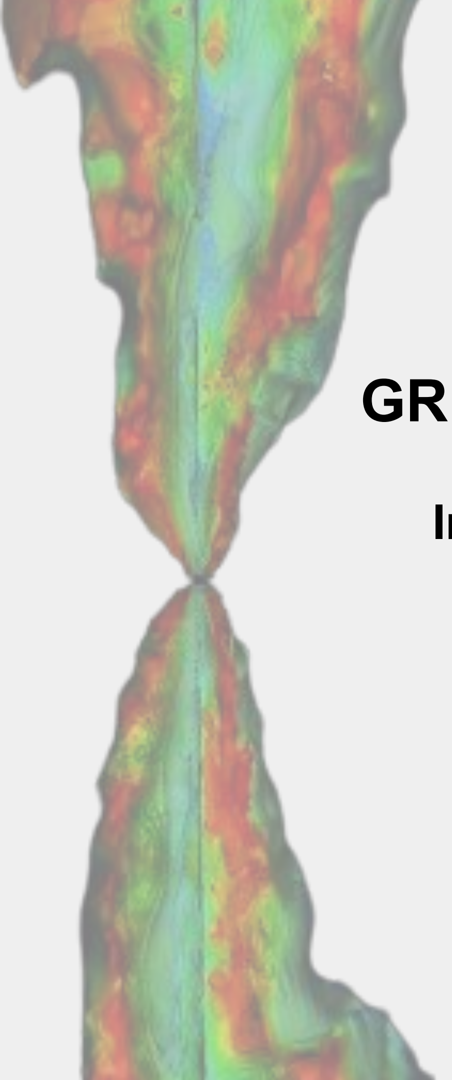


GRMHD Simulations of Accretion Disk Winds:

Implications for Kilonova Emission and r-Process Element Formation

Joseph Saji
Center for Theoretical Physics
Polish Academy of Sciences, Warsaw, Poland

PAiP-2025; 21/02/2024

Short Gamma ray burst; SGRBs

- Short intense flashes of high energy radiation detected in gamma rays
- Transient event that originates from the merger of compact objects; NS-NS; NS-BH (<2s)

Two stages of emission

1. Prompt emission (gamma rays)
2. Afterglow emission: (Multi wavelength)

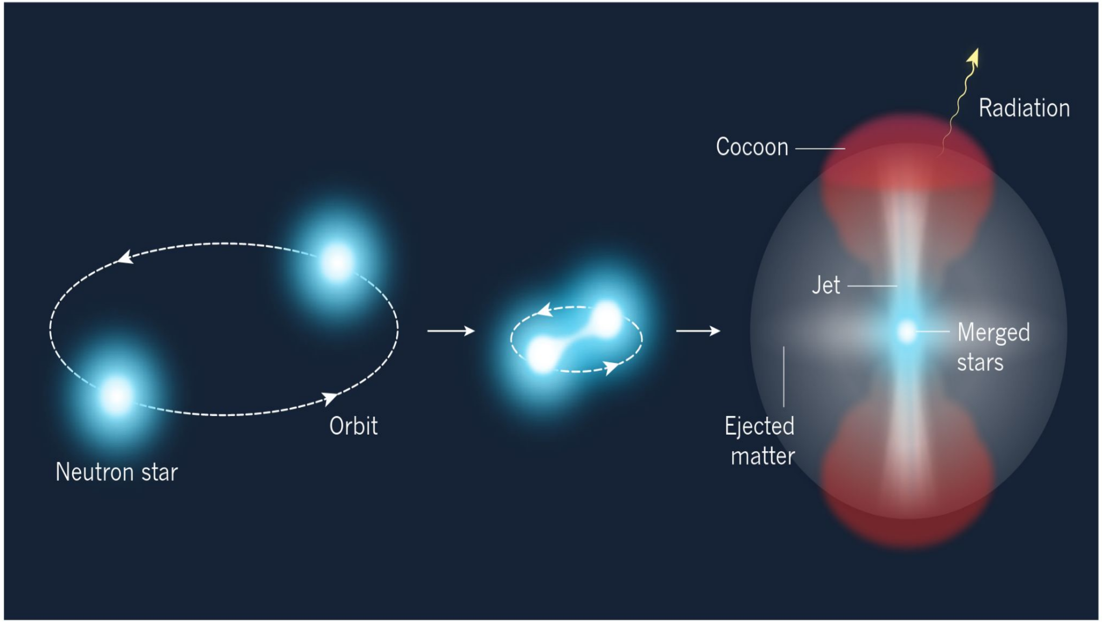
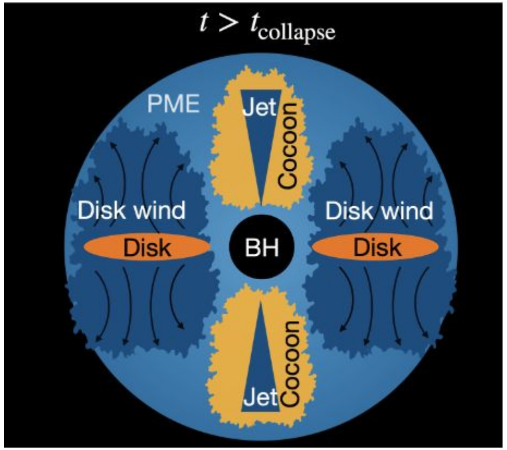


Illustration showing origin of short GRBs.
Nature 554, 178-179 (2018)

Kilonova

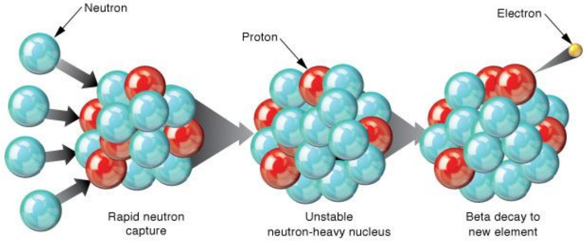
Bright transient astronomical event powered by the **radioactive decay of heavy elements** synthesized in the ejecta of NS Mergers



A non scaled cartoon of a post binary NSNS (or BHNS) merger.
Credits: Urrutia G. et al, 2024, Preprint Arxiv:2401.10094

- Merger events eject neutron-rich material at high velocities (0.1 − 0.3c), providing conditions for **rapid neutron capture** (r-process nucleosynthesis) to occur.

- **R-Process Nucleosynthesis:**



Free neutrons rapidly absorbed by nucleus → Formation of neutron rich unstable Nuclei → beta decay + Heavy elements

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}.$$

Ejecta composition of Kilonova

✔ **Dynamical ejecta** (Ye<0.2, v~0.1c) → Neutron-rich, heavy r-process elements (lanthanides, actinides)

✔ **Disk wind ejecta** (0.2<Ye<0.4, v~0.05−0.15c) → Moderately neutron-rich, light r-process elements

Kilonova observation;

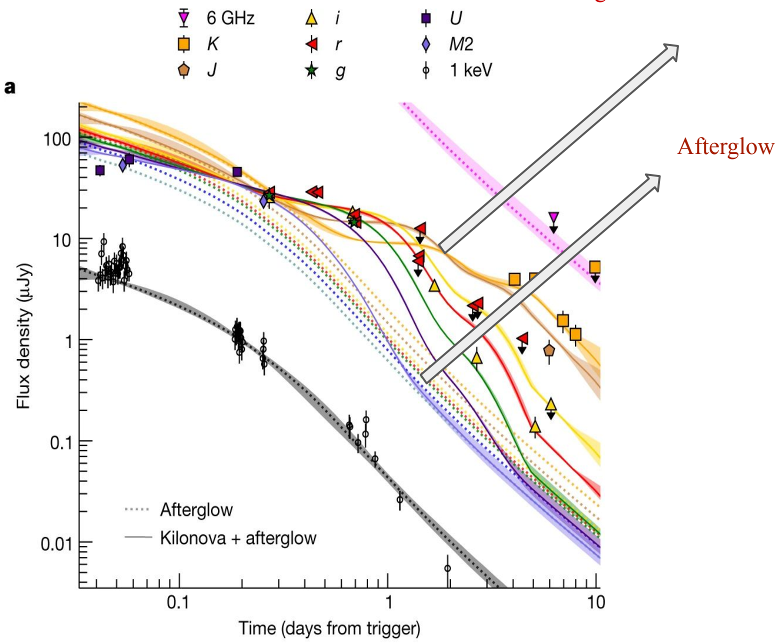
GRB 211211A

Kilonova emission appear as an excess in Optical-NIR light curves of GRB afterglow

The afterglow model is well constrained by the radio and X-ray light curves and provides a good fit to the optical data at ≲0.1 day post-burst.

The **NIR detections are approximately four magnitudes brighter** than that **predicted by the afterglow model** and require a kilonova component to fit.

Afterglow + Kilonova



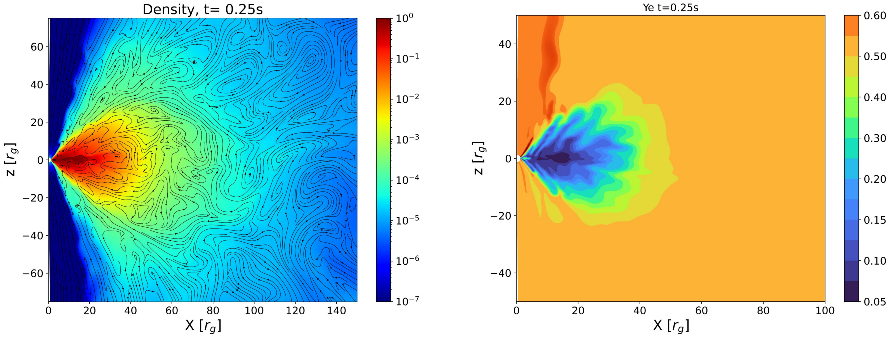
Afterglow

Multiwavelength lightcurve of GRB211211A afterglow.
Excess in Optical-IR band is the kilonova emission

Source: Rastinejad, J.C., Gompertz, B.P., Levan, A.J. *et al* .(2022).

- **By analyzing different multiwavelength bands, we can track the evolution of kilonova and infer the composition of the ejecta.**

GRMHD Results → Kilonova Modeling



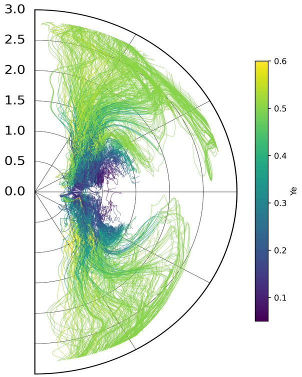
Left Panel: Density and magnetic field streamlines in the innermost regions of the central engine.
Right Panel: electron fraction map in the GRB central engine, for the same model.

Numerical Framework

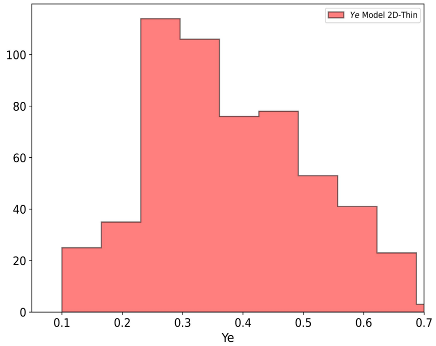
- **G**eneral **R**elativistic **M**agneto**H**ydro**D**ynamic simulations **Code**: HARM_EOS - Developed in CFT-PAN

Wind Outflows and Ejecta Dynamics

- **Disk winds** — outflows of matter propelled outward by magnetic and thermal forces from the disk
- **Tracer Particles**
  Track disk winds — **coordinates**, **time, density, temperature, and electron fraction.**



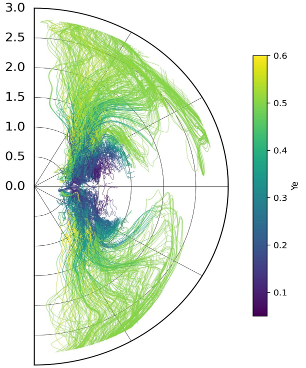
Trajectories of disk wind particles; colorbar represent Ye



Electron fraction distribution from tracers

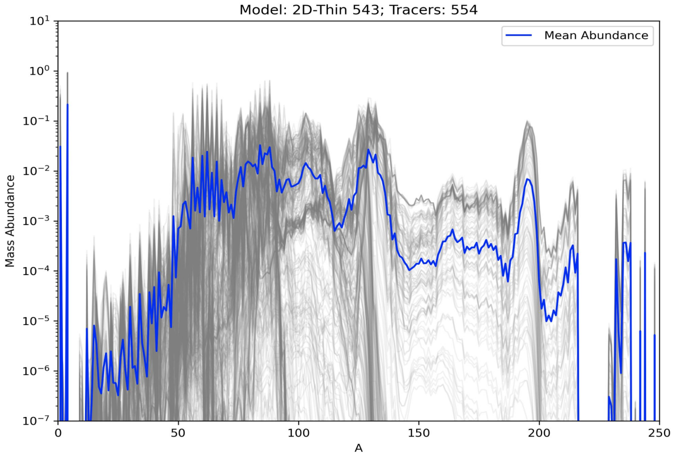
Post Processing & NRN Results

GRMHD → Nuclear Reaction Network → Radiation transport → Kilonova (Spectrum+Light Curves)



Sky Net
github.com/jlippuner/SkyNet

Skynet (nuclear reaction network) Evolves the abundances of nuclear species under the influence of nuclear reactions.



Abundance profile of isotopes from nuclear reaction network utilising the tracer input from GRMHD-(HARM-EOS) simulations

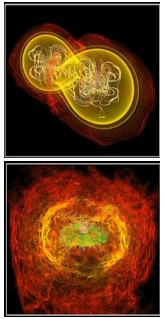
- The elemental abundance profile depend heavily on the multiple parameters → Accretion Disk Composition, Mass Ejection, Magnetic Fields, Jet Interaction, Neutrino Irradiation etc.
- Abundances + radiation transport (SuperNU, MOSFiT) → **Spectrum & Light Curves**

Thank You

Dynamic Ejecta + Disk Winds : Combined results

Fujibayashi et al. 2023

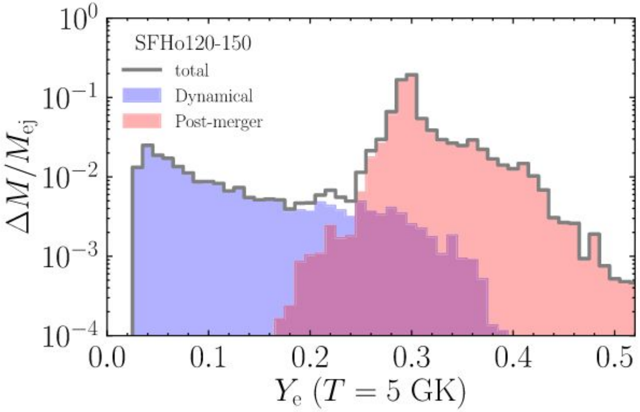
BNS-Merger
Inspiral phase till formation of compact object

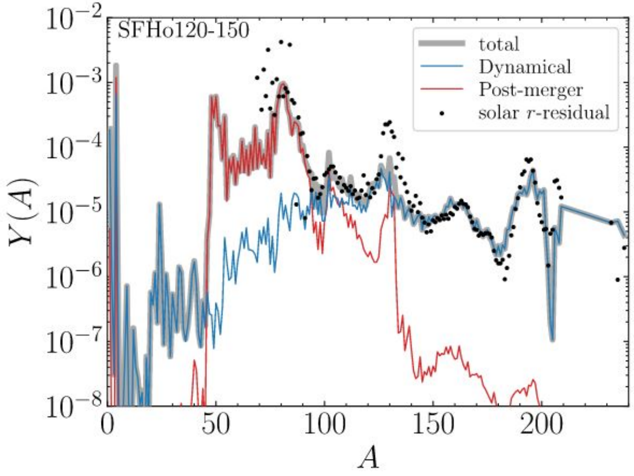


Numerical relativity
Timescales: μ_s to s
Codes: Einstein Toolkit (ET), SpEC, etc.

Accretion disk + GRB

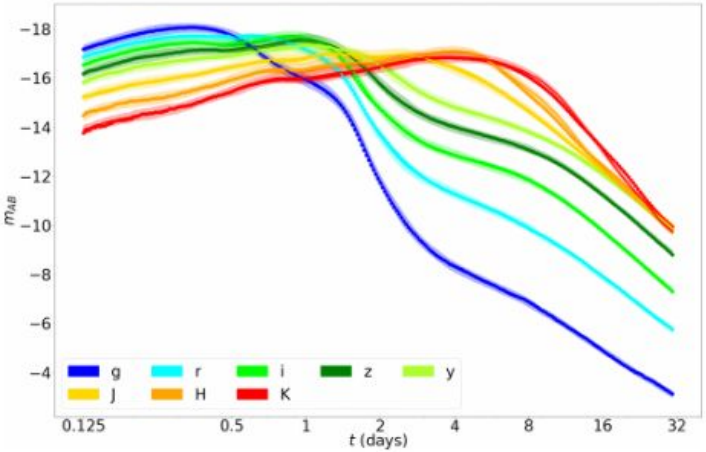
GRMHD
Timescales: ms to s
Code: HARM_EOS, nubhlight



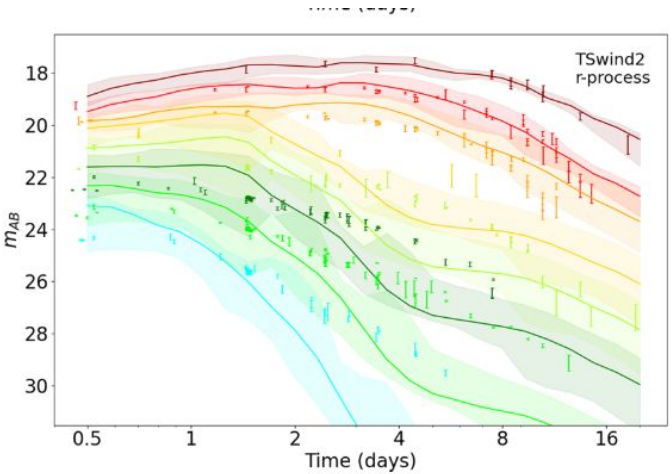


SuperNU - light curves

Kedia et al. 2022



Simulated Light Curves of kilonova emission. Different colors denote different filter bands



predicted LCs for AT2017gfo, compared with AT2017gfo observations. Points and error bars denote the observations,