Neutrino flavor conversions in binary neutron star merger remnants

Ian Padilla-Gay*

Based on: I. Padilla-Gay, S. Shalgar, I. Tamborra
JCAP01(2021)017, arXiv: 2009.01843

Niels Bohr Institute,
University of Copenhagen

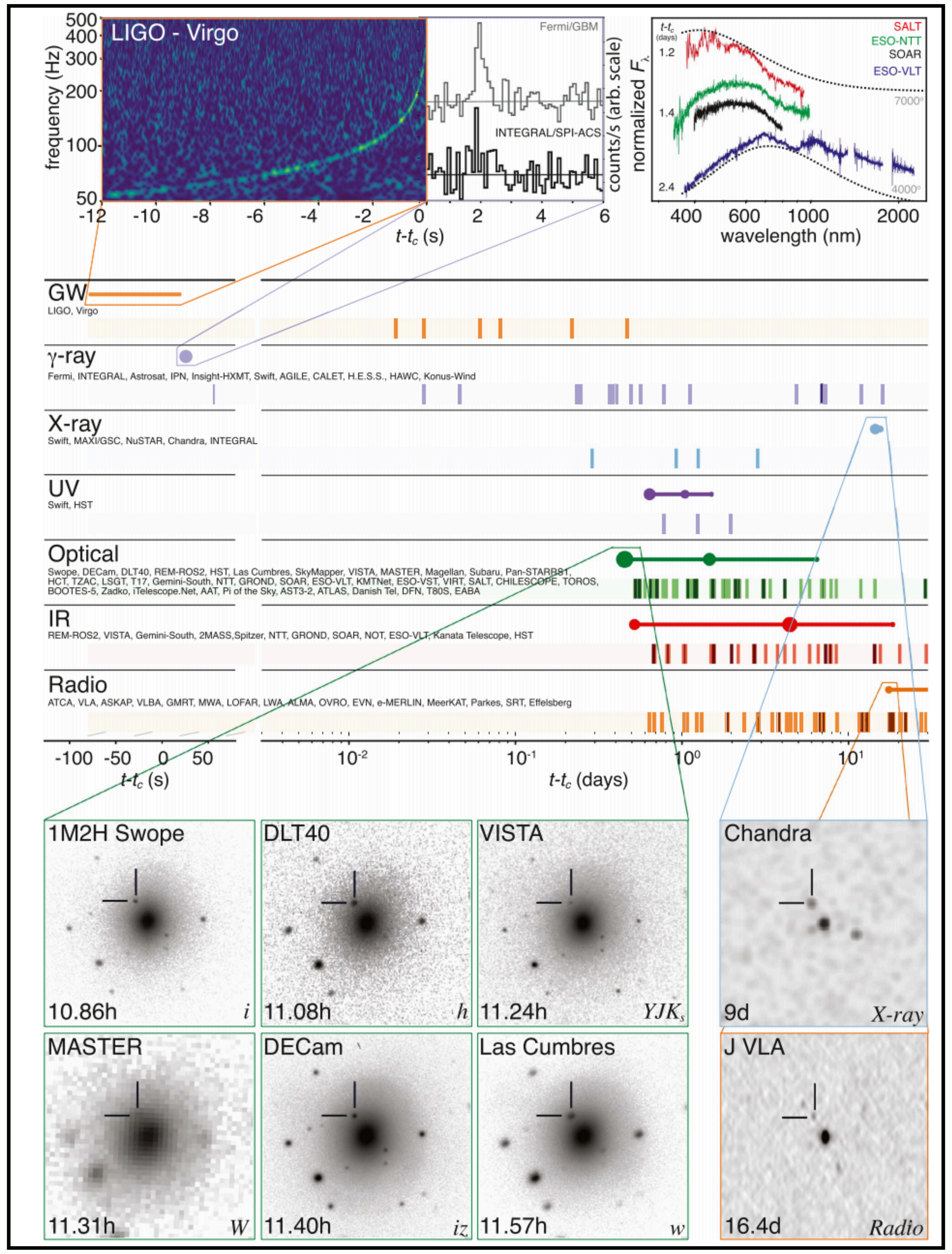
XIX International workshop on neutrino telescopes, February 22, 2021

**Email: ian.padilla@nbi.ku.dk*

Motivation

The role of neutrinos in multi-messeger astronomy

- Coalescence of NS+NS or NS+BH → compact binary merger. LIGO/Virgo GW170817 event.
- GW170817 consistent with the merger of two neutron stars in NGC 4993.
- Followed by a short gamma-ray burst (GRB 170817A)
- And a kilonova (AT 2017gfo) powered by radioactive decay of r-process nuclei synthesized in the ejecta.
- Nucleosynthesis in neutrino-dense outflows in NS mergers is flavor dependent ($\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$).



Abbott et al 2017

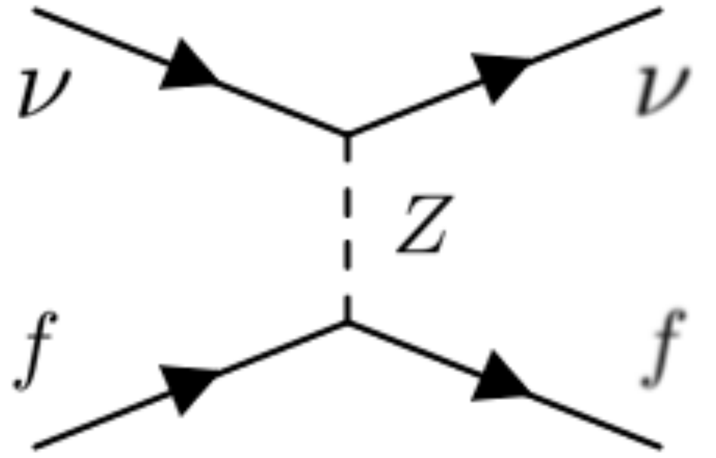
Timeline of the discovery of GW170817, GRB 170817A, SSS17a/AT 2017gfo

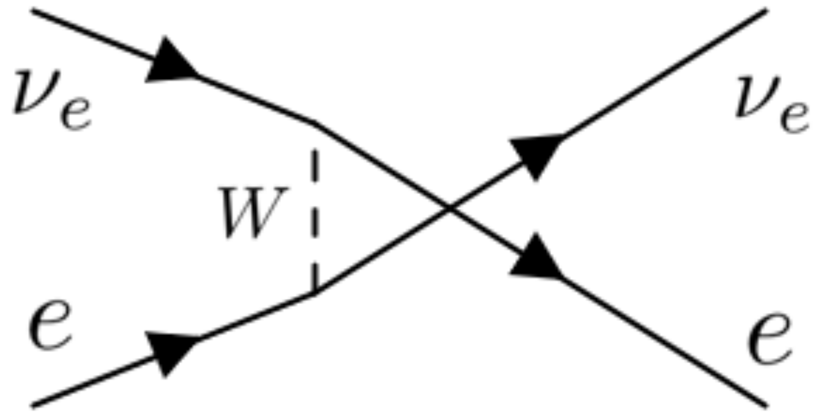
I. Padilla-Gay

Recent developments

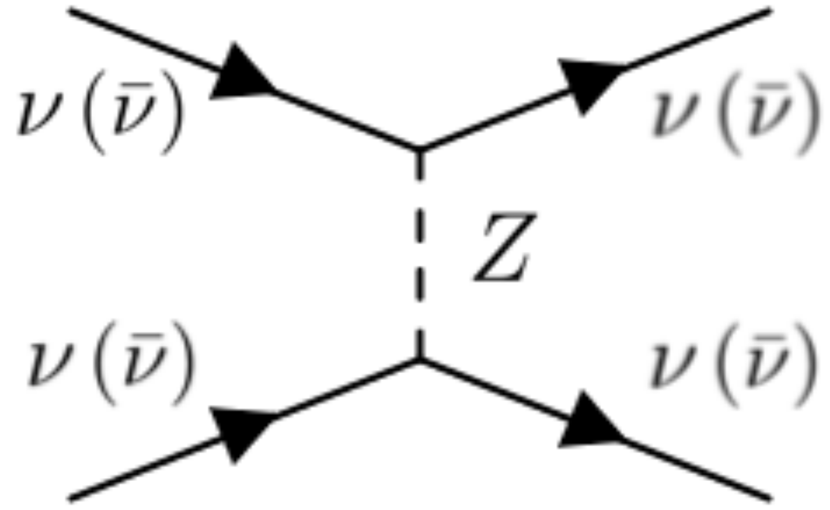
Neutrino oscillations in dense media

- **MSW effect:** Neutrinos experience a refractive index due to coherent forward scattering with background fermions $f = p, n, e$.





- ν—ν **coherent forward scattering:** Neutrinos also constitute a background to other neutrinos → *Fast pairwise neutrino flavor conversion* ($\Delta m^2 = 0$)



$$\nu_e(p) + \bar{\nu}_e(k) \to \nu_x(p) + \bar{\nu}_x(k)$$

$$\nu_e(p) + \nu_x(k) \to \nu_x(p) + \nu_e(k)$$

Highly non-linear feedback onto the neutrino flavor field

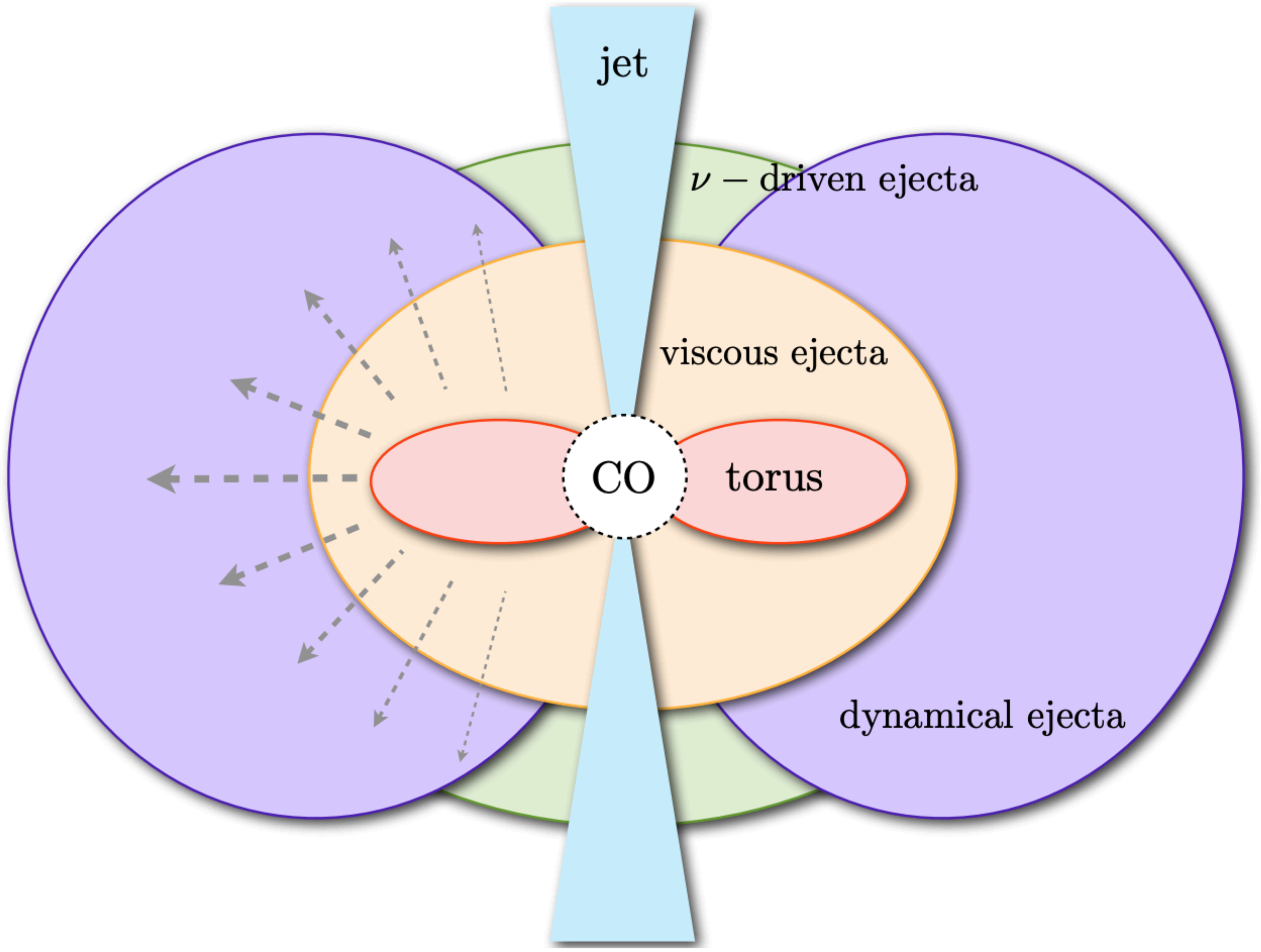
Neutrinos oscillate in a **collective fashion**

I. Padilla-Gay

Recent developments

Neutrino oscillations in neutron star mergers

- Binary NS merger offer favourable conditions for neutrino *fast flavor conversions* due to (Wu and Tamborra 2017):
  1. Disk geometry
  2. Protonization of remnant (more $\bar{\nu}_e$ than ν_e)
- Neutrino-driven winds dominate the ejecta in a cone in the polar region. Qualitatively similar scenarios BH/NS and NS/NS remnants.



Tamborra and Shalgar 2021

Recent developments

The model: Neutrino oscillations in neutron star mergers

Density matrices:

$$\rho(\vec{x},\theta,t) = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{ex}^{*} & \rho_{xx} \end{pmatrix} \quad \text{and} \quad \bar{\rho}(\vec{x},\theta,t) = \begin{pmatrix} \bar{\rho}_{ee} & \bar{\rho}_{ex} \\ \bar{\rho}_{ex}^{*} & \bar{\rho}_{xx} \end{pmatrix}$$

Hamiltonian:

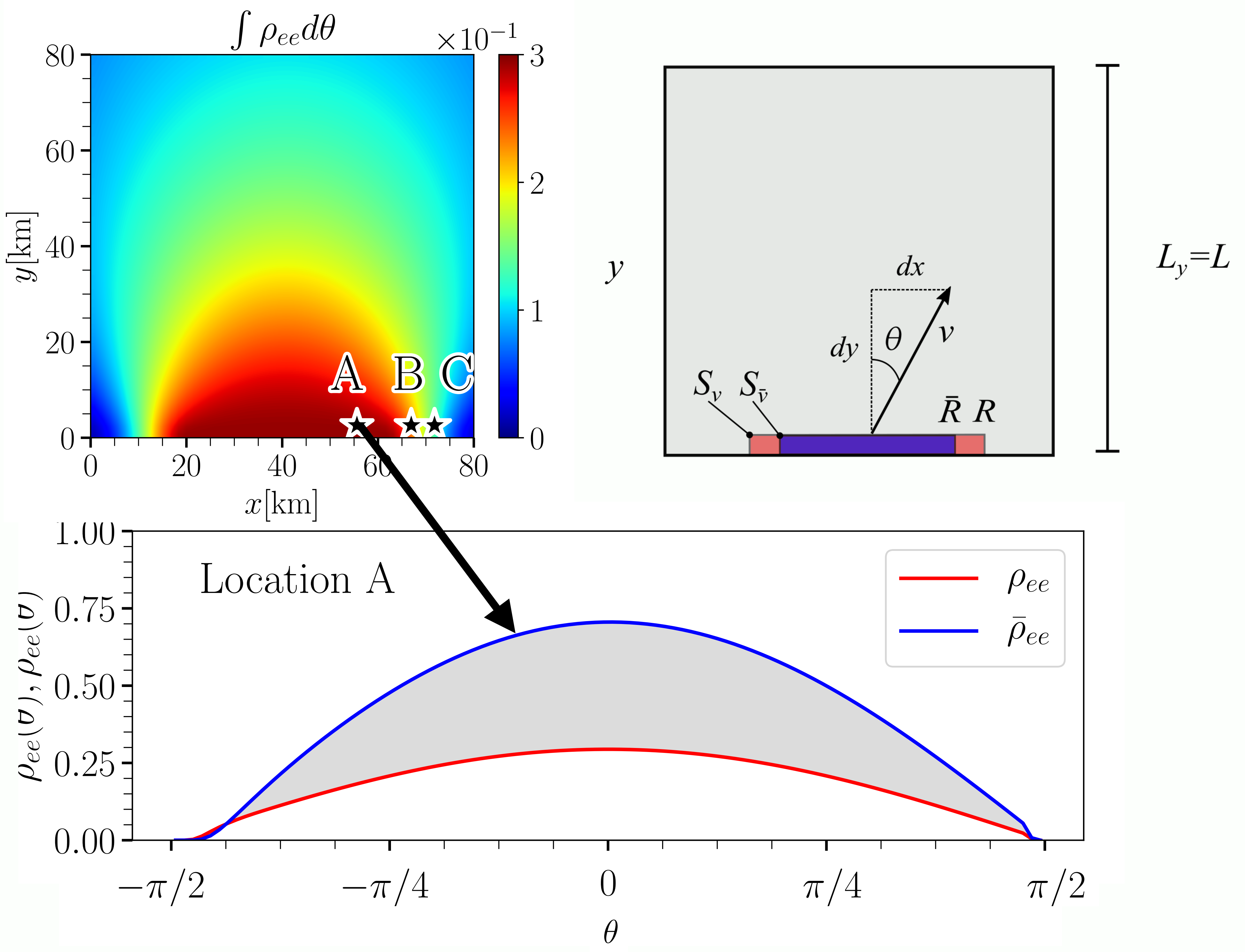
$$H(\theta) = H_{\text{vac}} + H_{\text{mat}} + \mu \int d\theta' \left(\rho - \bar{\rho}\right) \left[1 - \cos(\theta - \theta')\right]$$

Neutrino quantum kinetic equations:

$$i\left(\frac{\partial}{\partial t} + \vec{v}\cdot\vec{\nabla}\right)\rho(\vec{x},\theta,t) = [H(\theta), \rho(\vec{x},\theta,t)]\ ,$$

$$i\left(\frac{\partial}{\partial t} + \vec{v}\cdot\vec{\nabla}\right)\bar{\rho}(\vec{x},\theta,t) = [\bar{H}(\theta), \bar{\rho}(\vec{x},\theta,t)]\ .$$

Spatial distribution of (anti)neutrinos



Angular distribution of (anti)neutrinos

I. Padilla-Gay

Recent developments

Our results: minimal neutrino conversion

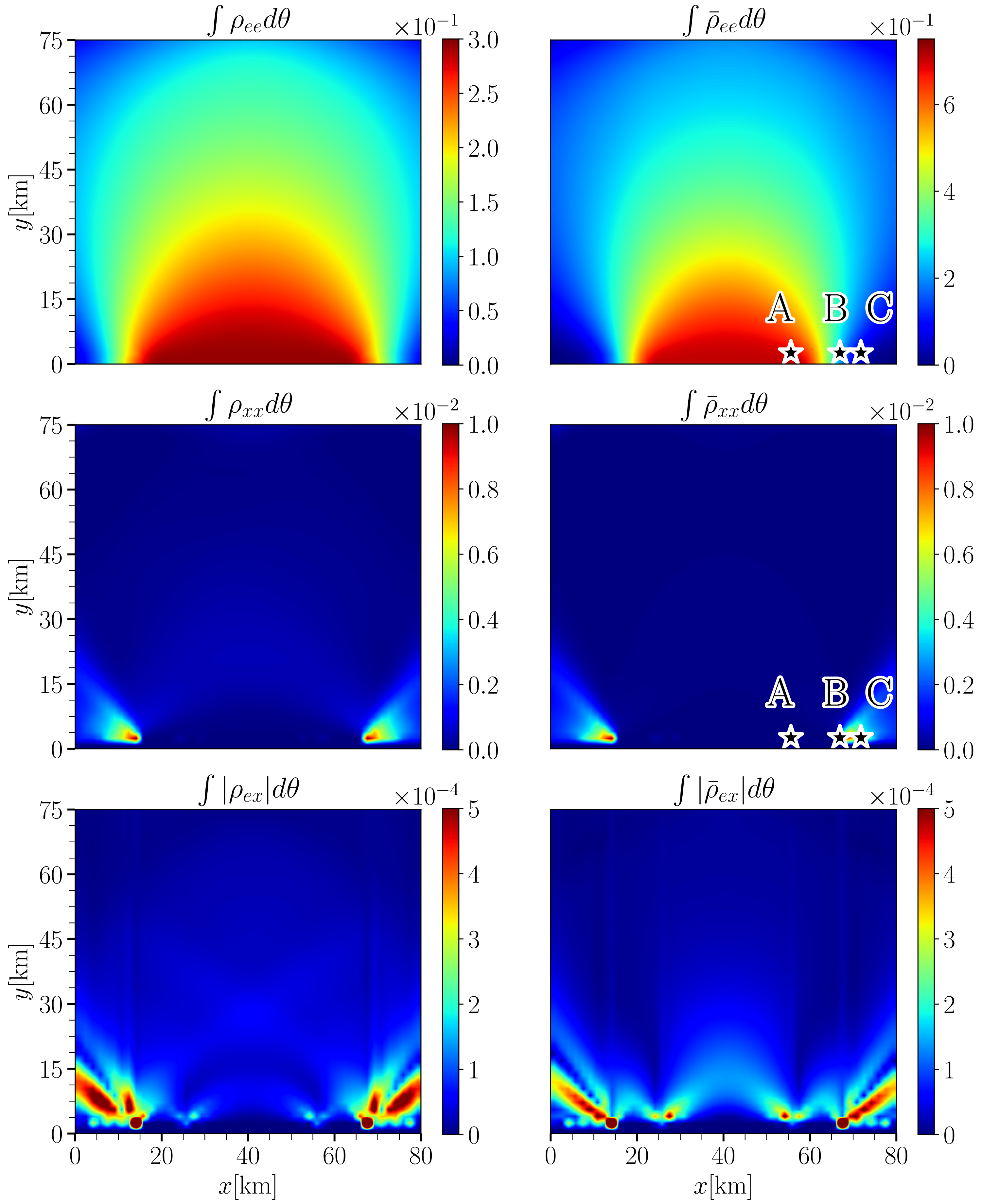
Neutrino and antineutrino decoupling regions approximation

$\nu_e, \bar{\nu}_e$

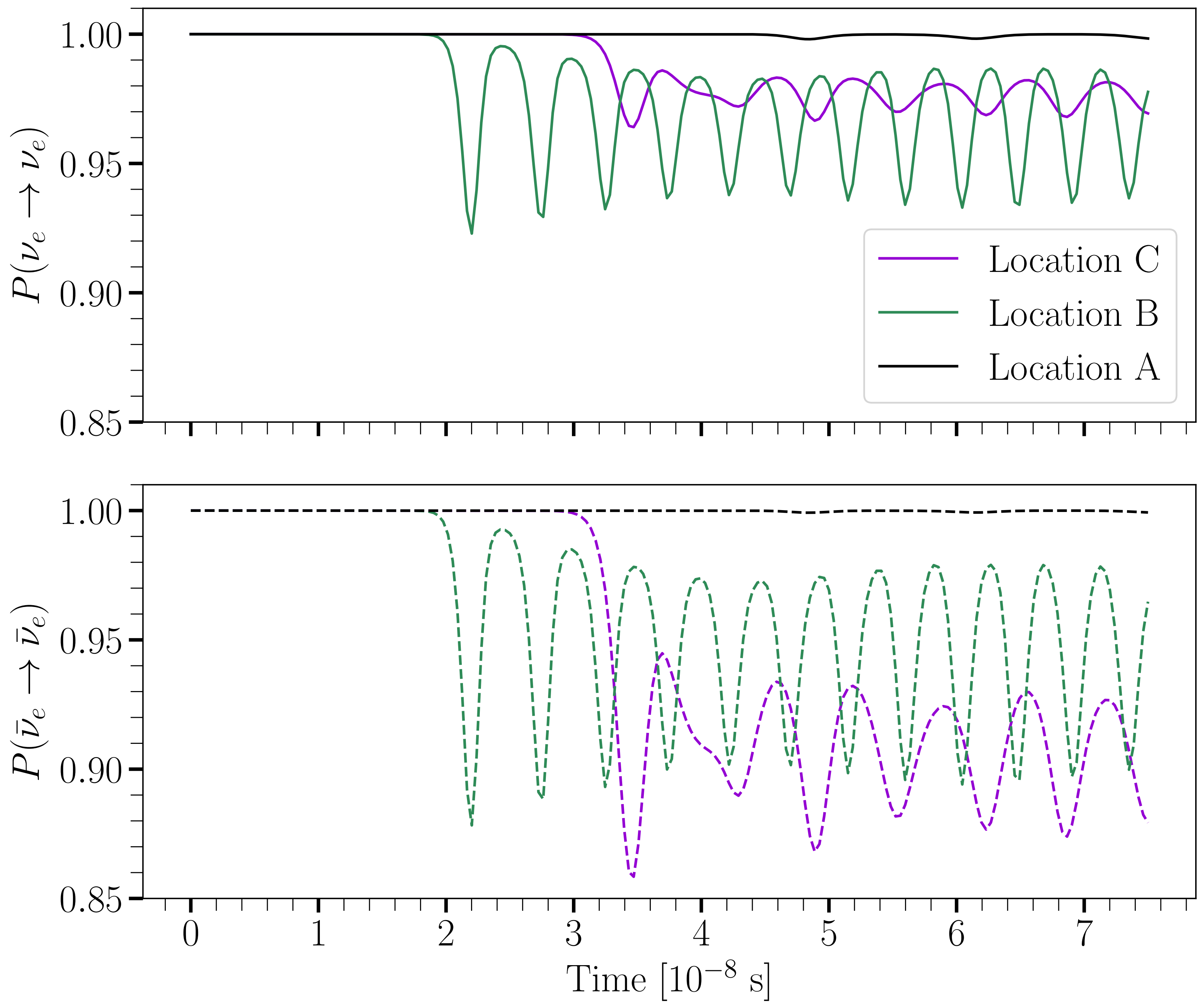
Newly converted ν_x's (small fraction)

$\nu_x, \bar{\nu}_x$

Flavor unstable regions are localized



Our simulations show a minimal neutrino conversion (less 1%).

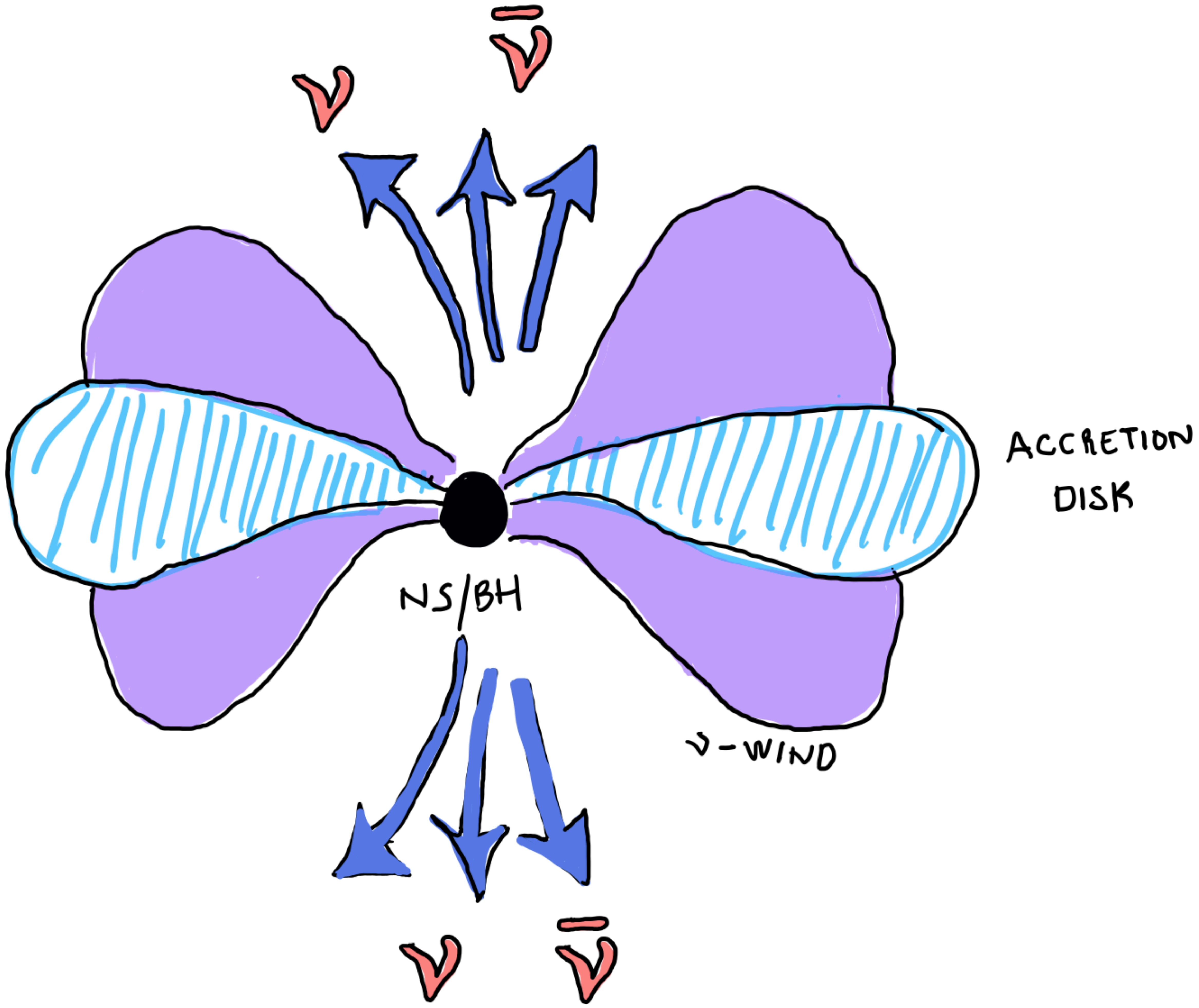


I. Padilla-Gay

Conclusions

- Binary NS merger remnants can host *(collective) fast flavor neutrino oscillations*.
- Equipartition of neutrino flavors is not achieved in this study. The polar region is unaffected by neutrino conversions.
- Approximate model: Our findings are not yet conclusive. Major step forward.
- More work is needed to quantify the effect of neutrinos on the EM observations.

Thanks, questions?

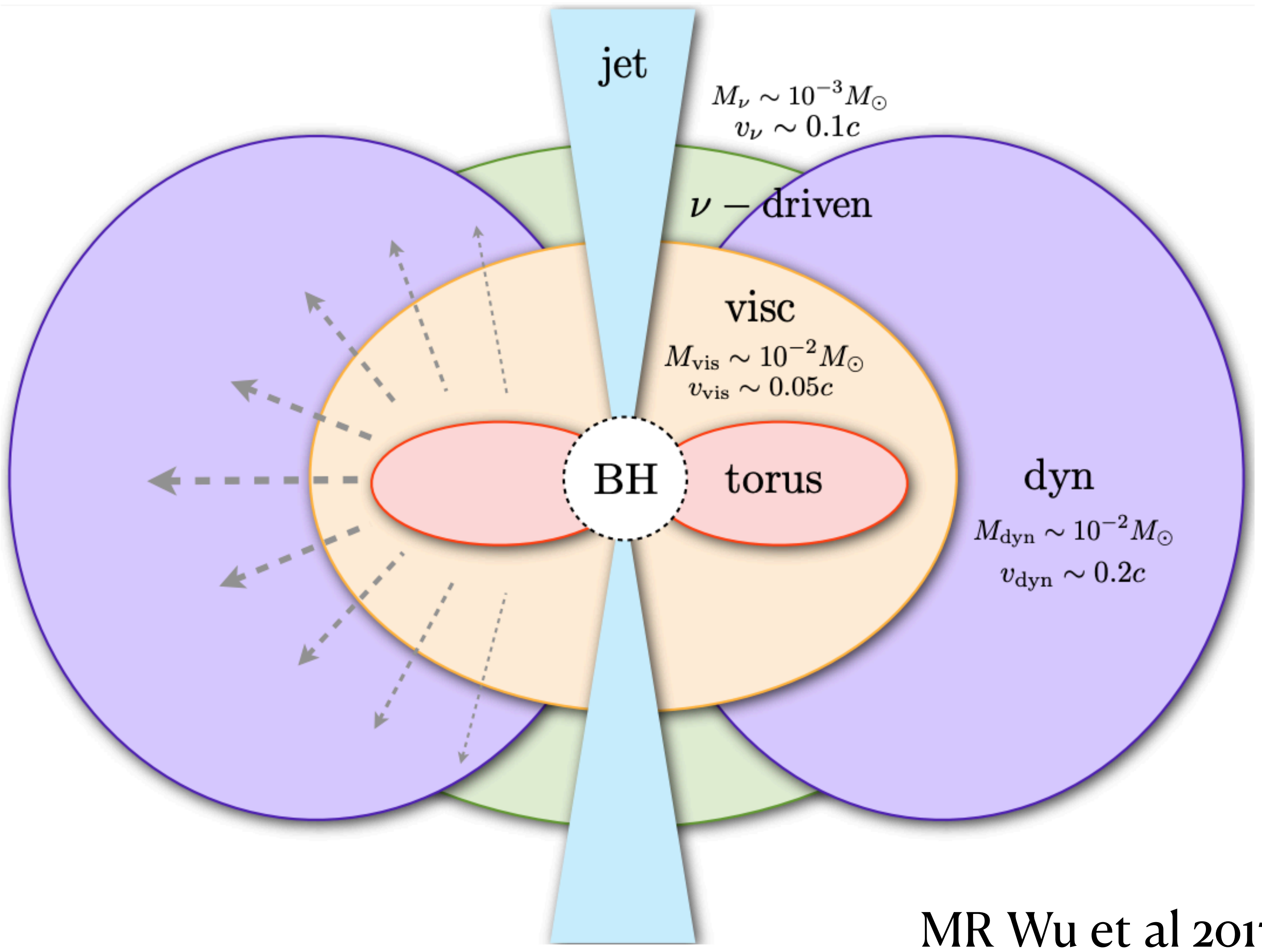


Backup slides

Backup slides

Neutrino oscillations are important in dense media

- In our Sun: vacuum oscillations and e—ν forward scattering (Wolfenstein 1978).
- High neutrino density → ν—ν coherent forward scattering (Pantaleone 1992).
- Nucleosynthesis in neutrino-dense outflows NS mergers are flavor dependent ($\nu_e + n \rightarrow p + e^-$).
- Possible impact on what we observe at Earth? ~1/2 of elements heavier than iron are synthesized via the r-process.



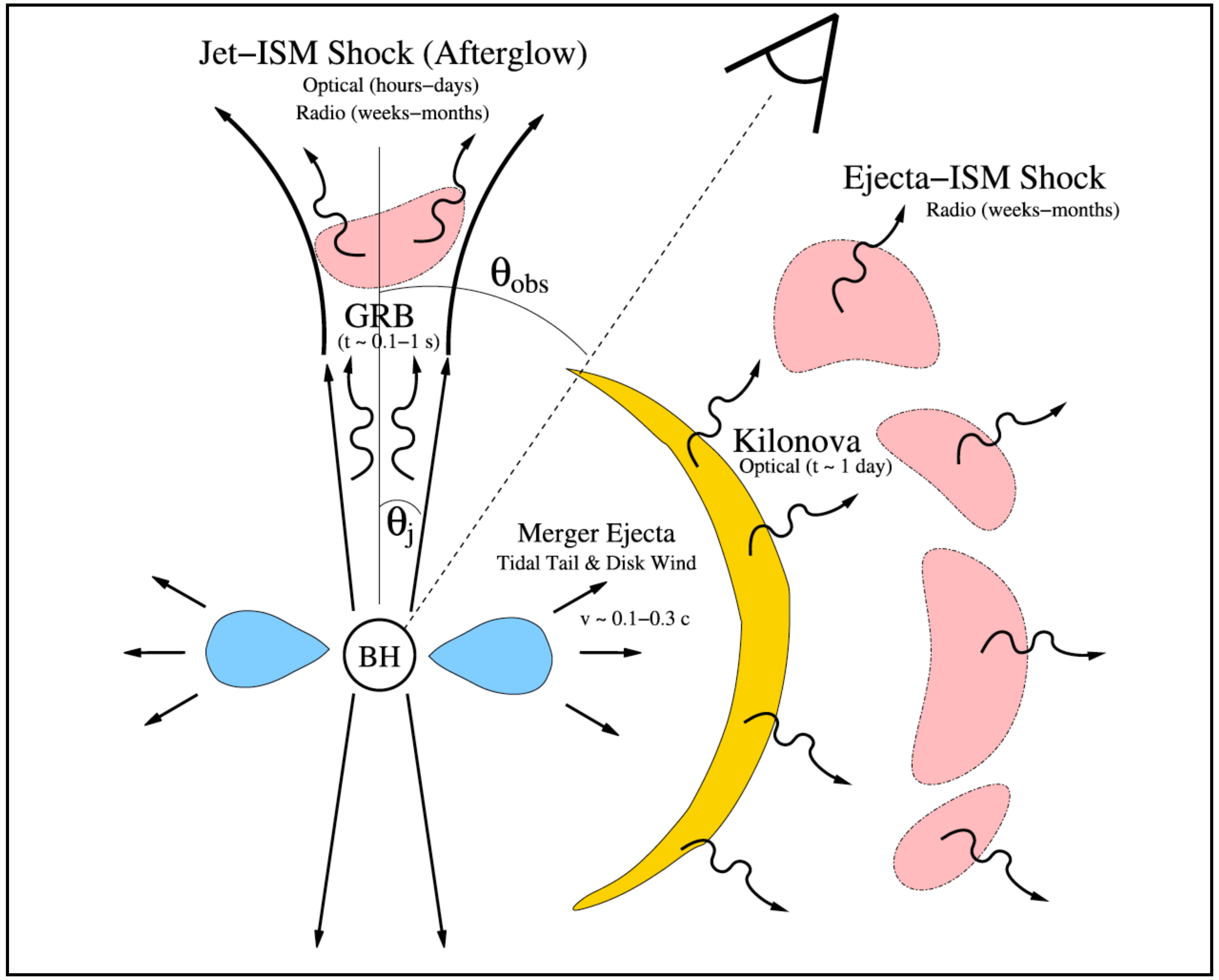
MR Wu et al 2017

Neutrino-driven winds may dominate the ejecta in a cone in the polar region. Qualitatively, one has the same for the NS-torus remnant, except that more massive neutrino-driven winds are expected with a central NS.

Backup slides

EM counterparts of NS-NS/BH-NS mergers

- The radioactive decay of isotopes of the heavy elements is predicted (L. Li et al 1998) to power a distinctive thermal glow: 'kilonova'.
- Critical quantity: $Y_e \equiv n_p/(n_n + n_p)$ of the ejecta characterizes viability for r-process (Cameron 1957).
- r-process is possible only if $Y_e \lesssim 0.5$ (neutron-rich).
- $Y_e \lesssim 0.3$ for lanthanides (Lippuner et al 2015) → significant increase in opacity (Tanaka & Hotokezaka 2013).



Metzger and Berger 2012

Backup slides

Neutrino oscillations in neutron star mergers

Fast pairwise neutrino flavor conversion

$$\nu_e(p) + \bar{\nu}_e(k) \to \nu_x(p) + \bar{\nu}_x(k) \quad \text{and} \quad \nu_e(p) + \nu_x(k) \to \nu_x(p) + \nu_e(k)$$

Density matrices: $\rho(\vec{x}, \theta, t) = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{ex}^* & \rho_{xx} \end{pmatrix}$ and $\bar{\rho}(\vec{x}, \theta, t) = \begin{pmatrix} \bar{\rho}_{ee} & \bar{\rho}_{ex} \\ \bar{\rho}_{ex}^* & \bar{\rho}_{xx} \end{pmatrix}$

Hamiltonian:

$$H(\theta) = \frac{\omega}{2} \begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} + \begin{pmatrix} \lambda & 0 \\ 0 & 0 \end{pmatrix} + \mu \int d\theta' \left[\rho(\vec{x}, \theta', t) - \bar{\rho}(\vec{x}, \theta', t)\right] \left[1 - \cos(\theta - \theta')\right]$$

Neutrino quantum kinetic equations:

$$i \left(\frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla} \right) \rho(\vec{x}, \theta, t) = [H(\theta), \rho(\vec{x}, \theta, t)] \ ,$$

$$i \left(\frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla} \right) \bar{\rho}(\vec{x}, \theta, t) = [\bar{H}(\theta), \bar{\rho}(\vec{x}, \theta, t)] \ .$$

I. Padilla-Gay