Report on Research Activity

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SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

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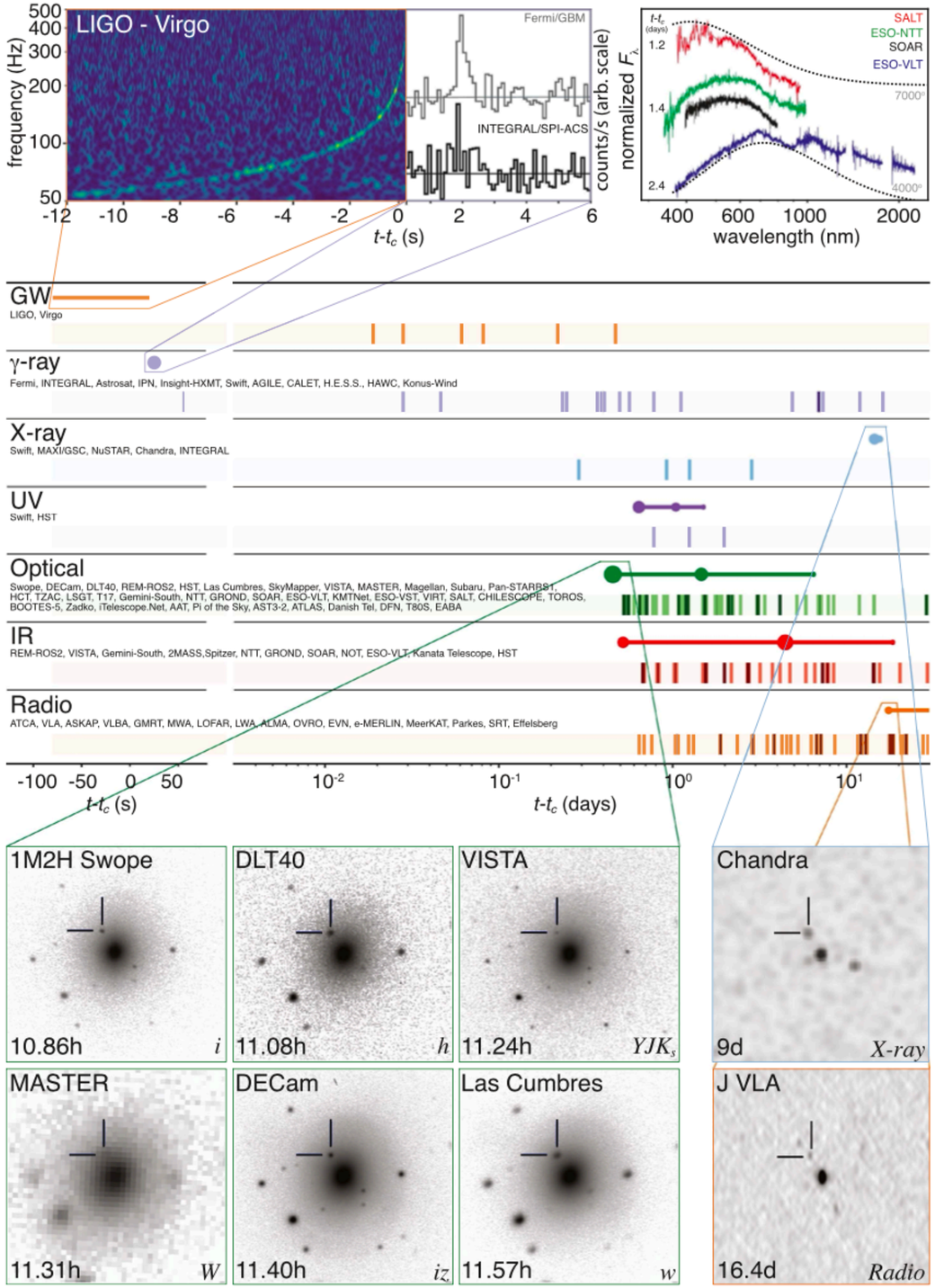
Binary Neutron Star mergers

The first detection

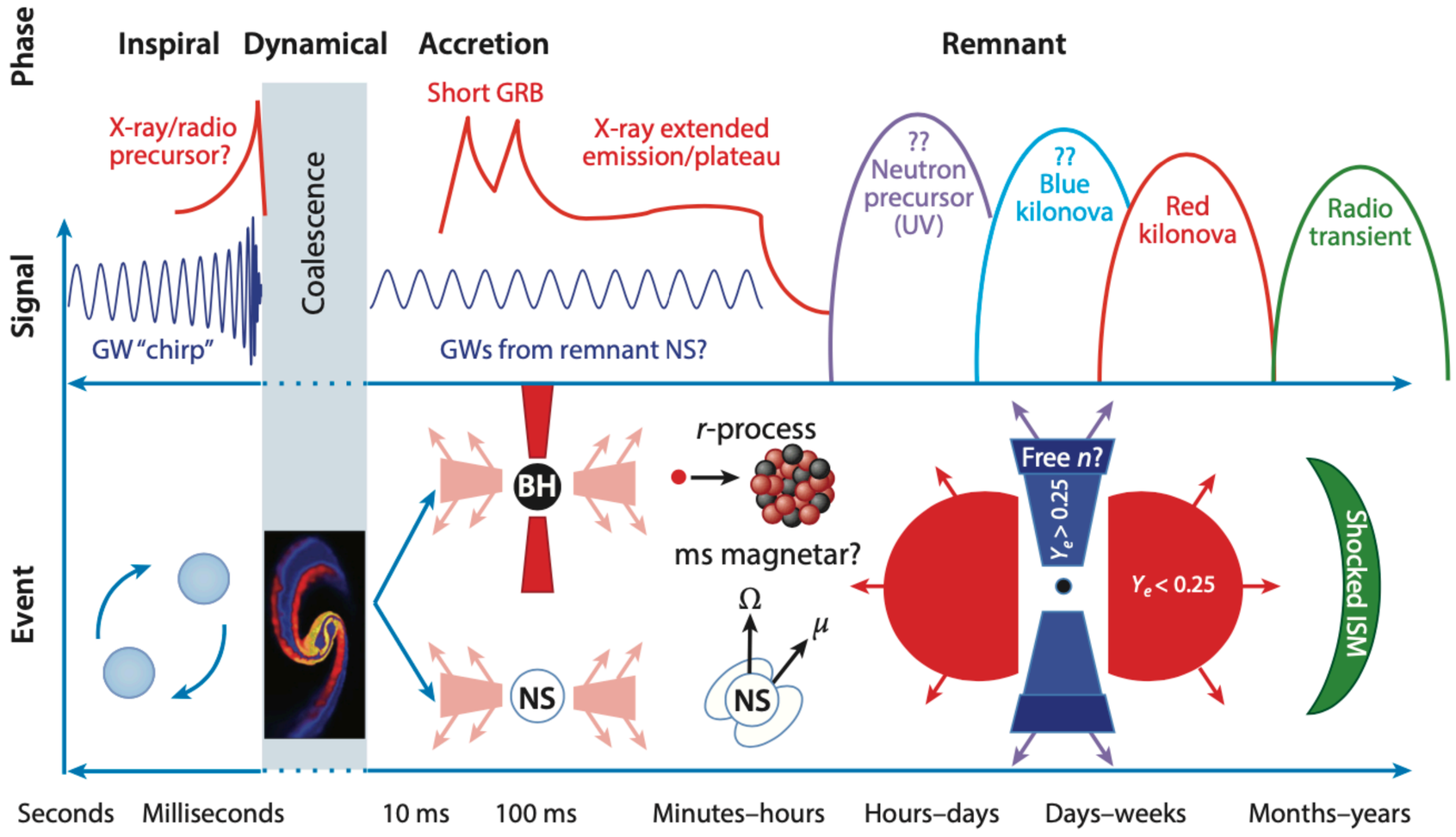
- August 2017: first detection of gravitational waves & electromagnetic counterparts from a BNS merger

- New insights on fundamental physics, in particular on Gamma Ray Bursts and Kilonovae



Credits: LVC+astronomers, Abbott et al. 2017, ApJL, 848

The Kilonova (KN)

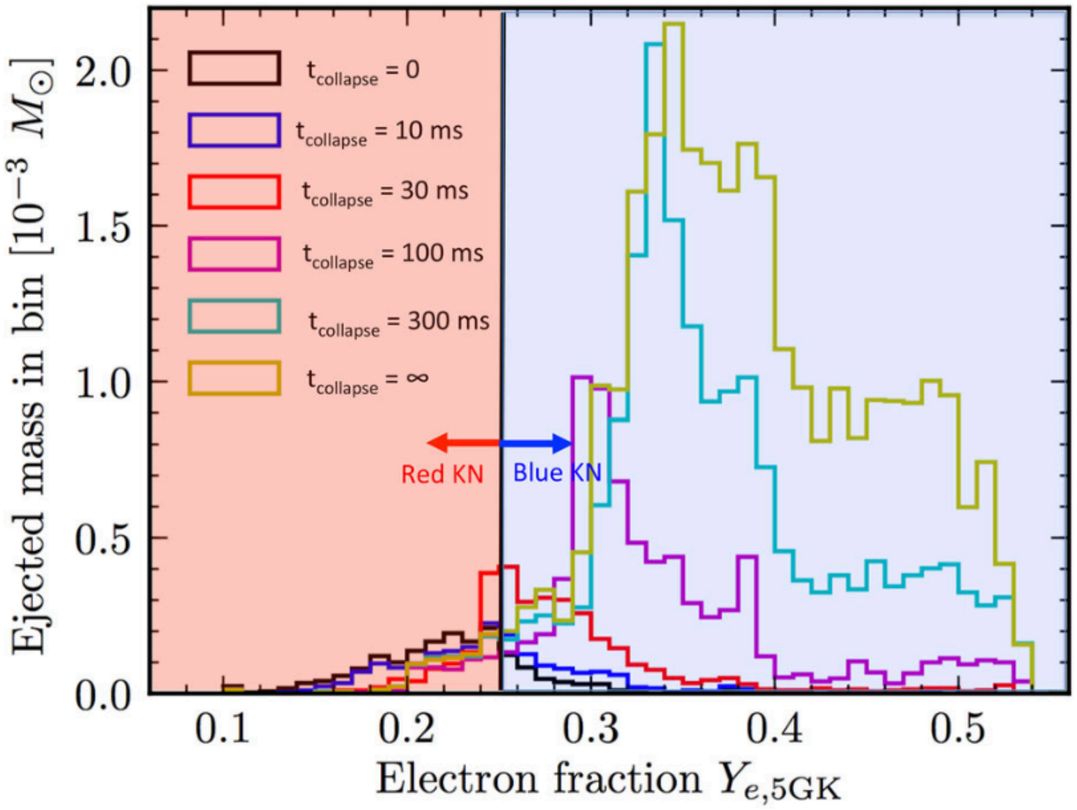


Credits: Fernández, Metzger 2016

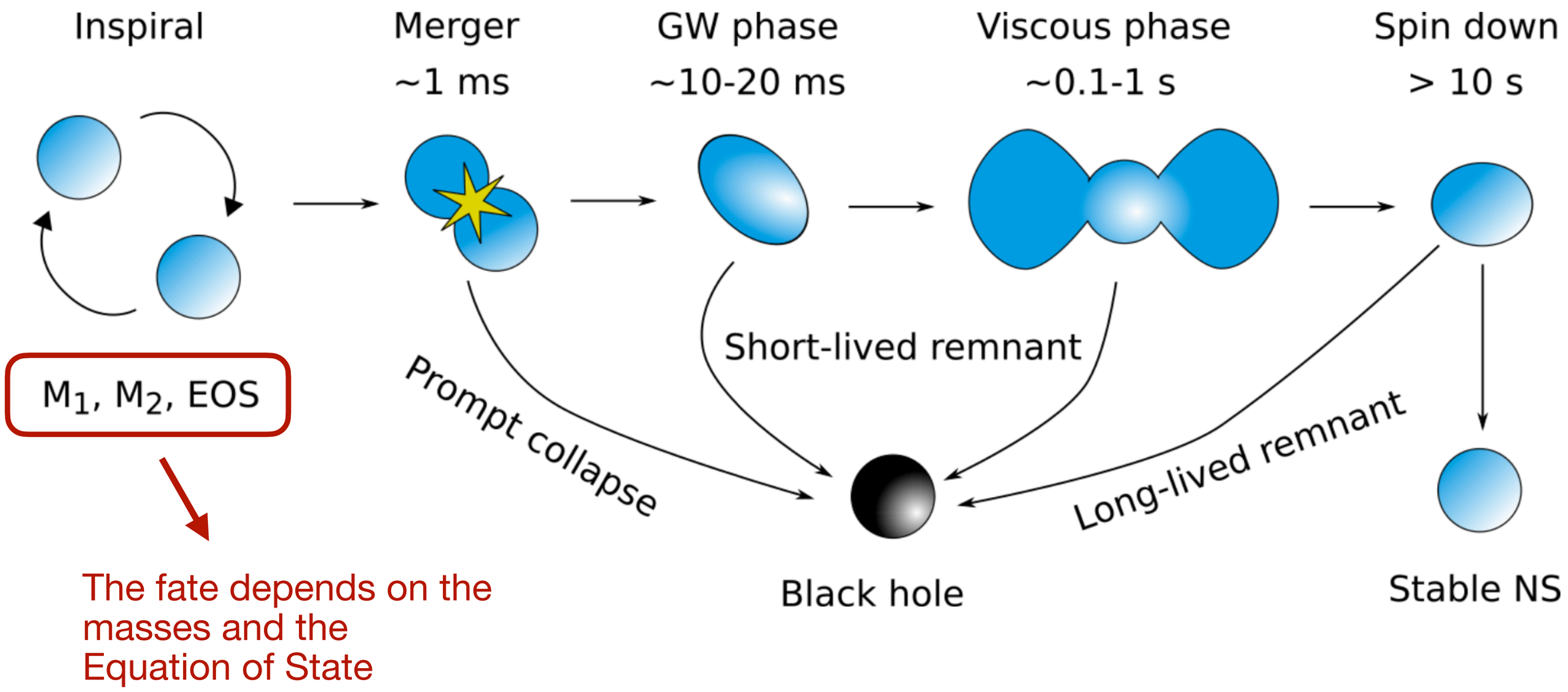
The Kilonova (KN)

The KN signal depends on the properties of the ejected matter, which are related to the microphysics and the fate of the merger (time of collapse to a Black Hole).

Credits: Metzger 2019



Which is the fate of a Binary Neutron Star (BNS) merger?

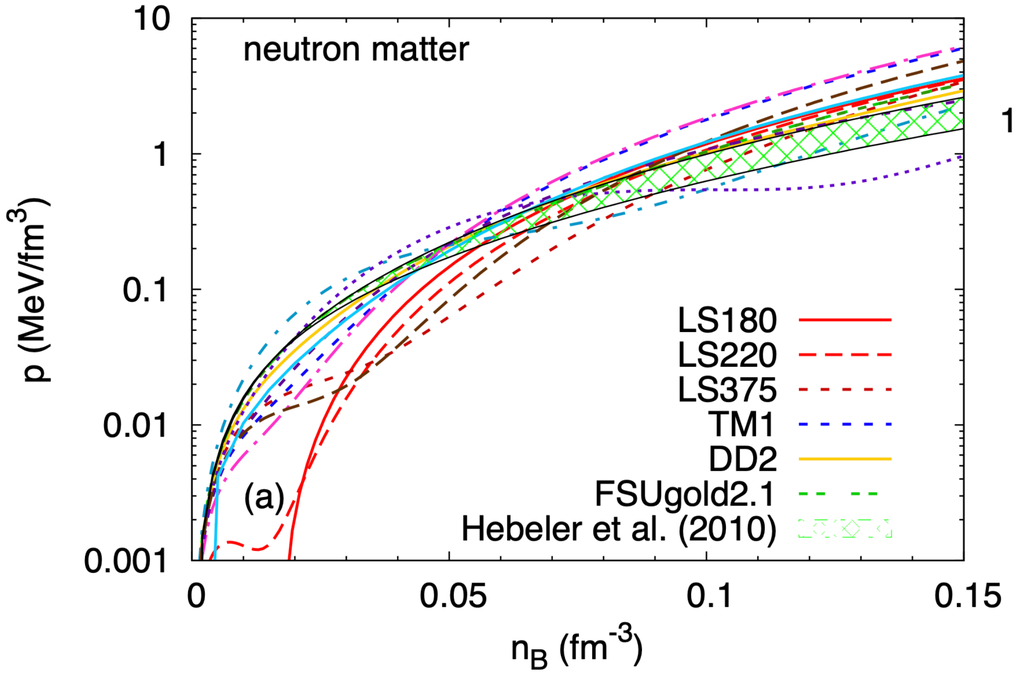


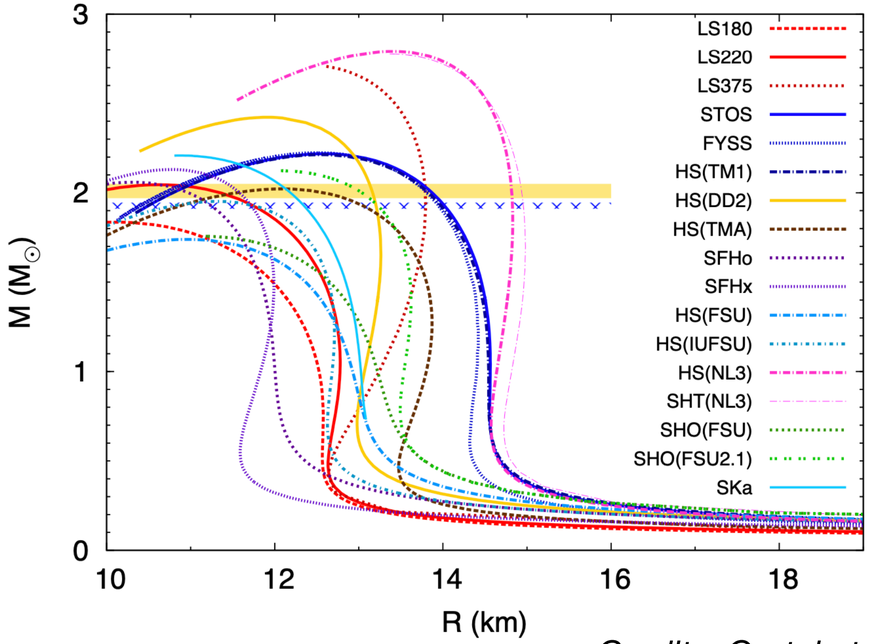
The fate depends on the masses and the Equation of State

Credits: Radice, Bernuzzi, Perego 2020

The Equation of State of nuclear matter

- EOS: relation between matter density, temperature and thermodynamic variables
- The EOS of Neutron Stars is unknown
- Stiffer vs softer EOS
- Modelling of nuclear interaction and relevant degrees of freedom: neutrons, protons, pions, free quarks, muons, …
- The relevant degrees of freedom depend on the temperature other than the density





Credits: Oertel et al. 2016

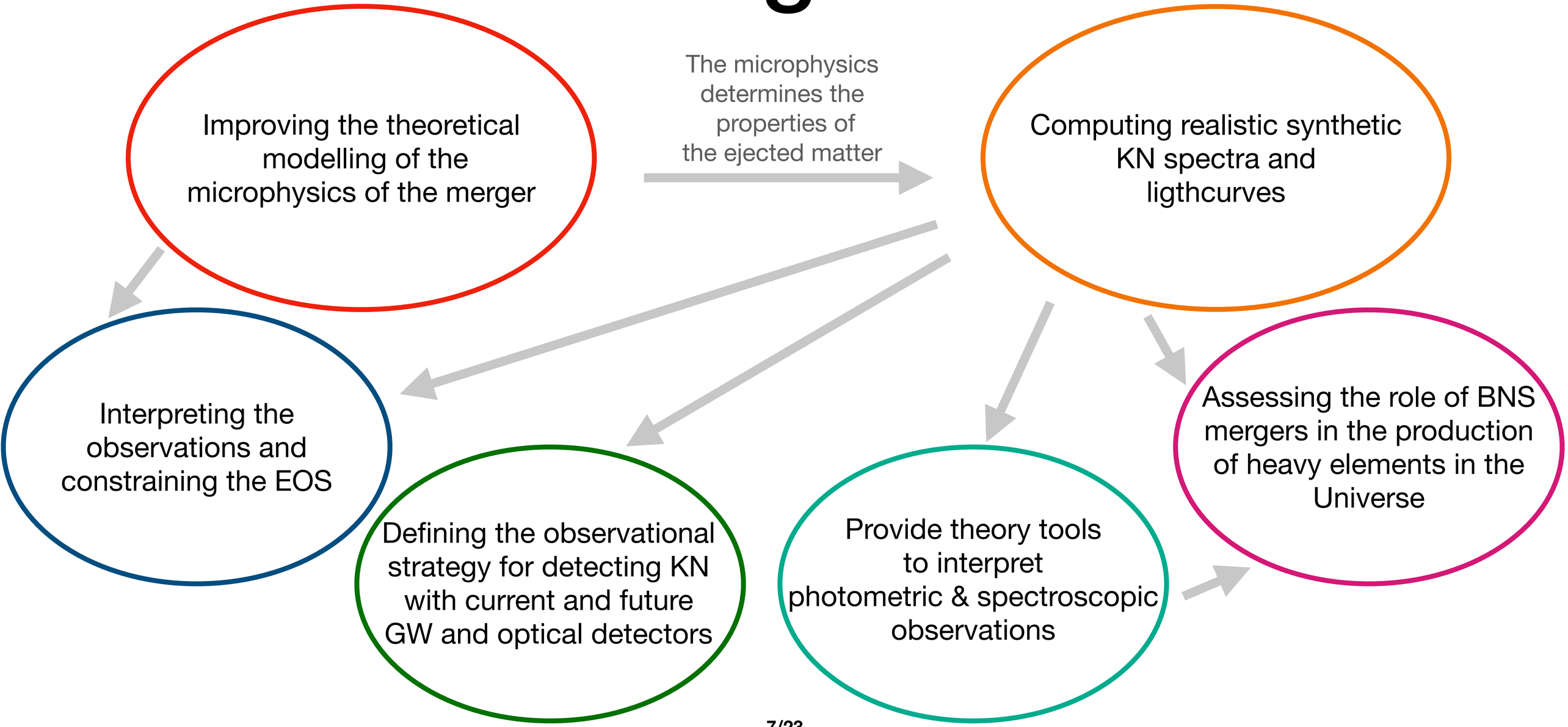
Our goals

Improving the theoretical modelling of the microphysics of the merger

The microphysics determines the properties of the ejected matter

Computing realistic synthetic KN spectra and ligthcurves

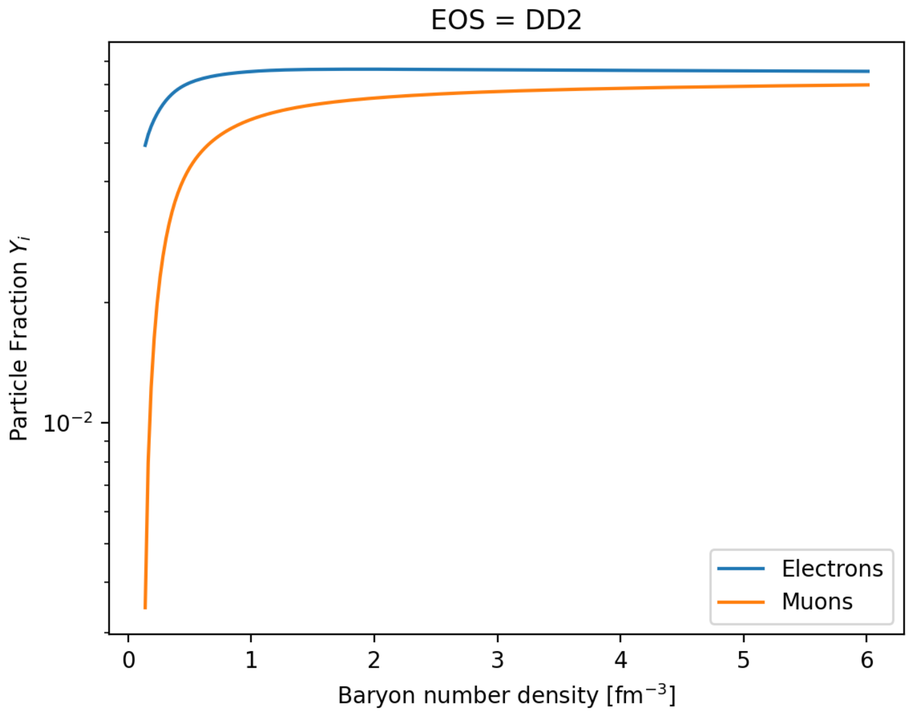
Our goals

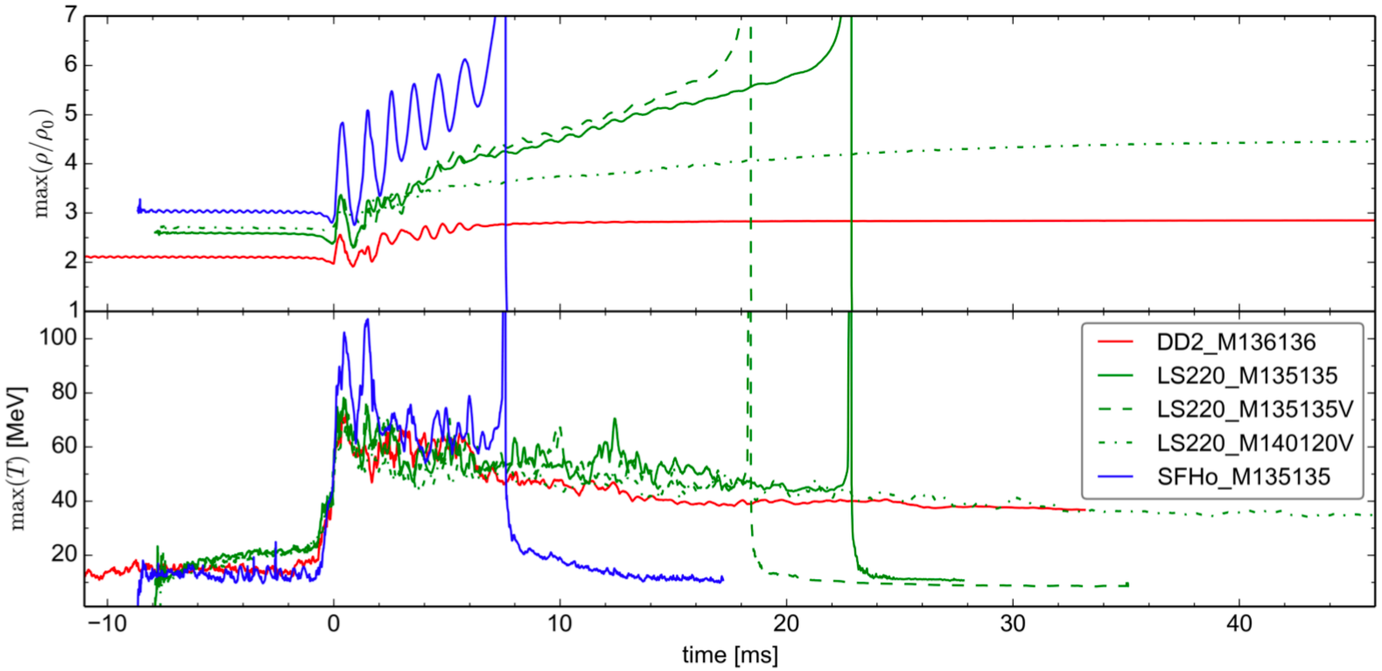

Improving the theoretical modelling of the microphysics of the merger
The microphysics determines the properties of the ejected matter
Computing realistic synthetic KN spectra and ligthcurves
Interpreting the observations and constraining the EOS
Defining the observational strategy for detecting KN with current and future GW and optical detectors
Provide theory tools to interpret photometric & spectroscopic observations
Assessing the role of BNS mergers in the production of heavy elements in the Universe

Improving the microphysics modelling

Muons production and Neutrino Trapping

- Muons are included in cold Neutron Star EOS
- Thermodynamics conditions in BNS mergers favour muons and neutrinos production and neutrino trapping
- Trapped neutrinos can make the EOS softer





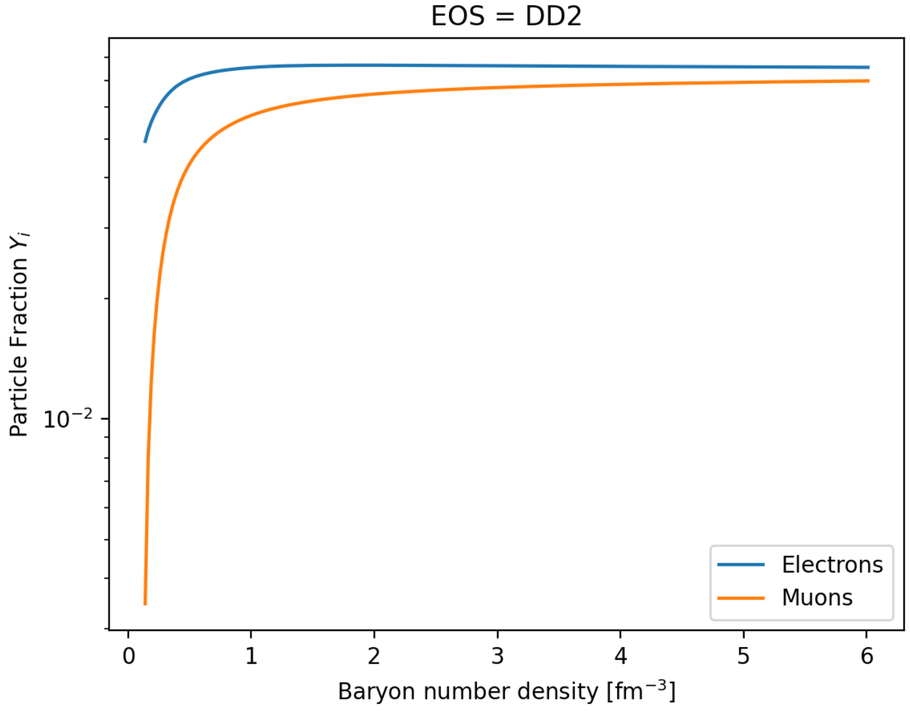
Credits: Perego et al. 2019

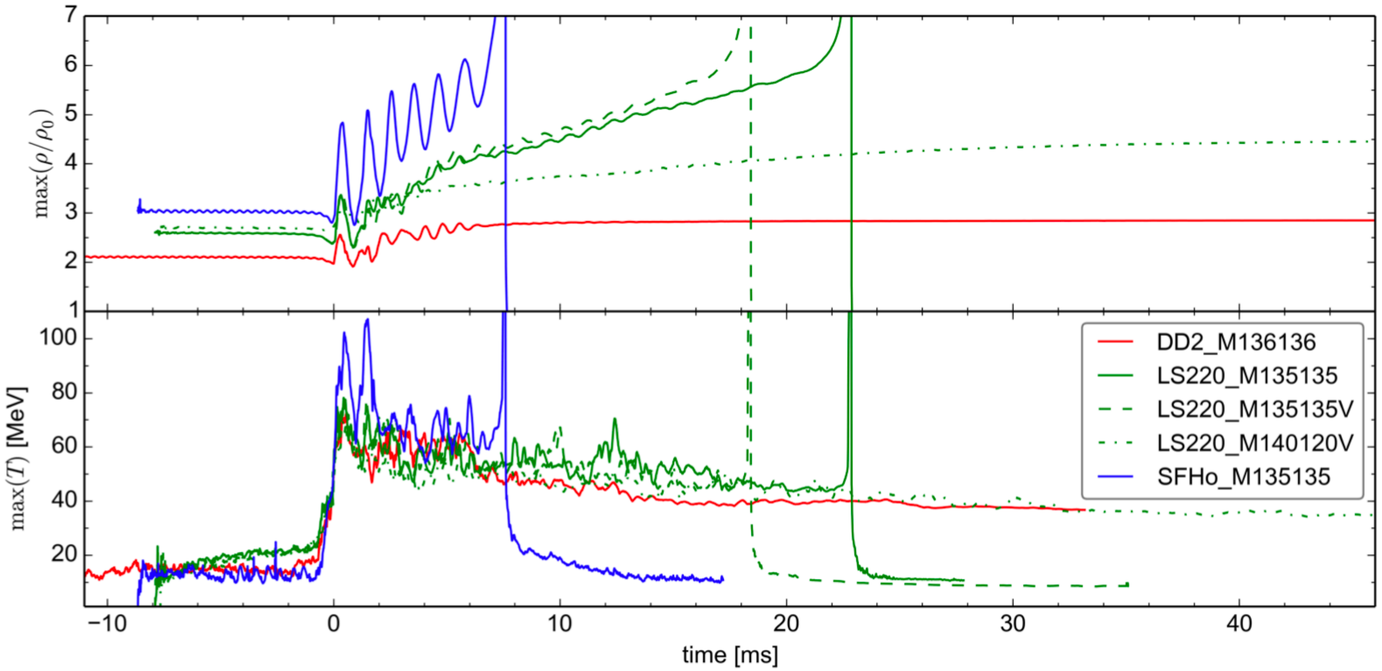
Improving the microphysics modelling

Muons production and Neutrino Trapping

State of the art simulations of BNS mergers **don't** include muons and trapped neutrinos. The **aim** of this work is to estimate their impact on the merger remnant**.**

Work in collaboration with Prof. A. Perego





Credits: Perego et al. 2019

Improving the microphysics modelling

Method

- Degrees of freedom: baryons, electrons, positrons, muons, anti-muons, photons and neutrinos
- Thermodynamic variables determined by baryon number density n_b, temperature T and particle fractions $Y_i = n_i/n_b$ where $i = p, e^-, e^+, \mu^- \ldots$
- Charge neutrality $Y_p = Y_e + Y_\mu$ where $Y_e = Y_{e^-} - Y_{e^+}$ and $Y_\mu = Y_{\mu^-} - Y_{\mu^+}$
- Assume thermal and weak equilibrium
- Under these assumptions the relevant variables are n_b, T, Y_e and Y_μ

Improving the microphysics modelling

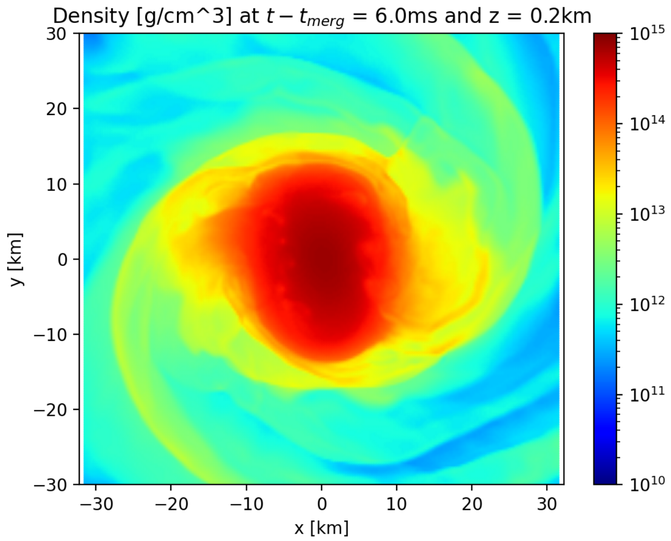
Method - The post-processing technique

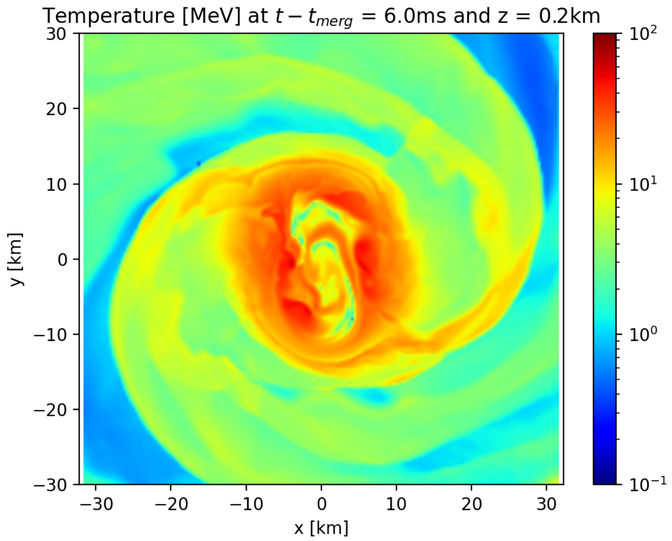
- During the merger the temperature of fluid elements increase → creation of muons and neutrinos
- At high enough density the neutrinos are trapped → $Y_{l,e}, Y_{l,\mu}$ conserved
- On a time-scale $t_{weak} \ll dt \ll t_{dyn}$ the internal energy u stays the same

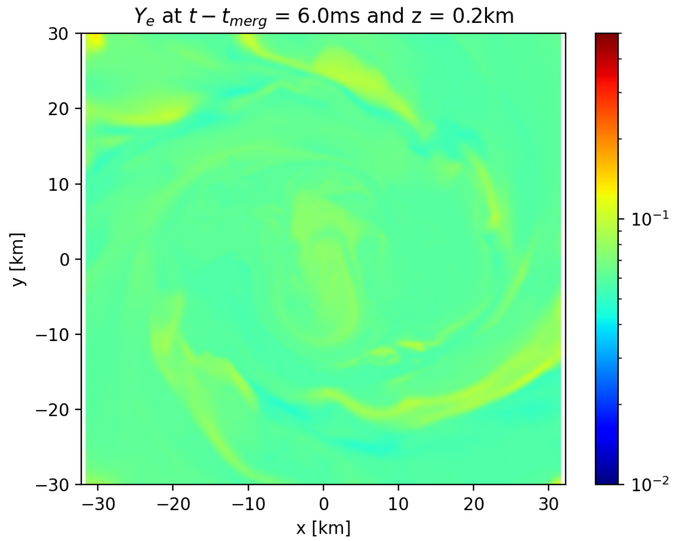
$$\begin{cases} Y_{l,e} = Y_e + Y_{\nu_e}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_e}(n_b, T, Y_e, Y_\mu) \\ Y_{l,\mu} = Y_\mu + Y_{\nu_\mu}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_\mu}(n_b, T, Y_e, Y_\mu) \\ u = \sum_i e_i(n_b, T, Y_e, Y_\mu) \quad i = b, e^{+/-}, \mu^{+/-}, \gamma, \nu, \bar{\nu} \end{cases}$$

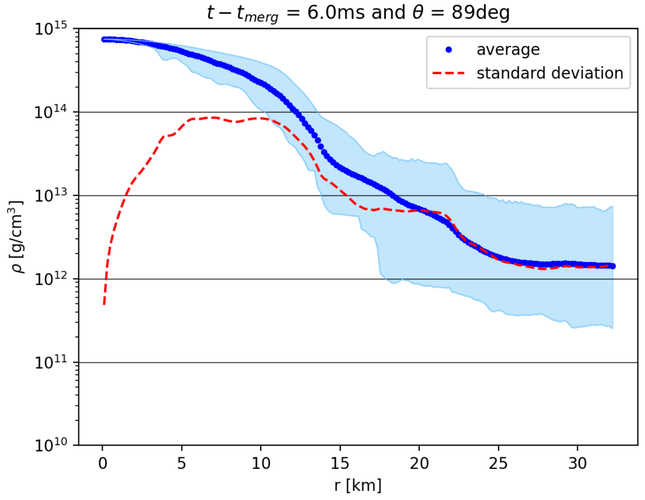
- Numerical relativity simulations provide $(Y_{l,e}, Y_{l,\mu}, u)$ $\forall (t, x, y, z)$ under the assumptions $Y_{l,e} = Y_e$ and $Y_{l,\mu} = Y_\mu = 0$ and no contributions from neutrino trapping
- By solving the system we get the *true* values of Y_e, Y_μ, T and all thermodynamic quantities

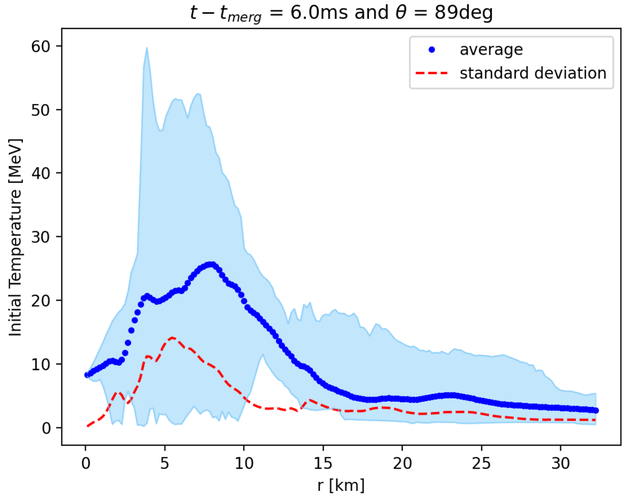
The outcome of the simulation

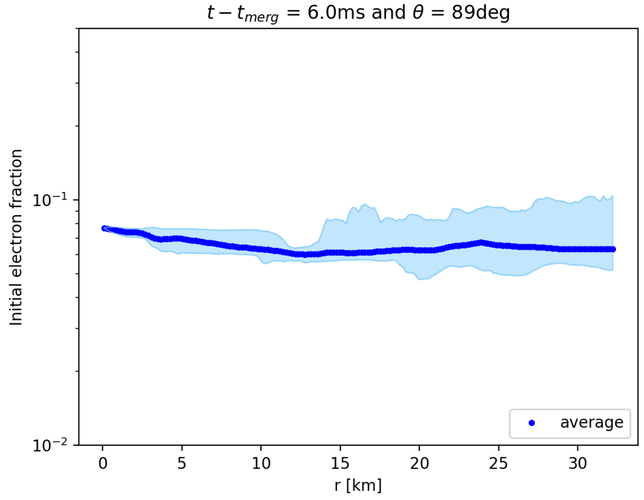






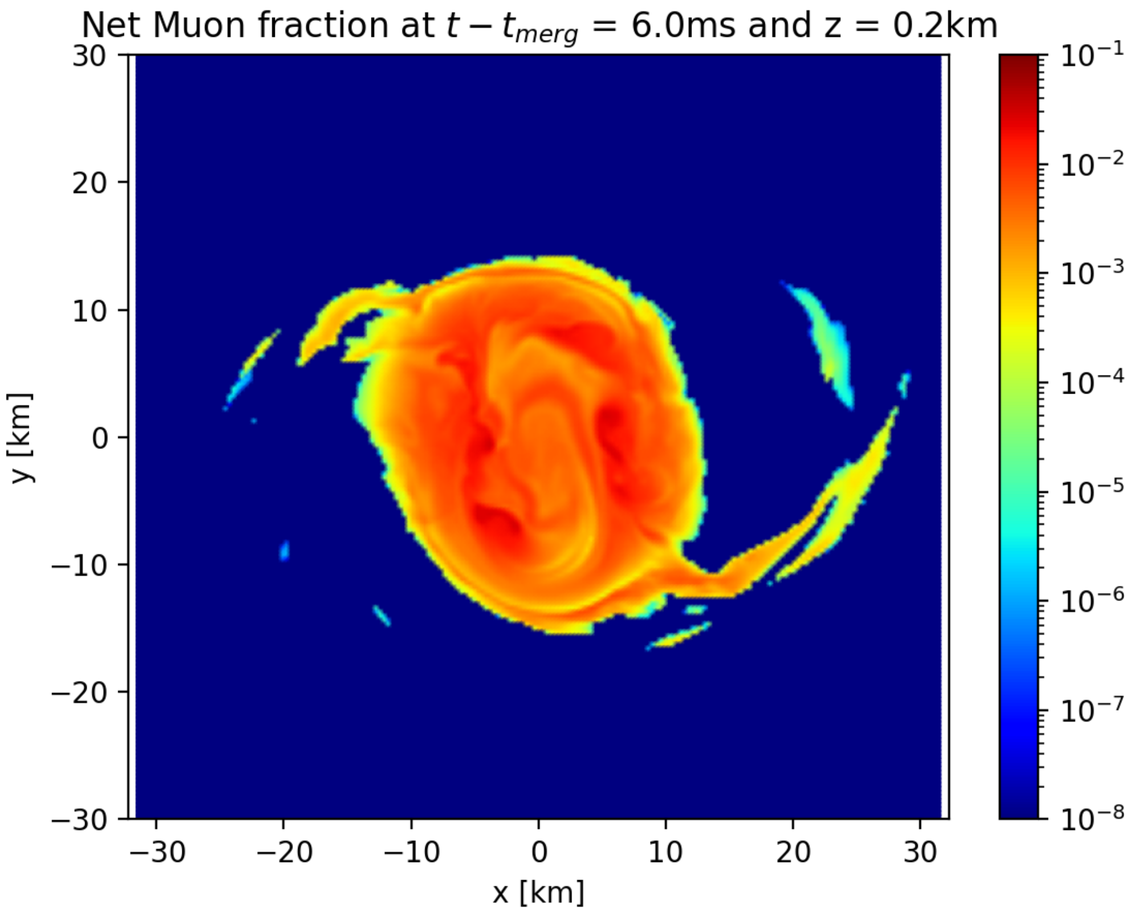


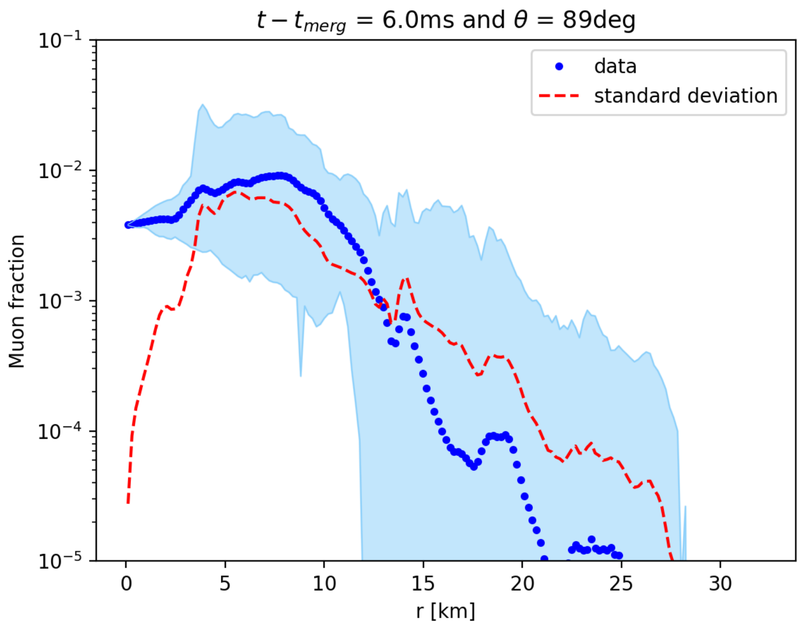


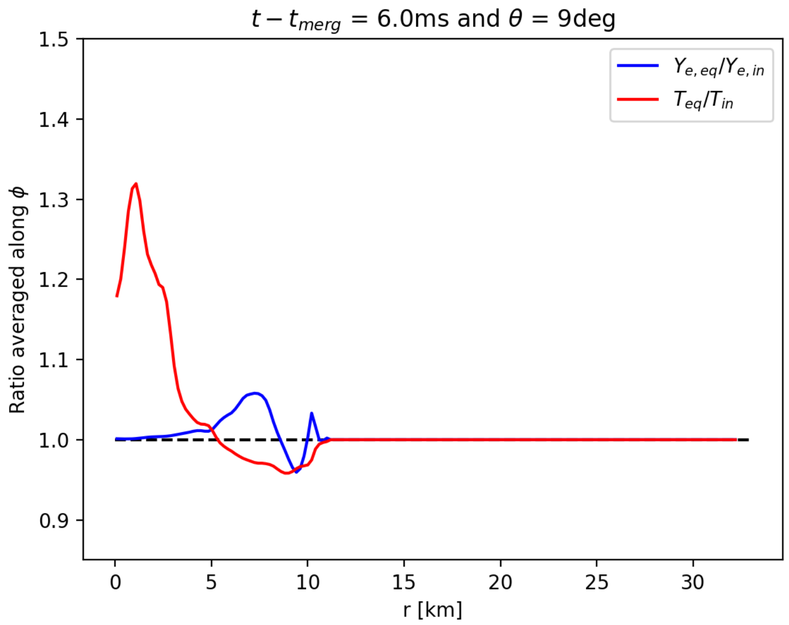


Results

Post-processing: the appearance of muons







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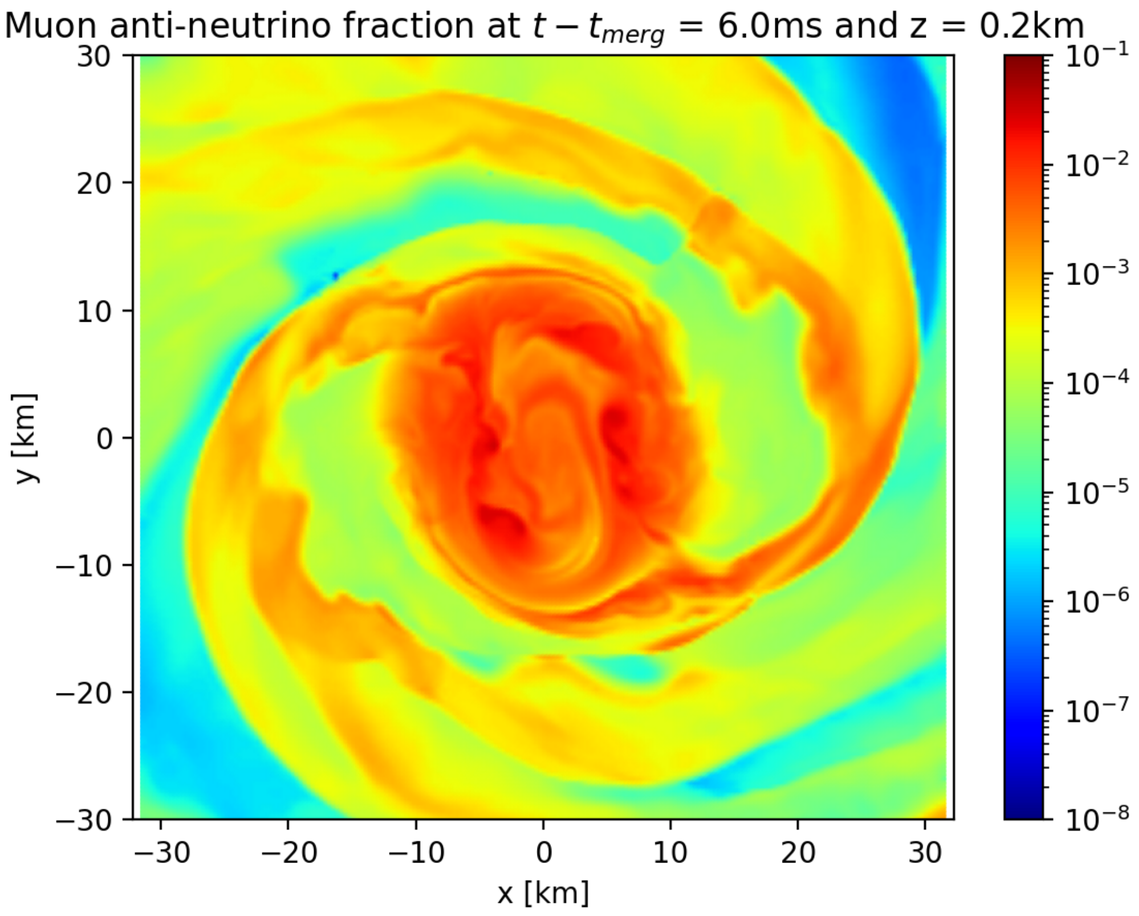
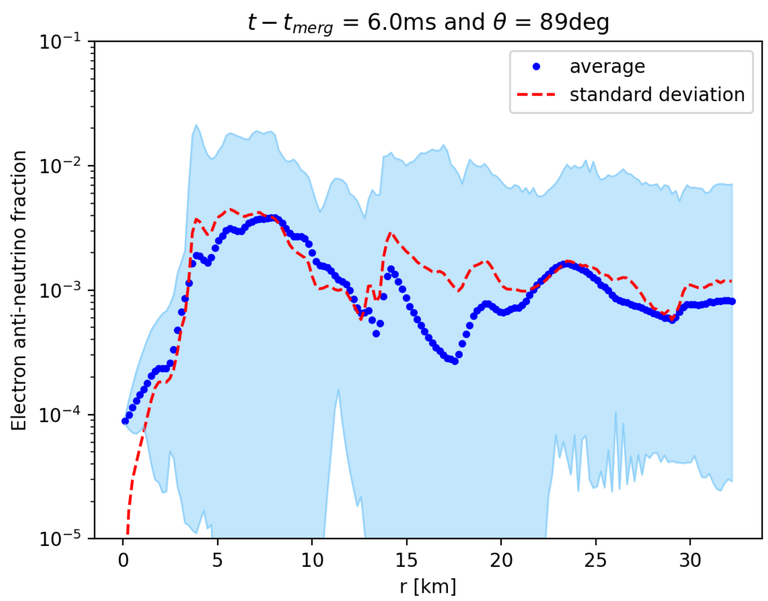
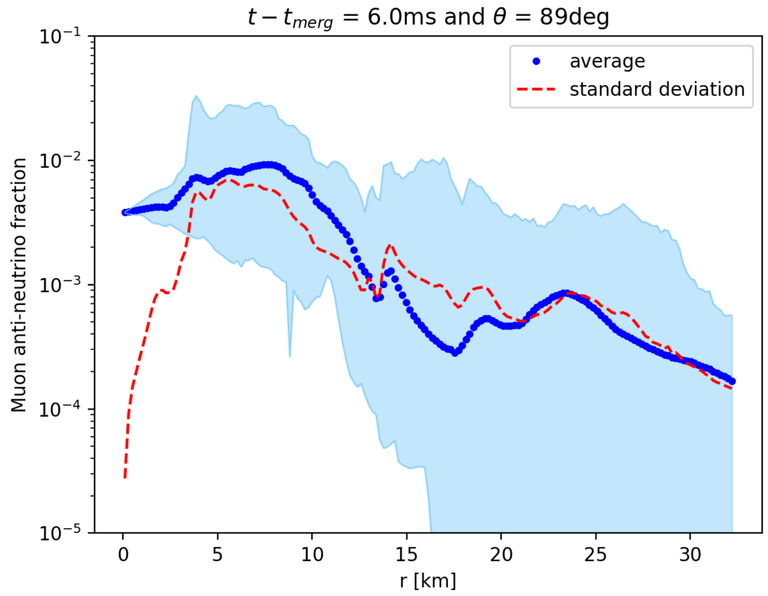
Post-processing: the trapping of neutrinos







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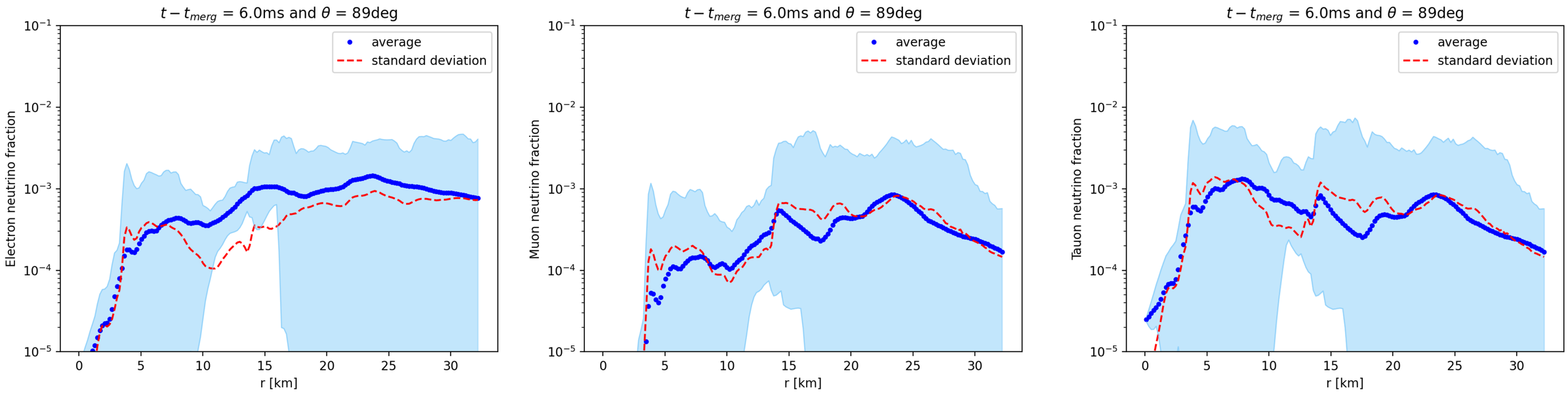


Results

- The fraction of muons and/or trapped neutrinos is $\simeq 10\,\%$ of Y_e . The inclusion of muons and trapped neutrinos will improve state of the art simulations.

- Trapped neutrinos tend to increase Y_e and to soften the EOS → possibly faster collapse of the remnant

Work in Progress

- Check the pressure variation…

- What if we consider $Y_{l,\mu} \neq 0$ in simulation post-processing?

- What if we change the baryonic EOS?

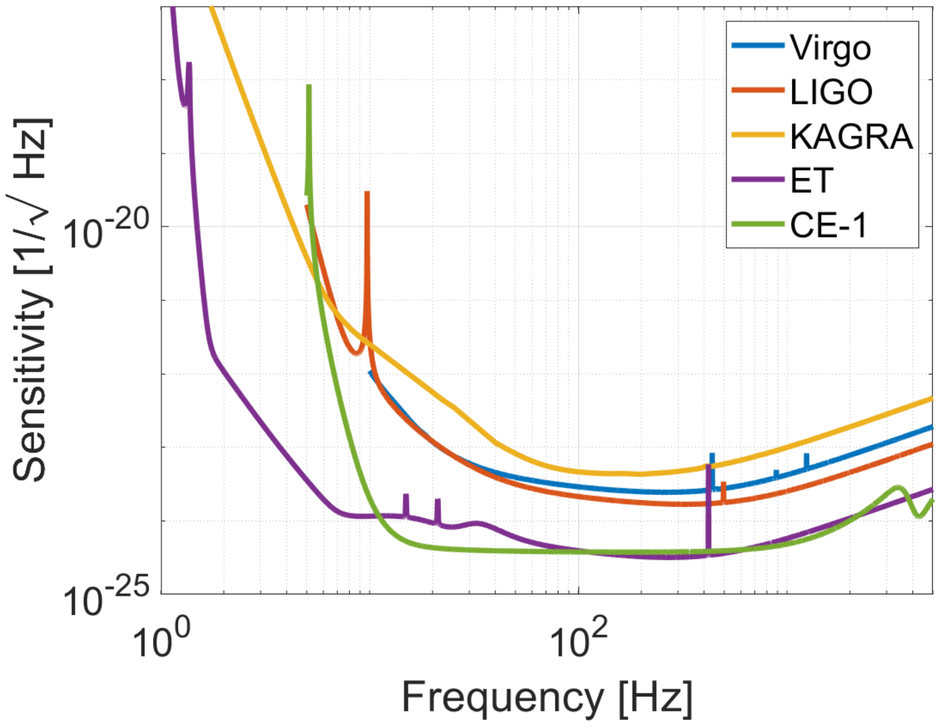
- What if we change the binary mass ratio?

A publication will be finalised soon

Modelling the Kilonovae lightcurves

Motivation

- Next runs of LIGO, Virgo, KAGRA, and LIGO-India will detect more BNS mergers at a larger horizon
- The Einstein Telescope (ET) and Cosmic Explorer will further enlarge the observable horizon
- We will see BNS mergers at non-negligible redshift!
- KN are faint and rapidly evolving: predictions of lightcurves needed for coordinating the joint detection



Credits: Branchesi, Harms

Modelling the Kilonovae lightcurves

Method

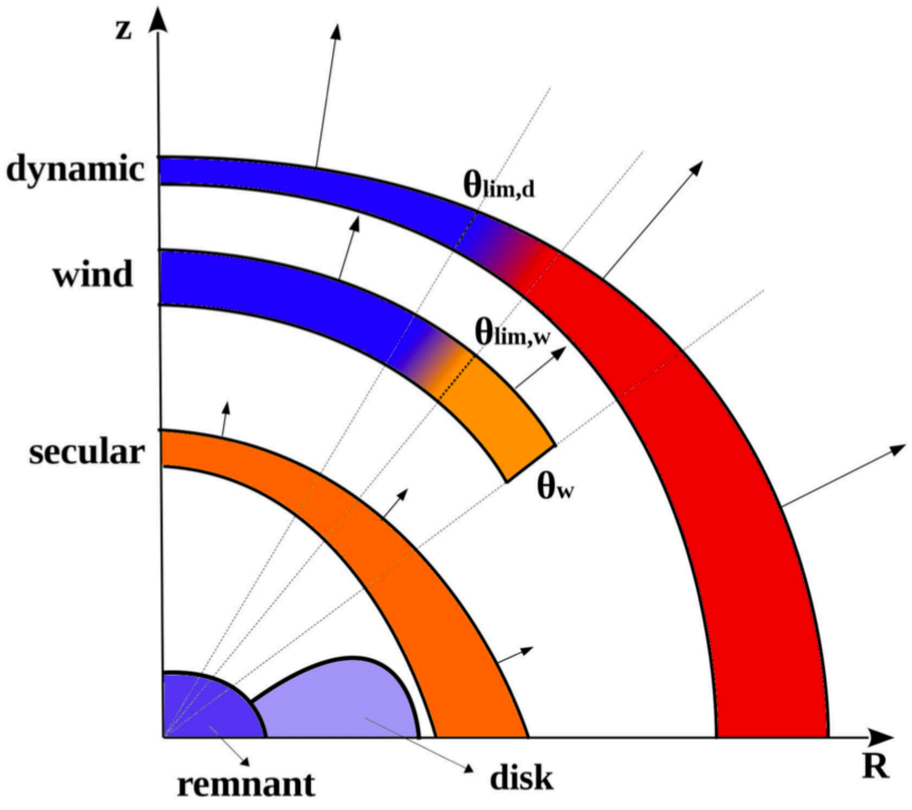
- Starting point: code from A. Perego based on anisotropic three-component semi-analytical model

- We improved the code by adding cosmological and k-correction

$$\nu_{obs} = \frac{\nu_{em}}{1+z} \qquad t_{obs} = (1+z)\ t_{em}$$

$$F_\nu(\nu_{obs}) = (1+z)\frac{L_{\nu_{em}}\left((1+z)\ \nu_{obs}\right)}{4\pi D_L^2}$$

Credits: Perego et al., 2017



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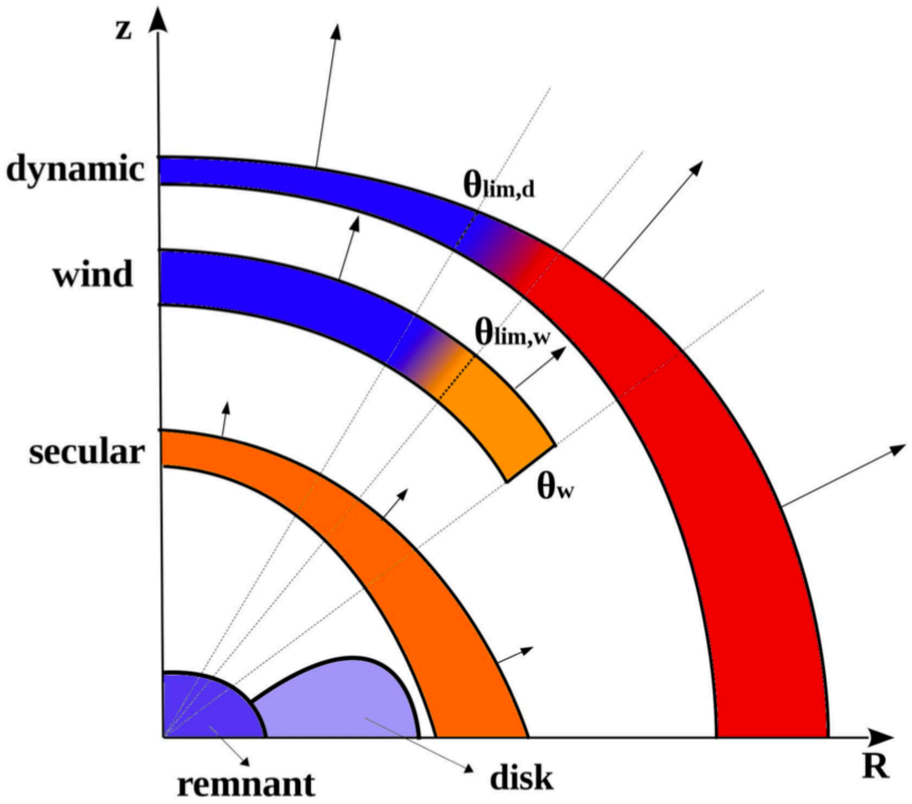


On ArXiv 2021

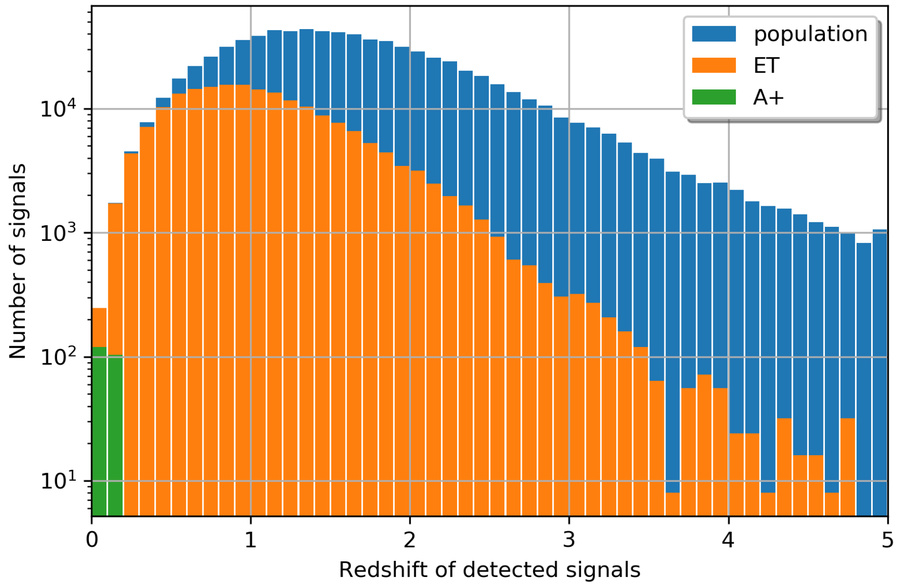
The peculiar short-duration GRB 200826A and its supernova*

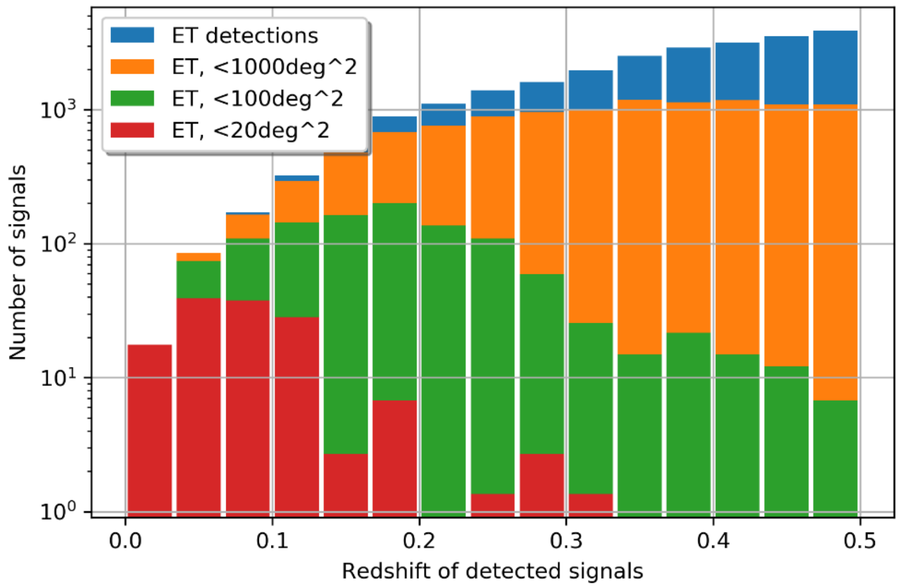
A. Rossi,[1] B. Rothberg,[2,3] E. Palazzi,[1] D. A. Kann,[4] P. D'Avanzo,[5] S. Klose,[6] A. Perego,[7,8] E. Pian,[1] S. Savaglio,[9] G. Stratta,[1] G. Agapito,[10] S. Covino,[5] F. Cusano,[1] V. D'Elia,[11,12] M. De Pasquale,[13] M. Della Valle,[14] C. Guidorzi,[15,16,1] O. Kuhn,[2] L. Izzo,[17] E. Loffredo,[18,19] N. Masetti,[1,20] A. Melandri,[5] A. Nicuesa Guelbenzu,[6] D. Paris,[12] C. Plantet,[10] F. Rossi,[10] R. Salvaterra,[21] and C. Veillet[2]

Predicting the KN joint detections

Method

- Given a realistic BNS population, compute the number of detections and parameter estimation of ET (code by J. Harms et al.)
- Select detections with sky-localisation < 20 deg^2 (detected 150 sources up to z=0.3)
- Considering pointed observations (600 s) with Vera Rubin Observatory: detection efficiency larger than 99% at z=0.3
- Compute synthetic KN lightcurves (assume they behave at the source as AT2017gfo)



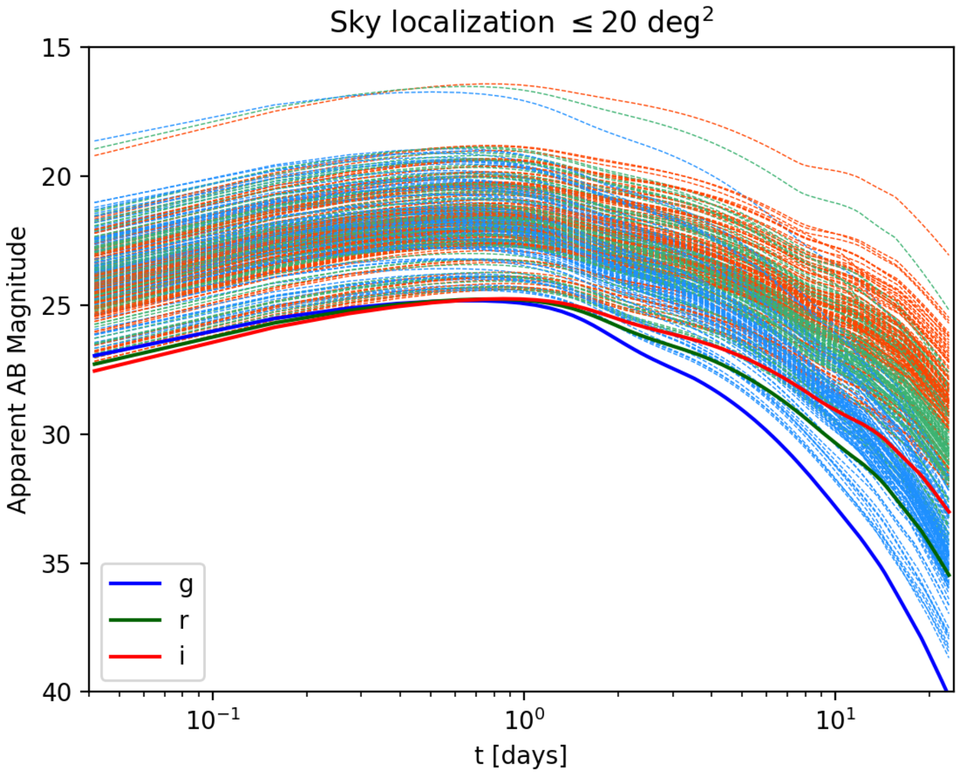


Credits: M. Branchesi, J. Harms

Predicting the KN joint detections

Results and Outlook

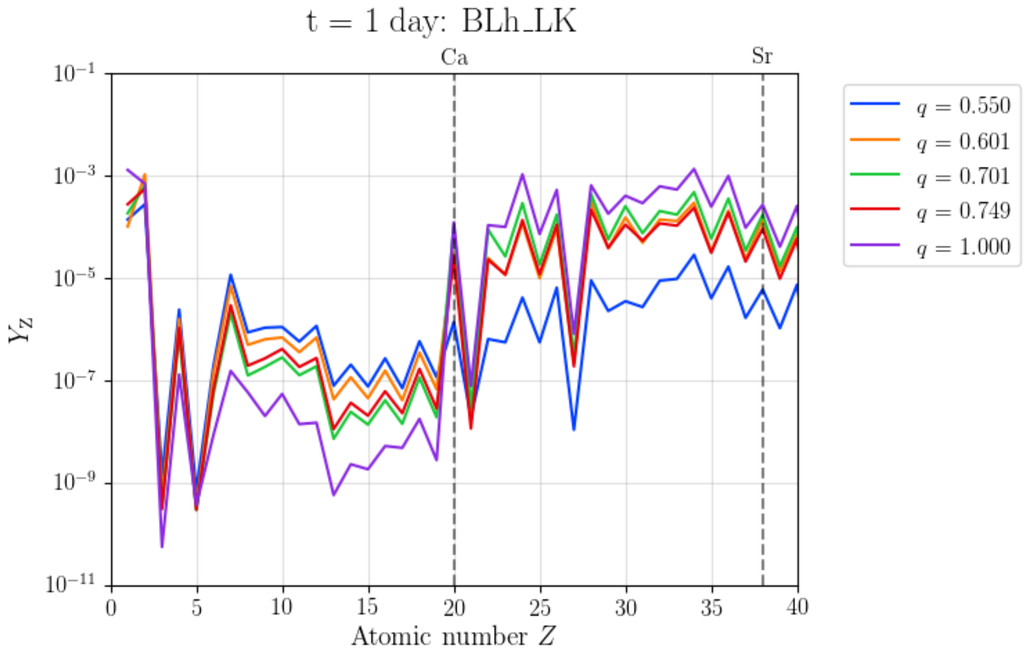
- Using the expected fluxes, we evaluate the number of joint detections ET/VRO
- Joint detections ET + VRO: 60 per year
- In a few years, with this joint detection number and parameter estimations it will be possible to measure the Hubble constant
- Next step: use fitting formulas to relate the lightcurve to source mass and the EOS (see e.g. Nedora et al, 2021)

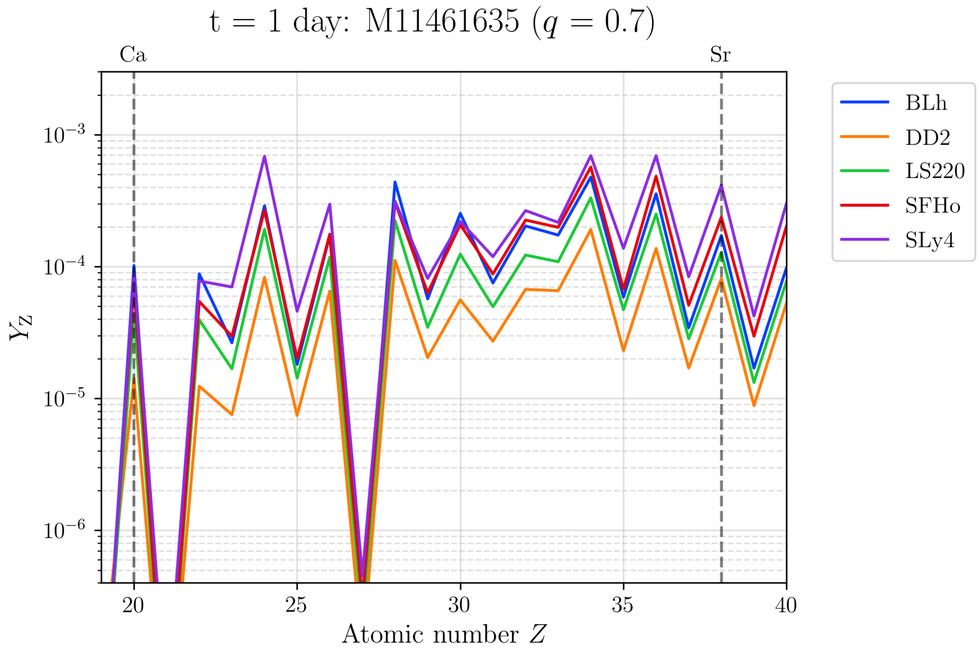


Modelling the KN Spectra

Motivation

- Synthetic spectra are pivotal to interpret the observed ones
- KN spectra are angular dependent, but to date synthetic KN spectra assume isotropy
- The nucleosynthesis of light elements depends strongly on the binary mass ratio and the EOS. Then, KN spectra can provide constraints on the EOS!





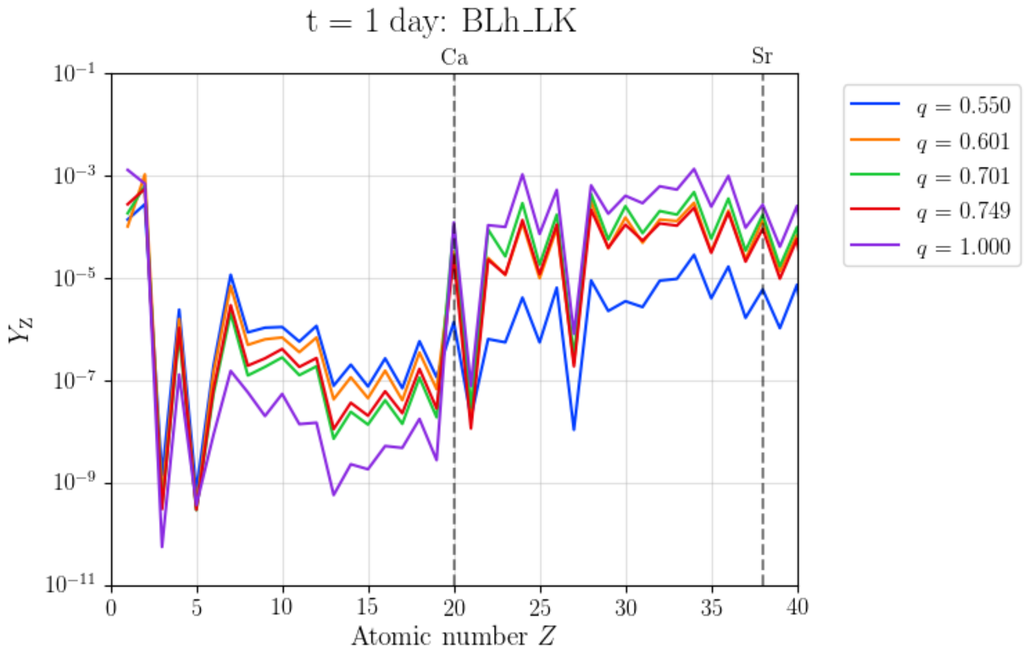
Credits: Leonardo Chiesa, Master Thesis, 2021

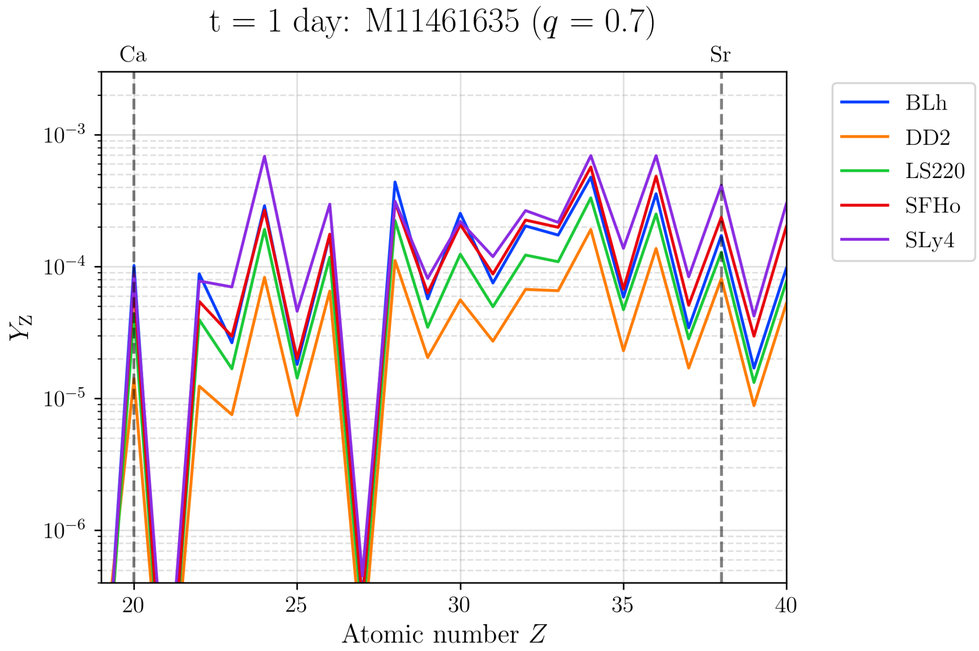
Modelling the KN Spectra

Motivation

The aim of our work is to provide realistic angle dependent synthetic spectra

- Goal 1: identification of light elements production in BNS mergers
- Goal 2: constraining the EOS of neutron stars ⟶ constraining the microphysics!





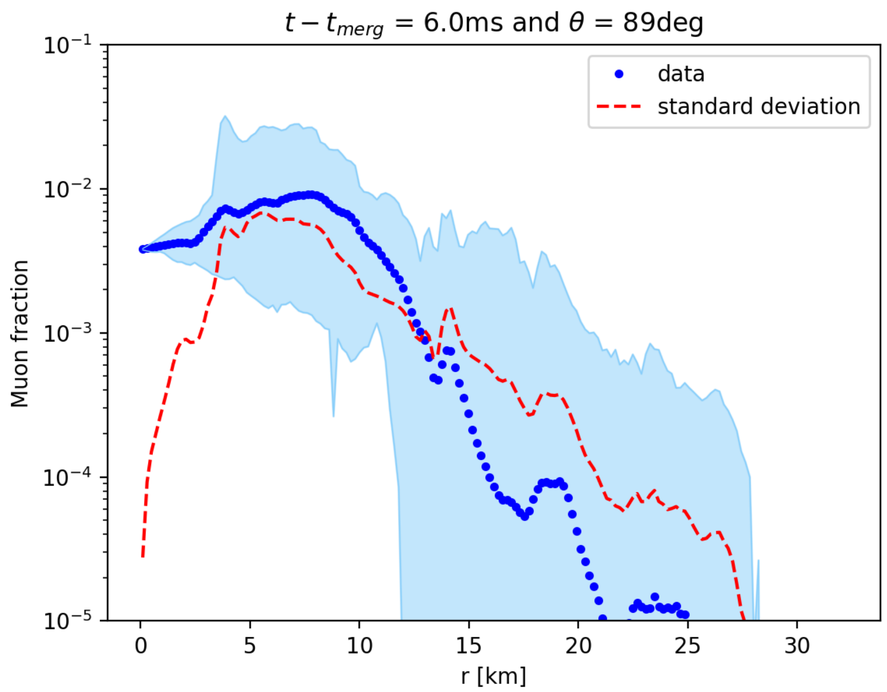
Credits: Leonardo Chiesa, Master Thesis, 2021

Modelling the KN Spectra

Method

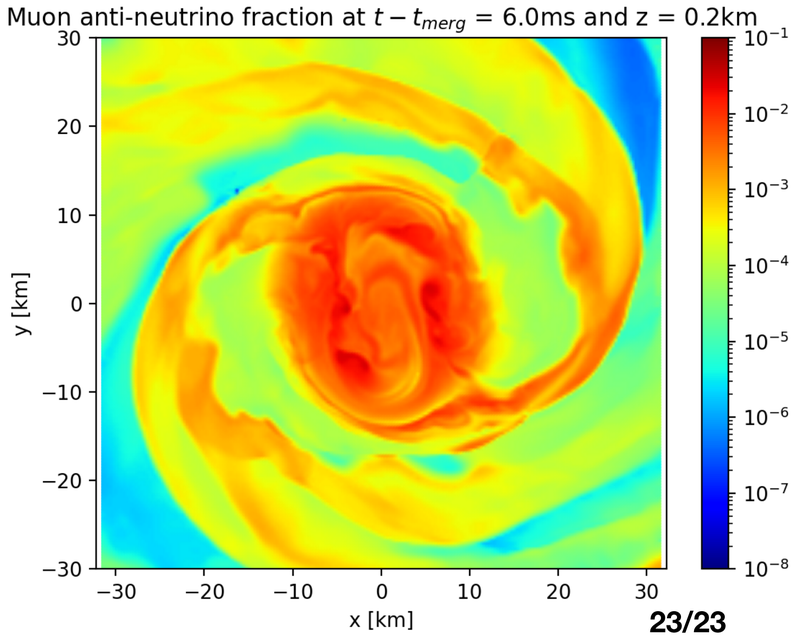
- Starting point: the outcome of numerical relativity simulation of BNS mergers and nucleosynthesis calculation
- Modelling the KN spectra using TARDIS
- Improving the modelling of TARDIS by implementing angle dependence
- Look for features depending on light elements and/or the EOS
- Compare synthetic spectra with data of GW170817 and future KN observations

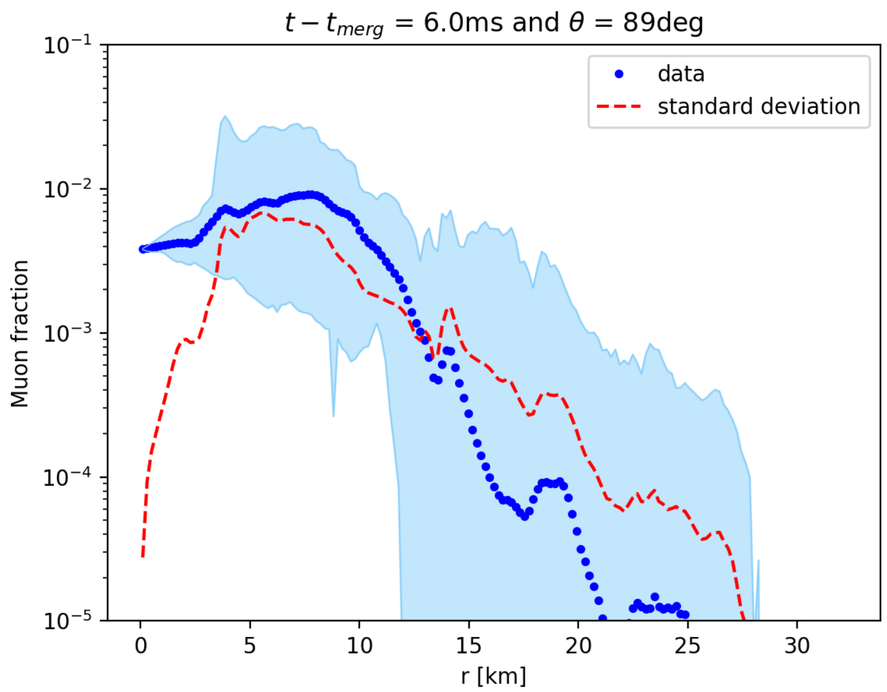
MORE NEWS COMING SOON



Summary

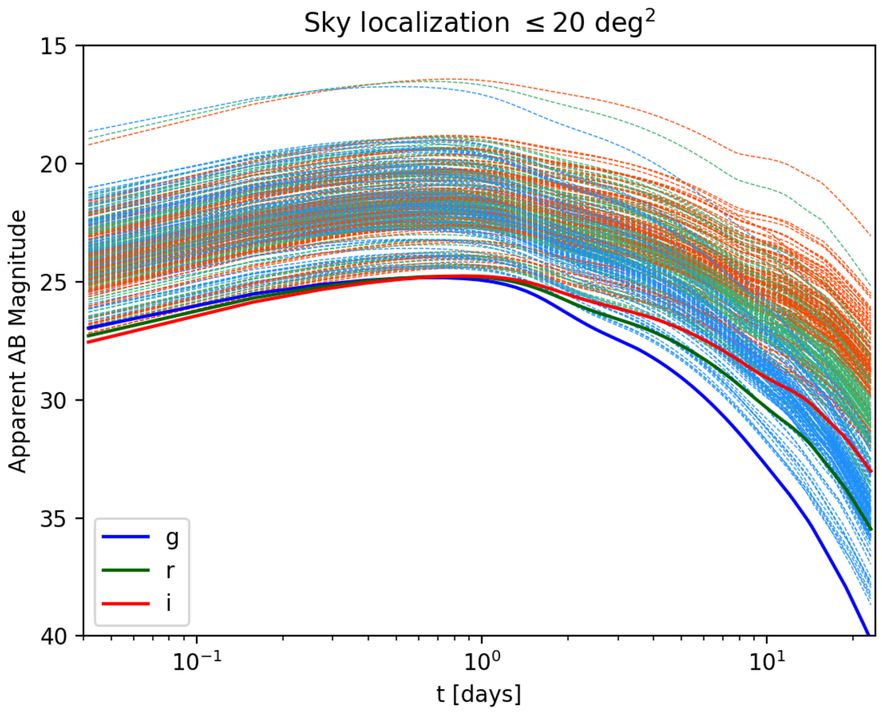
- Muons creation & neutrino trapping
- Relative abundance of (Anti)Neutrinos
- Softening of the EOS





- Modelling the KN lightcurves
- Joint detections ET+VRO
- Coordinating the follow-up

Summary



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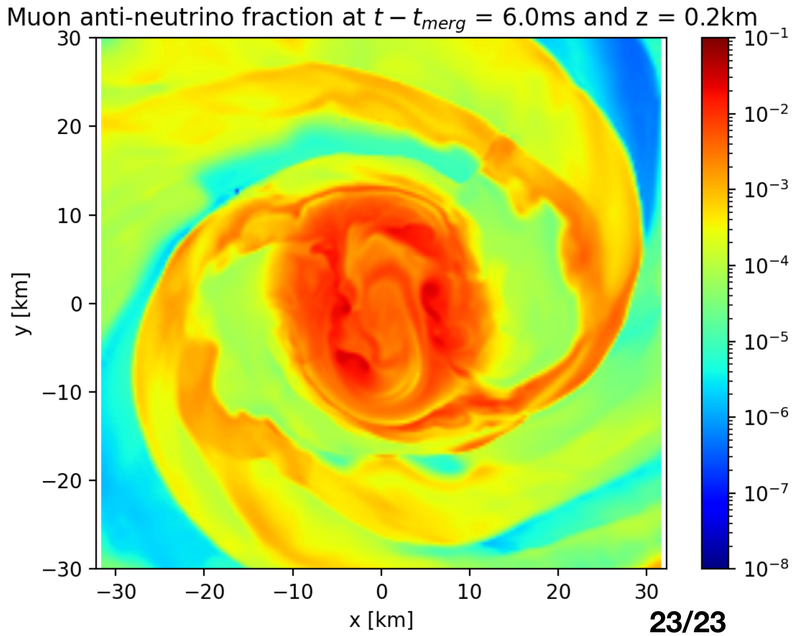

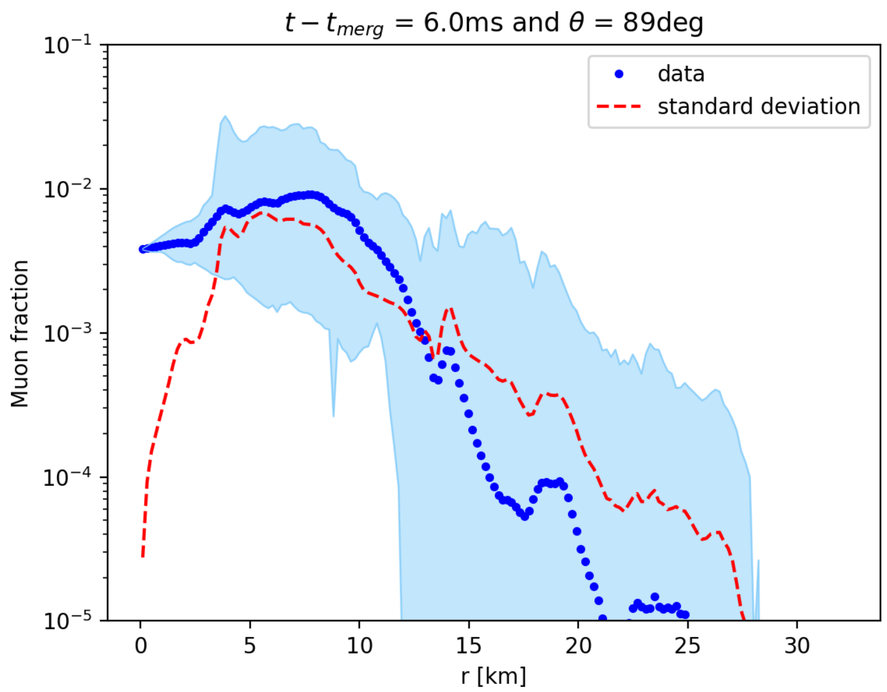

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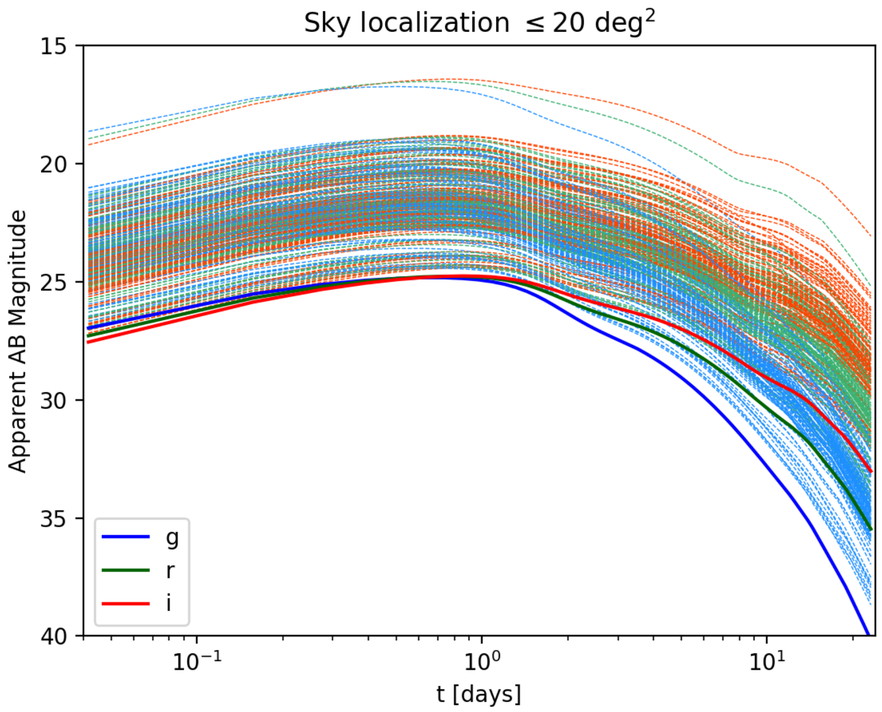

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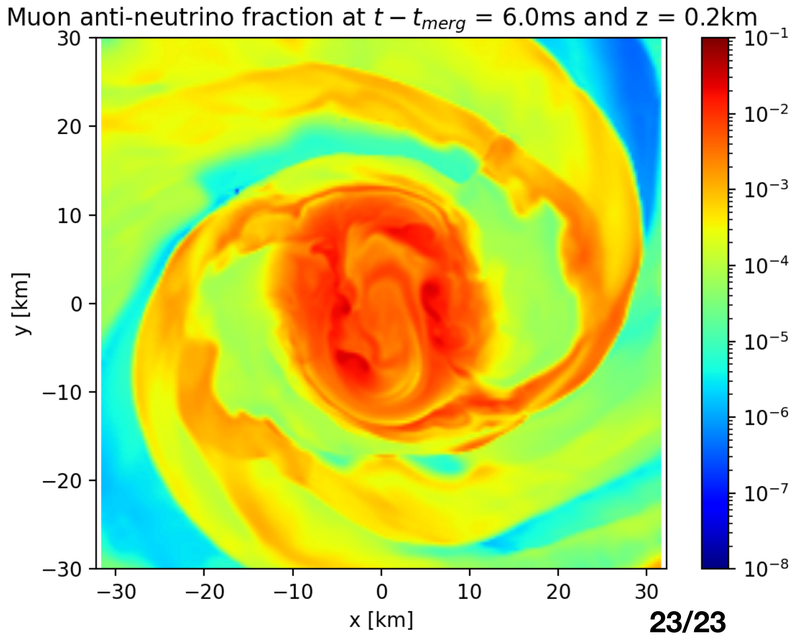
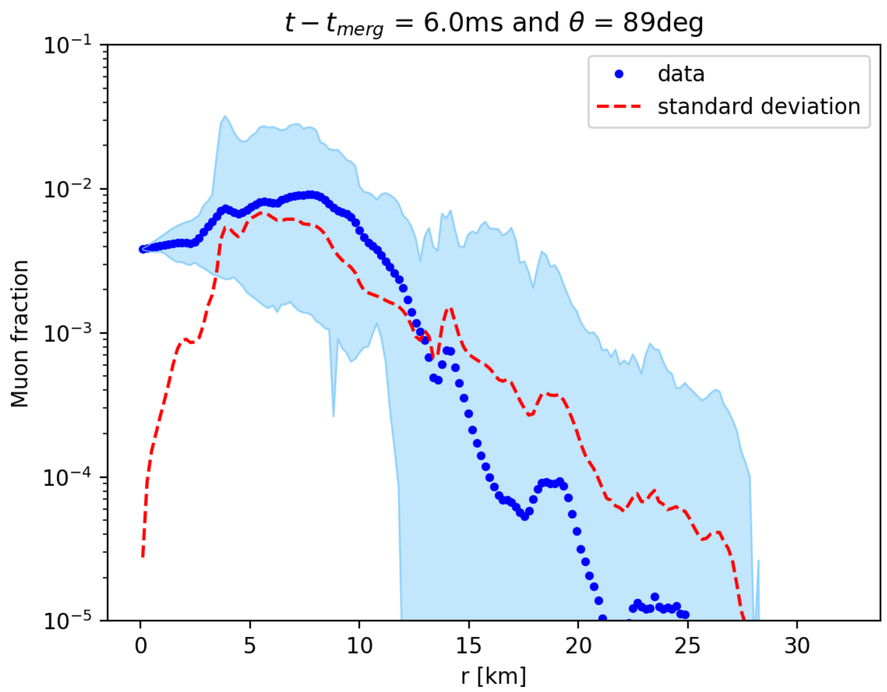


- Synthetic angular dependent KN spectra
- Identification of light elements
- Constraining the EOS

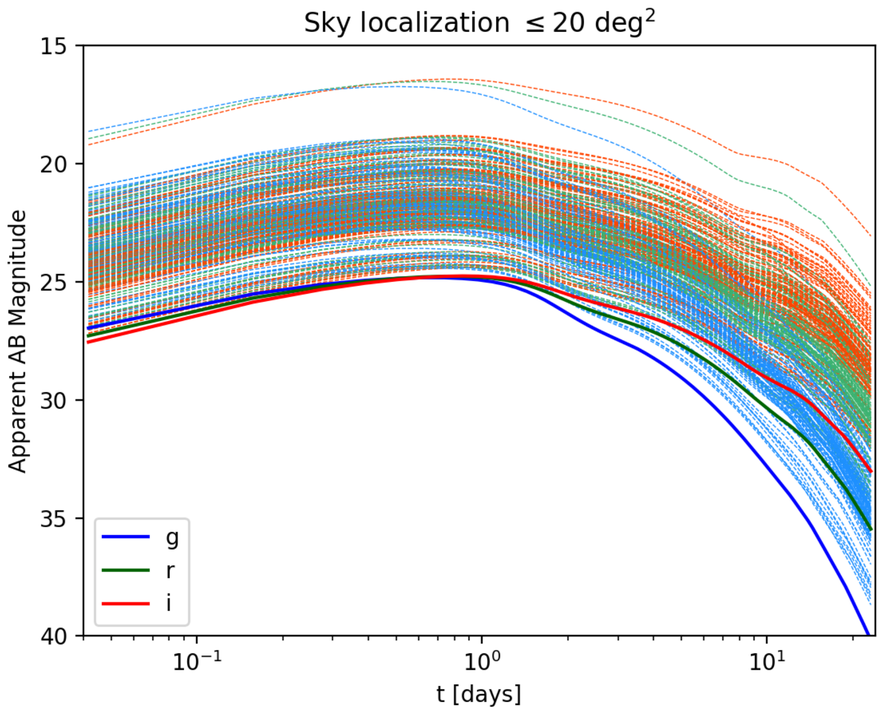
TARDIS !

Exploring supernovae made easy

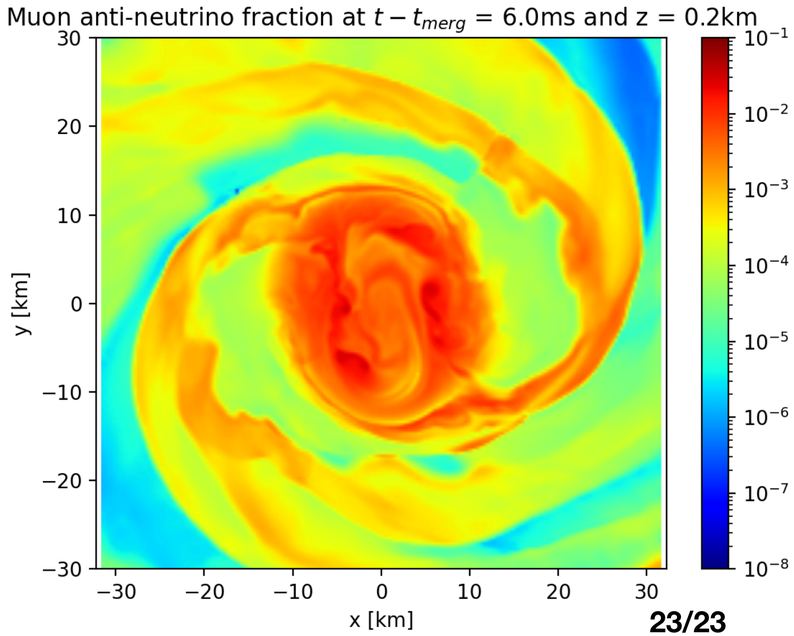


- Modelling the KN lightcurves
- Joint detections ET+VRO
- Coordinating the follow-up

Thank You!



- Muons creation & neutrino trapping
- Relative abundance of (Anti)Neutrinos
- Softening of the EOS



- Synthetic angular dependent KN spectra
- Identification of light elements
- Constraining the EOS

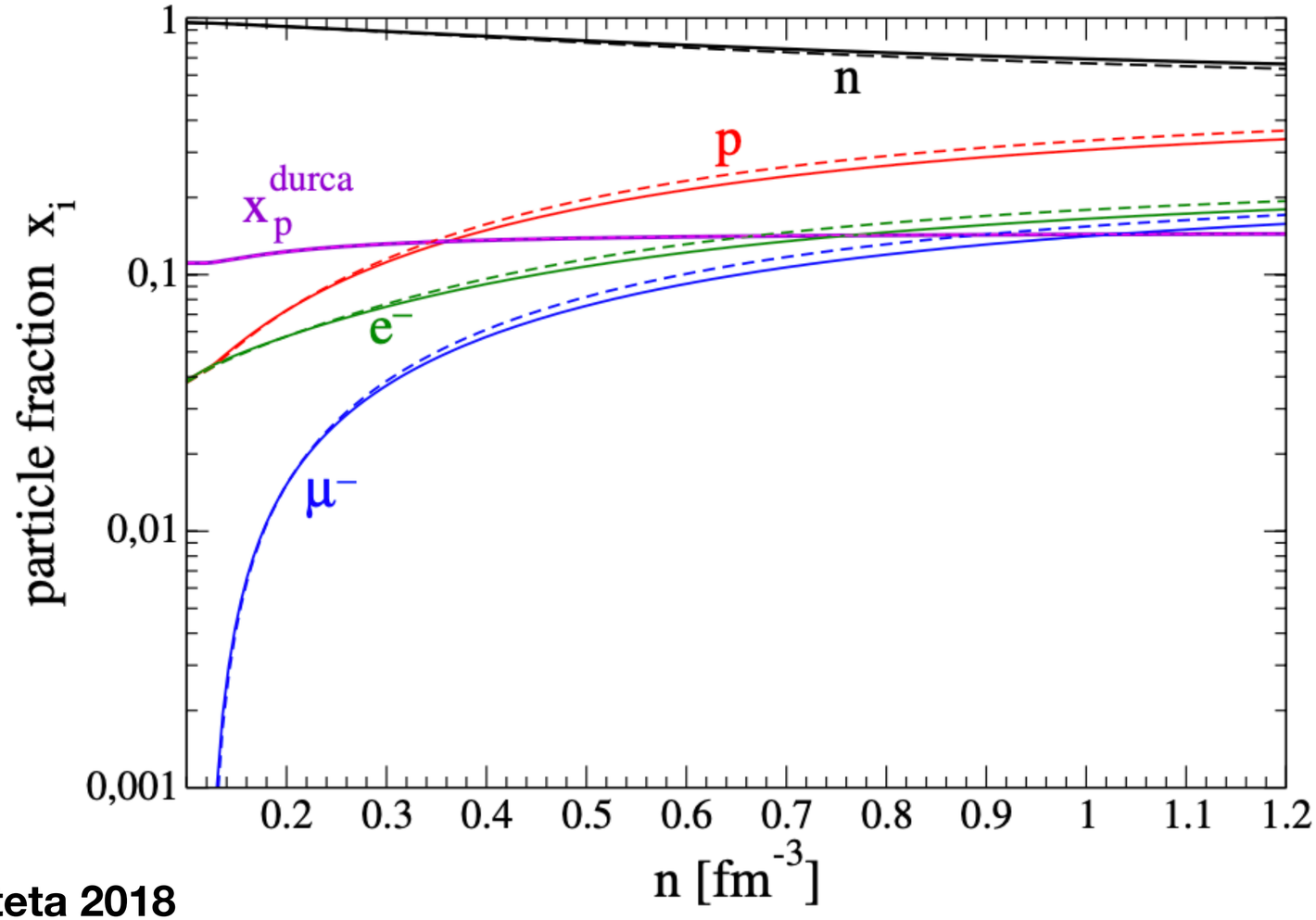
TARDIS !

Exploring supernovae made easy

BACK UP

Improving the microphysics modelling

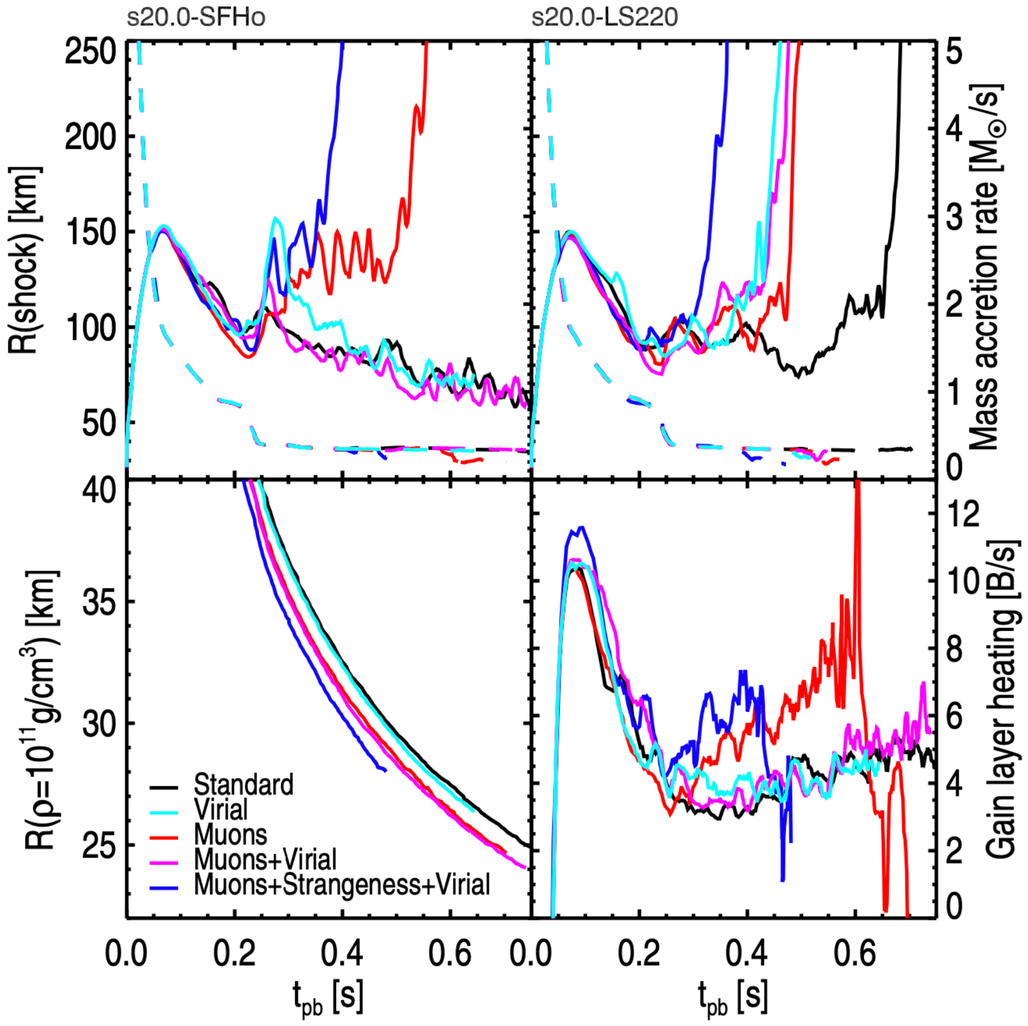
Cold Equilibrium in Neutron Stars



Credits: Bombaci, Logoteta 2018

Improving the microphysics modelling

Muons facilitate SN explosion



Credits: Bolligs et al, 2017

Method

The EOS of electrons and muons - Important Parameters

Density of Baryons: $\rho = m_u \frac{N_b}{V}$

Relativity parameter: $\theta_p = \frac{k_B T}{m_p c^2}$

Net fraction of particles: $Y_p = \frac{N_p - N_{\bar{p}}}{N_b}$

Degeneracy parameter: $\eta_p = \frac{(\mu_p - m_p c^2)}{k_B T}$

Method

The EOS of electrons and muons - Generalised Fermi Functions

- All thermodynamic functions are linear combinations of the GFFs:

$$F_k(\eta, \theta) = \int_0^{+\infty} \frac{x^k \sqrt{1 + \theta x/2}\ dx}{e^{x-\eta} + 1}$$

- Example:

$$Y_p(n_b, \eta_p, \theta_p) = \frac{K_p \theta_p^{3/2}}{n_b} \left[F_{1/2}(\eta_p, \theta_p) - F_{1/2}(\eta_{\bar{p}}, \theta_p) + \theta_p F_{3/2}(\eta_p, \theta_p) - \theta_p F_{3/2}(\eta_{\bar{p}}, \theta_p) \right]$$

- Computational method: split the GFF into 4 integrals, then use Gauss-Lagendre and Gauss-Laguerre quadrature methods

Method

Modelling the microphysics

$\gamma + \gamma \longleftrightarrow \mu^+ + \mu^-$	$e^+ + e^- \longleftrightarrow \mu^+ + \mu^-$
$\gamma + \gamma \longleftrightarrow e^+ + e^-$	$e^+ + e^- \longleftrightarrow \nu_x + \bar{\nu}_x$
$\gamma + \gamma \longleftrightarrow \nu_x + \bar{\nu}_x$	$\nu_x + \mu^\pm \longrightarrow \nu_x + \mu^\pm$
$\nu_\mu + e^- \longleftrightarrow \nu_e + \mu^-$	$\bar{\nu}_\mu + p \longleftrightarrow n + \mu^+$
$\nu_\mu + \bar{\nu}_e + e^- \longleftrightarrow \mu^-$	$\bar{\nu}_e + e^- \longleftrightarrow \bar{\nu}_\mu + \mu^-$
$\nu_\mu + n \longleftrightarrow p + \mu^-$	$\nu_e + n \longleftrightarrow p + e^-$
$\bar{\nu}_e + p \longleftrightarrow n + e^+$	$\bar{\nu}_\mu + e^+ \longleftrightarrow \bar{\nu}_e + \mu^+$
$\bar{\nu}_\mu + \nu_e + e^+ \longleftrightarrow \mu^+$	$\nu_e + e^+ \longleftrightarrow \nu_\mu + \mu^+$

- We assume thermal and weak equilibrium
- Under these assumptions the relevant variables are n_b, T, Y_e and Y_μ

Method

The lepton fractions

- Consider a fluid element in thermal and weak equilibrium at high enough density

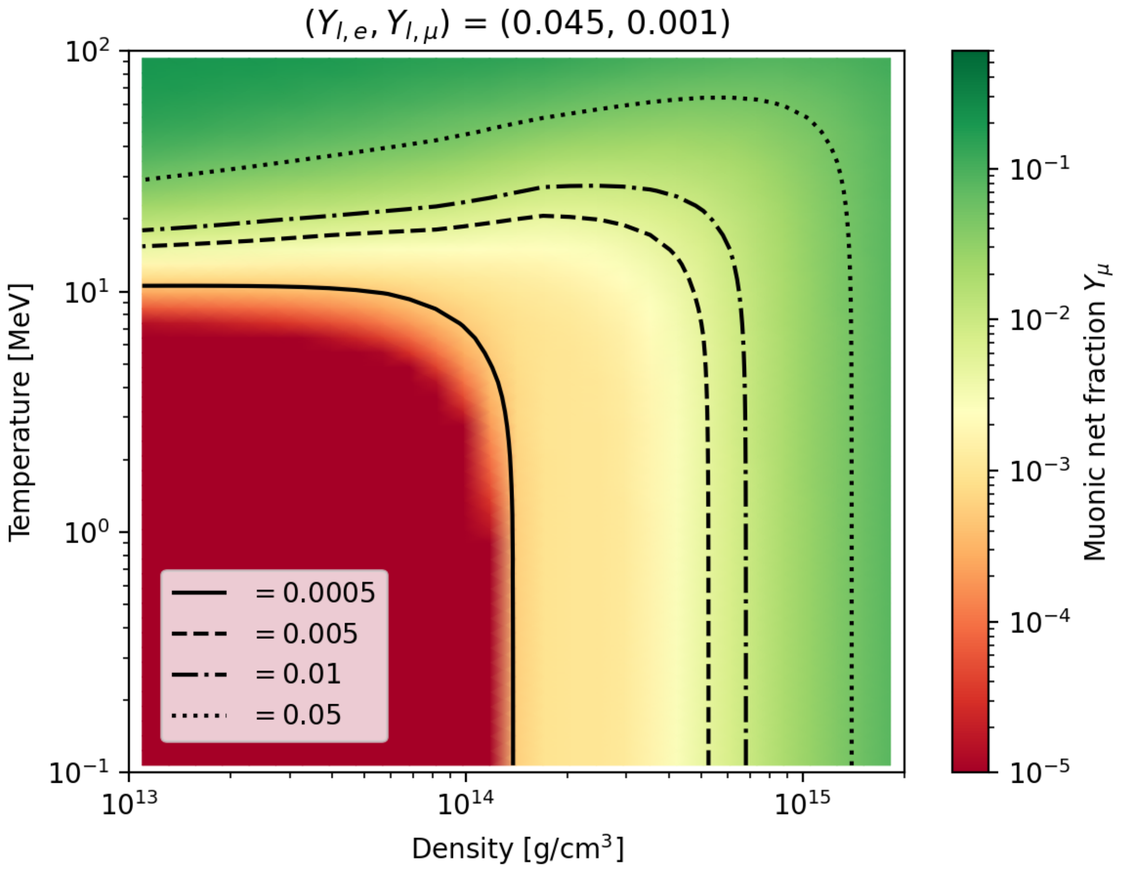
- Neutrinos are trapped, and electron lepton number $Y_{l,e}$ and muon lepton number $Y_{l,\mu}$ are conserved

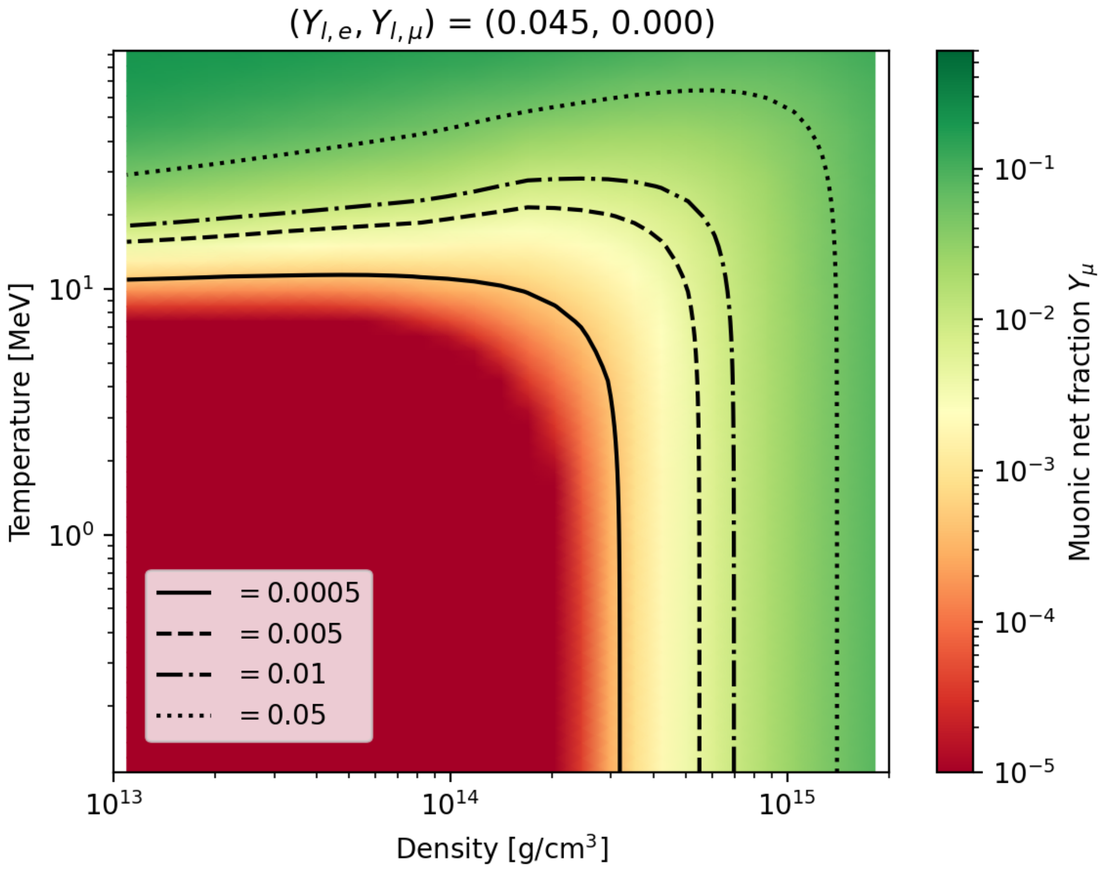
$$\begin{cases} Y_{l,e} = Y_e + Y_{\nu_e}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_e}(n_b, T, Y_e, Y_\mu) \\ Y_{l,\mu} = Y_\mu + Y_{\nu_\mu}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_\mu}(n_b, T, Y_e, Y_\mu) \end{cases}$$

- Equivalent set of variables $(Y_e, Y_\mu) \longleftrightarrow (Y_{l,e}, Y_{l,\mu})$

Results

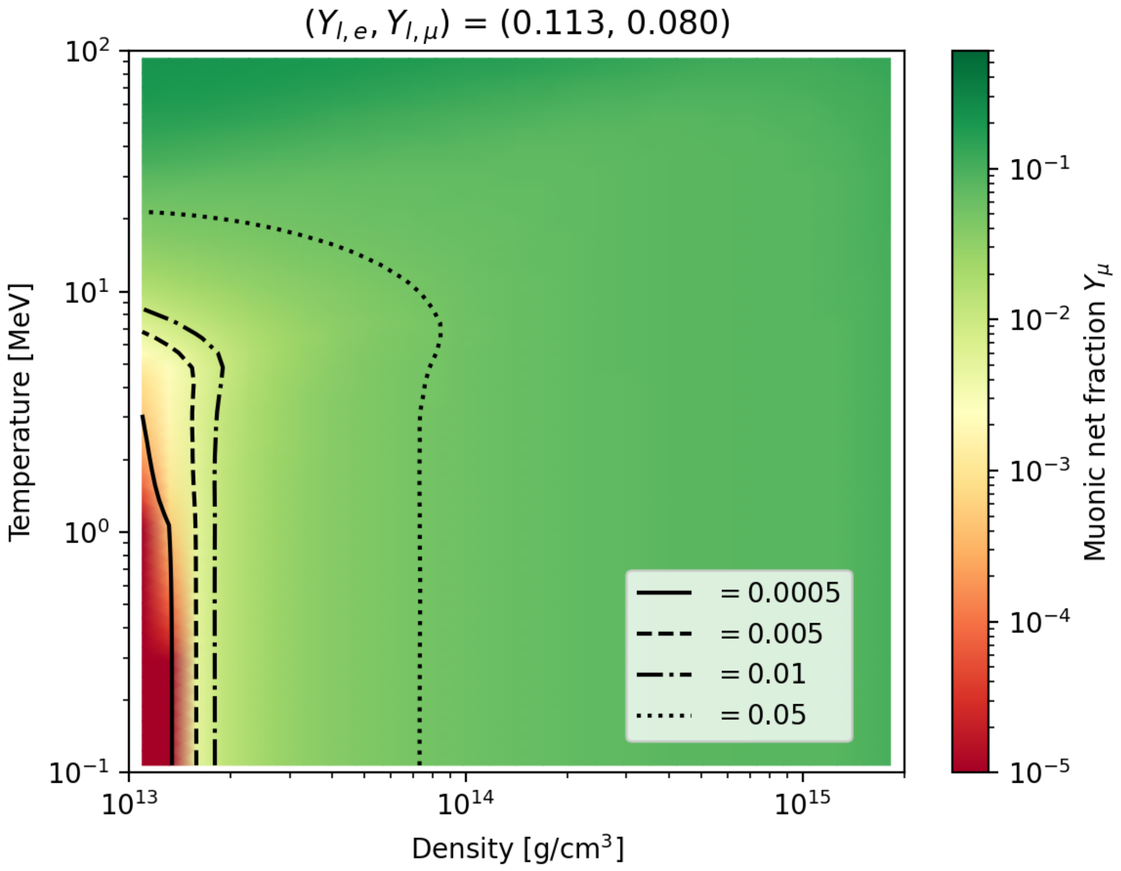
The density-temperature plane - Muons

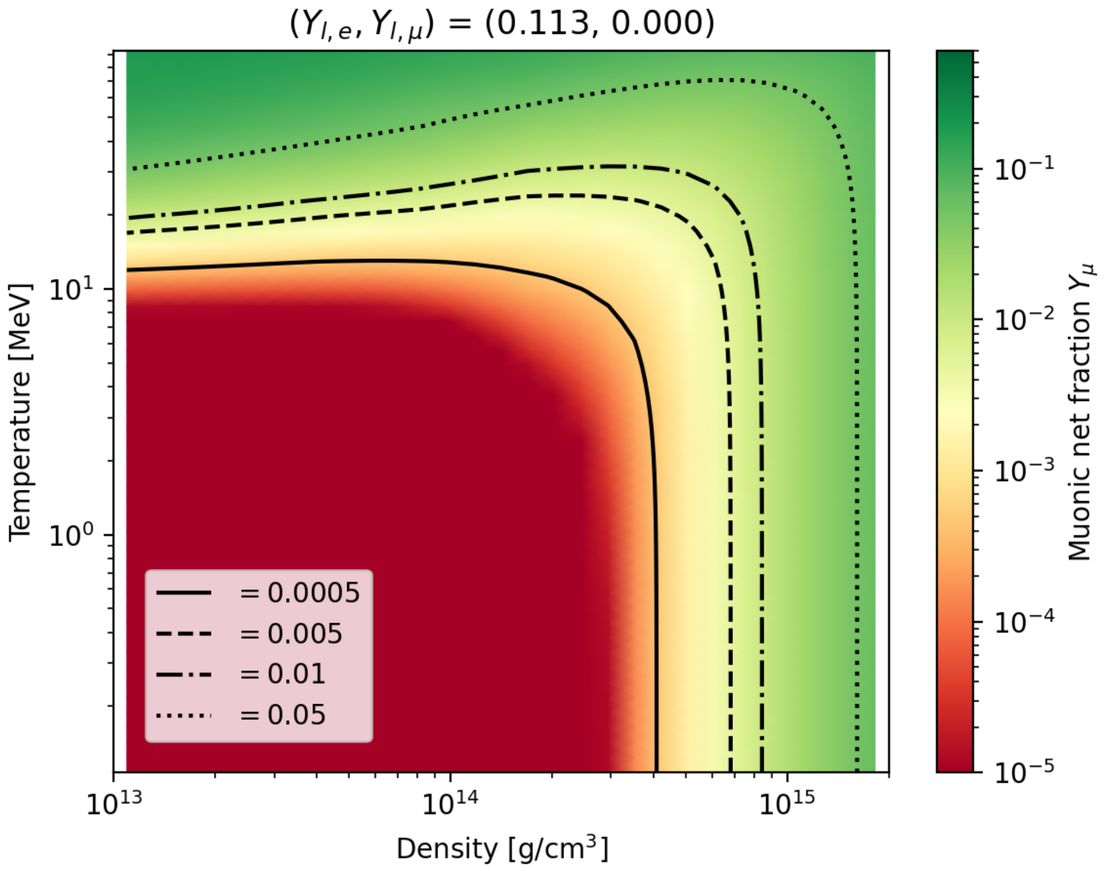




Results

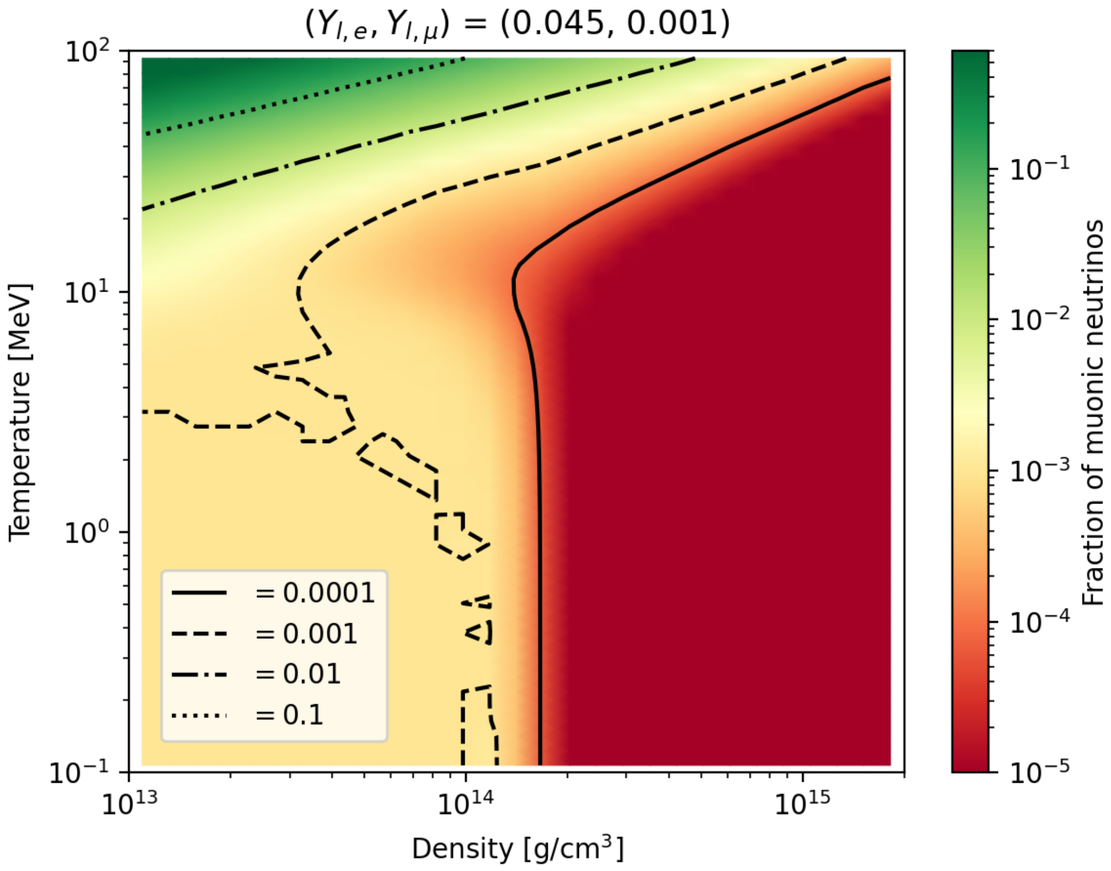
The density-temperature plane - Muons

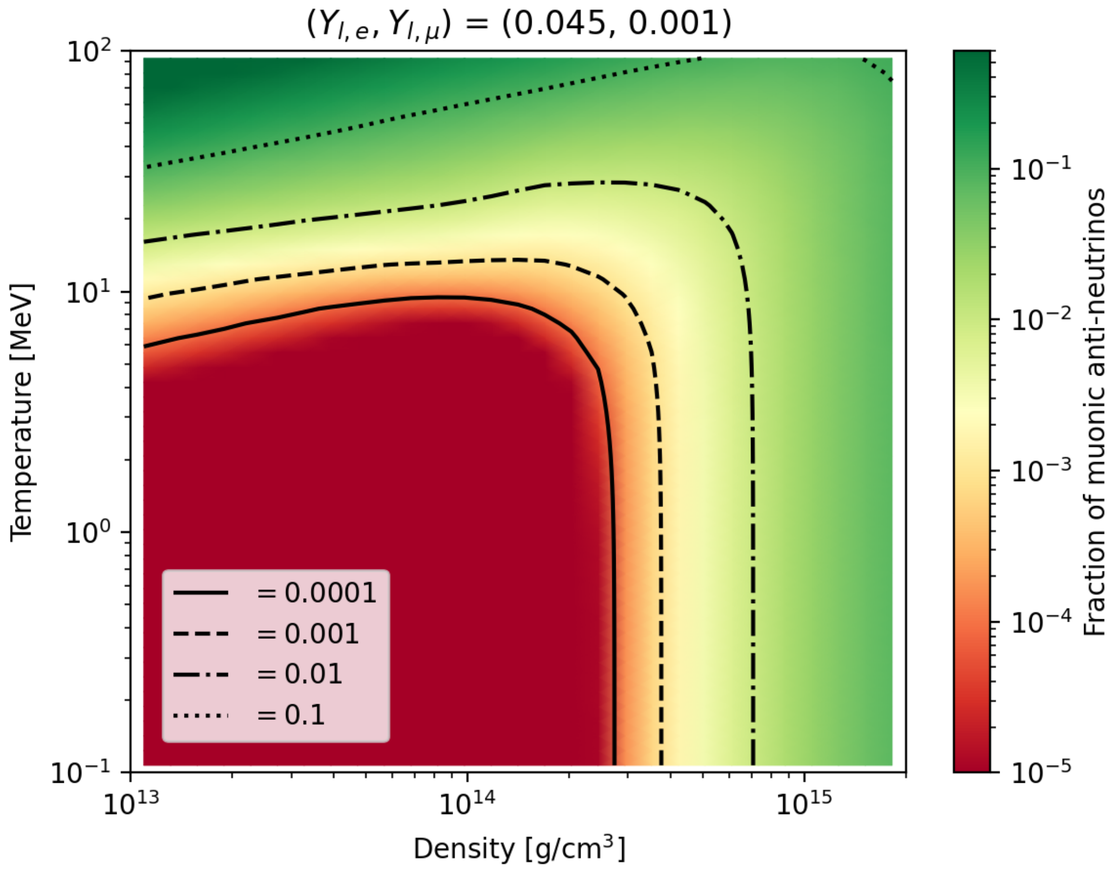




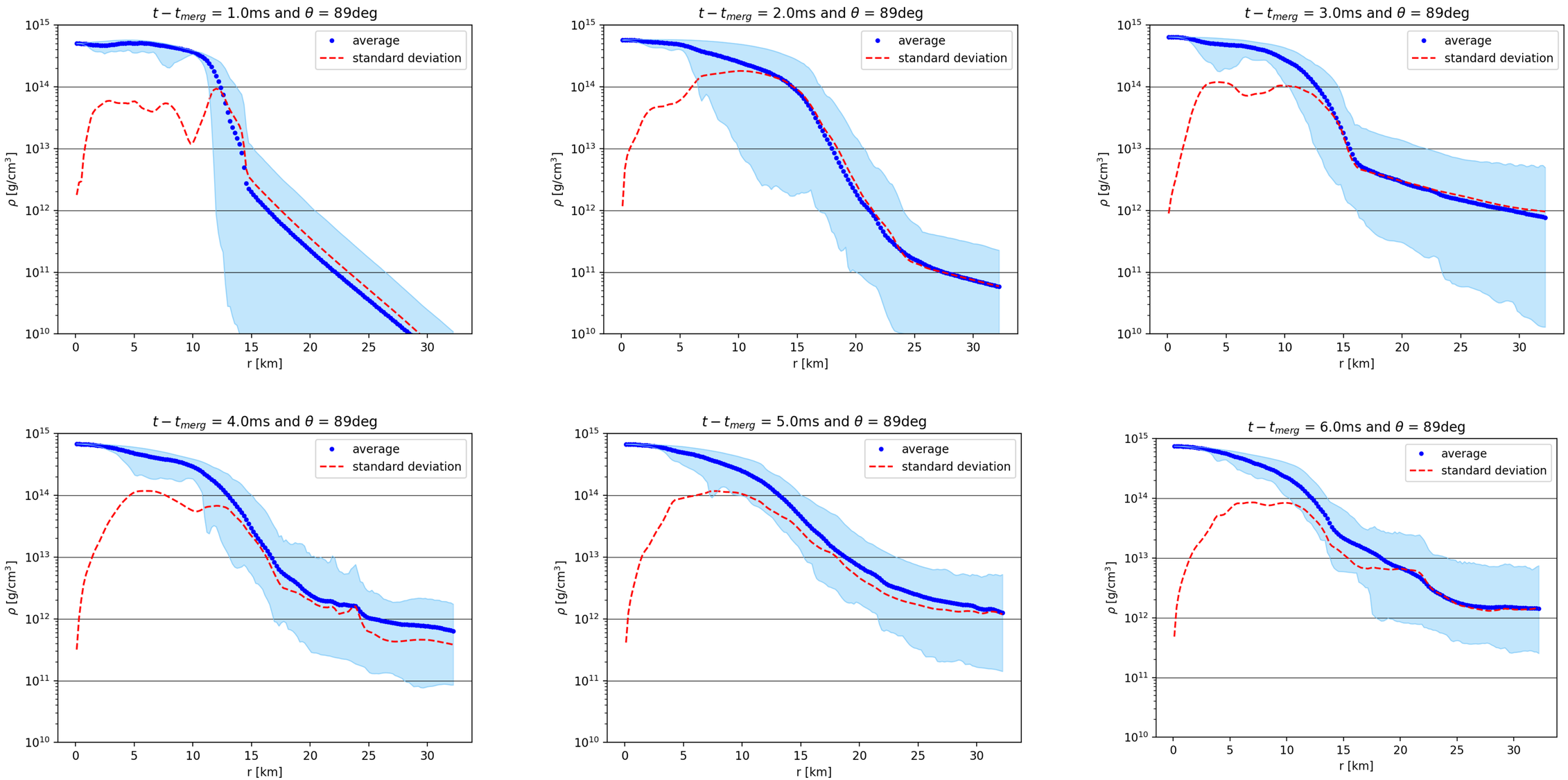
Results

The density-temperature plane - Neutrinos

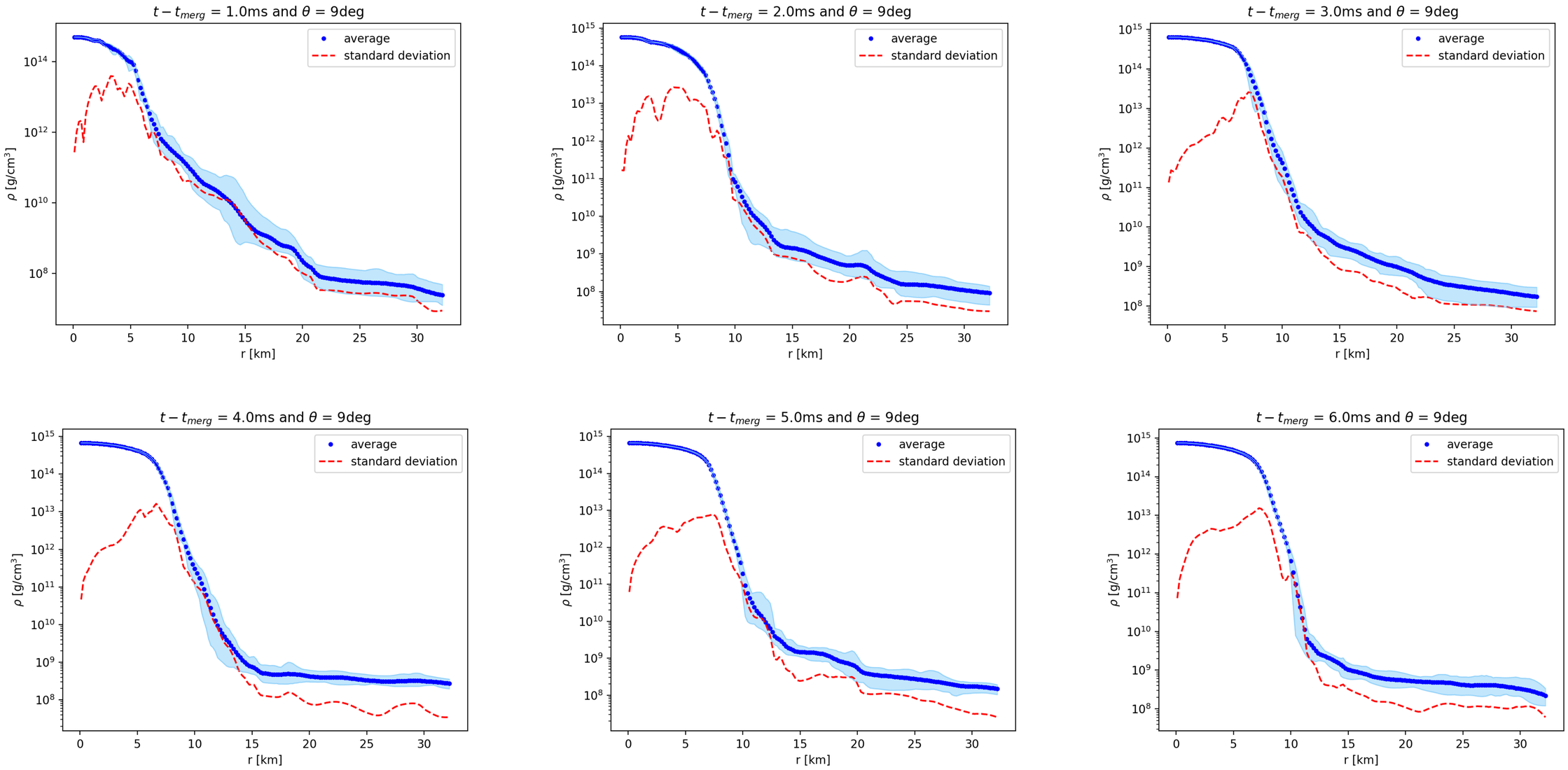




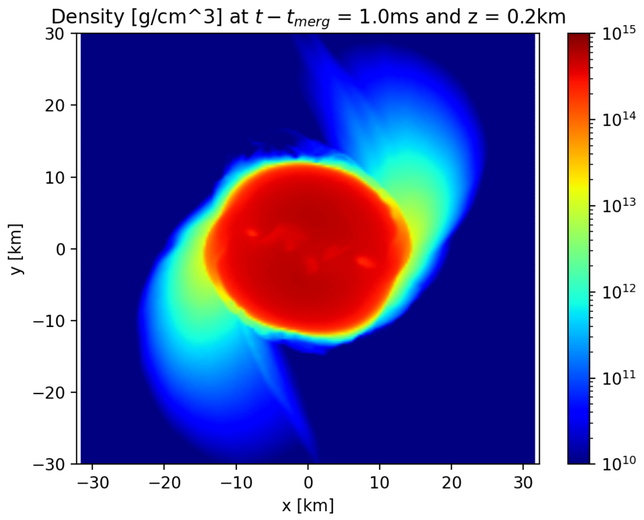
Density evolution - Equator

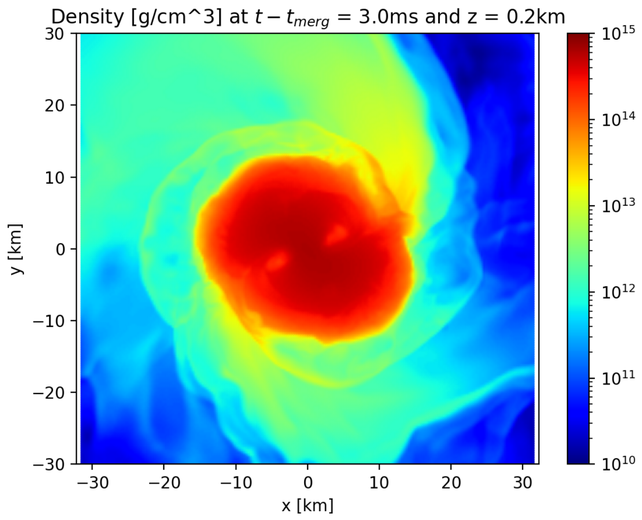


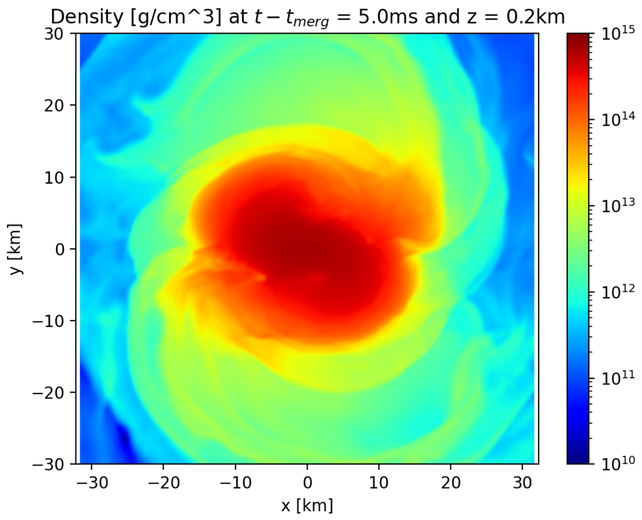
Density evolution - Pole

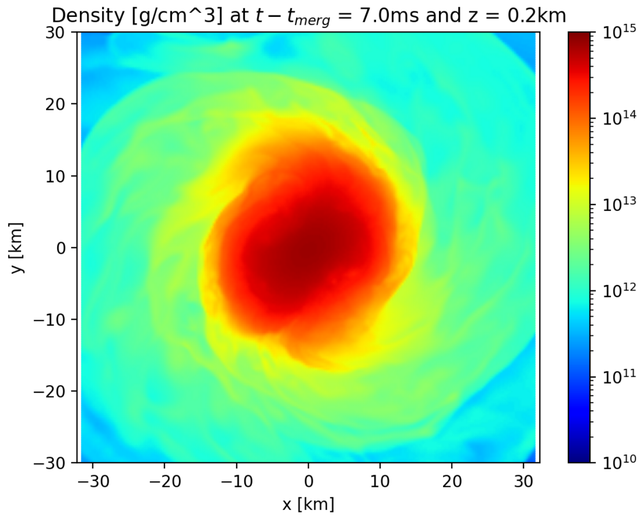


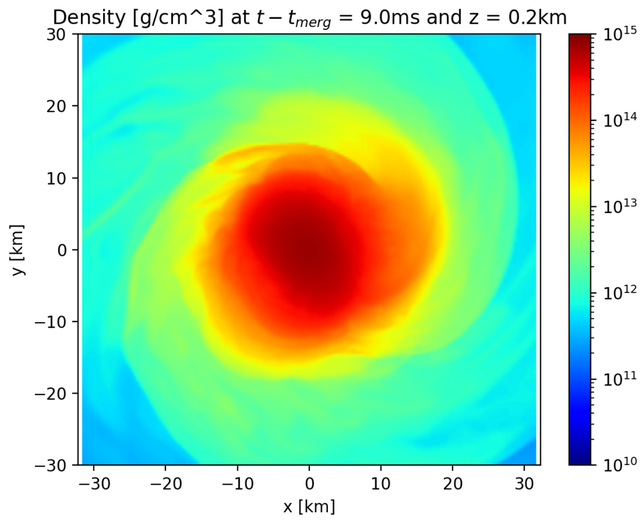
Density evolution - XY plane



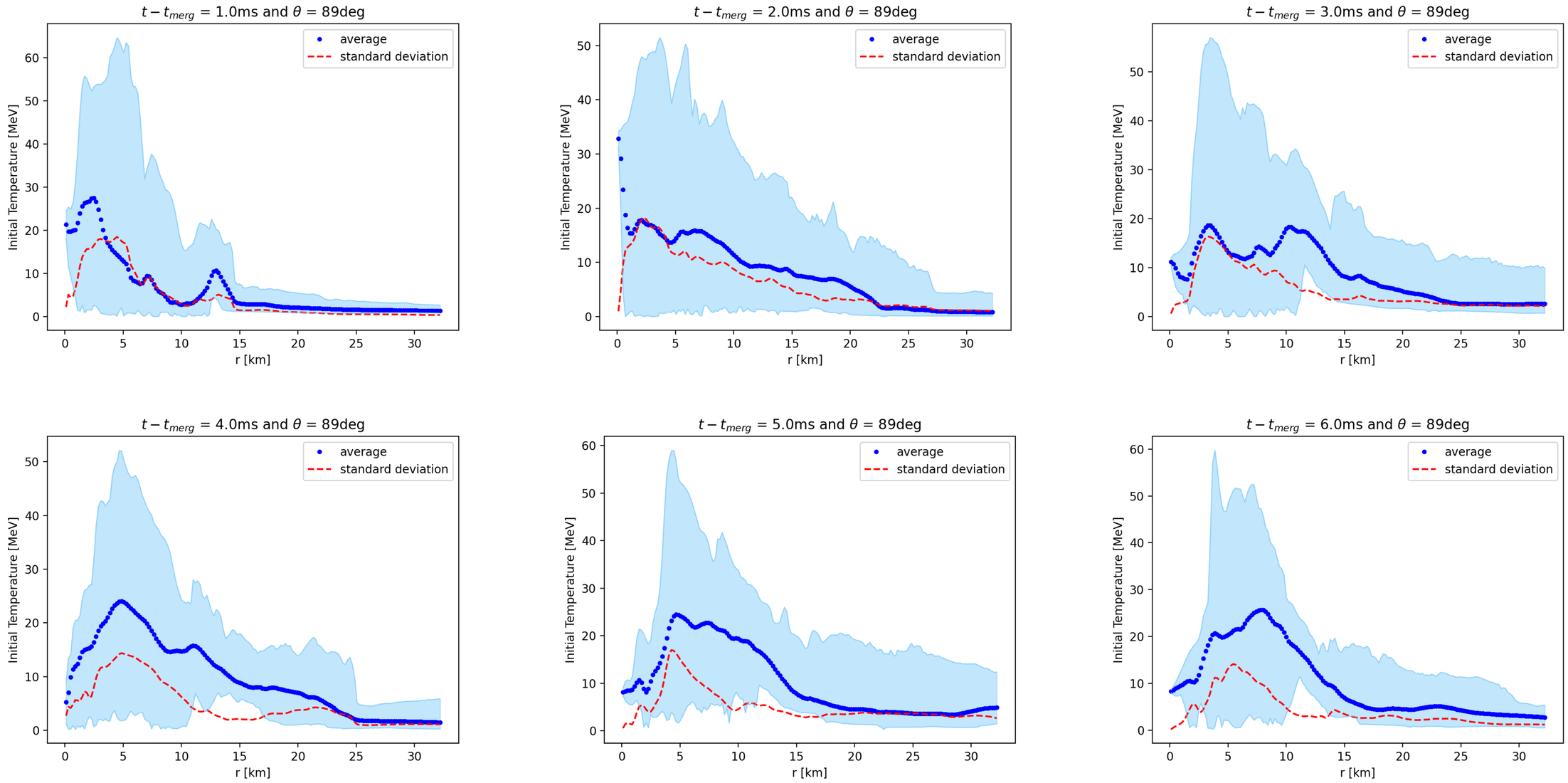




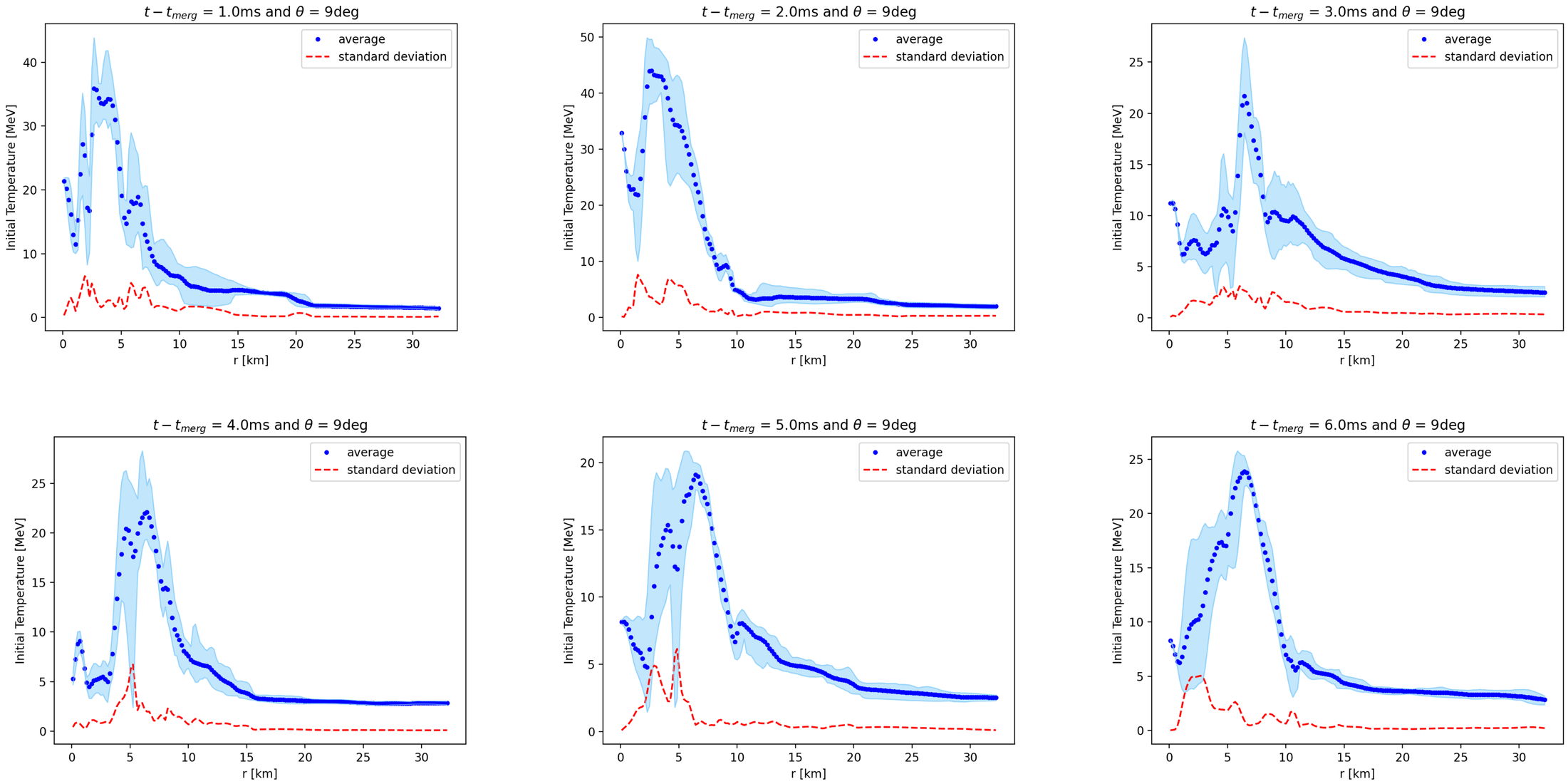




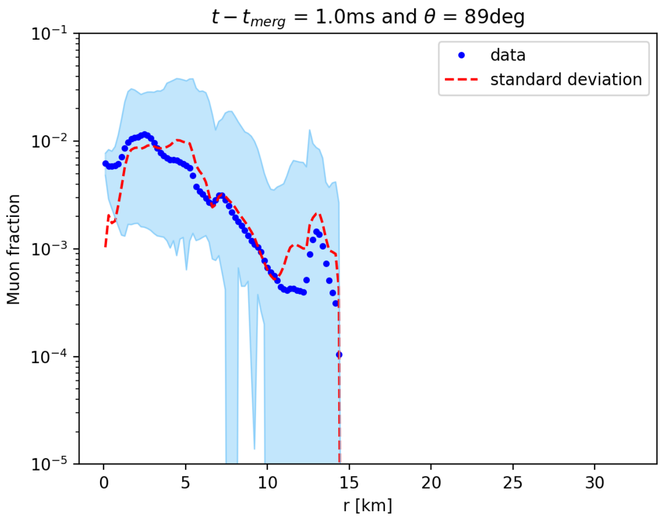
Initial Temperature - Equator

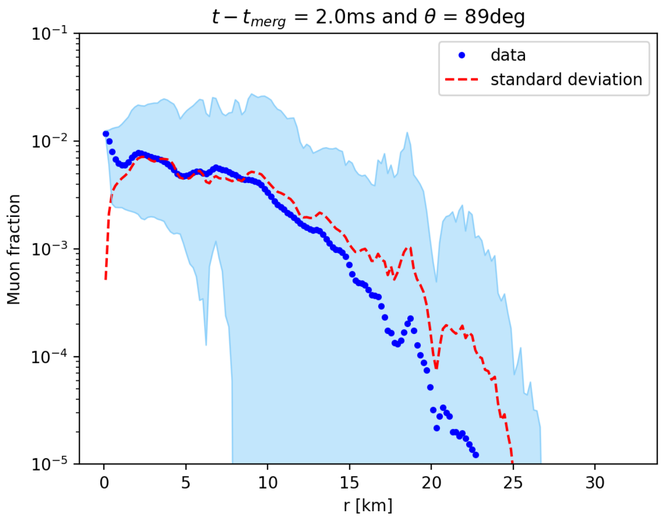


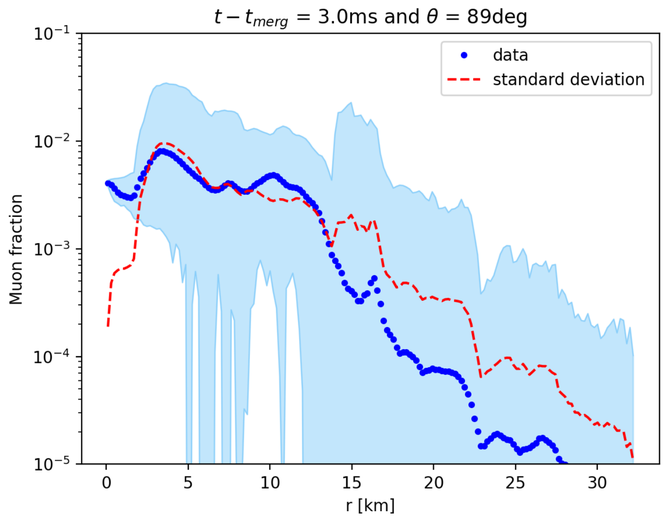
Initial Temperature - Pole

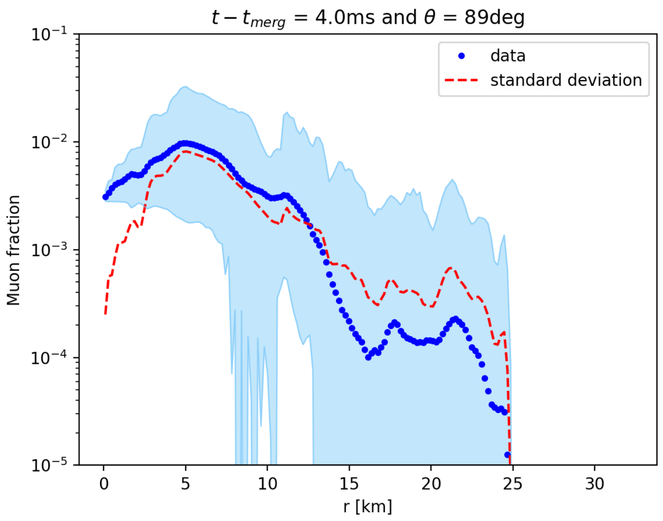


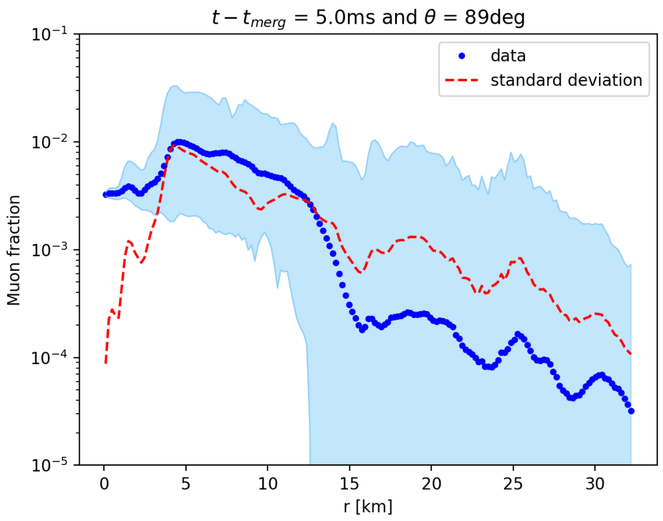
Muon Fraction - Equator

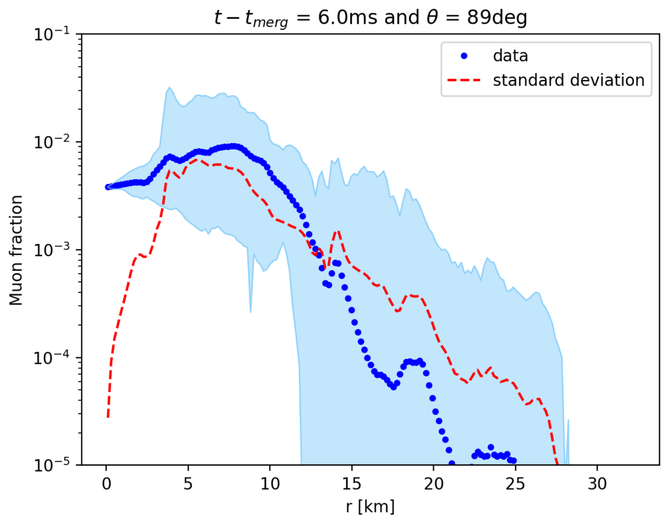




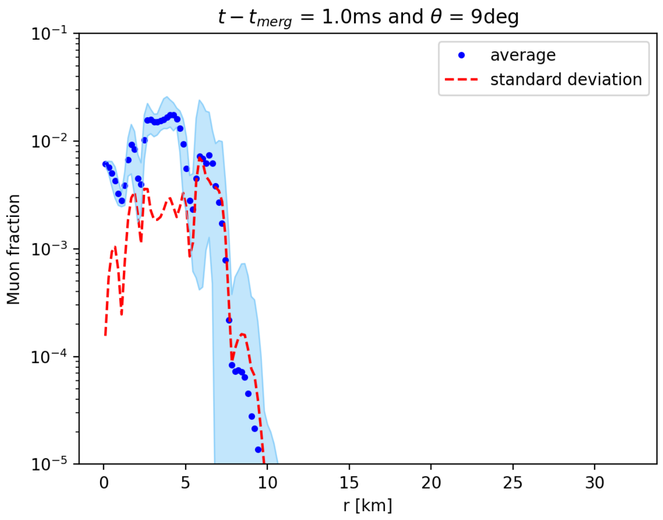


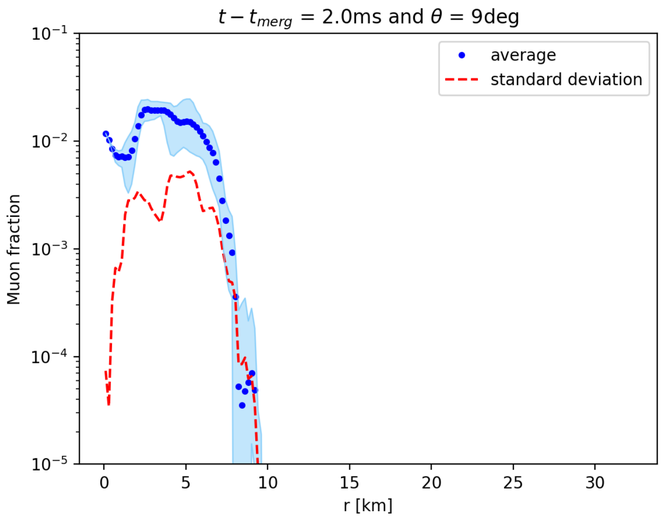


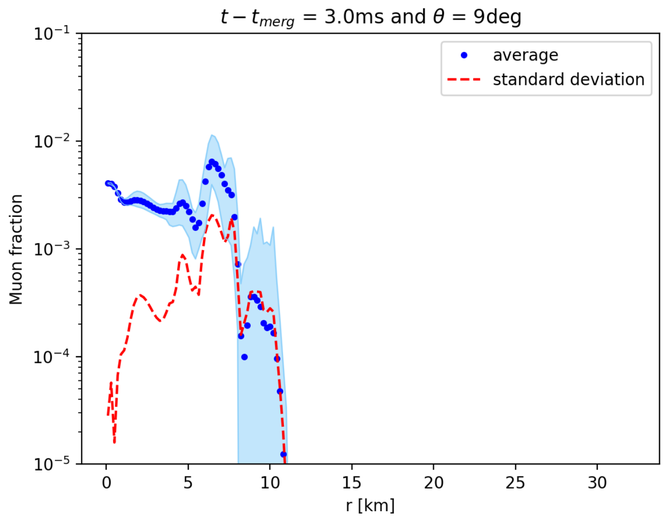


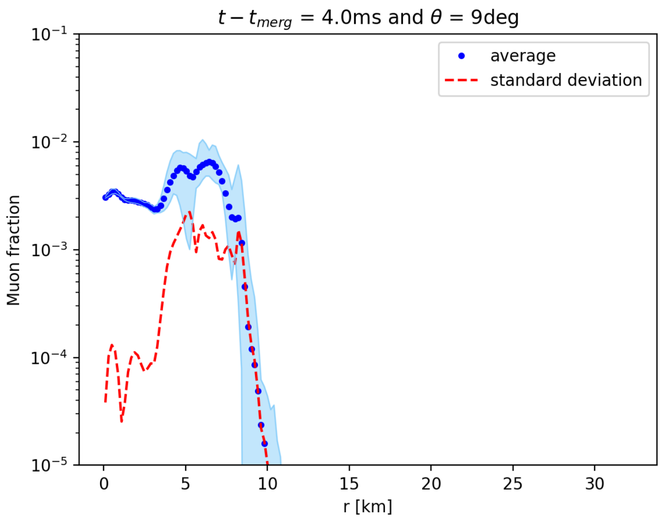


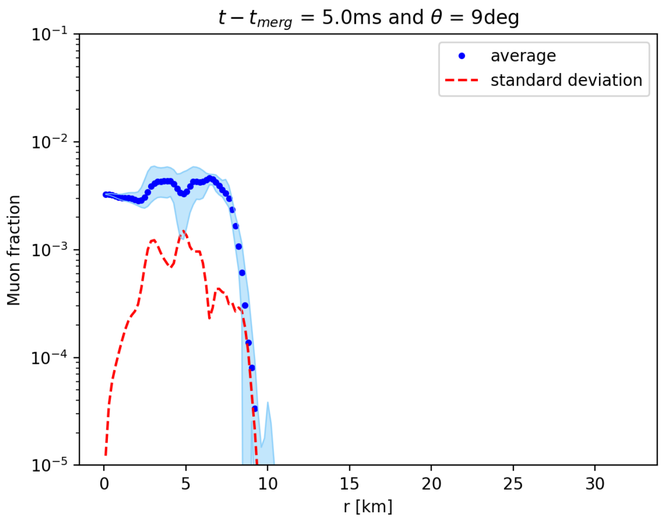
Muon Fraction - Pole

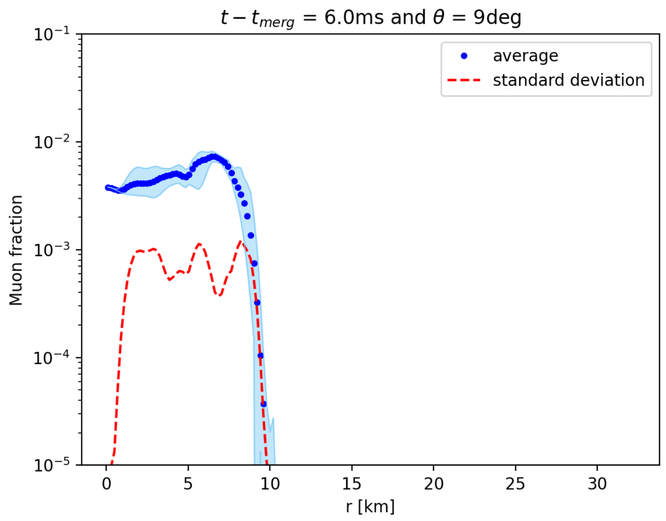




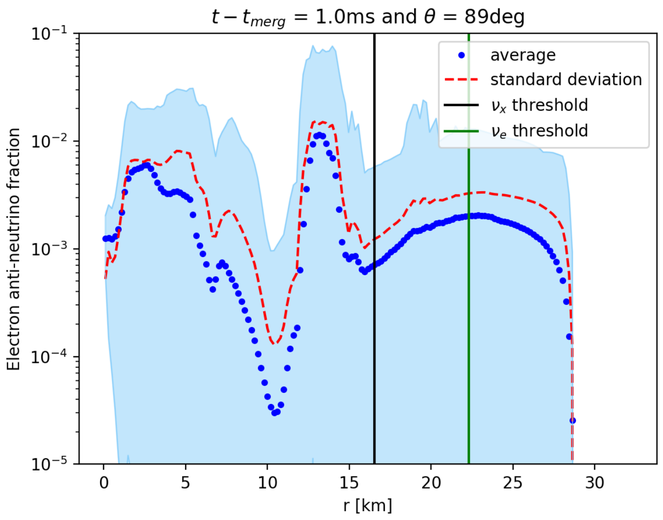


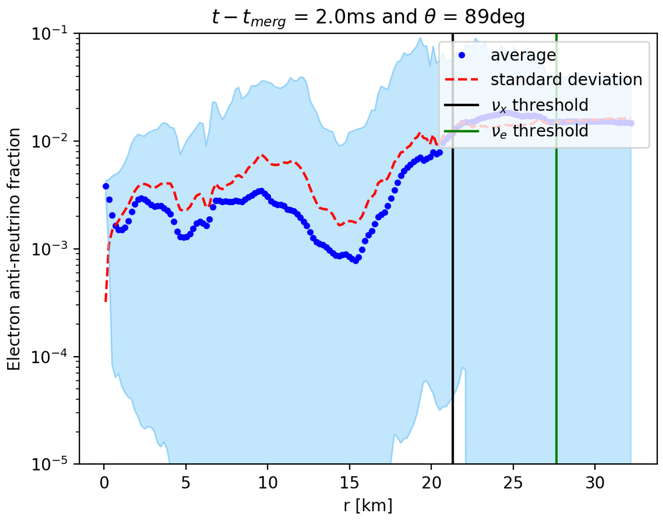


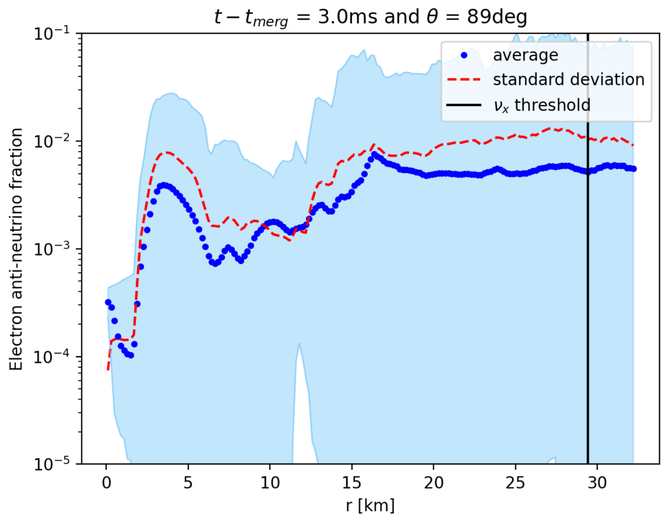


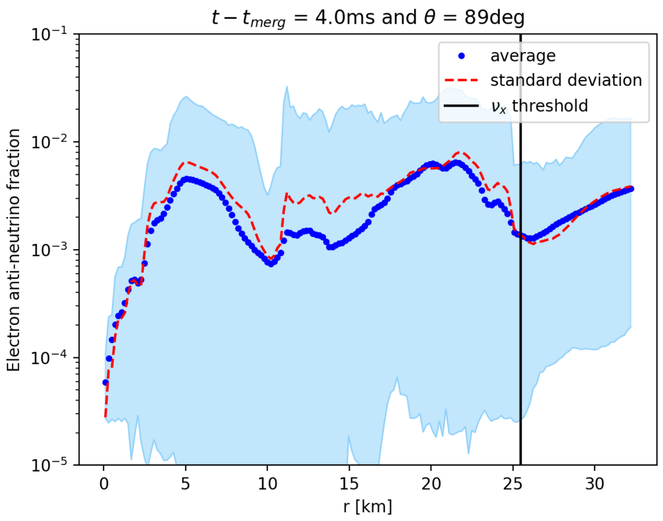


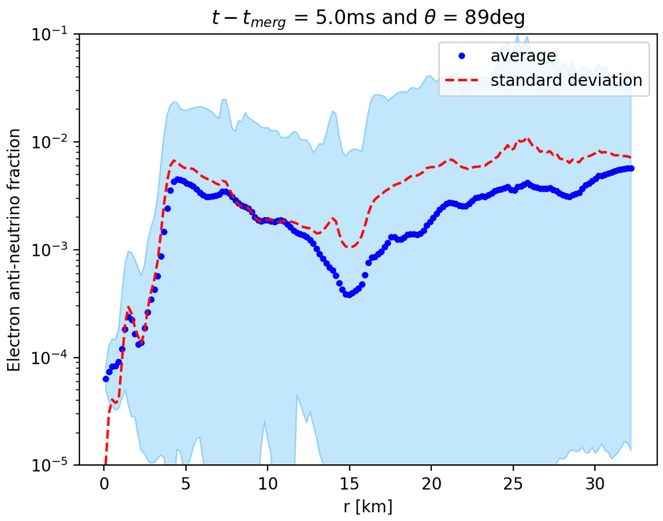
Electron Anti-neutrino - Equator

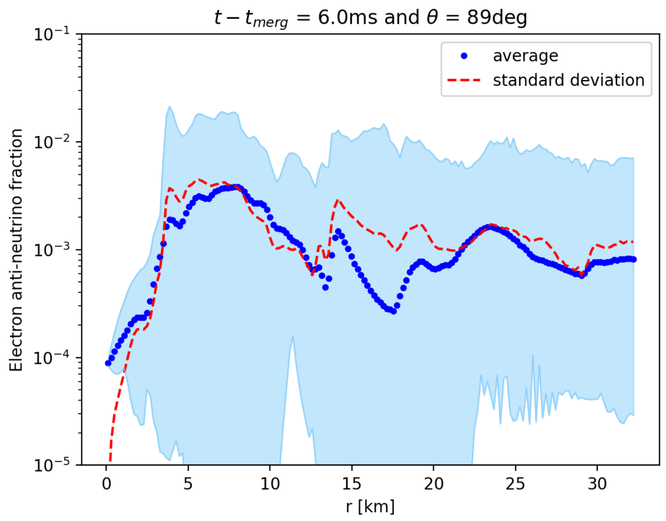




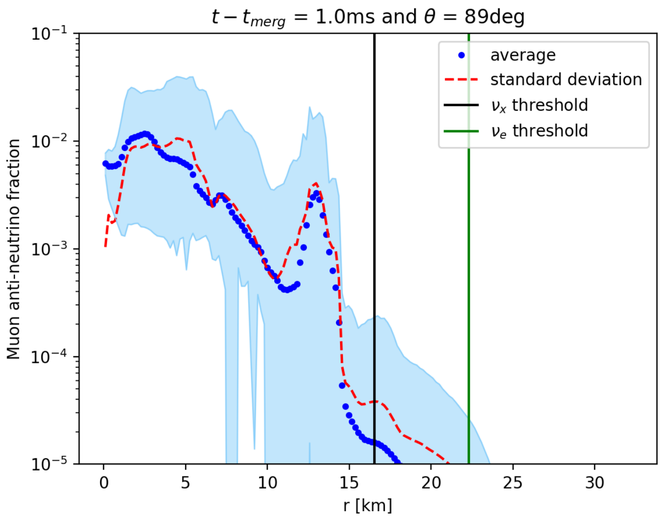


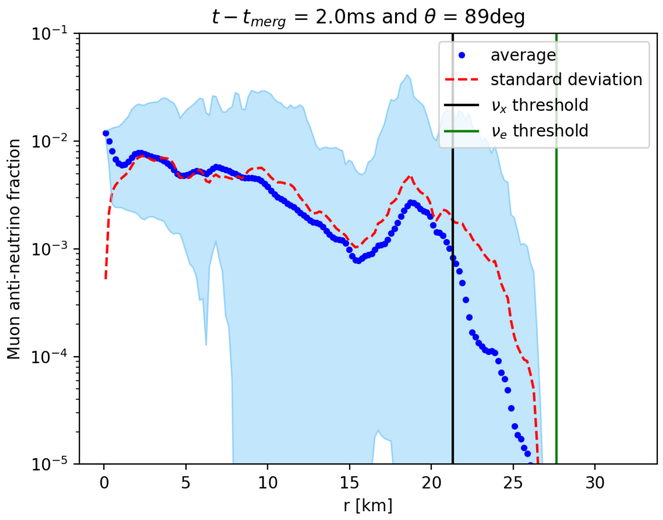


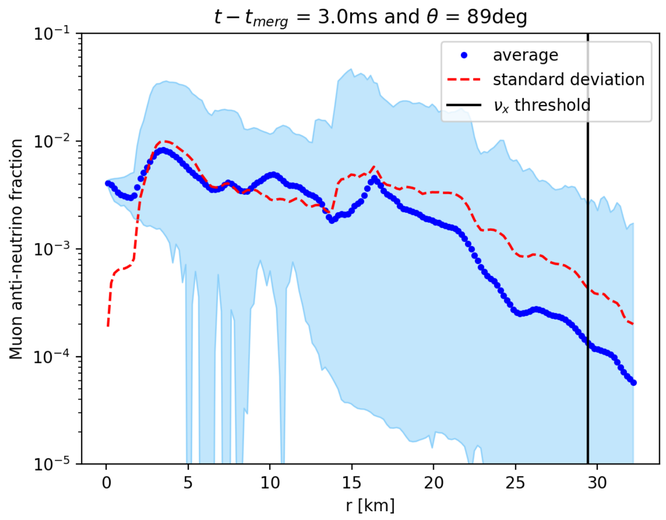


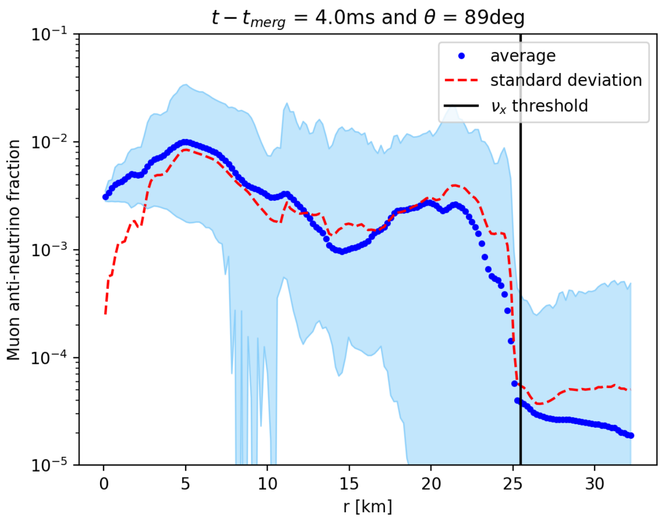


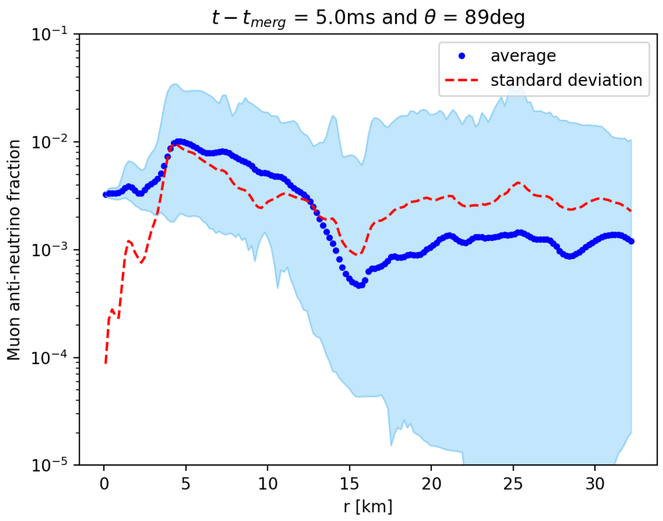
Muon Anti-neutrino - Equator

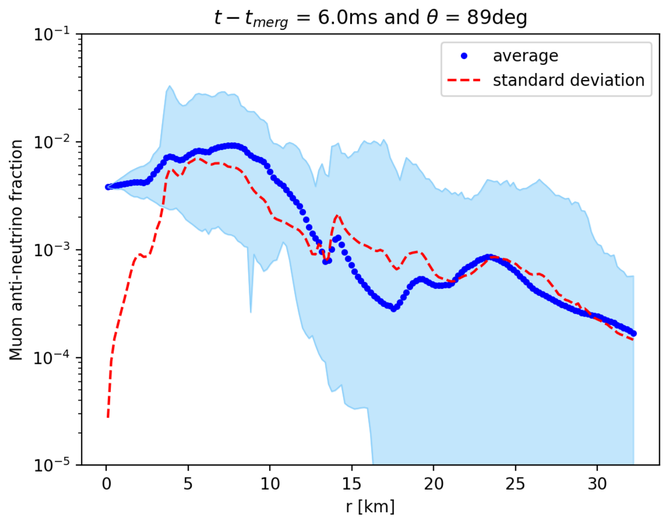




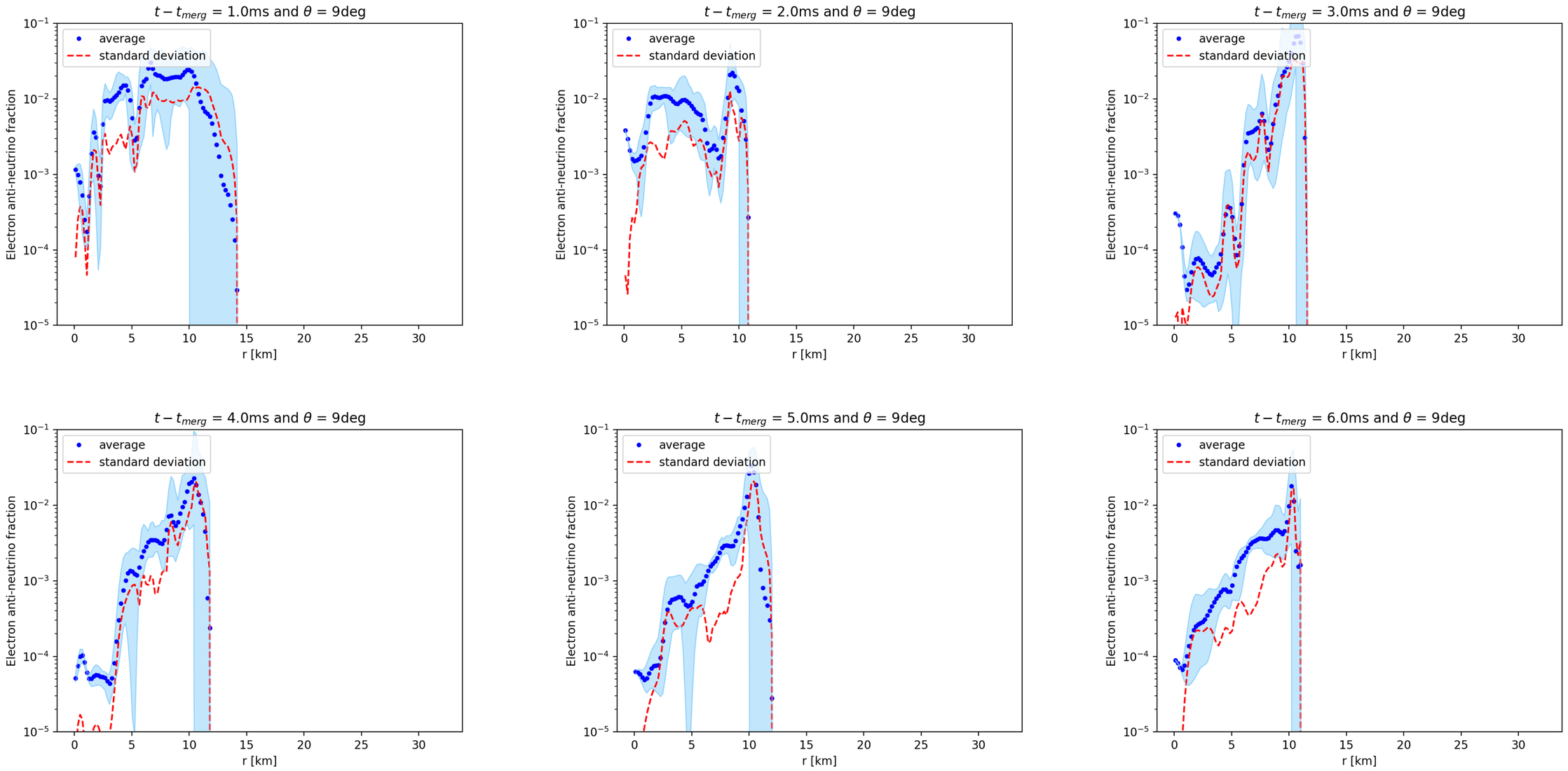




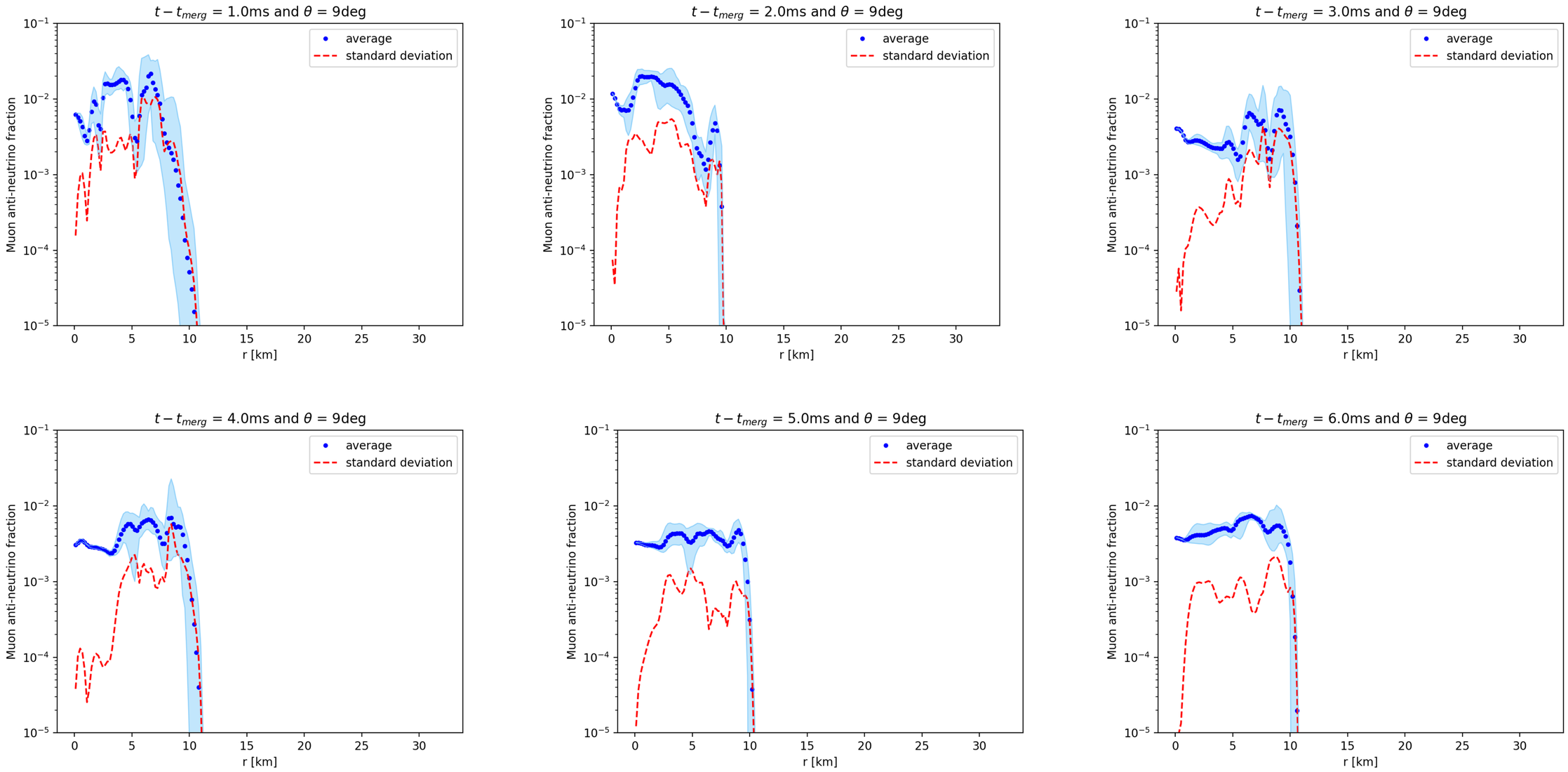




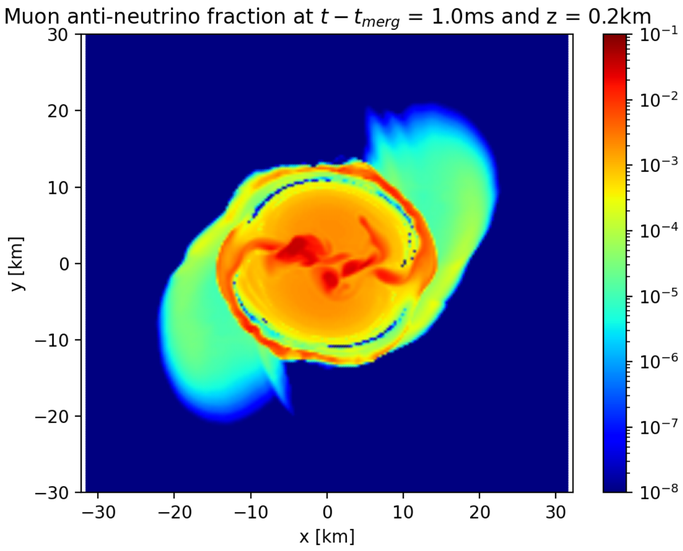
Electron Anti-neutrino - Pole

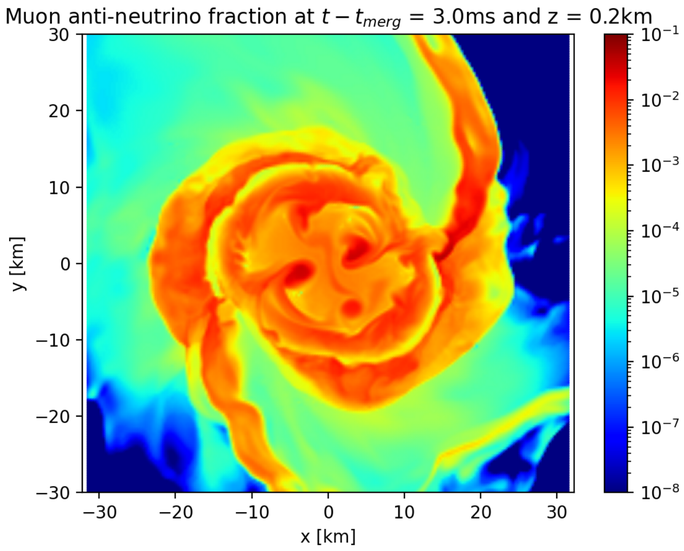


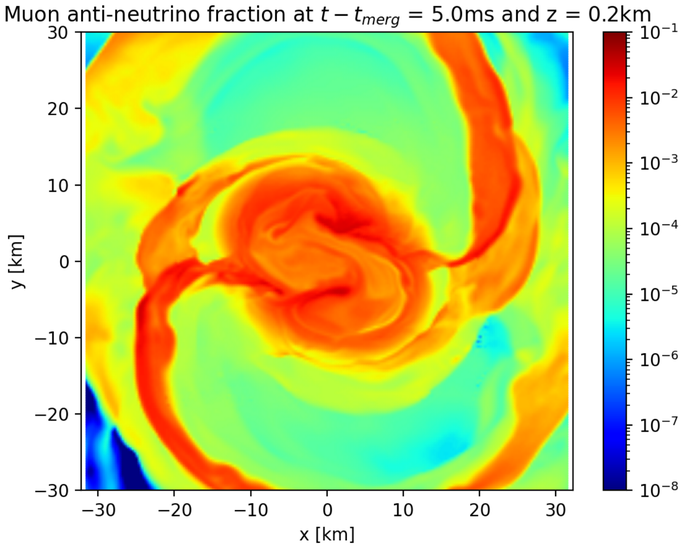
Muon Anti-neutrino - Pole

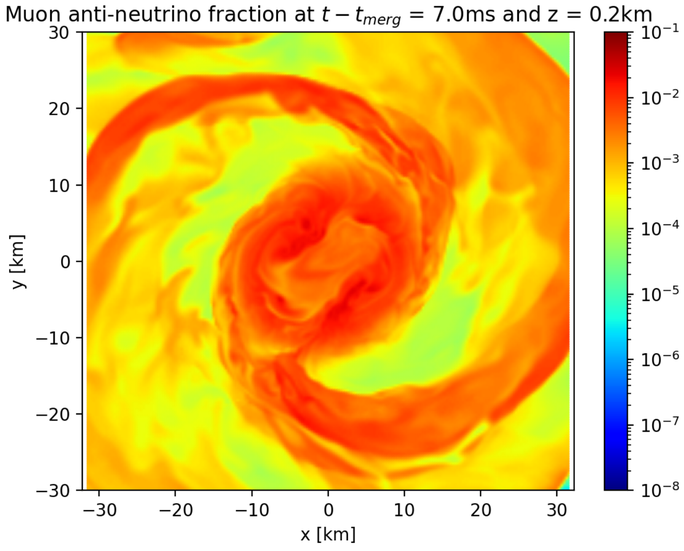


Muon Anti-neutrinos - XY plane









Muons - XY plane