Pheno 2017

Building on the new data

Pheno Symposia are supported by the US DOE, NSF, and PITT PACC

Astro-particle physics in a new era

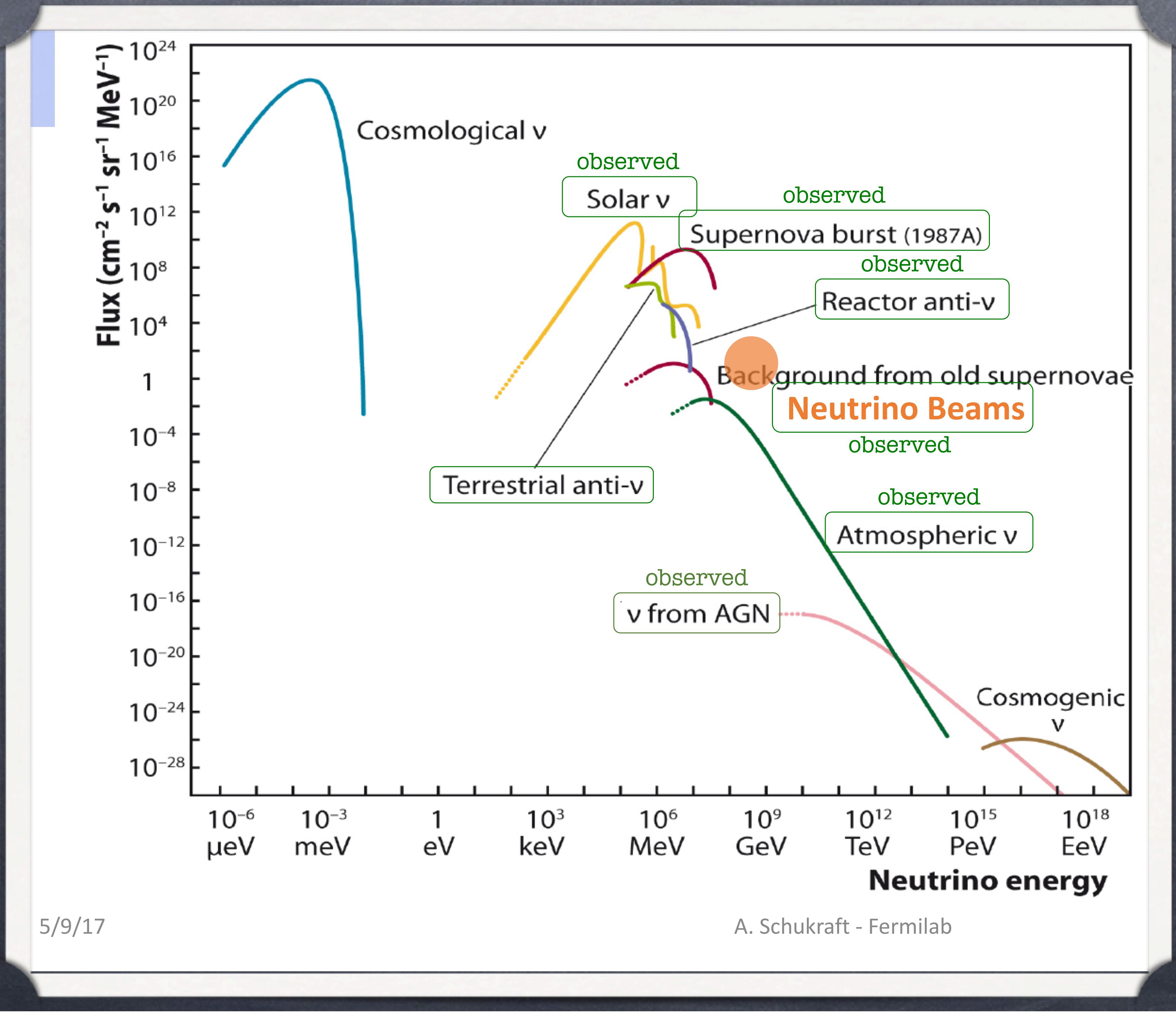
Alex Friedland

SLAC NATIONAL ACCELERATOR LABORATORY

May 10, 2017

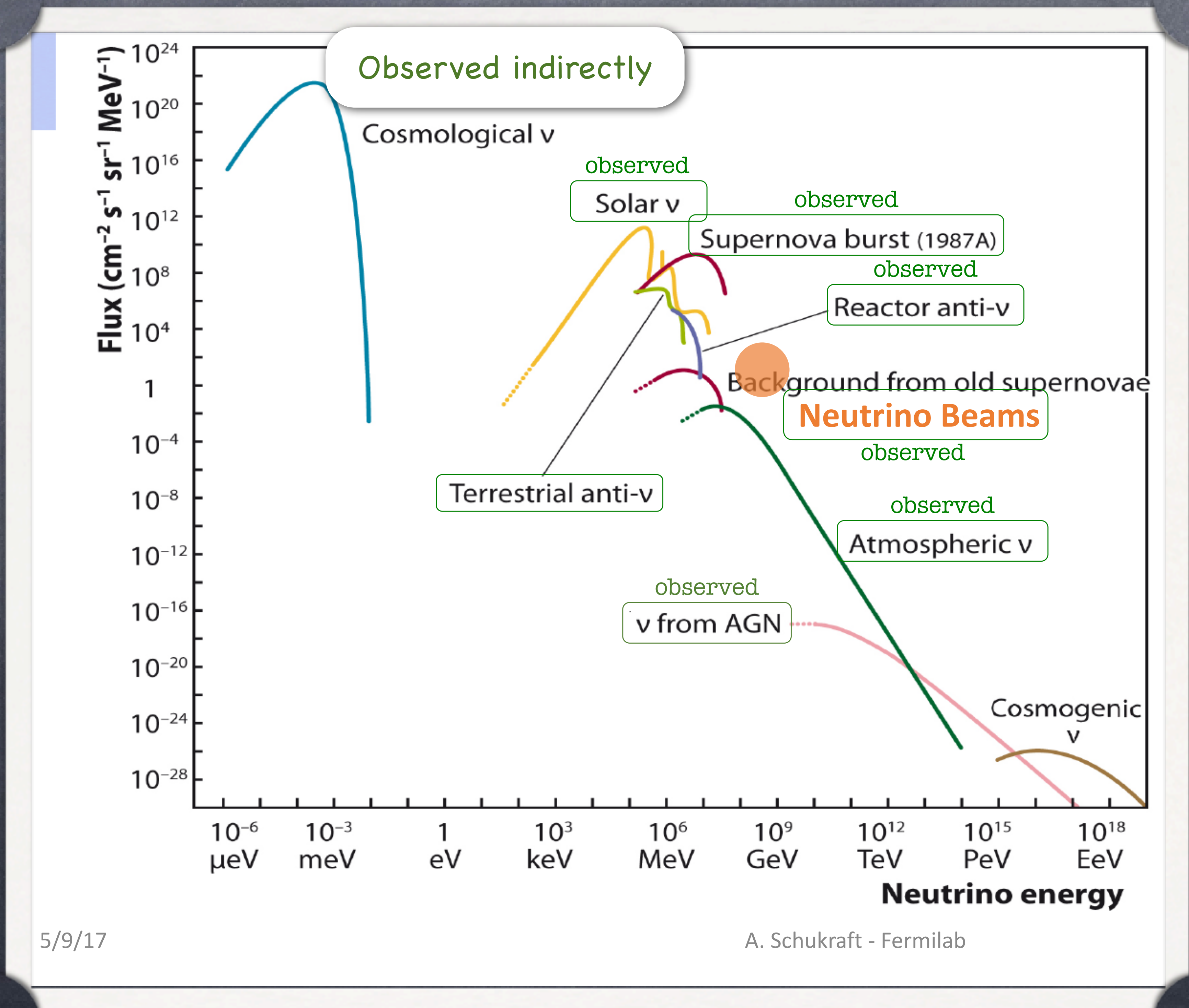
Neutrinos in the universe

(Anne Schukraft yesterday morning)



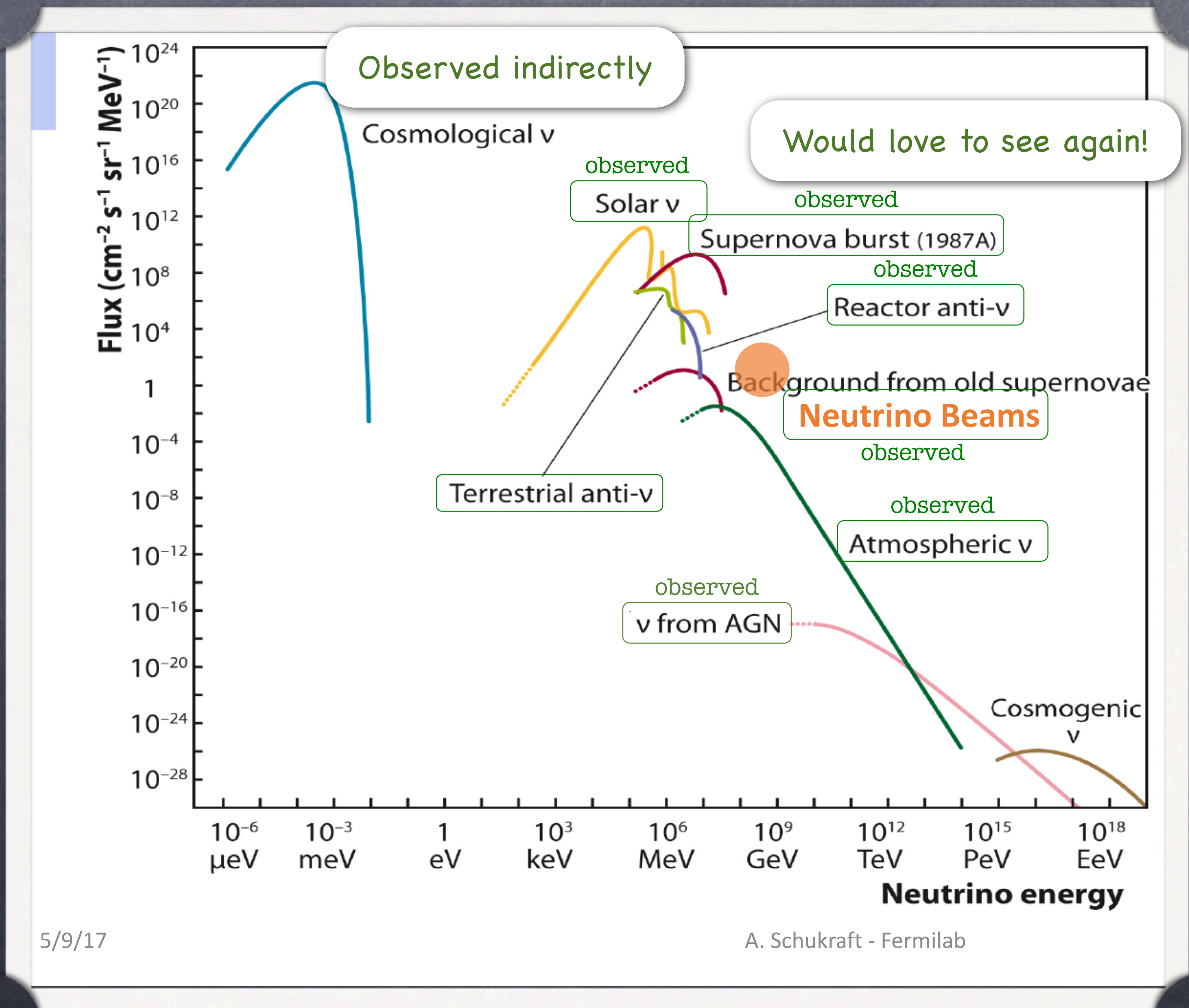
Neutrinos in the universe

(Anne Schukraft yesterday morning)



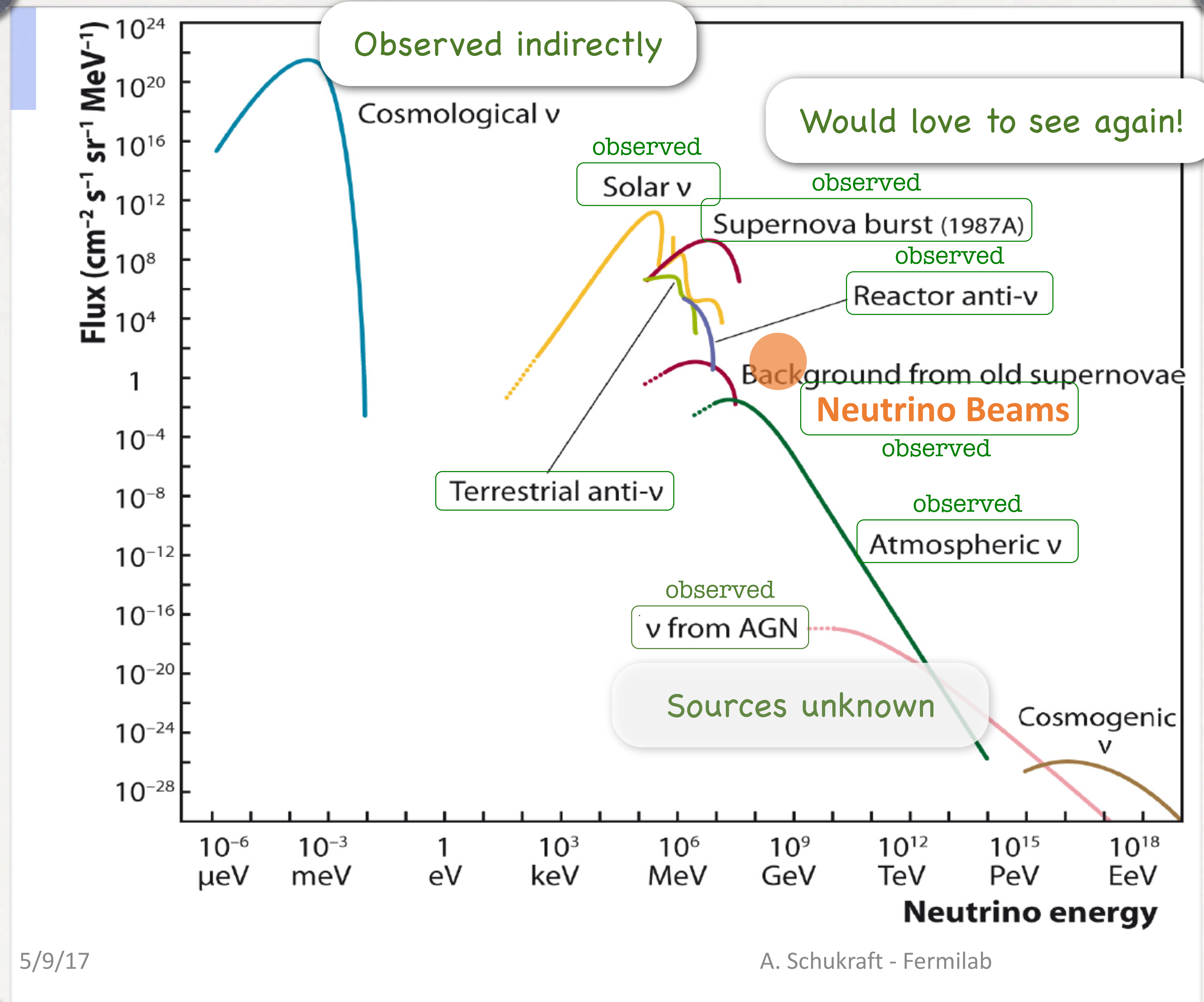
Neutrinos in the universe

(Anne Schukraft yesterday morning)



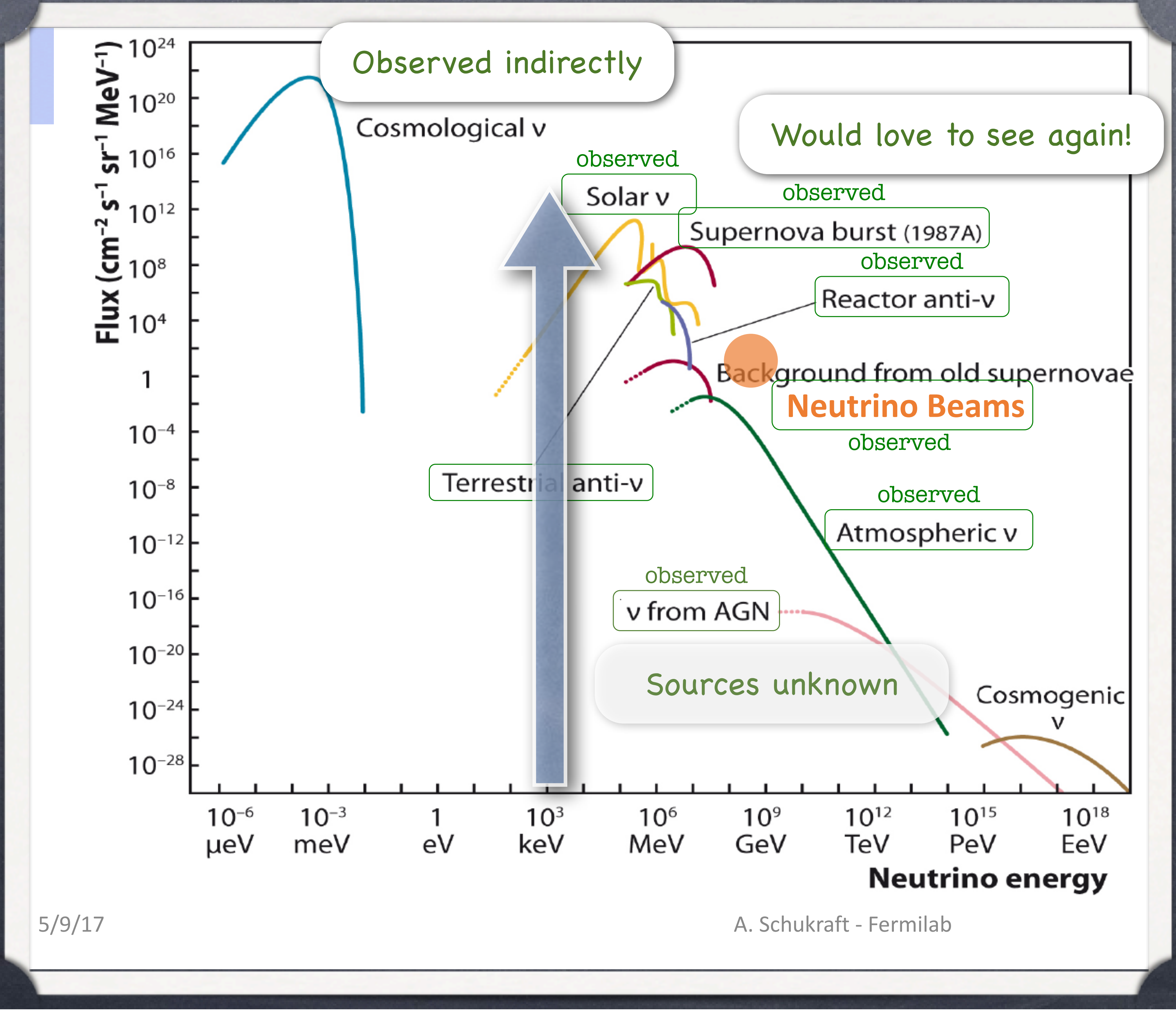
Neutrinos in the universe

(Anne Schukraft yesterday morning)



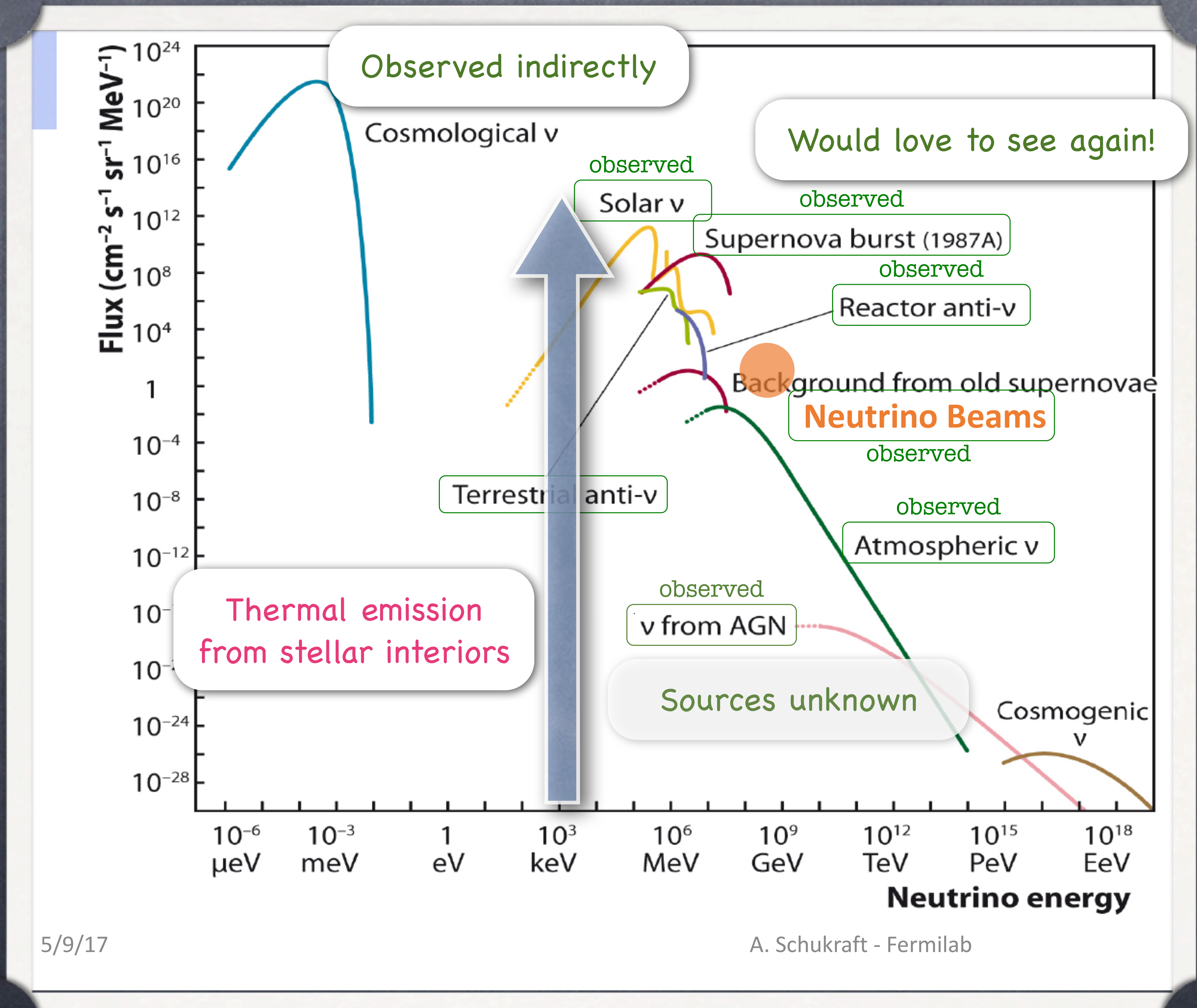
Neutrinos in the universe

(Anne Schukraft yesterday morning)



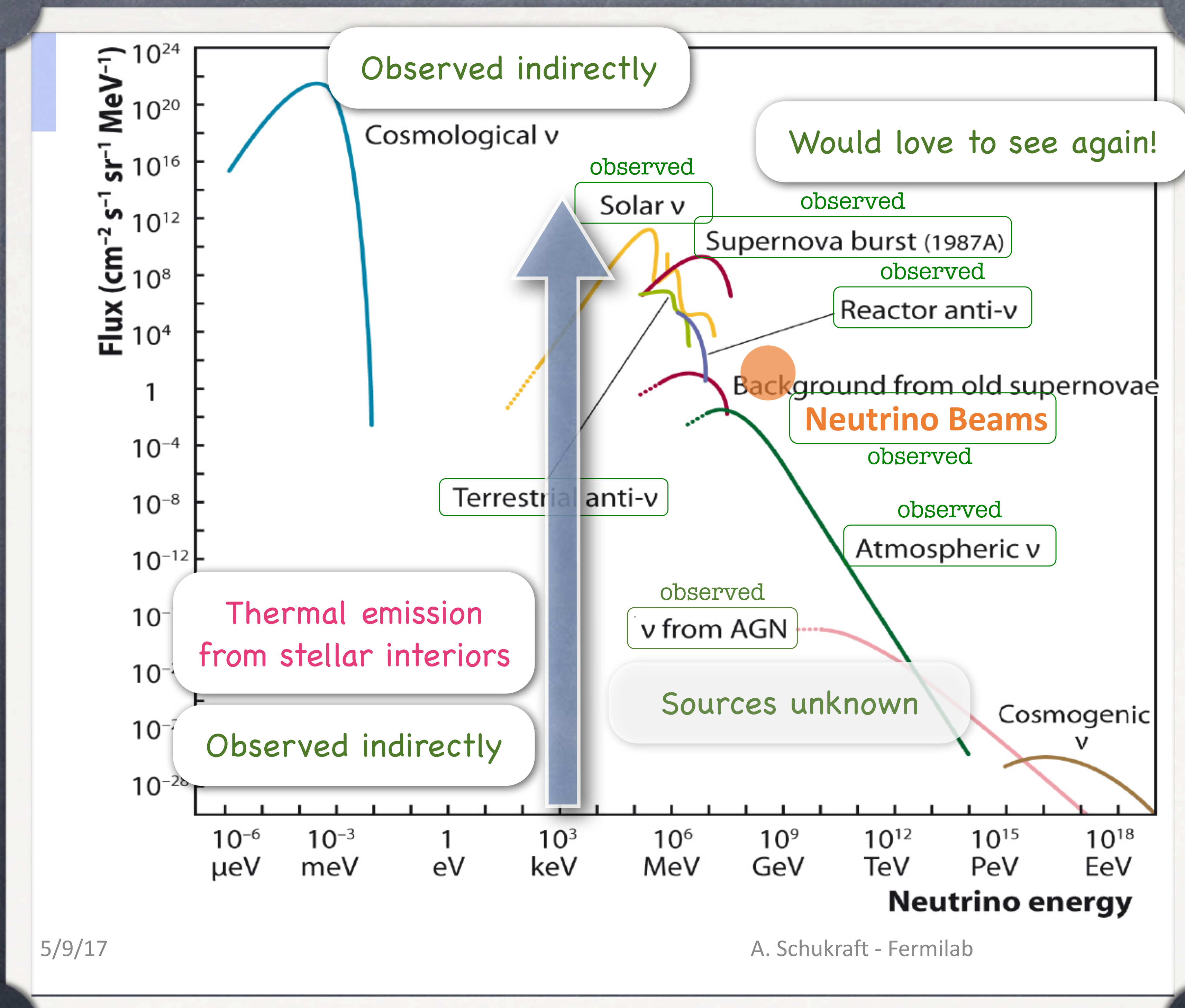
Neutrinos in the universe

(Anne Schukraft yesterday morning)

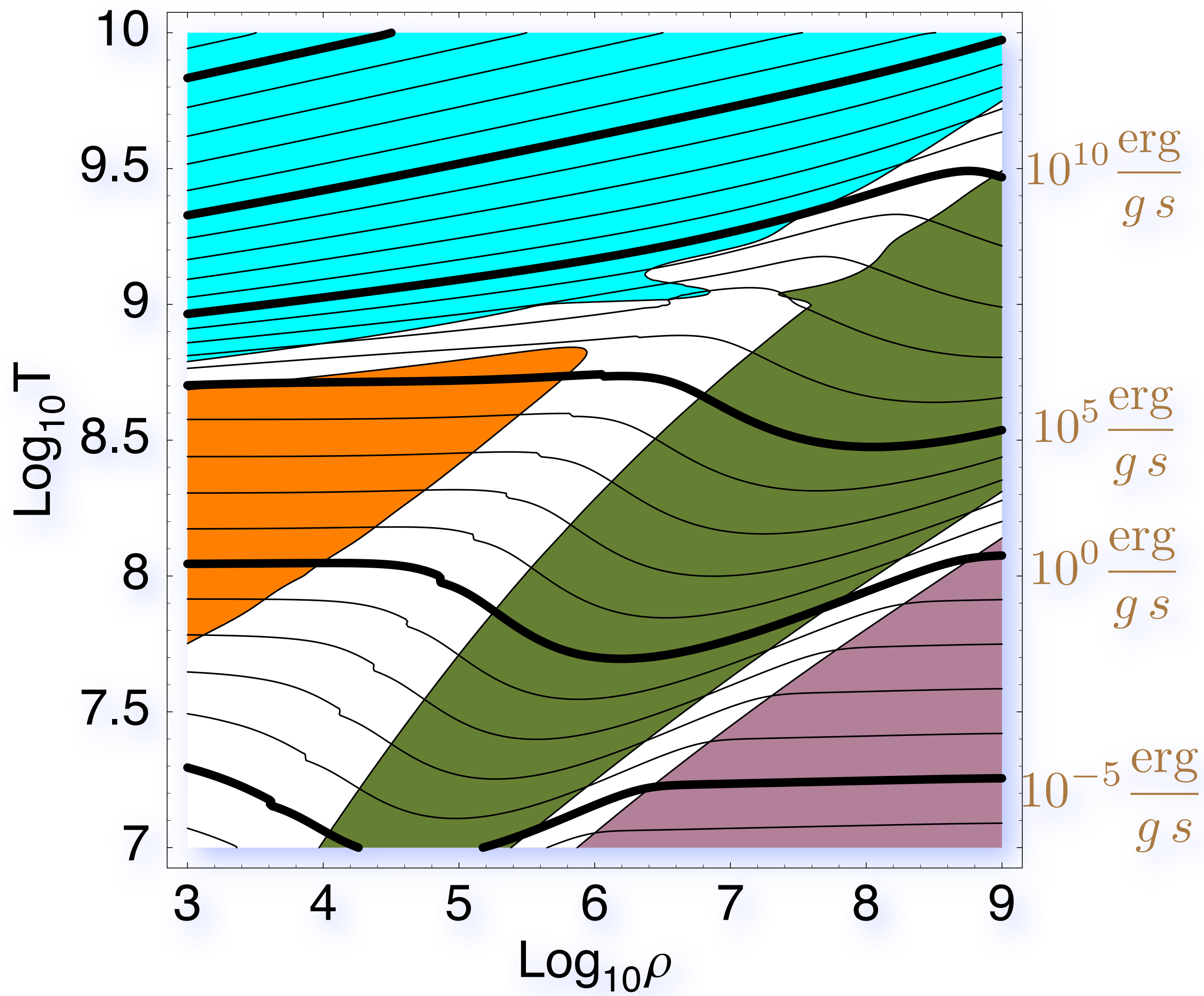


Neutrinos in the universe

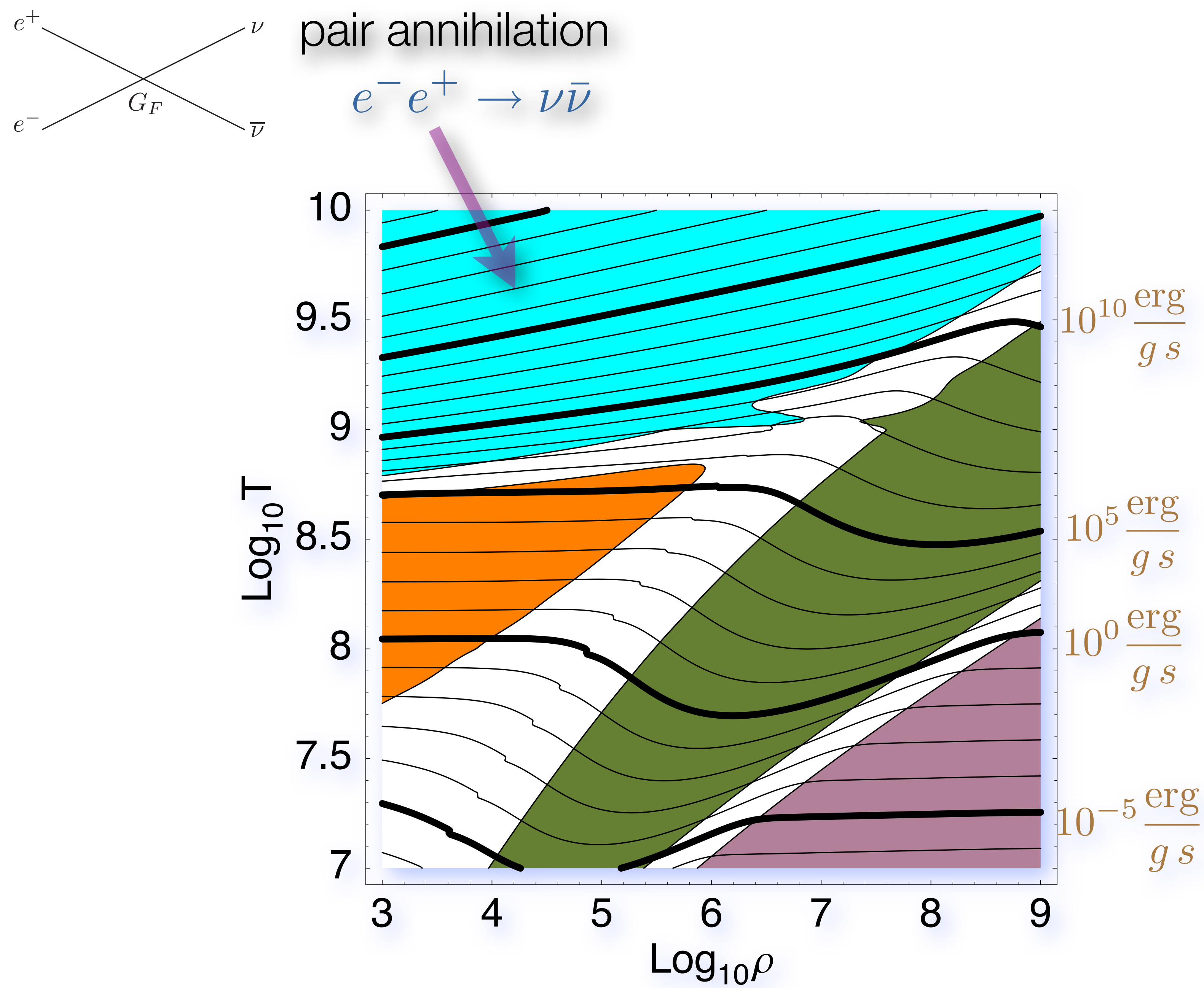
(Anne Schukraft yesterday morning)



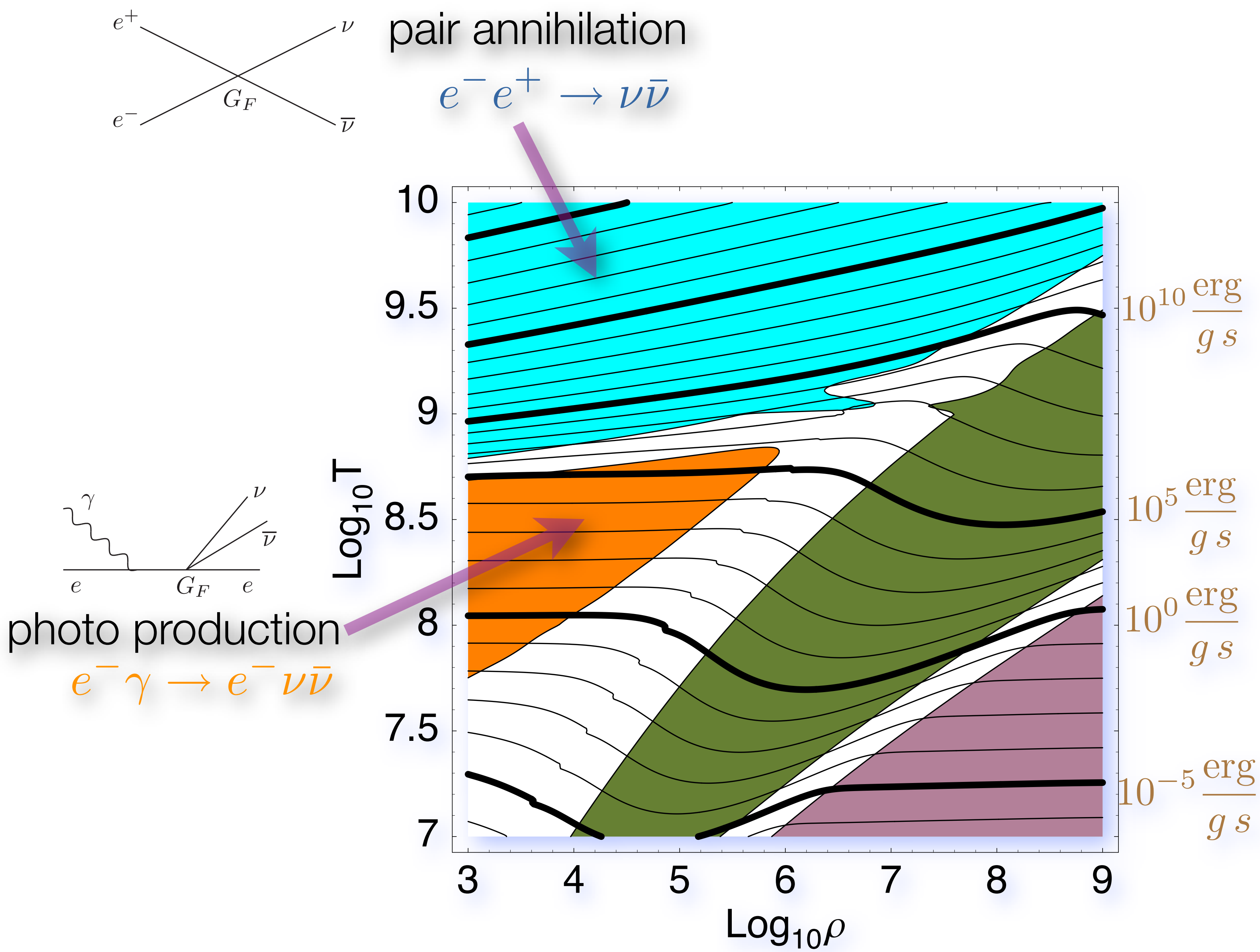
Standard neutrino cooling



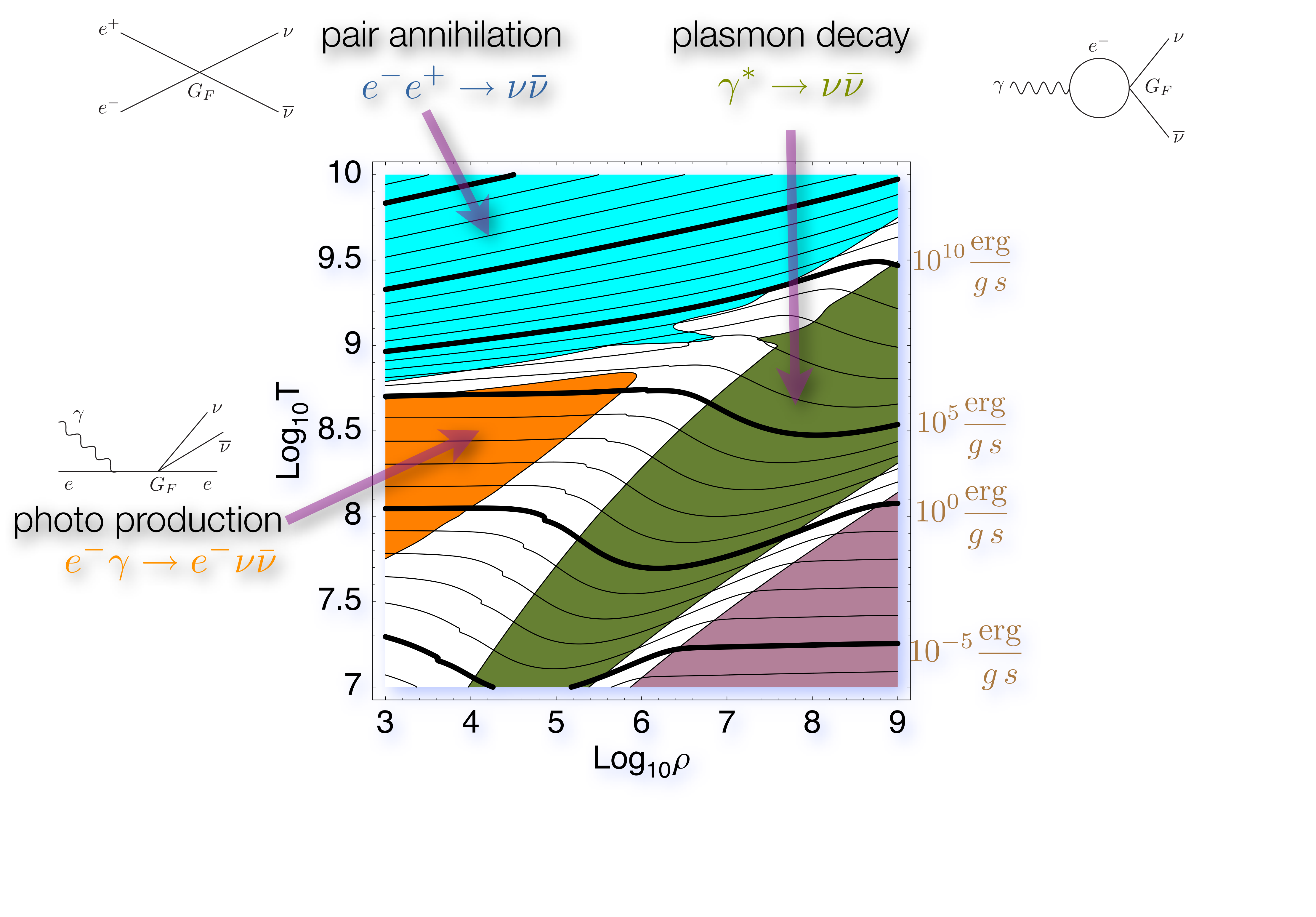
Standard neutrino cooling



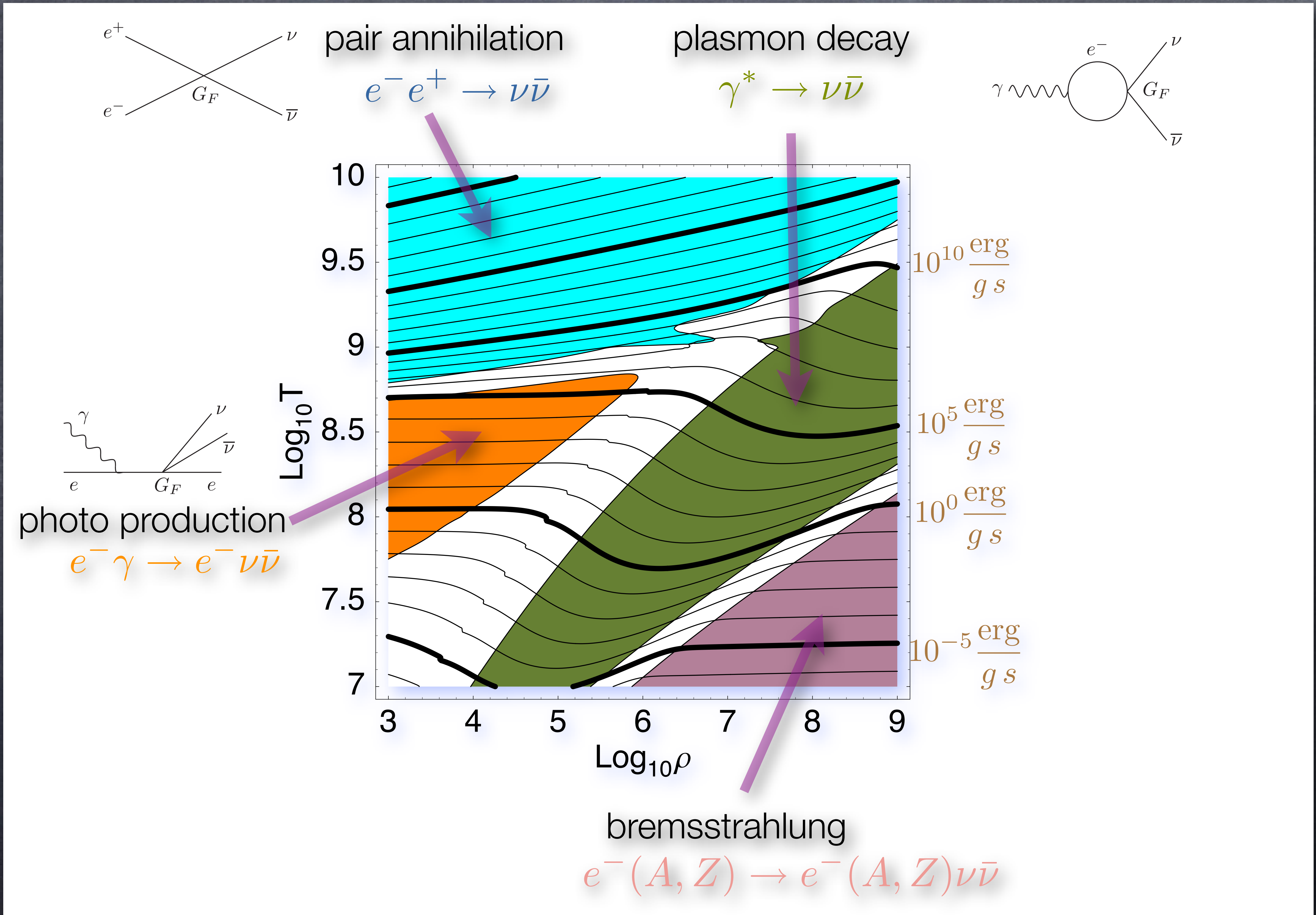
Standard neutrino cooling



Standard neutrino cooling



Standard neutrino cooling

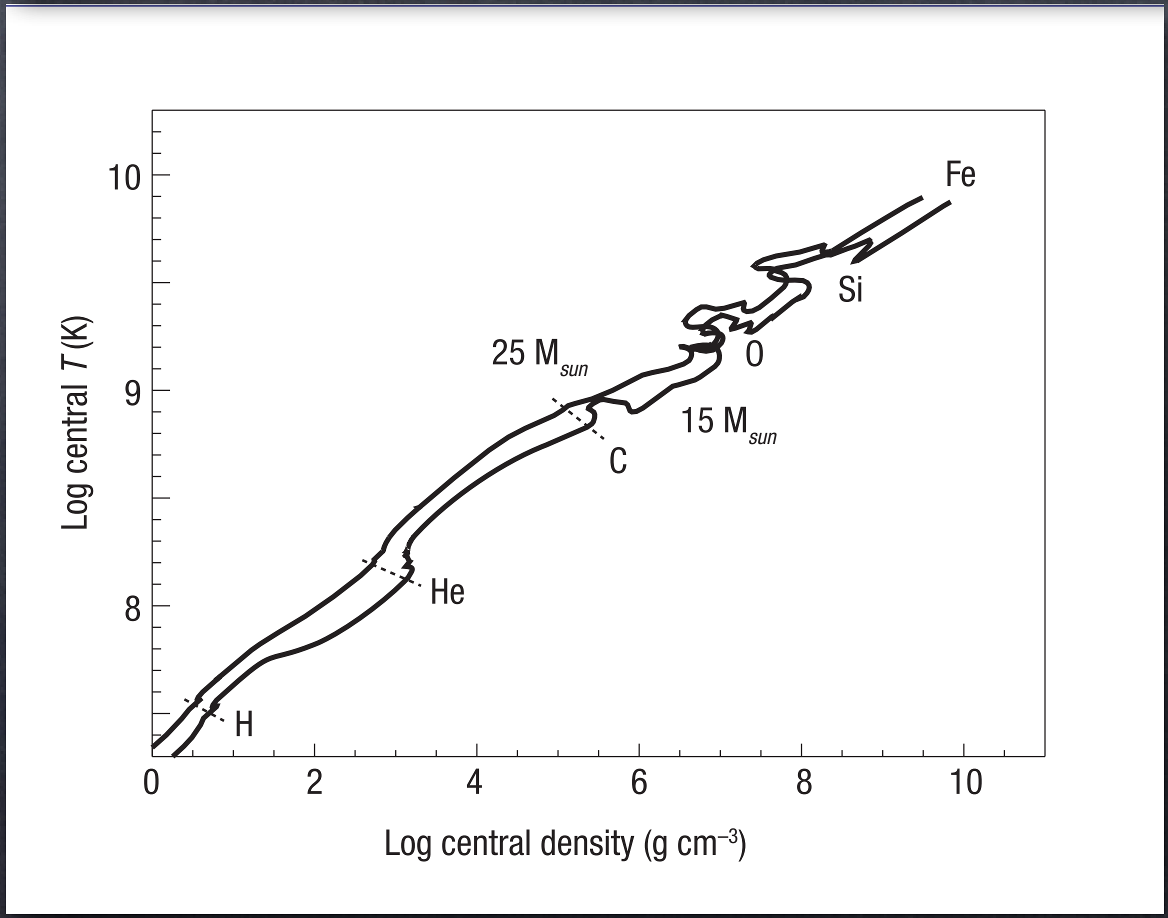


Example: Massive stars

Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, ...	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, ...	Neutron star	$>$7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.



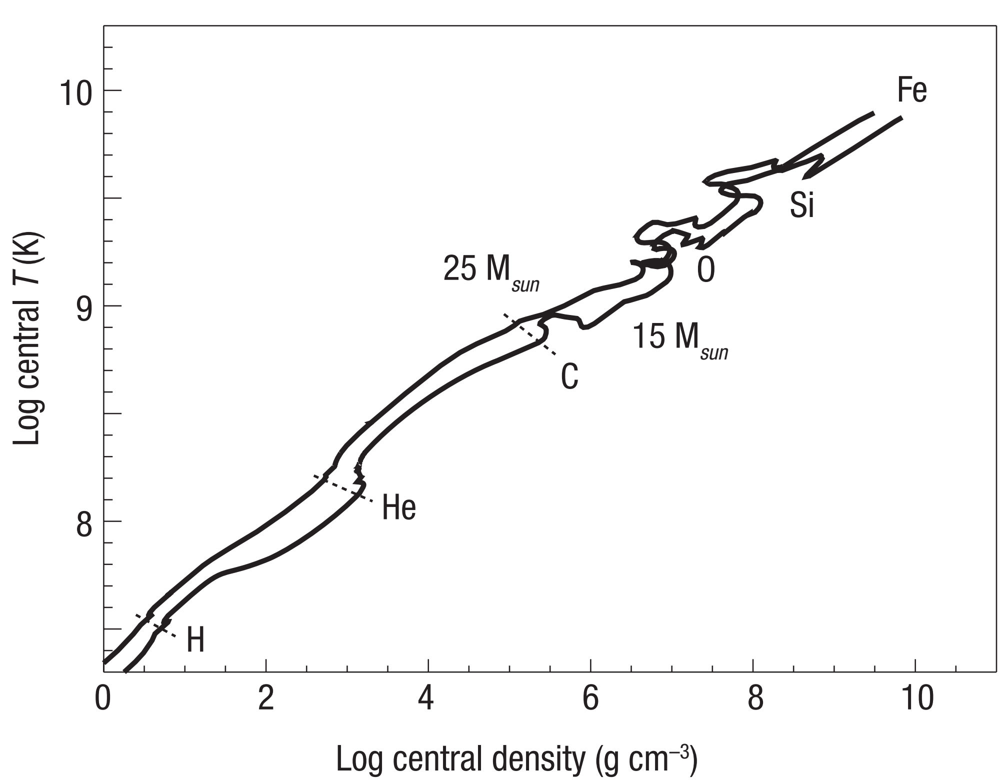
Woosley,
Janka,
Nature Physics
V. 1, p. 147 (2005)

Example: Massive stars

Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

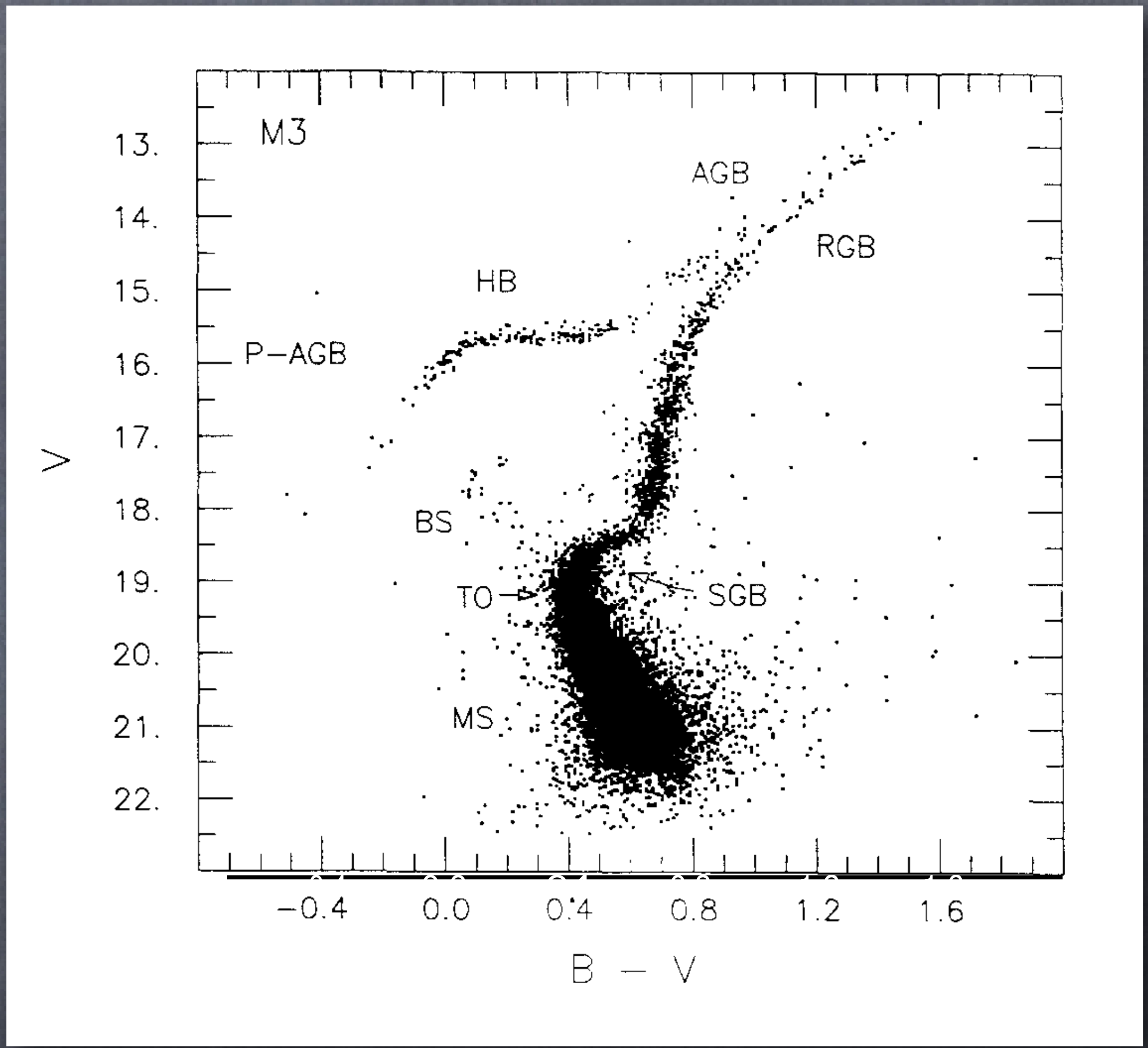
* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.



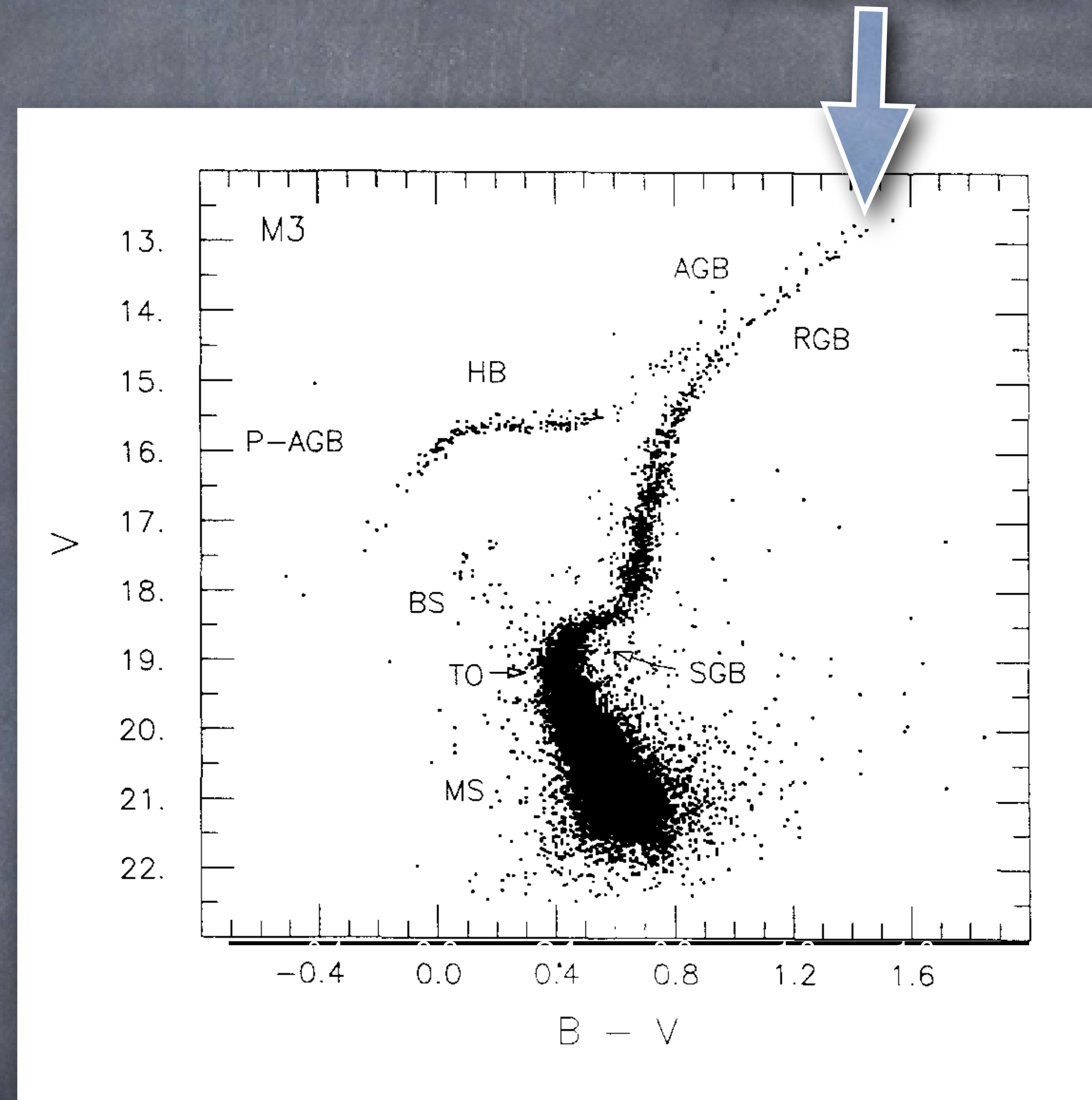
Woosley,
Janka,
Nature Physics
V. 1, p. 147 (2005)

Stars are extremely hermetic detectors

- The branching ratio for e^+e^- -> neutrino pair is
  - ~ 10^{-18} for ~ 1 MeV energies
  - Dominant mode is $e^+e^- \to \gamma\ \gamma$
- Plasmon decay γ -> neutrino pair probability between collisions is ~ 10^{-26}
- Yet, neutrino energy losses are crucial for stellar evolution

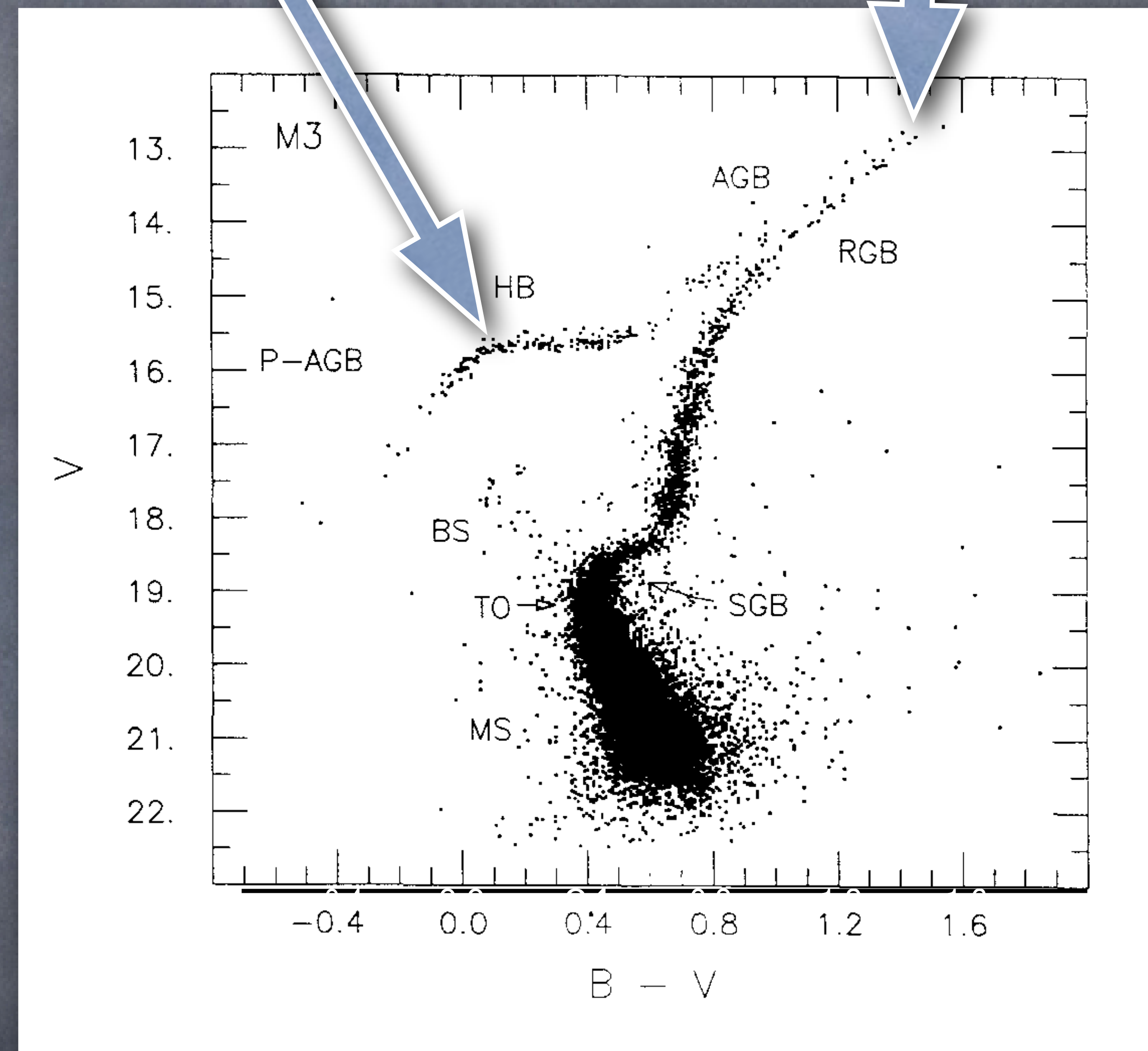

M3
AGB
RGB
HB
P–AGB
BS
TO
SGB
MS
V
B – V
13.
14.
15.
16.
17.
18.
19.
20.
21.
22.
−0.4
0.0
0.4
0.8
1.2
1.6

ν magnetic moment



ν magnetic moment

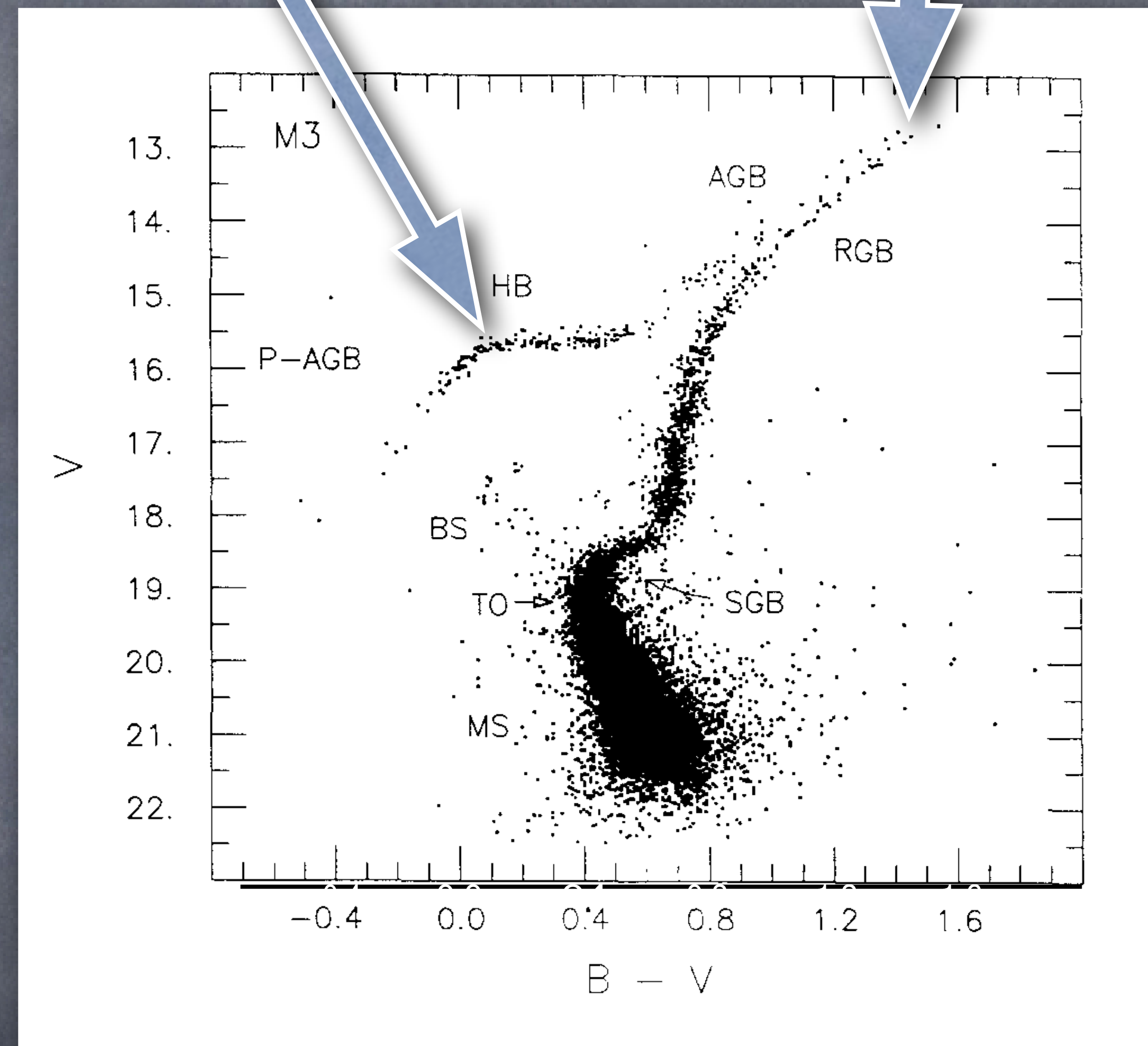
Axion-photon



ν magnetic moment

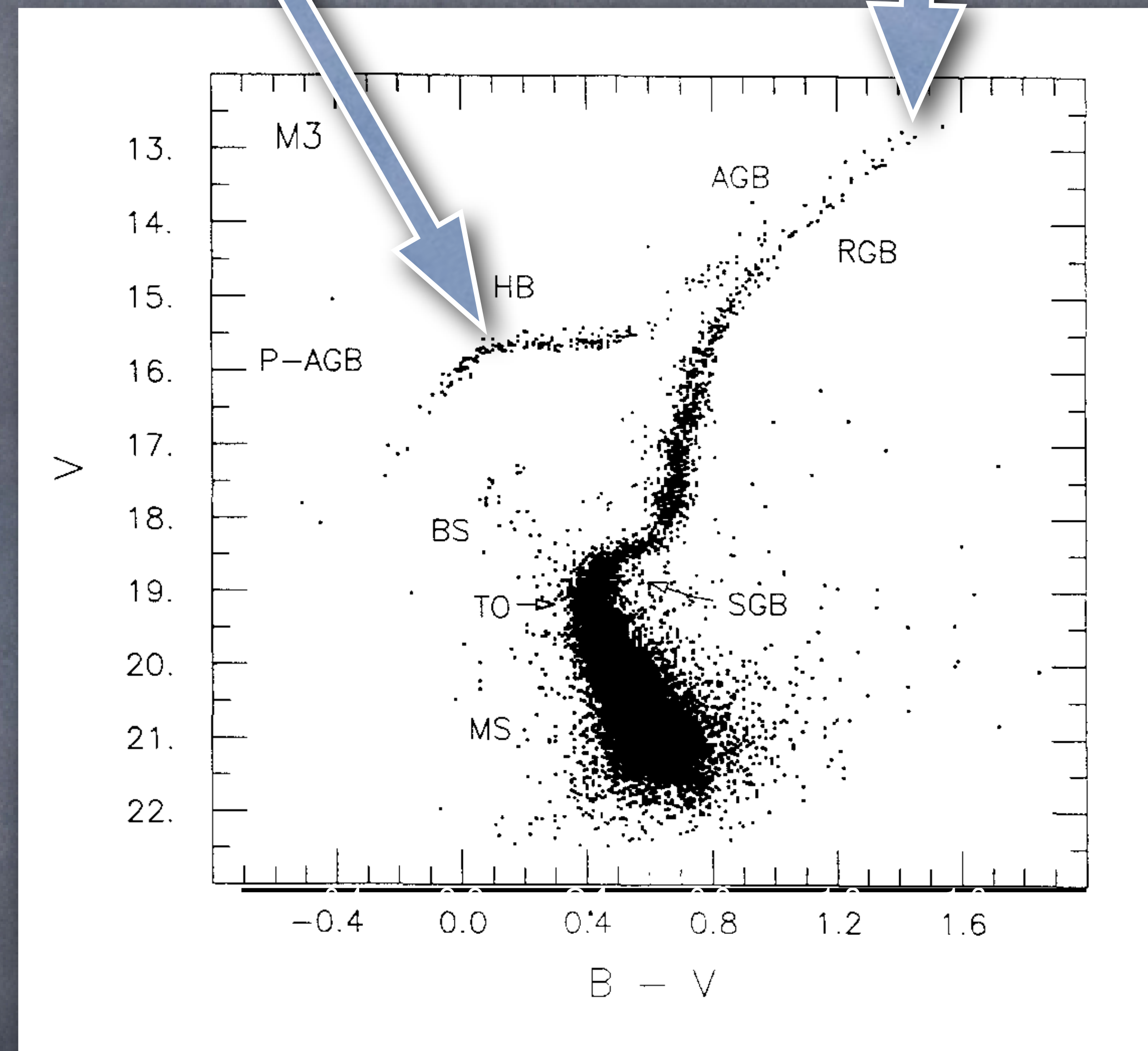
Axion-photon

Larger losses require more burning (shorter HB stage) or else greater core size before He flash

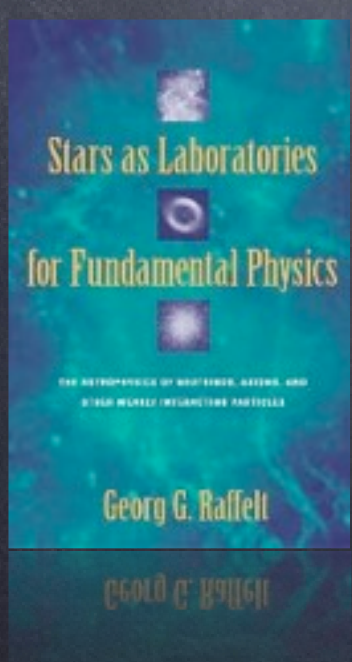


ν magnetic moment

Axion-photon



Larger losses require more burning (shorter HB stage) or else greater core size before He flash

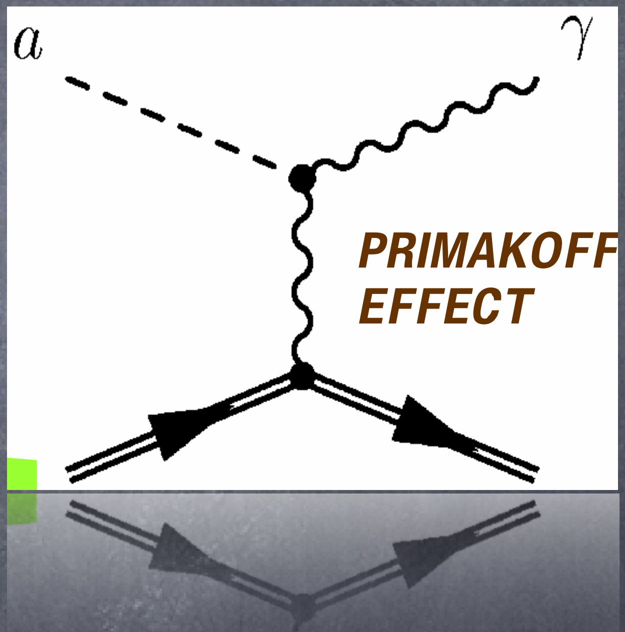


A great reference is a book by Georg Raffelt

In stellar cooling, axions are also neutrinos!

Primakoff process

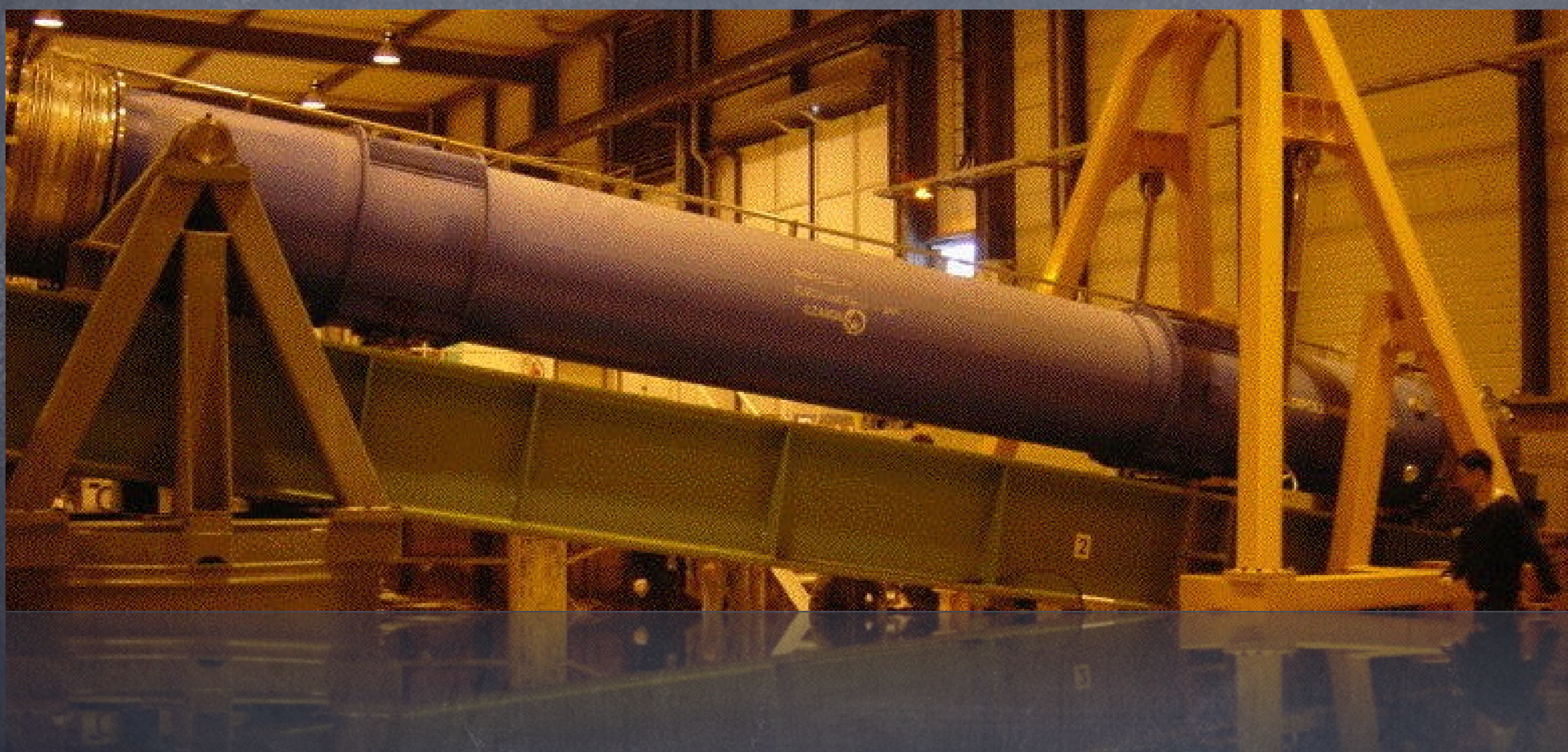
- In stars, photons would convert into axions in the background fields of nuclei
- Soft process, regulated by plasma screening (Raffelt 1986)



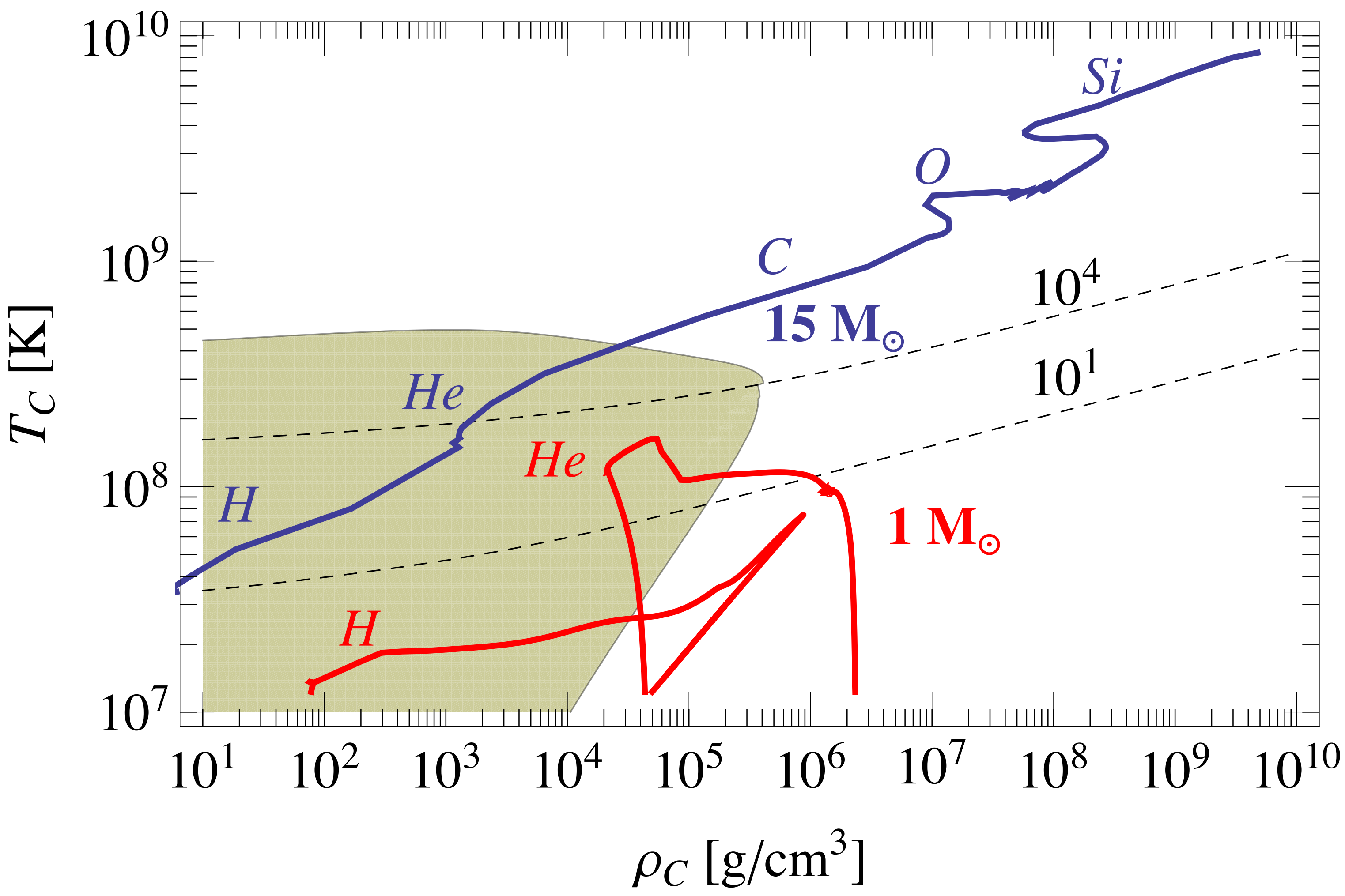
$$\epsilon_A = Z(\xi^2)\frac{G^2_{A\gamma\gamma}}{4\pi^2}\frac{T^7}{\rho} = 27.2\frac{\mathrm{erg}}{\mathrm{g\cdot s}}Z(\xi^2)g^2_{10}T^7_8\rho_3^{-1},$$

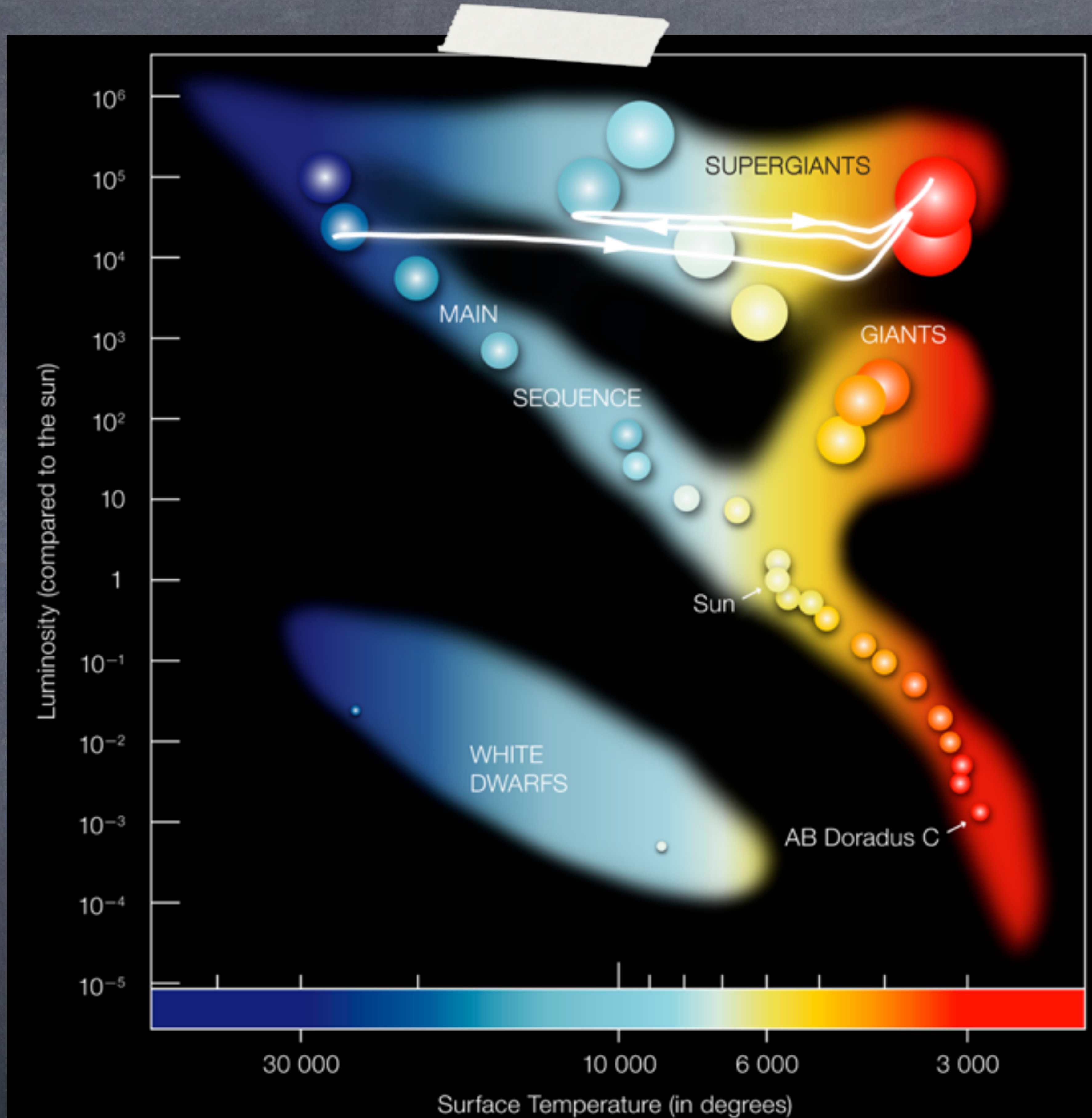
CAST axion telescope

- LHC dipole magnet, mounted to point at the Sun



Helium burning

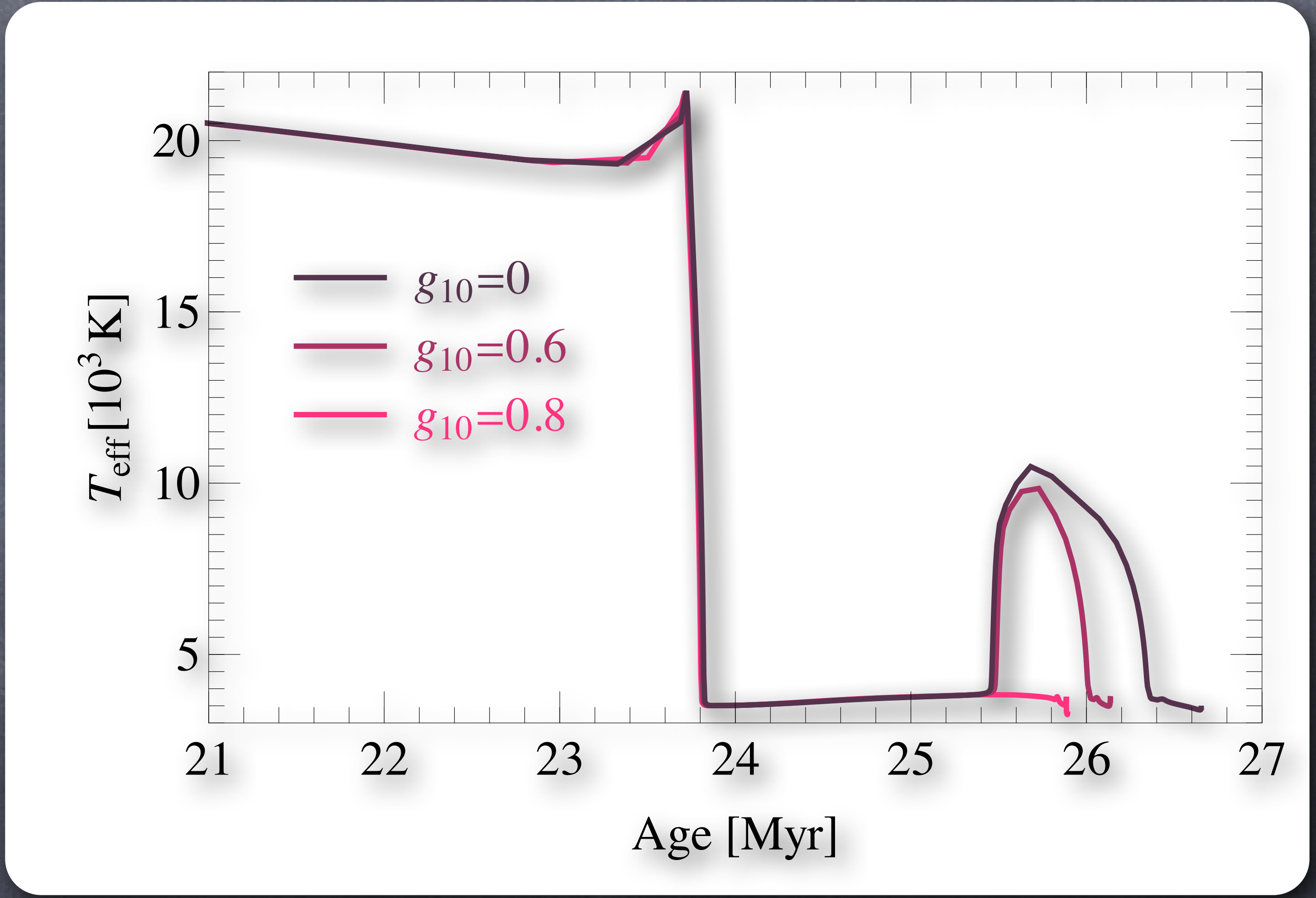




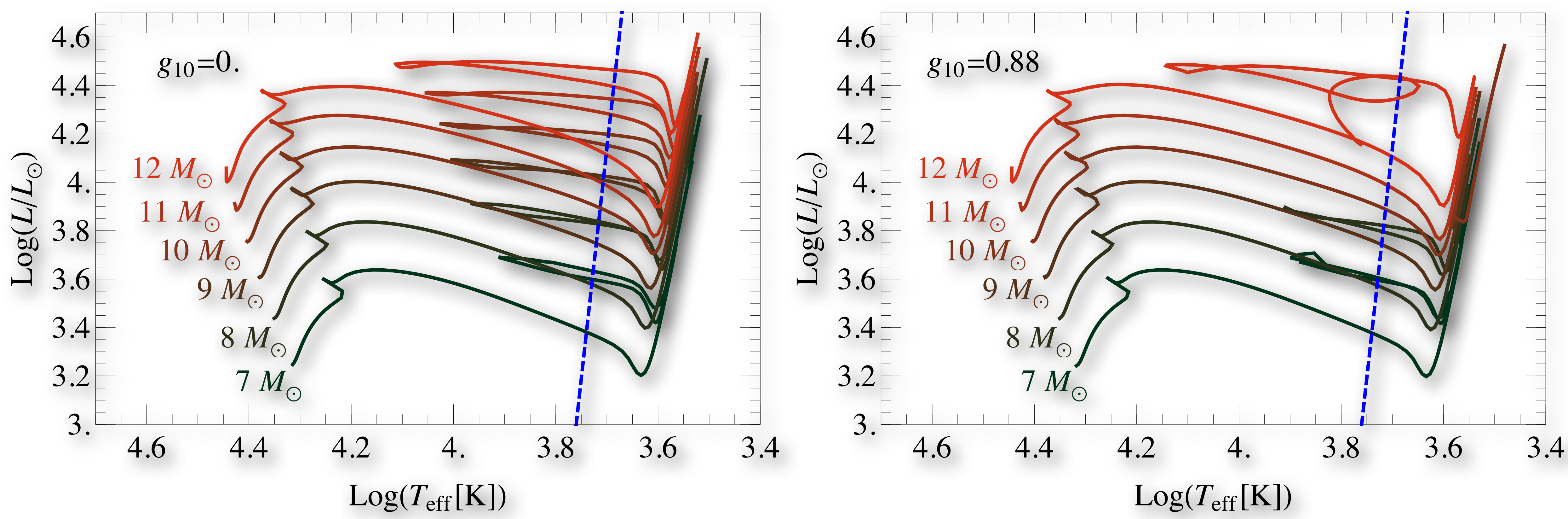
http://physics.aps.org/articles/large_image/f1/10.1103/Physics.6.14

Surface temperature, with axion cooling

- Axion cooling accelerates He burning in the center, so that the time for the blue loop never comes



No need to count stars!



- **No Cepheid variables in a range of periods**
- Details in AF, Giannotti, Wise PRL (2013)

Short-baseline, Planck and IceCube

Sterile neutrinos at oscillation experiments

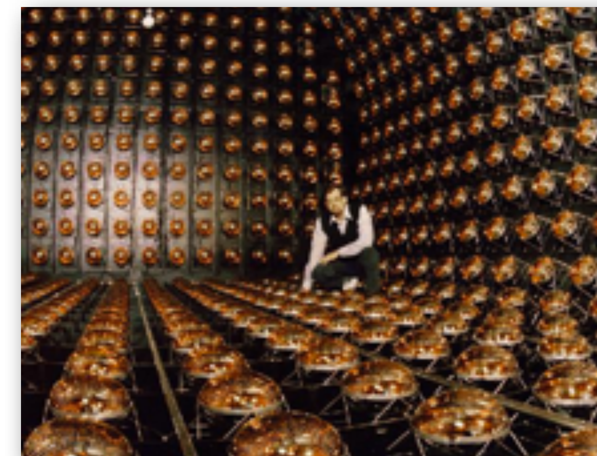
VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

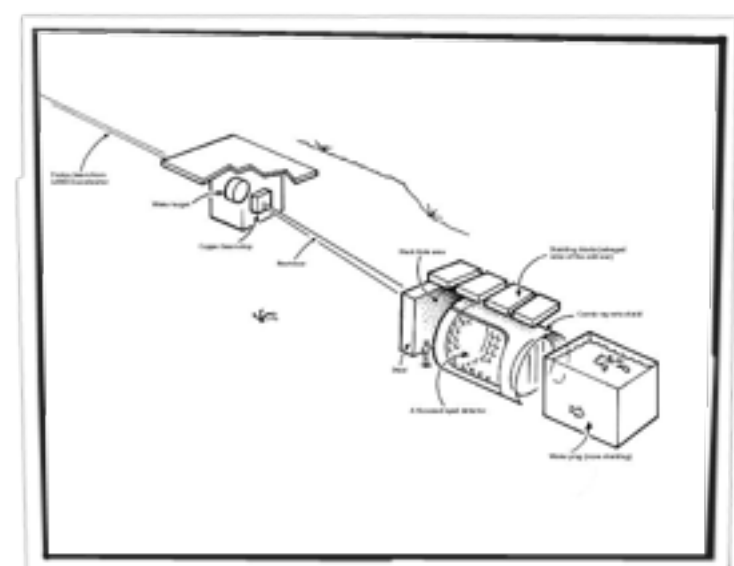
Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations from the LSND Experiment at the Los Alamos Meson Physics Facility

C. Athanassopoulos,[12] L. B. Auerbach,[12] R. L. Burman,[7] I. Cohen,[6] D. O. Caldwell,[3] B. D. Dieterle,[10] J. B. Donahue,[7] A. M. Eisner,[4] A. Fazely,[11] F. J. Federspiel,[7] G. T. Garvey,[7] M. Gray,[3] R. M. Gunasingha,[8] R. Imlay,[8] K. Johnston,[9] H. J. Kim,[8] W. C. Louis,[7] R. Majkic,[12] J. Margulies,[12] K. McIlhany,[1] W. Metcalf,[8] G. B. Mills,[7] R. A. Reeder,[10] V. Sandberg,[7] D. Smith,[5] I. Stancu,[1] W. Strossman,[1] R. Tayloe,[7] G. J. VanDalen,[1] W. Vernon,[2,4] N. Wadia,[8] J. Waltz,[5] Y-X. Wang,[4] D. H. White,[7] D. Works,[12] Y. Xiao,[12] S. Yellin[3]

LSND Collaboration

[1] University of California, Riverside, California 92521



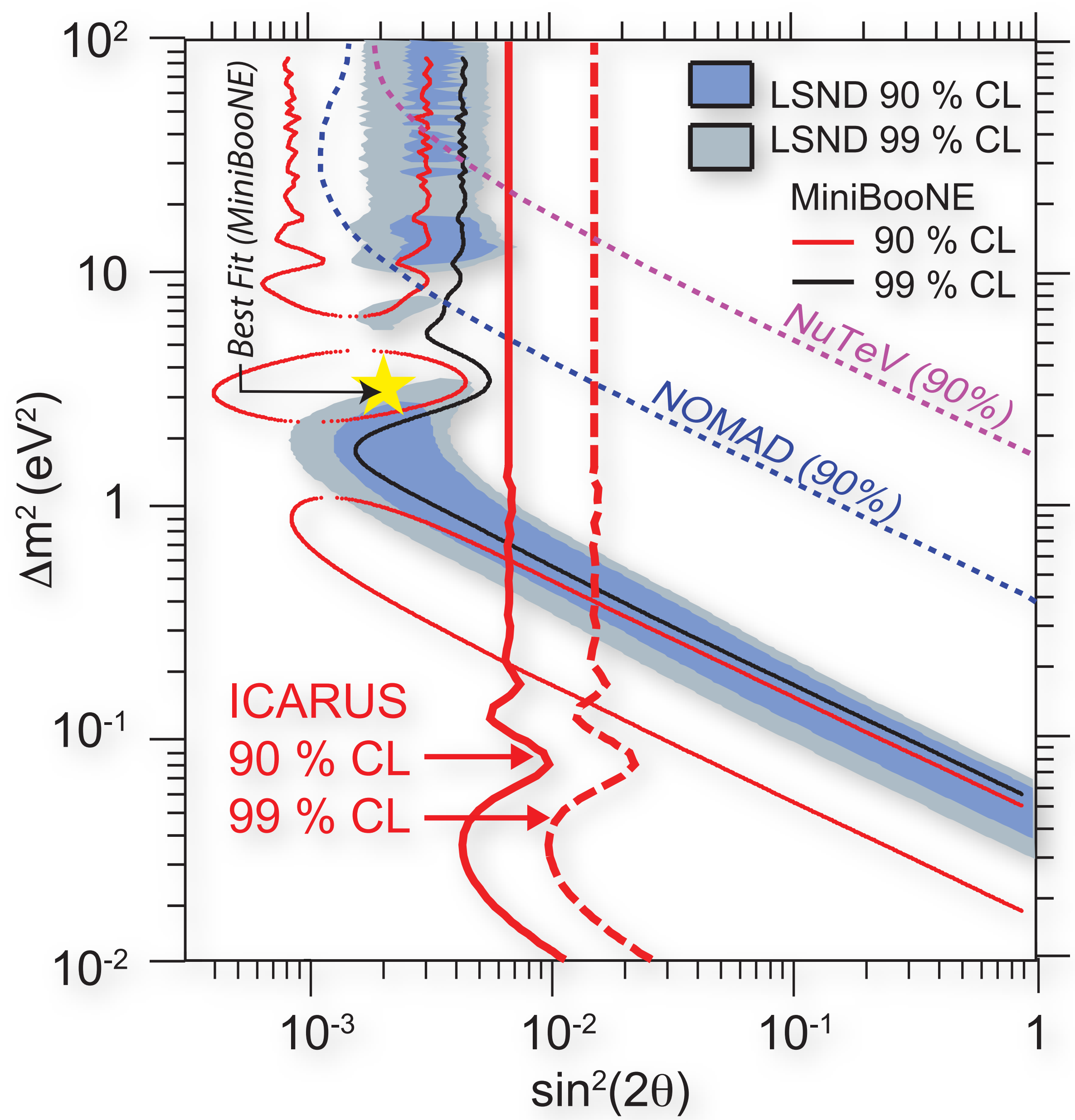


(Received 9 May 1996)

A search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility by using $\overline{\nu}_\mu$ from μ^+ decay at rest. The $\overline{\nu}_e$ are detected via the reaction $\overline{\nu}_e\, p \rightarrow e^+\, n$, correlated with a γ from $np \rightarrow d\gamma$ (2.2 MeV). The use of tight cuts to identify e^+ events with correlated γ rays yields 22 events with e^+ energy between 36 and 60 MeV and only 4.6 ± 0.6 background events. A fit to the e^+ events between 20 and 60 MeV yields a total excess of $51.0^{+20.2}_{-19.5} \pm 8.0$ events. If attributed to $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31 \pm 0.12 \pm 0.05)\%$. [S0031-9007(96)01375-0]

Short-baseline oscillations?

- Hints for $\Delta m^2 \sim$ 1-3 eV^2
  - Accumulated by a number of experiments: LSND, MiniBOONE, reactor data
  - While a number of other oscillation searches have obtained valuable constraints (ICARUS, IceCube, etc), no conclusive resolution after two decades
  - See, e.g., C. Giunti, arXiv: 1609.04688 for review



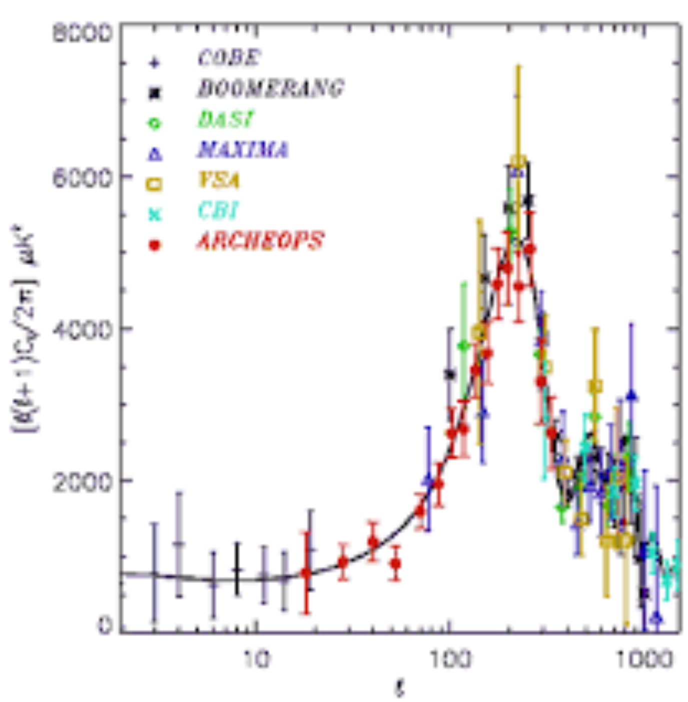
ICARUS, 1307.4699

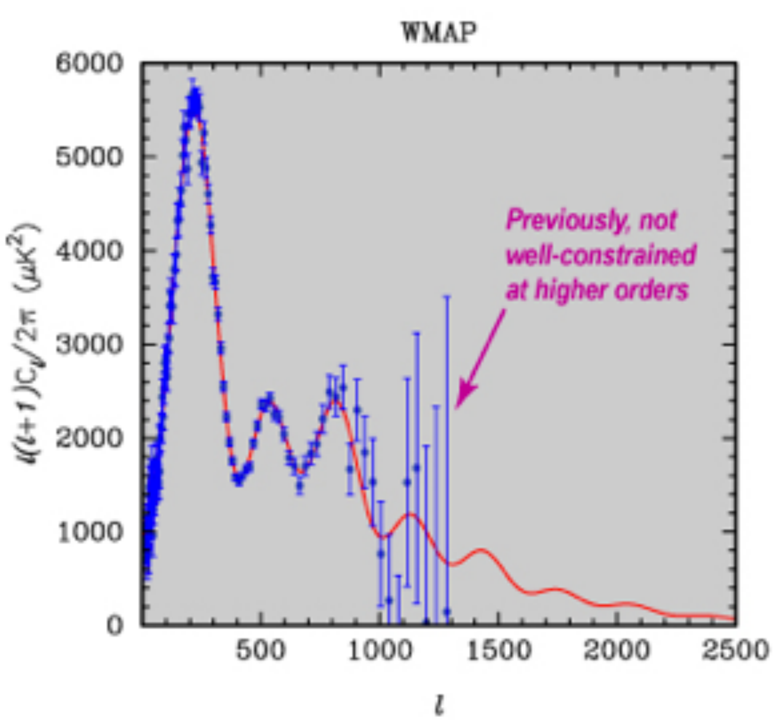
Sterile neutrinos: cosmological problems?

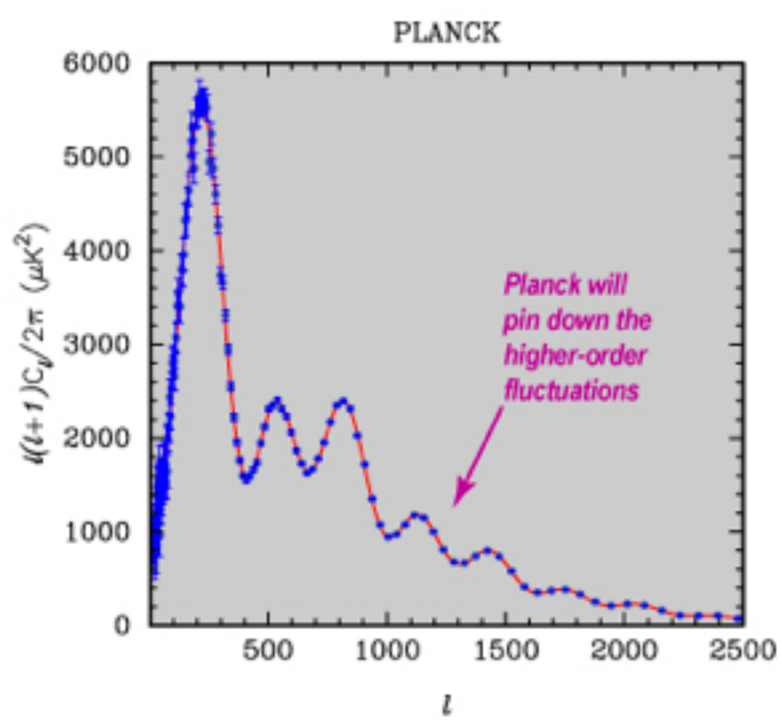
- Recent results from Planck measure relativistic energy density in the universe at matter/rad equality -> CMB decoupling

- Planck 2015 [arXiv:1502.01589] reports $N_{eff}=3.15\pm0.23$ and for the mass $m_\nu < 0.23$ eV

- *Are sterile neutrinos that the SBN program plans to search for already ruled out by cosmology?*

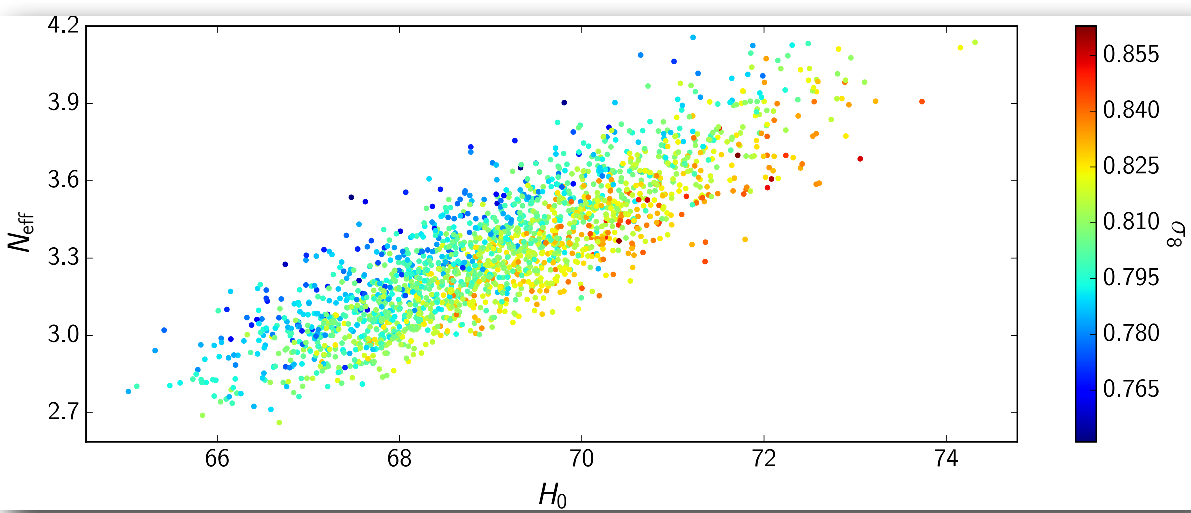






Window into new physics?

- If the new neutrinos are truly sterile, they will fully thermalize with the SM
- However, if they have interactions of their own, these interactions could induce a MSW potential that would suppress mixing in the early universe
    - Babu & Rothstein, Phys.Lett. (1992) + many since
- BUT thermalization cannot be delayed below $T_0 \sim (\sin^2 2\theta (\Delta m^2)^2 M_{pl})^{1/5} \sim 200 \text{ keV}$ close to weak freezeout (1 MeV) -> fractional N_eff will be produced
    - Cherry, A. F., Shoemaker, arXiv:1605.06506
- This may help to fit the data better. (Local measurements of the Hubble constant are higher than what is preferred by Planck in standard cosmology



Will be conclusively tested by CMB-Stage4 experiment

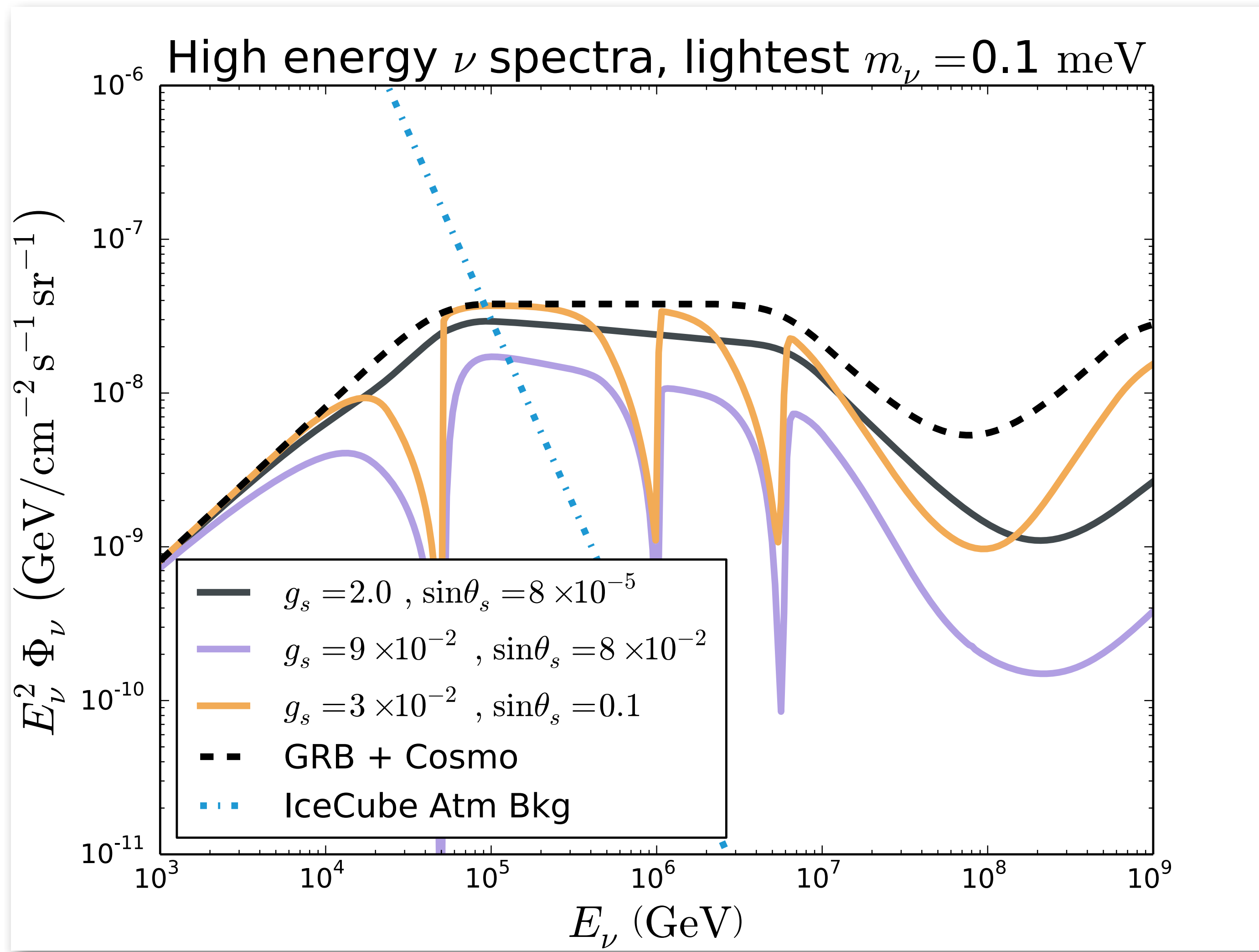
see talk by Joel Meyers

Window into new physics?

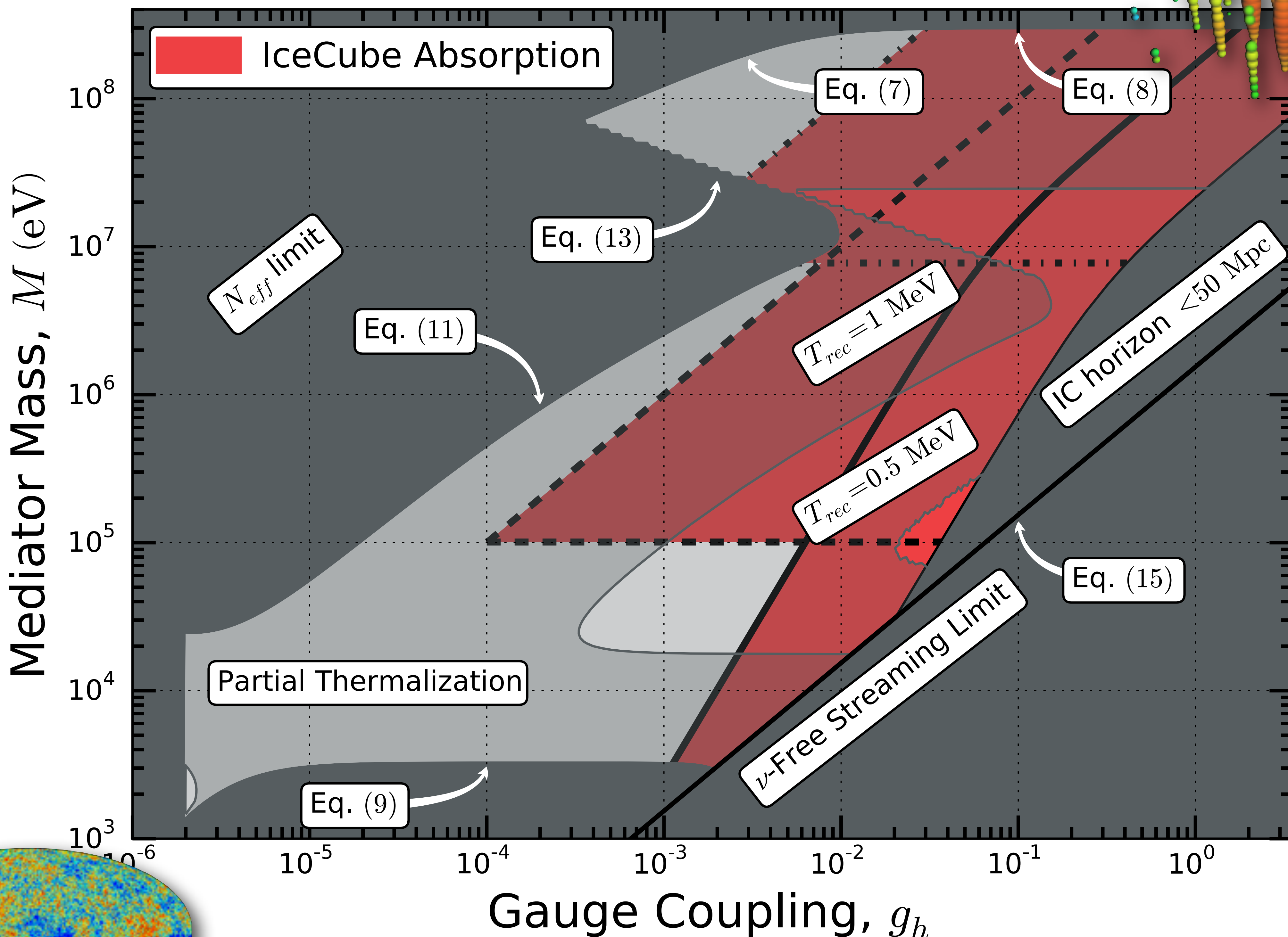
- Also, hidden interactions will make neutrino mass eigenstates scatter on each other

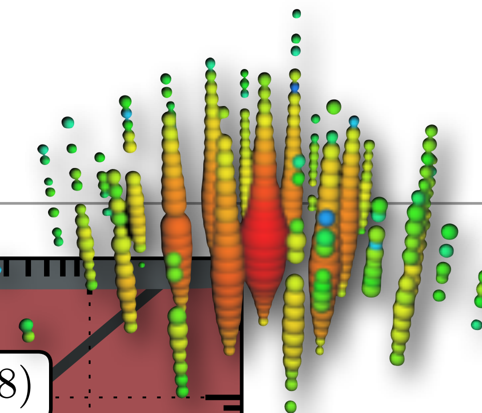
- The universe is filled with relic neutrinos. May no longer be transparent to neutrinos of ultra high energies

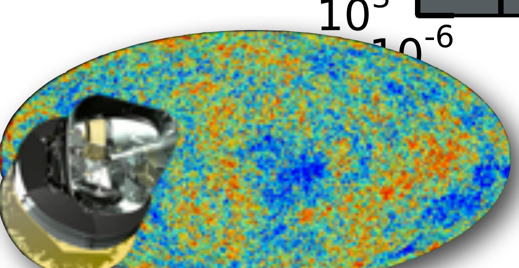
- Recently, IceCube has observed such neutrinos! Next generation upgrade in the works. It will have 10 times statistics, tell us if there are indeed absorption features in the spectrum (presently, there are hints)



Detail in arXiv:1605.06506



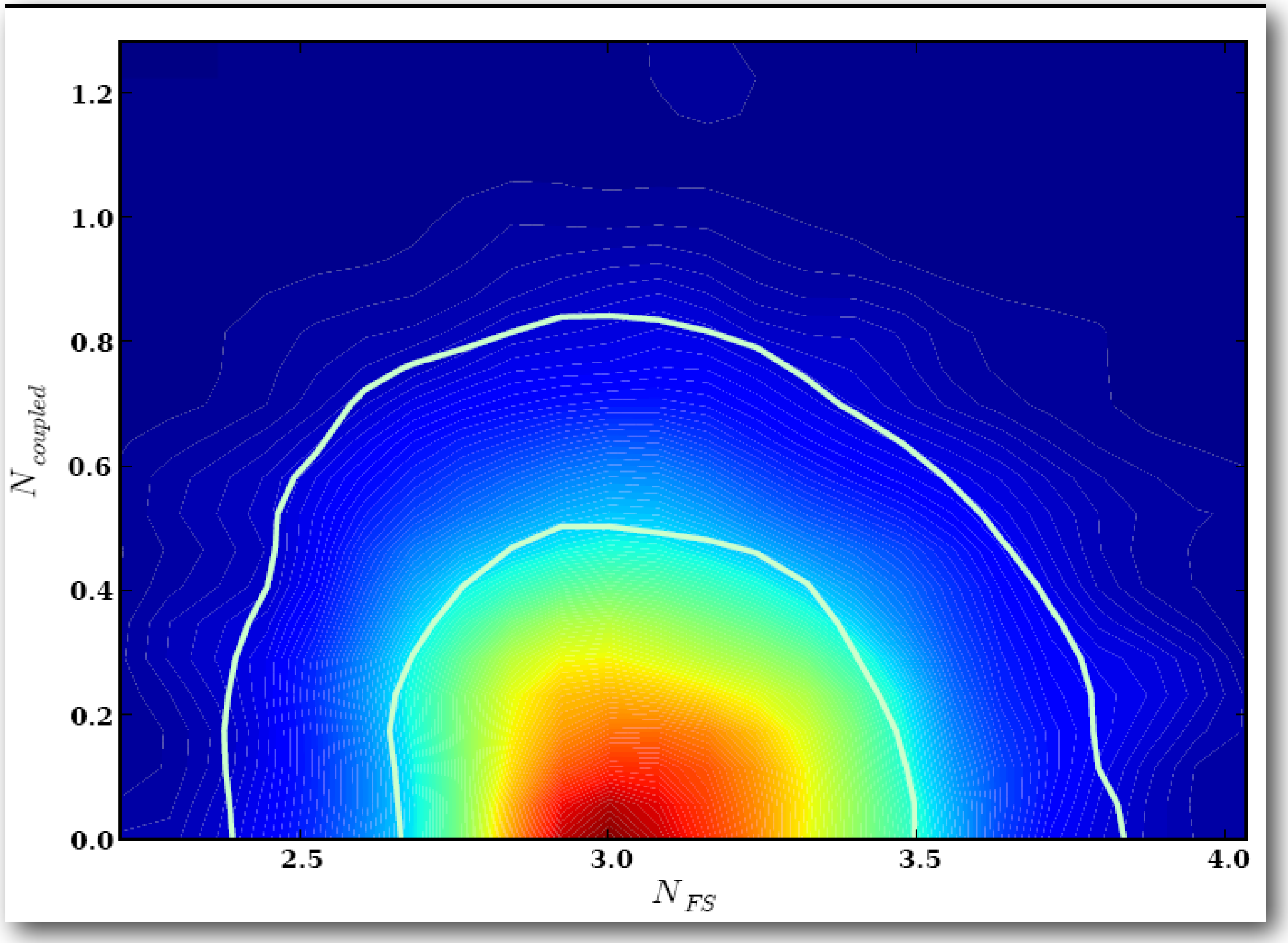




Light mediators: excluded by free-streaming

- For sufficiently large coupling, neutrinos, even the ones predominantly active, scatter even at the CMB epoch
- In conflict with PLANCK

$$g_{eff} < (T_{rec}/M_{pl})^{1/4}(m_\phi/T_{rec})$$



Friedland, Zurek, Bashinsky,
0704.3271

$$g_{eff} < 10^{-7}(m_\phi/1\text{ eV})$$

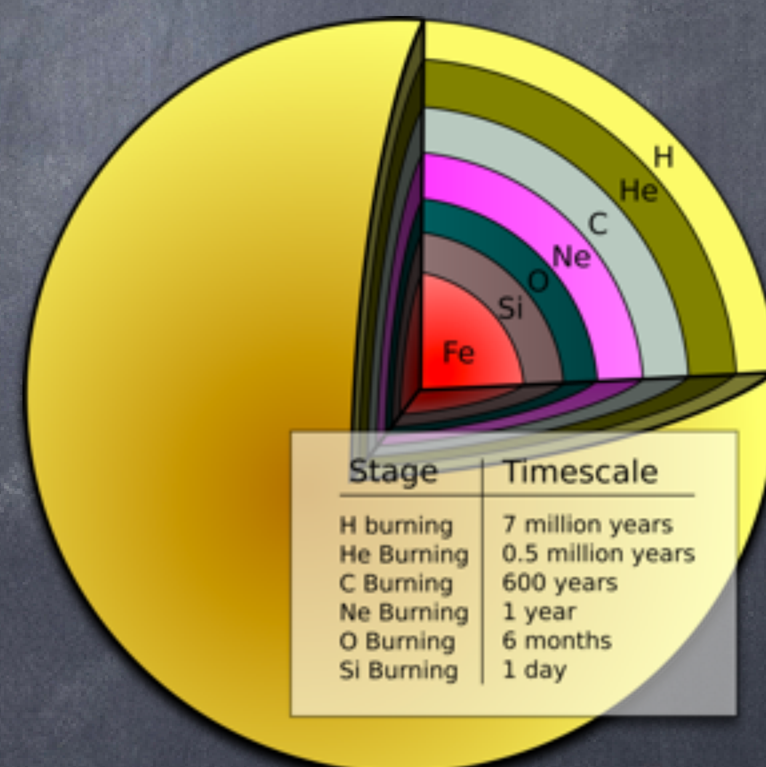
Here, g_{eff} is effective coupling, g sin$\boldsymbol{\theta}$□ □

Supernova neutrinos

What is our beam for this measurement?

- A massive star that runs out of fuel to support itself against gravity
- The core can be supported by the electron degeneracy pressure only while electrons are non-relativistic
  - $M_{\circledast} \sim (M_{Pl}/M_N)^2 M_{Pl} \sim 1.4 M_\odot$!! Chandrasekhar mass. (We live in an amazing universe!)
- The Fe core collapses in free fall, at $v \sim c/4$, until reaching (supra)nuclear densities, 10^{10} g/cm^3 $\rightarrow$ 10^{14} g/cm^3

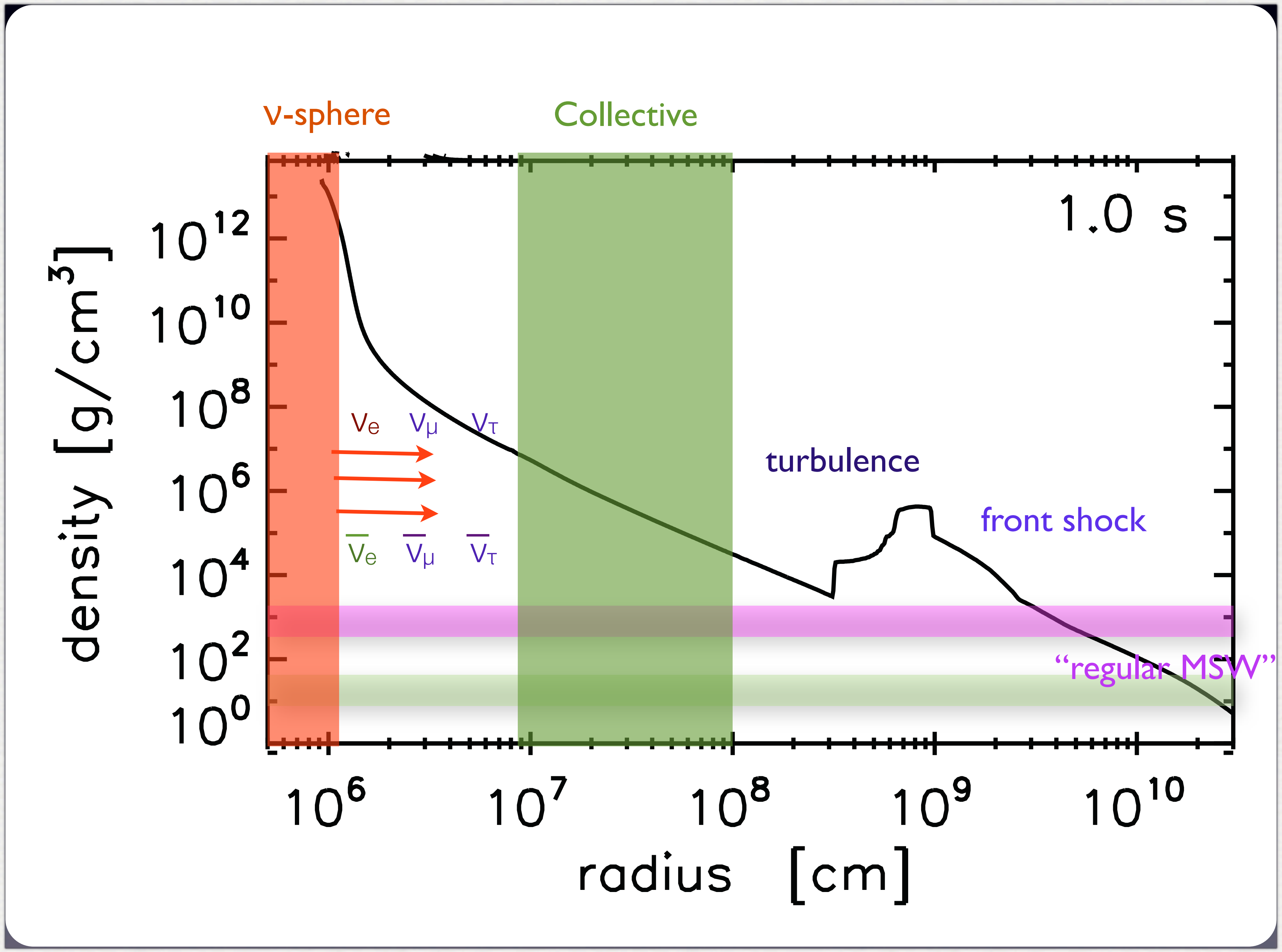
Central "white dwarf"



Gravity-powered neutrino bomb

- The gravitational binding energy $G_N M^2/R \sim 3*10^{53}$ ergs (~10% of rest mass!) and trapped lepton number are carried out by diffusing neutrinos. The weak interactions mean free path: $\lambda \sim (G_F^2\ E^2\ n)^{-1} \sim$ a few cm
  - $t \sim R^2/c\lambda \sim 10^{12}\ cm^2/(3\ cm\ 3*10^{10} cm/s) \sim 10\ s$
- For comparison, solar luminosity is $3.8*10^{33}$ ergs/s. A core-collapse supernova in neutrinos instantaneously outshines the visible universe.
- The visible explosion is <1% of energy.

SN ν: the most complicated known oscillation problem



Neutrino self-refraction

- 10% of the rest mass of the collapsed core (~ 1.4 $M_\odot$) is emitted in 10^{58} neutrinos in a burst lasting δt ~ seconds
- At ~ 100 km, the number density of streaming neutrinos is
  - ~ $10^{58}/4\pi r^2 c\delta t \sim 10^{32}$ cm^{-3}
  - Comparable to the number density of matter

Neutrino "self-refraction"

Fuller et al, 1988;
Pantaleone 1992;
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

- Above the neutrino-sphere, streaming neutrinos are so dense that their flavor evolutions become coupled
- A given neutrino scatters on an ensemble of the "background" neutrinos
- One has to evolve an ensemble of neutrinos as a whole
- Rich many-body physics, with many regimes

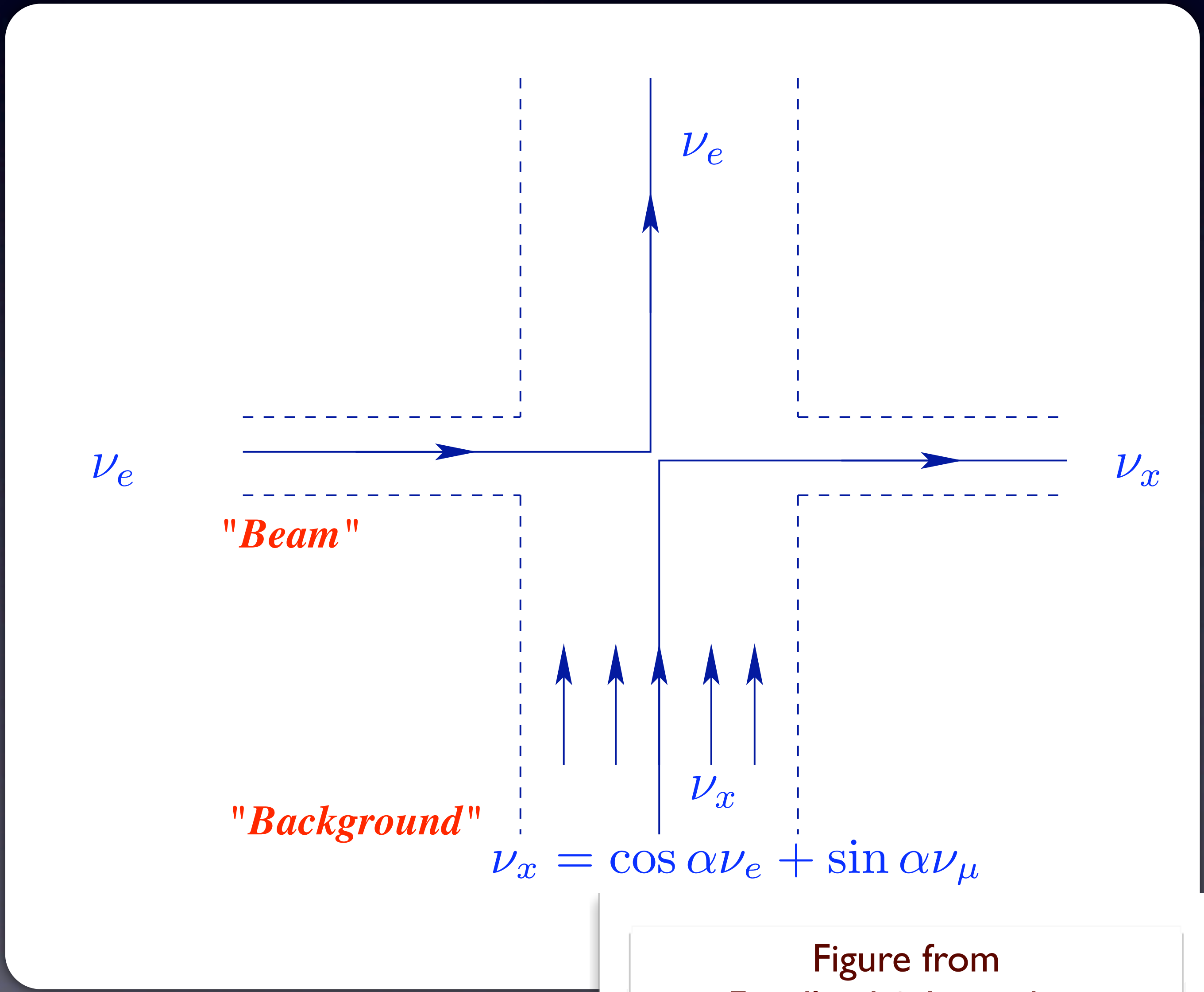
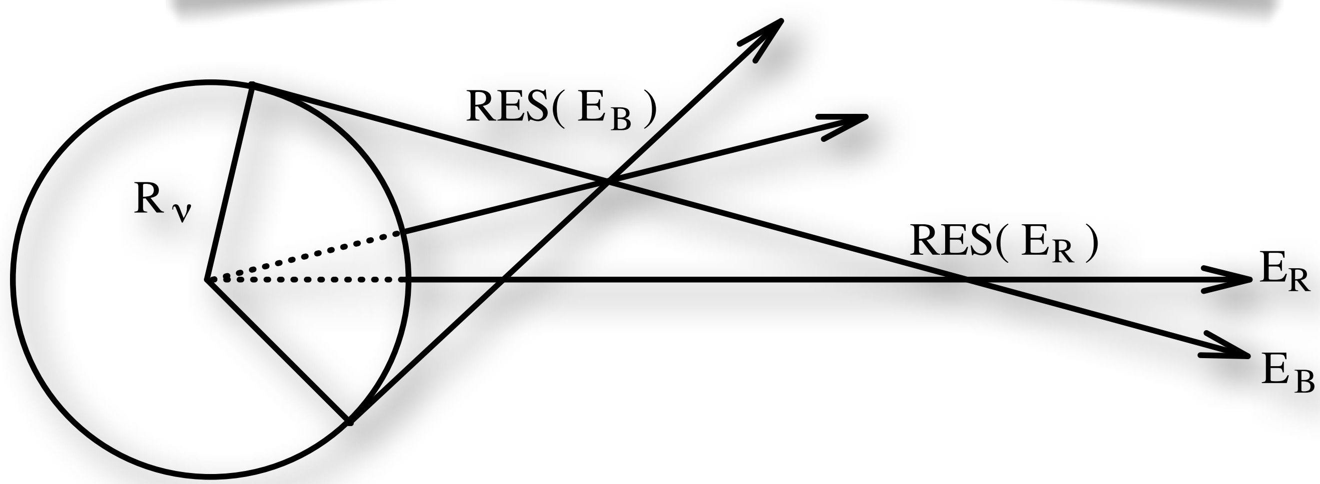


Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

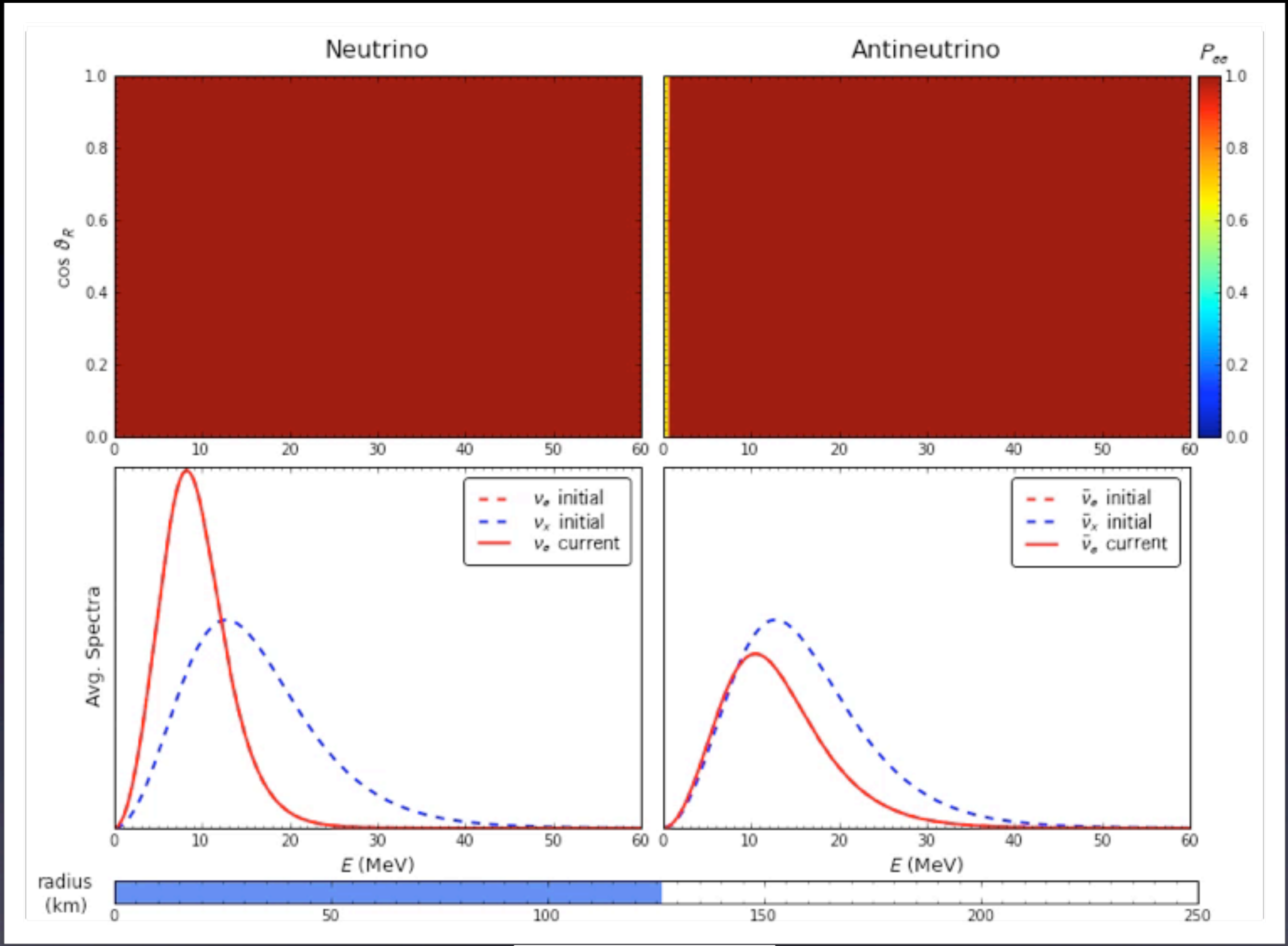
- Known physics: Z-mediated coherent neutrino scattering
  - Not optional!

Multiangle, multienergy problem

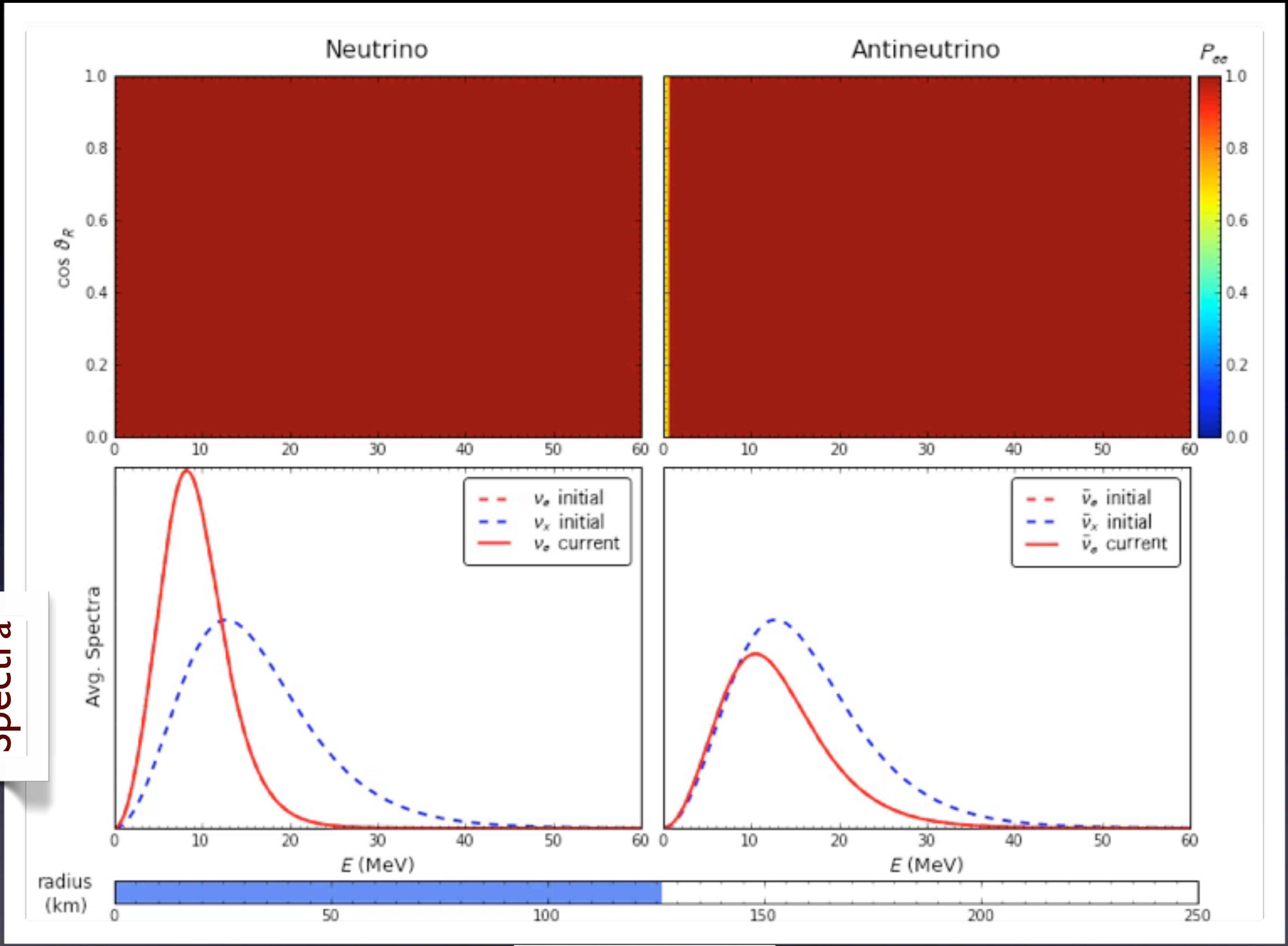
Figure from Qian & Fuller, astro-ph/9406073



- Typical calculations: 10^3 energy bins and 10^4 angle bins
  - Rapid oscillations in all bins
  - Computer intensive
  - Moore's Law caught up with this problem in 2005


Neutrino
Antineutrino
P_{ee}
$\cos\vartheta_R$
Avg. Spectra
ν_e initial
ν_x initial
ν_e current
$\bar{\nu}_e$ initial
$\bar{\nu}_x$ initial
$\bar{\nu}_e$ current
E (MeV)
radius (km)

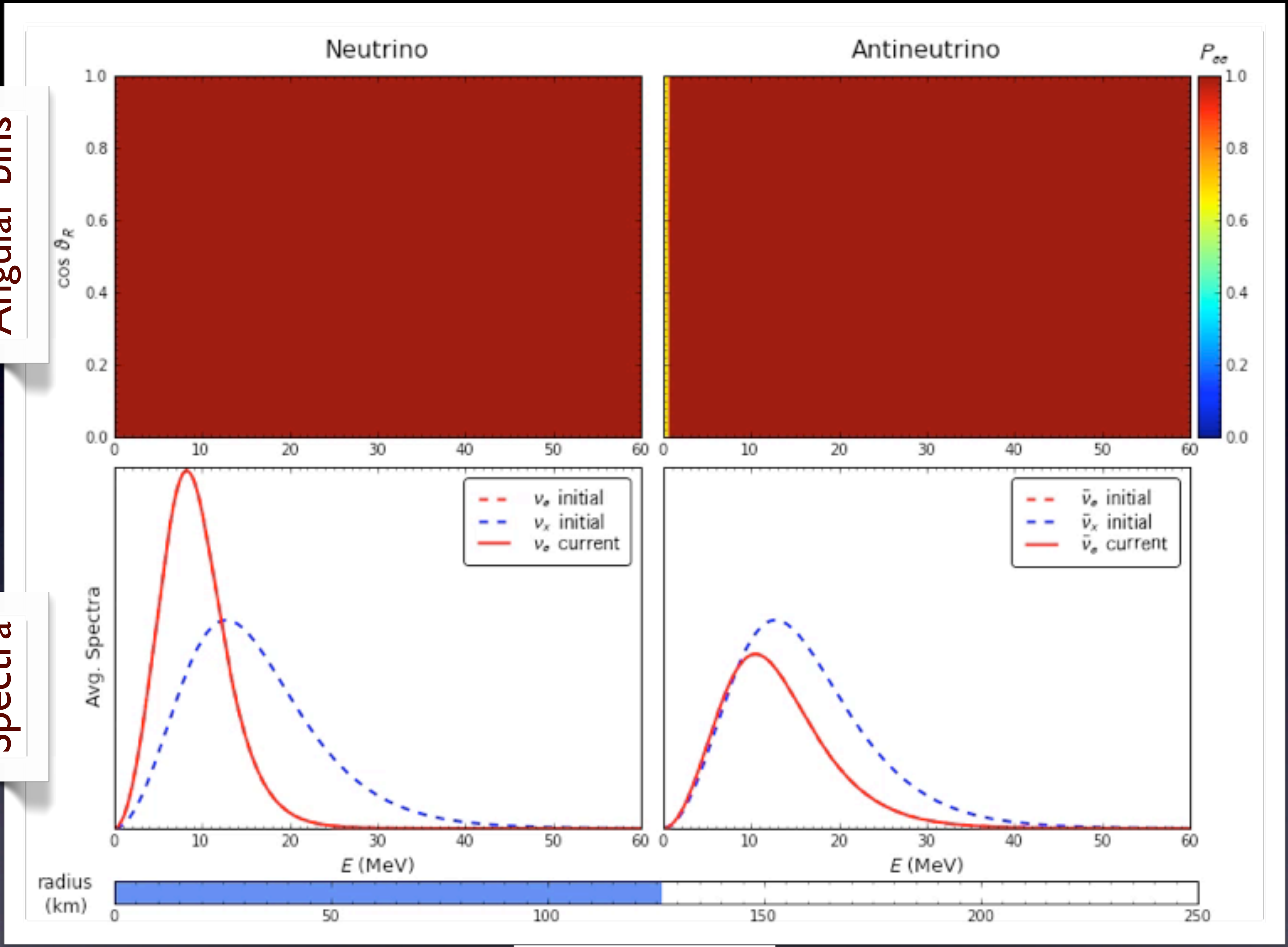
Energy bins



Spectra

Energy bins

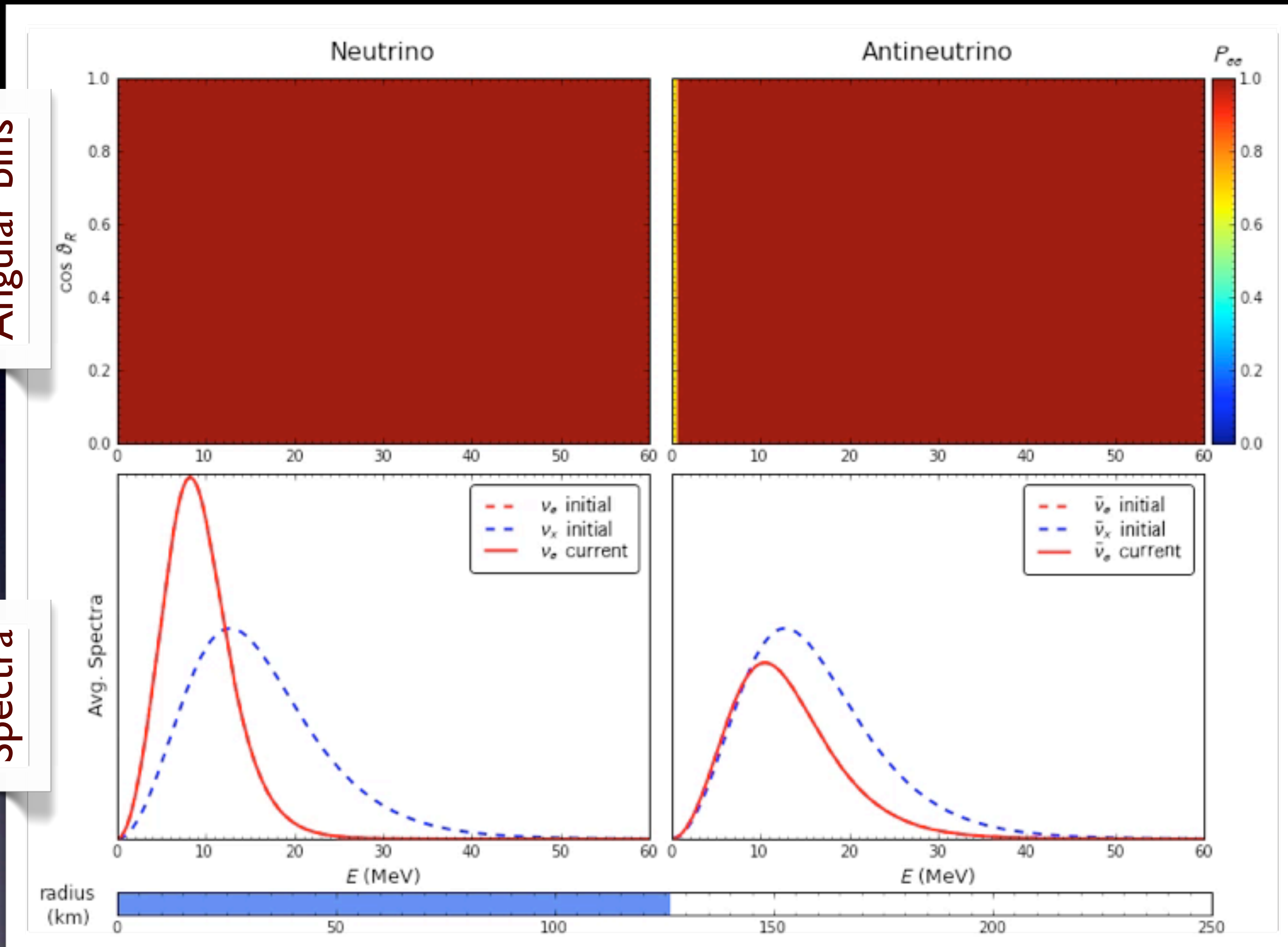
Angular bins
Spectra


Neutrino
Antineutrino
P_{ee}
$\cos\vartheta_R$
Avg. Spectra
ν_e initial
ν_x initial
ν_e current
$\bar{\nu}_e$ initial
$\bar{\nu}_x$ initial
$\bar{\nu}_e$ current
E (MeV)
radius (km)

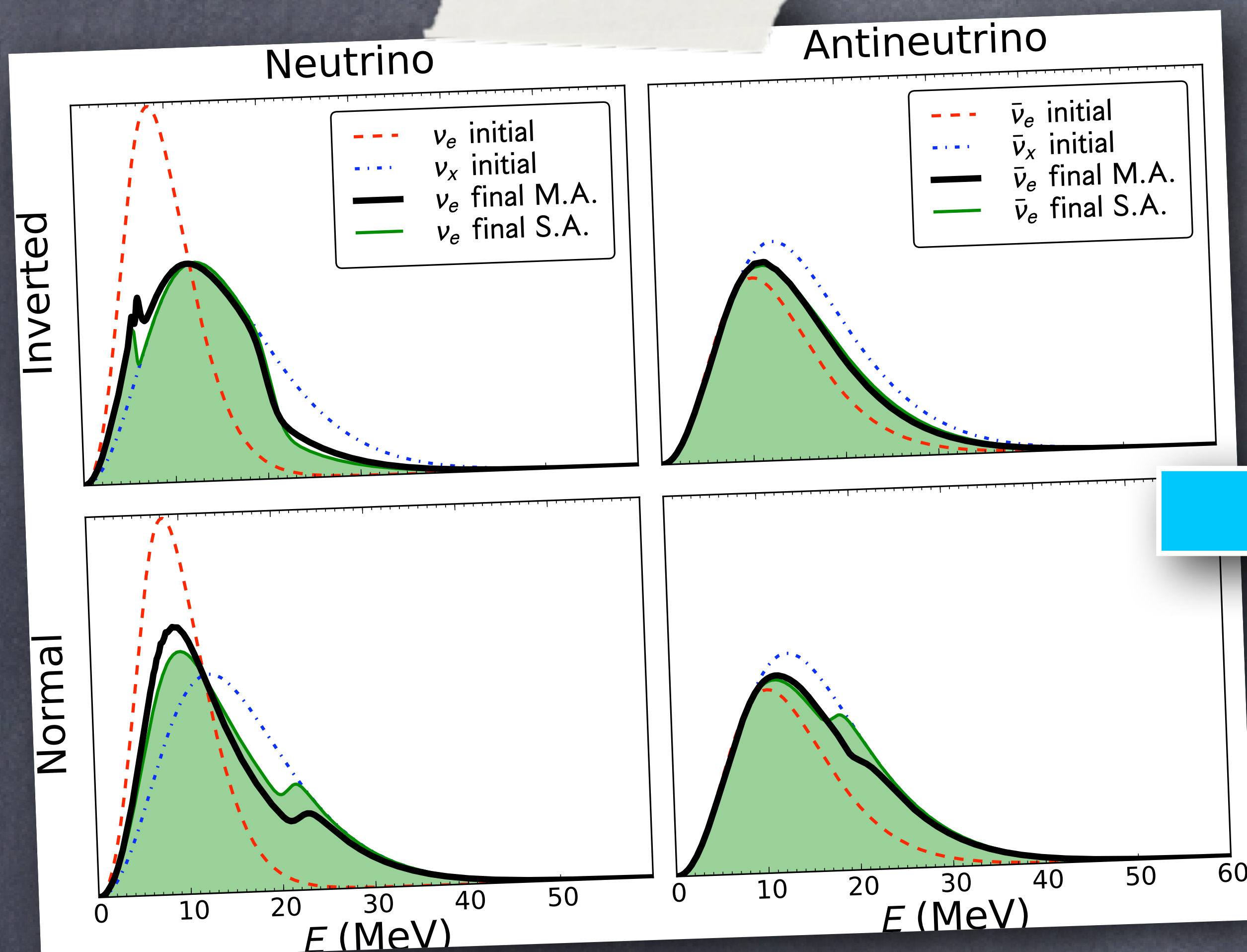
Energy bins

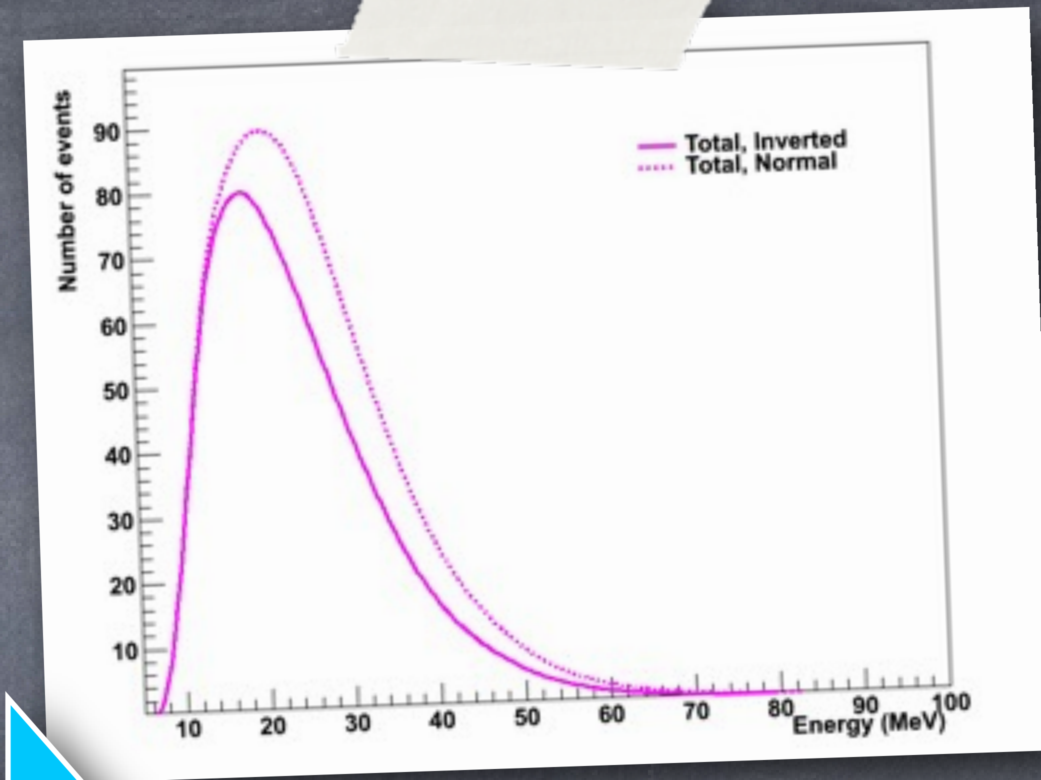
Angular bins

Spectra

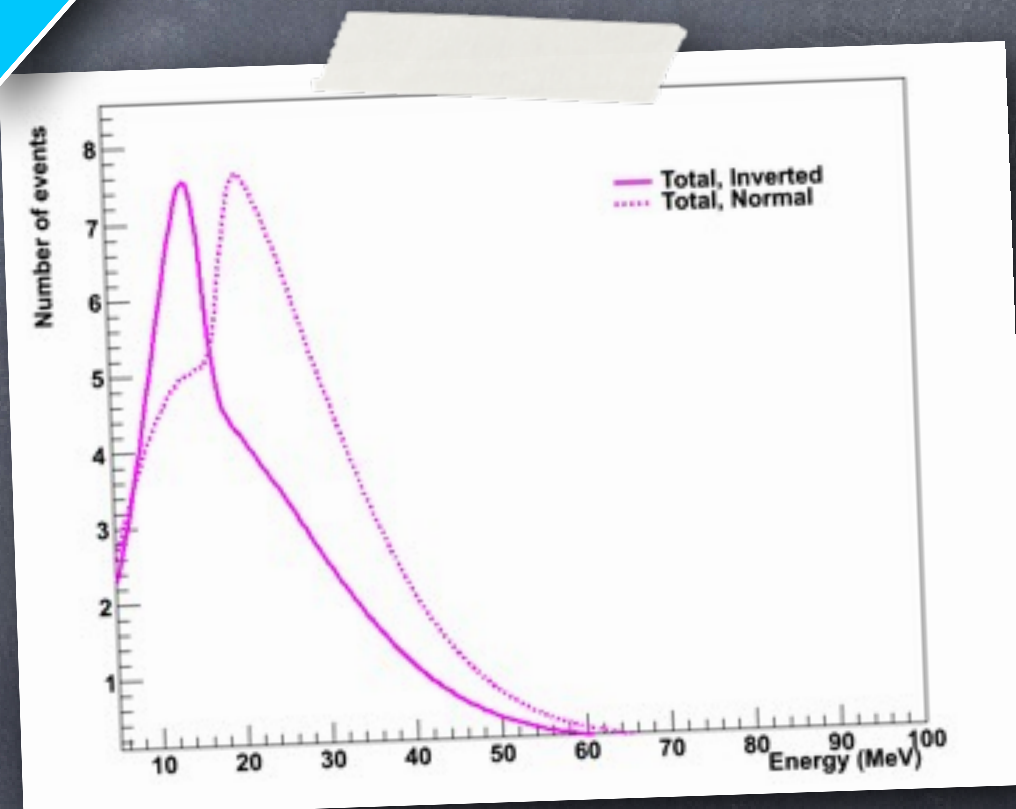


Energy bins





WC



LAr

* See LBNE science document, 1307.7335

Conclusions

- Neutrinos are one of the key players in the Universe
- Astrophysical environments offer amazing laboratories for probing neutrinos and light hypothetical particles
- In supernova, in particular, we expect collective flavor oscillations, a phenomenon not reproducible on Earth
- If a “sterile” neutrino is confirmed in the lab, a combination of future IceCube and CMB-S4 data may open portal into the Dark Sector
- Stay tuned!