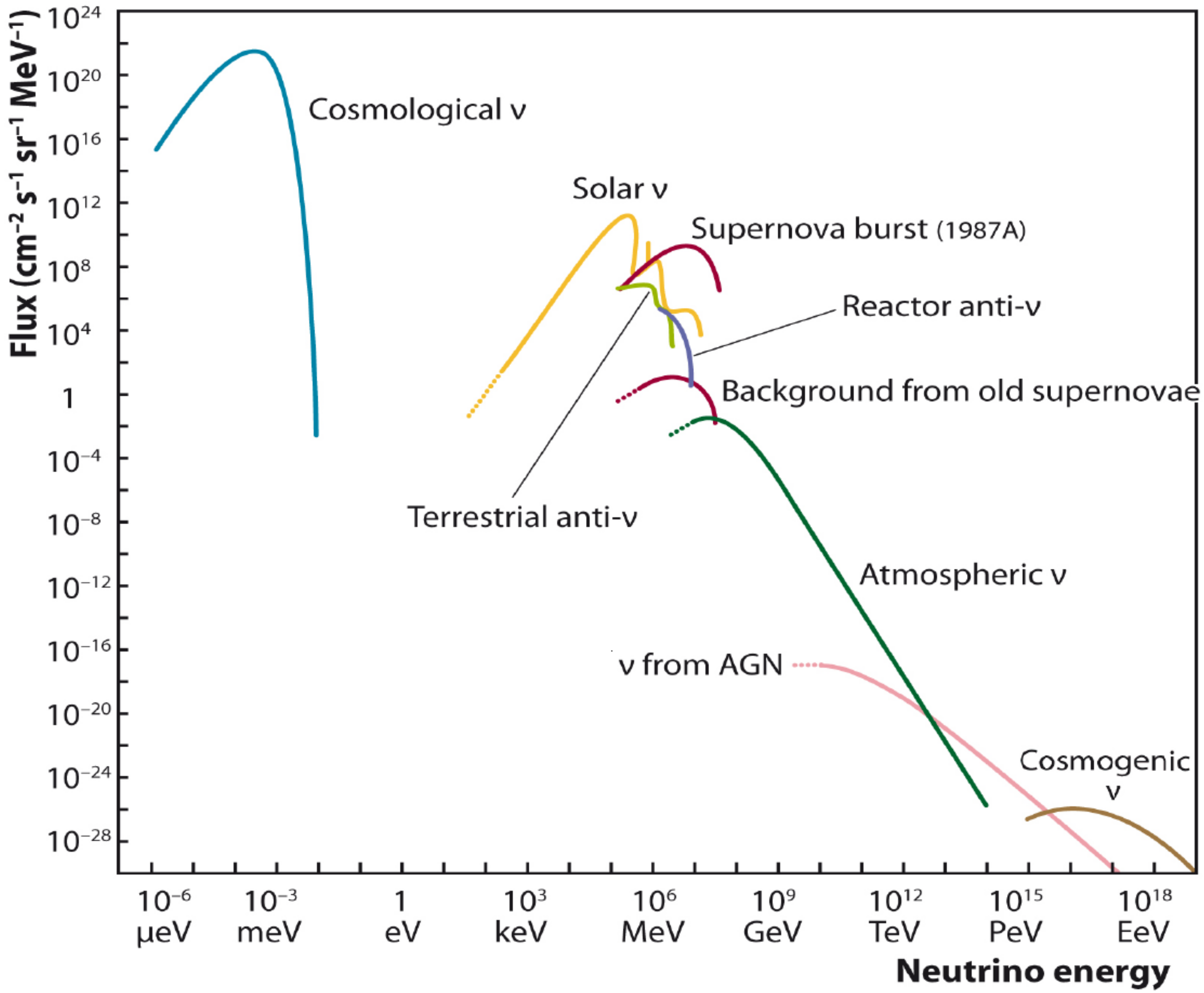
Cosmic Neutrino Searches as Dark Matter Detectors

David McKeen
TRIUMF

KEK Theory Meeting
December 6, 2018

Let’s start with a plot



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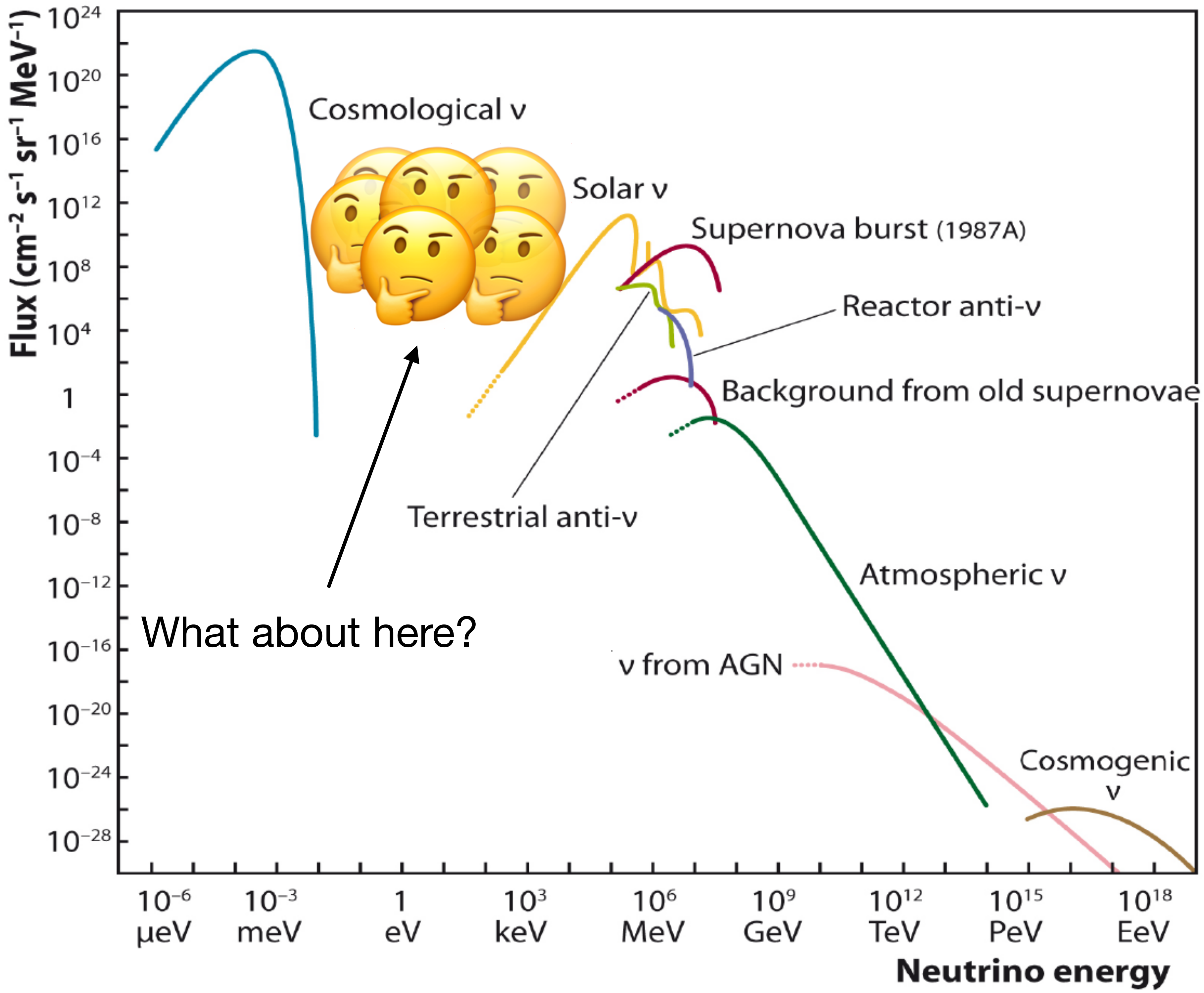

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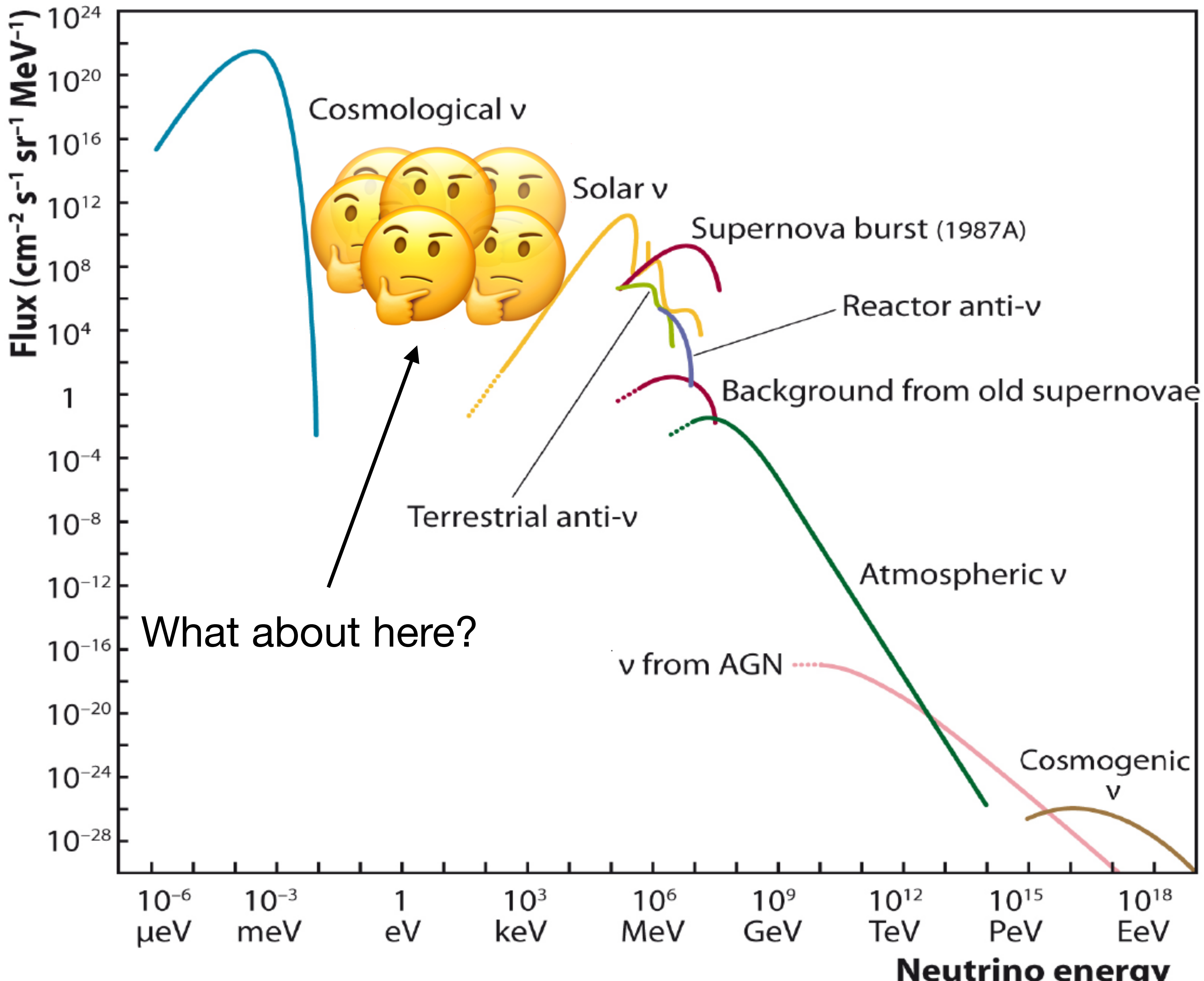


Similar work by Cui, Pospelov, Pradler; Heeck

Plan

How this gap can be populated

What cosmological observations tell us about these possibilities

How the gap can be probed

How could this gap be populated?

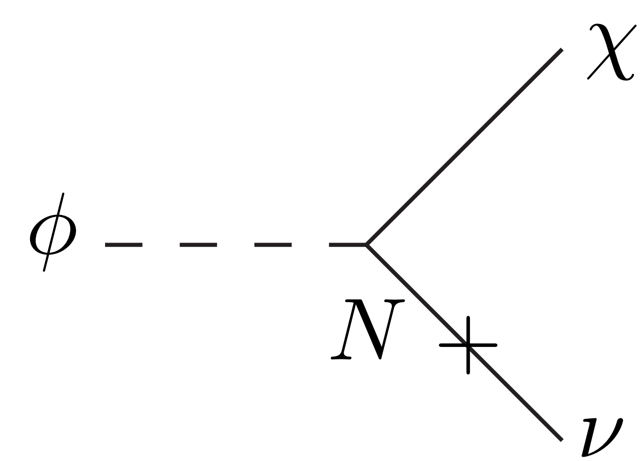
Dark Matter decay:

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

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

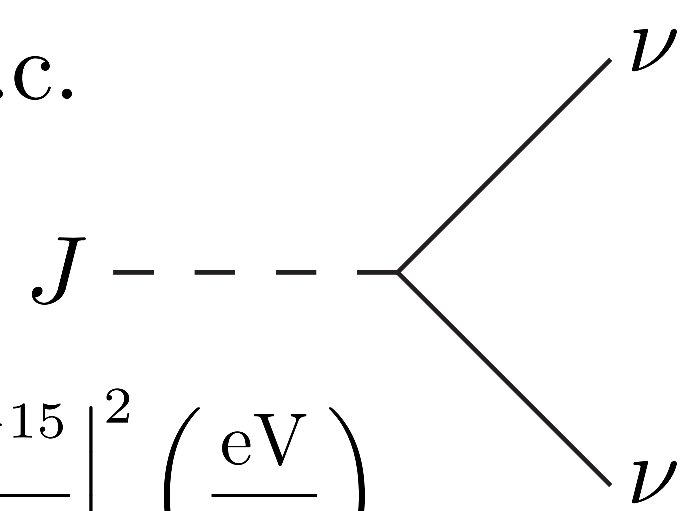


Neutrinos redshift until today $E_\nu \simeq (m_\phi - m_\chi) \dfrac{a_{\text{decay}}}{a_{\text{today}}}$

Let's make it even simpler

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

$$\mathcal{L}_{\rm int} = -\frac{g}{2} J\nu\nu + {\rm h.c.}$$



This state decays to (only) neutrinos

$$\tau_J = \frac{32\pi}{|g|^2 m_J} = 2.10 \times 10^9 \ {\rm yr} \left|\frac{10^{-15}}{g}\right|^2 \left(\frac{\rm eV}{m_J}\right)$$

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 $\tau_J \lesssim 1$ s: neutrinos thermalize, no effect
1. After BBN, before recombination 1 s $\lesssim \tau_J \lesssim 4\times10^5$ yr: neutrinos contribute to N_{eff} measured in CMB
2. After recombination $\tau_J \gtrsim 4\times10^5$ 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

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

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

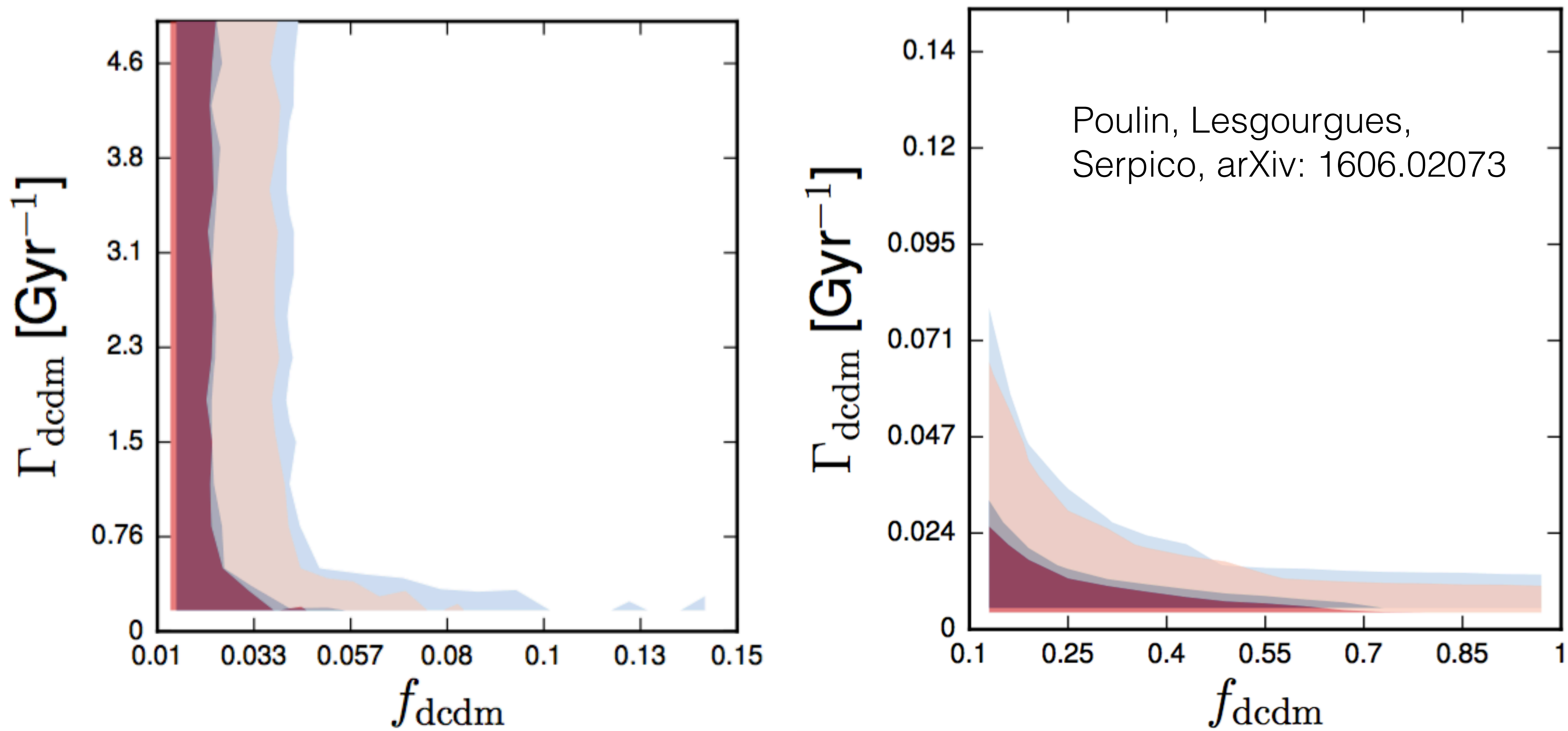
or $$\tilde{n}_\nu = \frac{1.0\times 10^{-2}}{{\rm cm}^3}\left(\frac{\Delta N_{\rm eff}}{0.28}\right)\left(\frac{100\ {\rm keV}}{m_J}\right)\sqrt{\frac{10^3\ {\rm yr}}{\tau_J}}$$

Strong constraint on neutrinos from $\boldsymbol{J}$ decays before CMB last scattering

Typical energy today: $E_\nu^{\rm av} \simeq 1\ {\rm eV}\left(\frac{m_J}{100\ {\rm keV}}\right)\sqrt{\frac{\tau_J}{10^3\ {\rm yr}}}$

2. Decays after recombination

Now J acts a decaying DM component & impacts CMB



Roughly 5% of DM allowed to decay

$$\Rightarrow \tilde{n}_\nu \sim \frac{10}{\rm cm^3}\left(\frac{10\ {\rm eV}}{m_J}\right) \quad \text{with} \quad E_\nu^{\rm av} \simeq 1\ {\rm eV}\left(\frac{m_J}{10\ {\rm eV}}\right)\left(\frac{\tau_J}{10^{10}\ {\rm yr}}\right)^{2/3}$$

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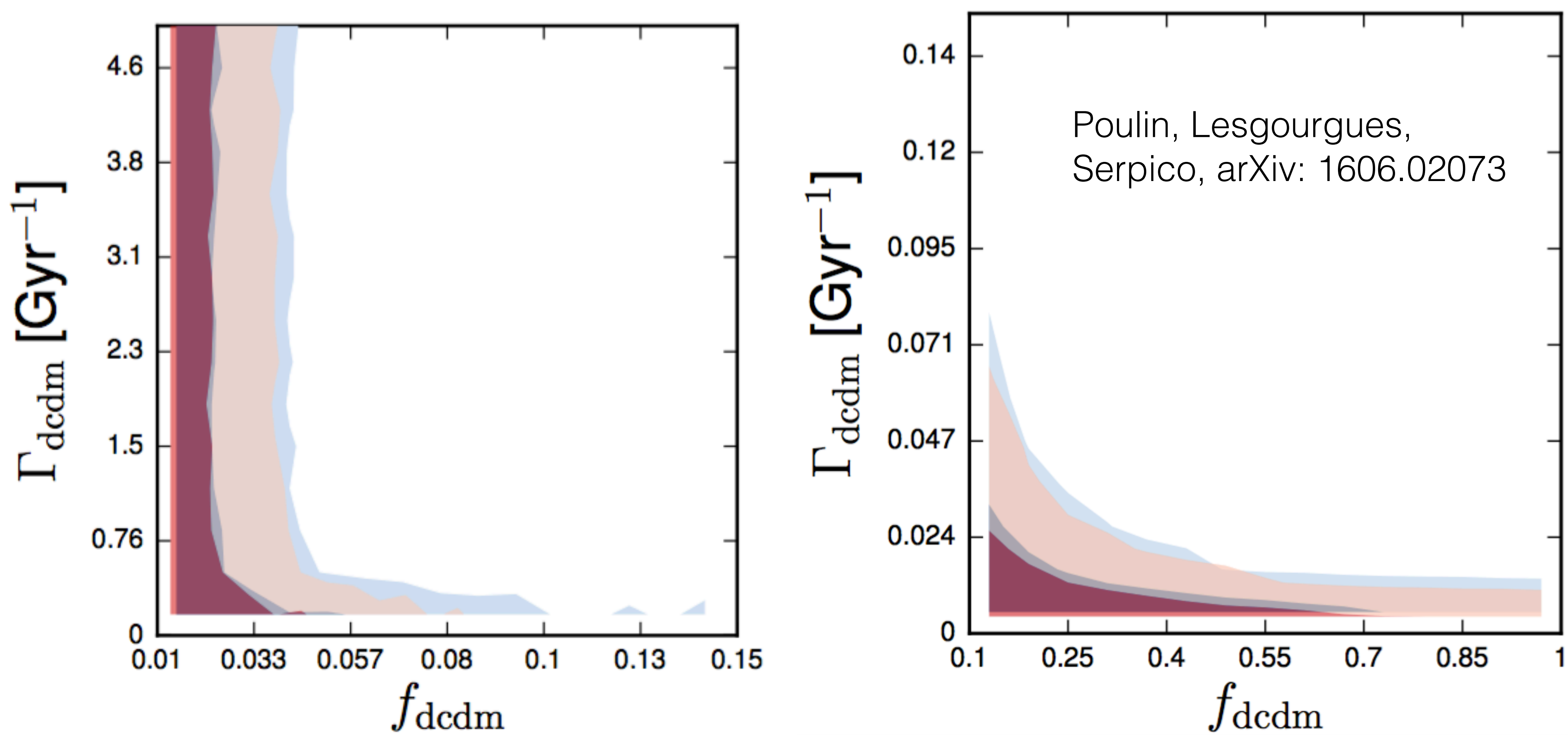

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Focus on this case

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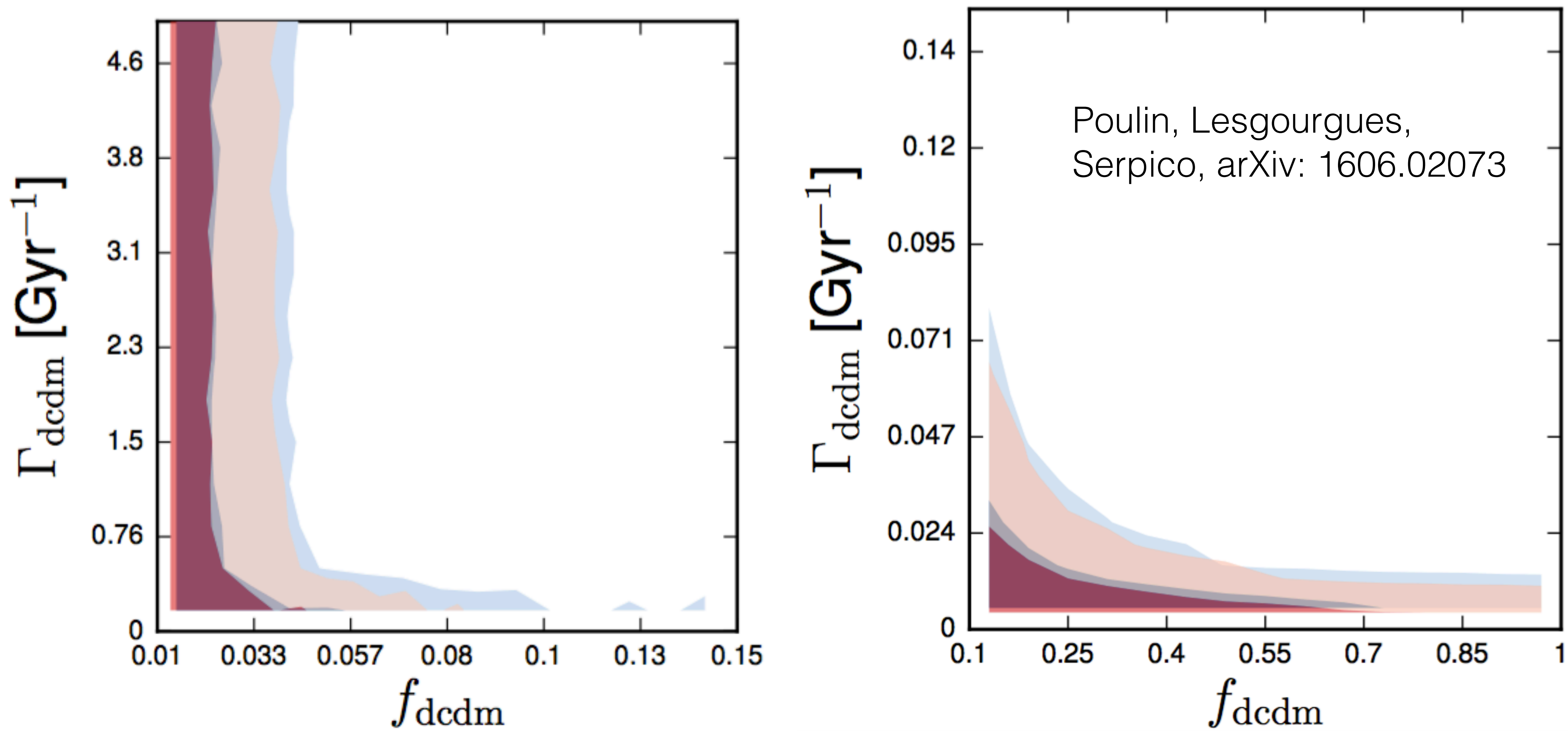

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Focus on this case

Note: invoked as explanation of $\boldsymbol{\sigma}_8$ and $\boldsymbol{H}_0$ tensions (Berezhiani et al.; Enqvist et al.)

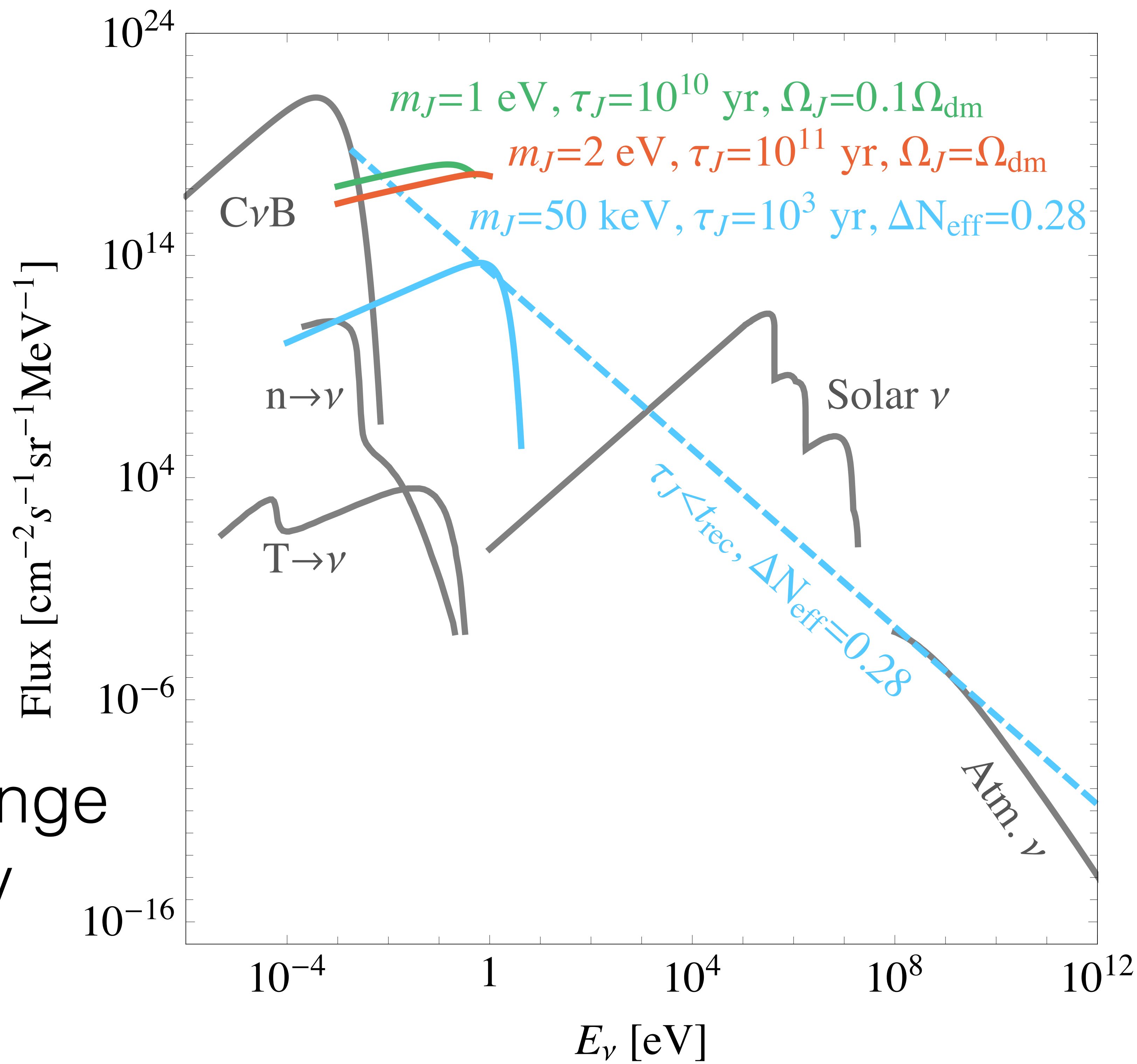
Back to the plot

Flux is given by

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

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

Width determined by range of redshifts for decay



About the CνB

See talk by Martin Spinrath yesterday

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

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

Number density per flavor

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

(fermions)

Huge number density but extremely low energy and challenging to detect

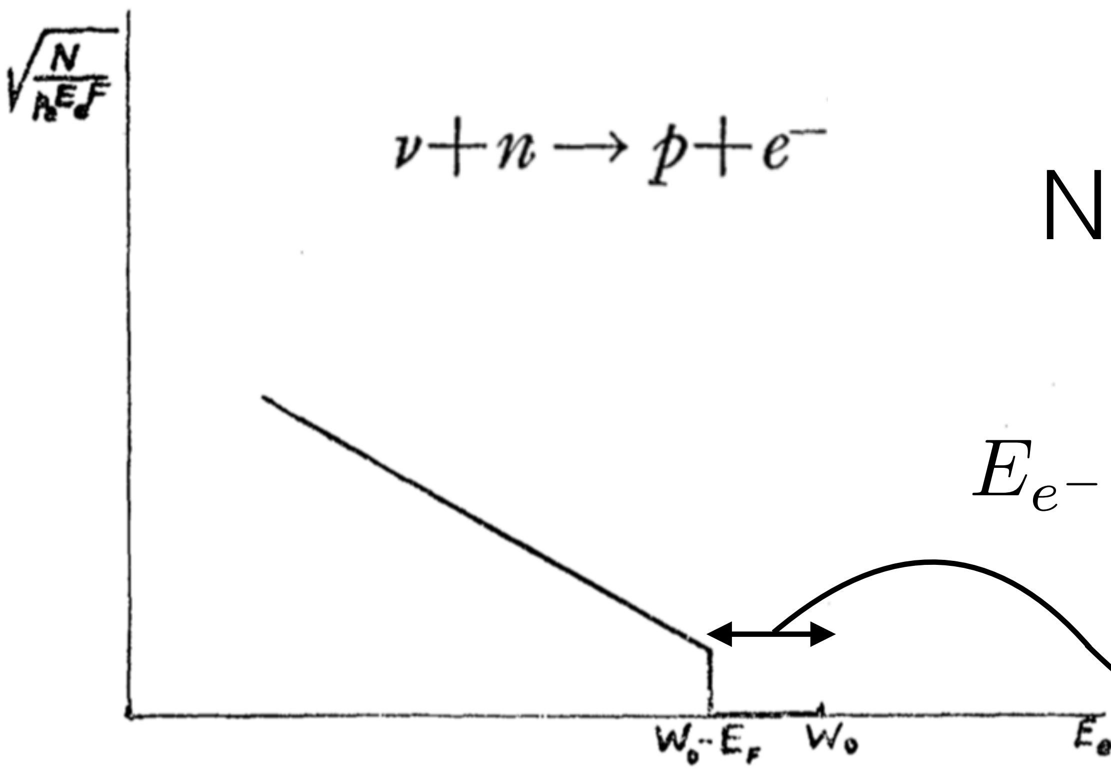
Detecting the CνB

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)



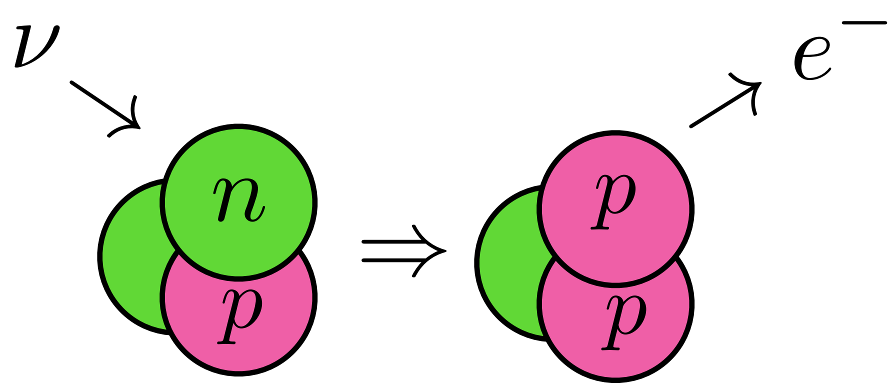
Neutrino capture on neutron (nucleus), no threshold

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

for nonrel. neutrinos

Need incredible energy resolution…

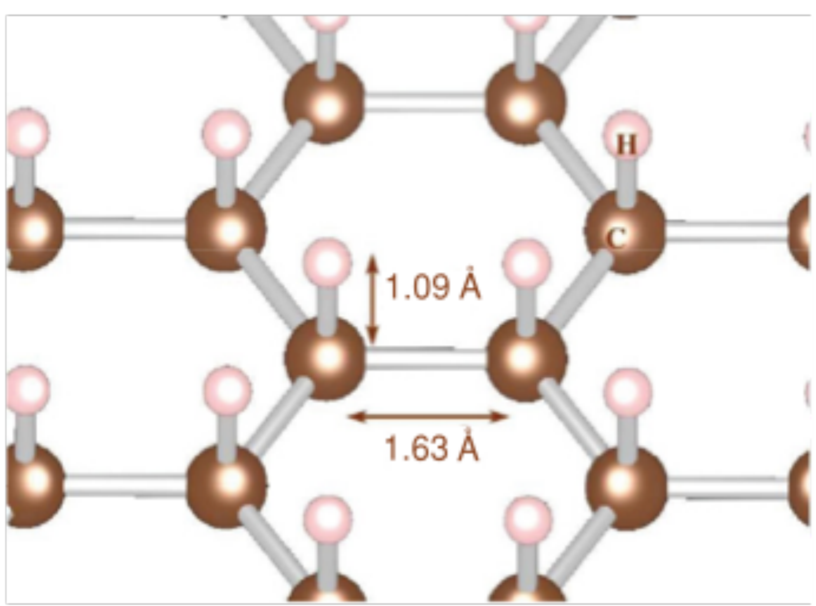
CνB capture on Tritium

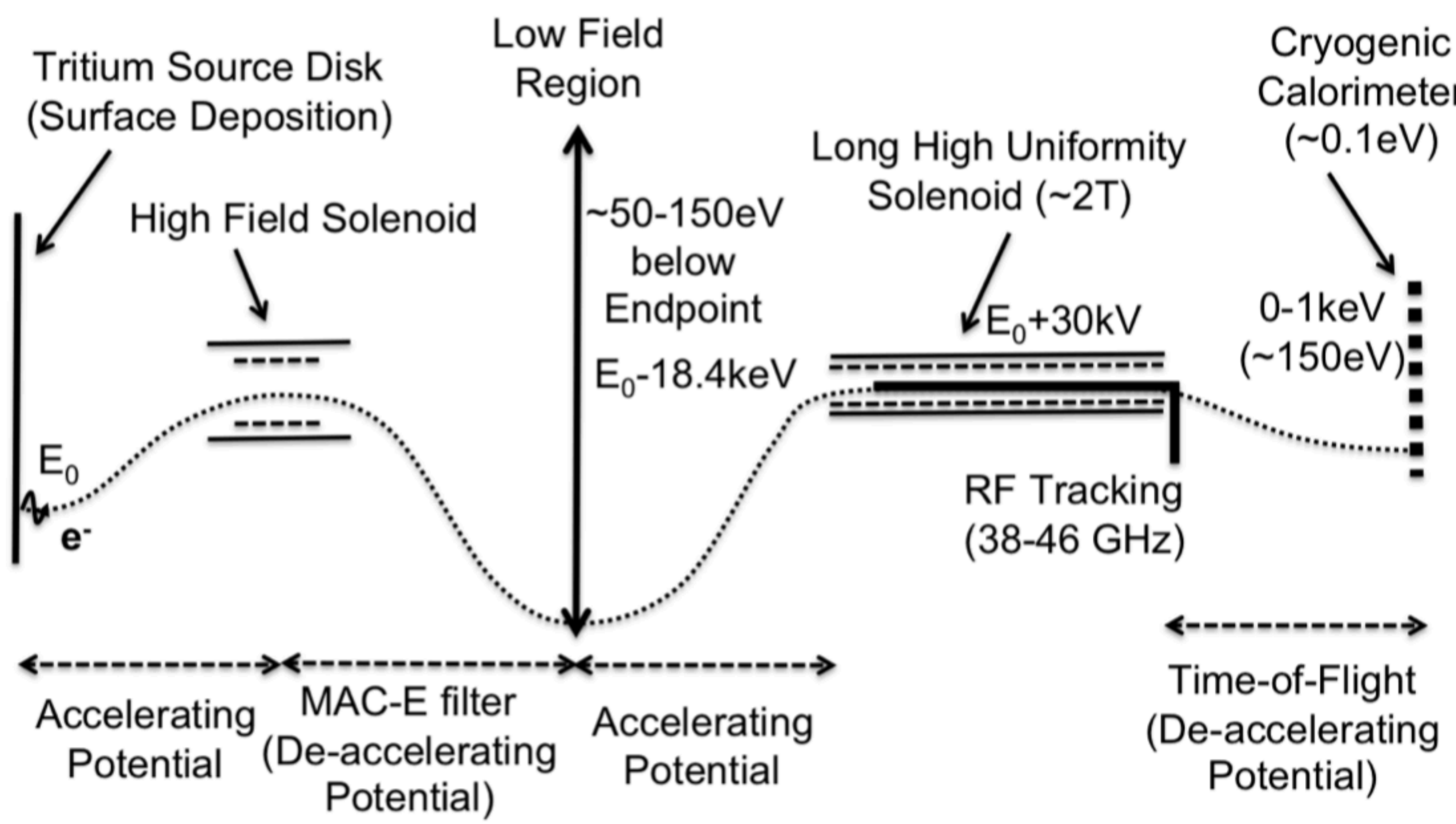


β-decays with long lifetime

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

PTOLEMY Experiment:

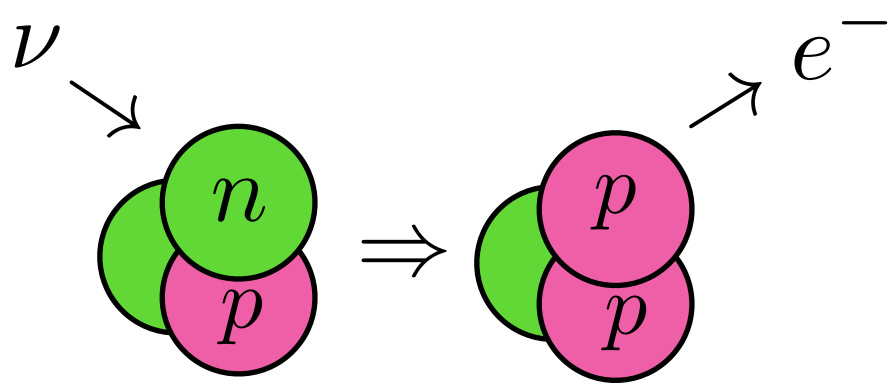




Tritiated graphene to reduce molecular smearing

Electrons below endpoint filtered out

CνB capture on Tritium

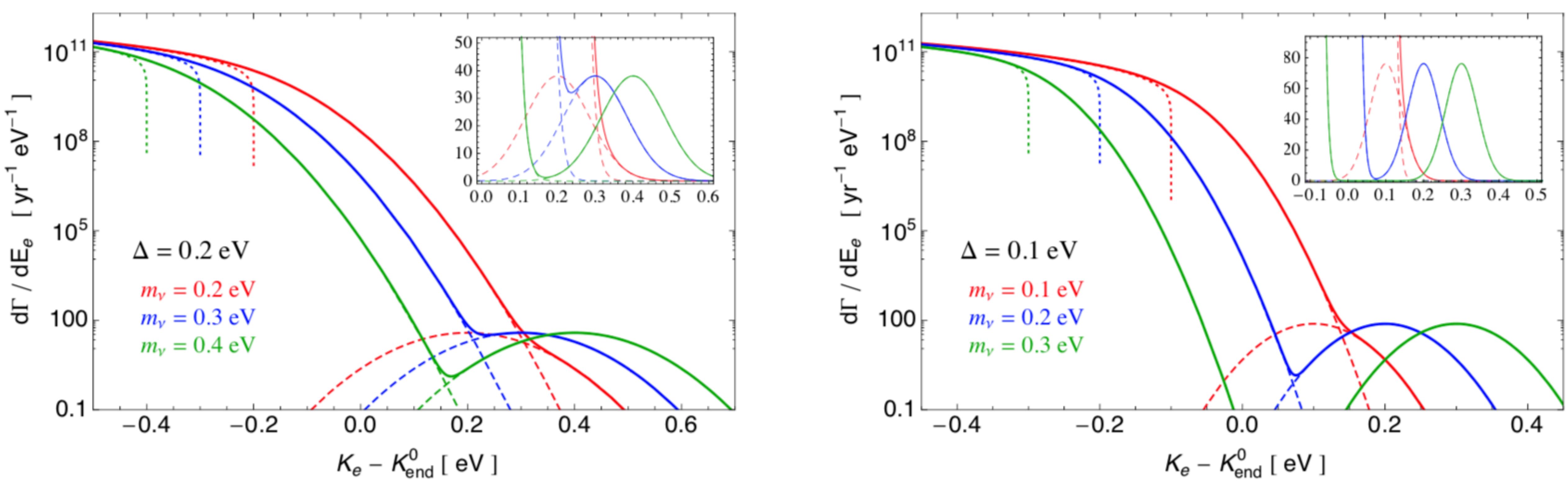


β-decays with long lifetime

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

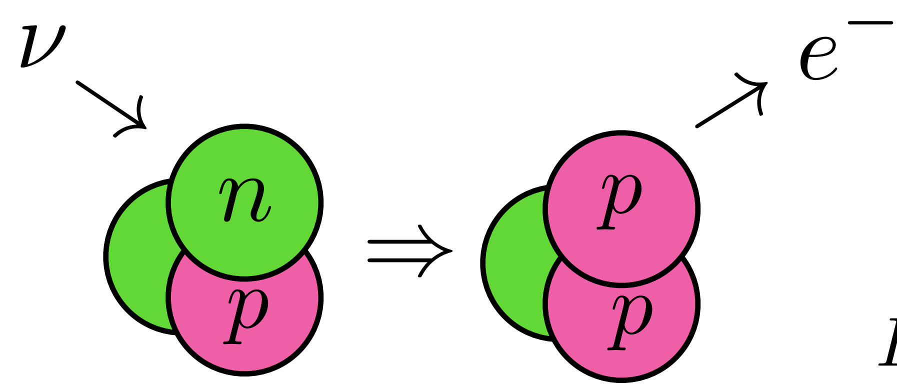
$$\sigma = 3.8 \times 10^{-45} \text{ cm}^2 \quad \Rightarrow \Gamma_{\text{Dir.}} = \frac{1}{2}\Gamma_{\text{Maj.}} = \frac{4}{\text{yr}} \left(\frac{M_T}{100 \text{ g}}\right) \left(\frac{n_\nu}{56 \text{ cm}^{-3}}\right)$$

Long, Lunardini, Sabancilar



Tiny rates but a crucial target

ν from DM decay on Tritium

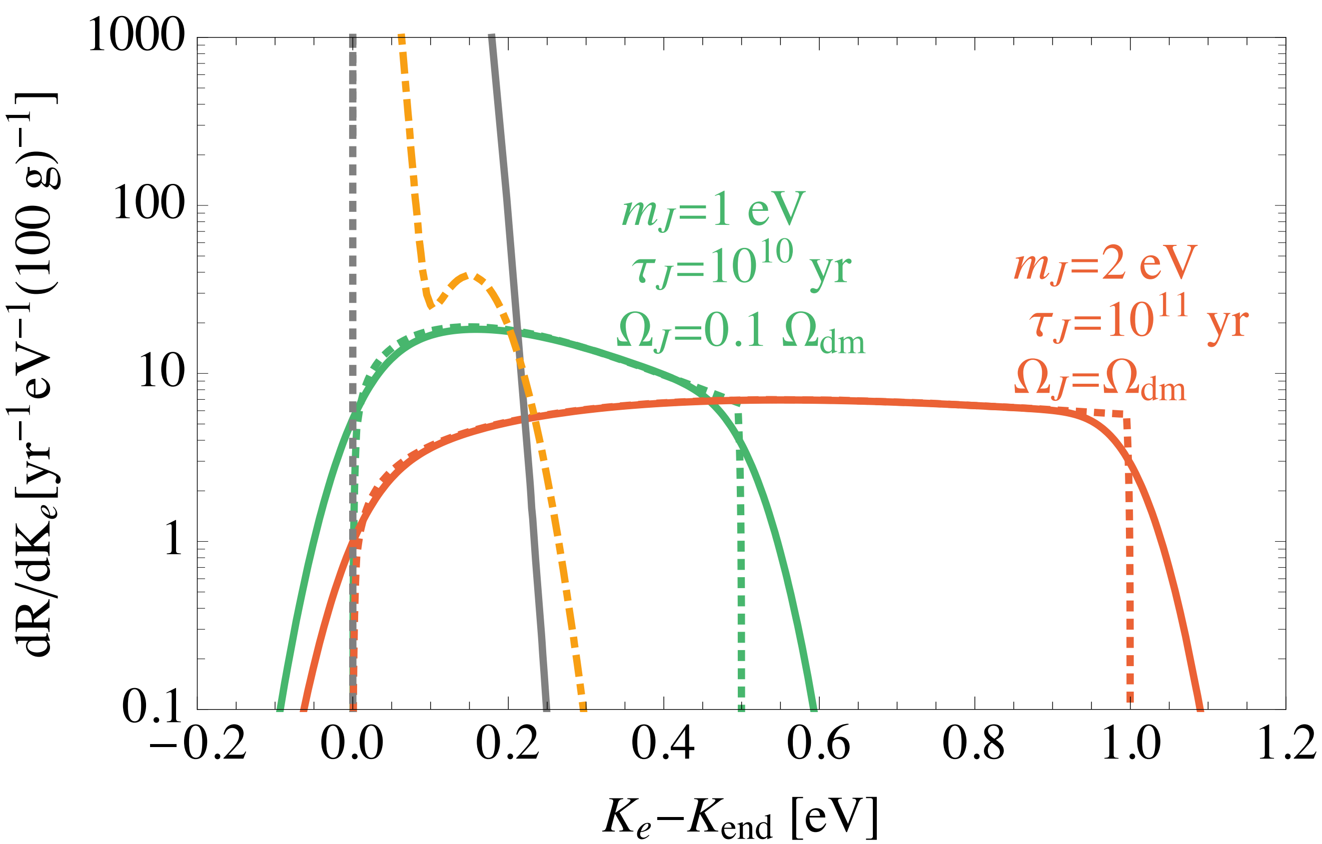


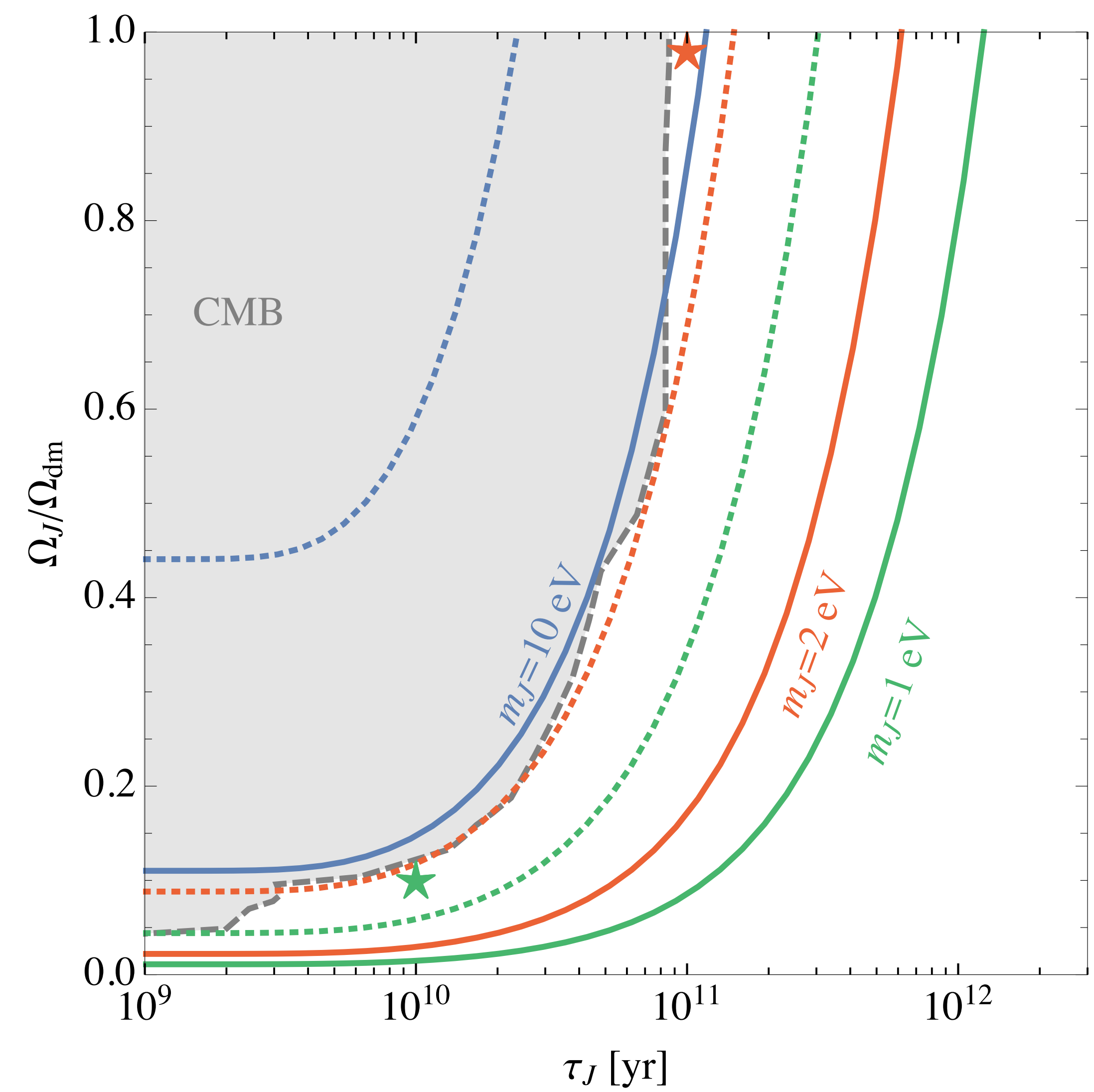
The electron energy gap can be larger in this case

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

$$\tilde{n}_\nu \sim \frac{10}{\rm cm^3}\left(\frac{10\ {\rm eV}}{m_J}\right) \qquad \tau_J > t_{\rm rec}$$

$$R = \frac{2.42}{\rm yr}\left(\frac{M_T}{100\ {\rm g}}\right)\left(\frac{f_{\nu_e}}{1/3}\right)\left(\frac{\tilde{n}_\nu}{100\ {\rm cm^3}}\right)$$





A Lesson from History?

UTLICEPP-82-04
Jun. 1982

"KAMIOKANDE"

- The KAMIOKA Nucleon Decay Experiment -

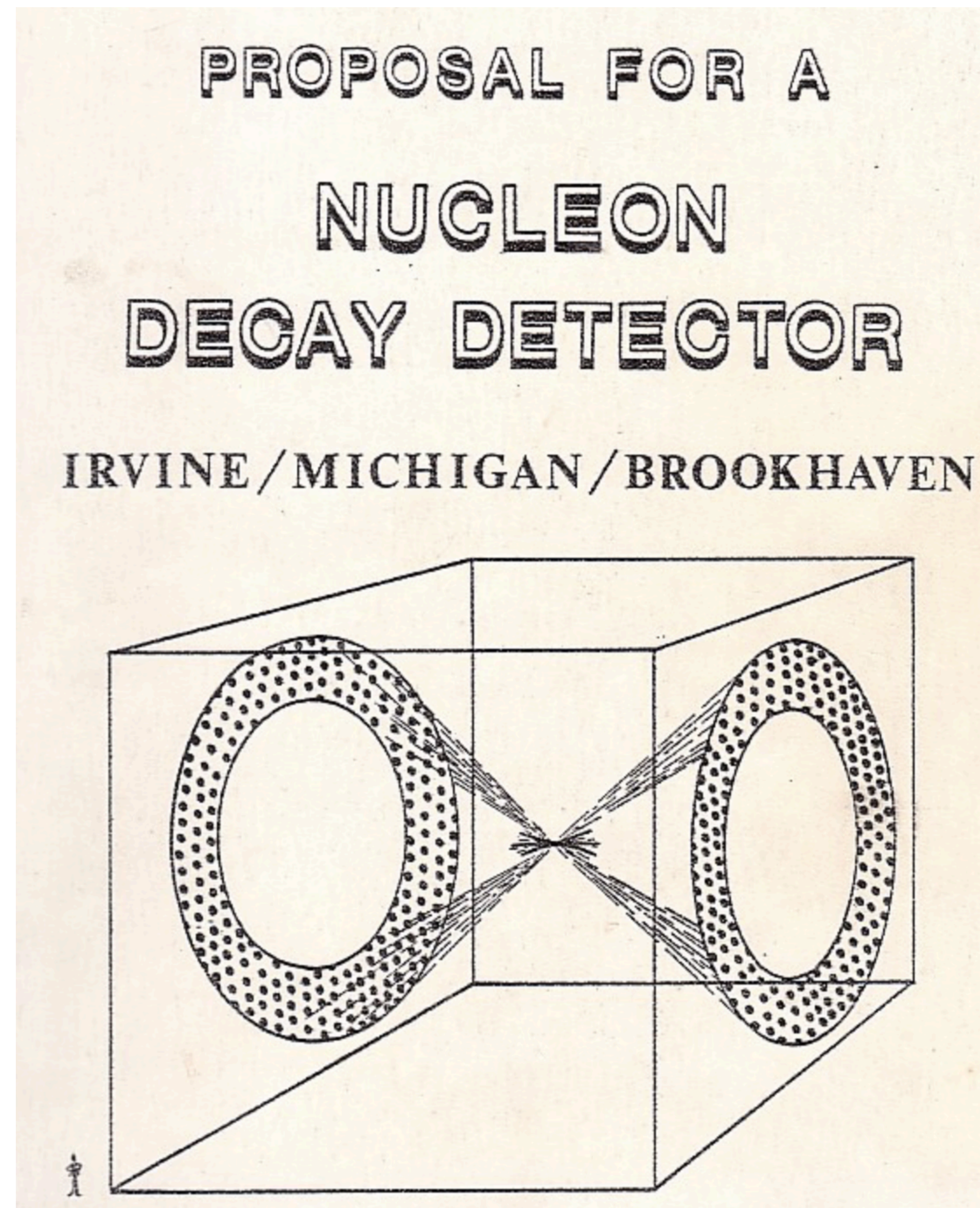
H.Ikeda, A.Nishimura, H.Sugawara, and K.Takahashi
KEK, National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken 305, Japan

K.Arisaka, T.Fujii, T.Kajita, K.Kawagoe, M.Kobayashi, M.Koshiba, T.Mashimo, M.Nakahata, A.Suzuki, and Y.Totsuka
Department of Physics and LICEPP, University of Tokyo,
Hongo, Tokyo 113, Japan

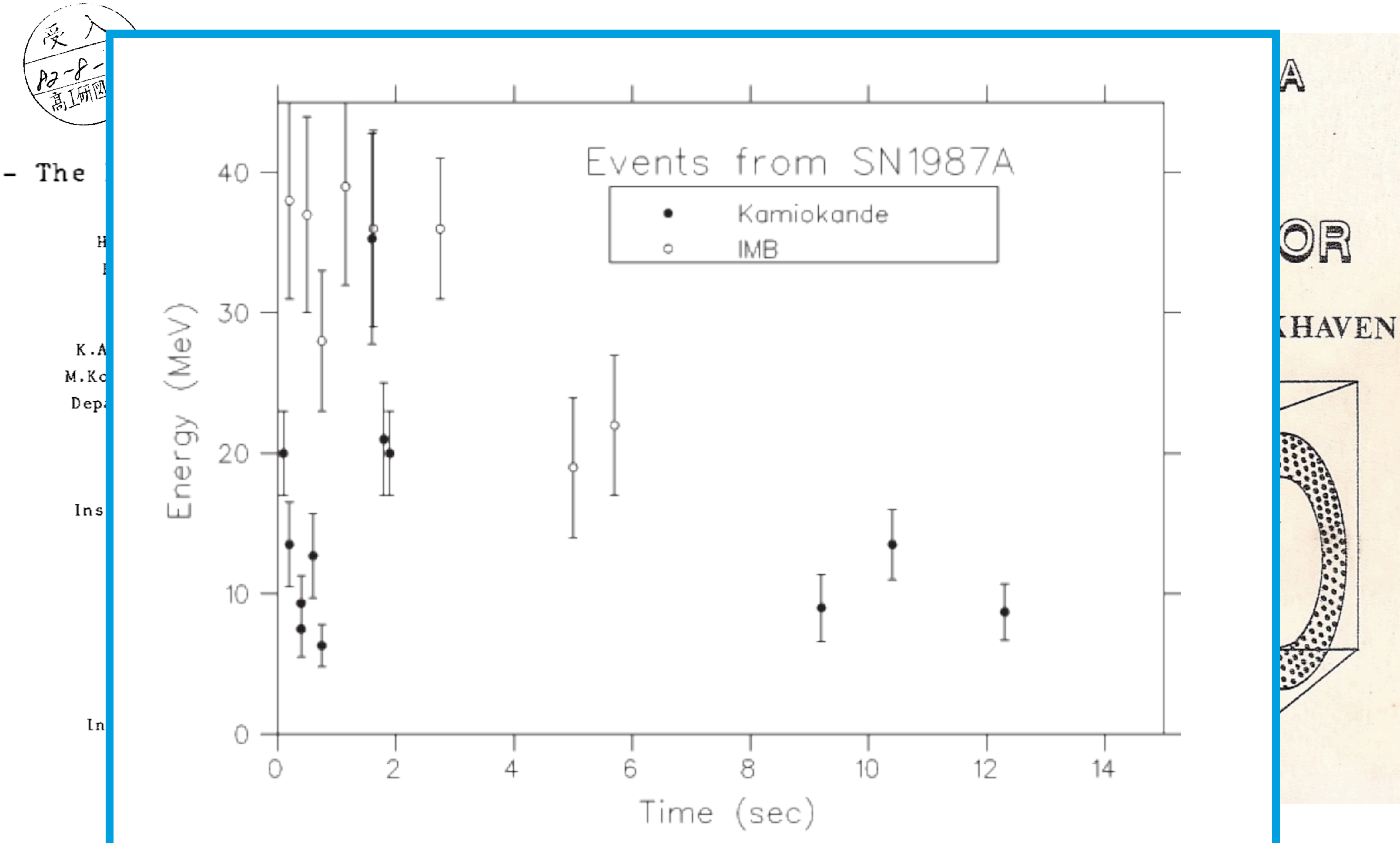
J.Arafune, T.Kifune, and T.Suda
Institute for Cosmic Ray Research, University of Tokyo
Tanashi, Tokyo 188, Japan

K.Miyano
Department of Physics, University of Niigata,
Niigata 950-21, Japan

Y.Asano
Institute for Applied Physics, University of Tsukuba
Sakura-mura, Ibaraki-ken 305, Japan



A Lesson from History?



Wrap up

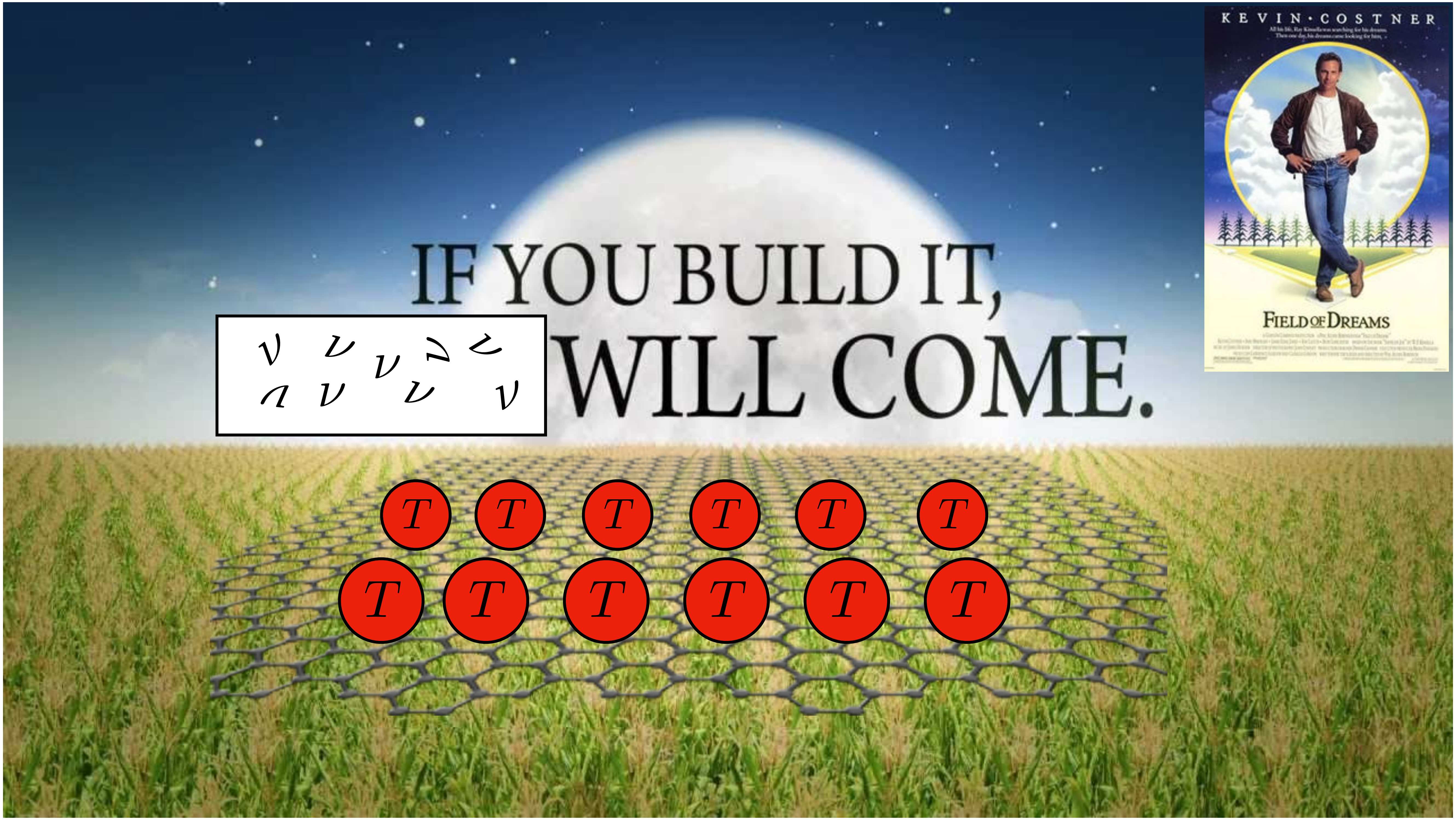
Cosmic neutrino background is an extremely important target to probe cosmology

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 so that we don’t miss anything—only nature gets a vote


IF YOU BUILD IT,
THEY WILL COME.
KEVIN · COSTNER
FIELD OF DREAMS


IF YOU BUILD IT,
ν ν ν ν ν ν ν ν ν
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T T T T T T
KEVIN·COSTNER
FIELD OF DREAMS

Back up

If $\boldsymbol{J}$ is "the" majoron $\quad \mathcal{L}_{\text{int}} = \frac{i m_\nu}{f} J \nu\nu + \text{h.c.}$

$\tau_J \sim 10^9\ \text{yr} \Leftrightarrow f \sim 100\ \text{TeV}$ for $m_J \sim \text{eV}$

Model building exercise to get right mass/abundance

Flavor content: