Cosmic Neutrino Searches as Dark Matter Detectors

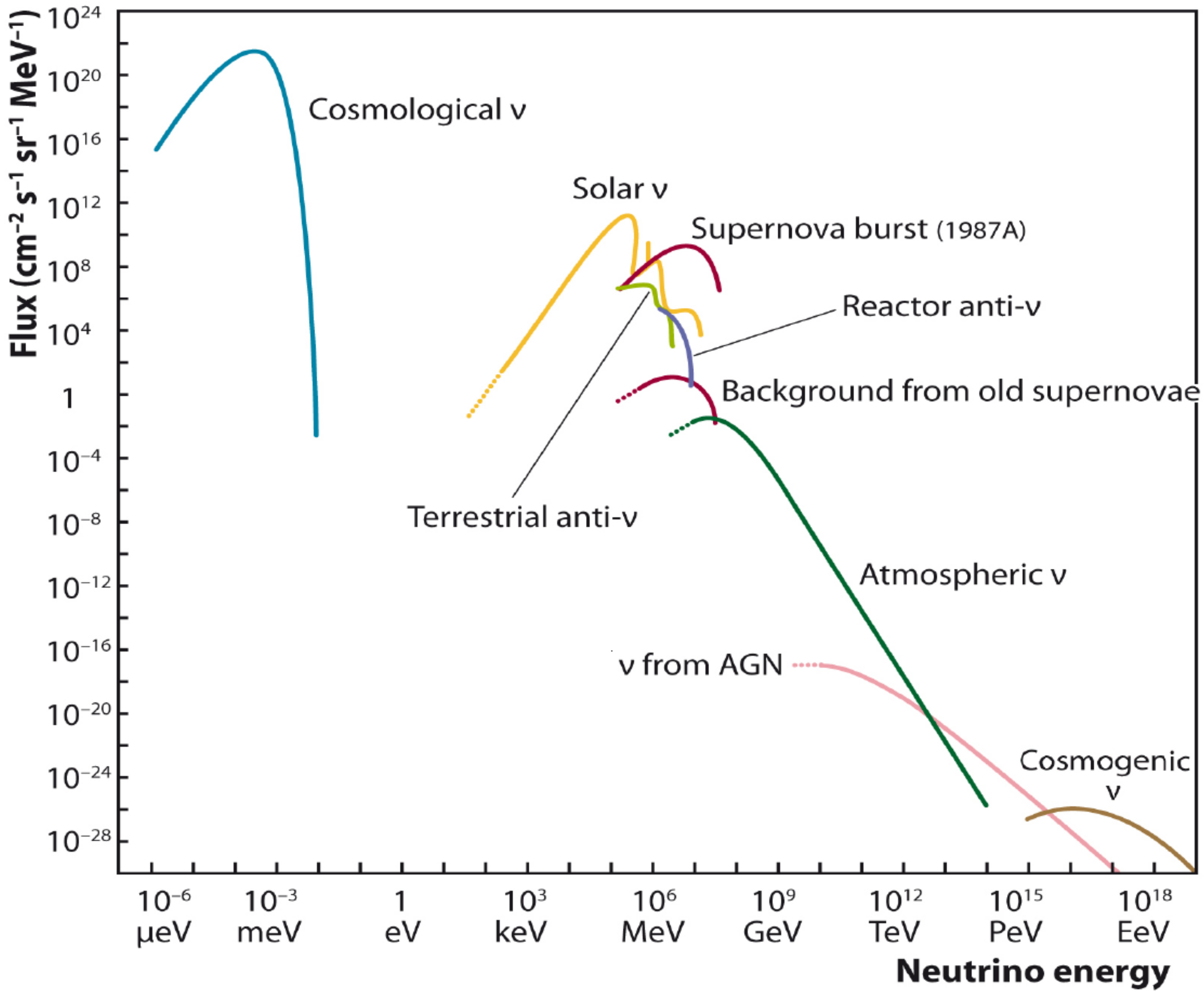
David McKeen

TRIUMF

NuTheories
November 5, 2018

Based on work in progress with Nikita Blinov & Ann Nelson

Let's start with a plot



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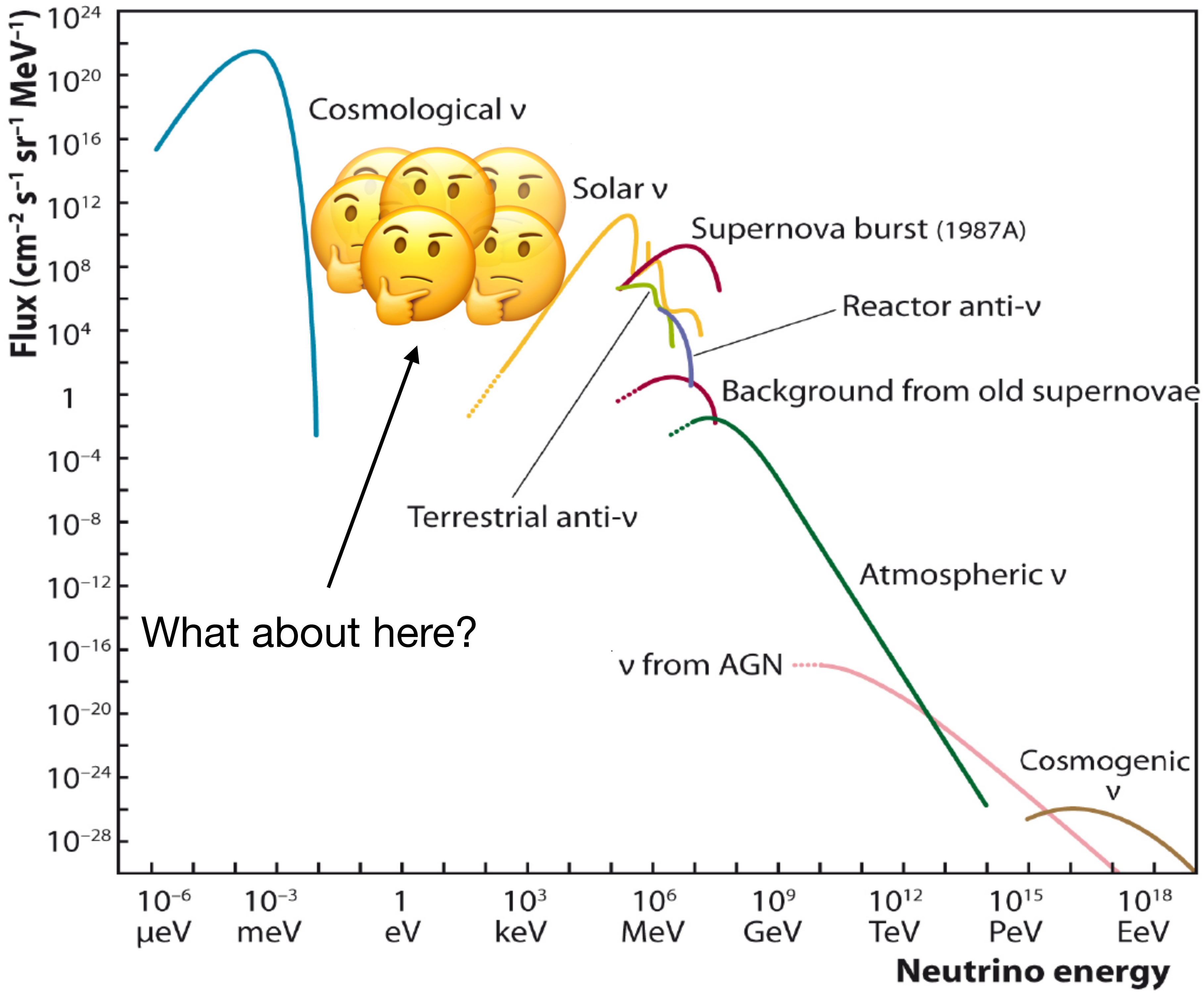

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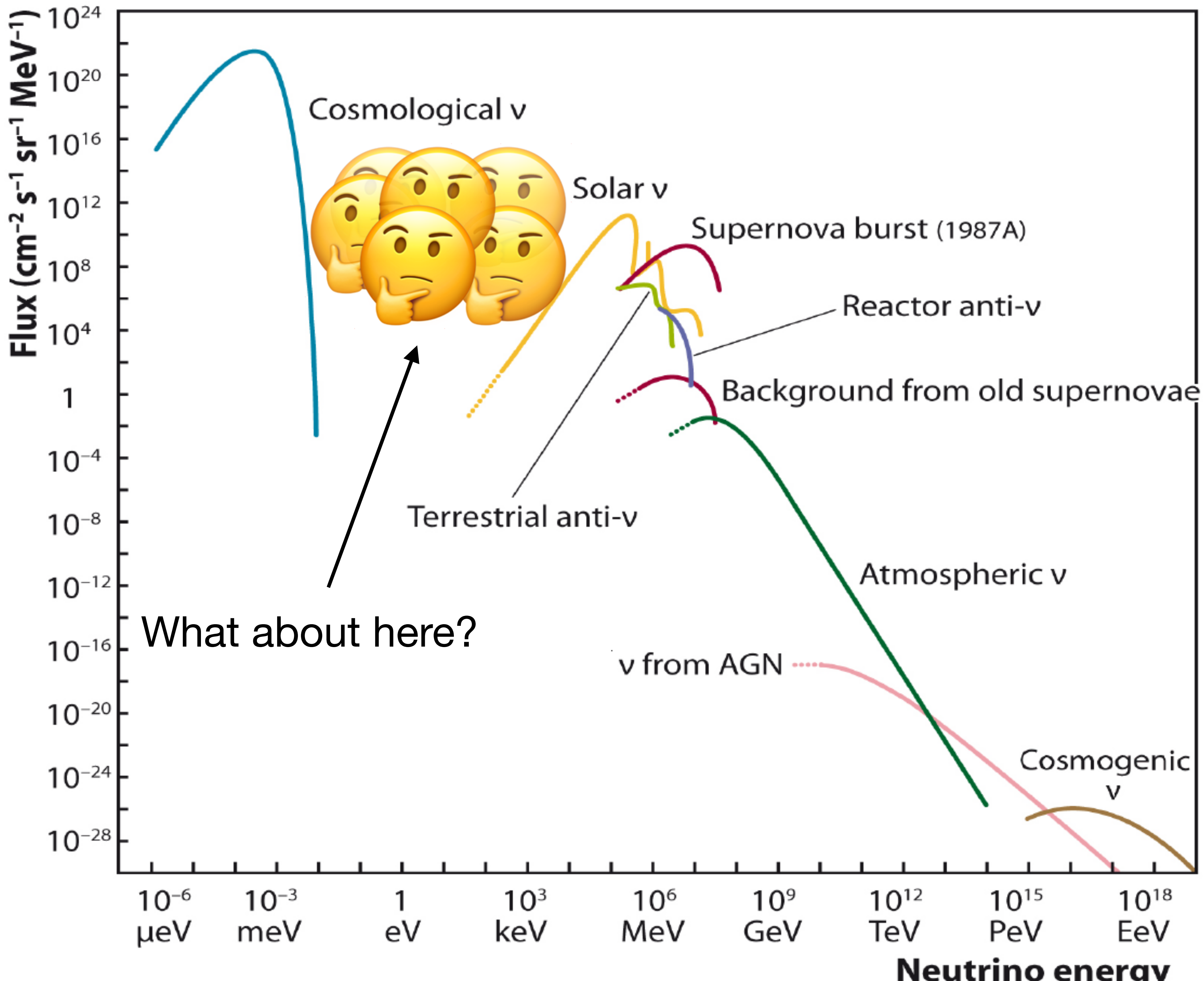


Similar to work by Cui, Pospelov, Pradler; Heeck

How could this gap be populated?

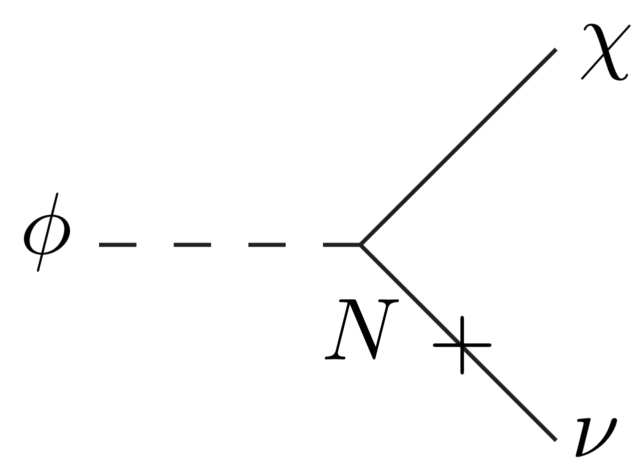
Dark Matter decay:

$$\mathcal{L} \supset -\lambda \bar{L} H N - y \bar{N} \chi \phi + \text{h.c.} \rightarrow -\lambda v \bar{\nu} N - y \bar{N} \chi \phi + \text{h.c.}$$

Odd under e.g. Z_2, lightest is stable

Imagine degeneracy in dark sector $|m_\phi - m_\chi| \ll m_{\phi,\chi}$

Heavy state, e.g. ϕ, could be metastable, decay to neutrinos



Neutrinos redshift until today $E_\nu \simeq (m_\phi - m_\chi) \dfrac{a_{\text{decay}}}{a_{\text{today}}}$

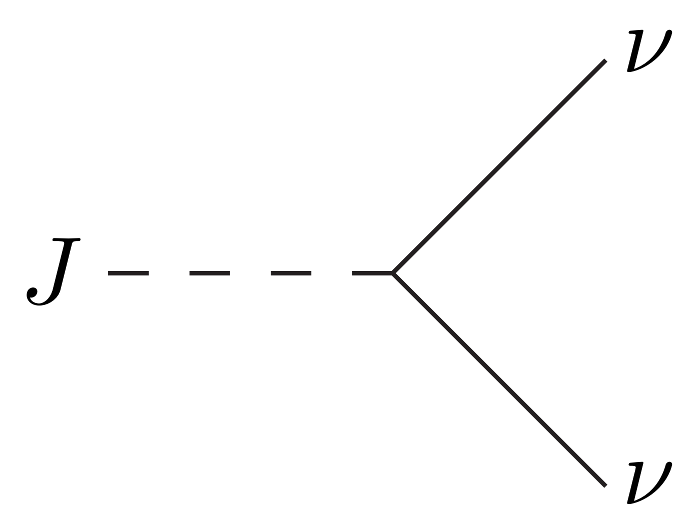
Let's make it even simpler

(Some of the) Dark Matter weakly coupled to neutrinos, similar to Majoron

(See Julian's talk yesterday)

$$\mathcal{L} \supset gJ\overline{\nu^c}\nu$$

This state decays to (only) neutrinos



Again, neutrinos redshift until today $E_\nu \simeq \frac{m_J}{2}\frac{a_{\rm decay}}{a_{\rm today}}$

What sort of flux can we imagine?

Constraints on this scenario

Roughly speaking there are three possibilities
for DM lifetime τ_N (two are interesting)

0. Before BBN $\tau_N \lesssim 1$ s: neutrinos thermalize, no effect
1. After BBN, before recombination 1 s $\lesssim \tau_N \lesssim 4\times10^5$ yr: neutrinos contribute to N_{eff} measured in CMB
2. After recombination $\tau_N \gtrsim 4\times10^5$ yr: J acts as decaying DM component, affects CMB

Number densities

Assuming that $\boldsymbol{J}$ is nonrelativisitic before decay, its number density is

$$n_J(t) = \Omega_J \frac{\rho_{\mathrm{cr},0}}{m_J} \left(\frac{a_0}{a}\right)^3 e^{-t/\tau_J}$$

$$= \frac{62.5}{\mathrm{cm}^3} \left(\frac{\Omega_J/\Omega_{\mathrm{dm}}}{0.05}\right) \left(\frac{\mathrm{eV}}{m_J}\right) \left(\frac{a_0}{a}\right)^3 e^{-t/\tau}$$

The number density of the neutrinos from $\boldsymbol{J}$ is then

$$\frac{d\tilde{n}_\nu}{dt} + 3H\tilde{n}_\nu = \frac{2n_J}{\tau_J}$$

$$\Rightarrow \quad \tilde{n}_\nu(t) = \frac{2\,\Omega_J \rho_{\mathrm{cr},0}}{m_J} \frac{1 - e^{-t/\tau_J}}{a^3}$$

$$= \frac{125}{\mathrm{cm}^3} \left(\frac{\Omega_J/\Omega_{\mathrm{dm}}}{0.05}\right) \left(\frac{\mathrm{eV}}{m_J}\right) \frac{1 - e^{-t/\tau_J}}{a^3}$$

1. Decays before recombination

Energy density in neutrinos from $\boldsymbol{J}$ is important quantity here

$$\frac{d\tilde{\rho}_\nu}{dt} + 4H\tilde{\rho}_\nu = \frac{m_J n_J}{\tau_J}$$

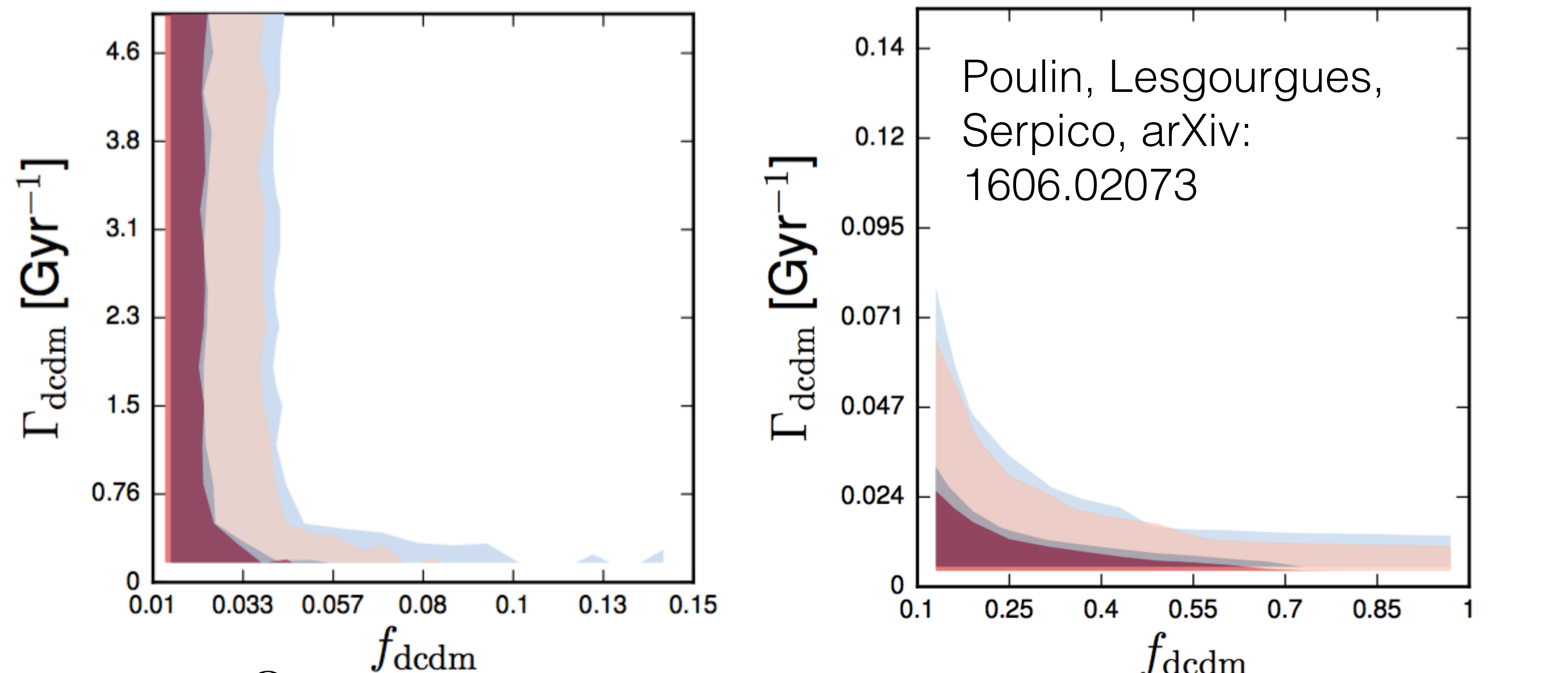
$$\Rightarrow \left.\frac{\tilde{\rho}_\nu}{\rho_\gamma}\right|_{t_{\rm rec}\gg t\gg\tau_J} = \frac{\sqrt{\pi}}{2}\frac{\Omega_J}{\Omega_\gamma}\sqrt{\frac{\tau_J}{\bar{t}_r}} = 0.154\left(\frac{\Omega_J}{\Omega_{\rm dm}}\right)\sqrt{\frac{\tau_J}{10^3\ {\rm yr}}} = 0.23\Delta N_{\rm eff}$$

or $$\tilde{n}_\nu = \frac{1.0\times10^{-2}}{{\rm cm}^3}\left(\frac{\Delta N_{\rm eff}}{0.28}\right)\left(\frac{100\ {\rm keV}}{m_J}\right)\sqrt{\frac{10^3\ {\rm yr}}{\tau_J}}$$

This is a strong constraint on neutrinos from $\boldsymbol{J}$ decays before CMB last scattering

2. Decays after recombination

Now $\boldsymbol{J}$ acts a decaying DM component impacts CMB



$$\Rightarrow \quad \frac{\Omega_J}{\Omega_{\rm dm}} \lesssim 0.038 \quad \text{for} \quad \tau_J \ll t_U \simeq 13.8 \times 10^9 \text{ yr}$$

$$\frac{\Omega_J}{\Omega_{\rm dm}} \lesssim \min(1, \tau_J / 1.59 \times 10^{11} \text{ yr}) \qquad \text{for longer lifetimes}$$

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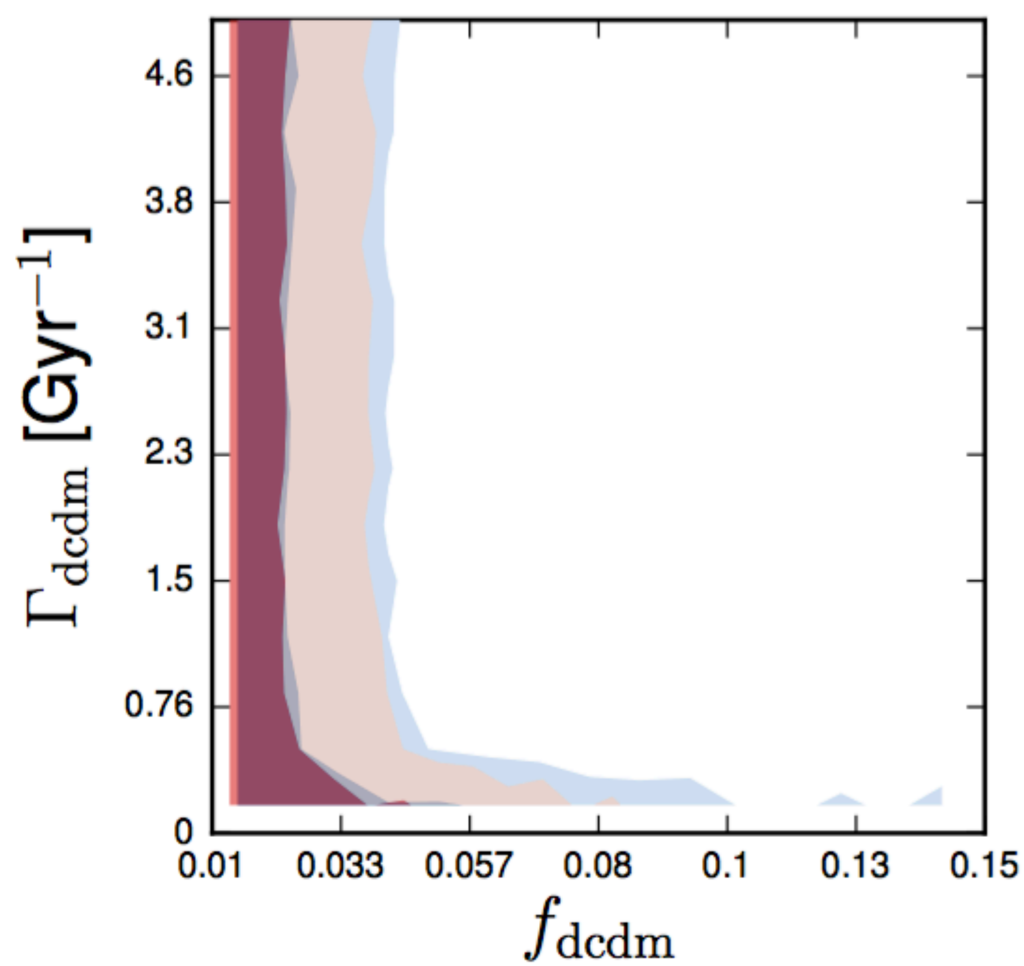

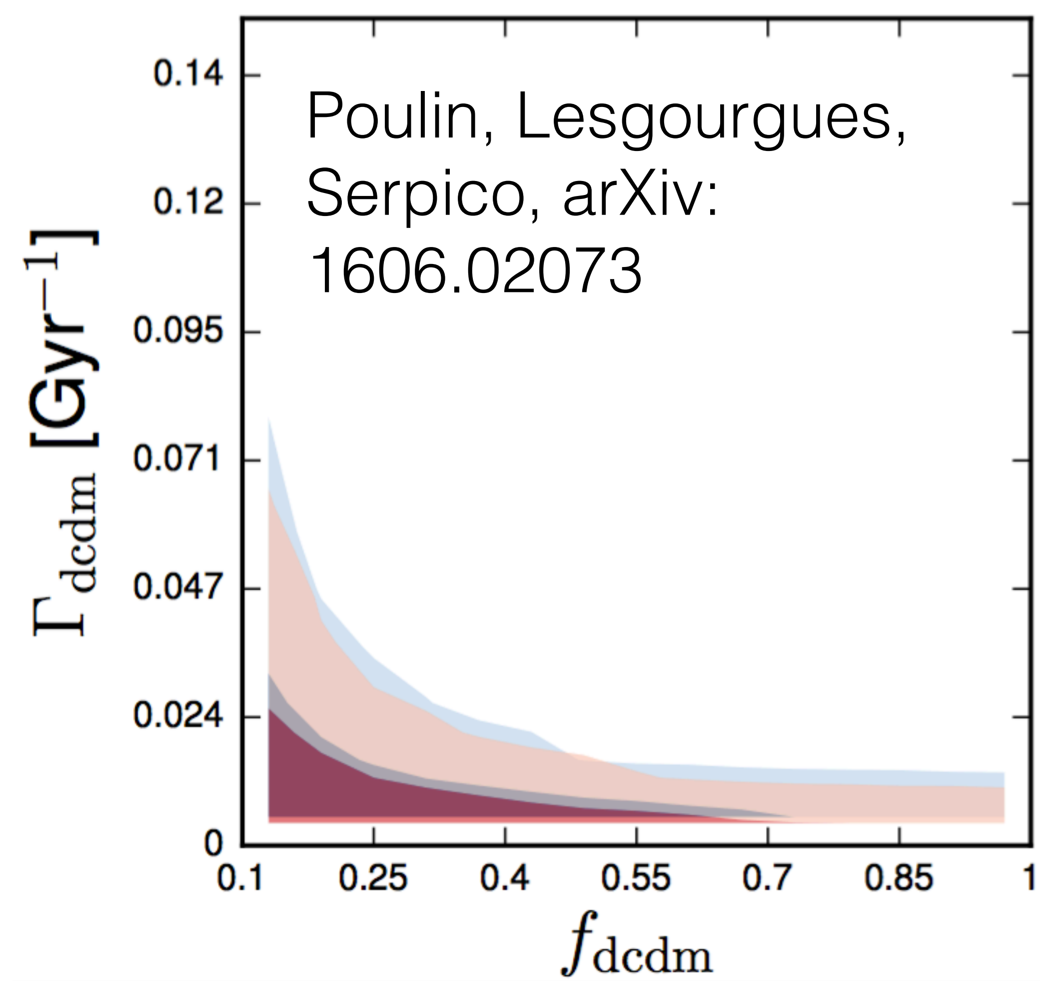

for $\tau_J \ll t_U \simeq 13.8 \times 10^9$ yr

$\Rightarrow$

for longer lifetimes

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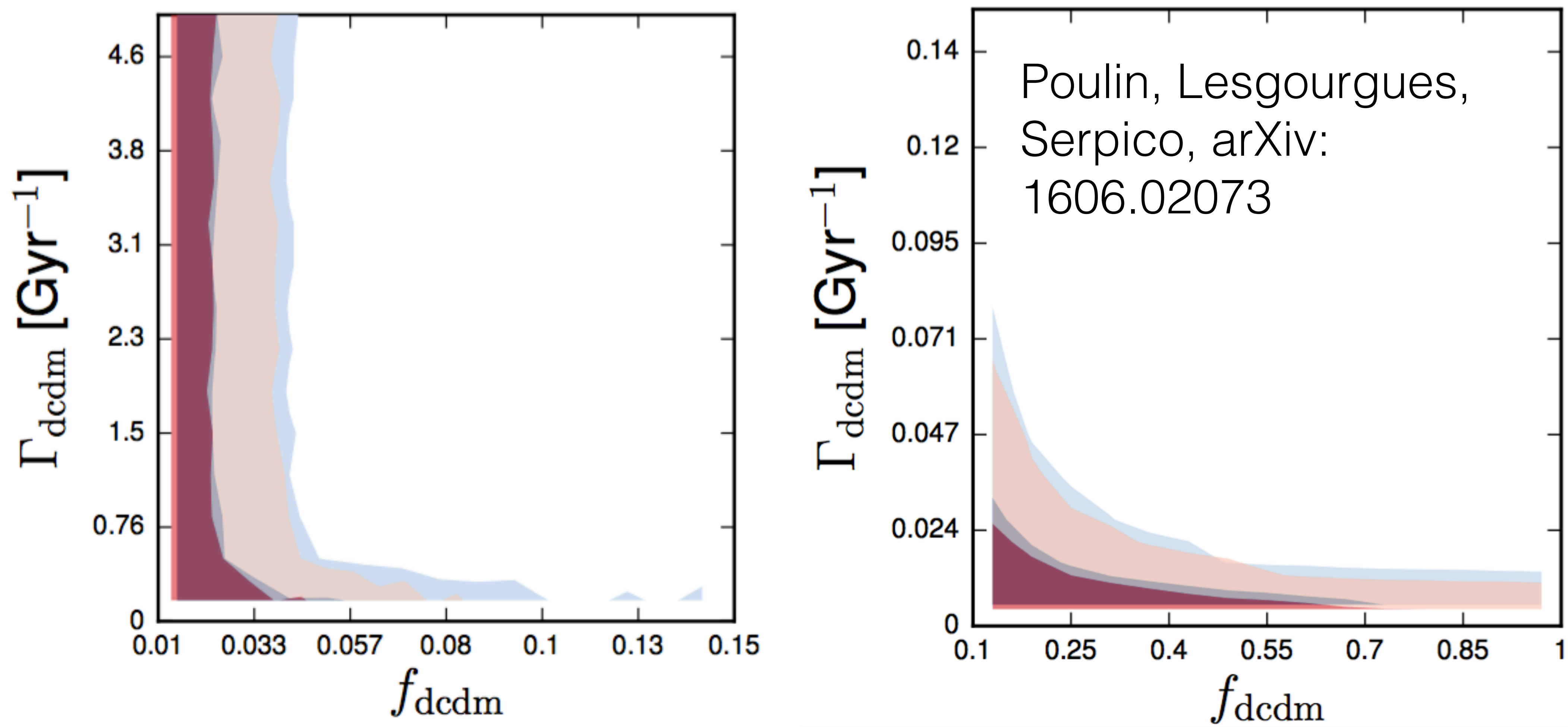


$$\Rightarrow \quad \tilde{n}_\nu(t) \lesssim \frac{95.0}{\mathrm{cm}^3}\left(\frac{\mathrm{eV}}{m_J}\right) \text{ for } \tau_J \ll t_U \simeq 13.8 \times 10^9 \text{ yr}$$

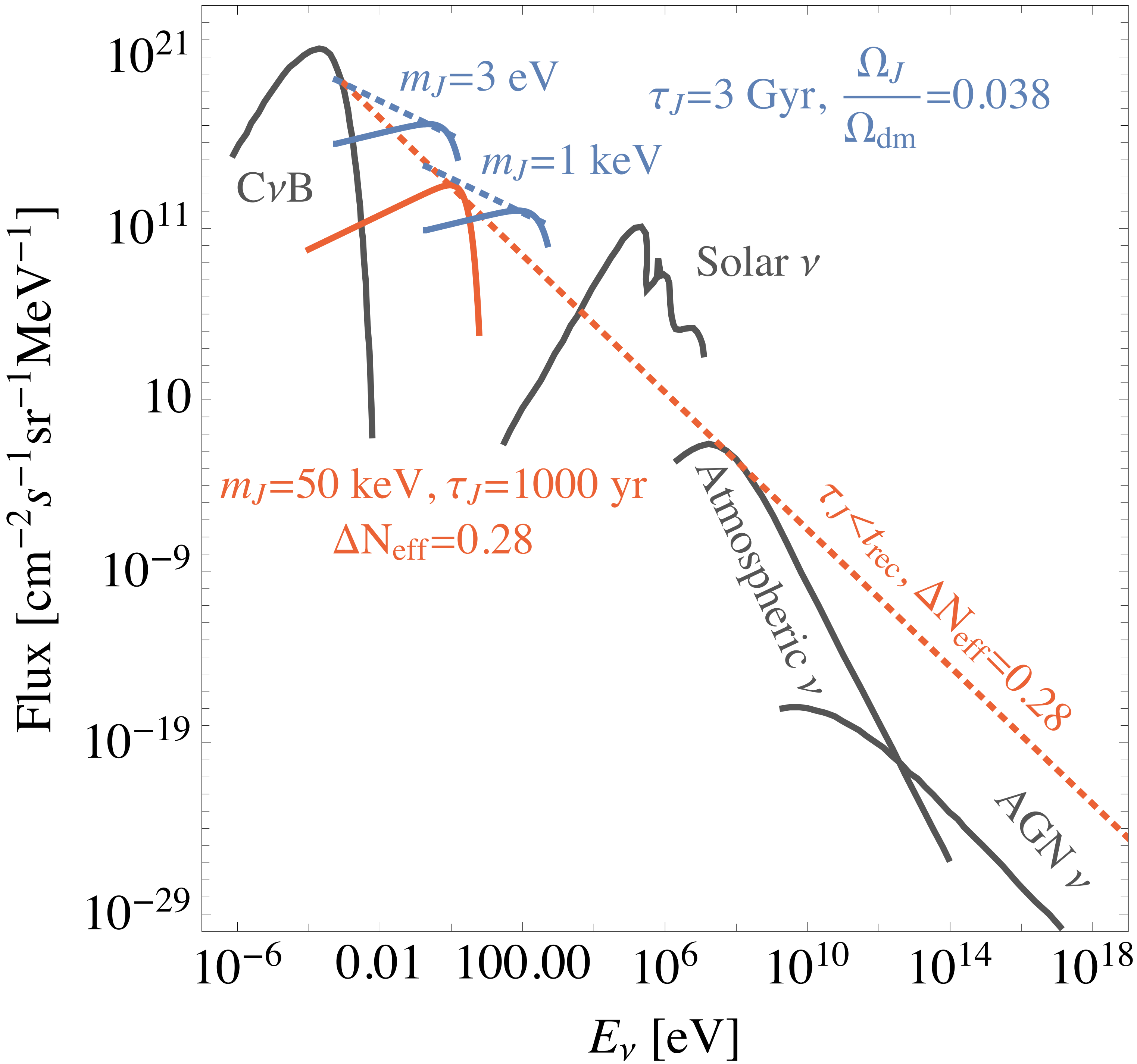
$$\tilde{n}_\nu(t) \lesssim \frac{2500}{\mathrm{cm}^3}\left(\frac{\mathrm{eV}}{m_J}\right)\left(1 - e^{-\tau_U/\tau_J}\right) \times \min\left(1, \frac{\tau_J}{1.59 \times 10^{11} \text{ yr}}\right) \text{ for longer lifetimes}$$

Back to the plot

Flux is given by

$$\tilde{\Phi}_\nu = \frac{d(a^3 \tilde{n}_\nu)}{dE_\nu}\Big|_{a=2E_\nu/m_J}$$

$$= \frac{2\,\Omega_J}{E_\nu}\,\frac{\rho_{\mathrm{cr},0}}{m_J}\,\frac{e^{-t/\tau_J}}{H\tau_J}$$



About the CνB

Thermal relics that decoupled when T=3-4 MeV

$$\frac{G_F^2}{\pi} T^5 \sim H \simeq \frac{T^2}{M_{\rm Pl}}$$

Slightly colder than CMB sincephotons heated by $e^+ e^-$ annihilation

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma = 1.9 \text{ K} = 1.7 \times 10^{-4} \text{ eV}$$

Number density per flavor

$$n_{\nu_i} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma = \frac{3}{4}\left(\frac{4}{11}\right)\left(\frac{411}{\text{cm}^3}\right) = \frac{112}{\text{cm}^3}$$

(fermions)

Huge number density but extremely low energy and challenging to detect

Detecting the CνB

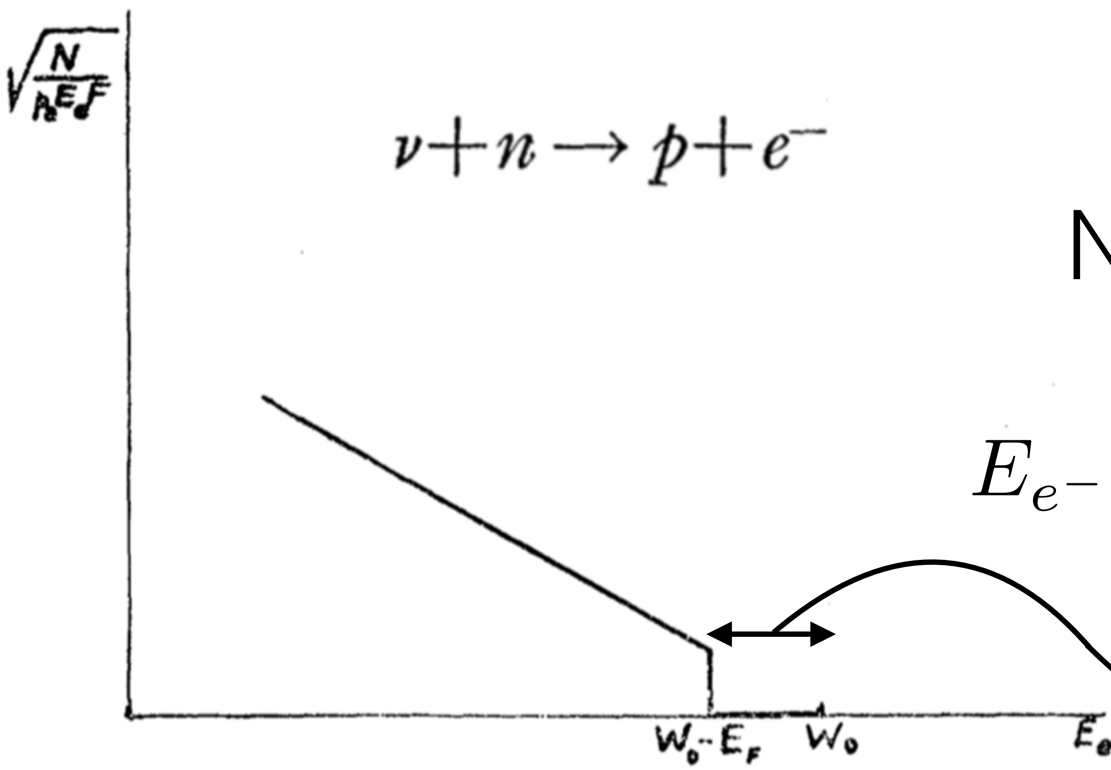
PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

A very old idea

Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

$$\nu + n \rightarrow p + e^-$$



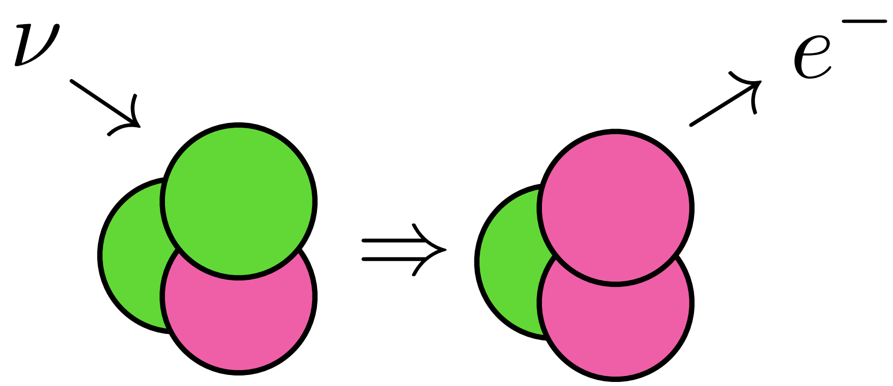
Neutrino capture on neutron (nucleus), no threshold

$$E_{e^-} = E_{\rm end} + m_\nu + E_\nu \simeq E_{\rm end} + 2m_\nu$$

for nonrel. neutrinos

Need incredible energy resolution…

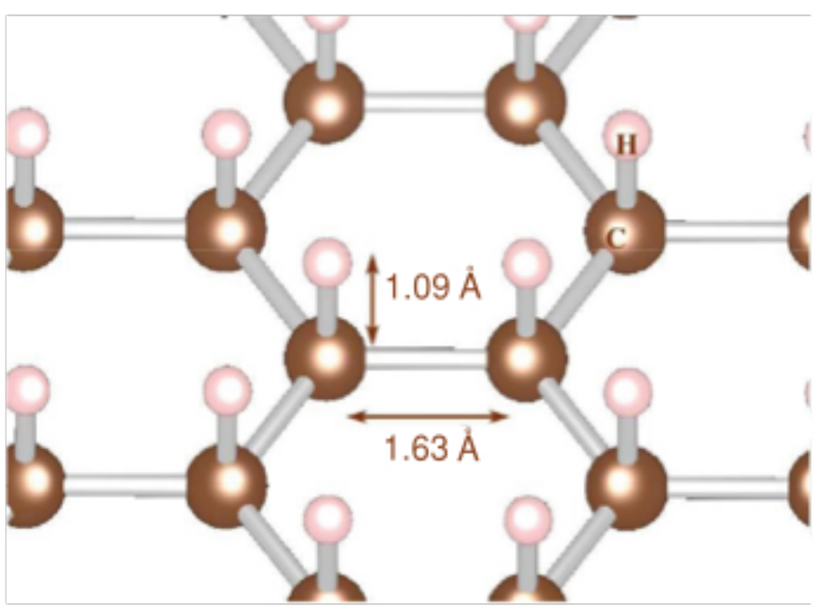
CνB capture on Tritium

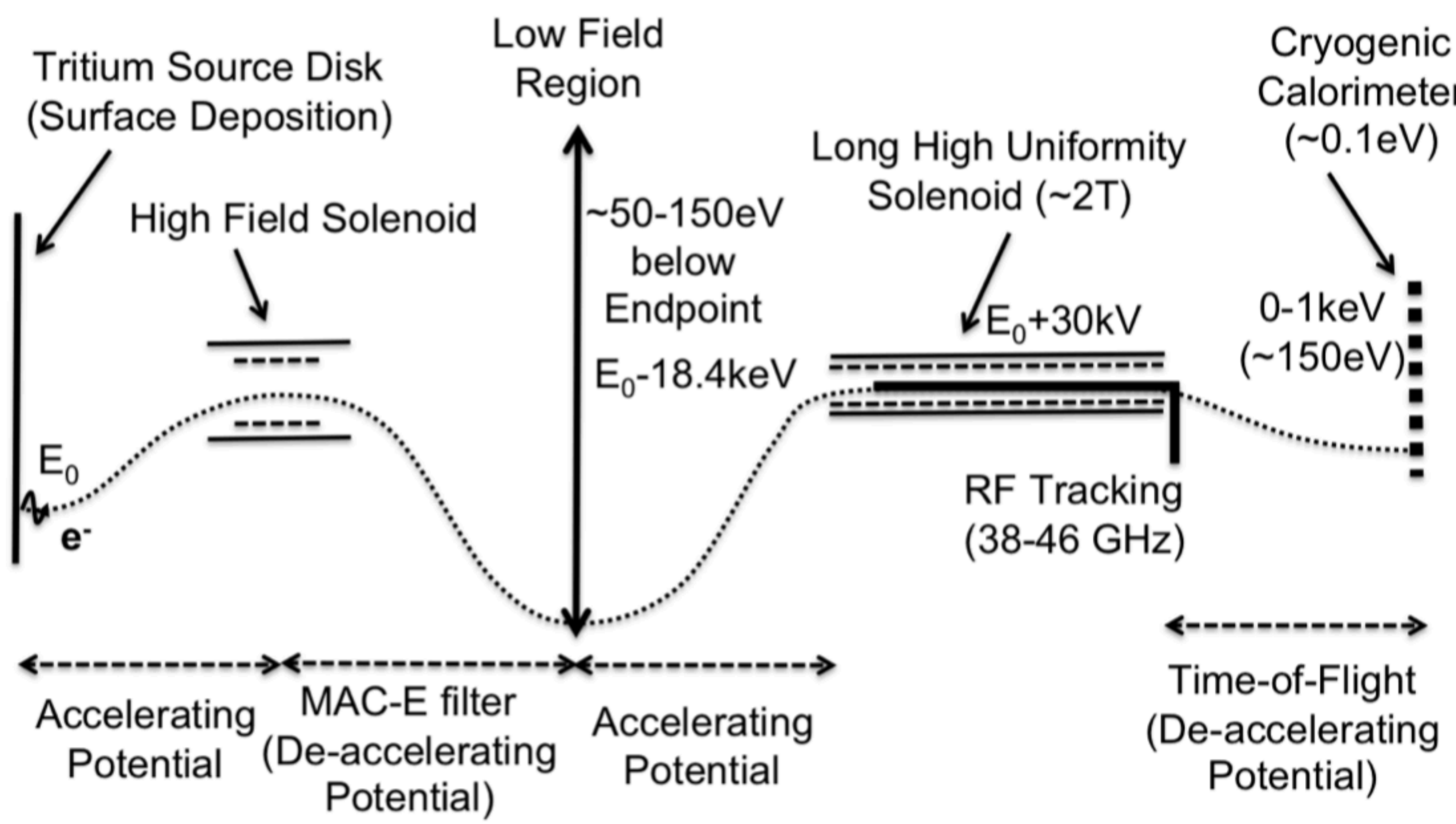


β-decays with long lifetime

$$t_{1/2} \simeq 12 \text{ yr}$$

PTOLEMY Experiment:

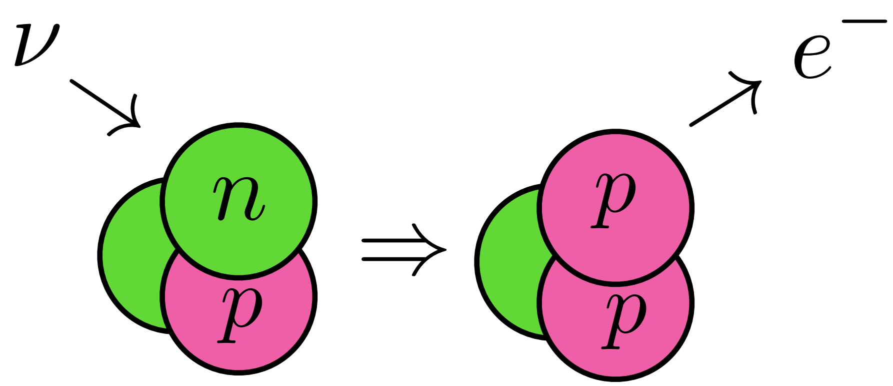




Tritiated graphene to reduce molecular smearing

Electrons below endpoint filtered out

CνB capture on Tritium

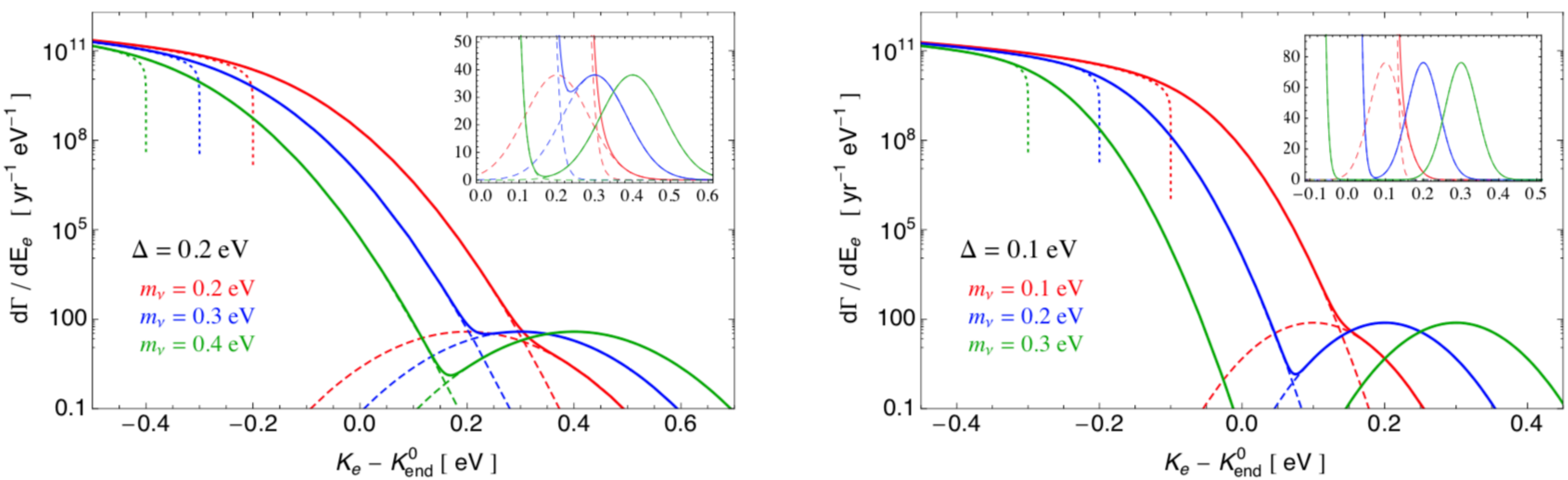


β-decays with long lifetime

$$t_{1/2} \simeq 12 \text{ yr}$$

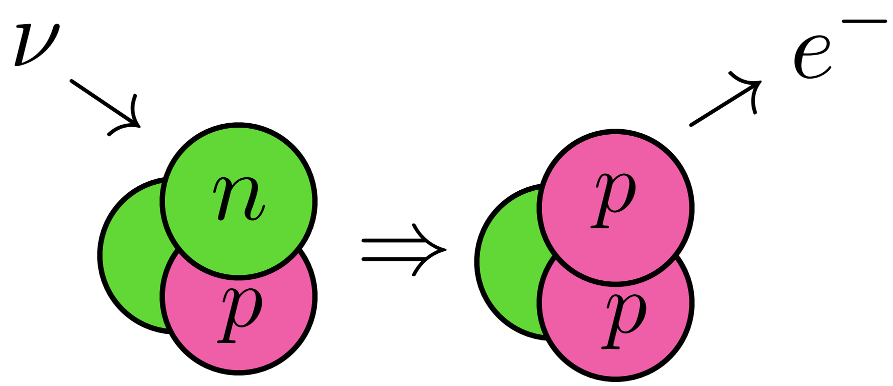
$$\sigma = 3.8 \times 10^{-45} \text{ cm}^2 \quad \Rightarrow \Gamma_{\text{Dir.}} = \frac{1}{2}\Gamma_{\text{Maj.}} = \frac{4}{\text{yr}} \left(\frac{M_T}{100 \text{ g}}\right) \left(\frac{n_\nu}{56 \text{ cm}^{-3}}\right)$$

Long, Lunardini, Sabancilar



Tiny rates but a crucial target

ν from DM decay on Tritium



The electron energy gap can be larger in this case

$$E_{e^-} = E_{\rm end} + m_\nu + E_\nu \simeq E_{\rm end} + m_\nu + \frac{m_J}{2}\frac{a_{\rm decay}}{a_{\rm today}}$$

$$\Gamma = \frac{4}{\rm yr}\left(\frac{M_T}{100\ {\rm g}}\right)\left(\frac{\tilde{n}_\nu}{56\ {\rm cm}^{-3}}\right)$$

$\tau_J < t_{\rm rec}$

$$\tilde{n}_\nu = \frac{1.03\times 10^{-2}}{{\rm cm}^3}\left(\frac{\Delta N_{\rm eff}}{0.28}\right) \times \left(\frac{100\ {\rm keV}}{m_J}\right)\sqrt{\frac{10^3\ {\rm yr}}{\tau_J}}$$

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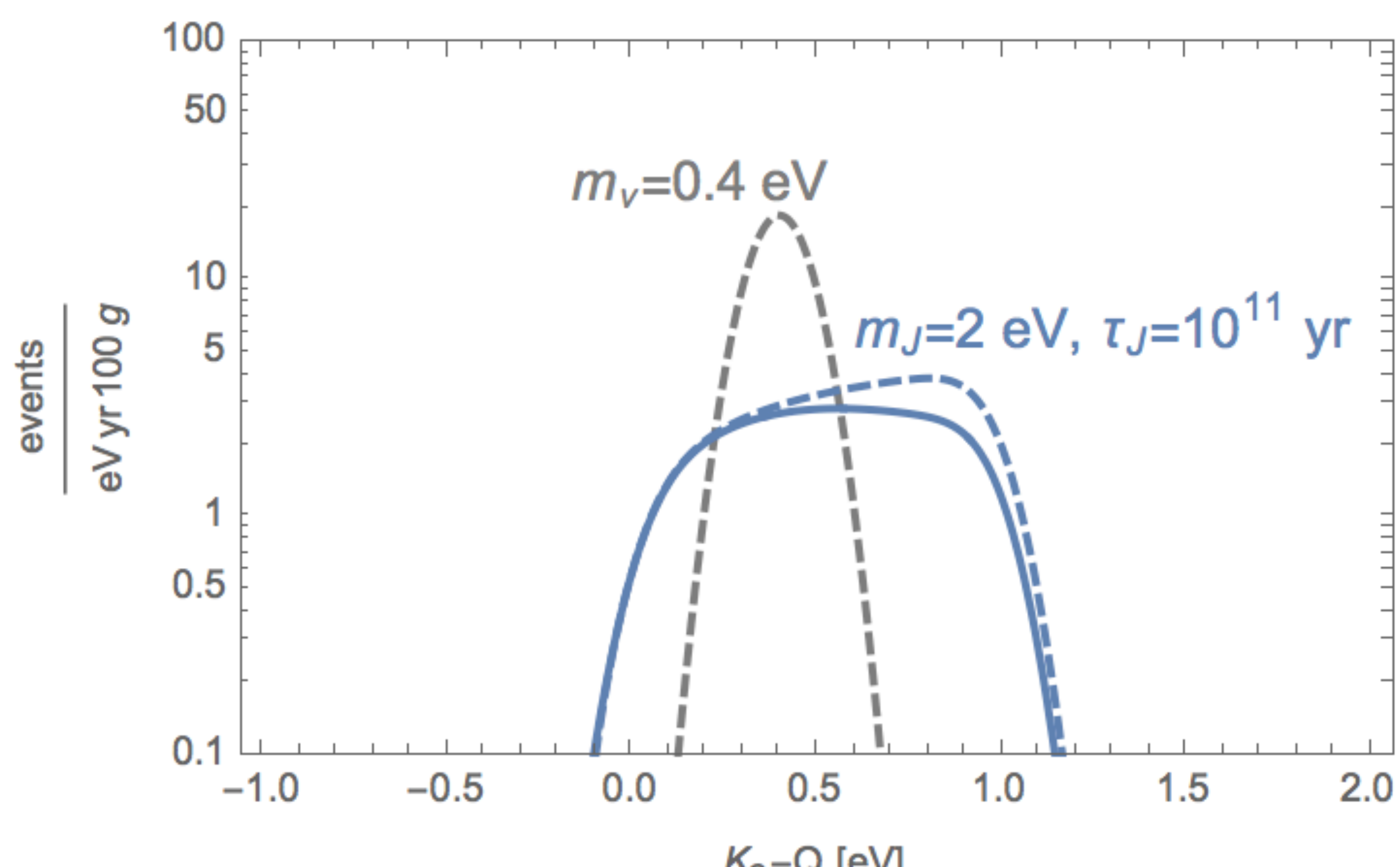
$$\tilde{n}_\nu(t) \lesssim \frac{2500}{{\rm cm}^3}\left(\frac{\rm eV}{m_J}\right)\left(1-e^{-\tau_U/\tau_J}\right) \times \min\left(1, \frac{\tau_J}{1.59\times 10^{11}\ {\rm yr}}\right)$$



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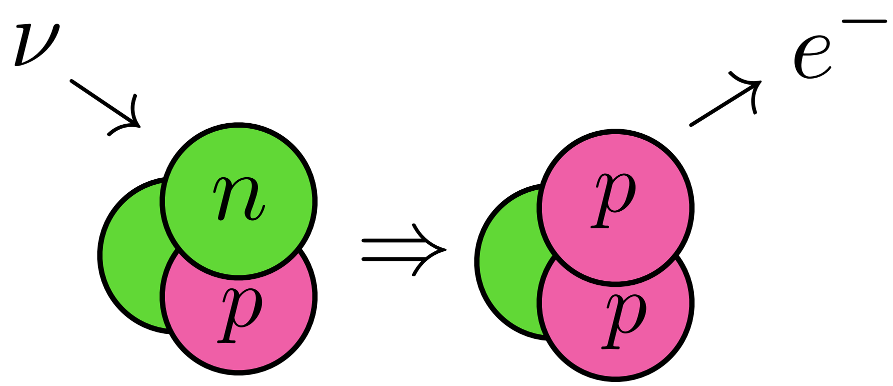

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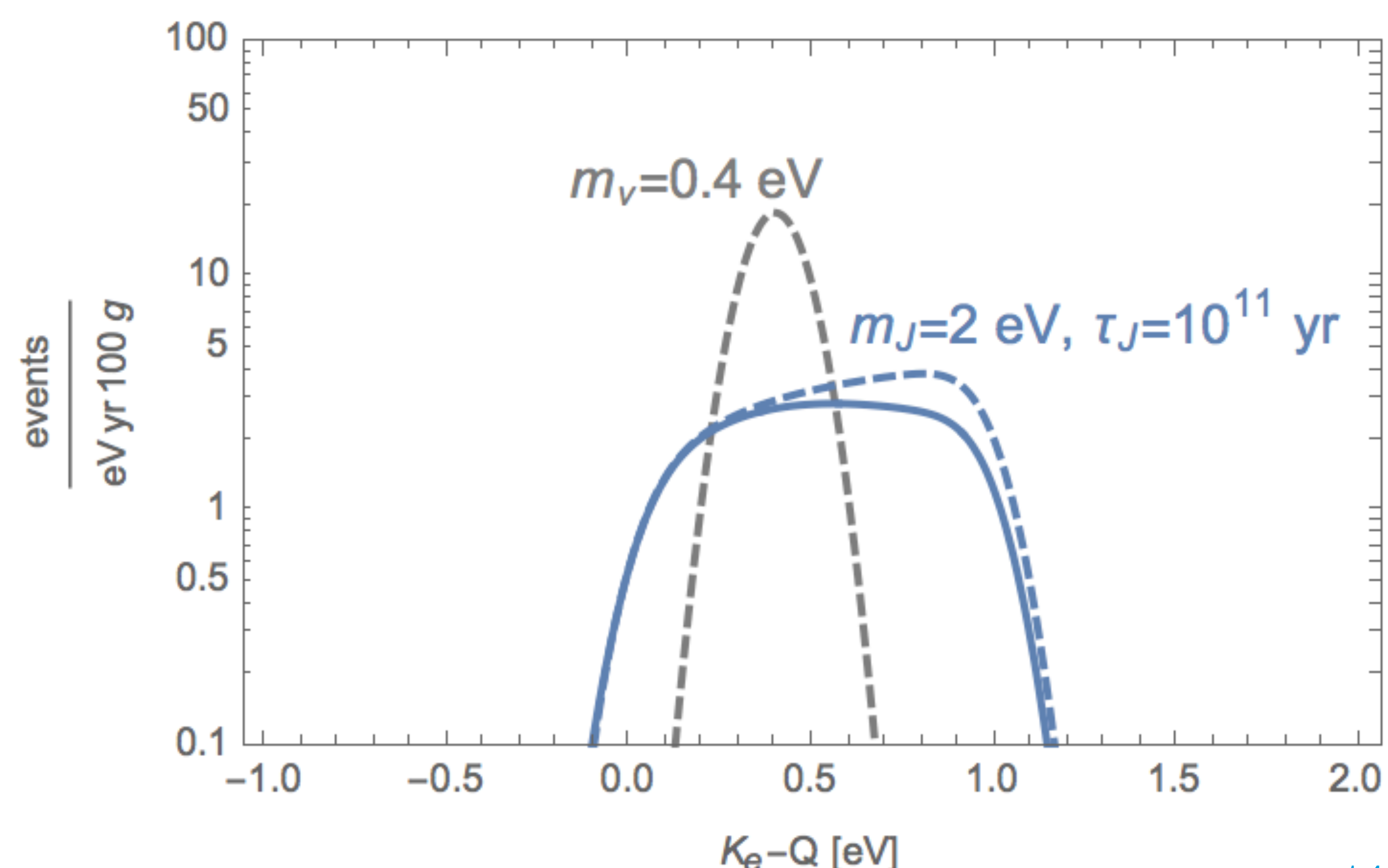

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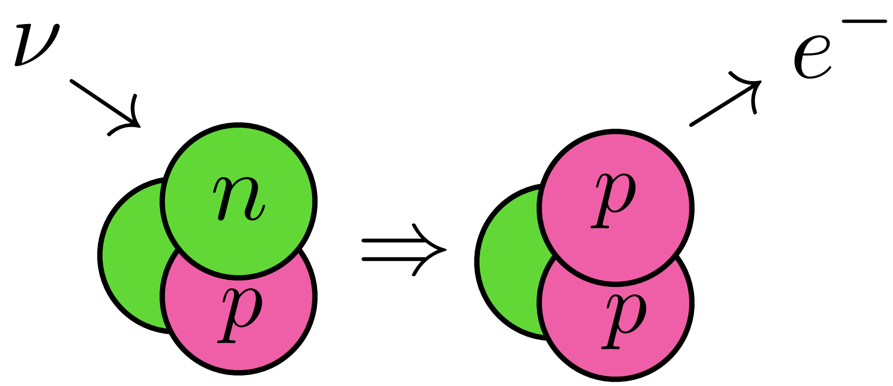

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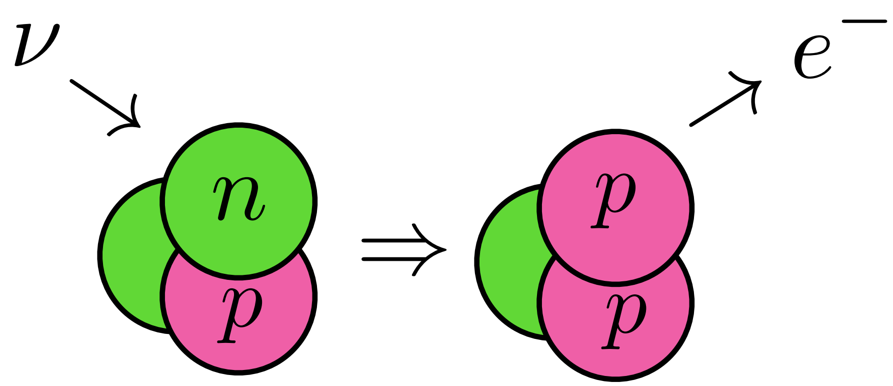

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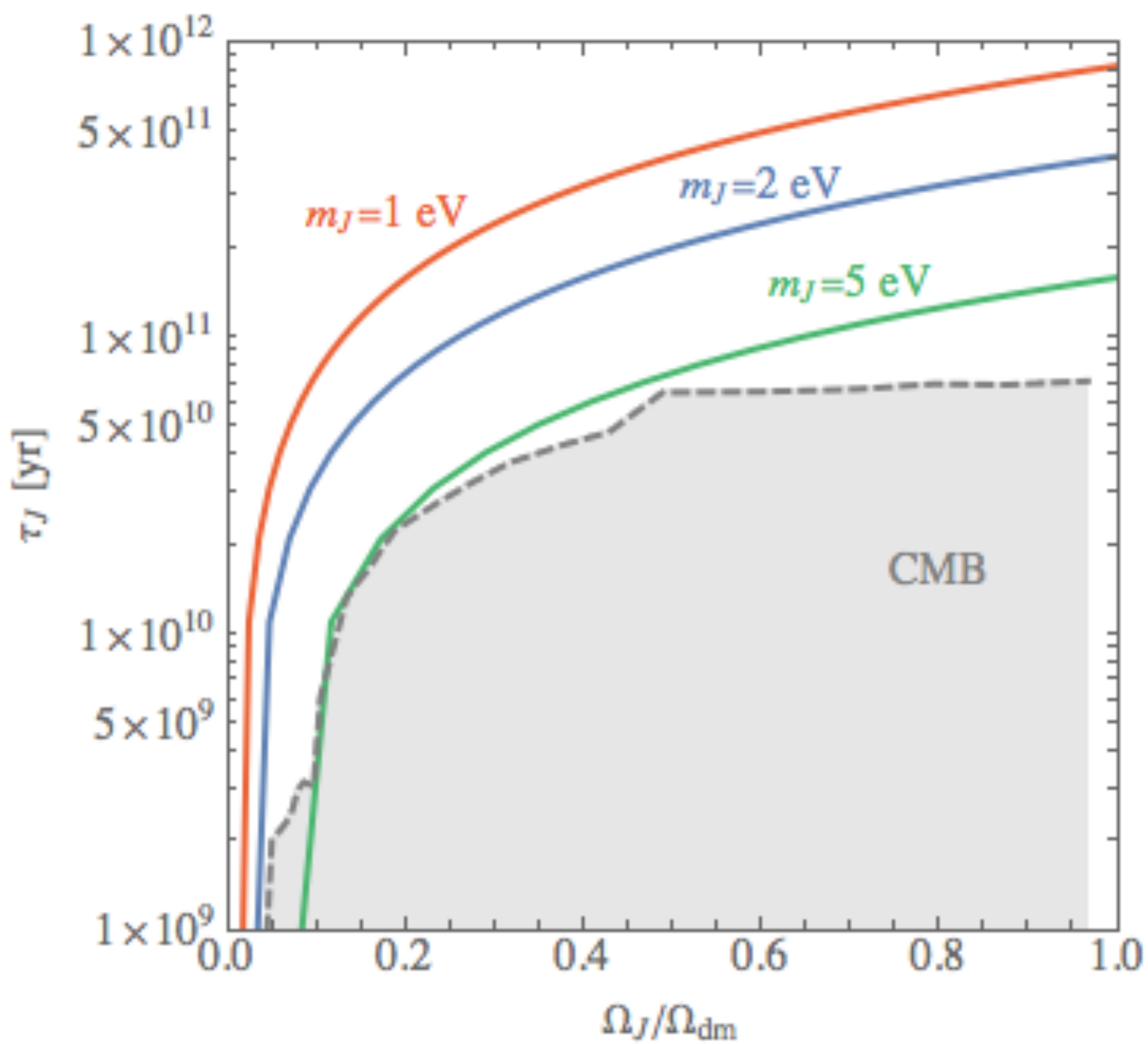

Wrap up

Cosmic neutrino background is an extremely important target to probe cosmology

PTOLEMY experiment hopes to explore this area

Interestingly, could also be sensitive to decaying dark matter, what else?

Important to be open minded about possible signs of new physics (beyond 3x3) so that we don't miss anything—only nature gets a vote