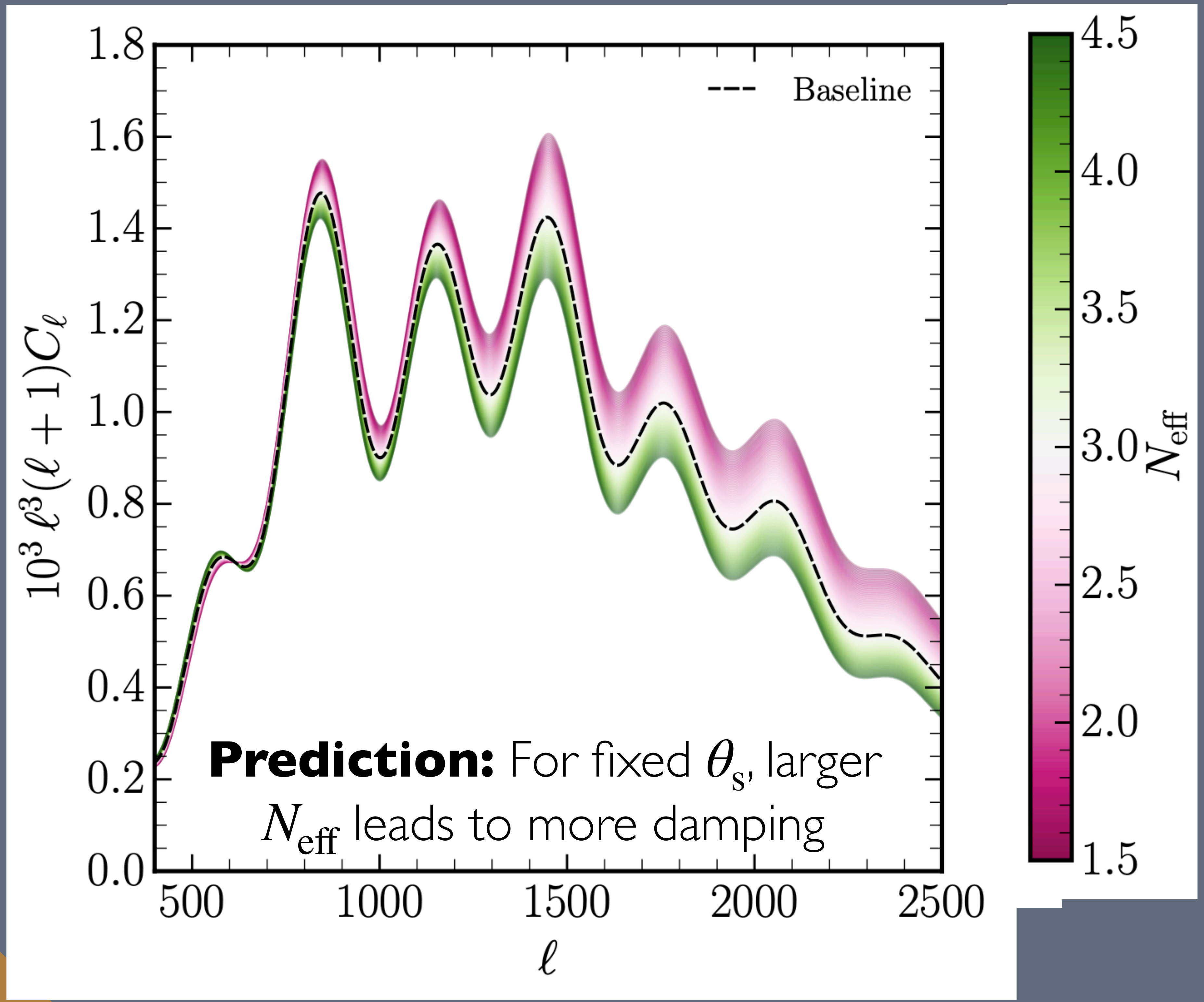
Directly sensitive to $N_{\rm eff}$

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

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:

$$\theta_s/\theta_d \sim H(z \geq 1100)^{-1/2} \sim N_{\rm eff}^{-1/4}$$

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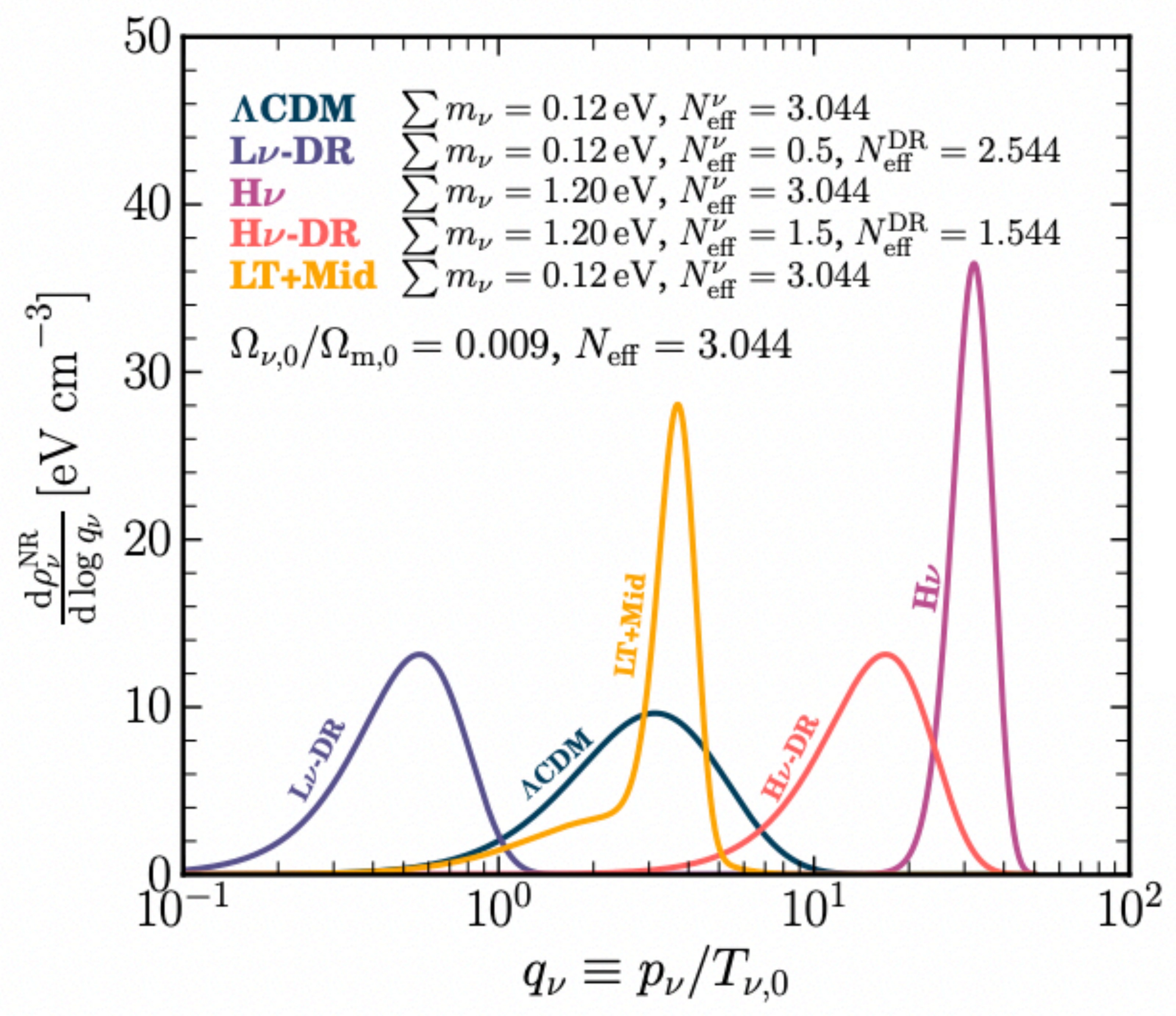
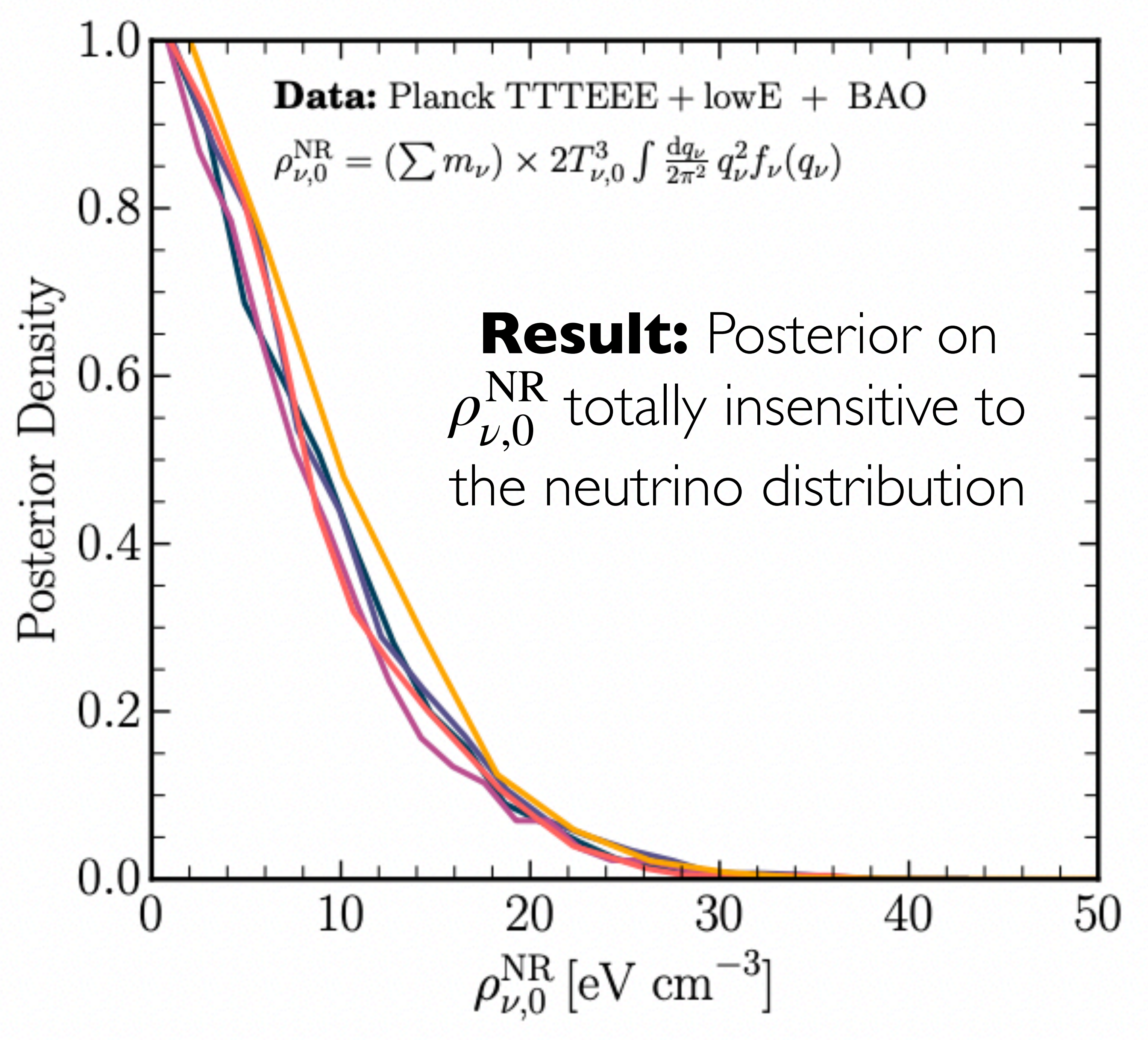
DIRECT MEASUREMENTS OF $\rho_{\nu,0}^{\rm NR}$?

Key Idea: We want to test the claim that you can only directly measure the combination $\rho_{\nu,0}^{\rm NR} = m_\nu n_{\nu,0}$ 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 $N_{\rm eff}$ to maintain $N_{\rm eff} \sim 3$





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Answer: In the most model-independent sense, we can only measure the relativistic (N_{eff}) and non-relativistic (ρ_ν^{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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Question: What happens to neutrinos in and around galactic halos?

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TRAPPING NEUTRINOS IN HALOS

Relic neutrino

(set by cosmology)

Escape Velocity v_{esc}

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

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

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

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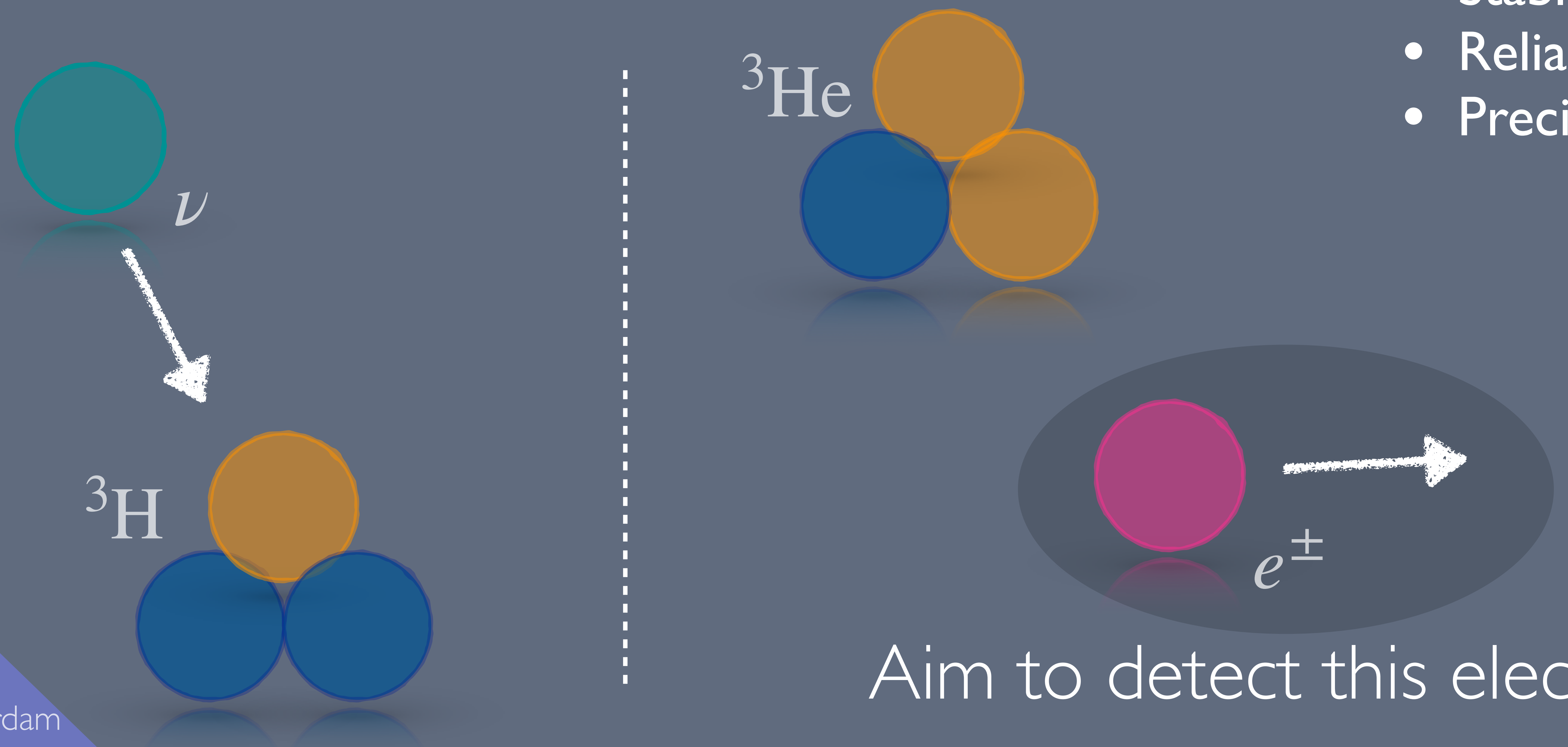
PTOLEMY DETECTION STRATEGY

Inverse β Capture: The current PTOLEMY proposal aims to detect relic neutrinos using inverse β 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



Monochromatic

$$E_e = E_{\text{end},0} + m_\nu$$

Aim to detect this electron

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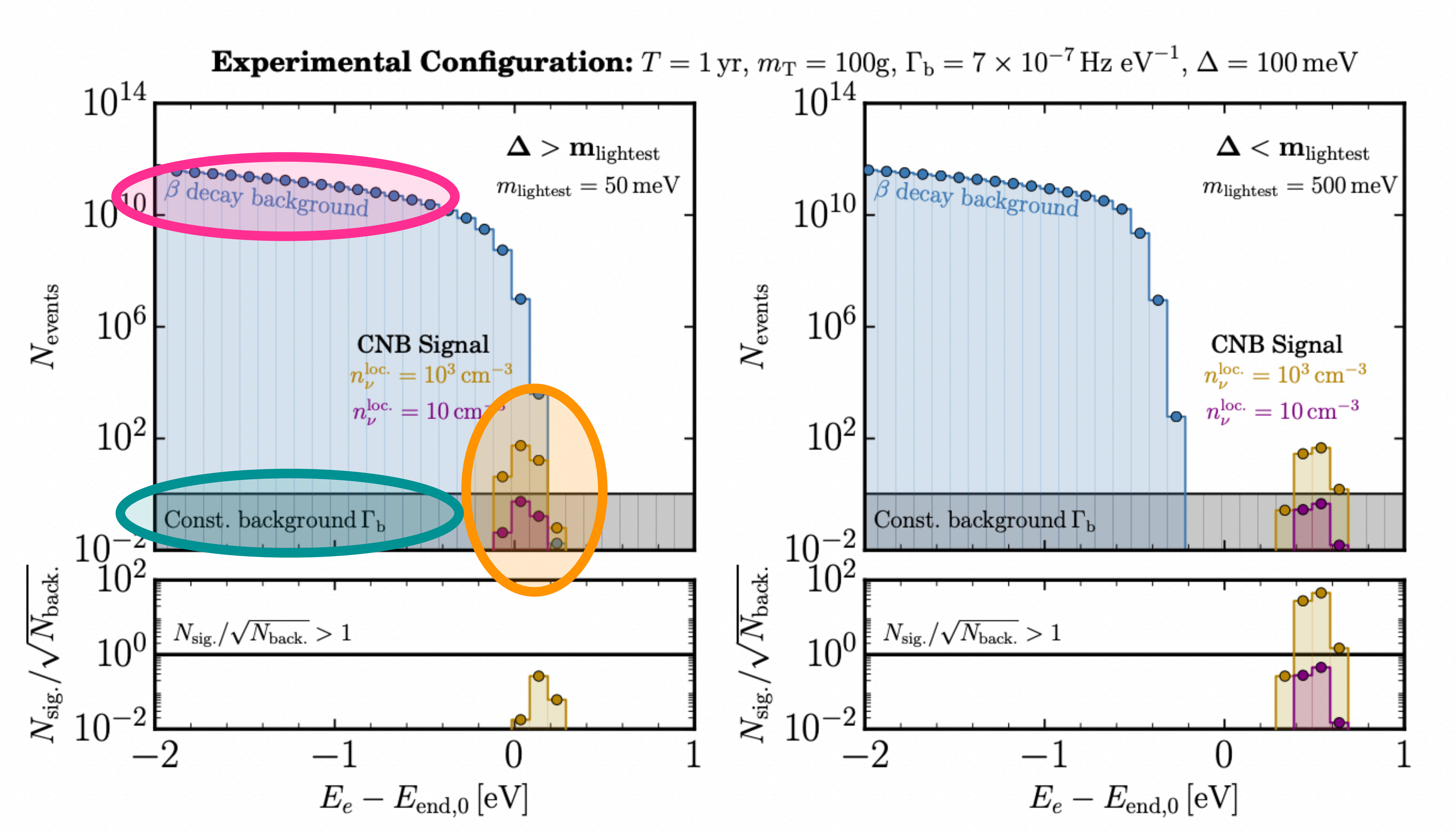
TYPES OF EVENTS AT PTOLEMY

- **Signal Events:** Genuine CNB capture events, $\Gamma_{\text{CNB}} \propto n_\nu^{\text{loc.}} N_T \langle \sigma_{\text{cap.}} v_\nu \rangle$
- **Beta Decay:** Any nuclei that can be used for β-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} Hz (1 or 2 events a year)



Sensitivity: The reach of PTOLEMY is controlled by the detector resolution Δ and the overall signal to background rate $\Gamma_{\text{CNB}}/\Gamma_b$

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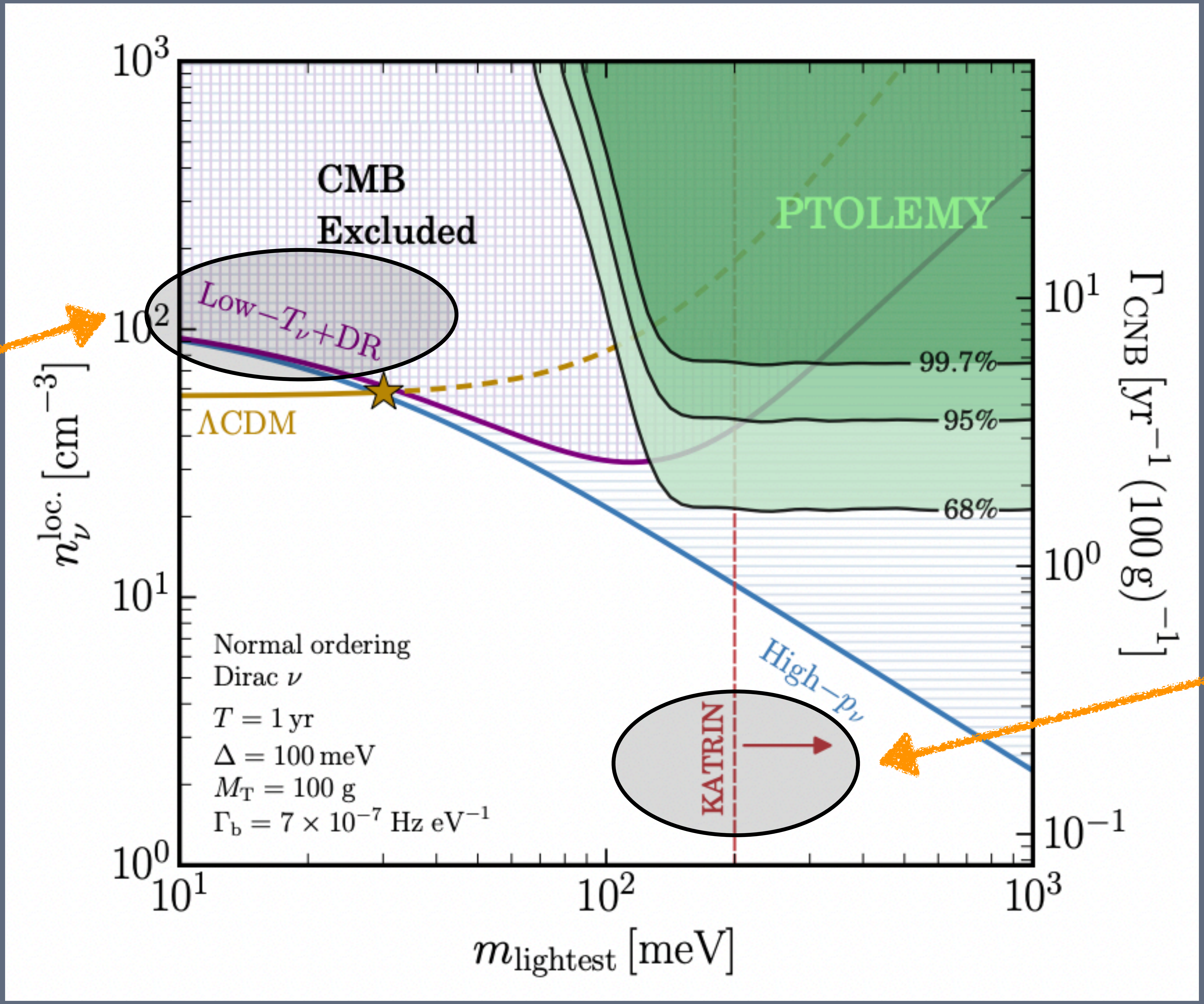
Question: Is the signal separate from the background?

PTOLEMY SENSITIVITY

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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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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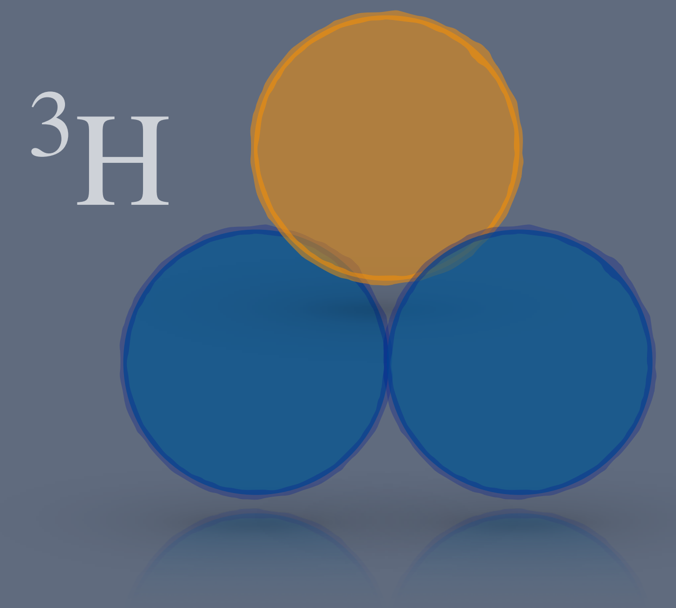
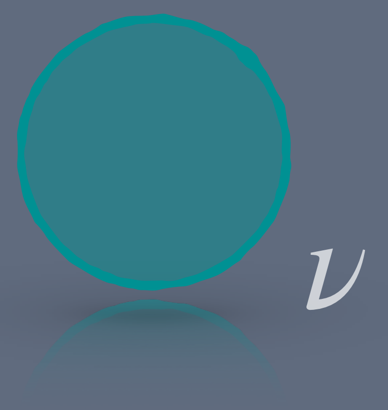
OUTLOOK: WHAT DOES THE FUTURE HOLD?



Experimental Design: Recently, issues around the possible detector resolution have been raised, and alternatives such as heavy nuclei (^{171}Tm etc.) 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.



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SUMMARY: CAN WE DETECT THE CνB?

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STEP #5 DETECTION (AT PTOLEMY)

- **Detection of the CνB** would represent a huge milestone in neutrino physics
- It plays an important role in the **evolution of the early Universe**, 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 $(N_{\rm eff}, \rho_{\nu,0}^{\rm NR})$
- Considering the **wider experimental landscape**, 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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Also, thanks to my collaborators! (Nash Sabti, Miguel Escudero, Thomas Schwetz)

BACKUP SLIDES

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

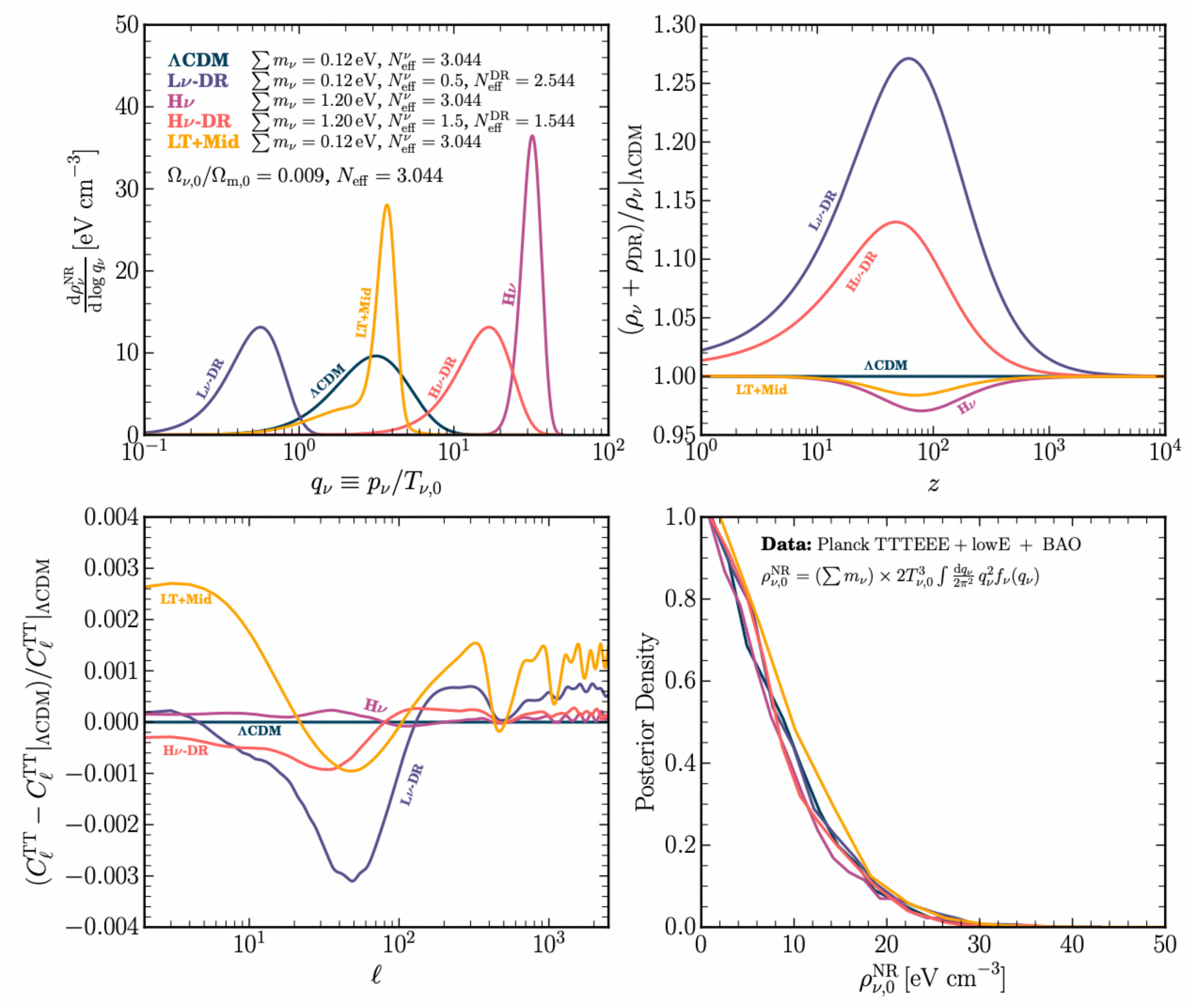
$$\textbf{Gaussian} = \left\{ \begin{array}{l} f_\nu(q_\nu|N_{\rm eff}^\nu, y_*, \sigma_*) = \\ A(N_{\rm eff}^\nu, y_*, \sigma_*) \exp\left(-\frac{(q_\nu - y_*)^2}{2\sigma_*^2}\right) \end{array} \right. ,$$

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

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

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

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



- **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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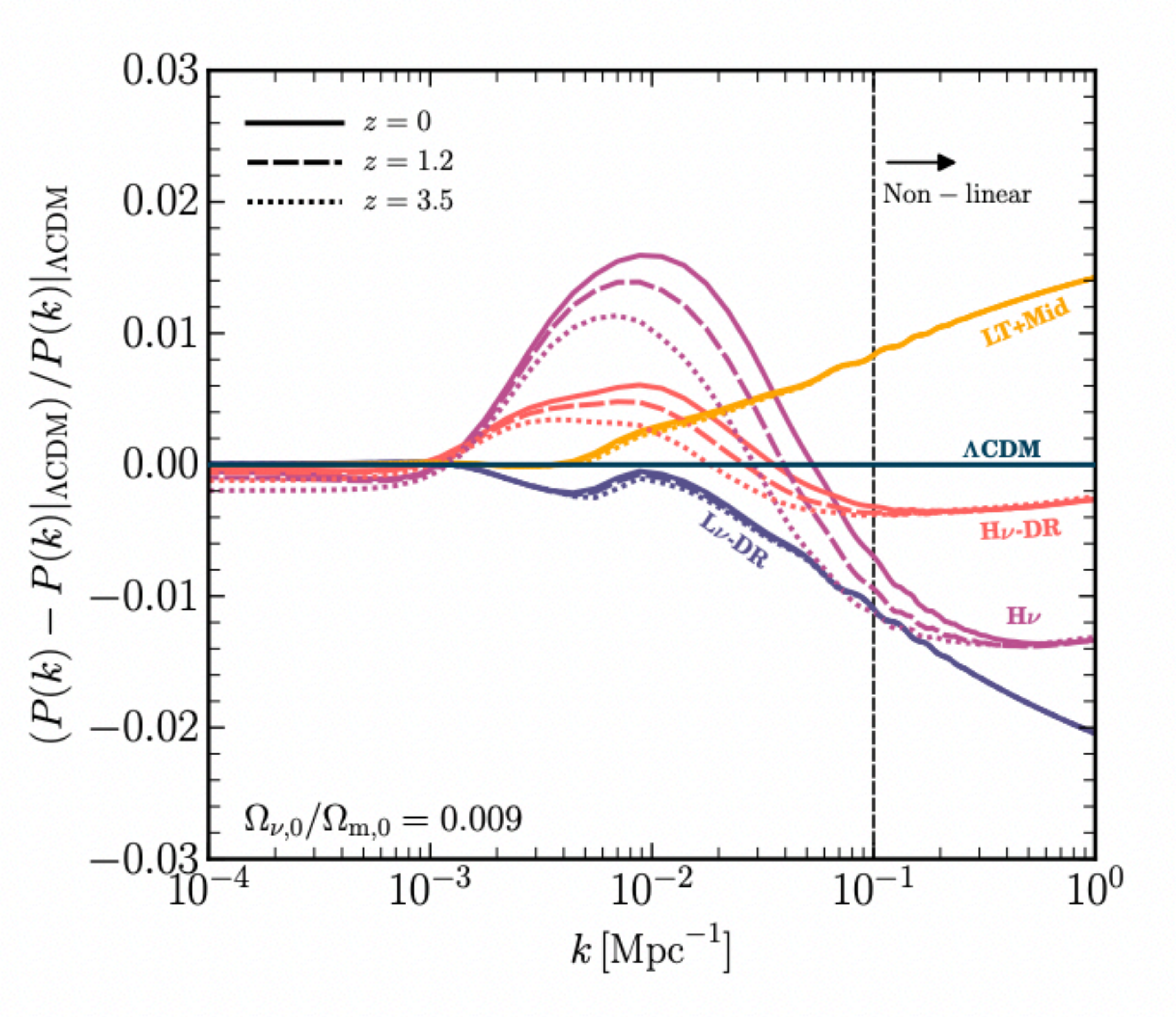

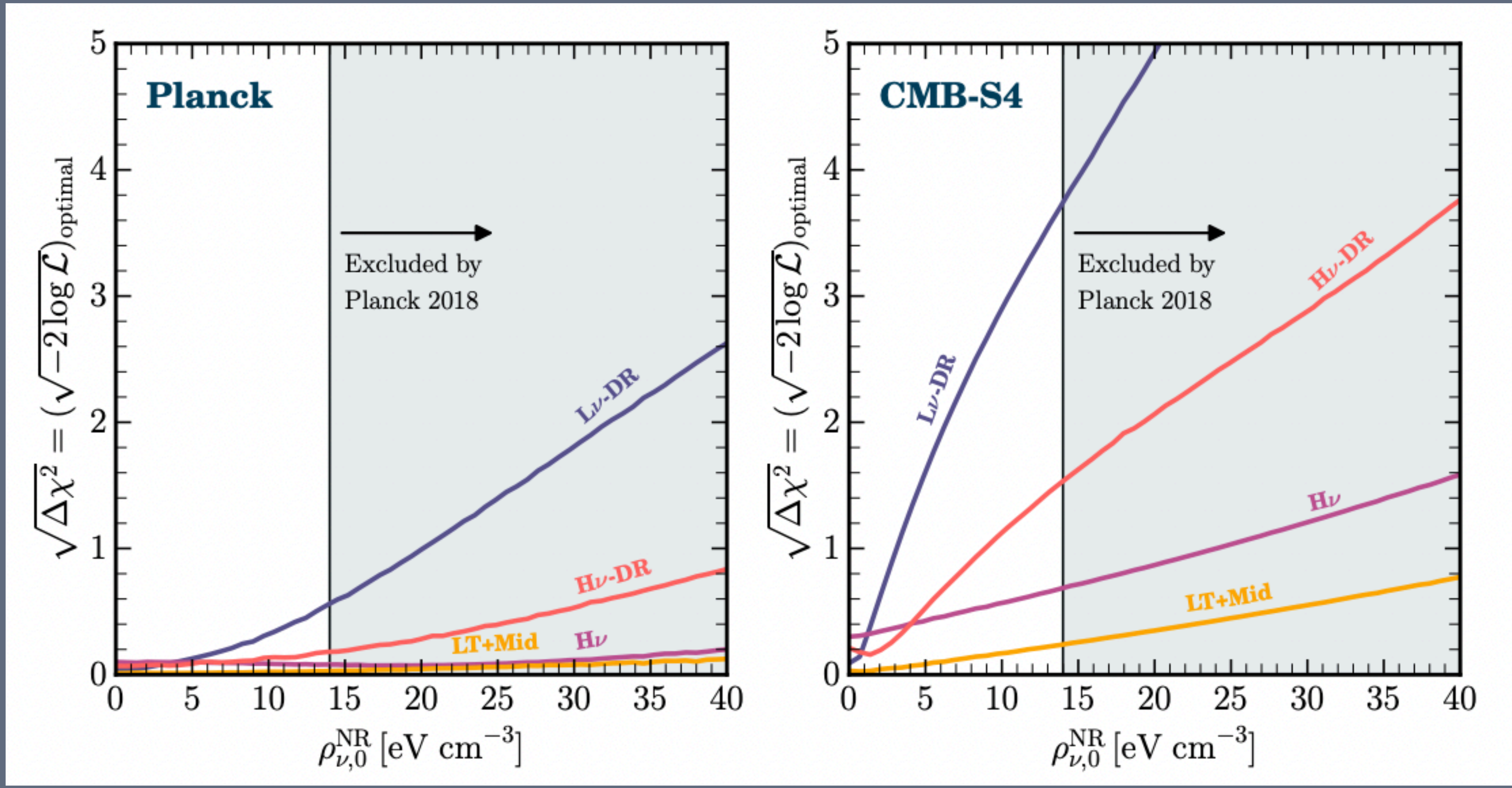

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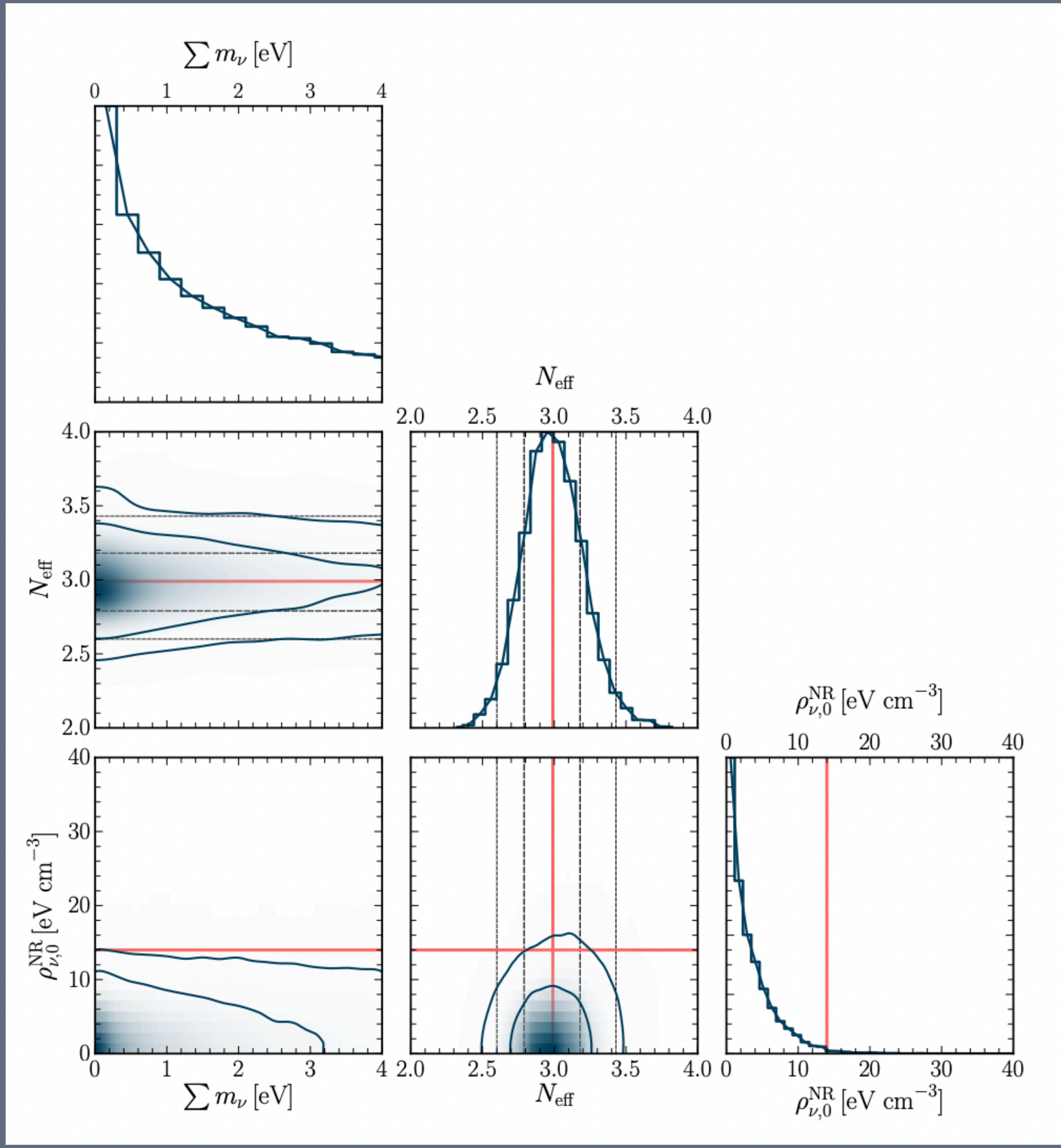
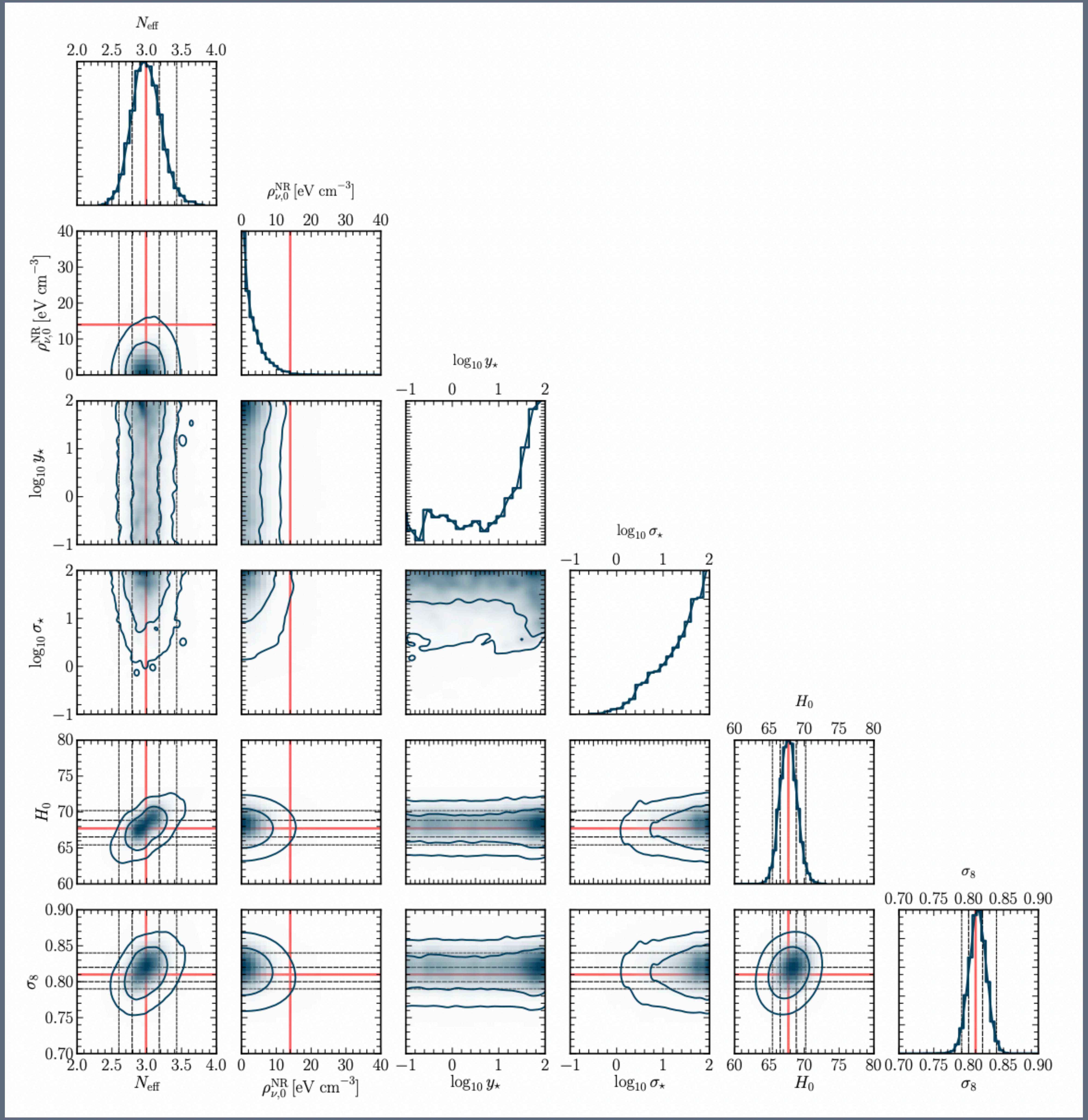
BACKUP





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BACKUP

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

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

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

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

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

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

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

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

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

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

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

$$\frac{\mathrm{d}\widetilde{\Gamma}_\beta}{\mathrm{d}E_e} = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8\ln 2})}\int \mathrm{d}E'\,\frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E'} \times \exp\left[-\frac{(E_e - E')^2}{2(\Delta/\sqrt{8\ln 2})^2}\right],$$

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$$\frac{\mathrm{d}\widetilde{\Gamma}_{\mathrm{CNB}}}{\mathrm{d}E_e} = \frac{c_{\mathrm{D/M}}}{\sqrt{2\pi}(\Delta/\sqrt{8\ln(2)})} \times \sum_i \Gamma_i \exp\left\{-\frac{\left[E_e - (E_{\mathrm{end}}^{m_\nu=0} + m_i)\right]^2}{2\left(\Delta/\sqrt{8\ln(2)}\right)^2}\right\} ,$$

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

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

$$\frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E_e} = \frac{\bar{\sigma}}{\pi^2} N_{\mathrm{T}} \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i)$$

$$N^k(\boldsymbol{\theta}) = T\,\Delta\,\Gamma_{\mathrm{b}} + A_\beta N_\beta^k(T, \Delta, M_{\mathrm{T}}, m_{\mathrm{lightest}}, \delta E_{\mathrm{end}}) + A_{\mathrm{CNB}} N_{\mathrm{CNB}}^k(T, \Delta, M_{\mathrm{T}}, n_\nu^{\mathrm{loc}}, m_{\mathrm{lightest}}, \delta E_{\mathrm{end}}) ,$$

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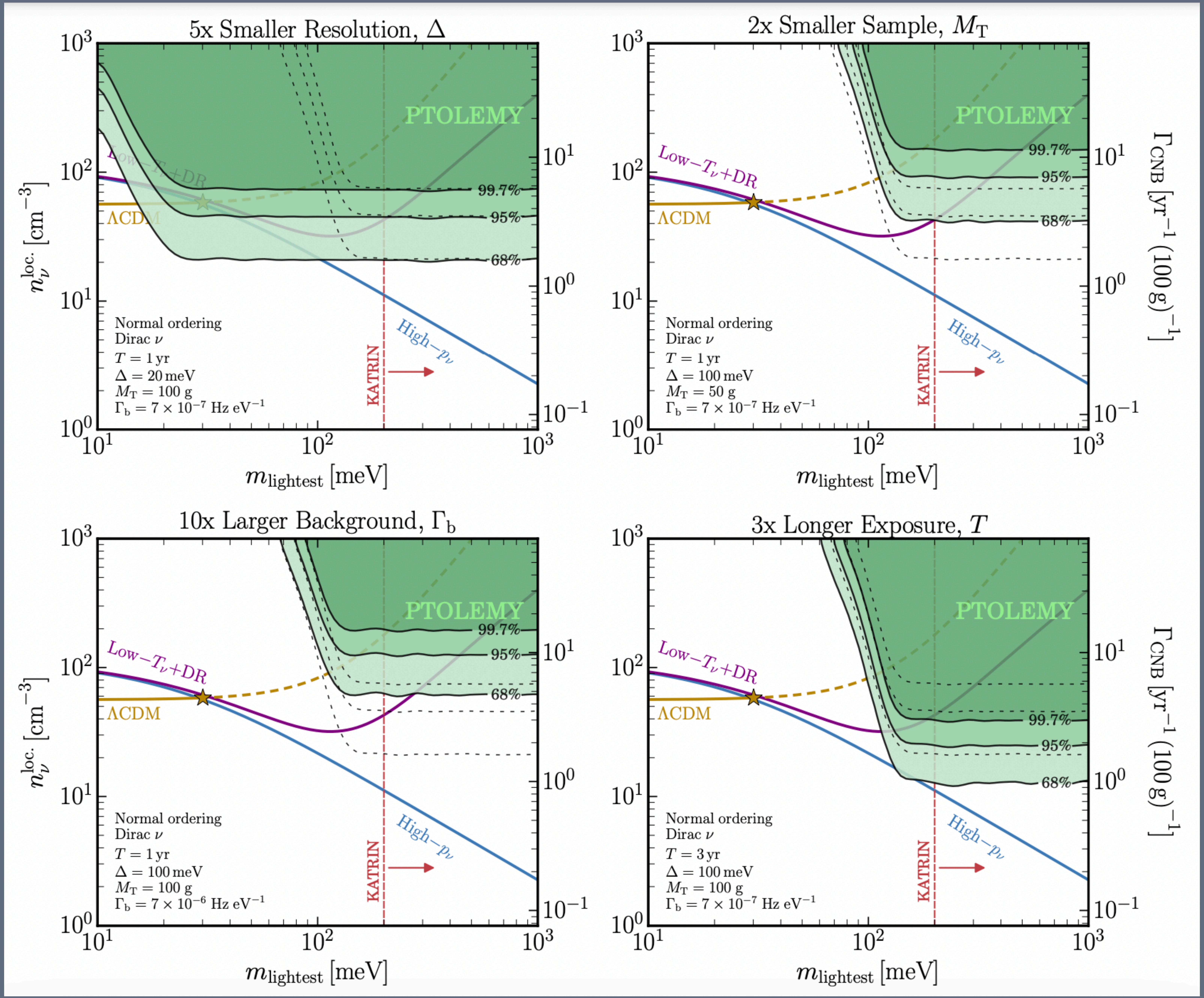

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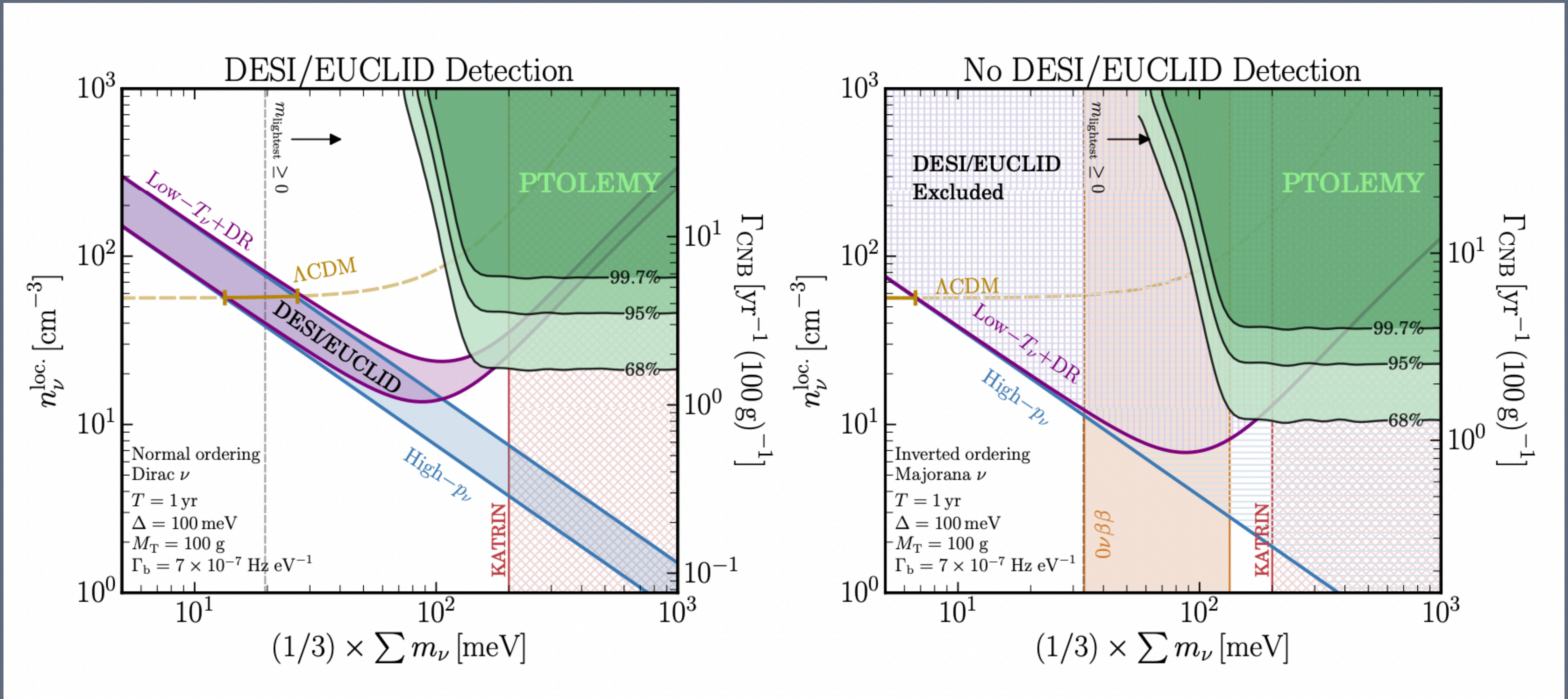

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