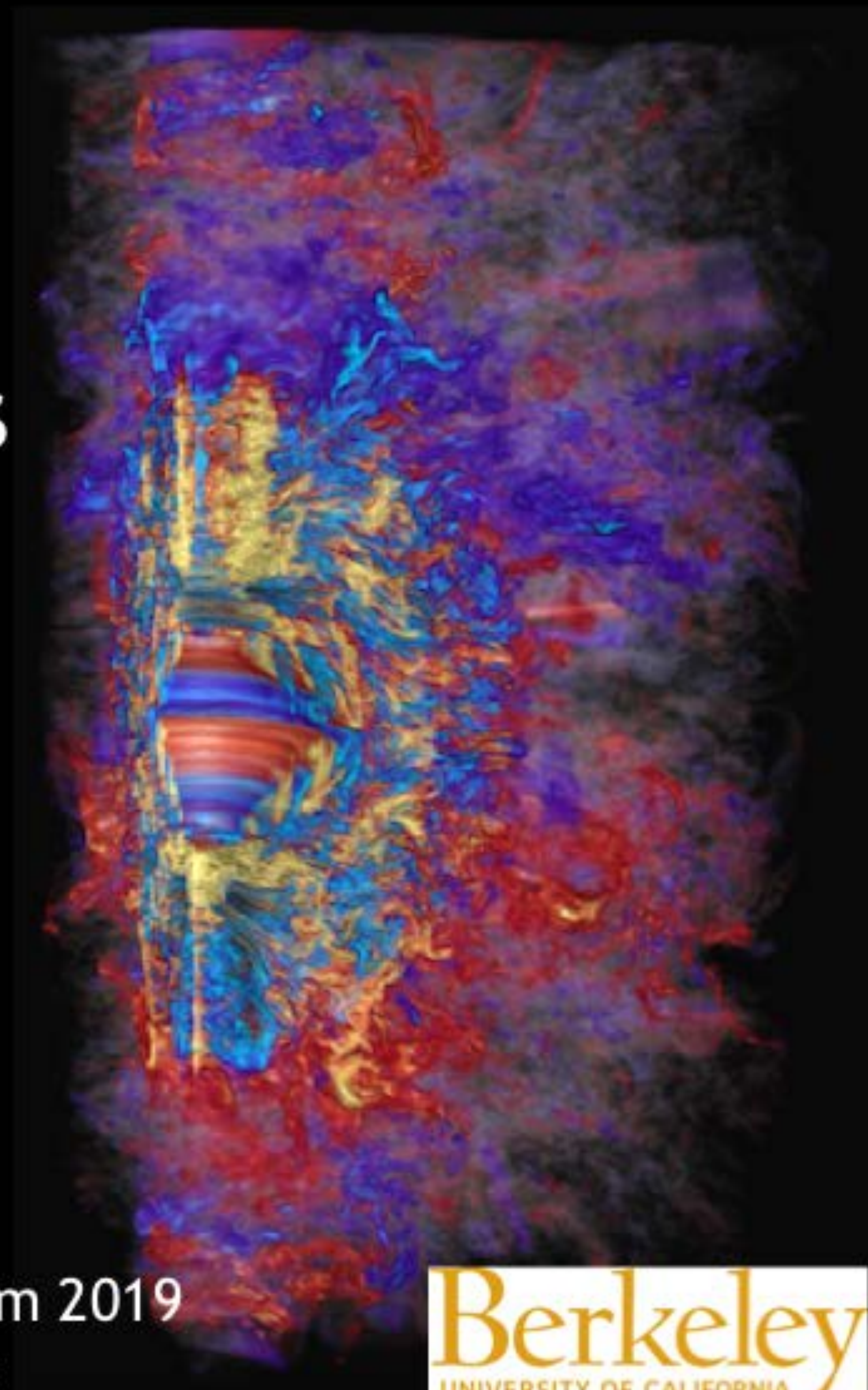
Magnetic field amplification in neutron-star mergers



Philipp Mösta

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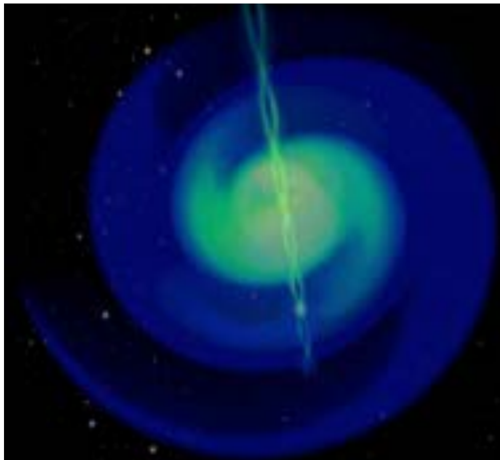
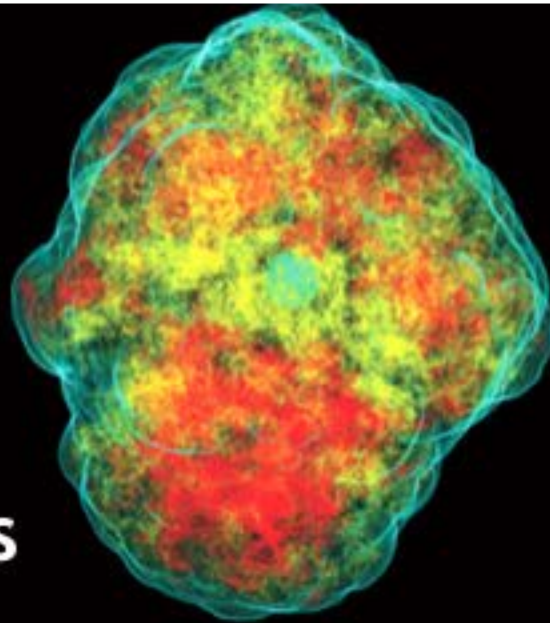
BLUE WATERS SUSTAINED PETASCALE COMPUTING

Blue Waters Symposium 2019
Sunriver Resort

Berkeley UNIVERSITY OF CALIFORNIA



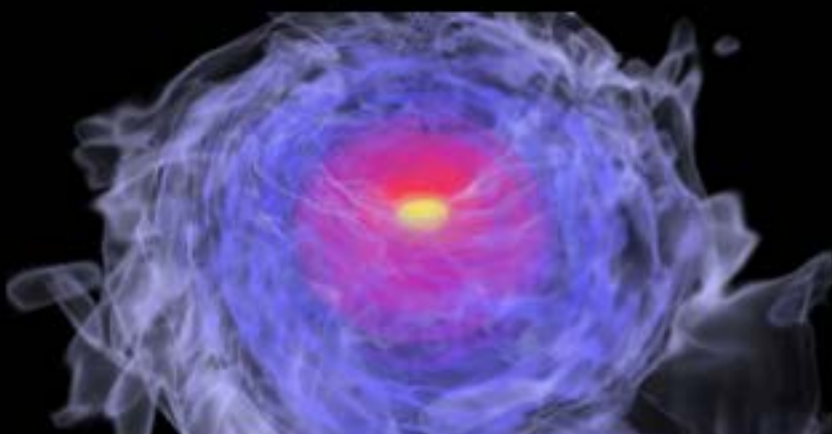


Core-collapse supernovae

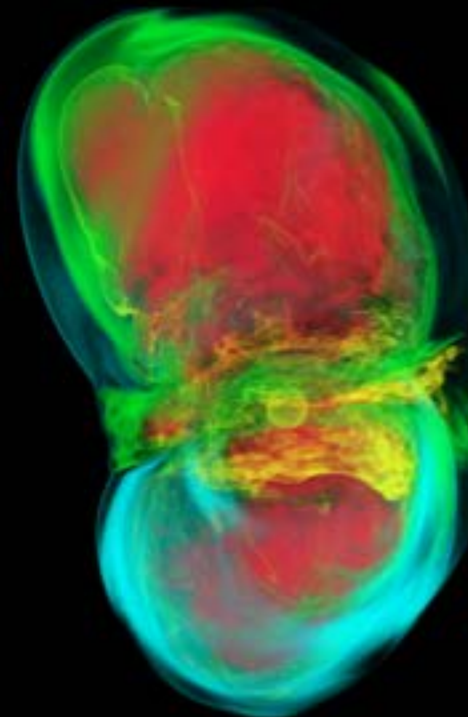
neutrinos
turbulence

(Binary) black holes

accretion disks
EM counterparts



Extreme transients

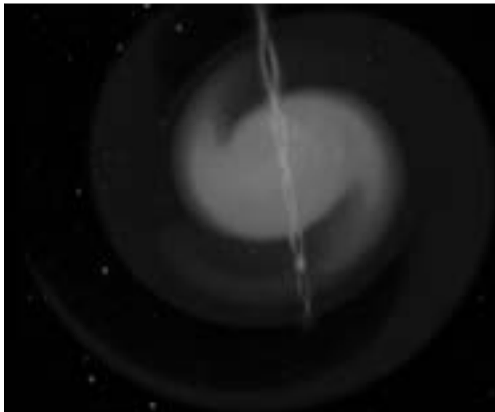


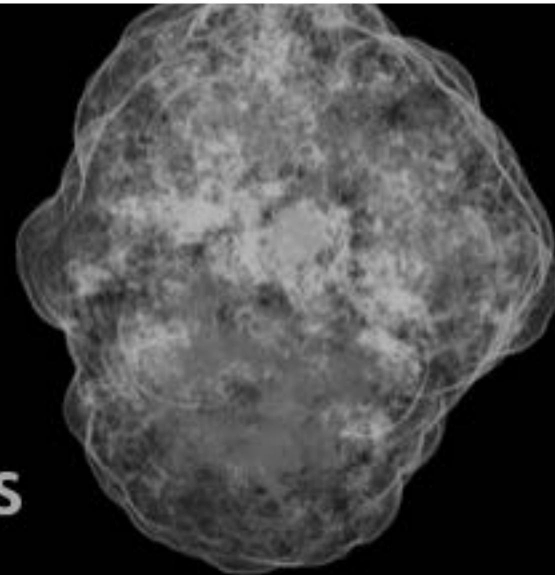
Binary neutron stars

gravitational waves +EM
sGRBs
heavy elements

Extreme core-collapse

hyperenergetic/superluminous
lGRBs
heavy elements





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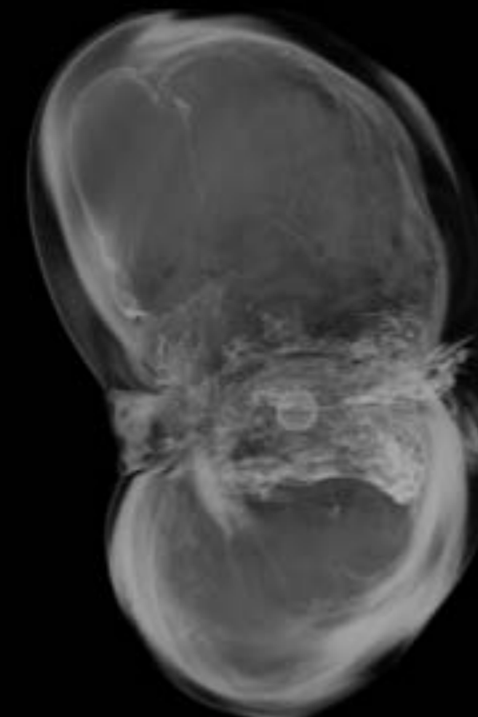
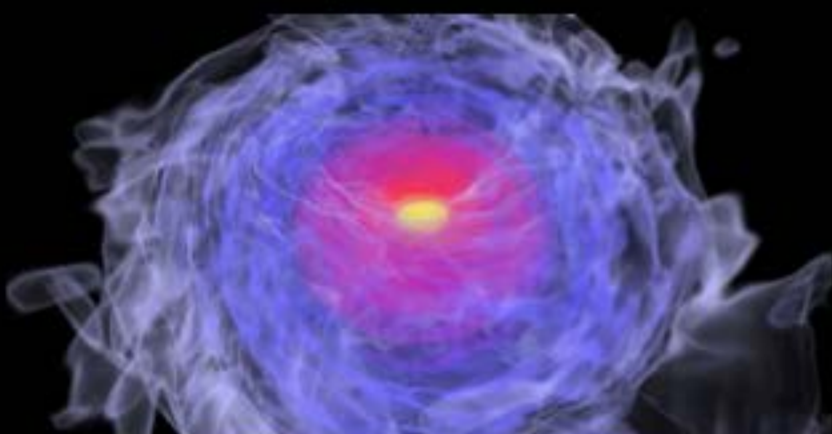


Extreme transients



Binary neutron stars
gravitational waves +EM
sGRBs
heavy elements

Extreme core-collapse
hyperenergetic/superluminous
lGRBs
heavy elements

Unique relativistic nuclear

astrophysics laboratories

nuclear EOS:

EOS, nucleosynthesis, optical/EM signal

neutrino transport:

composition, heating/cooling, winds

magnetic fields:

lifetime, winds, outflows, jets

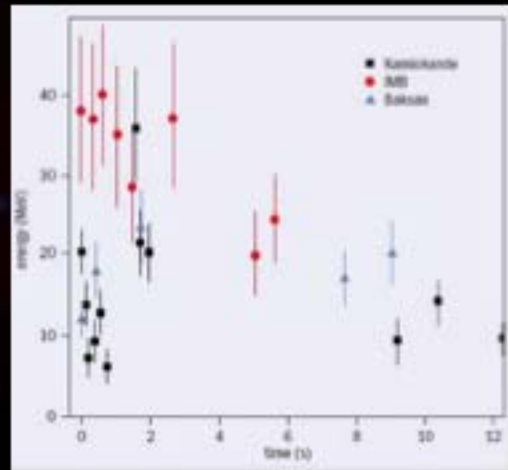
relativity

gravitational waves, mergers, jets

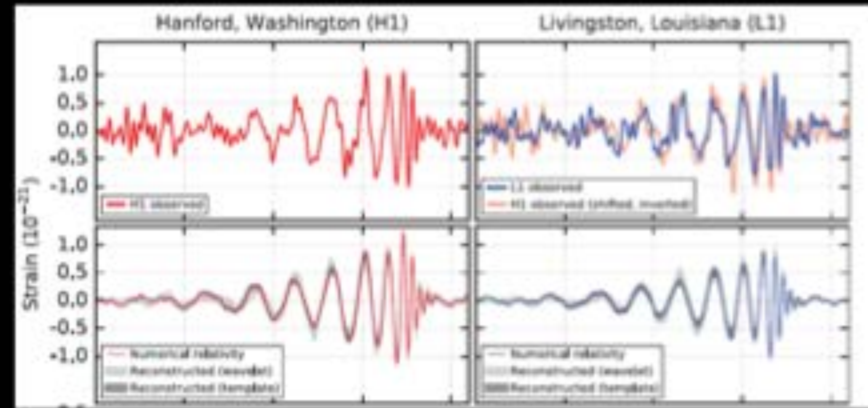
Astrophysics of extreme transients

M82/Chandra/NASA

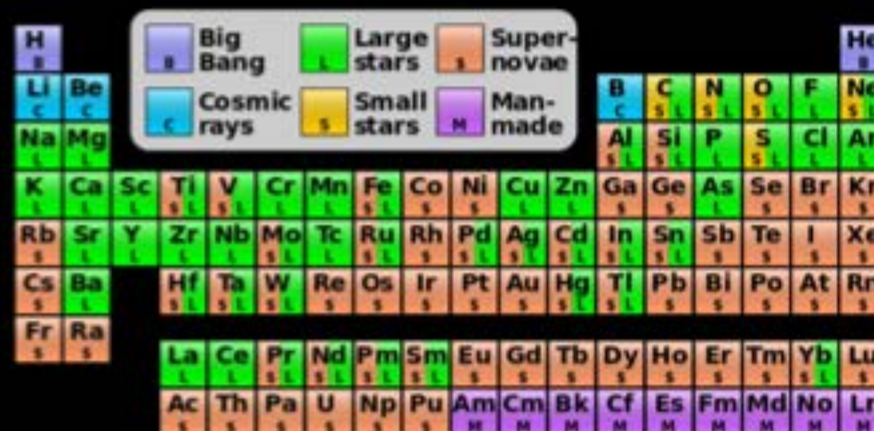
Galaxy evolution



Neutrinos



Gravitational waves



Heavy element nucleosynthesis

Birth sites of black holes / neutron stars

New era of transient science

- Current (PTF, DeCAM, ASAS-SN) and upcoming wide-field time domain astronomy (ZTF, LSST, ...) -> wealth of data
- adv LIGO / gravitational waves detected
- Computational tools at dawn of new exascale era

Image: PTF/ZTF/COO

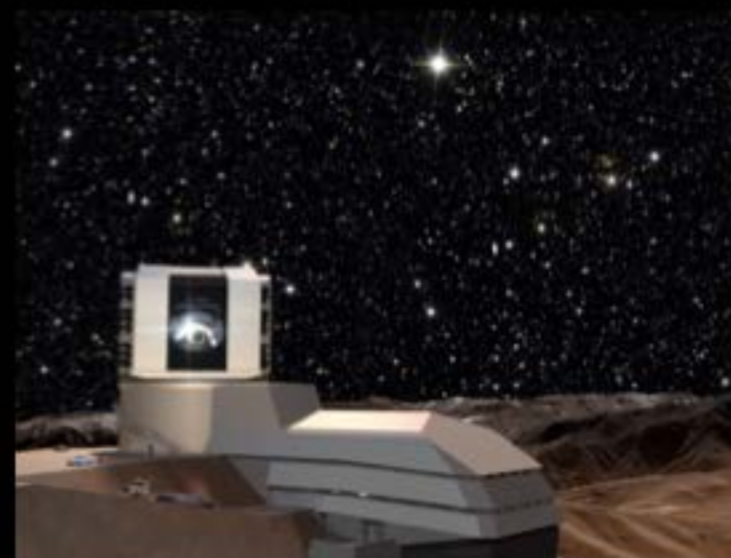


Image: LSST

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Transformative years ahead for our understanding of these events

Image: PTF/ZTF/COO

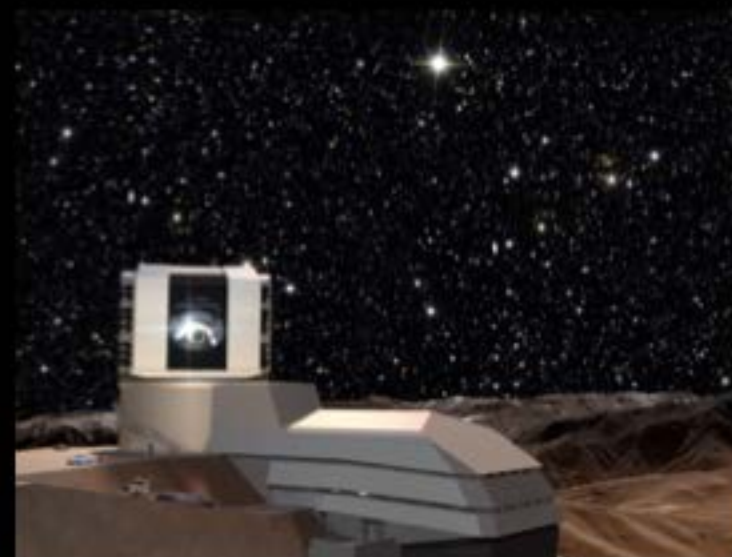
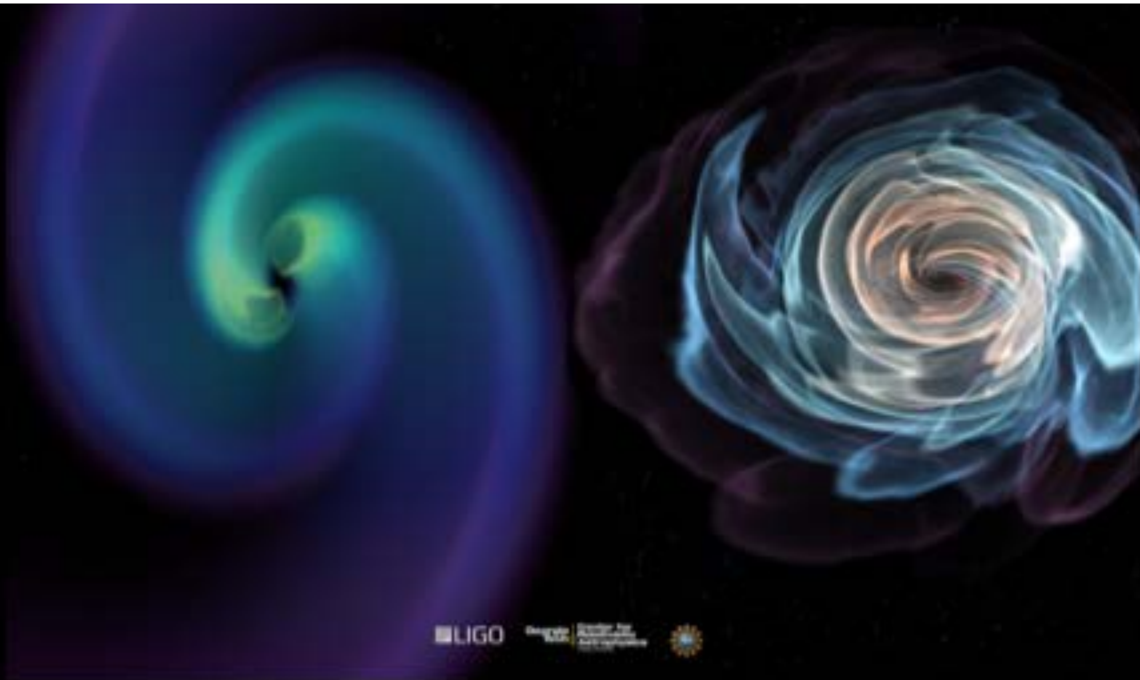
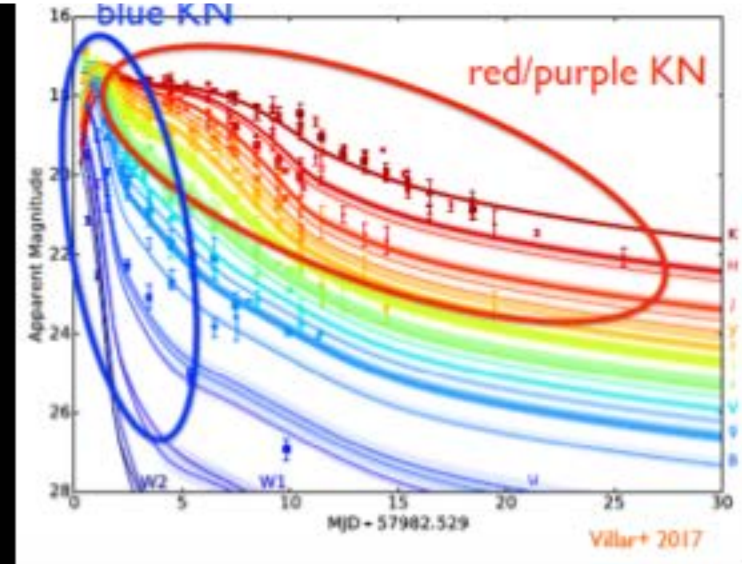


Image: LSST

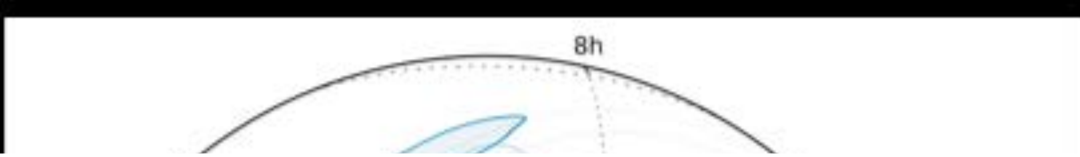
Neutron star mergers, kilonovae and sGRBs

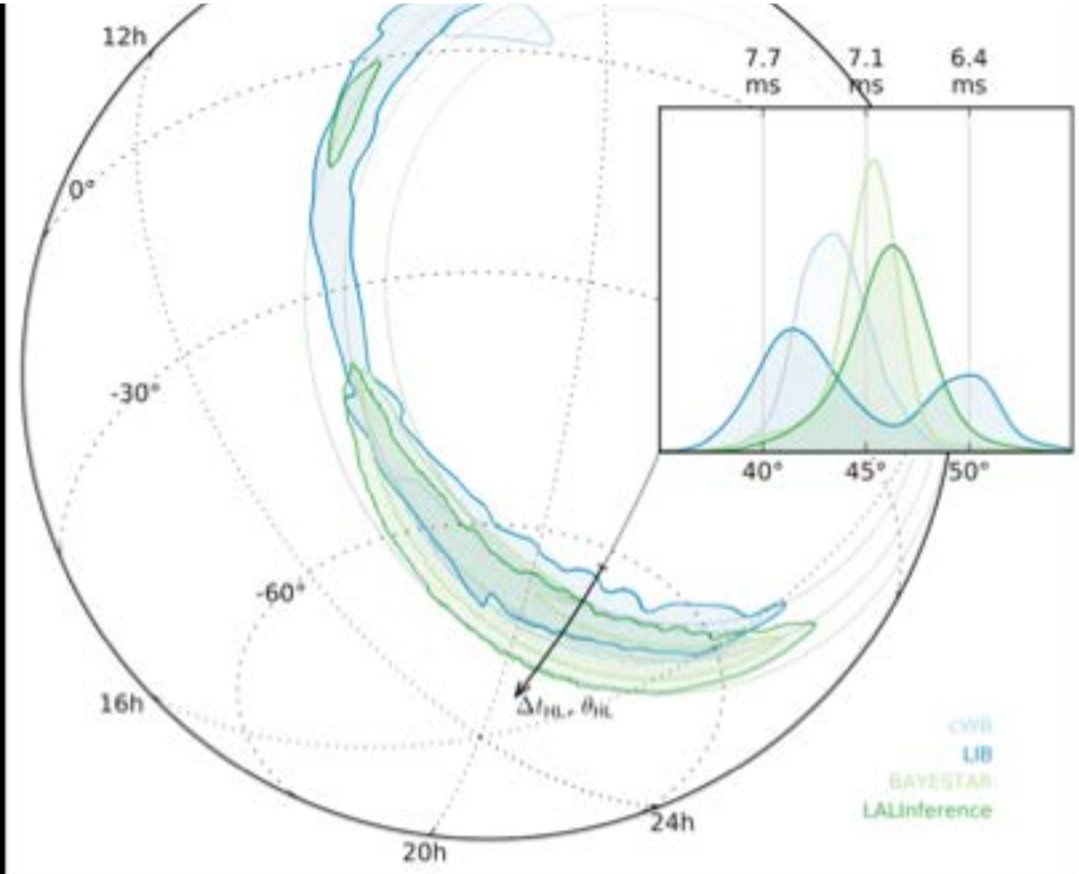




- Remnant lifetime and fate
- sGRB engine: black hole vs magnetar, structure of the jet
- Dynamical ejecta and disk outflows: composition and amount of ejecta -> EM observations

advanced LIGO - EM follow up





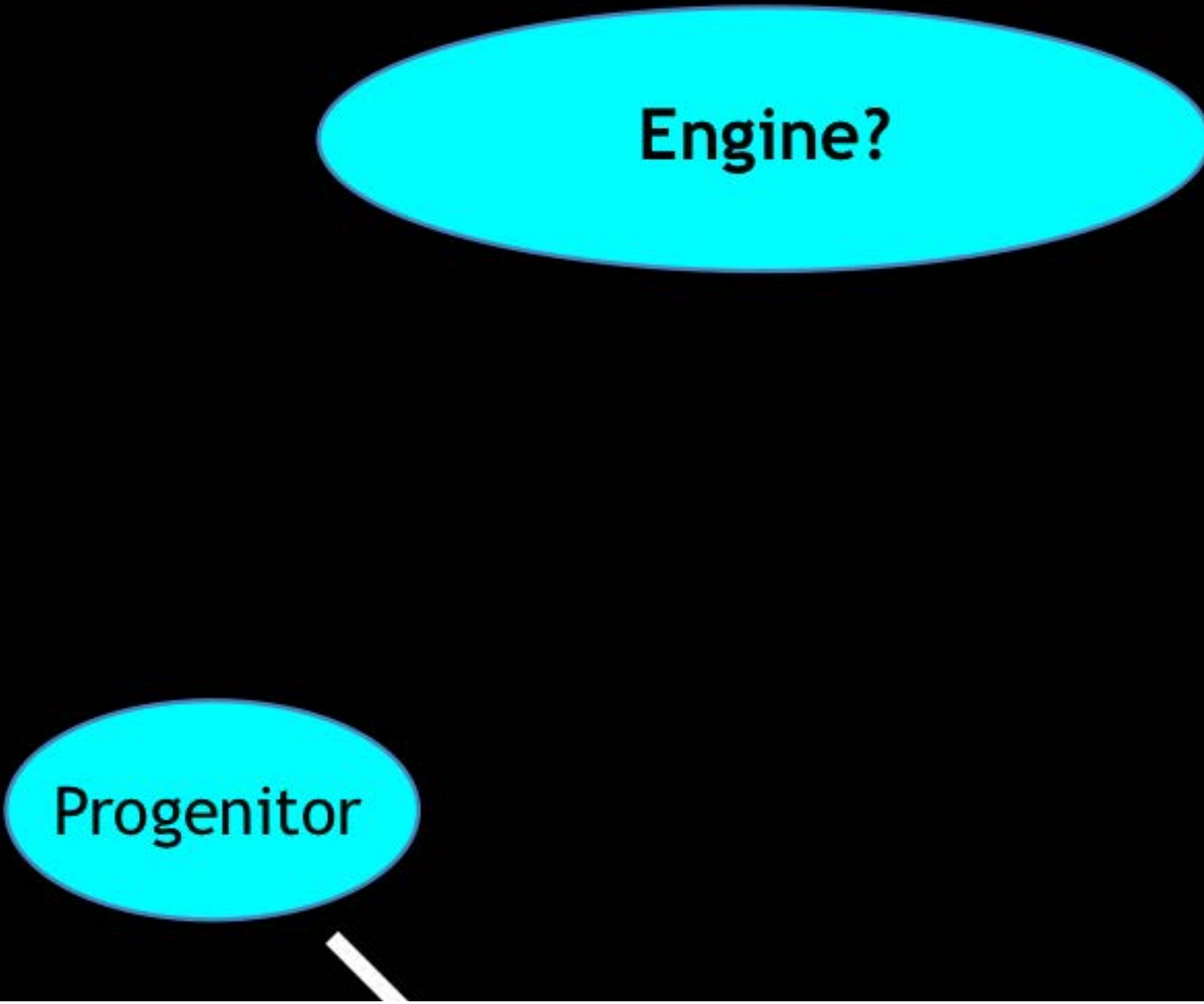
Aasi+ 2016, LIGO

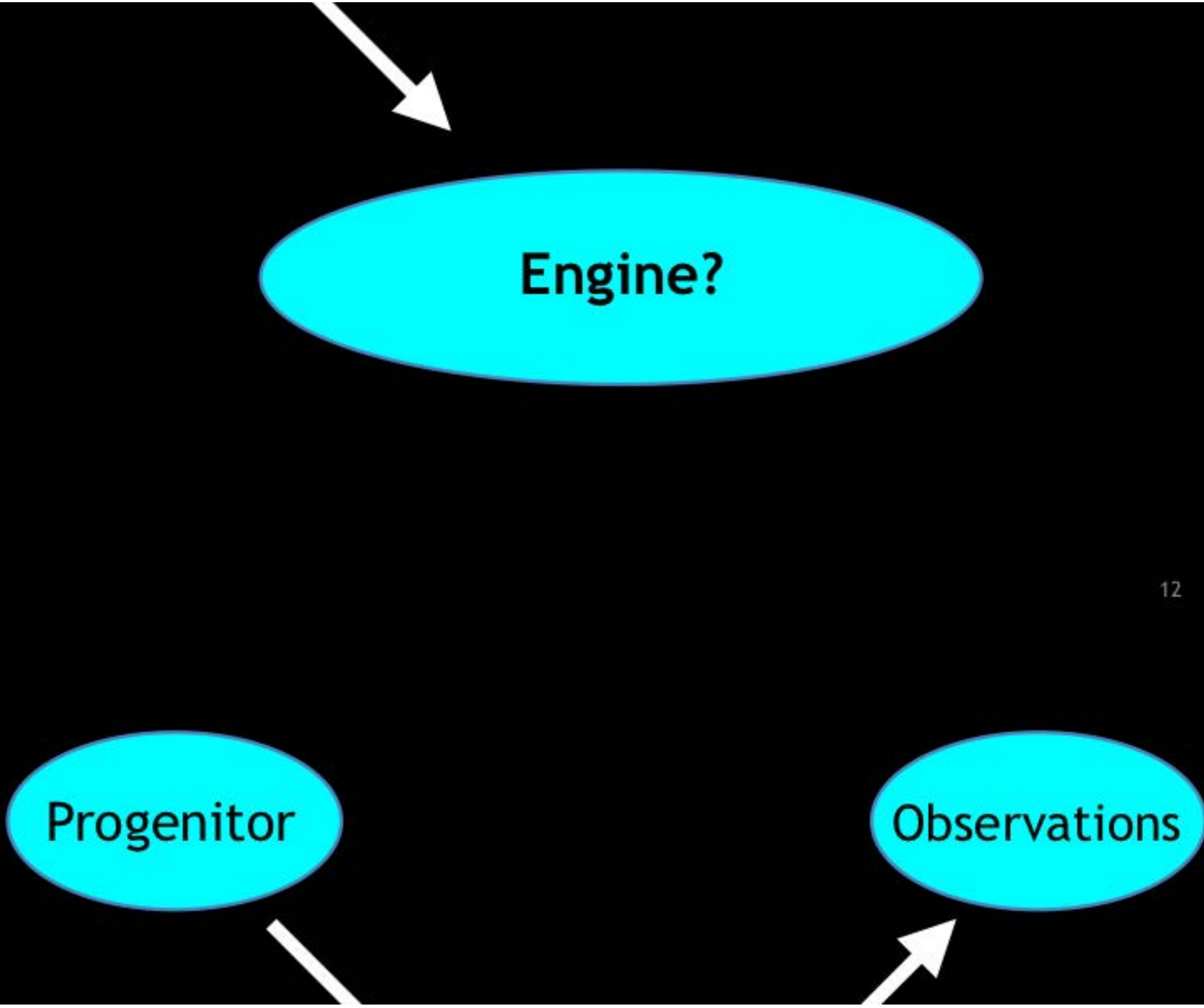
Image:PanSTARRS

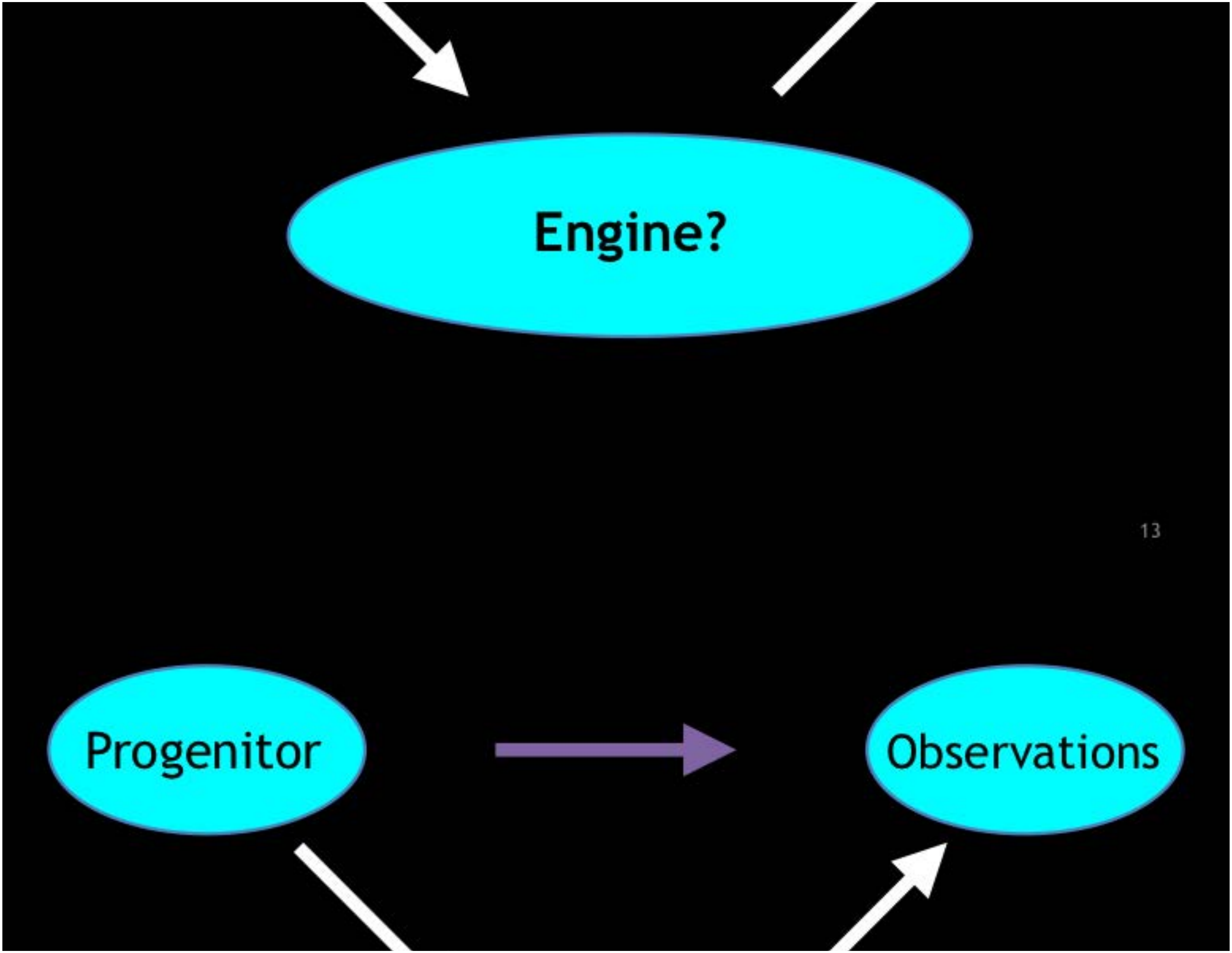
GW + EM counterpart = detailed engine observations

The engine(s) driving these transients

Engine?


Engine?
Progenitor


Engine?
Progenitor
Observations


Engine?
Progenitor
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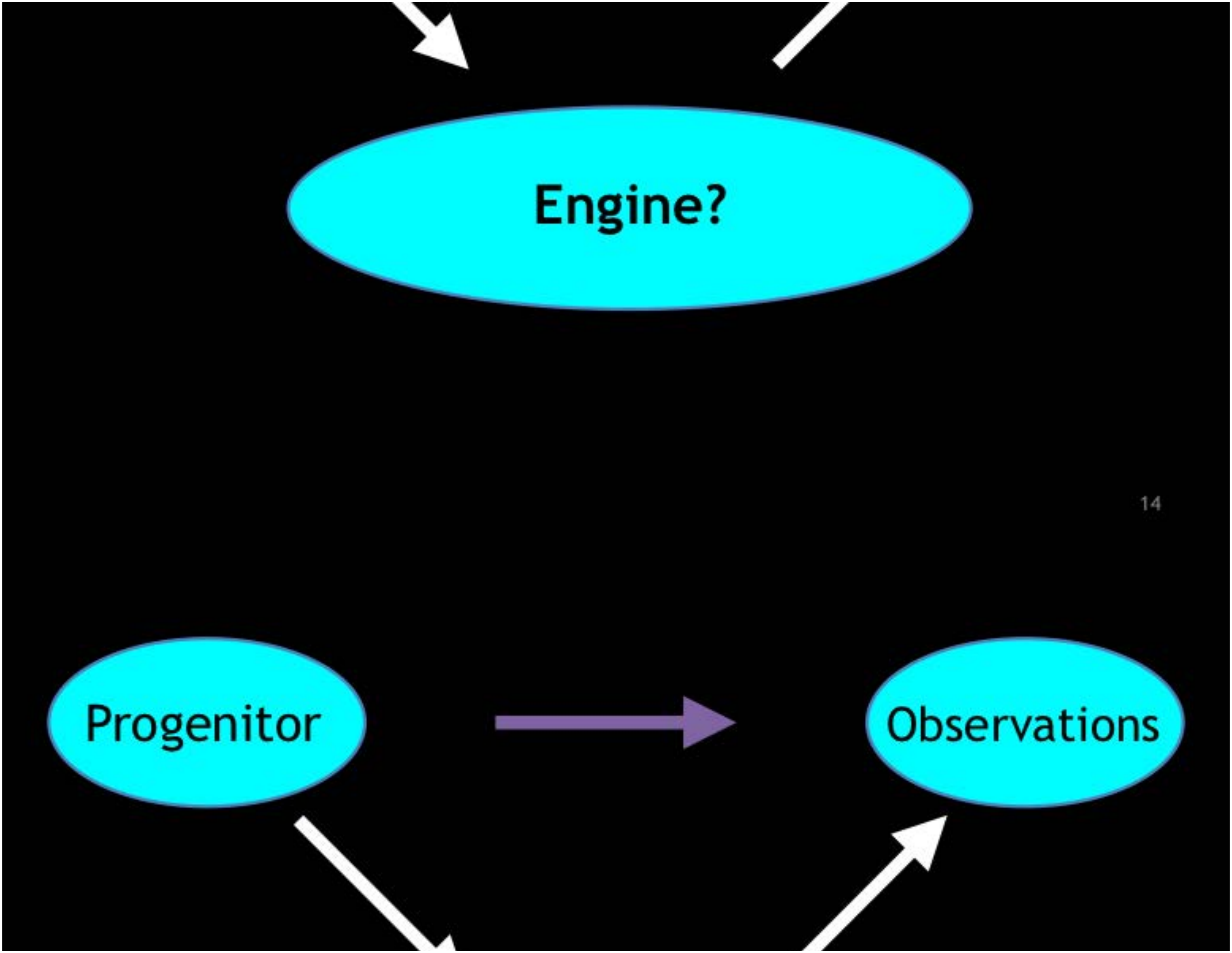

Engine?
Progenitor
Observations

Establish mapping

progenitor -> engine -> observations

A multiphysics challenge

Magneto-Hydrodynamics → Gas/plasma dynamics

A multiphysics challenge

Magneto-Hydrodynamics	→	Gas/plasma dynamics
General Relativity	→	Gravity

A multiphysics challenge

Magneto-Hydrodynamics → Gas/plasma dynamics

General Relativity → Gravity

Nuclear and Neutrino Physics → **Nuclear EOS**, nuclear reactions & ν interactions

A multiphysics challenge

- Magneto-Hydrodynamics → Gas/plasma dynamics
- General Relativity → Gravity
- Nuclear and Neutrino Physics → **Nuclear EOS**, nuclear reactions & ν interactions
- Boltzmann Transport Theory → **Neutrino transport**

A multiphysics challenge

Fully coupled!

Magneto-Hydrodynamics	→	Gas/plasma dynamics
General Relativity	→	Gravity
Nuclear and Neutrino Physics	→	**Nuclear EOS**, nuclear reactions & ν interactions
Boltzmann Transport Theory	→	**Neutrino transport**

All four forces!

A multiphysics challenge

Fully coupled!

Magneto-Hydrodynamics	→ Gas/plasma dynamics
General Relativity	→ Gravity
Nuclear and Neutrino Physics	→ **Nuclear EOS**, nuclear reactions & ν interactions
Boltzmann Transport Theory	→ **Neutrino transport**

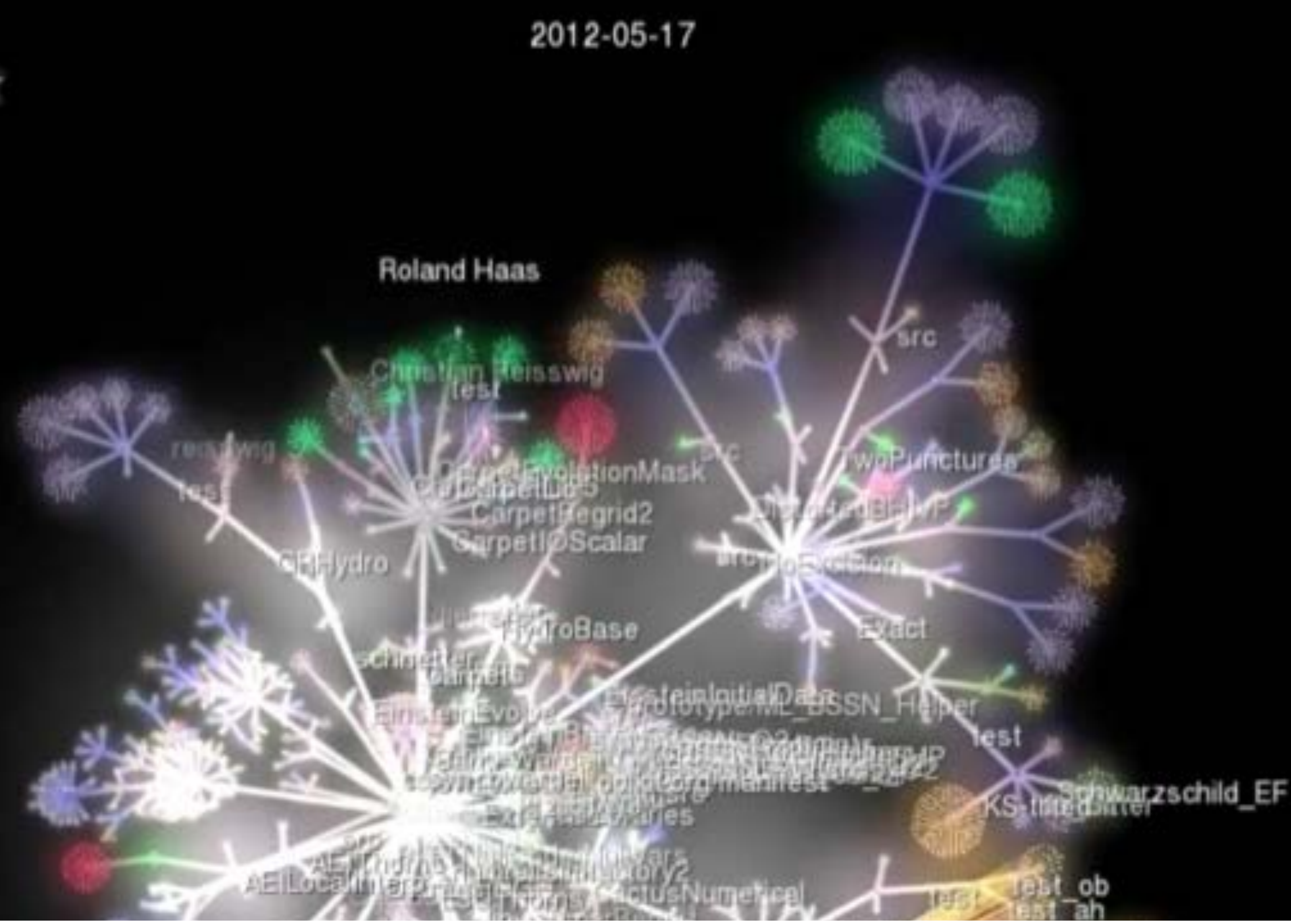
All four forces!

Additional Complication: Needs to be modeled in **3D**

- rotation
- **fluid and MHD instabilities,** multi-D structure, spatial scales

Need 21st century tools:

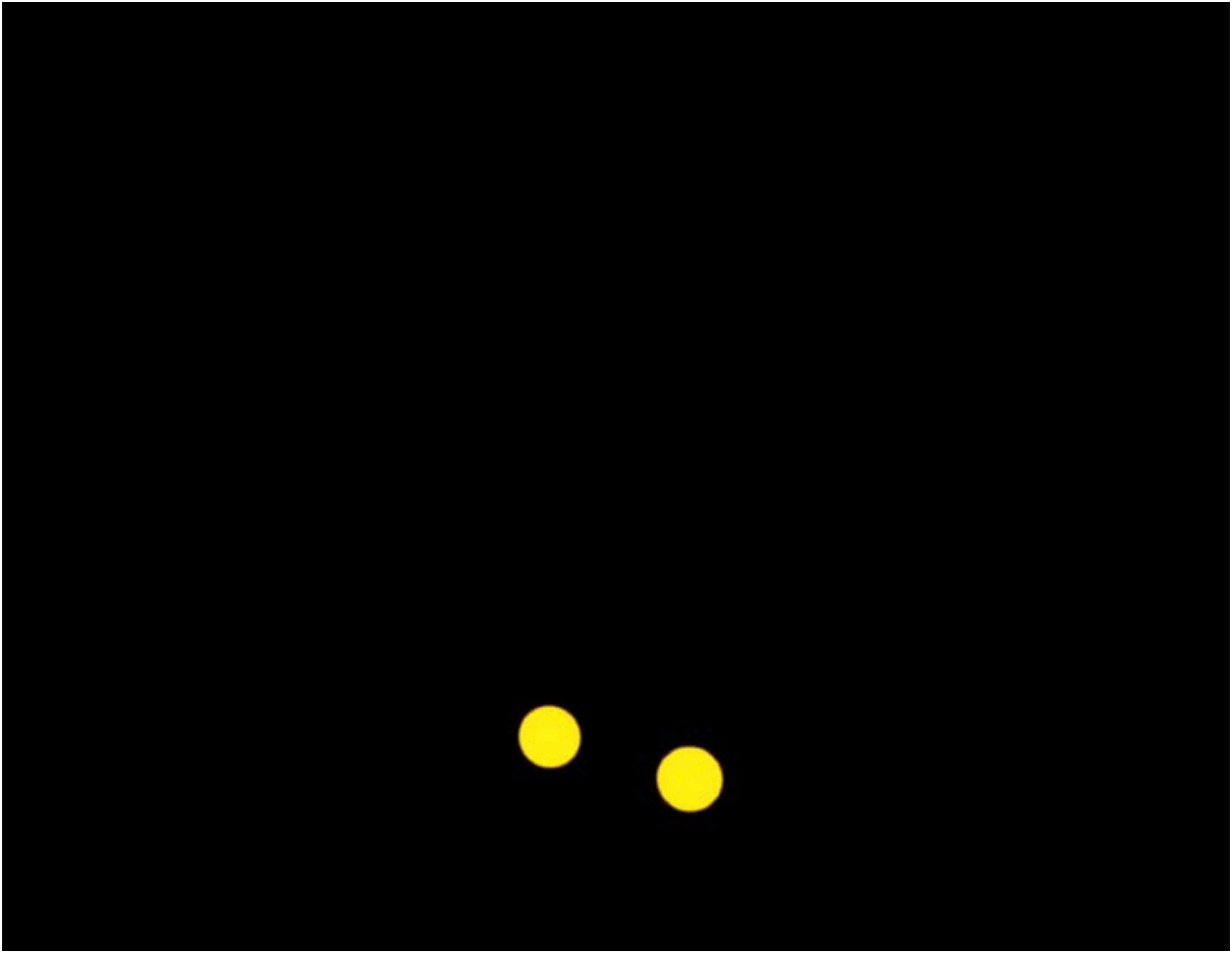
- cutting edge numerical algorithms
- sophisticated **open-source** software infrastructure
- peta/exascale computers like Blue Waters



einstein toolkit

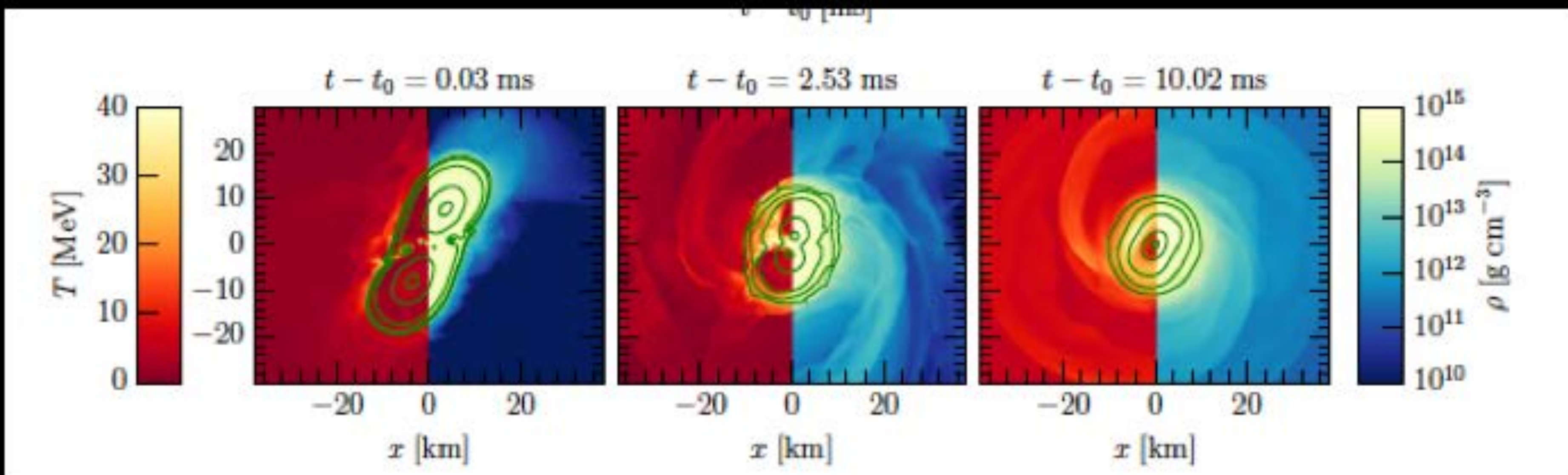
http://einsteintoolkit.org

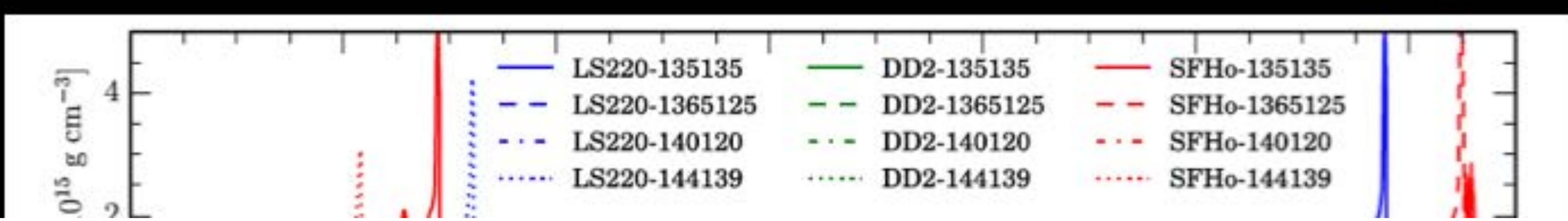
Magnetic field amplification in neutron star merger remnants

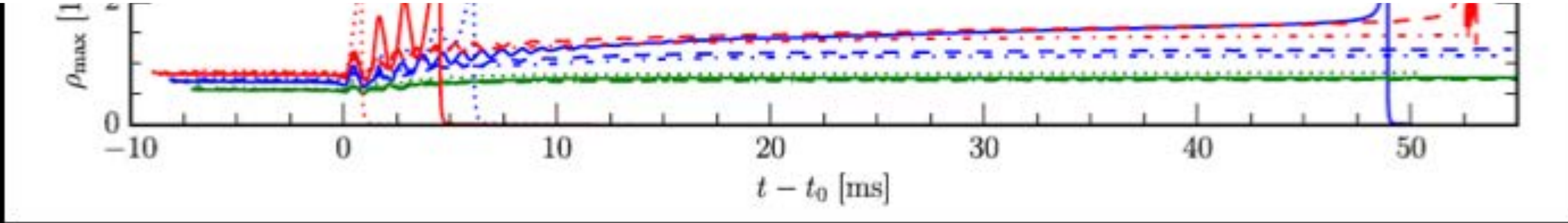


Radice, Bernuzzi, **PM 16**

Original hydro simulations







Radice, Bernuzzi, …, PM+ 16

3 outcomes

stable neutron star:
- low mass

prompt collapse to black hole:
- soft EOS + high mass

hypermassive neutron star + torus -
delayed collapse to black hole:

- delayed collapse to black hole?
- everything in between?

Hypermassive neutron star lifetime

TOV equations for cold non-rotating star:
maximum mass 1.8-2.3 solar masses

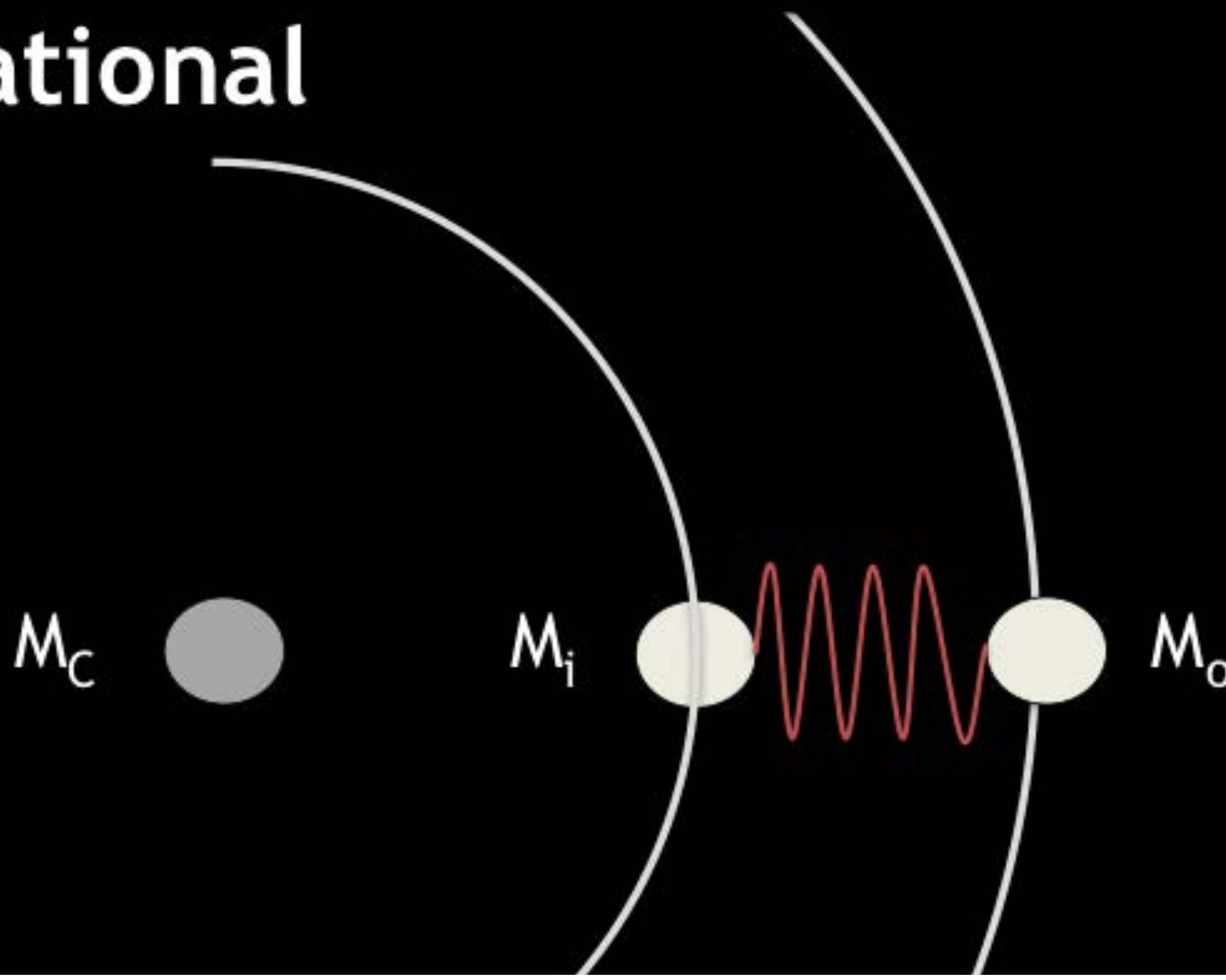
Thermal pressure and uniform rotation increase maximum mass by 10-30% (for specific EOS)

Differential rotation able to support maximum mass beyond 3 solar masses

Angular momentum transport and magnetic fields determine lifetime - key to GWs and EM counterparts: winds, outflows, sGRBs

Key for angular momentum transport:

Magnetorotational instability

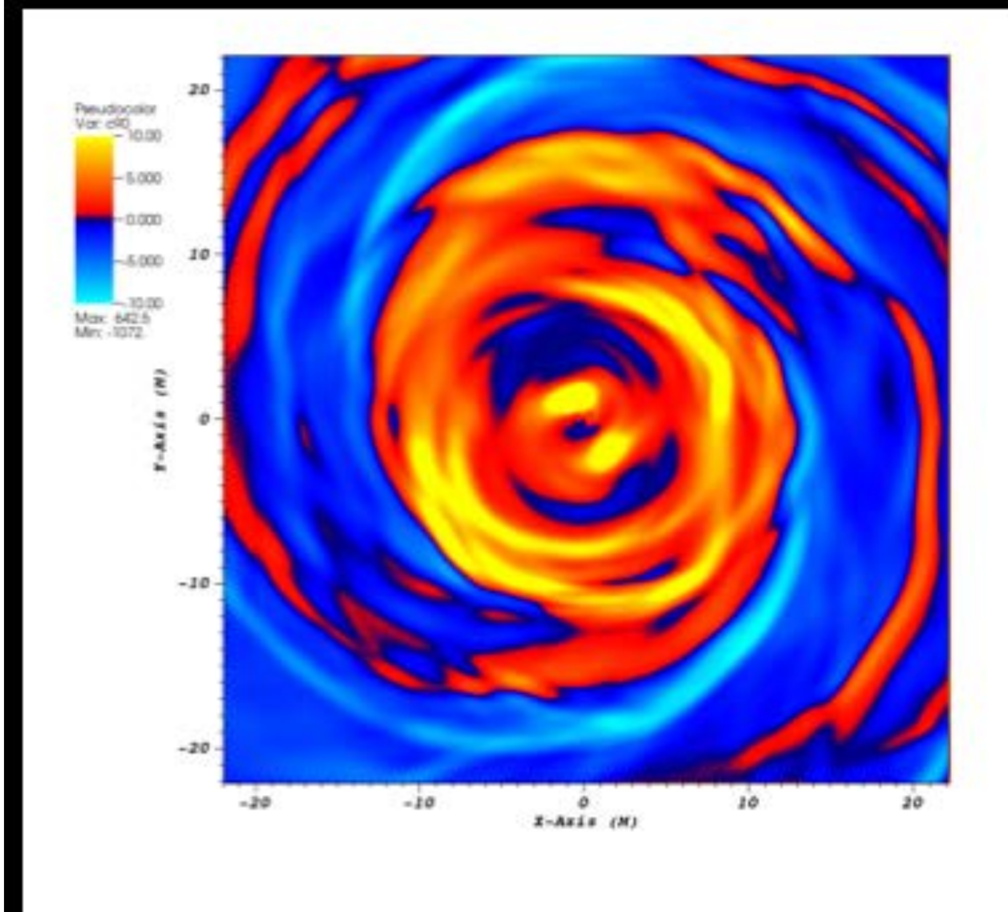


MRI Basics

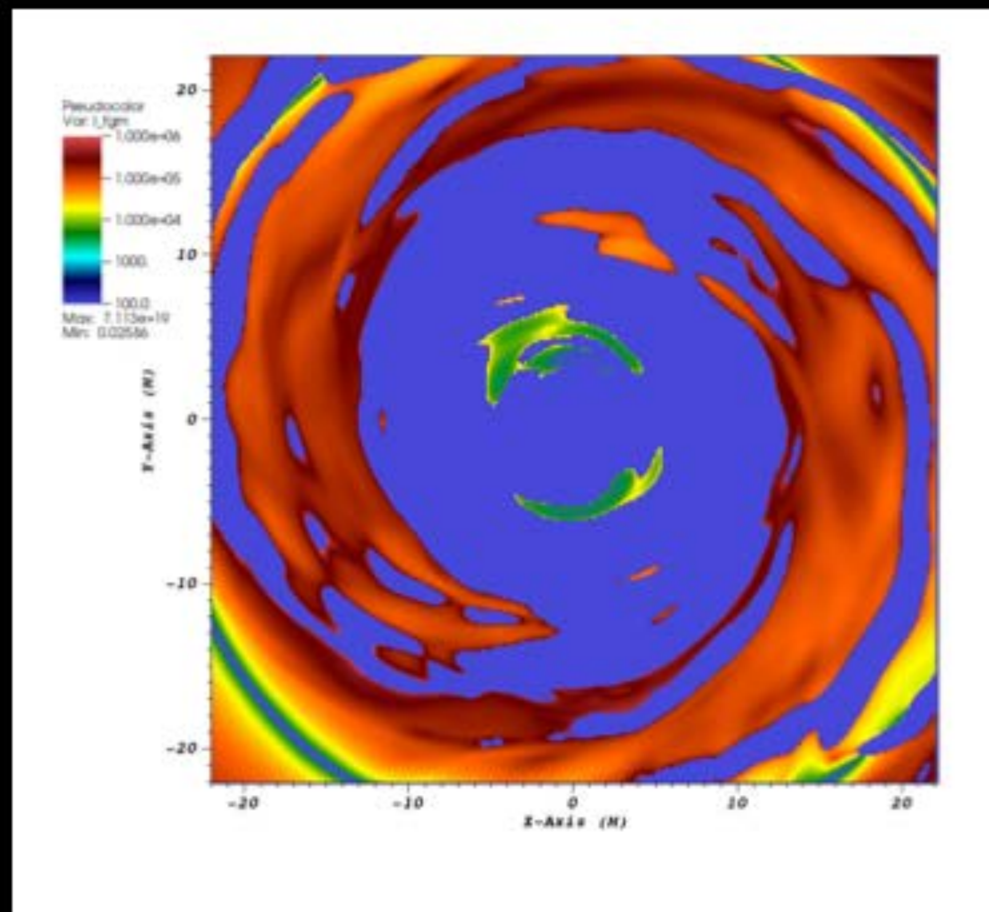
- Weak field instability
- Requires negative angular velocity gradient
- Can build up magnetic field exponentially fast
- Extensively researched in accretion disks: ability to modulate angular momentum transport and grow large scale field

Situation after merger:

Stability criterion

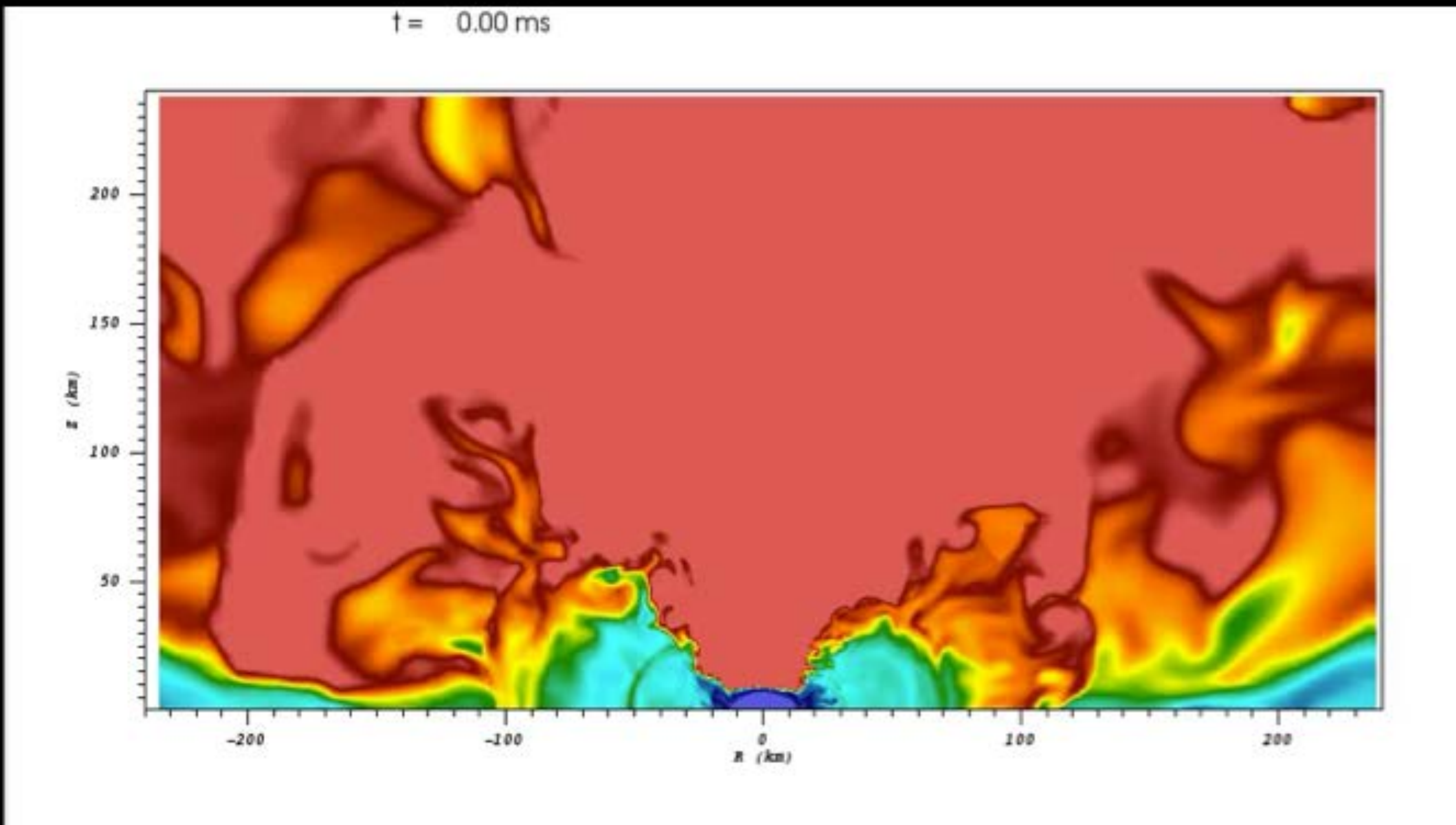


Wavelength of FGM



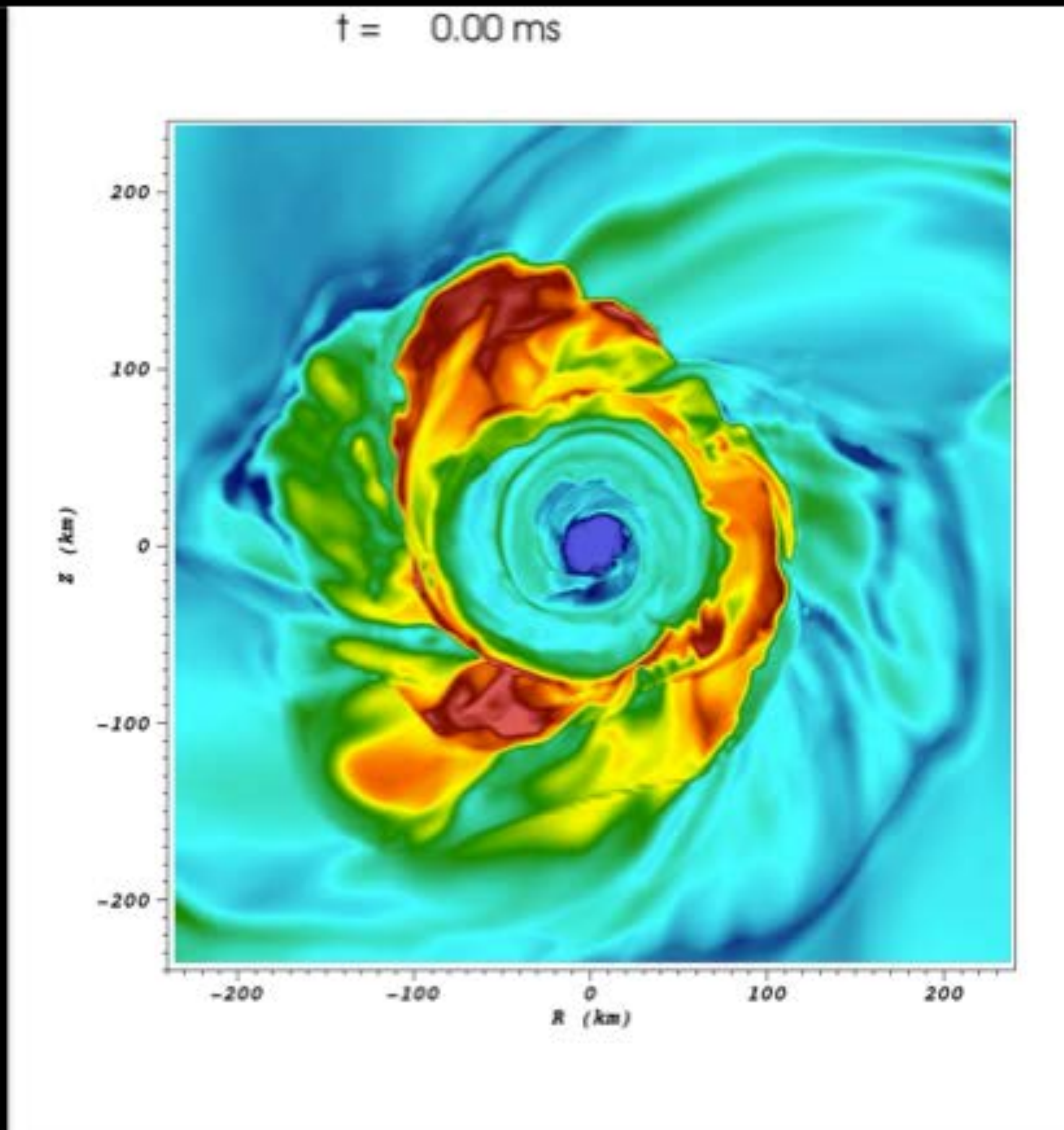
blue unstable $B_0 \sim 5 \times 10^{14}$ G

Merger remnant evolution



PM+ 19 (in prep.)

Merger remnant evolution



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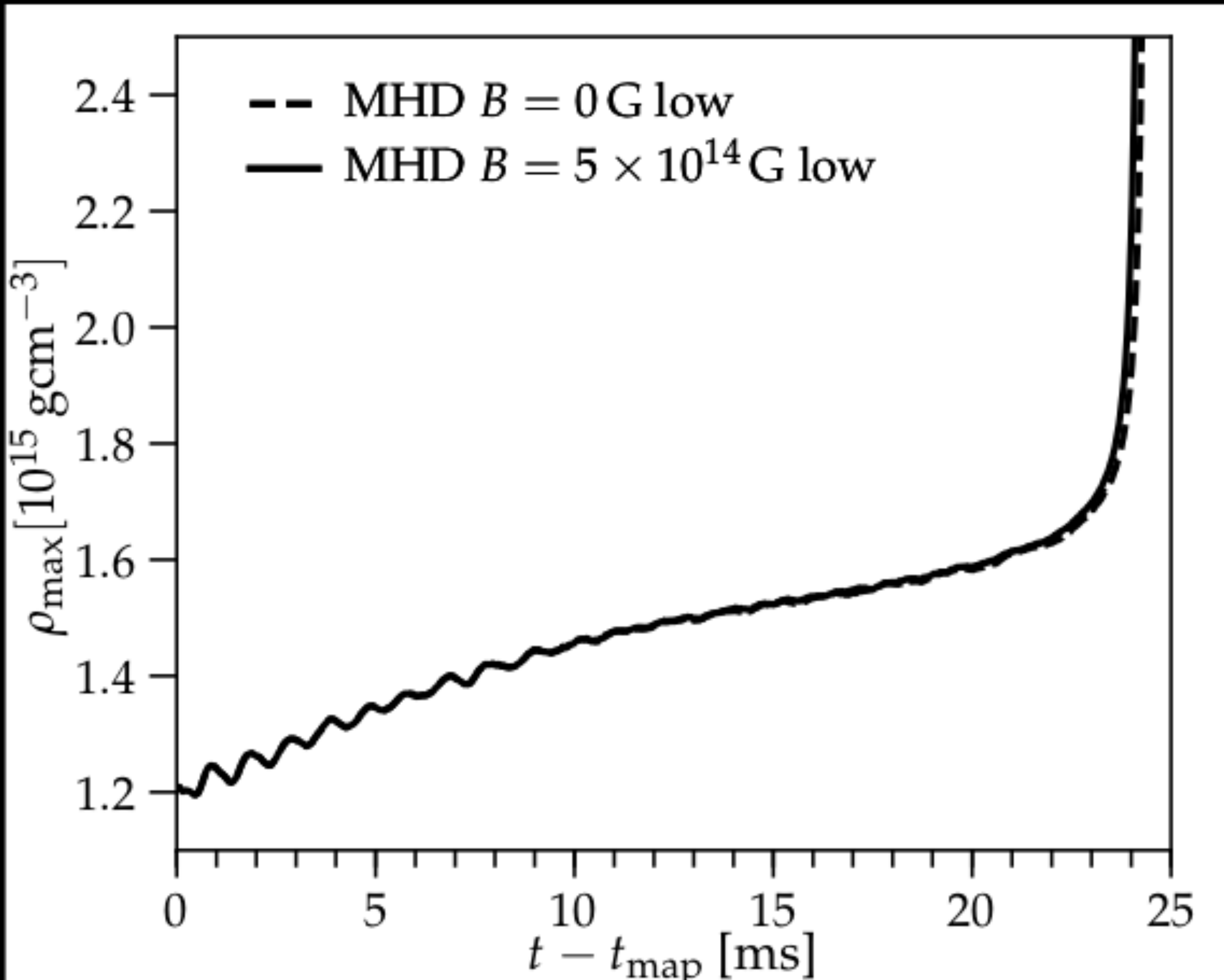

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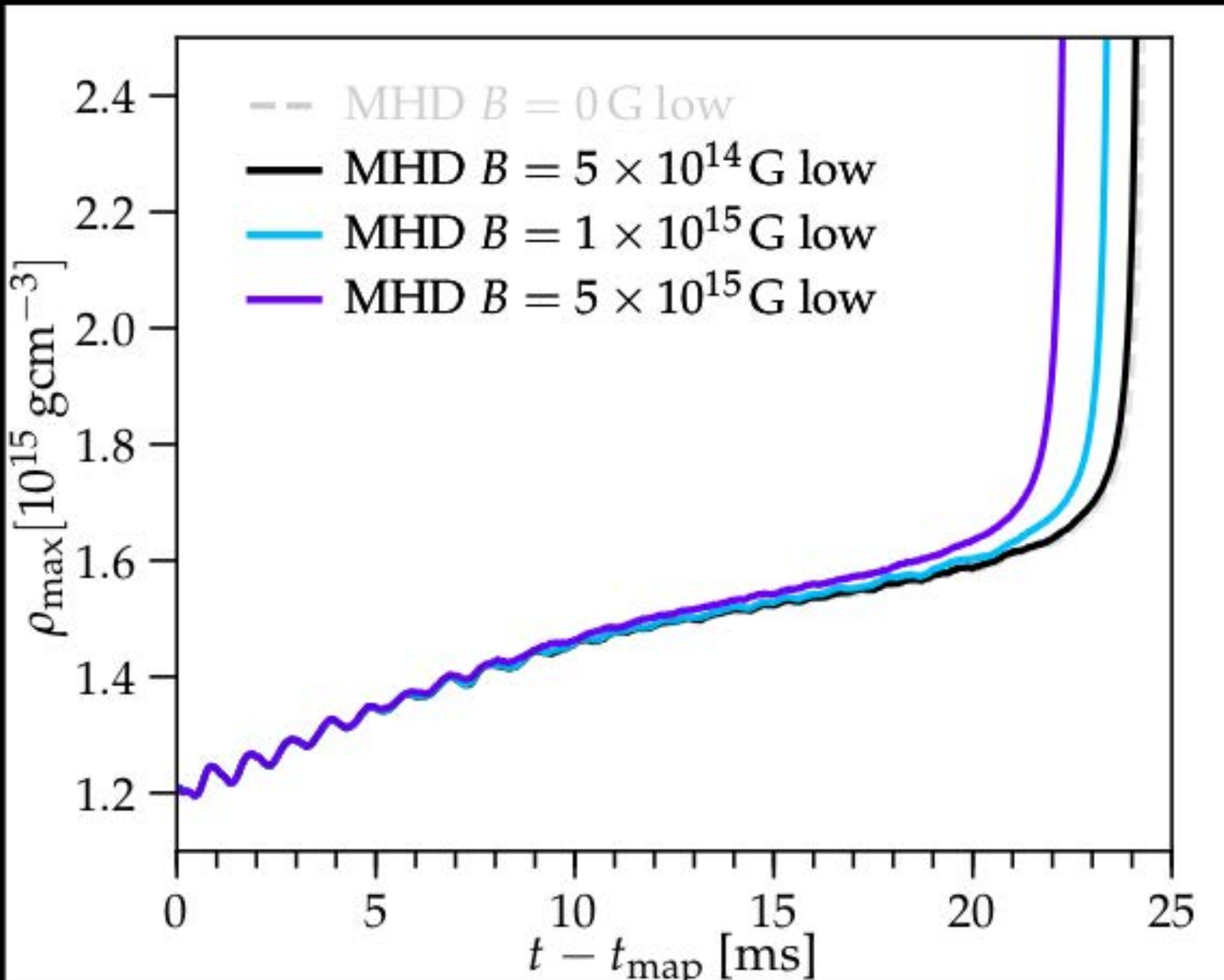

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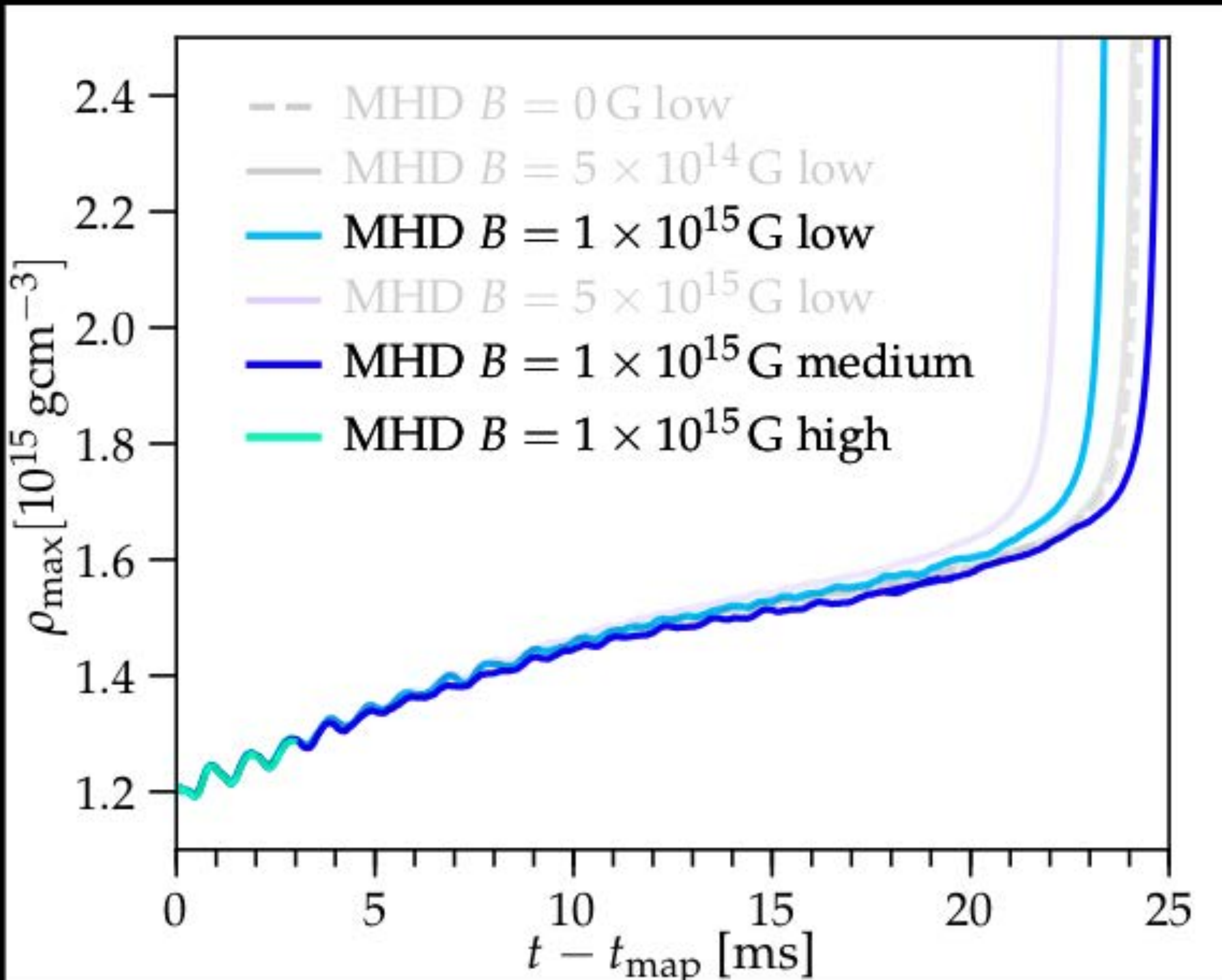

PM+ 19 (in prep.)

3) From simulations to observations

From simulations to observations

State of the art now:

Detailed simulations
full physics
~0.1s
inner ~100km

Current frontier:

1) Engine model from
full-physics simulations
2) Simplified simulations
with engine model to
late times

From simulations to observations

State of the art now:

Detailed simulations
full physics
~0.1s
inner ~100km

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1) Engine model from full-physics simulations
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Future:

Full-scale simulations
full physics
late time / ejecta

detailed light curves
detailed spectra
connect observations and engines
map progenitor params

Summary

New transient observations challenge our engine models

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

Magnetic fields in neutron star mergers key to remnant lifetime, disk and outflow properties

High-performance computing and BlueWaters key to solving these puzzles