Cosmic Neutrinos

Joachim Kopp (CERN & JGU Mainz)
PASCOS 2022 | 28 July 2022

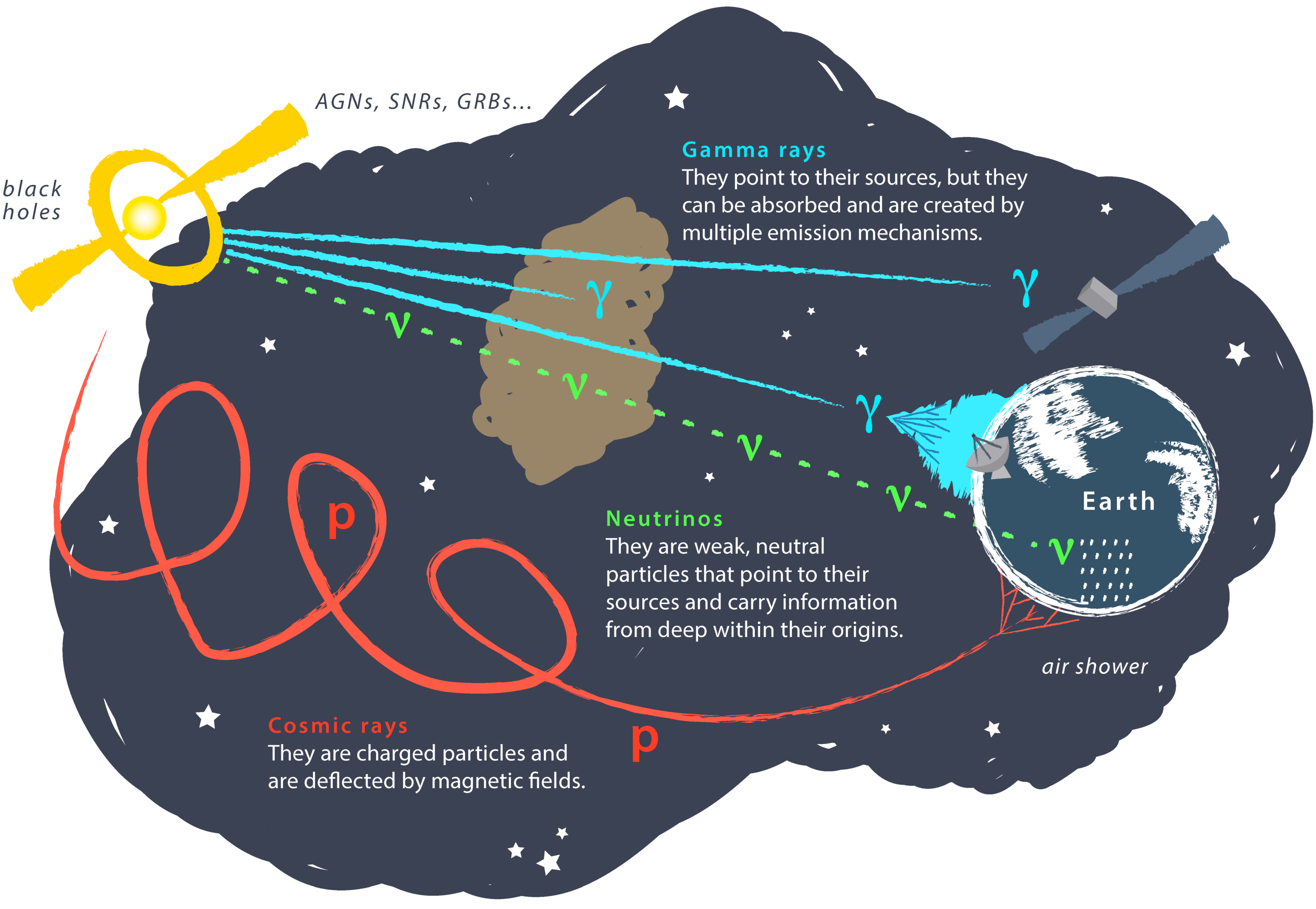


image: Juan Antonio Aguilar and Jamie Yang, IceCube/WIPAC

Neutrinos as Cosmic Messengers

- ★ point back to the source
- ★ are not absorbed along the way

Outline

- ☑ High Energy Astrophysical Neutrinos
- ☑ Supernova Neutrinos
- ☑ Neutrinos from Neutron Stars

High Energy Astrophysical Neutrinos

CERN

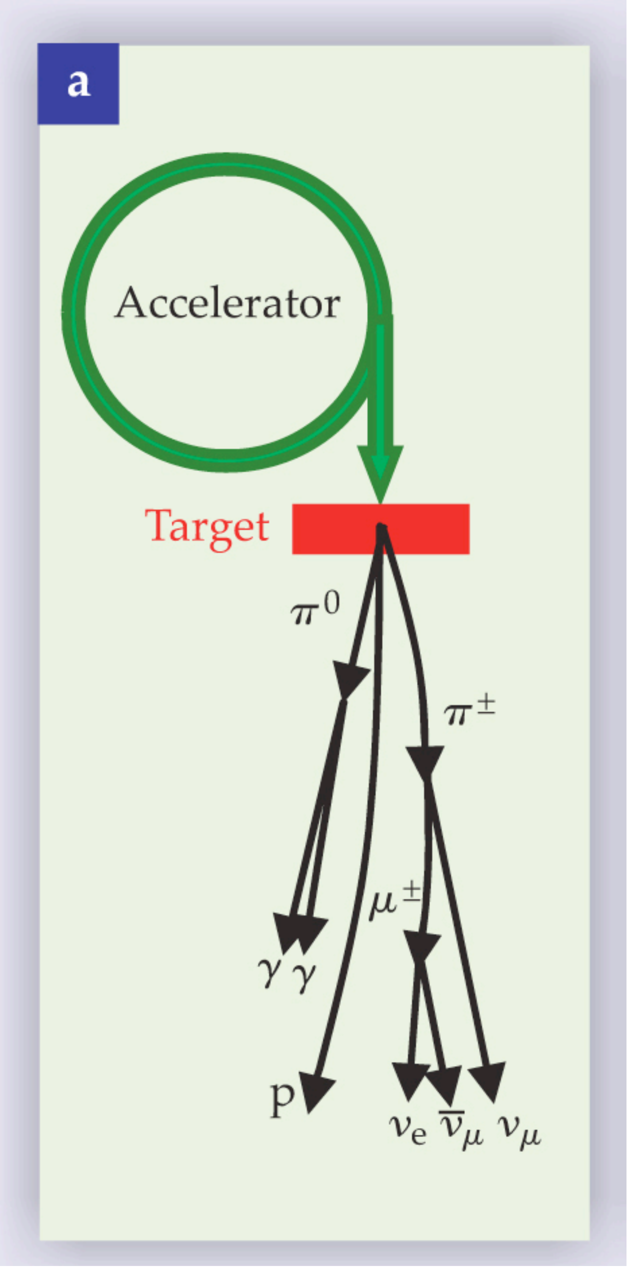
Neutrino PLATFORM

erc

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

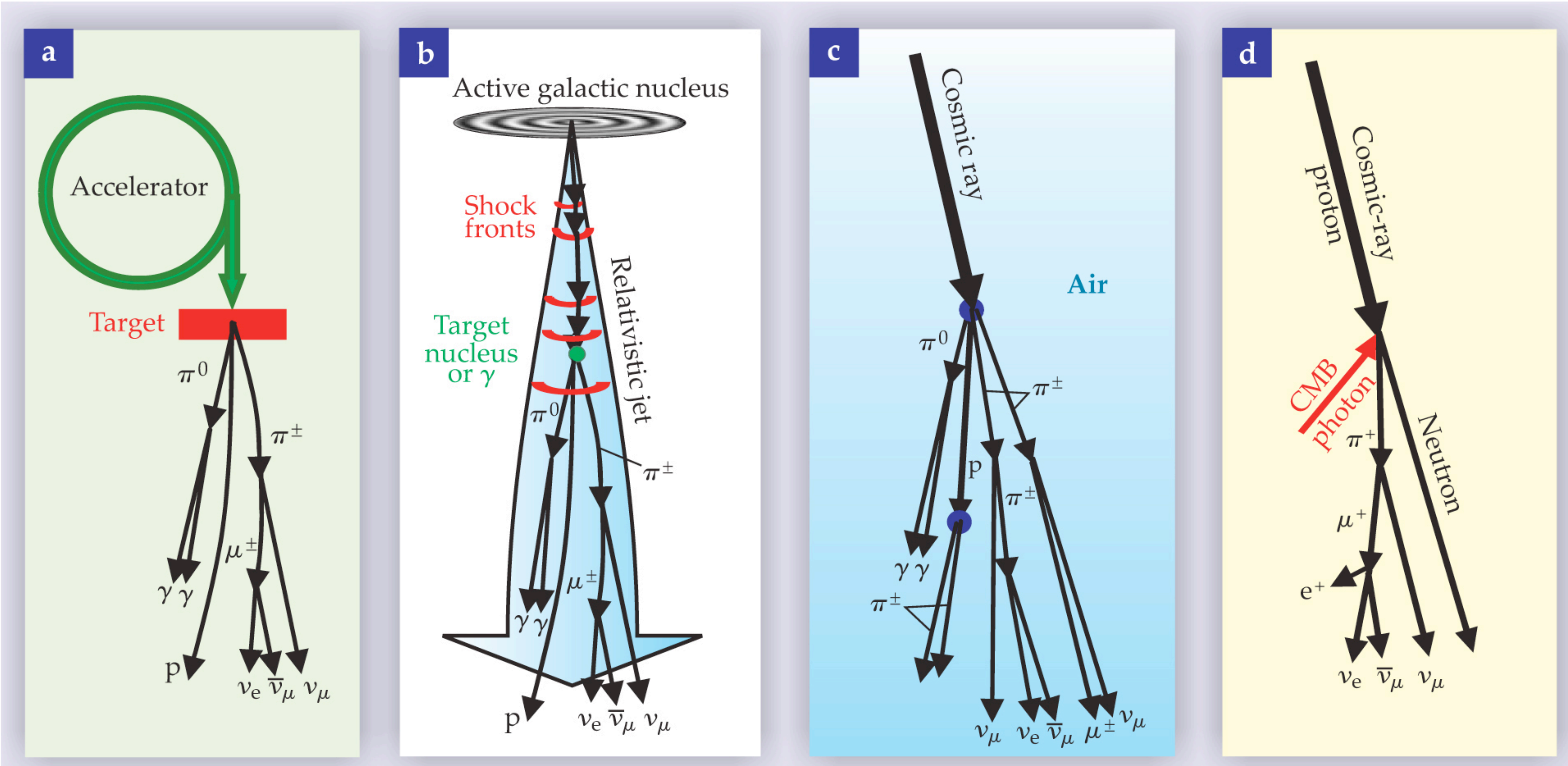
Astrophysical Neutrinos

Halzen Klein 2008



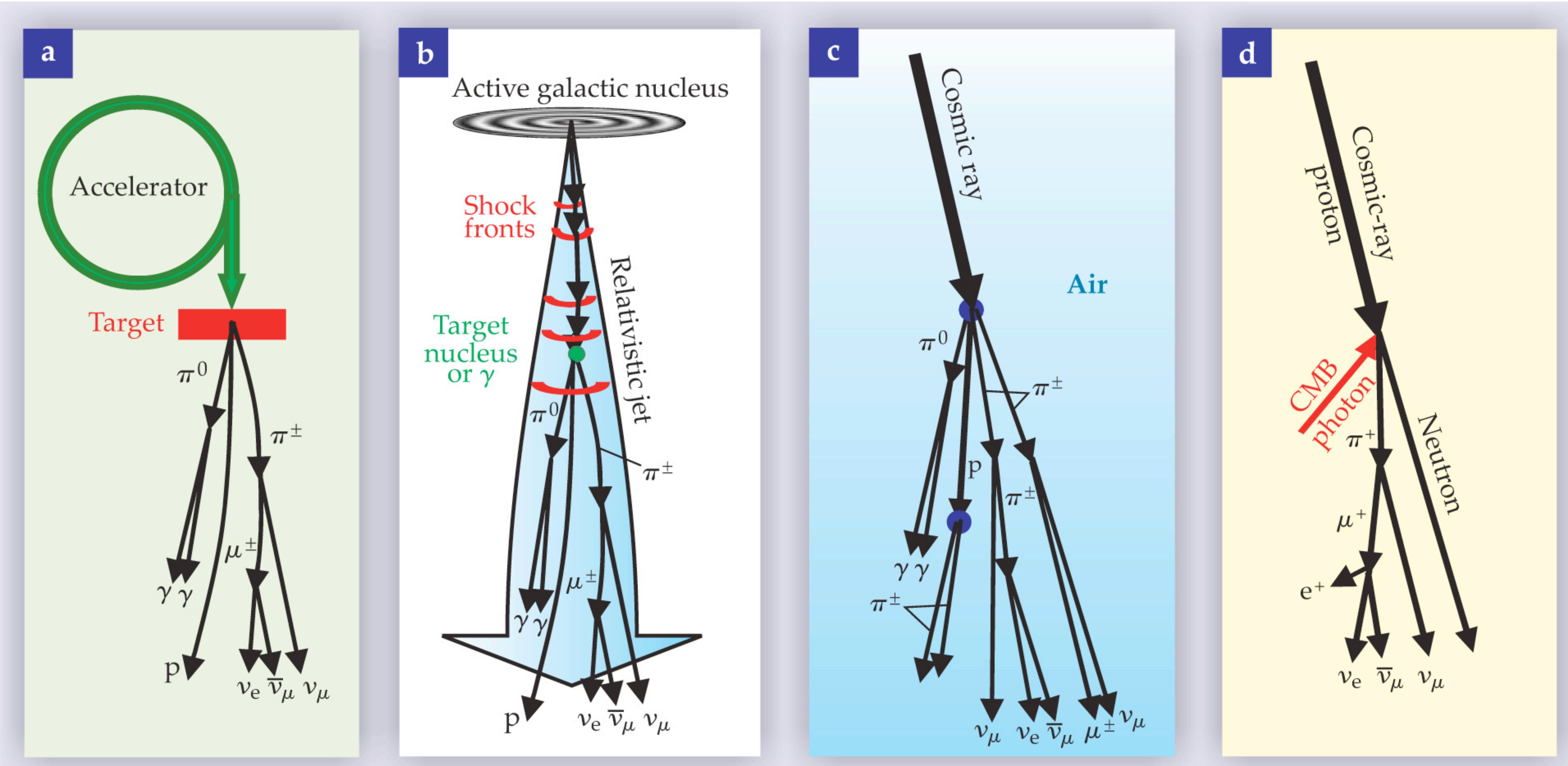
Astrophysical Neutrinos

Halzen Klein 2008



Astrophysical Neutrinos

Halzen Klein 2008

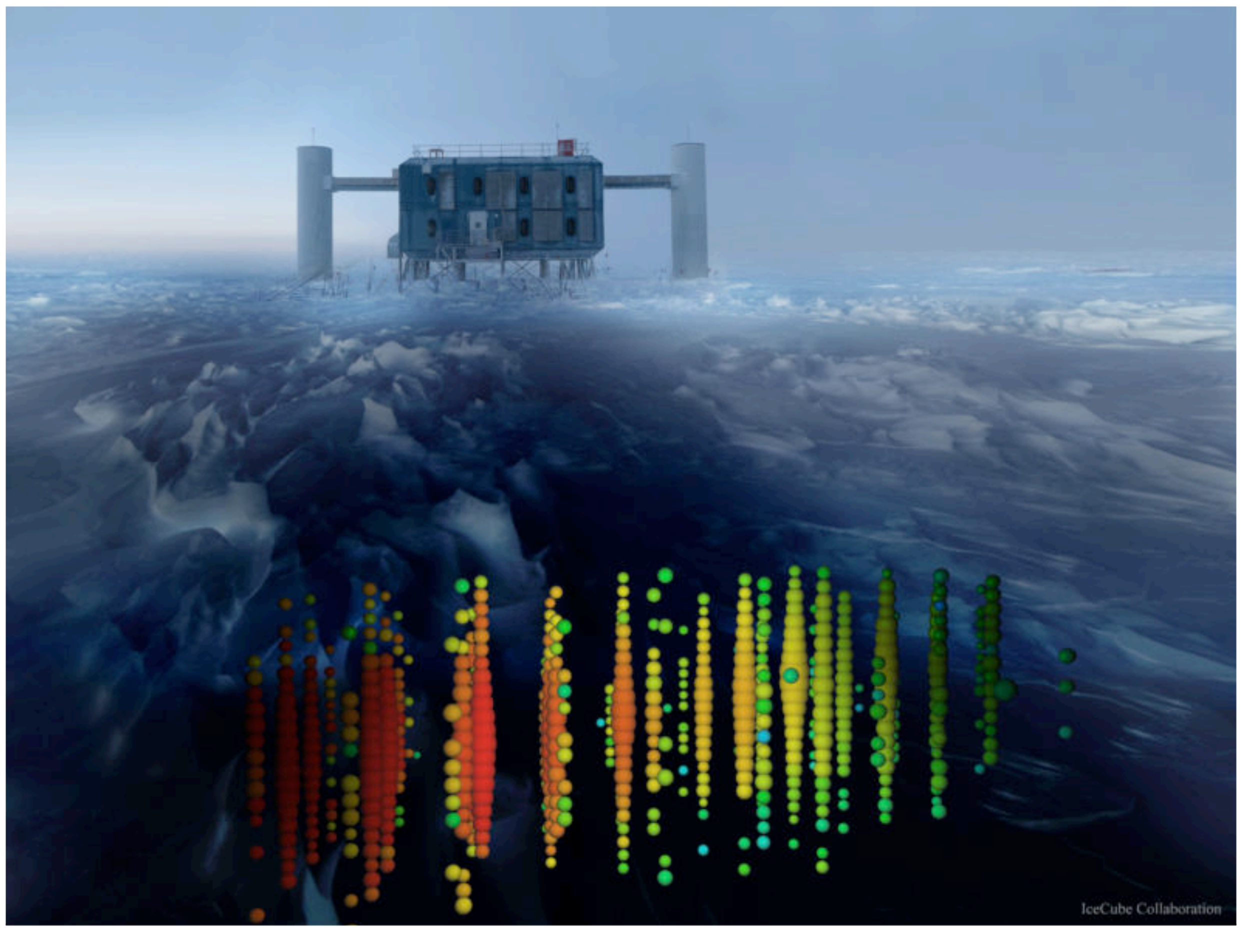


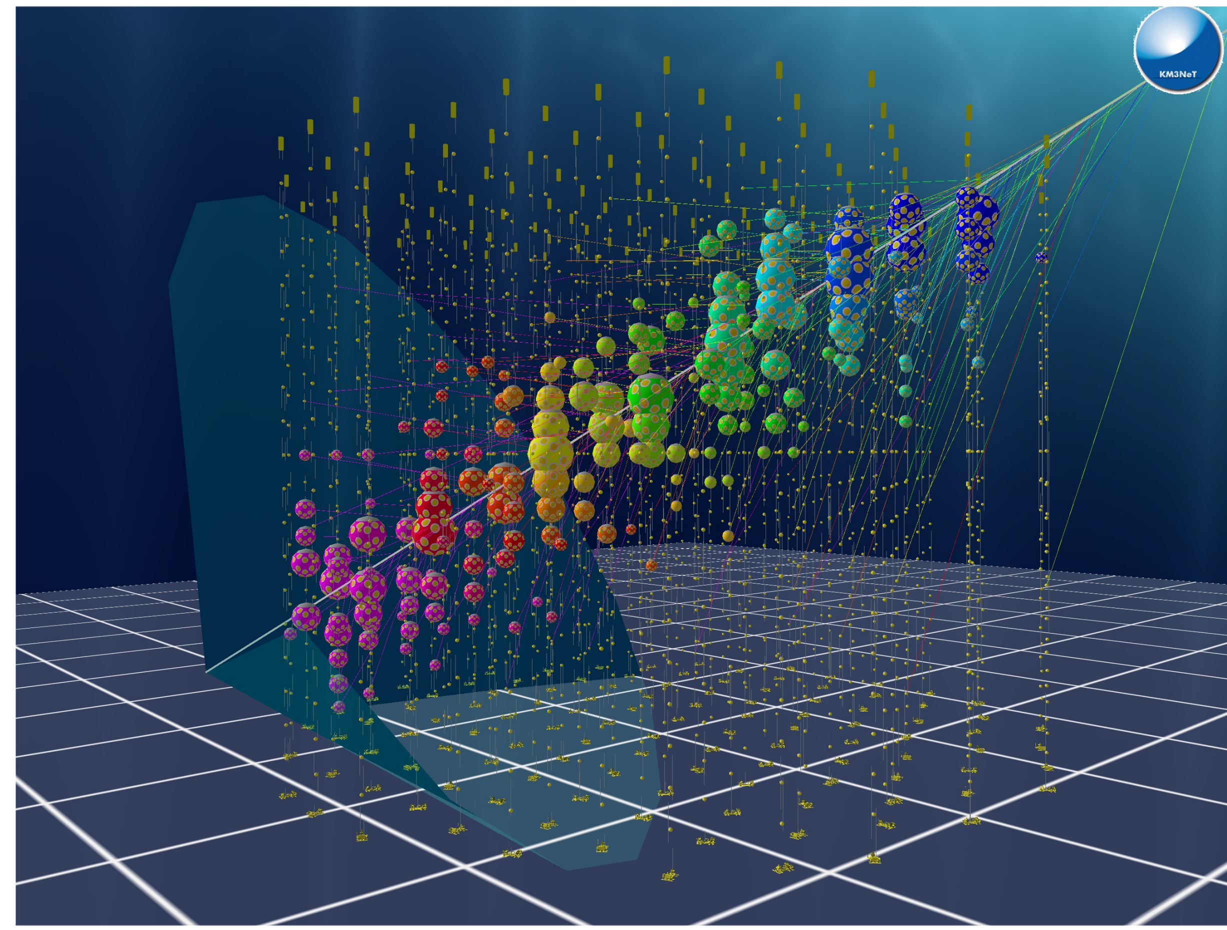
ν from astrophysical point sources

atmospheric ν background

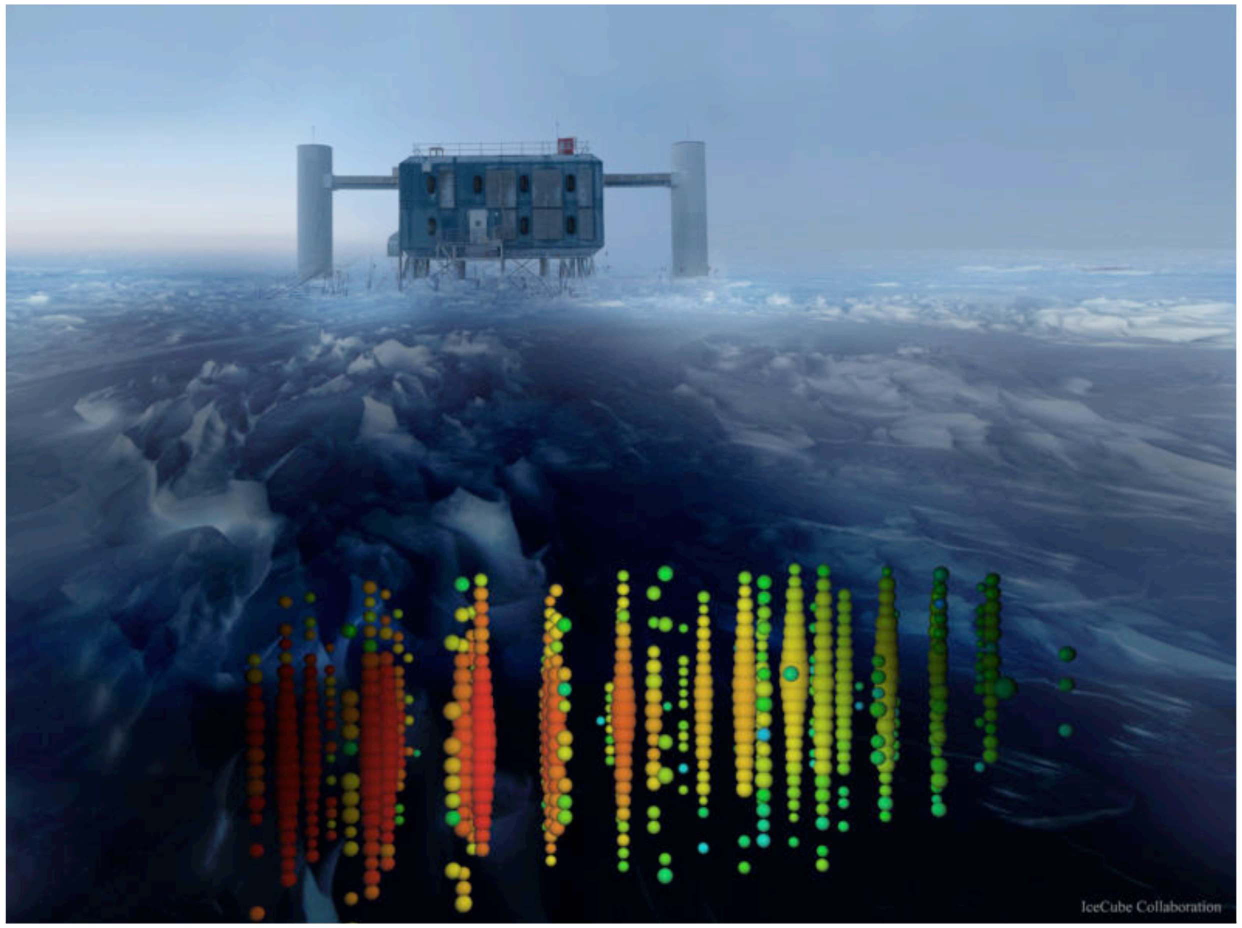
GZK ν (“cosmogenic ν”)

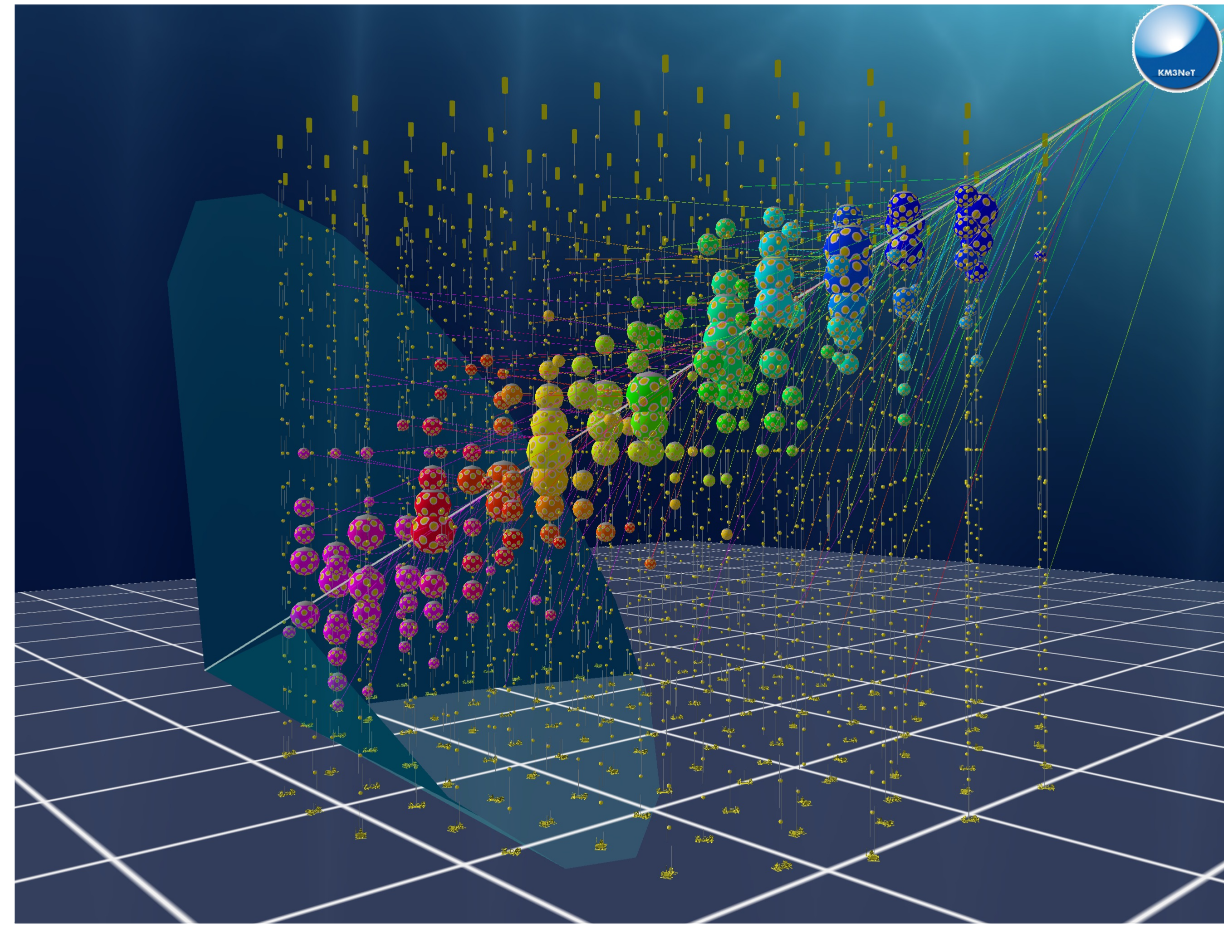
Detecting Astrophysical Neutrinos



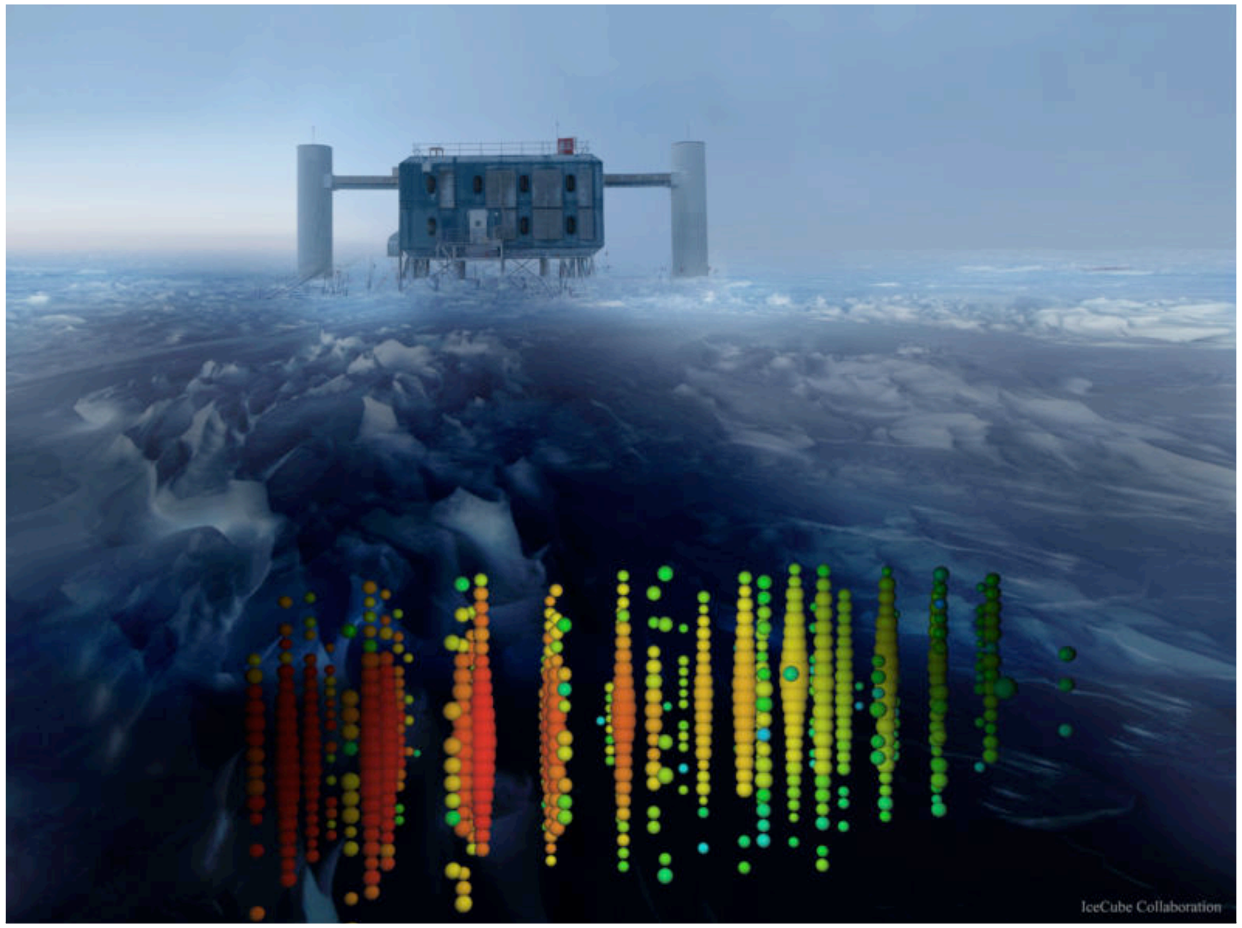


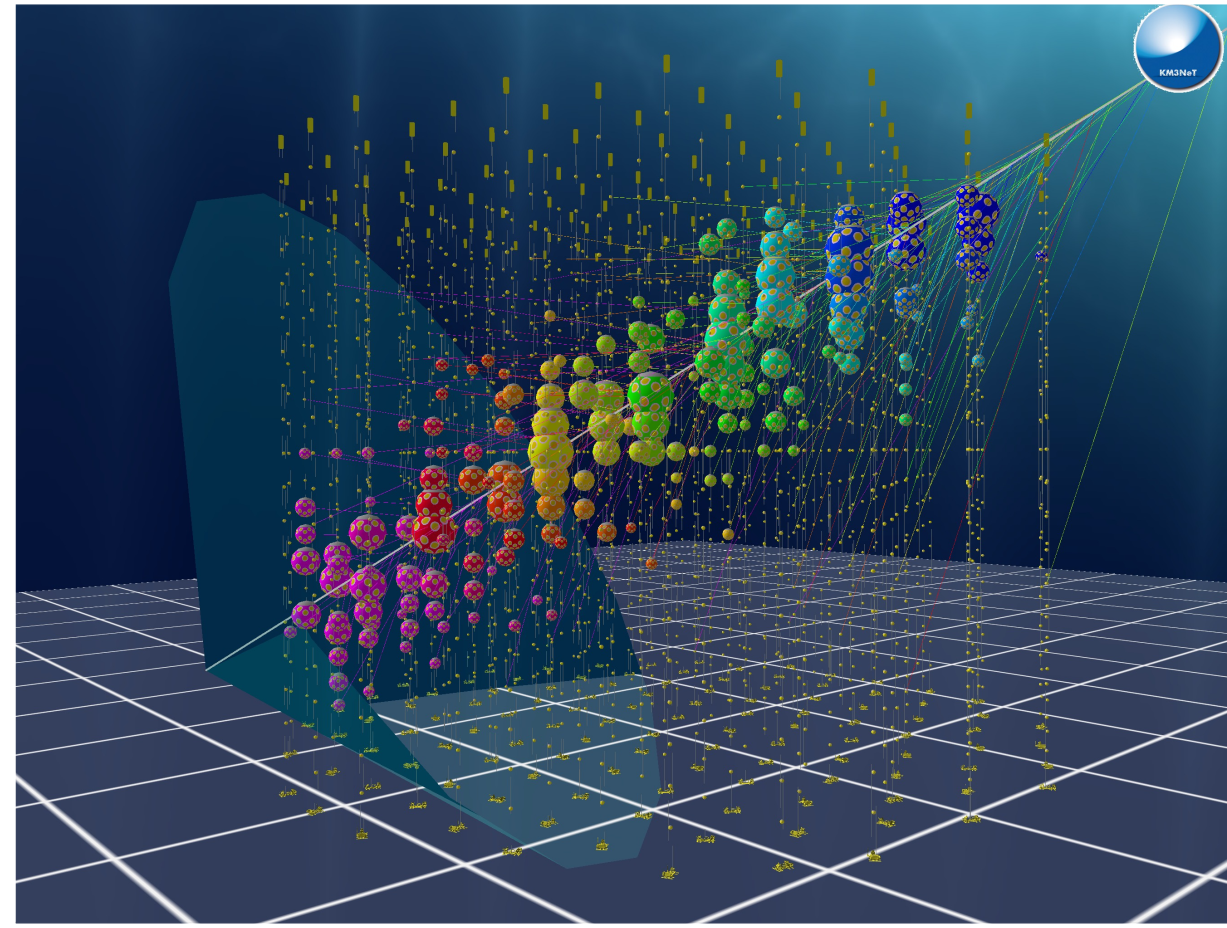
Detecting Astrophysical Neutrinos





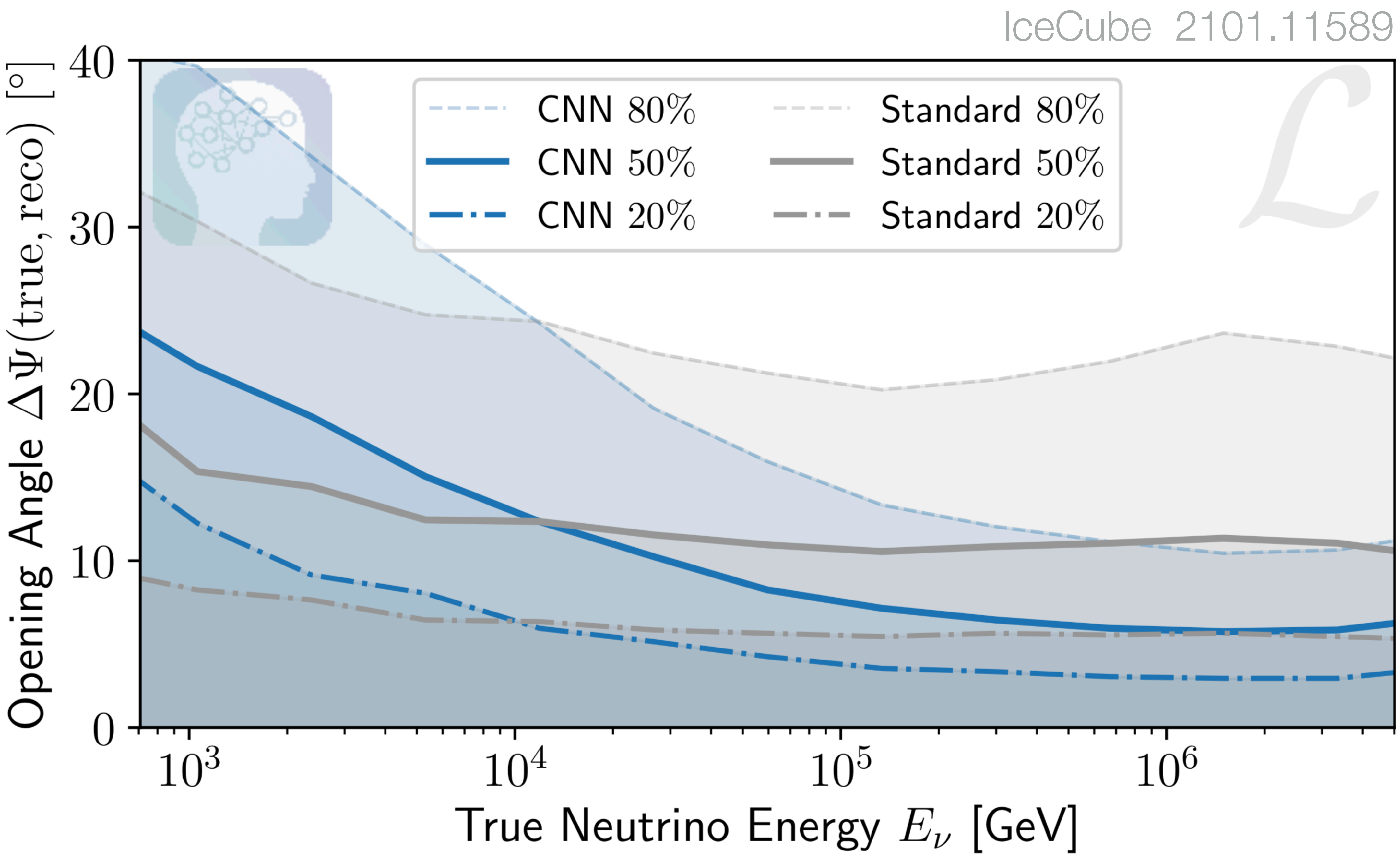
Detecting Astrophysical Neutrinos





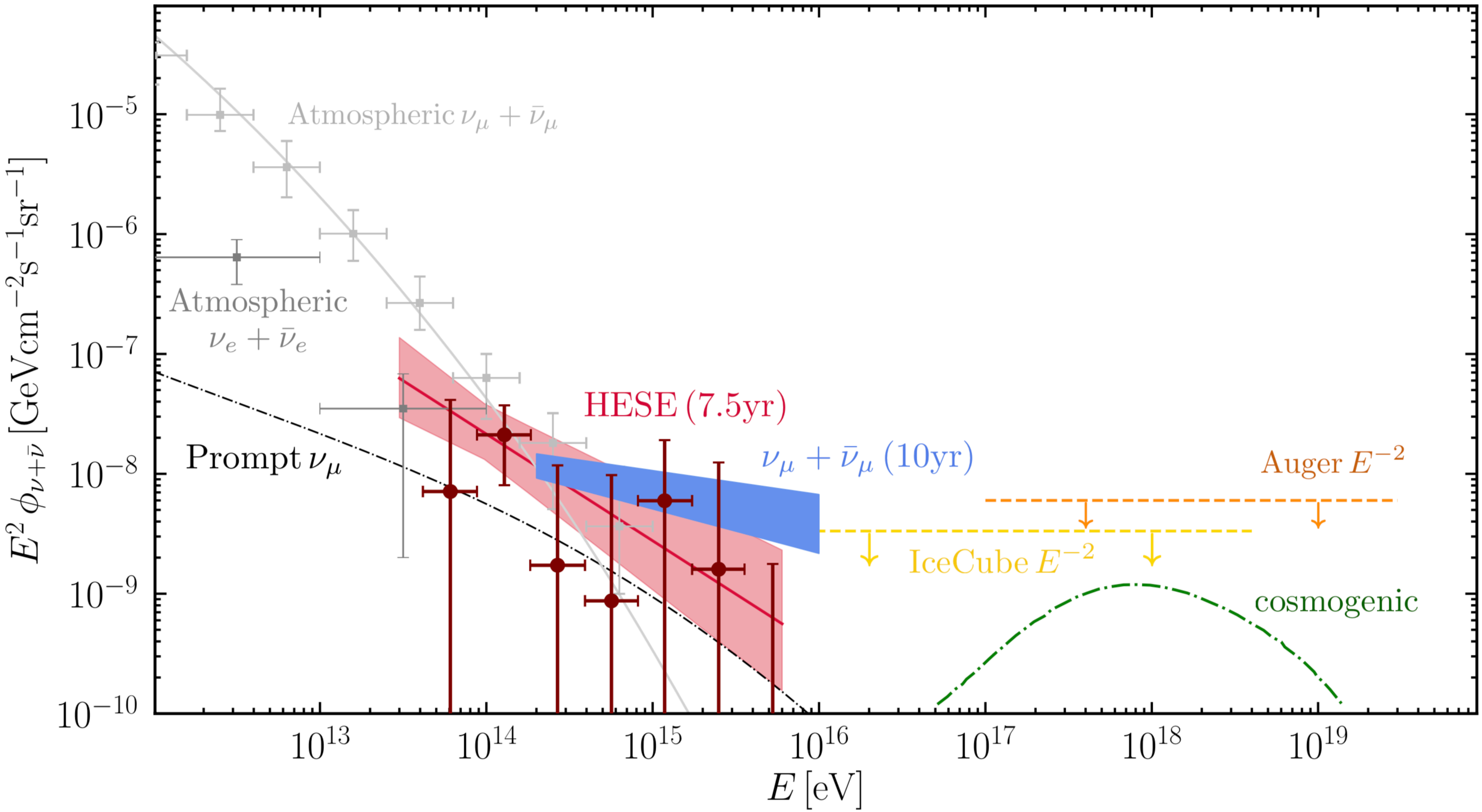
- traditional reconstruction distinguishes spherically symmetric showers (CC ν_e, CC ν_τ, NC) from tracks (CC ν_μ)
- event substructure: classical machine learning problem (but in 4D rather than 2D)

Improved Angular Resolution

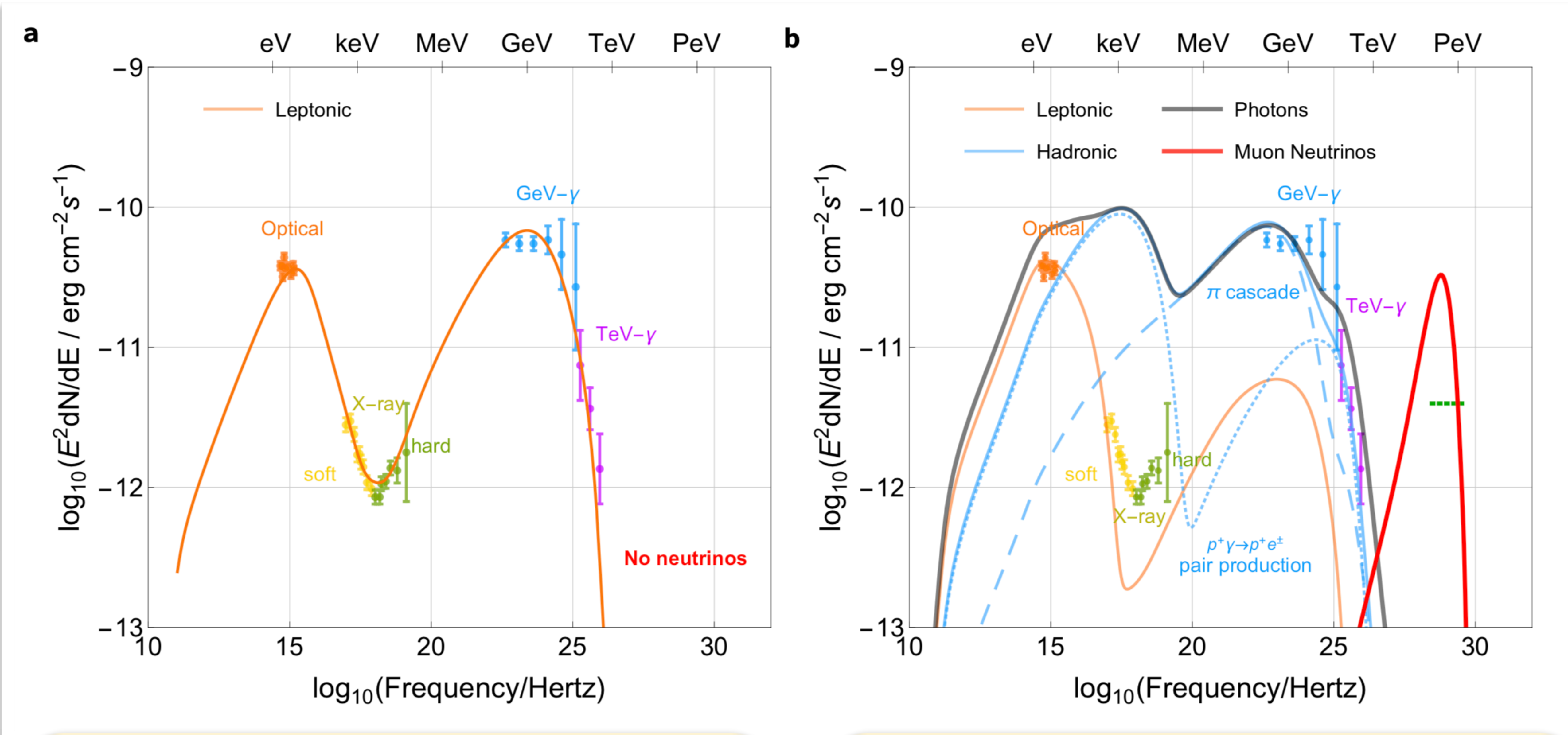


Results – Diffuse Flux

Halzen Kheirandish 2202.00694



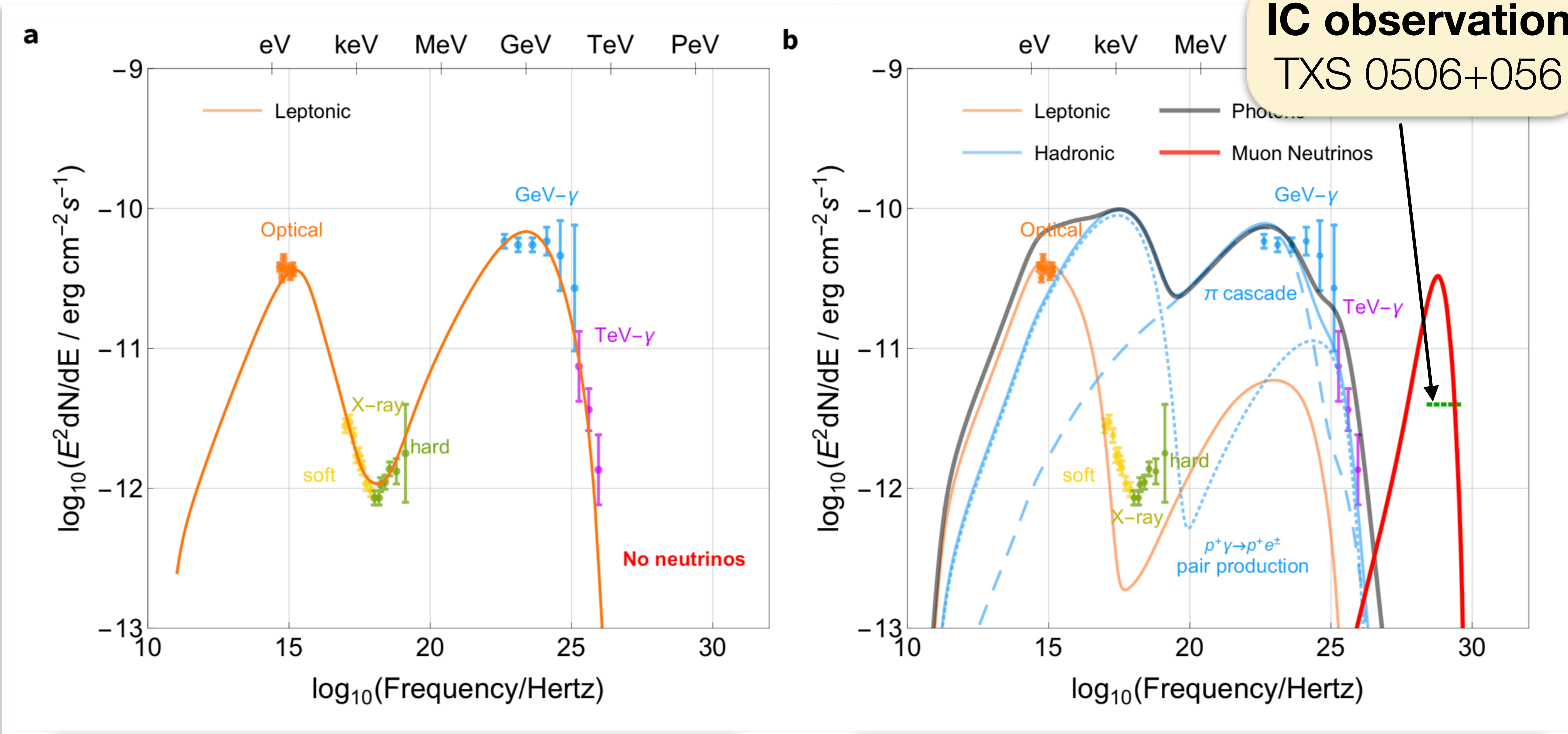
Results – Point Sources



leptonic model:
synchrotron + inverse Compton
no neutrinos

hadronic model:
high-*E* protons interact with gas
too many x-rays

Results – Point Sources



IC observation
TXS 0506+056

leptonic model:
synchrotron + inverse Compton
no neutrinos

hadronic model:
high-*E* protons interact with gas
too many x-rays

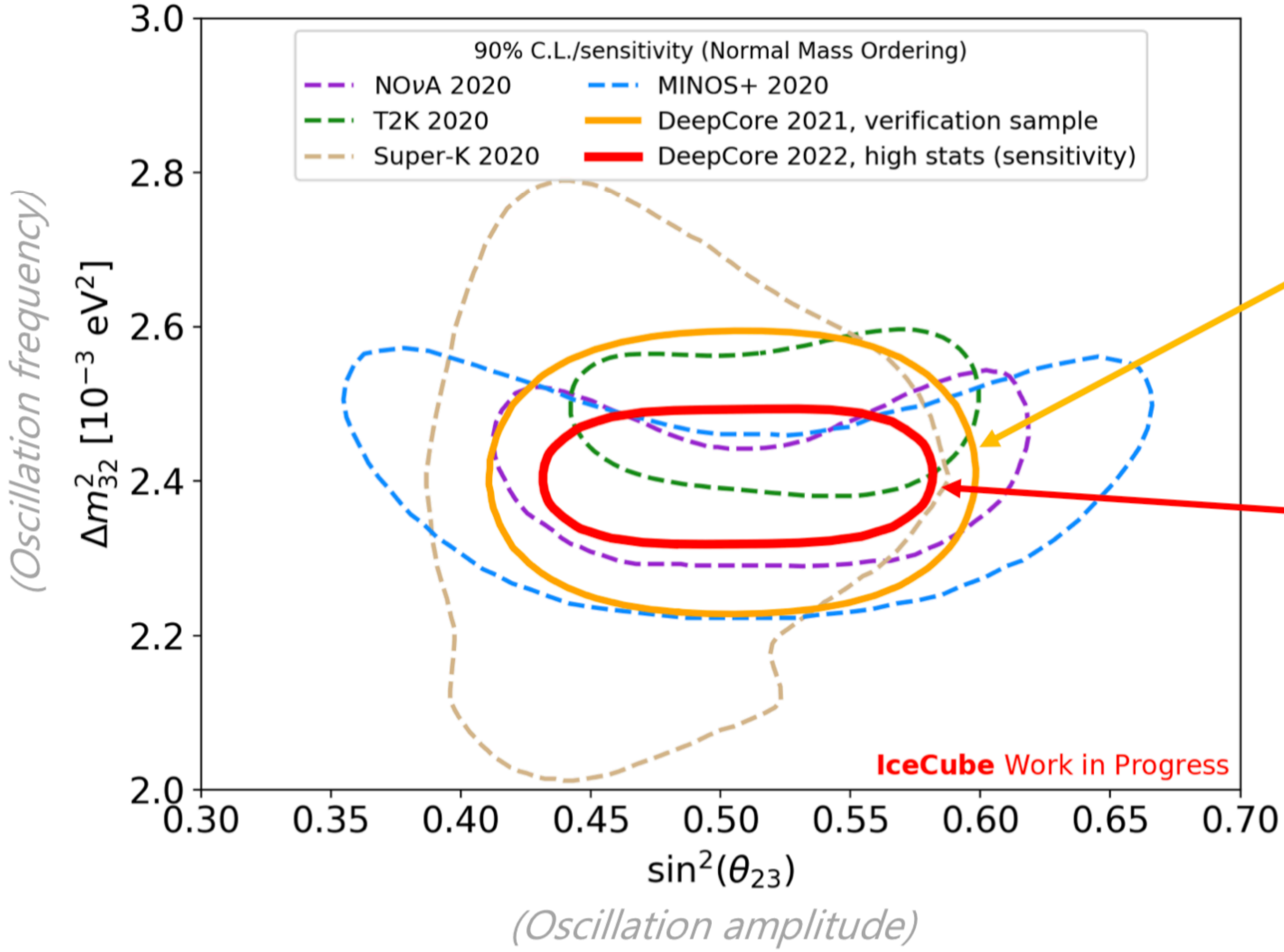
Results – Point Sources

☑ Ways out:

- hybrid (leptonic + hadronic) models — Gao *et al.* 1807.04275
- γ absorption in ambient medium — Kun et al. 2009.09792, Halzen et al. 1811.07439
- ...

Results – Neutrino Oscillations

Oscillation parameter precision/sensitivity



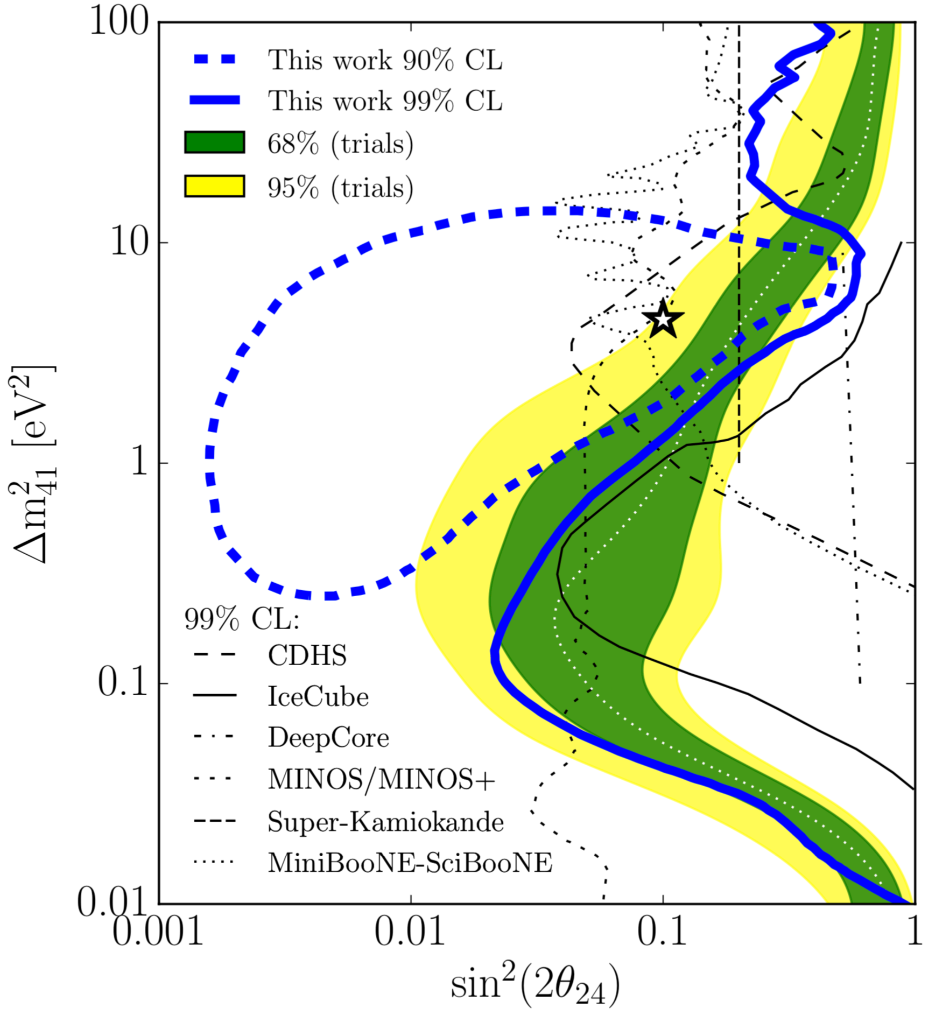
Recent result!
"Golden" sub-sample of 23,000 ideal neutrinos

Upcoming result!
All 210,000 neutrinos
Sensitivity competitive with accelerators

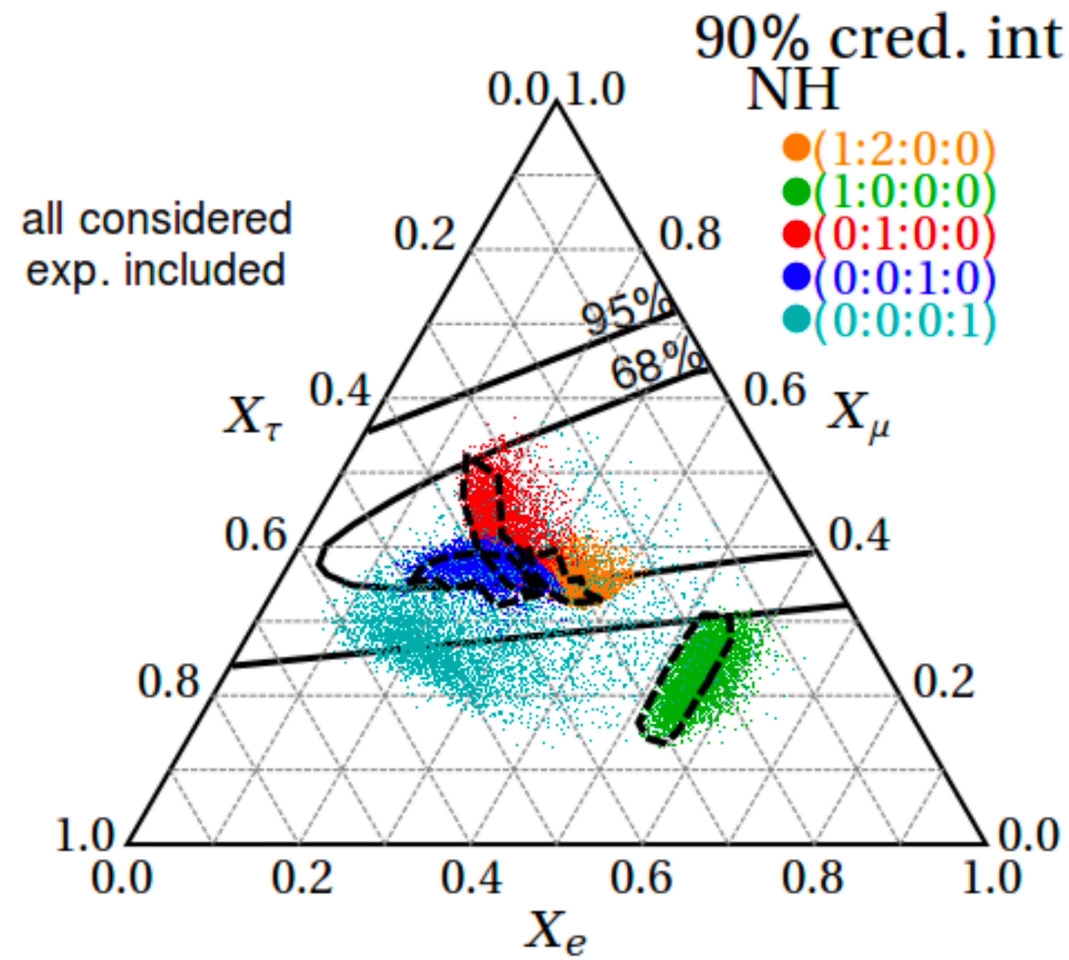
slide by Tom Stuttard

Searches Beyond the SM: Sterile Neutrinos

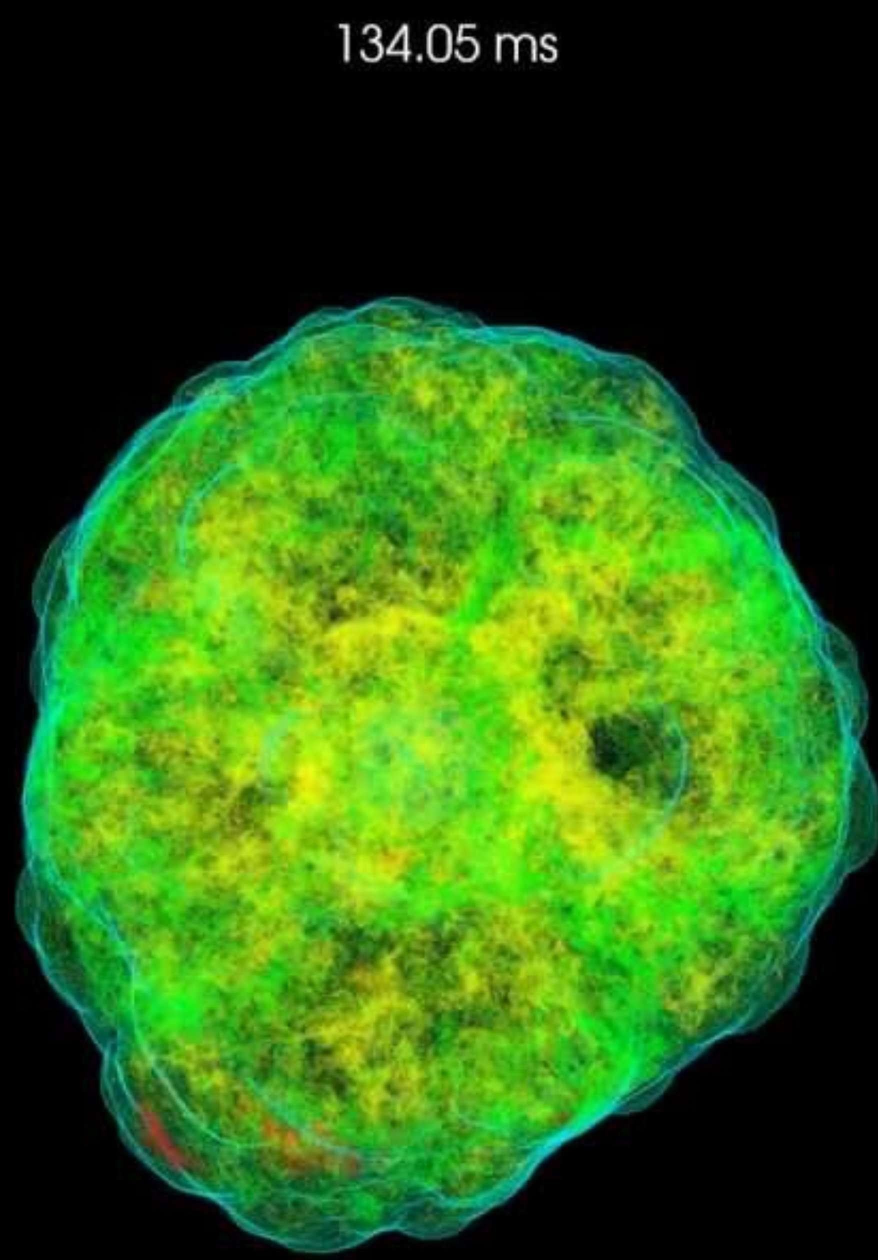
sterile ν via atm. ν
IceCube 2020



sterile ν via UHE events
Brdar JK Wang 1611.04598



Supernova Neutrinos



SXS Collaboration, Christian Ott *et al.*

Collective Neutrino Oscillations

☑ flavor evolution described by von Neumann equation

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\rm vac} + H_{\rm MSW} + H_{\nu\nu},\ \rho_{\vec{r},\vec{p}}]$$

Collective Neutrino Oscillations

- flavor evolution described … ann equation

density matrix
in flavour space

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

Collective Neutrino Oscillations

- ☑ flavor evolution described … ann equation

density matrix
in flavour space

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

vacuum oscillations

$$H_{\text{vac}} = \frac{1}{2E} U_{\text{PMNS}} M^2 U^\dagger_{\text{PMNS}}$$

Collective Neutrino Oscillations

- ☑ flavor evolution described by … ann equation

$$i(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\mathrm{vac}} + H_{\mathrm{MSW}} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

density matrix
in flavour space

vacuum oscillations

$$H_{\mathrm{vac}} = \frac{1}{2E} U_{\mathrm{PMNS}} M^2 U_{\mathrm{PMNS}}^\dagger$$

matter effects

$$H_{\mathrm{MSW}} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

Collective Neutrino Oscillations

- ☑ flavor evolution described … ann equation

density matrix
in flavour space

$$i(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\mathrm{vac}} + H_{\mathrm{MSW}} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

vacuum oscillations

$$H_{\mathrm{vac}} = \tfrac{1}{2E} U_{\mathrm{PMNS}} M^2 U_{\mathrm{PMNS}}^\dagger$$

matter effects

$$H_{\mathrm{MSW}} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

self-interactions

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{\vec{p}\vec{q}})(\rho_{\vec{r},\vec{q}} - \bar{\rho}_{\vec{r},\vec{q}})$$

Collective Neutrino Oscillations

- flavor evolution described … ann equation

density matrix
in flavour space

$$i(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\rm vac} + H_{\rm MSW} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

vacuum oscillations

$$H_{\rm vac} = \frac{1}{2E} U_{\rm PMNS} M^2 U^\dagger_{\rm PMNS}$$

matter effects

$$H_{\rm MSW} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

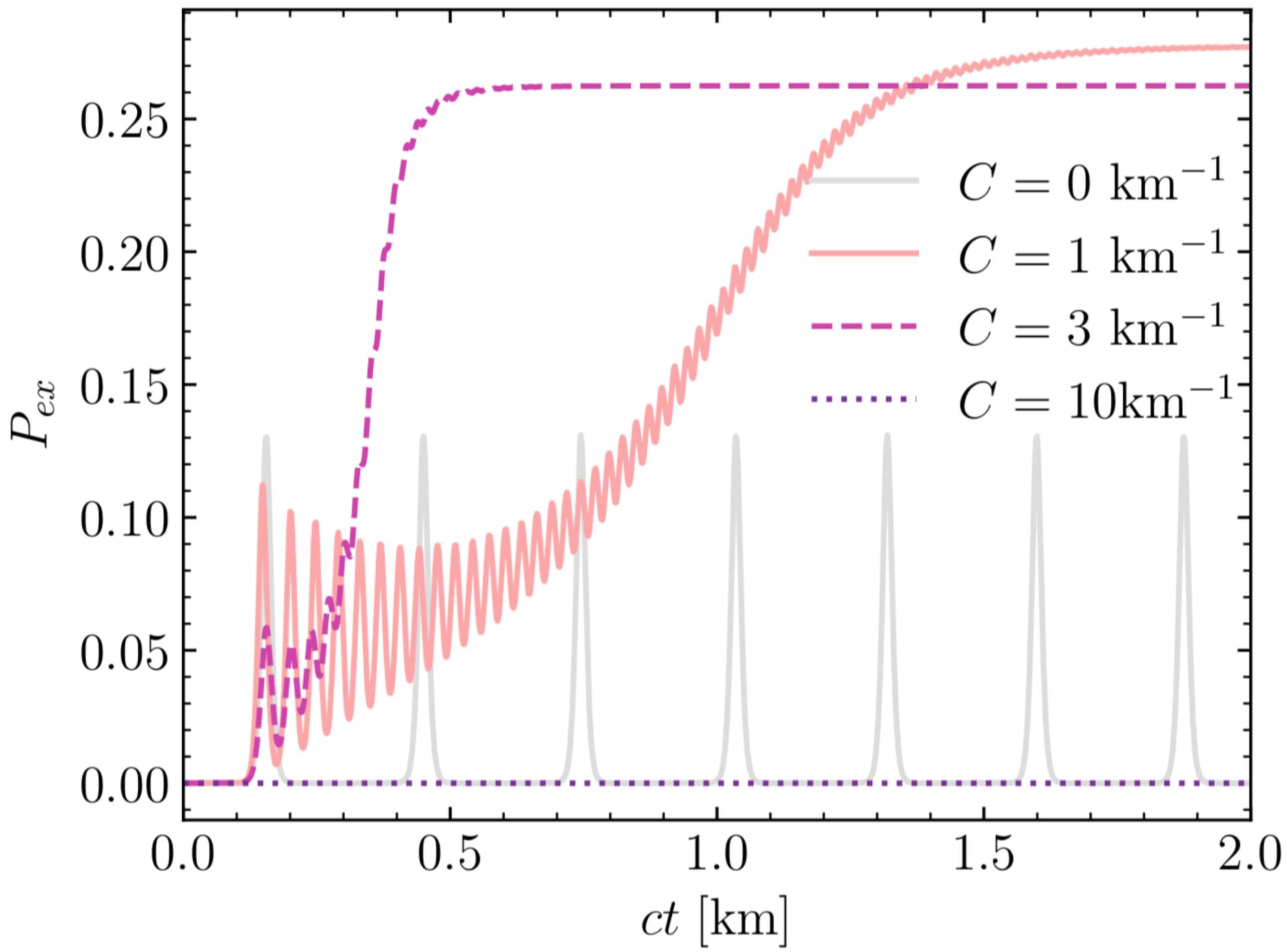
self-interactions

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{\vec{p}\vec{q}})(\rho_{\vec{r},\vec{q}} - \bar{\rho}_{\vec{r},\vec{q}})$$

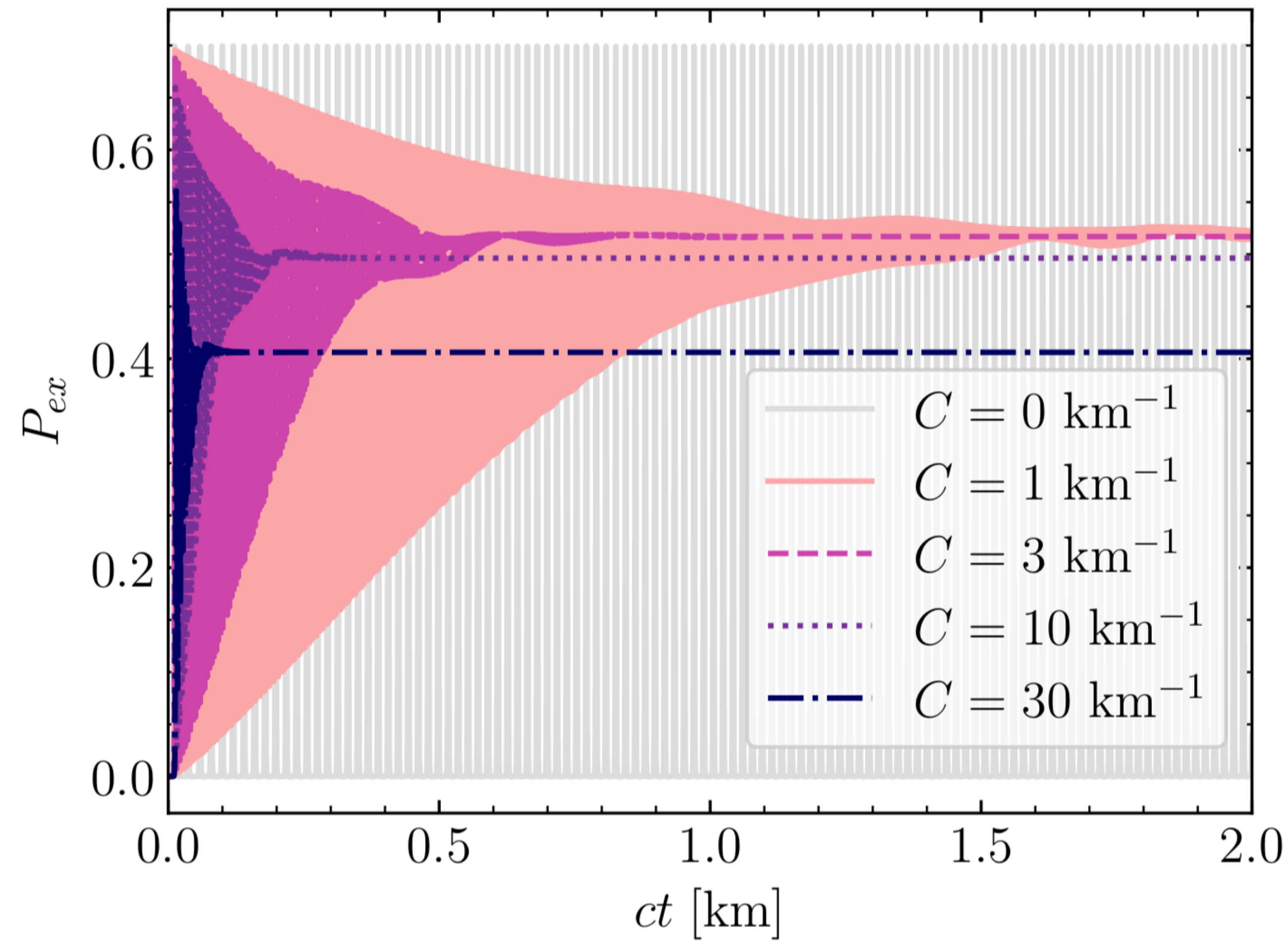
- at large n_ν:
  - same equation for all energies ➠ synchronization
  - non-trivial angular dependence
- non-linear equation ➠ all kinds of instabilities
- each neutrino flavour behaves differently (SN contain muons!)

Collective Neutrino Oscillations

Nearly Isotropic ν Fluxes



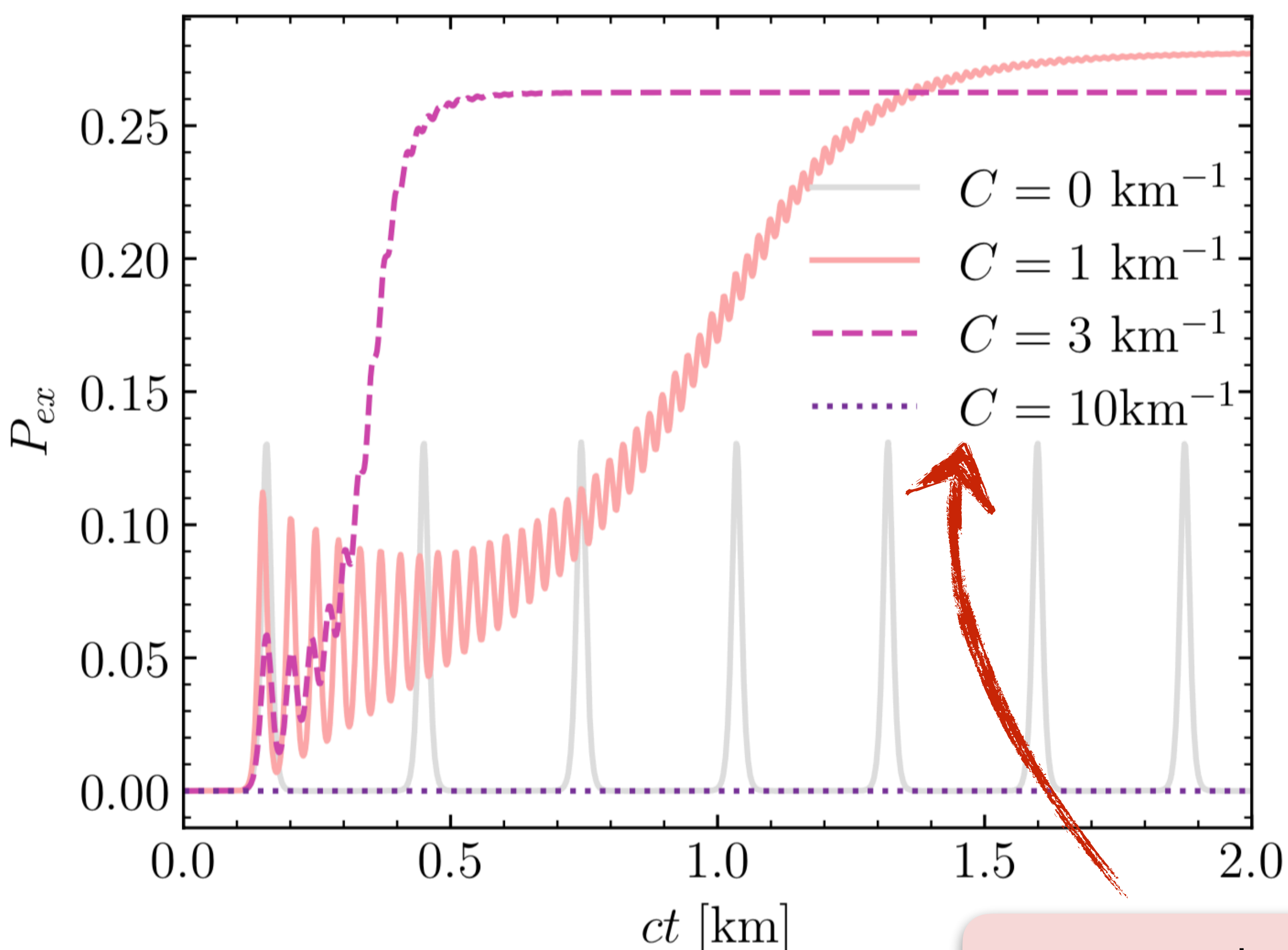
Mostly Forward ν Fluxes



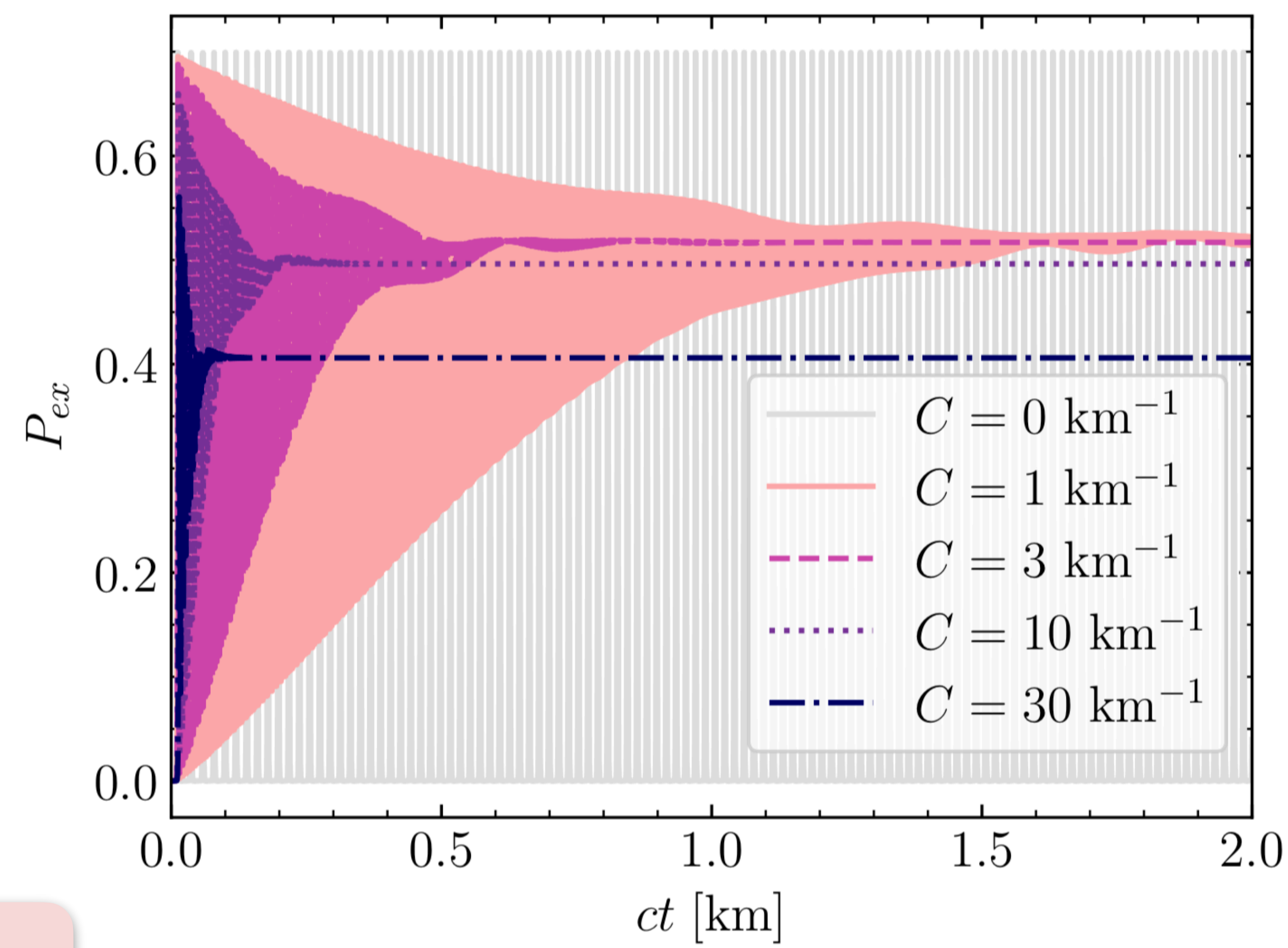
Hansen Shalgar Tamborra 2204.11873

Collective Neutrino Oscillations

Nearly Isotropic ν Fluxes



Mostly Forward ν Fluxes

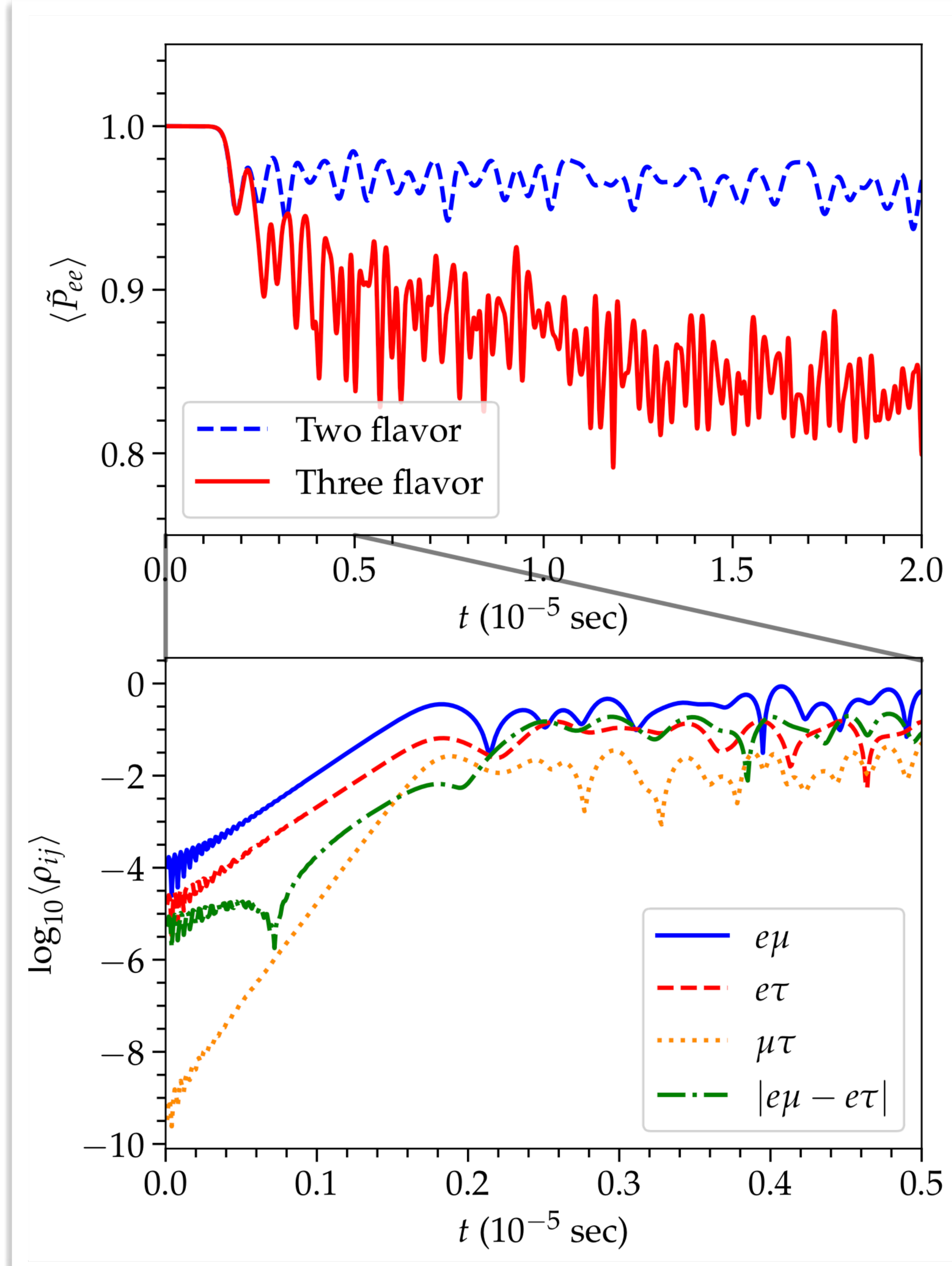


strength of collision term

Hansen Shalgar Tamborra 2204.11873

Muons in Supernovae

- ☑ Production somewhat Boltzmann-suppressed ($\sim e^{-m_\mu/T}$), but non-negligible at T~10 MeV
- ☑ In addition: 3-flavour effects in the vacuum oscillation term
- ☑ Substantial impact on flavour conversion probabilities



Shalgar Tamborra 2103.12743
Capozzi et al. 2005.14204

Collective Neutrino Oscillations

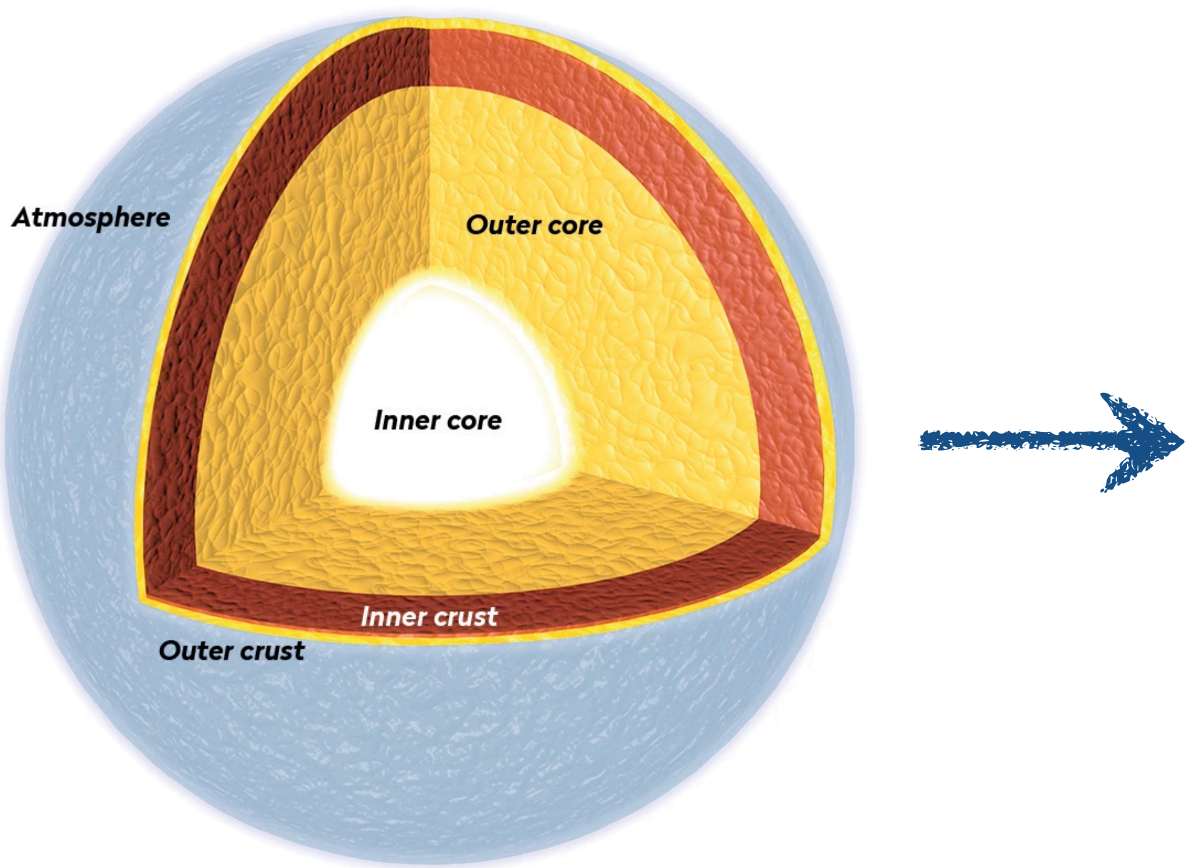
- ☆ pure Standard Model problem
- ☆ solution will be crucial for the next Galactic supernova
- ☆ **the neutrinos are already on their way**

see parallel talks by
Pedro Dedin Neto (collective oscillations)
Yago P. Porto Silva (a BSM searche with SN ν)

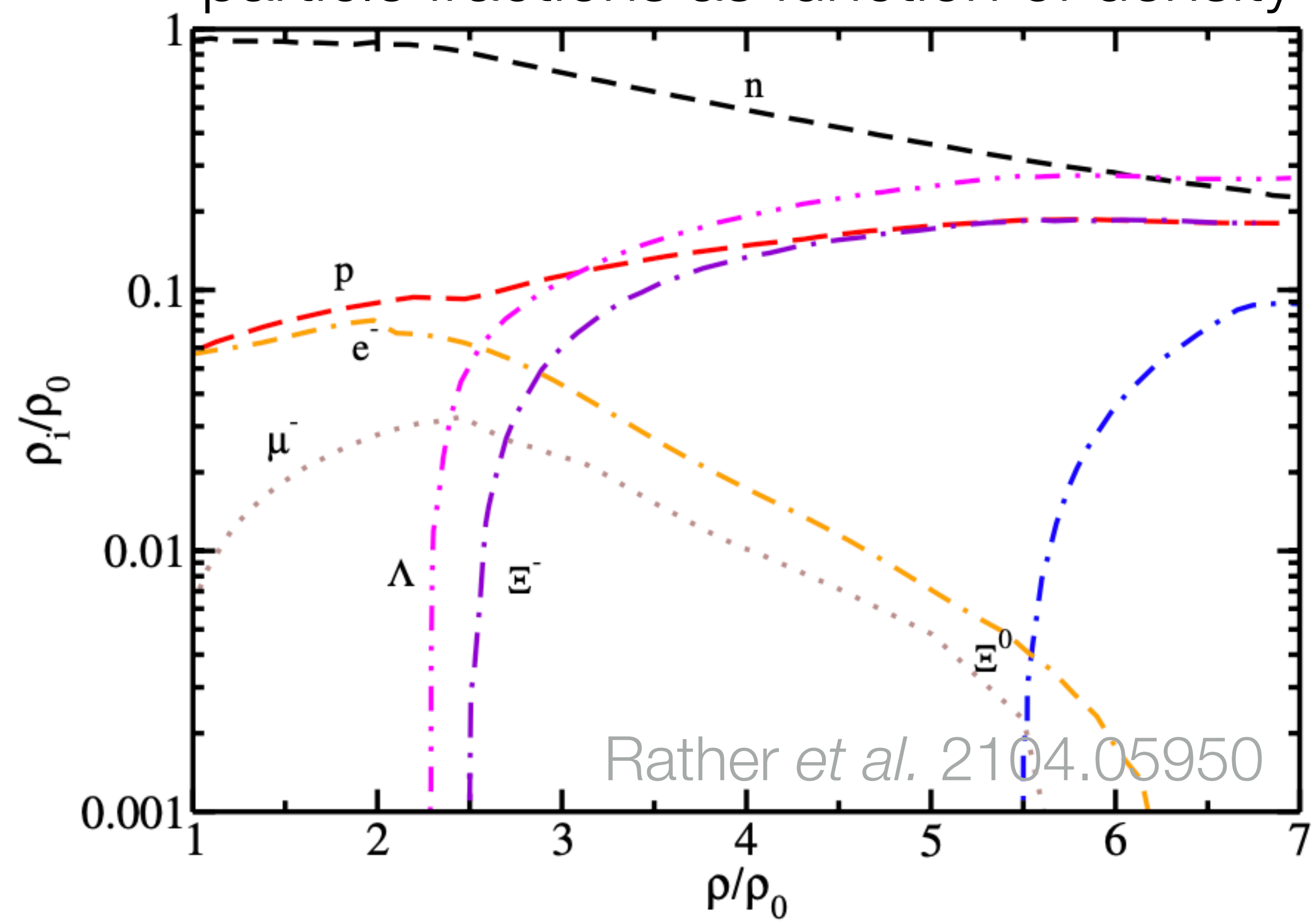
Neutrinos from Neutron Stars

Muons in Neutron Stars

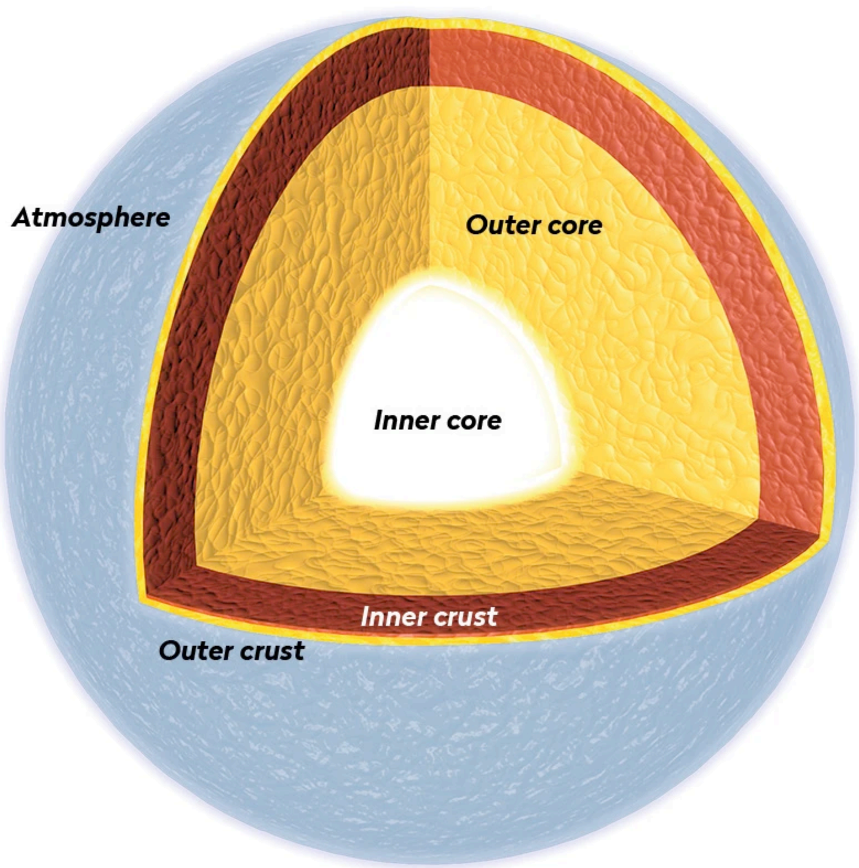
- ☑ Muons are produced in supernova cores
- ☑ Cannot decay because of Pauli blocking



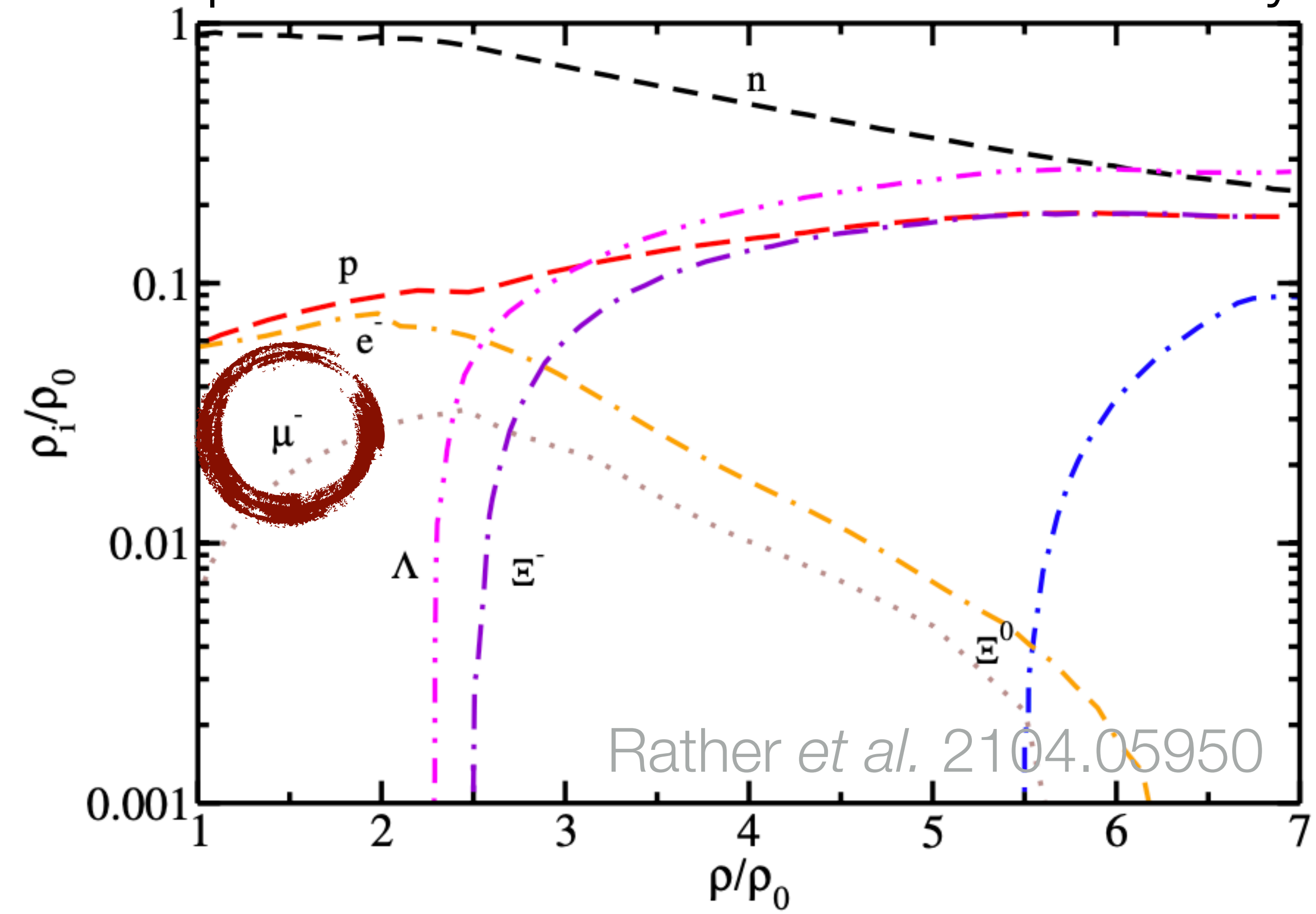
particle fractions as function of density



- ☑ Muons are produced in supernova cores
- ☑ Cannot decay because of Pauli blocking

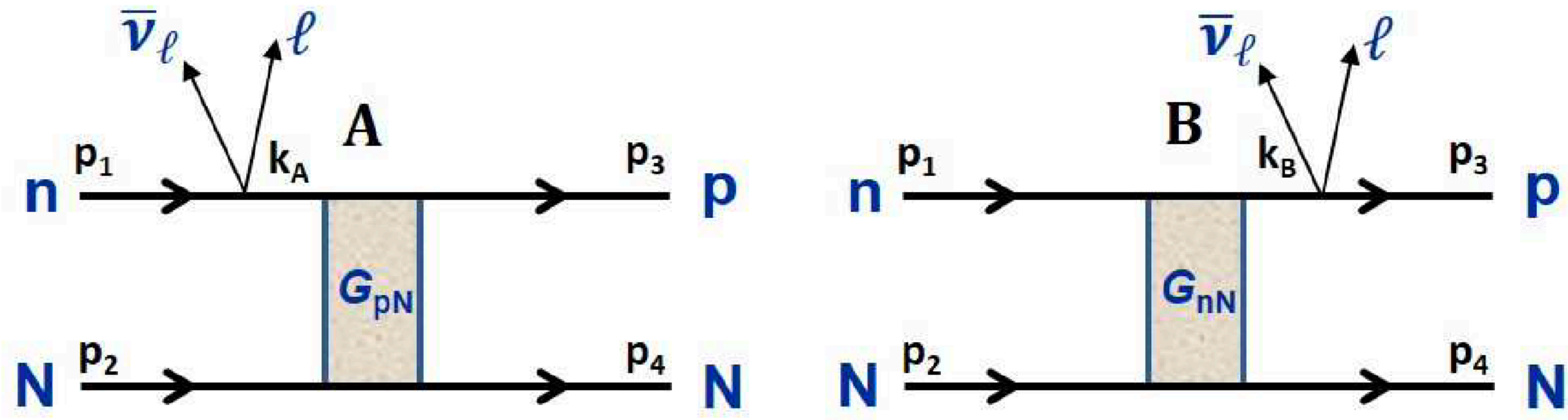


particle fractions as function of density



Muon Production & Absorption

- "Urca" processes:



- resulting ν luminosity scales $\sim T^8$
  ➠ muon production/absorption inefficient after $\mathcal{O}(10^3)$ yrs

Muon Diffusion

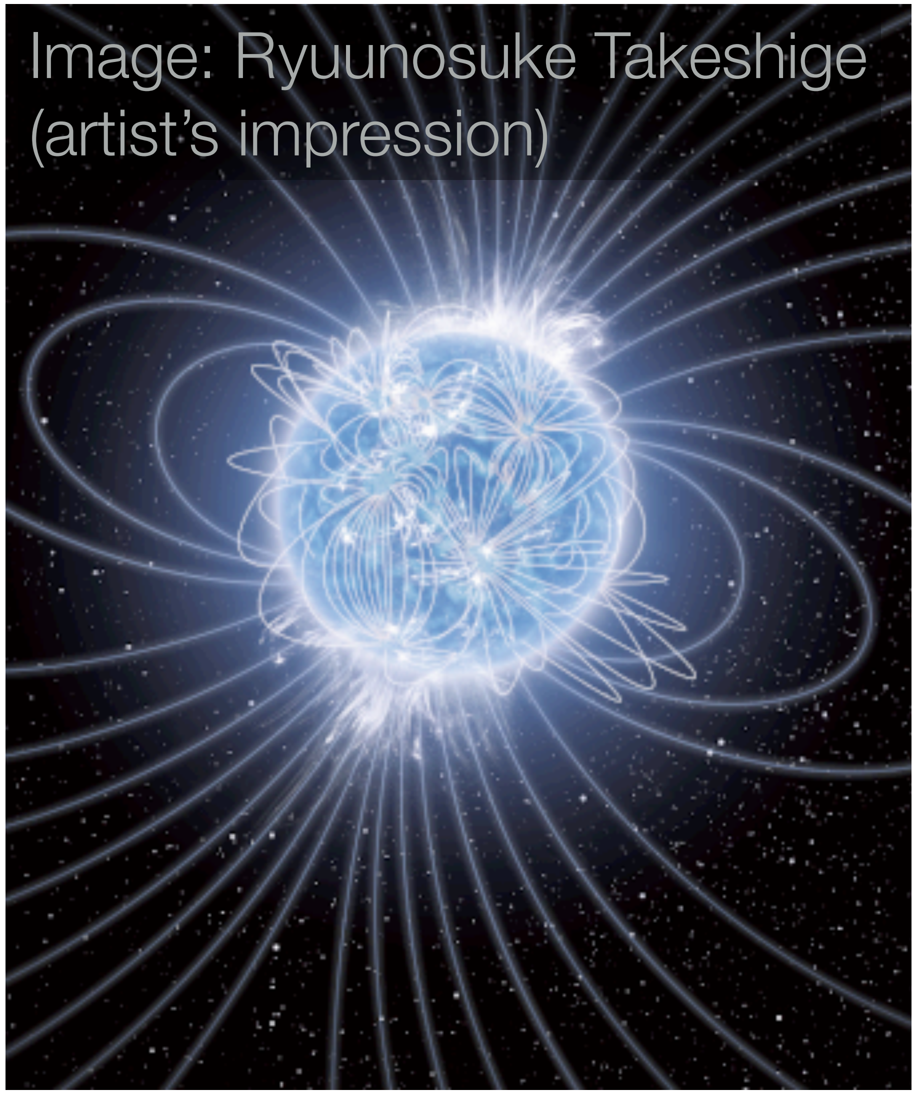
- Mean free path
  $\lambda \sim 10^{-8}$ cm at $t \sim$ hrs
  $\lambda \sim 10^{-6}$ cm at $t \sim 10^5$ yrs
- Diffusion distance

$$\langle \Delta x \rangle = \sqrt{\Delta t \, v_{F\mu} \lambda_\mu}$$

➠ $\Delta x \sim$ km is possible over time intervals $\Delta t \sim$ yrs

- **Muons can diffuse out of the star's core and into regions where their decay is not Pauli-blocked**
- ... but in a static star, there is no thermodynamic incentive for them to do so.
  (charge neutrality requires each decayed muon to be replaced by an electron, which is thermodynamically unfavourable)

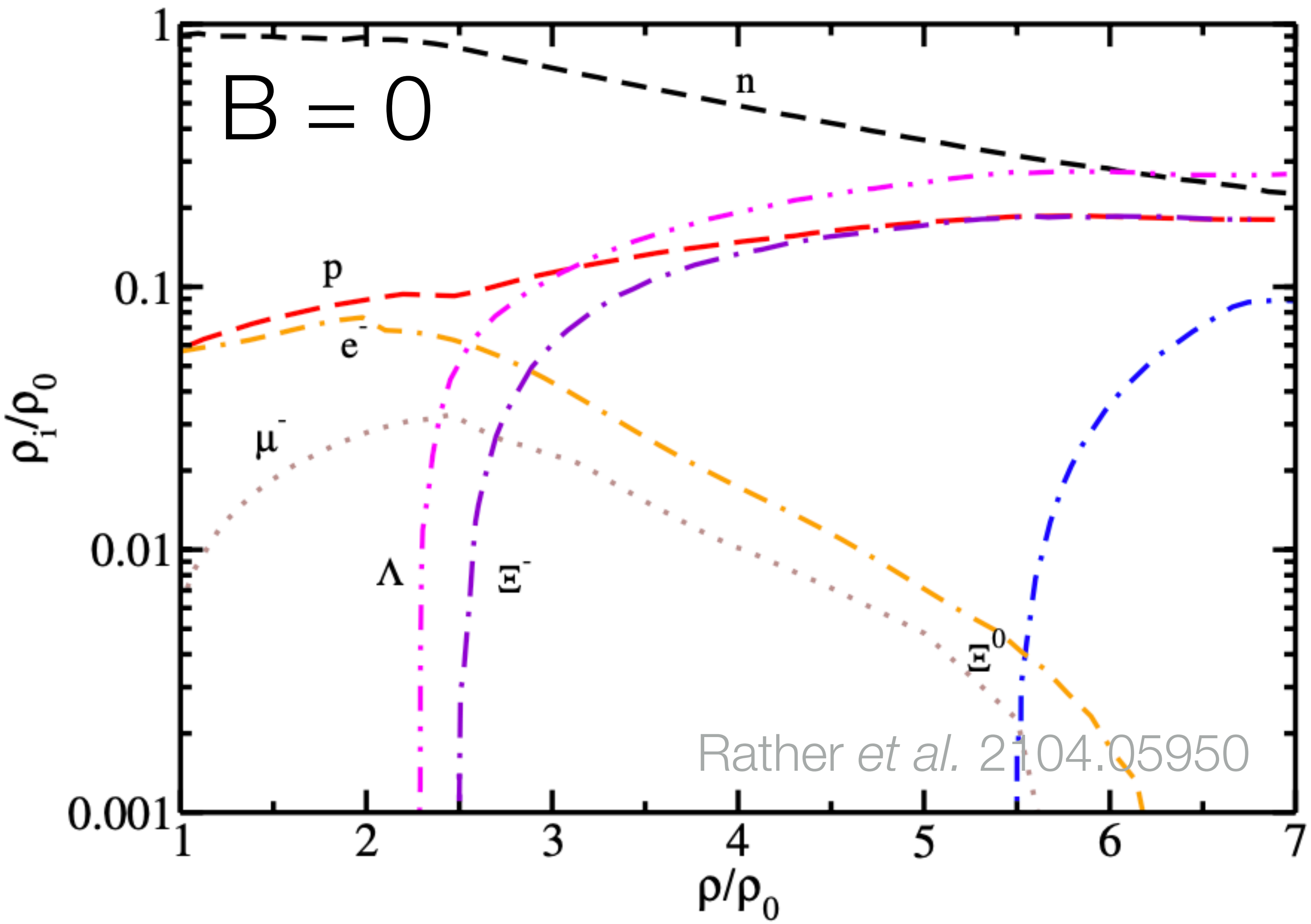
Magnetars



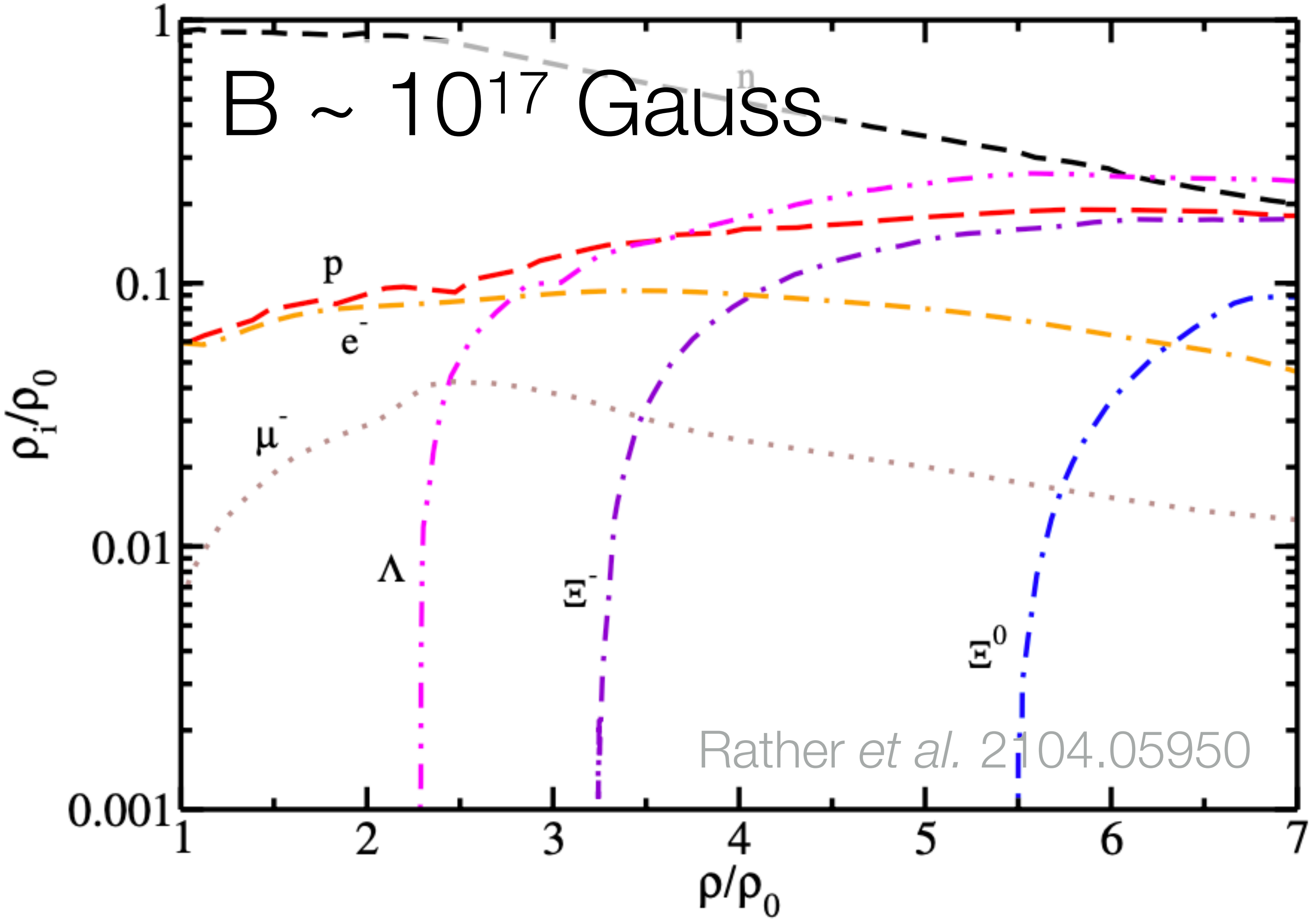
- ☑ Neutron stars with extreme *B*-fields (surface: 10^{15} Gauss, core: 10^{18} Gauss)
- ☑ B-fields may be expelled from the core over Myr–Gyr timescales
- ☑ this implies structural change
- ☑ notably a change in the equilibrium muon abundance

JK Opferkuch, *in preparation*

Magnetar Composition



Magnetar Composition



Muon Diffusion in Magnetars

- ☑ The star can only maintain chemical equilibrium by expelling muons from the core via diffusion (muon absorption is inefficient)
- ☑ these muons
  - diffuse outward
  - decay
  - produce a flux of $\mathcal{O}$(10 MeV) neutrinos

$$\phi_\nu \sim 0.3\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\left(\frac{N_\mathrm{mag}}{10^6}\right)\left(\frac{N_\mu}{10^{55}}\right)\left(\frac{10\,\mathrm{kpc}}{d_\mathrm{avg}}\right)^2\left(\frac{1\,\mathrm{Gyr}}{t_\mathrm{exp}}\right)$$

JK Opferkuch, *in preparation*

Muon Diffusion in Magnetars

- ☑ The star can only maintain chemical equilibrium by expelling muons from the core via diffusion (muon absorption is inefficient)
- ☑ these muons
  - diffuse outward
  - decay
  - produce a flux of $\mathcal{O}(10\ \mathrm{MeV})$ neutrinos

number of magnetars in the Milky Way

$$\phi_\nu \sim 0.3\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\left(\frac{N_{\mathrm{mag}}}{10^6}\right)\left(\frac{N_\mu}{10^{55}}\right)\left(\frac{10\,\mathrm{kpc}}{d_{\mathrm{avg}}}\right)^2\left(\frac{1\,\mathrm{Gyr}}{t_{\mathrm{exp}}}\right)$$

JK Opferkuch, *in preparation*

Muon Diffusion in Magnetars

- ☑ The star can only maintain chemical equilibrium by expelling muons from the core via diffusion (muon absorption is inefficient)
- ☑ these muons
  - diffuse outward
  - decay
  - produce a flux of $\mathcal{O}$(10 MeV) neutrinos

number of magnetars in the Milky Way

number of expelled muons

$$\phi_\nu \sim 0.3\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\left(\frac{N_\mathrm{mag}}{10^6}\right)\left(\frac{N_\mu}{10^{55}}\right)\left(\frac{10\,\mathrm{kpc}}{d_\mathrm{avg}}\right)^2\left(\frac{1\,\mathrm{Gyr}}{t_\mathrm{exp}}\right)$$

JK Opferkuch, *in preparation*

Muon Diffusion in Magnetars

- ☑ The star can only maintain chemical equilibrium by expelling muons from the core via diffusion (muon absorption is inefficient)
- ☑ these muons
  - diffuse outward
  - decay
  - produce a flux of $\mathcal{O}$(10 MeV) neutrinos

number of magnetars in the Milky Way

number of expelled muons

avg. magnetar distance

$$\phi_\nu \sim 0.3\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1} \left(\frac{N_{\rm mag}}{10^6}\right) \left(\frac{N_\mu}{10^{55}}\right) \left(\frac{10\,\mathrm{kpc}}{d_{\rm avg}}\right)^2 \left(\frac{1\,\mathrm{Gyr}}{t_{\rm exp}}\right)$$

JK Opferkuch, *in preparation*

Muon Diffusion in Magnetars

- ☑ The star can only maintain chemical equilibrium by expelling muons from the core via diffusion (muon absorption is inefficient)
- ☑ these muons
  - diffuse outward
  - decay
  - produce a flux of $\mathcal{O}$(10 MeV) neutrinos

number of magnetars in the Milky Way

number of expelled muons

avg. magnetar distance

$$\phi_\nu \sim 0.3\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1} \left(\frac{N_{\mathrm{mag}}}{10^6}\right) \left(\frac{N_\mu}{10^{55}}\right) \left(\frac{10\,\mathrm{kpc}}{d_{\mathrm{avg}}}\right)^2 \left(\frac{1\,\mathrm{Gyr}}{t_{\mathrm{exp}}}\right)$$

timescale of B-field and muon expulsion

JK Opferkuch, *in preparation*

Muon Diffusion in Magnetars

$$\phi_\nu \sim 0.3\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1} \left(\frac{N_{\rm mag}}{10^6}\right)\left(\frac{N_\mu}{10^{55}}\right)\left(\frac{10\,\mathrm{kpc}}{d_{\rm avg}}\right)^2\left(\frac{1\,\mathrm{Gyr}}{t_{\rm exp}}\right)$$

- For comparison
  - diffuse supernova neutrino background: ~ 1 cm^{-2} sec^{-1}
  - solar ν: ~ 10^6 cm^{-2} sec^{-1} (but only at E ≲ 20 MeV)
  - atmospheric ν_e and $\bar{\nu}_e$: ~ 10^{-2} cm^{-2} sec^{-1}
  - reactor $\bar{\nu}_e$: can be large but only up to ~12 MeV

JK Opferkuch, *in preparation*

Muon Diffusion in Magnetars

$$\phi_\nu \sim 0.3\,\text{cm}^{-2}\,\text{sec}^{-1}\left(\frac{N_\text{mag}}{10^6}\right)\left(\frac{N_\mu}{10^{55}}\right)\left(\frac{10\,\text{kpc}}{d_\text{avg}}\right)^2\left(\frac{1\,\text{Gyr}}{t_\text{exp}}\right)$$

- For comparison
  - diffuse supernova neutrino background: ~ 1 cm^{-2} sec^{-1}
  - solar ν: ~ 10^{6} cm^{-2} sec^{-1} (but only at E ≲ 20 MeV)
  - atmospheric ν_e and $\bar{\nu}_e$: ~ 10^{-2} cm^{-2} sec^{-1}
  - reactor $\bar{\nu}_e$: can be large but only up to ~12 MeV

Magnetars should emit a **novel**, potentially **detectable**, **neutrino flux!**

Summary

Summary

☑ High Energy Astrophysical Neutrinos
a fantastic new tool for particle physics and astrophysics alike

☑ Supernova Neutrinos
collective oscillations are a highly non-trivial SM effect,
but understanding them will be crucial

☑ Neutrinos from Neutron Stars
new potential insights from magnetar emission

Thank You!