CONSTRAINTS ON SELF-INTERACTING RADIATIONS FROM COSMOLOGICAL DATA

Based on:

Thejs Brinckmann, JHC, and Marilena LoVerde, ArXiv:2012.11830

Thejs Brinckmann, JHC, Peizhi Du, and Marilena LoVerde, To Appear

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05/10/2022 Phenomenology 2022 Symposium

Light Relics

- **Relics** : A species of particles that is produced in the early universe and remains at late times
- **Light** : Relativistic at least at epochs probed by the CMB and BBN
- Photons and neutrinos are obvious examples
- Many BSM models predict novel light relics

$N_{\rm eff}$ Parameter

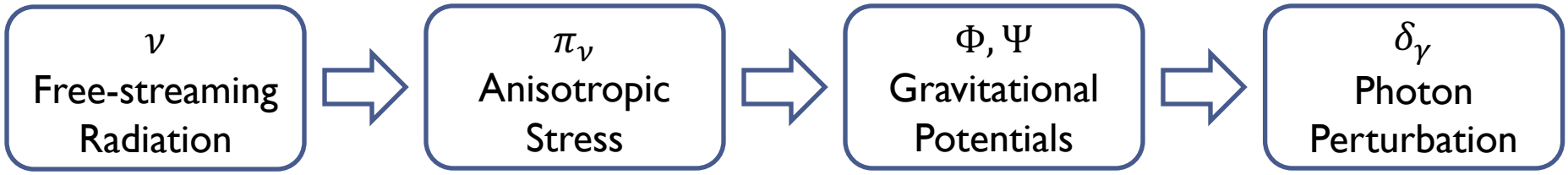
$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu + \rho_X = \rho_\gamma \left(1 + N_{\rm eff} \frac{7}{8} \left(\frac{T_\nu}{T_\gamma} \right)^4 \right)$$

- Most important physical quantity of light relics is energy density
- Total radiation energy density is parameterized with $N_{\rm eff}$
- Larger $N_{\rm eff}$ changes CMB power spectrum
  - Amplitude suppression
  - Phase shift

Beyond $N_{\rm eff}$

Even for the same $N_{\rm eff}$,
interacting and non-interacting radiations
leave **different** imprints on observables

Effects of Neutrinos on CMB



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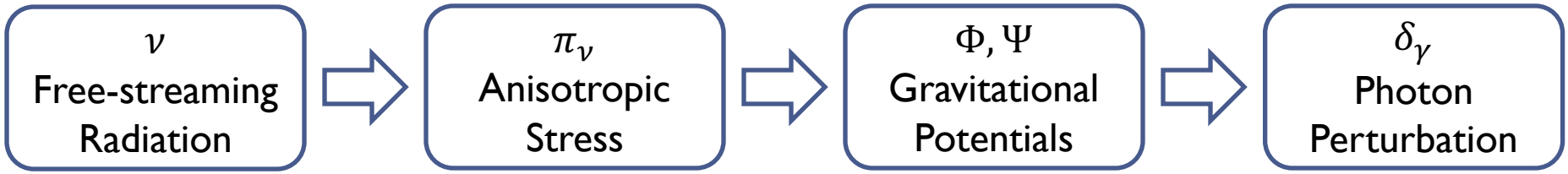

$$F_\nu(\mathbf{n};\eta,\mathbf{k}) = \frac{4\pi}{\rho_\nu a^4}\int \kappa^3 d\kappa f_\nu^{(0)}(\kappa)\cdot\delta f_\nu(\boldsymbol{\kappa};\eta,\mathbf{x})\cdot \mathrm{e}^{i\mathbf{kx}} d^3\mathbf{x} = \sum_{l=0}^{\infty}(2l+1)(-i)^l\cdot F_{\nu,l}(\eta,\mathbf{k})\cdot P_l\left(\frac{\mathbf{kn}}{k}\right)$$

Gorbunov and Rubakov, 2011

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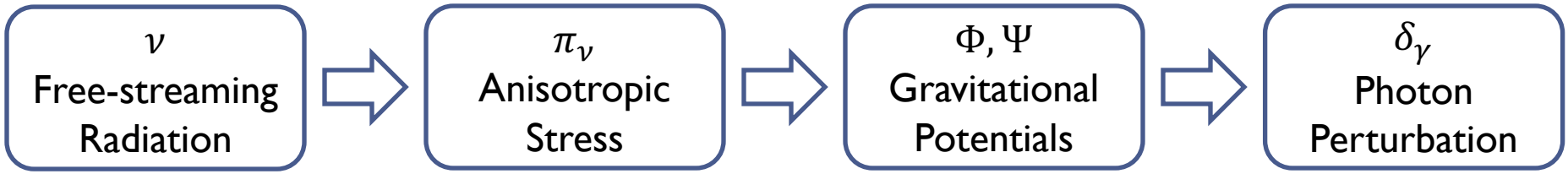

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Neutrino Perturbations

Gorbunov and Rubakov, 2011

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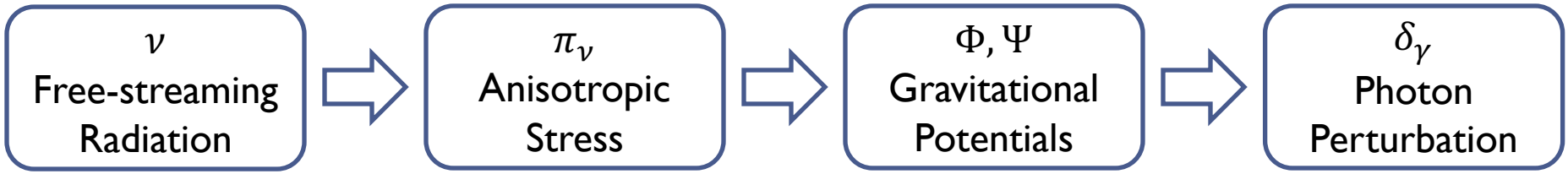

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Neutrino Perturbations

Decompose with Legendre polynomial

Gorbunov and Rubakov, 2011

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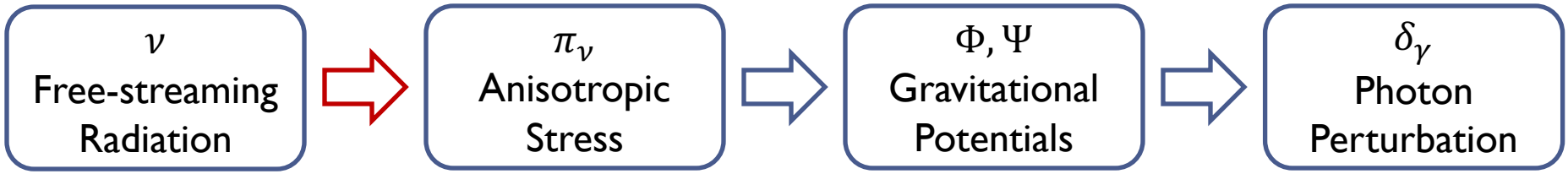

$$\pi_\nu = \frac{3}{16\pi}\int d\mathbf{n}\left(\left(\frac{\mathbf{kn}}{k}\right)^2 - \frac{1}{3}\right)F_\nu = \frac{6\pi}{16\pi}\int_{-1}^{1} dx \frac{2}{3} P_2(x) F_\nu = -\frac{1}{2}F_{\nu,2}$$

Gorbunov and Rubakov, 2011

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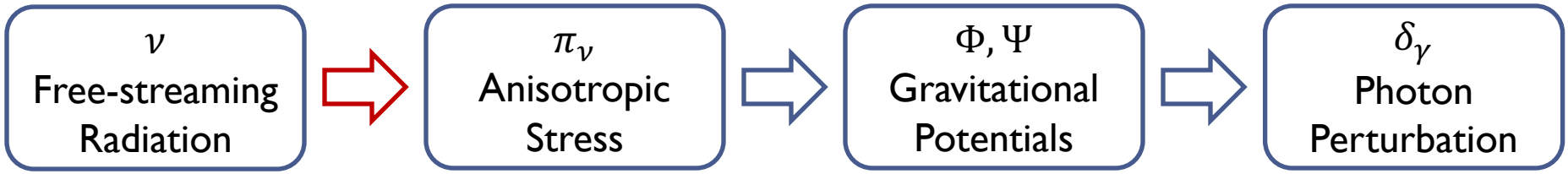

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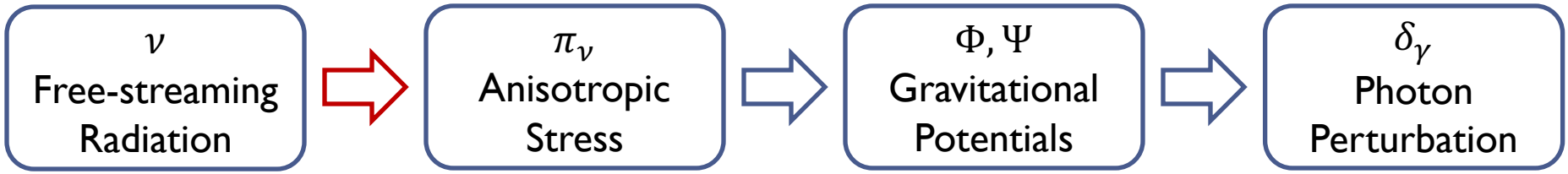

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For neutrino

$$\pi_\nu' = \frac{4}{15}k^2 v_\nu + \frac{3}{10}kF_{\nu,3}$$

Gorbunov and Rubakov, 2011

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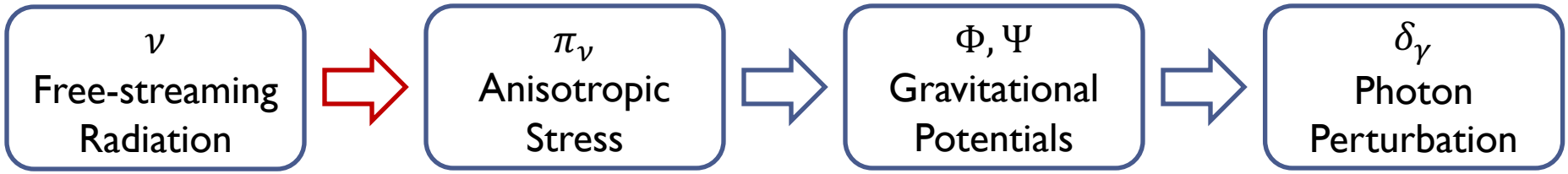

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For photon

$$\pi'_\gamma - \frac{4}{15}k^2 v_\gamma - \frac{3}{10}kF_{\gamma,3} = -\frac{9}{10}\tau'\pi_\gamma$$

Gorbunov and Rubakov, 2011

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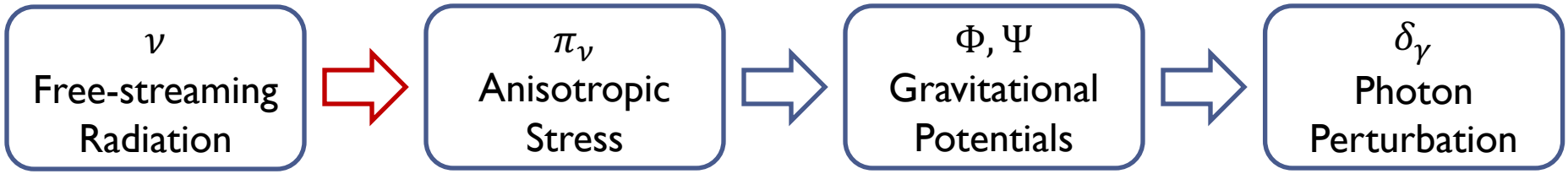

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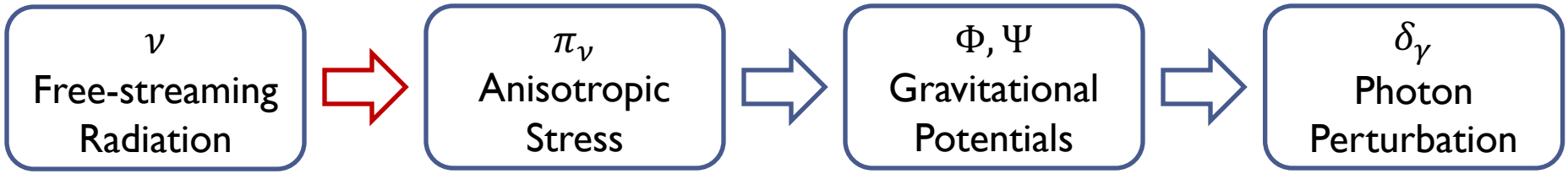

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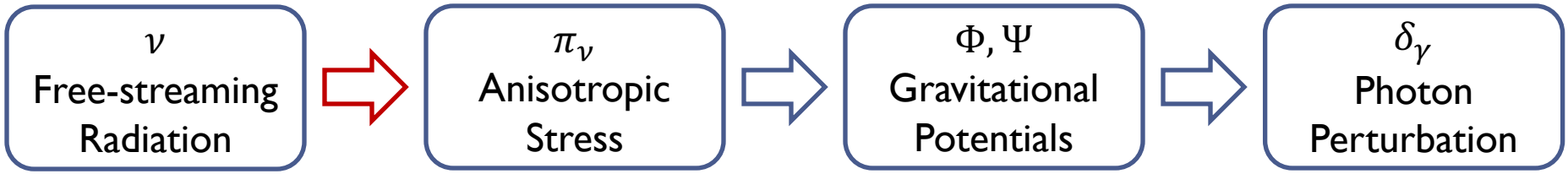
$$\pi'_\gamma - \frac{4}{15}k^2 v_\gamma - \frac{3}{10}kF_{\gamma,3} = -\frac{9}{10}\tau'\pi_\gamma$$

- τ' is the interaction rate
- The interaction suppresses π_γ

Gorbunov and Rubakov, 2011

Effects of Neutrinos on CMB



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For neutrino

$$\pi'_\nu = \frac{4}{15}k^2 v_\nu + \frac{3}{10}kF_{\nu,3}$$

- π_ν evolves freely

For photon

$$\pi'_\gamma - \frac{4}{15}k^2 v_\gamma - \frac{3}{10}kF_{\gamma,3} = -\frac{9}{10}\tau'\pi_\gamma$$

- τ' is the interaction rate
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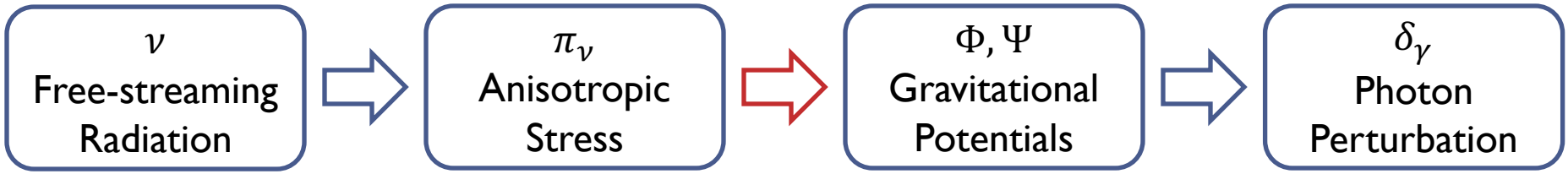
Gorbunov and Rubakov, 2011

Effects of Neutrinos on CMB



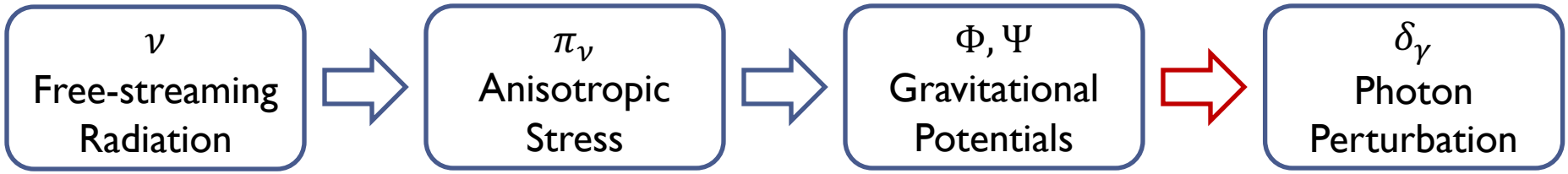
$$ds^2 = a^2(\eta)[(1+2\Phi)d\eta^2 - (1+2\Psi)d\mathbf{x}^2]$$

$$\Delta\left(\Phi+\Psi\right) = -12\pi G a^2 \cdot \left[\left(\rho+p\right)\pi\right]_{tot}$$

- If $\pi = 0$, we have $\Psi = -\Phi$
- In Standard Model, $\Psi = -\left(1+\frac{2}{5}\mathrm{R}_\nu\Phi\right) \approx -1.16\Phi$
  where $R_\nu = \frac{\rho_\nu}{\rho} \approx 0.41$ due to neutrinos

Gorbunov and Rubakov, 2011

Effects of Neutrinos on CMB



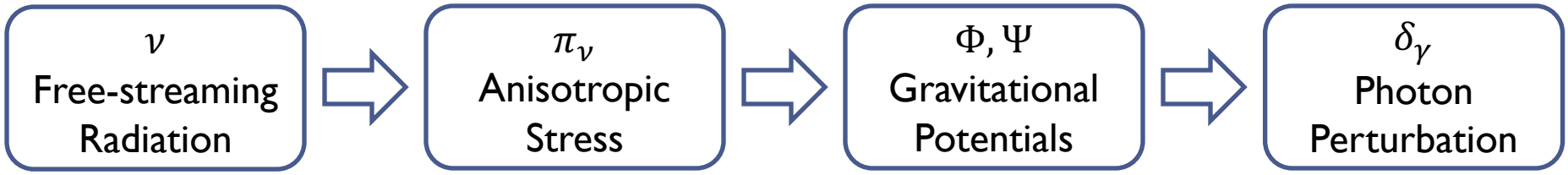
$$\delta'_\gamma - \frac{4k^2}{3} v_\gamma + 4\Psi' = 0,$$

$$v'_\gamma + \frac{1}{4}\delta_\gamma + \pi_\gamma + \Phi = -\left(v_\gamma - v_B\right)\frac{\tau'}{k}$$

- Amplitude suppression
- Phase shift

Gorbunov and Rubakov, 2011

If Neutrinos have Self-Interaction



For neutrino

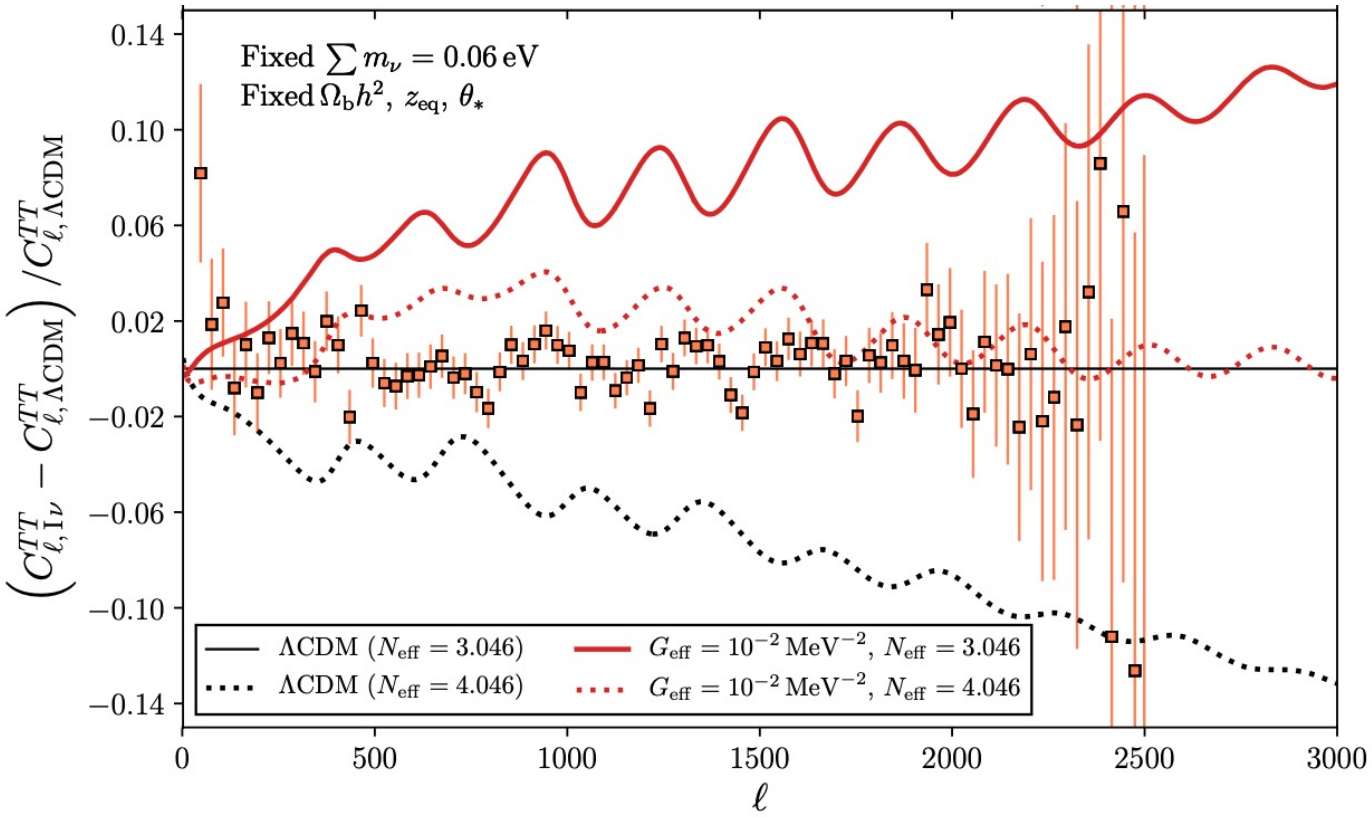
$$\pi'_\nu = \frac{4}{15}k^2 v_\nu + \frac{3}{10}kF_{\nu,3} - \alpha\tau'_\nu\pi_\nu$$

For photon

$$\pi'_\gamma - \frac{4}{15}k^2 v_\gamma + \frac{3}{10}kF_{\gamma,3} = -\frac{9}{10}\tau'\pi_\gamma$$

- π_ν suppressed at early time
- The effect of free-streaming decreases
- Can compensate the effect of additional radiation

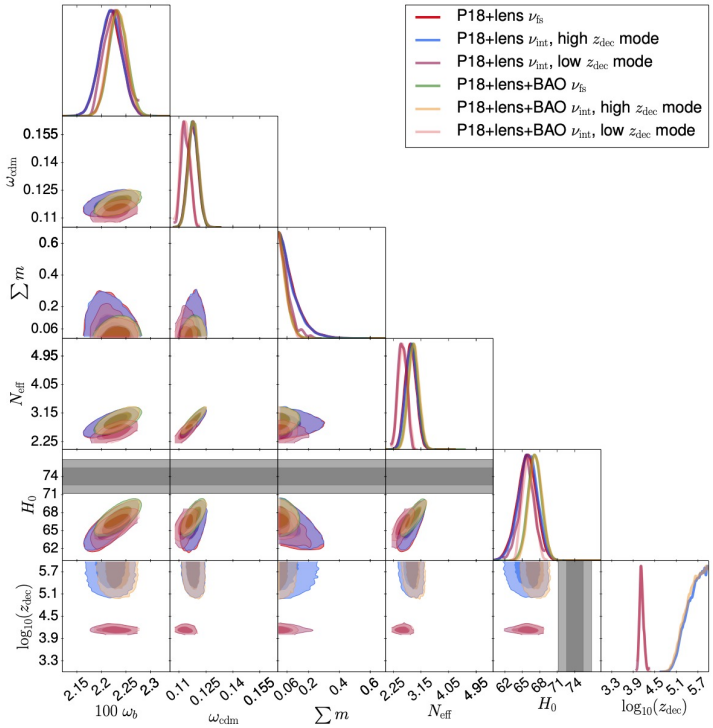
Self-interacting Neutrinos



- Self-interacting neutrino was proposed as a solution to the Hubble tension

Kreisch, Cyr-Racine, Doré, 1902.00534

Self-interacting Neutrinos



	Free-streaming		Self-interacting (Case 1)			
	P18 +lens	+BAO	P18 +lens		+BAO	
			mode 1	mode 2	mode 1	mode 2
ω_b	0.02219 ± 0.00022	0.02234 ± 0.00019	0.02219 ± 0.00022	0.02226 ± 0.00020	0.02233 ± 0.018	0.02230 ± 0.0017
ω_{cdm}	0.1177 ± 0.0029	0.1179 ± 0.0028	0.1180 ± 0.0029	0.1136 ± 0.0024	0.1182 ± 0.0029	0.1135 ± 0.0025
$100 \times \theta_s$	1.04226 ± 0.00051	1.04217 ± 0.00050	1.04225 ± 0.00051	1.04679 ± 0.00055	1.04217 ± 0.00049	1.04678 ± 0.00055
$\ln(10^{10} A_s)$	3.037 ± 0.017	3.042 ± 0.017	3.035 ± 0.017	2.967 ± 0.014	3.040 ± 0.016	2.967 ± 0.014
n_s	0.9573 ± 0.0085	0.9631 ± 0.0071	0.9560 ± 0.0085	0.9209 ± 0.0061	0.9613 ± 0.0071	0.9226 ± 0.0055
z_{reio}	7.57 ± 0.76	7.75 ± 0.73	7.56 ± 0.76	7.45 ± 0.67	7.74 ± 0.72	7.48 ± 0.65
$\log_{10}(z_{\rm dec})$	—	—	> 5.2 (95%CL)	4.14 ± 0.058	> 5.1 (95%CL)	4.14 ± 0.056
$N_{\rm eff}$	2.82 ± 0.18	2.90 ± 0.17	2.84 ± 0.18	2.55 ± 0.14	2.92 ± 0.17	2.57 ± 0.14
$\sum m$	< 0.227 (95%CL)	< 0.108 (95%CL)	< 0.225 (95%CL)	< 0.160 (95%CL)	< 0.107 (95%CL)	< 0.108 (95%CL)
$H_0 \left[\frac{\rm (km/s)}{\rm Mpc}\right]$	65.8 ± 1.6	67.2 ± 1.1	65.9 ± 1.7	65.7 ± 1.3	67.3 ± 1.1	66.1 ± 1.0
S_8	0.835 ± 0.013	0.828 ± 0.012	0.835 ± 0.013	0.825 ± 0.013	0.829 ± 0.011	0.821 ± 0.011
$\ln(E)$	-0.5282×10^3	-0.5320×10^3	-0.5333×10^3	-0.5388×10^3	-0.5370×10^3	-0.5418×10^3
$E_{\rm int}/E_{\rm fs}$	—	—	6.1×10^{-3}	2.5×10^{-5}	6.7×10^{-3}	5.5×10^{-5}
Best fit						
$N_{\rm eff}$	2.846	2.922	2.859	2.572	2.819	2.519
$\log_{10}(z_{\rm dec})$	—	—	5.953	4.119	5.997	4.126
$\chi^2_{\rm eff}$	1011.08	1016.72	1011.67	1018.35	1016.94	1023.39
$\Delta\chi^2_{\rm eff}$	—	—	+0.59	+7.27	+0.22	+6.67

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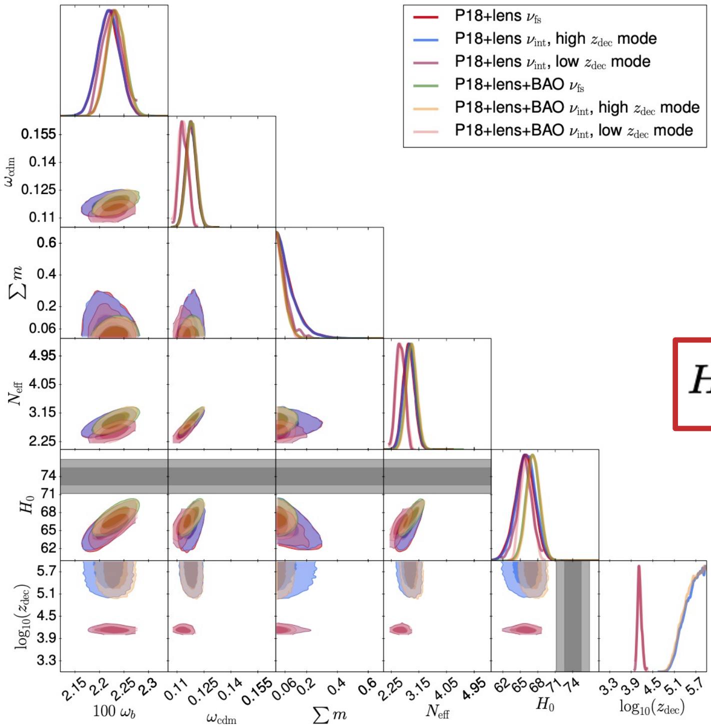
Self-interacting Neutrinos



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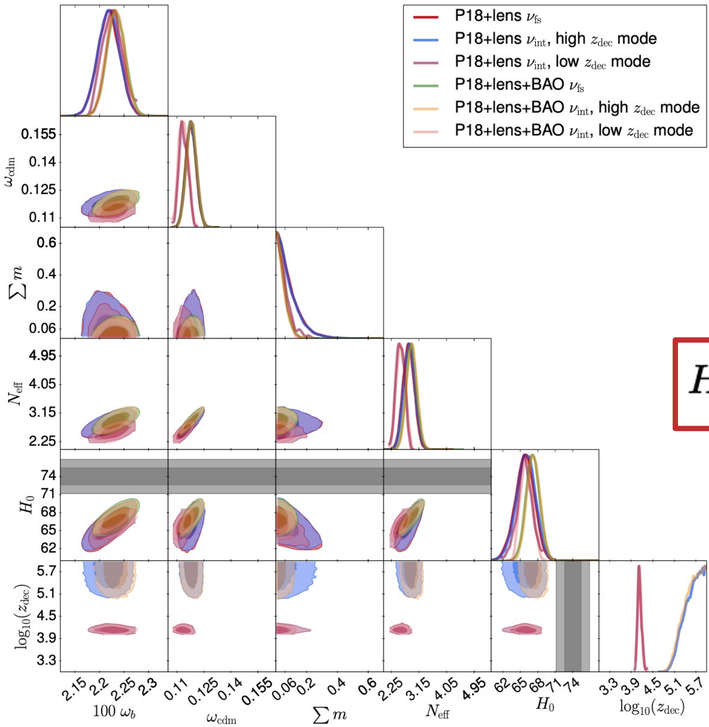

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- Unfortunately, this is not true with the most recent data
- CMB polarization data constrain N_{eff} tightly

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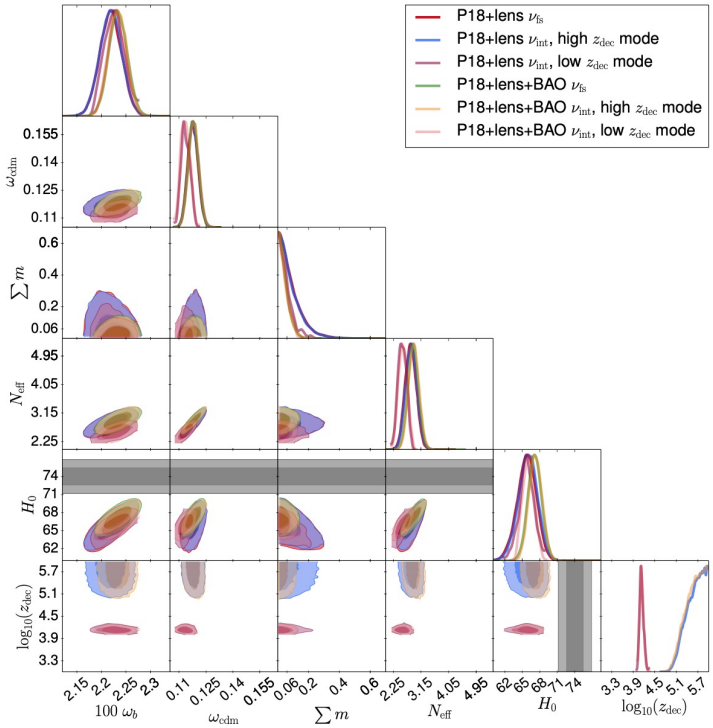

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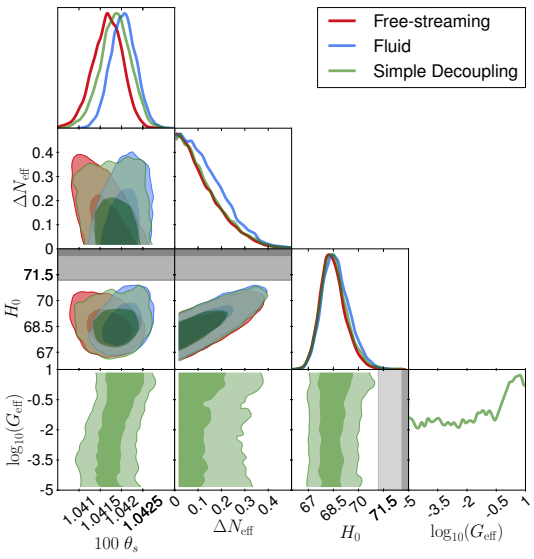
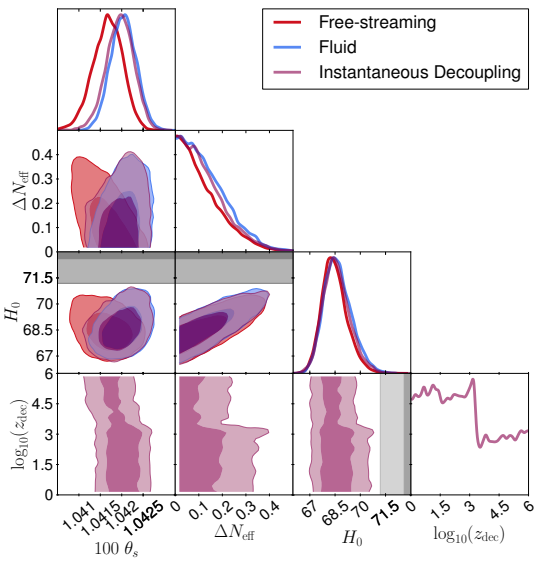
	P18 +lens	+BAO	P18 +lens		+BAO	
			mode 1	mode 2	mode 1	mode 2
ω_b	0.02219 ± 0.00022	0.02234 ± 0.00019	0.02219 ± 0.00022	0.02226 ± 0.00020	0.02233 ± 0.018	0.02230 ± 0.0017
ω_{cdm}	0.1177 ± 0.0029	0.1179 ± 0.0028	0.1180 ± 0.0029	0.1136 ± 0.0024	0.1182 ± 0.0029	0.1135 ± 0.0025
$100 \times \theta_s$	1.04226 ± 0.00051	1.04217 ± 0.00050	1.04225 ± 0.00051	1.04679 ± 0.00055	1.04217 ± 0.00049	1.04678 ± 0.00055
$\ln(10^{10} A_s)$	3.037 ± 0.017	3.042 ± 0.017	3.035 ± 0.017	2.967 ± 0.014	3.040 ± 0.016	2.967 ± 0.014
n_s	0.9573 ± 0.0085	0.9631 ± 0.0071	0.9560 ± 0.0085	0.9209 ± 0.0061	0.9613 ± 0.0071	0.9226 ± 0.0055
z_{reio}	7.57 ± 0.76	7.75 ± 0.73	7.56 ± 0.76	7.45 ± 0.67	7.74 ± 0.72	7.48 ± 0.65
$\log_{10}(z_{\rm dec})$	—	—	> 5.2 (95%CL)	4.14 ± 0.058	> 5.1 (95%CL)	4.14 ± 0.056
$N_{\rm eff}$	2.82 ± 0.18	2.90 ± 0.17	< 0.107 (95%CL)		< 0.108 (95%CL)	
	< 0.227 (95%CL)	< 0.108 (95%CL)				
$H_0 \left[\frac{\rm (km/s)}{\rm Mpc}\right]$	65.8 ± 1.6	67.2 ± 1.1	65.9 ± 1.7	65.7 ± 1.3	67.3 ± 1.1	66.1 ± 1.0
S_8	0.835 ± 0.013	0.828 ± 0.012	0.835 ± 0.013	0.825 ± 0.013	0.829 ± 0.011	0.821 ± 0.011
$\ln(E)$	-0.5282×10^3	-0.5320×10^3	-0.5333×10^3	-0.5388×10^3	-0.5370×10^3	-0.5418×10^3
$E_{\rm int}/E_{\rm fs}$	—	—	6.1×10^{-3}	2.5×10^{-5}	6.7×10^{-3}	5.5×10^{-5}
Best fit						
$N_{\rm eff}$	2.846	2.922	2.859	2.572	2.819	2.519
$\log_{10}(z_{\rm dec})$	—	—	5.953	4.119	5.997	4.126
$\chi^2_{\rm eff}$	1011.08	1016.72	1011.67	1018.35	1016.94	1023.39
$\Delta\chi^2_{\rm eff}$	—	—	+0.59	+7.27	+0.22	+6.67

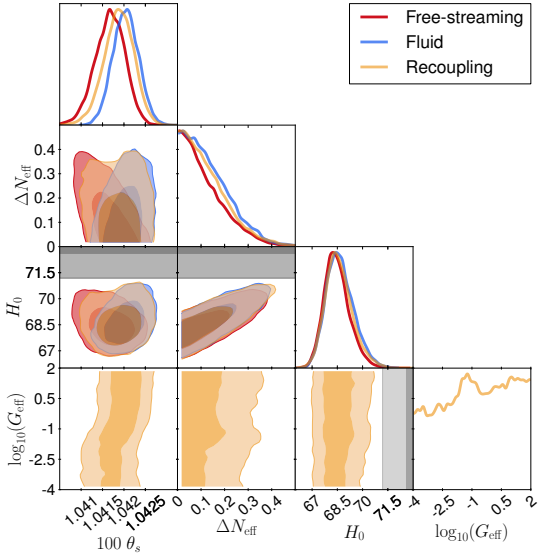
- Unfortunately, this is not true with the most recent data
- CMB polarization data constrain $N_{\rm eff}$ tightly
- Instead, we put constraints on self-interacting neutrinos

Brinckmann, JHC, and LoVerde, ArXiv:2012.11830

Self-interacting Dark Radiation







Preliminary

- We put constraints on self-interacting radiation for different types
  - Through a heavy mediator $\left(\Gamma \sim \frac{T^5}{\Lambda^4}\right)$: Decoupling
  - ϕ^4 theory $(\Gamma \sim g^2 T\ )$: Recoupling
  - Dark recombination : Instantaneous decoupling

- Constraints depends on model parameters

Conclusions

- Interacting and non-interacting radiations have different effects on observables

- We study constraints on self-interacting neutrinos and self-interacting dark radiations from cosmological data

THANK YOU