Probing Decoupling in Dark Sector with CMB

Work in collaboration with Marilena LoVerde and Chi-Ting Chiang
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A way to test a BSM model with "dark radiation (DR)". Especially about its interaction.

Especially DRs decouple later than neutrino and before photon

- What is Dark Radiation (DR) ?

- After e+ e- annihilation,

$$\rho_r = \frac{\pi^2 k_B^4}{15\hbar^3 c^3}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right] T_\gamma^4 ,$$

- Standard cosmology → $N_{eff} = 3.046$ G. Mangano et al

- DR : nonzero $\Delta N_{eff} = N_{eff} - 3.046$

- Yp (Helium mass fraction)
  → $\Delta N_{eff,BBN} \leq 1.0$ (95% C.L.)

G. Mangano et al

- BAO+CMB
  → $N_{eff,CMB+BAO}=3.15+-0.23$ (68% C.L.)

Planck 2015

- There is a room for non-zero ΔN_{eff}

A way to test a BSM model with "dark radiation (DR)". Especially about its interaction.

Especially DRs decouple later than neutrino and before photon

Some lessons from neutrinos…

Neutrinos decouple at T~1MeV

Then, start to "free-streaming"

Why is this the case?

- Compare **Γ** with H

$$\sigma \sim \left| \quad \right|^2$$

$$\sim G_F^2 T^2$$

$$\frac{\Gamma}{H} \sim \frac{\alpha^2 M_{\rm pl} T^3}{M_W^4} \sim \left(\frac{T}{1\,\mathrm{MeV}} \right)^3$$

- T_{dec} (z_{dec}) hints for interaction!

- $T_{dec} \sim 1$MeV , $z_{dec} \sim$ 1E9

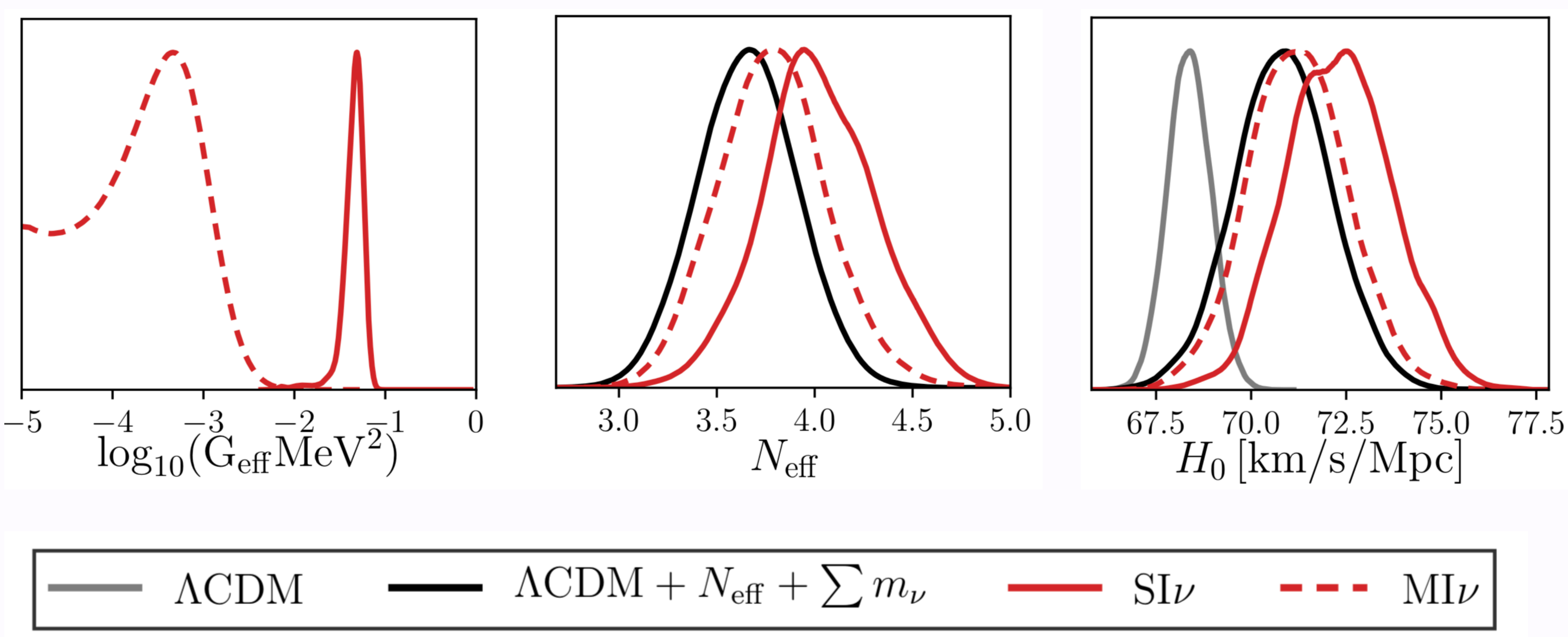
Model 1

Cyr-Racine & Sigurdson (2014)
Kreisch, Cyr-Racine & Dore (2019)

- Self-Interacting Neutrino (SIν)

$$\mathcal{L}_{\rm int} = g_{ij}\bar{\nu}_i\nu_j\varphi$$

- Posterior for $G_{\rm eff}$~g^2/M^2 → multimodal

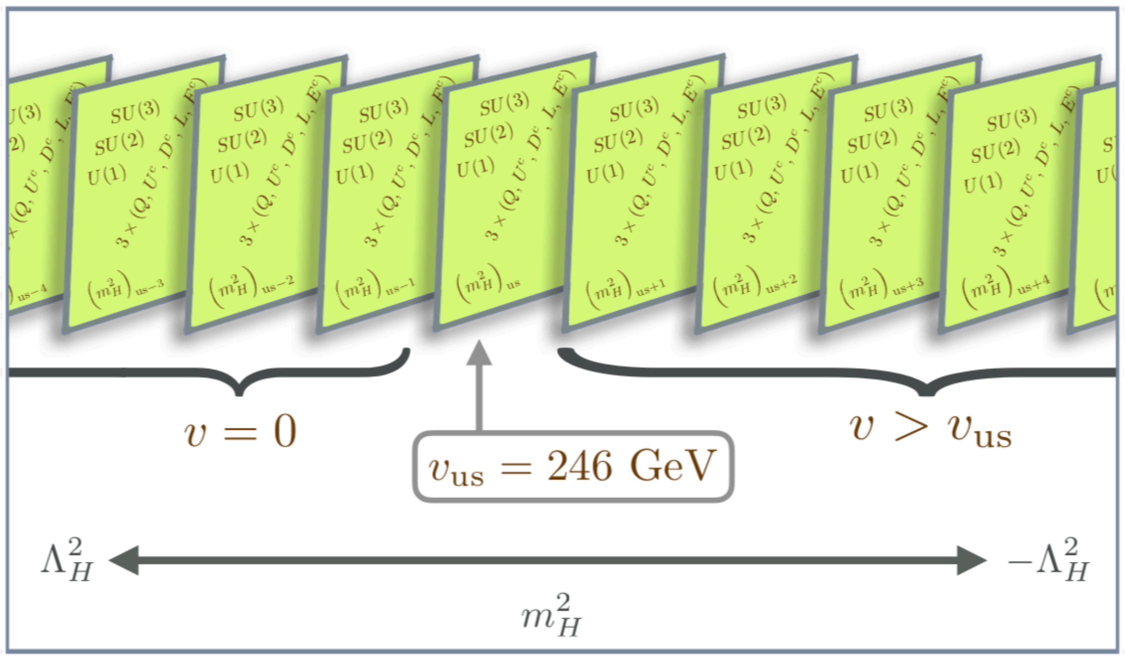


- $Z_{\rm dec,SI\nu}$ ~ 8000

Model 2

N. Arkani-Hamed et al. (2016)

- N-copies of SM



$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}(2\,i + r), \qquad -\frac{N}{2} \leq i \leq \frac{N}{2},$$

$$\left(m_H^2\right)_{\rm us} = -r \times \Lambda_H^2/N \simeq -(88\ {\rm GeV})^2$$

- Each sector produces "its own photons"

sector	heaviest relativistic particle	$g_{*,i}$	$T_i(a_{RH})$ [GeV]	$T_{dec,i}$ [eV]	$z_{dec,i}$	$N_{eff,i}$	$\ell_{dec,i}$
0 (us)	top quark	106.75	100	0.3232	1376	N.A.	325
1	Z boson	95.25	38.22	0.7227	8349	0.081	1511
2	bottom quark	86.25	33.83	0.9696	13083	0.044	2300
3	bottom quark	86.25	30.86	1.1653	17238	0.030	2991

GC, Chiang, LoVerde

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→ …..Changes to γ-b plasma ??

Cosmological PT

- Metric in Newtonian gauge

$$ds^2 = a^2(\tau)[(-1-2\Phi)d\tau^2 + (1-2\Psi)\delta_{ij}dx^i dx^j]$$

- Define

$$\Phi_{\pm} \equiv \Phi \pm \Psi$$

- particle number perturbation per proper volume

$$\delta_a \equiv \frac{\delta n_a}{\bar{n}_a}$$

- and per comoving volume

$$d_a \equiv \delta_a - 3\Psi$$

Cosmological PT

- Perturbed stress-energy tensor

$$T^0_{0,a} = -(\bar{\rho}_a + \delta\rho_a), \quad T^0_{i,a} = (\bar{\rho}_a + \bar{P}_a) v_{i,a},$$

$$T^i_{j,a} = (\bar{P}_a + \delta P_a)\delta^i_j + (\bar{\rho}_a + \bar{P}_a)\Sigma^i_{j,a}$$

- with

$$v_{i,a} = -\nabla_i u_a \,, \qquad \Sigma^i_{j,a} = \frac{3}{2}(\partial^i \partial_j - \frac{1}{3}\delta^i_j \nabla^2)\,\sigma$$

Cosmological PT

- Now CMB. For photon,

$$T^{\nu}_{\mu;\nu} = 0 \quad \rightarrow \quad d''_{\text{fl}} + d_{\text{fl}} = -c_\gamma^{-2}\Phi_+ \quad (y = c_\gamma k\tau)$$

- Einstein eqn tells us

1. $$\Phi_- = -12\pi G a^2 \sum_a (\bar{\rho}_a + \bar{P}_a)\,\sigma$$

2. How $\Phi_\pm \equiv \Phi \pm \Psi$ are related

Decoupling → Split $\mathbf{\Phi}$ and $\mathbf{\Psi}$

($\mathbf{\Phi} - \mathbf{\Psi} = \mathbf{\Phi}_{-} \sim \sigma$)

↓

$\mathbf{\Phi}_{+}$ dynamics changes

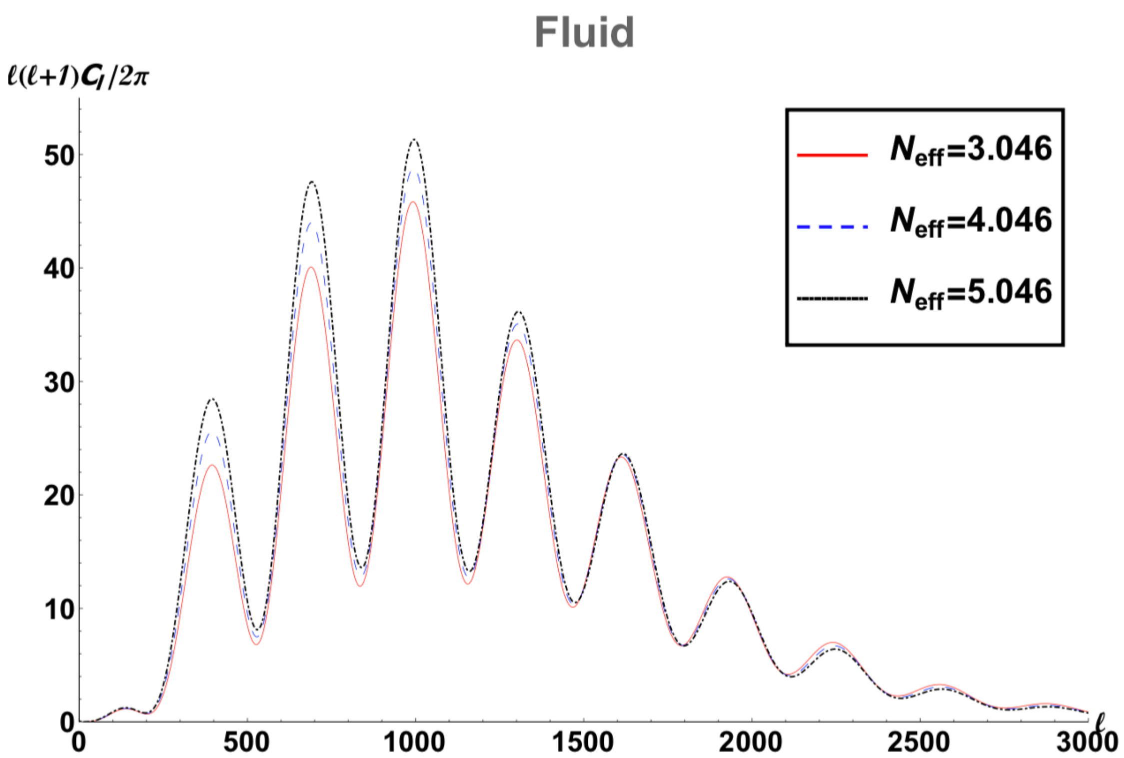
←

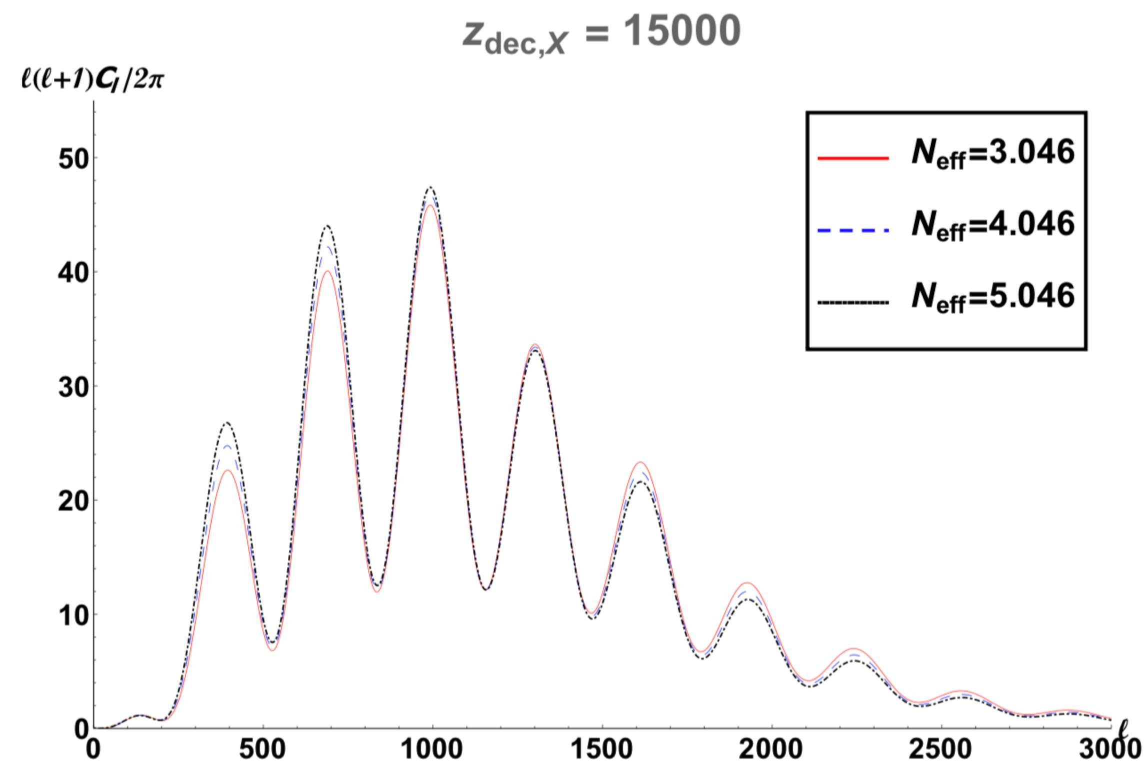
Phase shift in $\boldsymbol{\delta} T_\gamma / T_\gamma \sim d_\gamma$

↘

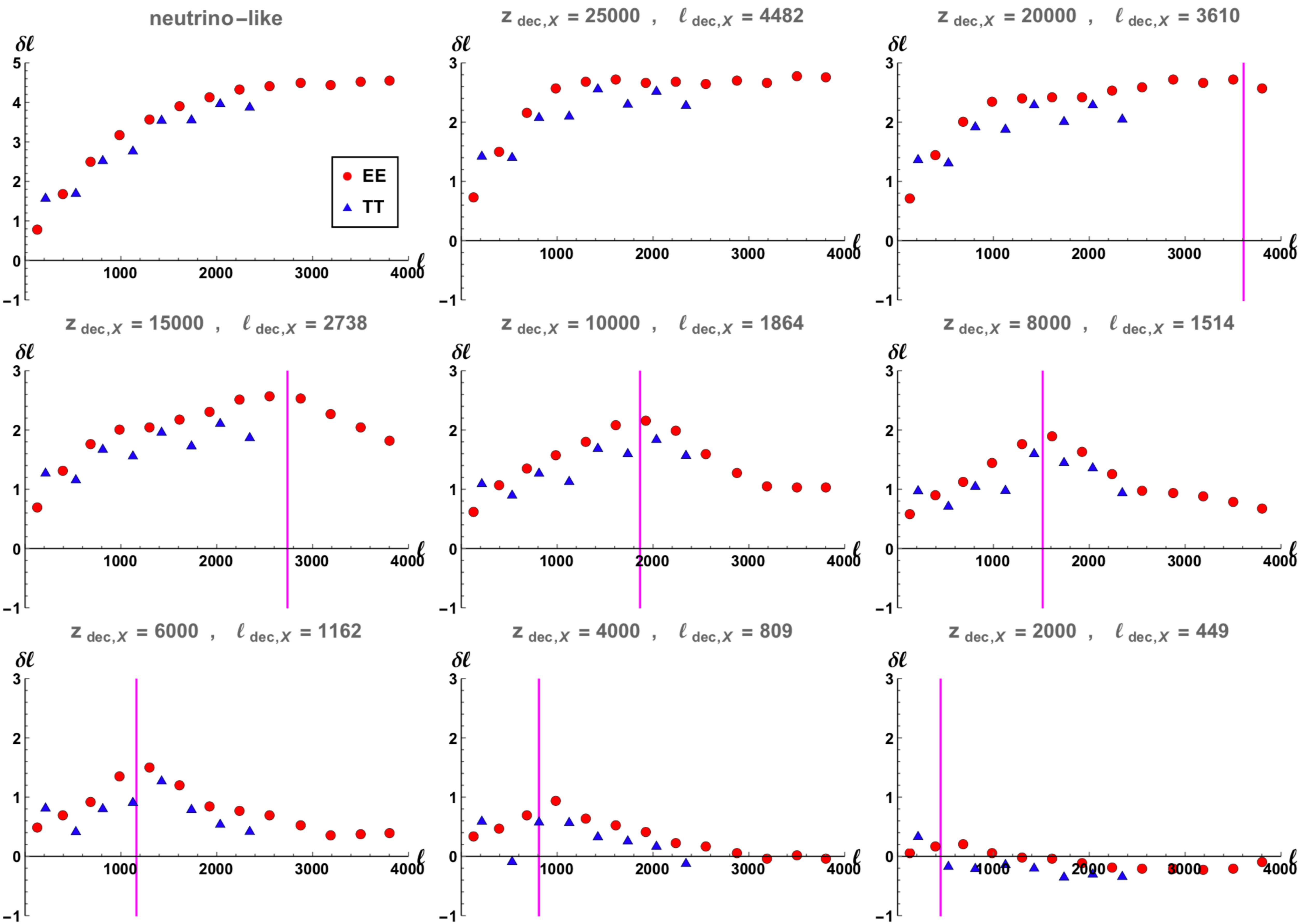
$\boldsymbol{\delta}\ell_{peak}$ in CMB power spectrum

- Compare the identical two cosmologies except for z_{dec} of DR





$$\delta\ell \equiv \ell_{\mathrm{fl}} - \ell(z_{dec,X})$$


neutrino−like
z dec,X = 25000 , ℓ dec,X = 4482
z dec,X = 20000 , ℓ dec,X = 3610
z dec,X = 15000 , ℓ dec,X = 2738
z dec,X = 10000 , ℓ dec,X = 1864
z dec,X = 8000 , ℓ dec,X = 1514
z dec,X = 6000 , ℓ dec,X = 1162
z dec,X = 4000 , ℓ dec,X = 809
z dec,X = 2000 , ℓ dec,X = 449
δℓ
ℓ
EE
TT
1000
2000
3000
4000

Conclusion

For those BSM models with DR,

If you want to test the model,

Compute the decoupling time of DR

Compare 1. CMB power spectrum data

And 2. pseudo-CMB power spectrum with a fluid

Thanks!