

Filling the gap in the GUNS: the solar neutrino flux at keV energies

6th Symposium on Neutrinos and Dark Matter in Nuclear Physics (NDM18),
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elusi^{ves}
neutrinos, dark matter & dark energy physics



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



Based on arXiv:1708.02248 w/ J.Redondo and G.Raffelt

What I am going to discuss

Weakly interactive, low mass particles (like **neutrinos** or BSM particles, e.g. axions)
can be produced in stars

MeV Neutrinos produced in the Sun are a signal for solar physics studies and background for dark matter searches

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MeV Neutrinos produced in the Sun are a signal for solar physics studies and background for dark matter searches

THIS IS TRUE ALSO AT keV ENERGIES

Outline

What

- Introduction to the Grand Unified Neutrino Spectrum
- Filling the gap: keV neutrinos from the Sun

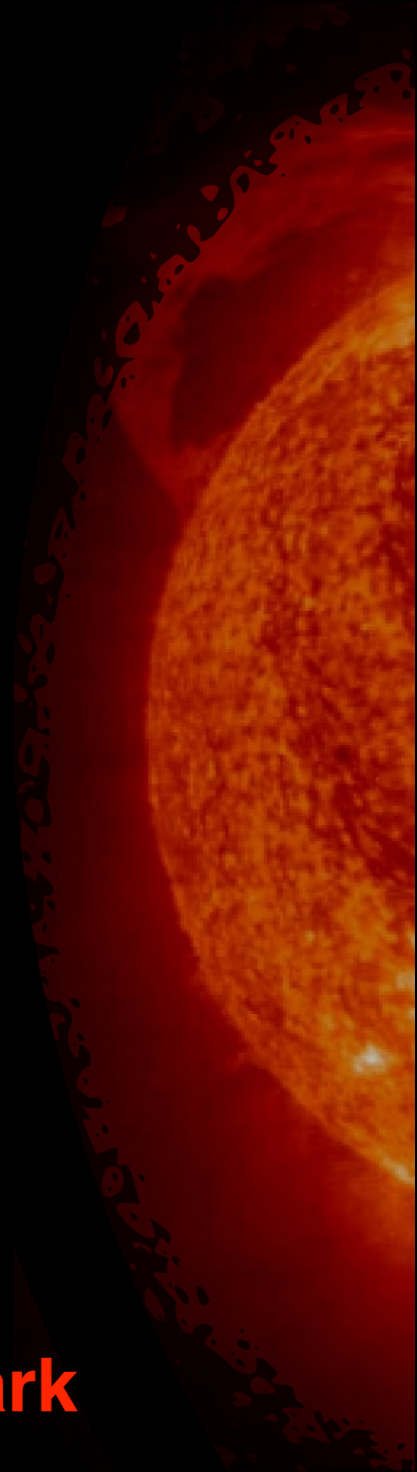
Why

- New window on solar physics
- Background to keV mass sterile neutrinos

How

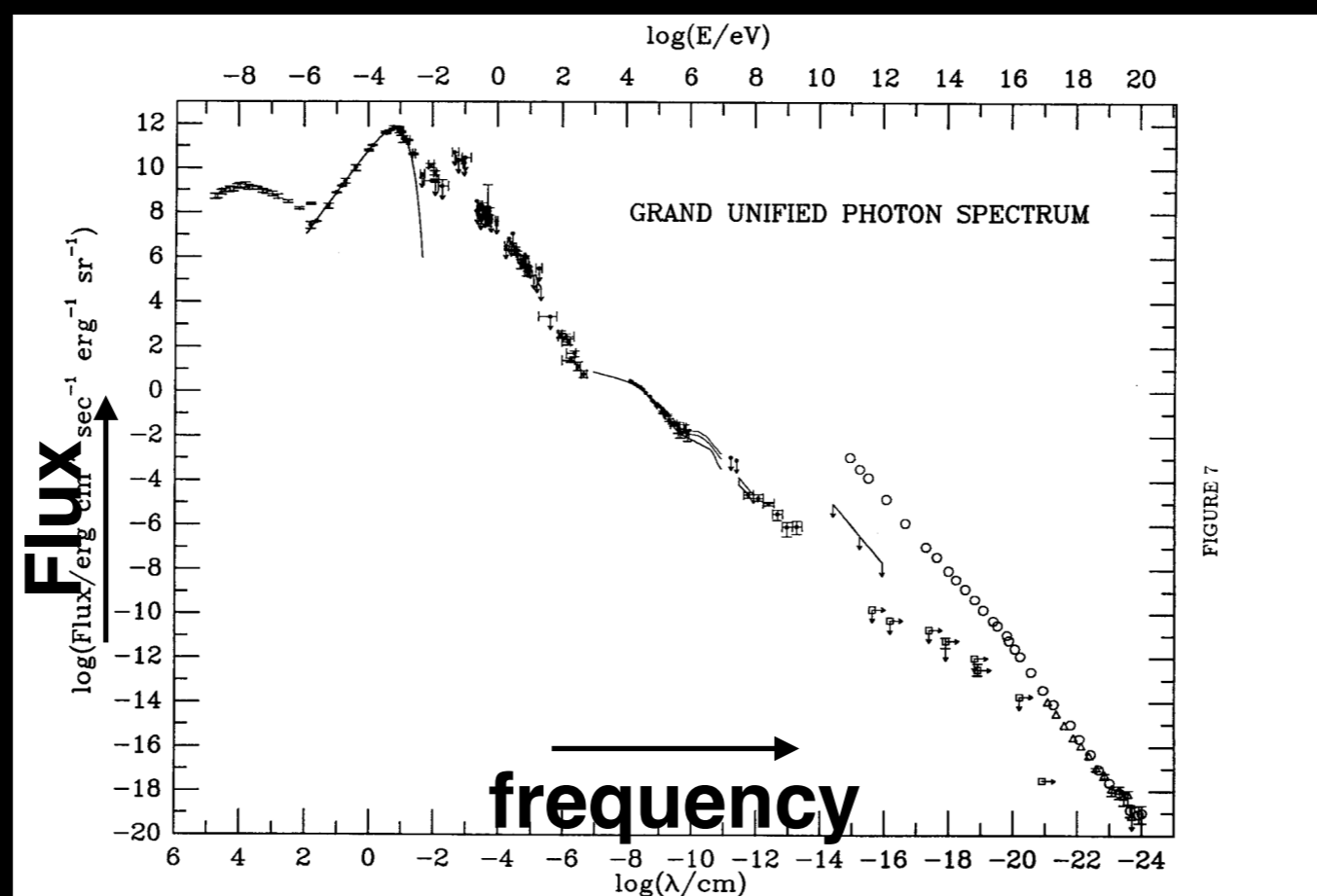
- Fun with thermal physics!

Featuring concepts useful for early universe cosmology, dark matter etc.



THE GRAND UNIFIED PHOTON SPECTRUM

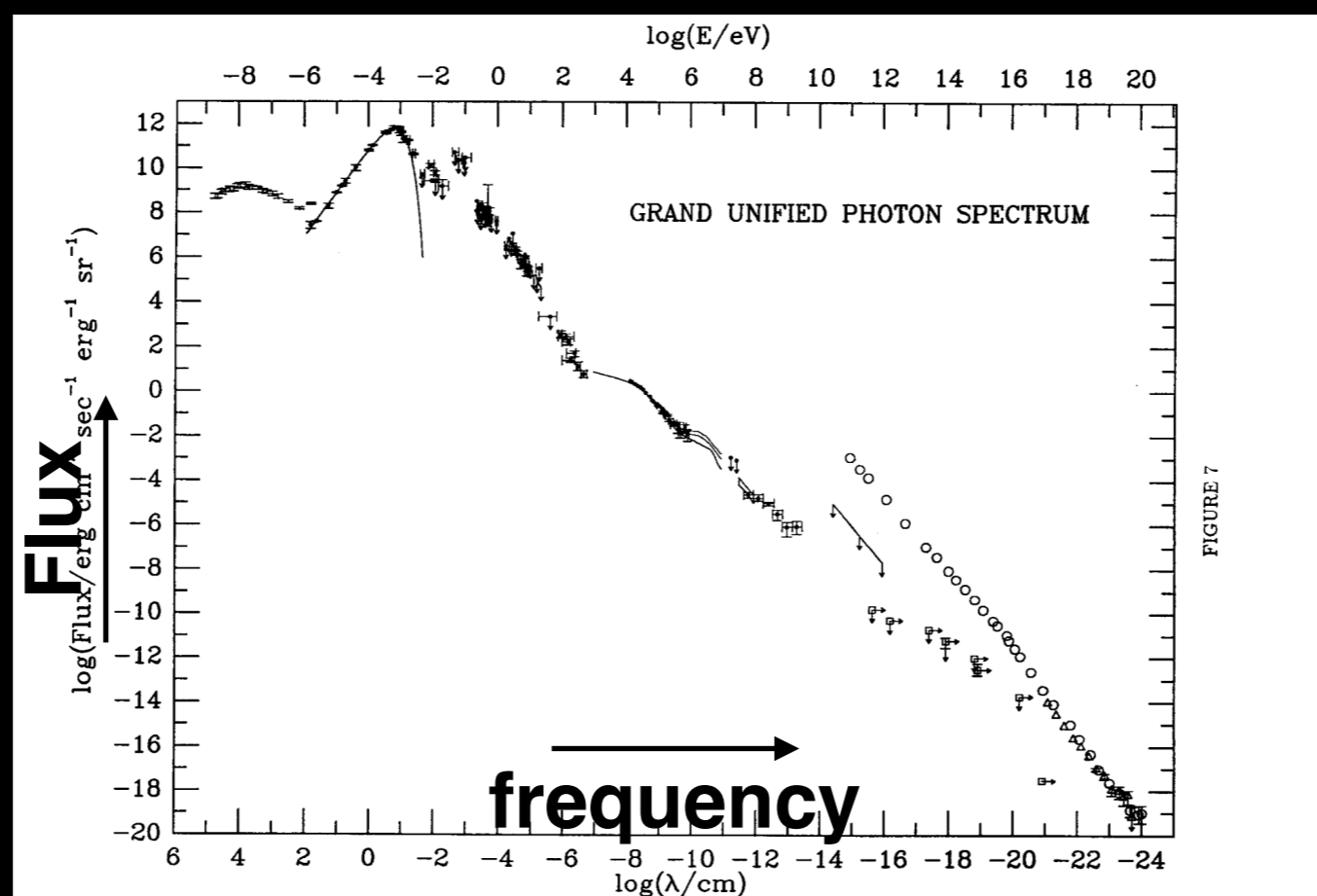
(The diffuse extragalactic background spectrum at all energies)



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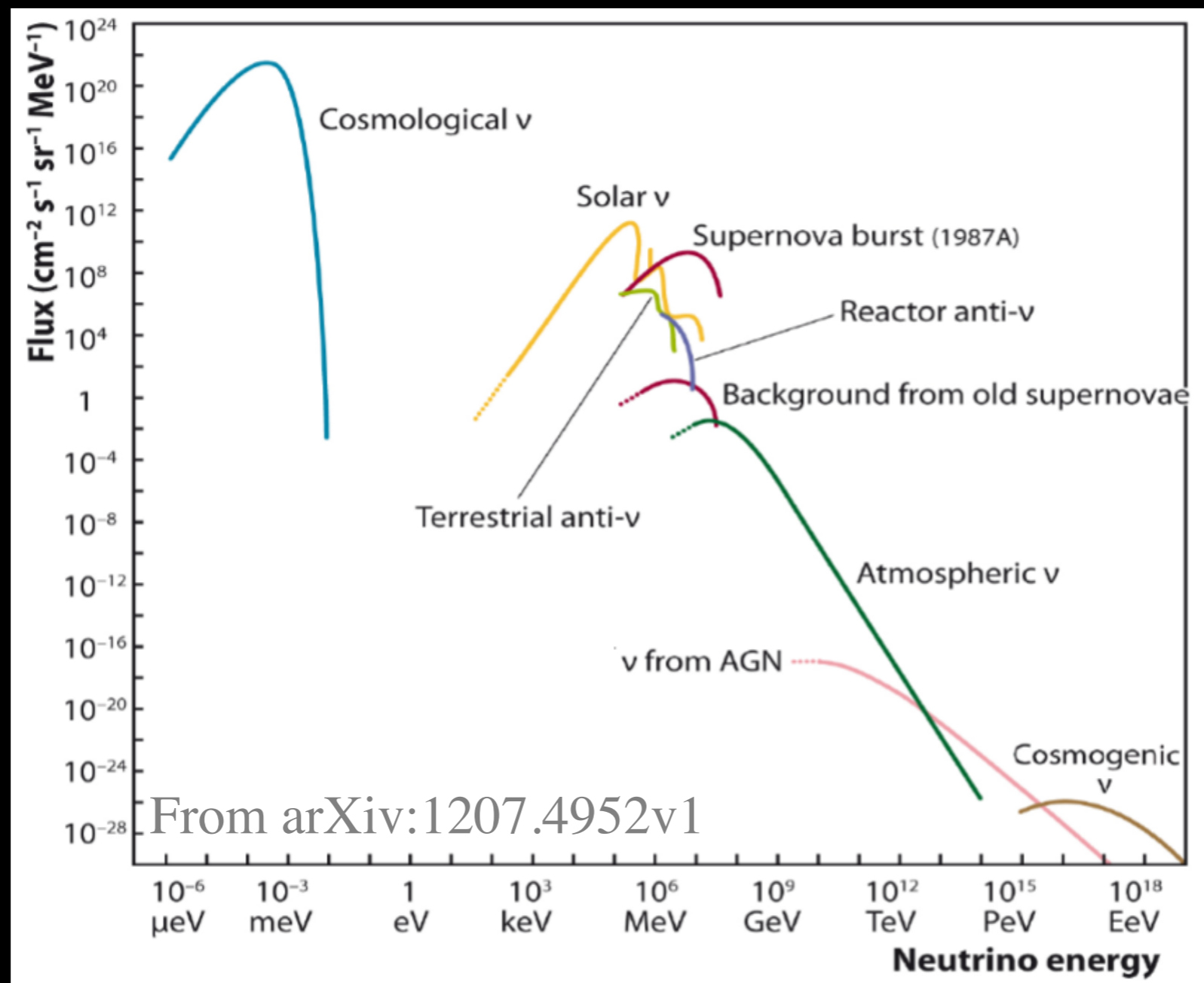
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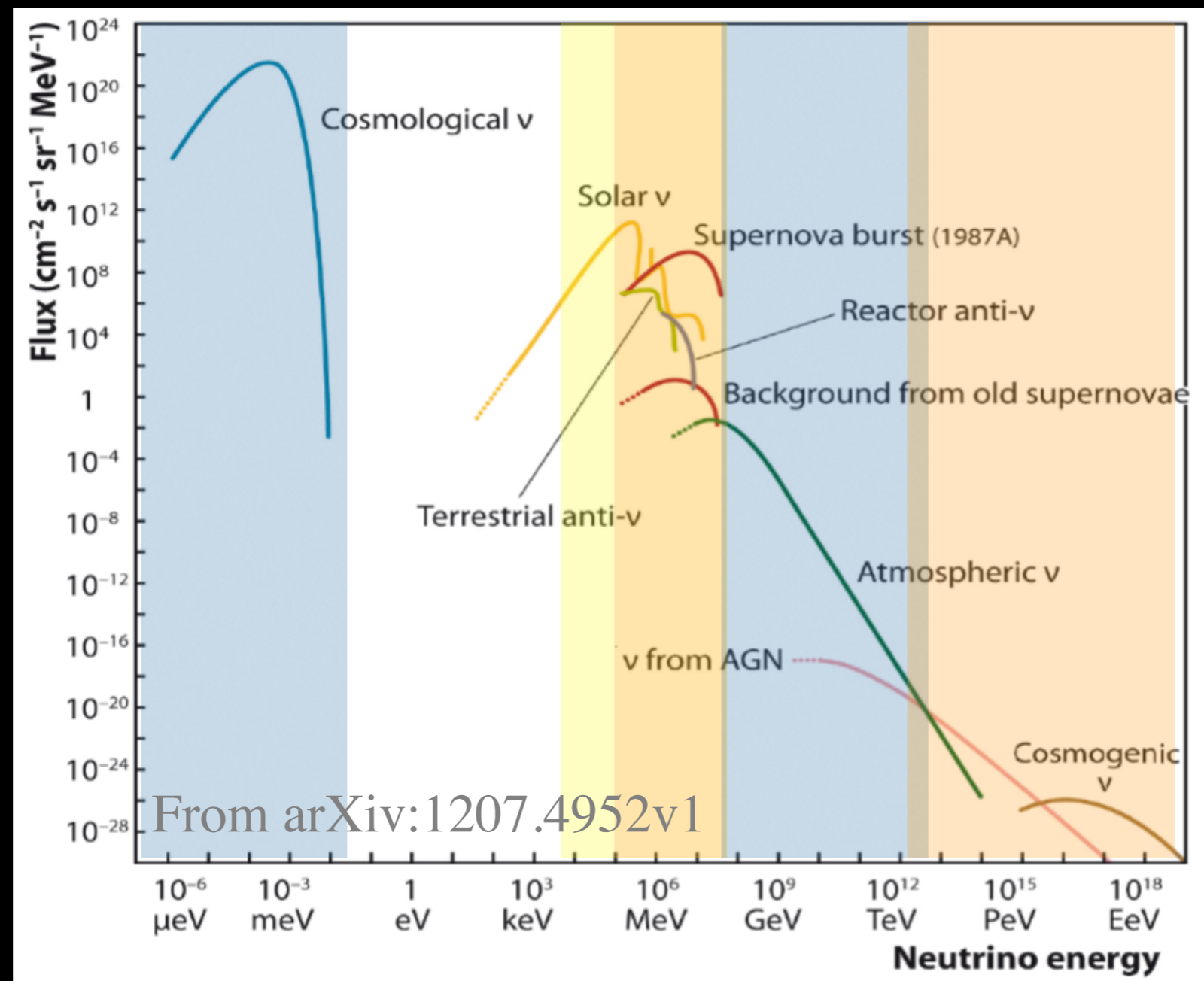
in the multi-messenger
astronomy era...

THE GRAND UNIFIED NEUTRINO SPECTRUM (guns)

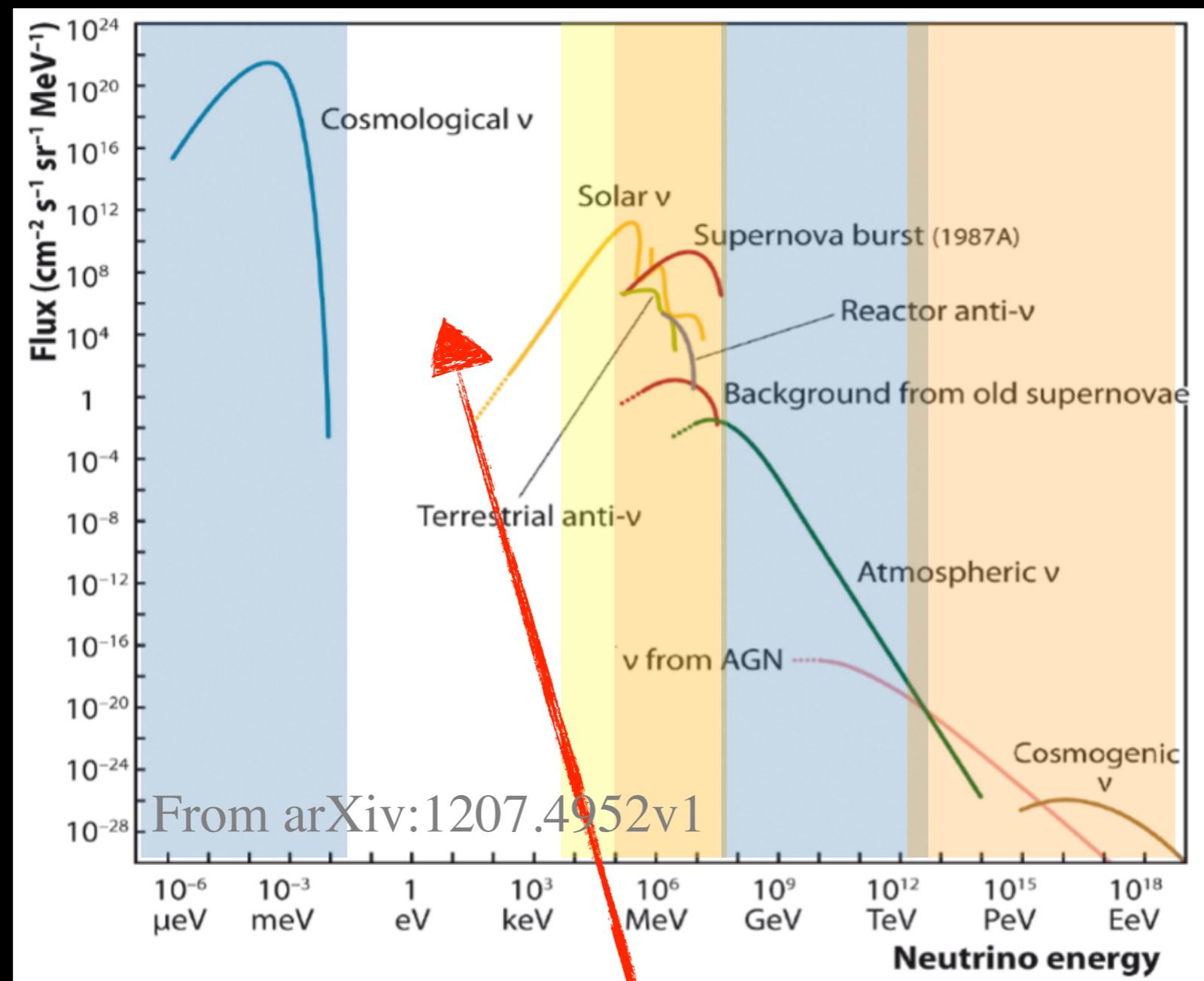


Spread the meme!

THE GRAND UNIFIED NEUTRINO SPECTRUM (guns)

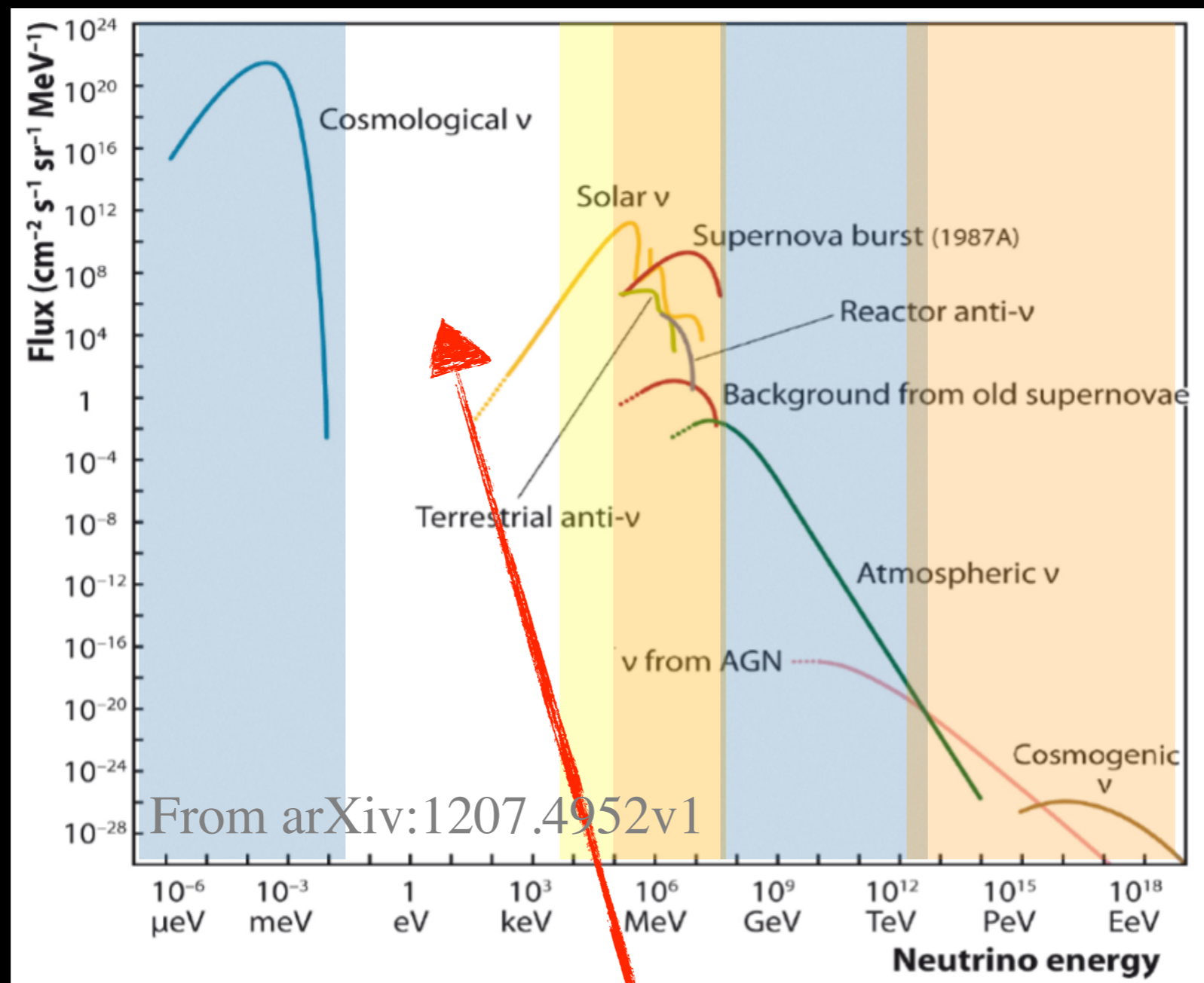


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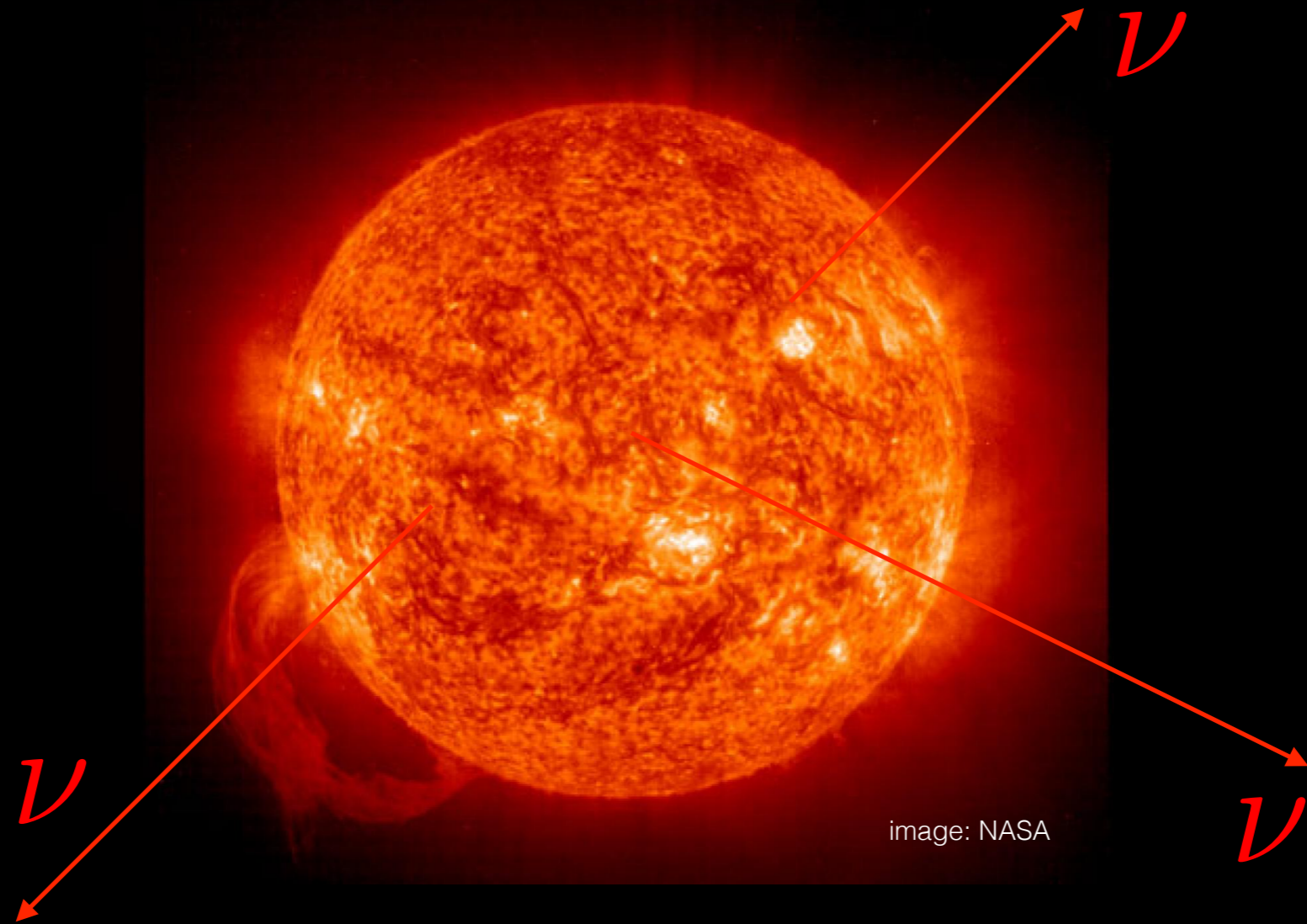
???

THE GRAND UNIFIED NEUTRINO SPECTRUM (guns)



Is there a source for keV neutrinos?

Yes! Directly from our domestic star...

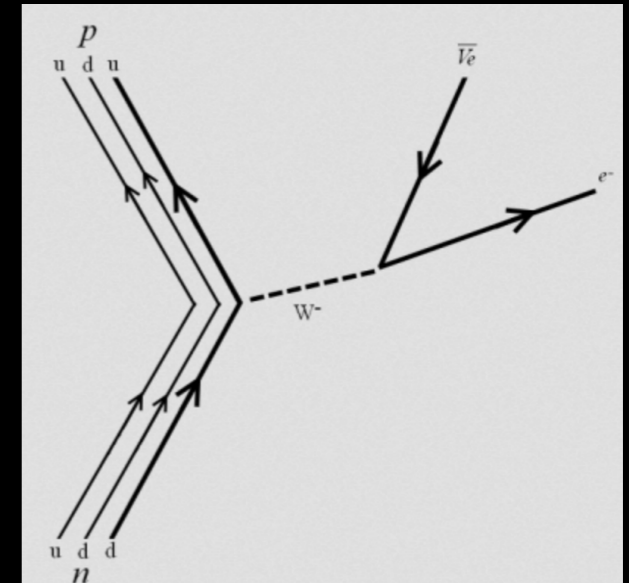
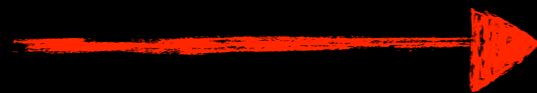


...keV neutrinos

Neutrino Solar production

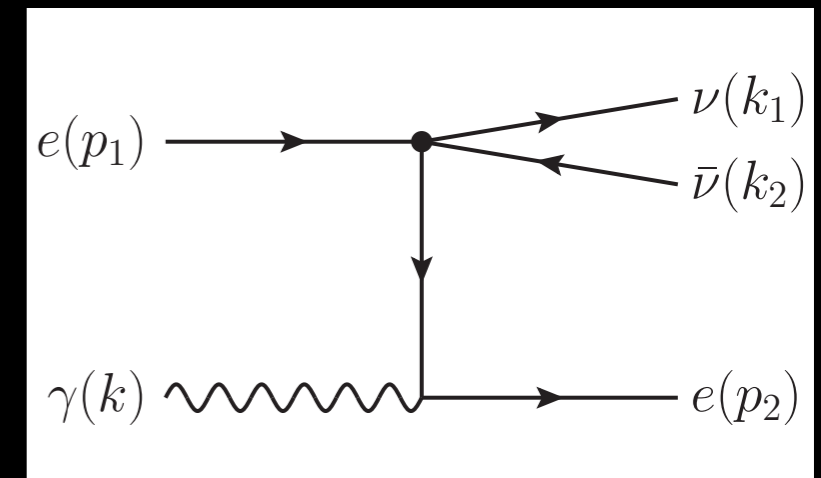
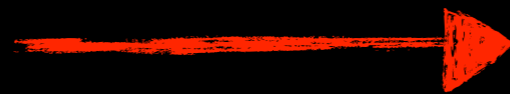
Nuclear processes:

- well known
- pp chain, CNO cycles etc.



Thermal processes:

- less analysed
- processes involving mostly photons and/or electrons



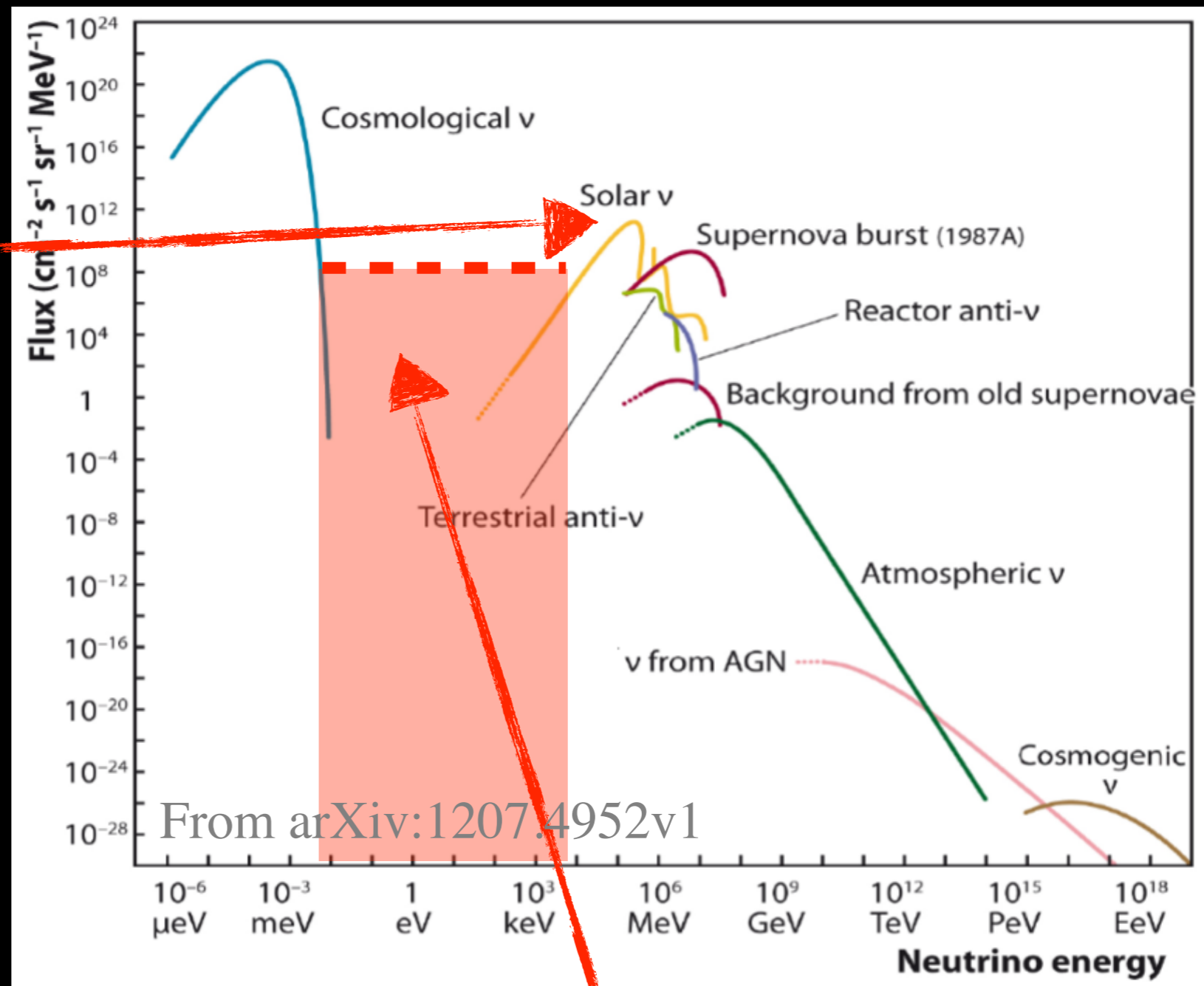
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!!!

(See also Haxton&Lin,
arXiv:nucl-th/0006055)

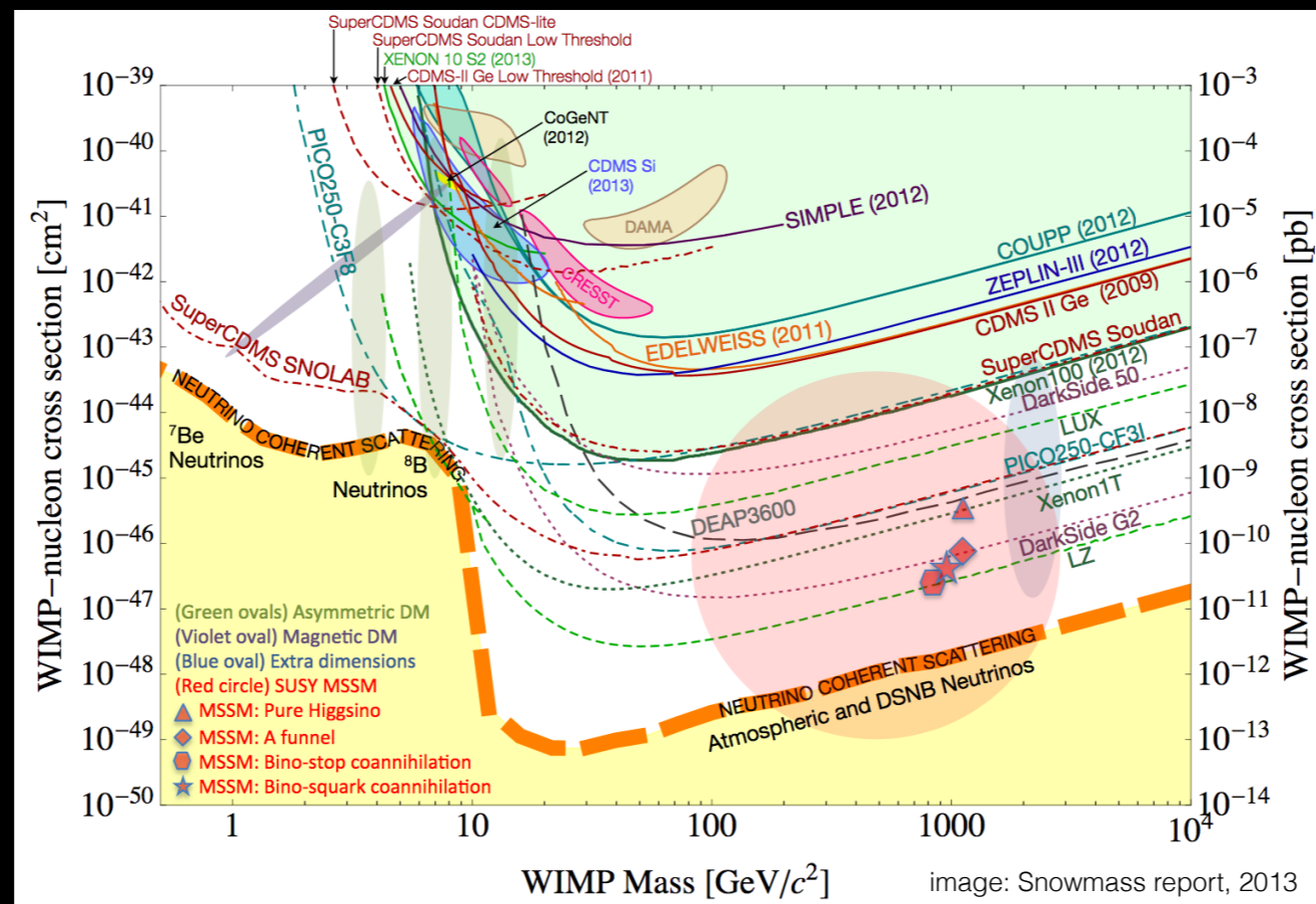
WHAT: ✓

An aside: beyond the WIMP paradigm

WIMPs searches are a success (*WIMP-Moore's Law*: factor of 10 every 6.5 years!)

Lots of discussions about several dark matter candidates (from axions to MACHOs...)

Time to discuss the possible background to the detection of these candidates



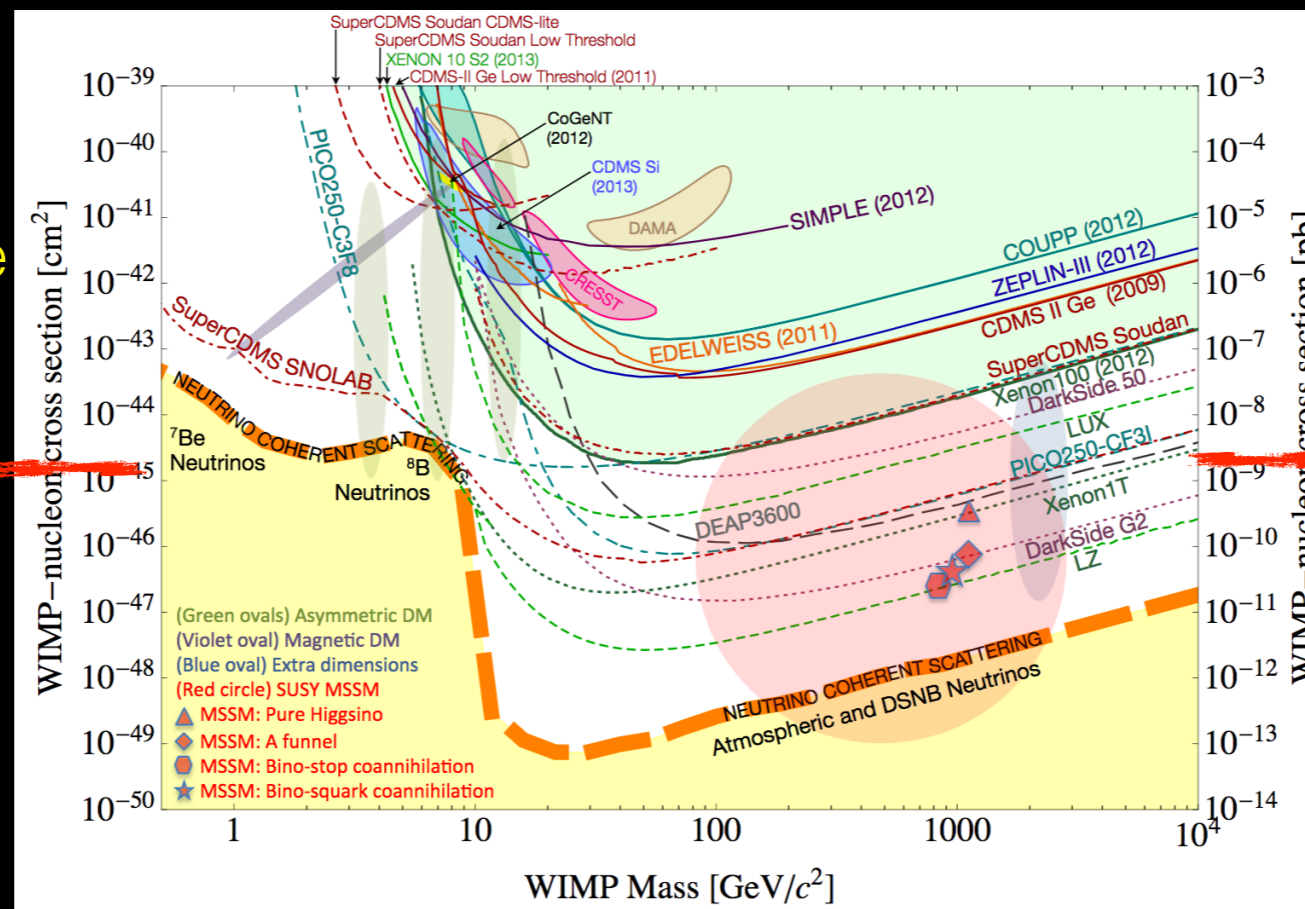
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ALPs, keV sterile neutrinos etc.



Superheavy dark matter etc.



e.g. arXiv:1507.01000

S.Boucenna, M.Chianese, G.Mangano,
G.Miele, S.Morisi, O.Pisanti, **E.V.**

arXiv:1601.02934

M.Chianese, G.Miele, S.Morisi, **E.V.**

Sterile neutrino dark matter

- Gives mass to neutrinos
- With mass above 0.4 keV no Tremaine-Gunn bound
- Solves the cusp-core problem

Journal of **C**osmology and **A**stroparticle **P**hysics
An IOP and SISSA journal

A White Paper on keV sterile neutrino Dark Matter

Editors: M. Drewes, T. Lasserre, A. Merle and S. Mertens

arXiv:1602.04816

A very good candidate!

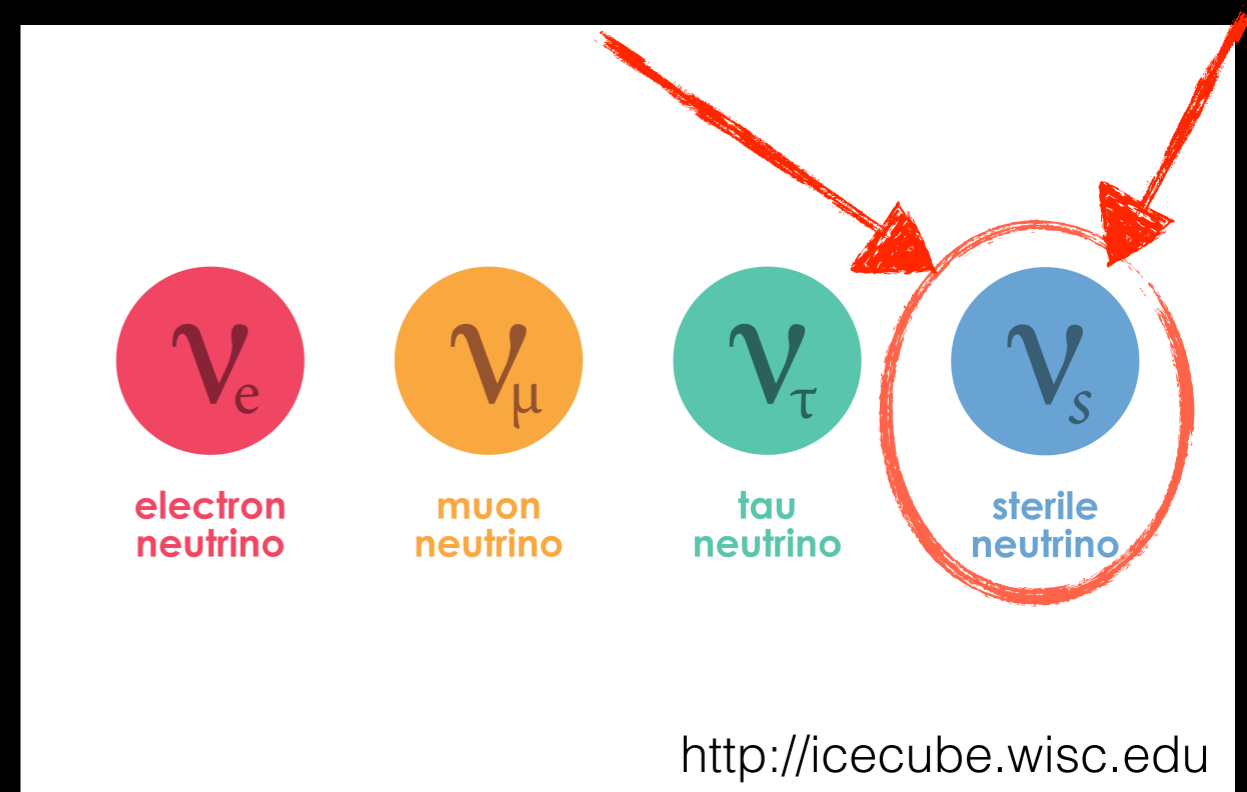
And now: why

We have a “**What**”, computing (and detecting...) the neutrino flux produced in the Sun at keV energies. **Why** is it interesting?

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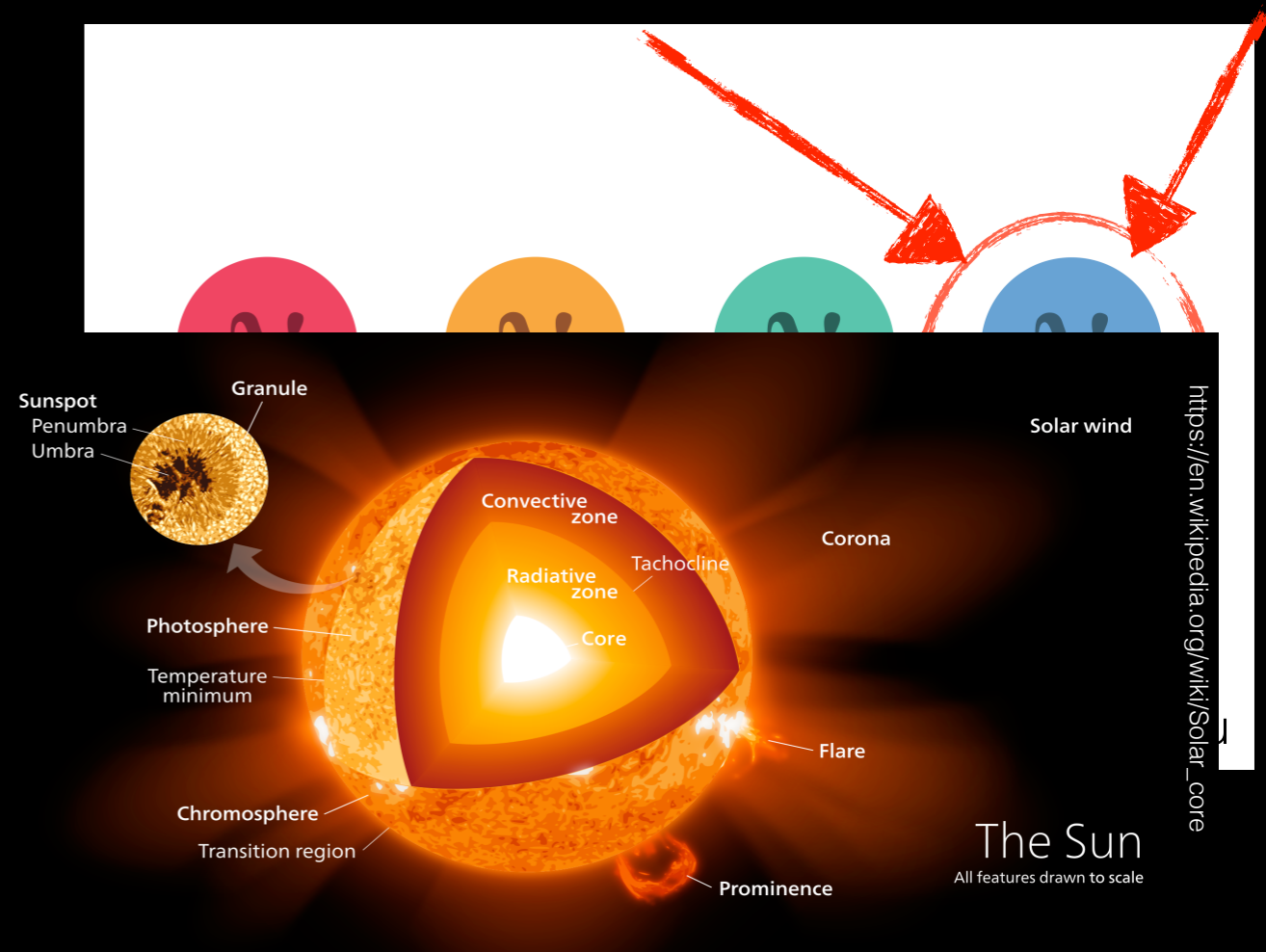
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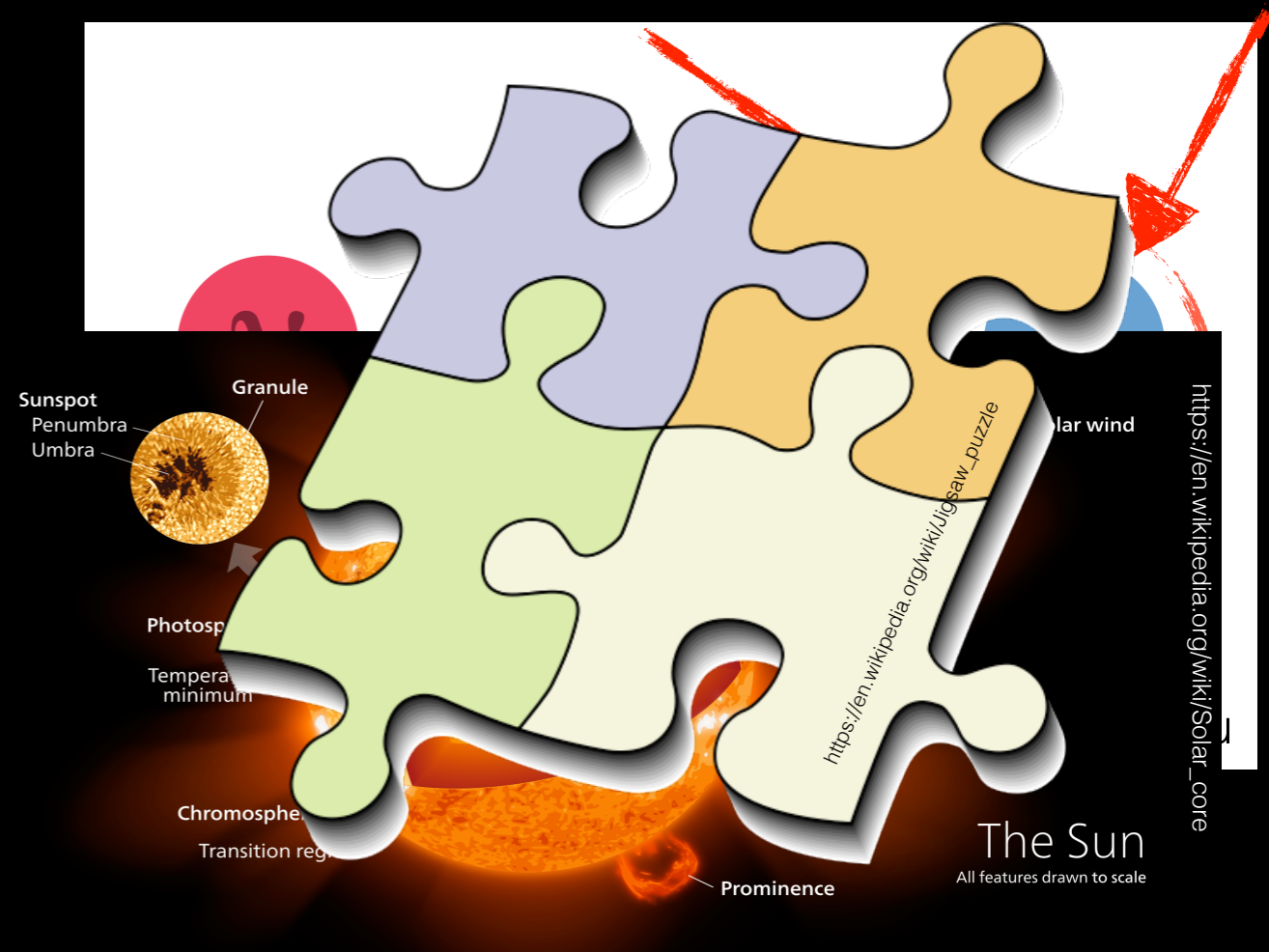
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- **Why 2**: new window on solar physics



And now: why

We have a “**What**”, computing (and detecting...) the neutrino flux produced in the Sun at keV energies. **Why** is it interesting?

- **Why 1**: background of keV-mass sterile neutrino
- **Why 2**: new window on solar physics
- aka the signal of today is the background of tomorrow (or vice versa)



WHY: ✓

WHY:

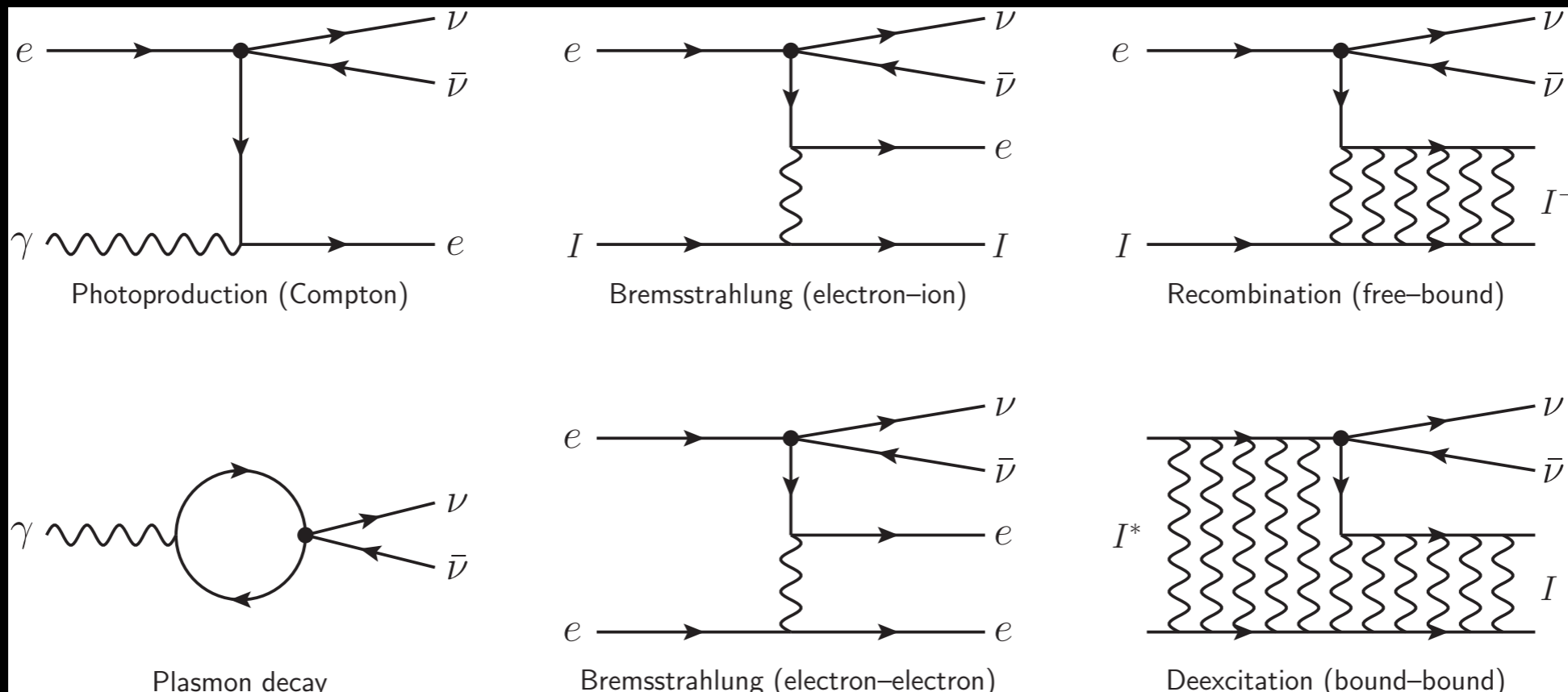


but...how?

How - the ABCD processes

- Atomic recombination (fb) and deexcitation (bb)
- Bremsstrahlung (ff)
- Compton process
- Decay of a plasmon

Let's start with this one!



Good old weak interaction in the Fermi interaction limit

All previously shown processes are mediated by the interaction

$$\mathcal{L}_{\text{int}} = \frac{G_F}{\sqrt{2}} \bar{\psi}_e \gamma^\mu (C_V - C_A \gamma_5) \psi_e \bar{\psi}_\nu \gamma_\mu (1 - \gamma_5) \psi_\nu$$

$$\begin{aligned} C_V &= \frac{1}{2}(4 \sin \Theta_W + 1) & \text{and} & & C_A &= +\frac{1}{2} & \text{for } \nu_e, \\ C_V &= \frac{1}{2}(4 \sin \Theta_W - 1) & \text{and} & & C_A &= -\frac{1}{2} & \text{for } \nu_\mu \text{ and } \nu_\tau \end{aligned}$$

$$C_V^2 = 0.9263 \text{ for } \nu_e \bar{\nu}_e \text{ and } C_V^2 = 0.0014 \text{ for } \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$$

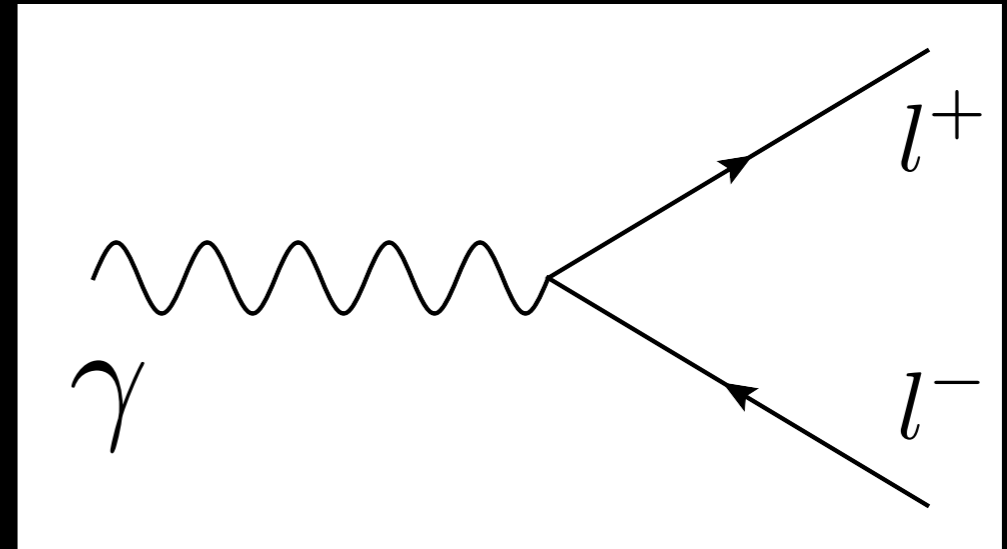
$$C_A^2 = 1/4$$

(different flavors, different vector couplings)

Plasmon decay to BSM particles

- It's different from Compton scattering! It's the photon gaining mass from the scattering
- The photon in the medium has nontrivial dispersion relation

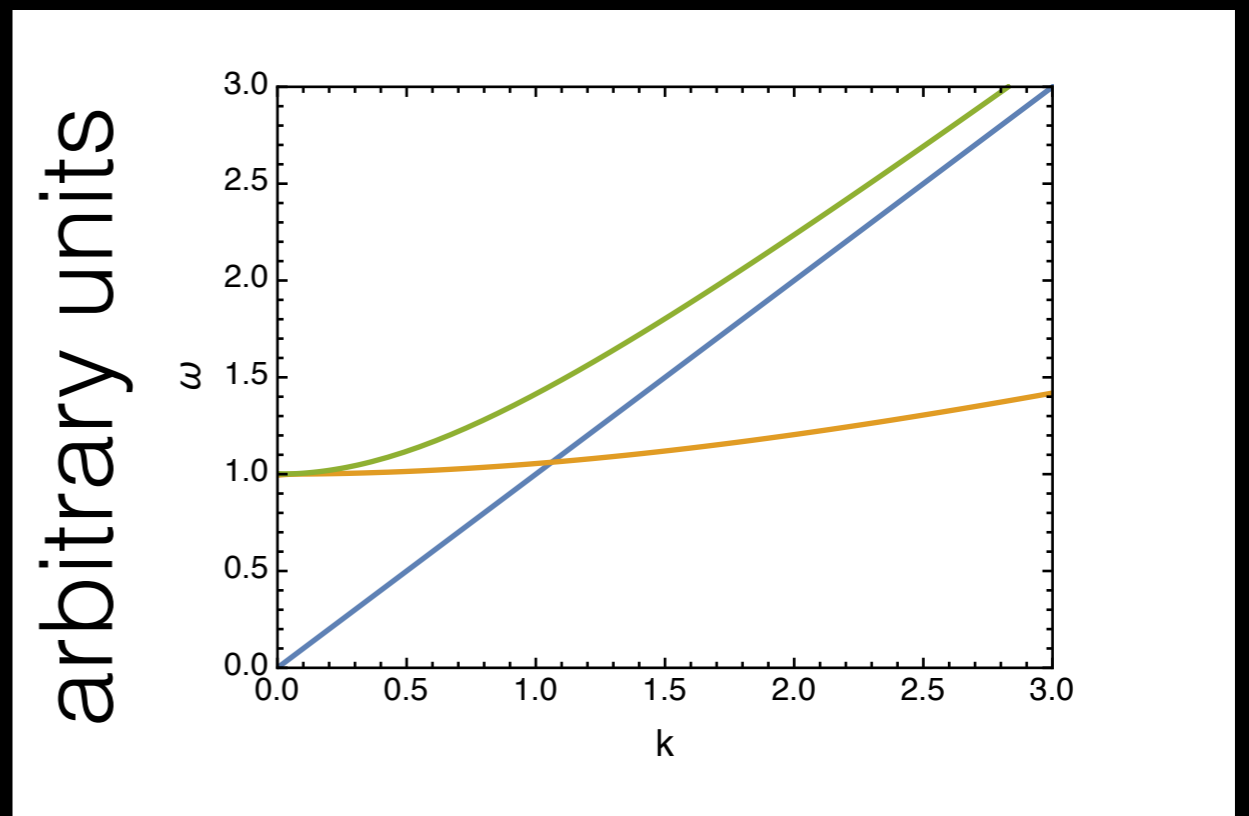
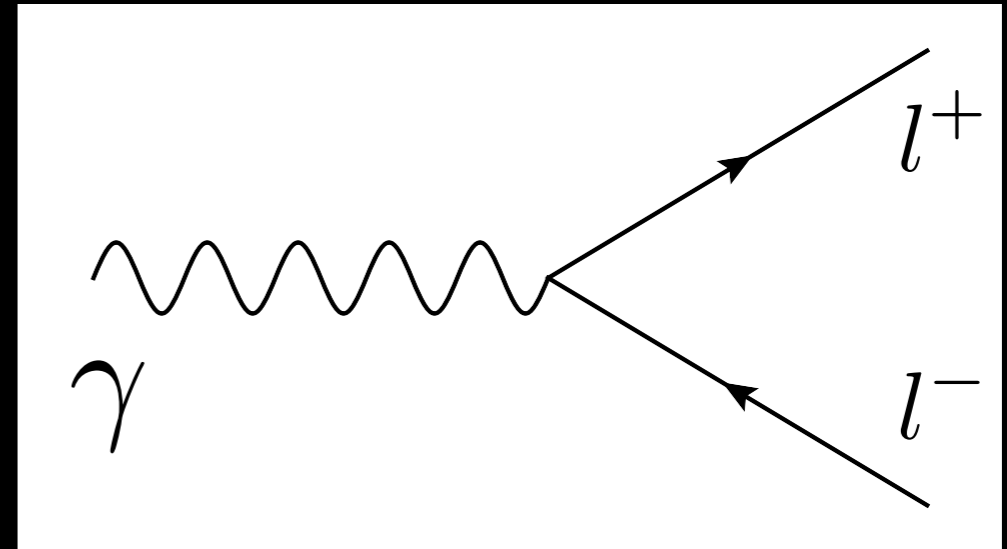
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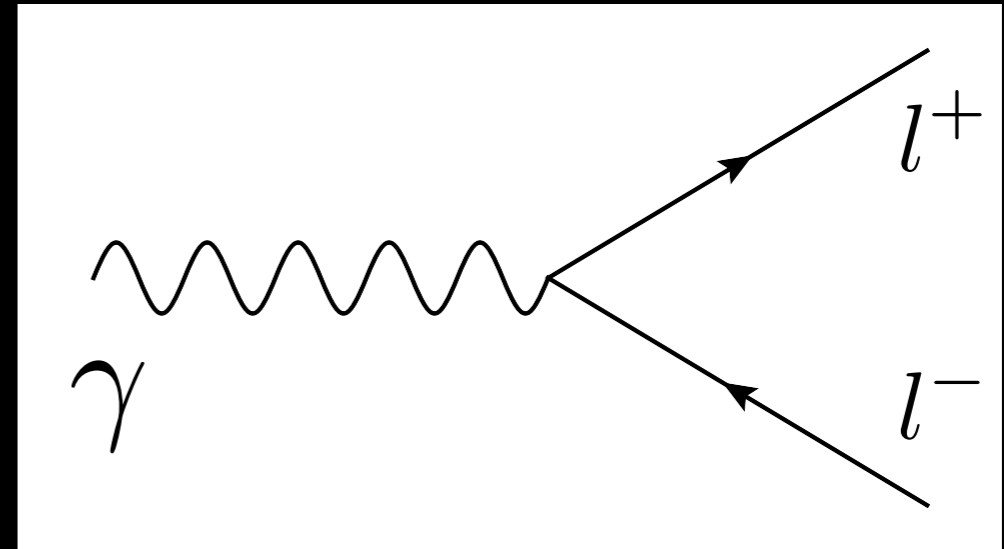
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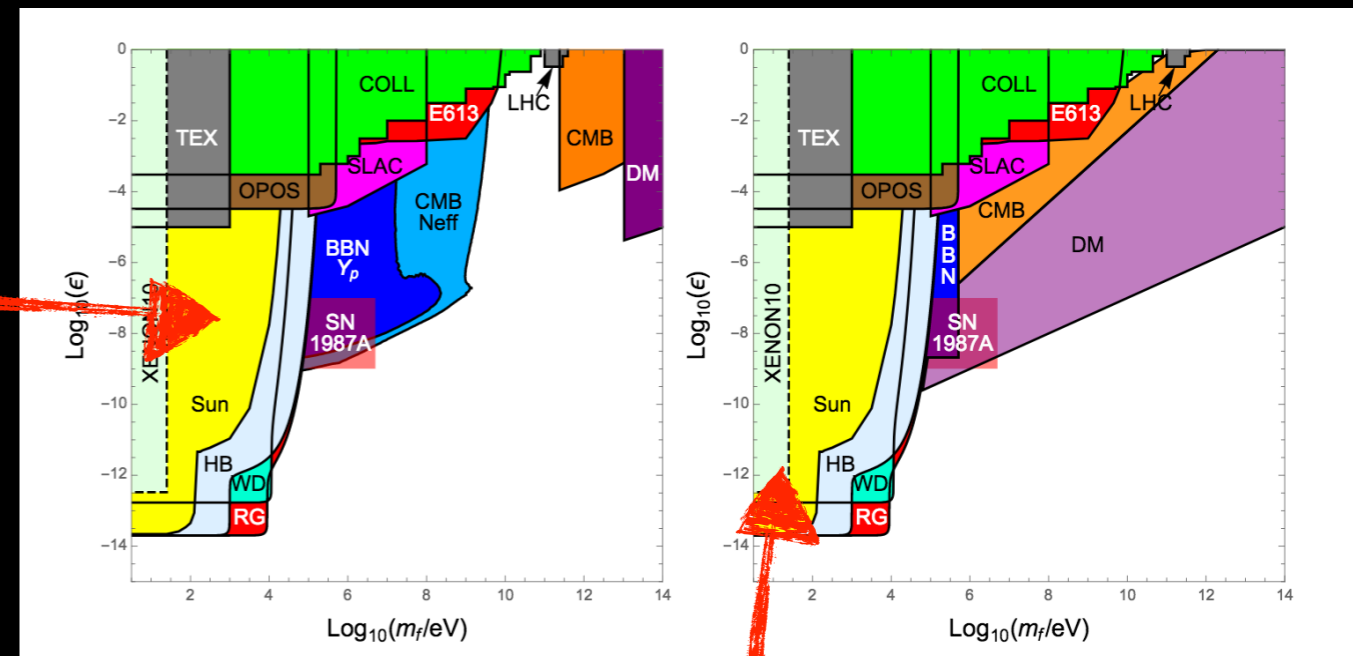
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- In this way, you produce e.g. mini charged particles in stars

Stars are laboratories of particle physics!

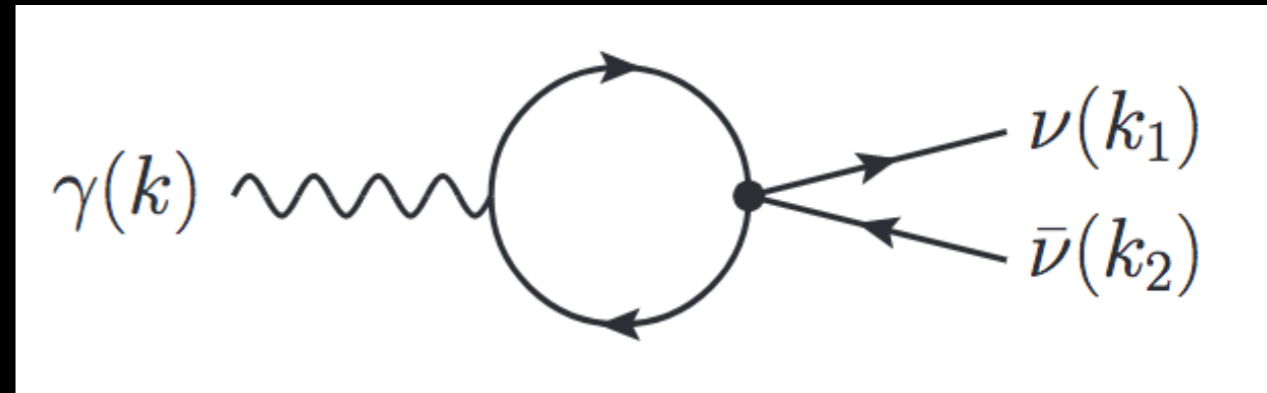


Vinyoles and Vogel, arXiv:1511.01122v2

More generally: Raffelt, Phys.Rept. 198 (1990) 1-113

Plasmon decay with neutrinos

- WE DON'T NEED BSM TO OBSERVE PHOTON DECAY!
- With neutrinos it's the same, but we need a thermal loop (the medium as spectator)



$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

$$\omega^2 - \mathbf{k}^2 = \Pi(\mathbf{k})$$



$$\omega^2|_T = \omega_p^2 \left(1 + \frac{\mathbf{k}^2}{\omega_p^2 + \mathbf{k}^2} \frac{T}{m_e} \right) + \mathbf{k}^2 \quad \text{and} \quad \omega^2|_L = \omega_p^2 \left(1 + 3 \frac{\mathbf{k}^2}{\omega_p^2} \frac{T}{m_e} \right)$$

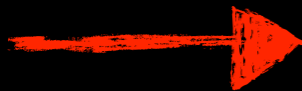
$$|\mathcal{M}_{\gamma \rightarrow \nu \bar{\nu}}|^2 = \frac{C_V^2 G_F^2}{8\pi\alpha} Z_{\mathbf{k}} \Pi_{\mathbf{k}}^2 \epsilon_\mu \epsilon_\nu^* N^{\mu\nu}$$



Renormalizing the coupling...

$$N^{\mu\nu} = 8(k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - k_1 \cdot k_2 g^{\mu\nu} + i\epsilon^{\alpha\mu\beta\nu} k_{1\alpha} k_{2\beta})$$

- In the end



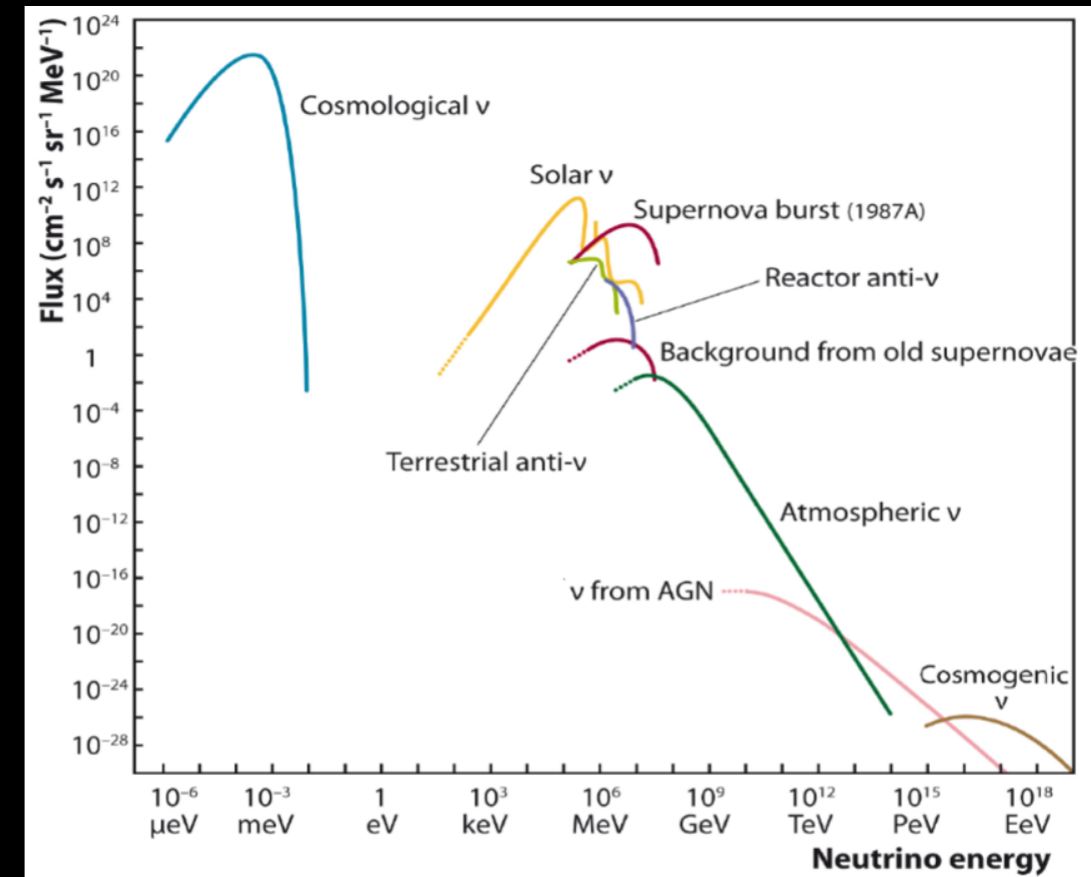
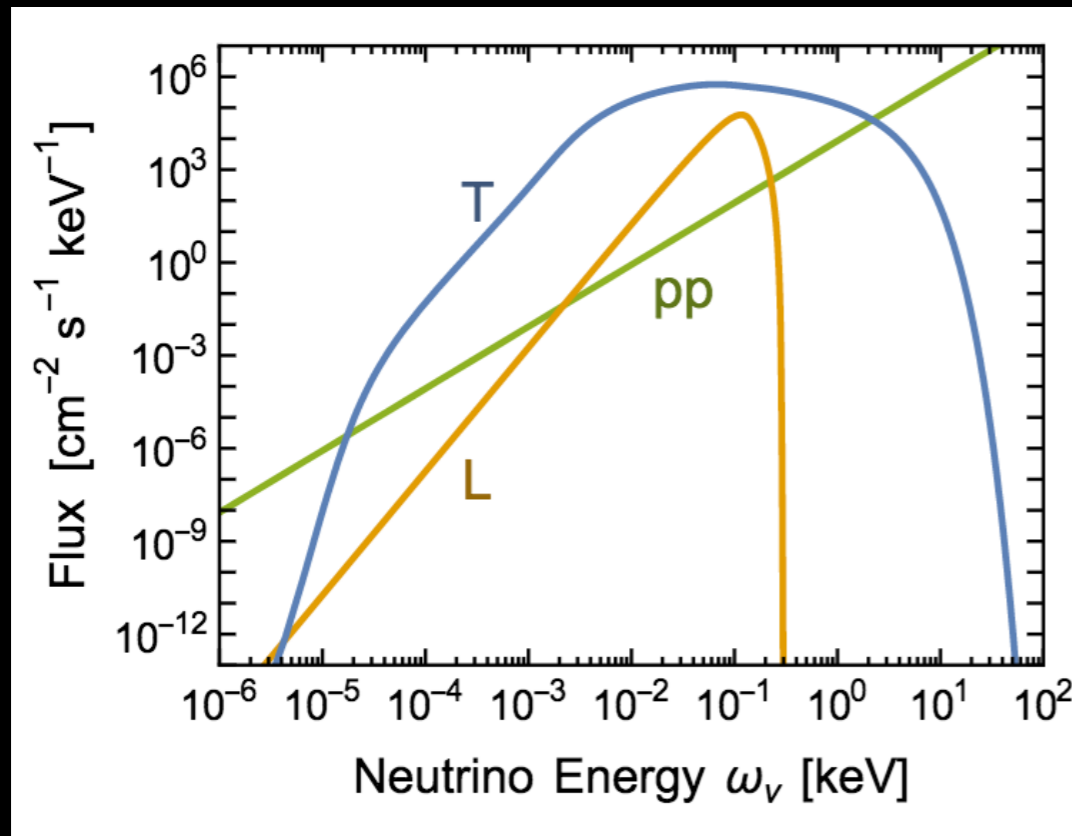
$$\left. \frac{d\dot{n}_\nu}{d\omega_\nu} \right|_L = \int \frac{d^3\mathbf{k}}{V_{\mathbf{k}}} \frac{\Gamma_L g_L(\omega_\nu)}{e^{\omega_p/T} - 1}$$

$$\left. \frac{d\dot{n}_\nu}{d\omega_\nu} \right|_T = \int \frac{d^3\mathbf{k}}{V_{\mathbf{k}}} \frac{2\Gamma_T g_T(\omega_\nu)}{e^{\omega_{\mathbf{k}}/T} - 1}$$

Statistical physics: solar model Saclay+GS98

(a theoretical description of the Sun which match initial conditions and today observations)

Plasmon decay with neutrinos



It seems relevant!

The ABCD processes in general

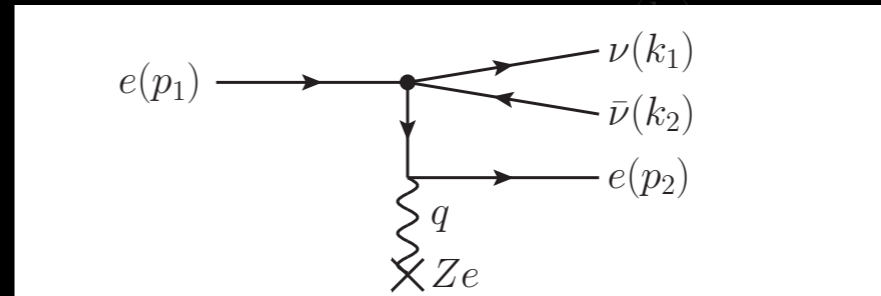
- Write down the term in the Boltzmann equation due to the specific process
- Account for correlation effects
- Do it for the all processes

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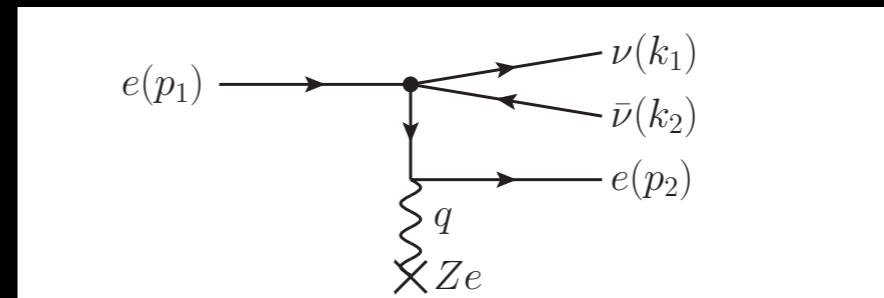
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- Example: bremsstrahlung



$$\dot{n}_\nu = n_Z \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} \frac{d^3\mathbf{p}_2}{(2\pi)^3} \frac{d^3\mathbf{k}_1}{(2\pi)^3} \frac{d^3\mathbf{k}_2}{(2\pi)^3} f_1(1 - f_2) \frac{\sum_{s_1, s_2} |\mathcal{M}|^2}{(2m_e)^2 2\omega_1 2\omega_2} 2\pi \delta(E_1 - E_2 - \omega)$$

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Statistical physics: solar model
(Saclay+GS98 & OP)

Particle physics

Long wavelength
approximation

Bremsstrahlung in terms of structure function

Structure function (encoding medium properties)


$$\begin{aligned} \mathcal{S}(\omega) &= \frac{(4\pi)^2}{(2m_e)^2} \frac{1}{n_e} \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} \frac{d^3\mathbf{p}_2}{(2\pi)^3} f_1(1-f_2) \frac{1}{\mathbf{q}^2} 2\pi\delta(E_1 - E_2 - \omega) \\ \frac{d\dot{n}_\nu}{d\omega_\nu} &= n_Z n_e \frac{8 Z^2 \alpha^2}{3} \left(\frac{G_F}{\sqrt{2}} \right)^2 \frac{1}{3\pi^4} \int_{\omega_\nu}^{\infty} d\omega \mathcal{S}(\omega) \frac{\omega_\nu^2 (\omega - \omega_\nu)^2}{\omega^4} \\ &\quad \times \left[C_V^2 (3\omega^2 - 2\omega\omega_\nu + 2\omega_\nu^2) + 2C_A^2 (3\omega^2 - 5\omega\omega_\nu + 5\omega_\nu^2) \right] \\ \frac{d\dot{n}_\gamma}{d\omega} &= n_Z n_e \frac{8 Z^2 \alpha^2}{3} \frac{\alpha}{\pi} \frac{\mathcal{S}(\omega)}{\omega} \\ \frac{d\dot{n}_\nu}{d\omega_\nu} &= \frac{G_F^2}{6\pi^3 \alpha} \int_{\omega_\nu}^{\infty} d\omega \left(\frac{d\dot{n}_\gamma}{d\omega} \right) \frac{\omega_\nu^2 (\omega - \omega_\nu)^2}{\omega^3} \\ &\quad \times \left[C_V^2 (3\omega^2 - 2\omega\omega_\nu + 2\omega_\nu^2) + 2C_A^2 (3\omega^2 - 5\omega\omega_\nu + 5\omega_\nu^2) \right] \end{aligned}$$

Bremsstrahlung in terms of structure function

Structure function (encoding medium properties)

ν flux

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photon flux

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ν flux in terms of the photon flux

Atomic processes

- A-processes are difficult (lot of atomic physics)
- But long wavelength approximation+detailed balance principle
- We can use photon opacities!
- We can take advantage from stars' axion and photon production calculation (axial current and vector current)

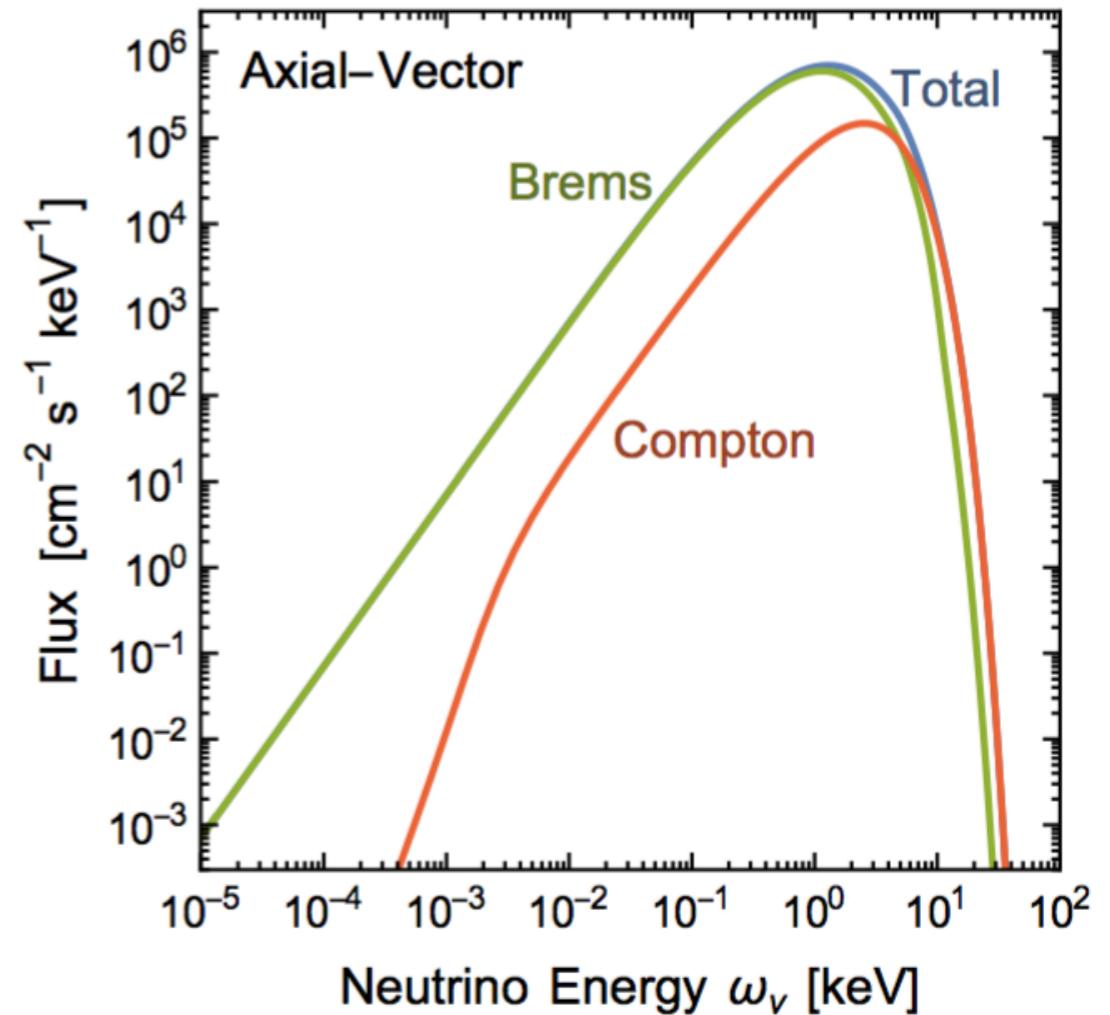
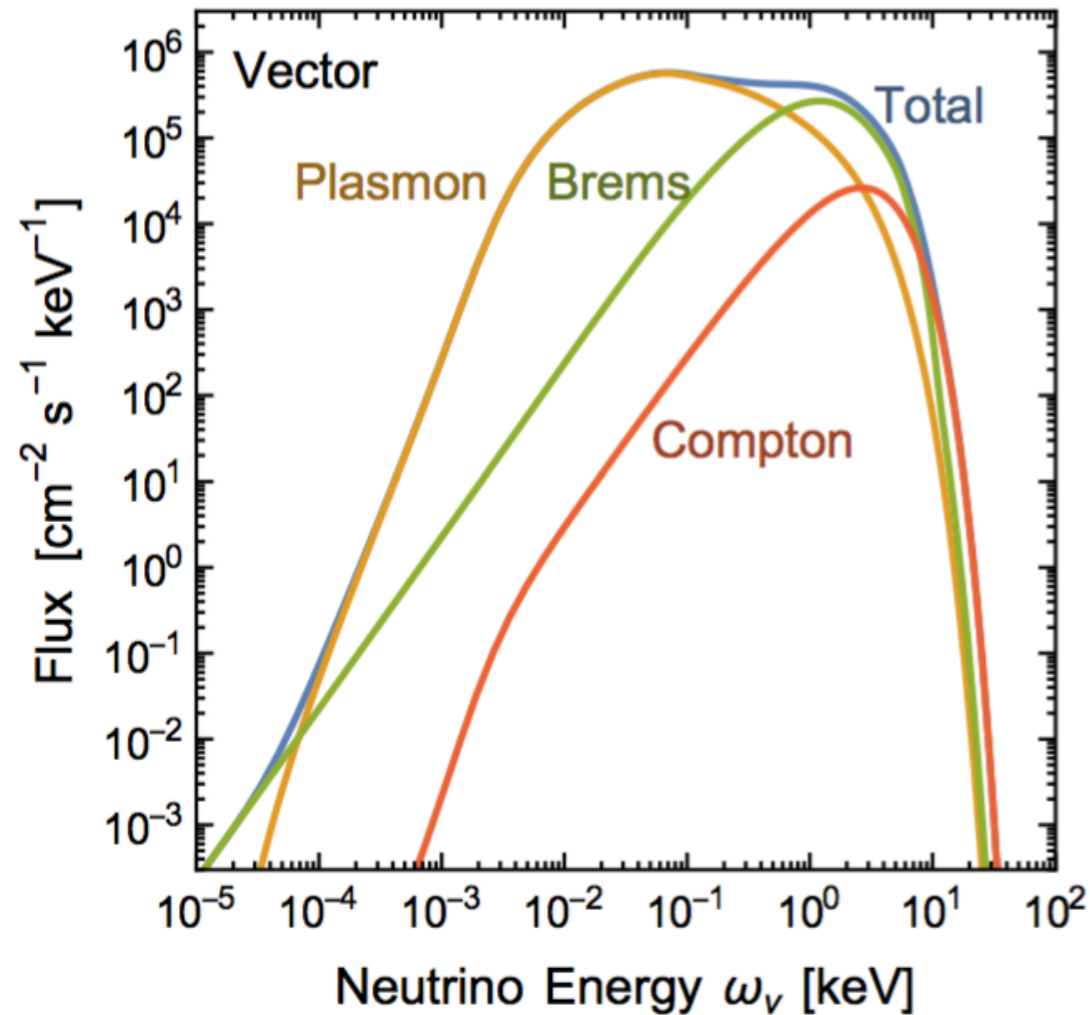
The Opacity Project - The Iron Project

The names Opacity Project (OP) and Iron Project (OP) refer to an international collaboration that was formed in 1984 to calculate the extensive atomic data required to estimate stellar envelope opacities and to compute Rosseland mean opacities and other related quantities. It

Neutrino emission rate as a
function of photon
absorption rate

see also J.Redondo,
arXiv:1310.0823, same
approach but for axions

ABCD processes



to be multiplied by C_V^2 and C_A^2

Total flux on Earth - with oscillation

Flux of mass eigenstates, no matter effect for keV neutrinos

Matter potential $\Delta V = \sqrt{2}G_F n_e = 7.6 \times 10^{-12} \text{ eV}$

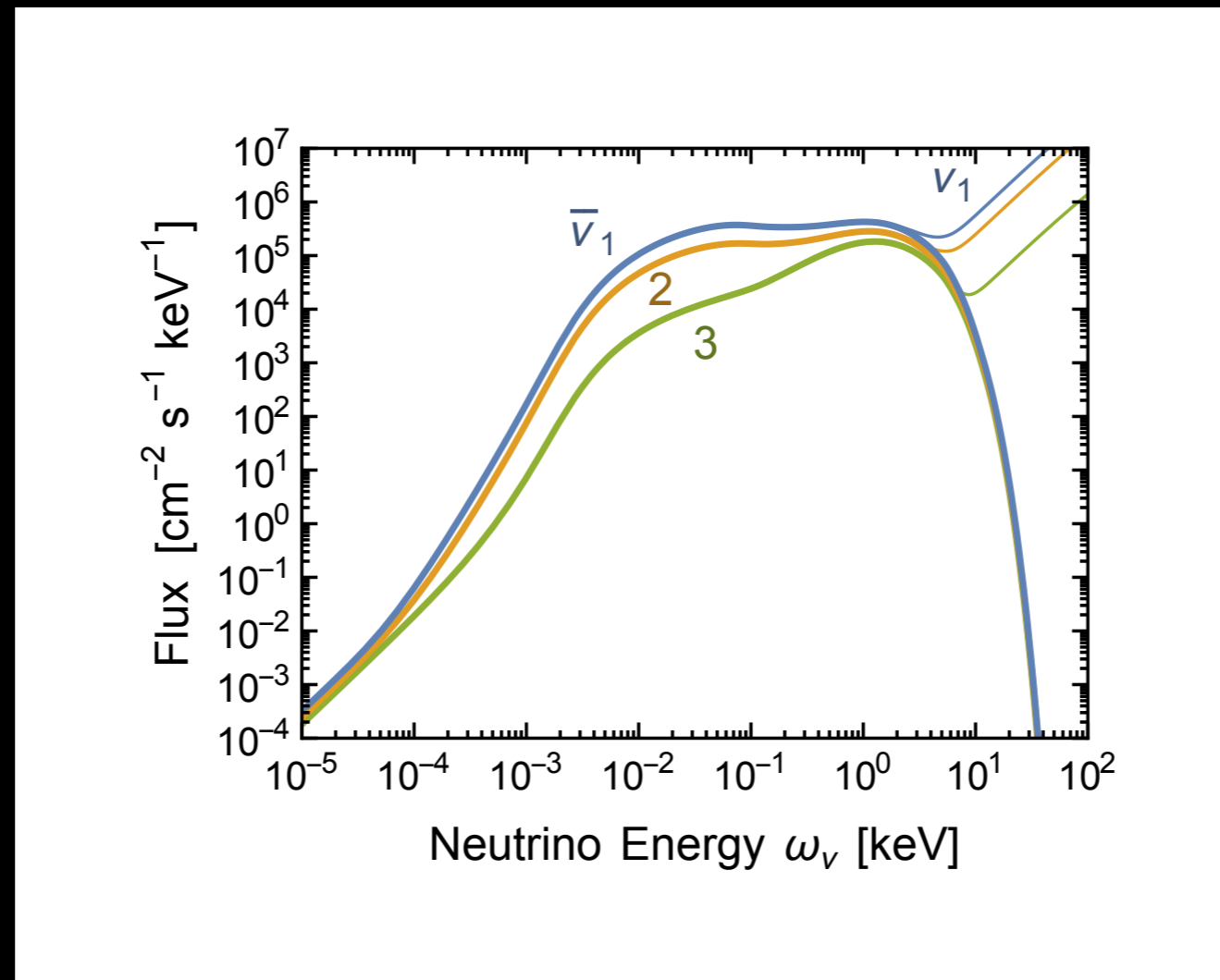
Solar

$$\omega_{\text{osc}} = \Delta m^2 / 2E = 3.8 \times 10^{-8} \text{ eV} / E_{\text{keV}}$$

$$E_{\text{keV}} = E / \text{keV}$$

Atmospheric

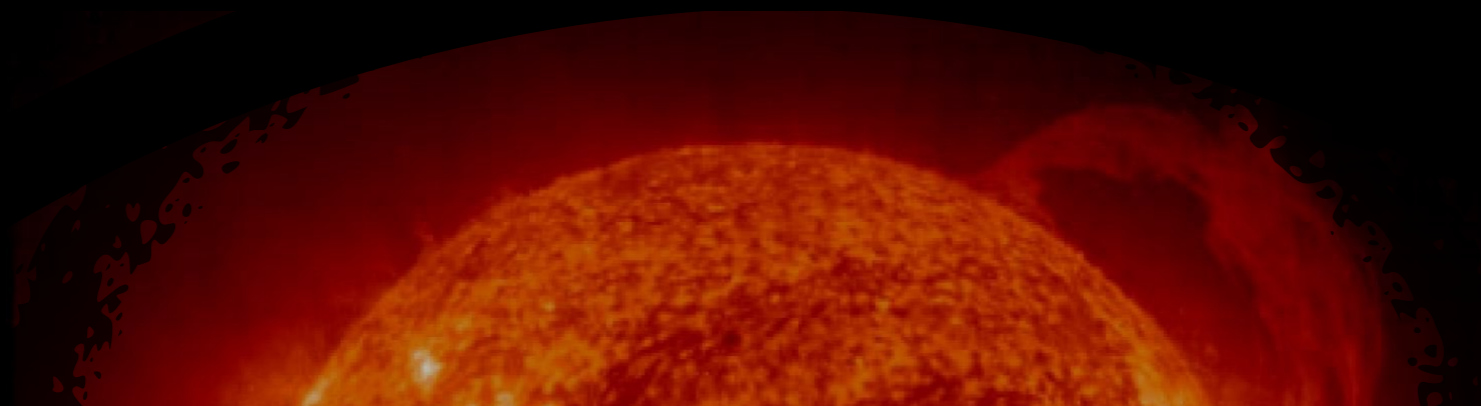
$$\omega_{\text{osc}} = 1.25 \times 10^{-3} \text{ eV} / E_{\text{keV}}$$



to be seen in a detector

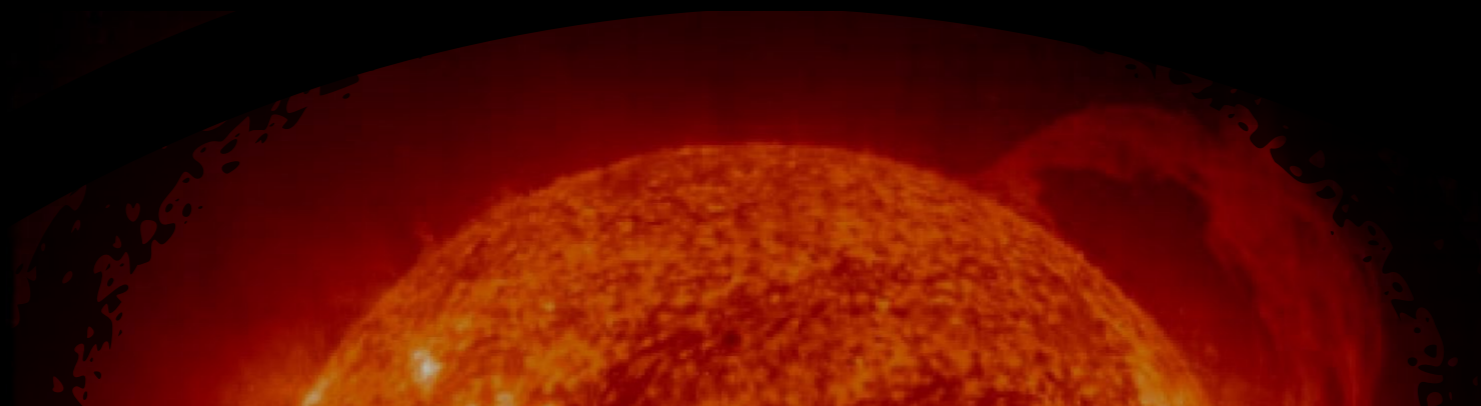
Summary

- For energies smaller than few keV, the dominant source is the Sun via thermal processes (ABCD)



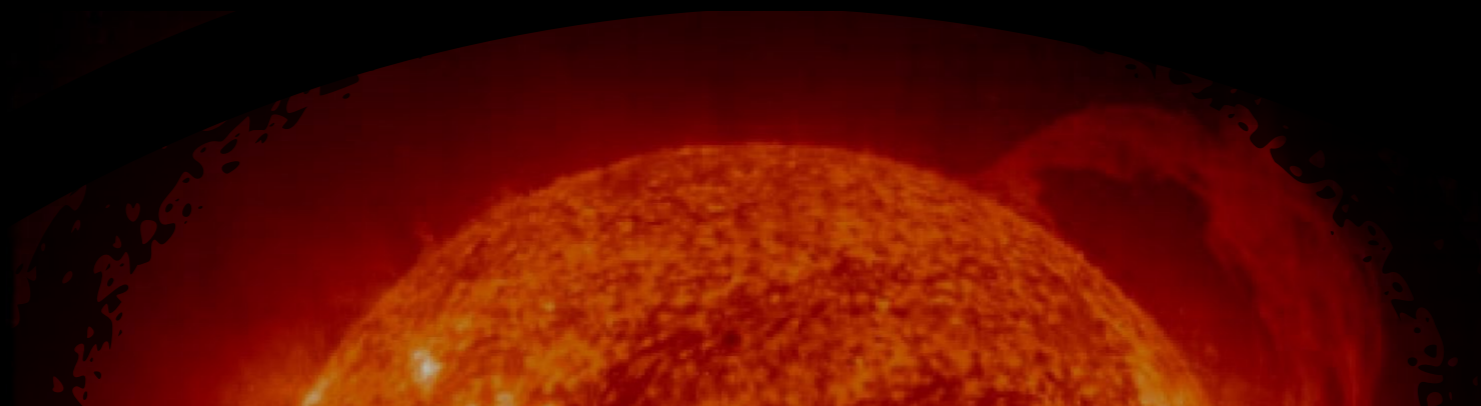
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- A new window on solar physics



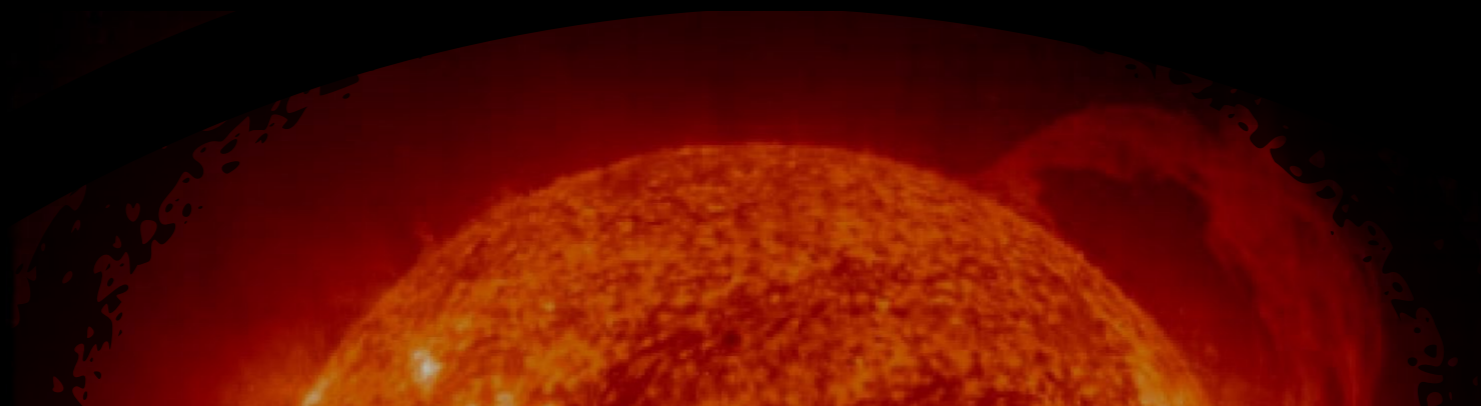
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Thank you!

Backup slides

Thermal physics: a lesson on star cooling

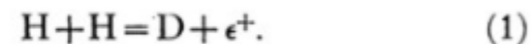
Weakly interactive, low mass particles (like **neutrinos** or axions) contribute to the energy loss (or transfer) in stars

Thermal physics: a lesson on star cooling

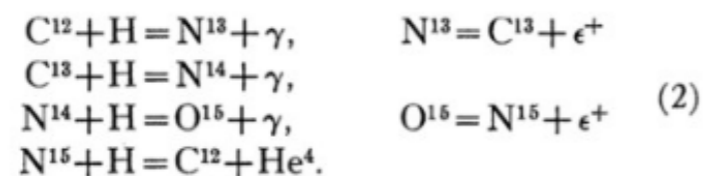
Weakly interactive, low mass particles (like **neutrinos** or axions) contribute to the energy loss (or transfer) in stars

Quite intuitive: inside a star, you have many interactions that produce particles. Either they interact strongly enough (affecting energy transport) or they don't (energy loss)

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*



The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

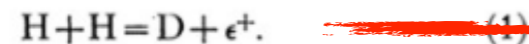


Thermal physics: a lesson on star cooling

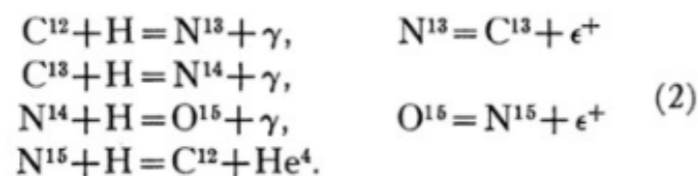
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!!!

Fun fact: first papers (e.g. by Bethe) on stars evolution didn't mention neutrinos at all

Thermal physics: a lesson on star cooling

- Frieman et al. 1987, nice quantitative analysis of what we have said
- Assuming that a new energy loss induce a homology transformation from a configuration to the other
- Long story short: the star contracts, surface luminosity increases, as well as central temperature



$$\frac{\delta R}{R} = \frac{-2\delta_x}{2\nu + 5}, \quad \frac{\delta L}{L} = \frac{\delta_x}{2\nu + 5}, \quad \frac{\delta T}{T} = \frac{2\delta_x}{2\nu + 5}$$

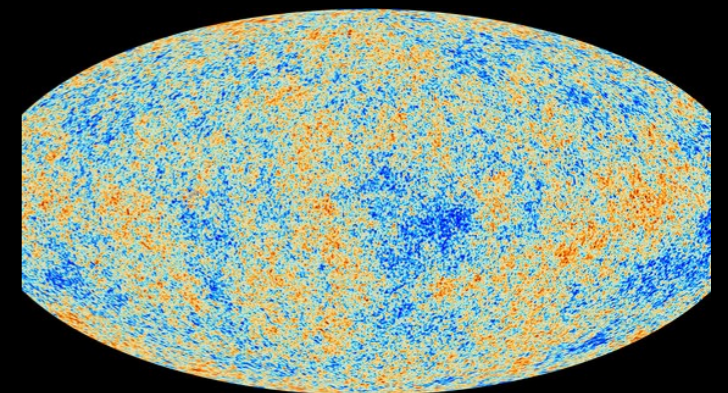
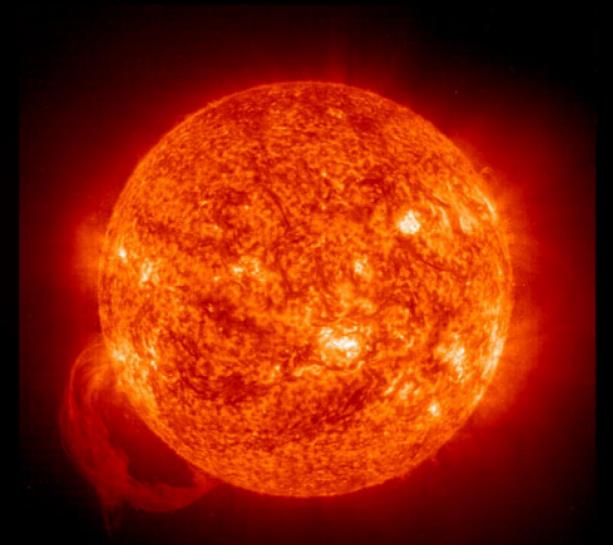
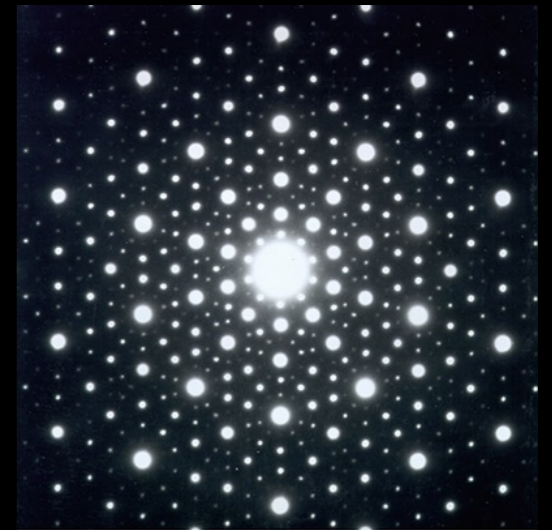
Why is it interesting?

While in other branches of physics (say, solid state physics) we are used to media, particle physics is usually studied in vacuum.

BUT

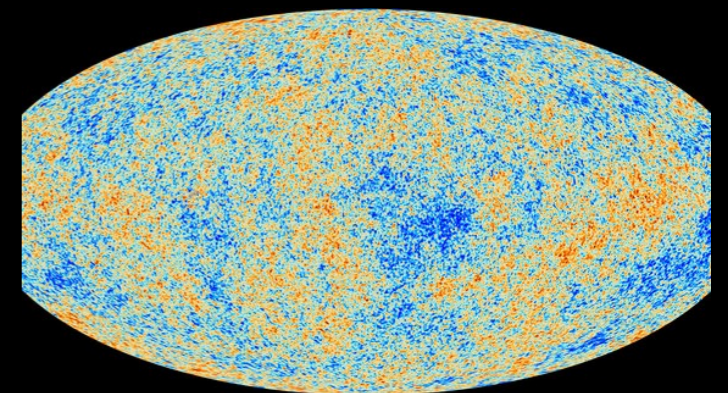
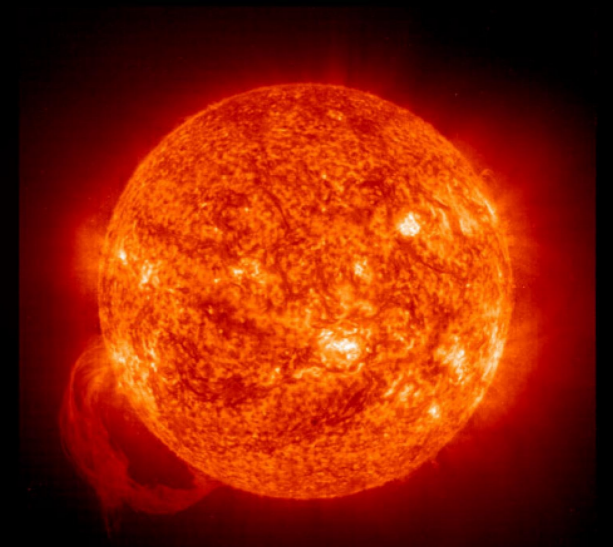
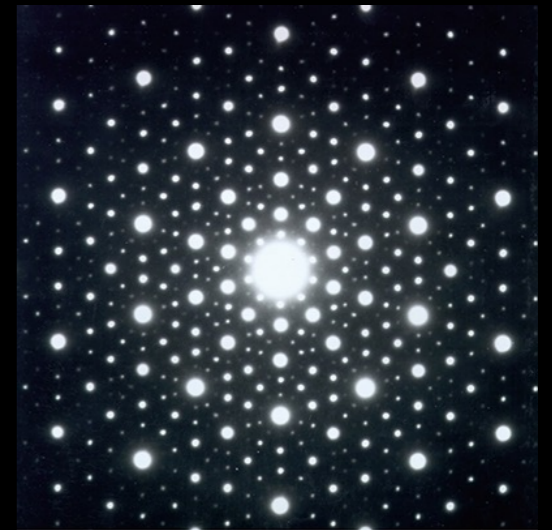
many particle backgrounds—> fundamental physics!
Example? MSW effect and neutrino masses.

Particles in stars and in the Early Universe propagate as light in crystals, and their interactions are with a complicated environment.



When is it interesting?

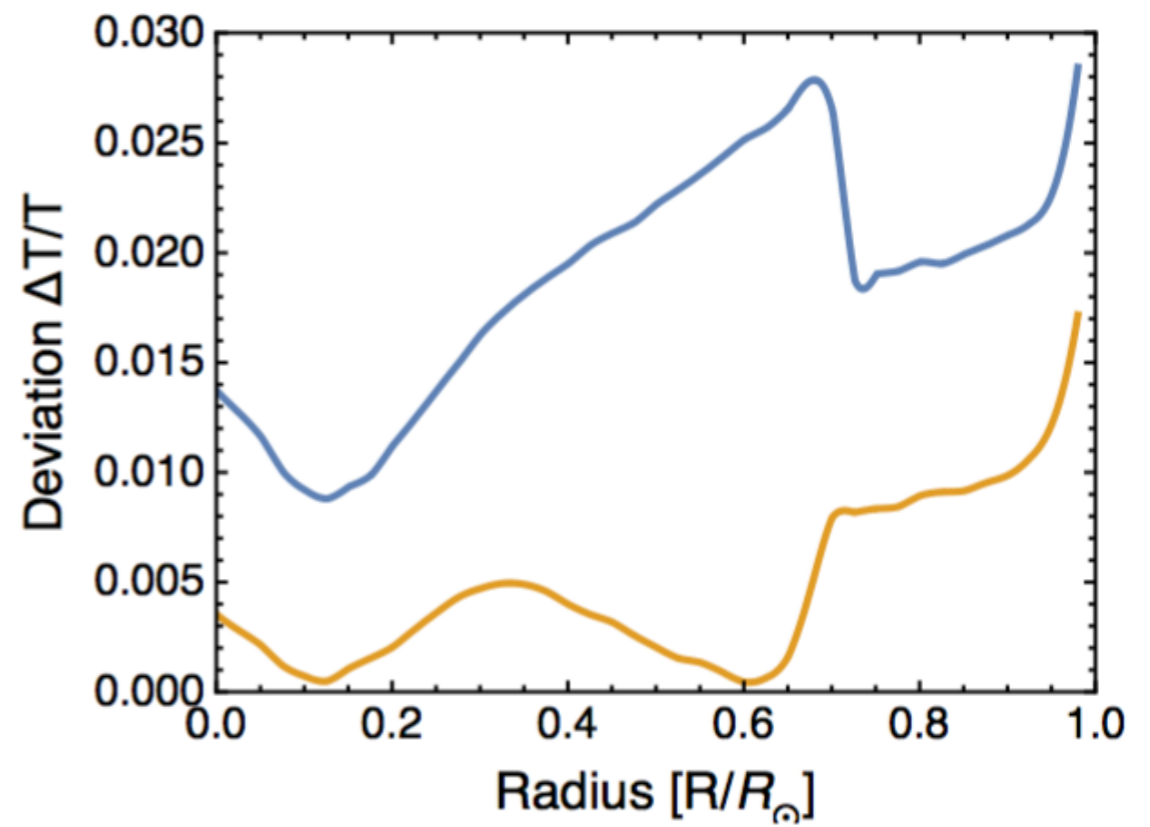
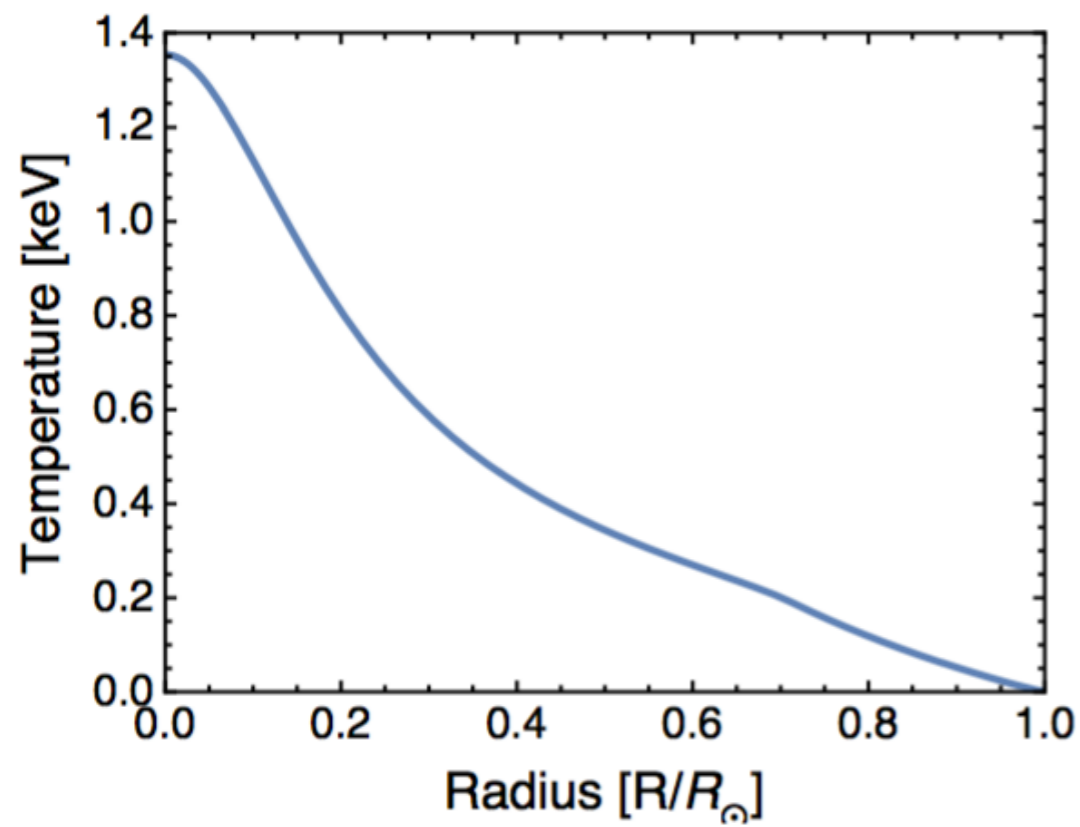
A (quasi) crystal, our domestic star and a map of the universe. Enough said.



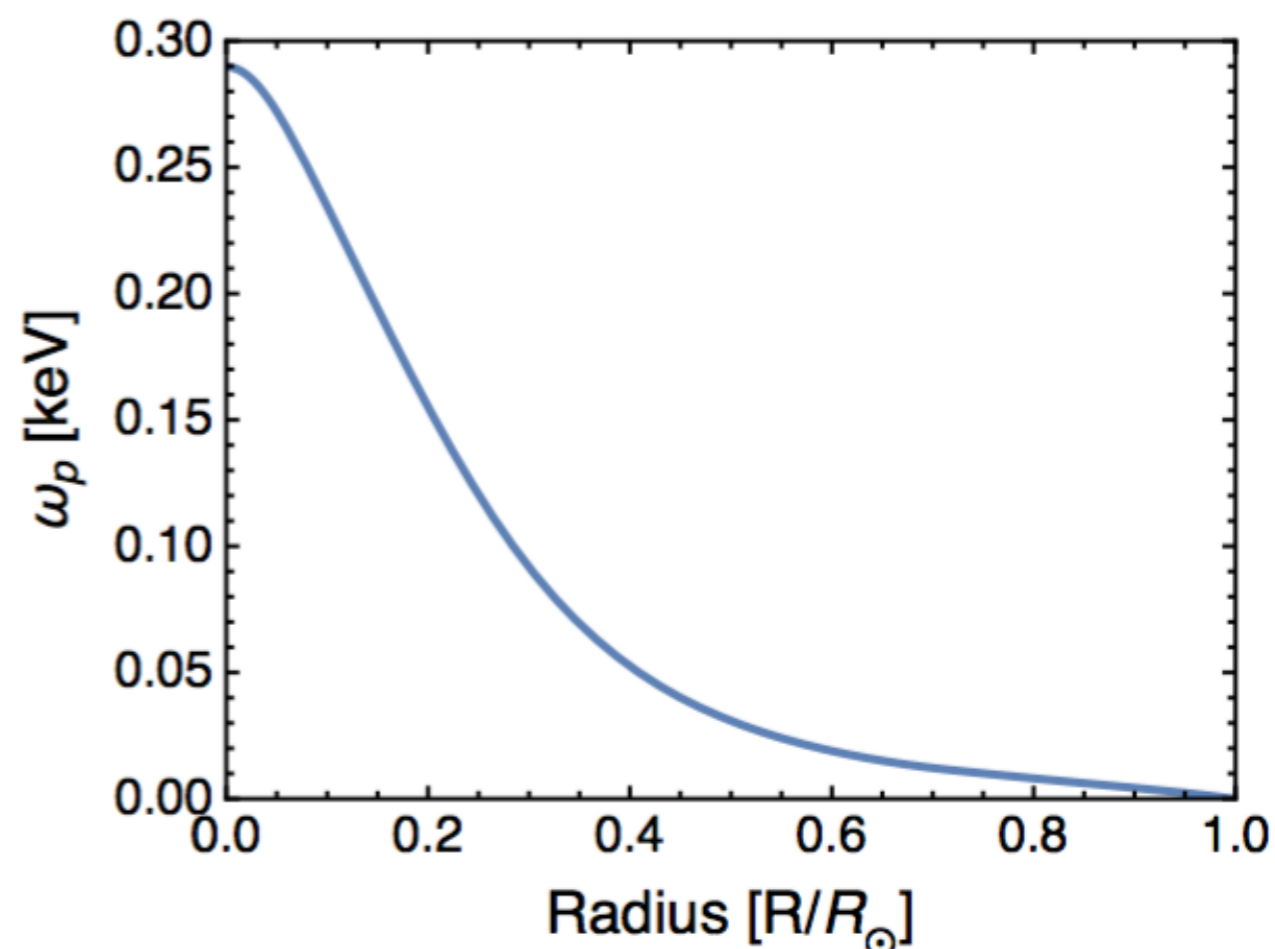
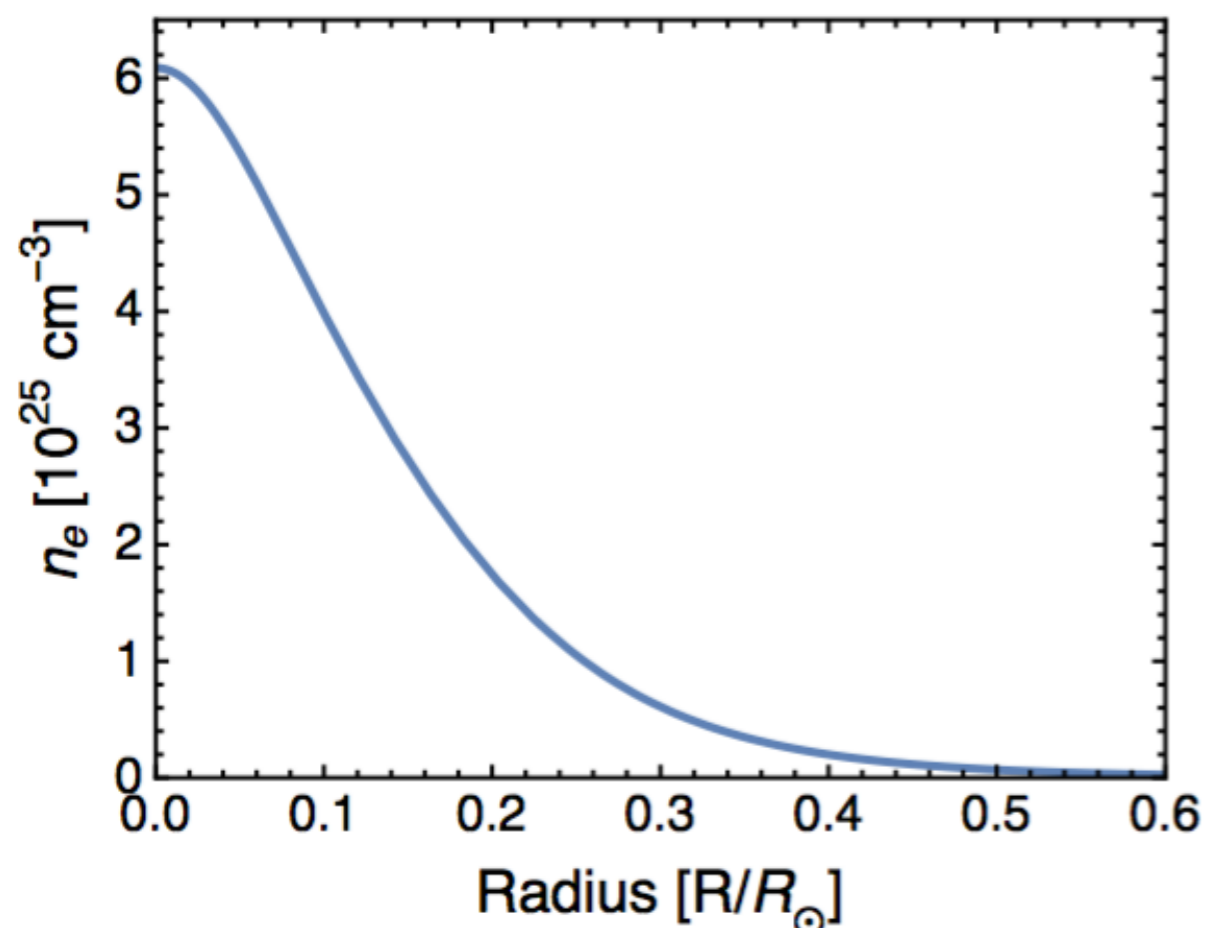
Solar model

- The Sun is a sphere of gas where the gravitational compression is balanced by the pressure gradient. Nuclei can overcome the nuclear barrier, so that fusion is possible.
- The energy transport is driven by radiation and convection. The inner part of the Sun (98% in mass) is radiative, so we need the opacity as a function of temperature, density and composition. In the outer part of the Sun, convection dominates the energy transport; this is modeled through a mixing length theory.
- The Sun energy is produced by fusing protons into ^4He via the pp-chain and the CN cycle.
- Boundary conditions include the initial mass of the Sun and today's radius, the luminosity, age and photospheric composition, related to the initial abundances.

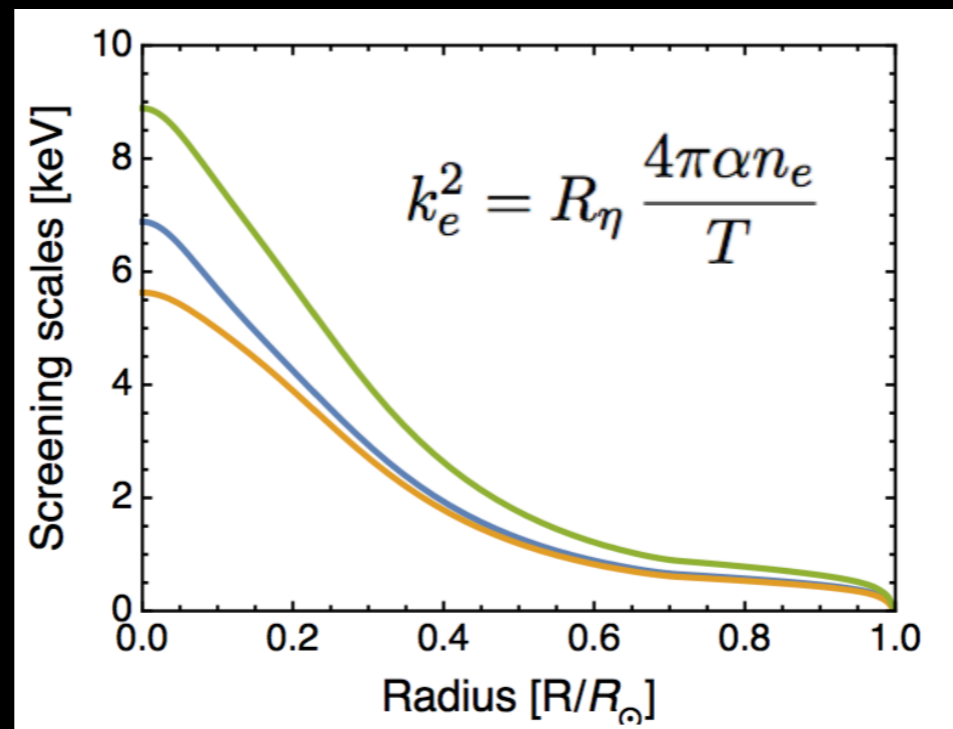
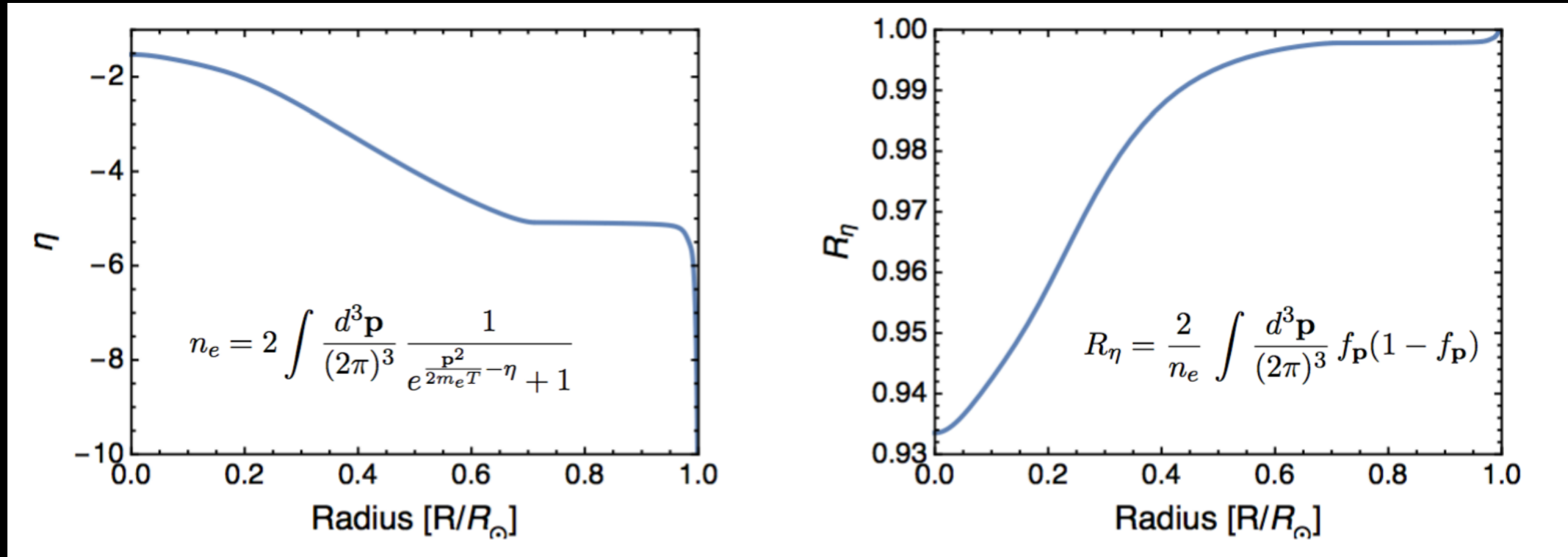
Temperature profile



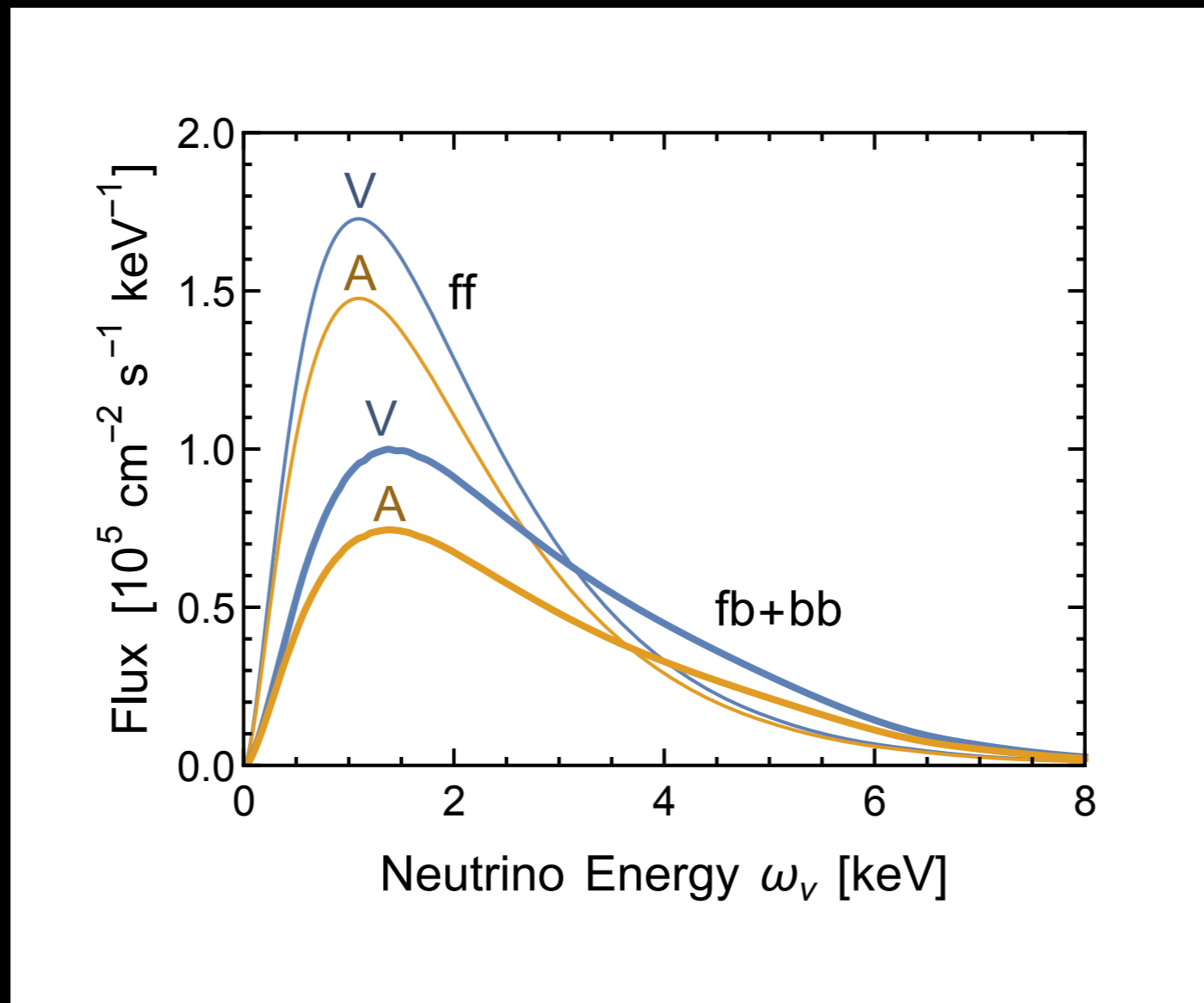
Electron density and plasma frequency profile



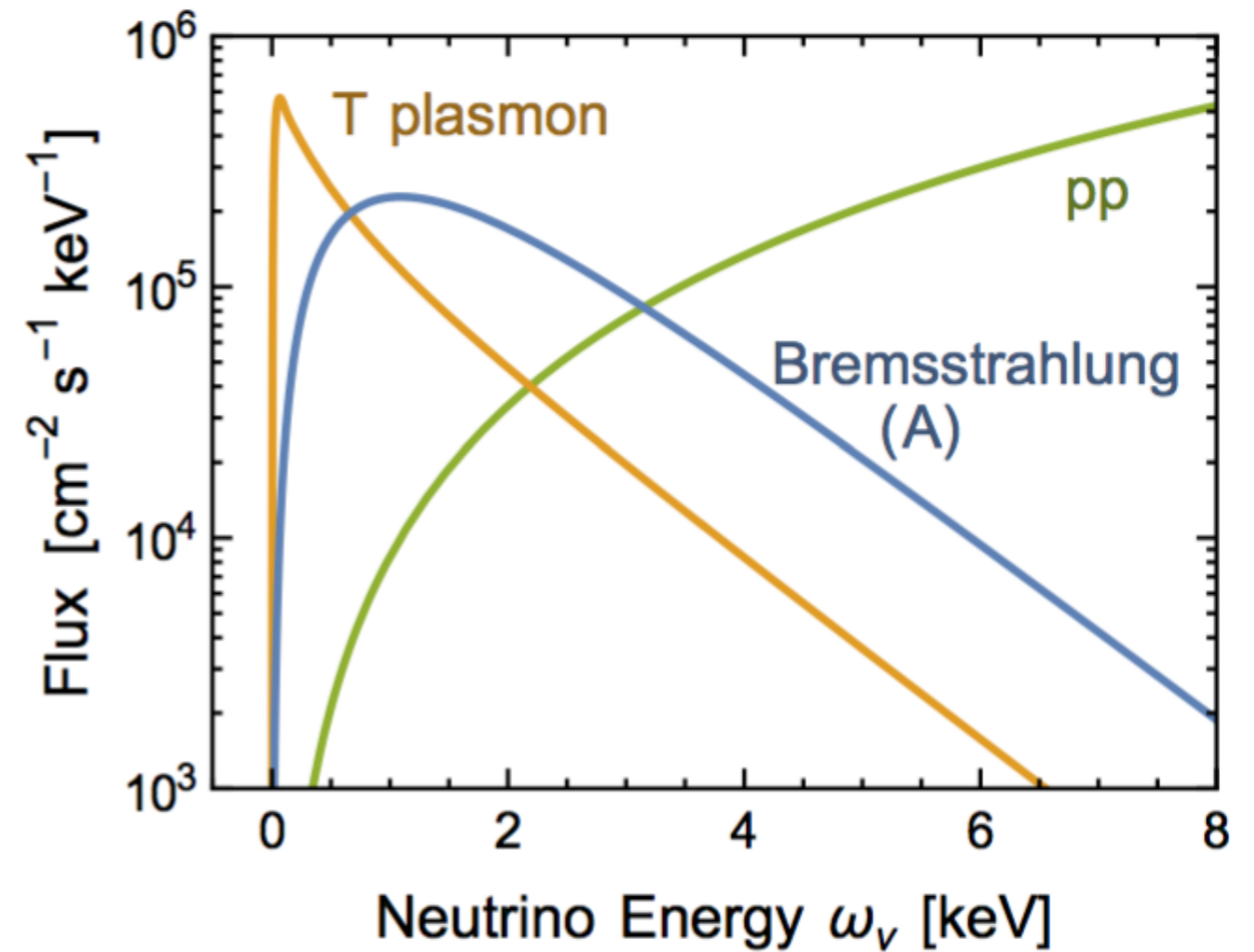
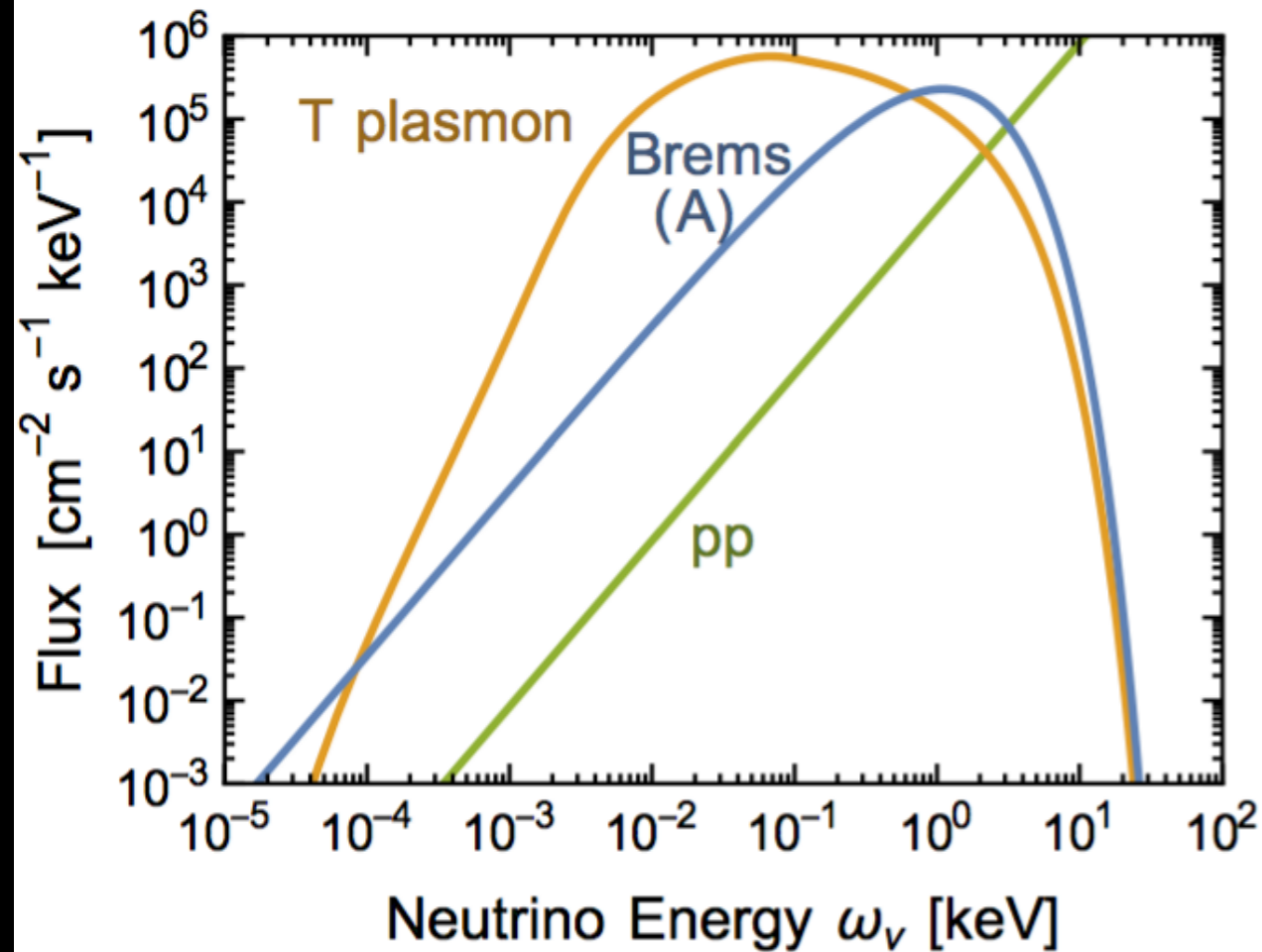
Degeneracy



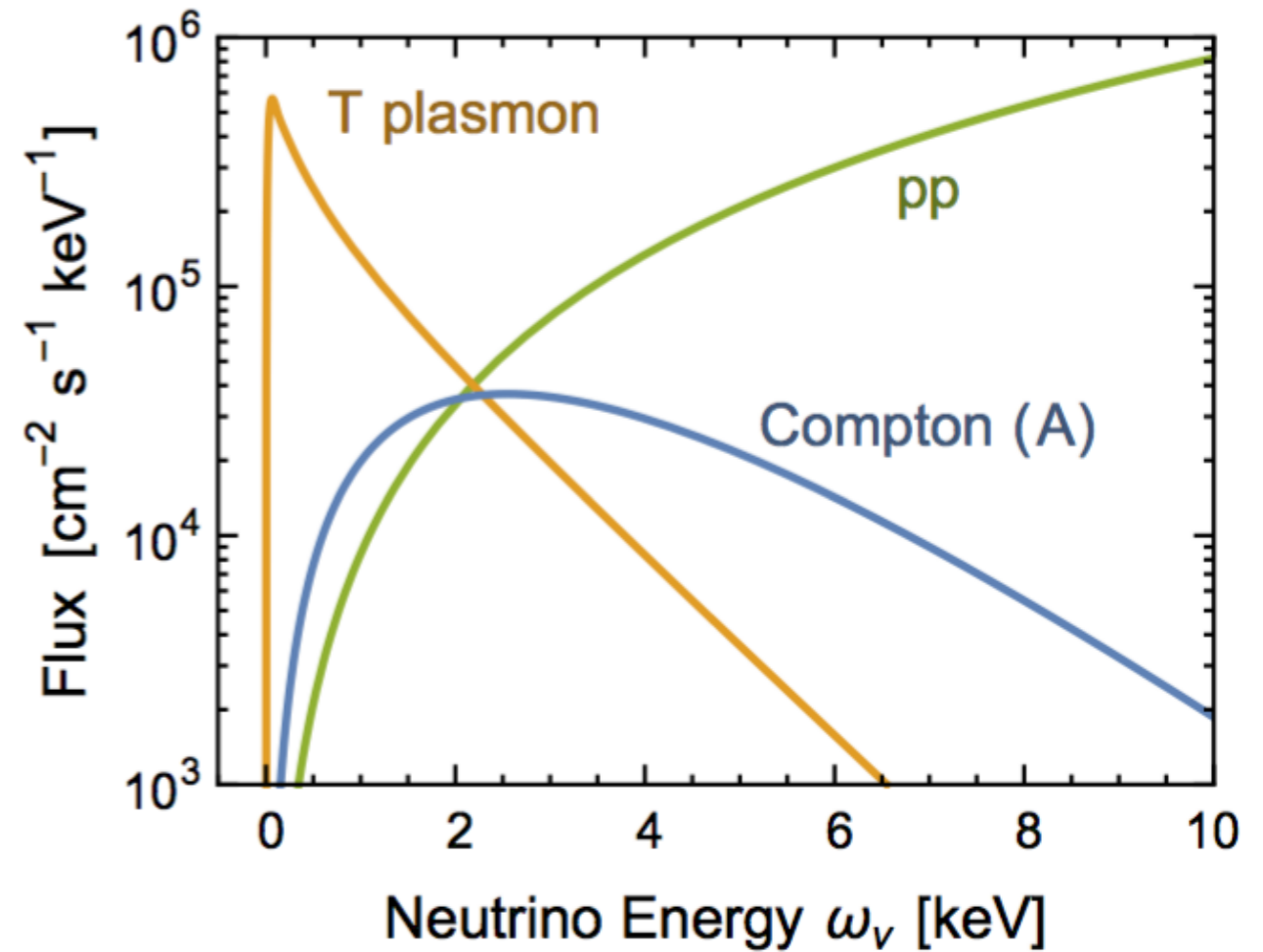
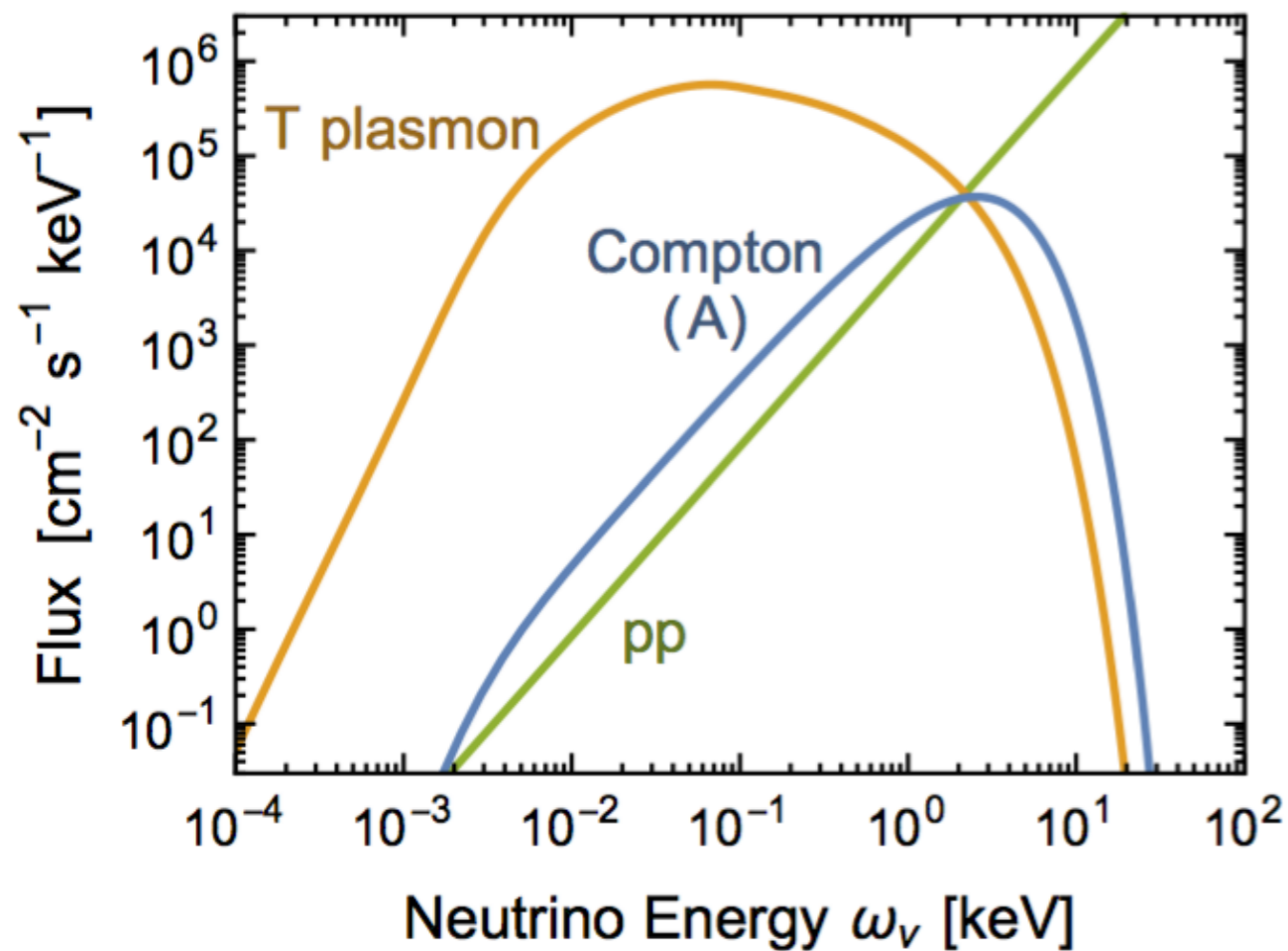
Atomic vs Bremsstrahlung (free-free) transitions



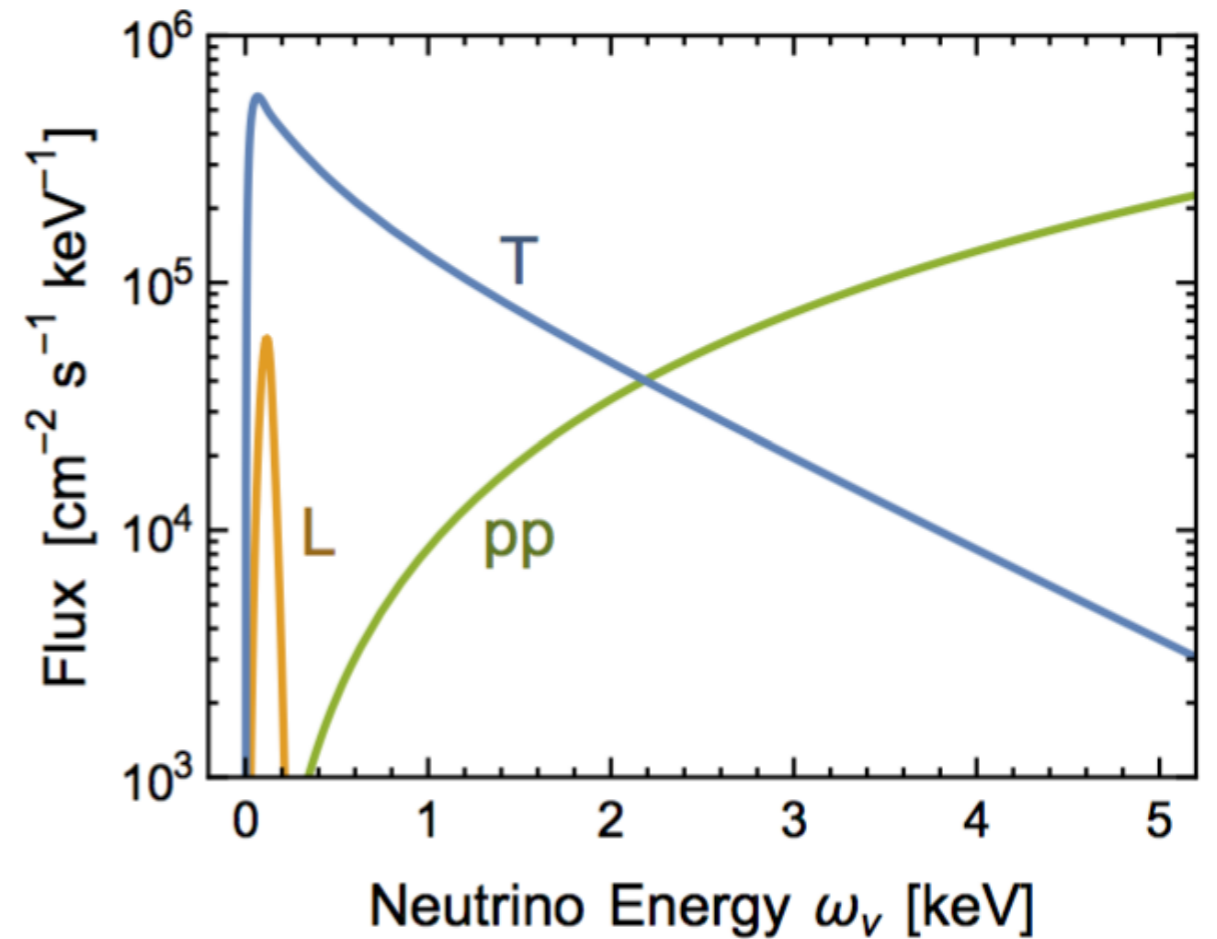
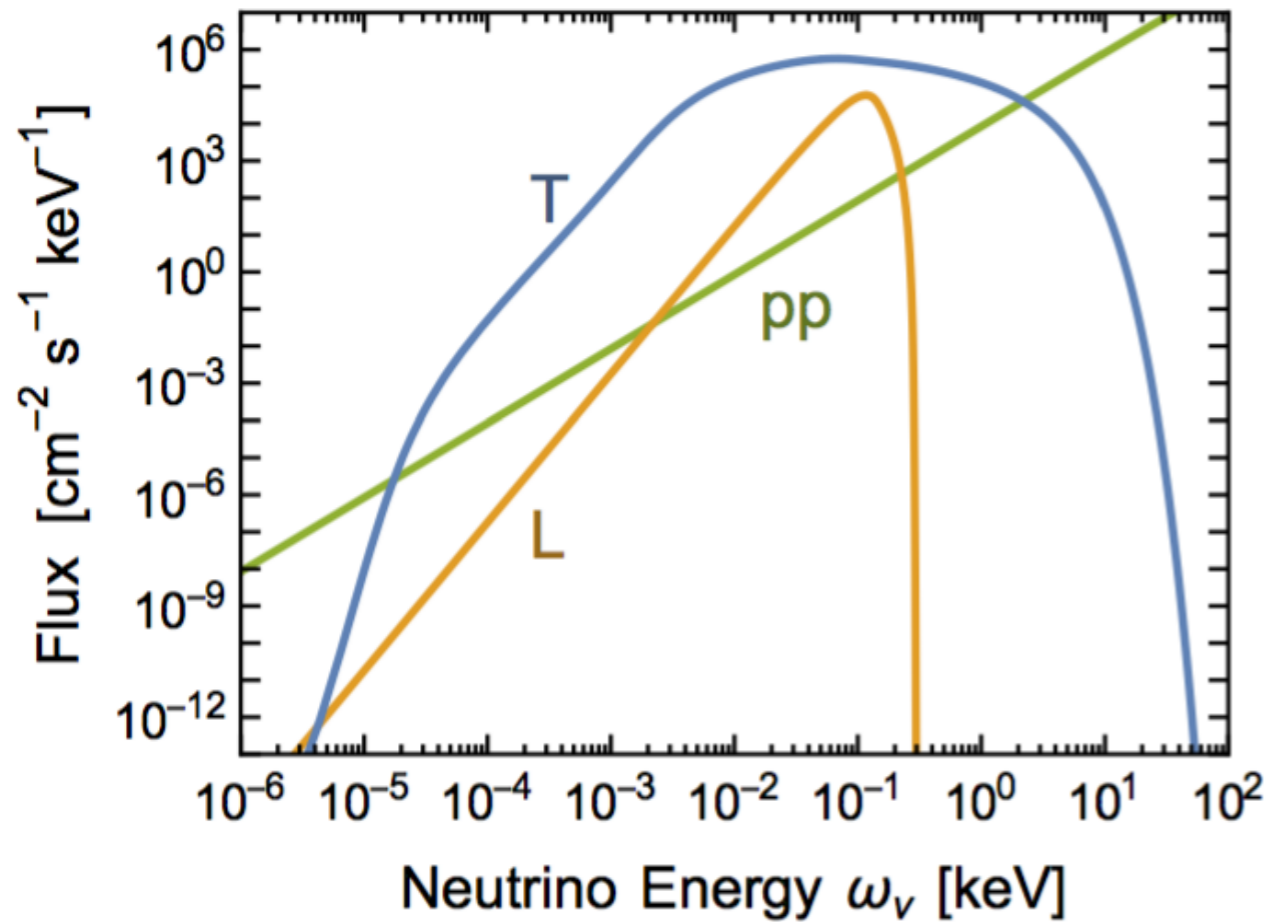
Bremsstrahlung process flux



Compton process flux

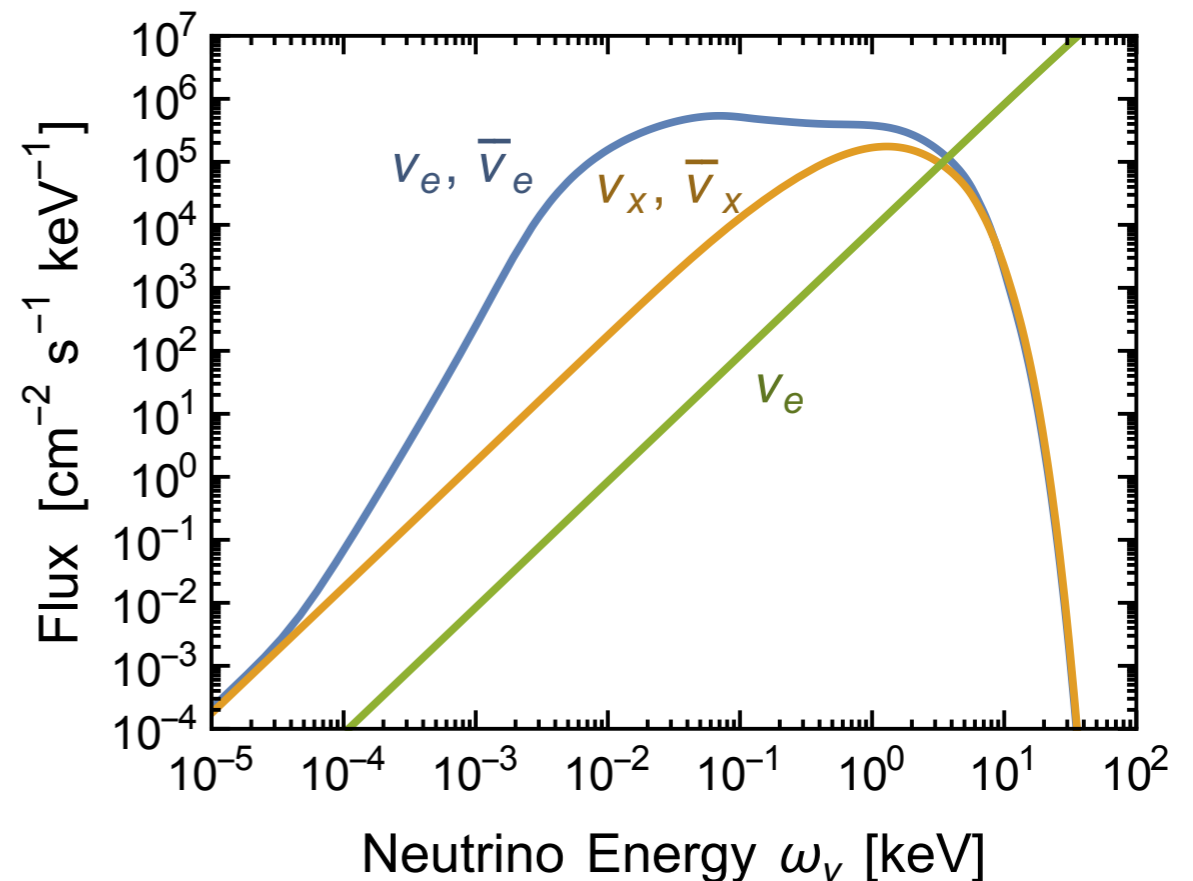


Plasmon decay process flux




Total flux on Earth - no oscillation

- Electron anti(neutrinos) produced by vector current
- All flavor produced by axial current
- electron neutrinos from pp



Look like quite standard stuff: previous attempts?



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The very low energy solar flux of electron and heavy-flavor neutrinos and antineutrinos

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Abstract

We calculate the thermal flux of low-energy solar neutrinos and antineutrinos of all flavors arising from a variety of neutrino pair processes: Compton production (including plasmon-pole diagrams), neutral current decay of thermally populated nuclear states, plasmon decay, and electron transitions from free to atomic bound states. The resulting flux density per flavor is significant (10^8 – 10^9 /cm²/sec/MeV) below ~ 5 keV, and the distributions fill much of the valley between the high-energy edge of the cosmic background neutrino spectrum and the low energy tails of the pp-chain electron neutrino and terrestrial electron antineutrino spectra. Thermal neutrinos carry information on the solar core temperature distribution and on heavy flavor neutrino masses for m_{ν_μ} or $m_{\nu_\tau} \gtrsim 1$ keV. The detection of these neutrinos is a daunting but interesting challenge. © 2000 Elsevier Science B.V. All rights reserved.

arXiv:nucl-th/0006055

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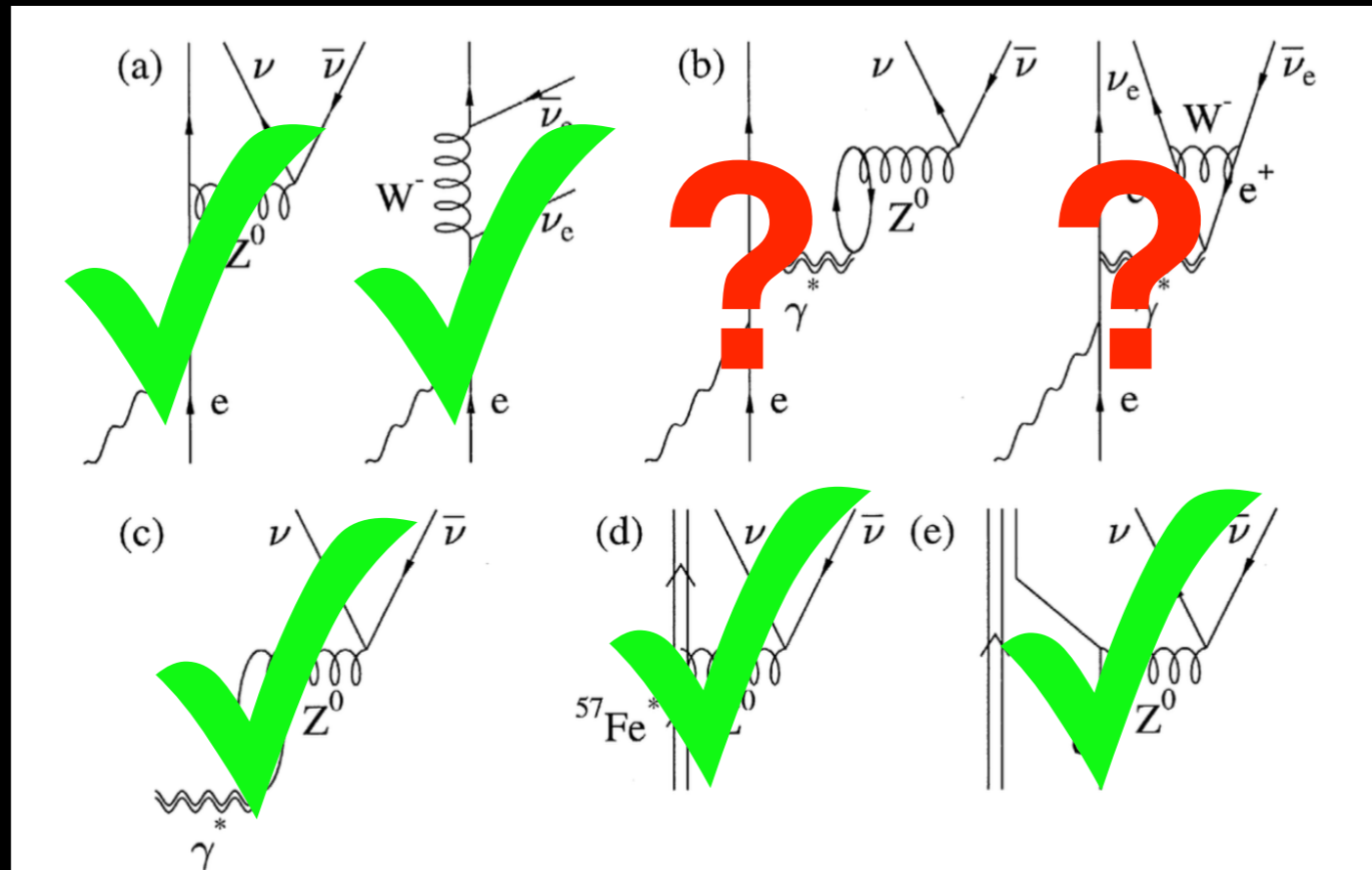


Fig.1. Representative diagrams for the various thermal neutrino pair processes considered here: a) Compton process; b) plasmon pole contribution to the Compton process; c) transverse plasmon decay; d) nuclear Z^0 emission; and e) pair production in free-bound atomic transitions.

+ something is missing