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Realistic Binary Neutron Stars Collisions Simulations: Challenges and Opportunities

Maria Babiuc-Hamilton

Realistic Binary Neutron Stars Collisions Simulations:

Challenges and Opportunities

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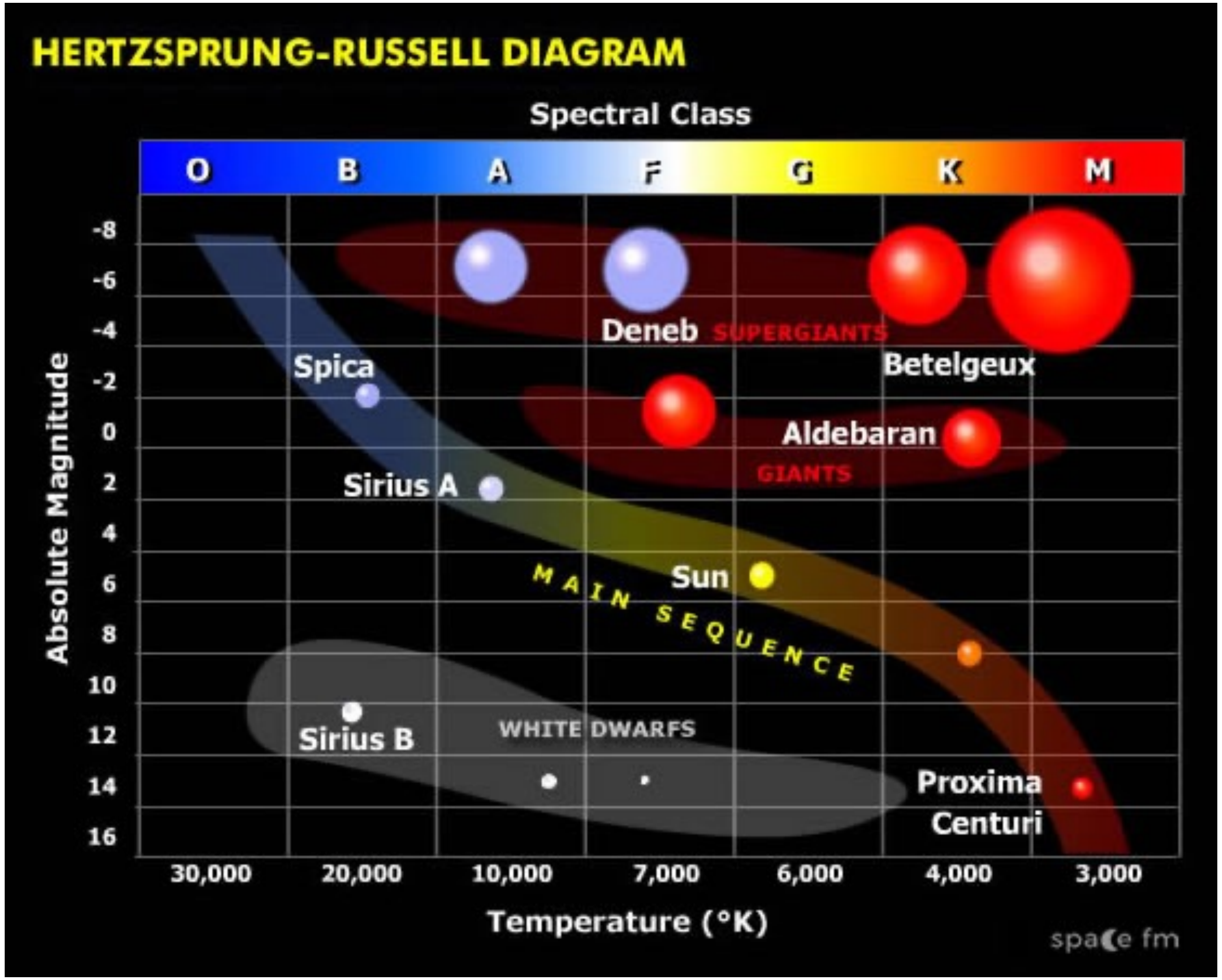
Workshop I: Computational Challenges in Multi-Messenger Astrophysics

OCTOBER 4 - 8, 2021

Institute for Pure & Applied Mathematics, University of California, Los Angeles, CA

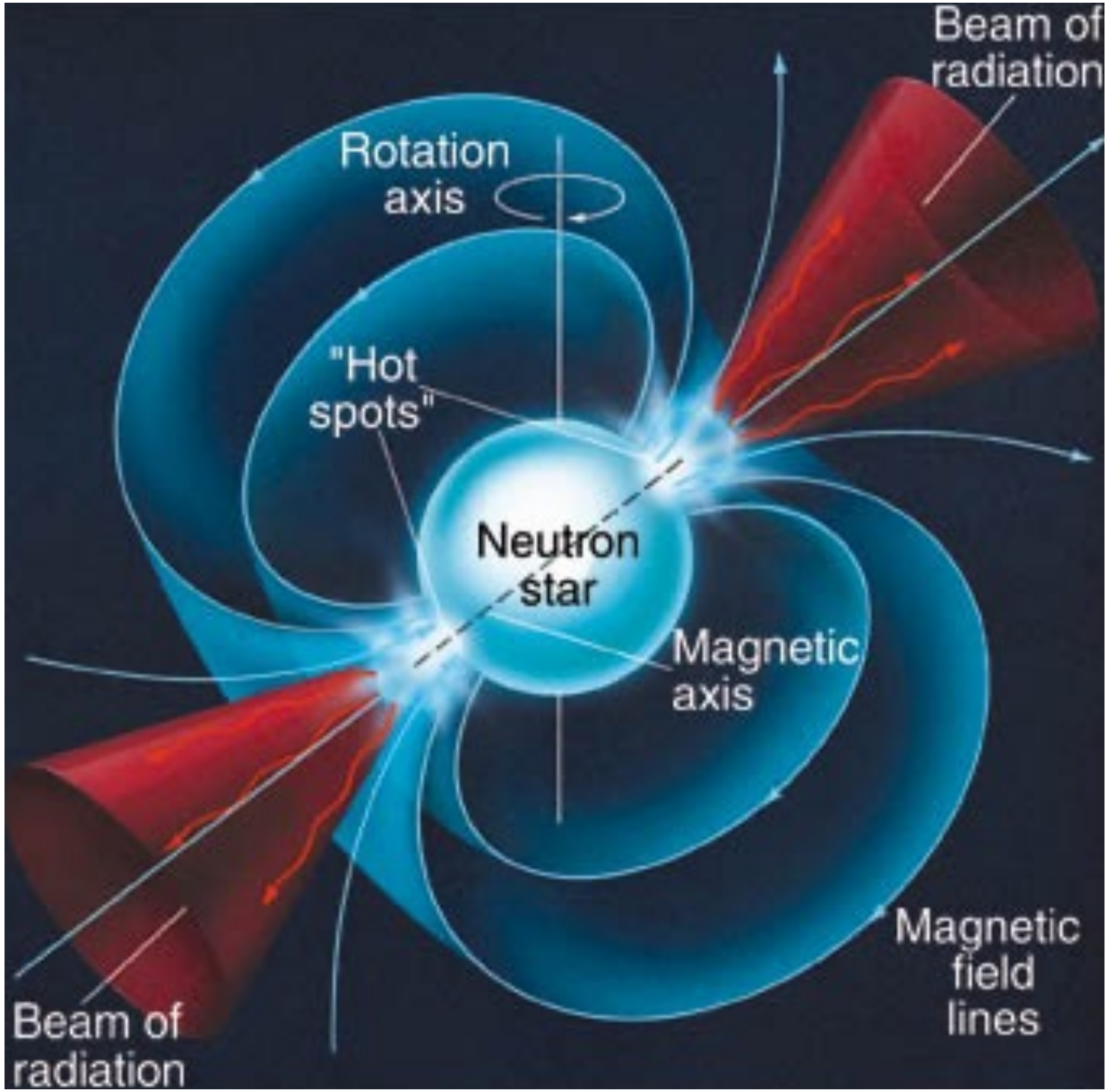
Life-cycle of Stars

- Star location reveals the evolutionary stage.
- Most stars are formed as binaries, in nebulas.
- Evolution depends on mass.
- Stars die either as white dwarfs, neutron stars or black holes.
- Stars 8 to 20 solar masses end up as supernovae.



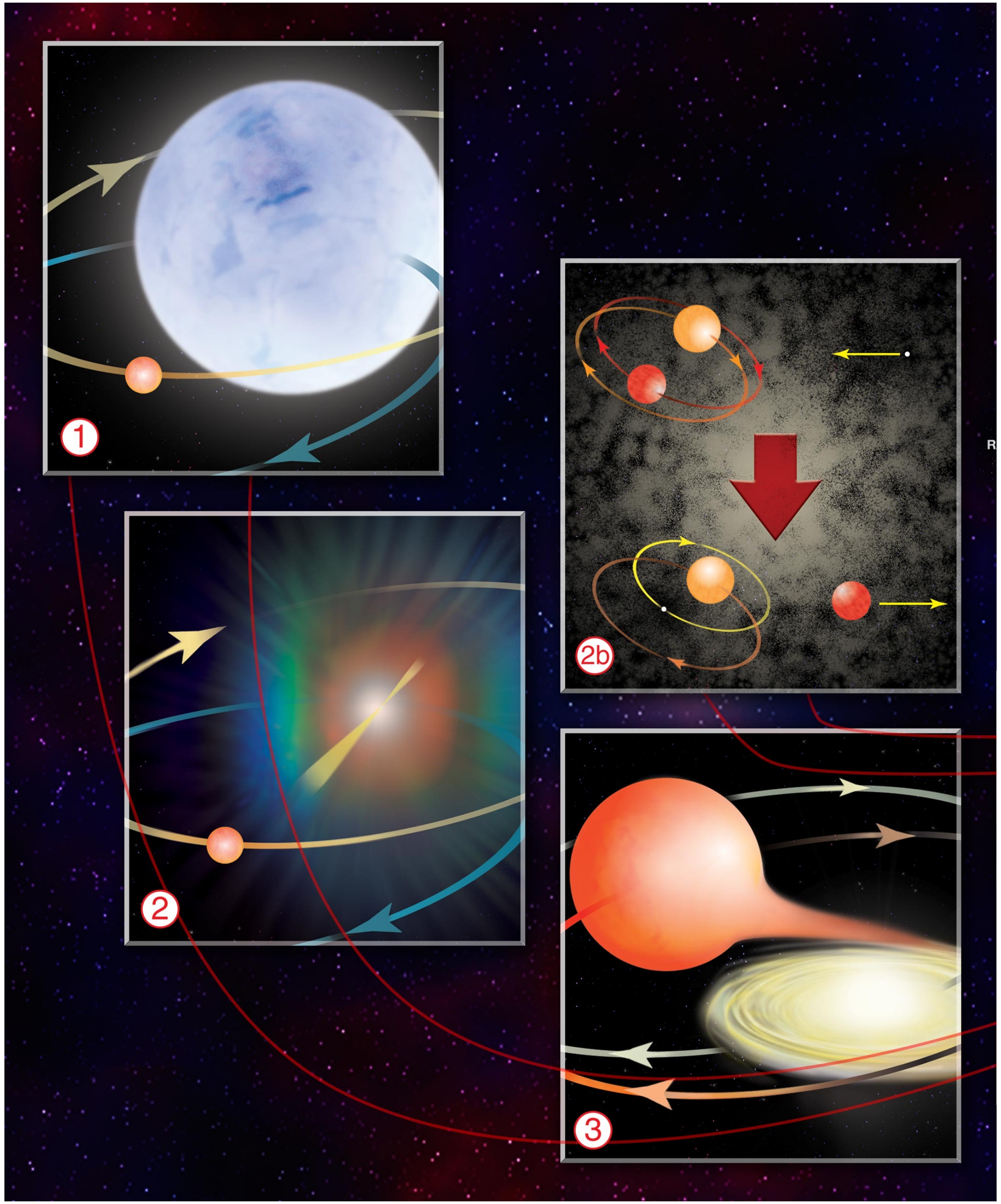
Neutron Stars

- Left behind is a neutron star.
- Narrow mass range: 1.3-1.6 M_{Sun}, 11-13 km radius.
- 10^9 Earth's gravity, density higher than the atomic nucleus, magnetic fields of 10^8-10^{15} G.
- Billions?, 2800 pulsars known.
- 20 are in binary system and have individual magnetic field of different strengths.



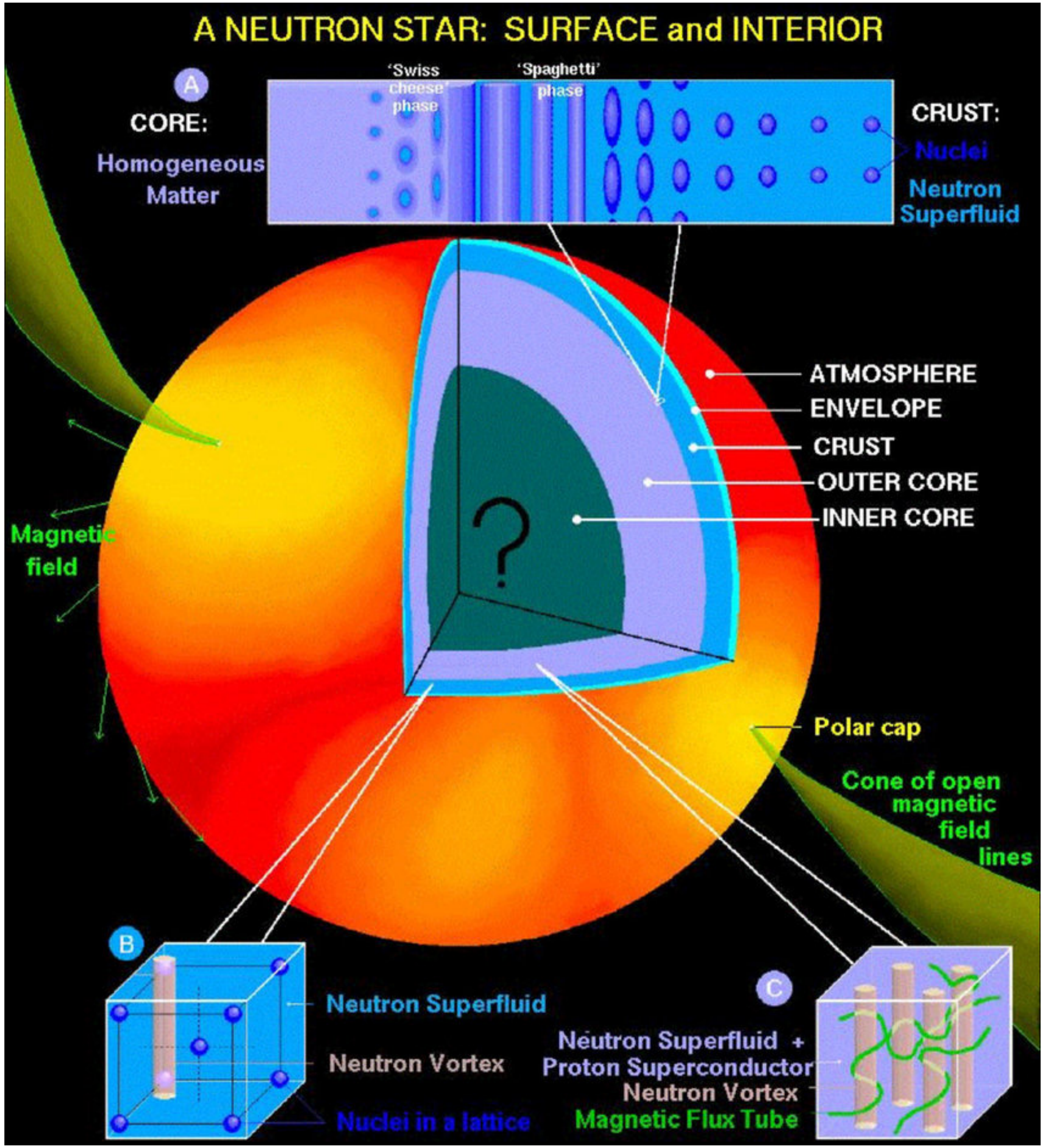
Binary Neutron Stars

- One star evolves quicker, and becomes a neutron star.
- During the evolution of the companion, the first neutron star is accreting matter and goes through a “recycling phase” spinning up.
- The mass of the recycled neutron star is 1.5-2 M_{Sun}, while the non-recycled star is around 1.3 M_{Sun}.
- Magnetic field of recycled star is 10^8G, of companion is 10^{14} G.



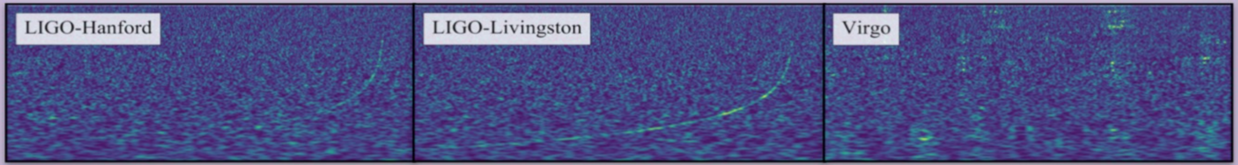
Neutron Stars Interior

- Surface temperature 10^8 K, super compression makes them cold: 0 K
- Surface, 0.1 m - normal matter (atmosphere & envelope)
- Crust, 1 km - outer (neutronization) & inner (neutron drip)
- Core, 10 km - mystery? super-saturation density, nuclear pasta.
- High-mass - exotic matter (hyperons, quarks, meson condensate)



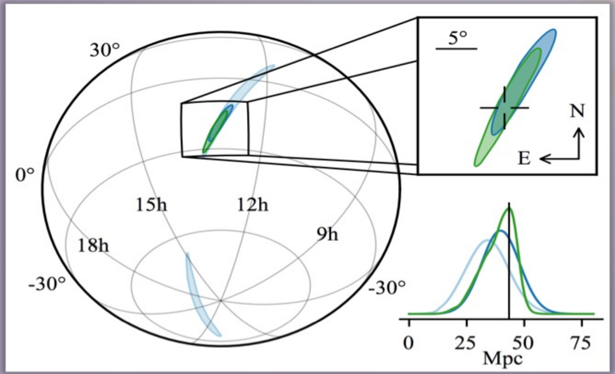
Astronomy News

GW170817 FACTSHEET



observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}



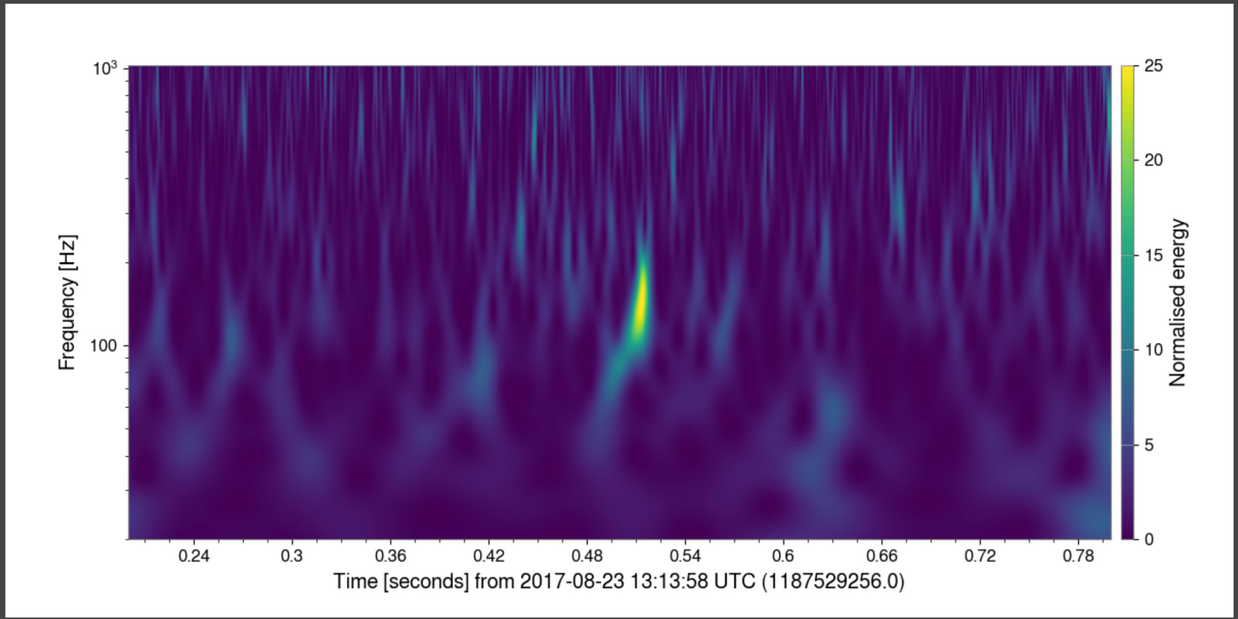
Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2×10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

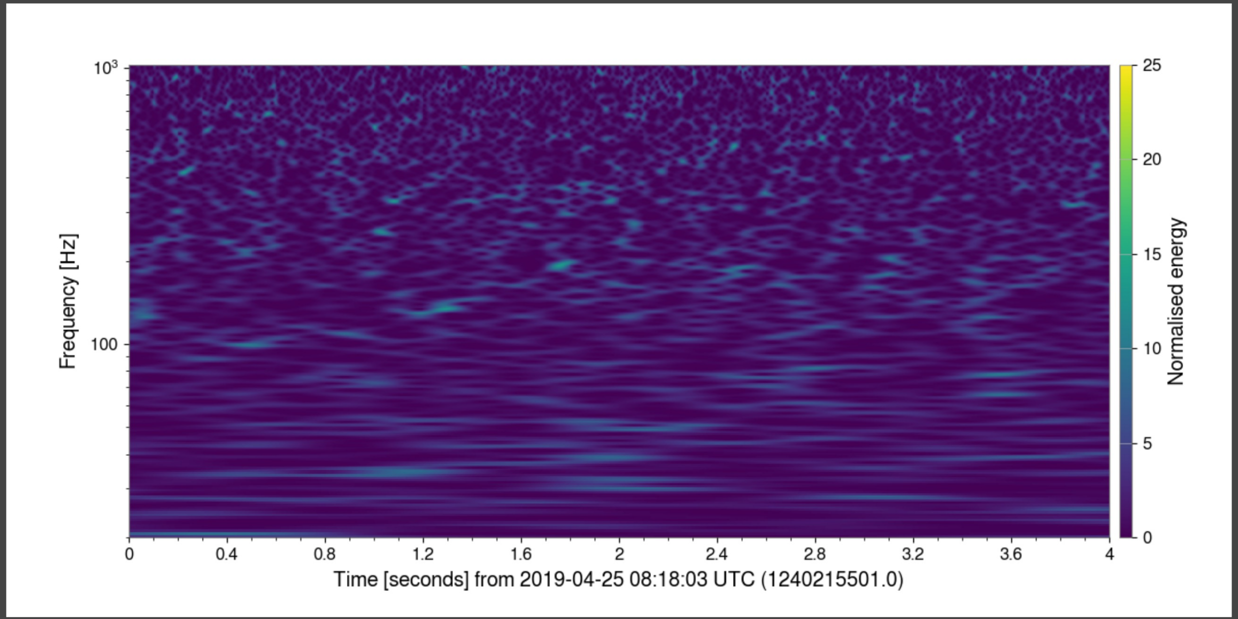
Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

H1 strain

https://www.gw-openscience.org/eventapi/

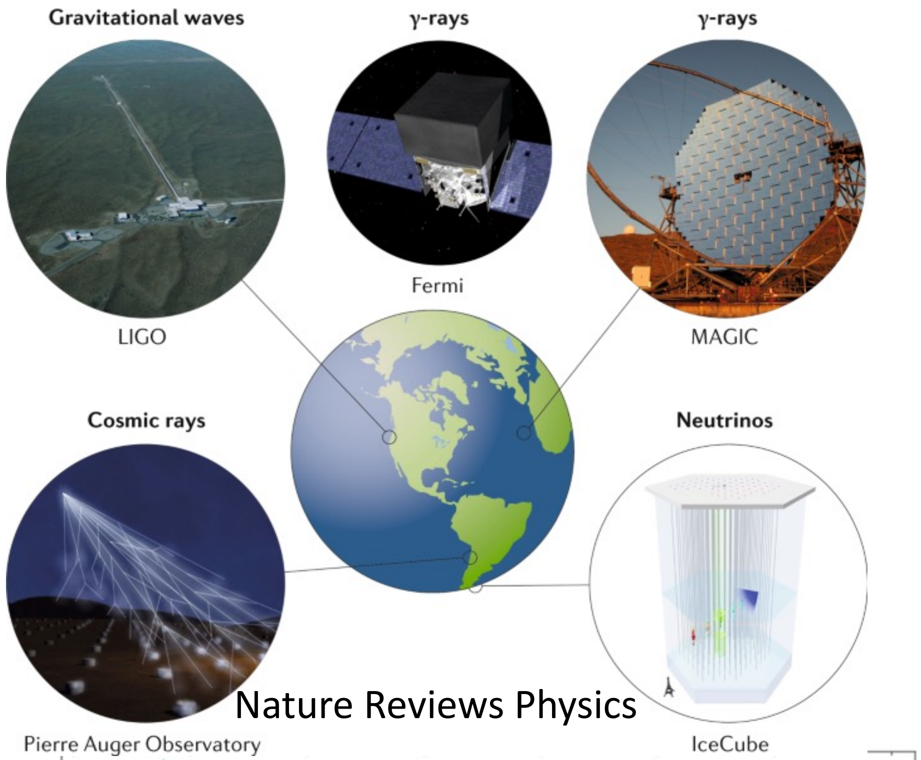


L1 strain

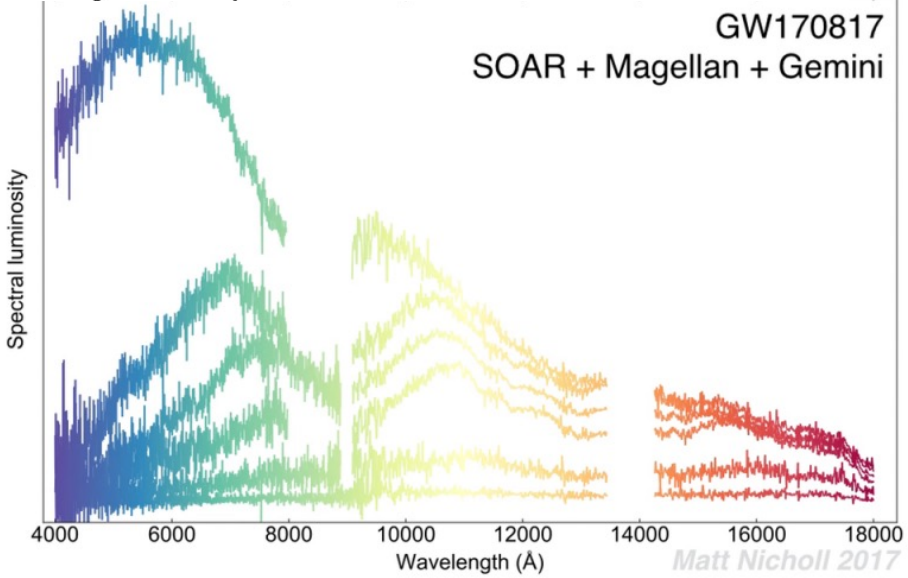


Multi-messenger Astrophysics

- Extension of multiwavelength astronomy.
- Use of multiple signals: photons, gravitational waves, neutrinos, cosmic rays from multi-messenger cosmic sources.
- *Golden age* for neutron star research.
- We just need about 100 more or so such discoveries!

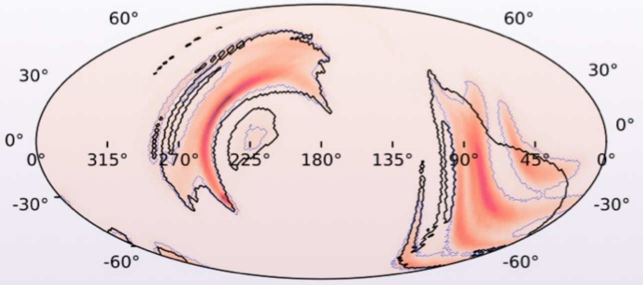


Nature Reviews Physics

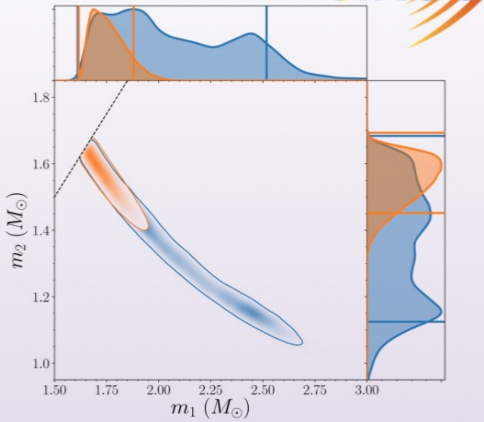


Matt Nicholl 2017

GW190425 FACTSHEET



observed by	LIGO Livingston, Virgo
source type	most likely a binary neutron star merger
date	25 April 2019
time of merger	08:18:05 UTC
Livingston signal-to-noise ratio	12.9
Virgo signal-to-noise ratio	2.5
false alarm rate	1 in 69 000 years
distance	287 to 744 million light-years
redshift	0.01 to 0.04
total mass	3.3 to 3.7 $M_\odot$
primary NS mass	1.61 to 2.52 $M_\odot$
secondary NS mass	1.12 to 1.68 $M_\odot$
mass ratio	0.4 to 1.0



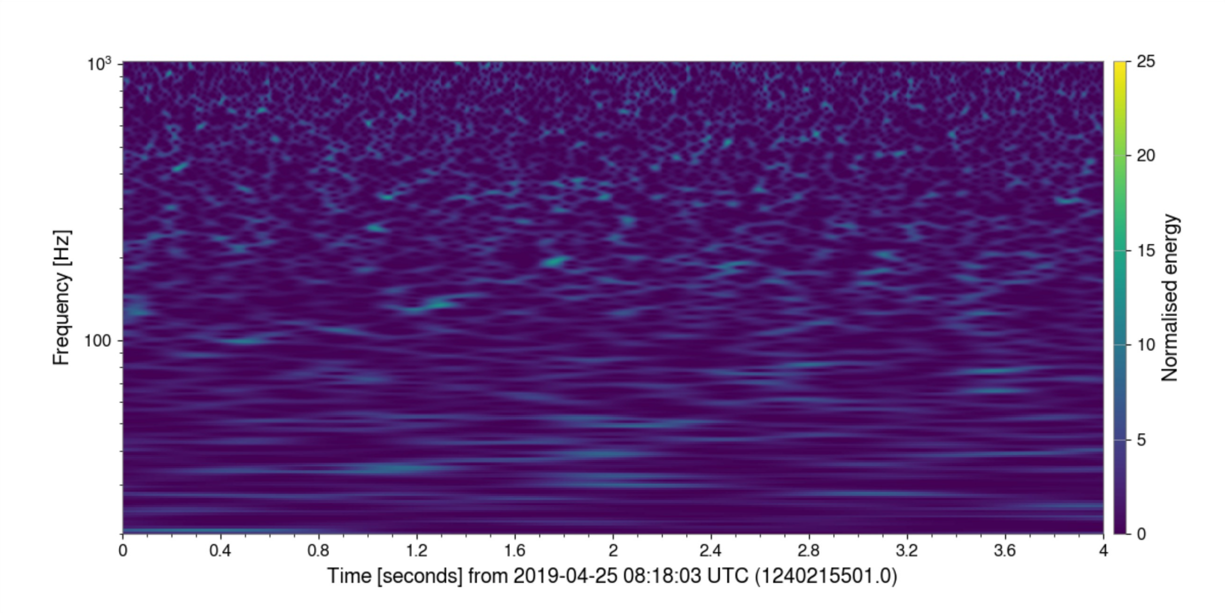
core density of primary NS	70 to 140 trillion times density of lead
inferred # of GW cycles from 19.4 Hz to 2048 Hz*	~ 3900
initial astronomer alert latency**	~43 min
sky area†	8284 deg²
improved binary NS merger rate	7 to 81 mergers per year per cubic billion light-years

Images: **GW sky map** (left): initial (black contours) and final (red and orange with grey contours) regions where source is likely to be located. Darker shading indicates increased likelihood source is in that region of sky. **Component mass distribution** (right): darker shading indicates an increased likelihood the pair of stars had that set of masses. The blue and orange lines denote 90% confidence intervals for two different assumptions—NS spins are allowed to be large (blue) and NS spins are constrained to be small (orange). The black diagonal line is the line m_1=m_2.

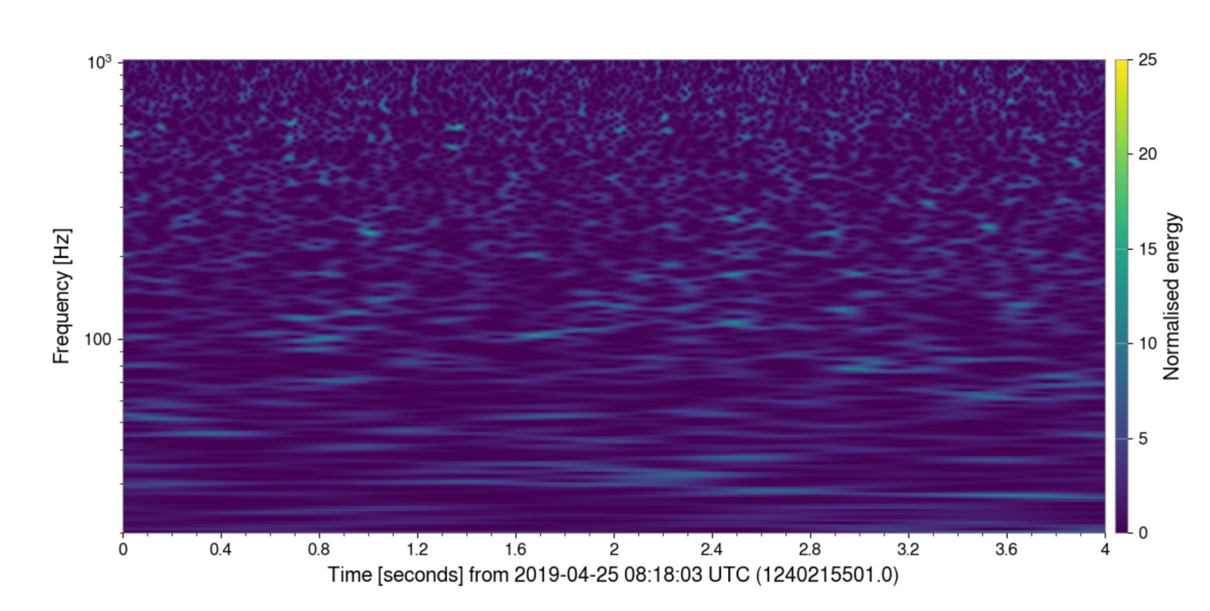
GW=gravitational wave, NS=neutron star, $M_\odot$=1 solar mass=2x10³⁰ kg

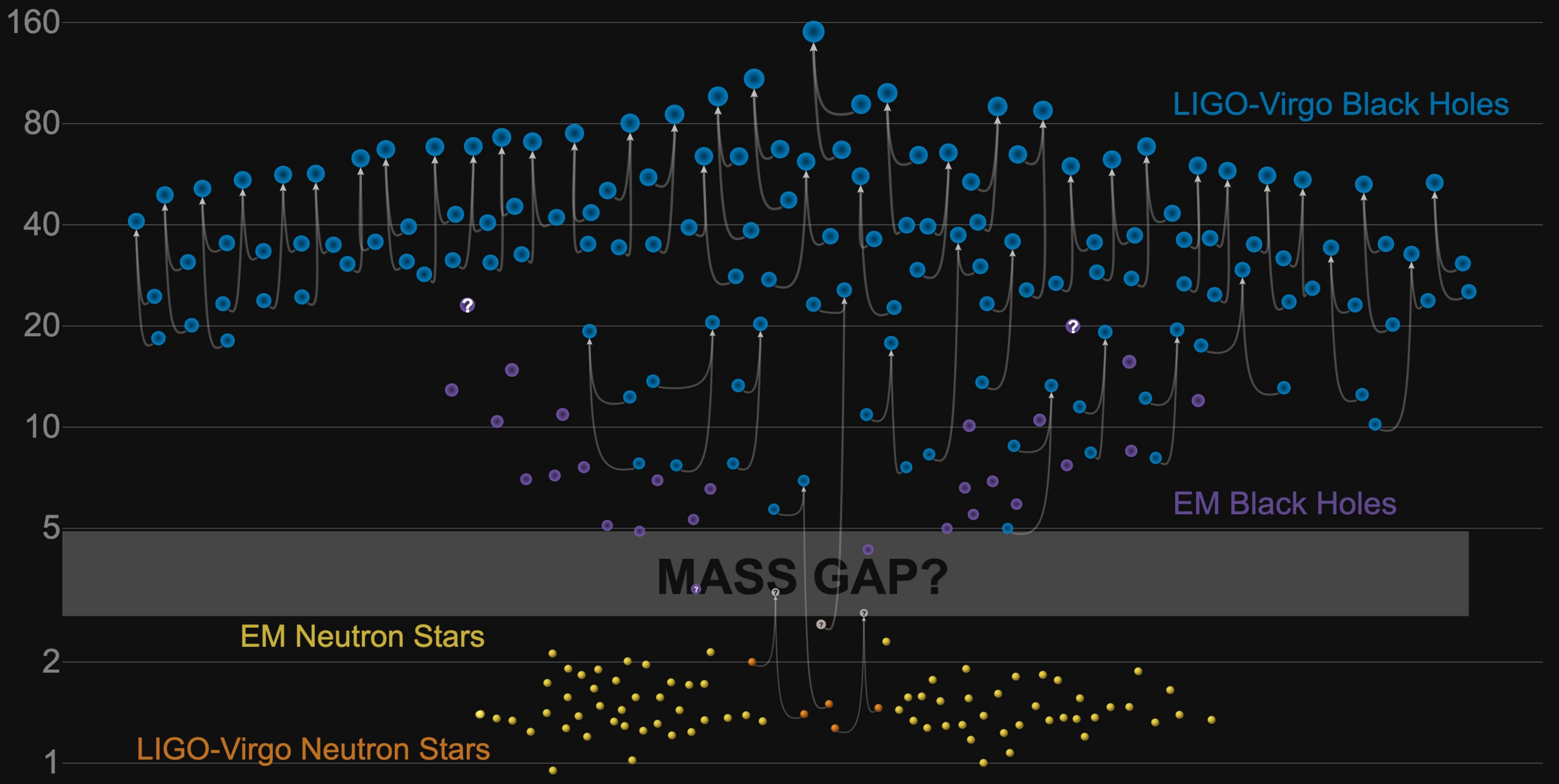
L1 strain

https://www.gw-openscience.org/eventapi/

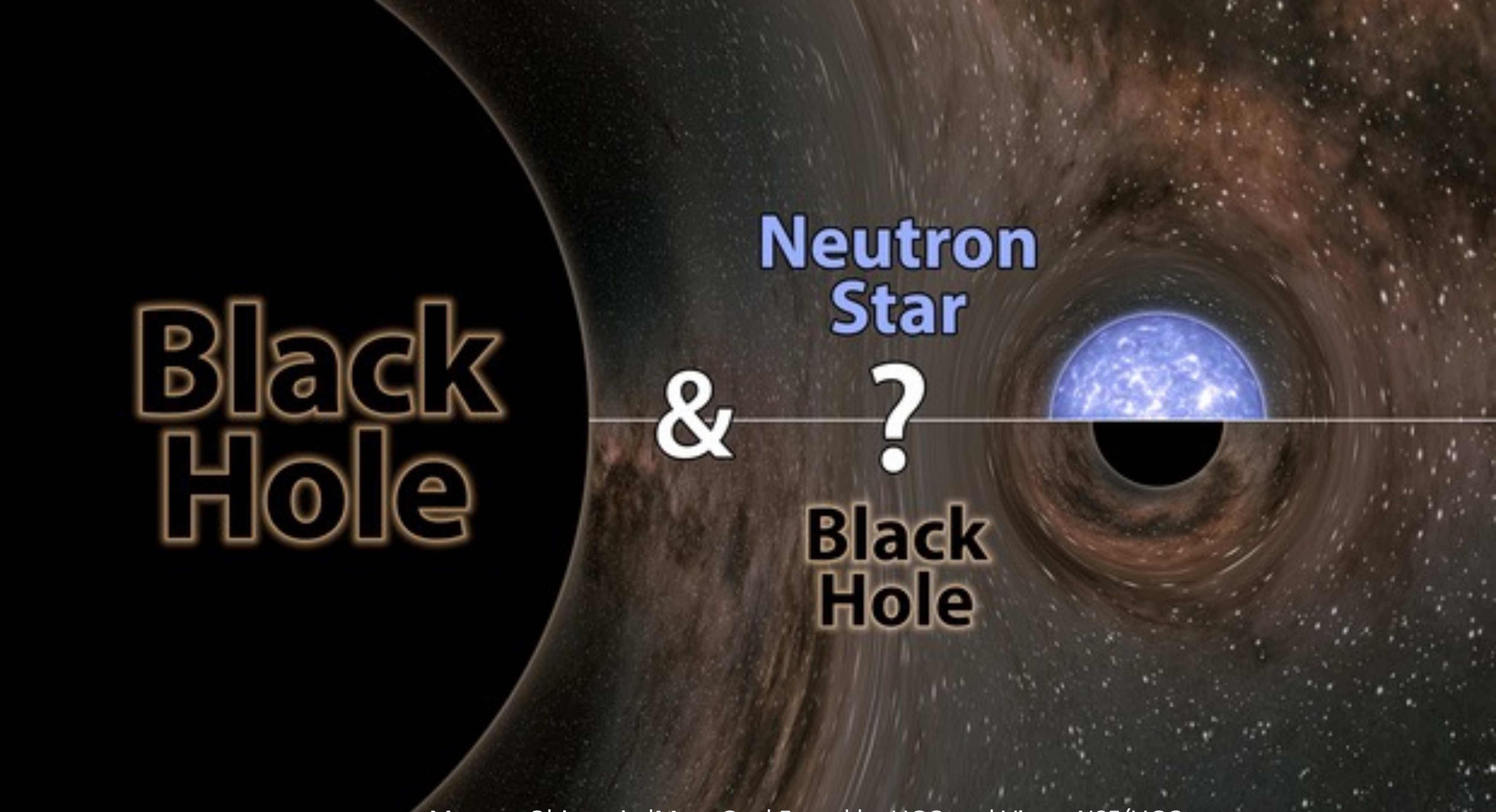


V1 strain





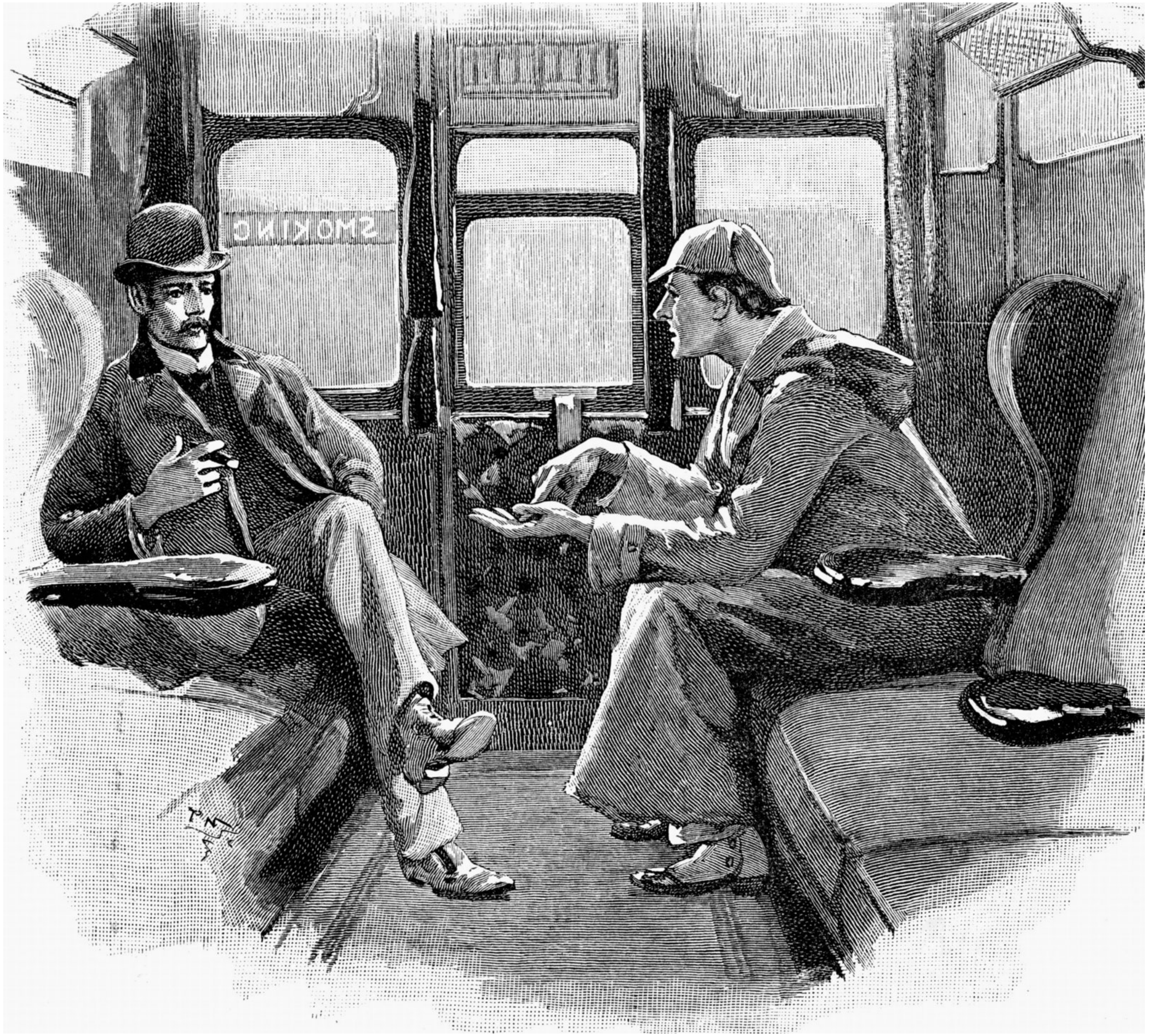
Catalog of gravitational-wave candidates reported by the LIGO and Virgo detectors, Aug. 2021. *NSF/LIGO*



Mystery Objects in 'Mass Gap' Found by LIGO and Virgo. *NSF/LIGO*

Curious Incidents

- What is the connection between gravitational waves, magnetic field and equation of state in neutron star mergers?
- What is the engine that triggers jet production?
- What is the nature of the remnant object?
- What is the correlation between gravitational waves, matter ejecta and light emission?
- Numerical simulations needed!



An illustration by Sidney E. Paget for "The Adventure of Silver Blaze," by Arthur Conan Doyle published in 1892

Multi-physics Modeling

- One of the most complicated problem to model:
    - General Relativity
    - Hydrodynamics
    - Electric and Magnetic fields
    - Realistic equations of state
    - General relativistic radiation
    - Neutrino leakage scheme

$$G^{\mu\nu} = 8\pi T^{\mu\nu}$$

$$\nabla_\mu\left(\rho_0 u^\mu\right) = 0$$

$$\nabla_\mu T^{\mu\nu} = 0,\ T_{\mu\nu} = T_{\mu\nu}^{\mathrm{matter}} + T_{\mu\nu}^{\mathrm{EM}}$$

$$\nabla_\nu F^{*\mu\nu} = \frac{1}{\sqrt{-g}}\partial_\nu\left(\sqrt{-g}\,F^{*\mu\nu}\right) = 0$$

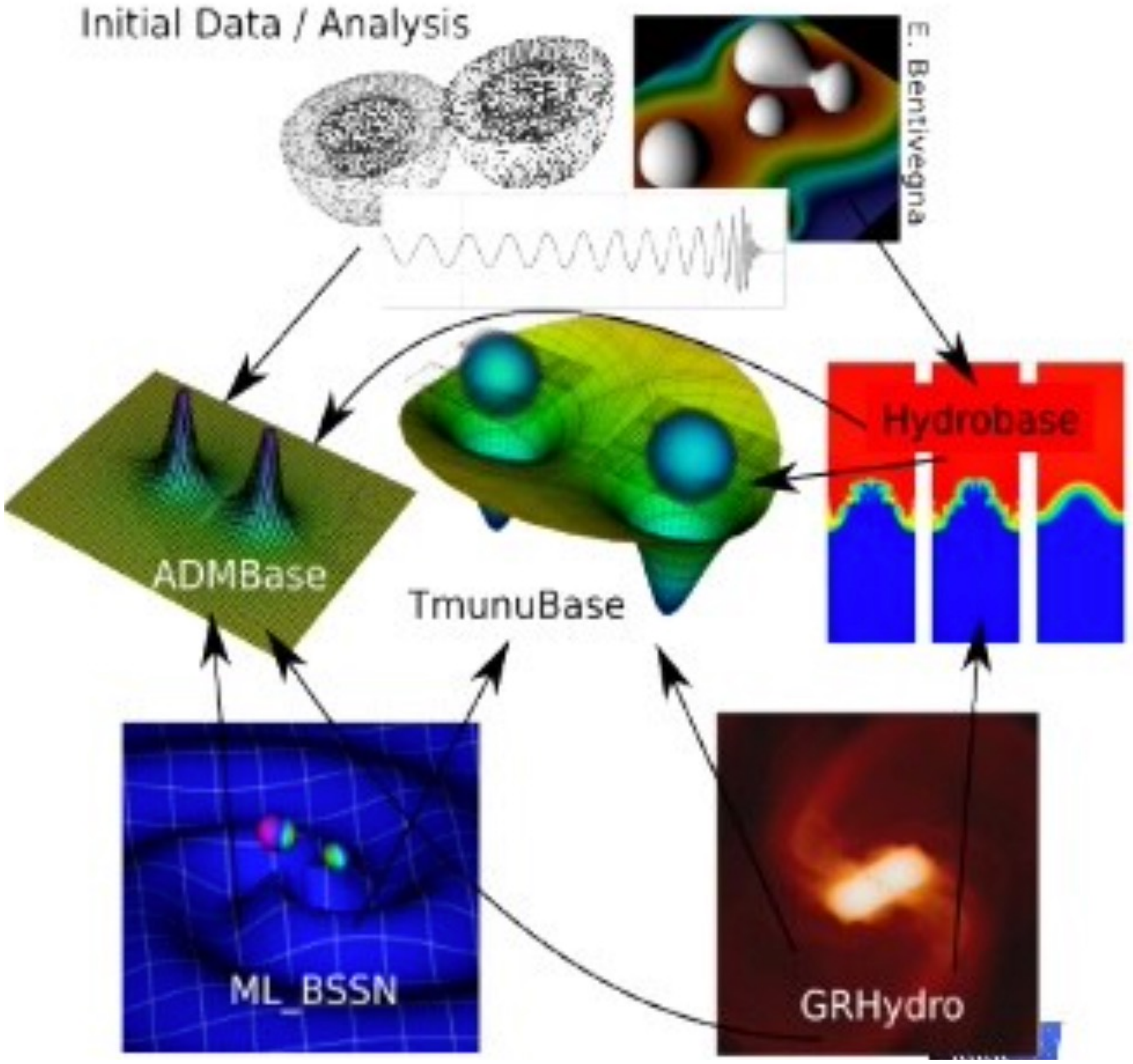
$$P(\rho,\epsilon) = \kappa_i\rho^{\Gamma_i} + (\Gamma_{th}-1)\rho\epsilon_{th}$$

$$p^\alpha\nabla_\alpha f = c\mathcal{E} - \frac{h}{c}\mathcal{A}f$$

$$\nabla_\alpha(\rho Y_e u^\alpha) \;=\; -R_\nu m_U$$

Advanced Numerical Algorithms

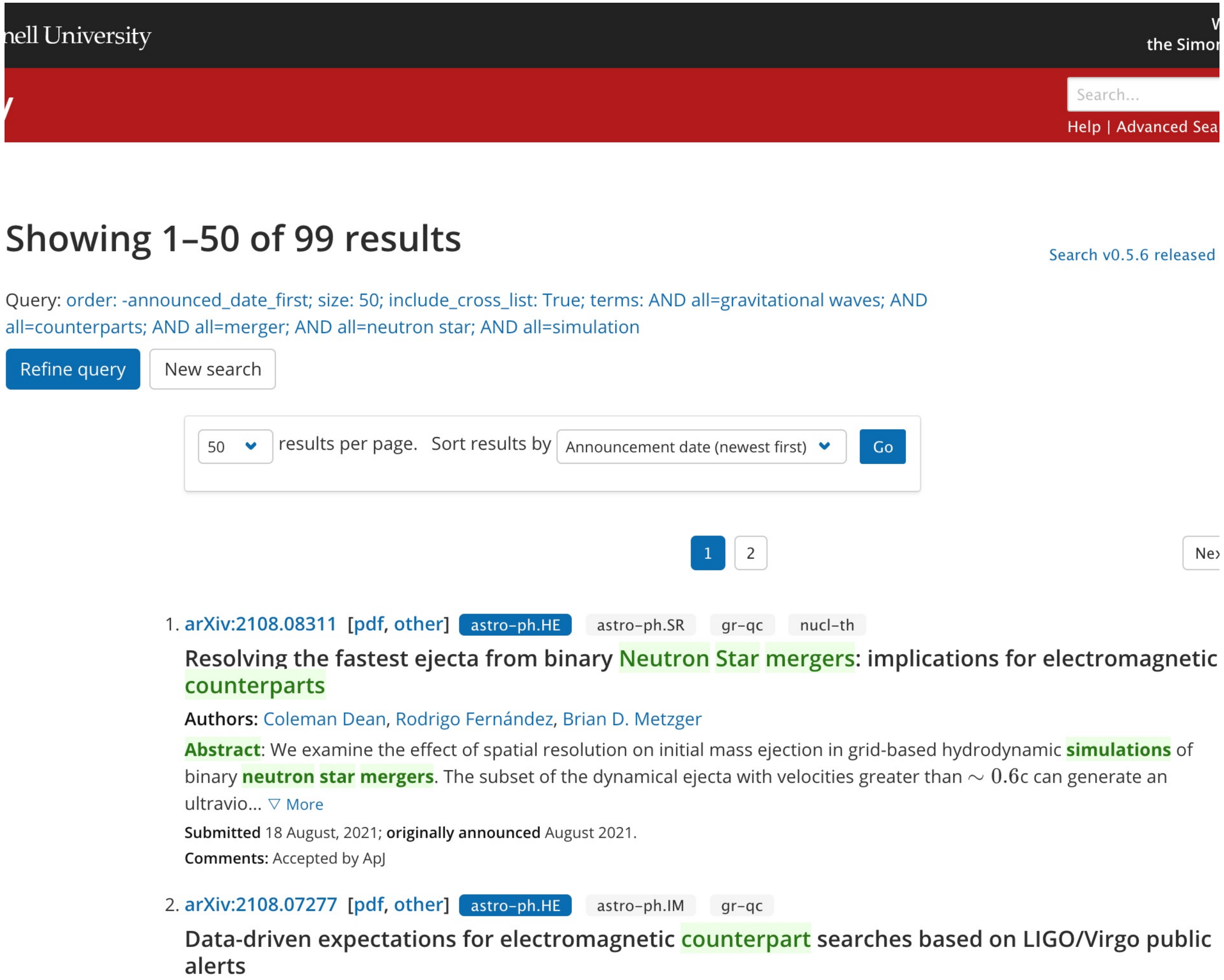
- Equation of state solvers
- Evolution schemes for dynamic spacetime, gauge and singularities
- Numerical capturing methods for instabilities, shocks and discontinuities
- Conservative to primitive reconstruction algorithms
- Magnetic field structure and evolution
- Neutrino and radiation transport
- Multi-spatial scale, very expensive simulations (millions CPU hours)
    - Resolving the ejecta and disc
    - Resolving the magnetic field
    - Extracting gravitational waves



Einstein Toolkit

Progress in the Field

- First basic model for neutron star mergers: Li-Xin Li and Bohdan Paczyski (1998)
- Thousand individual BNS simulations over the last decades
- Progress towards
  - populating the parameter space with EOS and mass ratio,
  - Improving numerical schemes
  - Adding multi-physics
  - Estimating mass ejecta
  - Electromagnetic counterparts



Showing 1–50 of 99 results

Query: order: -announced_date_first; size: 50; include_cross_list: True; terms: AND all=gravitational waves; AND all=counterparts; AND all=merger; AND all=neutron star; AND all=simulation

results per page. Sort results by Announcement date (newest first)

1. arXiv:2108.08311 [pdf, other] astro-ph.HE astro-ph.SR gr-qc nucl-th

   Resolving the fastest ejecta from binary Neutron Star mergers: implications for electromagnetic counterparts

   Authors: Coleman Dean, Rodrigo Fernández, Brian D. Metzger

   Abstract: We examine the effect of spatial resolution on initial mass ejection in grid-based hydrodynamic **simulations** of binary **neutron star mergers**. The subset of the dynamical ejecta with velocities greater than $\sim 0.6c$ can generate an ultravio... ▽ More

   Submitted 18 August, 2021; **originally announced** August 2021.

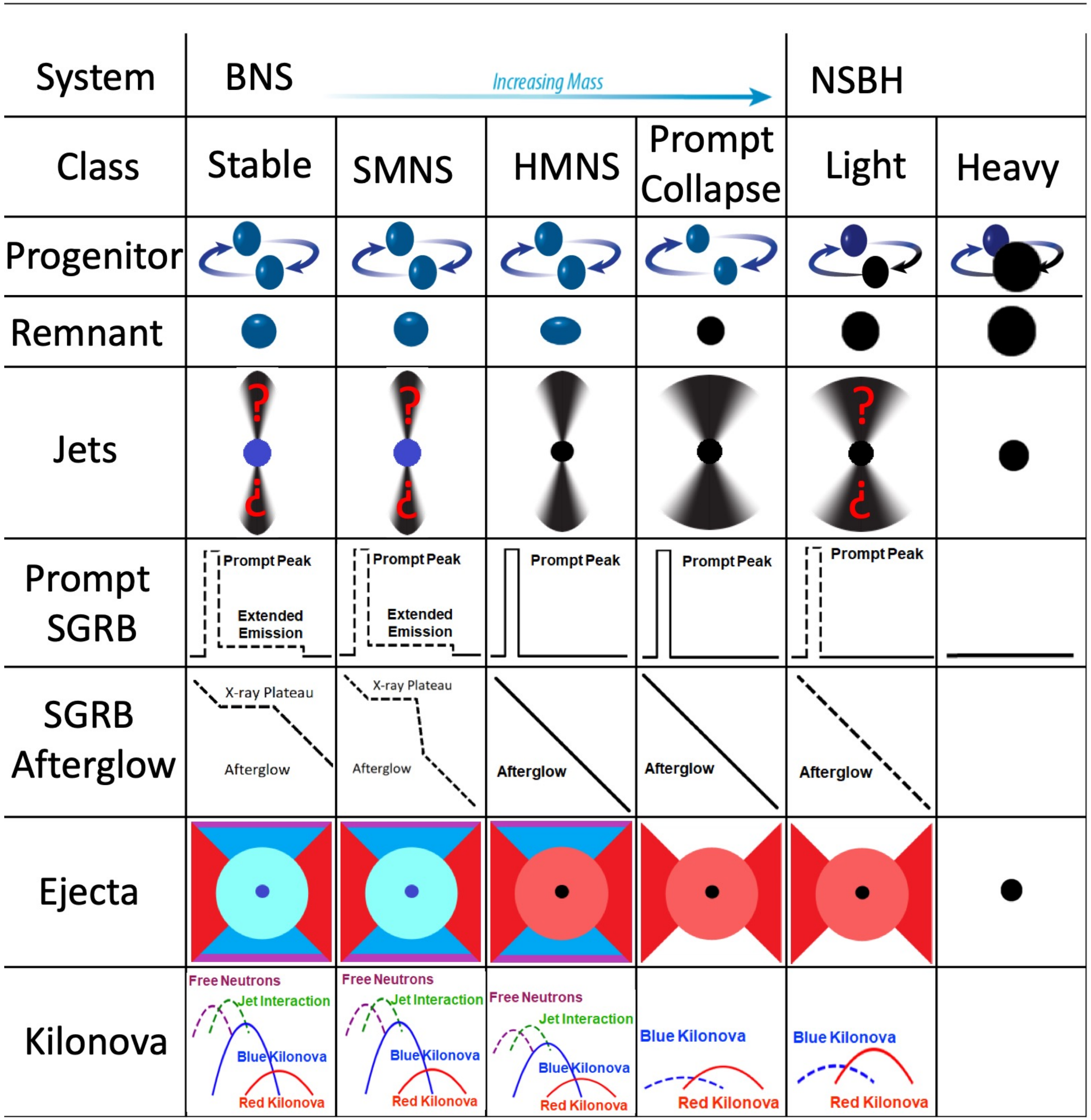
   Comments: Accepted by ApJ

2. arXiv:2108.07277 [pdf, other] astro-ph.HE astro-ph.IM gr-qc

   Data-driven expectations for electromagnetic counterpart searches based on LIGO/Virgo public alerts

Work to be Done

- Vast parameter space of the EOSs, mass ratios and magnetic fields.
- Conditions for the generation of electromagnetic counterparts to gravitational wave signals.
- Reproducibility of the results!
- Open-source General-Relativistic Magnetohydrodynamics codes:
    - **GRHydro** (R. DePietri)
    - **IGM** (Z. Etienne, L. Werneck)
    - **Spritz** (B. Giacomazzo, R. Ciolfi+)
- Forge a path and make it approachable to new comers.



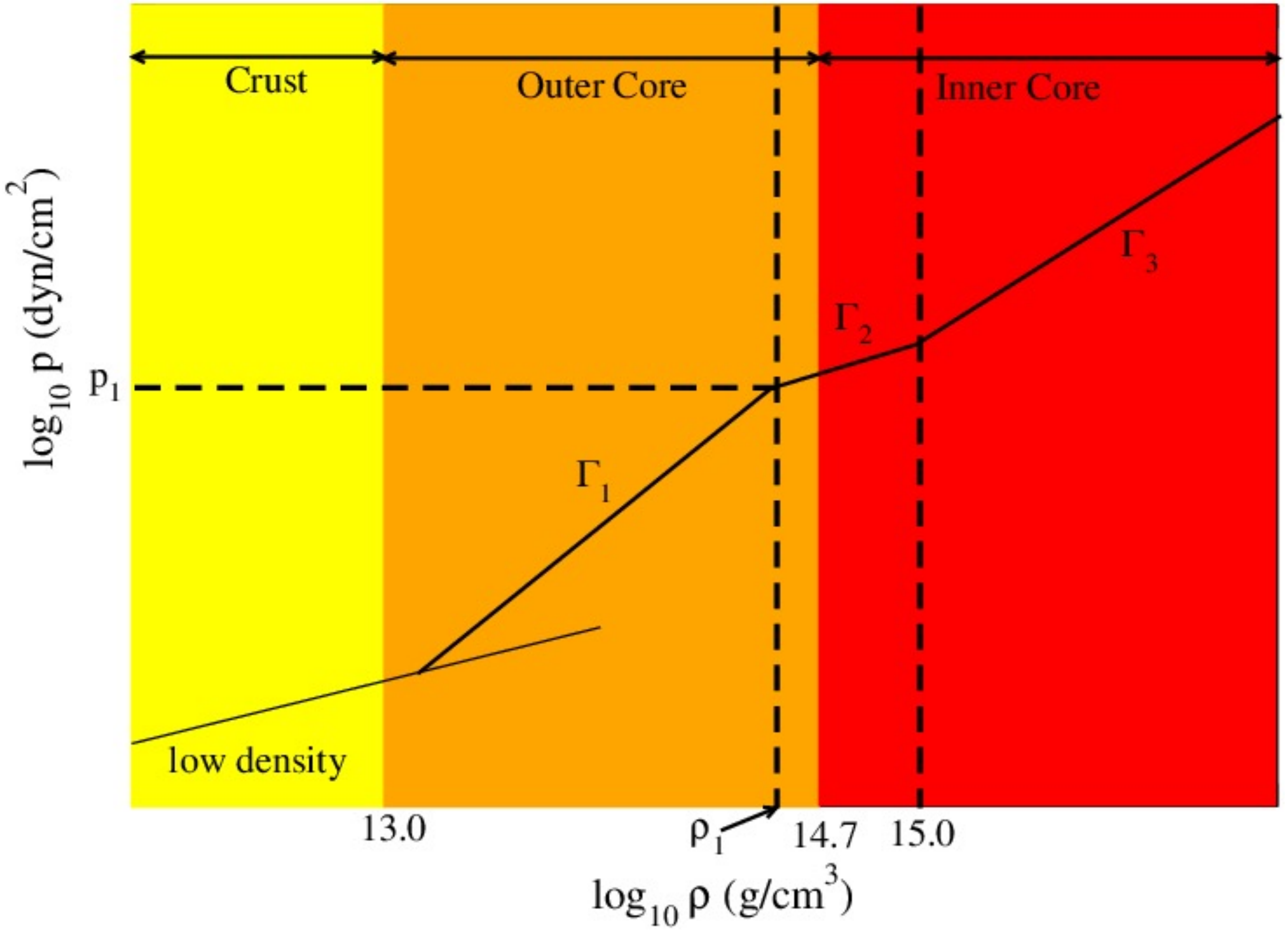
System	BNS		Increasing Mass		NSBH	
Class	Stable	SMNS	HMNS	Prompt Collapse	Light	Heavy
Progenitor						
Remnant						
Jets	? ¿	? ¿			? ¿	
Prompt SGRB	Prompt Peak Extended Emission	Prompt Peak Extended Emission	Prompt Peak	Prompt Peak	Prompt Peak	
SGRB Afterglow	X-ray Plateau Afterglow	X-ray Plateau Afterglow	Afterglow	Afterglow	Afterglow	
Ejecta						
Kilonova	Free Neutrons Jet Interaction Blue Kilonova Red Kilonova	Free Neutrons Jet Interaction Blue Kilonova Red Kilonova	Free Neutrons Jet Interaction Blue Kilonova Red Kilonova	Blue Kilonova Red Kilonova	Blue Kilonova Red Kilonova	

E Burns, arXiv:1909.06085

The Equation of State

- Most popular: Nucleonic Skyrme-Lyon (Sly) 4 pieces EOS (Douchin +,arxiv:astro-ph/0111092)
- 34 types of EOSs (Read+, arXiv:0812.3955)
- 7-parameters, low density 4 Sly, impose continuity in pressure
- EOS constraints
  - stiff - NICER
  - soft - GW170817
  - mild - GW190425 & GW190814

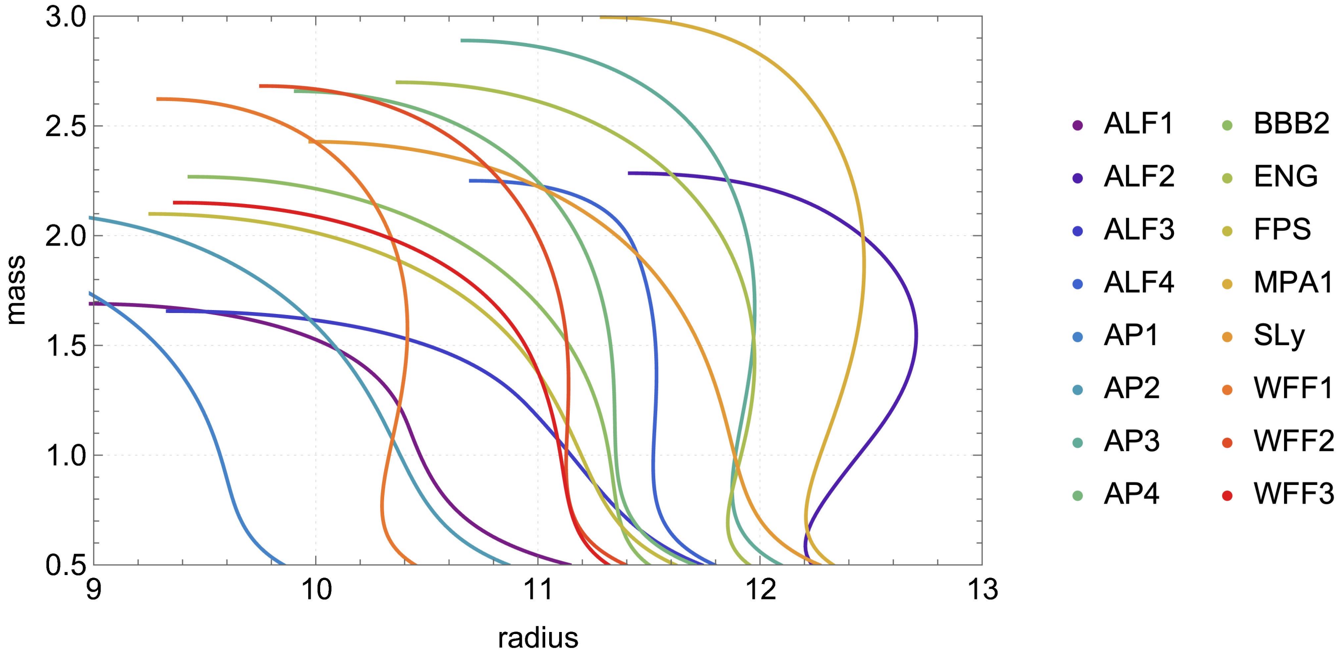
$$P(\rho_i) = K_i \rho_i^{\Gamma_i} = K_{i+1} \rho_i^{\Gamma_{i+1}}$$

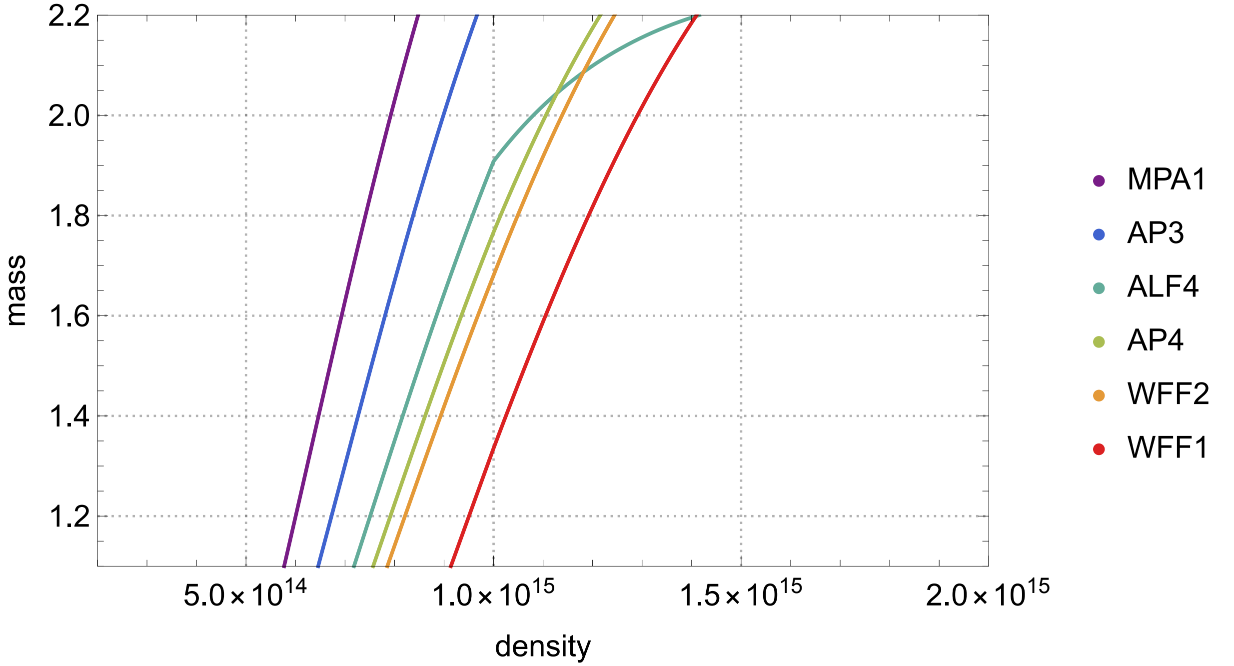


K. Yagi, arXiv:1406.7587

Constrained EOS

- Astronomical observations
  - ALF 1 – 4 (nuclear & quark matter)
  - AP 1 – 4 (2 & 3 nucleon interaction)
  - BBB2 (nonrelativistic)
  - ENG, MPA1 (relativistic)
  - FPS (pion condensates)
  - WFF 1 – 3 (variational method)
- Maximum mass
  - stiff – MPA1 & AP3
  - mild – ALF4 & AP4 & WFF2
  - soft – WFF1

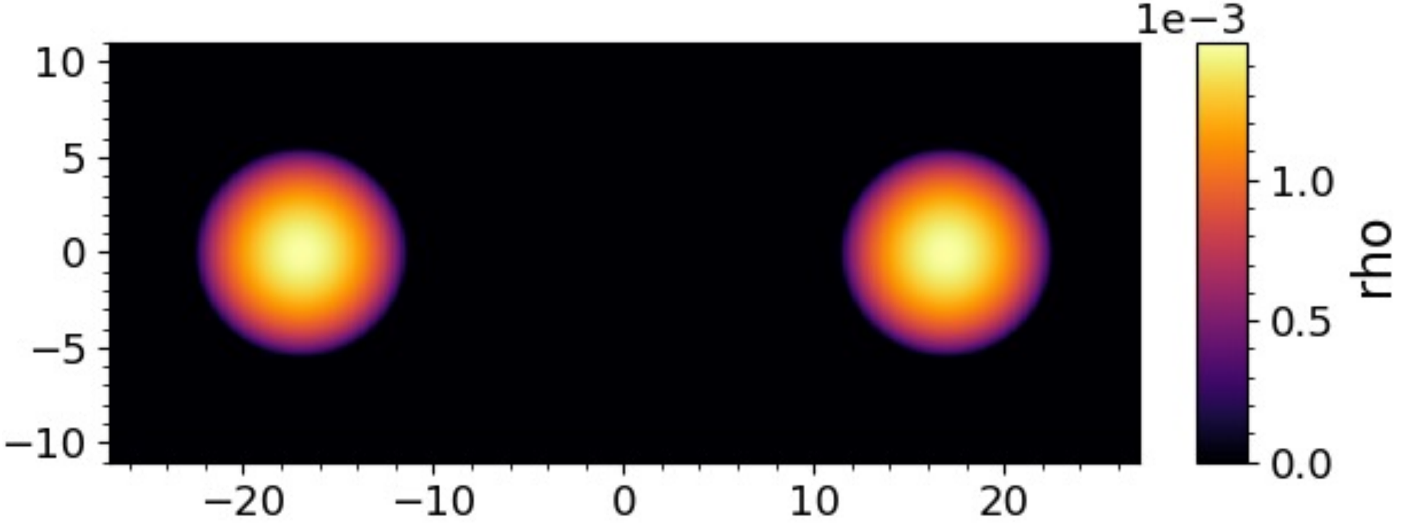




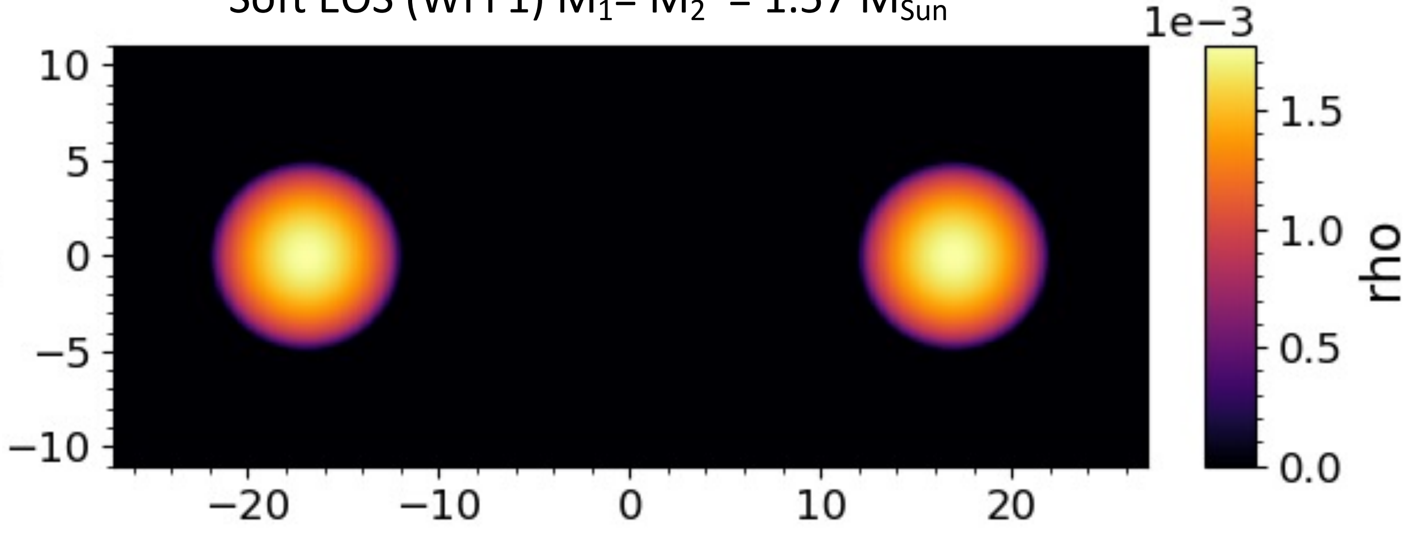
Initial Data

- Tolman–Oppenheimer–Volkoff equation (Lorene, E. Gourgoulhon+ https://lorene.obspm.fr) -> M(r)
- Primary mass: 1.5 – 2.4 M_{Sun}
- Mass ratio q =1, 1.3, 1.6, secondary mass GW detections:
  - $M_{chirp} \approx 1.18$, M_{Sun}, $M_{total} \approx 2.7\ M_{sun}$
  - $M_{chirp} \approx 1.44\ M_{Sun}$, $M_{total} \approx 3.3\ M_{sun}$
- Coordinate separation: 50 km
- Visualization: **kuibit** (G Bozzola)

Mild EOS (ALF4) $M_1 = M_2 = 1.55\ M_{Sun}$



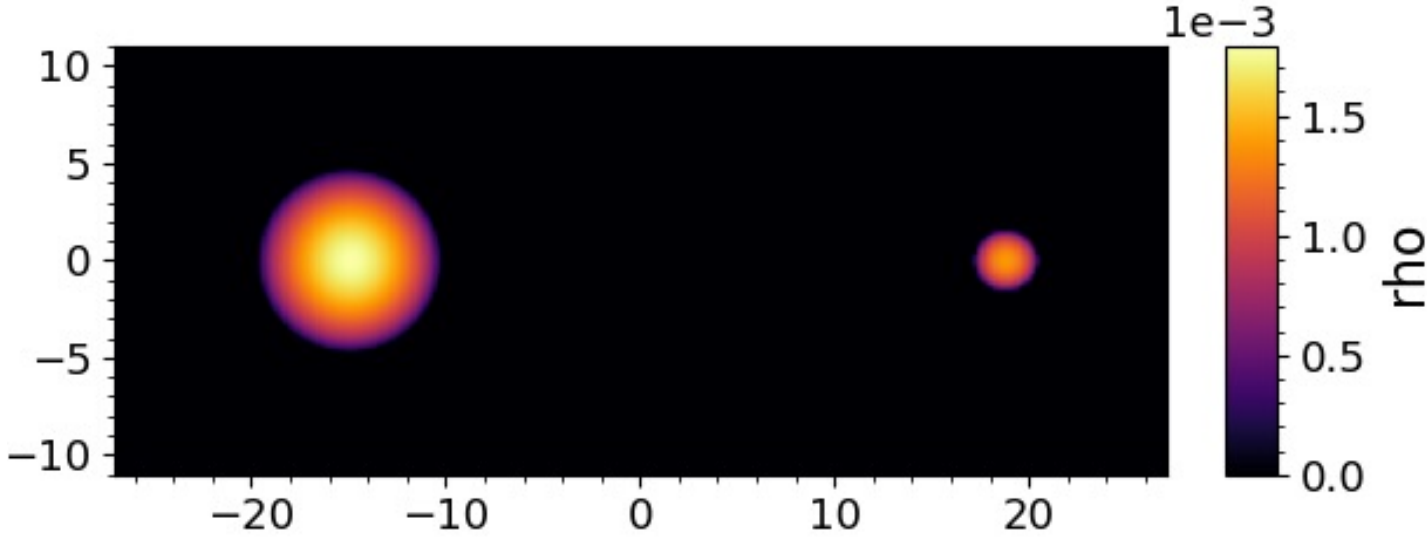
Soft EOS (WFF1) $M_1 = M_2 = 1.57\ M_{Sun}$



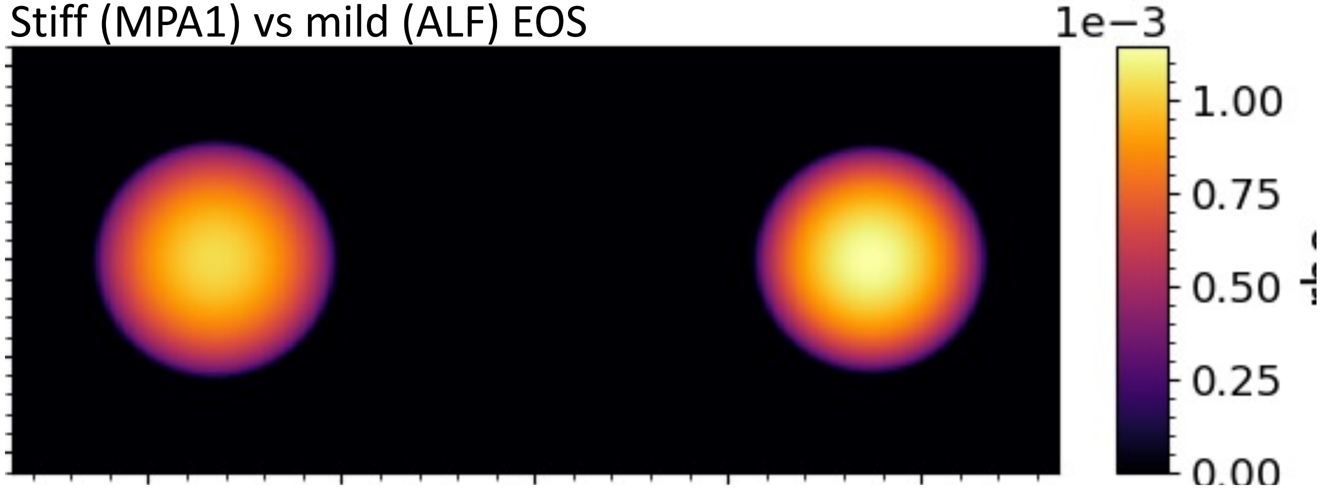
Initial Data Challenges

1. **Lorene** gives wrong results for unequal mass binaries!
2. **Lorene** can generate initial data for mixed EOS binaries but there is no evolution scheme for it.
3. Lorene implements only two types of EOS:
    - Parametrized piecewise
    - Tabulated polytropic

Soft EOS (AP4) M_1= 1.5 M_{Sun} , M_2= 2.1 M_{sun} (original)



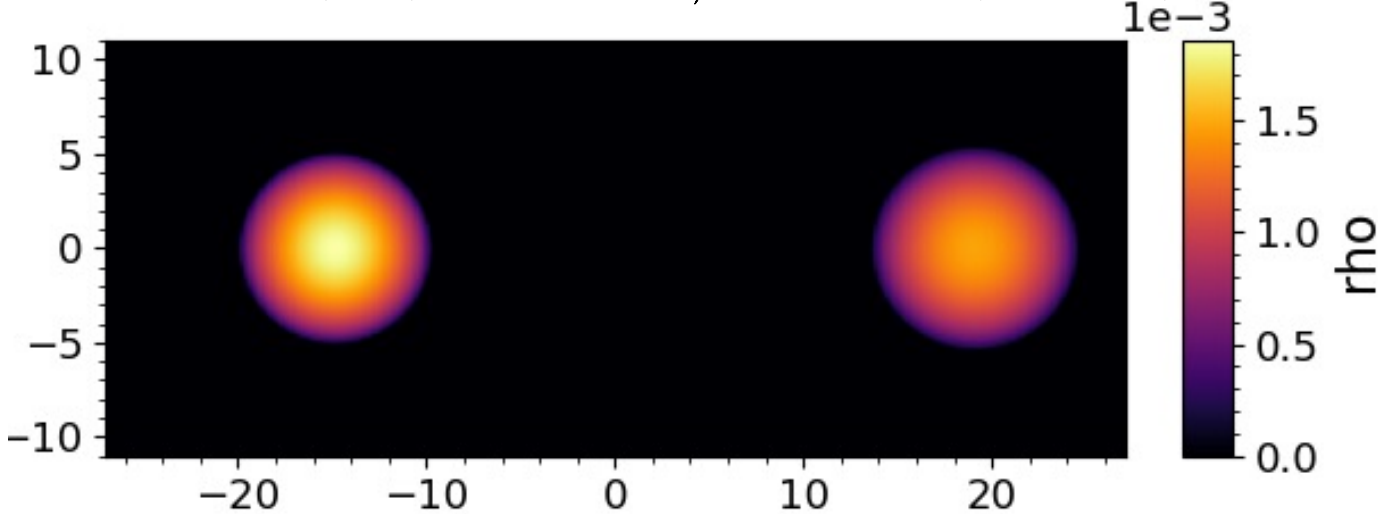
Stiff (MPA1) vs mild (ALF) EOS



Initial Data Opportunities

1. Use freely available Lorene initial data for unequal binaries
2. Implement the capability of evolving different initial data for each neutron star in the binary.
3. Implement the Generalized Parametrized Piecewise Polytropic EOS that accounts for the continuity in the speed of sound, and *tidal deformability*.

Soft EOS (AP4) M_1= 1.5 M_{Sun} , M_2= 2.1 M_{sun} (modified)



(https://ccrgpages.rit.edu/~jfaber/BNSID/Data)

$$P(\rho_i) = K_i \rho_i^{\Gamma_i} + \Lambda_i$$

$$\gamma = \frac{d \lg p}{d \lg \rho} = \frac{\rho d p}{p d \rho}$$

(MF O'Boyle +, arxiv:2008.03342)

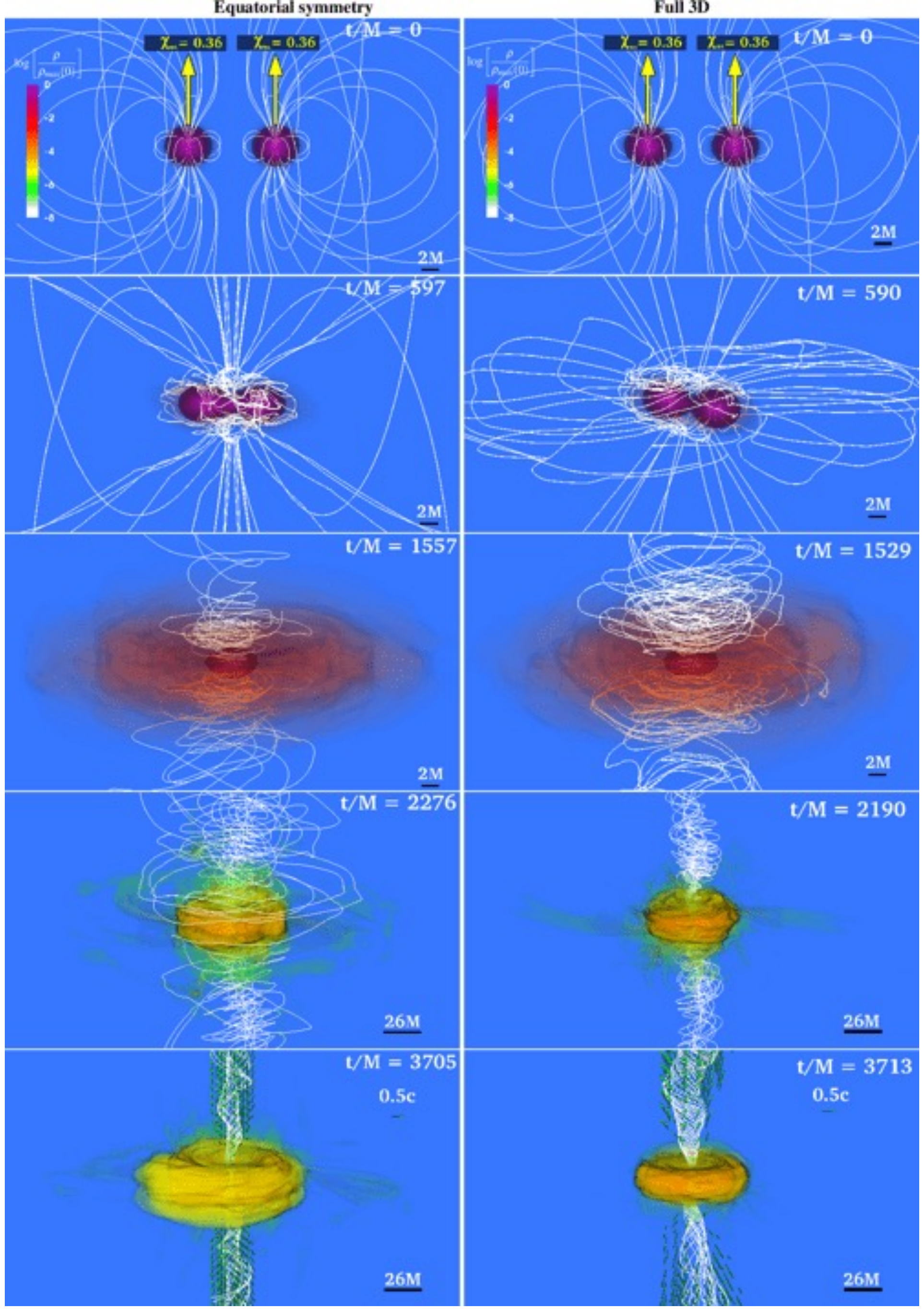
Magnetic Field of Neutron Stars

- Pulsars were thought to have dipolar magnetic field, marked by hot polar caps.
- NICER X-ray telescope revealed hot regions not at the dipolar magnetic poles
- One region is stretched – toroidal component.
- The origin, evolution and structure of this magnetic field is open to debate.

A Hotspot Map of Neutron Star J0030's Surface
Credit: NASA's Goddard Space Flight Center

Magnetic Field of Binary Neutron Stars

- Magnetic fields strength of neutron stars are very stable in time.
- Decay only for “recycled” millisecond pulsars in binaries, to 10^8-10^{10} G
- The companion’s magnetic field stays constant around 10^{11}-10^{13} G.
- The magnetic field gets amplified to 10^{15} G during merger, and determines the jet and the outflow dynamics.
- Is this amplification enough for jet launching, or must a black hole form?



M. Ruiz+, arxiv:2001.09153

Magnetic Field Models

- Seed internal poloidal magnetic field (B. Giacomazzo+, arxiv: 1009.2468) **GRHydro, Spritz, IGM**

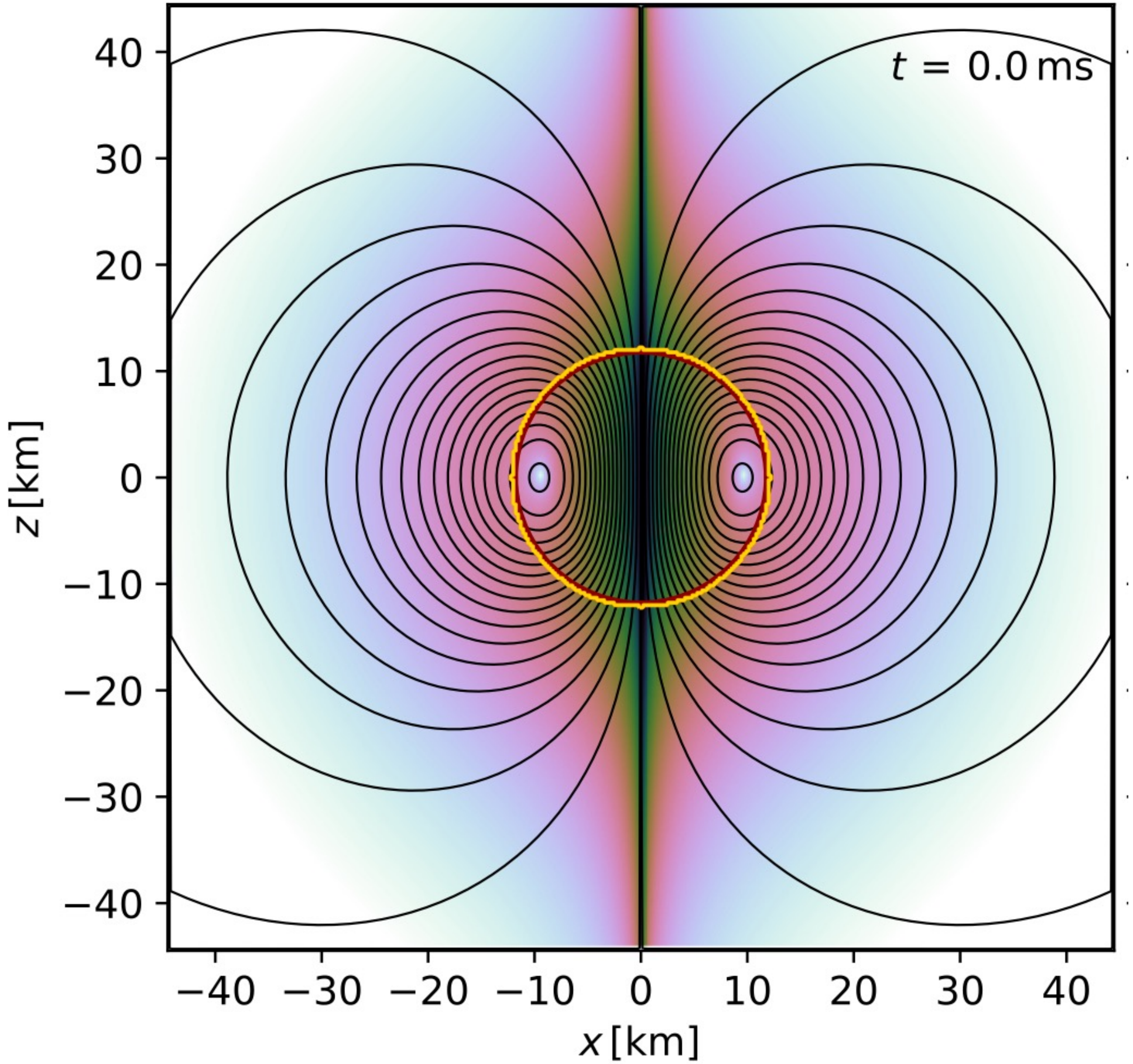
$$A_\phi = A_b \varpi \; max(p - p_{cut}, 0)^{n_s}$$

- Seed poloidal magnetic field (V. Paschalidis, arxiv: 1304.1805) **IGM**

$$A_\phi = \frac{\pi r_0^2 I_0 \varpi^2}{(r_0^2 + r^2)^{3/2}} \left(1 + \frac{15 r_0^2 (r_0^2 + \varpi^2)}{8 (r_0^2 + r^2)^2}\right)$$

- Dipolar field extending to the exterior (P. Moesta, arxiv:2003.06043) **NA**

$$A_\phi = B_0 \frac{r_0^3}{r^3 + r_0^3} r \sin\theta$$



J. Kalinani, arxiv:2107.10620.pdf

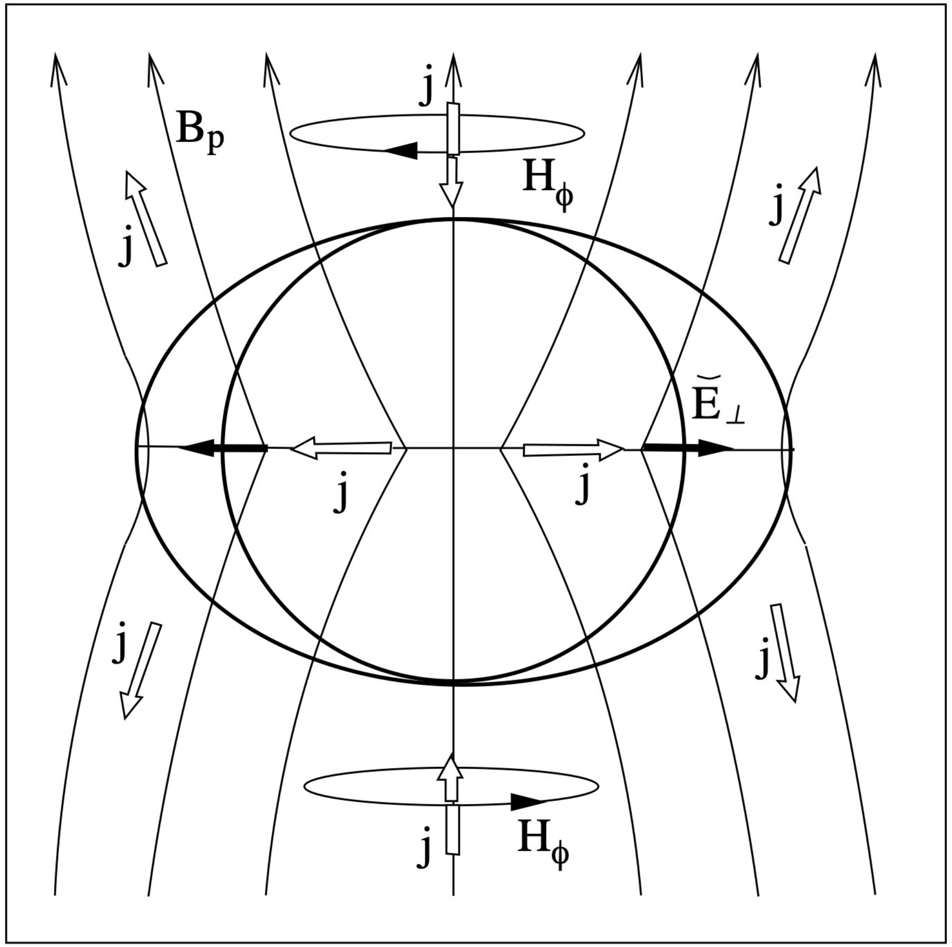
Magnetosphere Modeling

- Numerical General Relativistic Force-Free Electrodynamics.
- Maxwell's equations in the "force-free" MHD limit.
    - Strong magnetic field
    - No mass/low inertia
    - Particles injected and traced

$$E_iB^i = 0$$

$$B^2 > E^2$$

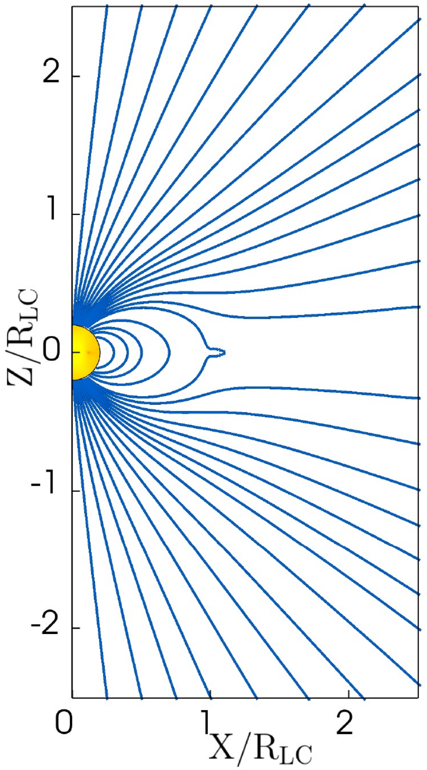
- A thin current sheet is imposed and maintained at equator.
- Divergenceles B-field evolution anc$S = n^i\epsilon_{ijk}\sqrt{\gamma}E^jB^k$lculation.



S. Komissarov, arxiv: 0402403

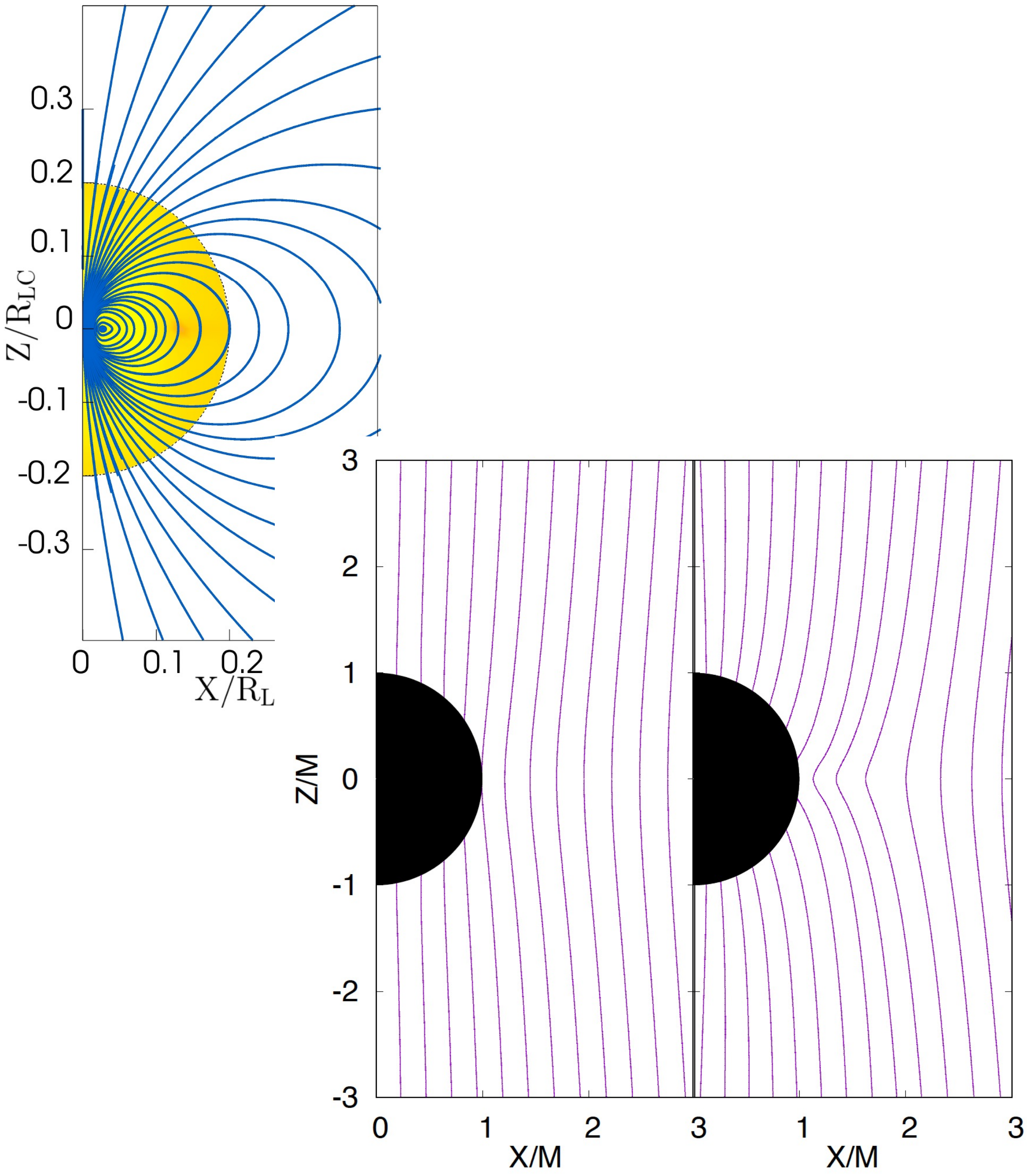
Pulsar and Wald Magnetosphere

- GiRaFFE (**G**eneral **R**elativistic and **F**orce-**F**ree **E**lectrodynamics) code (Z. Etienne, **MBH+**, arxiv:1704.00599)
- Pulsar magnetosphere: aligned rotator
- Rotation black hole magnetosphere: magnetospheric Wald



$$A_\phi = \frac{\mu\varpi^2}{r^3}$$

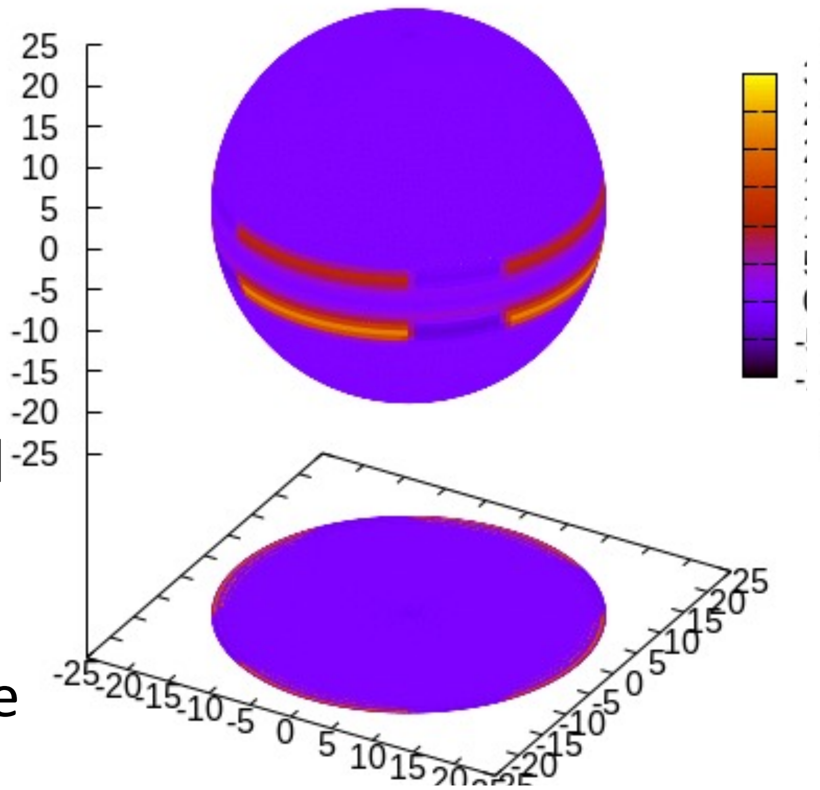
$$A_i = \frac{B_0}{2}(g_{i\theta} + 2ag_{it})$$

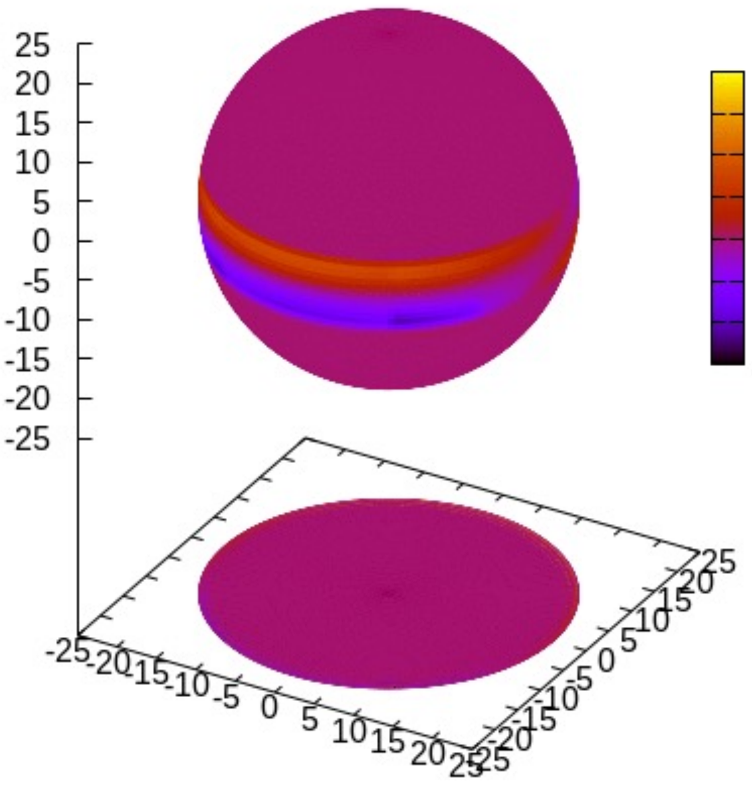


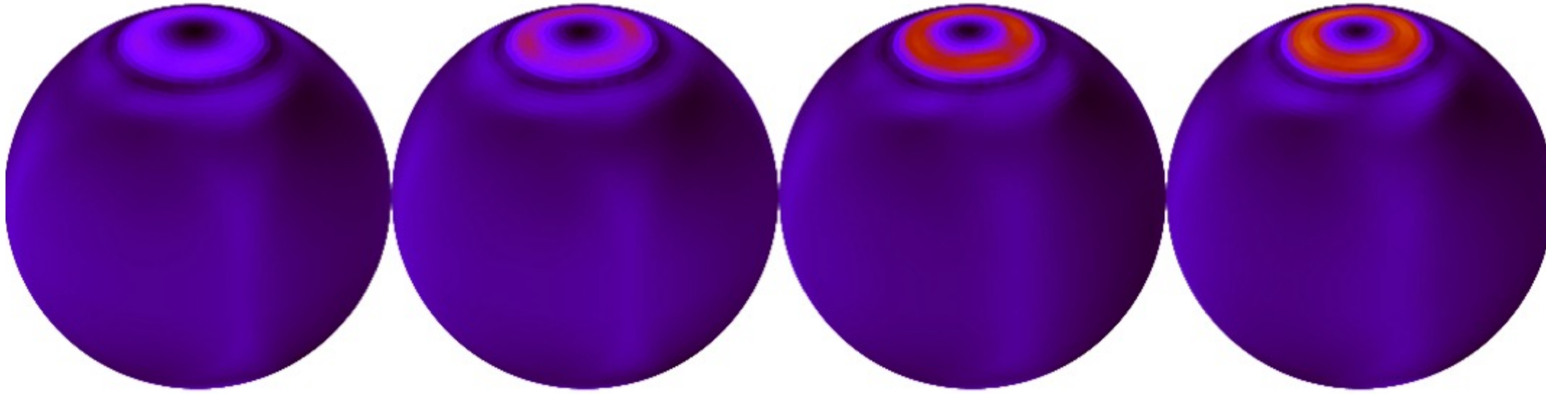
Rotating Black Hole Magnetosphere

- Blandford-Znajekfor mechanism for spinning black holes in aligned and tilted magnetosphere (**MBH**, arxiv:1901.00025)
- Spin effect analysis for the radio loud – radio quite transitions in quasars
- Binary black holes in external magnetosphere

$$A_i = \frac{B_0}{2}(y, -x\cos\chi, x\sin\chi)$$







Code Improvement Opportunities

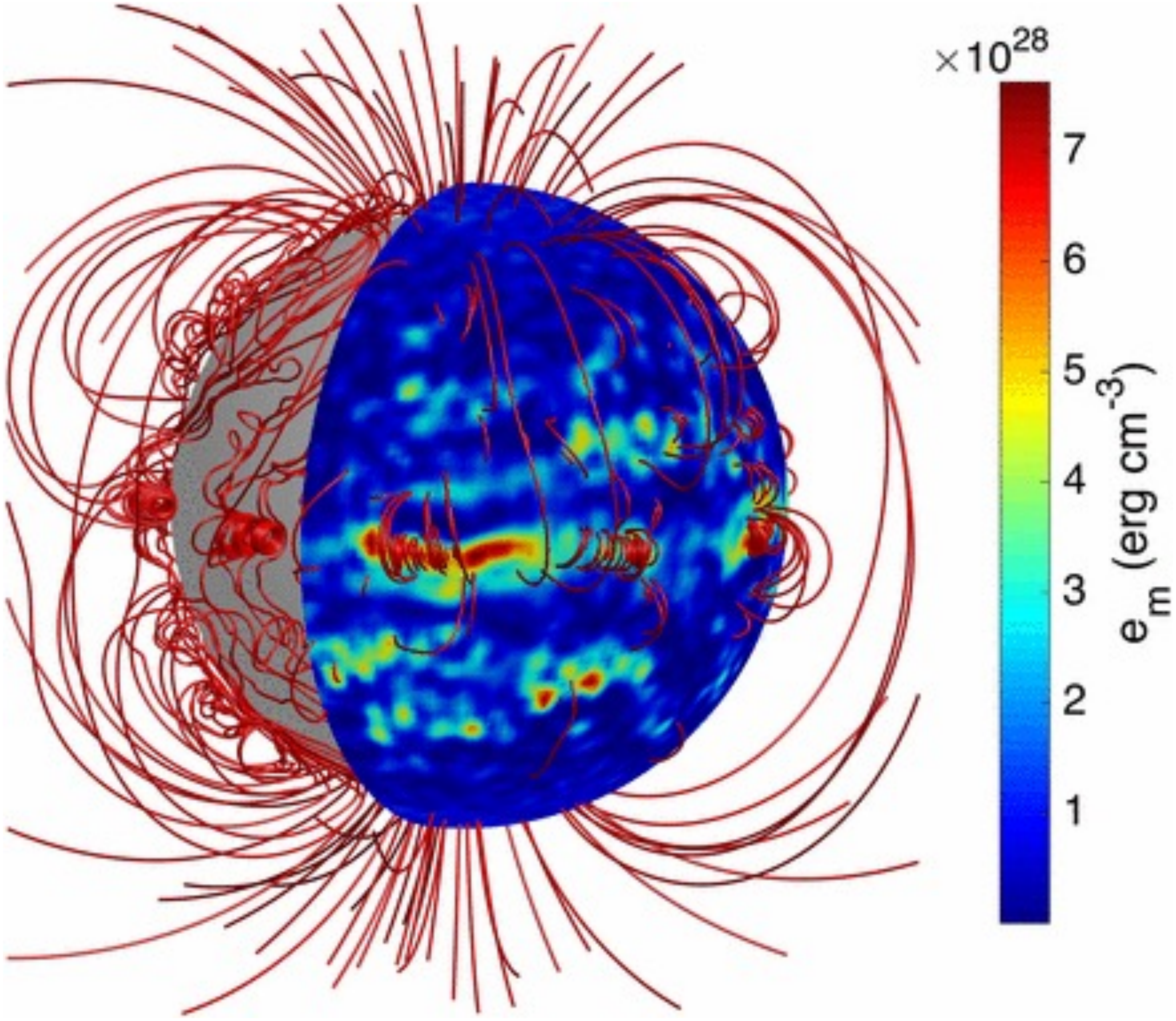
- Realistic interior magnetic field (A. Bansgrove+,arxiv:1709.09167) :

$$B^{int} = B_p + B_t$$

- Multipolar exterior magnetic field:

$$V(r,\theta) = \sum_{l=1} \frac{a_l}{r^{l+1}} P_l(\cos\theta)$$

- Add extra poloidal B-field near merger to mimic amplification!
- Improvements to GiRaFFE:
  - Match the crust magnetic field to the magnetosphere
  - Dynamic current sheet location function of magnetic field strength
  - Particle-in-cell (PIC) evolution of plasma (S. Zenitani+, 1809.04378)



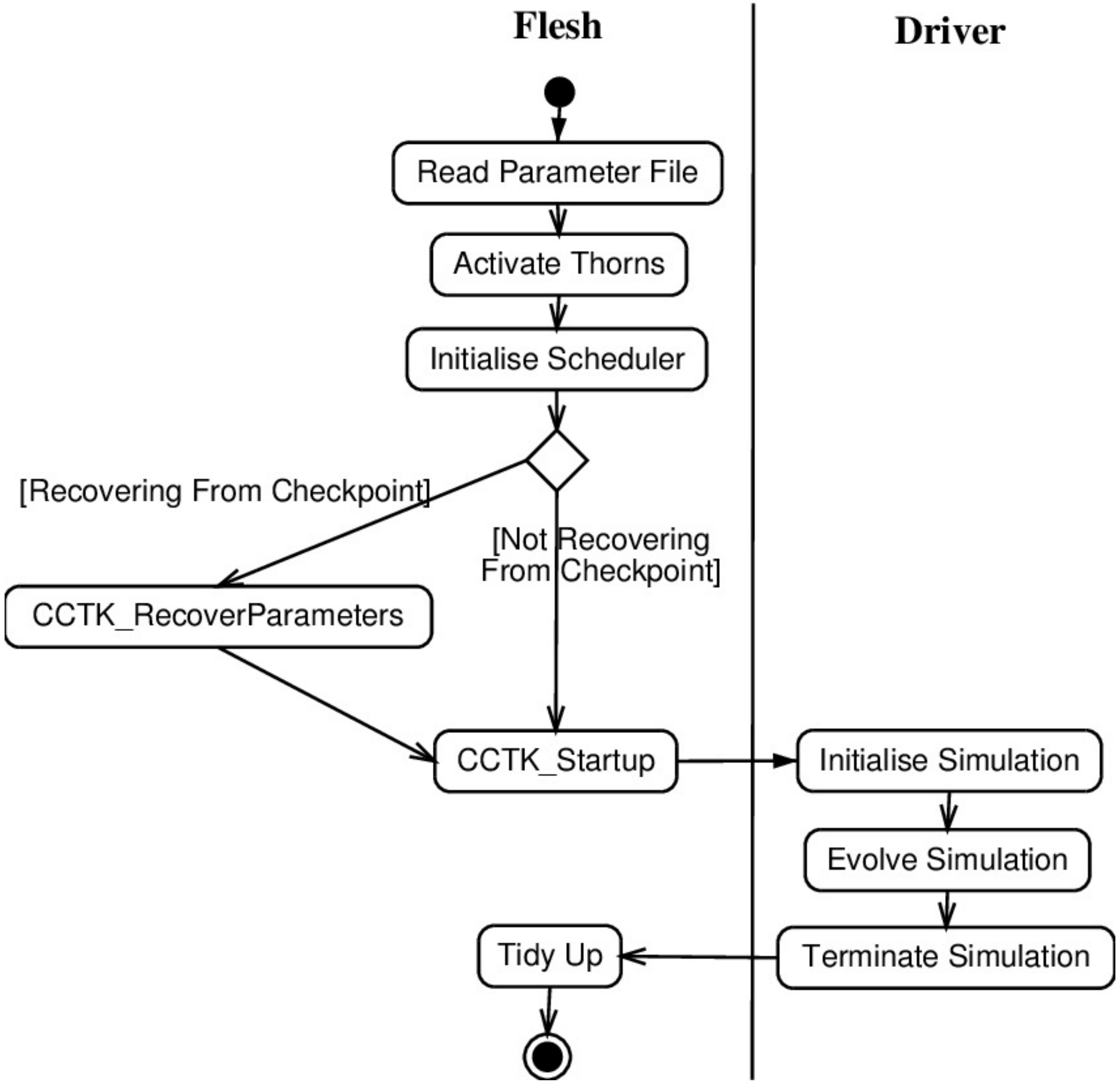
K. Gourgouliatos+, 2015

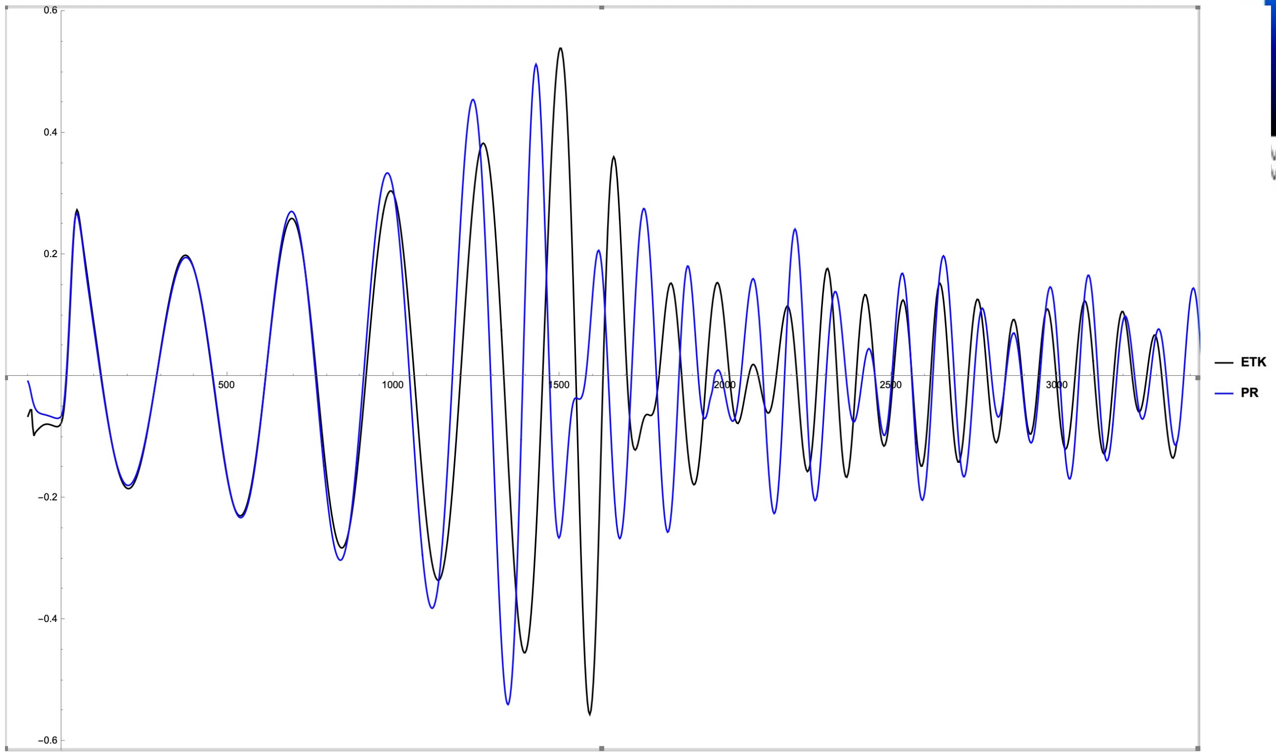
Computational Challenges and Opportunities

- EOS solver (Lorene) - laptop.
- BNS simulations - 10^6 cpu-hr.
- Most simulations carried out on the BigGreen cluster at Marshall University, WV.
- Current allocations:
    - BigGreen: 12 cores/node, 276 CPU cores
    - Thorny Flat, WVU: 40 cores per node, 4208 CPU cores
- Future: XSEDE, Pittsburgh Supercomputer Center:
    - Bridges-2, PSC: 64 cores per node, 31231 CPU cores

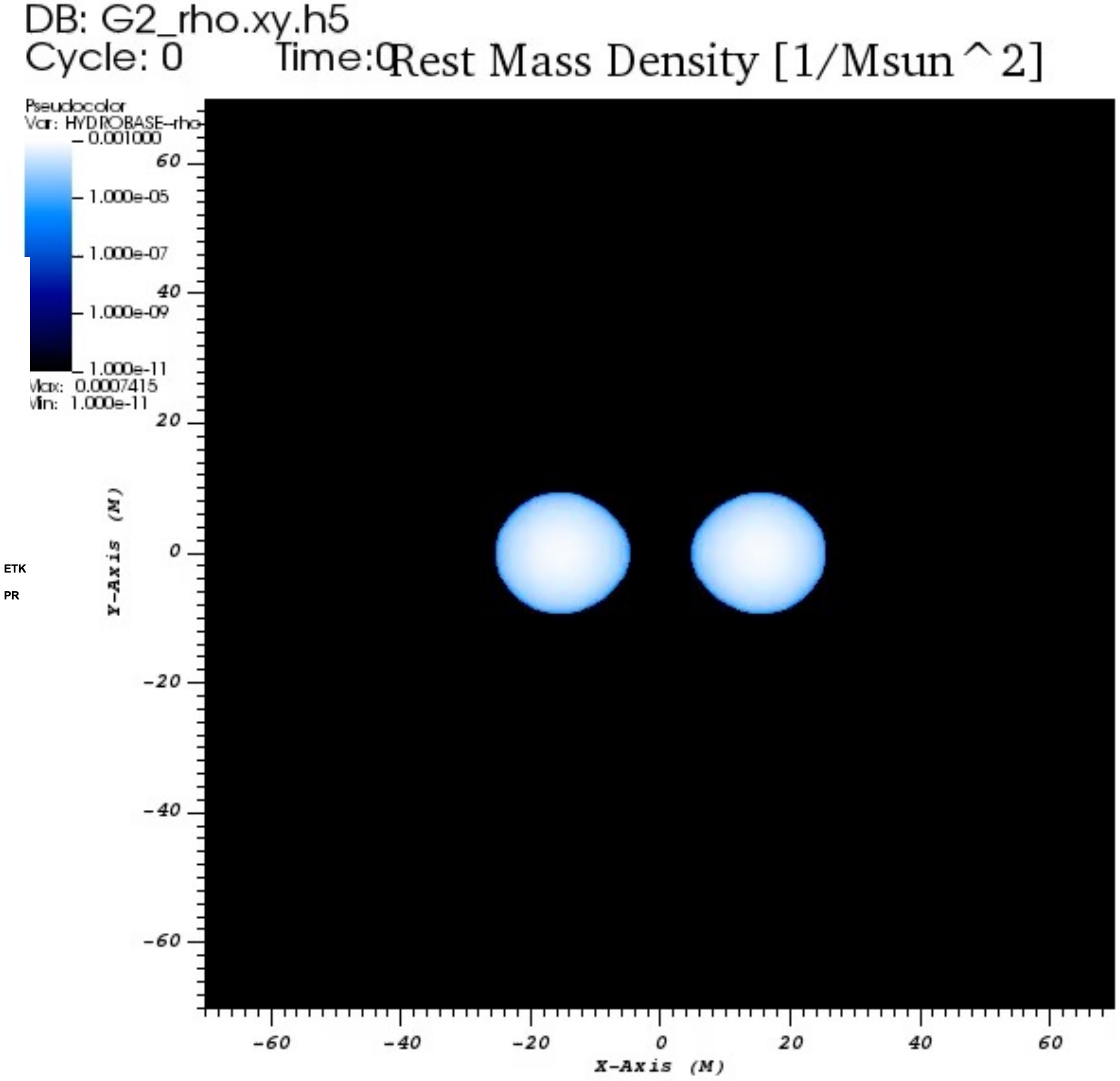
Simulations Specifications

- Final time 2s, spatial domain 10^3 km
- 6 refinement levels, Δx_{min}=180 m, Courant factor 0.25.
- 3 codes: Parma, IGM, Spritz
- 3 mass rations: 1, 1.3, 1.5
- 2 Magnetic fields strengths
  - B1 = B2 = 10^{12} G
  - B1 = 10^{10} G , B2 =10^{14} G
- 2 magnetic field configurations
- External magnetosphere $B_c = 10^{15}$ G.
- 36 runs per EOS × 5 EOSs × **control**

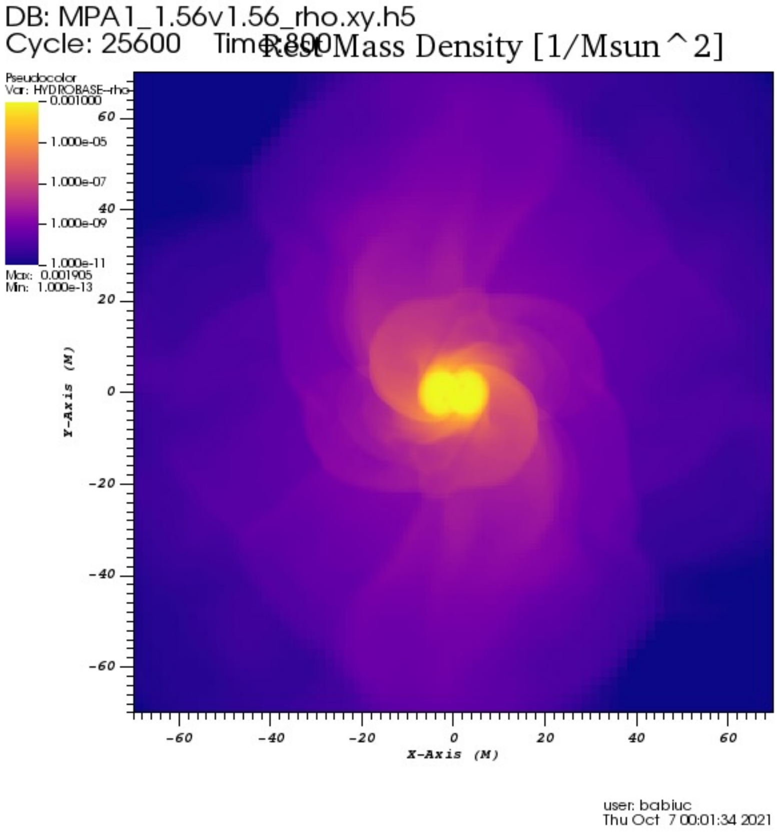


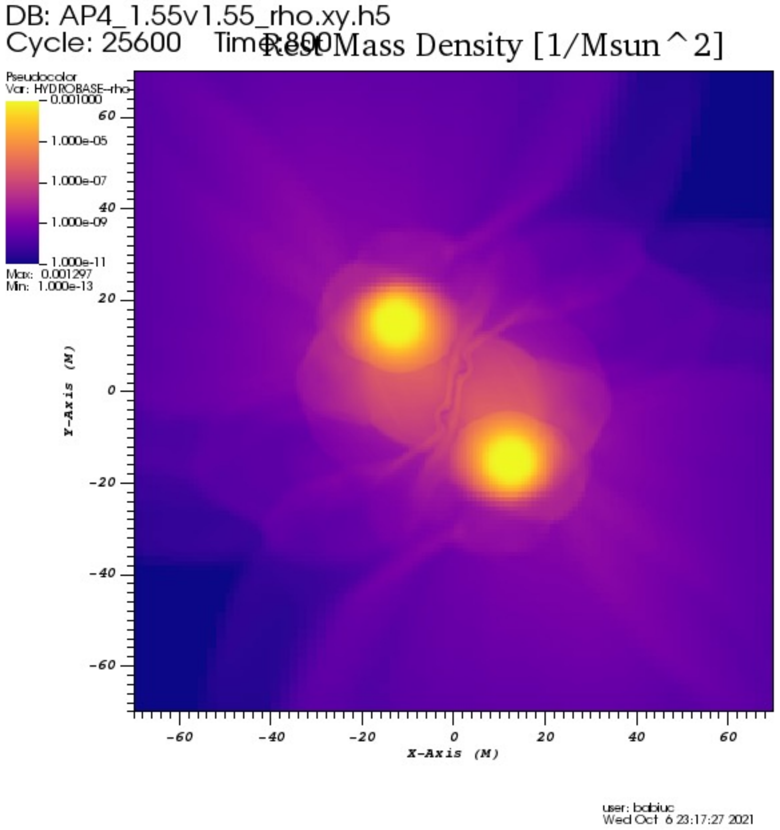


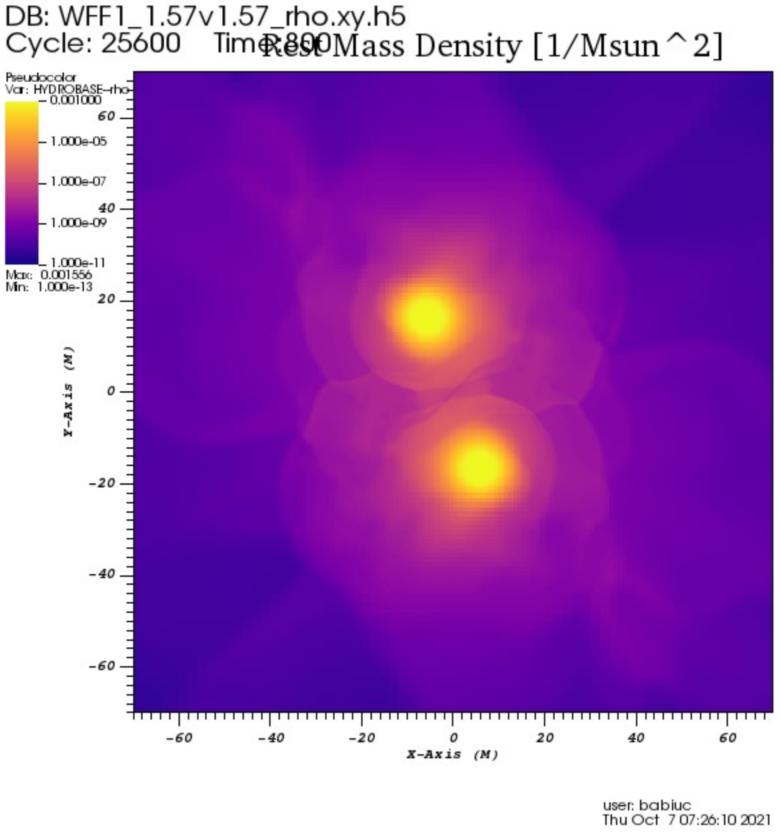
Postprocessing using SimuationTools
https://simulationtools.org



Visualization using VisIT
https://visit-dav.github.io/visit-website



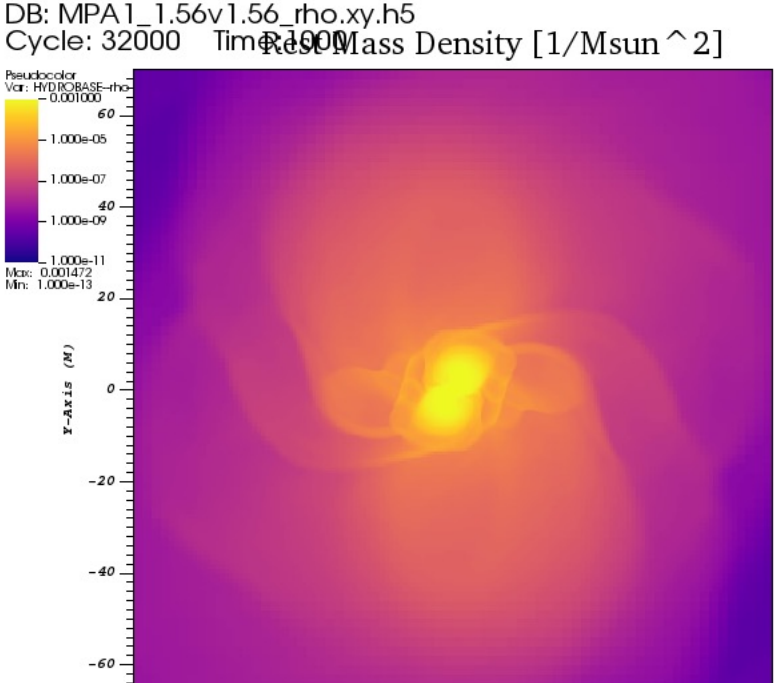


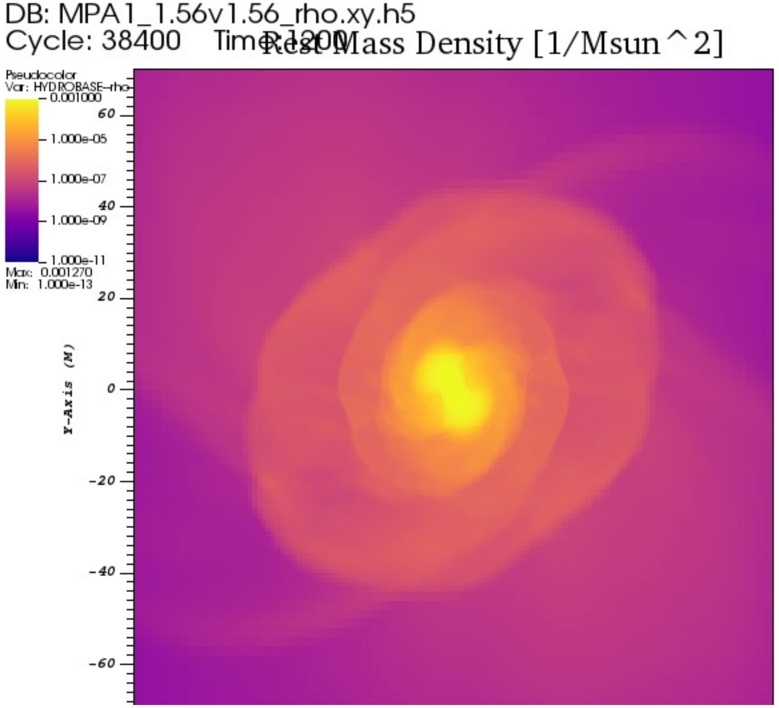


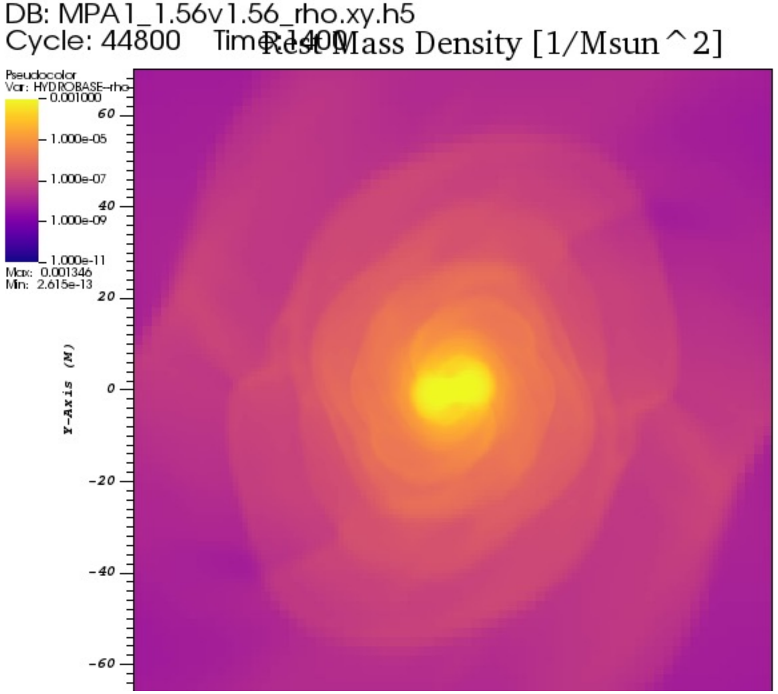
$$\tau_{\rm merge} = \tau_{\rm GW}/4$$

$$\begin{aligned}\tau_{\rm GW} &= \frac{5}{64}\frac{a^4}{\mu M^2} = \frac{5}{64}\frac{a^4}{q(1+q)M_1^3} \\ &= 2.2\times 10^8 q^{-1}(1+q)^{-1}\left(\frac{a}{R_\odot}\right)^4\left(\frac{M_1}{1.4\,M_\odot}\right) \quad \text{yr}\end{aligned}$$

J. Faber+, arxiv.org:1204.3858


DB: MPA1_1.56v1.56_rho.xy.h5
Cycle: 32000 Time: 1000
Rest Mass Density [1/Msun^2]
Pseudocolor
Var: HYDROBASE--rho
0.001000
1.000e-05
1.000e-07
1.000e-09
1.000e-11
Max: 0.001472
Min: 1.000e-13
60
40
20
0
-20
-40
-60
Y-Axis (M)


DB: MPA1_1.56v1.56_rho.xy.h5
Cycle: 38400 Time: 1200
Rest Mass Density [1/Msun^2]
Pseudocolor
Var: HYDROBASE--rho
0.001000
1.000e-05
1.000e-07
1.000e-09
1.000e-11
Max: 0.001270
Min: 1.000e-13
60
40
20
0
-20
-40
-60
Y-Axis (M)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Cycle: 44800 Time: 1400
Rest Mass Density [1/Msun^2]
Pseudocolor
Var: HYDROBASE--rho
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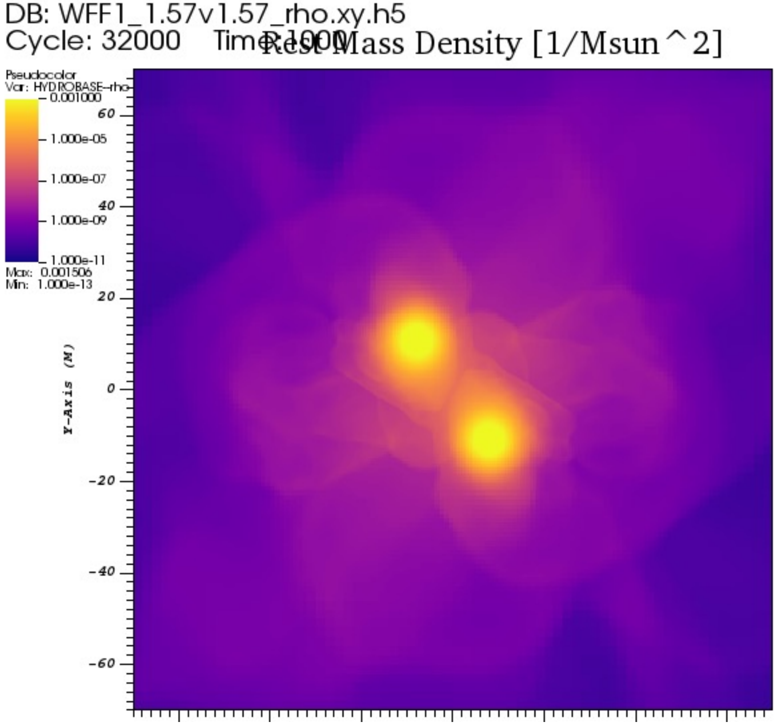
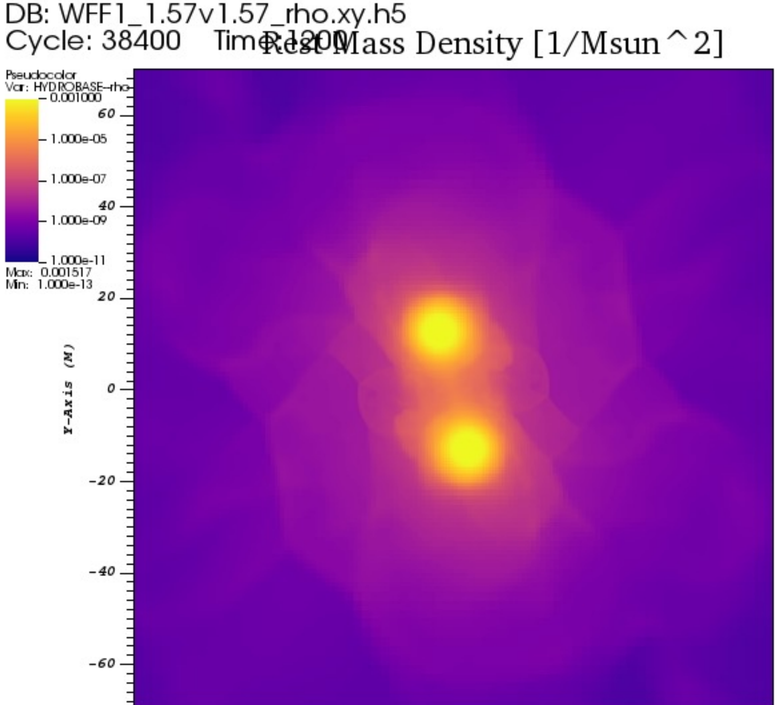
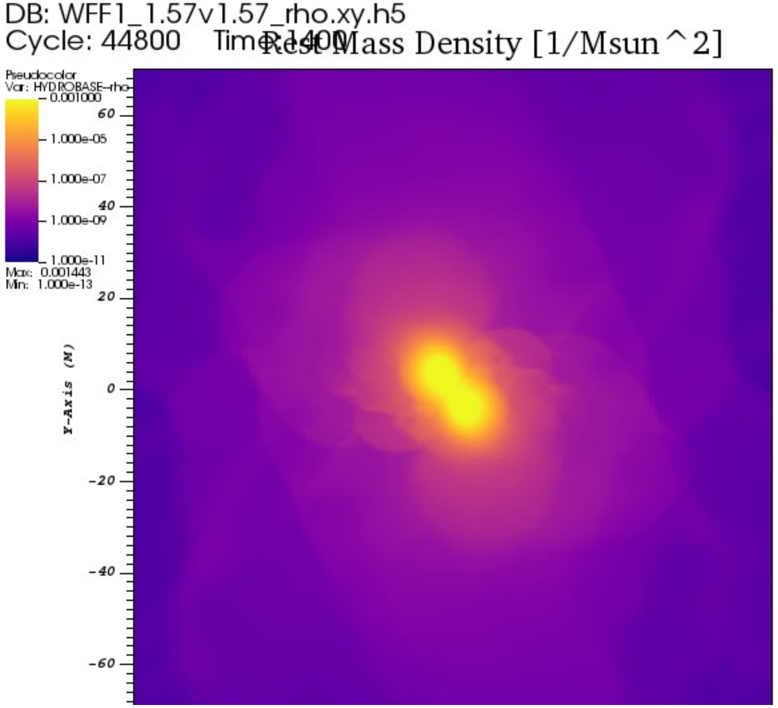
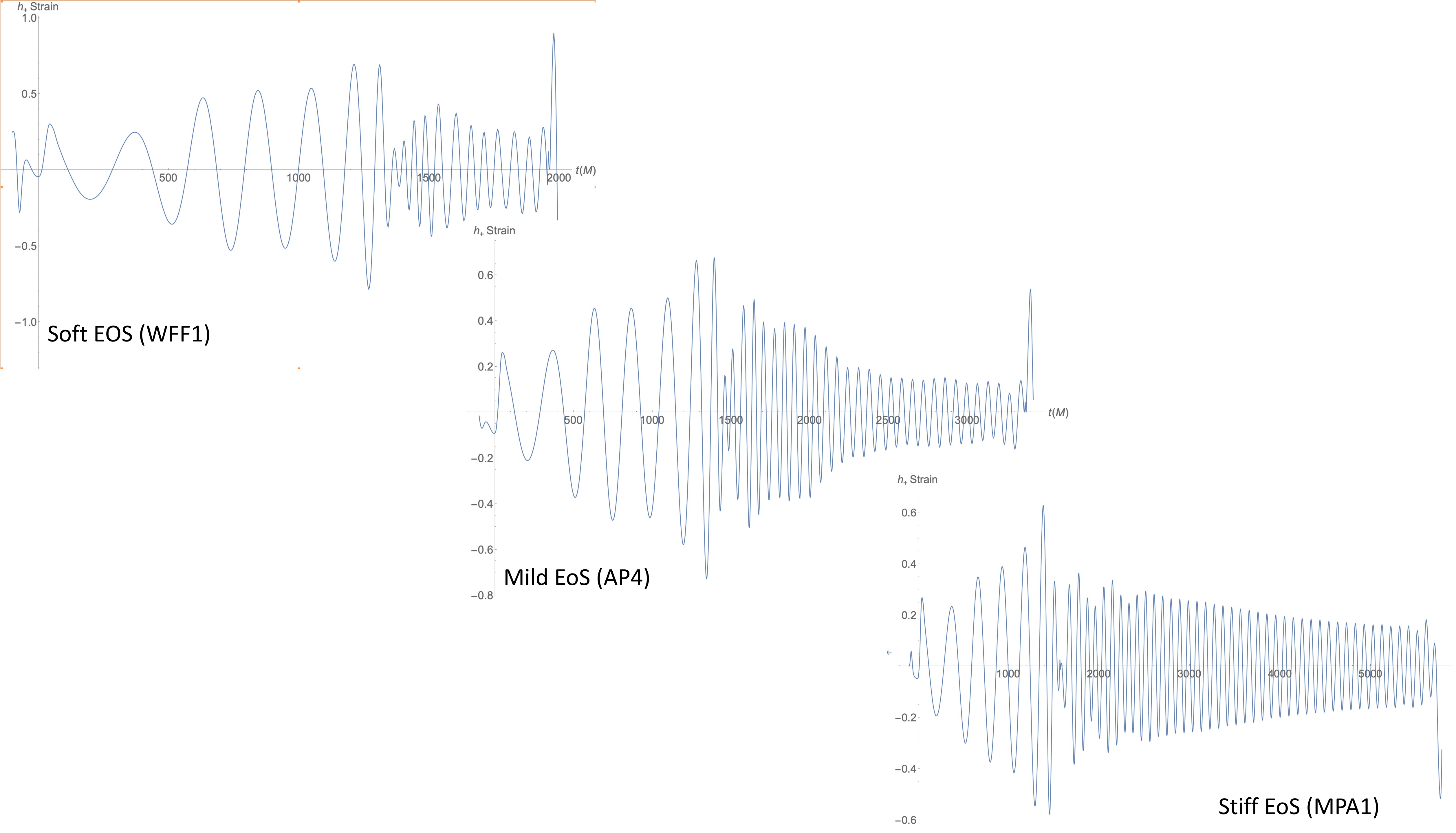
1.000e-05
1.000e-07
1.000e-09
1.000e-11
Max: 0.001346
Min: 2.615e-13
60
40
20
0
-20
-40
-60
Y-Axis (M)


DB: WFF1_1.57v1.57_rho.xy.h5
Cycle: 32000 Time: 1000
Rest Mass Density [1/Msun^2]
Pseudocolor
Var: HYDROBASE--rho
0.001000
1.000e-05
1.000e-07
1.000e-09
1.000e-11
Max: 0.001506
Min: 1.000e-13
60
40
20
0
-20
-40
-60
Y-Axis (M)


DB: WFF1_1.57v1.57_rho.xy.h5
Cycle: 38400 Time: 1200
Rest Mass Density [1/Msun^2]
Pseudocolor
Var: HYDROBASE--rho
0.001000
1.000e-05
1.000e-07
1.000e-09
1.000e-11
Max: 0.001517
Min: 1.000e-13
60
40
20
0
-20
-40
-60
Y-Axis (M)

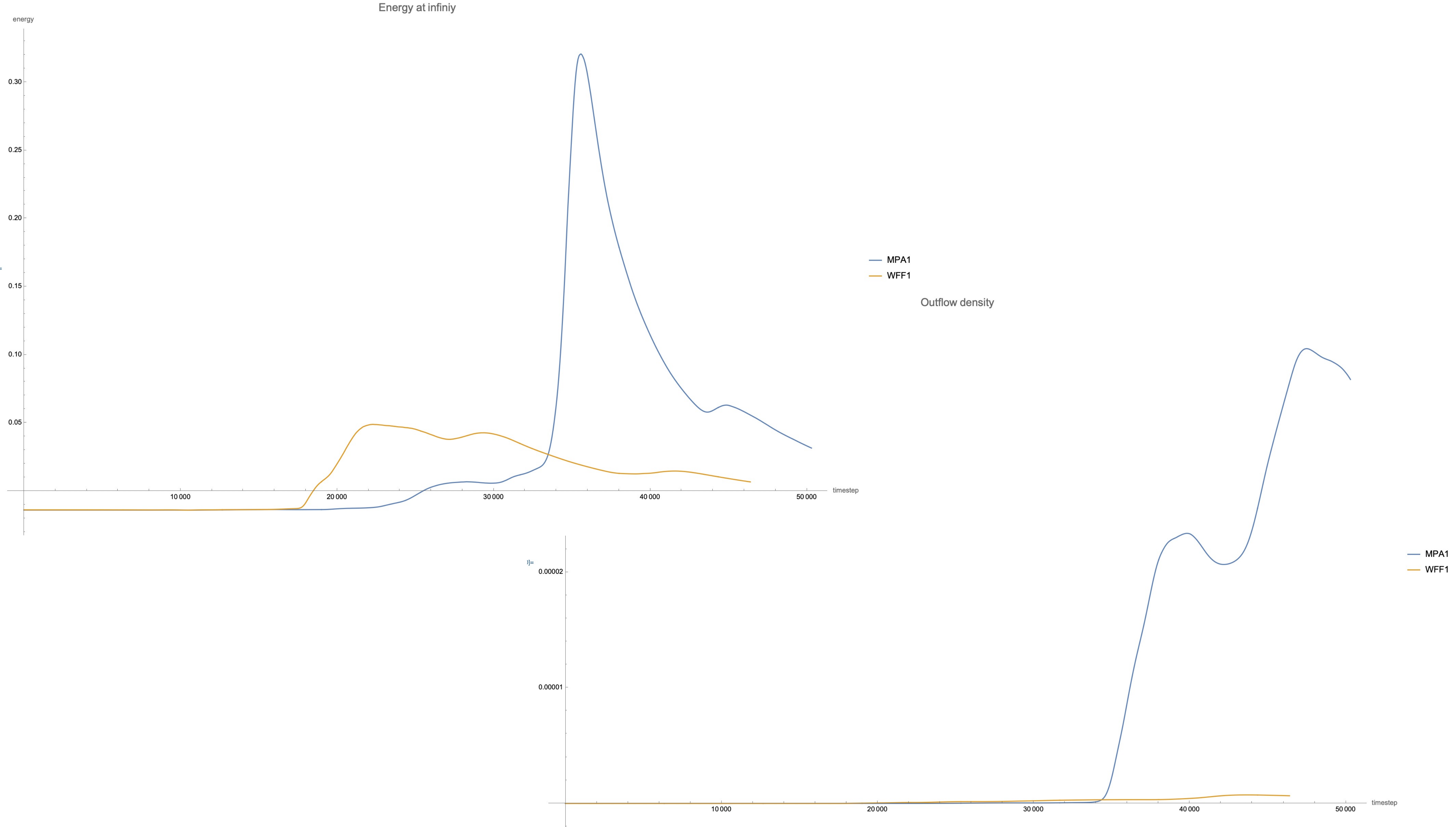

DB: WFF1_1.57v1.57_rho.xy.h5
Cycle: 44800 Time: 1400
Rest Mass Density [1/Msun^2]
Pseudocolor
Var: HYDROBASE--rho
0.001000
1.000e-05
1.000e-07
1.000e-09
1.000e-11
Max: 0.001443
Min: 1.000e-13
60
40
20
0
-20
-40
-60
Y-Axis (M)



Soft EOS (WFF1)

Mild EoS (AP4)

Stiff EoS (MPA1)


Energy at infiniy
energy
0.30
0.25
0.20
0.15
0.10
0.05
10 000
20 000
30 000
40 000
50 000
timestep
MPA1
WFF1
Outflow density
0.00002
0.00001
10 000
20 000
30 000
40 000
50 000
timestep
MPA1
WFF1

Code Benchmarking GRHydro, IGM & Spritz

1. Sly 4, q = 1, 1.3, 1.5
2. Sly 7, q = 1, 1.3, 1.5
3. Sly 7, 10^{12} G internal magnetic field, q = 1
4. Sly 7, 10^{12} G internal magnetic field + 10^{15} G central magnetosphere , q = 1
5. AP4, 10^{10} G & 10^{14} G internal magnetic field , q = 1, 1.3,
6. AP4, 10^{10} G & 10^{14} G internal magnetic field + 10^{15} G central magnetosphere , q = 1, 1.3, 1.5
7. WFF1 & MPA1, 10^{10} G & 10^{14} G internal magnetic field + 10^{15} G central magnetosphere , q = 1, 1.3

Code Development magnetosphere

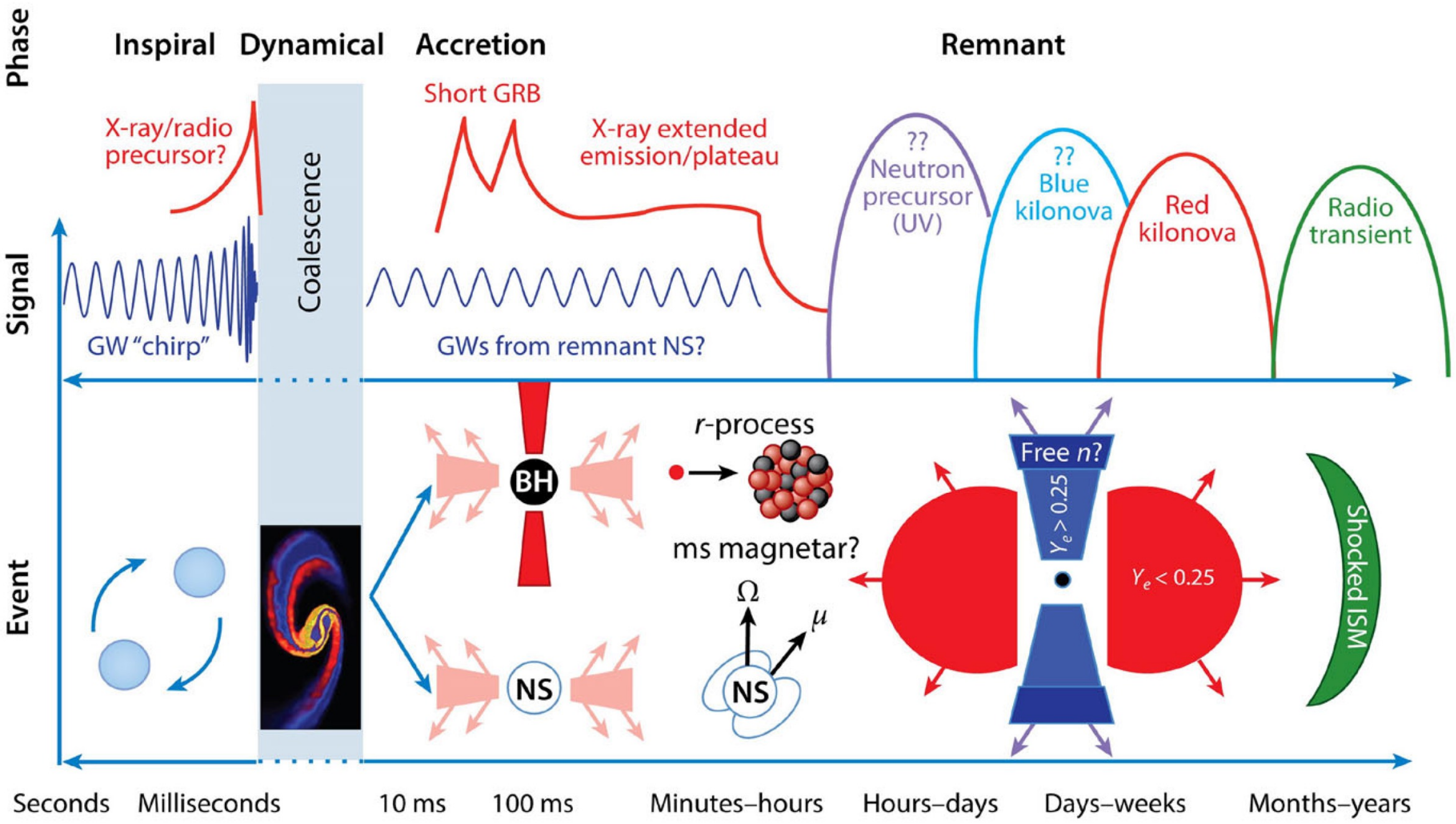
1. MPA1, 10^{10} G & 10^{14} G extended magnetic field, q = 1.3, 1.5
2. WFF1, 10^{10} G & 10^{14} G extended magnetic field, q = 1.3, 1.5
3. ALF4, 10^{10} G & 10^{14} G extended magnetic field, q = 1.3, 1.5
4. MPA1, 10^{10} G & 10^{14} G extended magnetic field + 10^{15} G merger magnetosphere, q = 1.3, 1.5
5. WFF1, 10^{10} G & 10^{14} G extended magnetic field + 10^{15} G merger magnetosphere , q = 1.3, 1.5
6. ALF4, 10^{10} G & 10^{14} G extended magnetic field + 10^{15} G merger magnetosphere , q = 1.3, 1.5

Code Development EOS and PIC

1. MPA1 & AP3, 10^{10} G & 10^{14} G extended magnetic field + magnetosphere , q = 1.3, 1.5
2. MPA1 & ALF4, 10^{10} G & 10^{14} G extended magnetic field + magnetosphere , q = 1.3, 1.5
3. MPA1 & WFF1, 10^{10} G & 10^{14} G extended magnetic field + magnetosphere , q = 1.3, 1.5
4. AP3 & ALF4, 10^{10} G & 10^{14} G extended magnetic field + magnetosphere , q = 1.3, 1.5
5. AP3 & WFF1, 10^{10} G & 10^{14} G extended magnetic field + magnetosphere , q = 1.3, 1.5
6. ALF4 & WFF1, 10^{10} G & 10^{14} G extended magnetic field + magnetosphere , q = 1.3, 1.5

Conclusions

- Neutron stars merges are expected to produce gravitational waves, outflow and electromagnetic signal.
- Detected mergers involving neutron stars left important unanswered questions about the electromagnetic counterparts and remnant.
- More detailed microphysics & realistic magnetic field needed.
- The signal is sensitive to the EOS, which is still largely unknown.
- BNS mergers simulations relevant to sGRB modeling must last at least 2s.



Fernandez and Metzger (2016)

Thank You