SoET SCHOOL OF ENERGY TECHNOLOGY

Vikram Discussion on Neutrino Astrophysics - 2025
PRL Ahmedabad

PANDIT DEENDAYAL ENERGY UNIVERSITY · A RESERVOIR OF KNOWLEDGE ·

Self-Interacting Neutrinos and their connection with 21-cm Radiation and GRB

Based on: M. Dhuria and B. Gupta Teli , Phys.Rev.D 110(2024)12,123033 (arXiv: 2406.19279 [hep-ph]),
M. Dhuria, Phys.Rev.D109(2024)6,063007 (arXiv: 2309.12264[hep-ph]),

Mansi Dhuria
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Gandhinagar, Gujarat, India

Outline

- Brief overview of the self-interacting nature of SM neutrinos and their effect on cosmology.
- Various astrophysical and cosmological implications of self-interacting neutrinos.
- Overview of 21-cm Radiation Physics .
- Connection of self-interacting neutrinos with 21-cm radiation
- Connection of self-interacting neutrinos with GRB bursts.
- Summary and open directions.

Neutrinos: possible self-interactions

In Standard model, we have three active neutrinos $\nu_a,\ a = e, \mu, \tau$

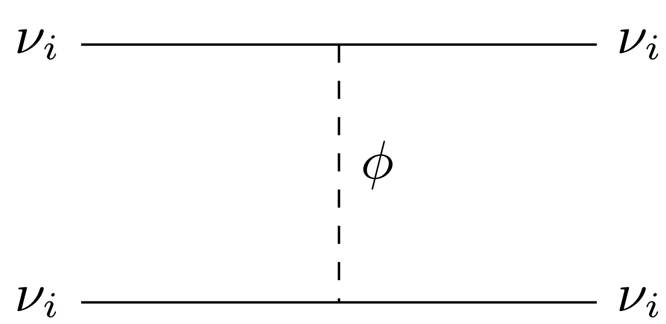
General Understanding: Neutrinos interact "weakly" with the rest, as well as with themselves.

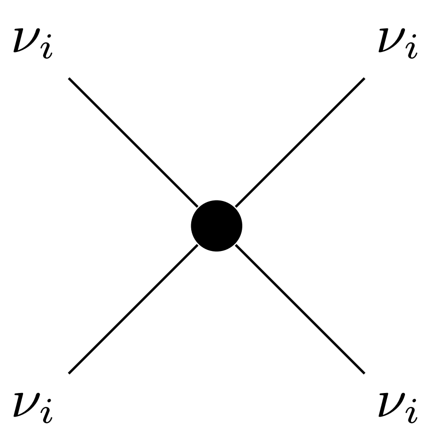
Neutrinos play an important role in early Universe Cosmology. The results from CMB measurements put stringent constraints on the masses of neutrino $m_\nu < 0.12$ eV.

A new Phenomenological Model motivated by Cosmology

$$\mathscr{L} \supset \frac{1}{2} g_{ij} \bar{\nu}_i \nu_j \phi, \quad g_{ij} = g\delta_{ij}$$

$$\mathscr{L} \supset G_{\text{eff}} \bar{\nu}\nu\bar{\nu}\nu, \quad G_{\text{eff}} = \frac{g^2}{m_\phi^2}$$





The mediator could be scalar or vector mediator.

Typical mass of mediator : $m_\phi \geq MeV$

Cosmology of Self-Interacting Neutrinos

The thermal average scattering cross section of neutrino:

$$\langle \sigma v \rangle \sim (G_{\text{eff}})^2 T_\nu^2$$

The neutrino interaction rate in the presence of new self-interaction of neutrinos:

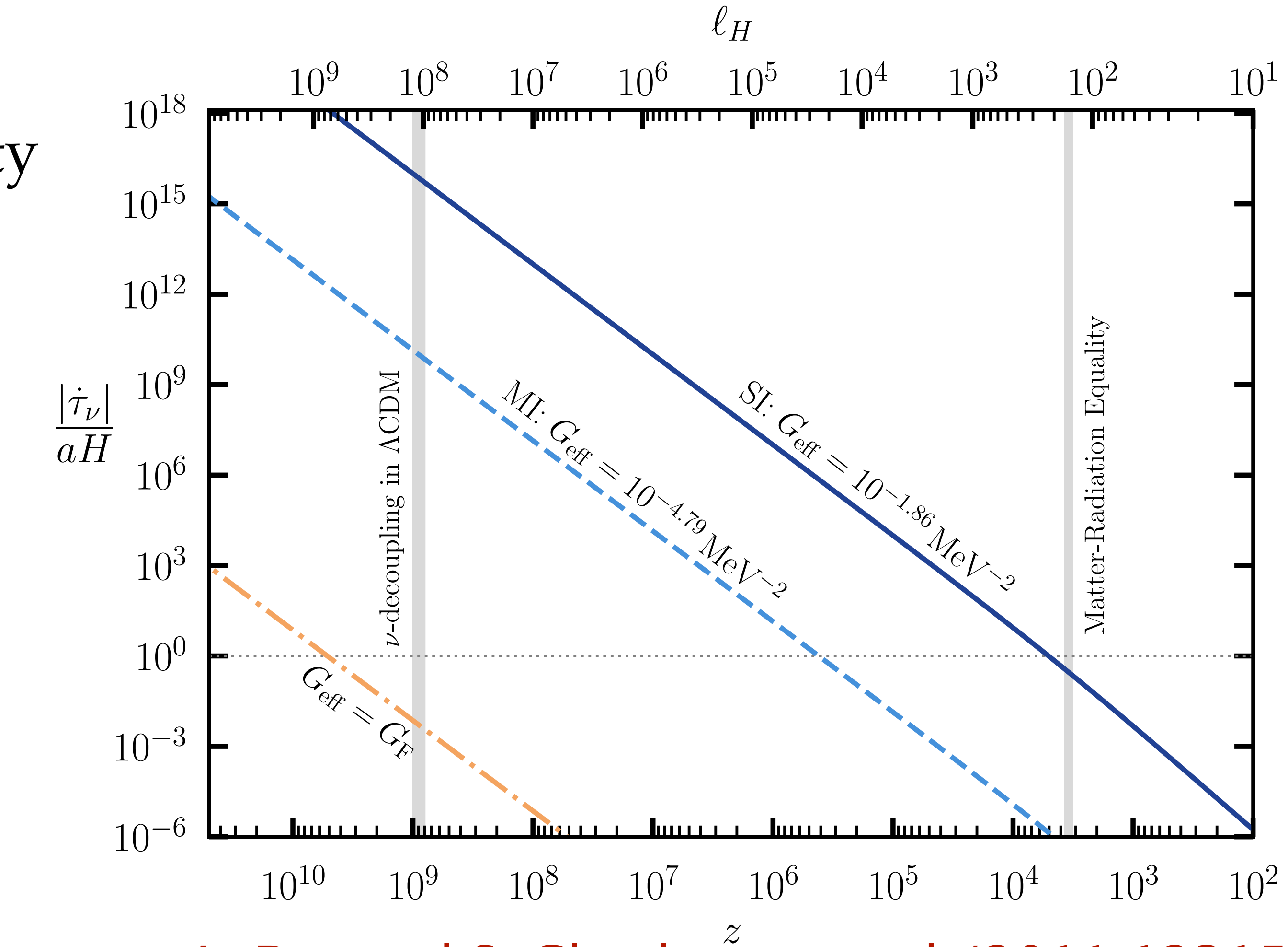
$$\Gamma_\nu \equiv n_\nu \langle \sigma v \rangle \sim (G_{\text{eff}})^2 T_\nu^5$$

The co-moving neutrino self-interaction opacity

$$\dot{\tau}_\nu = -a (G_{\text{eff}})^2 T_\nu^5$$

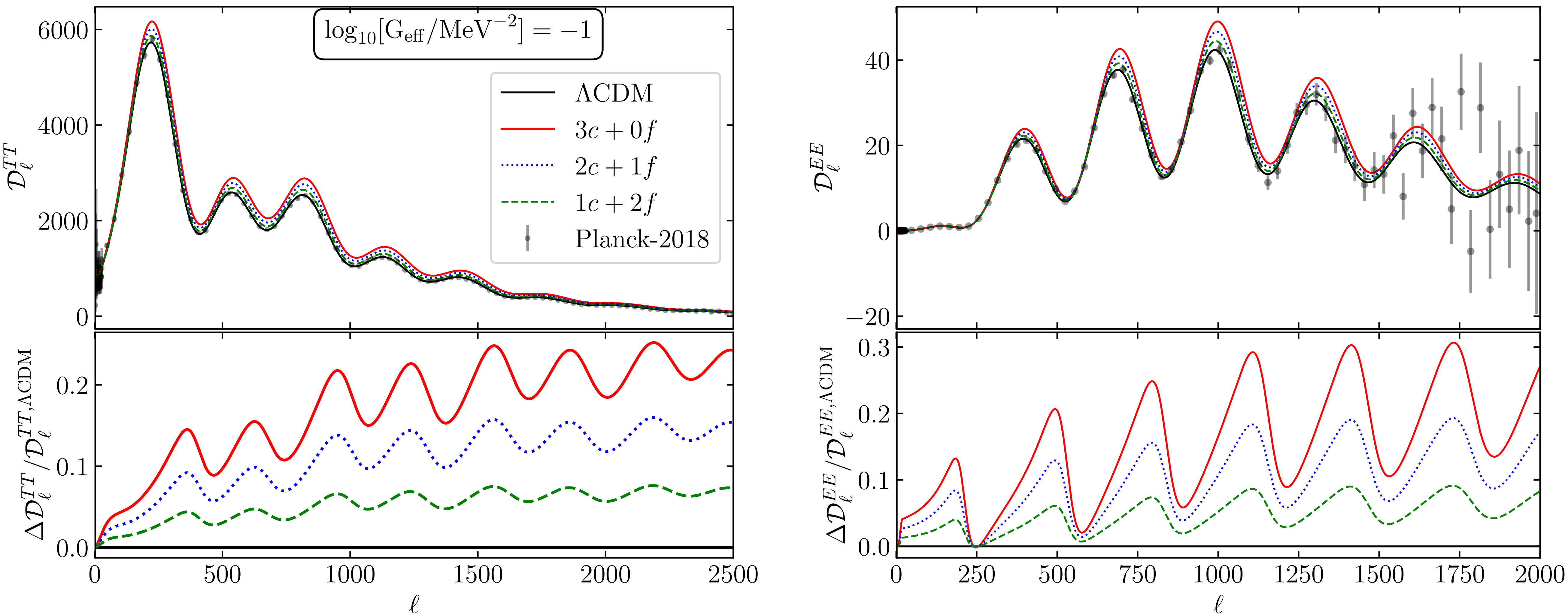
Neutrino decoupling redshift:

$$1 + z_{\text{dec}} \simeq 1.8 \times 10^4 \left(\frac{G_{\text{eff}}}{10^{-2}\,\text{MeV}^{-2}} \right)^{-\frac{2}{3}}$$



A. Das and S. Ghosh, astro-ph/2011.12315

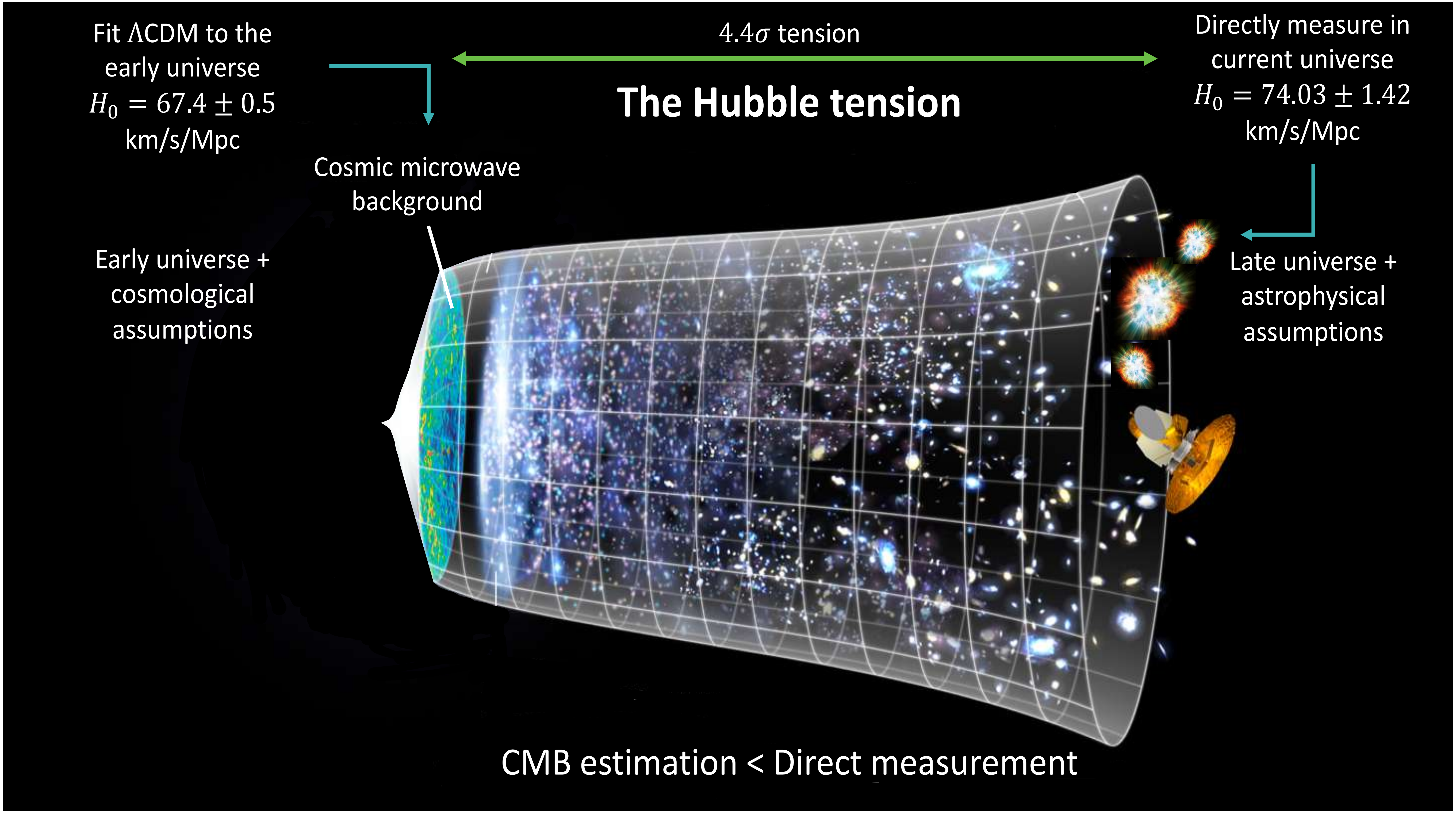
Cosmology of Self-Interacting Neutrinos



CMB TT and EE angular power spectra for 3 interacting neutrinos, 2 interacting neutrinos and one interacting neutrino.

A. Das and S. Ghosh, astro-ph/2011.12315

The Hubble Tension



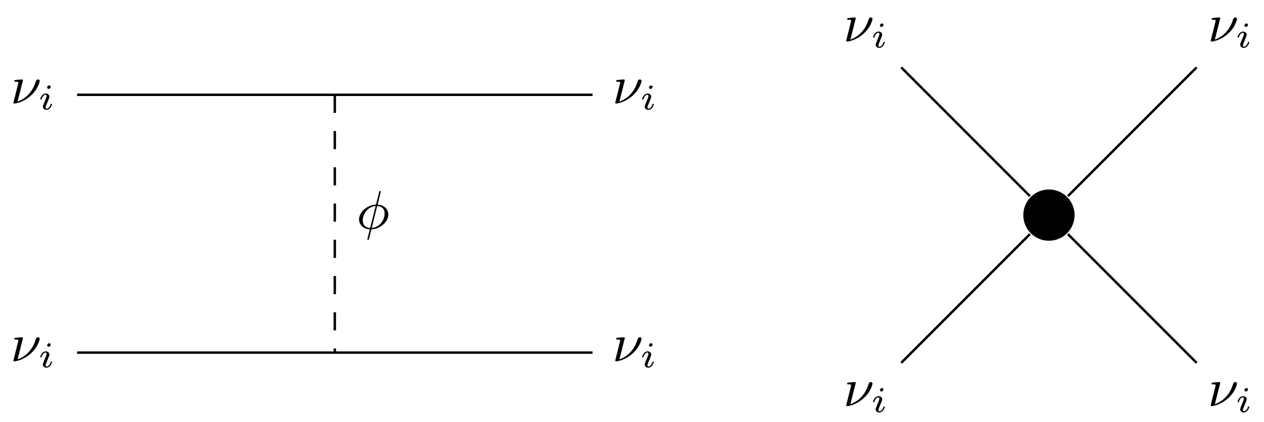
Source: NASA/WMAP Science Team

Resolving Hubble Tension: self-interacting neutrinos

$$\mathscr{L} \supset \frac{1}{2} g_{ij} \bar{\nu}_i \nu_j \phi, \quad g_{ij} = g\delta_{ij}$$

$$\downarrow$$

$$\mathscr{L} \supset G_{\text{eff}} \bar{\nu}\nu\bar{\nu}\nu, \quad G_{\text{eff}} = \frac{g^2}{m_\phi^2}$$



Racine and Sigurdson, astro-ph/1306.1536
Lancaster et. al., astro-ph/1704.06657
Kreisch et. al., astro-ph/1902.05534
A. Das and S. Ghosh, astro-ph/2011.12315

$$G_F = \left(2.9 \times 10^5 \text{ MeV}\right)^{-2} \text{(Standard Model)}$$

$$G_{\text{eff}} = \left(4.7^{+0.4}_{-0.6} \text{ MeV}\right)^{-2} \text{(strongly interacting)}, \quad G_{\text{eff}} = \left(89^{+171}_{-61} \text{ MeV}\right)^{-2} \text{(moderately interacting)}$$

$$G_{\text{eff}} \equiv \frac{g_\phi^2}{m_\phi^2} = (10 \text{ MeV})^{-2} \left(\frac{g_\phi}{10^{-1}}\right)^2 \left(\frac{\text{MeV}}{m_\phi}\right)^2$$

Constraints from Cosmology

- The two-mode puzzle: Confronting self-interacting neutrinos with the full shape of the galaxy power spectrum **D. Camarena et al, arXiv:astro-ph/2406.19279.**

- Self-Interacting Neutrinos in Light of Large-Scale Structure Data, **Adam He et al., arXiv:astro-ph/2309.03956.**

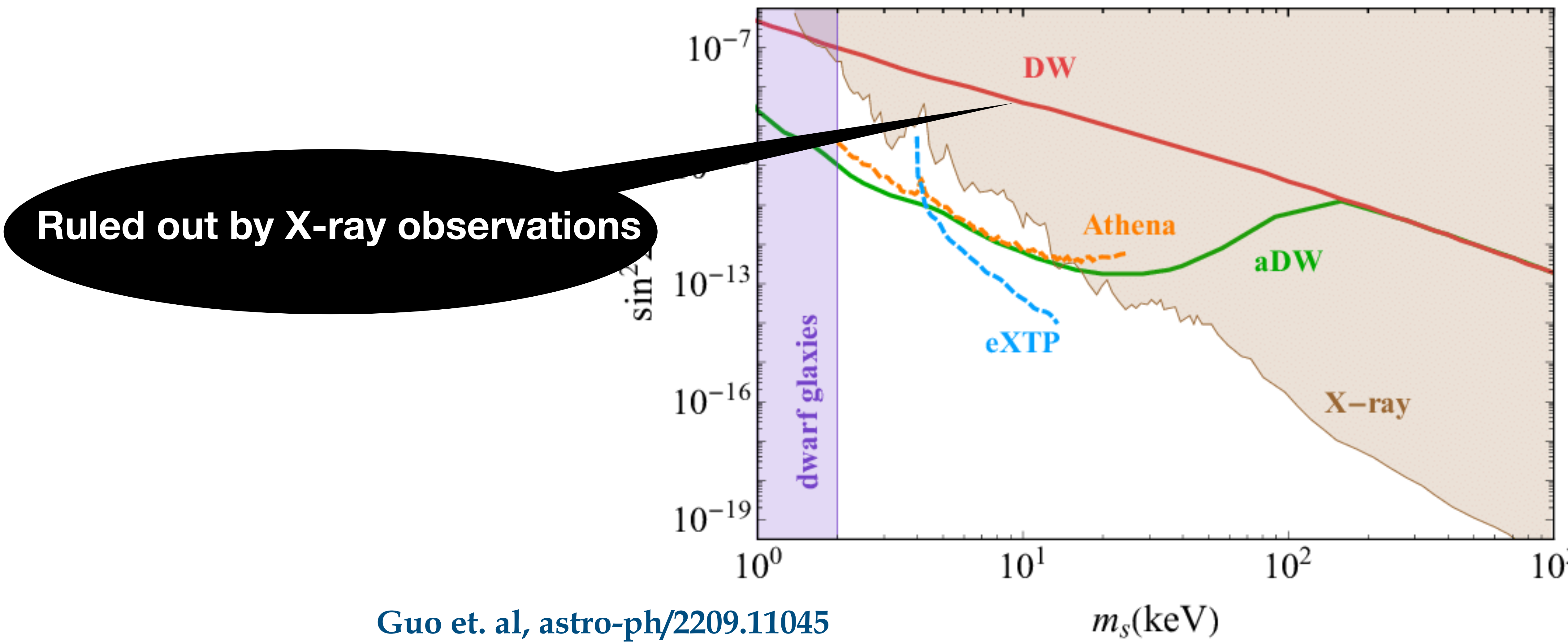
- Strong constraints on a simple self-interacting neutrino cosmology, **arXiv: astro-ph/2403.05496.**

- Massive neutrino self-interactions with a light mediator in cosmology, **J. Venzor et al, arXiv: astro-ph/2202.09310.**

KeV- Sterile Neutrino Dark Matter via Dodelson-Widrow Mechanism

- The sterile neutrino do not have strong interactions with SM particles and neutrinos.

- As SM neutrinos propagates through thermal plasma, they acquire the sterile neutrino component due to oscillations between active and sterile neutrinos.



Guo et. al, astro-ph/2209.11045

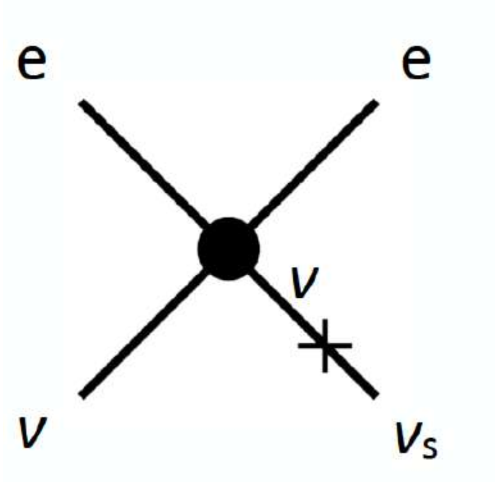
Constraints from keV sterile neutrino Dark Matter

Modified Dodelson Widrow Mechanism: production of KeV sterile neutrino through oscillations via self-interactions of neutrinos

$$T\frac{\partial}{\partial T}f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H} \langle P(\nu_a \to \nu_s)\rangle f_{\nu_a}$$

with

$$\langle P(\nu_a \to \nu_s)\rangle \approx \frac{\Delta^2 \sin^2\theta}{\Delta^2 \sin^2\theta + \frac{\Gamma^2}{4} + (\Delta\cos 2\theta - V_T)^2}; \quad \Delta = \frac{m_4^2}{2E}$$

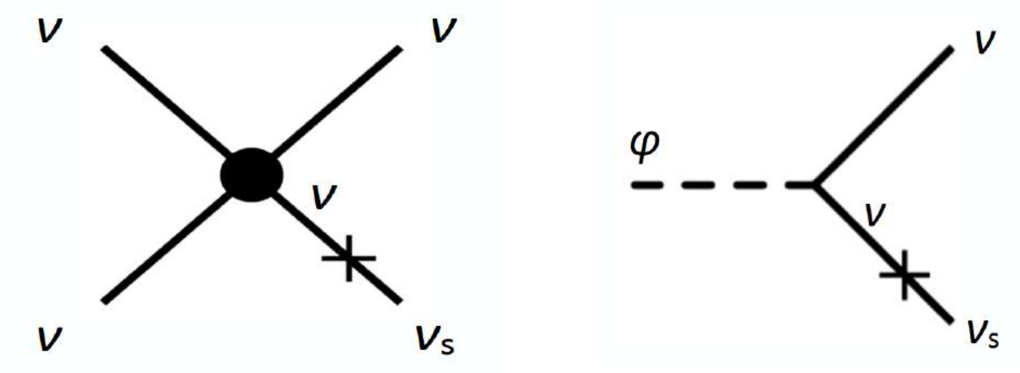


Sterile Neutrino in SM

Relic Abundance:

$$\Omega_{\nu_s}(0) = \frac{n_{\nu_s}(0)}{\rho_{\rm DM}} = \frac{m_{\nu_s}\rho_{\nu_s}(0)}{\rho_{\rm DM}(0)}$$

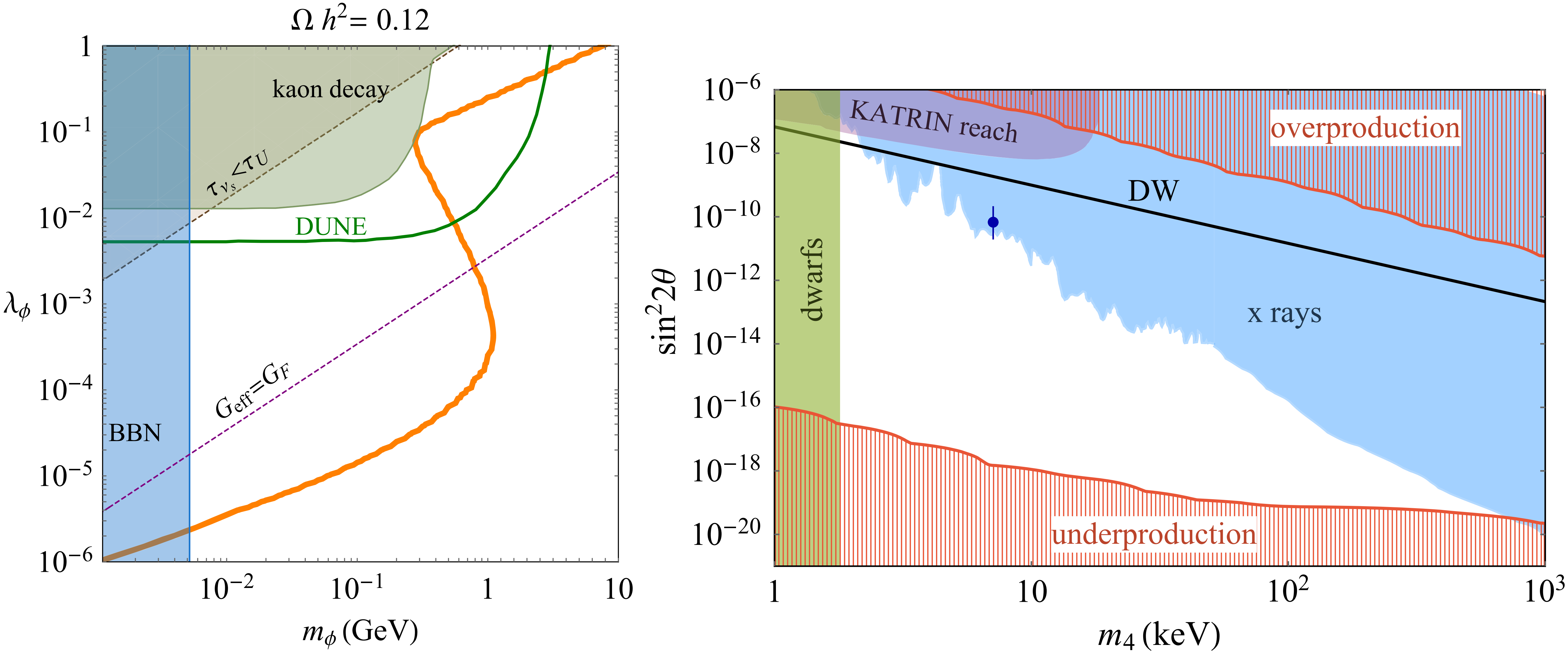
with $\quad n_{\nu_s}(0) = \int_0^\infty \frac{d^3E}{(2\pi)^3} f_{\nu_s}(E)$



Sterile Neutrino through self-interactions

M. Sen et. al., Phys.Rev.Lett. 124 (2020) 8, 081802, e-Print: 1910.04901 [hep-ph]
M.Sen et. al., Phys.Rev.D 101 (2020) 11, 115031 , e-print: 2005.03681

Dodelson-Widrow with self-interacting neutrinos

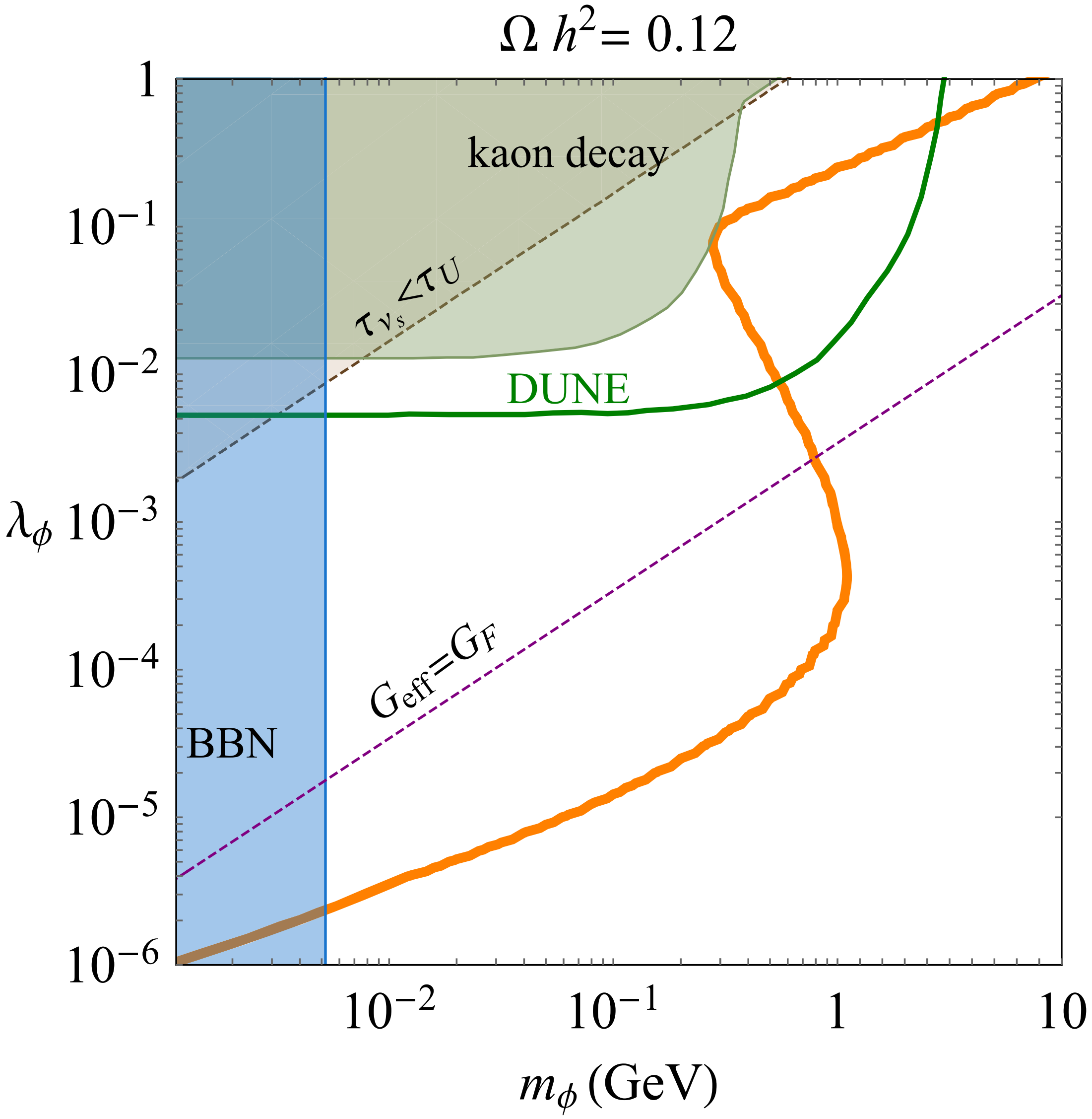


$\sin^2 2\theta = 7 \times 10^{-11}$ and $m_4 = 7.1$ keV

M. Sen et. al., Phys.Rev.Lett. 124 (2020) 8, 081802, e-Print: 1910.04901 [hep-ph]

Relic density ~ Interacting rate x mixing angle; Increasing interaction rate can reduce the mixing angle and allows to shift DW region below X-ray constraints

Dodelson-Widrow with self-interacting neutrinos



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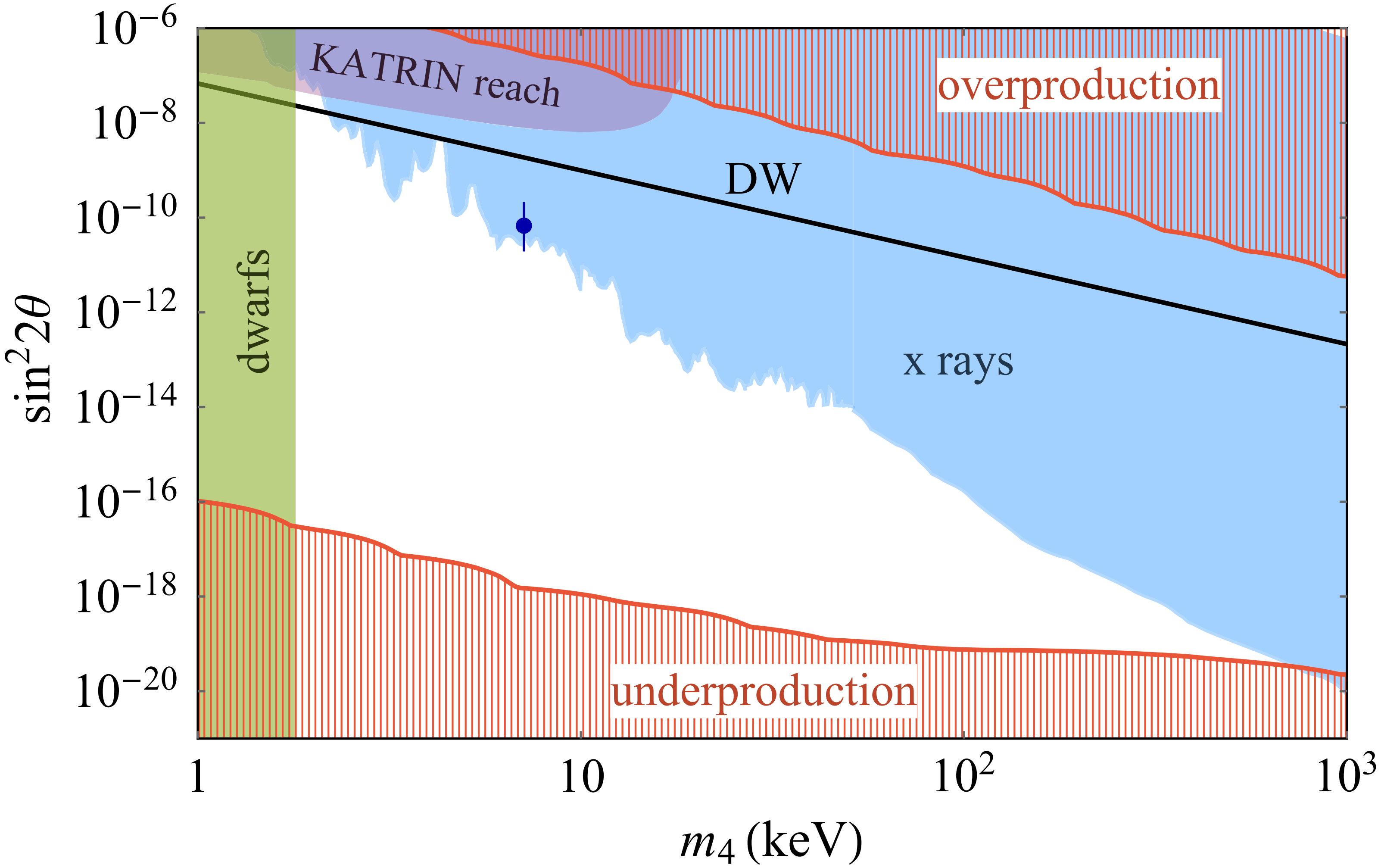


M. Sen et. al., Phys.Rev.Lett. 124 (2020) 8, 081802, e-Print: 1910.04901 [hep-ph]

Relic density ~ Interacting rate x mixing angle; Increasing interaction rate can reduce the mixing angle and allows to shift DW region below X-ray constraints

Allowed parameter space with restricted couplings

The Hubble tension solution prefers specific value of the effective coupling

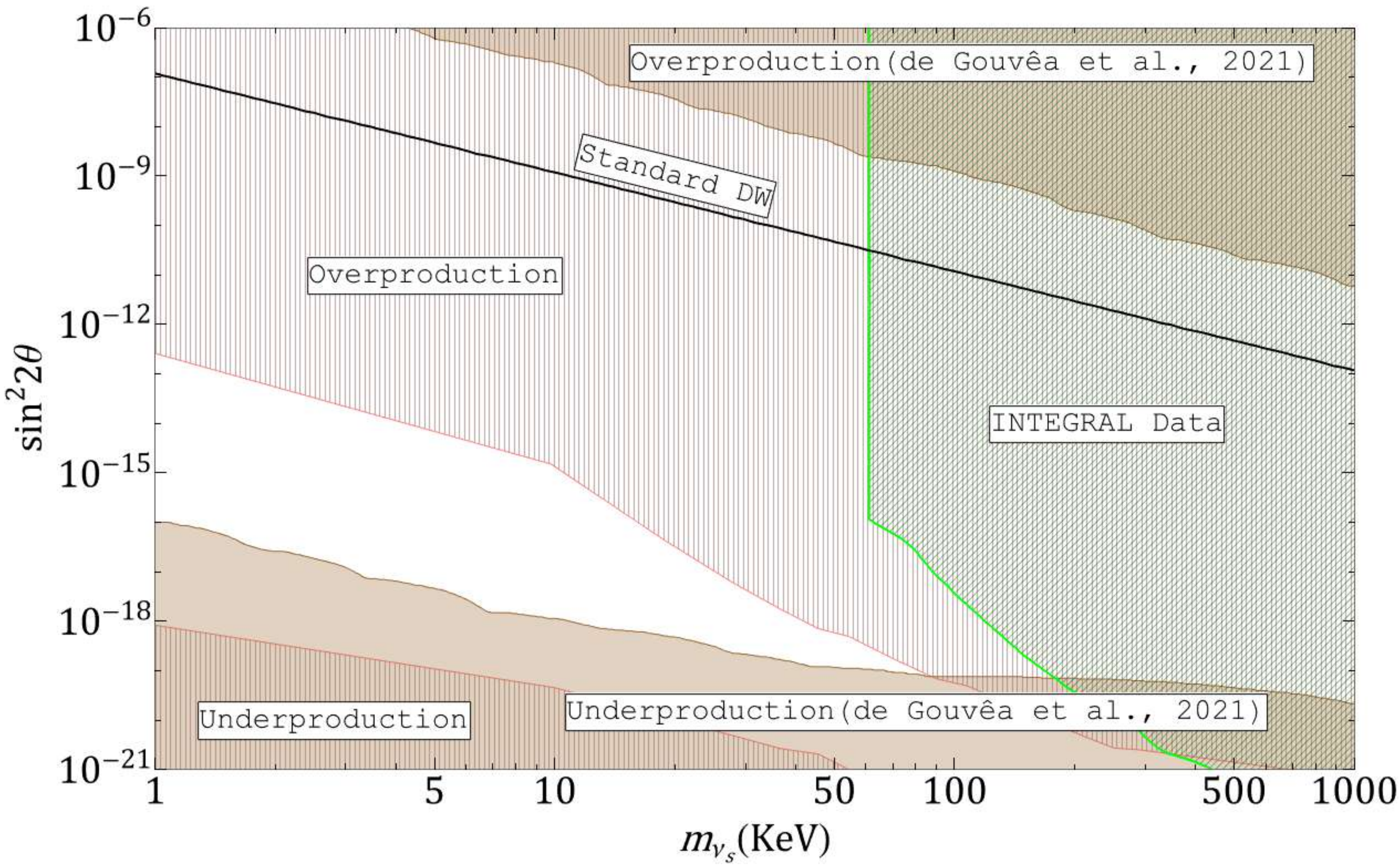
$$G_{\text{eff}} = \left(4.7^{+0.4}_{-0.6}\ \text{MeV}\right)^{-2}(\text{strongly interacting}), \quad G_{\text{eff}} = \left(89^{+171}_{-61}\ \text{MeV}\right)^{-2}(\text{moderately interacting})$$

$$G_{\text{eff}} \equiv \frac{g_\phi^2}{m_\phi^2} = (10\ \ \text{MeV})^{-2}\left(\frac{g_\phi}{10^{-1}}\right)^2\left(\frac{\text{MeV}}{m_\phi}\right)^2$$

Our aim: Can we have the parameter space of keV-sterile neutrino DM by specifically considering the coupling G_{eff} allowed by Hubble Tension solution?

MD and A. Pradhan, e-Print: 2301.09552 [hep-ph]

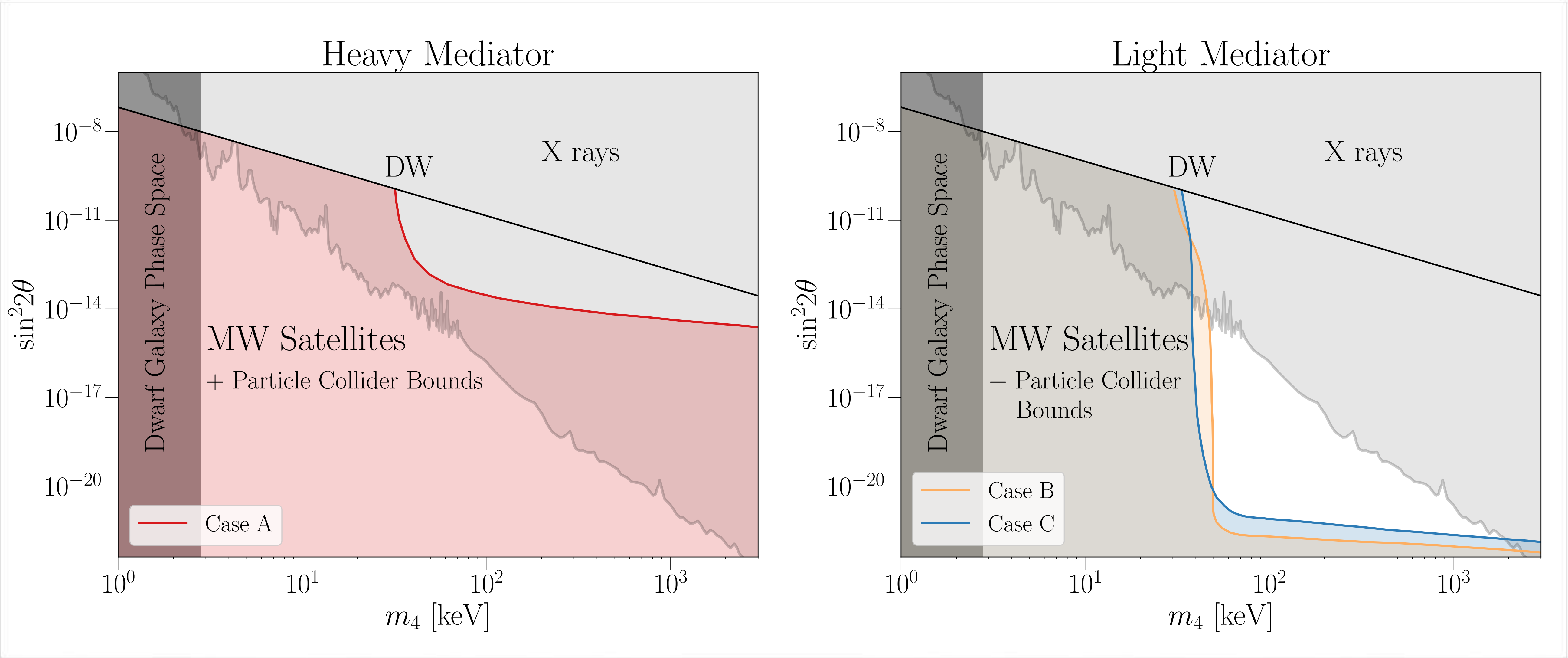
Dodelson-Widrow with self-interacting neutrinos



Comparison with results from M. Sen et. al., Phys.Rev.Lett. 124 (2020) 8, 081802

MD and A. Pradhan, e-Print: 2301.09552 [hep-ph]

Dodelson-Widrow with self-interacting neutrinos



Consistency of this production mechanism with the abundance of small-scale structure in the universe, as captured by the population of ultra-faint dwarf galaxies orbiting the Milky Way

Rui An et. al., e-Print: 2301.08299 [astro-ph]

Astrophysical Implications:

- Bounds on secret neutrino interactions from high-energy astrophysical neutrinos **Mauricio Bustamante et al, arXiv:astro-ph/2001.04994.**

- Uncovering Secret Neutrino Interactions at Tau Neutrino Experiments, **P. Bakhti et al, arXiv:hep-ph/2311.14945.**

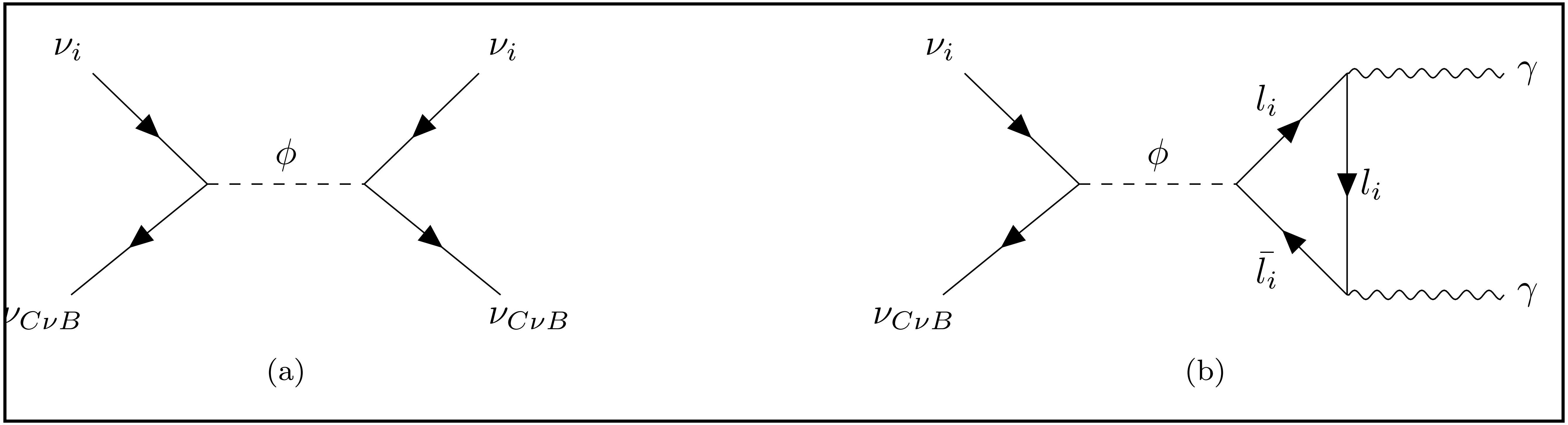
- Shedding light on neutrino self-interactions with solar antineutrino searches, Quanfeng Wu and Xun-Jie Xu, **arXiv:hep-ph/2308.15849.**

- Constraints on Neutrino Self-Interactions from IceCube Observation of NGC 1068, Jeffrey M. Hyde, **arXiv:hep-ph/2307.02361.**

- Neutrino secret self-interactions: A booster shot for the cosmic neutrino background, **A.Das et al, arXiv:hep-ph/2204.11885.**

- Widen the Resonance: Probing a New Regime of Neutrino Self-Interactions with Astrophysical Neutrinos, Isaac R. Wang et al, **arXiv:hep-ph/2501.07624.**

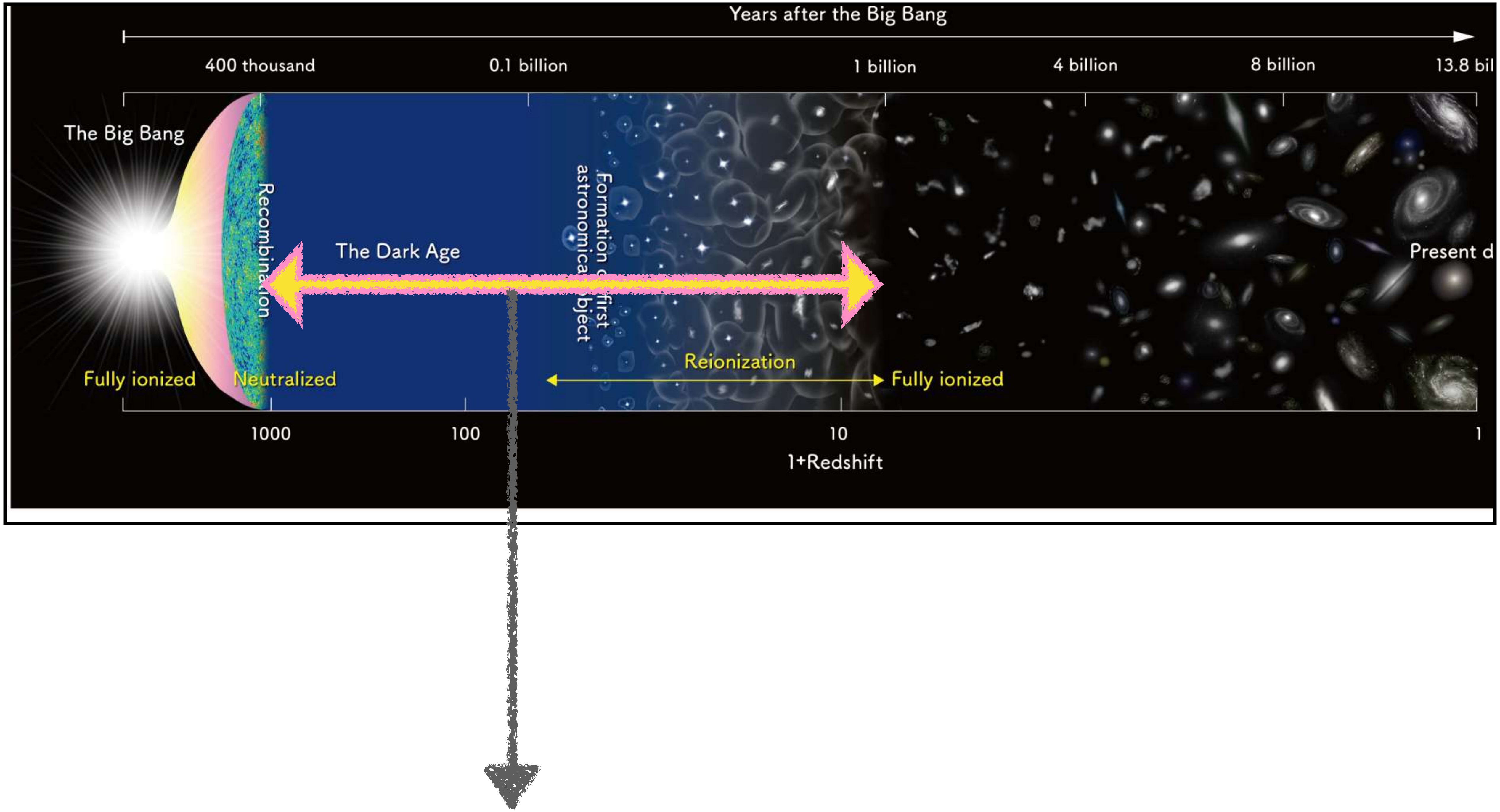
Implication of loop-level scattering of high energy neutrinos with CMB neutrinos



Two main implications:

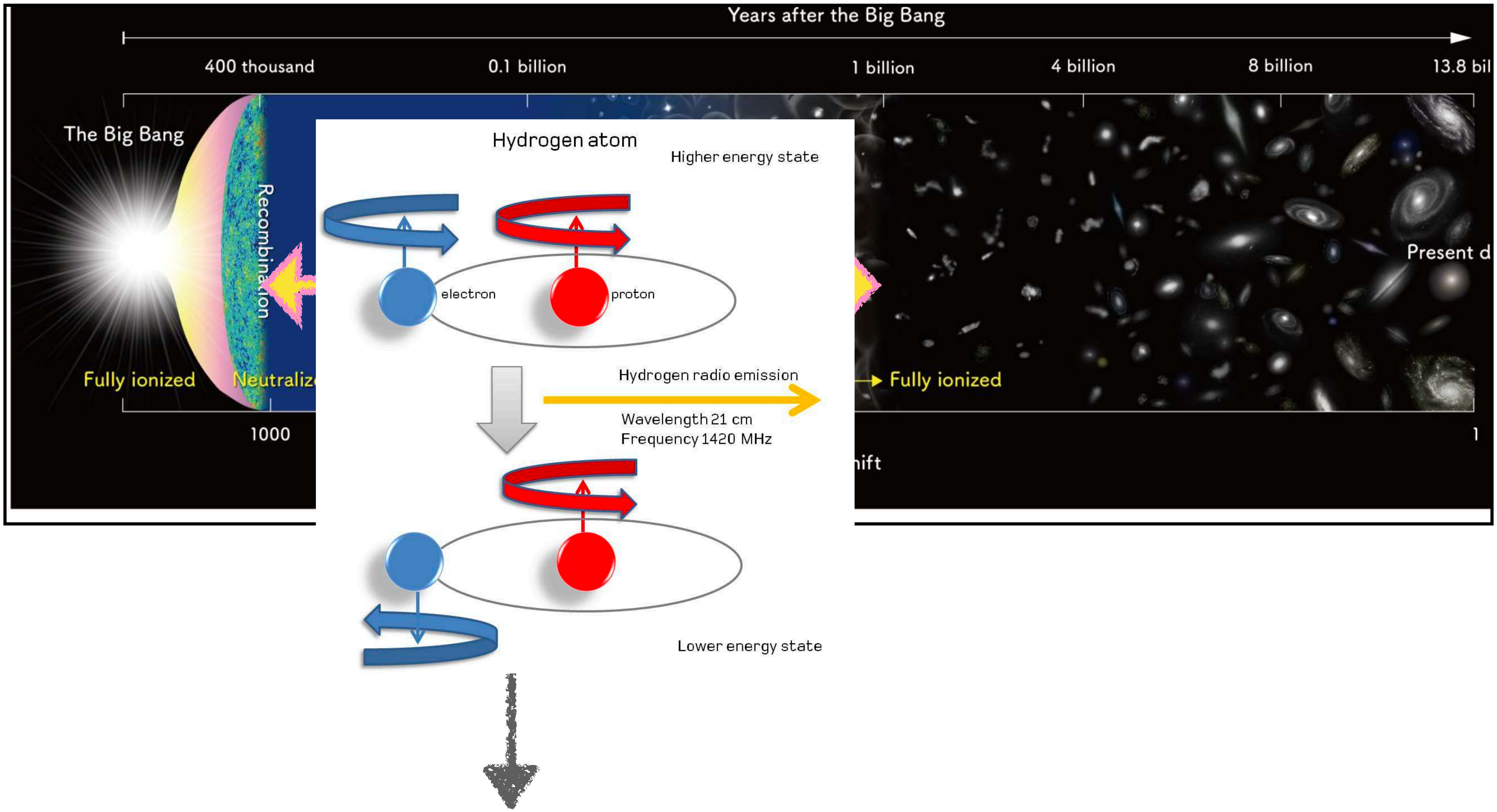
- Effect on the 21-cm Radiation
- Cosmic Gamma-ray burst (GRB221009A)

Timeline of the Universe...



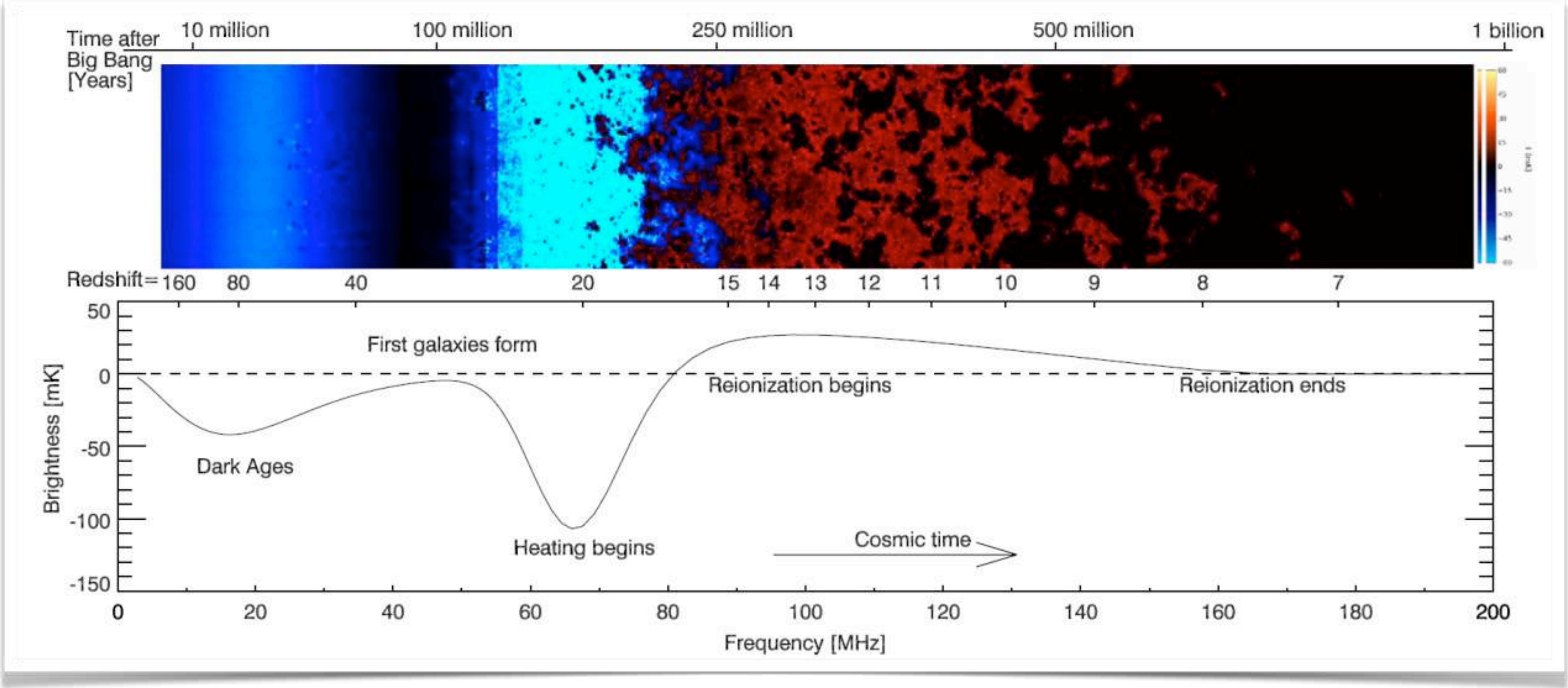
Epoch of 21-cm Hydrogen

Timeline of the Universe…



Epoch of 21-cm Hydrogen

Global 21-cm signal in standard cosmology



Pritchard and Loeb 2012

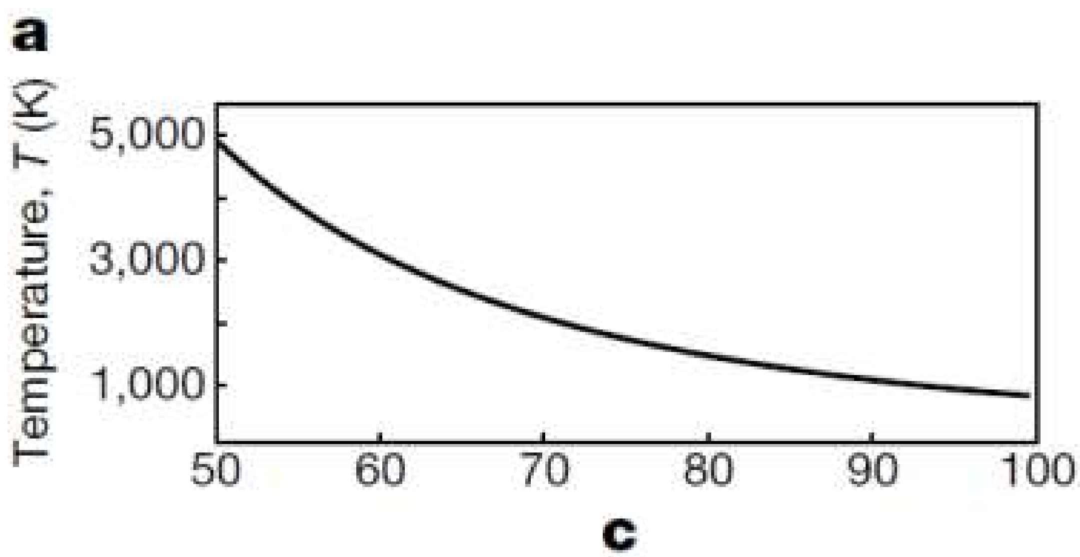
Results from EDGES Global 21-cm Signal

LETTER

doi:10.1038/nature25792

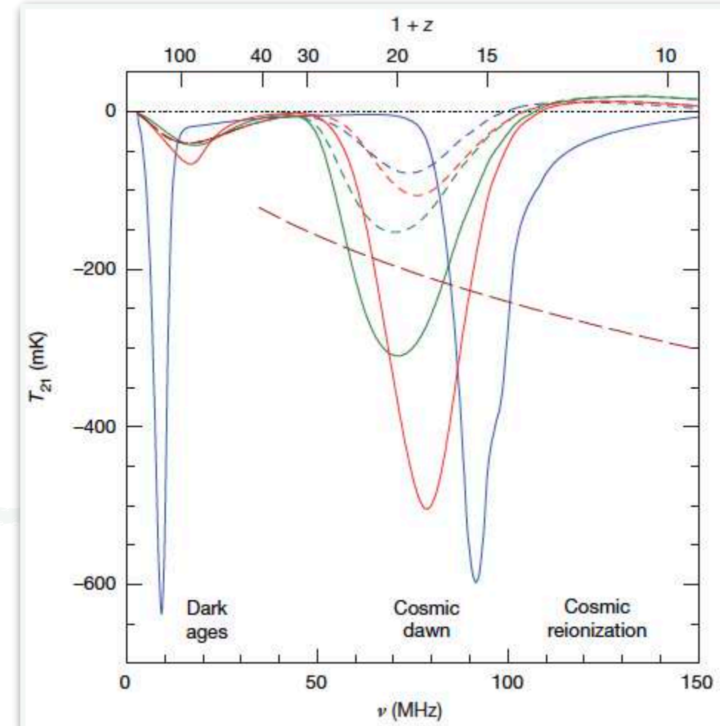
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]



Subsequent works...

Excess cooling of Hydrogen due to its interaction with CDM:



Barkana 2018,
Munoz and Loeb 2018,
Berlin, Hooper, Krnjaic, McDermott 2018,
Barkana, Outmezguine, Redigolo, Volansky, 2018
Kovetz et al 2018....

Concerns about Modelling of the EDGES Data

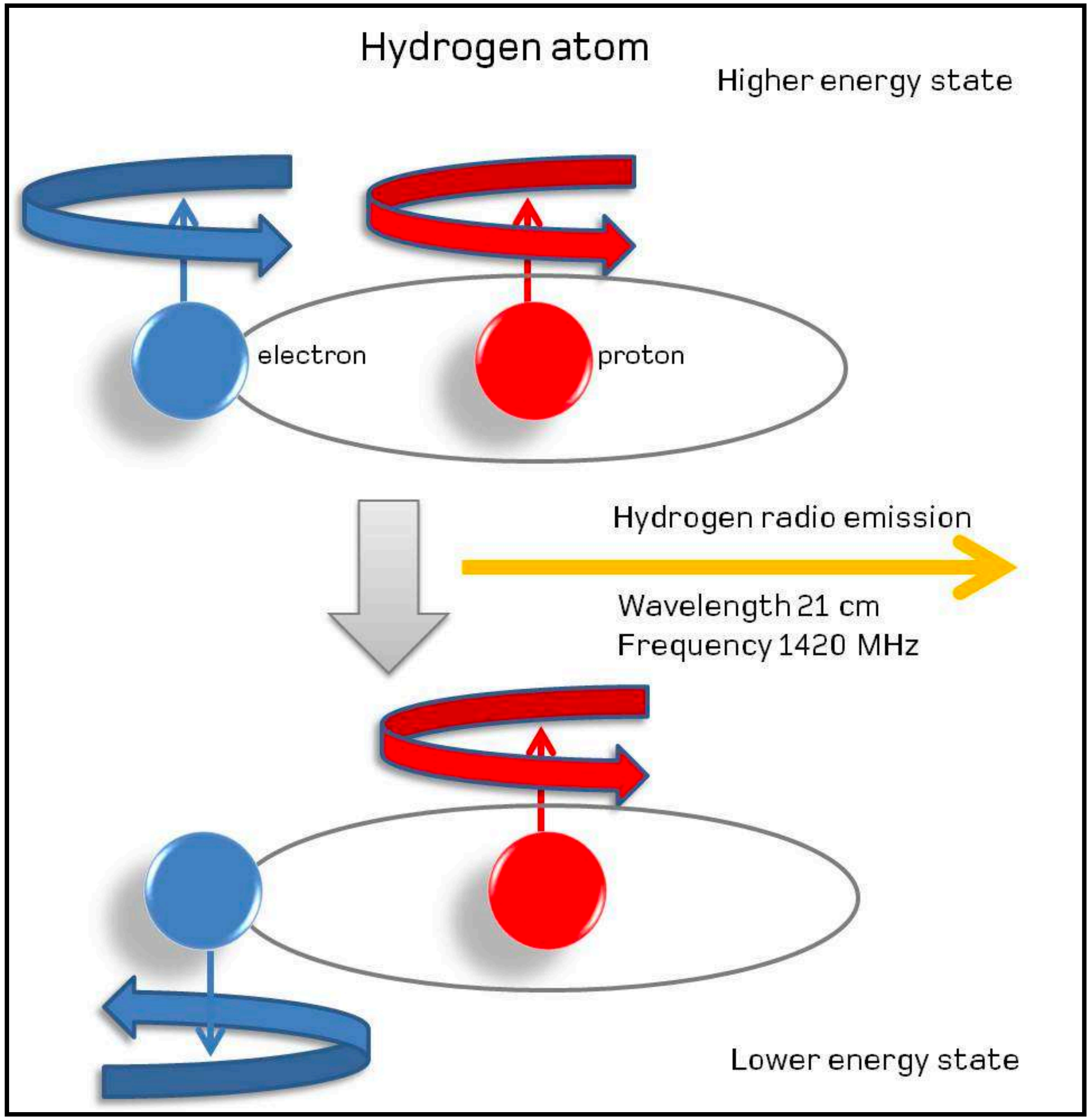
Richard Hills, Girish Kulkarni, P. Daniel Meerburg, & Ewald Puchwein

ARISING FROM J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen, & N. Mahesh *Nature* **555**, 67–70, (2018); https://doi.org/10.1038/nature25792.

Other experiments:

- **Low redshift- PRIZM, REACH, SARAS, SCI-HI, BIGHORNS (z ~15)**
- **Intermediate red-shift: LEDA (z~46), DAPPER (z~80)**
- **High red-shift: FARSIDE, PRATUSH, DARE, NCLE (z~1000)**

21-cm neutral hydrogen



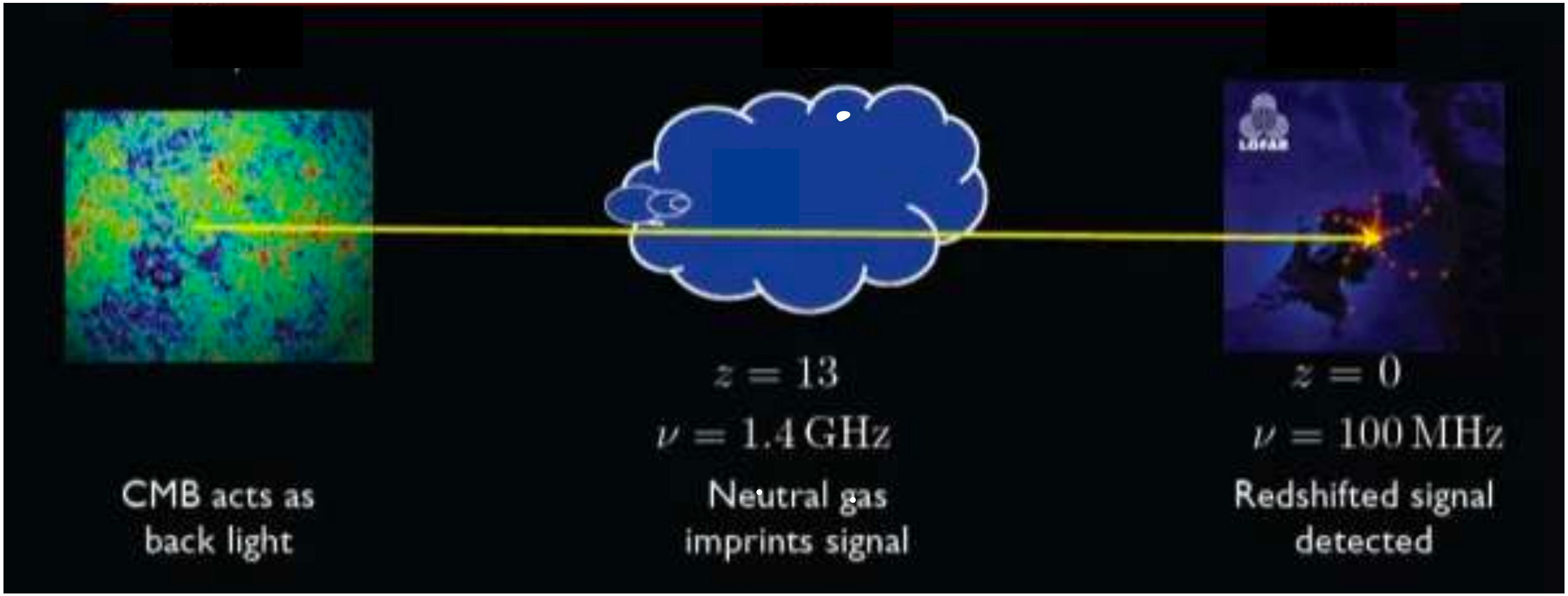
$$\frac{n_1}{n_0} = 3e^{-\frac{\Delta}{T_s}}$$

- n_1 - number of fermions in the singlet state

- n_0: Number of fermions in the triplet state

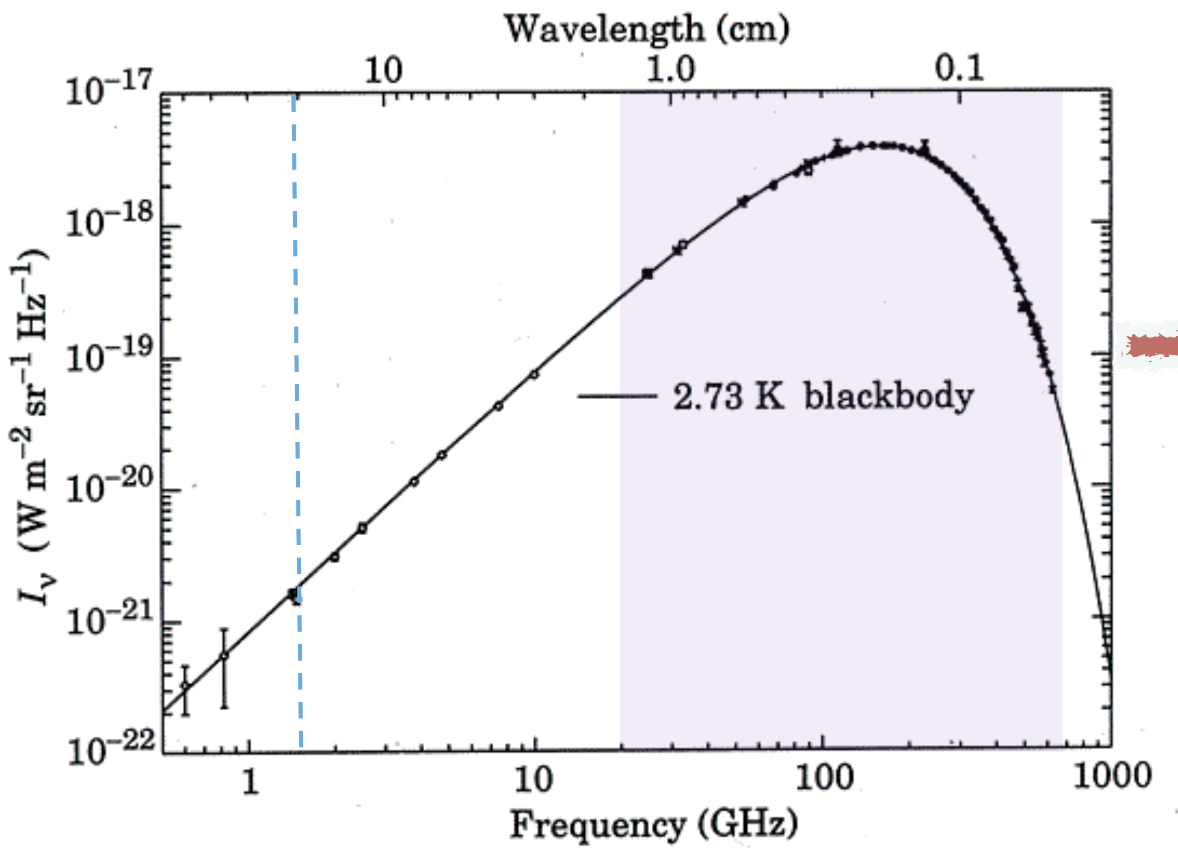
T_s - parameter describing the relative population of singlet and triplet states

Measuring 21-cm hydrogen



$$\nu = 1420/(1+z)\ \mathrm{MHz}$$

Differential Brightness Temperature



$$I_\nu^{\mathrm{CMB}} = 2K_B T \frac{\nu^2}{c^2}$$

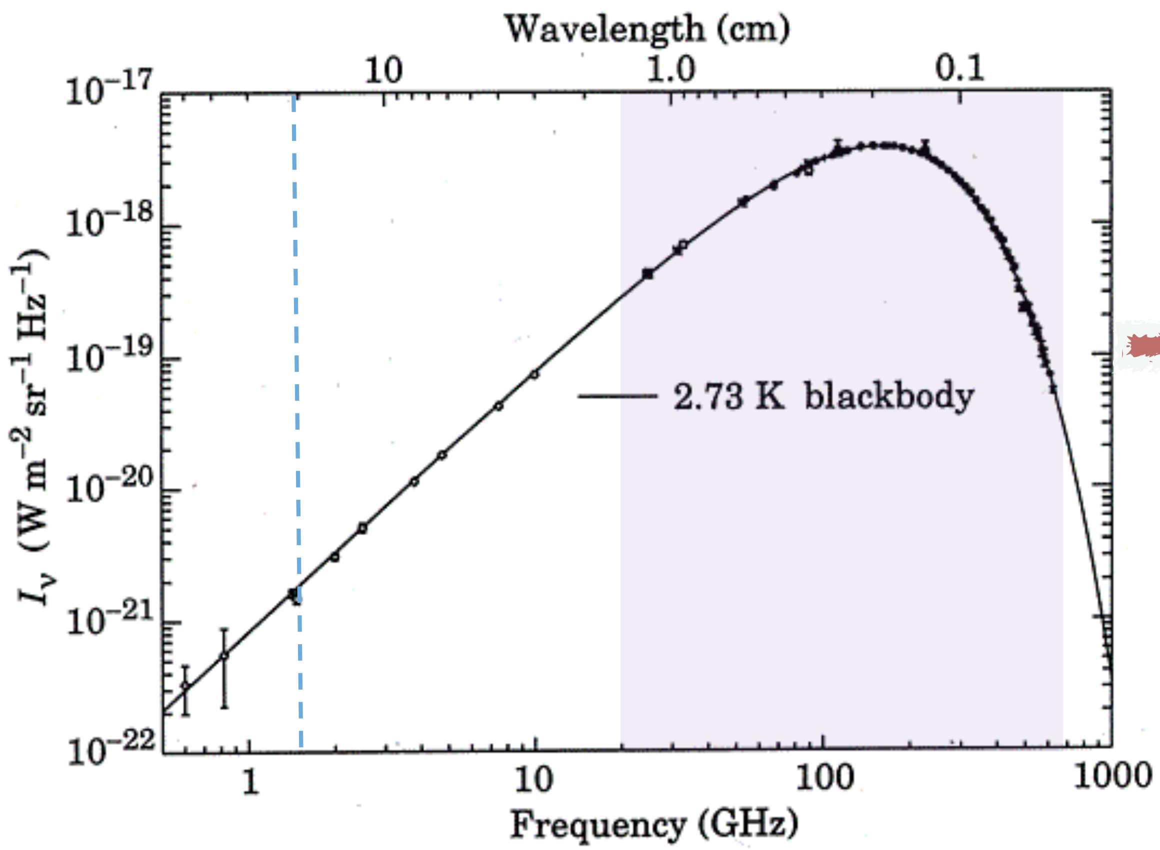
Black Body expectation

$$\delta T_b(z) \propto I_\nu^{\mathrm{measured}} - I_\nu^{\mathrm{CMB}} \propto x_{HI}(z) \left(\frac{T_s(z) - T_{\mathrm{CMB}}(z)}{T_s(z)} \right) \quad \mathrm{mK}$$

$\delta T_b > 0$: net **emission** if $T_s > T_{CMB}$, i.e. more excited than needed to be in equilibrium with CMB

$\delta T_b < 0$: net **absorption** if $T_s < T_{CMB}$,

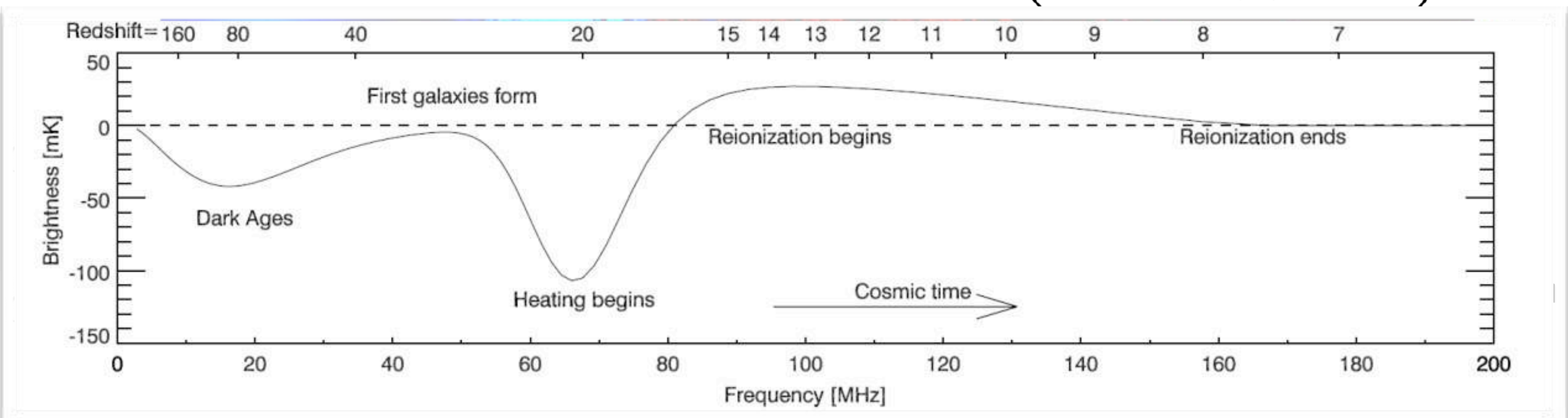
Differential Brightness Temperature



Black Body expectation

$$I_\nu^{\rm CMB} = 2K_BT\frac{\nu^2}{c^2}$$

$$\delta T_b(z) \propto I_\nu^{\rm measured} - I_\nu^{\rm CMB} \propto x_{HI}(z)\left(\frac{T_s(z)-T_{\rm CMB}(z)}{T_s(z)}\right) \;\; {\rm mK}$$

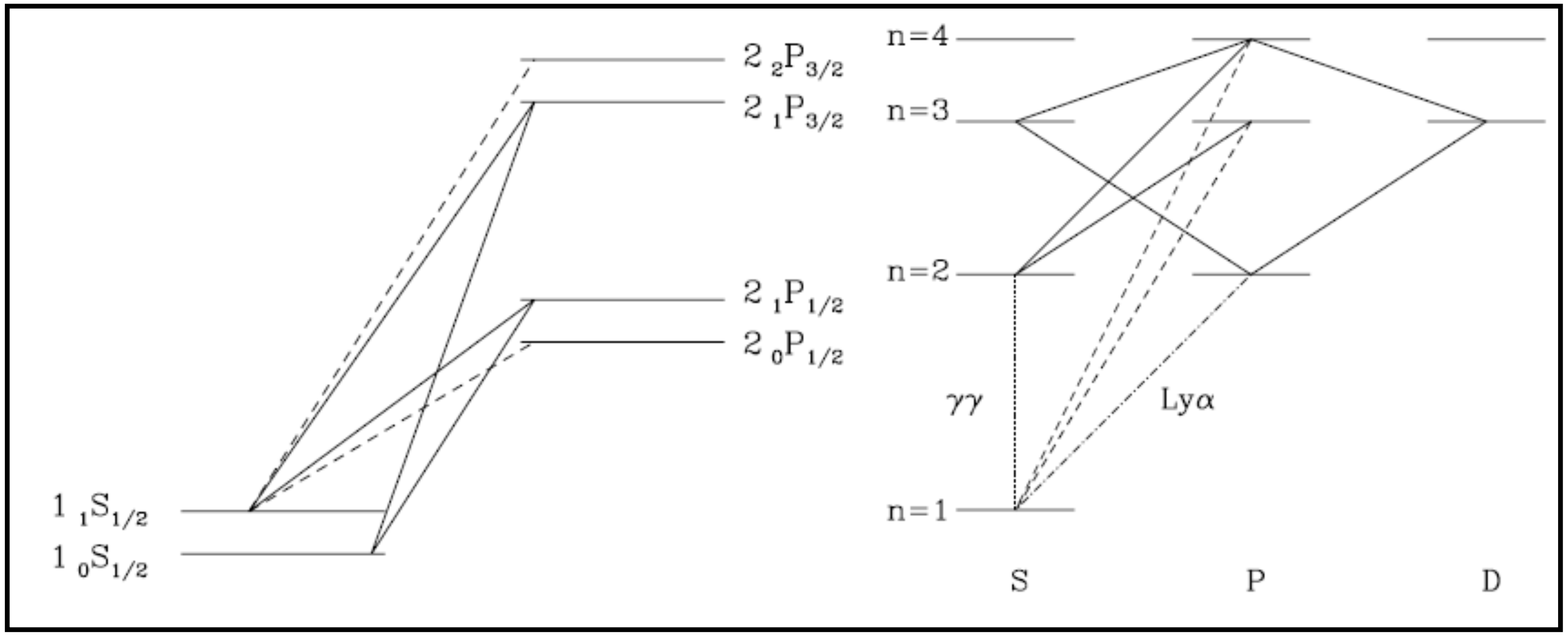


Processes altering the spin temperature

- CMB excitations and de-excitations: **A_{10} (spontaneous de-excitation), B_{01}(simulated excitation), B_{10} (simulated de-excitation)**

- Collisional coupling H0 + (H,e,p): **C_{01}, C_{10}**

- Lyman-α photons from the first stars (Wouthuysen-Field effect): **P_{01}, P_{10}**



Processes altering the spin temperature

$$n_0(B_{01} + C_{01} + P_{01}) = n_1(A_{10} + B_{10} + C_{10} + P_{10})$$

$$B_{10} = n_\gamma \langle \sigma(H_1 + \gamma \to H_0 + \gamma\gamma) v \rangle \simeq A_{10} \frac{T_{\rm CMB}}{\Delta}$$

$$A_{10} = (10 \ \ \text{million years})^{-1}$$

$$\frac{n_1}{n_0} = 3e^{-\frac{\Delta}{T_s}} \simeq 3\left(1 - \frac{\Delta}{T_s}\right)$$

$$\frac{C_{01}}{C_{10}} = 3e^{-\frac{\Delta}{T_K}} \simeq 3\left(1 - \frac{\Delta}{T_K}\right)$$

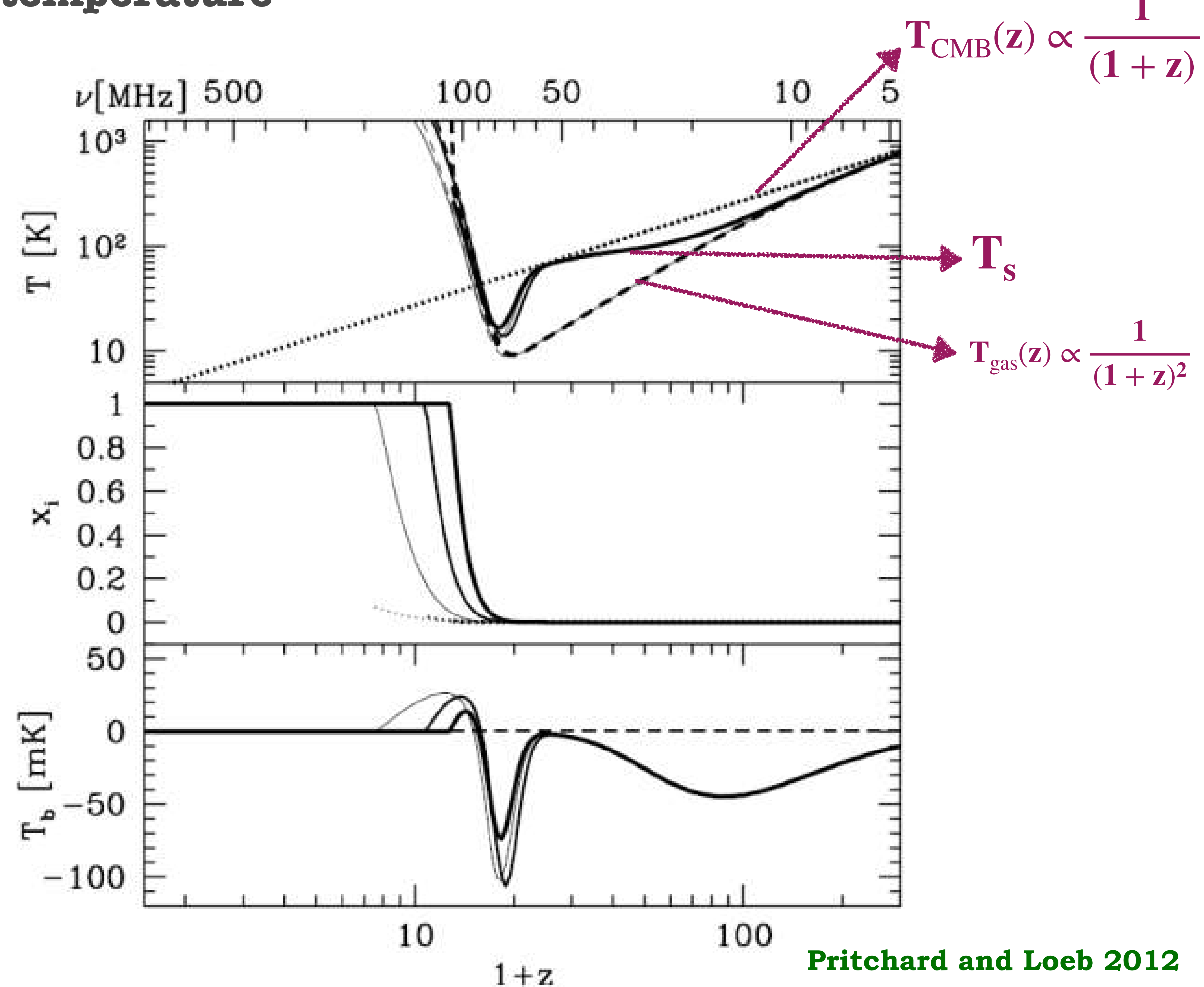
$$\frac{P_{01}}{P_{10}} = 3e^{-\frac{\Delta}{T_c}} \simeq 3\left(1 - \frac{\Delta}{T_c}\right)$$

$$x_\alpha = \frac{P_{10}}{B_{10}}$$

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_C T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_C + x_\alpha}$$

$$x_C = \frac{C_{10}}{B_{10}}$$

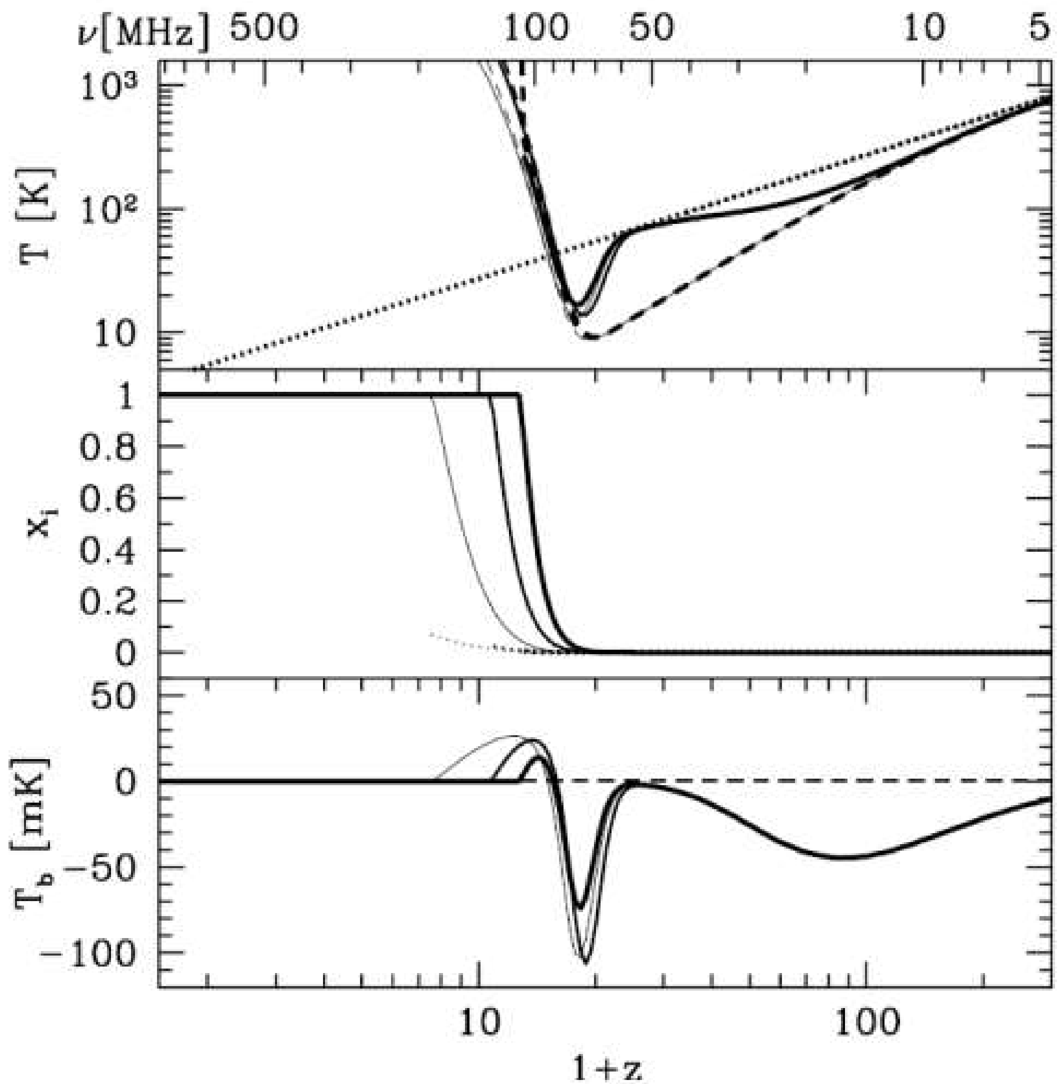
Evolution of the Spin temperature, gas temperature and brightness temperature

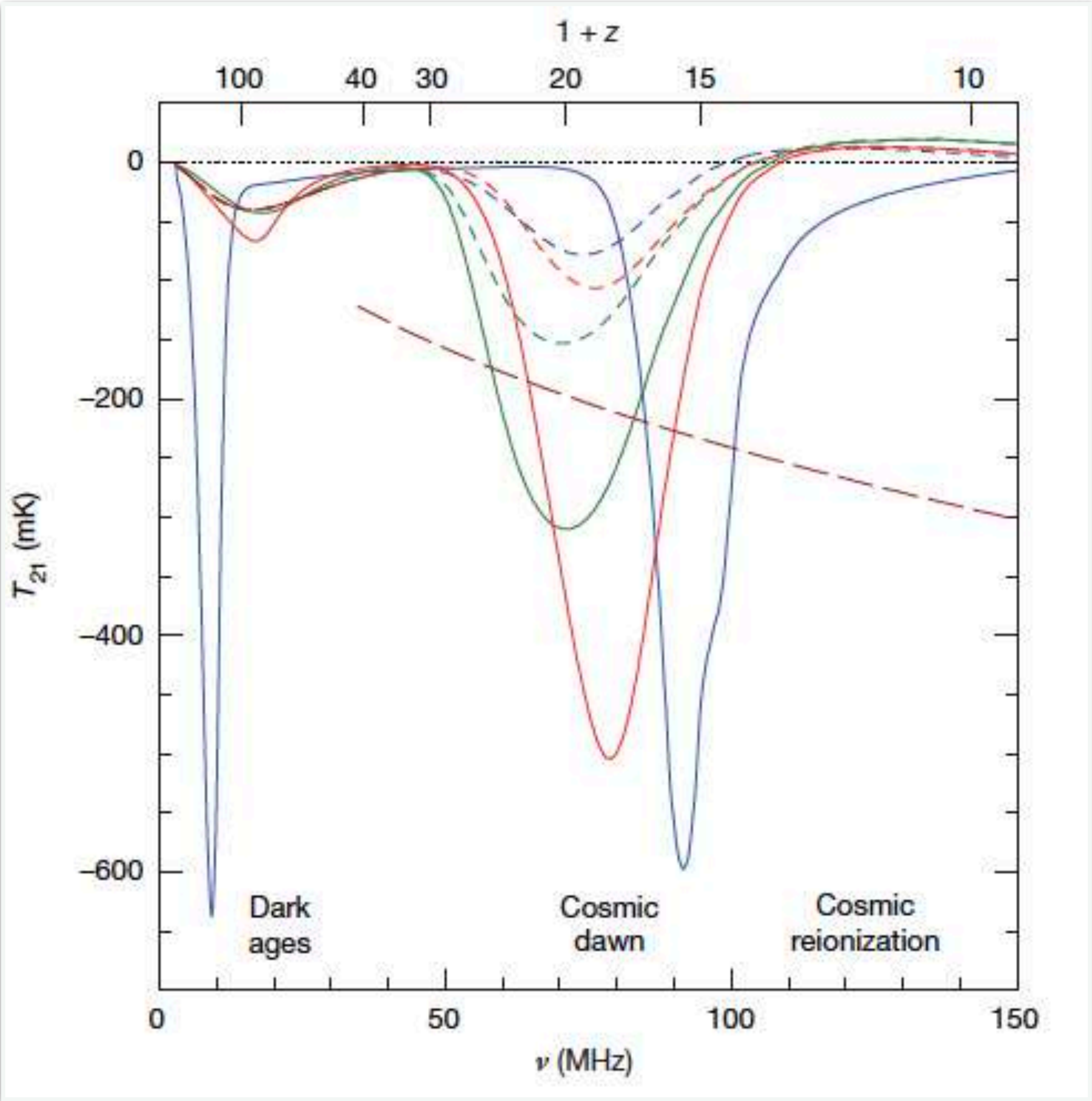


Pritchard and Loeb 2012

Standard Cosmology/Excess Cooling Models

R. Barkana 2018





$\sigma_{\chi-H} \sim \mathbf{8 \times 10^{-20}}\ \mathrm{cm}^2, \mathbf{m}_\chi \sim \mathbf{0.3}\ \mathrm{GeV}$

$\sigma_{\chi-H} \sim \mathbf{3 \times 10^{-19}}\ \mathrm{cm}^2, \mathbf{m}_\chi \sim \mathbf{2}\ \mathrm{GeV}$

$\sigma_{\chi-H} \sim \mathbf{3 \times 10^{-18}}\ \mathrm{cm}^2, \mathbf{m}_\chi \sim \mathbf{0.01}\ \mathrm{GeV}$

Heating due to decay of Dark Matter

- The metastable decaying Dark Matter particle can be a steady source of Standard Model particles.

- The energy injection from the decay of particles can increase the ionization fraction or increase the hydrogen gas temperature.

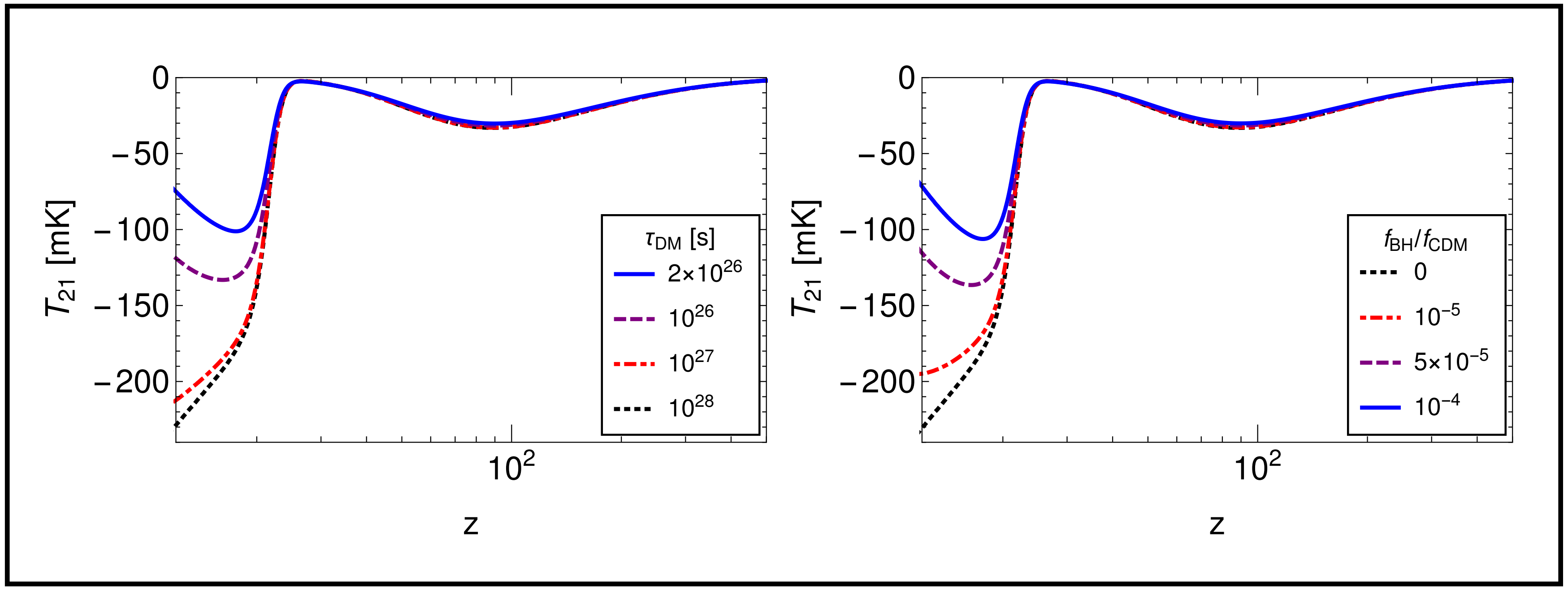
- The energy deposition: $\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t} = \Gamma_{\rm DM} \cdot \rho_{\rm c,0}\Omega_{\rm DM}(1+z)^3,$

- The evolution of ionisation fraction and gas temperature:

$$\frac{\mathrm{d}x_{\rm e}}{\mathrm{d}z} = \left.\frac{\mathrm{d}x_{\rm e}}{\mathrm{d}z}\right|_{\rm orig} - \frac{1}{(1+z)H(z)}[I_{\rm X_i}(z) + I_{\rm X_\alpha}(z)],$$

$$\frac{\mathrm{d}T_{\rm G}}{\mathrm{d}z} = \left.\frac{\mathrm{d}T_{\rm G}}{\mathrm{d}z}\right|_{\rm orig} - \frac{2}{3k_{\rm B}(1+z)H(z)}\frac{K_{\rm h}}{1+f_{\rm He}+x_{\rm e}}.$$

- The resulting evolution in brightness temperature:

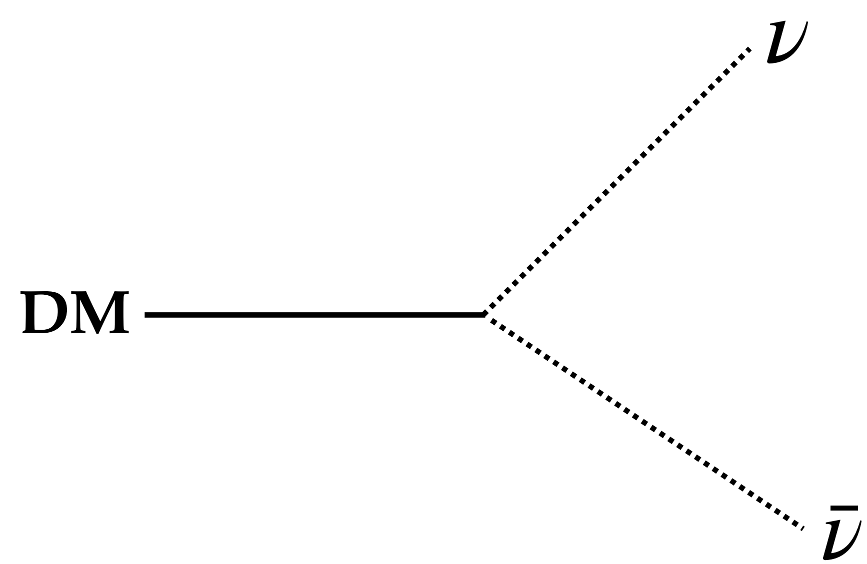


Steven Clark et al., arXiv: 1803. 09390 [hep-ph]

High energy Photons from scattering of self-interacting neutrinos

Consider the decay of superheavy Dark Matter into neutrinos

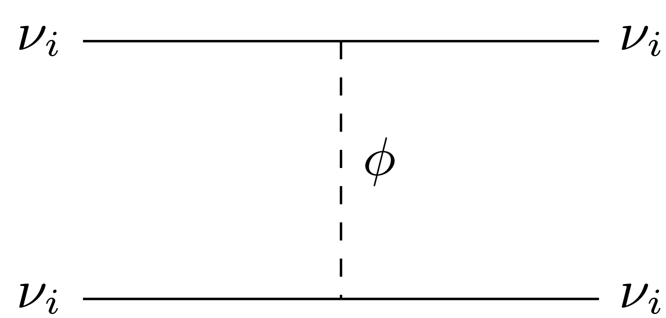
$$E_{\nu_h}' \approx m_{\rm DM}c^2$$

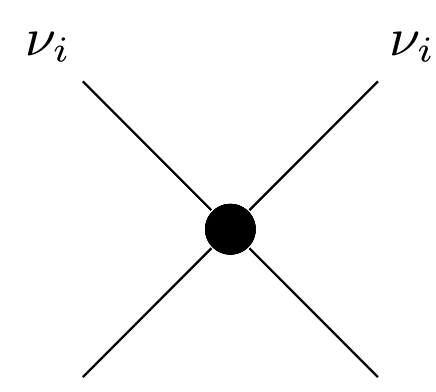


In the minimal model of neutrino self-interactions, consider a model in which the real singlet scalar interacts with neutrino and their leptonic partner

$$L \supset g_{\nu_i}\phi\nu_i\nu_i + g_{l_i}\phi\bar{l_i}l_i \qquad i = e, \mu, \tau$$

The tree level s-channel scattering of neutrinos can induce self-interacting between neutrinos.





M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

Scattering of emitted high energy neutrinos with CMB neutrinos

(a) (b)

Emission of Gamma rays can heat the Intergalactic medium, which in turn can effect the global 21-cm signal.

For loop level process:

$$\sigma = \frac{81\alpha^2 s}{4\pi^3} \frac{g_i^4}{(s - m_\phi^2)^2 + m_\phi^2 \Gamma_\phi^2} \times \left|1 + Q_i^2 m_i^2 C_0^\gamma\right|^2$$

$$C_0^\gamma(s, m_i) = \frac{1}{2s} \ln^2 \left(\frac{\sqrt{1 - 4m_i^2/s} - 1}{\sqrt{1 - 4m_i^2/s} + 1} \right)$$

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

EFFECT OF HEATING ON 21-CM SIGNAL

The evolution of gas temperature with red-shift.

$$\frac{dT_k}{dz} = \frac{2T_k}{1+z} + \frac{\Gamma_C}{(1+z)H}(T_k - T_{CMB})$$

With

$$\Gamma_C = \frac{8\sigma_T a_r T_{\mathrm{CMB}}^4 x_e}{3(1+f_{He}+xe)m_e c}$$

Including additional effects from heating of gas caused due to DM decay or any other process:

$$\frac{dT_k}{dz} = \frac{dT_k}{dz}\Bigg| \\ - \frac{2}{H(z)(1+z)3k_B n_H(z)(1+f_{He}+x_e)}\frac{dE}{dV\,dt}\Bigg|_{dep,h}$$

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

EFFECT OF HEATING ON 21-CM SIGNAL

Energy Injection Rate:

$$\left.\frac{dE}{dV\,dt}\right|_{dep,c} = f_c(z)\left.\frac{dE}{dV\,dt}\right|_{inj}$$

where $f_c(z)$ is the efficiency of energy deposited in the medium in different channels.

Evolution of free electron fraction with red-shift.

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}\left[R_s(z) - I_s(z) - I_X(z)\right]$$

$R_s(z)$– standard recombination rate from ionised gas to neutral gas

$I_s(z)$– standard recombination rate from neutral gas to ionised gas

$I_X(z)$– ionization rate due to the additional injection of energetic particles

$I_X(z) = I_{X_i}(z) + I_{X_\alpha}(z)$ (direct ionization rate + excitation plus ionization)

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

EFFECT OF HEATING ON 21-CM SIGNAL

$$I_{X_i} = \frac{1}{n_H(z)E_0} \frac{dE}{dV dt}\bigg|_{dep,i}$$

$$I_{X_\alpha} = \frac{(1-\mathcal{P})}{n_H(z)E_\alpha} \frac{dE}{dV dt}\bigg|_{dep,\alpha},$$

$\mathscr{P}$–Peeble coefficient, $n_H(z)$–number density of hydrogen atoms

E_α– Lyman alpha energy

The differential equation can be solved by assuming initial condition:

$$T_k(z=10000) = T_{\rm CMB}(z=10000) \text{ and } x_e(z=10000) = 1.$$

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EFFECT OF HEATING ON 21-CM SIGNAL

$$\langle \sigma v \rangle = \frac{1}{n_{\nu_i}} \int \frac{d^3p}{(2\pi)^3} f(\vec{p}) v_{M\o l} \sigma(s(E_{\nu_h}, \vec{p}))$$

For present day neutrino temperature: $T_\nu(z) = 1.9K$

$$n_{\nu_i}(0) = 112 \text{ cm}^{-3}$$

For CMB neutrinos with mass around 0.1 eV , neutrinos will be non-relativistic.

Thus, we consider:

$$s \approx 2E_{\nu_h} m_\nu \text{ and } v_{M\o l} = 1.$$

With this,

$$\langle \sigma v \rangle = \sigma(2E_{\nu_h} m_{\nu_i}),$$

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

ENERGY INJECTION RATE DUE TO SELF-SCATTERING OF NEUTRINOS

The evolution of number density of ultra high energy (UHE) neutrinos while scattering with CMB neutrinos:

$$\frac{dn_{\nu_h}}{dt} = n_{\nu_h} n_{\nu_i} \langle \sigma v \rangle,$$

Assuming UHE neutrinos are emitted from the decay of superheavy DM, the present day number density of UHE neutrino:

$$n_{\nu_h,0} = \frac{f_{\rm DM} \Omega_{\rm DM} \rho_c}{m_{\rm DM}},$$

For non-relativistic neutrino:

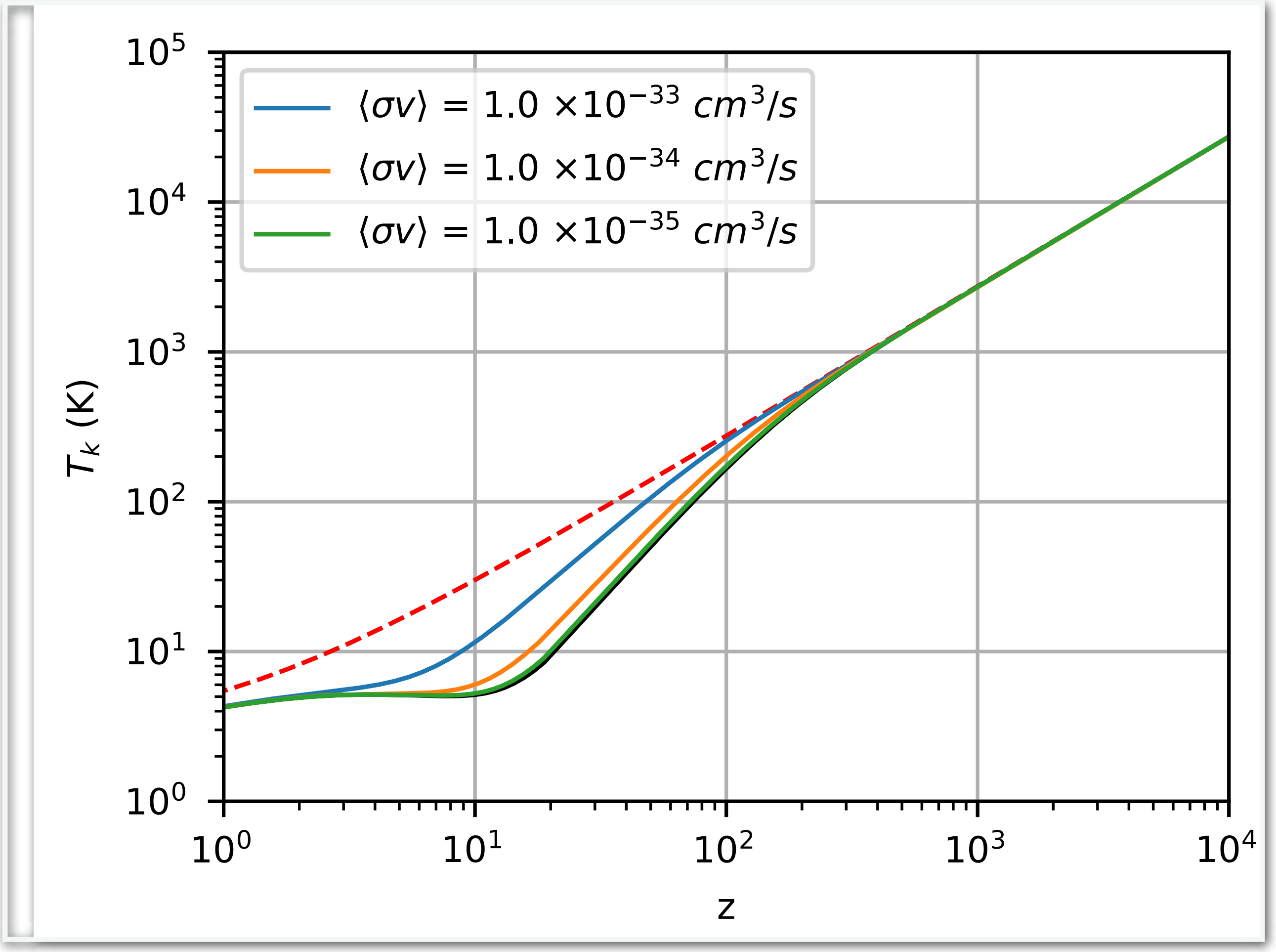
$$n_{\nu_h} = n_{\nu_{h,0}} (1+z)^3, \;\; n_{\nu_i} = n_{\nu_{i,0}} (1+z)^3$$

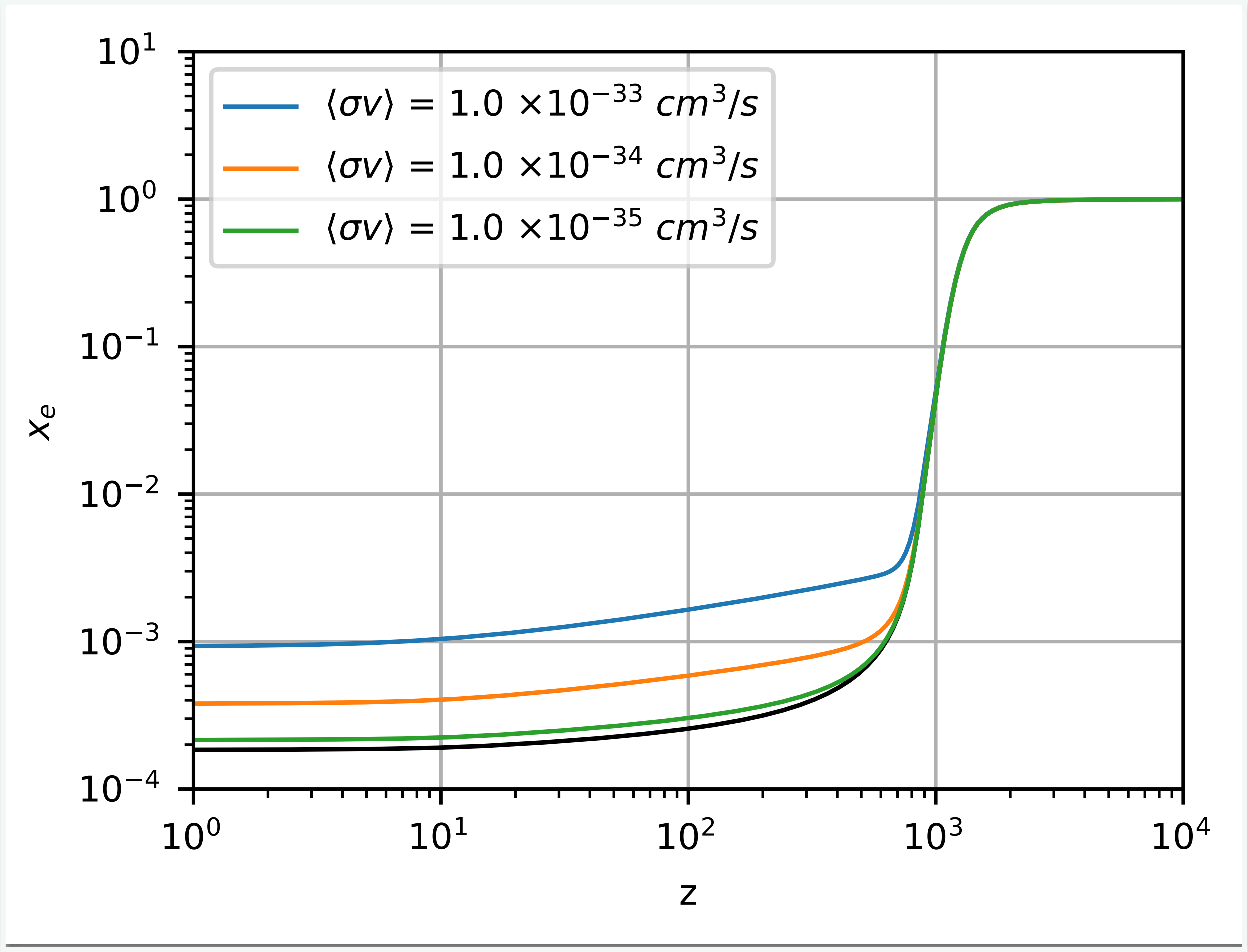
With this, the energy injection rate:

$$\left.\frac{dE}{dV\,dt}\right|_{inj} = (1+z)^6 f_{\rm DM} \Omega_{DM} n_{\nu_{i,0}} \rho_c c^2 \langle \sigma v \rangle$$

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

EVOLUTION OF GAS KINETIC TEMPERATURE

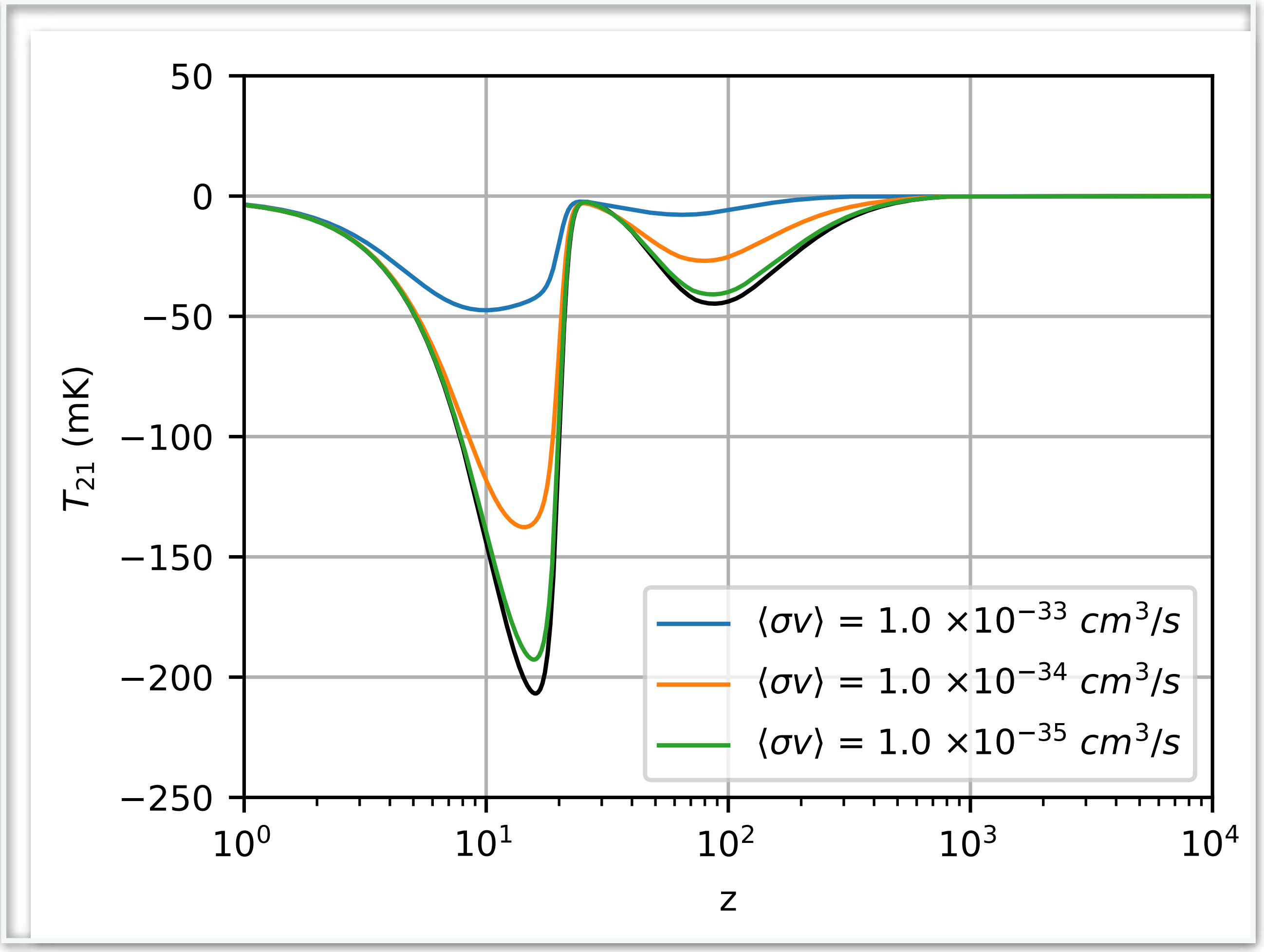


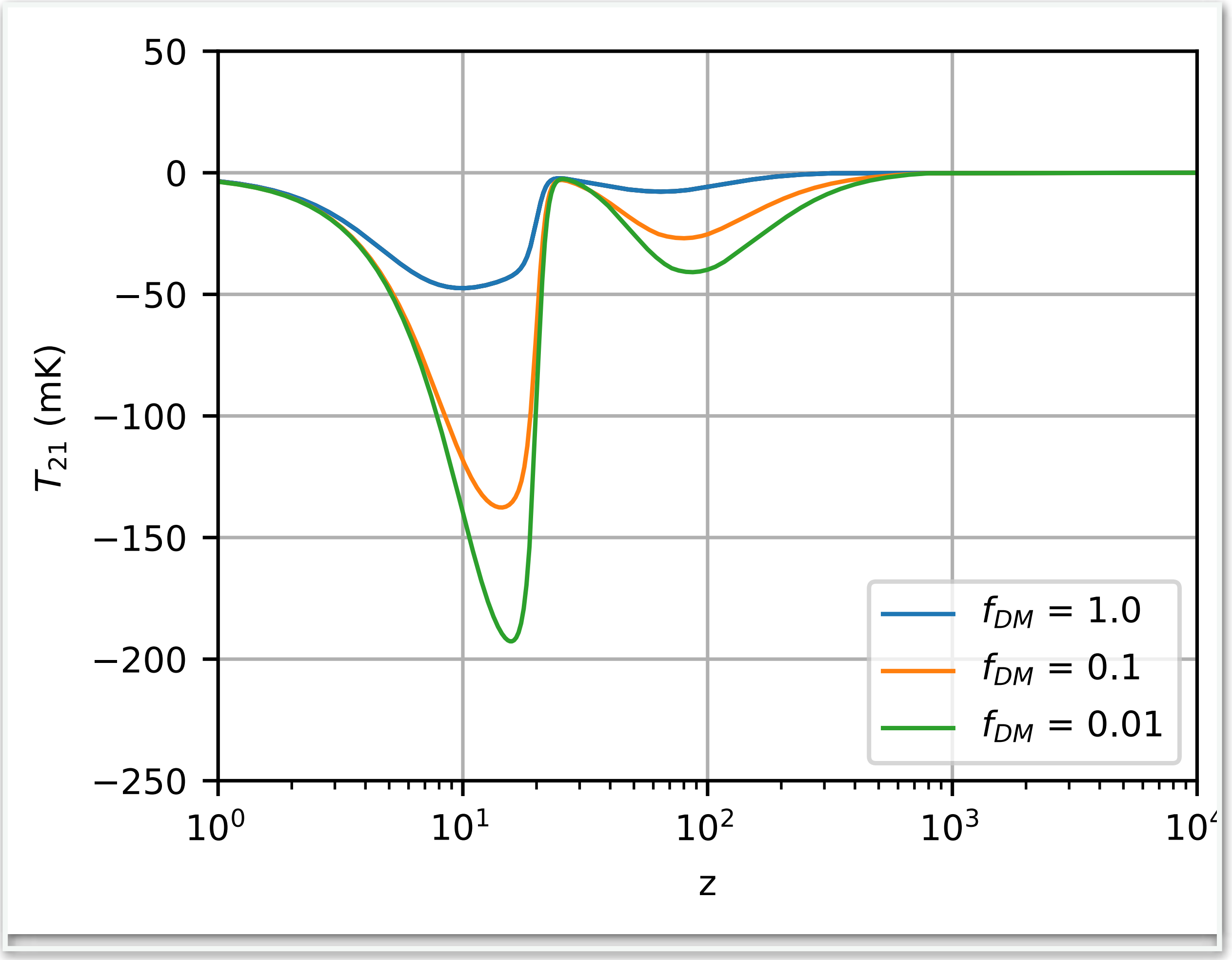


The results indicate that increasing cross-section results in the heating of the gas and increase in free electron fraction at lower red-shifts.

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

EVOLUTION OF BRIGHTNESS TEMPERATURE





The results indicate that increasing cross-section reduces the magnitude of absorption strength.

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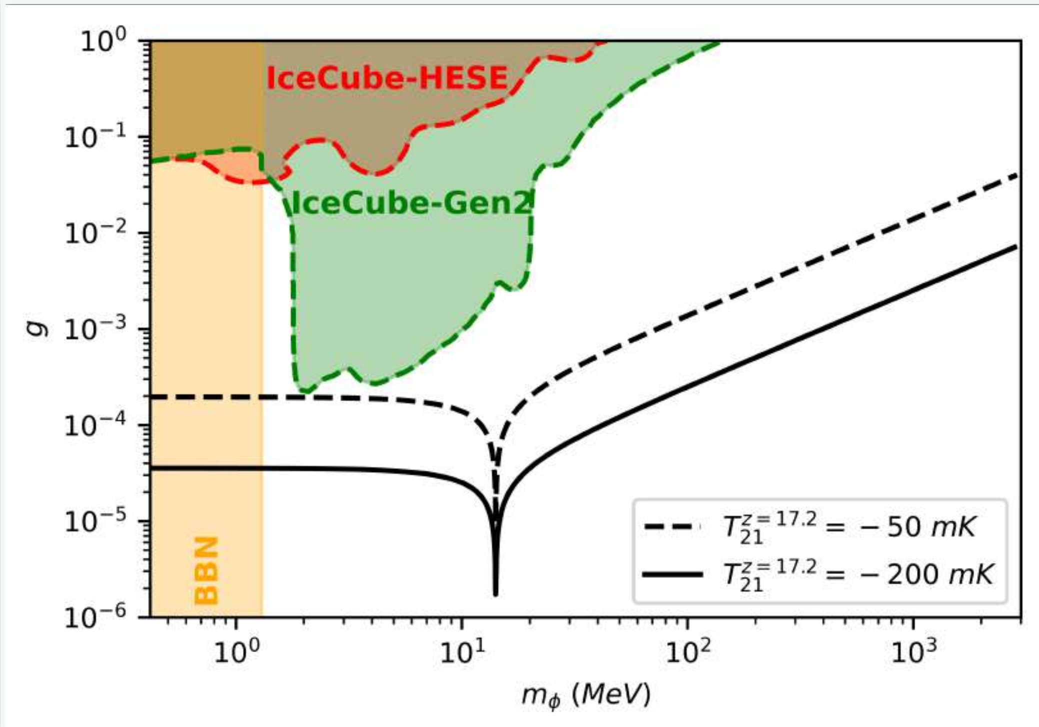
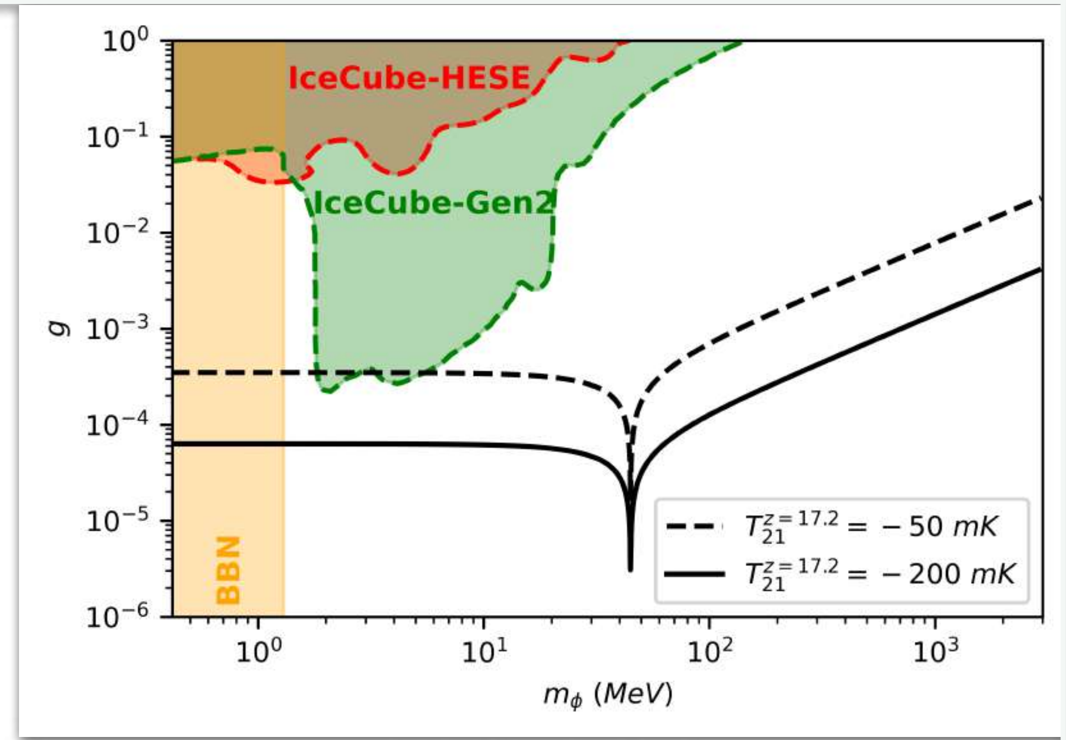
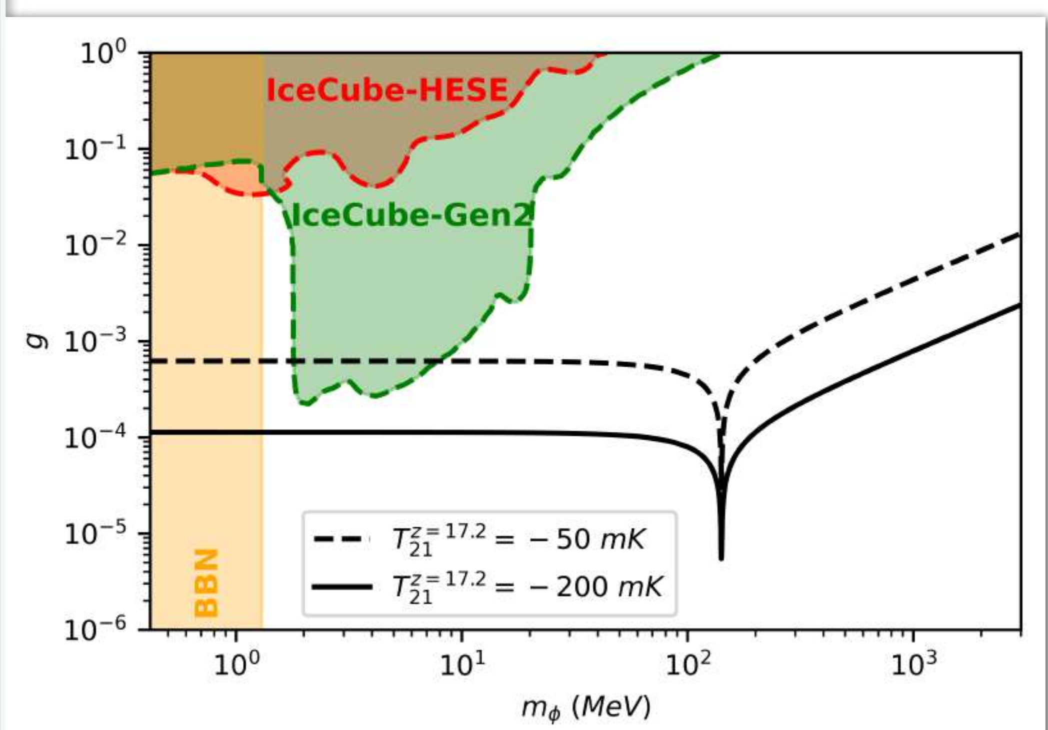
ALLOWED PARAMETER SPACE OF SELF-INTERACTING NEUTRINO COUPLING



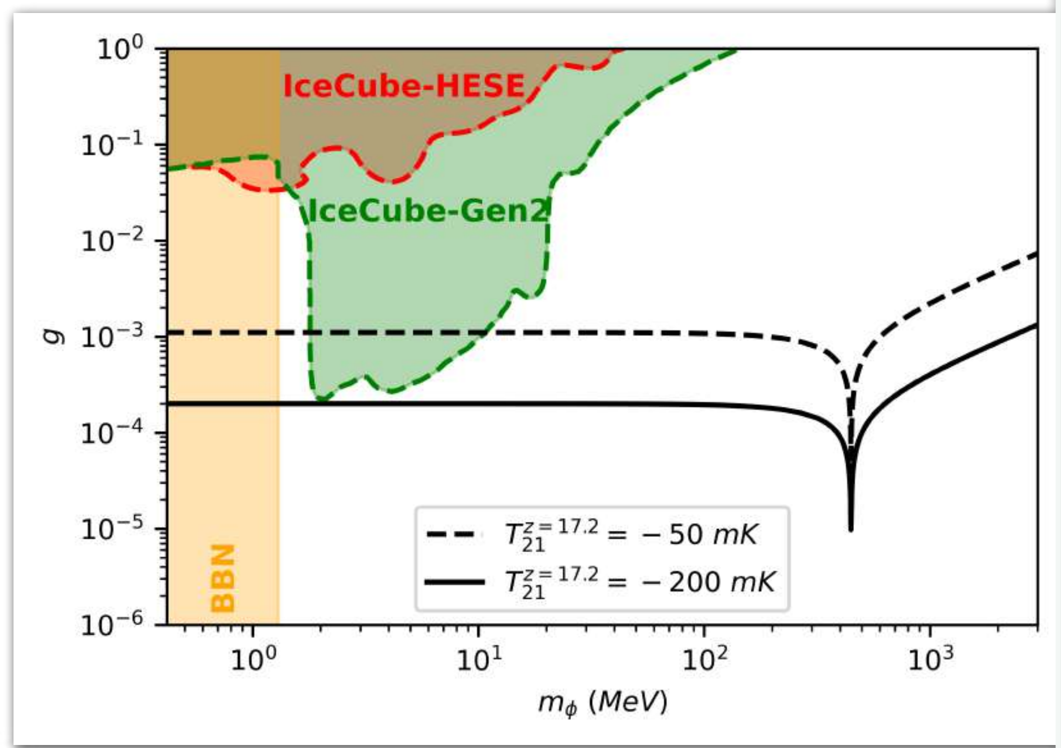
(a) $E_{\nu_h} = 1$ PeV



(b) $E_{\nu_h} = 10$ PeV



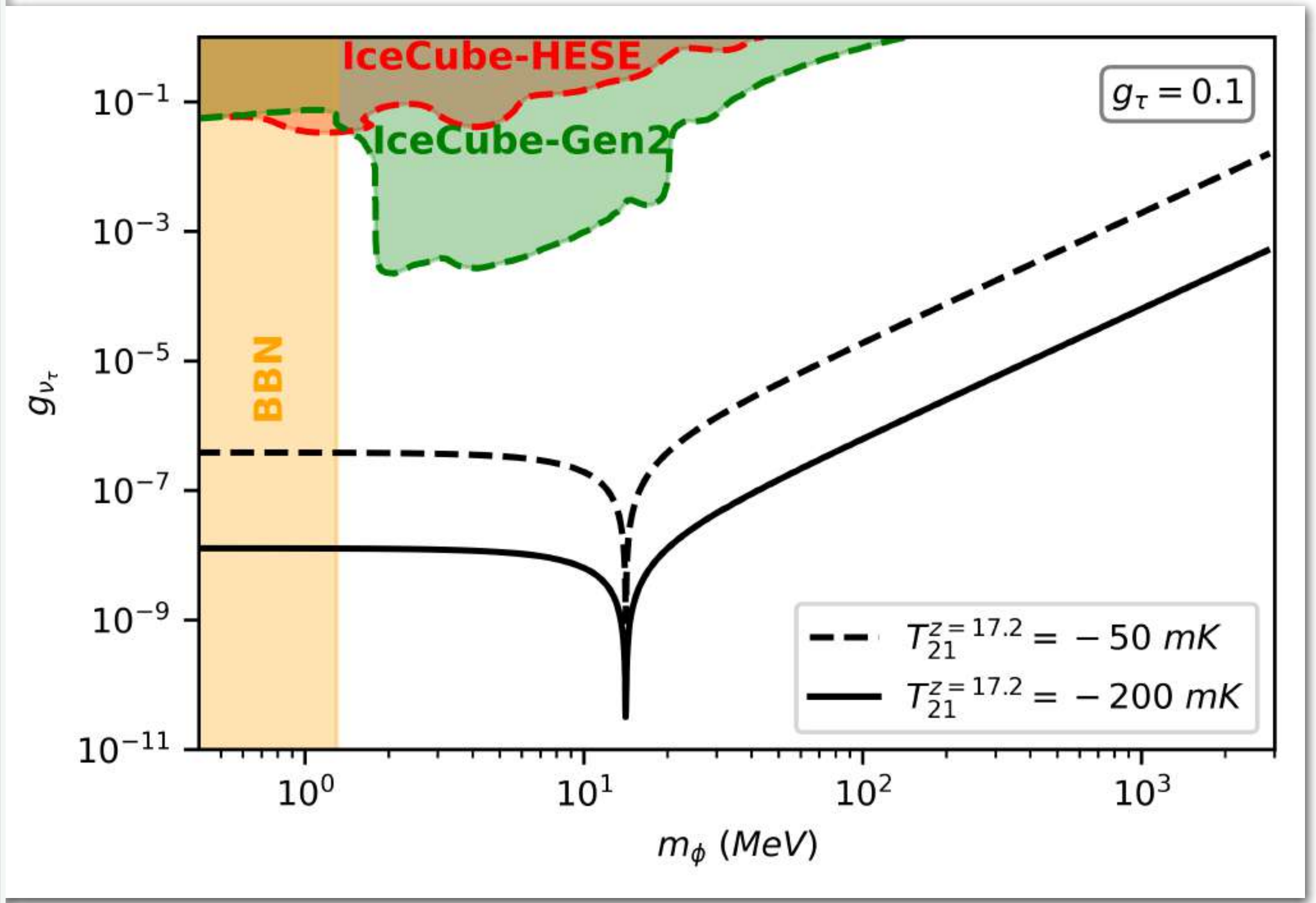
(c) $E_{\nu_h} = 100$ PeV



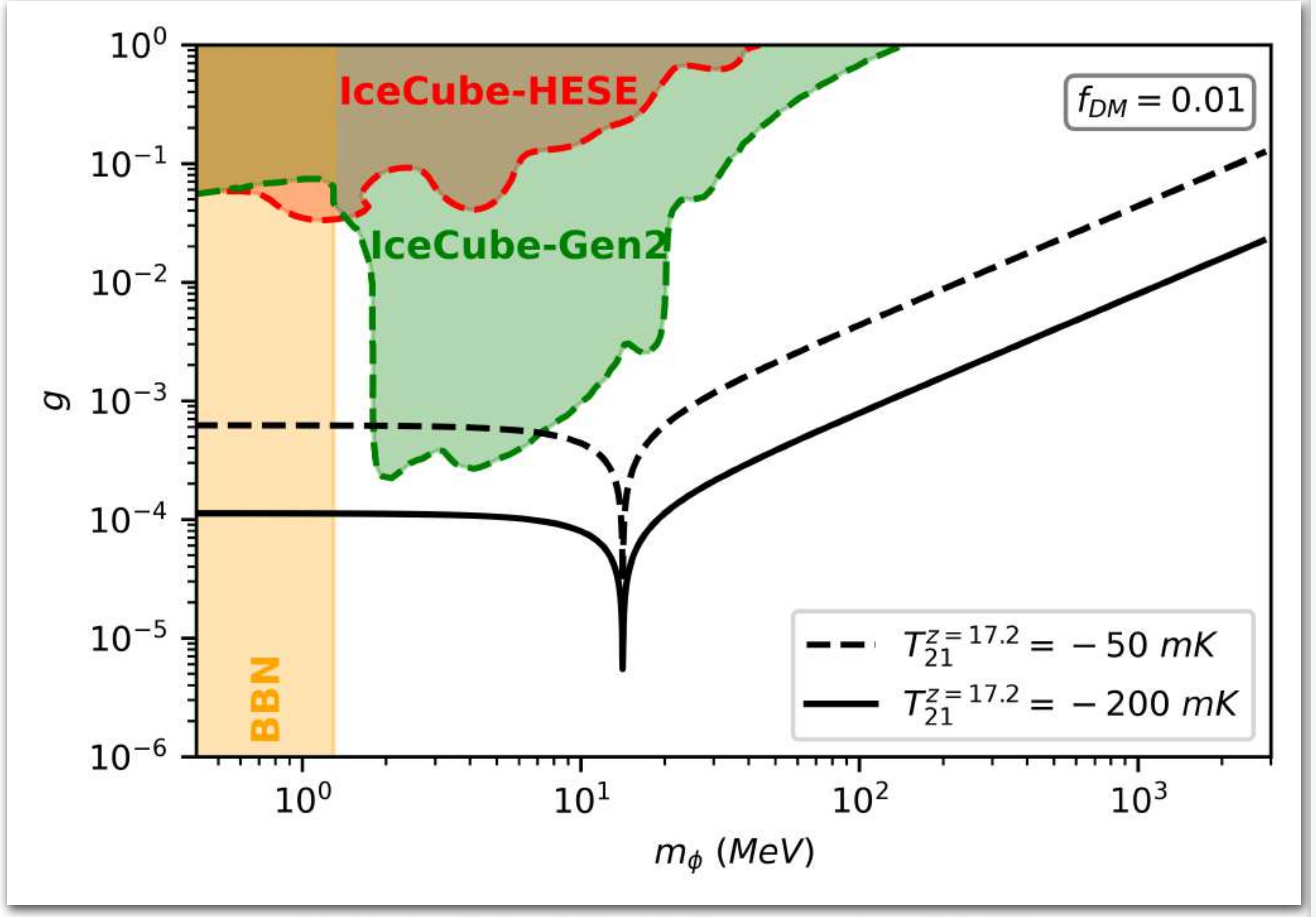
(d) $E_{\nu_h} = 1$ EeV

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

ALLOWED PARAMETER SPACE OF SELF-INTERACTING NEUTRINO COUPLING



(a) $E_{\nu_h} = 1$ PeV, $g_\tau \neq g_{\nu_\tau}, g_\tau = 0.1, f_{\rm DM} = 1$



(b) $E_{\nu_h} = 1$ PeV, $g_\tau = g_{\nu_\tau}, f_{\rm DM} = 0.01$

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

TAKE AWAY

- For UHE neutrino emitted from DM decay in PeV-EeV range, the coupling constant gets constrained gets constrained in the range from 10^{-4} to 10^{-3}.

- The constraints are much stronger than the predicted sensitivity for tau-neutrino self-interactions from IceCube.

- As the era of cosmic dawn utilises relatively simple astrophysical condition, this shall offers a clear signal for studying non-standard interactions of neutrinos.

- The potential detection of 21-cm signal by future experiments can provide clear insights into the nature of neutrino.

M. Dhuria and B. Gupta Teli, e-Print: 2406.19279 [hep-ph]

Work in Progress: neutrinos emitted from PBH decay

- As Primordial Black holes evaporate, their temperature keeps on increasing. As a consequence, at the final stage of evaporation, they are capable of emitting high energy particles.

- We consider the scattering of high energy neutrino emitted from the evaporation of PBH with CMB neutrinos.

- The Hawking radiation rate: $\frac{d^2 N_i}{dt dE} \approx \frac{g_i}{2\pi} \cdot \frac{\gamma_{\text{gray}}}{\exp(E/T_{\text{BH}}) - \eta}$, $T_{\text{BH}} = \frac{m_{\text{pl}}^2}{8\pi m_{\text{BH}}}$

- The distribution function of the emitted particles in the expanding Universe:

$$f_i\,(t,\ p) = \int_0^a \frac{\Gamma_{i,\,\text{prod}}(a',\ p')}{H(a')a'} da' \ , \quad \Gamma_{i,\,\text{prod}}^{(\text{PBH}\to i)} \approx n_{\text{BH}} \frac{(2\pi)^3}{4\pi p^2} \frac{d^2 N_i}{dt dp}$$

Quan Feng Wu and Xun-Jie Xu, e-Print: 2409.09468

- The number density of massless particles:

$$n_i \equiv \int f_i \frac{4\pi p^2}{(2\pi)^3} dp = f_{i0} \frac{c_\pm T_{\text{BH0}}^3}{48\pi^2} , \quad (t = t_{\text{ev}}) , \quad f_{i0} \equiv \frac{3^6}{4} \sqrt{3\gamma g_{\text{BH}}} \beta g_i \frac{m_{\text{pl}}}{m_{\text{BH0}}} , \ \beta \equiv \left. \frac{\rho_{\text{BH0}}}{\rho_{\text{tot}}} \right|_{t=t_F}$$

By considering the entire number density of neutrinos emitted from PBH evaporation, we will constrain the parameters of PBH from 21-cm brightness temperature measurements.

M. Dhuria, B. Gupta Teli and Havisha, in preparation, e-Print: 24XX.XXXX

High energy Gamma Rays from GRB221009A

- LHAASO reported the observation of very high energy photons with high energy up to 18 TeV in a 2000 sec window.
- The High energy photons will inevitably be attenuated by the extragalactic background light (EBL) as $\gamma + \gamma_{EBL} \rightarrow e^{+} + e^{-}$
- New physics beyond the Standard Model (SM) might explain the origin of high energy gamma rays.
- **BSM proposals:** axion-like particles, sterile neutrino decay, light scalar decay
- GRB are the powerful source of neutrinos. The gamma rays might get produced from the decay, scattering or annihilation of neutrinos emitted in GRB.

Gamma Rays from Neutrinos: GRB221009A

- The IceCube collaboration has also performed dedicated searches for co-relating some of the GRB events with diffuse extra-galactic neutrino background of very high energy neutrinos

- The non-observation of such events set an upper limit on muon neutrino flux.

$$E_\nu^2\, \Phi_\nu^{\rm int} < 3.9 \times 10^{-5}\, {\rm TeV cm^{-2}}$$

- The ratio of unattenuated Gamma rays to neutrinos is

$$r_{\nu\gamma} \equiv \frac{\Phi_\nu}{\Phi_\gamma^0}$$

- The unattenuated Gamma ray flux at high energy

$$\Phi_\gamma^0(E_\gamma) = \frac{2.1 \times 10^{-6}}{{\rm cm^2 s\, TeV}} \left(\frac{E_\gamma}{\rm TeV}\right)^{-1.87\pm0.04} .$$

- The average neutrino flux $\Phi_\nu = \Phi_\nu^{\rm int}/\Delta t$ gives

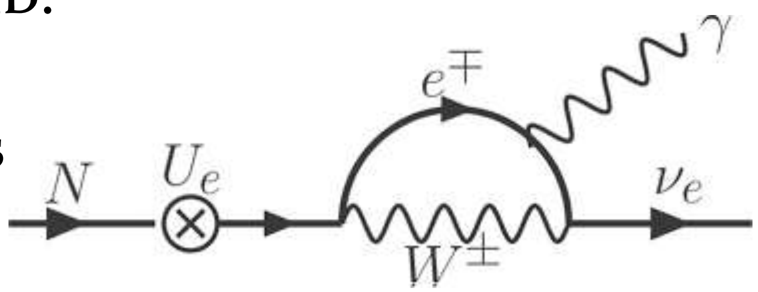
$$r_{\nu\gamma} \lesssim 3\times 10^{-2}$$

A. Smirnov and A.Trautner, e-Print: 2211.06374

Gamma Rays from Sterile Neutrino Decay

- Heavy neutrinos (N) are produced in GRB through mixing from the neutrinos emitted from the decay of Kaon/muons produced during GRB.

- The radiative process let the neutrino decay into Gamma rays



- The flux of heavy neutrinos $r_{N\nu} \equiv \frac{\Phi_N}{\Phi_\nu} = \frac{\sum_{\ell=e,\mu} |U_{N\ell}|^2 \Phi_{\nu_\ell}}{\sum_{\ell=e,\mu} \Phi_{\nu_\ell}}$

- For decay rate Γ_N, the decay length will be given by $\lambda_N = \frac{E_N}{\Gamma_N m_N}$.

- The average neutrino flux:

$$\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} = B_\gamma \frac{\Phi_N}{\Phi_\gamma^0} \frac{1}{\tau\lambda_N/d - 1} \left[e^{-d/\lambda_N} - e^{-\tau} \right]$$

Suppressed by mixing angle $|U_{N\ell}|^2 \sim 10^{-3}$ and $r_{\nu\gamma} \lesssim 3\times 10^{-2}$

For $\tau >> 1$, $\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} \approx B_\gamma \, r_{N\nu} \, r_{\nu\gamma} \, \frac{0.37}{\tau}$

Thus, for an effective area of 100 Km² and observation time of 2000 sec, the expected number of events turns out to be very less of the order 10^{-3}, which is quite small.

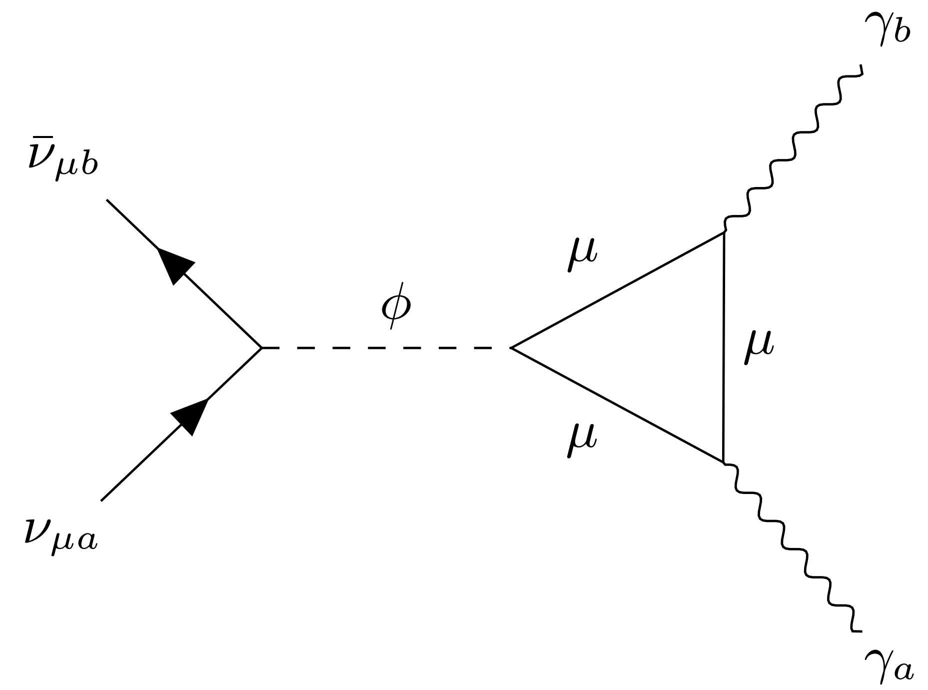
A. Smirnov and A.Trautner, e-Print: 2211.06374

Self-interactions of neutrinos: GRB221009A

- We consider the production of photons due to direct scattering of astrophysical neutrinos (emitted from GRB) with CMB neutrinos.

Phenomenological model

$$\mathscr{L} \supset g_\mu \phi \bar{\mu} \mu + g_{\nu_\mu} \phi \bar{\nu} \nu$$



Two cases:

$(i)\ g_\mu = g_{\nu_\mu}, (ii)\ g_\mu \neq g_{\nu_\mu}$

- The constraints on the muon neutrino flux from GRB221009A will be useful.

M.Dhuria, e-Print: 2309.XXXX , in preparation

Gamma Rays from Neutrinos: GRB221009A

The optical depth of neutrinos will be

$$\tau_N = \frac{\lambda_N}{d}, \quad \text{with } d = 645 \text{ Mpc}, \ \lambda_N - \text{Mean free path of neutrinos}$$

The probability of neutrino scattering with CMB neutrinos and producing gamma rays would be given by

$$e^{-x/\lambda_{\nu_\mu \to \gamma}} \frac{dx}{\lambda_{\nu_\mu \to \gamma}} e^{-(d-x)/\lambda_\gamma}$$

with $$\tau_\gamma = \frac{\lambda_\gamma}{d}, \ \lambda_\gamma - \text{Mean free path of Gamma} - \text{rays}$$

The mean free path can be calculated from

$$\lambda_{\nu_\mu \to \gamma} = \frac{1}{\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a \gamma_b)}$$

with

$$\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a \gamma_b) = \sigma(2E_{\nu_{\mu a}} m_{\nu_\mu}) n_{\nu_{\mu b}}$$

M.Dhuria, e-Print: hep-ph/2309.12264

Gamma Rays from Neutrinos: GRB221009A

The flux of gamma rays from neutrinos:

$$\phi^{\gamma}_{\nu_\mu} = \phi_{\nu_\mu} \frac{1}{(\lambda_{\mu\to\gamma}/\lambda_\gamma) - 1} \left[e^{-d/\lambda_\mu} - e^{-d/\lambda_\gamma}\right]$$

For $\phi_{\nu_{\mu a}} = r_{\nu\gamma} \times \phi^0_\gamma(E_\gamma) = 0.03\ \phi^0_\gamma(E_\gamma)$

$$\phi^{\gamma}_{\nu_\mu} = 0.03\ \frac{\phi^0_\gamma}{(\lambda_{\mu\to\gamma}/\lambda_\gamma) - 1} \left[e^{-d/\lambda_{\mu\to\gamma}} - e^{-d/\lambda_\gamma}\right]$$

Smirnov and Trautner (2211.06374)

The cross-section for neutrinos scattering into gamma rays through scalar mediator will be

$$\sigma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b) = \frac{81\alpha^2 s}{4\pi^3} \frac{(g_\mu g_{\nu_\mu})^2}{(s - m^2_\phi)^2 + m^2_\phi \Gamma^2_\phi}$$
$$\times \left|1 + \sum_f Q^2_\mu m^2_\mu C^\gamma_0\right|^2, \quad C^\gamma_0(s, m_\mu) = \frac{1}{2s} \ln^2\left(\frac{\sqrt{1 - 4m^2_\mu/s} - 1}{\sqrt{1 - 4m^2_\mu/s} + 1}\right).$$

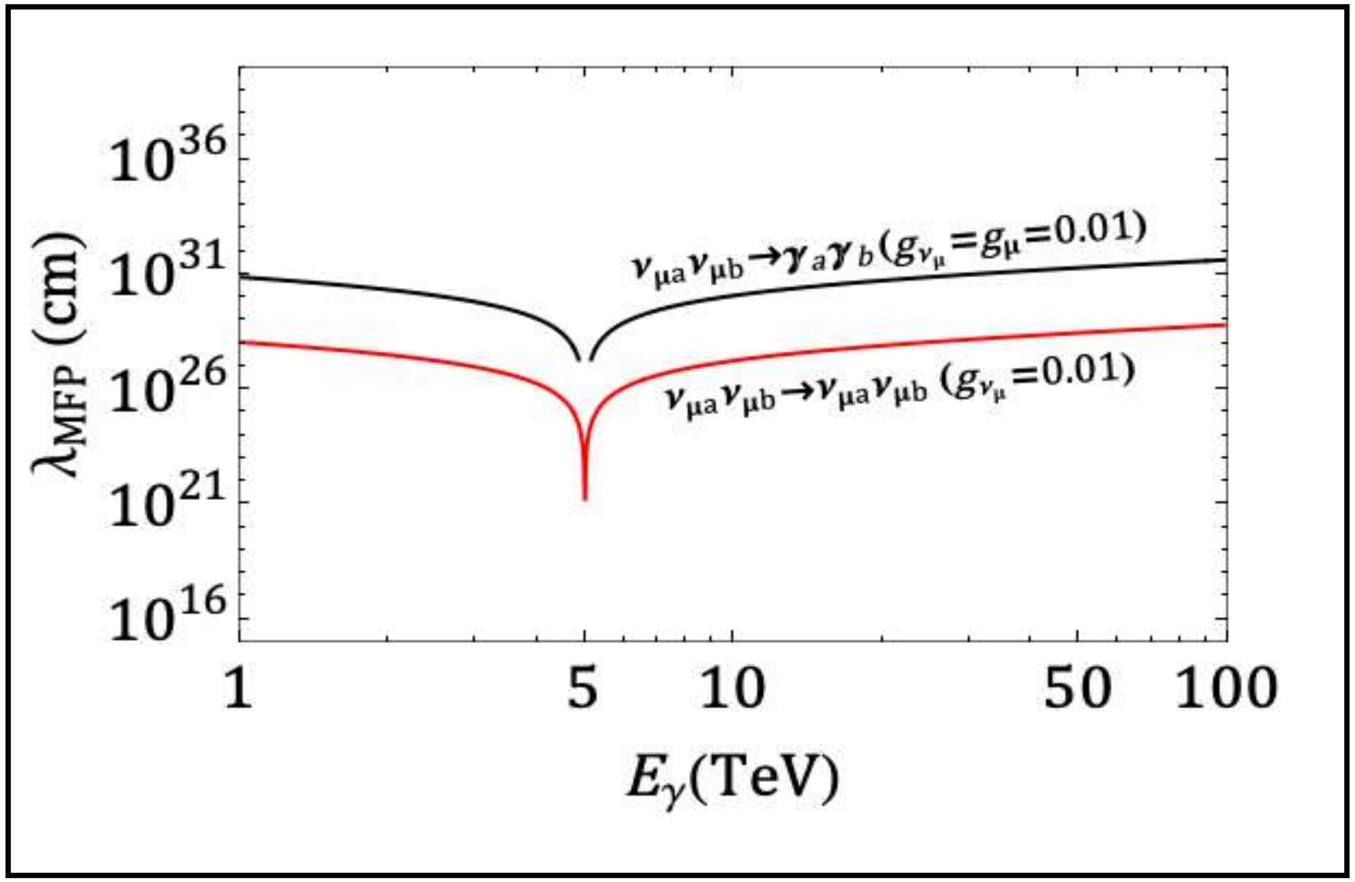
For non-relativistic neutrino with $\sqrt{s} = \sqrt{2m_{\nu_\mu} E_{\nu_{\mu a}}}$

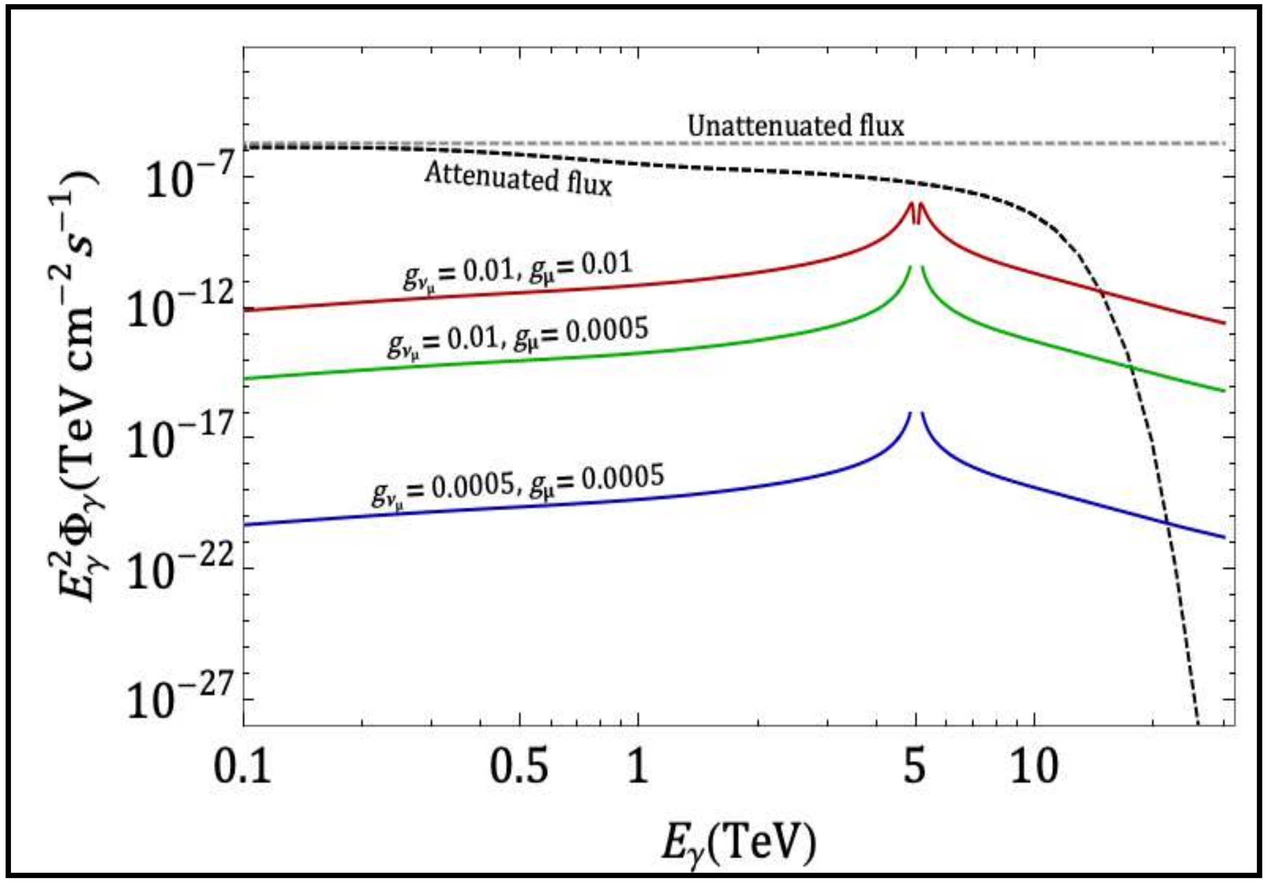
M.Dhuria, e-Print: hep-ph/2309.12264

Mean Free Path and flux of Gamma rays: GRB221009A

$$\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b) = \sigma(2E_{\nu_{\mu a}} m_{\nu_\mu}) n_{\nu_{\mu b}}$$

Mean Free path $$\lambda_{\nu_\mu \to \gamma} = \frac{1}{\sigma(2E_{\nu_{\mu a}} m_{\nu_\mu}) n_{\nu_{\mu b}}}$$





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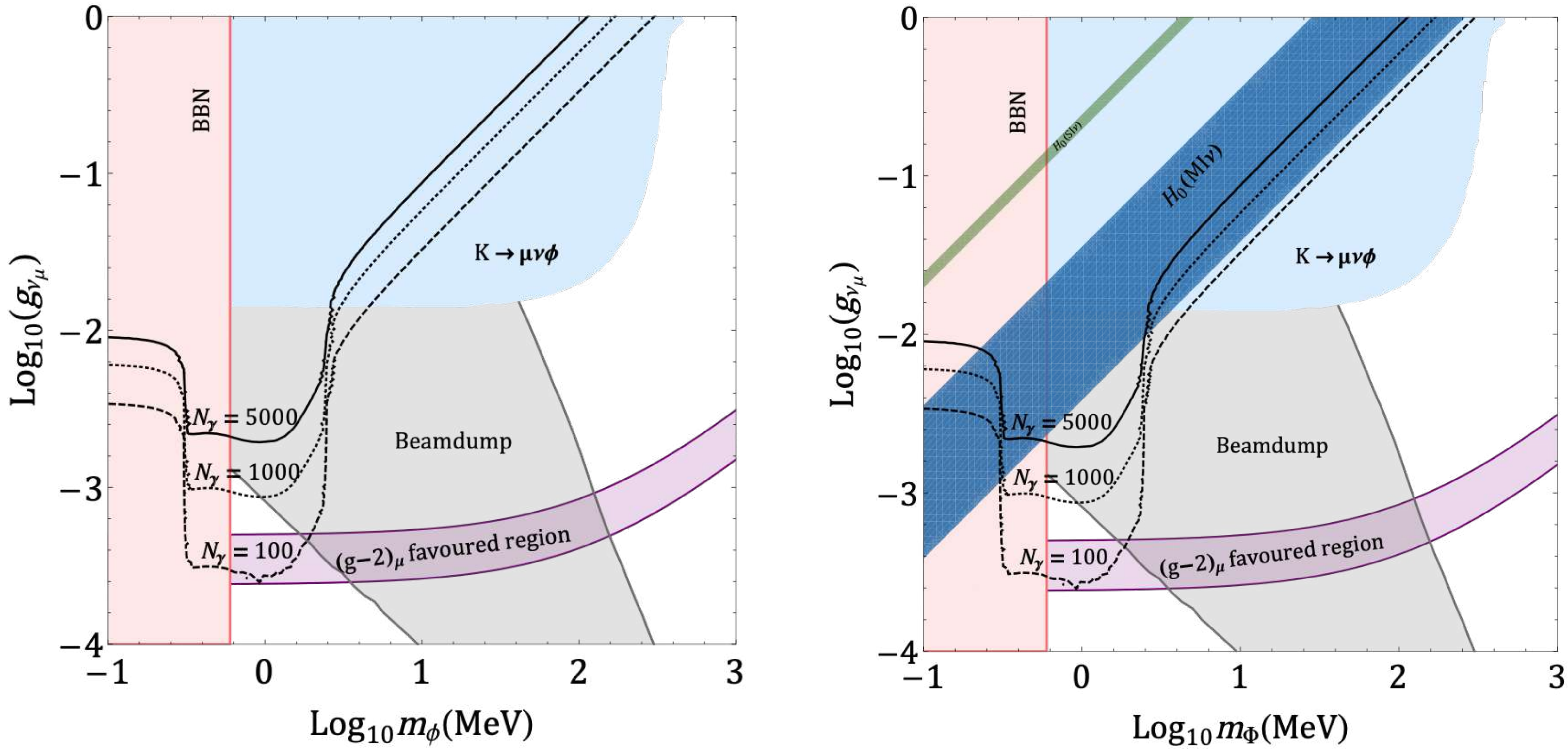
Parameter space of self-interaction coupling

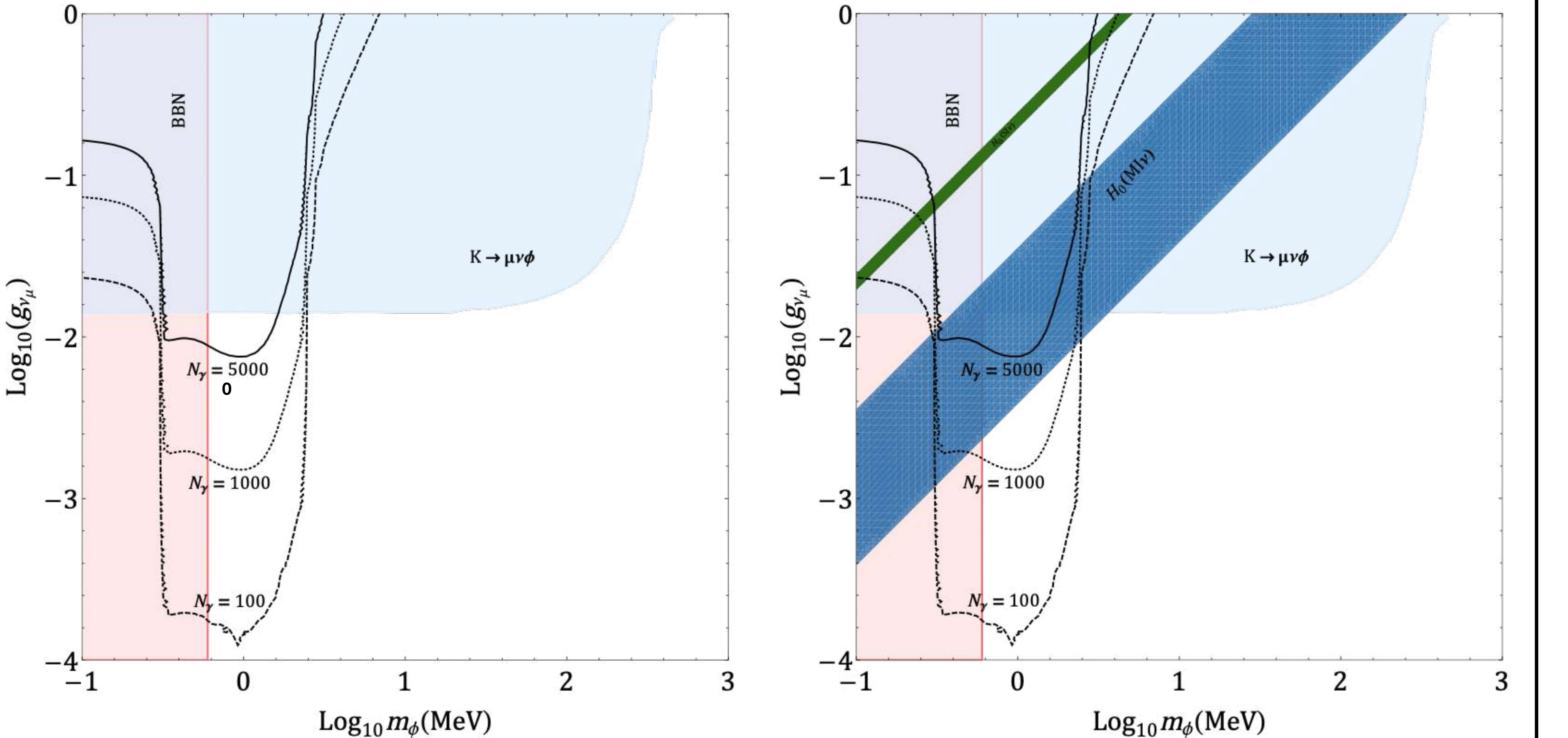
$$\text{Number of Events: } N_\gamma = \int_{1\text{TeV}}^{30\text{TeV}} \phi^\gamma_{\nu_\mu}(E_\gamma)\, dE_\gamma\, dA\, dt,$$



(a) $g_{\nu_\mu} = g_\mu$ (b) $g_{\nu_\nu} = g_\mu$ (including Hubble tension constraints)

M.Dhuria, e-Print: hep-ph/2309.12264

Parameter space of self-interaction coupling



(a) $g_{\nu_\nu} \neq g_\mu, g_\mu = 5 \times 10^{-4}$

(b) $g_{\nu_\nu} \neq g_\mu, g_\mu = 5 \times 10^{-4}$(including Hubble tension constraints)

M.Dhuria, e-Print: hep-ph/2309.12264

Summary

- The self-interacting nature of neutrinos offers interesting cosmological and astrophysical implications.
- The 21-cm cosmology, on the other hand, poses clean signal to the possible indication of Physics beyond SM.
- The self-interactions of neutrinos could also impact high energy gamma rays and neutrinos emitted from galaxies and other astrophysical events.
- Thus, the new non-standard self-interactions could lead to new roadmaps and need to be studied throughly in theoretical frameworks of physics beyond SM.

Open Directions

- Need promising theoretical model invoking self-interacting neutrino coupling.
- In the context of 21-cm radiation, the effect of the self-interactions can be understood from the 21-cm power spectrum.
- Consistency of the coupling parameters obtained from various astrophysical observations (such as IceCube) with CMB observations.
- Possible implications by considering light mediator (of mass around eV).

THANK YOU FOR YOUR KIND ATTENTION

Self-Interacting Neutrinos and the Hubble Tension

The change in the phase and amplitude of baryon acoustic oscillations of CMB power spectrum due to neutrino perturbations :

$$\phi_\nu \approx 0.19\pi R_\nu, \quad 1 + \Delta_\nu \approx 1 - 0.27 R_\nu,$$

with $$R_\nu = \frac{\rho_\nu}{\rho_\nu + \rho_\gamma}$$

ρ_ν - energy density of free streaming neutrinos

The CMB multiple for a particular mode:

$$l \approx (m\pi - \phi_\nu)\frac{D_A^*}{r_s^*}$$

D_A^* - distance to the last scattering surface from today

r_s^* - radius of sound horizon at the time of recombination

$$D_A^* = \int_0^{z^*} \frac{1}{H(z)} dz, \quad r_s^* = \int_{z^*}^{\infty} \frac{c_s}{H(z)} dz$$

$$H(z) = H_0 \sqrt{\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_\Lambda}$$

The small phase shift can shift the position of peaks in the CMB spectrum

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The small phase shift can shift the position of peaks in the CMB spectrum

↓

This can be compensated by decreasing the value of angular distance D_A

↓

Possible by slightly increasing the value of H_0 without effecting H(z) at high red shift