Black Hole-Neutron Star and Neutron Star Binaries as Progenitors of sGRBs

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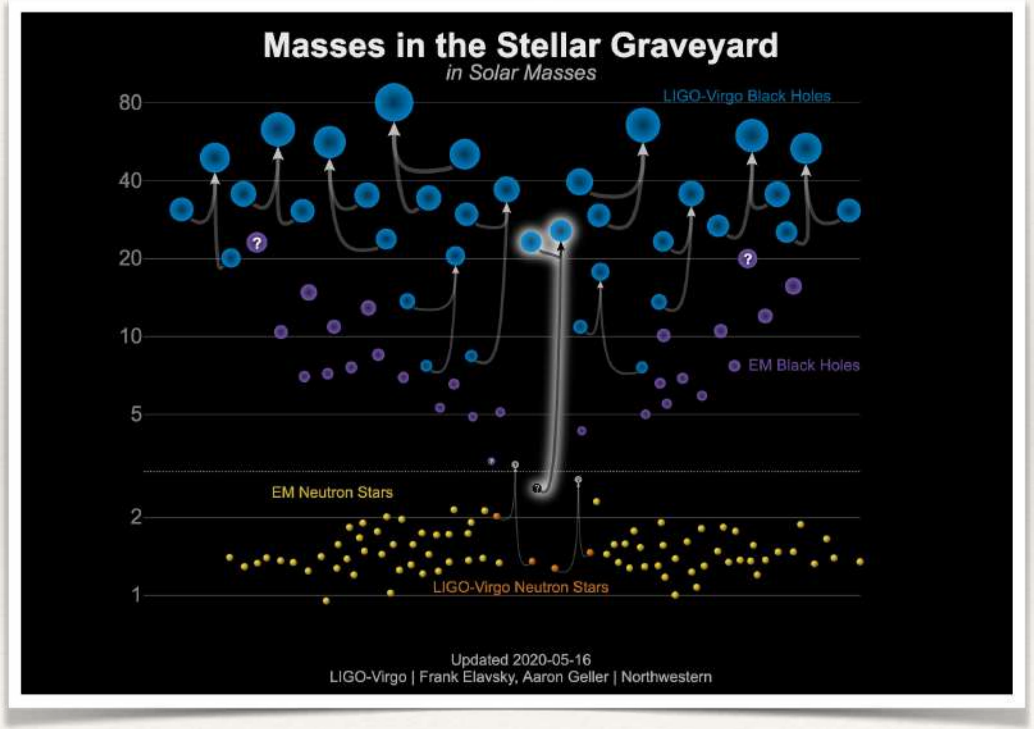
LIGO/Virgo GWs and EM Counterparts

- ➡ Events:
- GW170817 + EM counterpart GRB 170817A: classified as a BNS
- GW190425 + "GRB190425": classified as a BNS
- S190426c: 52% chance to be a BHNS, 13% to be BNS
- S190923y: 67% chance to be a BHNS
- …..

See A. Corsi's talk for a summary



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Merging BHNSs and BNSs are the most popular candidate progenitors of sGRBs: Eichler et al. '89, Narayan et al. '92, Mochkovitch et al. '93.

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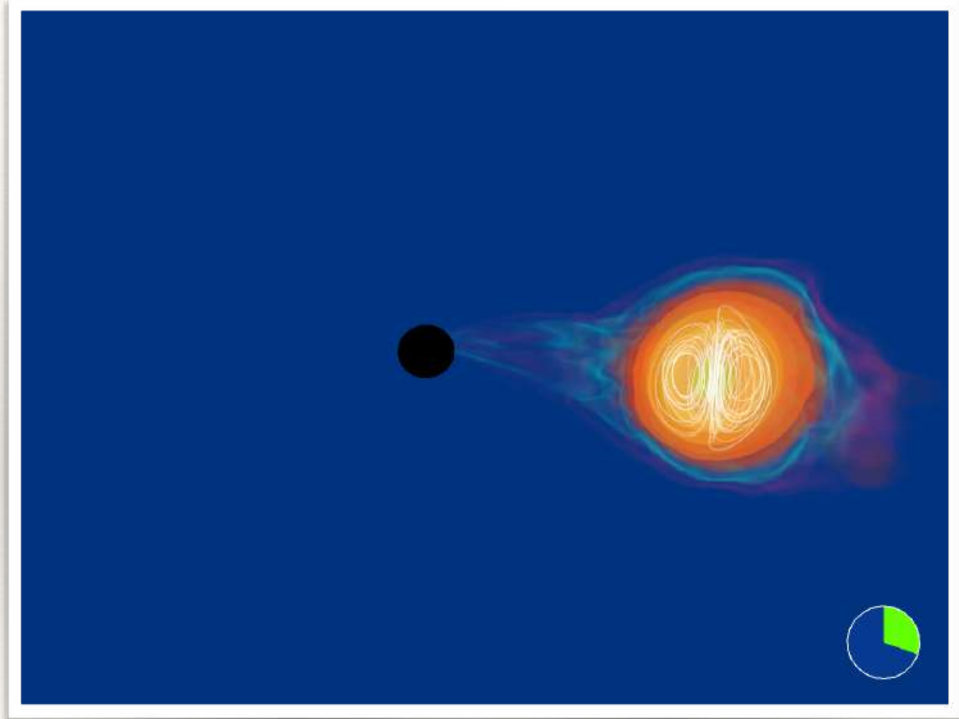
Our numerical results

Compact mergers: Magnetized BHNSs



Etienne et al, '12

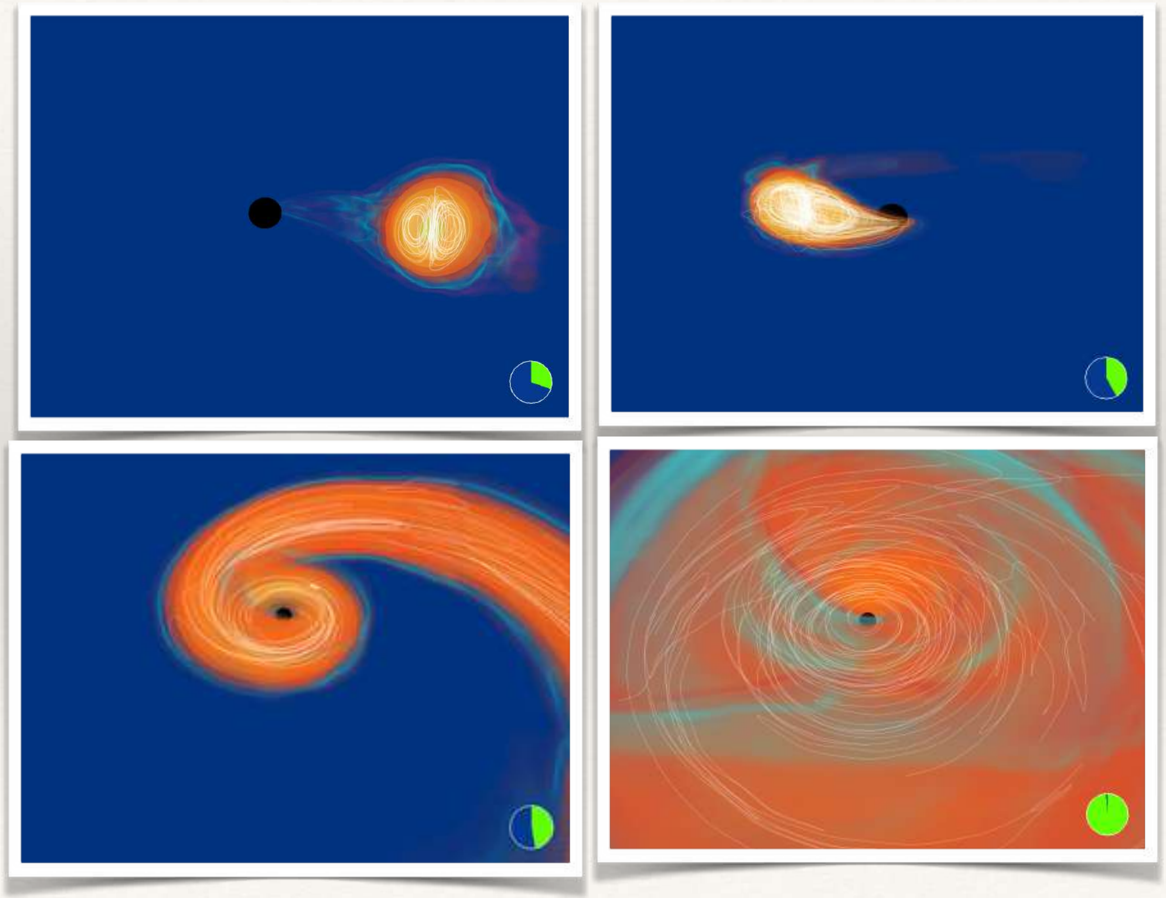
Magnetized BHNS Mergers I

Etienne et al, ’12: Following the BHNS merger , the B-field lines are wound into an almost purely toroidal configuration

BHNS: mas ratio $q = M_{BH}/M_{NS} = 3$
$\chi_{BH} = 0.75$

Evolution: Illinois GRMHD code
See Etienne-Werneck’s talk

No jets



Magnetized BHNS Mergers II

Beckwith et al. 08: BH + disk can launch a jet if the disk has a strong poloidal B-field component.

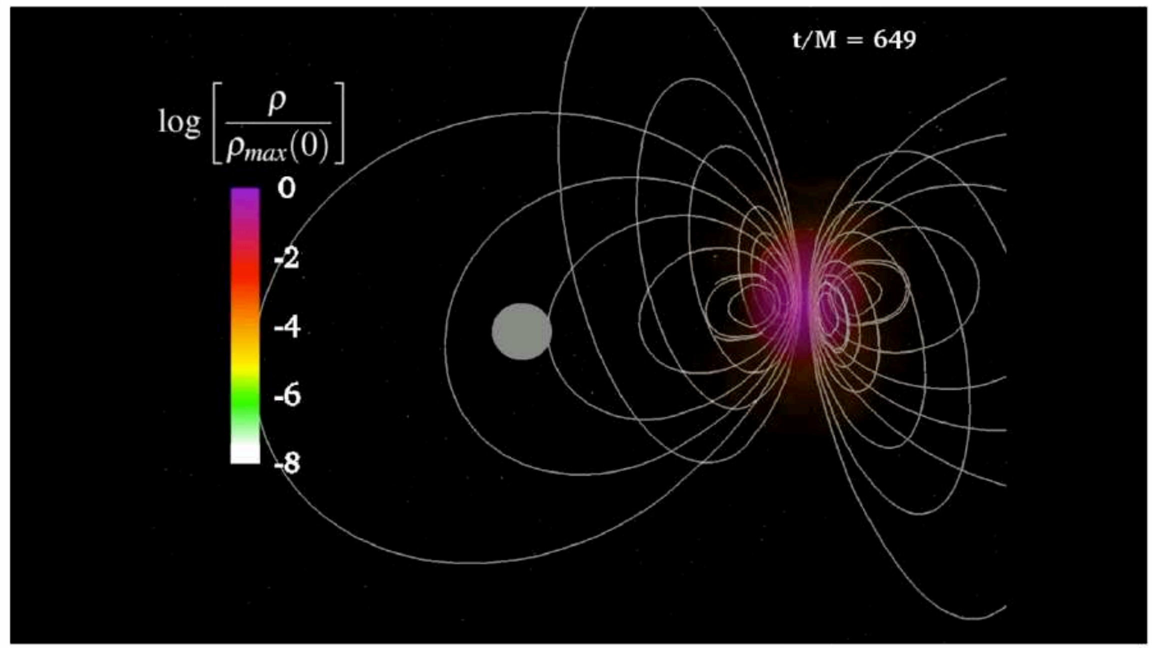
Right conditions: Pulsar-like B-field

Problem: Evolution of external B-field where $\rho_0 \approx 0$

Solution: External & variable atmosphere where exterior gas-to-magnetic-pressure ratio is

$$\beta_0 = \text{const.} \ll 1 \longrightarrow$$

Magnetic-pressure dominance, but not magnetic-energy density dominance.



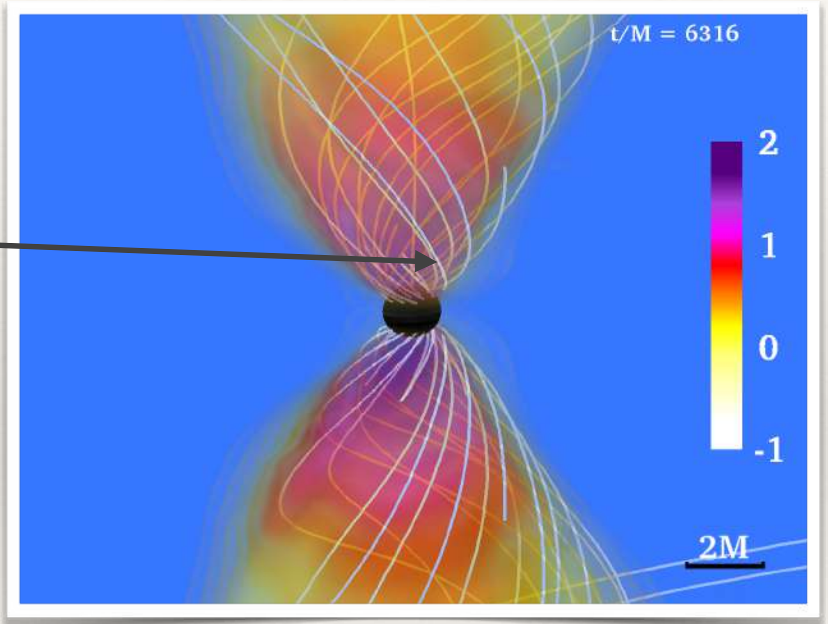
Paschalidis, MR, Shapiro, ‘14

BHNS as Progenitors of sGRBs

- Disk lifetime: $\boxed{\Delta t \sim M_{\rm disk}/\dot{M} \sim 0.1\ \mathrm{s}}$

consistent with sGRB T90

- Max. magnetization in the outflow: $\boxed{\sim \frac{b^2}{2\,\rho_0} = \frac{B^2}{8\,\pi\,\rho_0} \sim 100}$



Paschalidis, MR, Shapiro, '14

Vlahakis et al, '03: Terminal Γ in the jet equals $b^2/2\rho_0$

- Poynting Luminosity: $\boxed{L_{EM} = 10^{51}\ \mathrm{erg/s}}$

Consistent with Blandford-Znajek mechanism

$$\boxed{L_{EM} \sim 10^{51}\,(a/m)^2\,(m/5.6M_\odot)^2\,(B/10^{15}\,G)^2 \mathrm{erg\ \ s^{-1}}}$$

BHNS as Progenitors of sGRBs

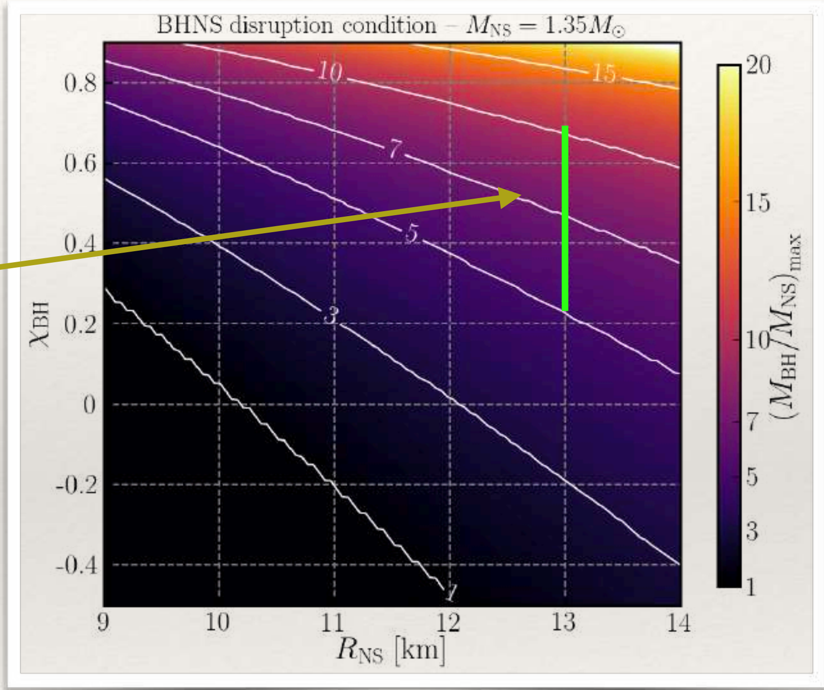
Population synthesis studies: most likely mass-ratio $q = M_{BH}/M_{NS}$ is ≈ 7

NS disruption requires $\chi_{BH} \approx 0.2–0.7$

LIGO/Virgo BBH detections: high mass-ratio and/or low-spin

Strong constraint!

Unlikely to observe sGRBs from BHNS



Foucart '20

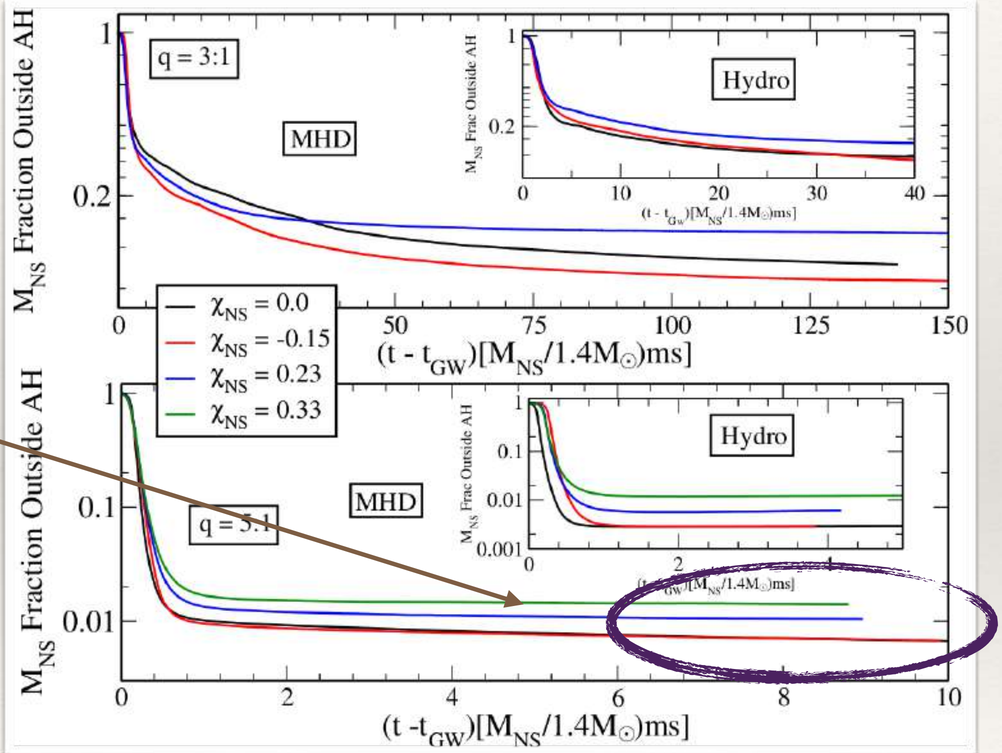
BHNS as Progenitors of sGRBs

What about other EM counterparts?

BHNS with a spinning NS: More ejecta

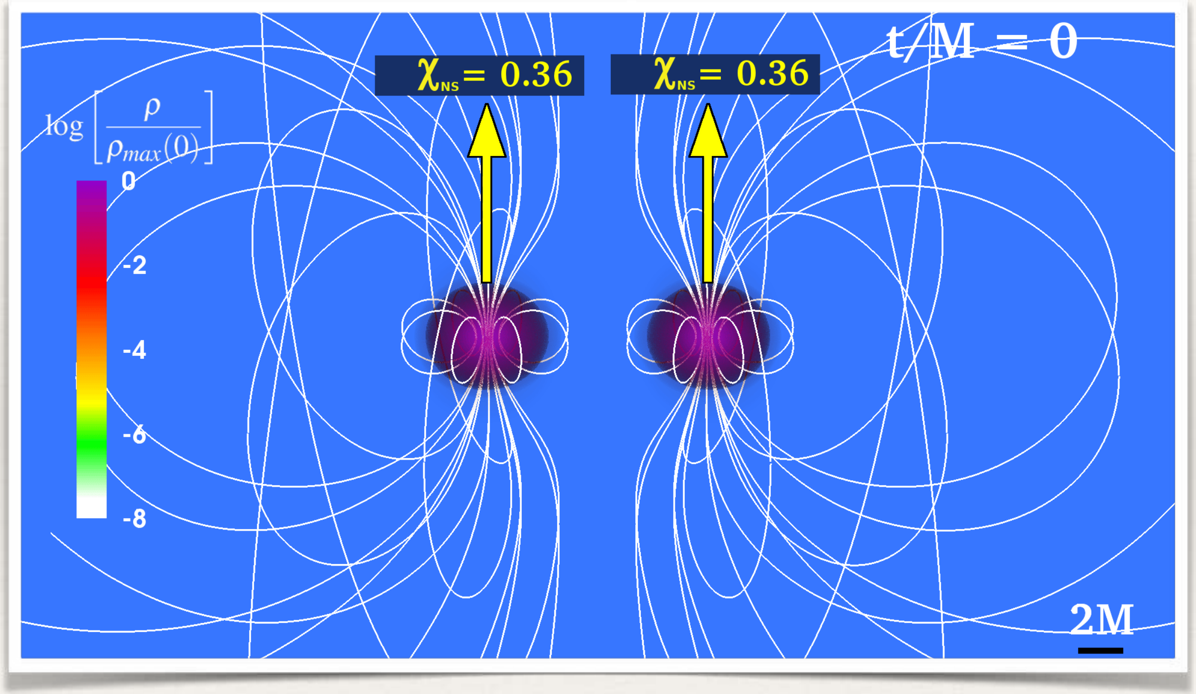
↓

May lead to an observable kilonova



MR et al. (in prep.)

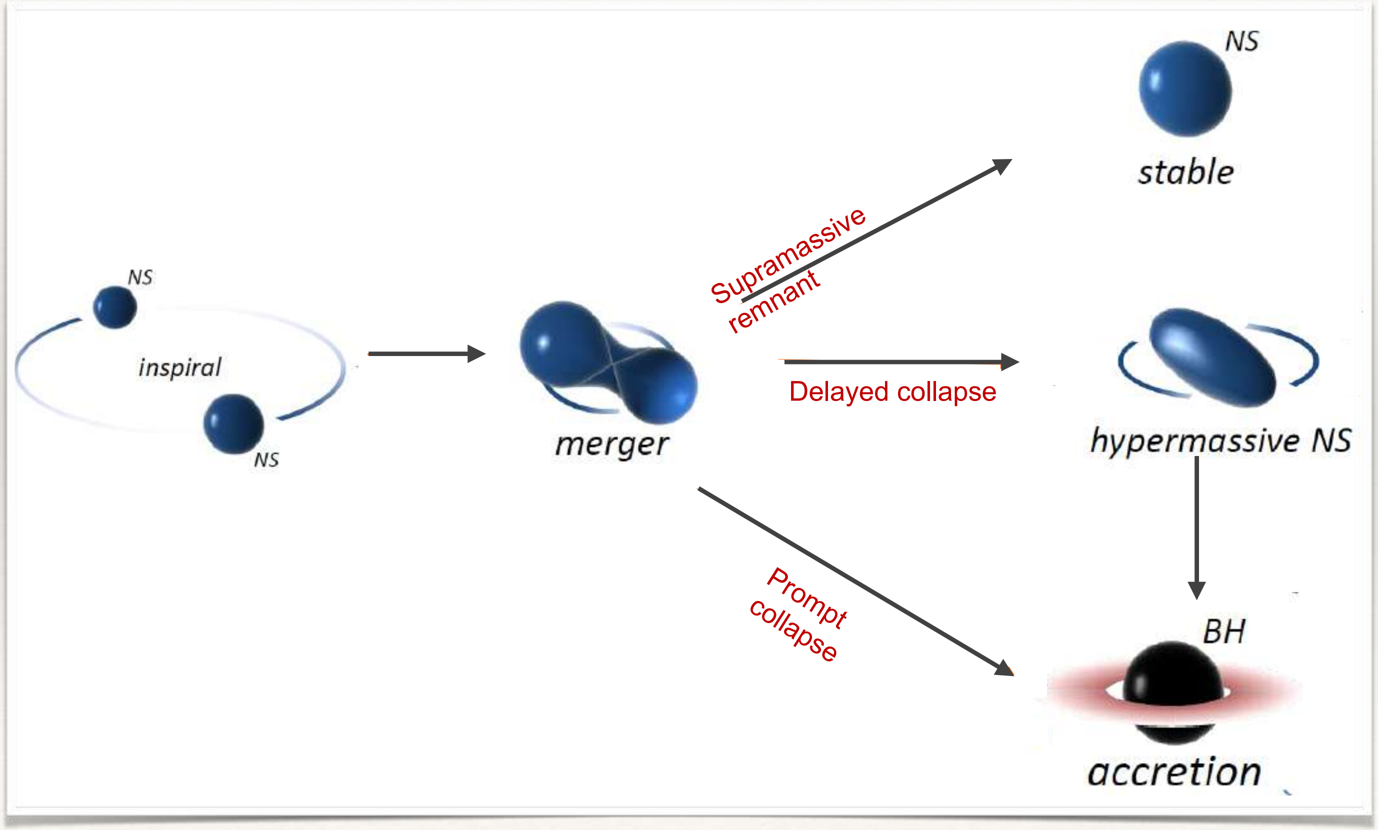
Compact mergers: Magnetized BNSs



MR et al. '16

BNS Scenario

At least three possible scenarios:

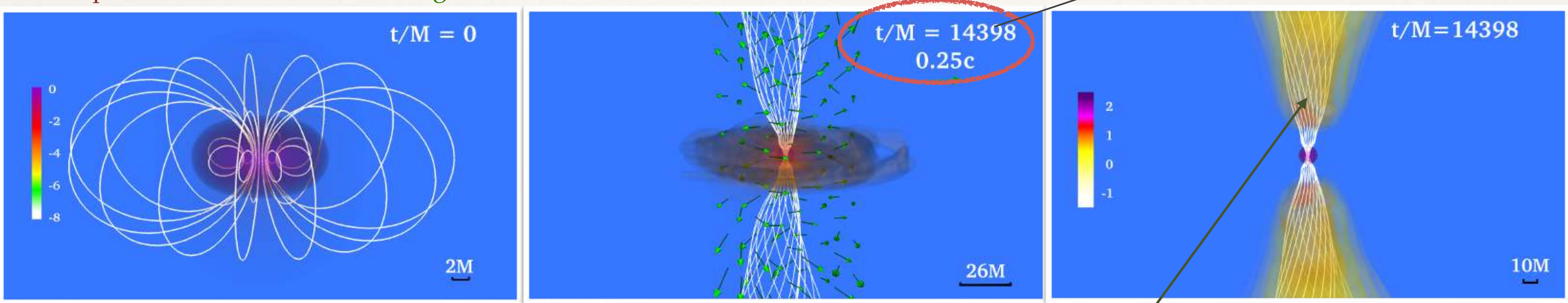


Bartos et al. ‘12

BNS Scenario: Stable Remnant I

~ $200ms$

Assumption: Remnant of a BNS merger



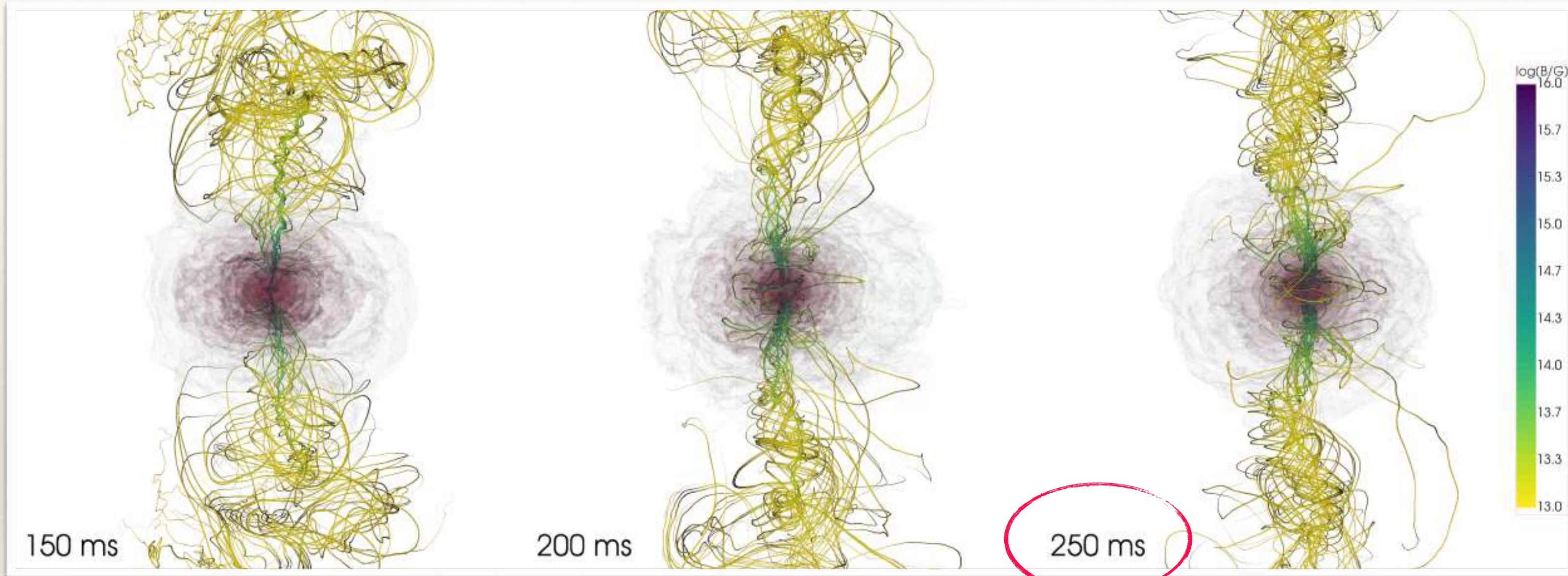
MR et al. '17

- B-field collimation
- Outflow: $\Gamma = 1.01 - 1.03$
- Pulsar-like luminosity ~ 10^{43} erg/s

$$\cancel{\sim \frac{b^2}{2\,\rho_0} = \frac{B^2}{8\,\pi\,\rho_0} \sim 100}$$

Inconsistent with sGRBs

BNS Scenario: Stable Remnant II



Ciolfi, '20

- B-field collimation
- Outflow $\Gamma \lesssim 1.05$

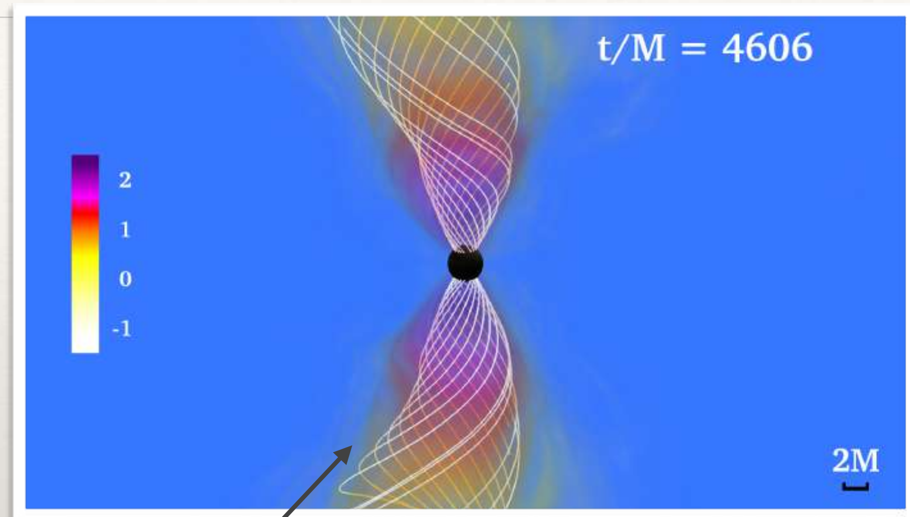
Inconsistent with sGRBs

Mösta et al. '20 : magnetized
Long-lived HMNS
+ neutrinos

See Radice's talk

Less baryon pollution then
terminal $\Gamma \approx 5$

BNS Scenario: Delayed Collapse



MR et al. '16-19

☑ Disk lifetime: $\Delta t \sim M_{\rm disk}/\dot{M} \sim 0.1$ s

consistent with sGRB T90

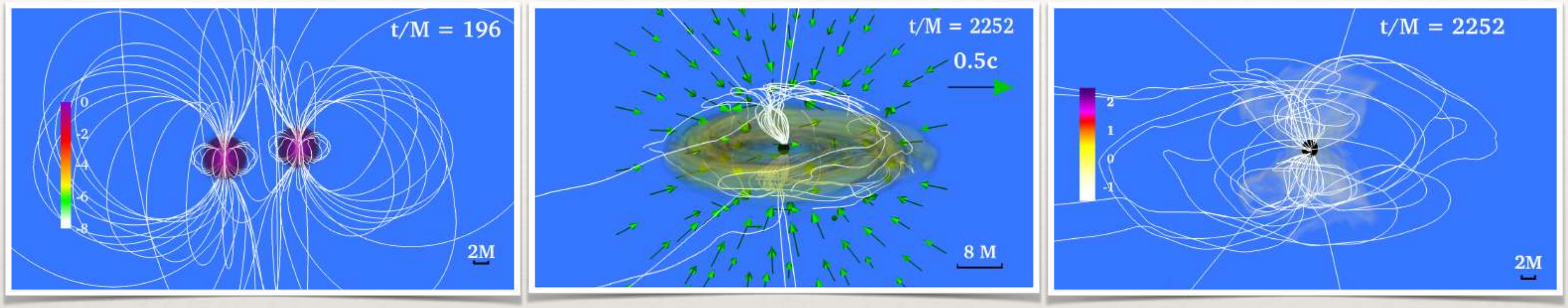
☑ Max. magnetization in the outflow: $\sim \dfrac{b^2}{2\,\rho_0} = \Gamma_L(asym) \sim 100$

☑ Blandford-Znajek effect

$L_{EM} \sim 10^{51}\,(a/m)^2\,(m/5.6M_\odot)^2\,(B/10^{15}\,G)^2 \mathrm{erg\ \ s^{-1}}$

Simulations: $L_{\rm EM} \sim 10^{51.5\pm1} \mathrm{erg/s}$

BNS Scenario: Prompt Collapse



MR & Shapiro '17

- No B-field collimation
- No outflow
- Really small accretion disk

No jet

EM counterpart before merger: see e.g. Lehner et al. '12

Progenitors of fast radio bursts: see e.g. Totani '13, …

GW170817, GRMHD and the NS maximum mass

$$M_{\rm max}^{\rm sph} \leq M \leq M_{\rm max}^{\rm sup}$$

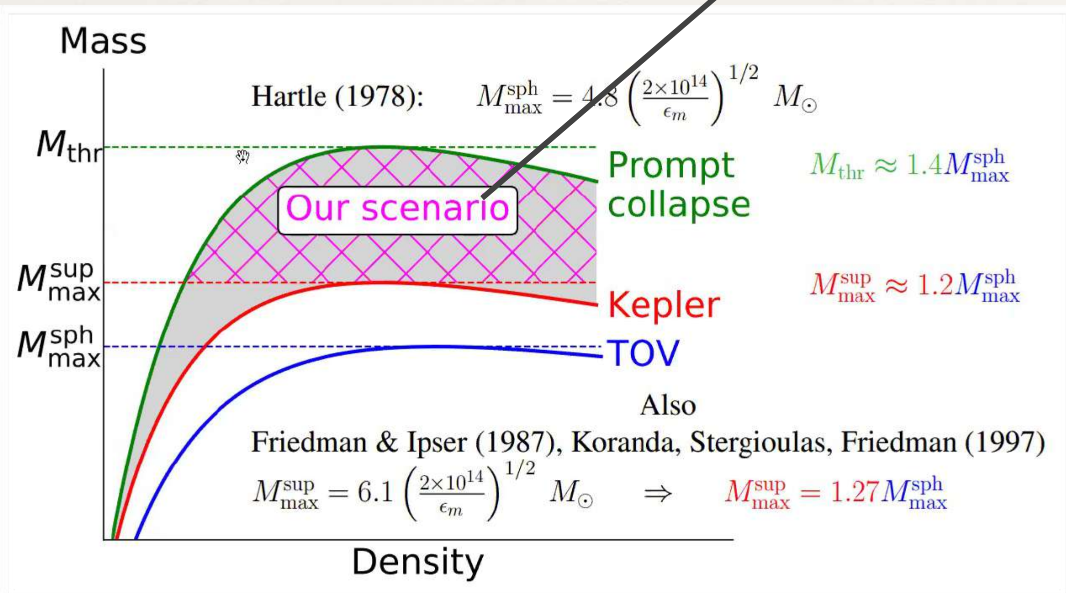
Supramasive

$$M_{\rm max}^{\rm sup} \leq M \leq M_{\rm thr}$$

Delayed collapse
Consistent with sGRBs

$$M_{\rm thr} \leq M$$

Prompt collapse



$$\beta M_{\rm max}^{\rm sph} \approx M_{\rm max}^{\rm sup} \lesssim 2.74 \lesssim M_{\rm thr} \approx \alpha M_{\rm max}^{\rm sph}.$$
$$2.74/\alpha \lesssim M_{\rm max}^{\rm sph} \lesssim 2.74/\beta$$

Typically

$$\beta \approx 1.2 \quad \Rightarrow \quad \boxed{M_{\rm max}^{\rm sph} \lesssim 2.28}$$

Using Hartle's causal argument:

MR et al. '17

$$\beta \approx 1.27 \quad \Rightarrow \quad \boxed{M_{\rm max}^{\rm sph} \lesssim 2.16}$$

Consistent with Margali et al., Rezzolla et al., Shibata et al.

Ergostars

Ergoregions are associated with two astrophysical processes which are both related to the extraction of energy from a spinning BH:

- Penrose process
- Powering of relativistic jets through the Blandford-Znajek process

key ingredient:
BH Horizon

↓

Membrane paradigm:
Energy and angular momentum are extracted along B-field lines threading from the horizon

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Membrane paradigm:
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key ingredient:
Ergoregion

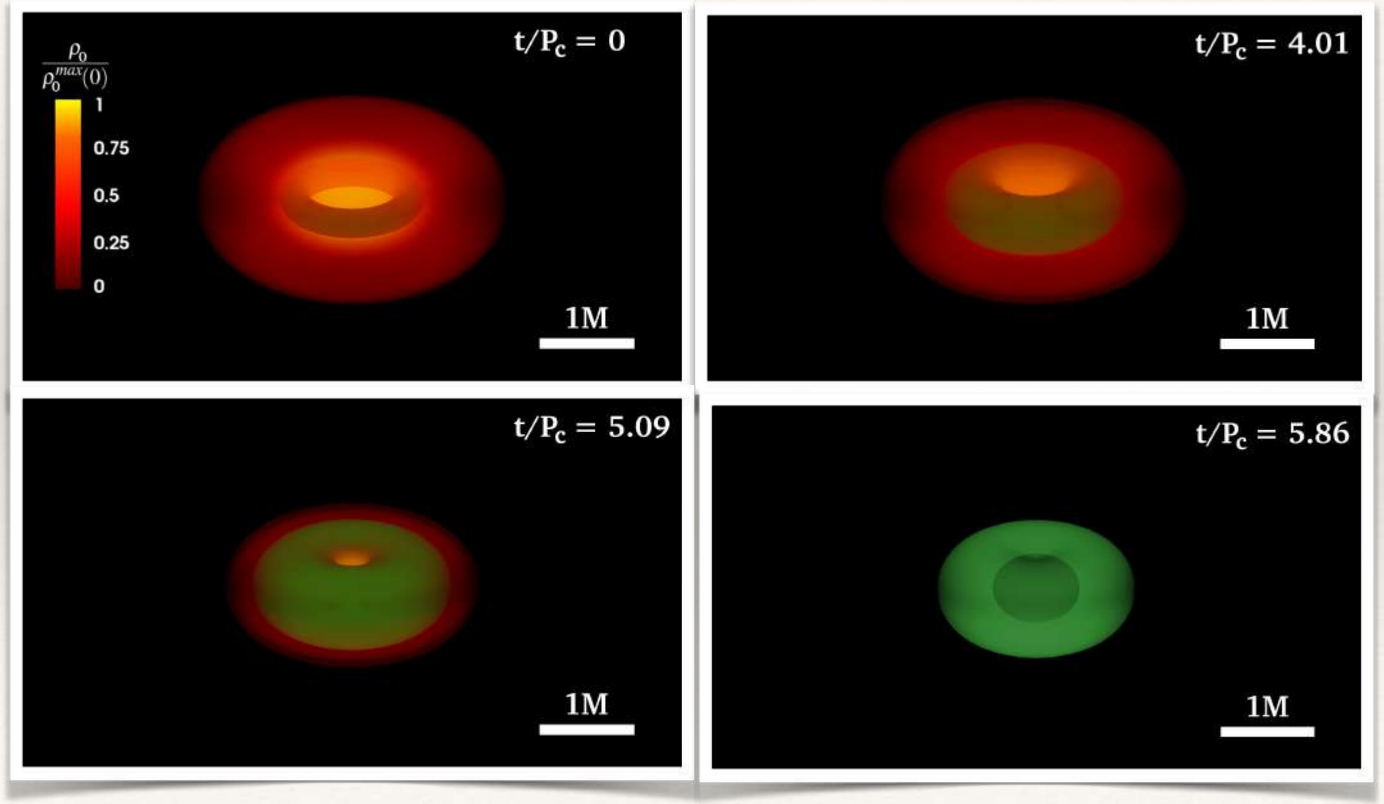
↓

Komissarov '04-'05:
Energy and angular momentum are extracted along B-field lines threading the ergoregion

Preliminary results using Force-Free evolutions + Cowling approx. seem to confirm this claim: MR et al. '12

Ergostars: Dinamically Unstable

Differentially rotating $\Gamma = 3$ polytropes:



Komatsu et al. '89

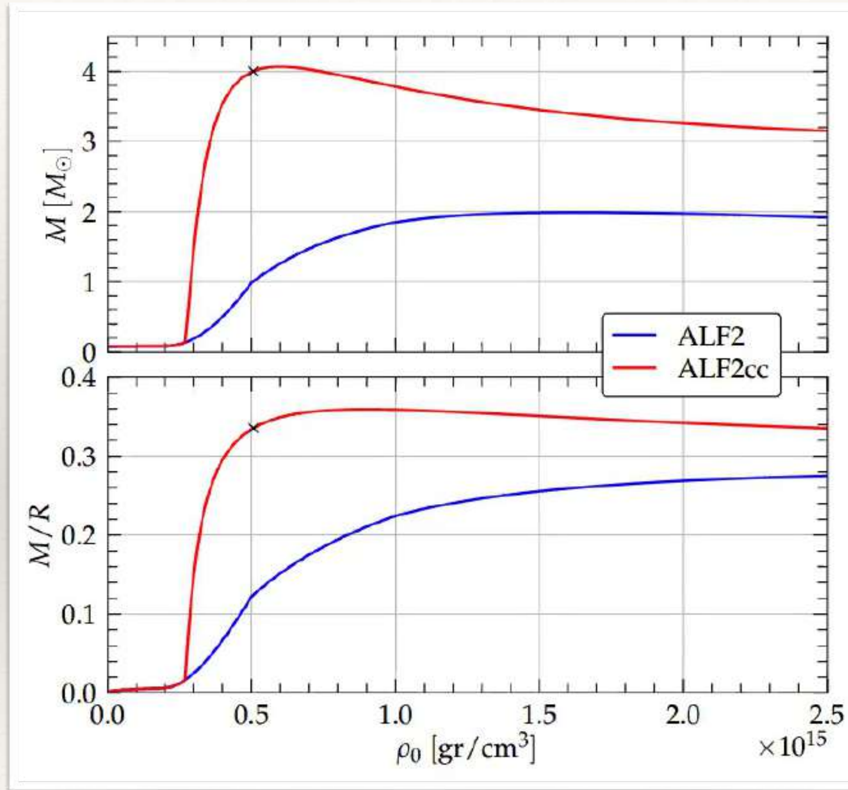
Ergostars

Following Hartle, we took the ALF2 EOS and replace $\rho_0 > \rho_{0s}$ with a compressible EOS

$$P = (\rho - \rho_s) + P_s$$

$\boxed{\text{maximum possible stiffness}}$

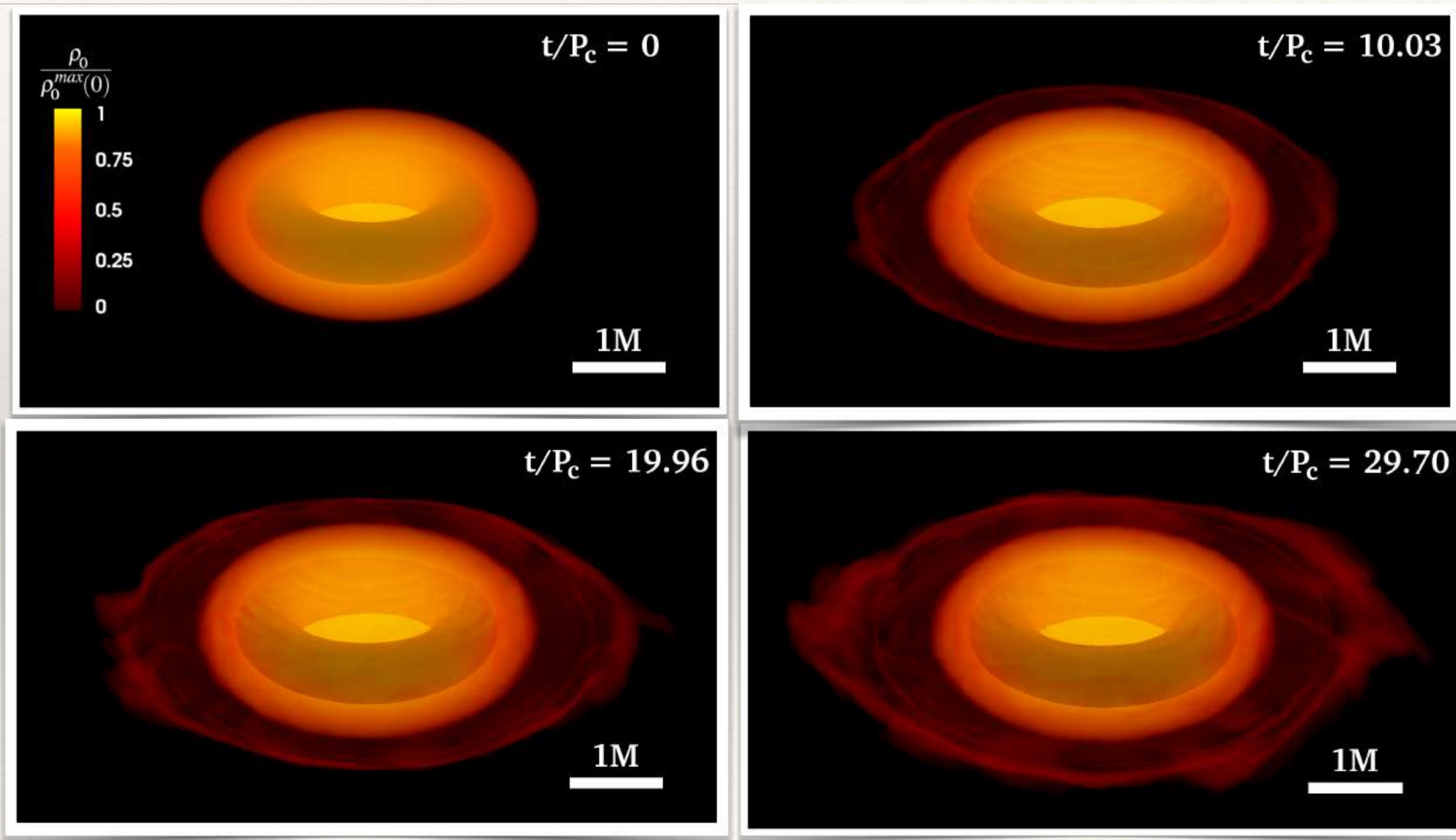
Here, we take $\rho_{0s} = 2.7x10^{14}\ gr/cm^3$



Tsokaros, MR et al. ‘20

Ergostars: Dinamically Stable

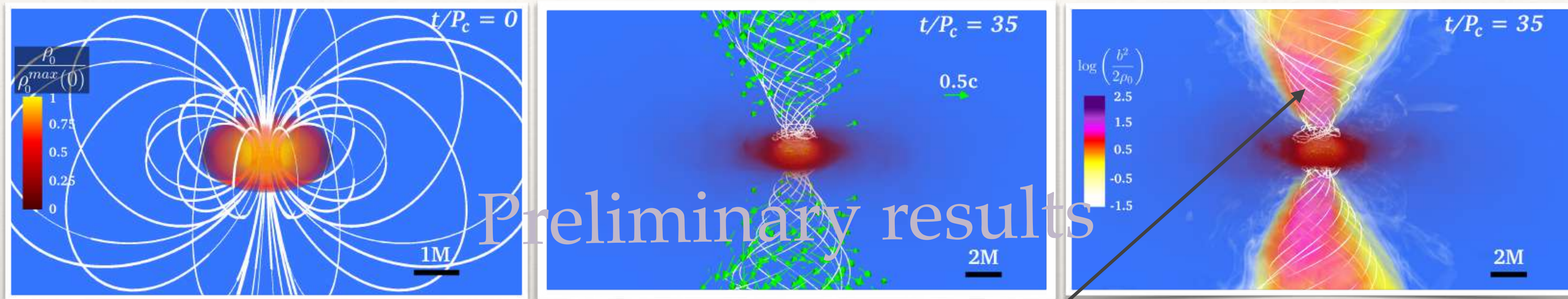
Differentially rotating NS with the ALF2cc EOS



Tsokaros, MR et al. ‘20

Ergostars: Magnetized Evolutions

Assumption: Ergostars are BNS remnants



MR in prep.

☑ Max. magnetization in the outflow: $\sim \dfrac{b^2}{2\,\rho_0} = \Gamma_L(asym) \sim 100$

☑ Blandford-Znajek effect $L_{\rm jet} \sim 10^{51.2} - 10^{51.6}$

Neutrino effects are ignored

Conclusions

We are in a golden era where we can test our theory/models against observations and numerical simulations. We can do now:

Multimessenger astronomy
Discover new physical effects,
Use simulations to constraints EoSs,
Constraint theory beyond GR

Computational astrophysics allows to explain some of the LIGO/Virgo GW detections.
However, more detailed microphysics + magnetic field are both needed.