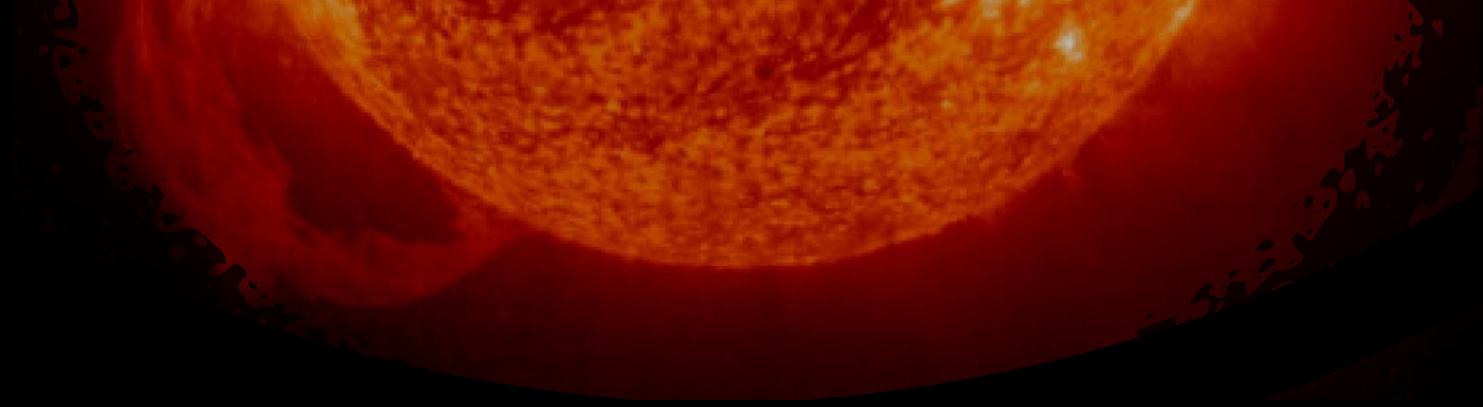

From plasmon decay to star cooling and beyond!

Particle Physics School Colloquium
April 26, 2018

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Max Planck Institute for Physics, Munich

elusives
neutrinos, dark matter & dark energy physics

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

Today’s topic: ~neutrinos

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Wait, wasn’t it stars?

Outline: three tracks

Star cooling

- How does a star cool?
- How can stars be particle physics laboratories?

Introduction to the GUNS

- What is the grand unified neutrino spectrum?
- What's missing in the GUNS?

Physics in a nonzero temperature environment

- What is the thermal flux from the Sun?
- How do we calculate it?

Conclusions

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

A LESSON ON STAR COOLING

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

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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.*

$$H+H=D+\epsilon^{+}. \qquad (1)$$

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

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^{+} \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^{+} \\ N^{15}+H=C^{12}+He^{4}. & \end{array} \qquad (2)$$

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

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

PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 36, NUMBER 8 15 OCTOBER 1987

Axions and stars

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Savas Dimopoulos

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(Received 24 February 1987; revised manuscript received 29 June 1987)

The emission of light, noninteracting particles, such as axions and Majorons, modifies the structure and evolution of stars. We show that the main effects of such an energy loss are to raise the central temperature and luminosity of stars and to reduce their lifetimes. We clarify previous discussions of stellar axion bounds by directly relating the effects of axions to observable stellar parameters. The concordance of the standard model of the Sun with observations yields a self-consistent bound on the coupling of light pseudoscalars to electrons: $g_{\phi e} < 5.4 \times 10^{-11}$. This corresponds to a lower limit on the Peccei-Quinn scale, $(F/2X_e') \geq 10^7$ GeV, comparable to the usually quoted solar bound. The lifetime of helium-burning stars can be used to place a very stringent and *confident* bound on the axion scale, $(F/2X_e') \geq 5.2 \times 10^8$ GeV, corresponding to $g_{\phi e} < 9.3 \times 10^{-13}$. We also discuss the consequences of axion emission for the solar-neutrino problem, for the ages of globular clusters, and for terrestrial solar axion detectors. Since the axion luminosity scales as a lower power of temperature than the nuclear-energy-generation rate, axion emission has a stronger influence on cool stars. We discuss the resultant changes in the mass-luminosity relation for low-mass stars and the effects on the low-mass cutoff for main-sequence stars.

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

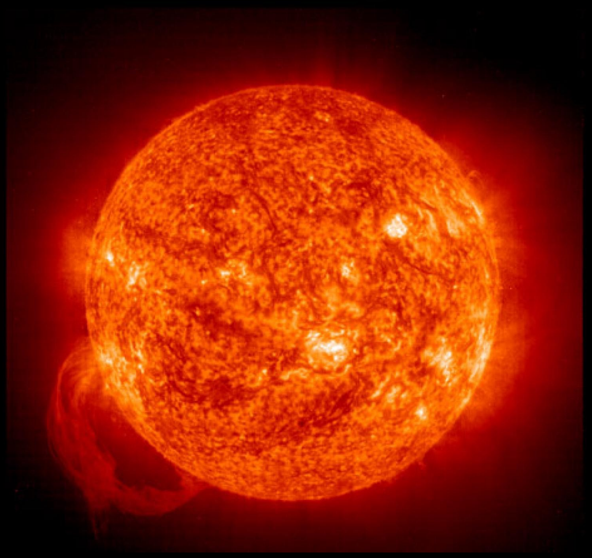
WHY IS IT INTERESTING?

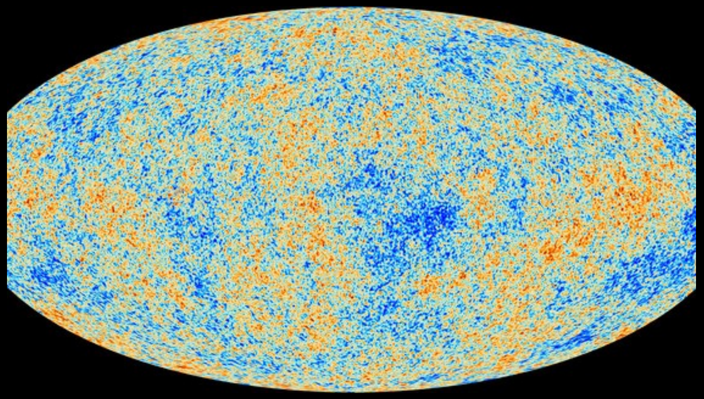
While in other branches of physics (say, solid state physics) we are used to media, particle physics is usually studied in vacuum.

BUT

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

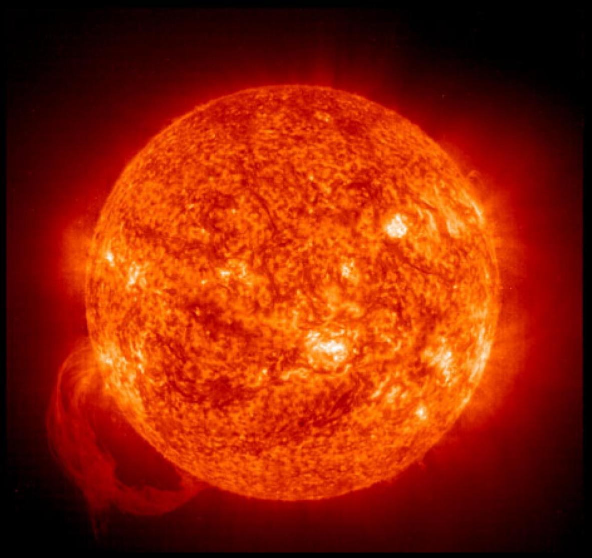
Particles in stars and in the Early Universe propagate as light in crystals, and their interactions are with a complicated environment.

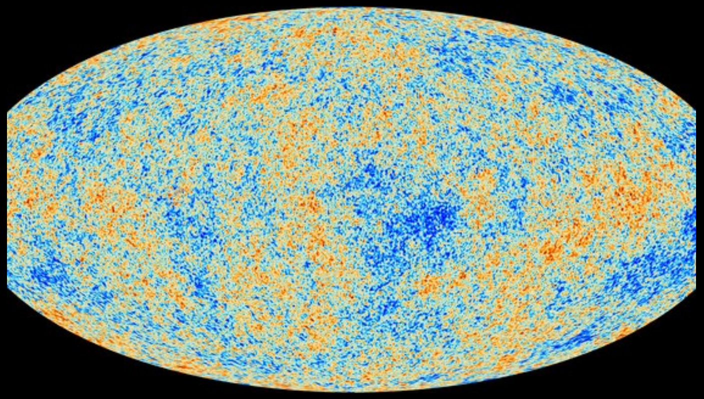




WHEN IS IT INTERESTING?

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

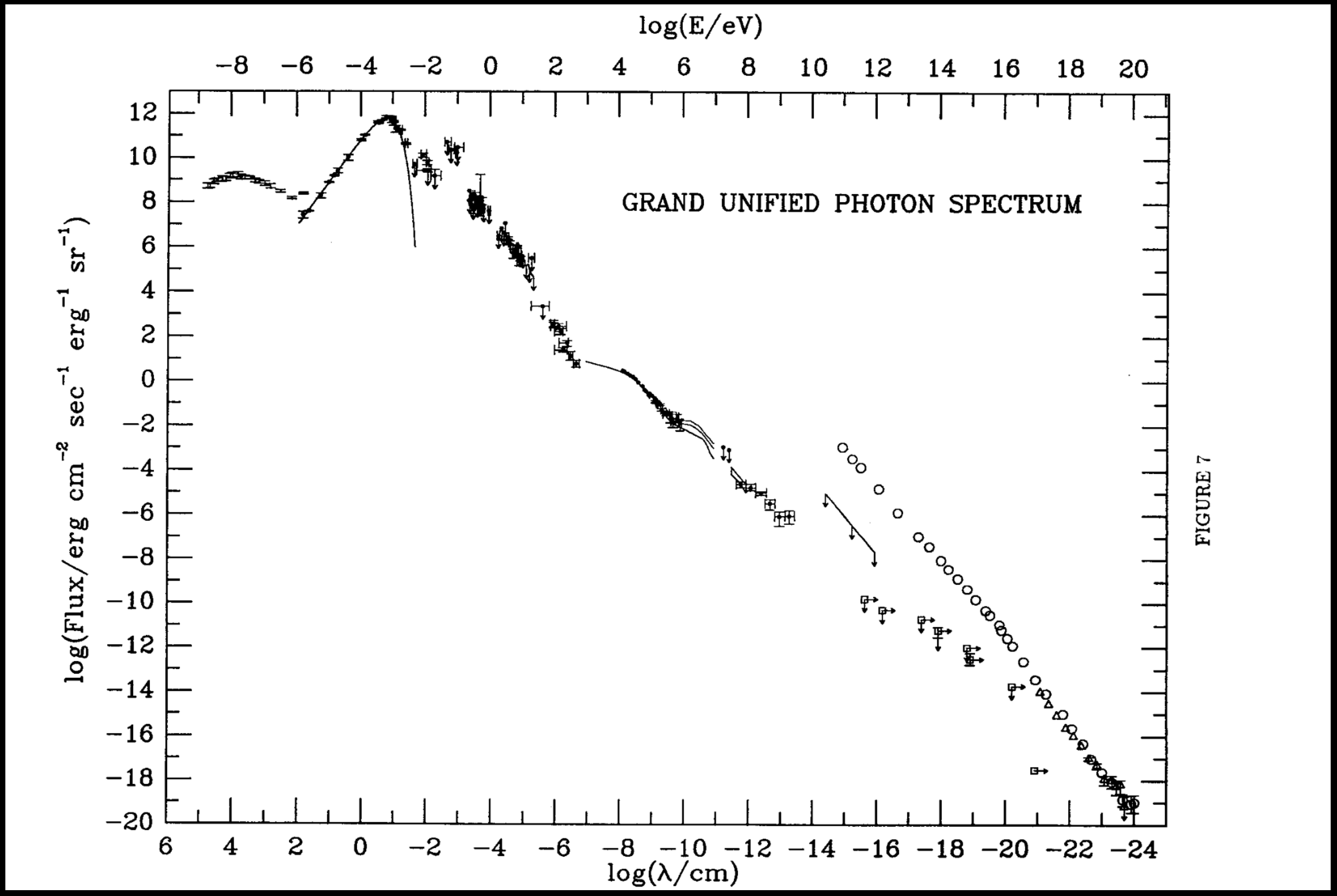




A fascinating example for astro people: GUNS

THE GRAND UNIFIED PHOTON SPECTRUM

(The diffuse extragalactic background spectrum at all energies)



M.T.Ressell, M.S.Turner, Comments Astrophys. 14 (1990) 323

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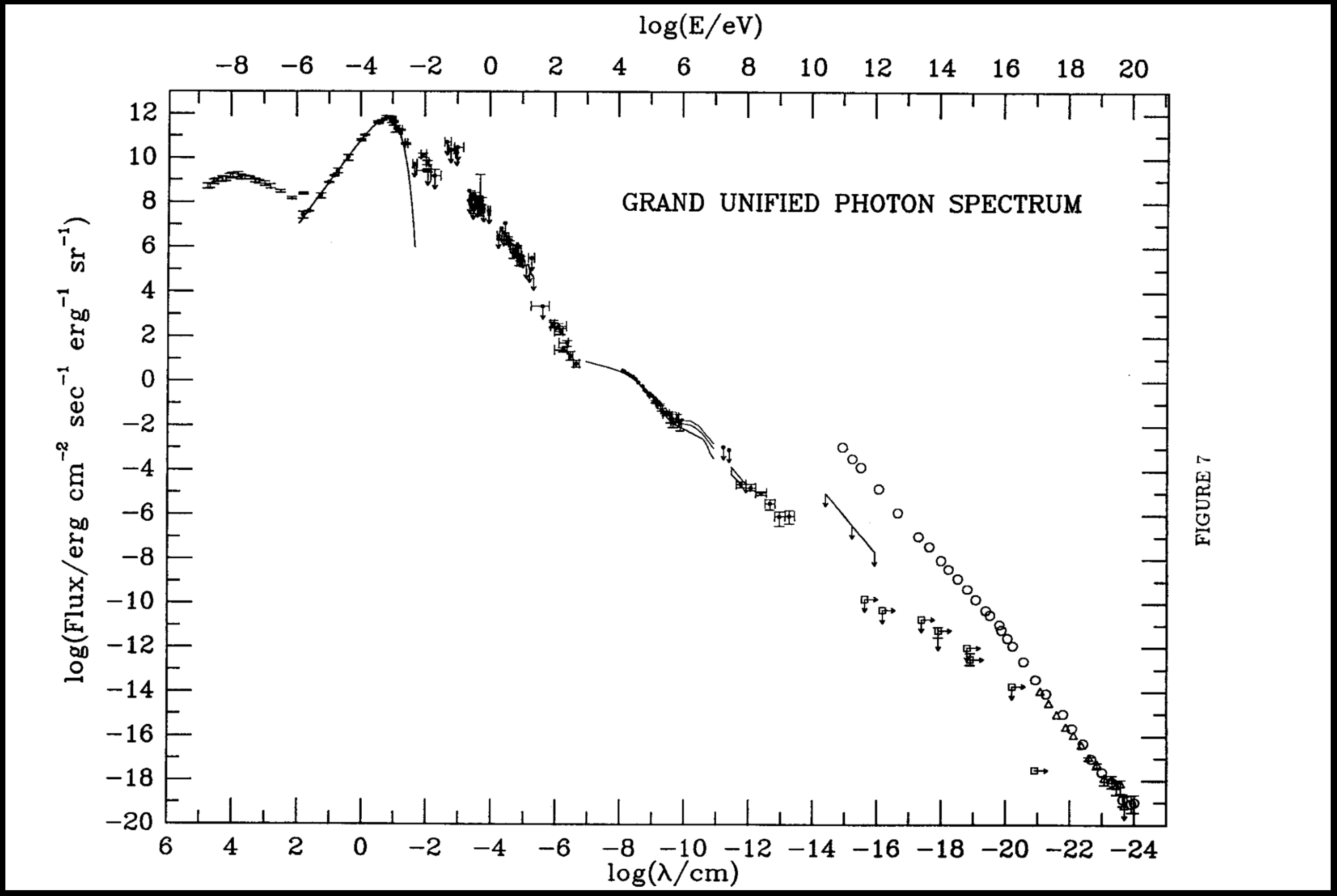
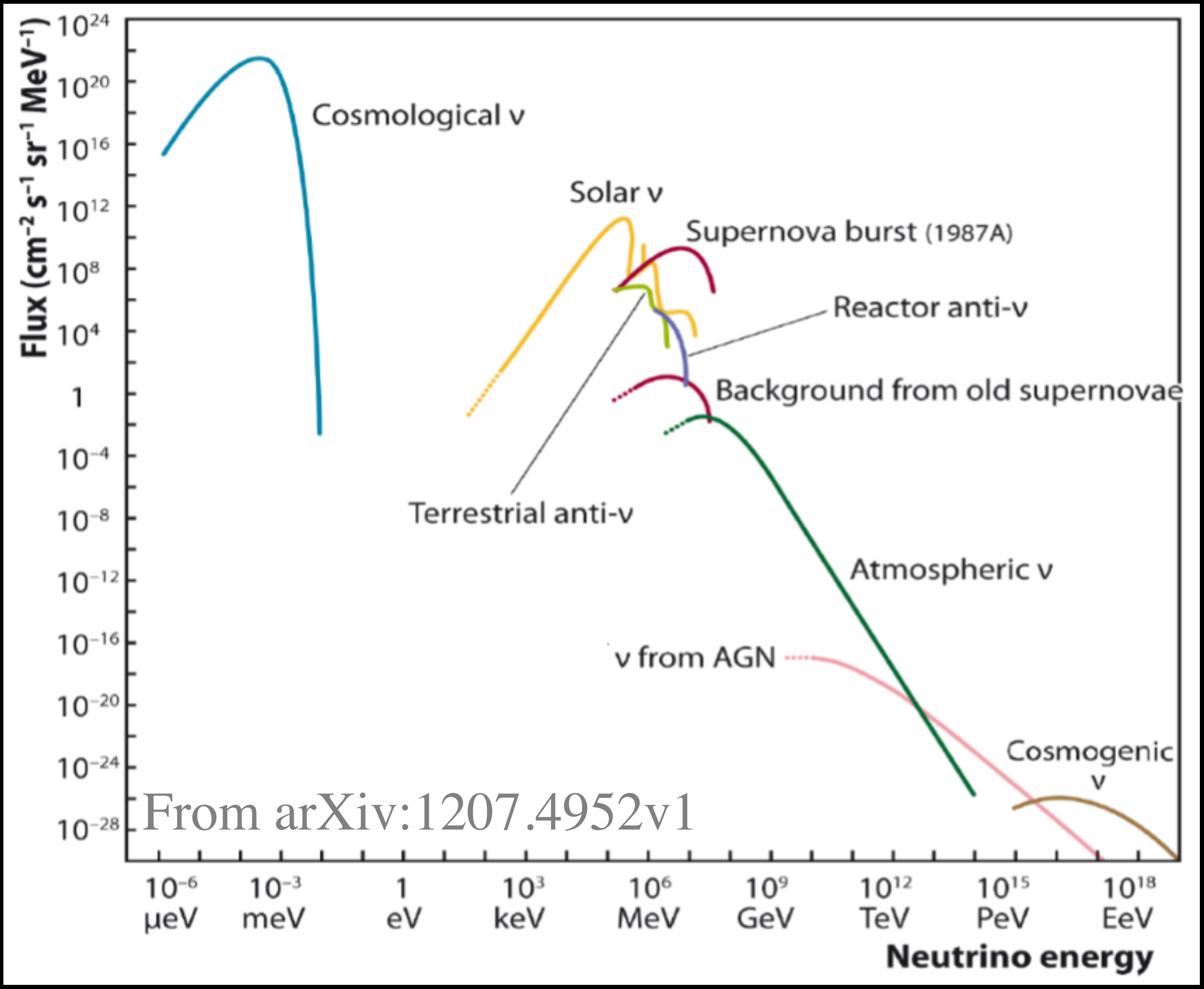


M.T.Ressell, M.S.Turner, Comments Astrophys. 14 (1990) 323

in the multi-messenger astronomy era…

THE GRAND UNIFIED NEUTRINO SPECTRUM (guns)



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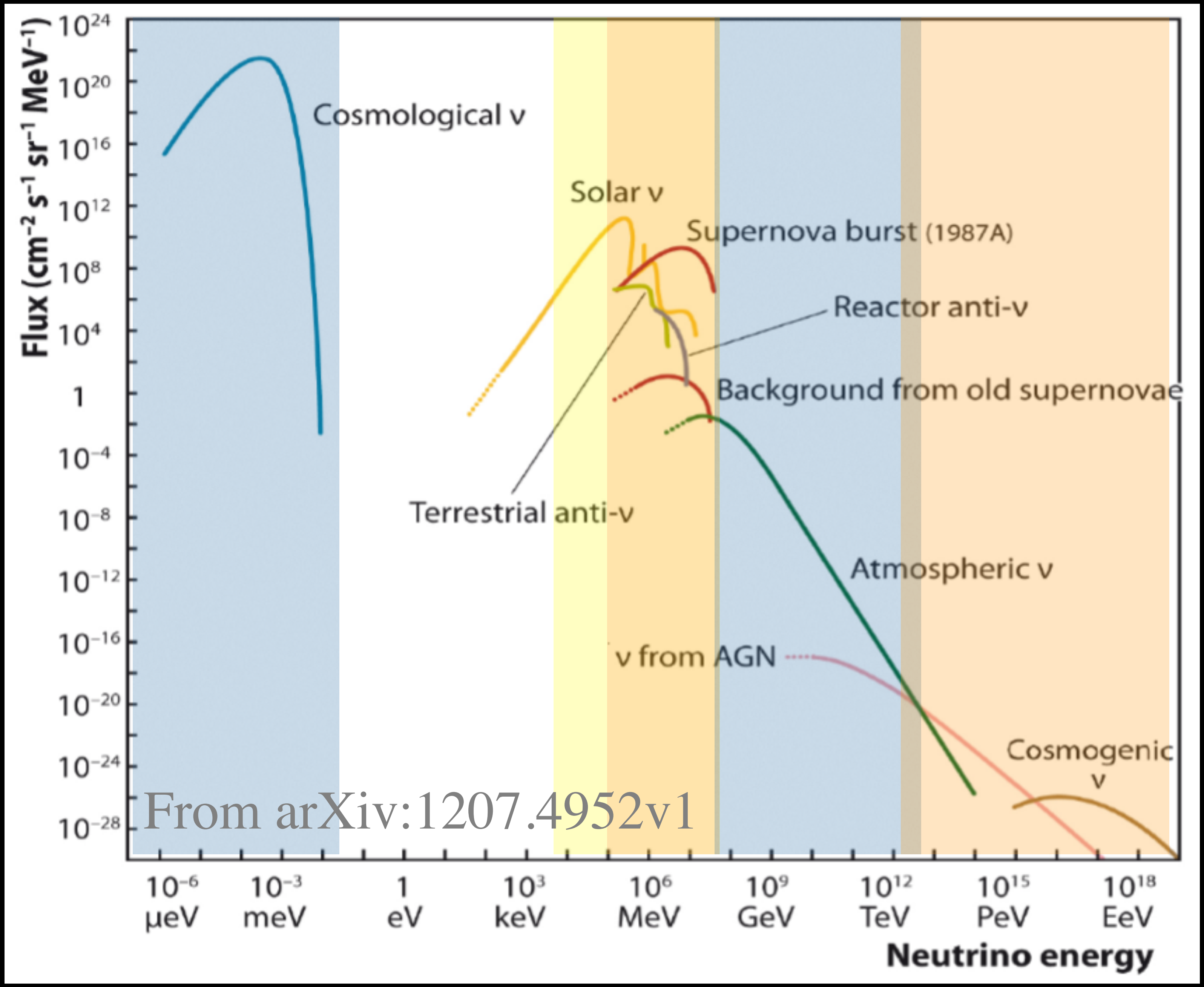

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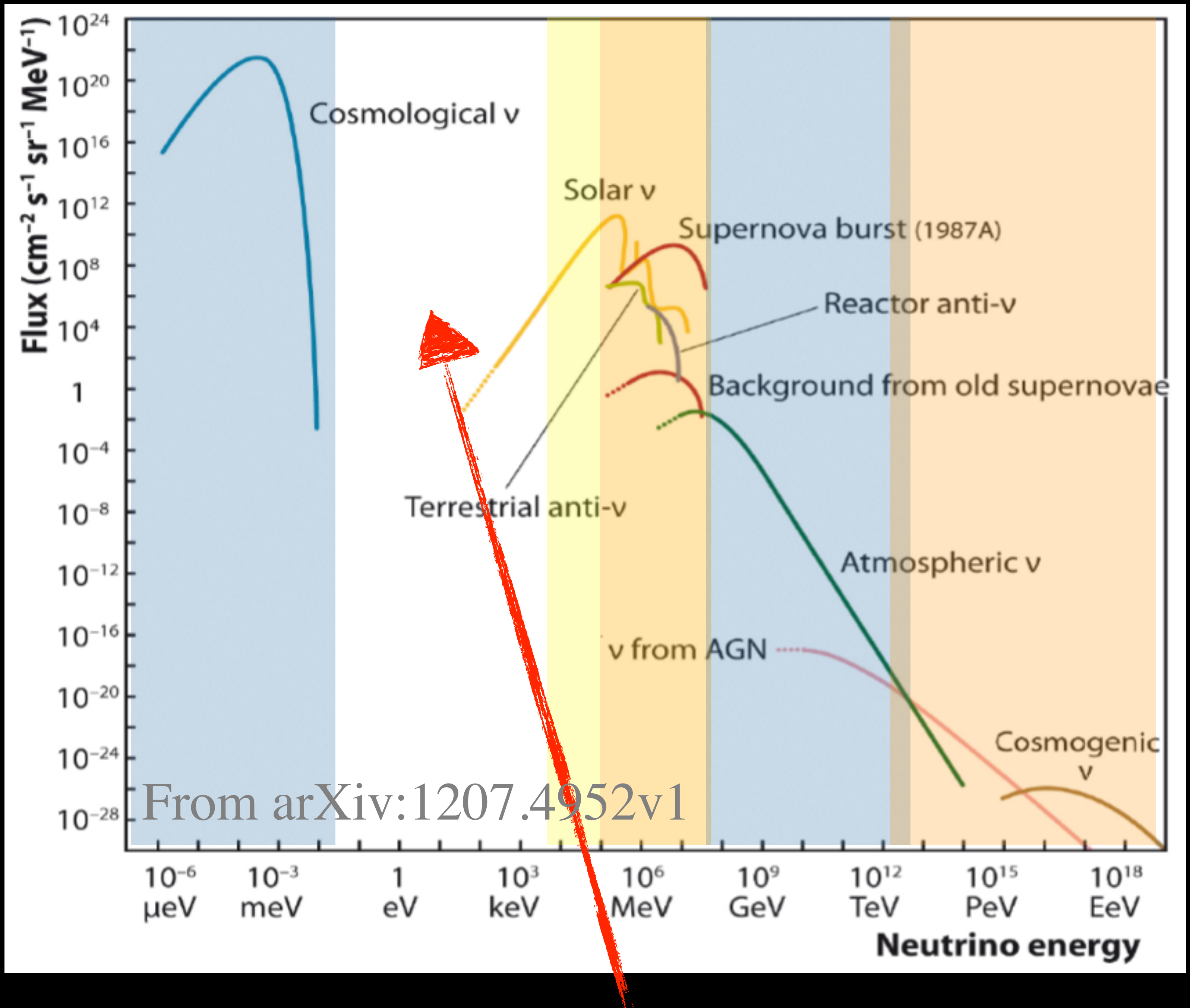

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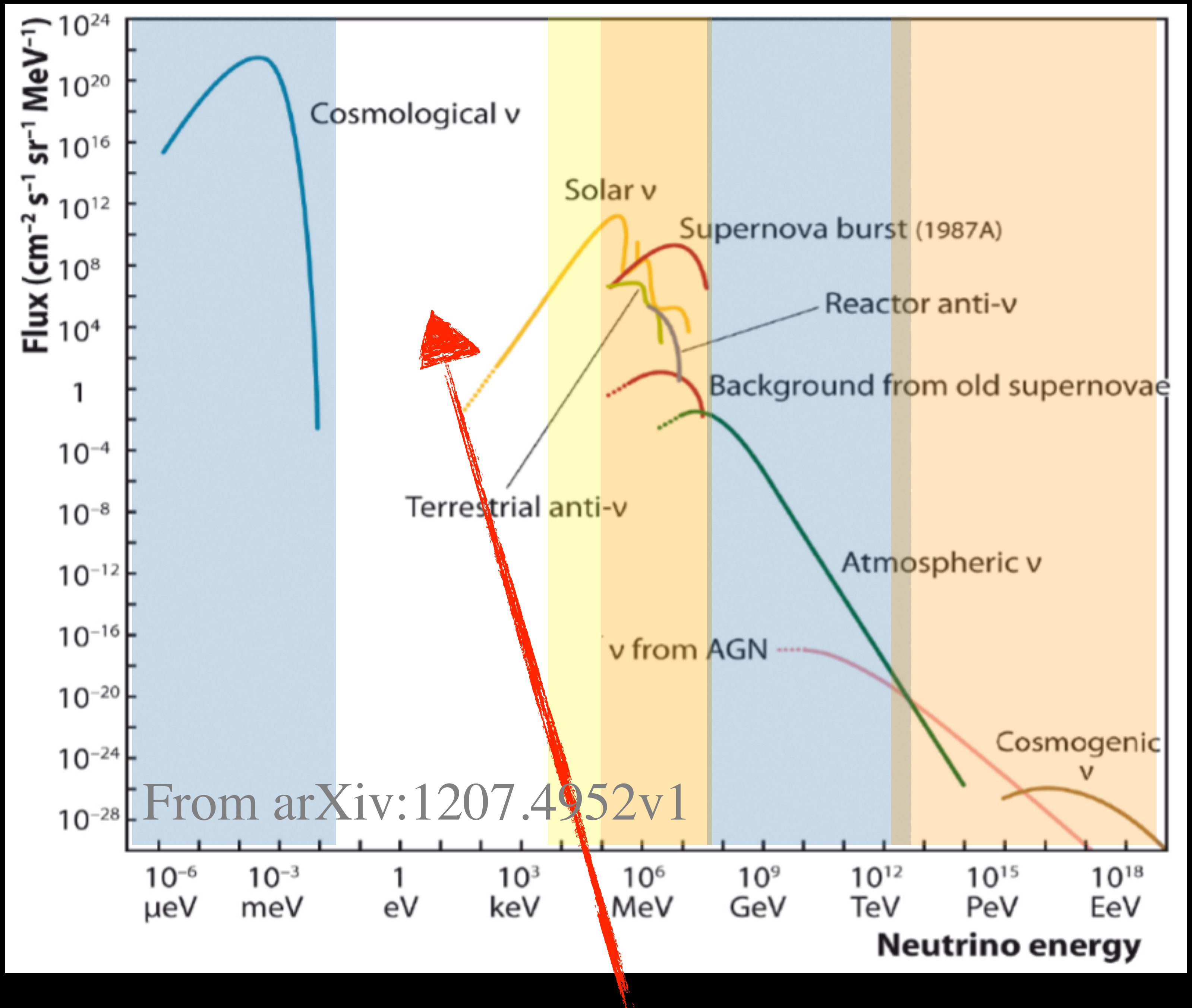
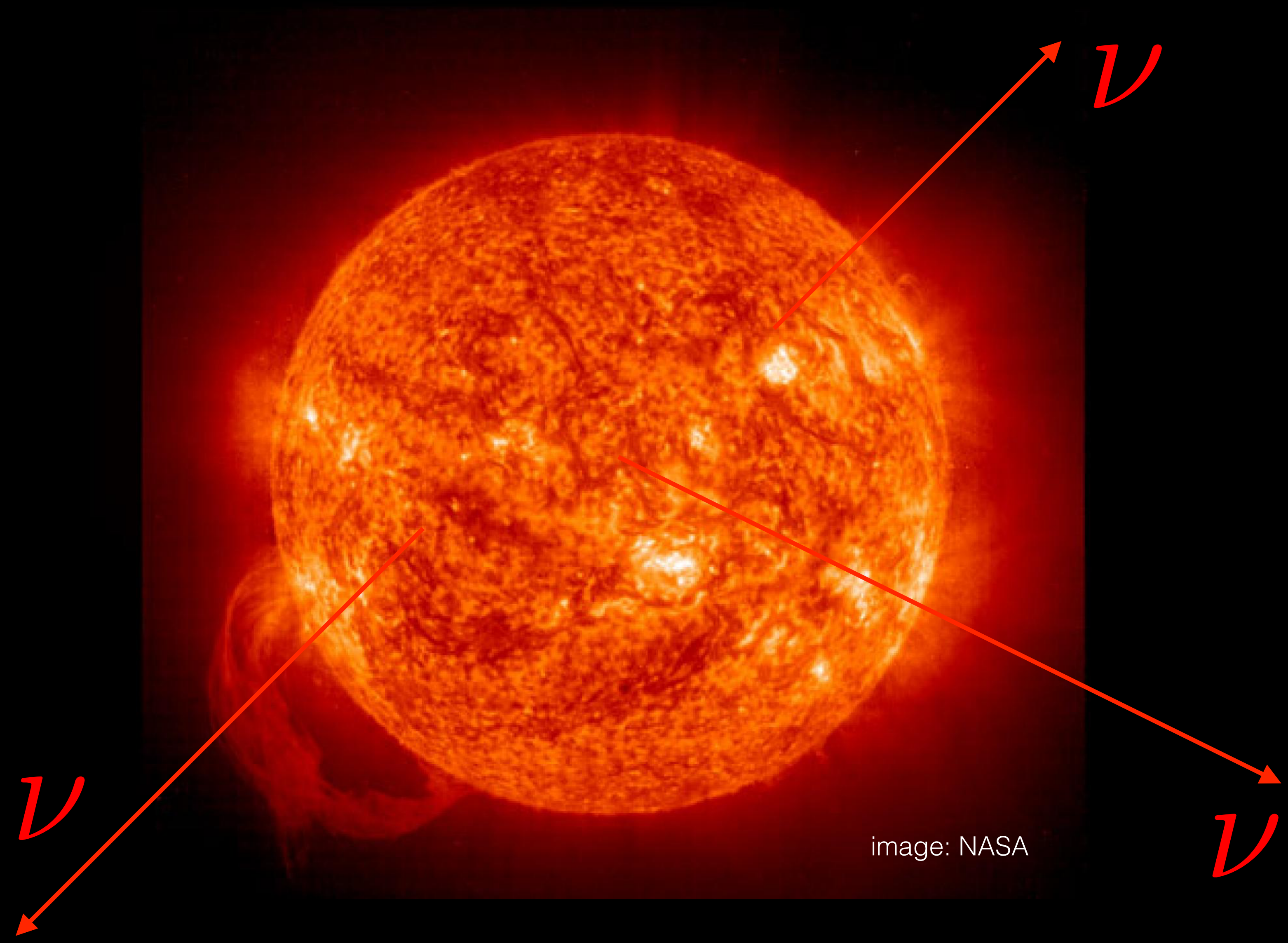
THE GRAND UNIFIED NEUTRINO SPECTRUM (guns)



Is there a source for keV neutrinos?

Yes! Directly from our domestic star…

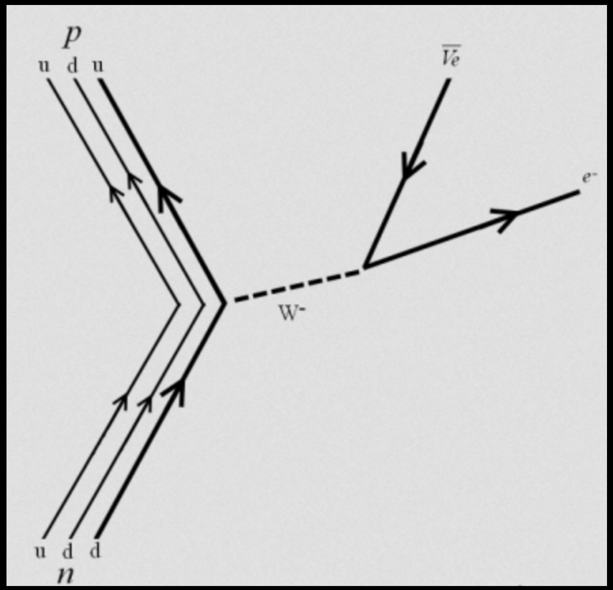


…keV neutrinos

Neutrino Solar production

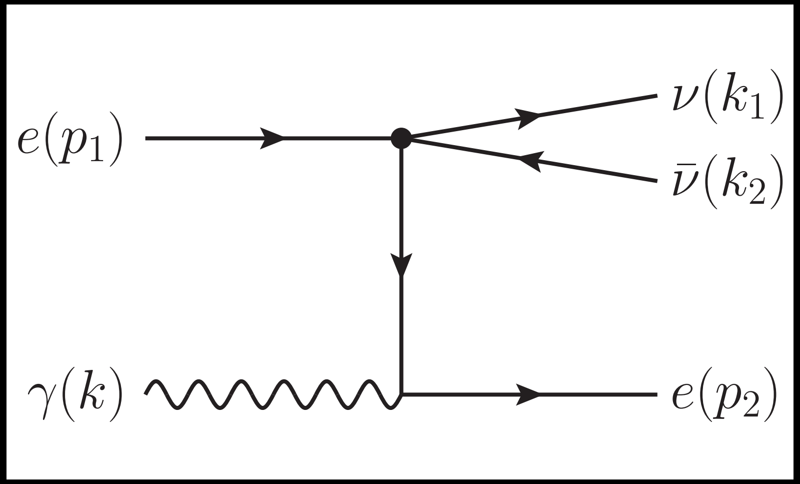
Nuclear processes (MeV):

- well known
- beta decay like processes



Thermal processes (keV):

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



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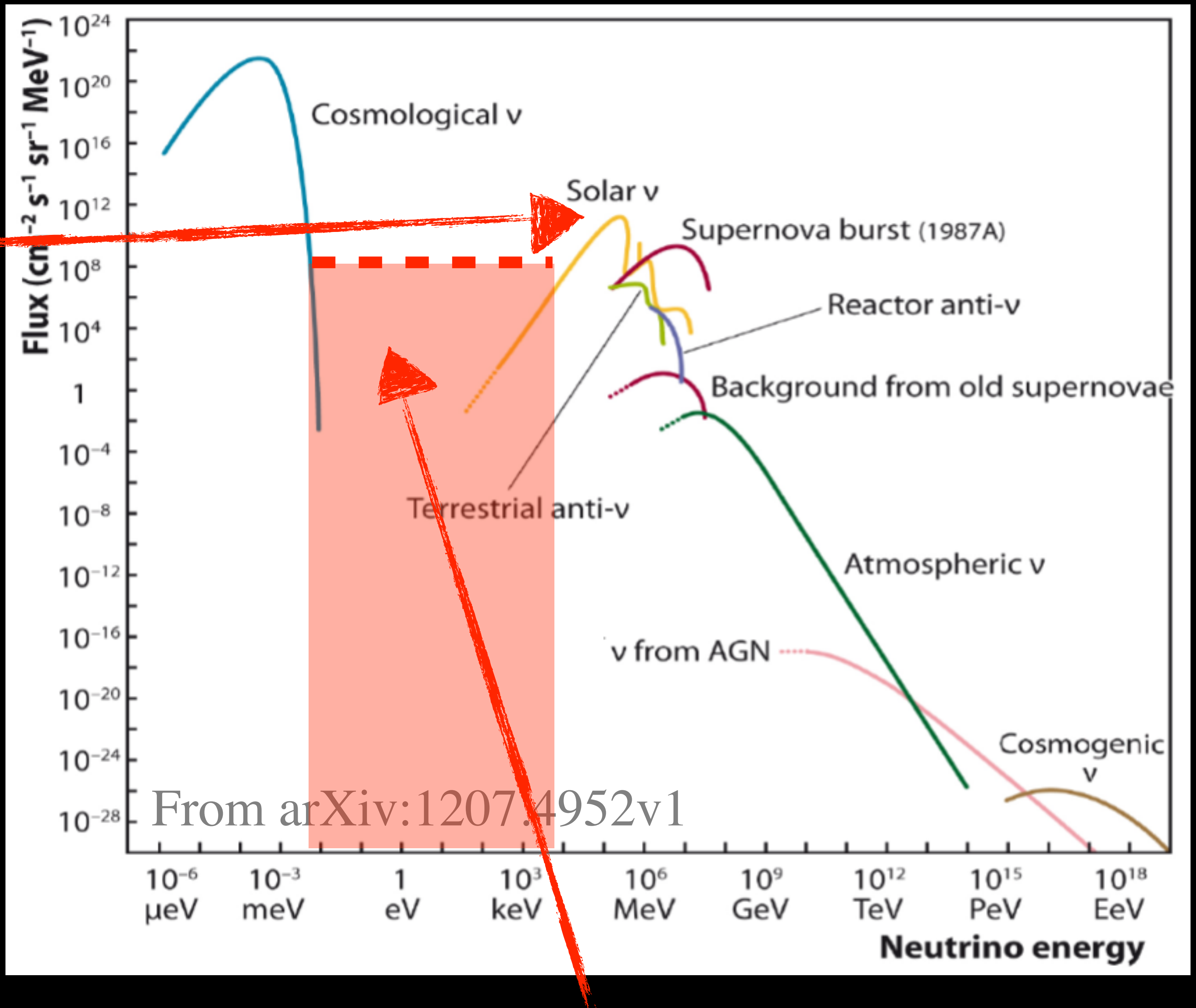
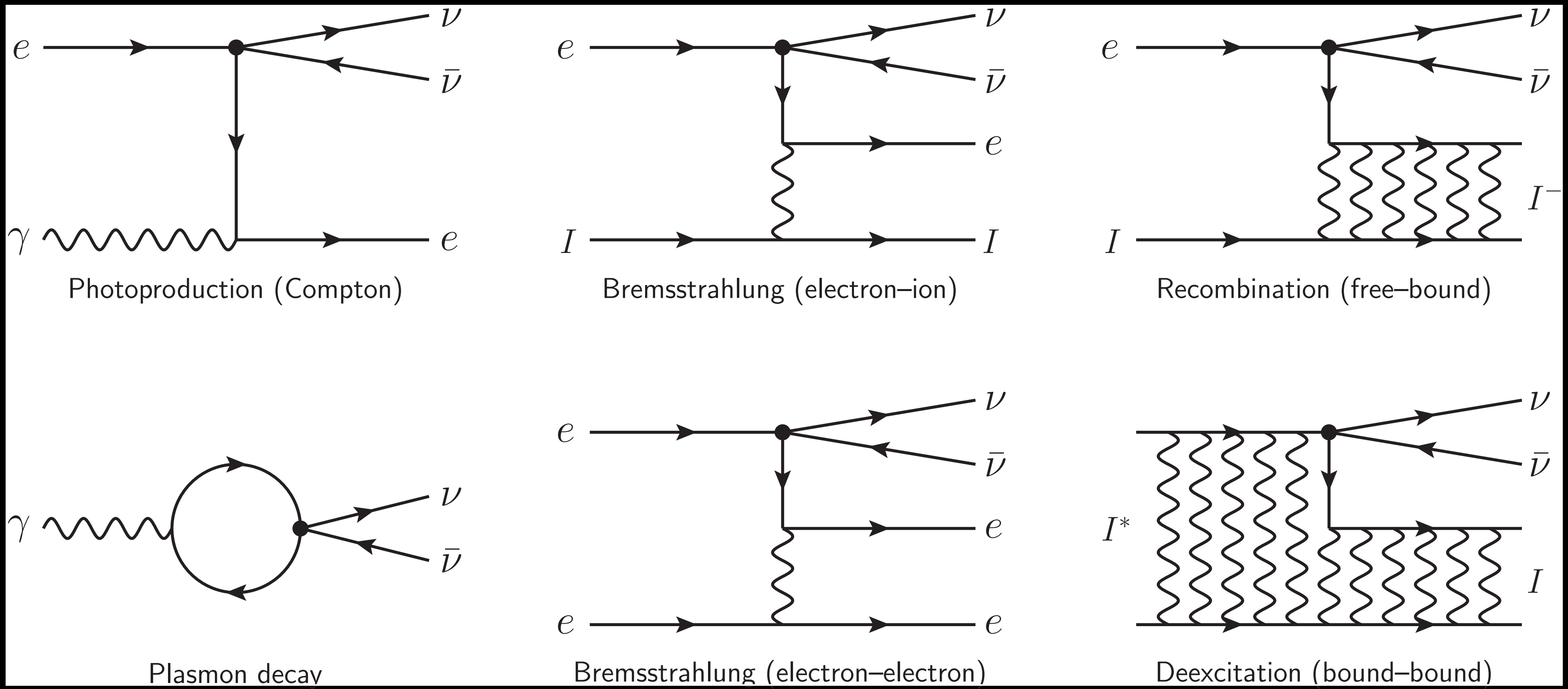


!!!

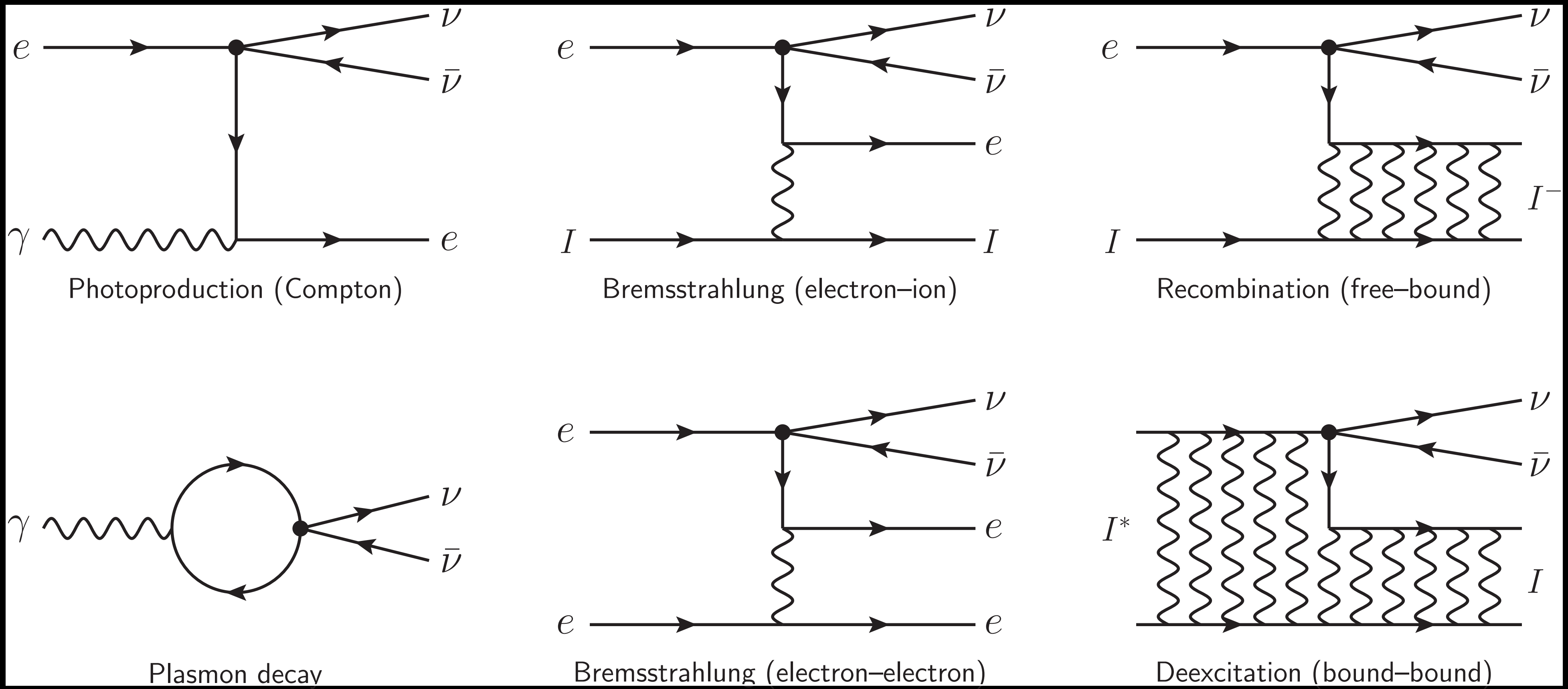
How - the ABCD processes

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



How - the ABCD processes

- Atomic recombination (fb) and deexcitation (bb)
- Bremsstrahlung (ff)
- Compton process
- Decay of a plasmon → We'll see this



Good old weak interaction in the non relativistic limit

All processes are mediated by the interaction

$$\mathcal{L}_{\rm int} = \frac{G_{\rm F}}{\sqrt{2}}\,\bar{\psi}_e\gamma^\mu(C_{\rm V} - C_{\rm A}\gamma_5)\psi_e\,\bar{\psi}_\nu\gamma_\mu(1-\gamma_5)\psi_\nu$$

$$\begin{array}{llll} C_{\rm V} = \frac{1}{2}(4\sin\Theta_{\rm W}+1) & \text{and} \quad C_{\rm A} = +\frac{1}{2} & \text{for} & \nu_e, \\ C_{\rm V} = \frac{1}{2}(4\sin\Theta_{\rm W}-1) & \text{and} \quad C_{\rm A} = -\frac{1}{2} & \text{for} & \nu_\mu \text{ and } \nu_\tau \end{array}$$

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

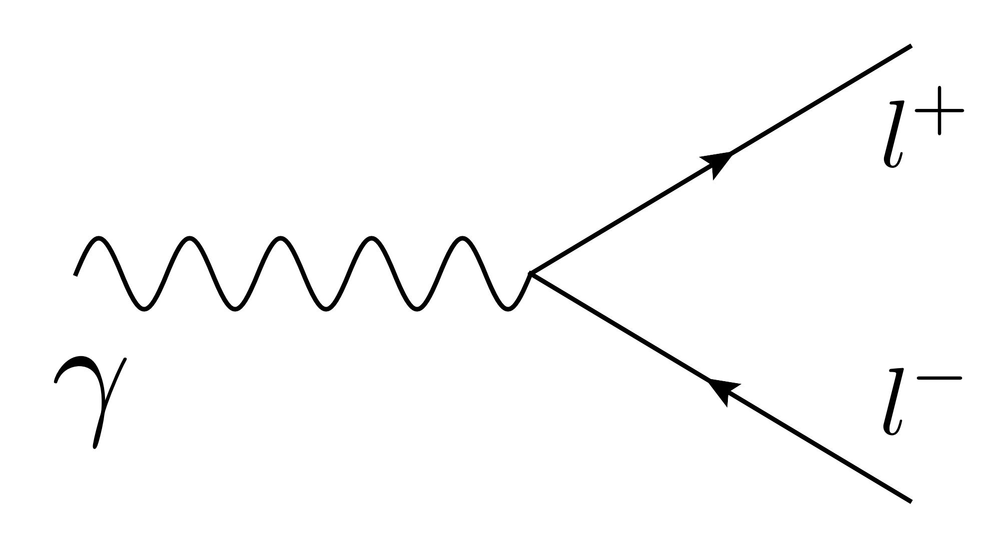
$C_{\rm A}^2 = 1/4$

(different flavors, different vector couplings)

Plasmon decay

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

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



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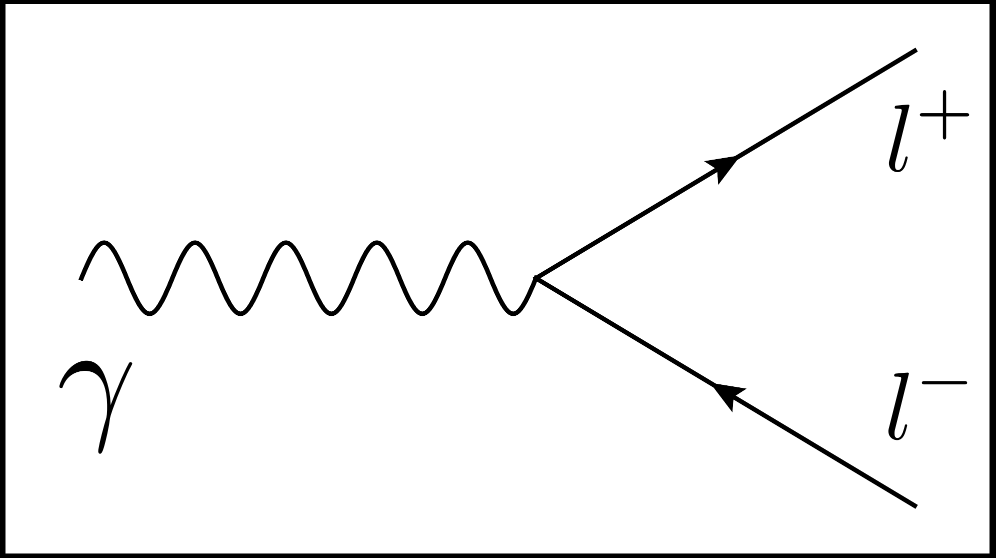

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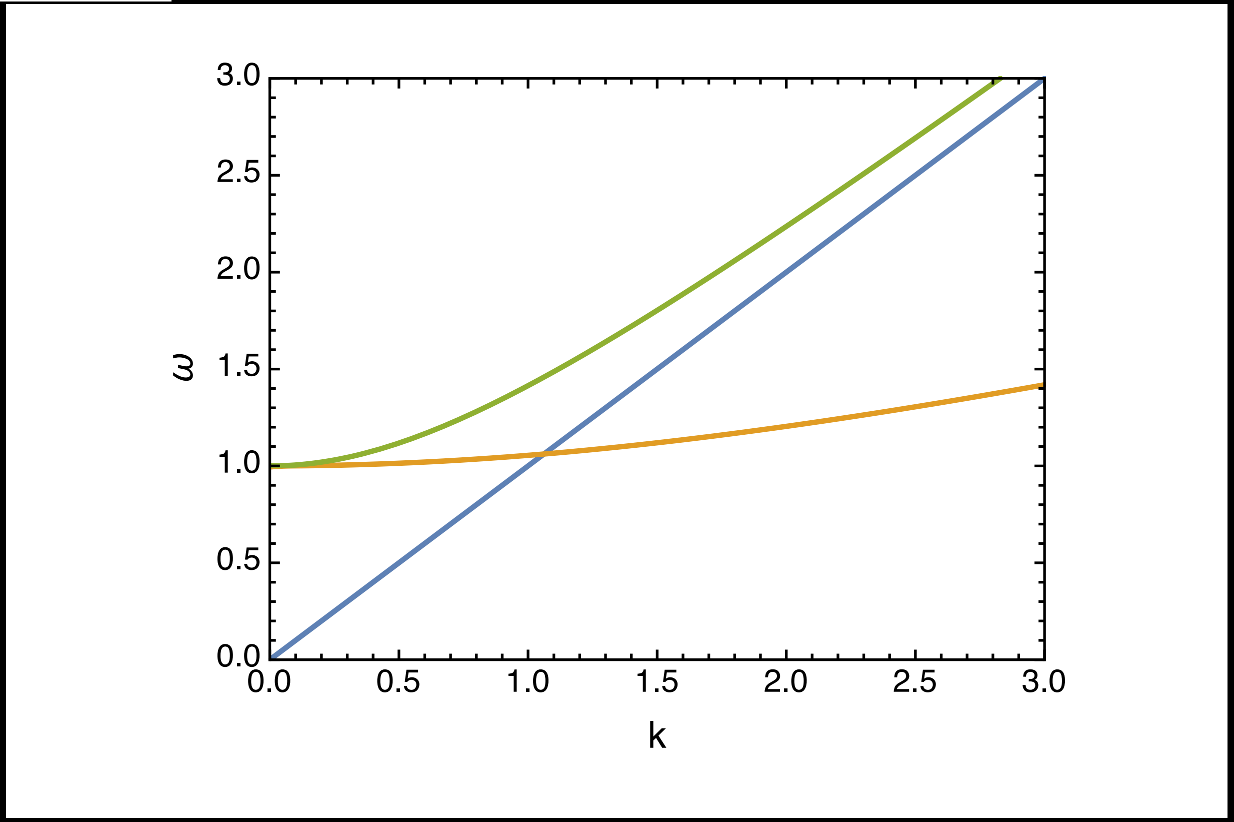

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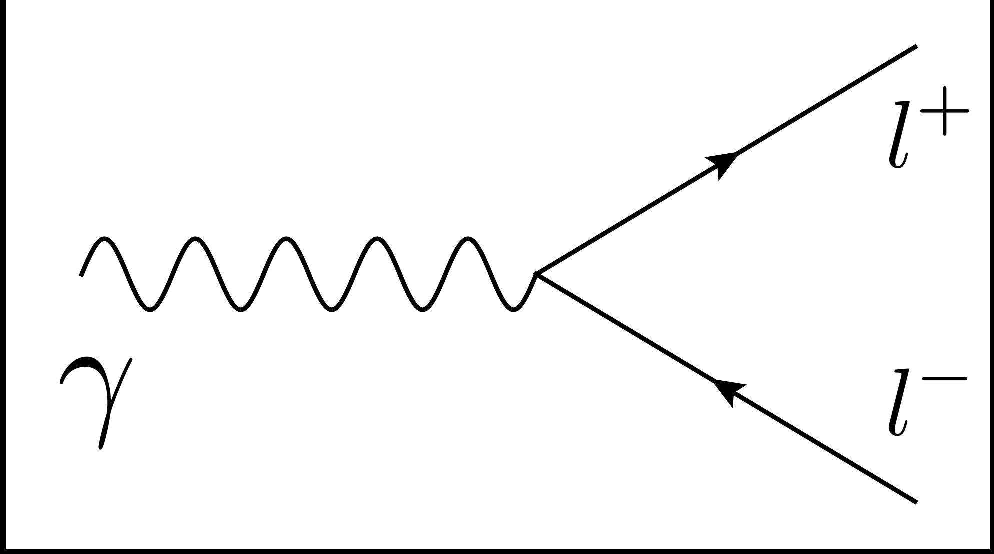
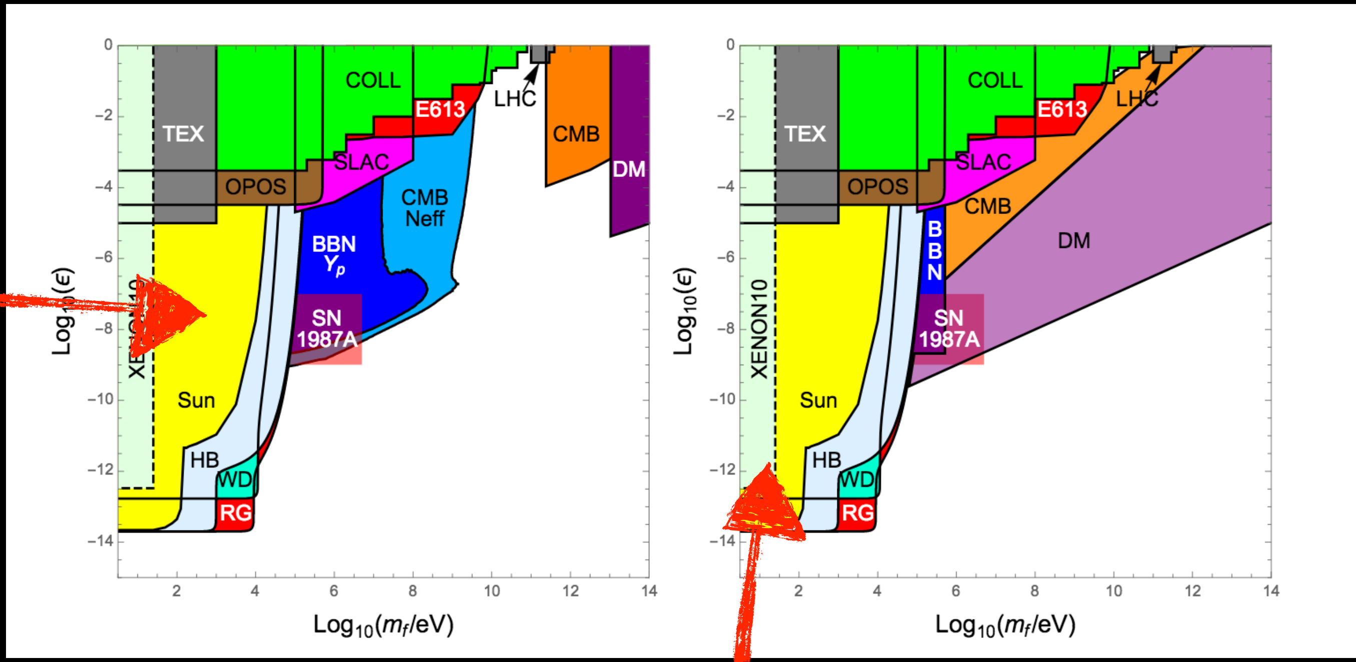


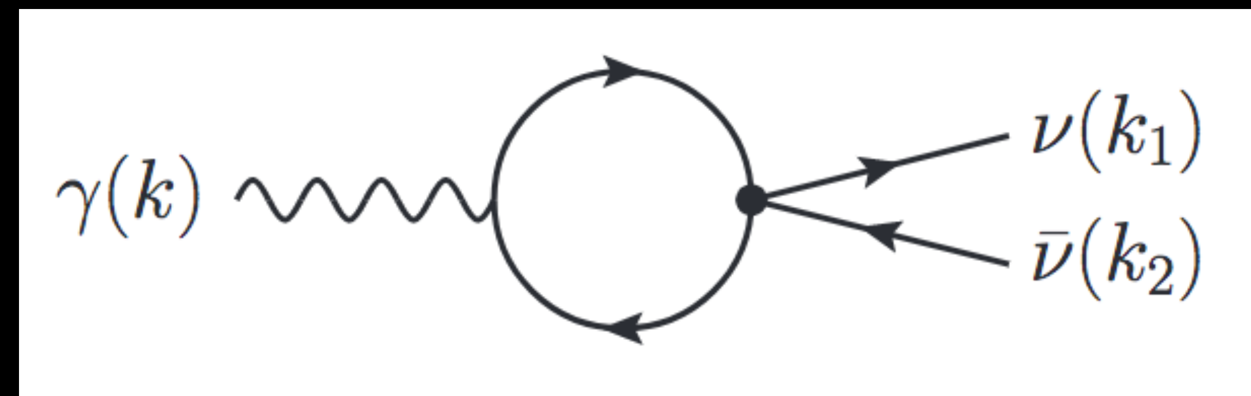
- In this way, you produce e.g. mini charged particles in stars
- Also, effective masses can arise in the early universe
- Plasmon decay bounds on new Weakly Interactive Slim Particles (WISPs) is just an example (see also Primakoff for axions)



Vinyoles and Vogel, arXiv:1511.01122v2
More generally: Raffelt, Phys.Rept. 198 (1990) 1-113

Plasmon decay with neutrinos

- With neutrinos it's the same, but we need a thermal loop (the medium as spectator)



$$\omega_{\rm p}^2 = \frac{4\pi\alpha\, n_e}{m_e}$$

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

$$\omega^2\big|_{\rm T} = \omega_{\rm p}^2\left(1 + \cancel{\frac{\mathbf{k}^2}{\omega_{\rm p}^2+\mathbf{k}^2}\frac{T}{m_e}}\right) + \mathbf{k}^2 \qquad \text{and} \qquad \omega^2\big|_{\rm L} = \omega_{\rm p}^2\left(1 + 3\,\cancel{\frac{\mathbf{k}^2}{\omega_{\rm p}^2}\frac{T}{m_e}}\right)$$

$$|\mathcal{M}_{\gamma\to\nu\bar\nu}|^2 = \frac{C_{\rm V}^2 G_{\rm F}^2}{8\pi\alpha}\, Z_{\mathbf{k}} \Pi_{\mathbf{k}}^2\, \epsilon_\mu \epsilon_\nu^* N^{\mu\nu}$$

Renormalizing the coupling…

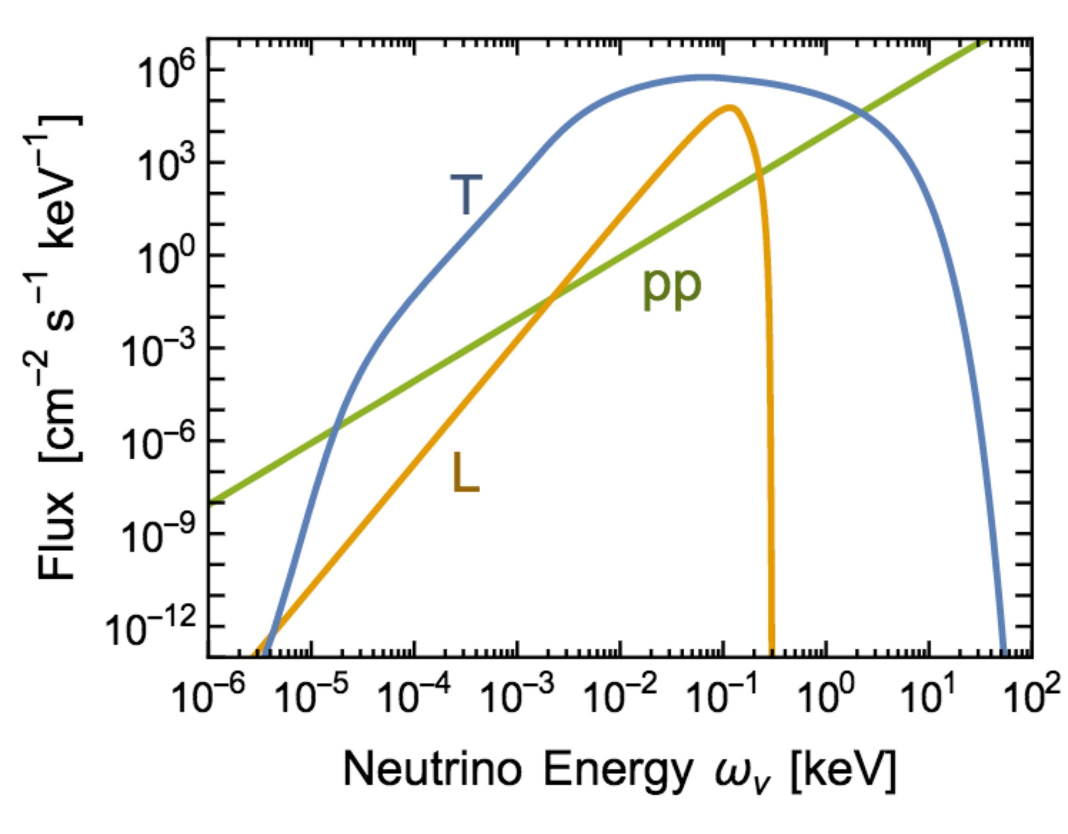
$$N^{\mu\nu} = 8\left(k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - k_1\!\cdot\! k_2\, g^{\mu\nu} + i\varepsilon^{\alpha\mu\beta\nu} k_{1\alpha} k_{2\beta}\right)$$

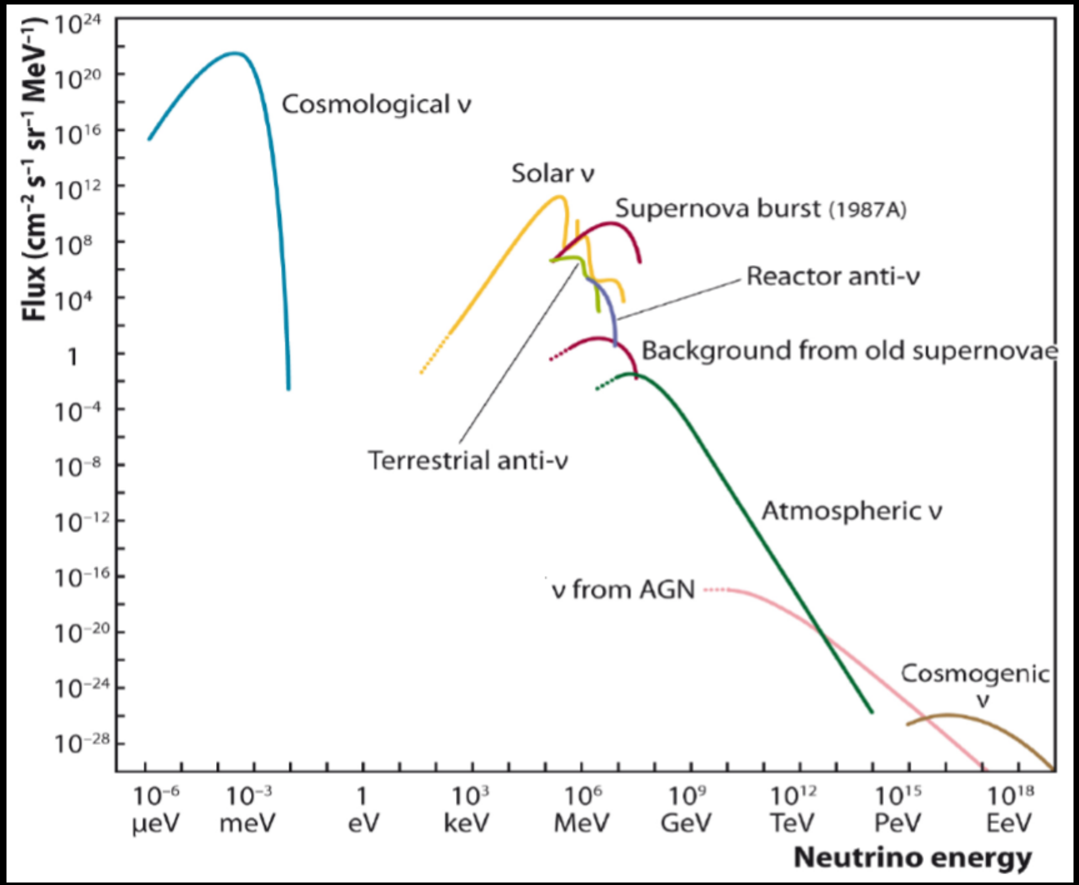
- In the end —->

$$\frac{d\dot n_\nu}{d\omega_\nu}\Big|_{\rm L} = \int_{V_{\mathbf{k}}} \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{\Gamma_{\rm L} g_{\rm L}(\omega_\nu)}{e^{\omega_{\rm p}/T} - 1} \qquad \frac{d\dot n_\nu}{d\omega_\nu}\Big|_{\rm T} = \int_{V_{\mathbf{k}}} \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{2\Gamma_{\rm T} g_{\rm T}(\omega_\nu)}{e^{\omega_{\mathbf{k}}/T} - 1}$$

Statistical physics: solar model (Saclay+GS98)

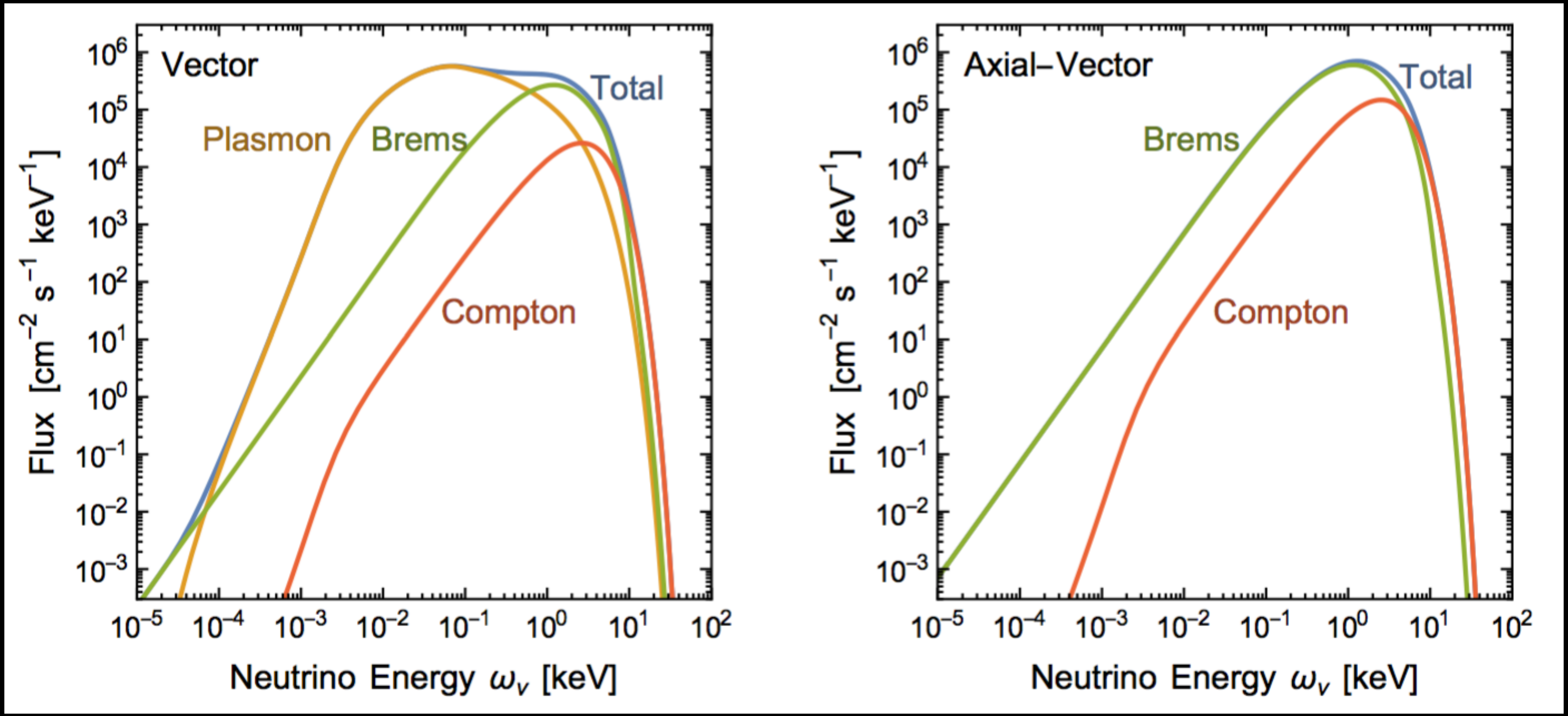
Plasmon decay with neutrinos





It seems relevant!

ABCD processes



to be multiplied by C_V^2 and C_A^2

Total flux on Earth - with oscillation

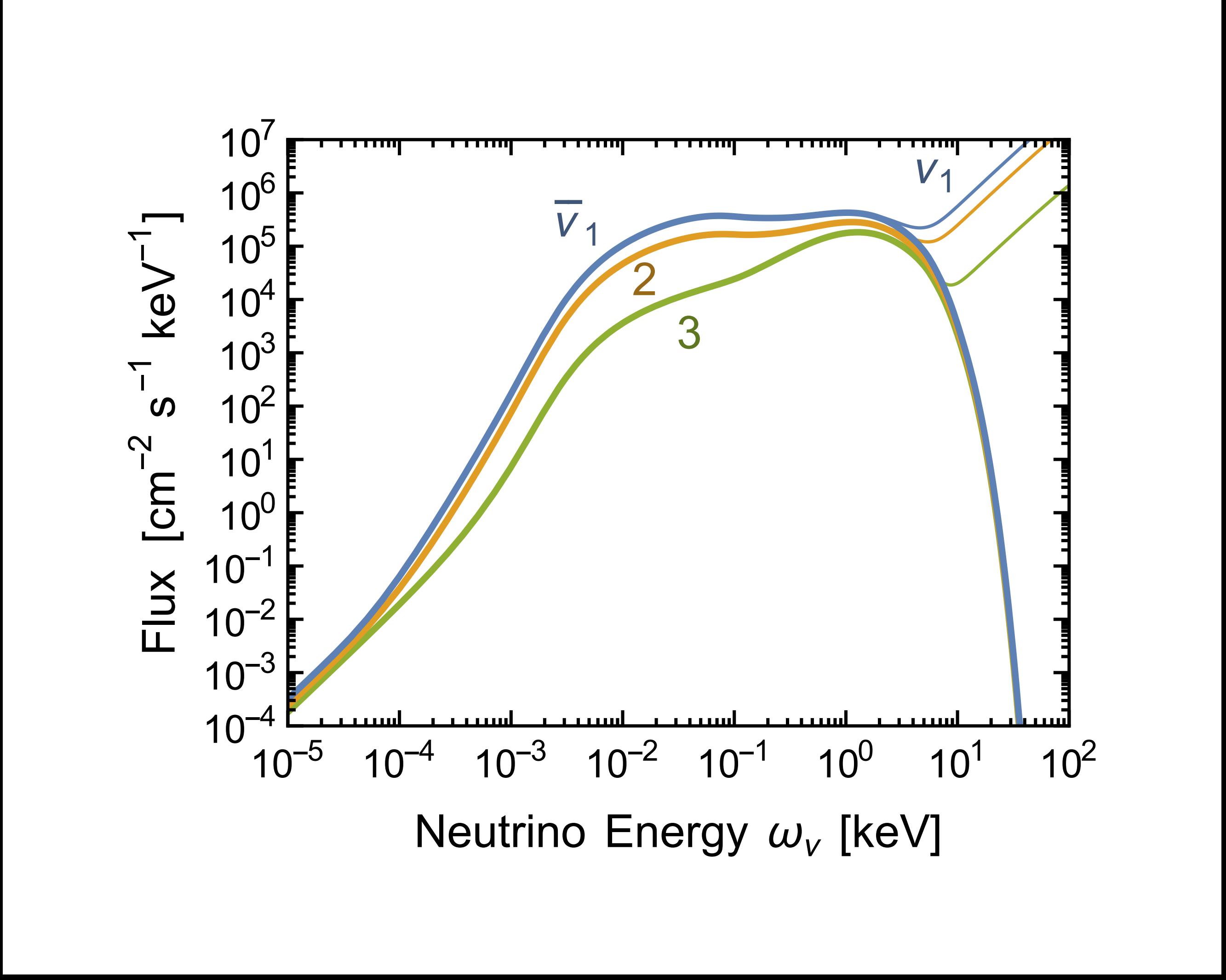
Flux of mass eigenstates, no matter effect for keV neutrinos

Matter potential $\Delta V = \sqrt{2} G_{\rm F} n_e = 7.6 \times 10^{-12}$ eV

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

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

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



to be seen in a detector

Summary

- Stars are laboratories of particle physics!
- Effective masses, WISPs astrophysical bounds and much more: lot of Physics in thermal environment
- Example: thermal processes (ABCD) in the Sun, plasmon decay
- We can gain information about the temperature and electrons density profiles in the Sun, as well as about metallicity of outskirts and core, and calculate the background to sterile neutrinos searches

Thank you!

Backup slides

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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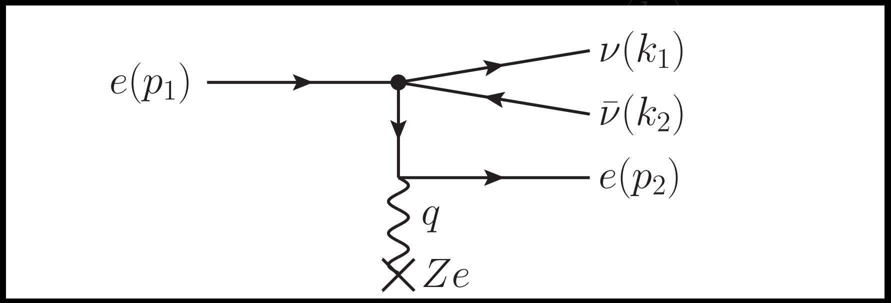
o(10%) effects, not today



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

The ABCD processes in general

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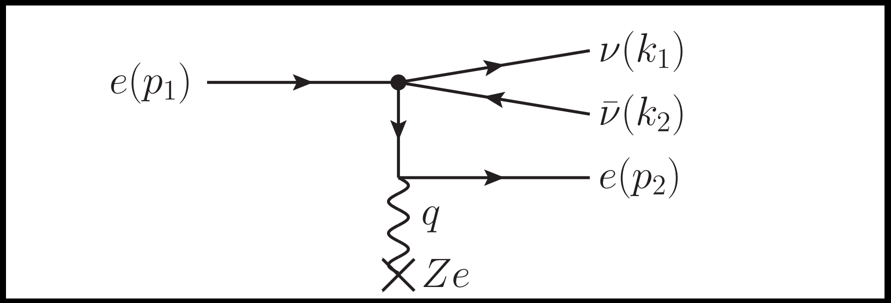

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Statistical physics: solar model (Saclay+GS98)

Particle physics

Long wavelength approximation

$$\mathcal{L}_{\rm int} = \frac{G_{\rm F}}{\sqrt{2}} \bar{\psi}_e \gamma^\mu (C_{\rm V} - C_{\rm A}\gamma_5)\psi_e \bar{\psi}_\nu \gamma_\mu (1-\gamma_5)\psi_\nu$$

Bremsstrahlung

Structure function (encoding medium properties)

$$\mathcal{S}(\omega)=\frac{(4\pi)^2}{(2m_e)^2}\frac{1}{n_e}\int\frac{d^3\mathbf{p}_1}{(2\pi)^3}\frac{d^3\mathbf{p}_2}{(2\pi)^3}f_1(1-f_2)\frac{1}{\mathbf{q}^2}2\pi\delta(E_1-E_2-\omega)$$

ν flux

$$\frac{d\dot{n}_\nu}{d\omega_\nu}=n_Z n_e\frac{8\,Z^2\alpha^2}{3}\left(\frac{G_\mathrm{F}}{\sqrt{2}}\right)^2\frac{1}{3\pi^4}\int_{\omega_\nu}^{\infty}d\omega\,\mathcal{S}(\omega)\frac{\omega_\nu^2(\omega-\omega_\nu)^2}{\omega^4}$$
$$\times\left[C_\mathrm{V}^2\left(3\omega^2-2\omega\omega_\nu+2\omega_\nu^2\right)+2C_\mathrm{A}^2\left(3\omega^2-5\omega\omega_\nu+5\omega_\nu^2\right)\right]$$

photon flux

$$\frac{d\dot{n}_\gamma}{d\omega}=n_Z n_e\frac{8\,Z^2\alpha^2}{3}\frac{\alpha}{\pi}\frac{\mathcal{S}(\omega)}{\omega}$$

$$\frac{d\dot{n}_\nu}{d\omega_\nu}=\frac{G_\mathrm{F}^2}{6\pi^3\alpha}\int_{\omega_\nu}^{\infty}d\omega\left(\frac{d\dot{n}_\gamma}{d\omega}\right)\frac{\omega_\nu^2(\omega-\omega_\nu)^2}{\omega^3}$$
$$\times\left[C_\mathrm{V}^2\left(3\omega^2-2\omega\omega_\nu+2\omega_\nu^2\right)+2C_\mathrm{A}^2\left(3\omega^2-5\omega\omega_\nu+5\omega_\nu^2\right)\right]$$

ν flux in terms of the photon flux

Atomic processes

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

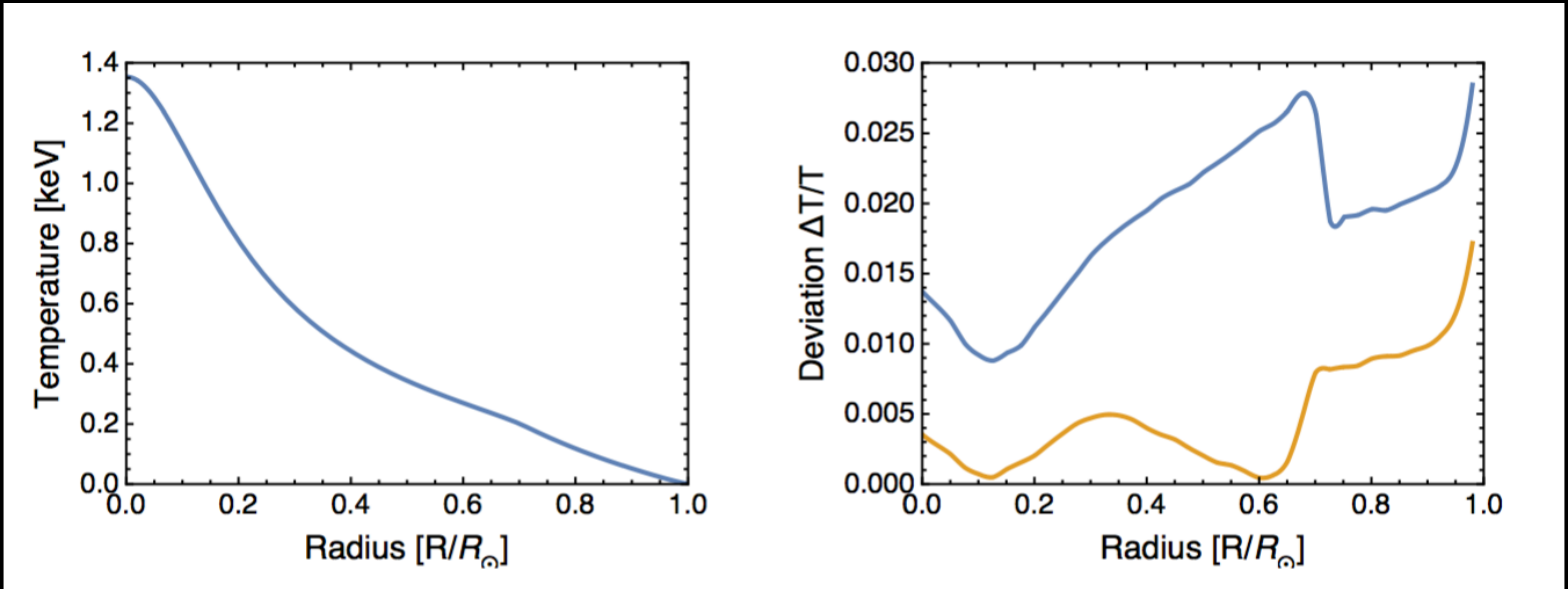
The Opacity Project - The Iron Project

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

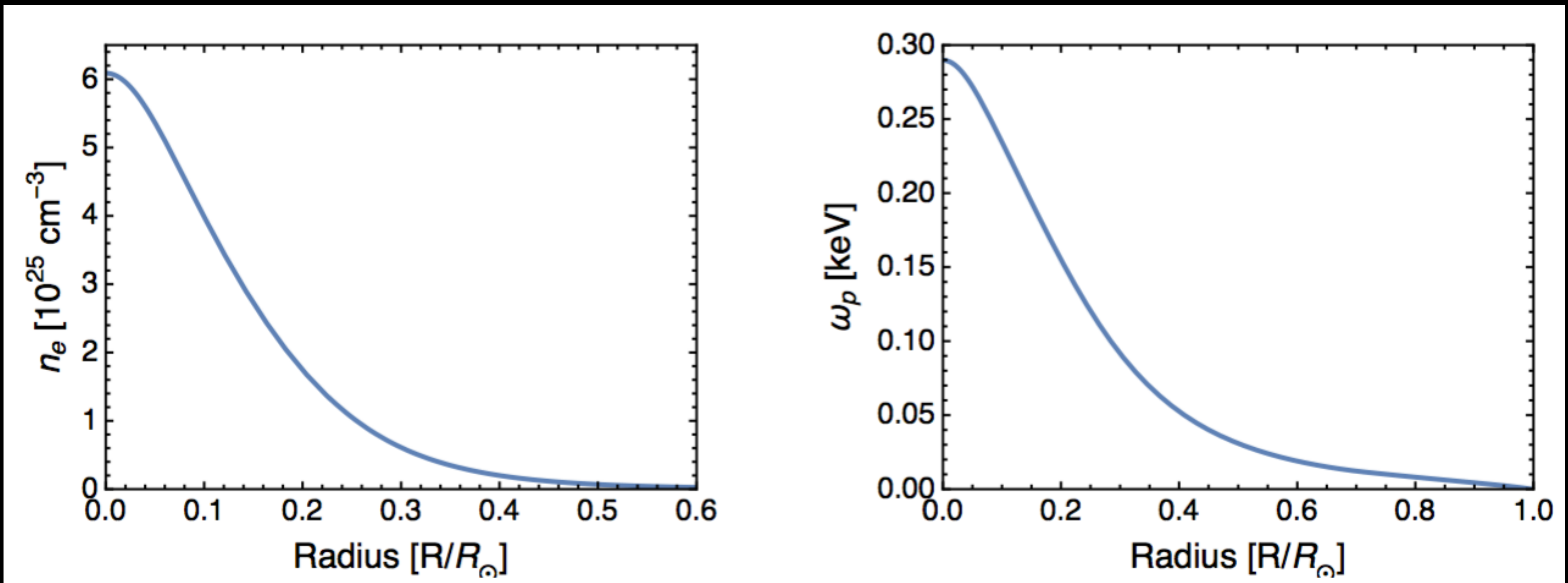
Neutrino emission rate as a function of photon absorption rate

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

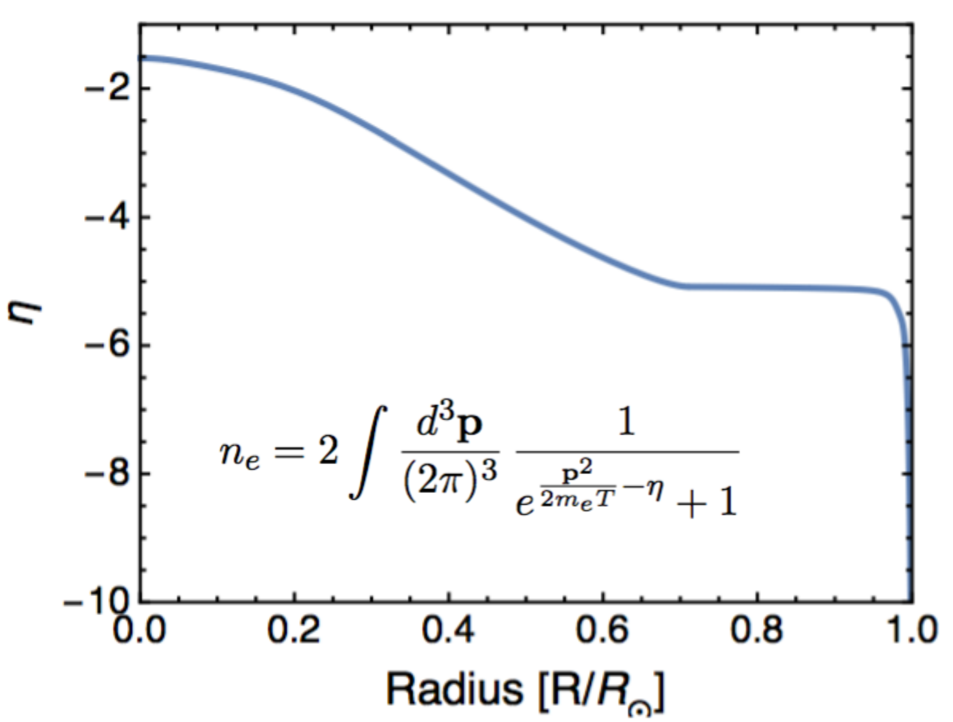
Temperature profile



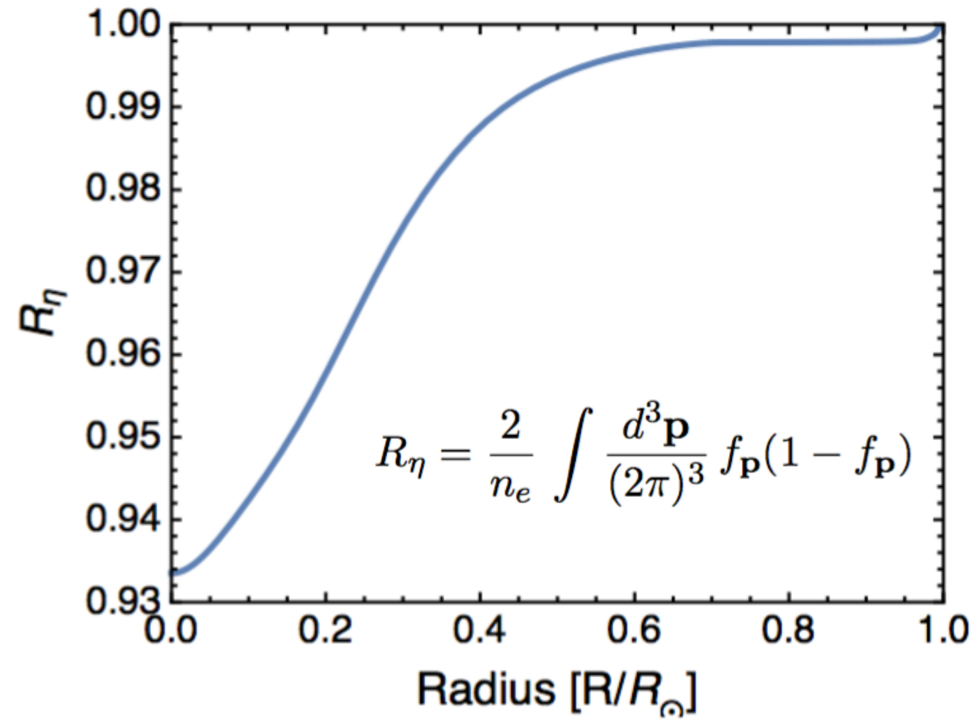
Electron density and plasma frequency profile



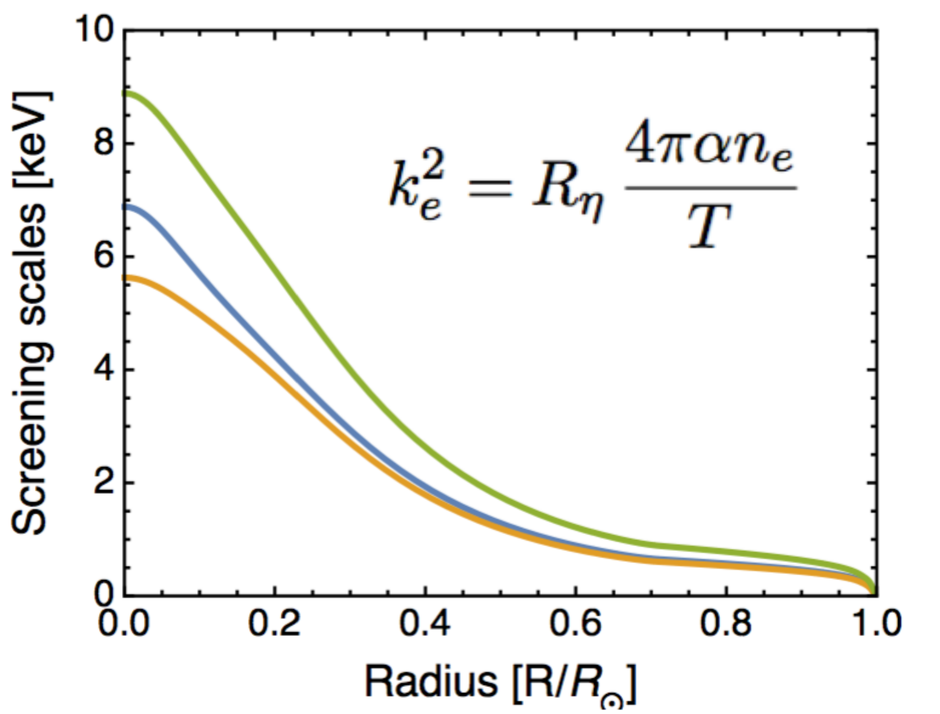
Degeneracy



η
-2
-4
-6
-8
-10
0.0
0.2
0.4
0.6
0.8
1.0
Radius [R/$R_\odot$]
$n_e = 2\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{1}{e^{\frac{\mathbf{p}^2}{2m_eT}-\eta}+1}$

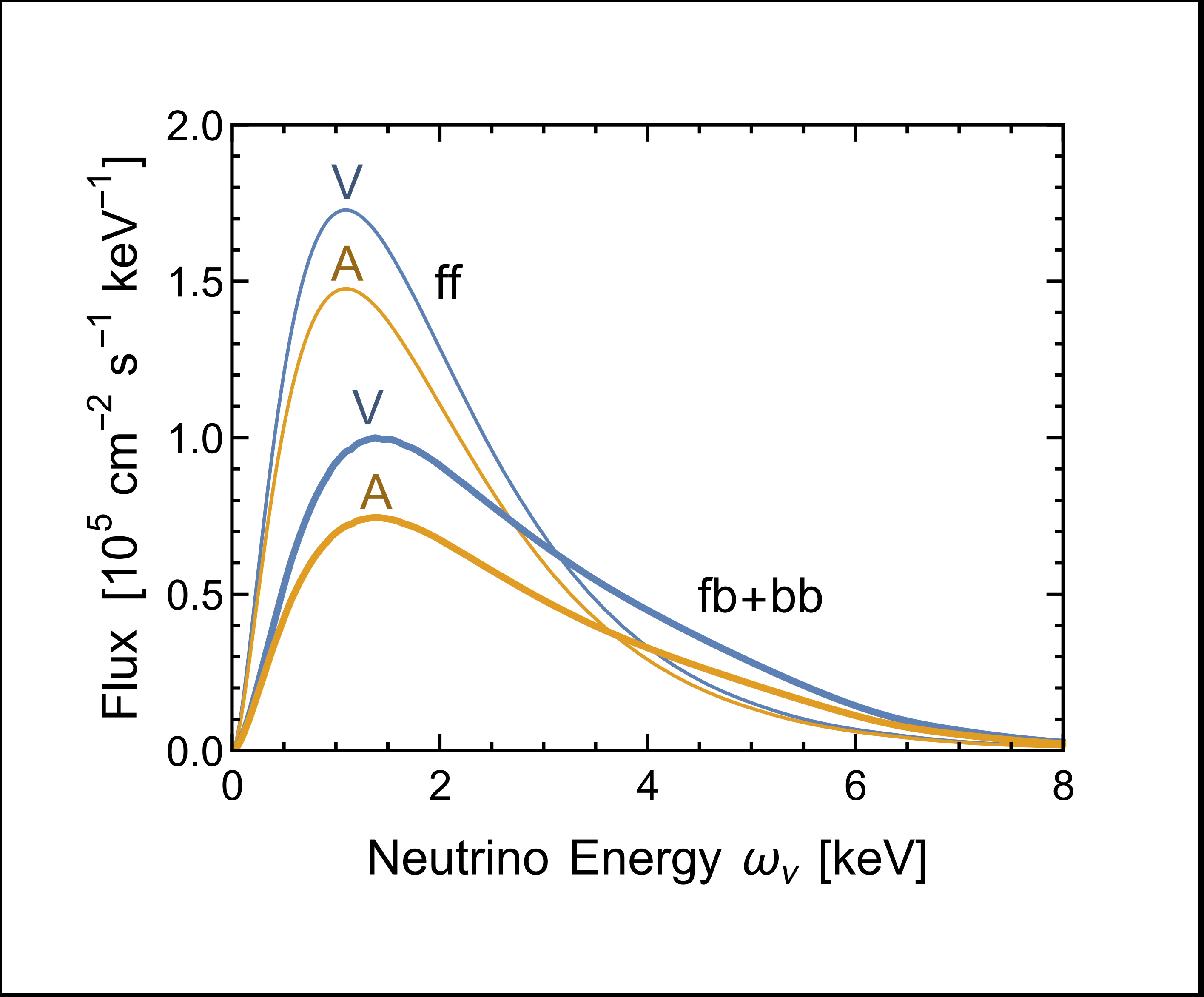


R_η
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.0
0.2
0.4
0.6
0.8
1.0
Radius [R/$R_\odot$]
$R_\eta = \frac{2}{n_e}\int \frac{d^3\mathbf{p}}{(2\pi)^3} f_\mathbf{p}(1-f_\mathbf{p})$

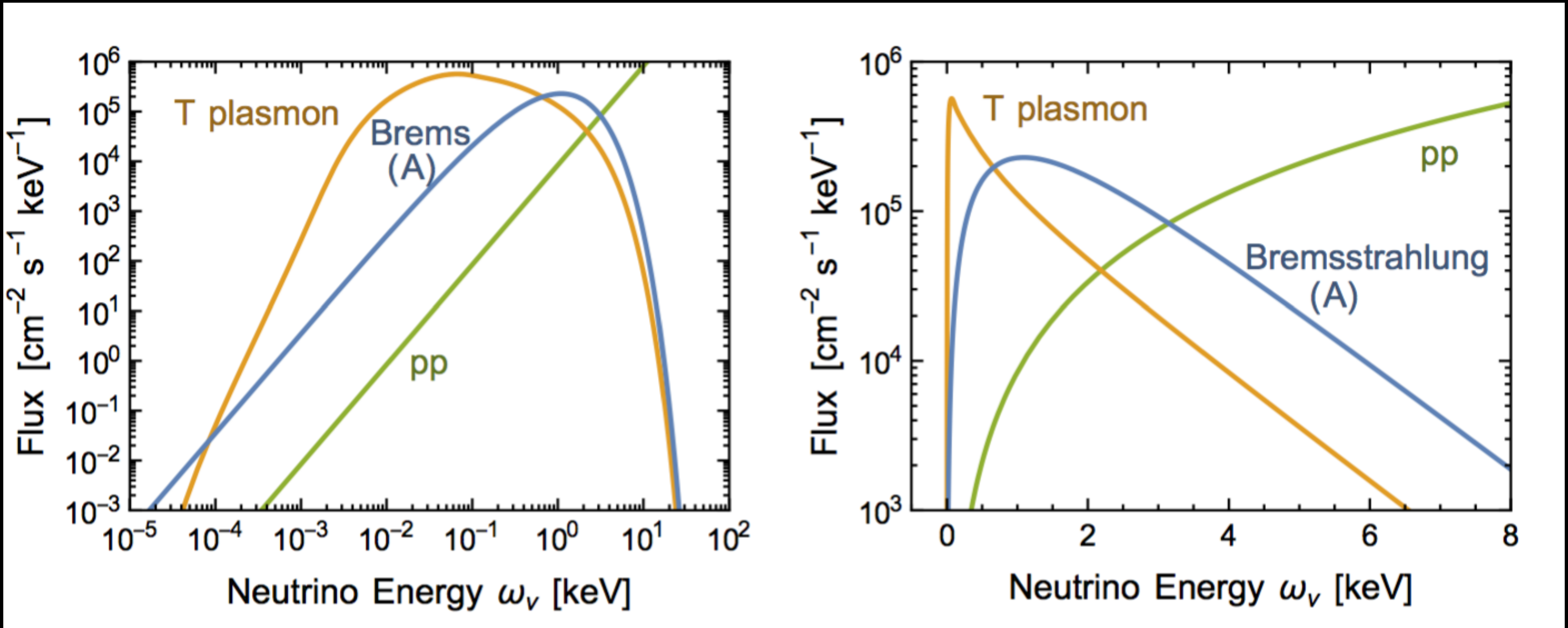


Screening scales [keV]
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
Radius [R/$R_\odot$]
$k_e^2 = R_\eta \frac{4\pi\alpha n_e}{T}$

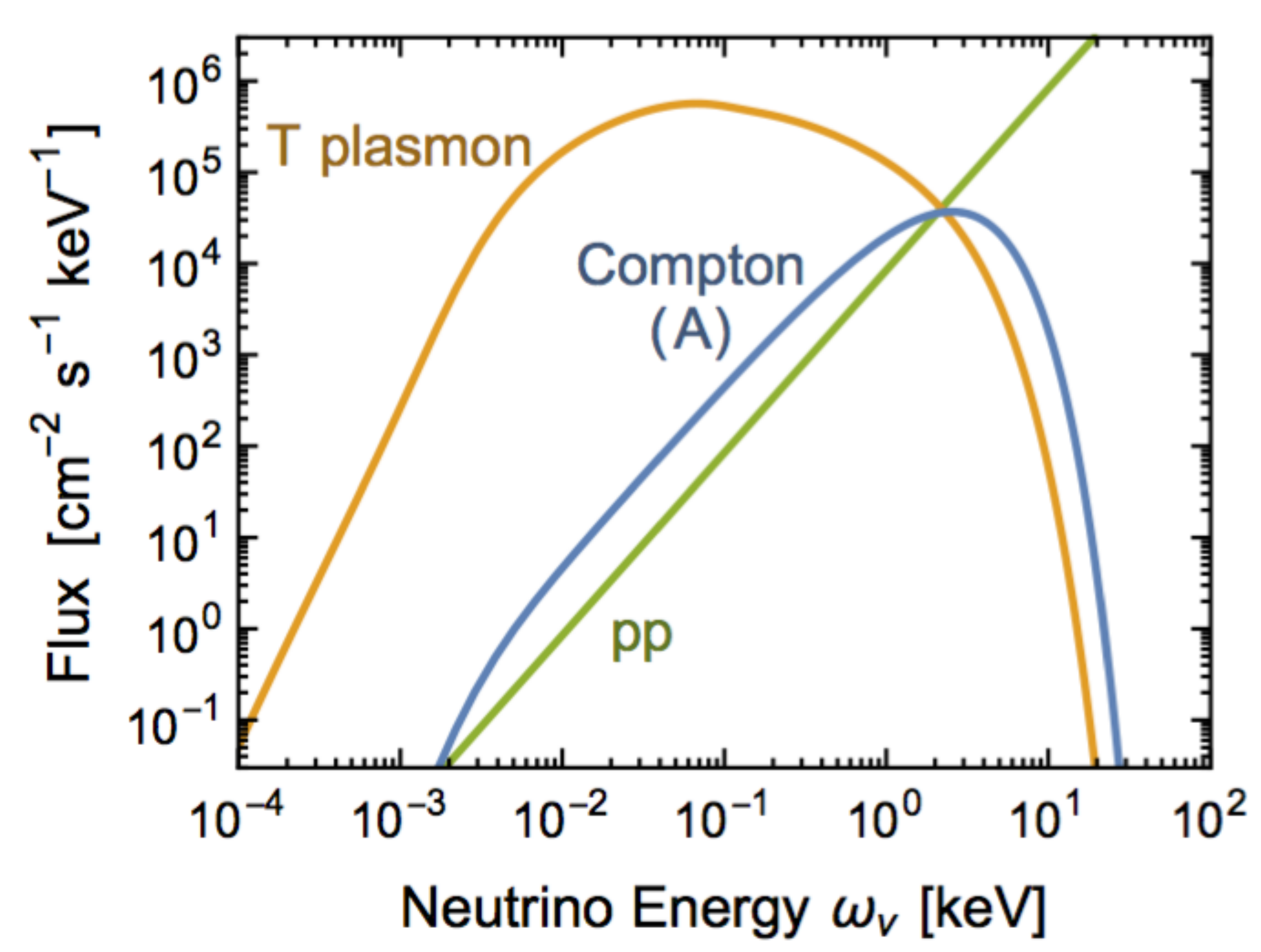
Atomic vs Bremsstrahlung (free-free) transitions

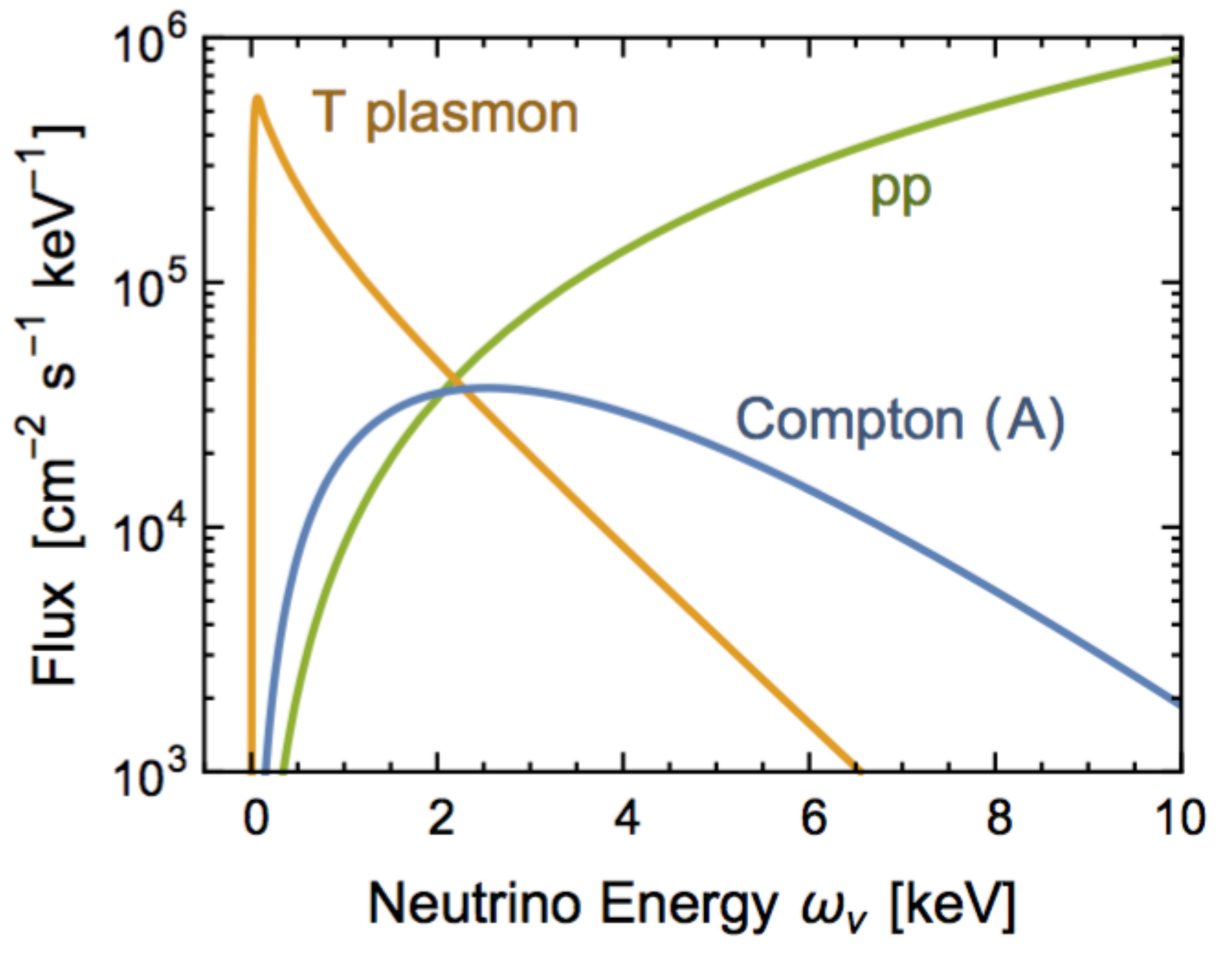


Bremsstrahlung process flux

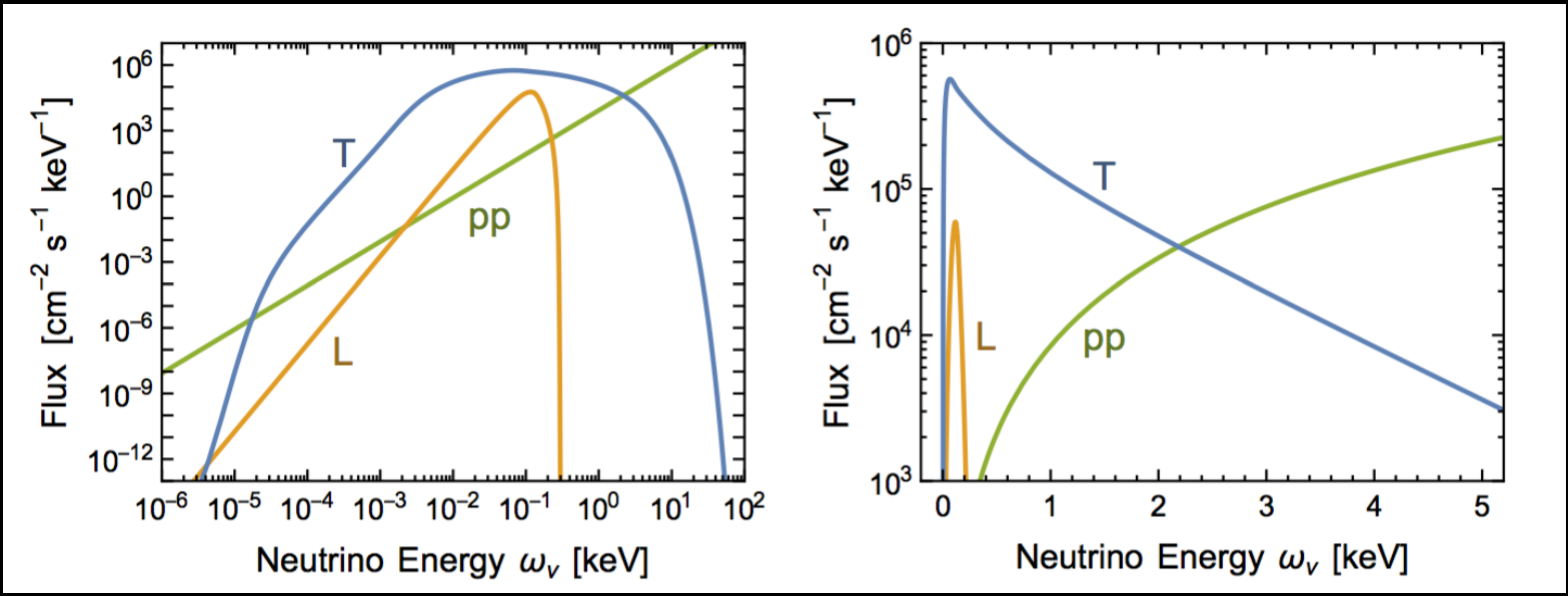


Compton process flux





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