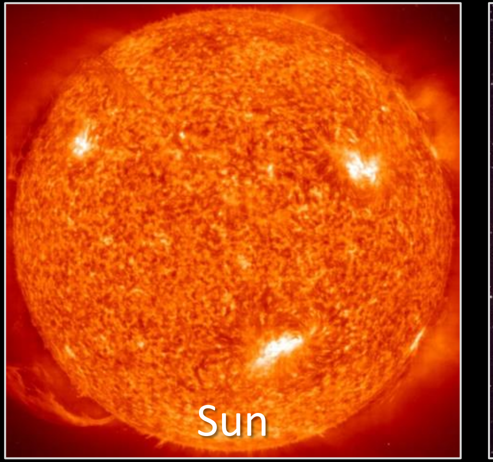
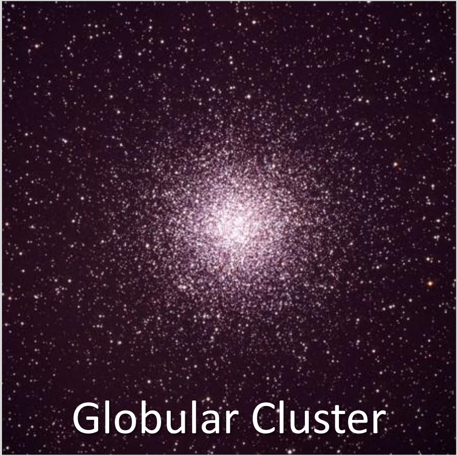
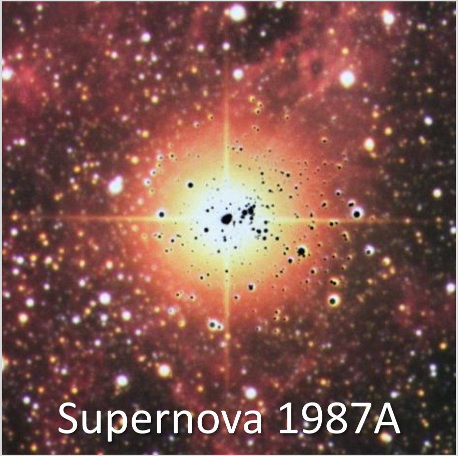


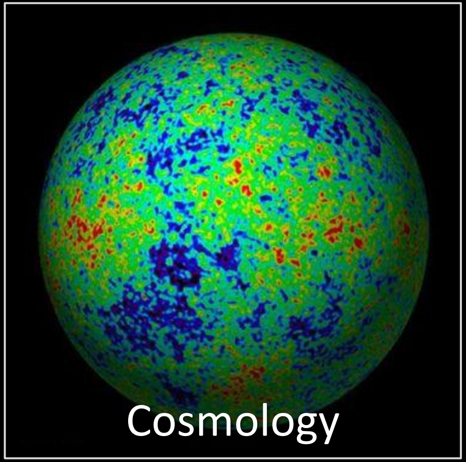
Sun



Globular Cluster



Supernova 1987A



Cosmology

# Astrophysical and Cosmological Neutrino Limits

Georg G. Raffelt, Max-Planck-Institut für Physik, München

# Questions about Neutrinos

## Standard properties of active neutrinos

- Absolute mass → Structure in cosmology, leptogenesis, supernova time of flight
- Mass ordering (hierarchy) → Supernova neutrino oscillations
- Leptonic CP violation → Leptogenesis
- Dirac vs Majorana → Leptogenesis

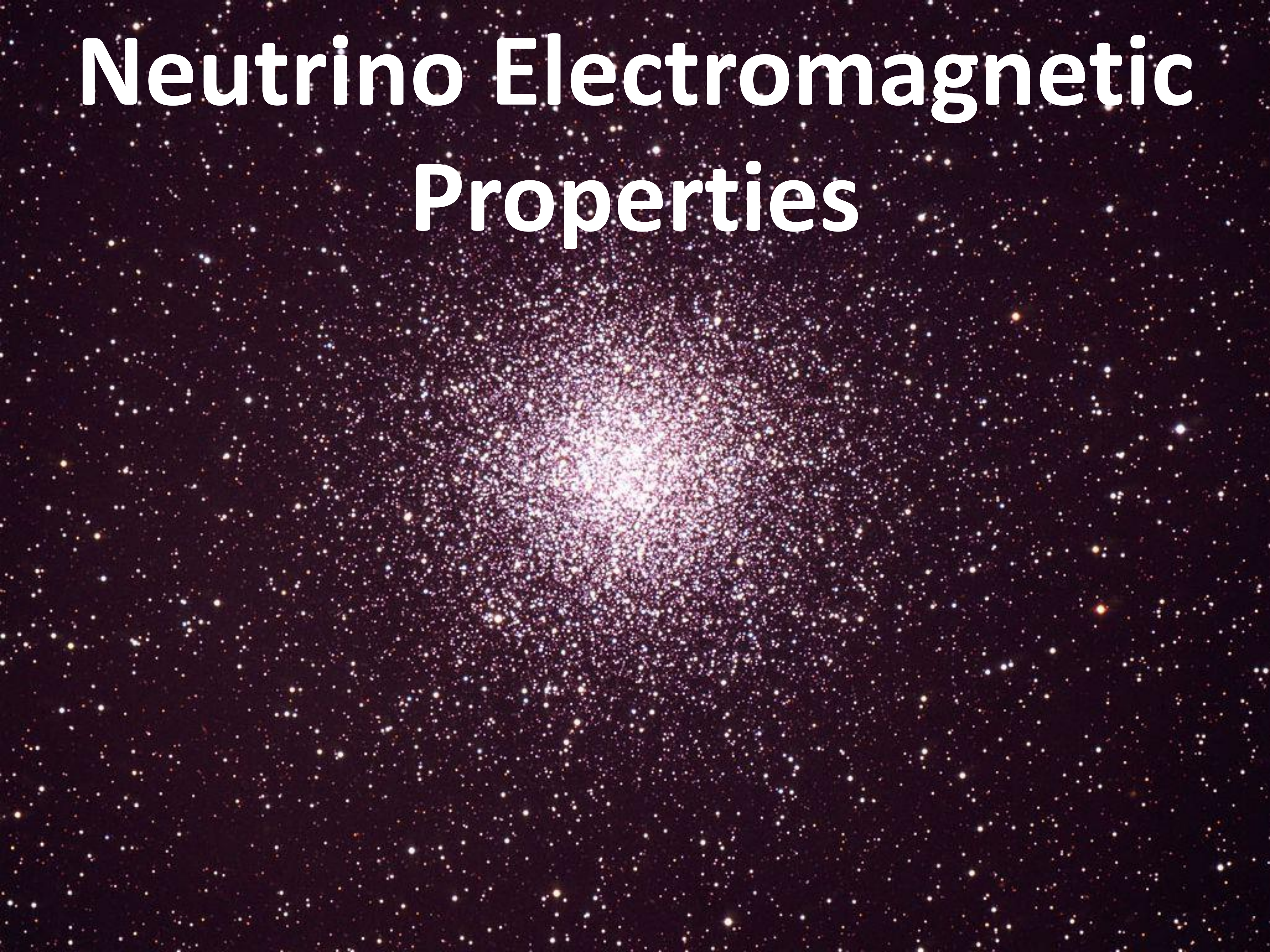
## Non-standard properties of active neutrinos

- Electromagnetic properties → Energy loss of ordinary stars & SNe
- Gravitational interaction → SN time of flight
- Non-standard/secret interactions → Cosmology, SNe, cosmic propagation

## Sterile neutrinos

- Evidence for existence → 3.5 keV x-ray signal, warm dark matter
- Masses & mixing parameters → Structure in cosmology (eV-scale masses)
  → SN neutrinos: energy loss & transfer flavor oscillations, nucleosynthesis

# Neutrino Electromagnetic Properties



# Neutrino Electromagnetic Form Factors

Effective coupling of electromagnetic field to a neutral fermion

$$\begin{aligned}\mathcal{L}_{\rm eff} = & -F_1\overline{\Psi}\gamma_\mu\Psi\, A^\mu \\ & -G_1\overline{\Psi}\gamma_\mu\gamma_5\Psi\,\partial_\nu F^{\mu\nu} \\ & -\frac{1}{2}F_2\,\overline{\Psi}\sigma_{\mu\nu}\Psi\,F^{\mu\nu} \\ & -\frac{1}{2}G_2\,\overline{\Psi}\sigma_{\mu\nu}\gamma_5\Psi\,F^{\mu\nu}\end{aligned}$$

Charge $e_\nu = F_1(0) = 0$

Anapole moment $G_1(0)$

Magnetic dipole moment $\mu = F_2(0)$

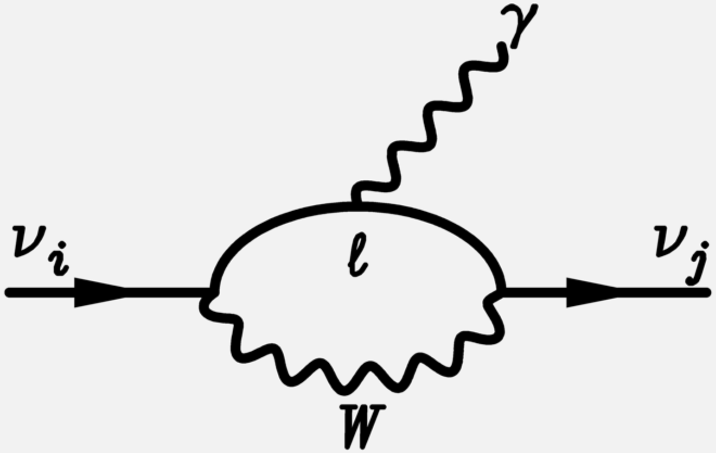
Electric dipole moment $\varepsilon = G_2(0)$

- Charge form factor $F_1(q^2)$ and anapole $G_1(q^2)$ are short-range interactions if charge $F_1(0) = 0$
- Connect states of equal helicity
- In the standard model they represent radiative corrections to weak interaction

- Dipole moments connect states of opposite helicity
- Violation of individual flavor lepton numbers (neutrino mixing)
  → Magnetic or electric dipole moments can connect different flavors or different mass eigenstates ("Transition moments")
- Usually measured in "Bohr magnetons" $\mu_B = e/2m_e$

# Standard Dipole Moments for Massive Neutrinos

Standard electroweak model:
Neutrino dipole and
transition moments
are induced at higher order



Massive neutrinos $\nu_i$ $(i = 1, 2, 3)$
mixed to form weak eigenstates

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i} \nu_i$$

Explicitly for Dirac neutrinos
- Magnetic moments $\mu_{ij}$
- Electric moments $\epsilon_{ij}$

$$\mu_{ij} = \frac{e\sqrt{2}G_{\mathrm{F}}}{(4\pi)^2}\left(m_i + m_j\right) \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^{*} f\left(\frac{m_\ell}{m_W}\right)$$

$$\epsilon_{ij} = \ldots \left(m_i - m_j\right) \ldots$$

$$f\left(\frac{m_\ell}{m_W}\right) = -\frac{3}{2} + \frac{3}{4}\left(\frac{m_\ell}{m_W}\right)^2 + \mathcal{O}\left(\frac{m_\ell}{m_W}\right)^4$$

# Standard Dipole Moments for Massive Neutrinos

Diagonal case:
Magnetic moments
of Dirac neutrinos

$$\mu_{ii} = \frac{3e\sqrt{2}G_{\mathrm{F}}}{(4\pi)^2} m_i = 3.20 \times 10^{-19} \mu_{\mathrm{B}} \frac{m_i}{\mathrm{eV}} \qquad \mu_{\mathrm{B}} = \frac{e}{2m_e}$$

$$\epsilon_{ii} = 0$$

Off-diagonal case
(Transition moments)

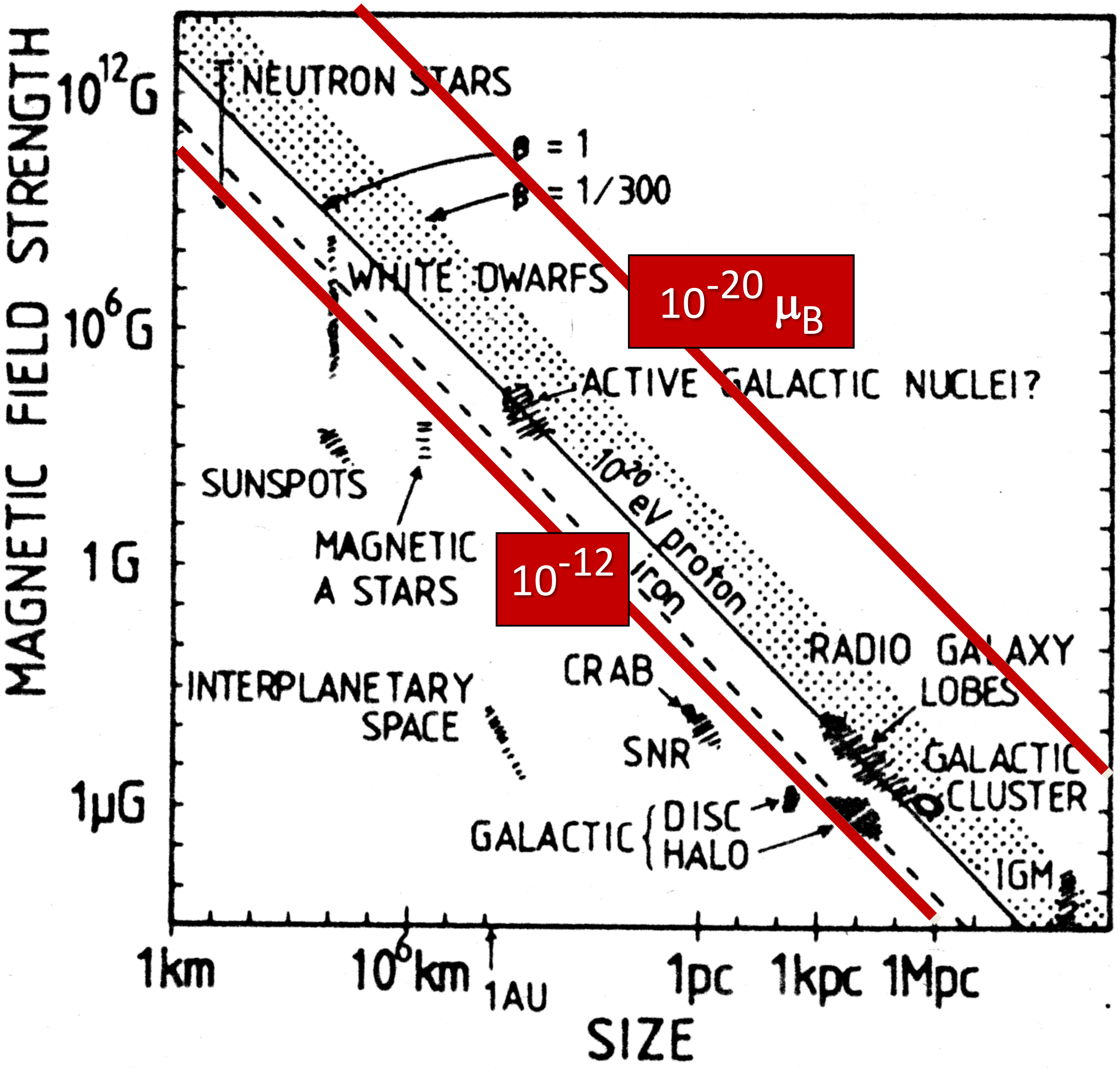
First term in $f(m_\ell/m_W)$
does not contribute:
“GIM cancellation”

$$\mu_{ij} = \frac{3e\sqrt{2}G_{\mathrm{F}}}{4(4\pi)^2} (m_i+m_j) \left(\frac{m_\tau}{m_W}\right)^2 \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \left(\frac{m_\ell}{m_\tau}\right)^2$$

$$= 3.96 \times 10^{-23} \mu_{\mathrm{B}} \frac{m_i + m_j}{\mathrm{eV}} \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \left(\frac{m_\ell}{m_\tau}\right)^2$$

Largest neutrino mass eigenstate $0.05\ \mathrm{eV} < m < 0.2\ \mathrm{eV}$
For Dirac neutrino expect
$1.6 \times 10^{-20} \mu_B < \mu_\nu < 6.4 \times 10^{-20} \mu_B$

# Astrophysical Magnetic Fields



Field strength and length scale where neutrinos with specified dipole moment would completely depolarize

"Hillas Plot"
ARAA 22, 425 (1984)

# Neutrino Spin-Flavor Oscillations in a Medium

Two-flavor oscillations of Majorana neutrinos with a transition magnetic moment μ and ordinary flavor mixing in a medium

$$i\partial_r \begin{pmatrix} \nu_e \\ \nu_\mu \\ \overline{\nu}_e \\ \overline{\nu}_\mu \end{pmatrix} = \begin{pmatrix} c\Delta + a_e & s\Delta & 0 & \mu B \\ s\Delta & -c\Delta + a_\mu & \mu B & 0 \\ 0 & \mu B & c\Delta - a_e & s\Delta \\ \mu B & 0 & s\Delta & -c\Delta - a_\mu \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \overline{\nu}_e \\ \overline{\nu}_\mu \end{pmatrix}$$

with $c = \cos(2\Theta)$, $s = \sin(2\Theta)$,

$\Delta = (m_2^2 - m_1^2)/4E$, $a_e = \sqrt{2} G_F \left(n_e - \frac{1}{2} n_n\right)$ and $a_\mu = \sqrt{2} G_F \left(-\frac{1}{2} n_n\right)$

- Resonant spin-flavor precession (RSFP) can be a subdominant effect for solar neutrino conversion and can produce a small solar anti-neutrino flux

- Can be important for supernova neutrinos

Limits on solar $\overline{\nu}_e$ flux (Borexino arXiv:1010.0029, KamLAND arXiv:1105.3516)

$p(\nu_e \to \overline{\nu}_e) < 5.3 \times 10^{-5}$ (90% CL)

Not yet sensitive to $\mu_\nu$ even for largest assumed solar B-fields

# Neutrinos from Thermal Processes

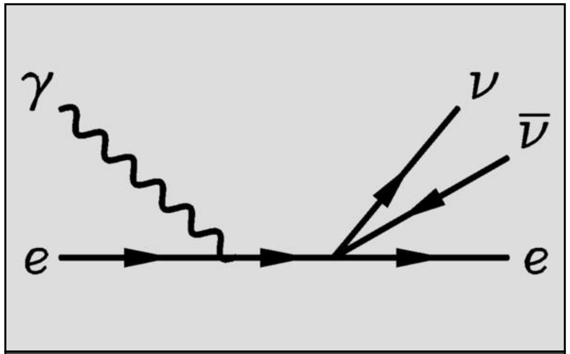
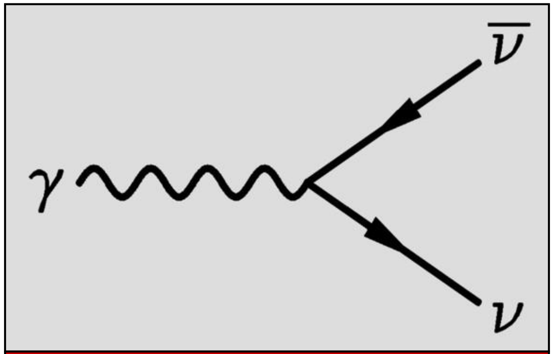
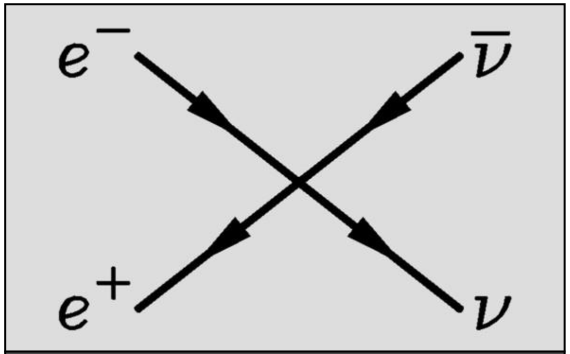


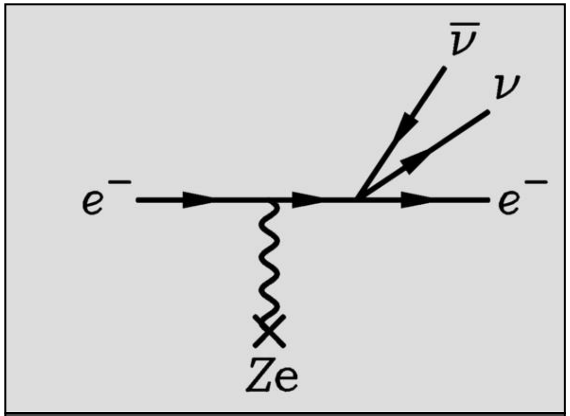
Photo (Compton)



Plasmon decay

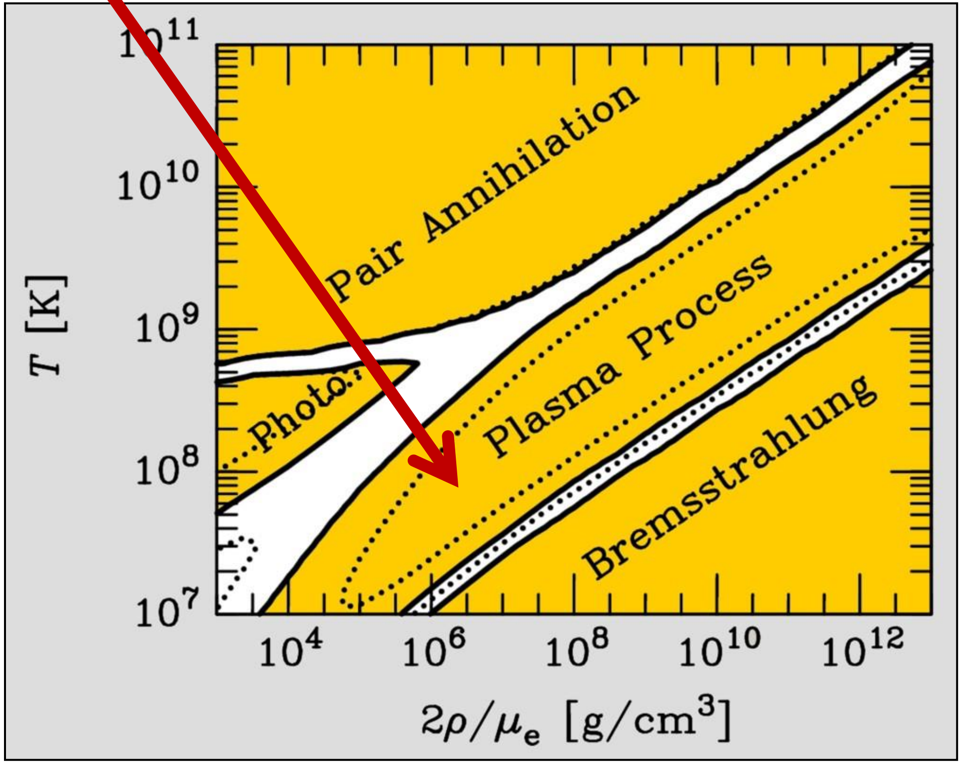


Pair annihilation



Bremsstrahlung

These processes were first discussed in 1961–63 after V–A theory



PHYSICAL REVIEW VOLUME 132, NUMBER 3 1 NOVEMBER 1963

# Electromagnetic Properties of the Neutrino

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(Received 11 June 1963)

In this note we make a detailed survey of the experimental information on the neutrino charge, charge radius, and magnetic moment. Both weak-interaction data and astrophysical results can be used to give precise limits to these quantities, independent of the supposition that the weak interactions are charge conserving.

## I. INTRODUCTION

MOST physicists now accept the prospect that there are two neutrinos—$\nu_e$ and $\nu_\mu$—identical except for interaction ($\nu_e$ couples weakly with electrons and $\nu_\mu$ with muons) and that these neutrinos have the simplest properties compatible with existing experimental evidence; i.e., zero mass, charge, electric, and magnetic dipole moments. However, the weak interactions have produced so many surprises that it is worthwhile, from time to time, to study the *experimental* limits that have been set on these quantities. In this note we present a systematic survey of the properties of the two neutrinos that can be inferred from experiment.

## II. PROPERTIES

We begin by listing the properties of the neutrinos to

tritium experiments give

$$m_{\nu_e} < 200\ \text{eV}, \tag{2}$$

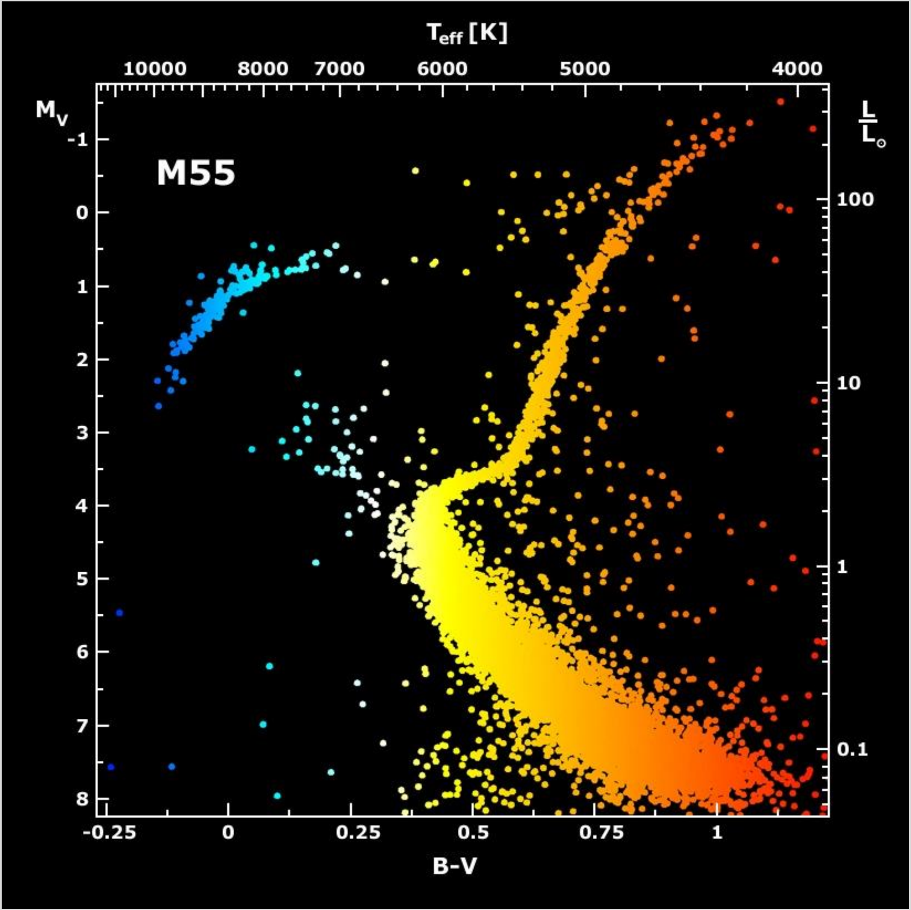
and the experiments are consistent with $m_{\nu_e} = 0$.

(2) $\nu_\mu$: The mass of the muon neutrino is the least well known of the parameters associated with either neutrino. The best measurements of it come from the energy-momentum balance in $\pi$ decay. The experiment of Barkas *et al.*[3] gives[4]

$$m_{\nu_\mu} < 3.5\ \text{MeV}. \tag{3}$$

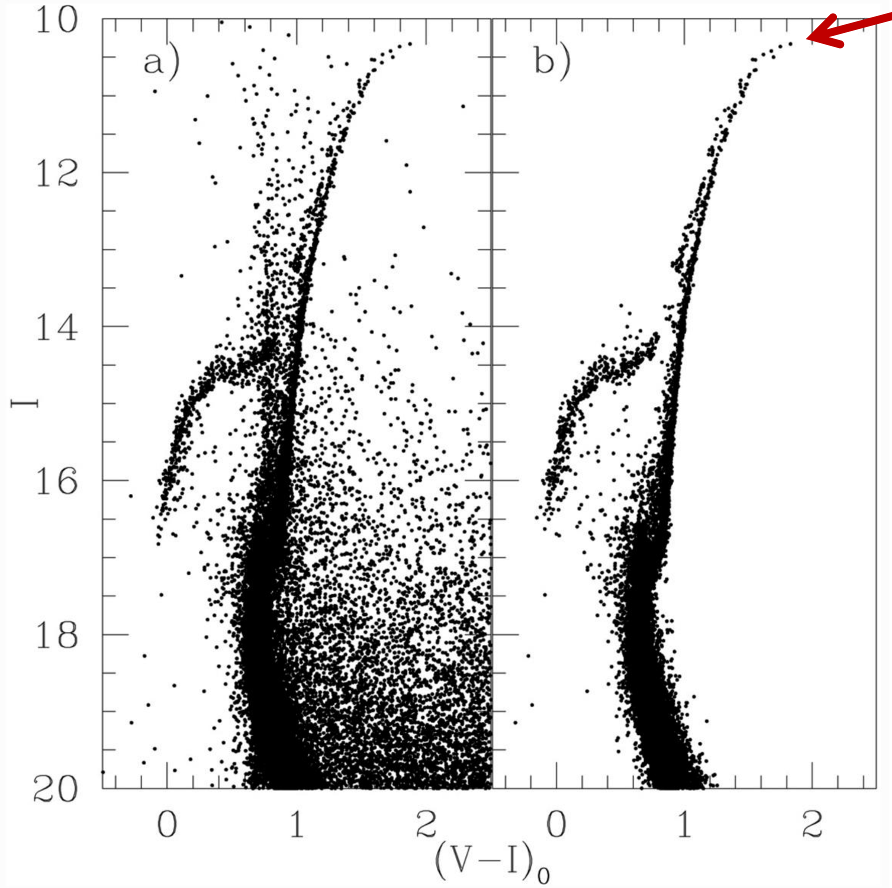
The reason for this uncertainty lies in the kinematic fact that the small neutrino mass is given as the difference between measured quantities of order 1. In the $\pi \rightarrow \mu + \nu$ decay, the accuracy with which the neutrino mass can be determined is given by

# Galactic Globular Cluster M55

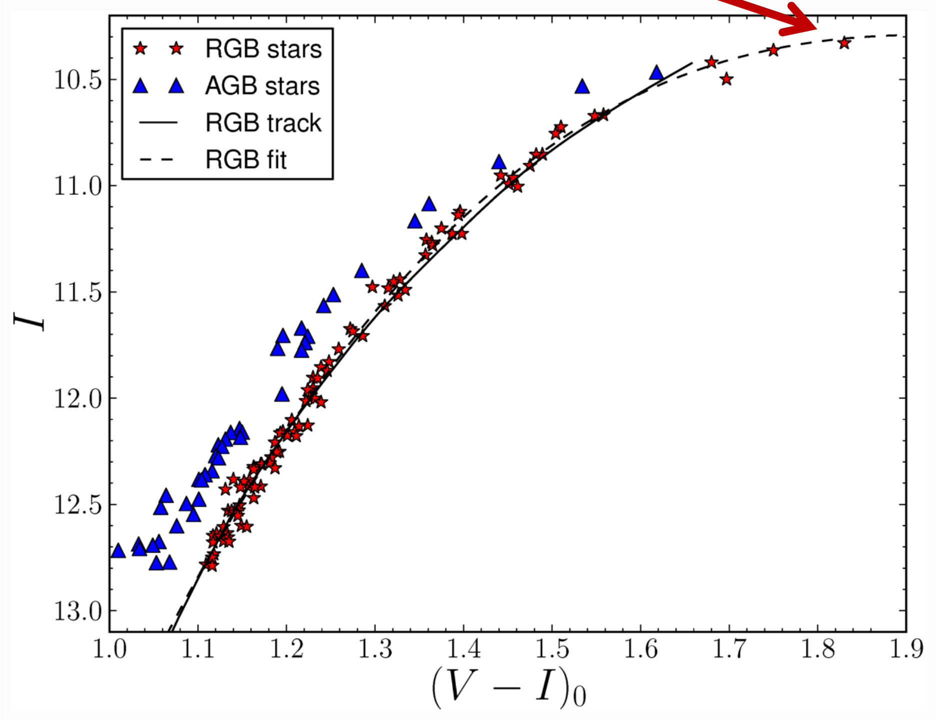


# Color-Magnitude Diagram of Globular Cluster M5

Brightest red giant
measures nonstandard energy loss



CMD (a) before and (b) after cleaning

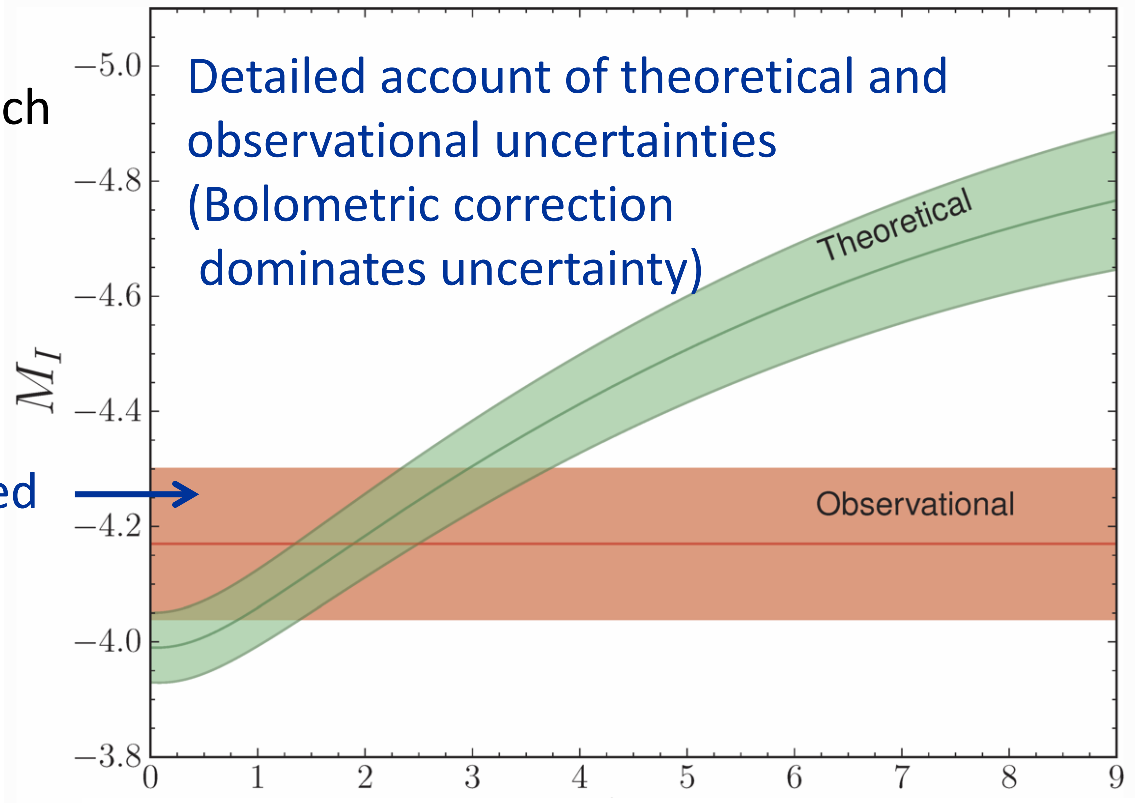


CMD of brightest 2.5 mag of RGB

Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

# Neutrino Dipole Limits from Globular Cluster M5

I-band brightness
of tip of red-giant brach
[magnitudes]



Detailed account of theoretical and observational uncertainties (Bolometric correction dominates uncertainty)

- Uncertainty dominated by distance
- Can be improved in future (GAIA mission)

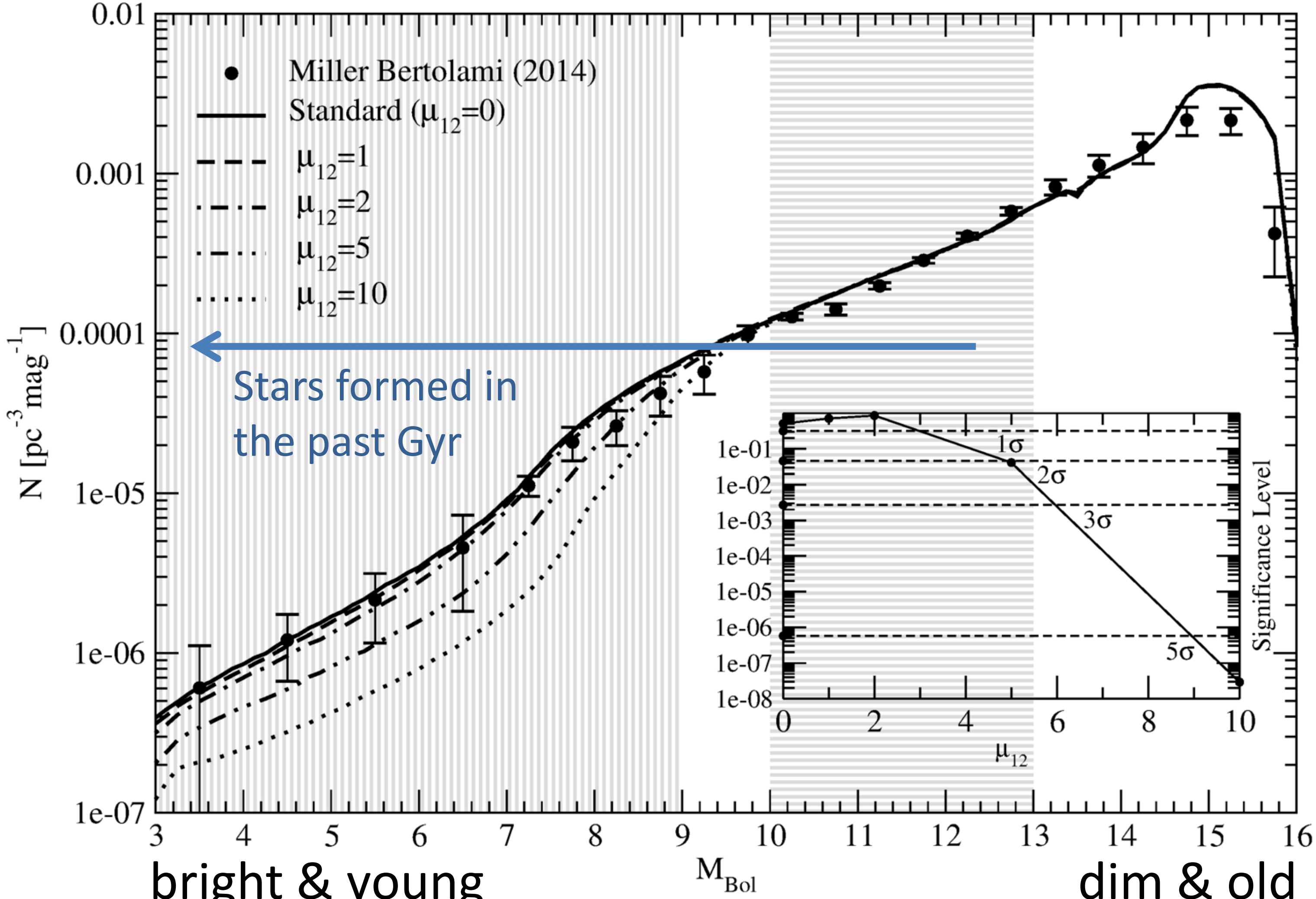
Neutrino magnetic dipole moment $[10^{-12}\mu_B]$

Most restrictive limit on neutrino electromagnetic properties

$$\mu_\nu < \begin{cases} 2.6\times 10^{-12}\mu_B & (68\%\ \mathrm{CL}) \\ 4.5\times 10^{-12}\mu_B & (95\%\ \mathrm{CL}) \end{cases}$$

Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

# White Dwarf Luminosity Function



Stars formed in the past Gyr

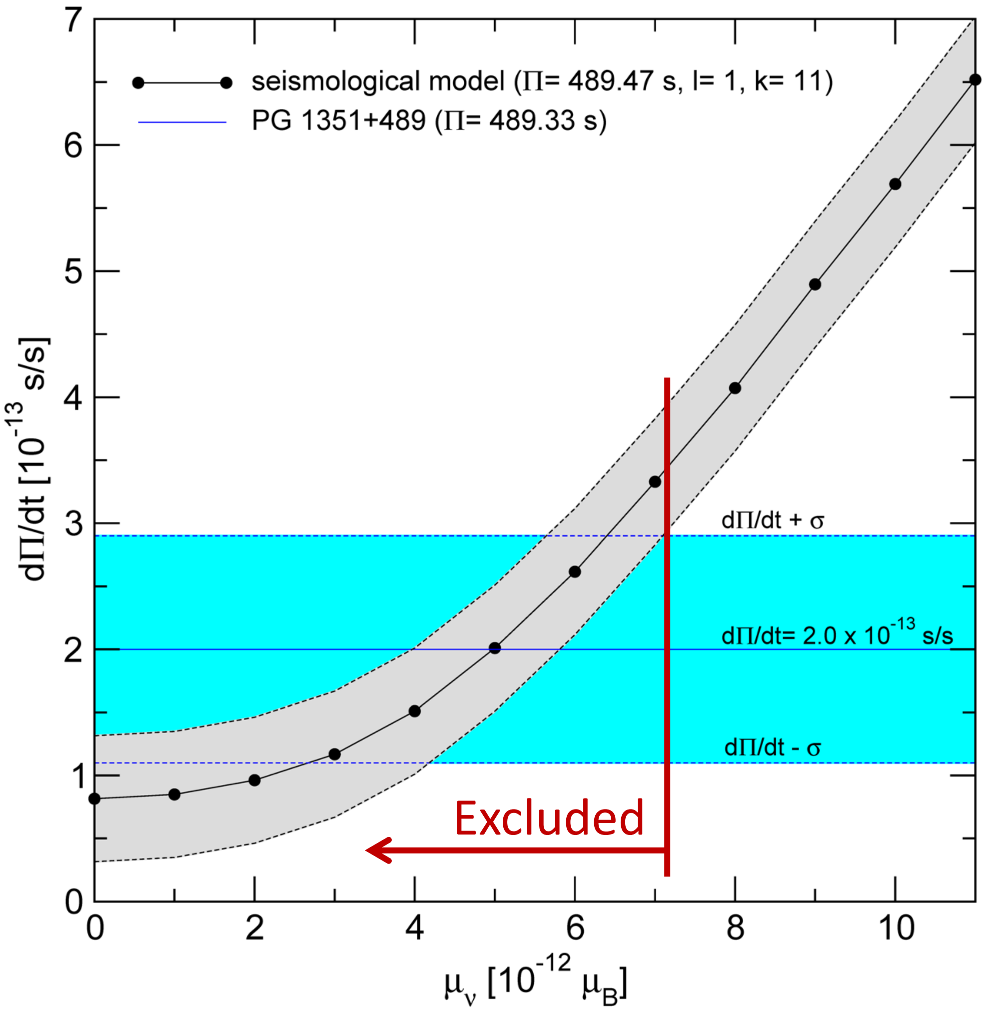
bright & young

dim & old

Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712, 1410.1677

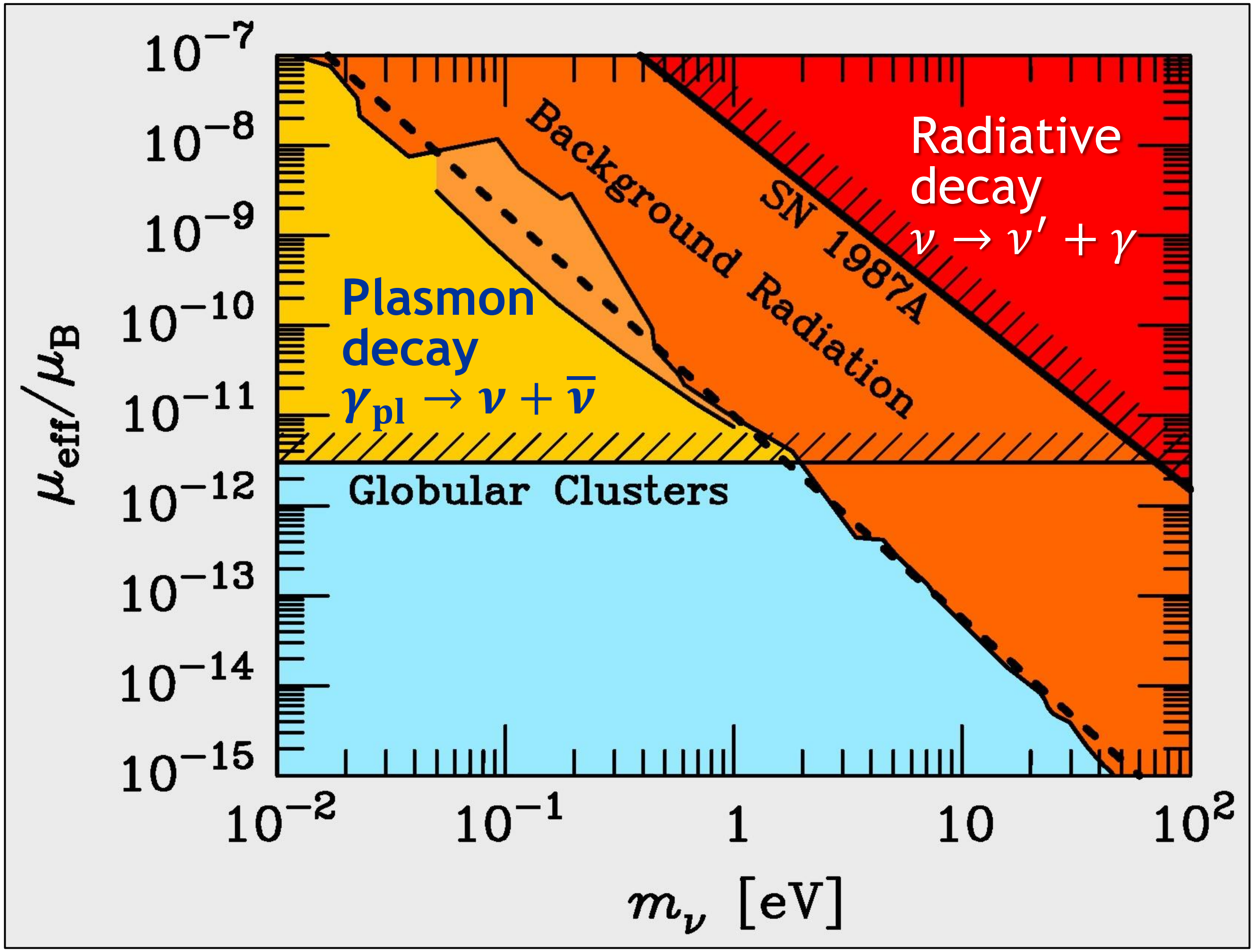
# Period Change of Variable White Dwarfs

Period change $\dot{\Pi}$ of pulsating white darfs depends on cooling speed



White dwarf  PG 1351+489,  Córsico et al., arXiv:1406.6034

# Neutrino Radiative Lifetime Limits



Raffelt, arXiv:astro-ph/9808299

$$\Gamma_{\nu\rightarrow\nu'\gamma} = \frac{\mu_{\rm eff}^2}{8\pi}\, m_\nu^3$$

$$\Gamma_{\gamma\rightarrow\nu\overline{\nu}} = \frac{\mu_{\rm eff}^2}{24\pi}\, \omega_{\rm pl}^3$$

For low-mass neutrinos, plasmon decay in globular cluster stars yields the most restrictive limits

# Neutrino Properties from Supernova Neutrinos

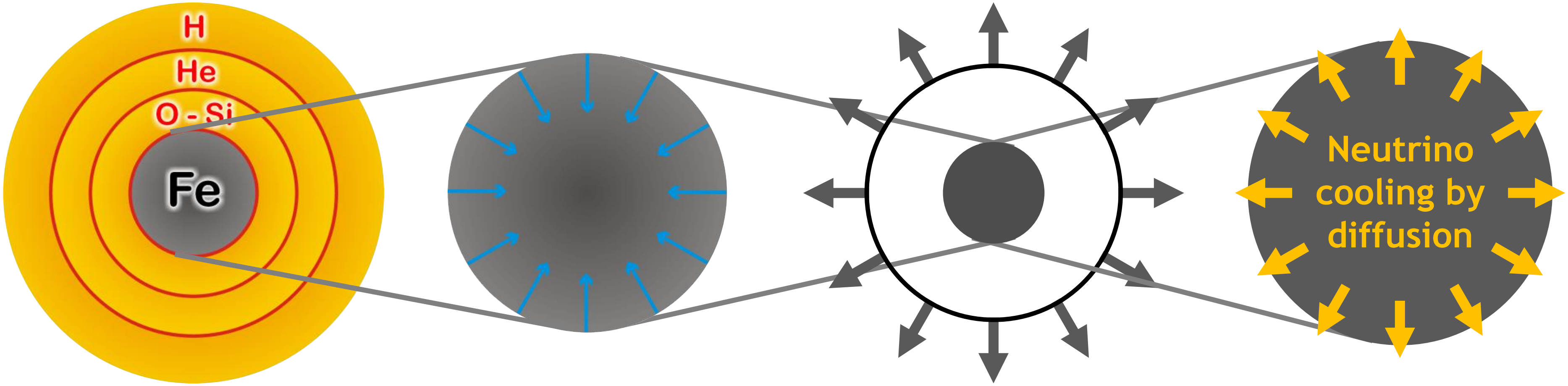
# Core-Collapse Supernova Explosion

End state of a massive star
$M \gtrsim 6\text{–}8\ M_\odot$

Collapse of degenerate core

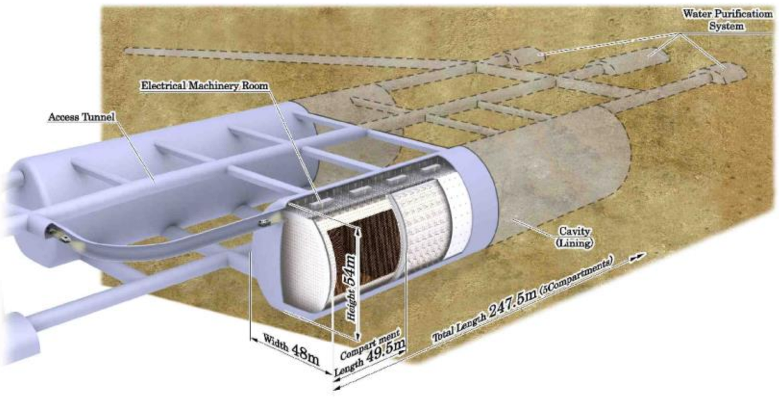
Bounce at $\rho_{\rm nuc}$
Shock wave forms explodes the star

Grav. binding E
$\sim 3 \times 10^{53}$ erg
emitted as nus of all flavors



Neutrino cooling by diffusion

- Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors
- A few core-collapse SNe in our galaxy per century
- Once-in-a-lifetime opportunity

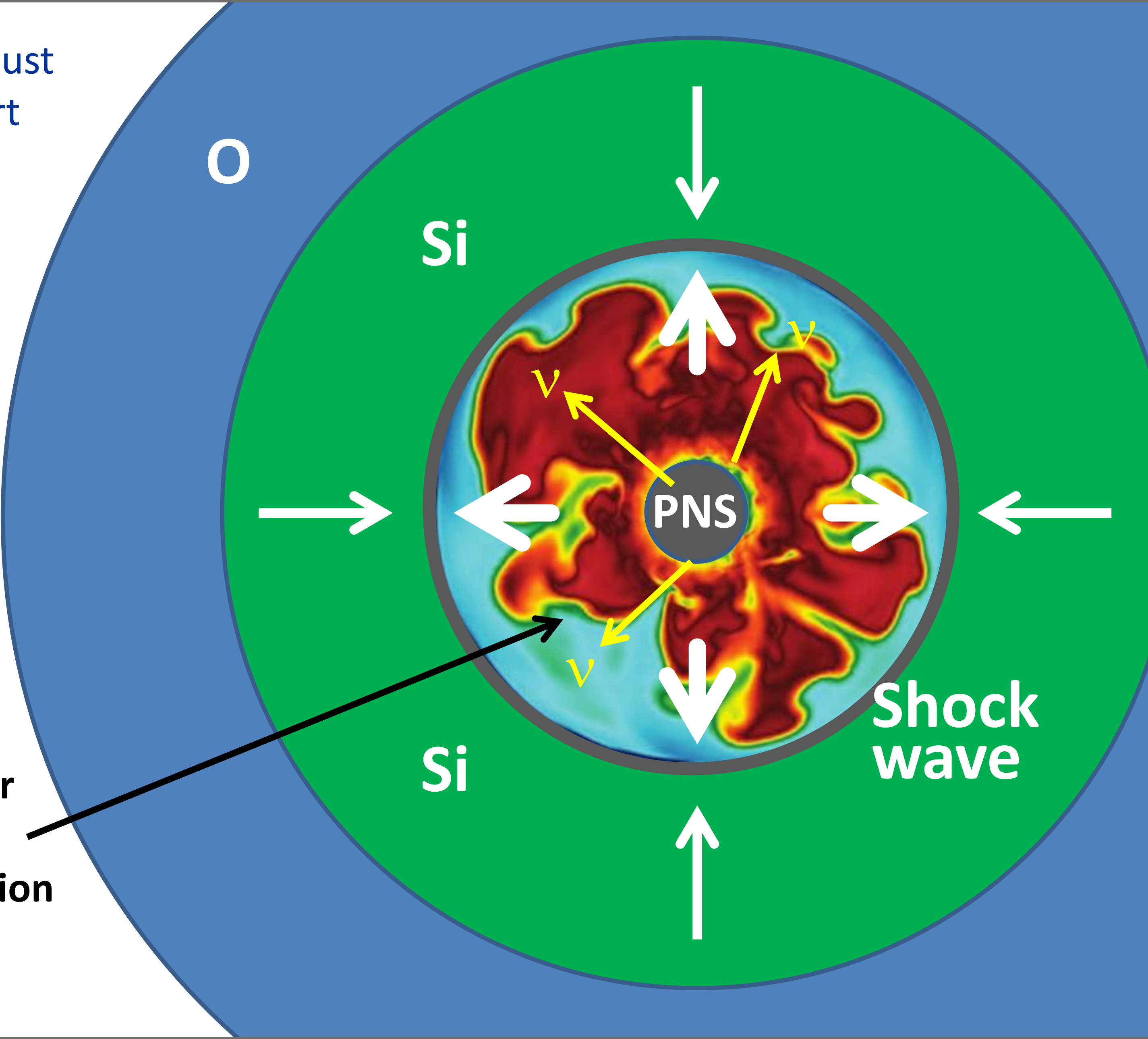


# Shock Revival by Neutrinos

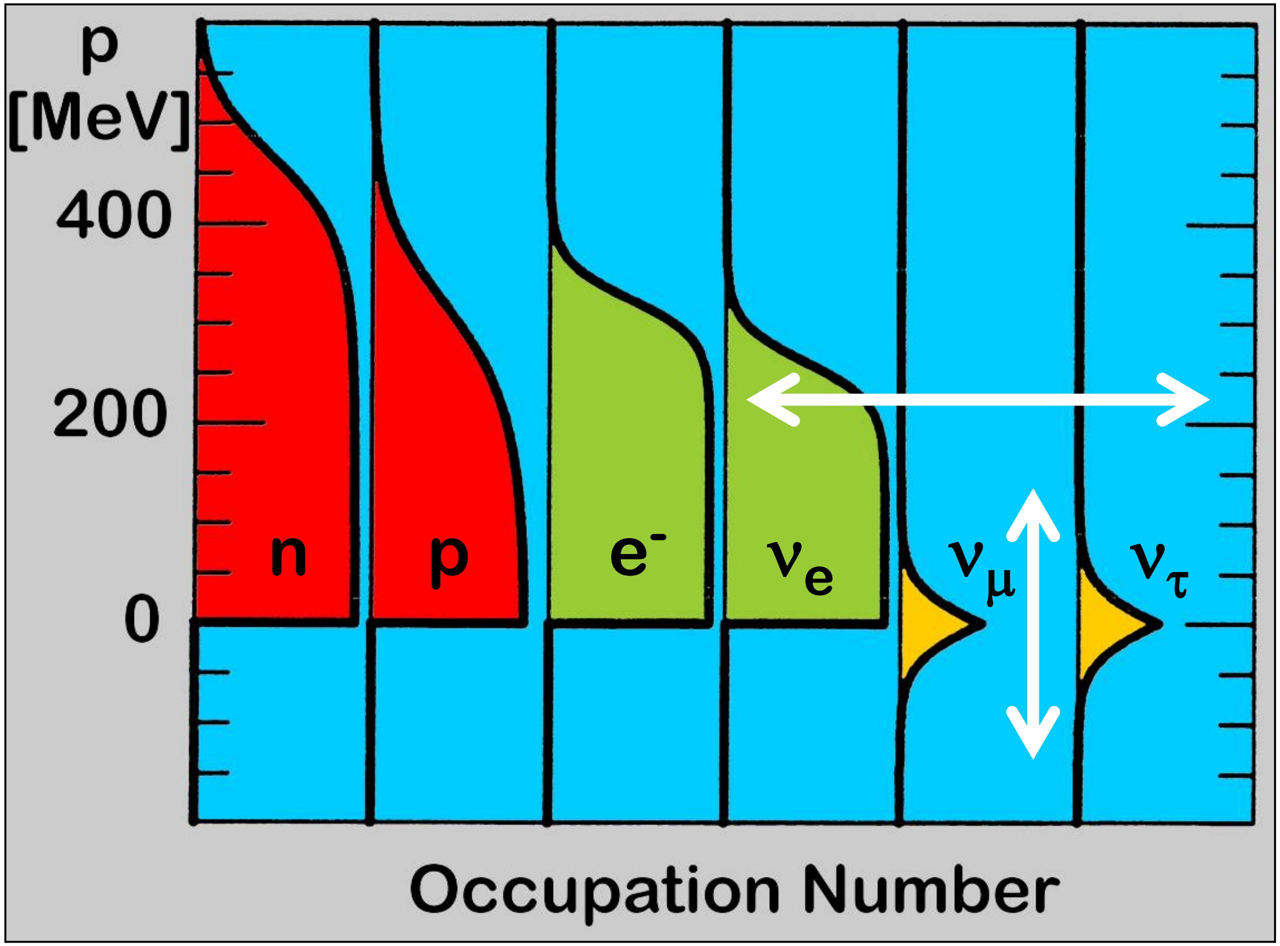
Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

**Shock can receive fresh energy from neutrinos!**

**Flavor oscilllations (active-active) suppressed by matter out to stalled shock. Self-induced conversion also suppressed (with caveats).**



# Degenerate Fermi Seas in a Supernova Core



Equilibration by flavor lepton number violation, but flavor oscillations ineffective (matter effect)

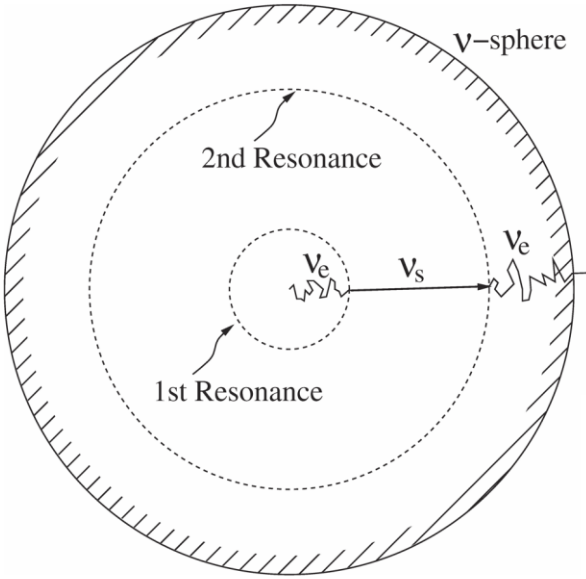
Non-standard interactions could be effective, most sensitive environment

Consequences in core collapse should be studied numerically

Equilibration by lepton number violation, but Majorana masses too small

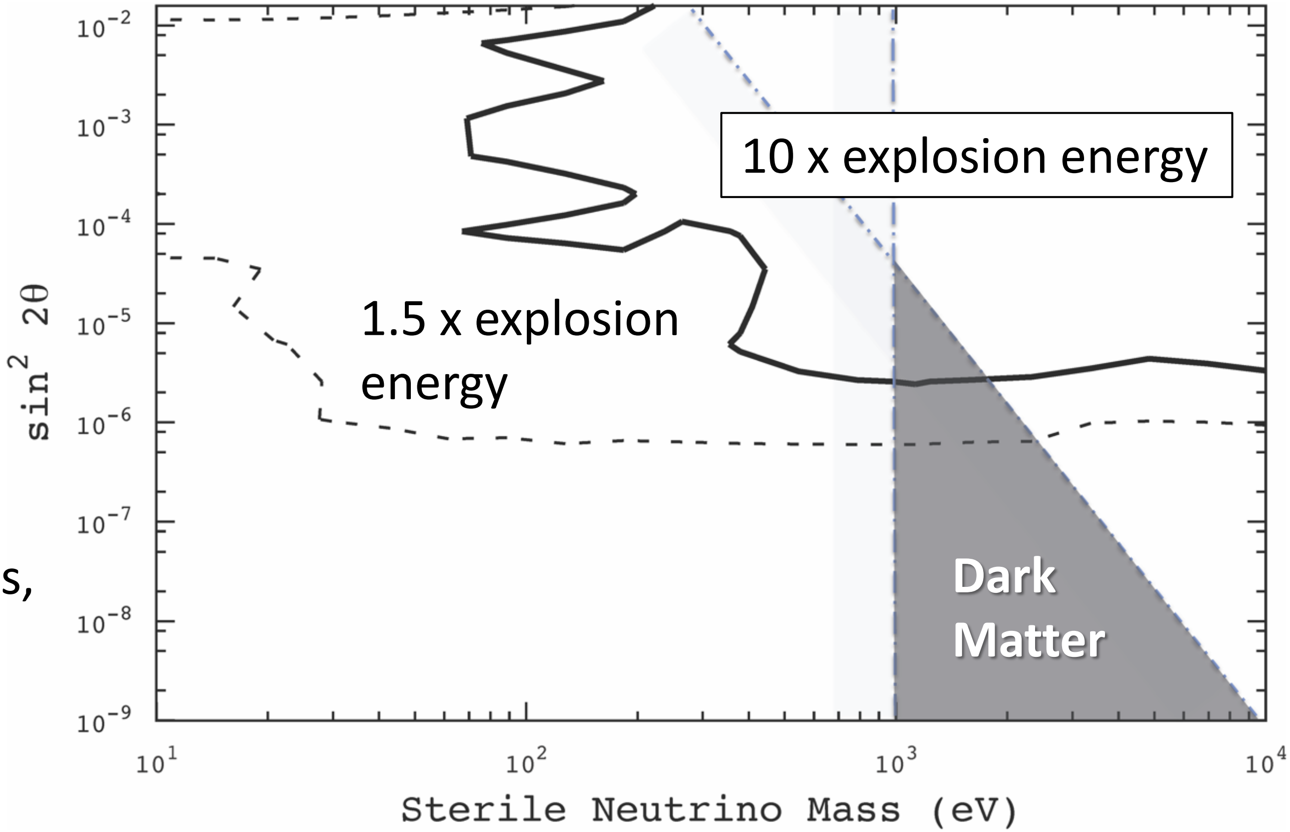
R-parity violating SUSY interactions?
TeV-scale bi-leptons?

# Sterile Neutrino Enhanced Supernova Explosions?



Non-local energy transfer from deep inside to neutrino sphere

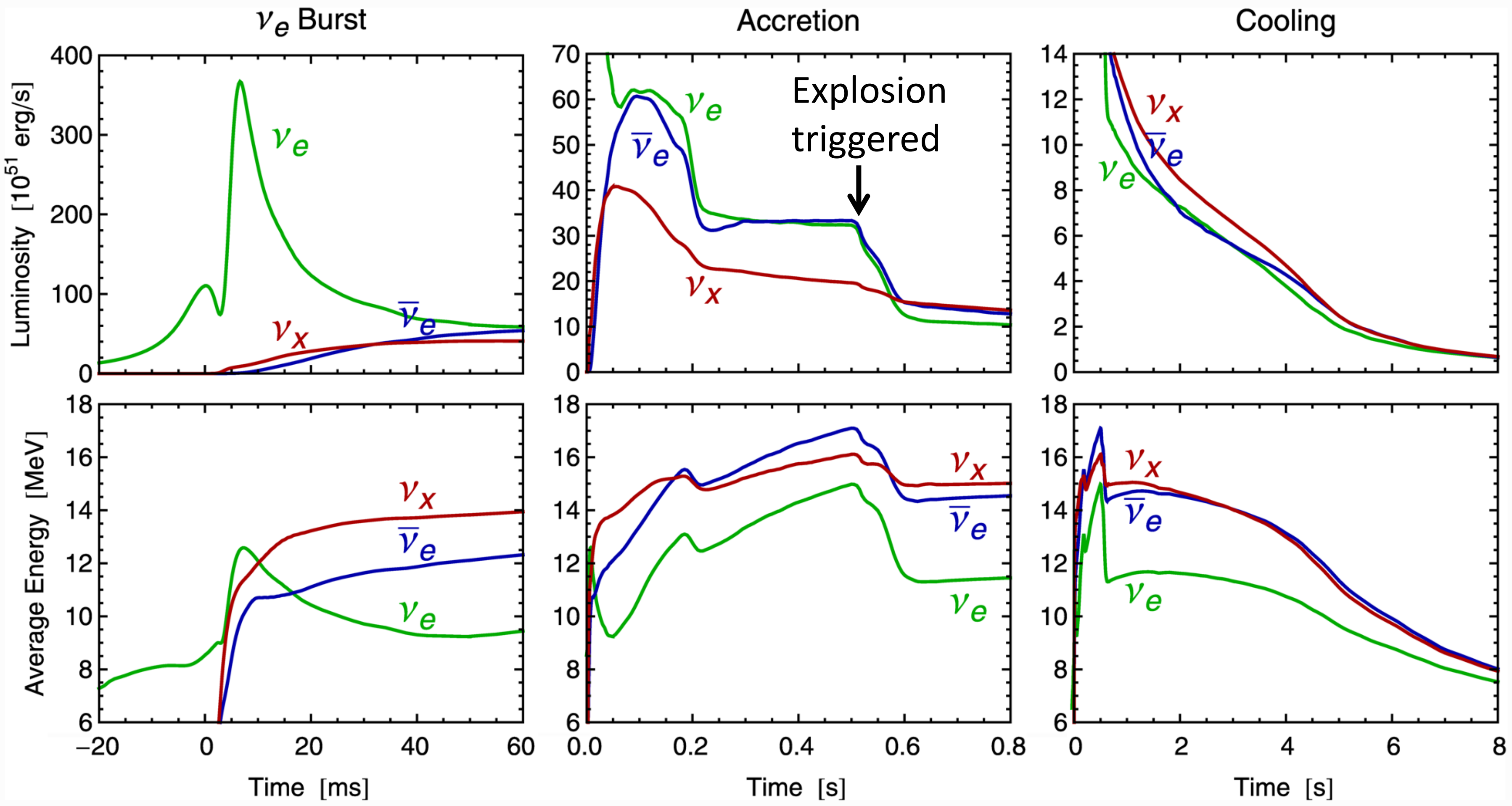
Hidaka & Fuller, astro-ph/0609425, arXiv:0706.3886



Numerical study:

Warren, Meixner, Mathews, Hidaka & Kajino, arXiv:1405.6101

# Three Phases of Neutrino Emission



- Shock breakout
- De-leptonization of outer core layers

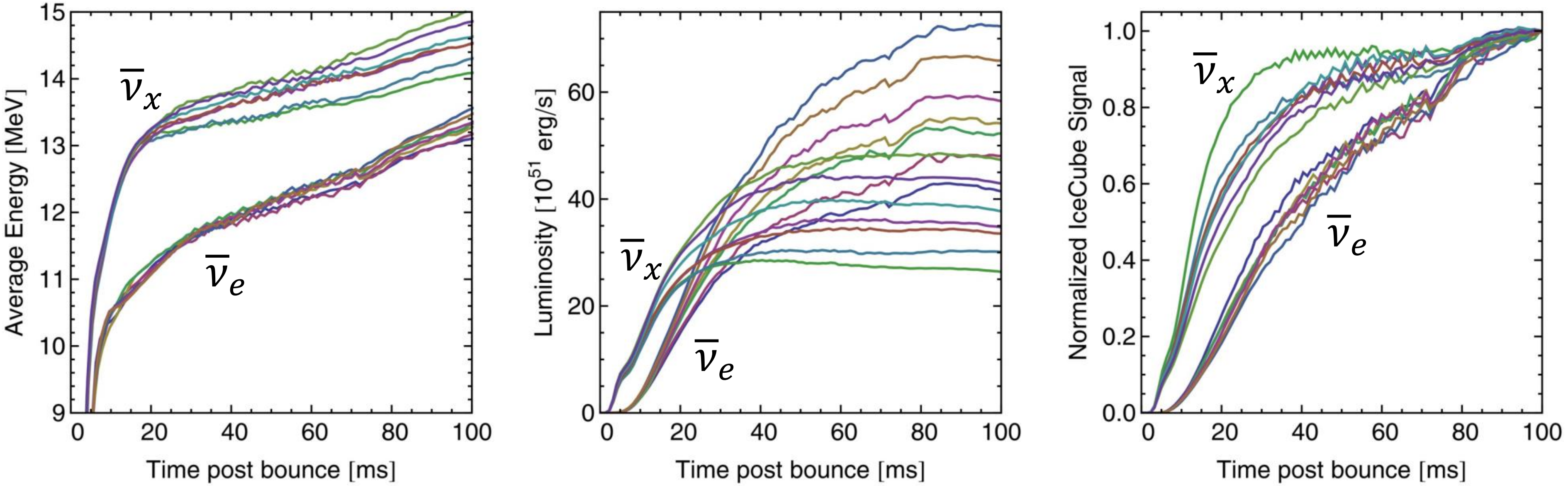
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

# Early-Phase Signal in Anti-Neutrino Sector

## Garching Models with $M = 12\text{–}40\ M_\odot$



**Average Energy**

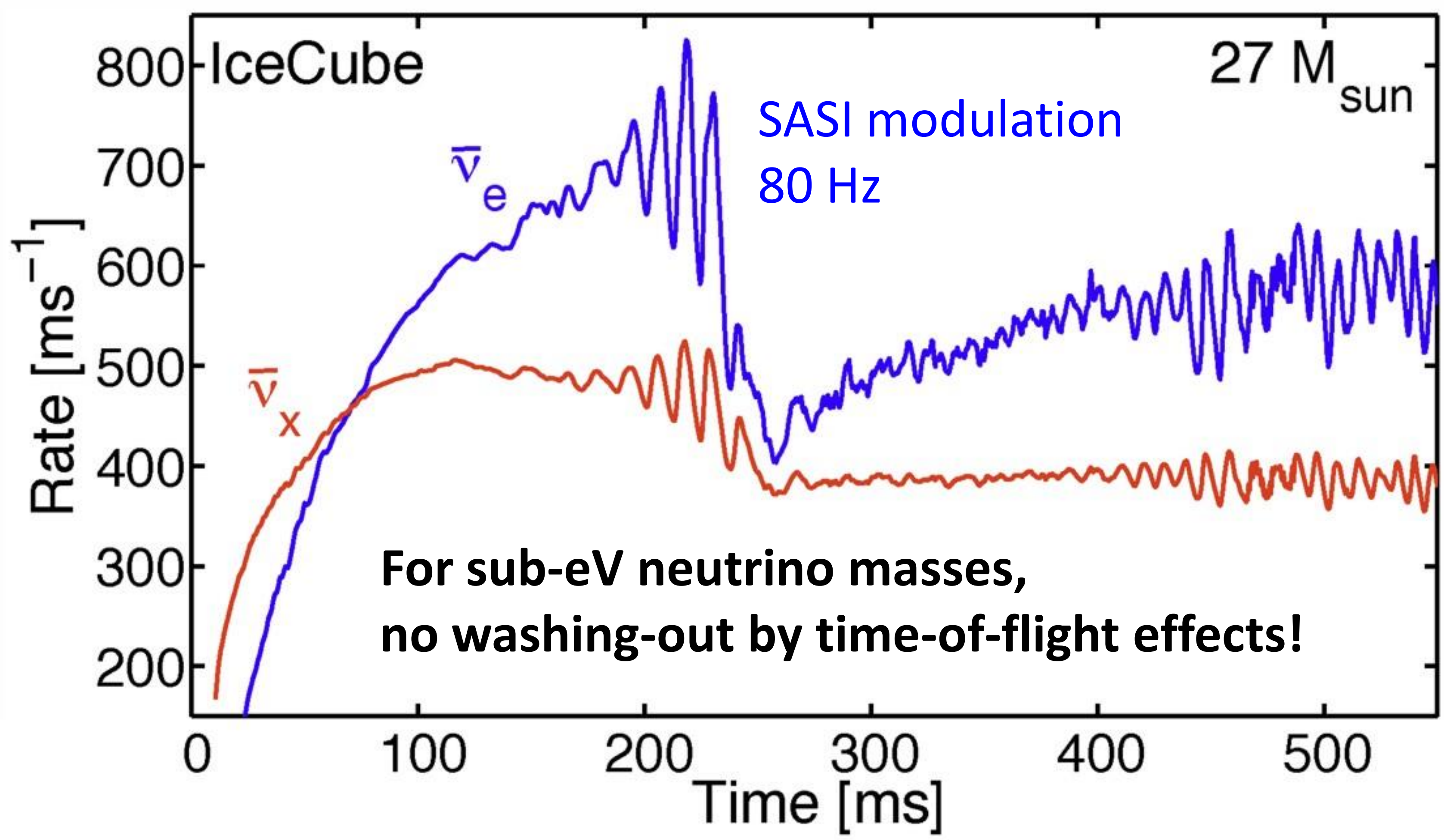
**Luminosity**

**IceCube Signature**

- In principle very sensitive to hierarchy, notably IceCube
- “Standard candle” to be confirmed by other than Garching models

Abbasi et al. (IceCube Collaboration) A&A 535 (2011) A109
Serpico, Chakraborty, Fischer, Hüdepohl, Janka & Mirizzi, arXiv:1111.4483

# Variability seen in Neutrinos (3D Model)



SASI modulation
80 Hz

**For sub-eV neutrino masses,**
**no washing-out by time-of-flight effects!**

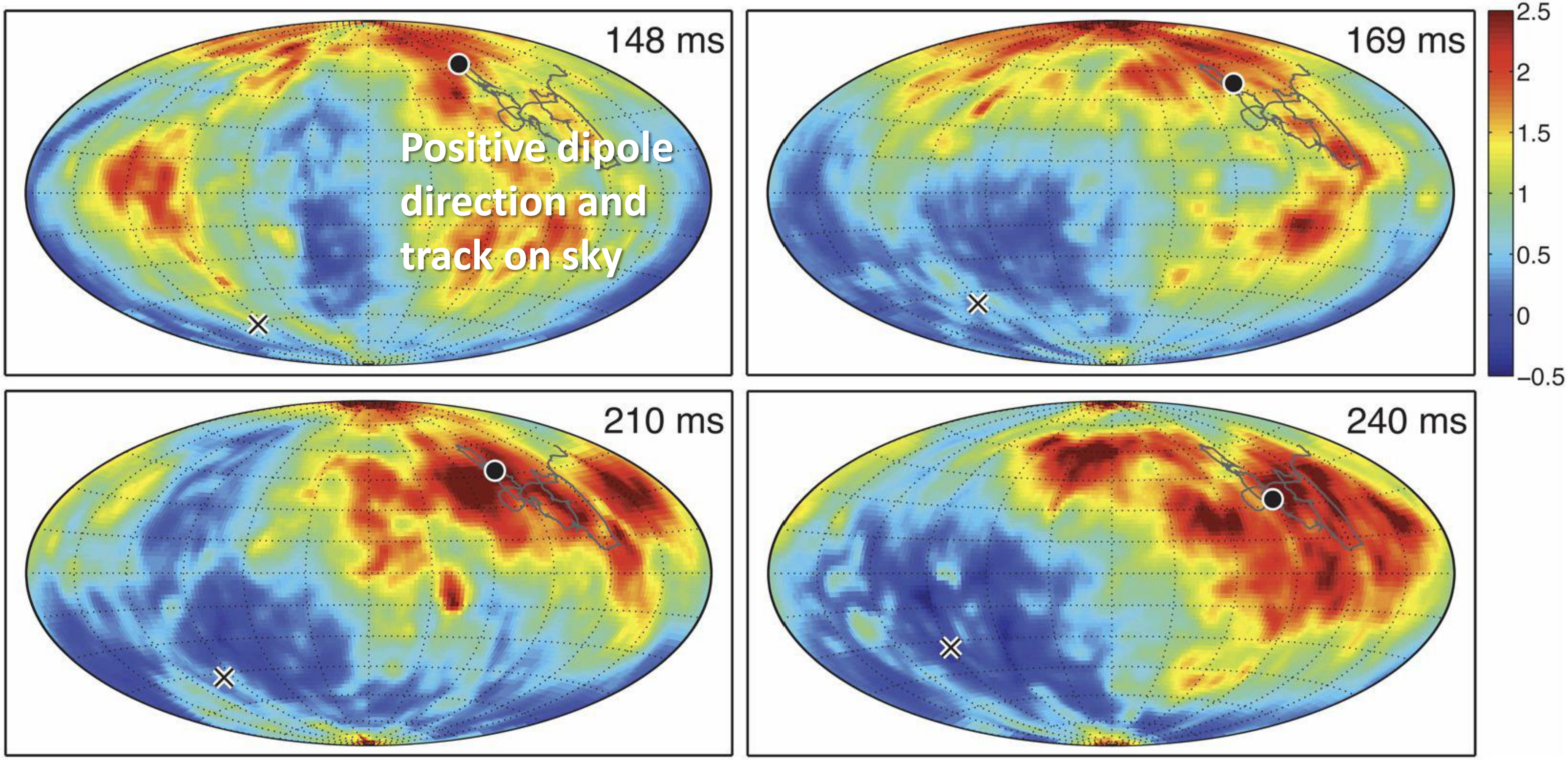
Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936
See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

# Sky Map of Lepton-Number Flux (11.2 $M_{SUN}$ Model)

**Lepton-number flux ($\nu_e - \bar{\nu}_e$) relative to 4π average**

**Deleptonization flux into one hemisphere, roughly dipole distribution**

**(LESA — Lepton Emission Self-Sustained Asymmetry)**

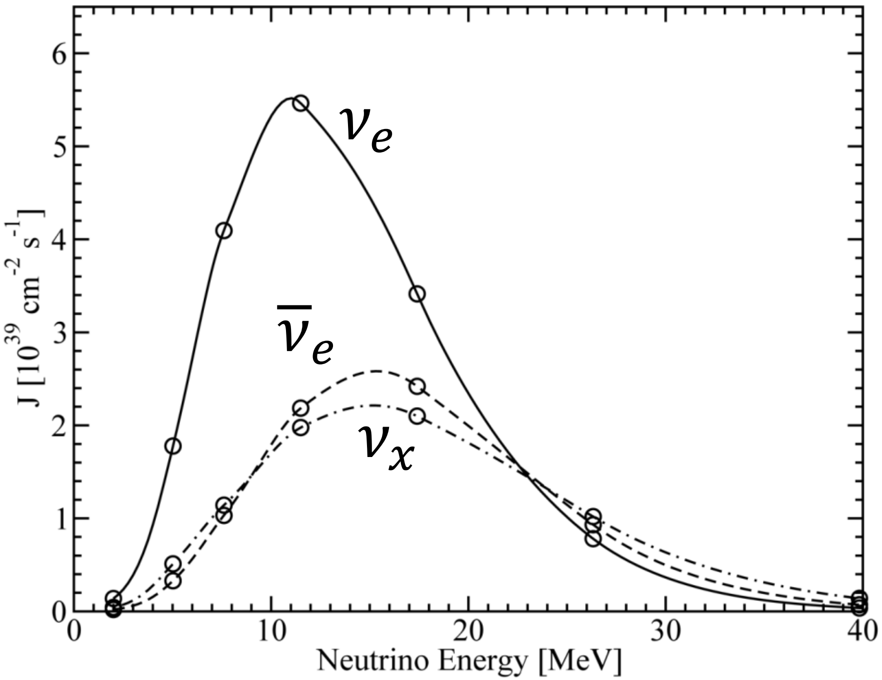


Tamborra, Hanke, Janka, Müller, Raffelt & Marek, arXiv:1402.5418

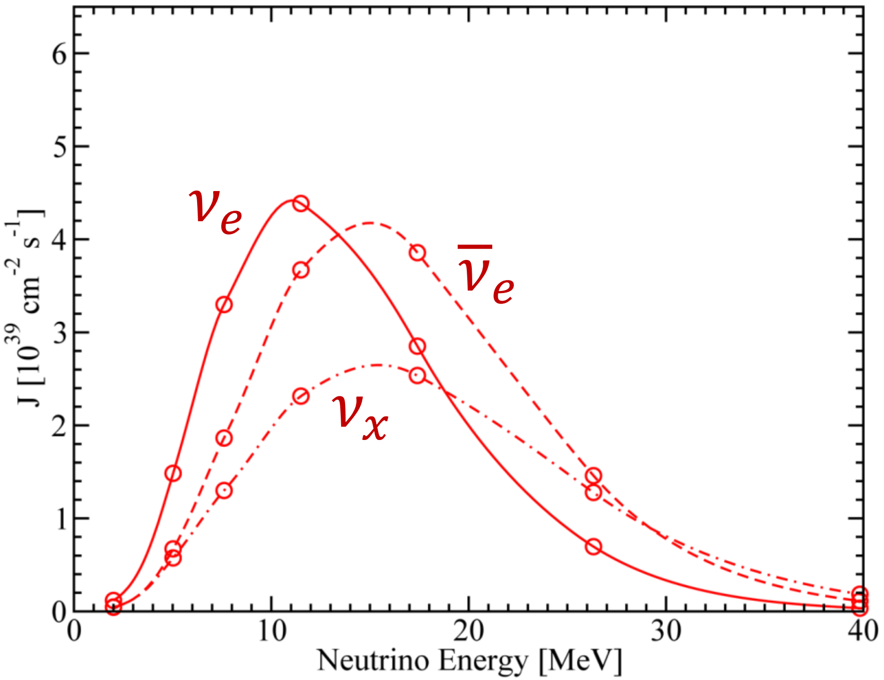
# Spectra in the two Hemispheres

**Neutrino flux spectra (11.2 $M_{SUN}$ model at 210 ms) in opposite LESA directions**

Direction of
**maximum** lepton-number flux



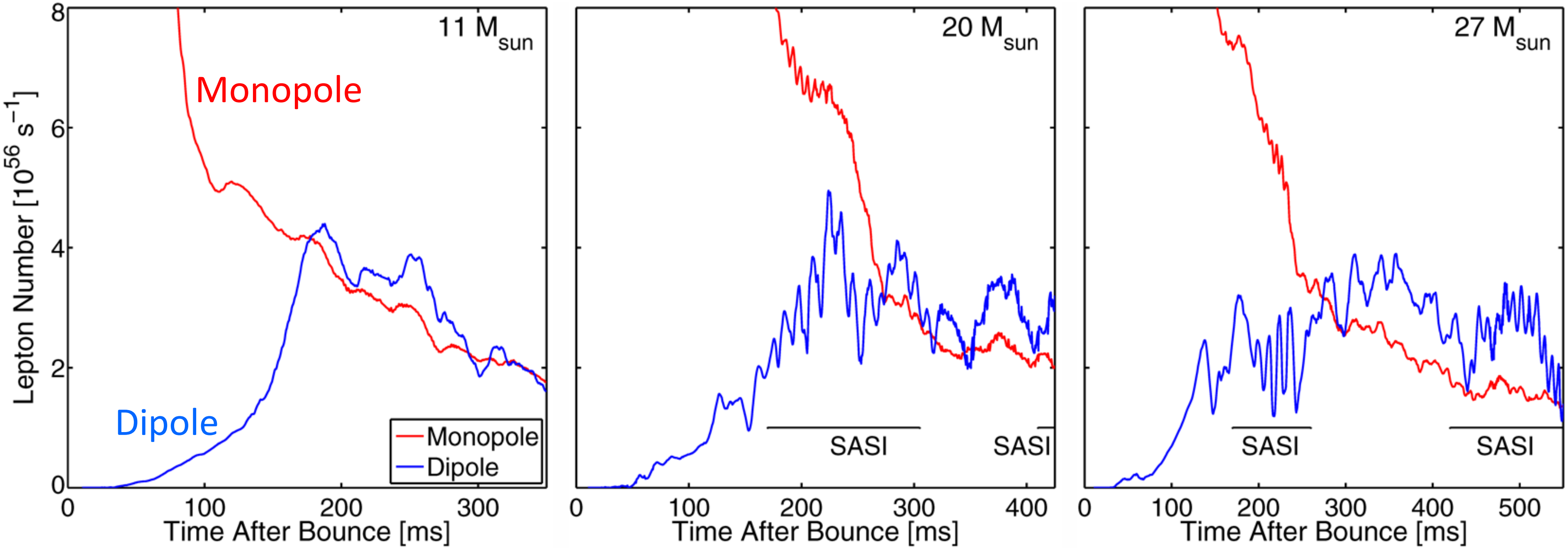
Direction of
**minimum** lepton-number flux



**During accretion phase, flavor-dependent fluxes
vary strongly with observer direction!**

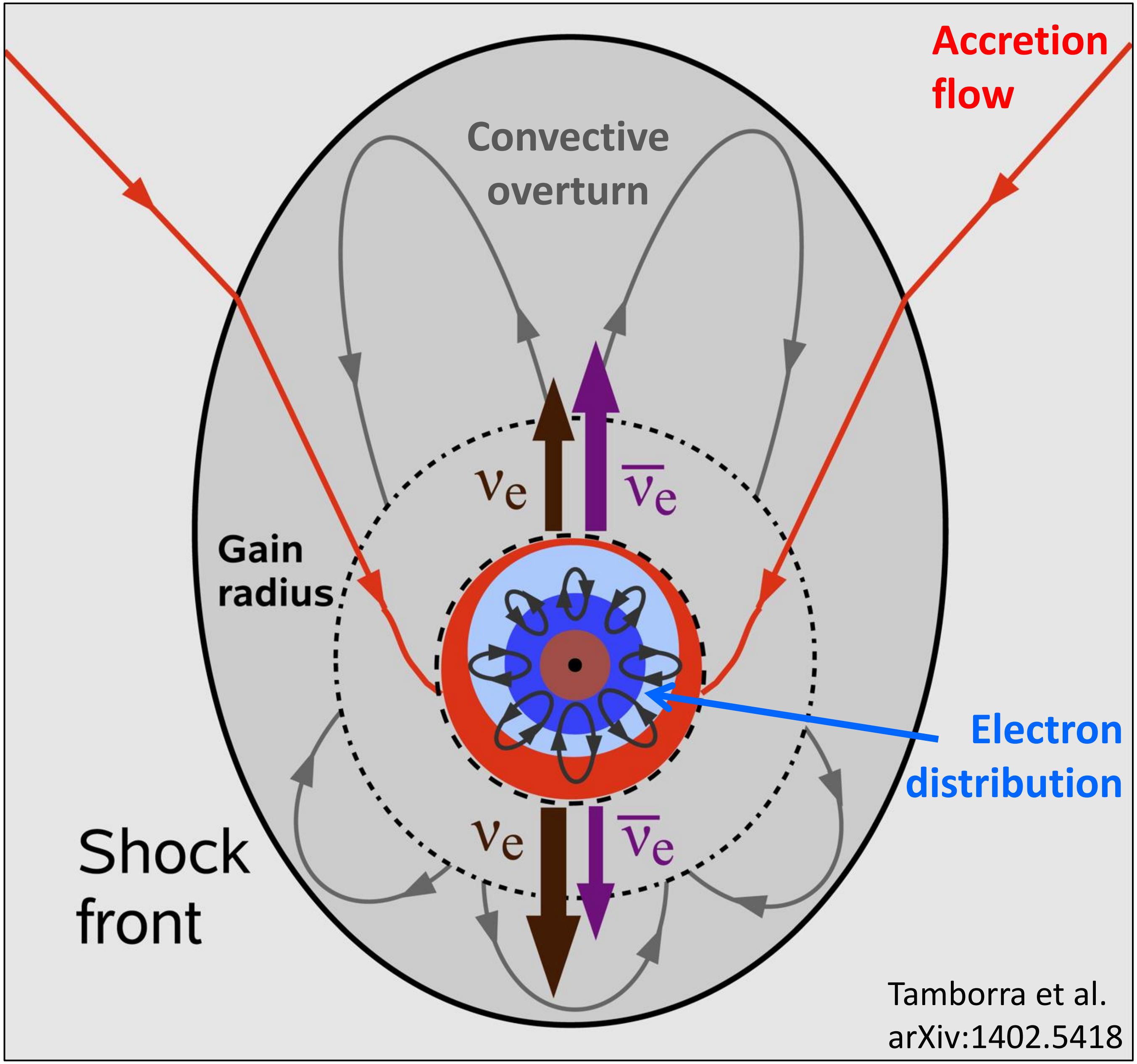
# Growth of Lepton-Number Flux Dipole

Tamborra et al., arXiv:1402.5418



- Overall lepton-number flux (monopole) depends on accretion rate, varies between models
- Maximum dipole similar for different models
- Dipole persists (and even grows) during SASI activity
- SASI and LESA dipoles uncorrelated

# Schematic Theory of LESA

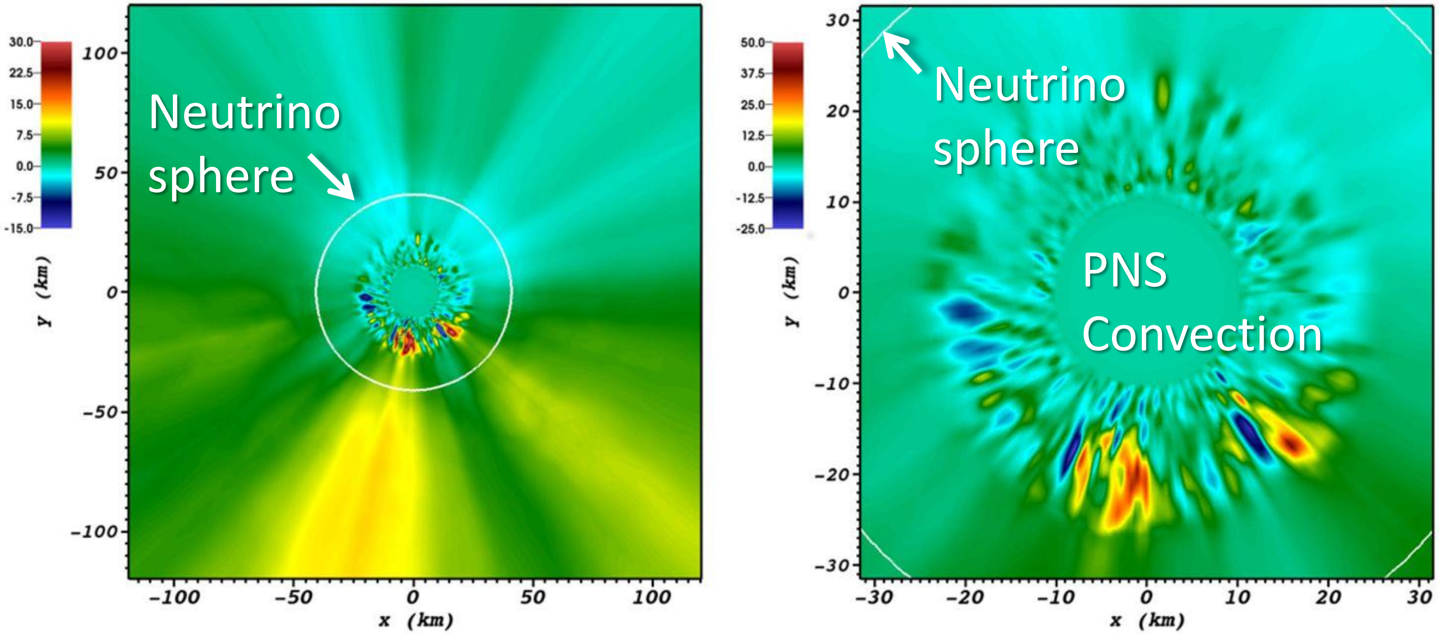


Tamborra et al.
arXiv:1402.5418

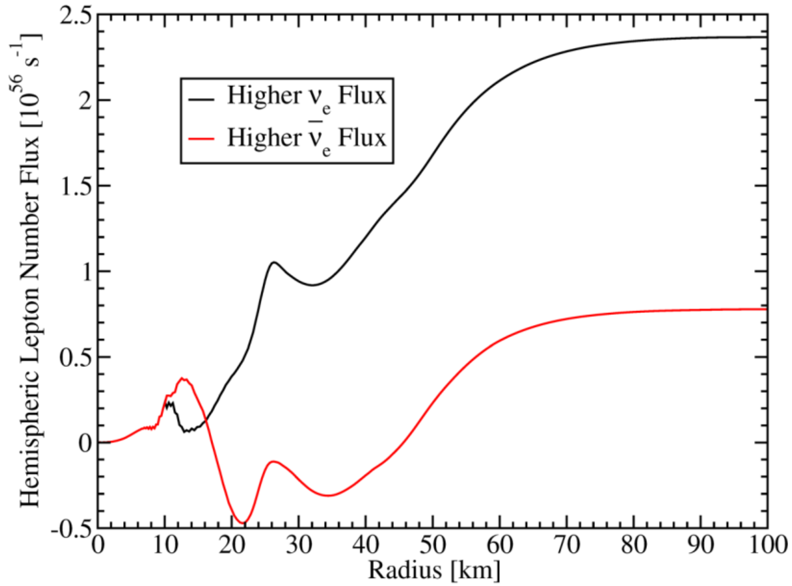
Feedback loop consists of asymmetries in

- accretion rate
- lepton-number flux
- neutrino heating rate
- dipole deformation of shock front

# LESA Dipole and PNS Convection

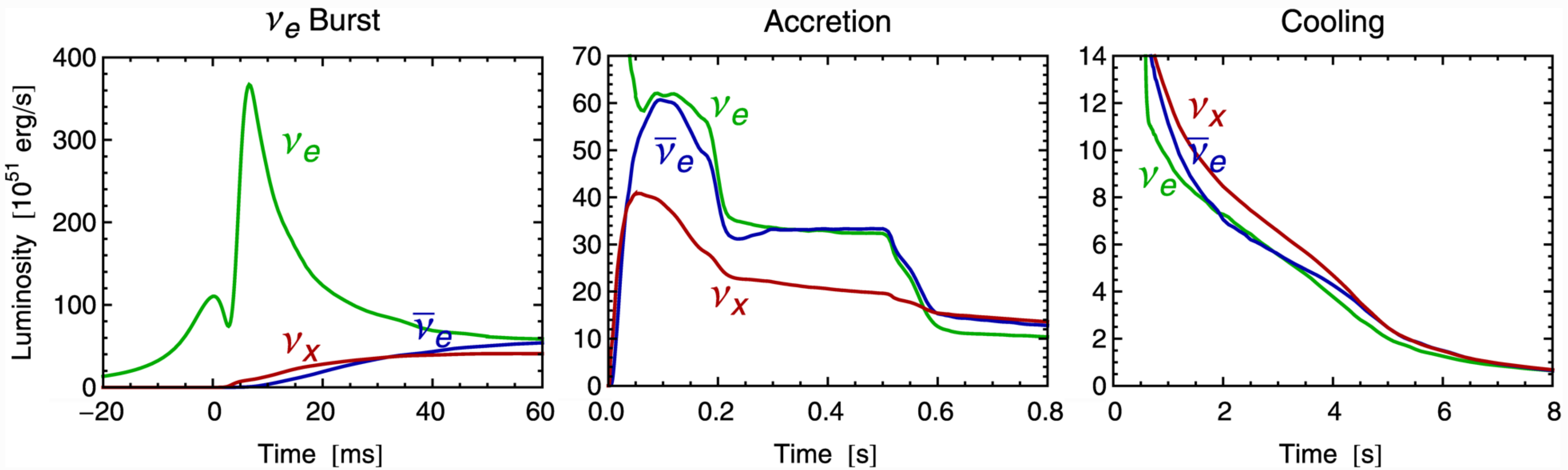


Color-coded lepton-number flux along radial rays ($11.2\ M_{SUN}$ model at 210 ms)



**Lepton flux dipole builds up mostly below the neutrino sphere in a region of strong convection in the proto-neutron star (PNS)**

# Three Phases – Three Opportunities



Standard Candle (?)

- SN theory
- Distance
- Flavor conversions
- Multi-messenger time of flight

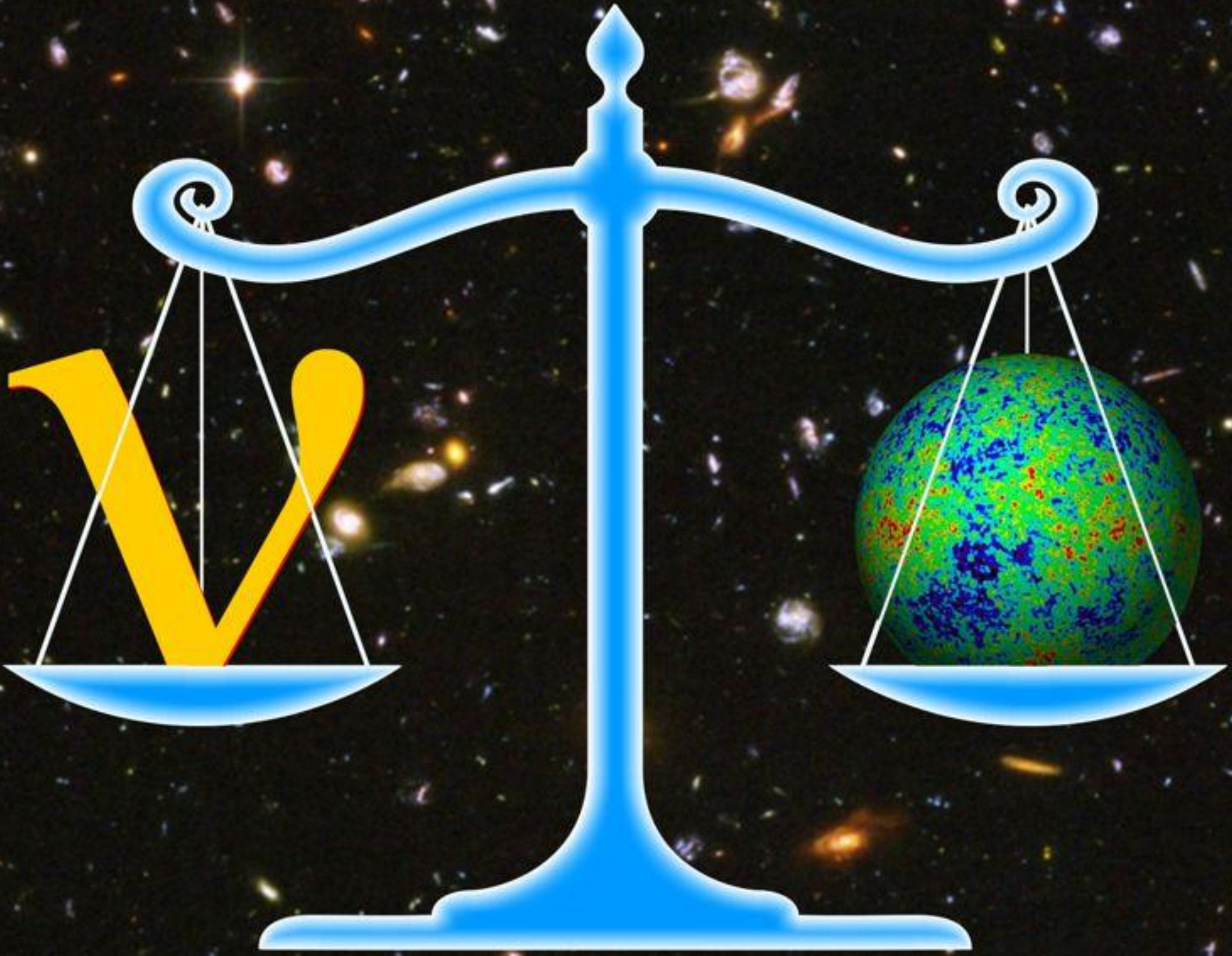
Strong variations (progenitor, 3D effects, black hole formation, …)

- Testing astrophysics of core collapse
- Flavor conversion has strong impact on signal

EoS & mass dependence

- Testing nuclear physics
- Nucleosynthesis in neutrino-driven wind
- Particle bounds from cooling speed (axions …)

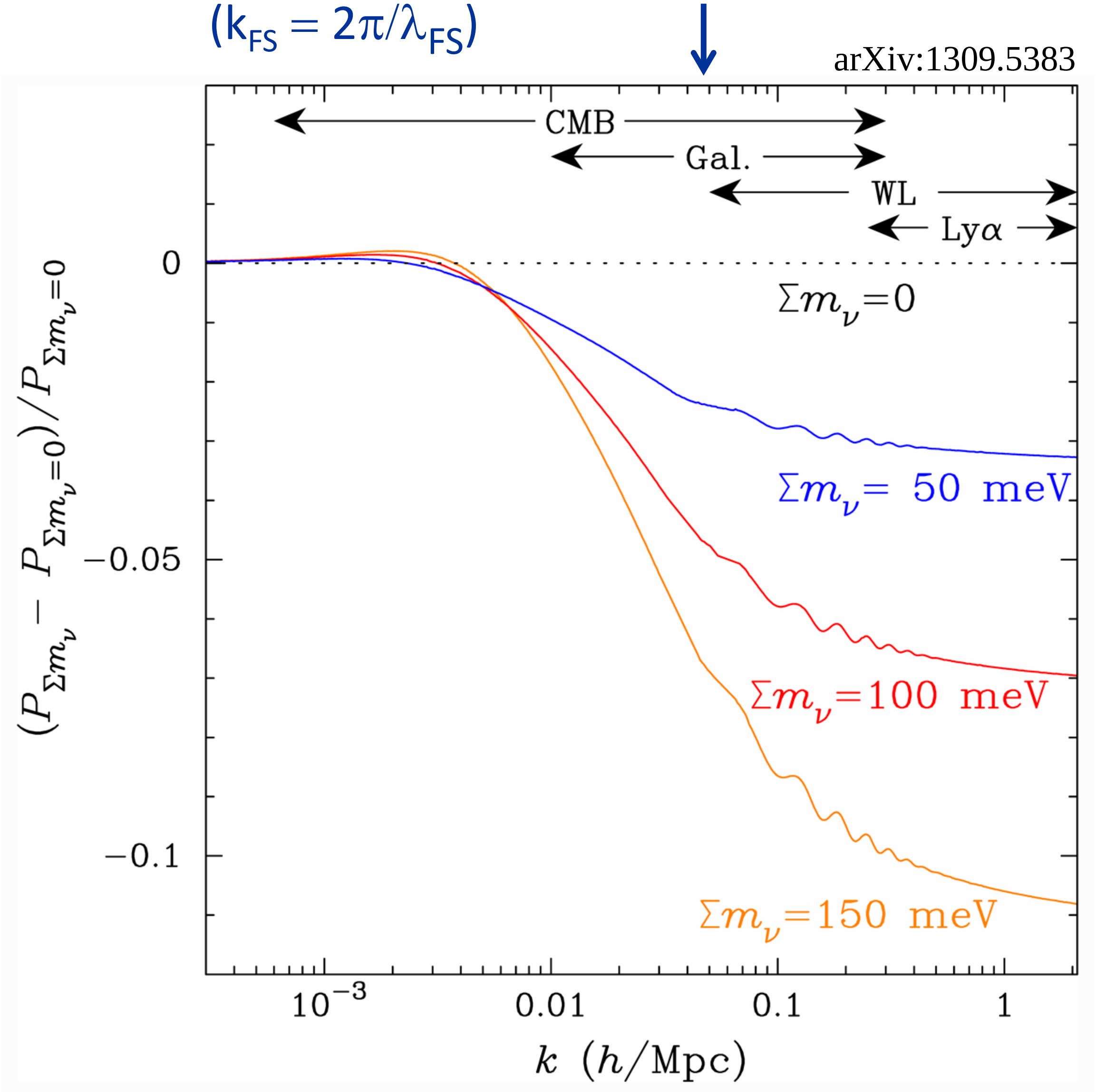
# Weighing Neutrinos with the Universe



# Transfer Function with Massive Neutrinos

Power suppression for $\lambda_{FS} \gtrsim 100$ Mpc/h
($k_{FS} = 2\pi/\lambda_{FS}$)

arXiv:1309.5383



Transfer function

$$P(k) = T(k)\, P_0(k)$$

Effect of neutrino free streaming on small scales

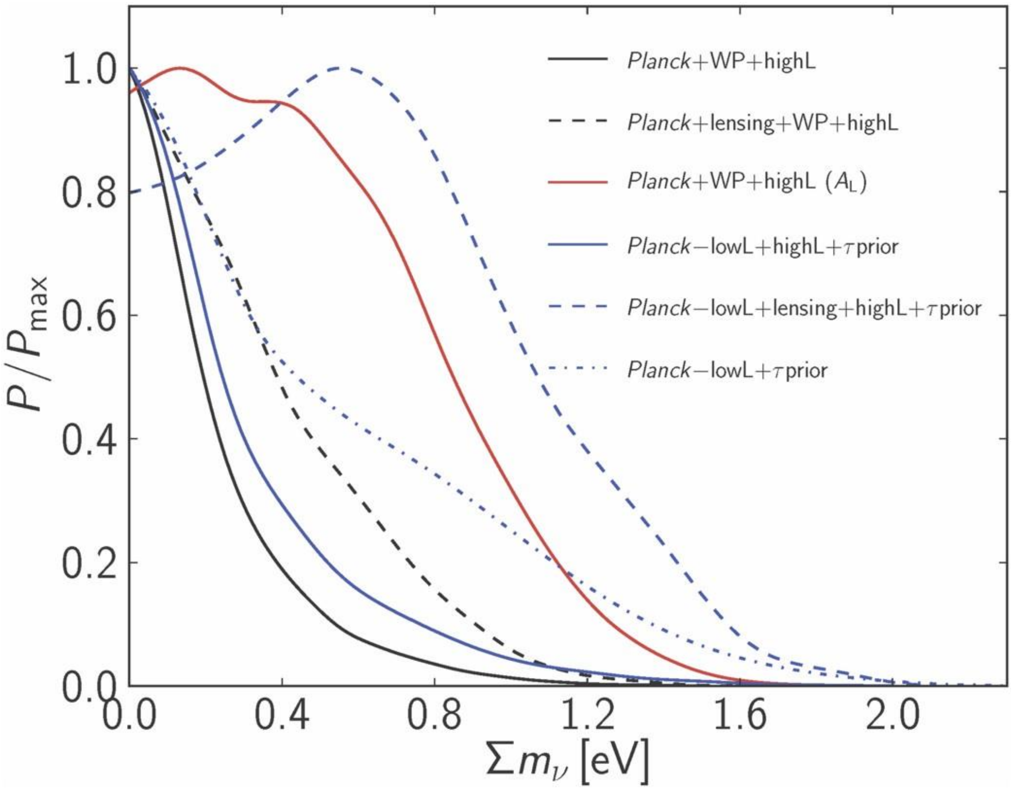
$$T(k) = 1 - 8\, \Omega_\nu/\Omega_M$$

valid for $8\Omega_\nu/\Omega_M \ll 1$

Power suppression much larger (factor 8) than corresponds to neutrino mass fraction!

# Neutrino Mass Limits Post Planck (2013)

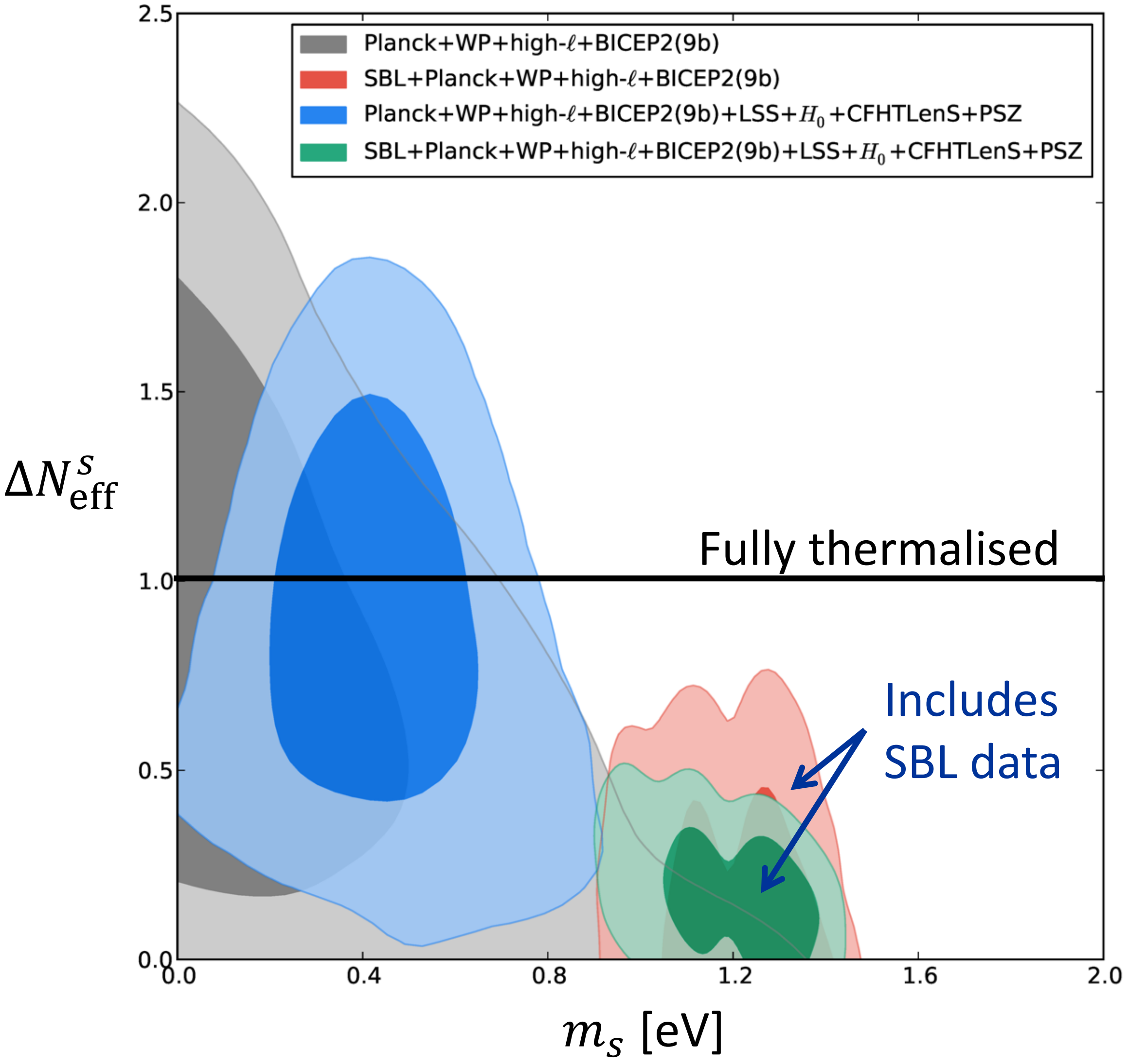
Depends on used data sets
Many different analyses in the literature



**Planck alone: $\Sigma m_\nu < 1.08$ eV (95% CL)**
**CMB + BAO limit: $\Sigma m_\nu < 0.23$ eV (95% CL)**

Ade et al. (Planck Collaboration), arXiv:1303.5076

# Constraints on Light Sterile Neutrinos

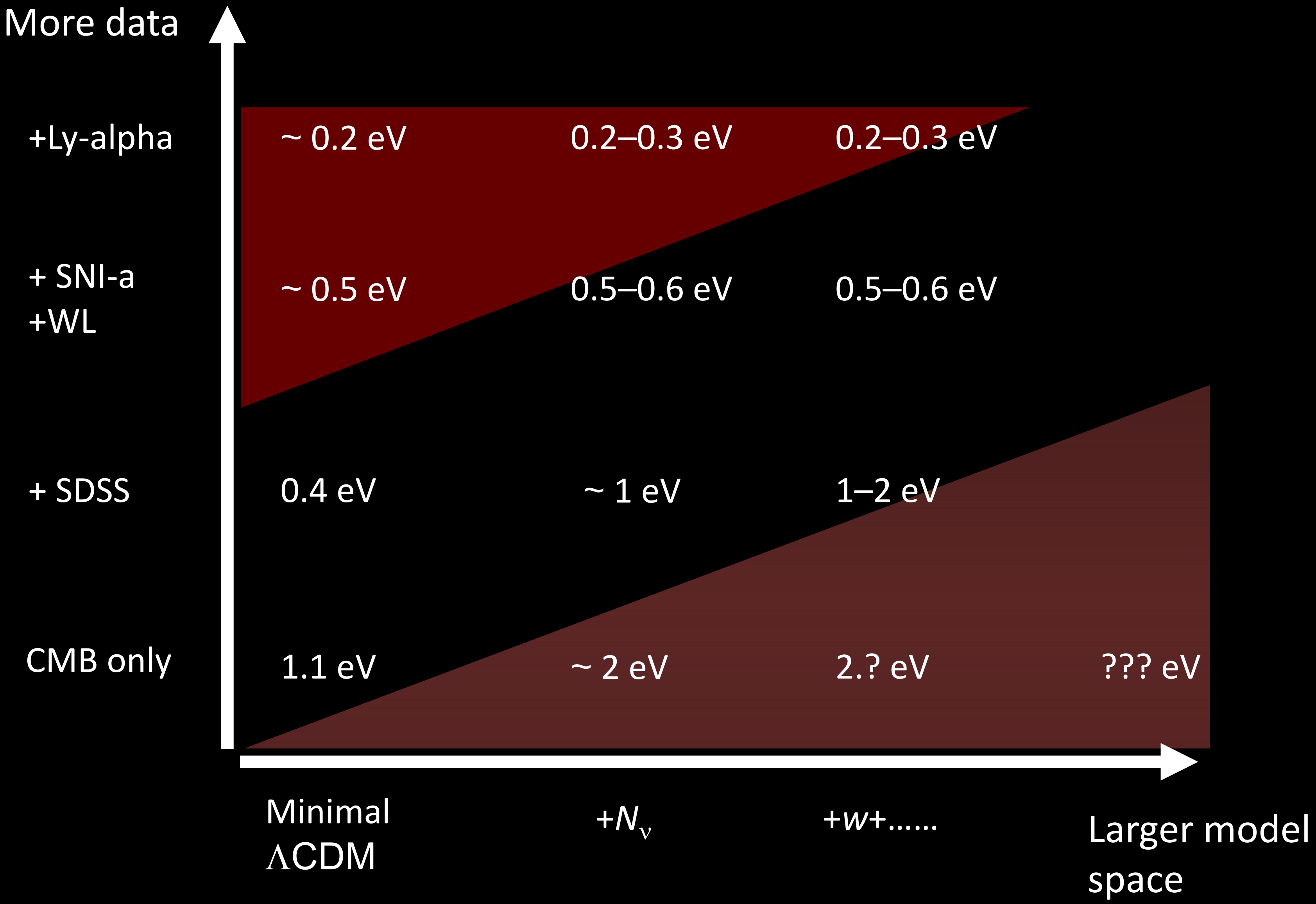


**Sterile neutrinos with parameters favored by short-baseline (SBL) experiments are in conflict with cosmology (complete thermalization)**

**But thermalization could be suppressed (matter effect from strong interactions among sterile nus or asymmetries among active nus) [arXiv:1303.5368, 1310.5926, 1310.6337, 1404.5915, 1410.1385]**

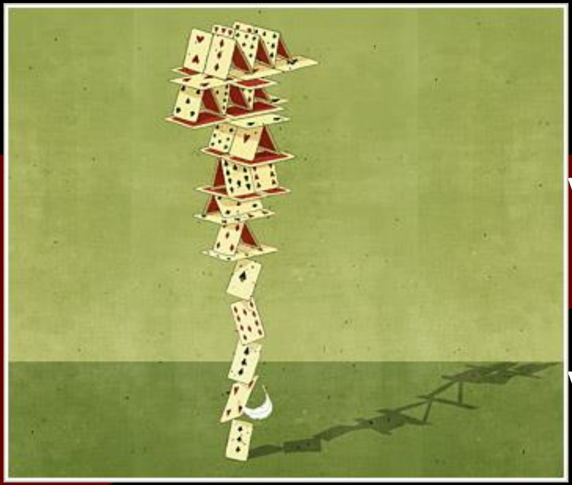
Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, arXiv:1404.1794

# Neutrino Mass from Cosmology Plot (Hannestad)



| More data | Minimal $\Lambda$CDM | $+N_\nu$ | $+w+$…… | Larger model space |
|---|---|---|---|---|
| +Ly-alpha | ~ 0.2 eV | 0.2–0.3 eV | 0.2–0.3 eV | |
| + SNI-a<br>+WL | ~ 0.5 eV | 0.5–0.6 eV | 0.5–0.6 eV | |
| + SDSS | 0.4 eV | ~ 1 eV | 1–2 eV | |
| CMB only | 1.1 eV | ~ 2 eV | 2.? eV | ??? eV |

# Neutrino Mass from Cosmology Plot (Hannestad)



More data

| | Minimal $\Lambda$CDM | $+N_\nu$ | $+w+$…… | Larger model space |
|---|---|---|---|---|
| +Ly-alpha | | V | 0.2–0.3 eV | |
| + SNI-a<br>+WL | | V | 0.5–0.6 eV | |
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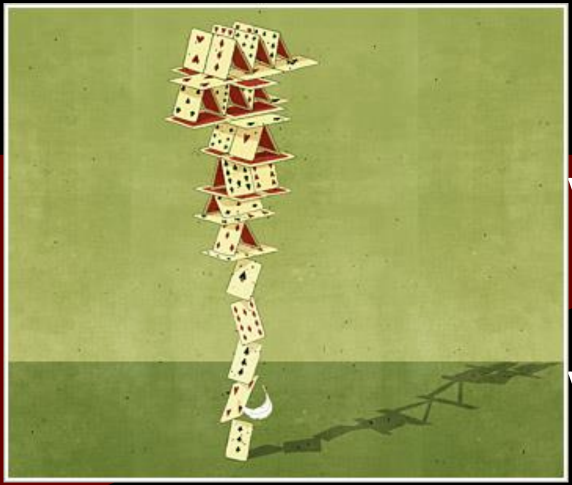
# Neutrino Mass from Cosmology Plot (Hannestad)

More data



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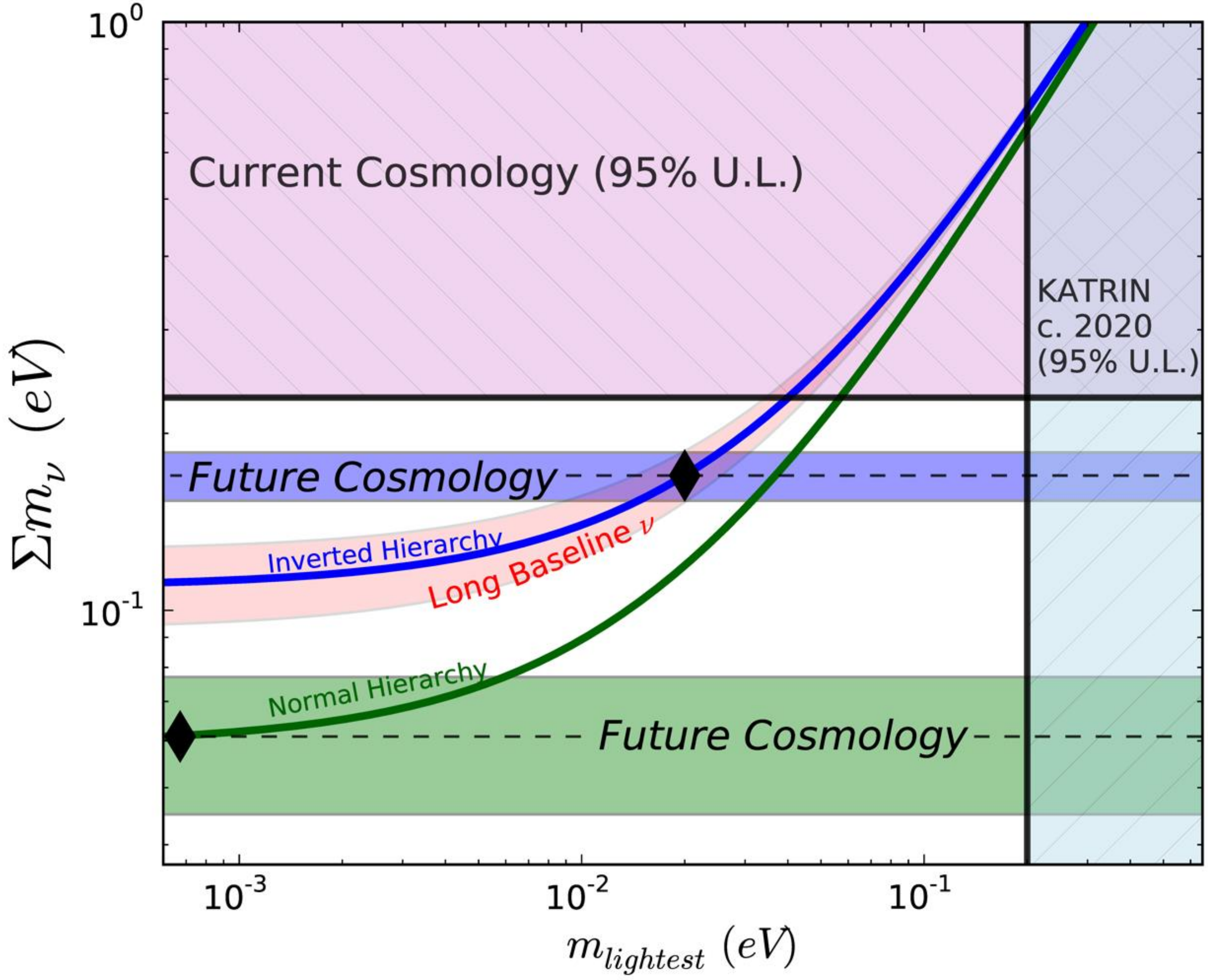
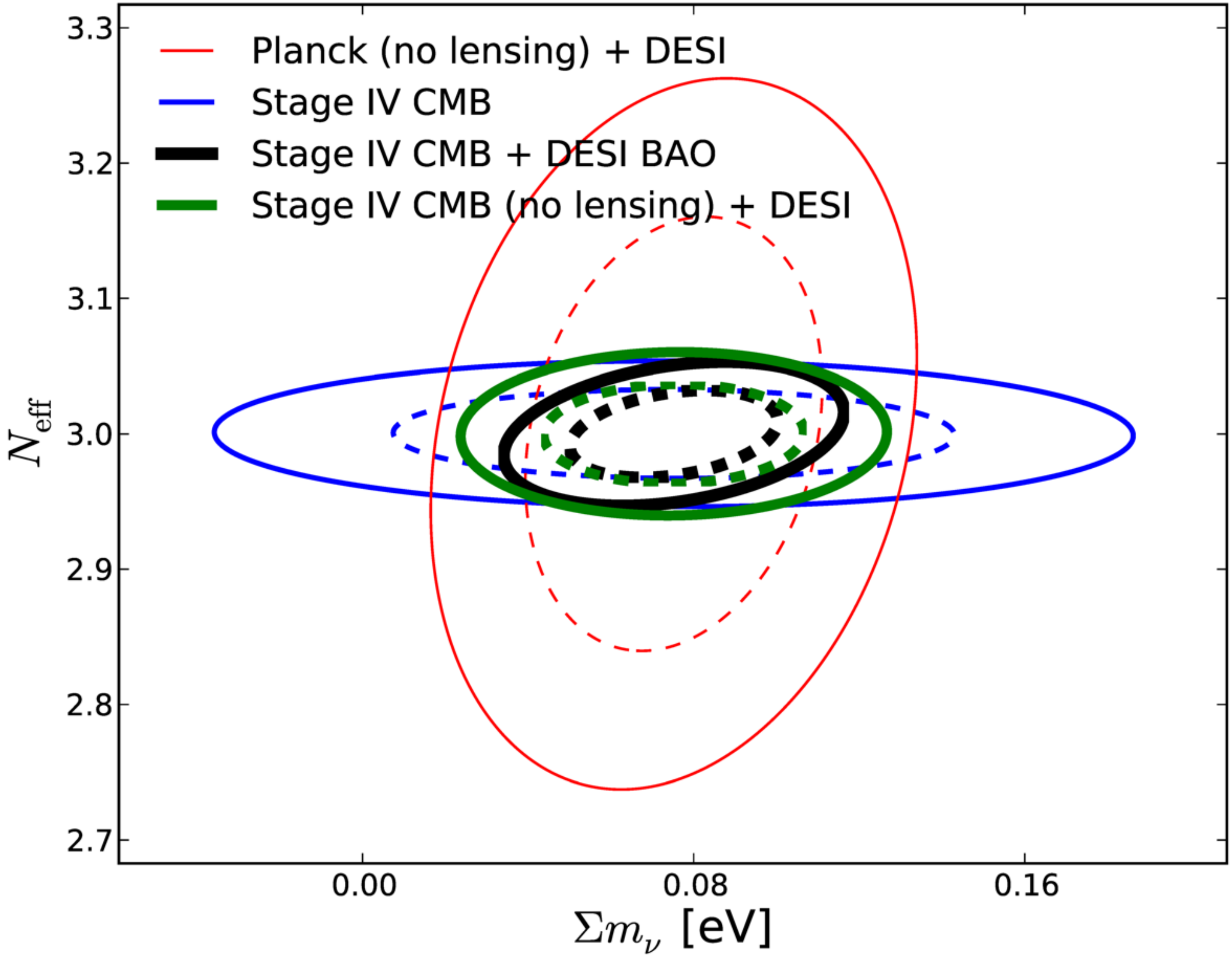
Larger model space

# Neutrino-Mass Sensitivity Forecast



Community Planning Study: Snowmass 2013, arXiv:1309.5383

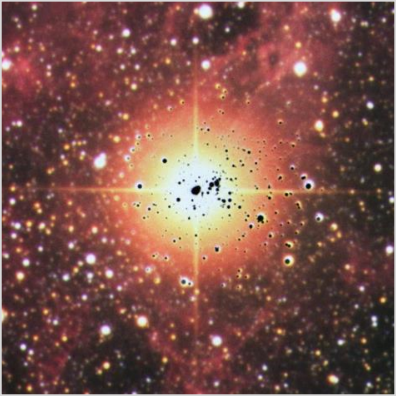
# Nu-Mass and N-eff Sensitivity Forecast



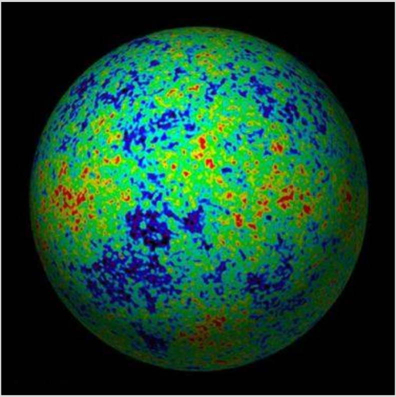
Community Planning Study: Snowmass 2013, arXiv:1309.5383

# Astro/Cosmo Neutrino Limits

- Neutrino electromagnetic properties (dipole moments) most severely constrained from plasmon decay in stars (low-mass stars He ignition, white dwarf luminosity function) $\mu_\nu \lesssim 3 \times 10^{-12}\ \mu_\mathrm{B}$
- Applies to active and sterile nus with $m_\nu \lesssim 10\ \mathrm{keV}$
- Can be improved later by GAIA distance determination



- Many limits on nonstandard nu properties from SN 1987A (gravitational interaction, r.h. interactions, steriles)
- Time of flight $m_\nu$ effects small: fast time variations caused by hydro instabilities observable
- Flavor oscillations (active-active or active-sterile) impacts explosion physics, kicks, nucleosynthesis, detected signal



- Most restrictive $m_\nu$ limits, measurement expected in future
- Dark radiation ($N_\mathrm{eff} > 3.046$) to be ruled in or out in future
- Probably has nothing to do with active neutrinos (enhanced density by asymmetries excluded by BBN)
- Thermalized eV-scale sterile nus excluded by HDM bounds, (but full thermalization can be suppressed by novel effects)