Semi-analytic modeling of Kilonovae

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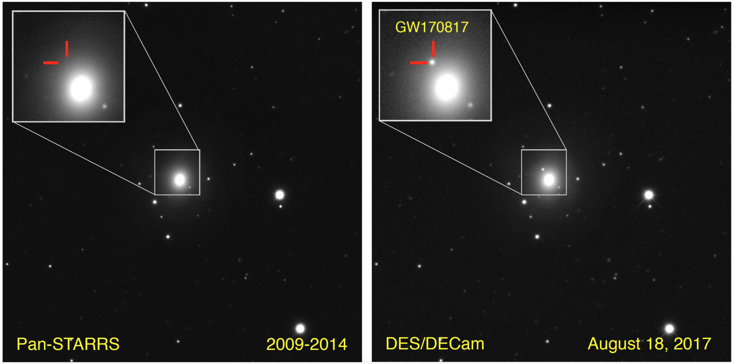
September 28, 2022

TECHNISCHE UNIVERSITÄT DARMSTADT

SFB 1245

The Kilonova

Thermal emission powered by decay of r-process nuclei



Reviews on the topic: Metzger Living Rev., Fernández & Metzger (2015)

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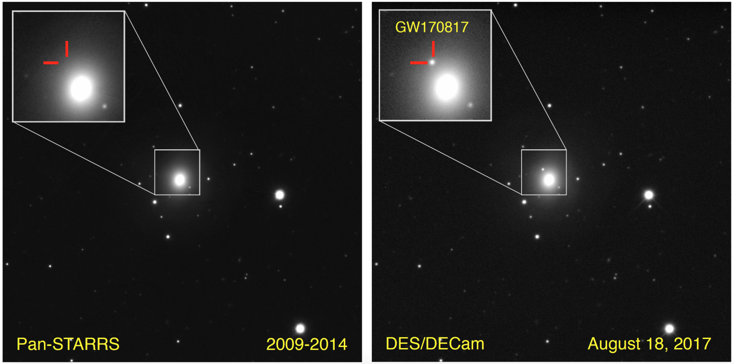
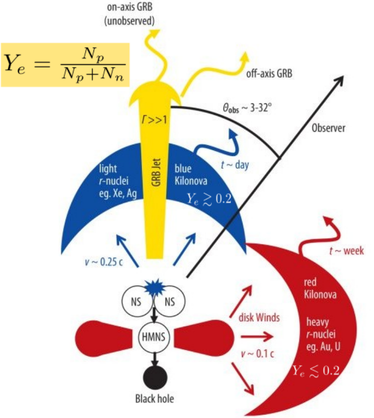


Scenario: NSNS and NSBH mergers



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Model characterization

Diffusive semi-analytic formula + thin layers correction

Outflow hypothesis:

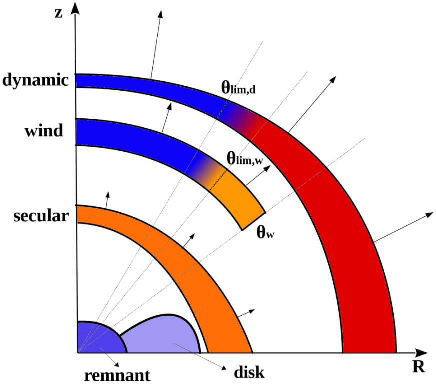
- Homologous expansion
- Optical thickness
- Radiation domination
- Quick decay energy re-processing

Model variables: $M_{\rm ej}$, $v_{\rm ej}$, κ

Starting point:
First two frequency-integrated moments of RT equation in comoving frame, $O(v/c)$ ...

Derivation: Wollaeger et al. (2017)

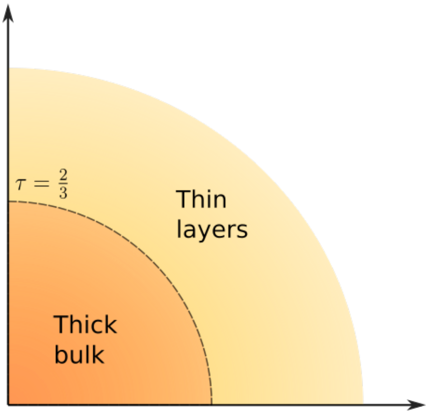
Anisotropic multi-component framework:



Perego et al. (2017)

Model characterization

Photosphere computation → Two contributions to total luminosity: $L(t) = L_{\mathrm{thick}}(t) + L_{\mathrm{thin}}(t)$



Full model description: Camilletti et al. (2022), Ricigliano et al. (in preparation)

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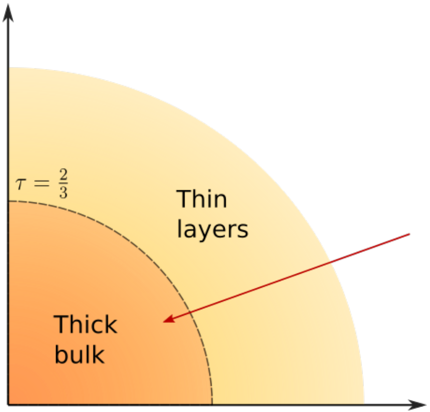

$$L_{\rm thick}(t) = \frac{M_{\rm thick}(t)}{M_{\rm ej}} A_0 \sum_{n=1}^{\infty} (-1)^{n+1} n\pi \phi_n(t)$$

with $\phi_n(t)$ obtained from solving:

$$\phi_n'(t) + \left(\frac{t}{B_0}\right)(n^2\pi^2)\phi_n(t) = C_0 \frac{(-1)^{n+1}}{n\pi} t^{1-\alpha}$$

→ convergence for ~ 500 basis components

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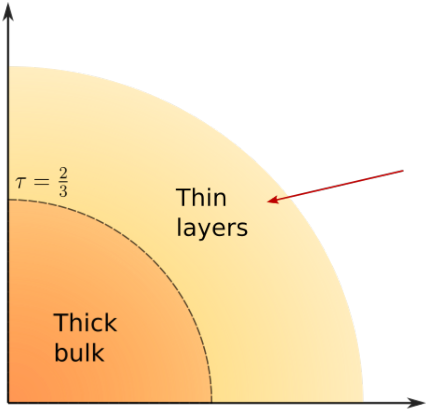


$$L_{\rm thin}(t) = \sum_{i:r>R_{\rm ph}} \epsilon_{{\rm th},i}(t)\dot{\epsilon}_{\rm r}(t){\rm d}M_i$$

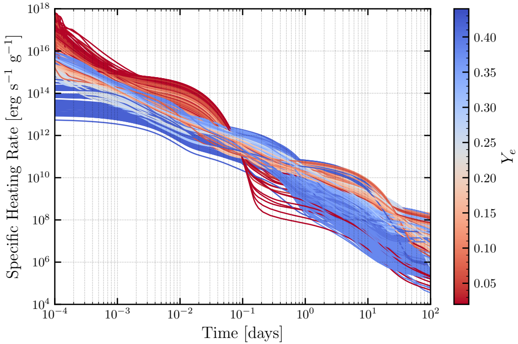
$\dot{\epsilon}_{\rm r}(t)$ radioactive heating rate

$\epsilon_{\rm th}(\rho)$ thermalization efficiency
Barnes et al. (2016)

Full model description: Camilletti et al. (2022), Ricigliano et al. (in preparation)

Model ingredients: heating rates and opacities

- Nuclear reaction network `SkyNet` calculations
  Perego et al. (2022), Wu et al. (2022)



→ Heating fit formula: $\dot{\epsilon}_{\rm r}(t) = At^{-\alpha}$

with $A, \alpha = f(Y_e, s, \tau)$

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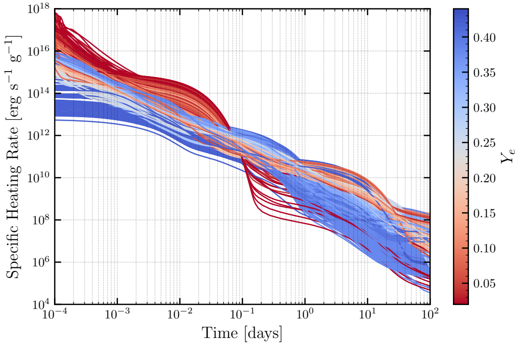

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- Systematic atomic structure `HULLAC` calculations
  Tanaka et al. (2020)

Y_e	X(La)	X(La+Ac)	κ cm^2 g^{-1}
0.10	7.1×10^{-2}	1.7×10^{-1}	19.5*
0.15	2.6×10^{-1}	2.6×10^{-1}	32.2
0.20	1.1×10^{-1}	1.1×10^{-1}	22.3
0.25	5.5×10^{-3}	5.5×10^{-3}	5.60
0.30	3.4×10^{-7}	3.4×10^{-7}	5.36
0.35	0.0	0.0	3.30
0.40	0.0	0.0	0.96
0.10-0.20	2.1×10^{-1}	2.3×10^{-1}	30.7
0.20-0.30	4.8×10^{-2}	4.8×10^{-2}	15.4
0.30-0.40	0.0	0.0	4.68

→ Planck mean opacities: $\kappa = \kappa(Y_e)$

GW190425: synthetic magnitudes

GRHD BNS simulations
Camilletti et al. (2022)

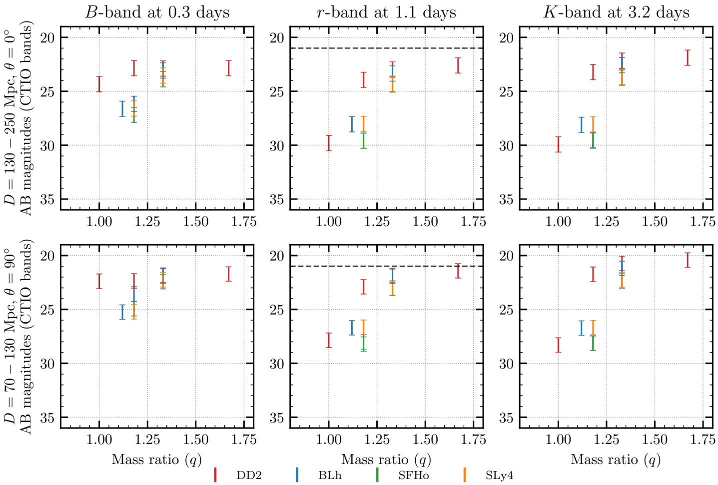
Dynamic ejecta:

- anisotropic
- $M_{\rm dyn} \sim 10^{-6} - 10^{-4}\ M_\odot$
- $v_{\rm dyn} \sim 0.2 - 0.3\ c$
- $Y_{\rm e,dyn} \sim 0.10 - 0.25$

Disk wind:

- isotropic
- $M_{\rm wind} \sim 10^{-4} - 10^{-2}\ M_\odot$
- $v_{\rm wind} \sim 0.06\ c$
- $\kappa_{\rm wind} \sim 5\ {\rm cm^2 g^{-1}}$

Distance: 130 Mpc



Camilletti et al. (2022)

Overview

Model achievements:

- Accuracy improved from radiative transfer
- Sensitivity to initial ejecta thermodynamic conditions

Code advantages:

- Runtime < 1 s
- Open to non-trivial ejecta profiles

Applications:

- Bayesian statistical analysis
- Event target (e.g. GW170817)