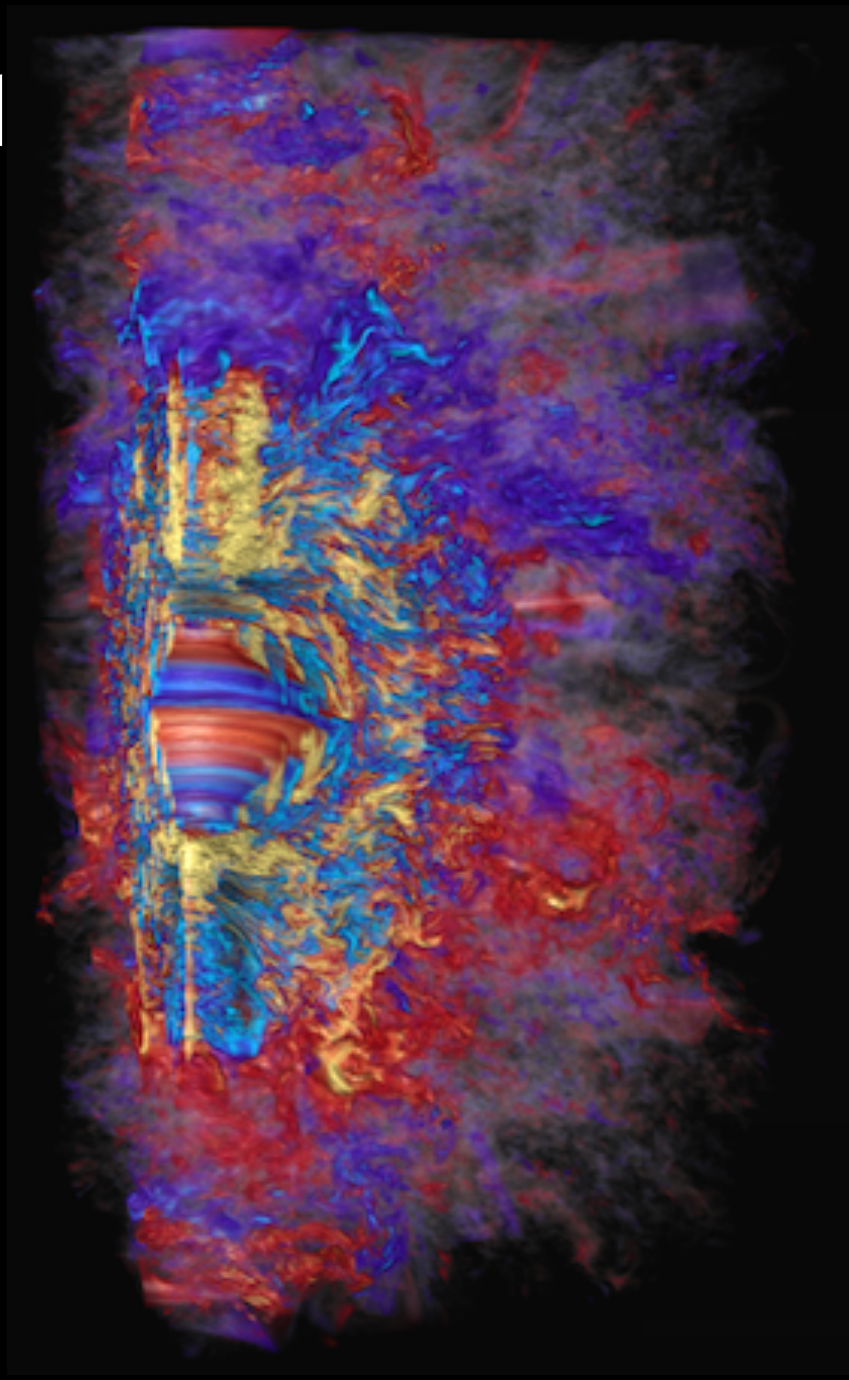
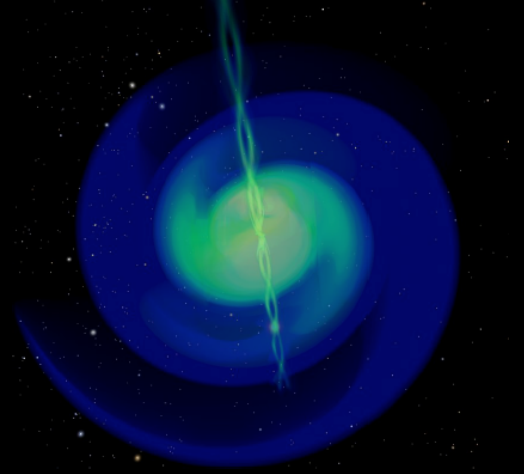
Magnetically-powered explosions in the multimessenger era

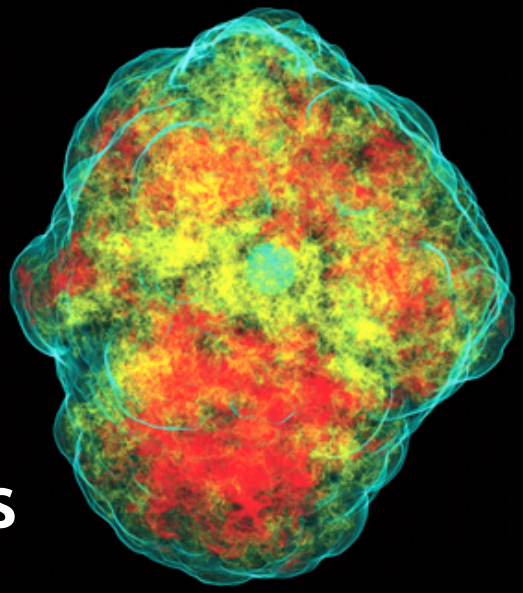


Philipp Mösta

GRAPPA/API/IoP
University of Amsterdam
p.moesta@uva.nl

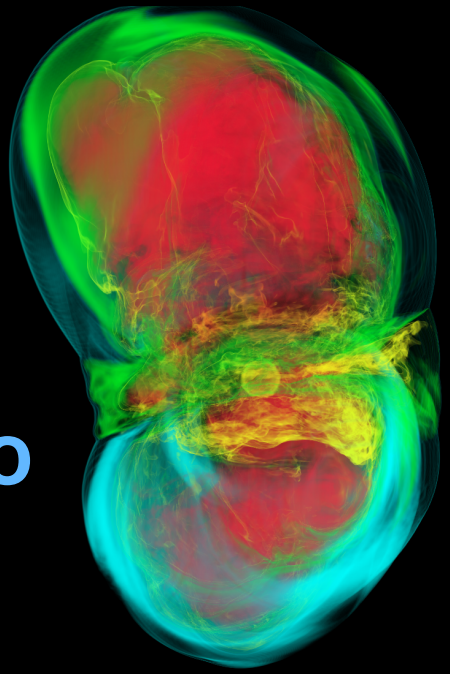
EMMI workshop nucleosynthesis
Jan 20, 2025



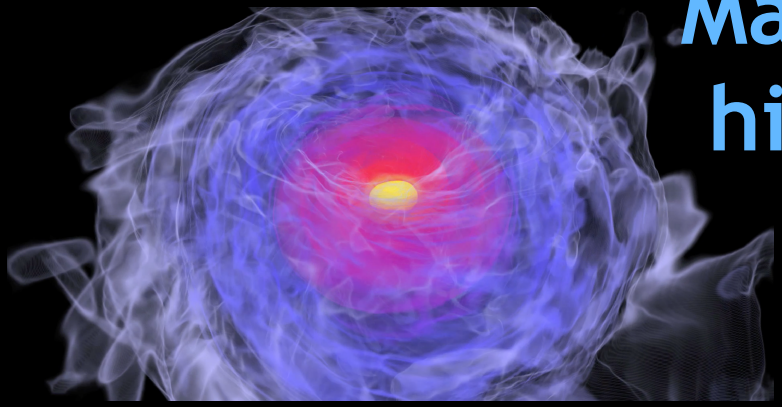


Core-collapse supernovae
neutrinos
turbulence

(Binary) black holes
accretion disks
EM counterparts

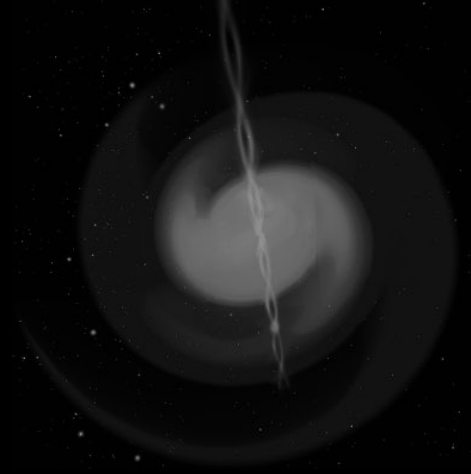


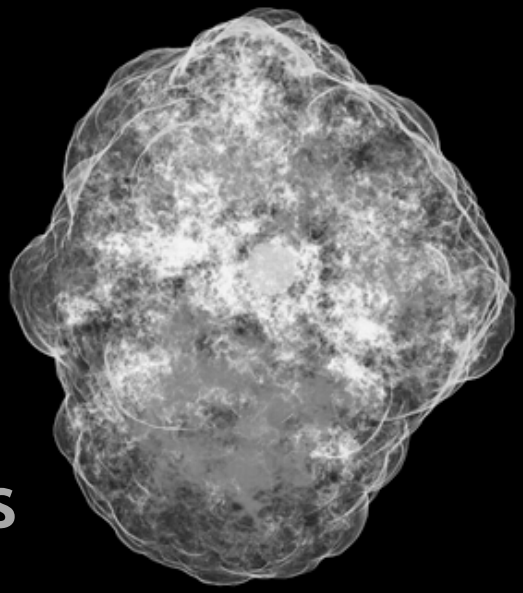
Magnetic fields in high-energy astro



Binary neutron stars
gravitational waves
EM counterparts
sGRBs

Extreme core-collapse
hyperenergetic
superluminous
lGRBs





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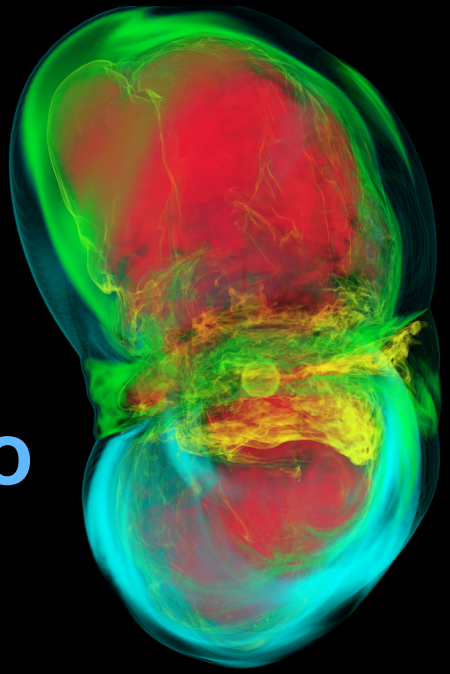

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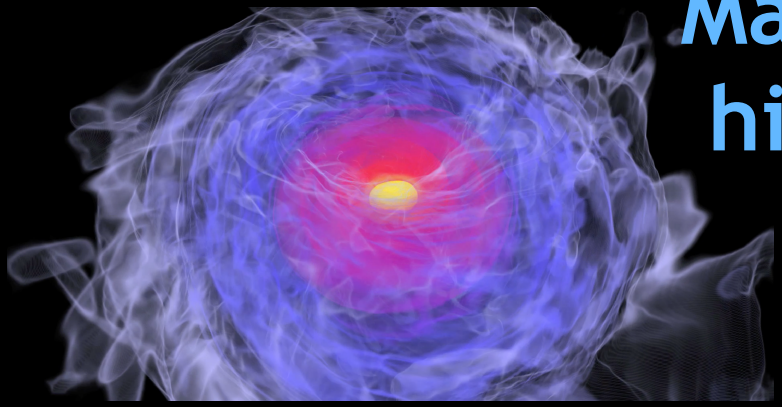

Binary neutron stars
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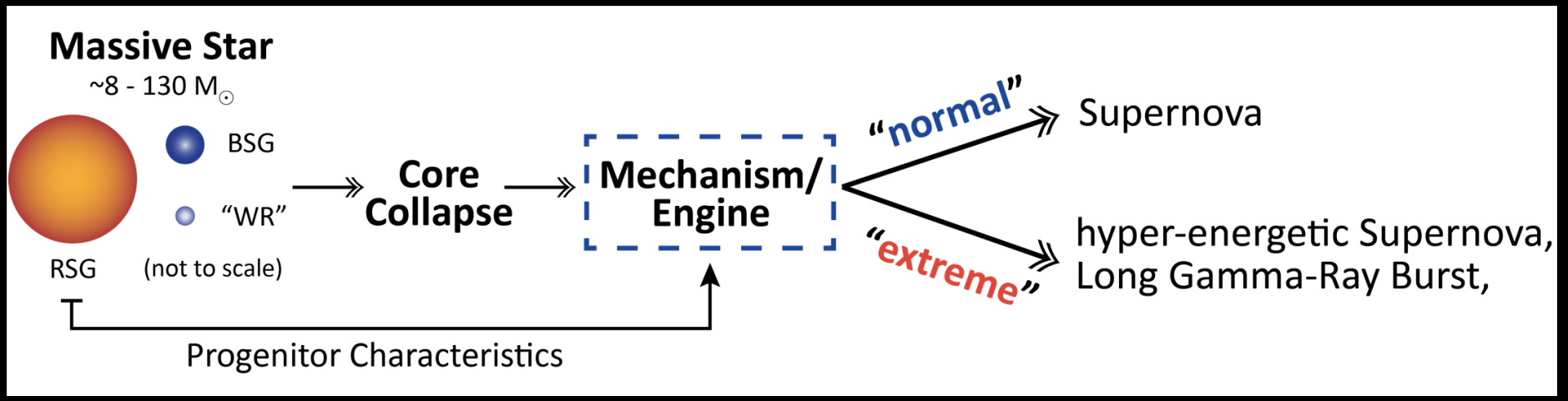
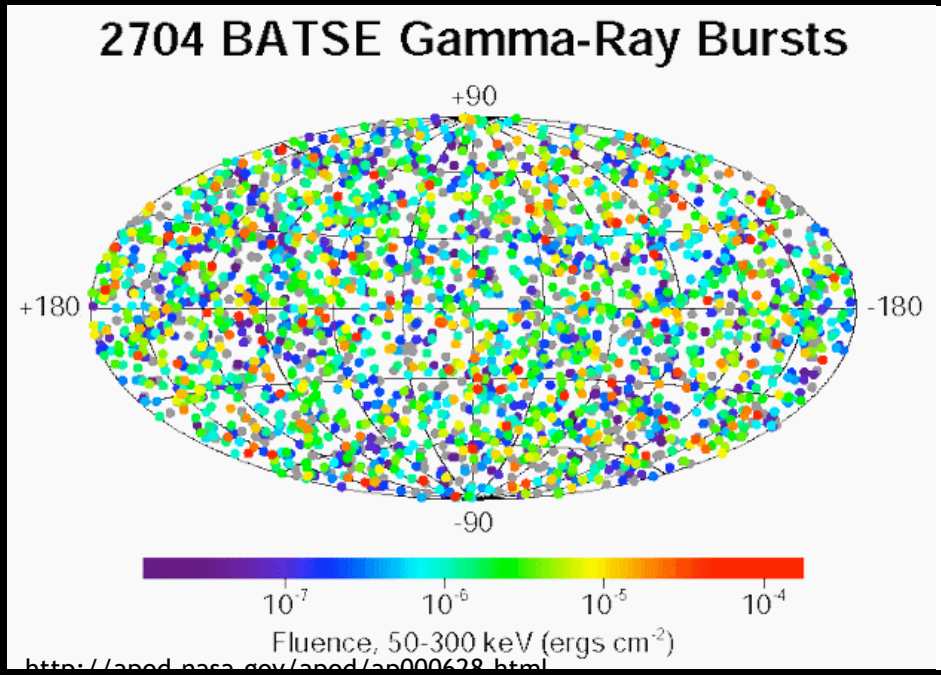
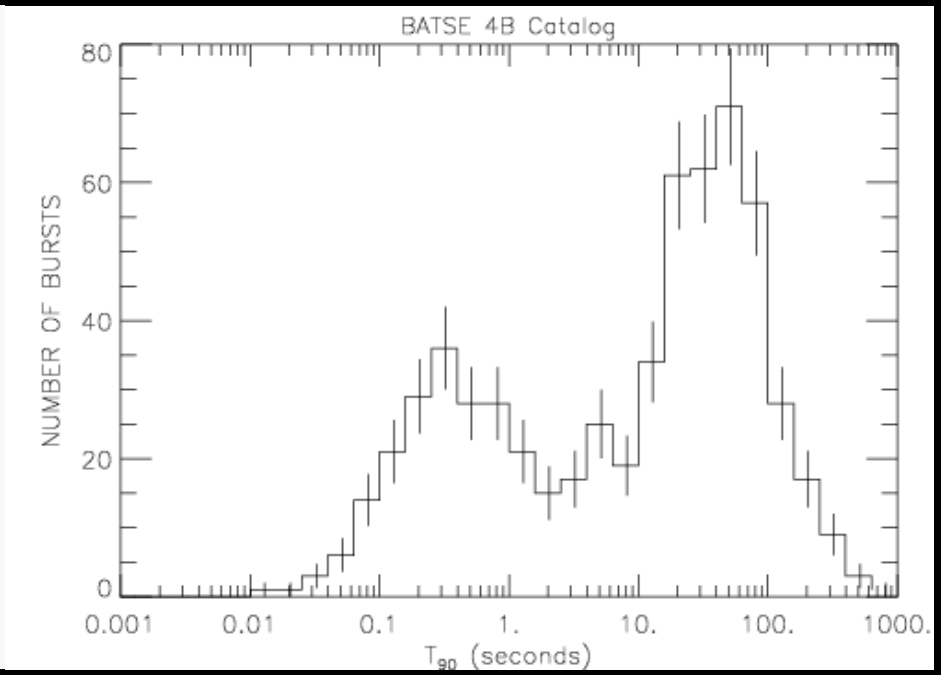
Extreme core-collapse
hyperenergetic
superluminous
lGRBs

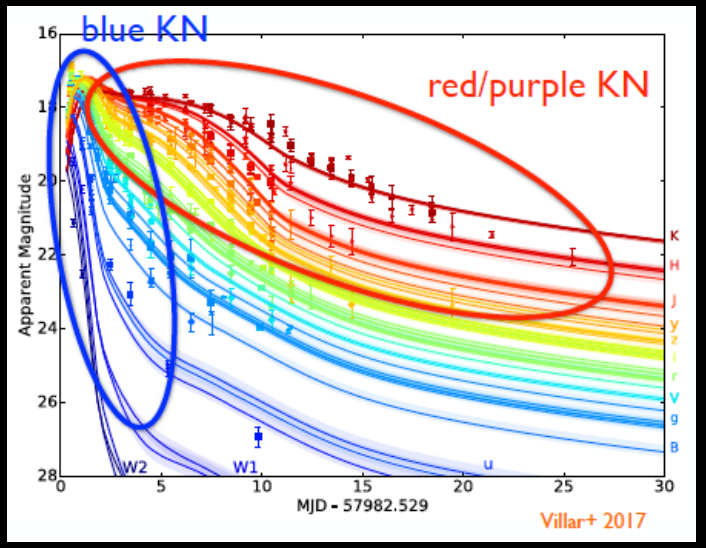
Hypernovae & GRBs





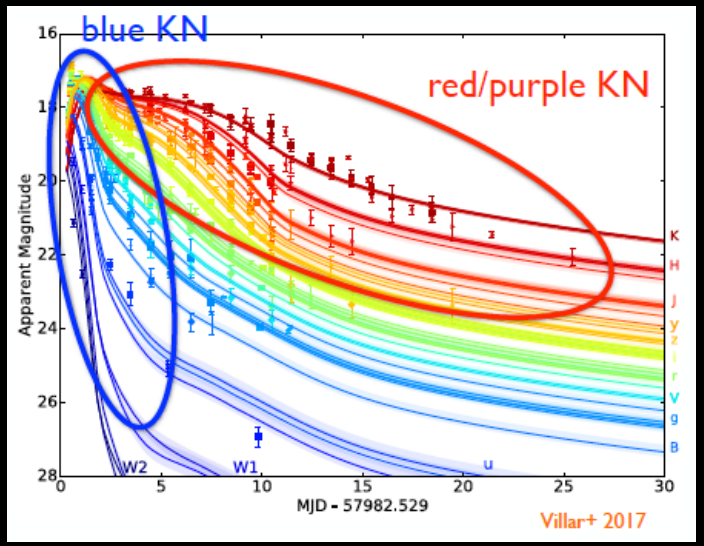


Neutron star mergers, kilonovae and sGRBs



GW170817 has demonstrated the massive potential in MMA but open questions remain:

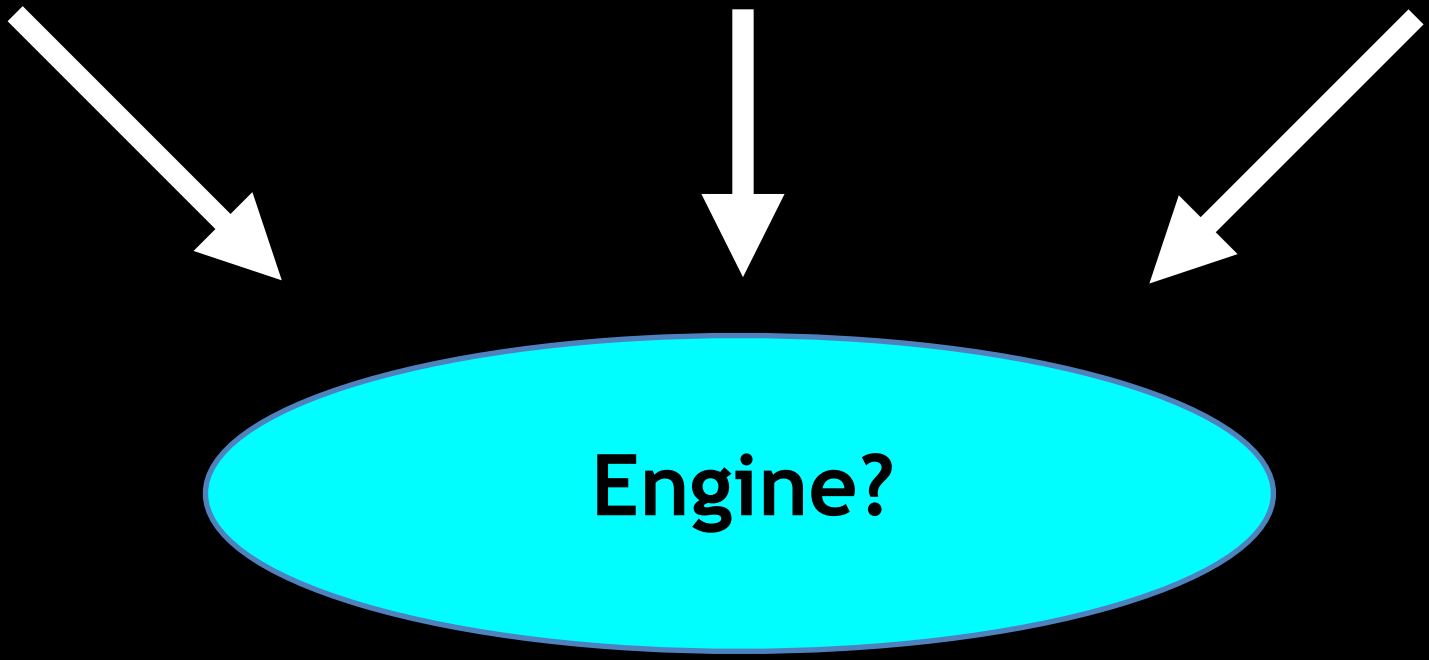
Neutron star mergers, kilonovae and sGRBs



- Remnant lifetime and fate
- sGRB engine: black hole vs magnetar, structure of the jet
- Dynamical ejecta and disk outflows: composition and amount of ejecta -> EM observations

The engine(s) driving these transients

Superluminous Hyperenergetic SNe lGRBs



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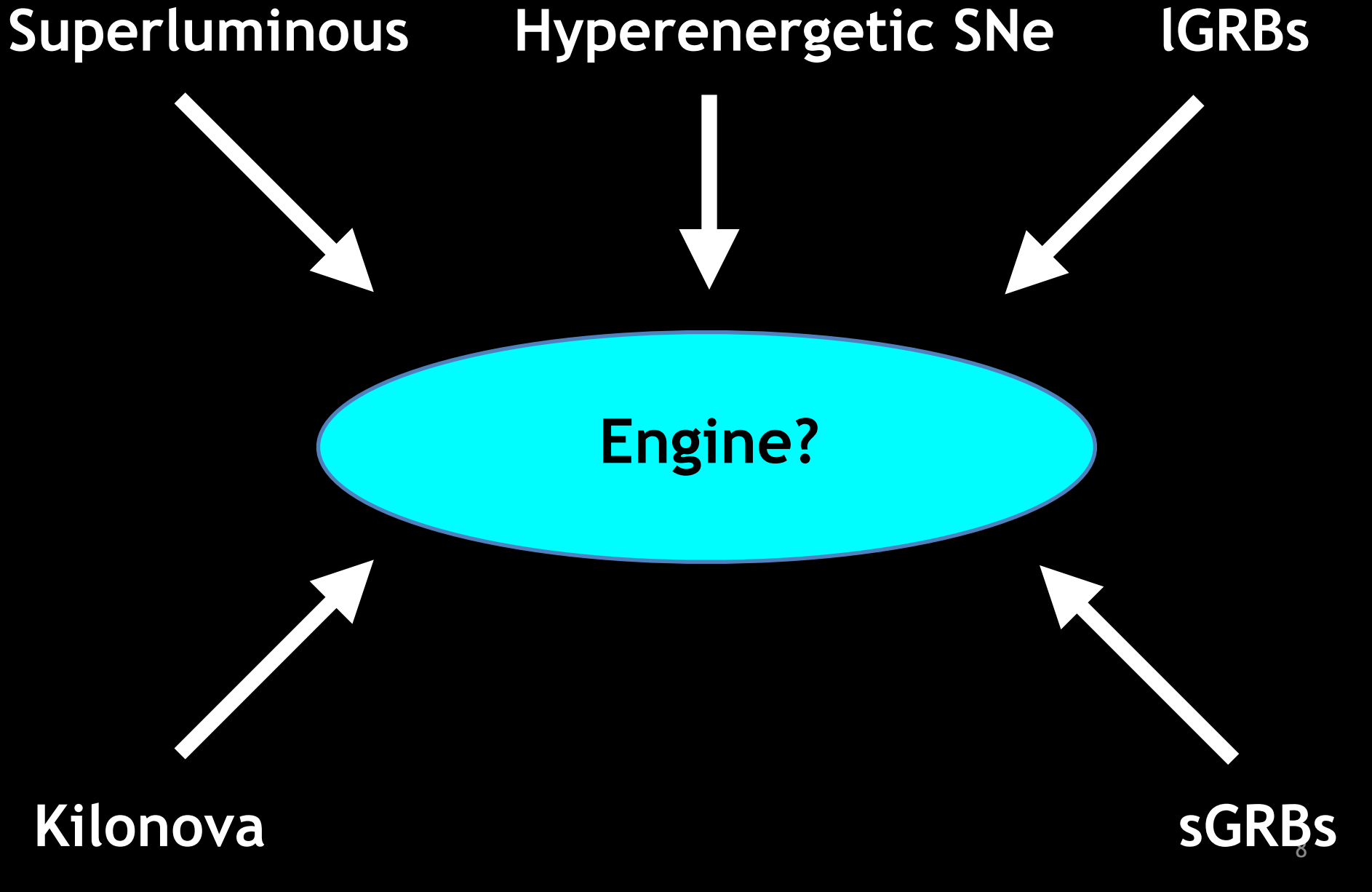

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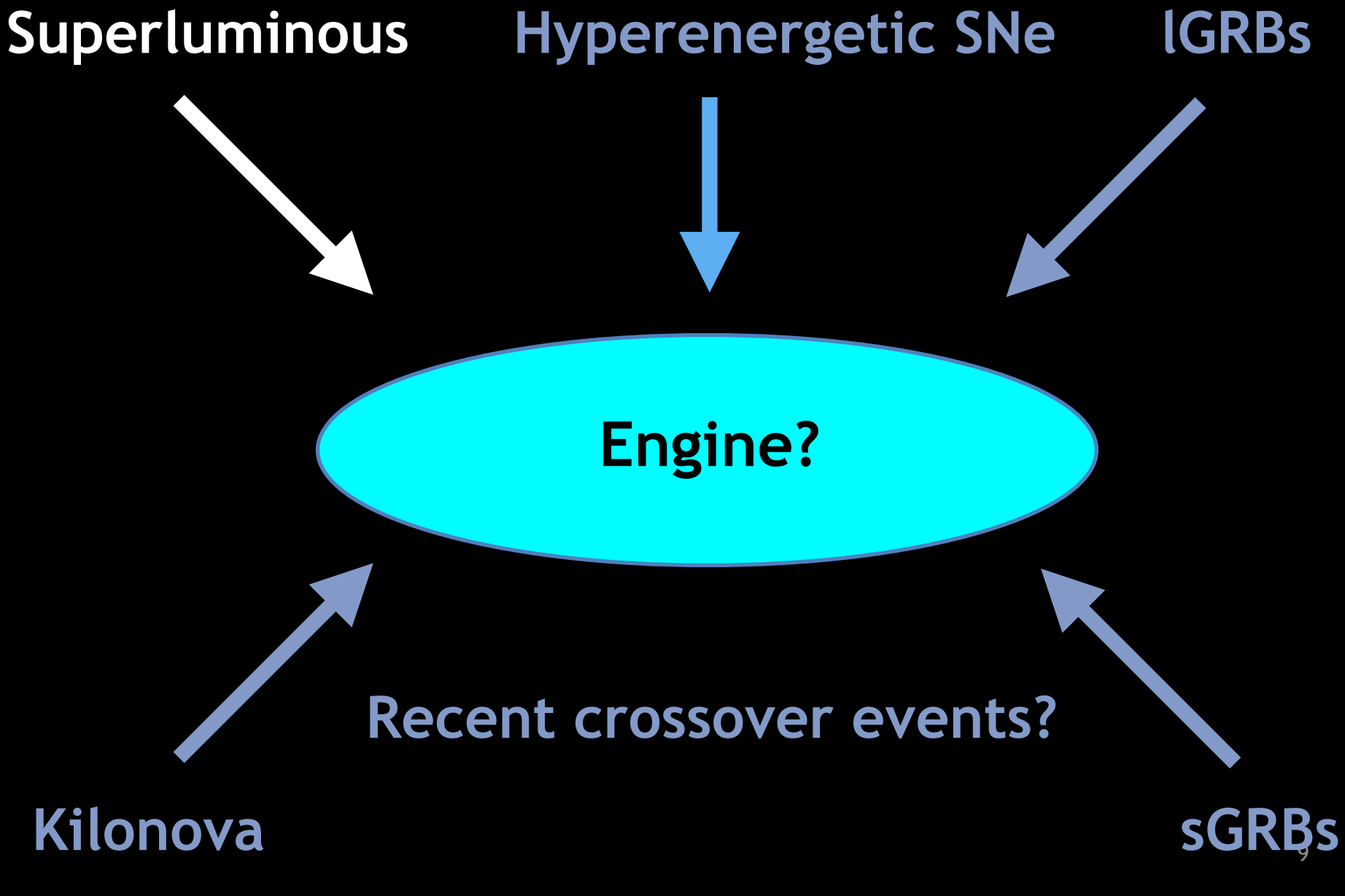
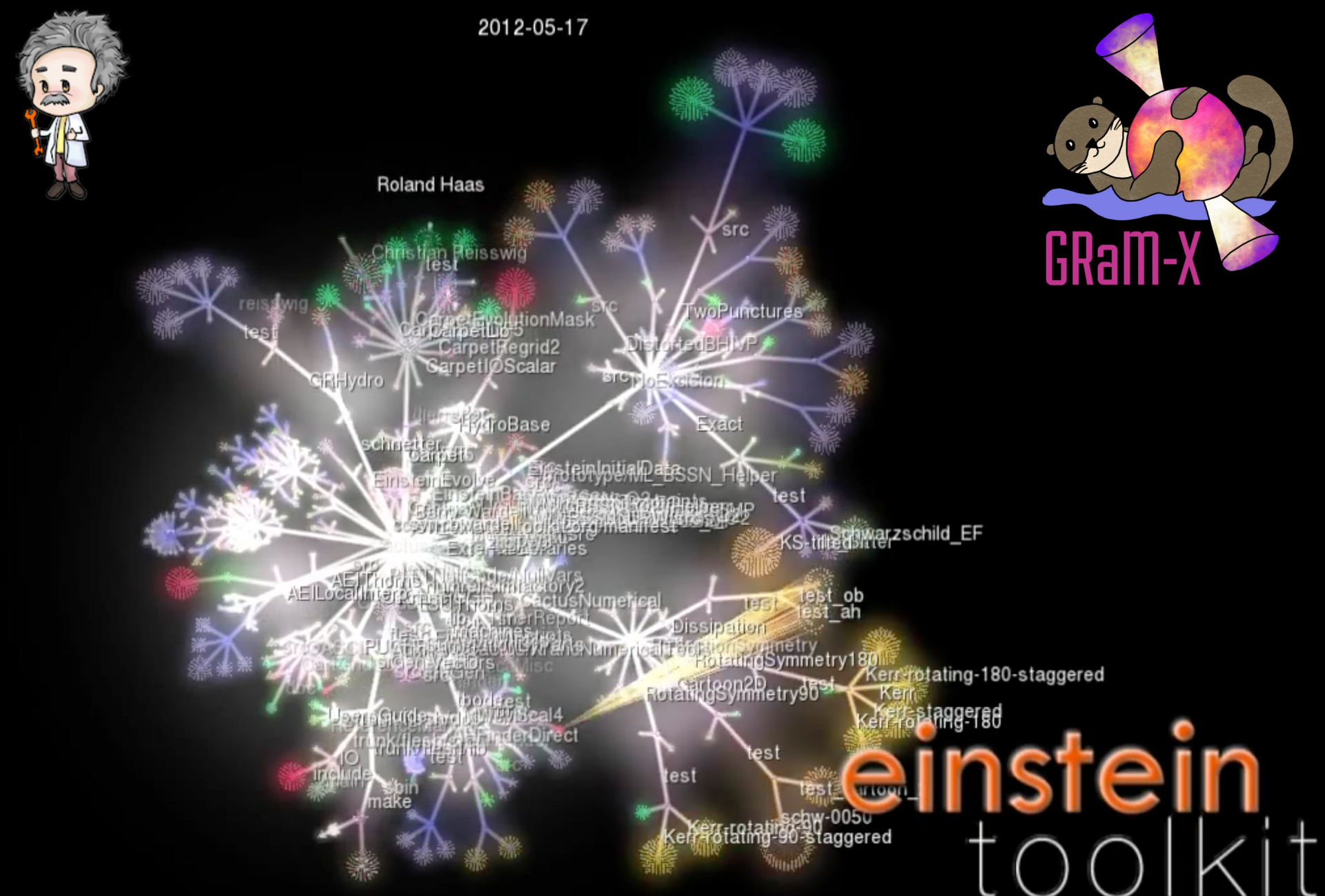




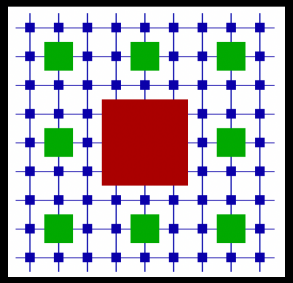
einstein toolkit

http://einsteintoolkit.org

GRaM-X: GPUs

Dynamical-spacetime simulations of supernova and neutron-star mergers on GPUs on the world's fastest supercomputers

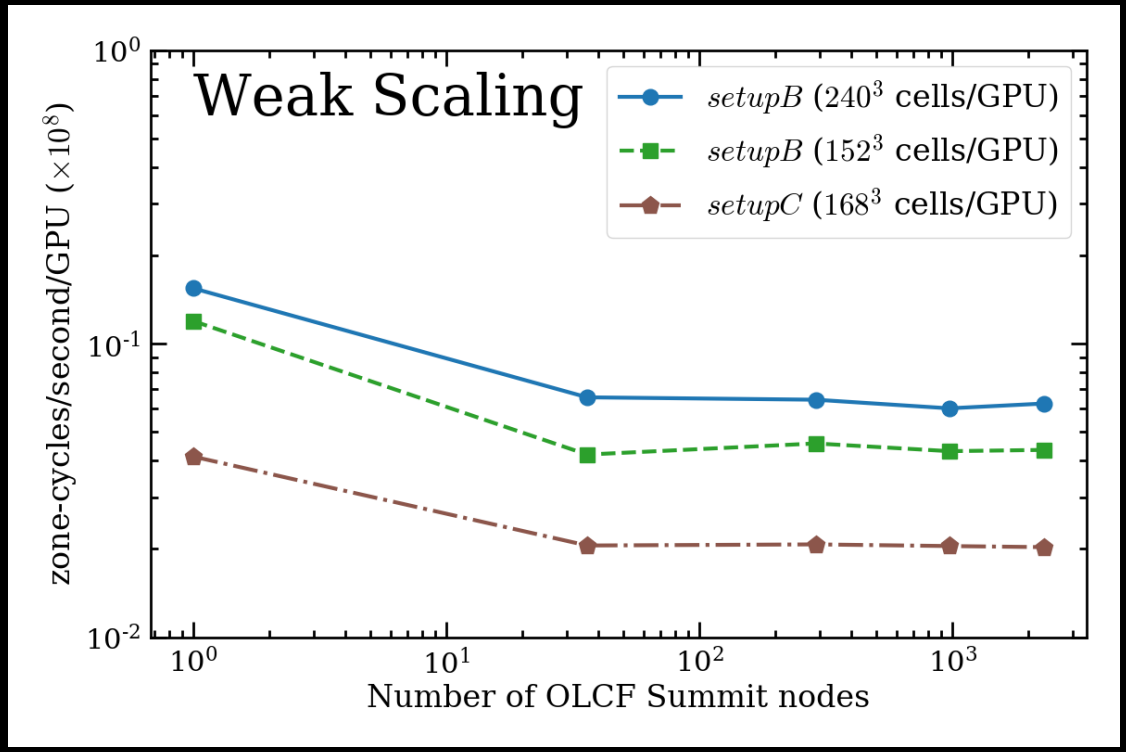
Developed within the CarpetX/Einstein Toolkit framework

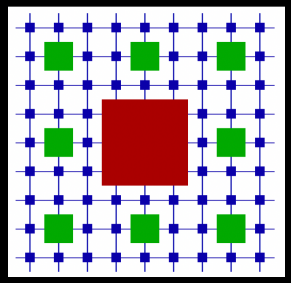


with Swapnil Shankar

einstein toolkit

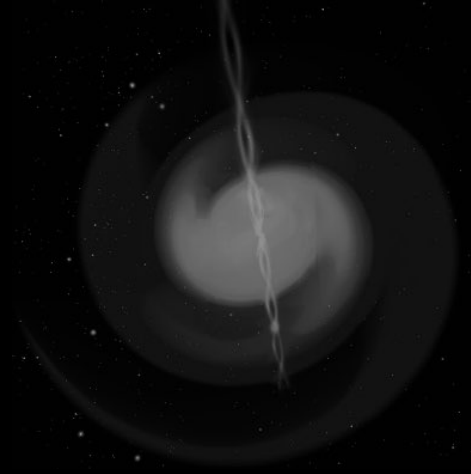
GRaM-X: GPUs

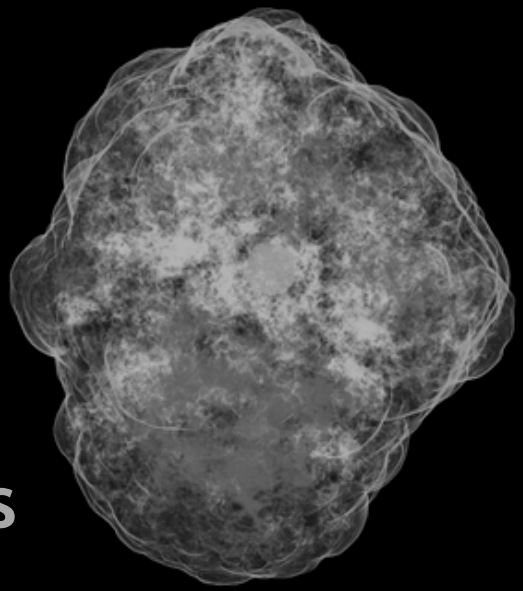




Efficiency of 40-50% on 2304 Summit nodes (13824 GPUs)

einstein toolkit





Core-collapse supernovae
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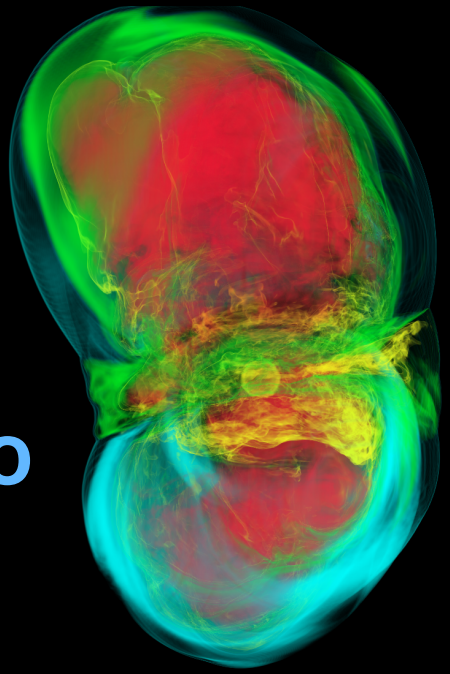
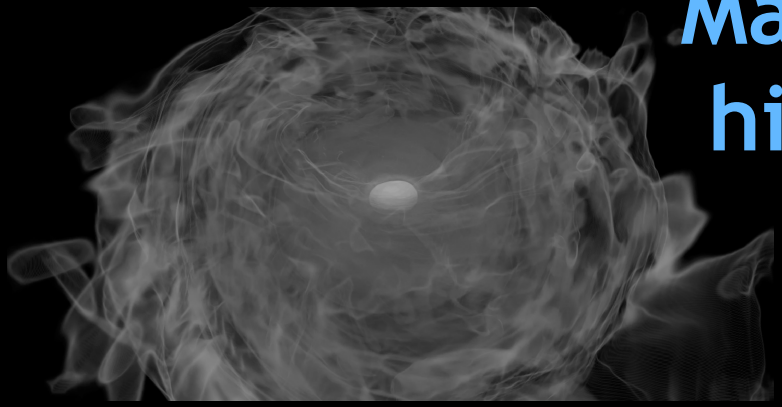


Magnetic fields in high-energy astro



Binary neutron stars
gravitational waves
EM counterparts
sGRBs

Extreme core-collapse
hyperenergetic
superluminous
lGRBs

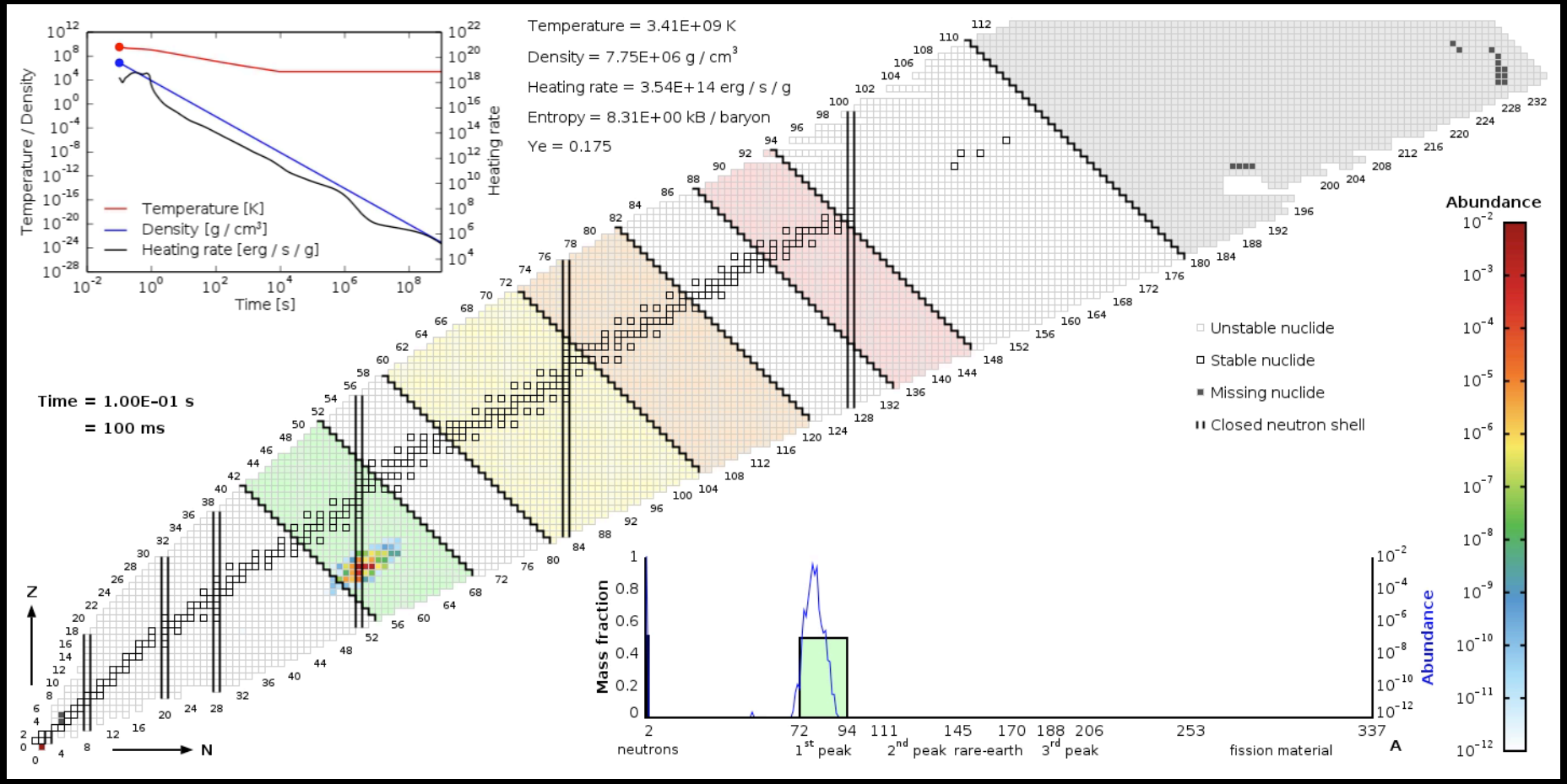
3D Volume Visualization of

t = -3.00 ms

Entropy

PM+ 14

Making the heaviest elements

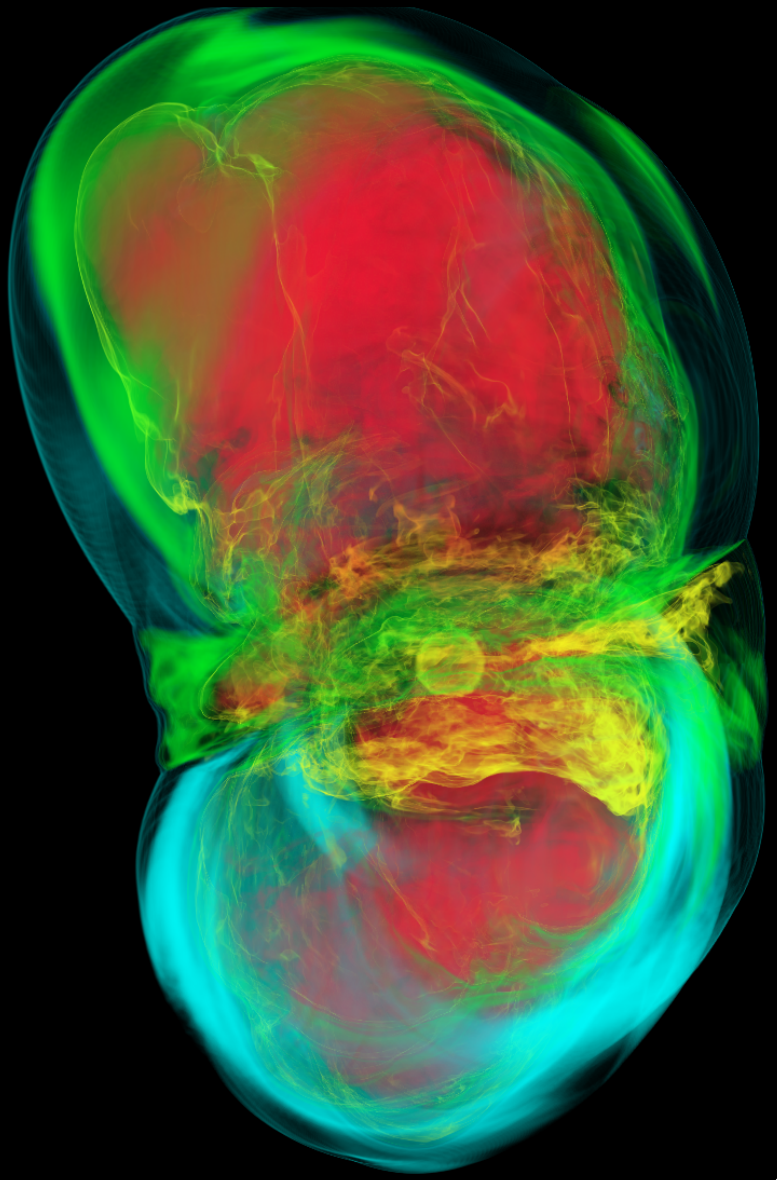


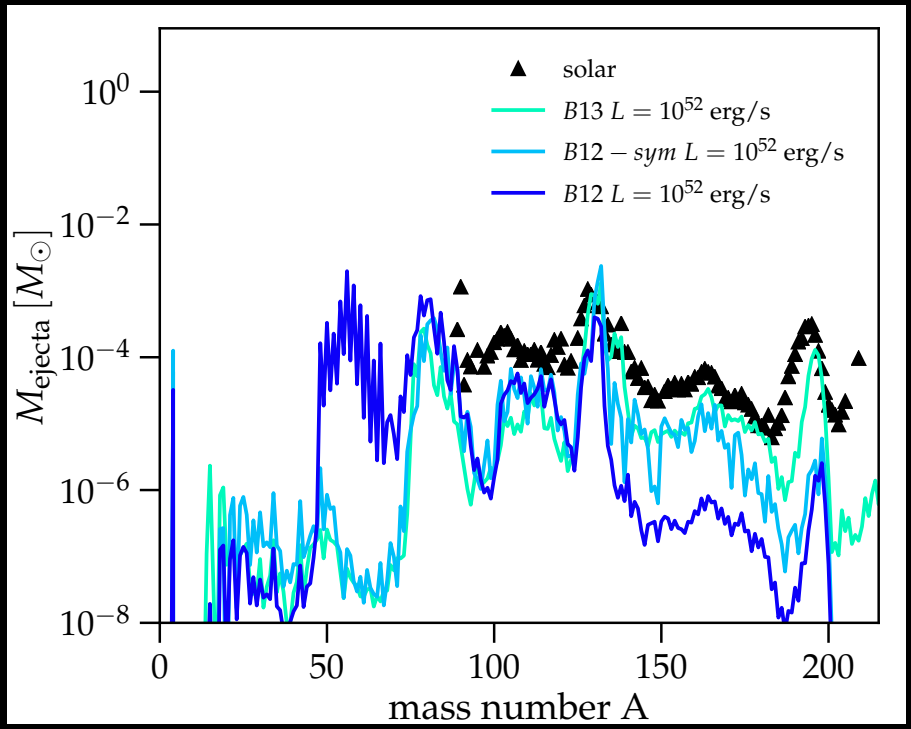
PM+ 18

Halevi, **PM**+ 18

with Goni Halevi

R-process nucleosynthesis in supernovae



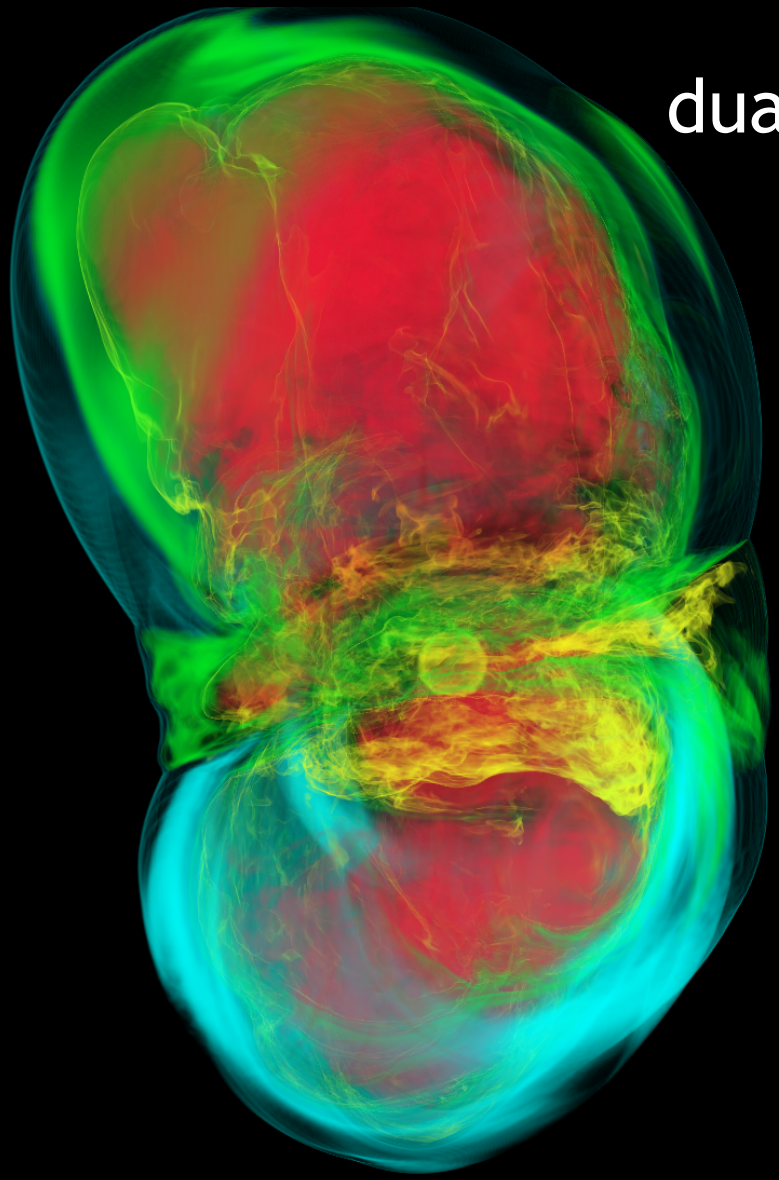


Explosion type determines nucleosynthetic outcome

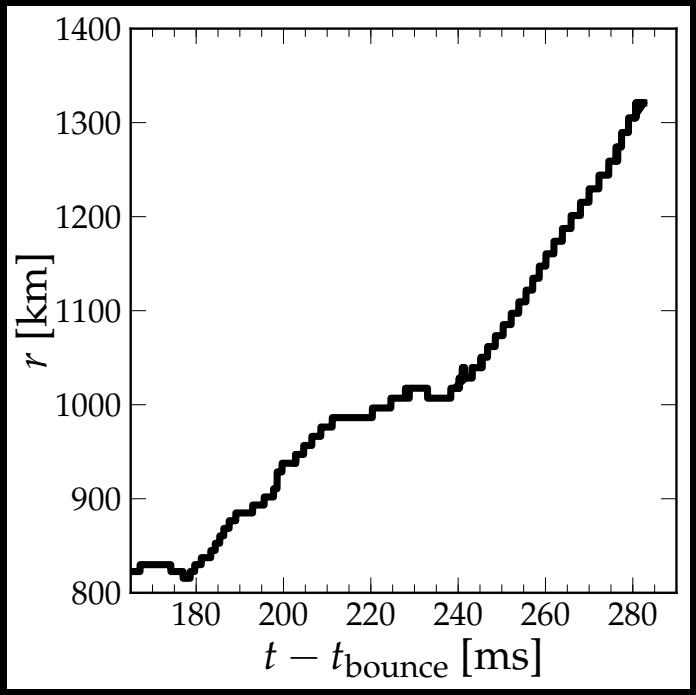
see also Martin's talk directly after

PM, Roberts, Halevi+ 18

Following the explosion



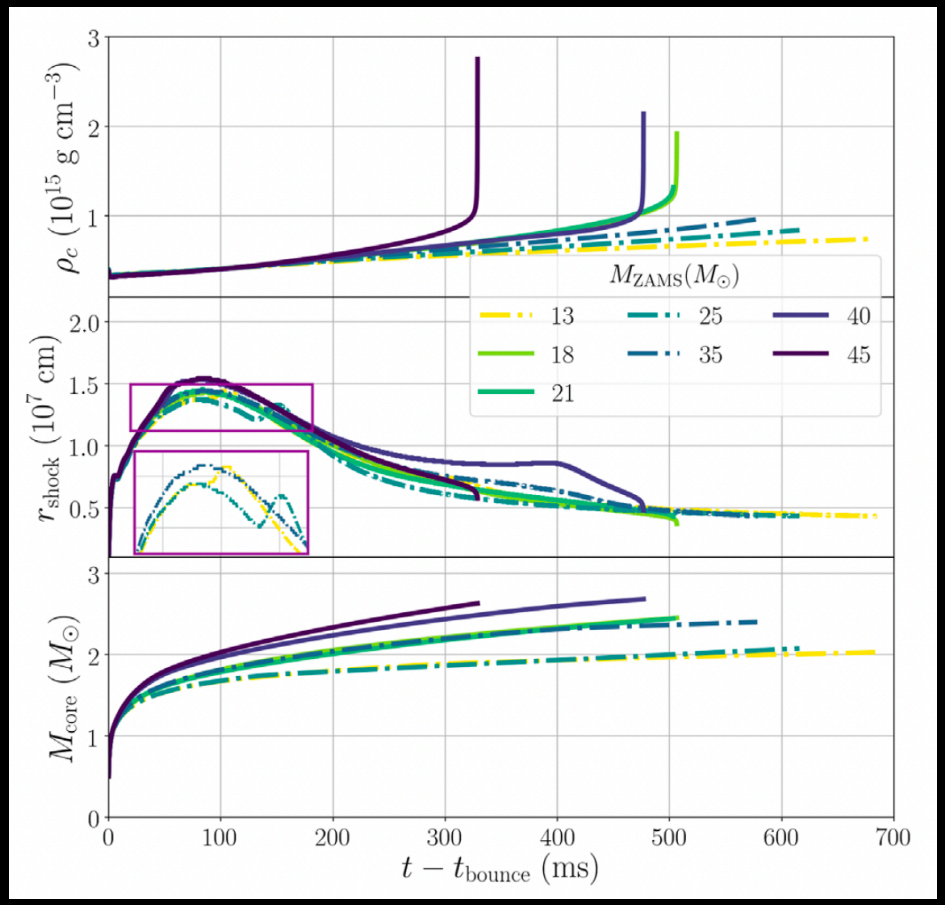
dual-lobe ‘slow’ explosion

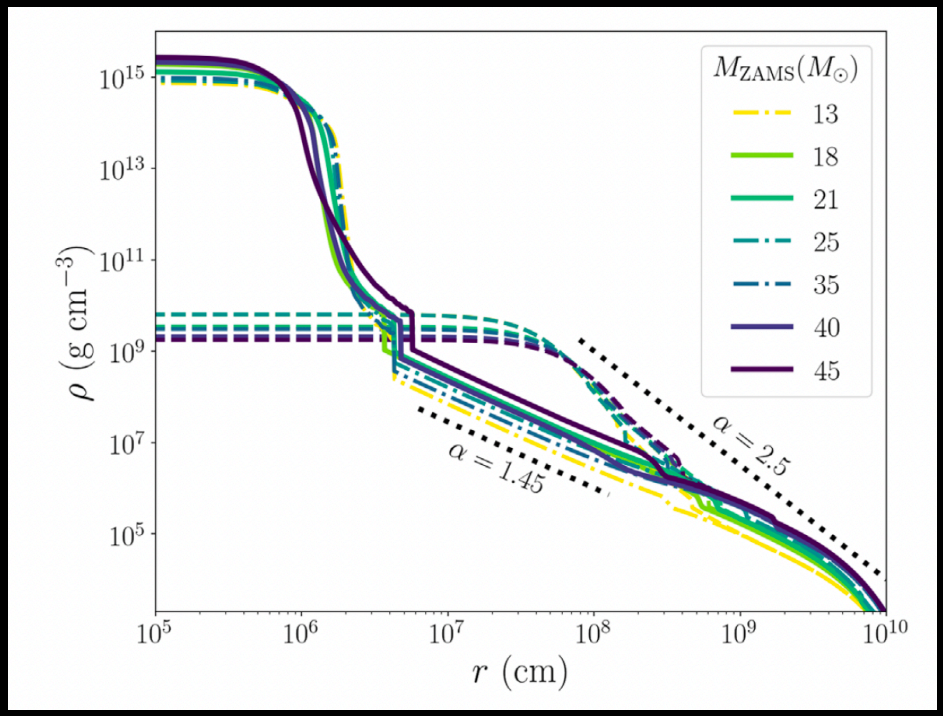


Continued accretion -> Black hole engine possible!

PM+ 18

All the way to black-hole formation



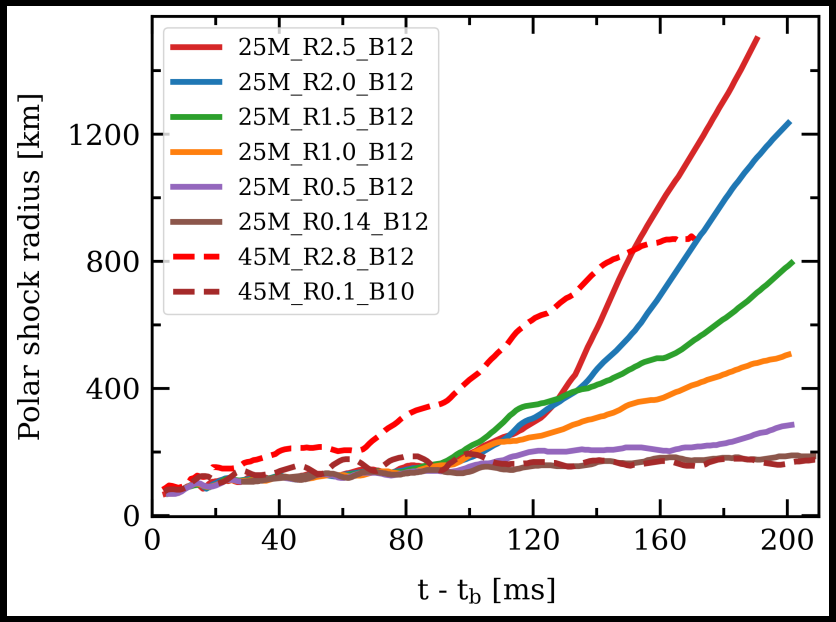


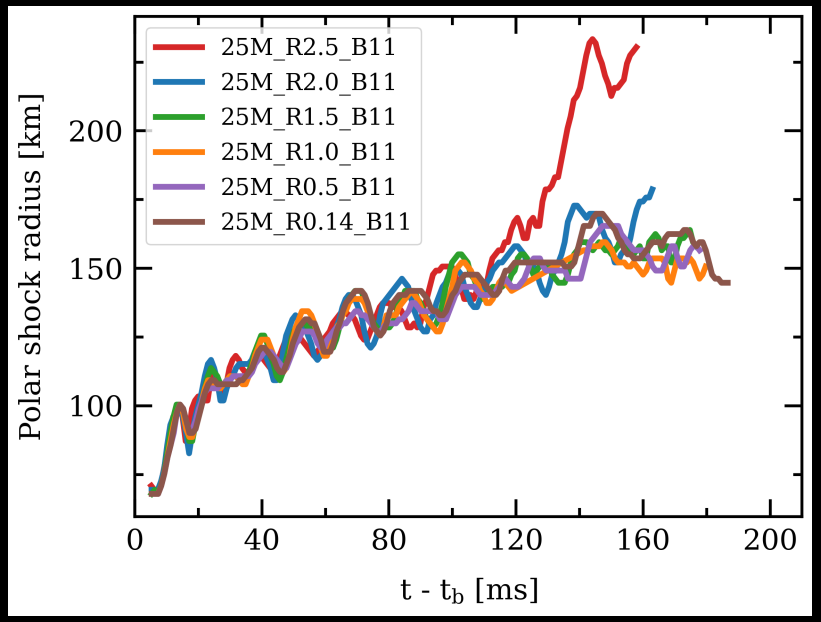
Halevi, Wu, **PM+ 23**

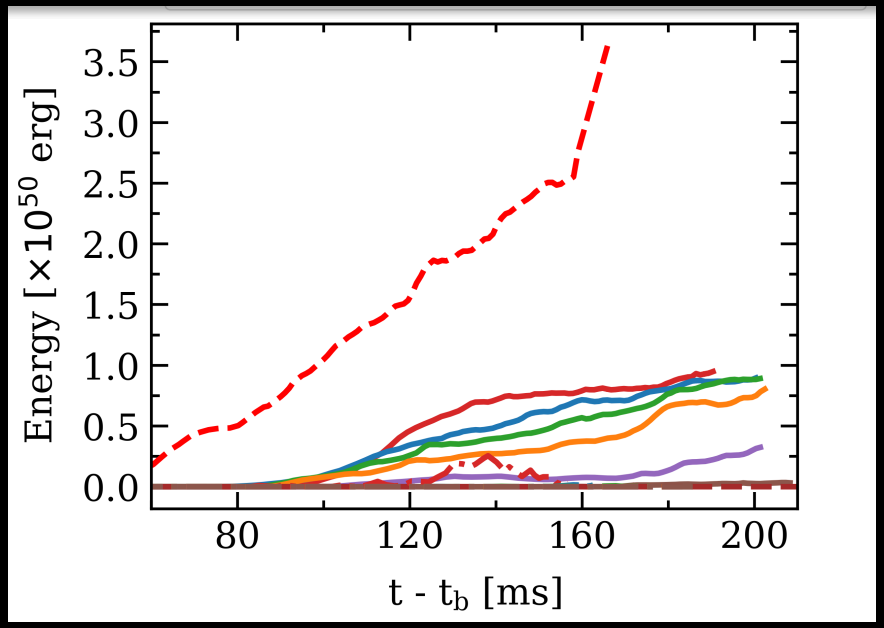
Simulations in 1.5d shows that these progenitors are favorable for lGRBs under the collapsar model

with Goni Halevi

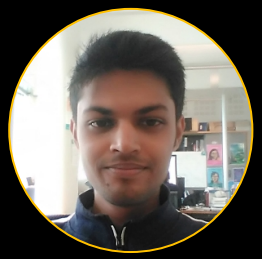
Towards a catalog of 3D supernova simulations





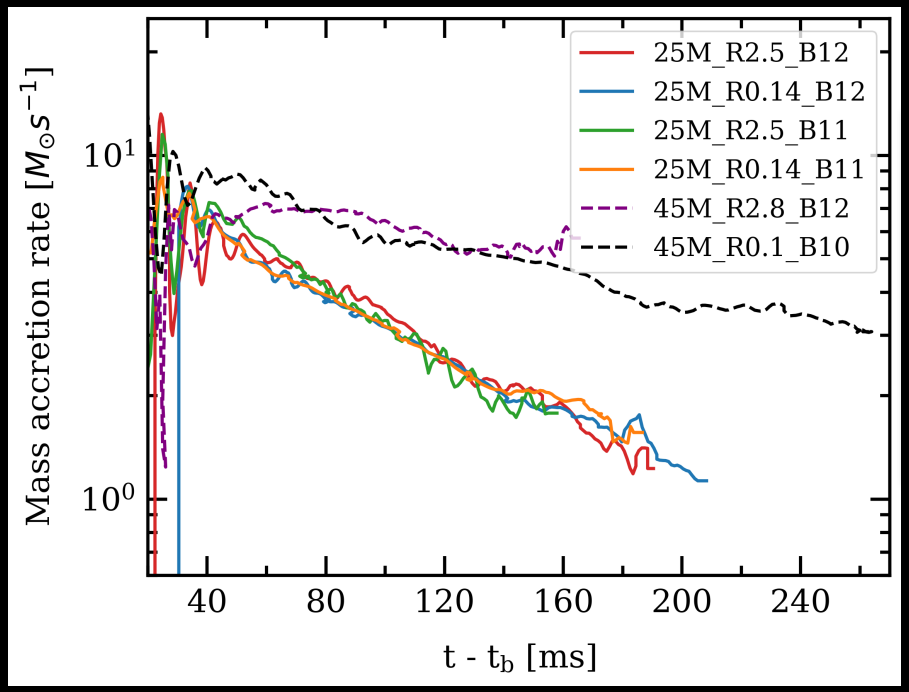


Shankar, **PM+** in prep 25



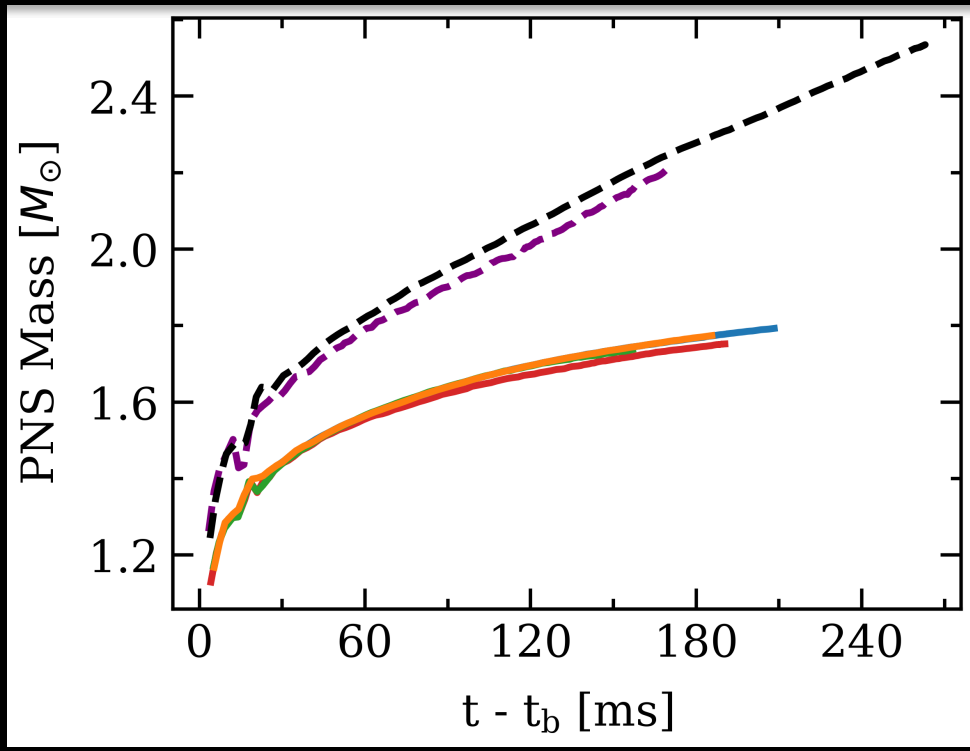
with Swapnil Shankar

Towards a catalog of 3D supernova simulations

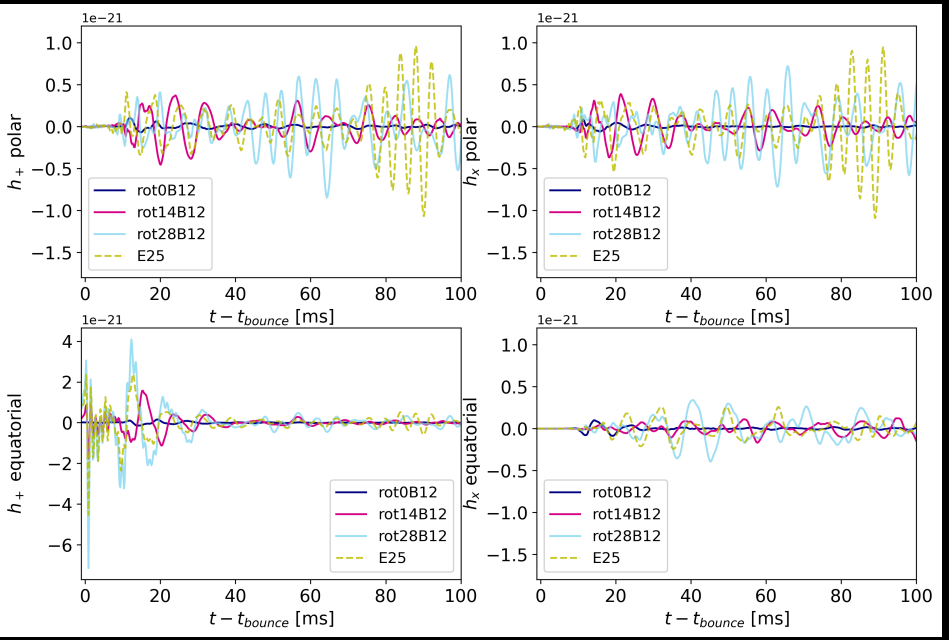


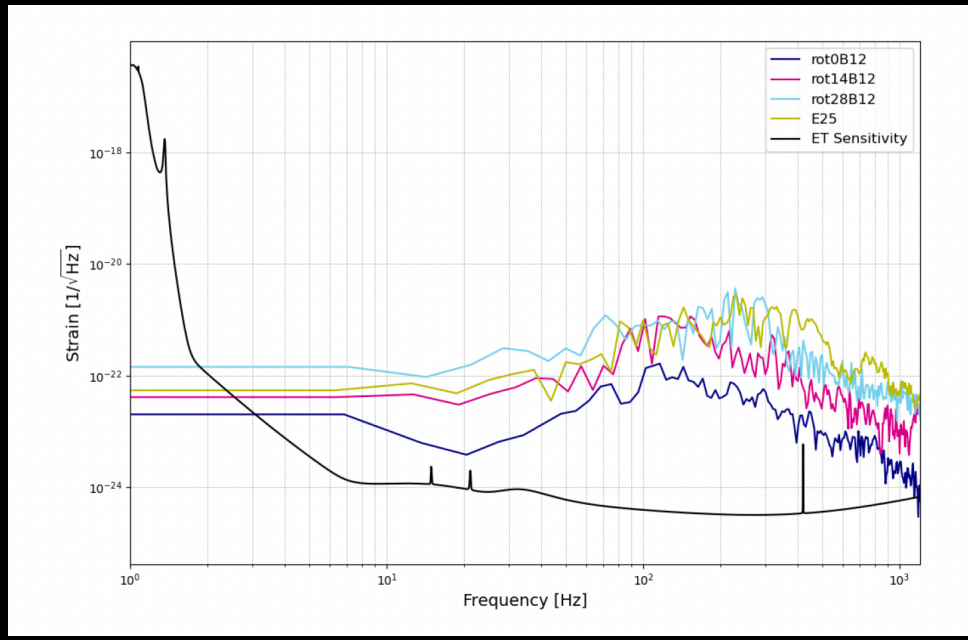
Shankar, **PM+** in prep 25

with Swapnil Shankar



Gravitational-wave signatures





Schnauck, **PM+**, in prep 25

MHD-powered explosion promising gravitational wave sources for 3rd-generation detectors

Need to massively upgrade our understanding of dynamics and gravitational-wave emission from rotating explosions

with Sophia Schnauck

From simulations to observations

Observations:

- new transients classes and subclasses
- need detailed predictions to constrain engines

Simulations

- initial 3D simulations open up diverse outcomes
- magnetic fields crucial component for signatures

Need mapping:

progenitor -> engine -> observations

From simulations to observations

State of the art now:

Detailed simulations
full physics
0.1-1s
~10000km

engine formation/dynamics
gravitational waves
nucleosynthesis

From simulations to observations

State of the art now:

Detailed simulations
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From simulations to observations

State of the art now:

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Current challenge:

1) engine model from full-physics simulations
2) simplified simulations with engine model to shock breakout

explosion geometry explosion energy
nucleosynthesis
basic engine model

with Swapnil Shankar

From simulations to observations

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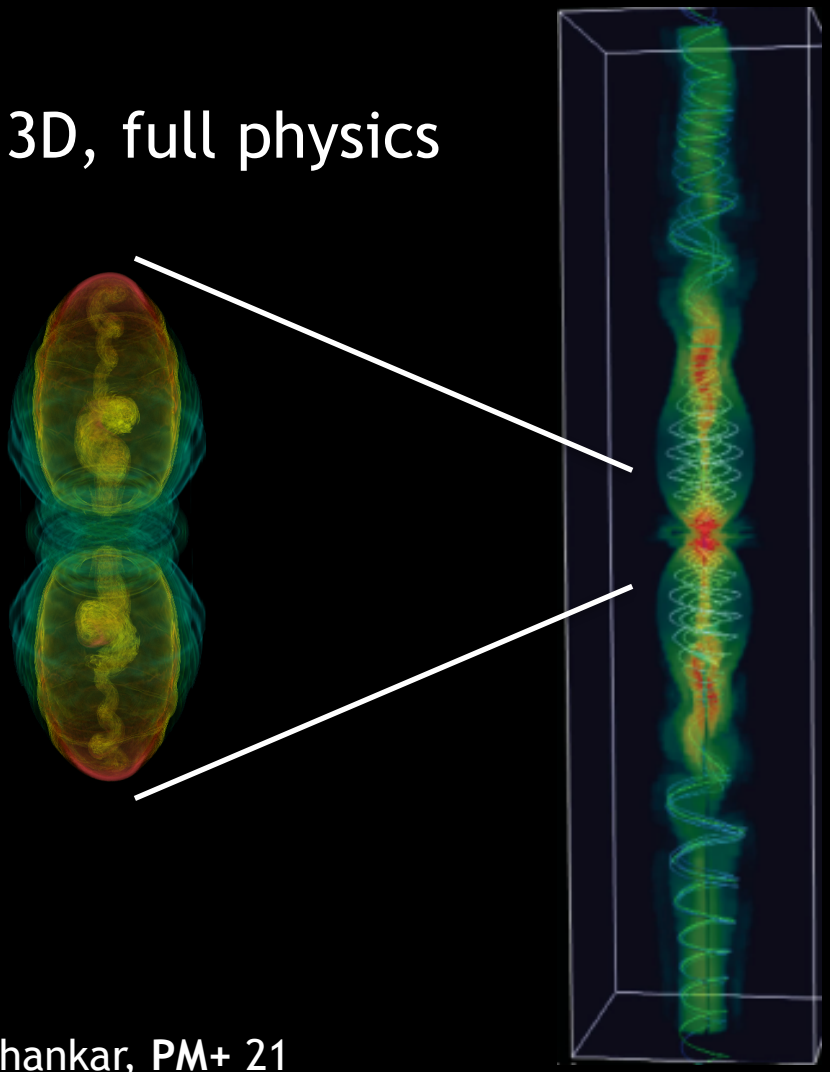
with Swapnil Shankar

Full 3D, full physics

Full star



Shankar, **PM+** 21

From simulations to observations

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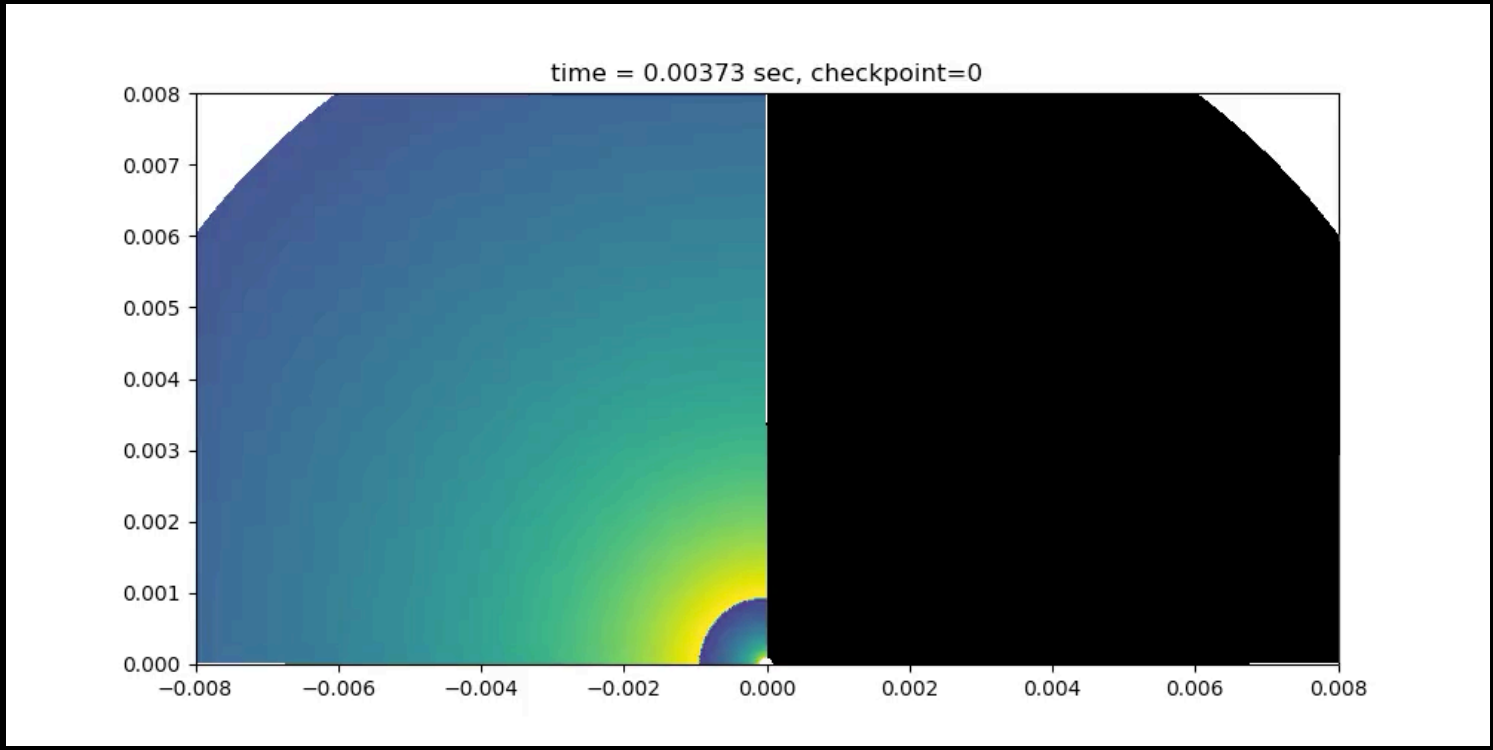
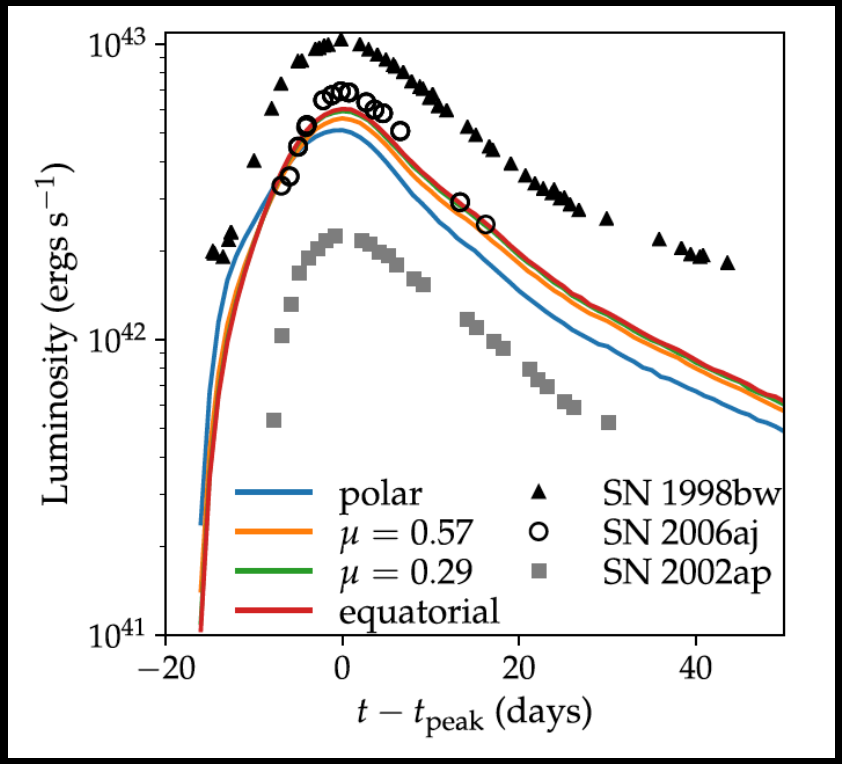


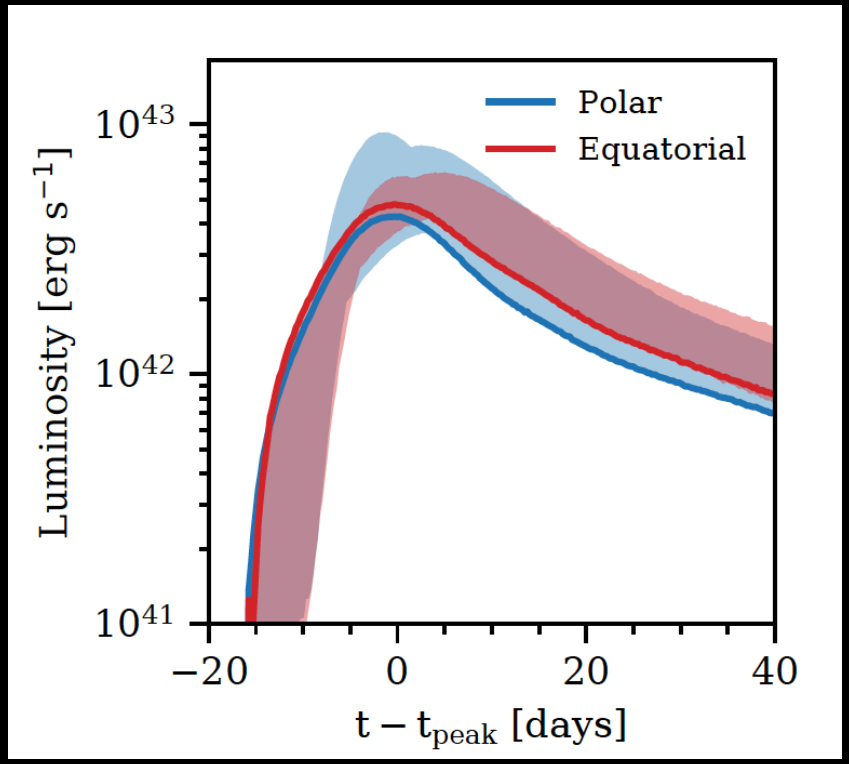
Shankar, PM+ 21

From simulations to observations

Simplified simulations with engine model

Engine model from full 3D simulation



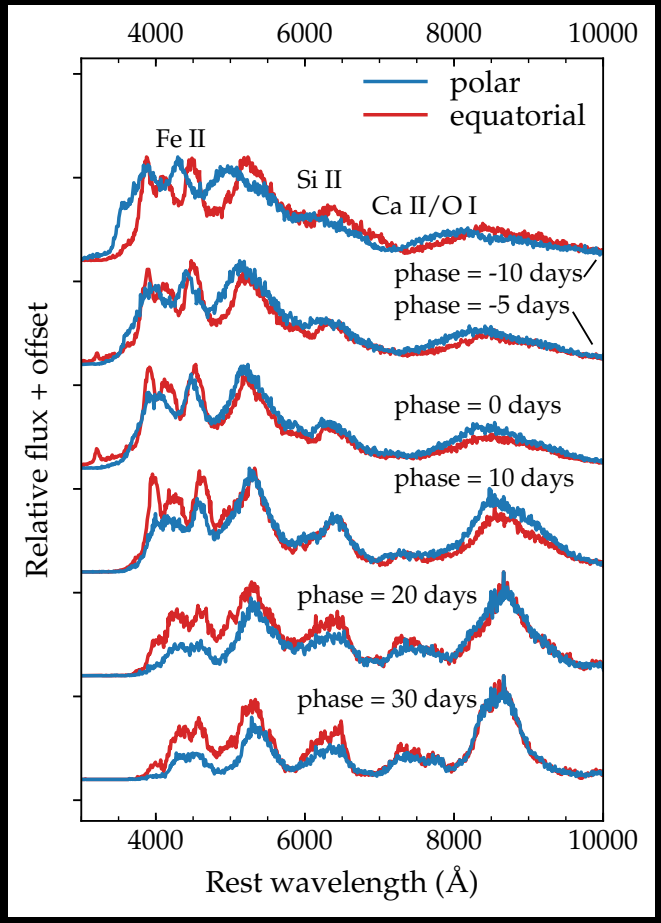


Barnes+ **18**

Shankar, **PM**+ 21

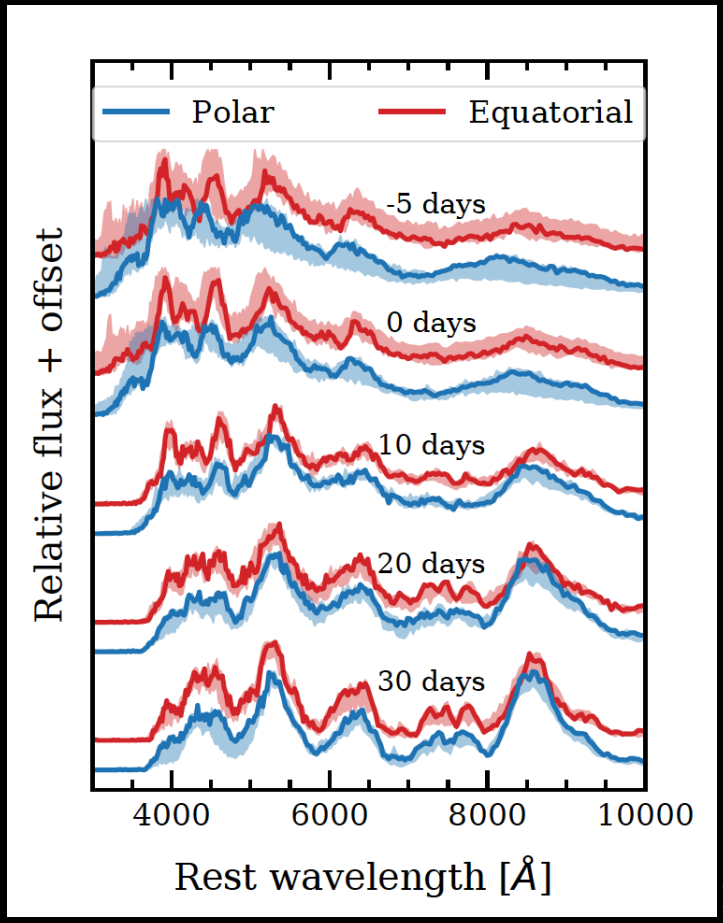
From simulations to observations

Simplified simulations with engine model



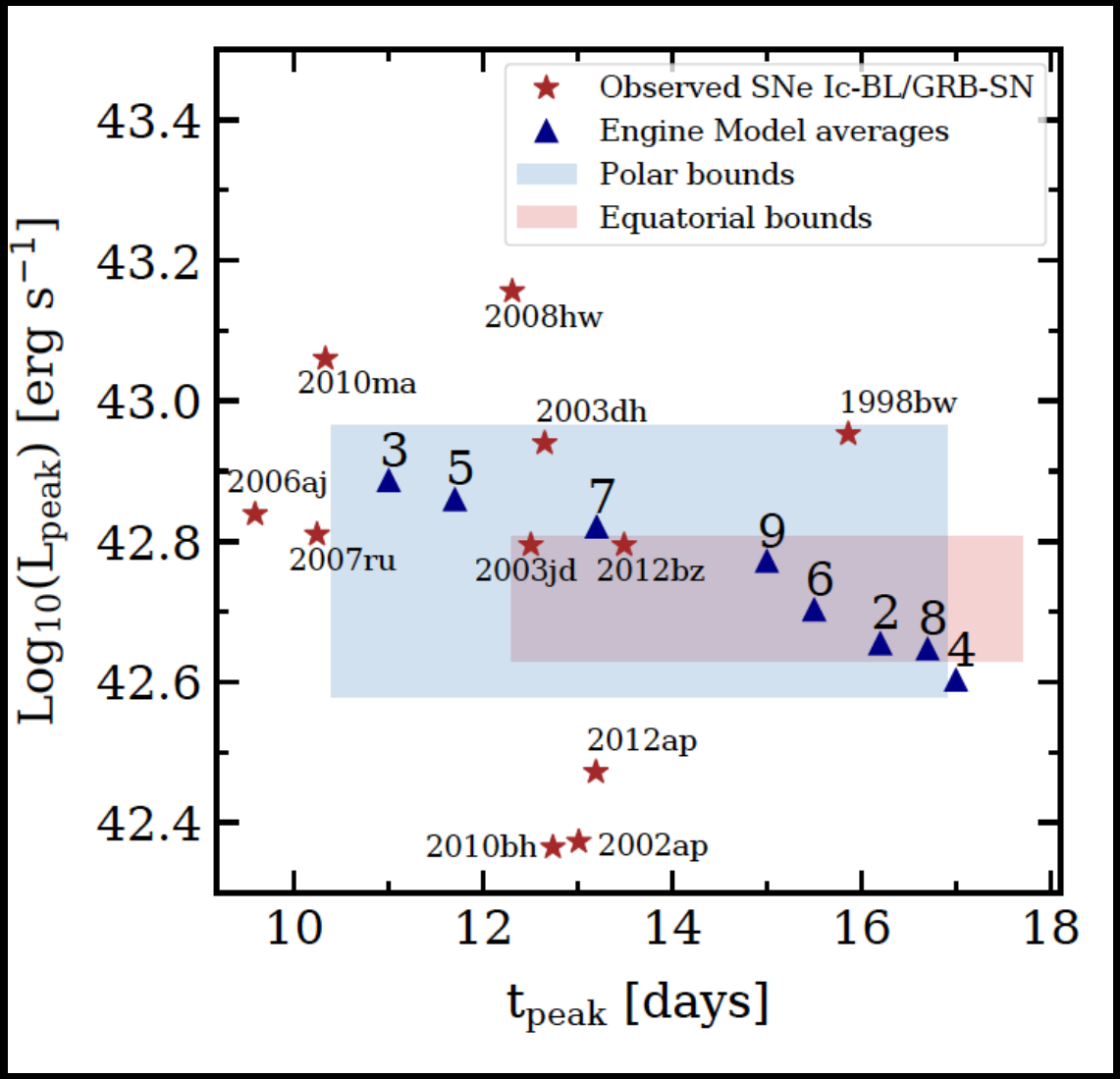
Barnes+ 18

Engine model from full 3D simulation



Shankar, PM+ 21

From simulations to observations



Shankar, **PM**+ 21

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~10000km

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Where do we want to go?

full-scale simulations
propagation effects

detailed emission
detailed radio signatures
connect observations and engines
map engine parameters, environment

From simulations to observations

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Where do we want to go?

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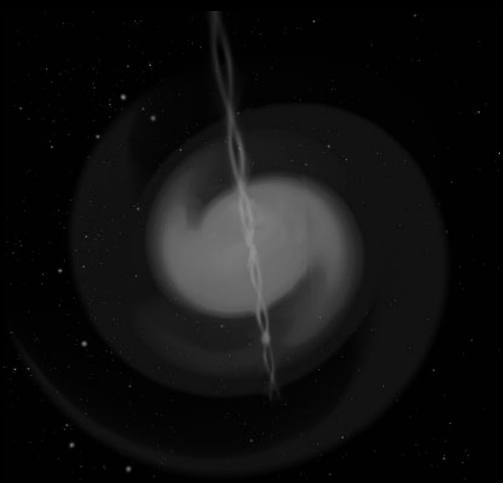
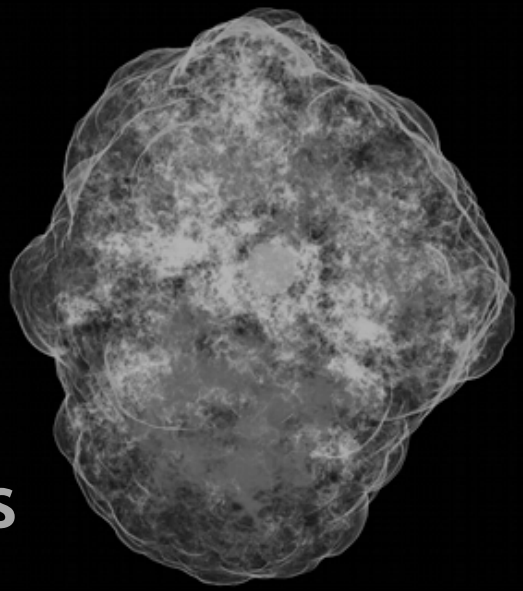
But how do we do this? GPUs? Sophisticated computational algorithms





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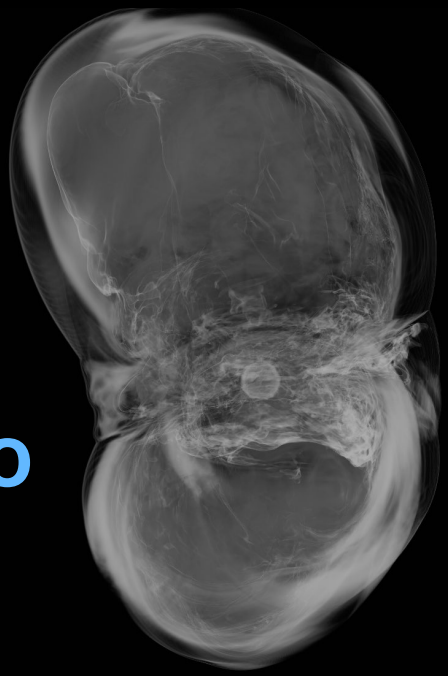
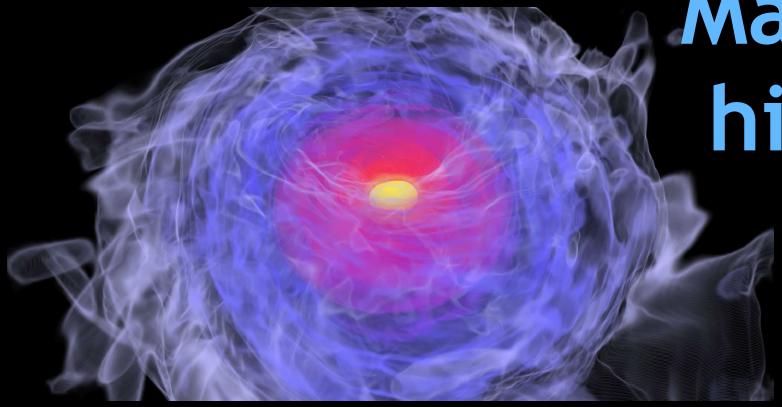


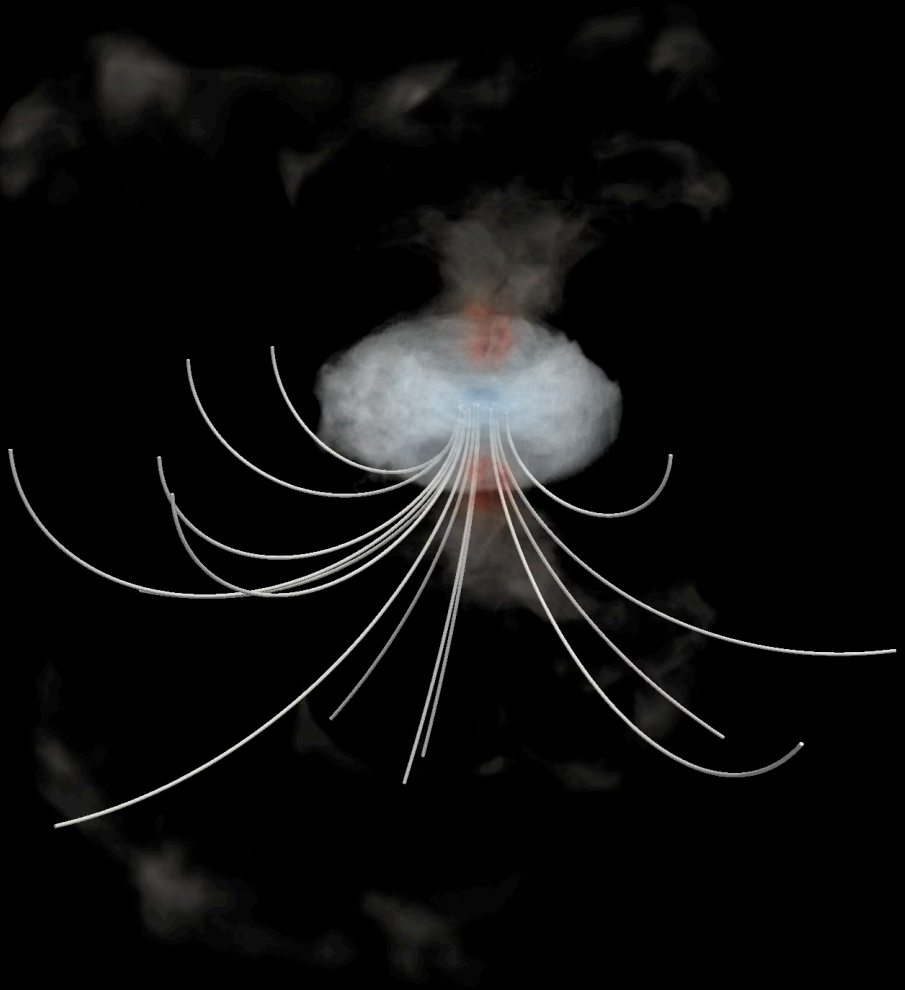
Magnetic fields in high-energy astro



Binary neutron stars
gravitational waves
EM counterparts
sGRBs

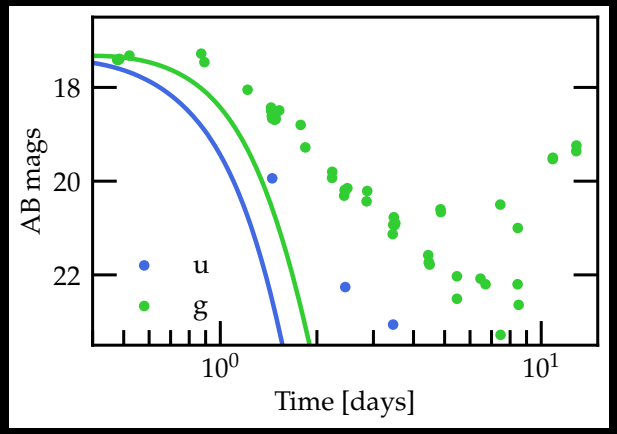
Extreme core-collapse
hyperenergetic
superluminous
lGRBs

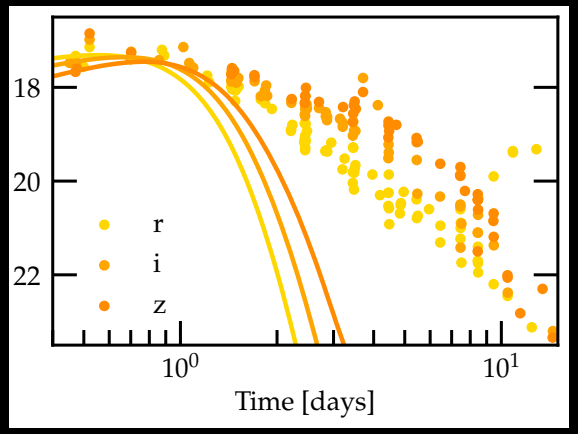
Merger remnant evolution

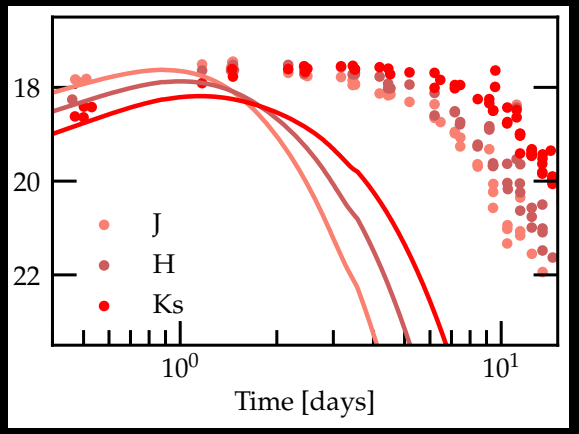


Nathanyel Schut

Kilonova from HMNS outflows





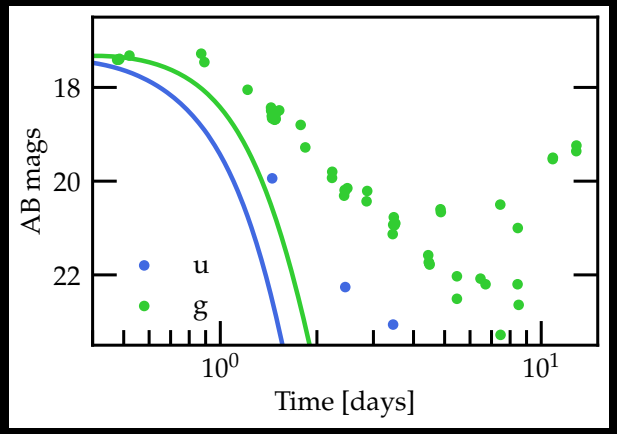


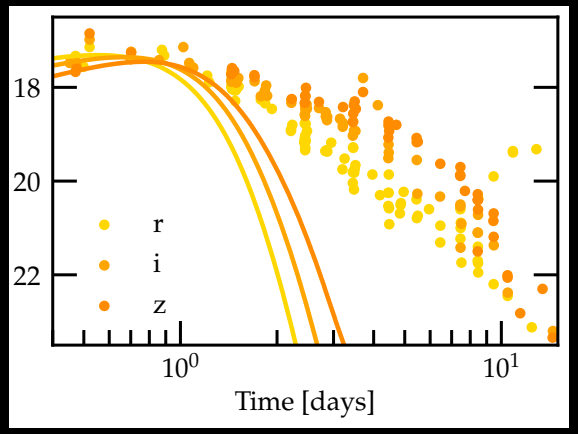
Curtis, Bosch, PM+ 23

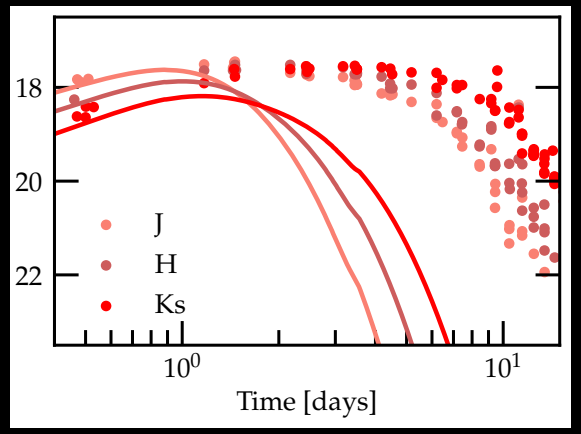
Curtis, PM+ 21

with Sanjana Curtis

Kilonova from HMNS outflows







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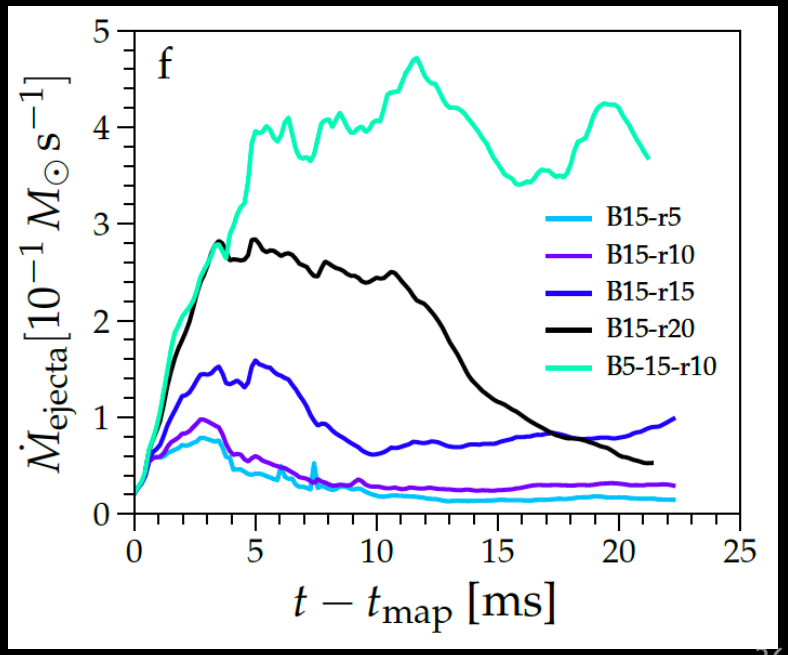
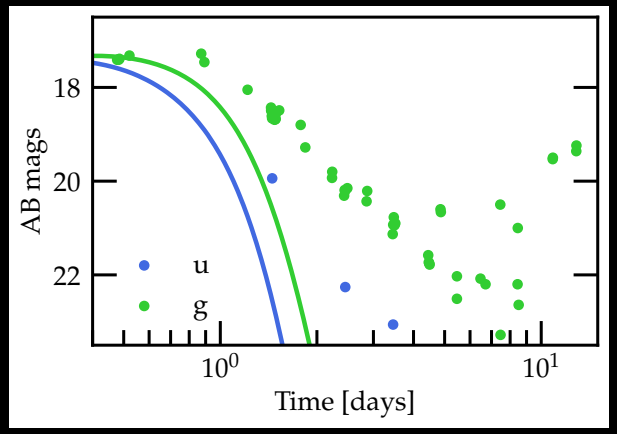
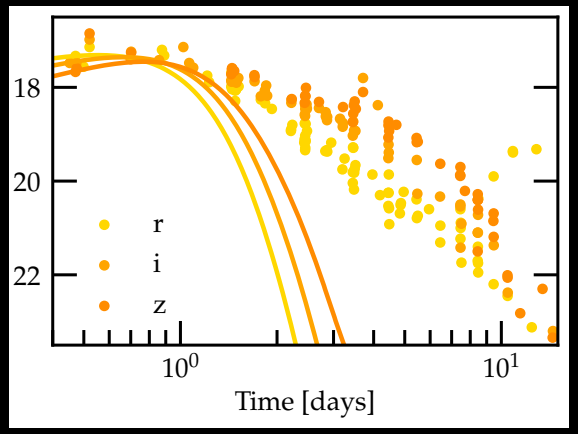
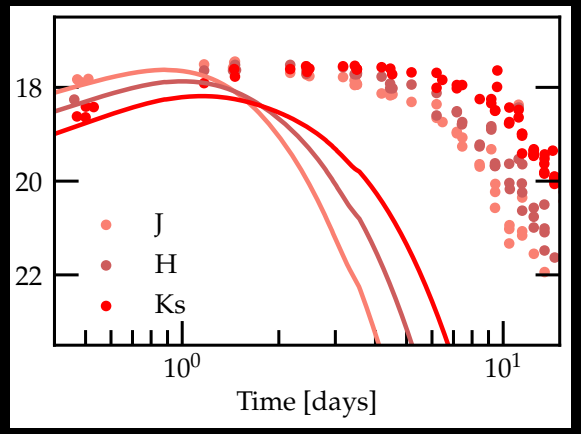


with Sanjana Curtis

Kilonova from HMNS outflows



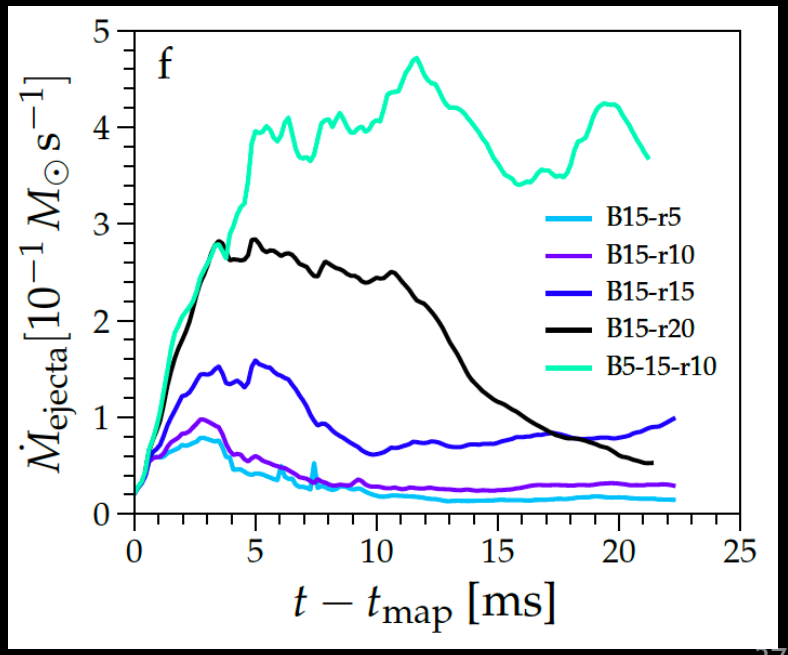




Curtis, Bosch, PM+ 23

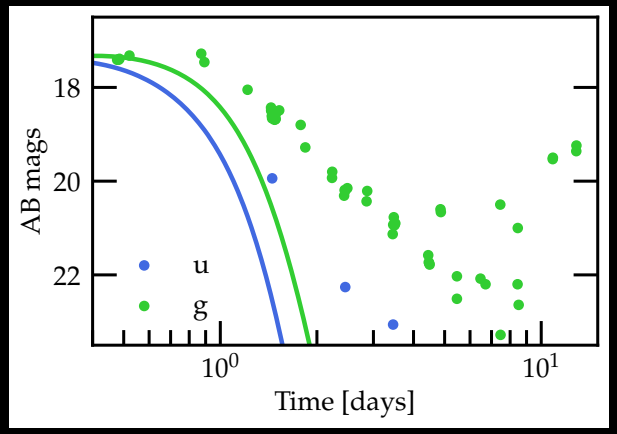
Curtis, PM+ 21

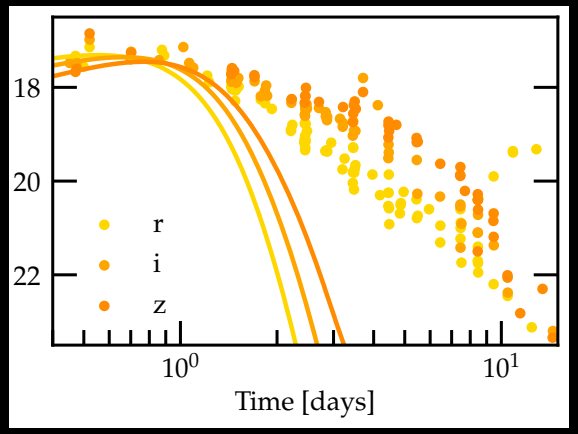
Steady-state operation allows us to predict kilonova outcomes

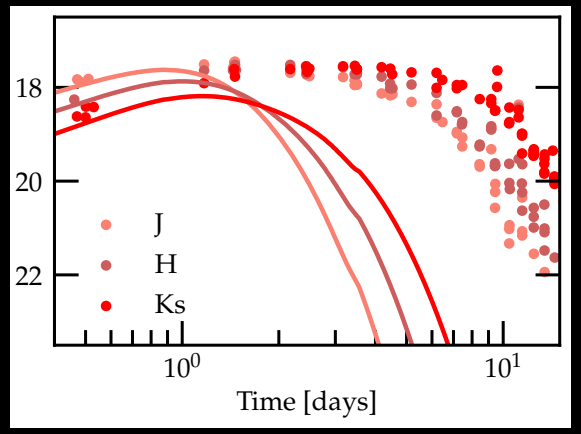


with Sanjana Curtis

Kilonova from HMNS outflows







Curtis, Bosch, PM+ 23

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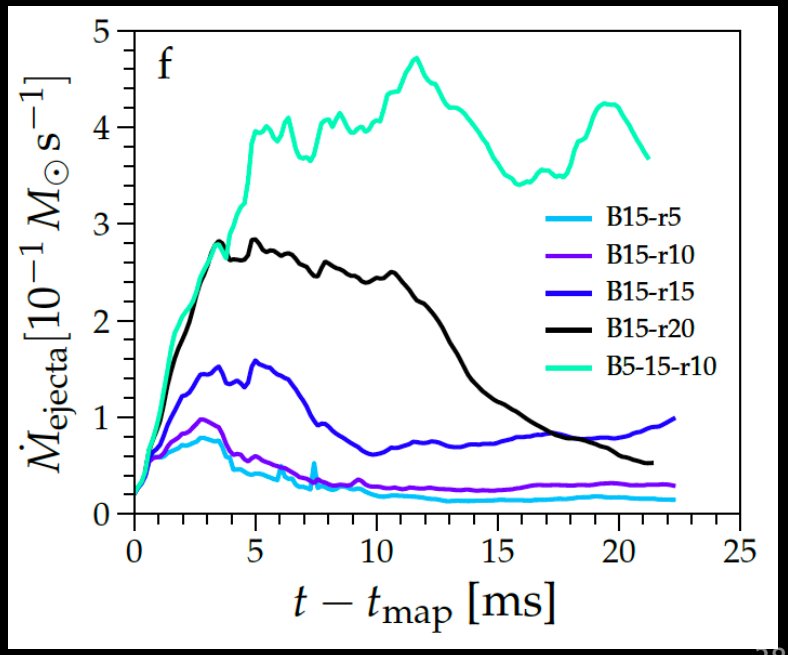
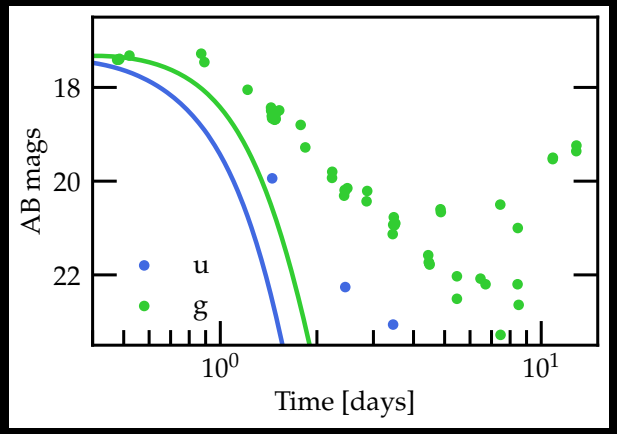
Steady-state operation allows us to predict kilonova outcomes

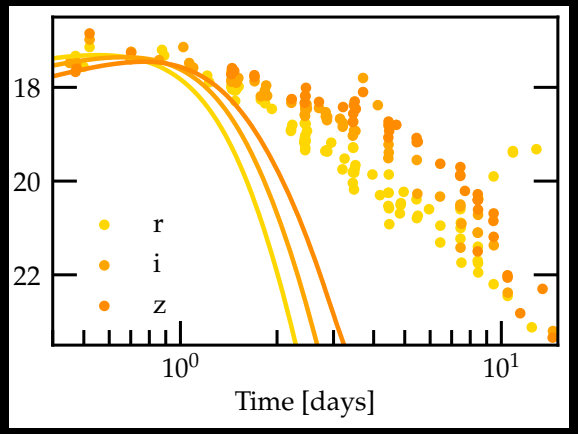
with Sanjana Curtis

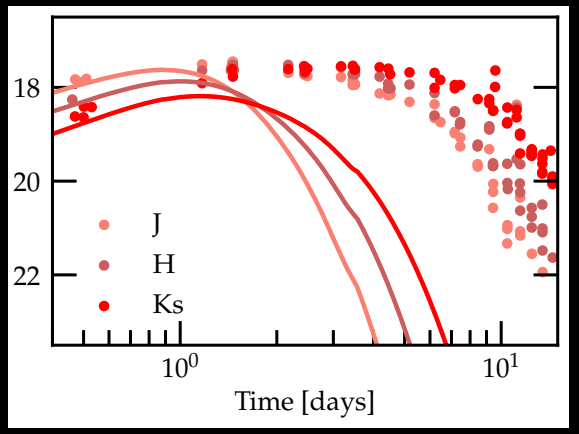
Can we disentangle engine parameters?



Kilonova from HMNS outflows







Curtis, Bosch, PM+ 23

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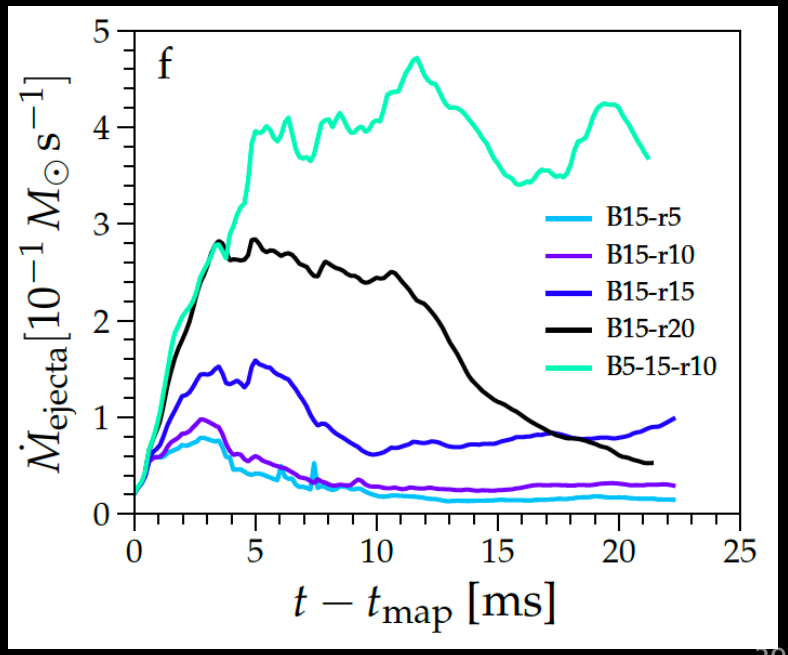
Steady-state operation allows us to predict kilonova outcomes

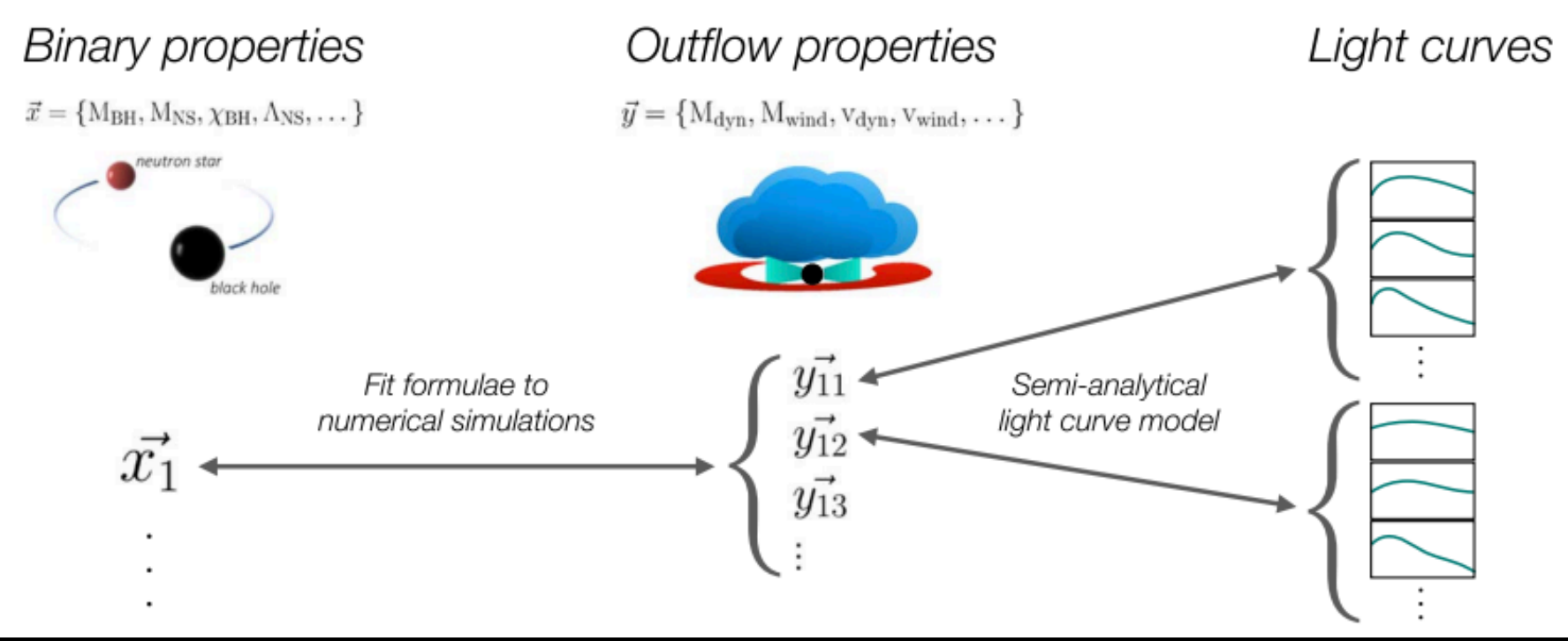
with Sanjana Curtis

Can we disentangle engine parameters?

See also Daniel and Kenta's talks



How can we put all of this together?



Raaijmakers+21

Ultimately need simulation-informed (semi-)analytic or machine-learning models for parameter estimation

Summary

New explosive transients challenge our engine models

Need detailed massively parallel 3D GRMHD simulations to interpret observational data

But also meaningful and efficient ways of producing observables from simulations

Summary

New explosive transients challenge our engine models

Need detailed massively parallel 3D GRMHD simulations to interpret observational data

A lot of potential/work in connecting detailed ab-initio models to observations and utilizing modern (GPU) compute environments

Establish mapping

progenitor -> engine -> observations