#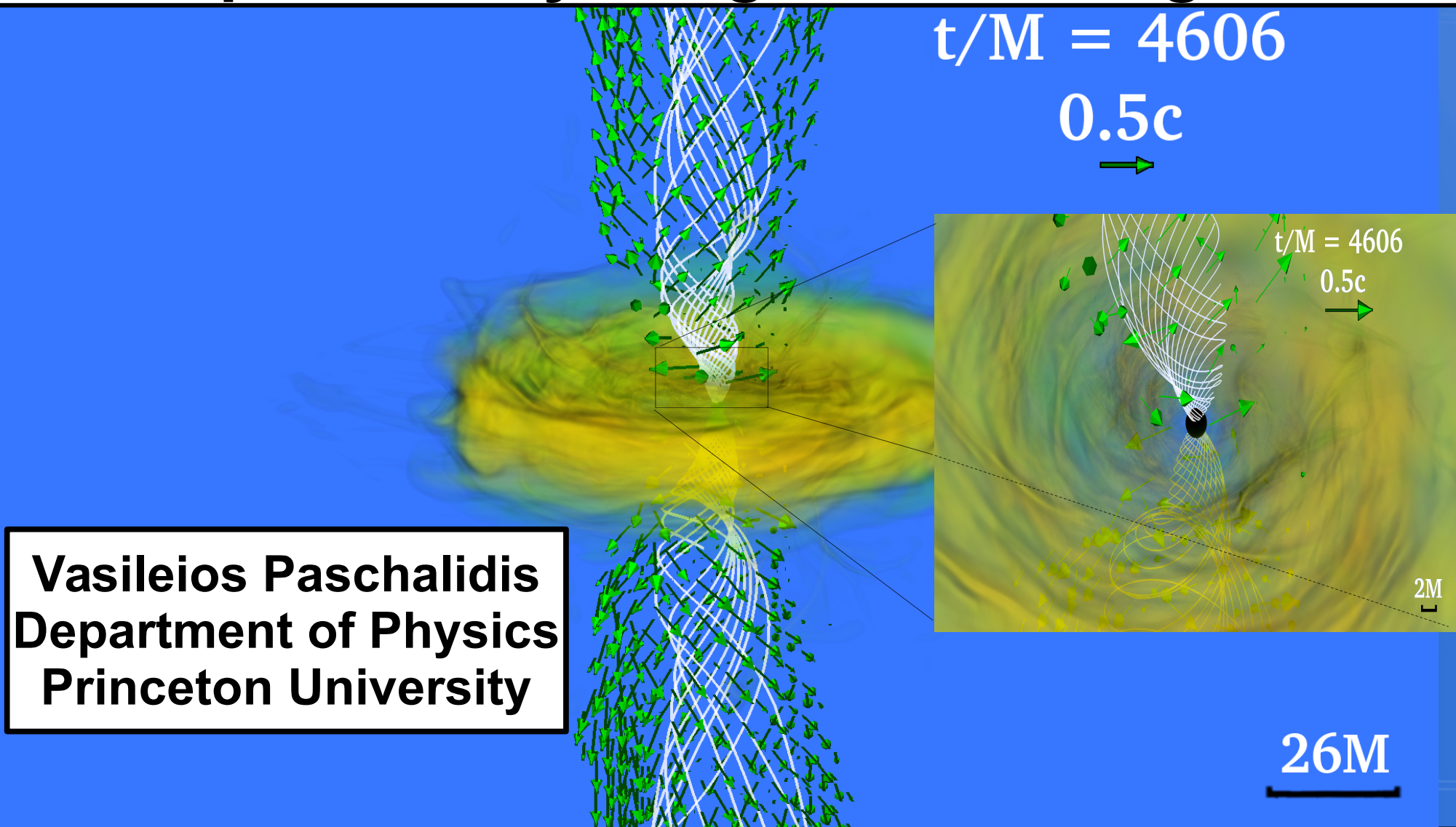 New paths to probing the nuclear equation of state via multimessenger signals from compact binary mergers involving NSs


$t/M = 4606$

$0.5c$

$t/M = 4606$

$0.5c$

2M

26M

Vasileios Paschalidis
Department of Physics
Princeton University

SUMMARY

- Black hole – neutron star (BHNS) and neutron star- neutron star (NSNS) binaries are viable short gamma-ray burst (sGRB) progenitors

- Even one BHNS-generated gravitational wave (GW) signal coincident with a sGRB could potentially rule out a large number of (cold) nuclear equations of state (EOS) for $M_{NS} < 2M_{sun}$

- NSNS mergers form hypermassive NSs that generically undergo a one-arm (m=1) spiral instability; instability $\rightarrow$ signal!
- GWs generated by the m=1 instability can constrain the finite-temperature nuclear EOS for $M_{NS} > 2M_{sun}$

- Numerical relativity is crucial for GW science and constraining the NS EOS

Gravitational waves exist!
GW150914
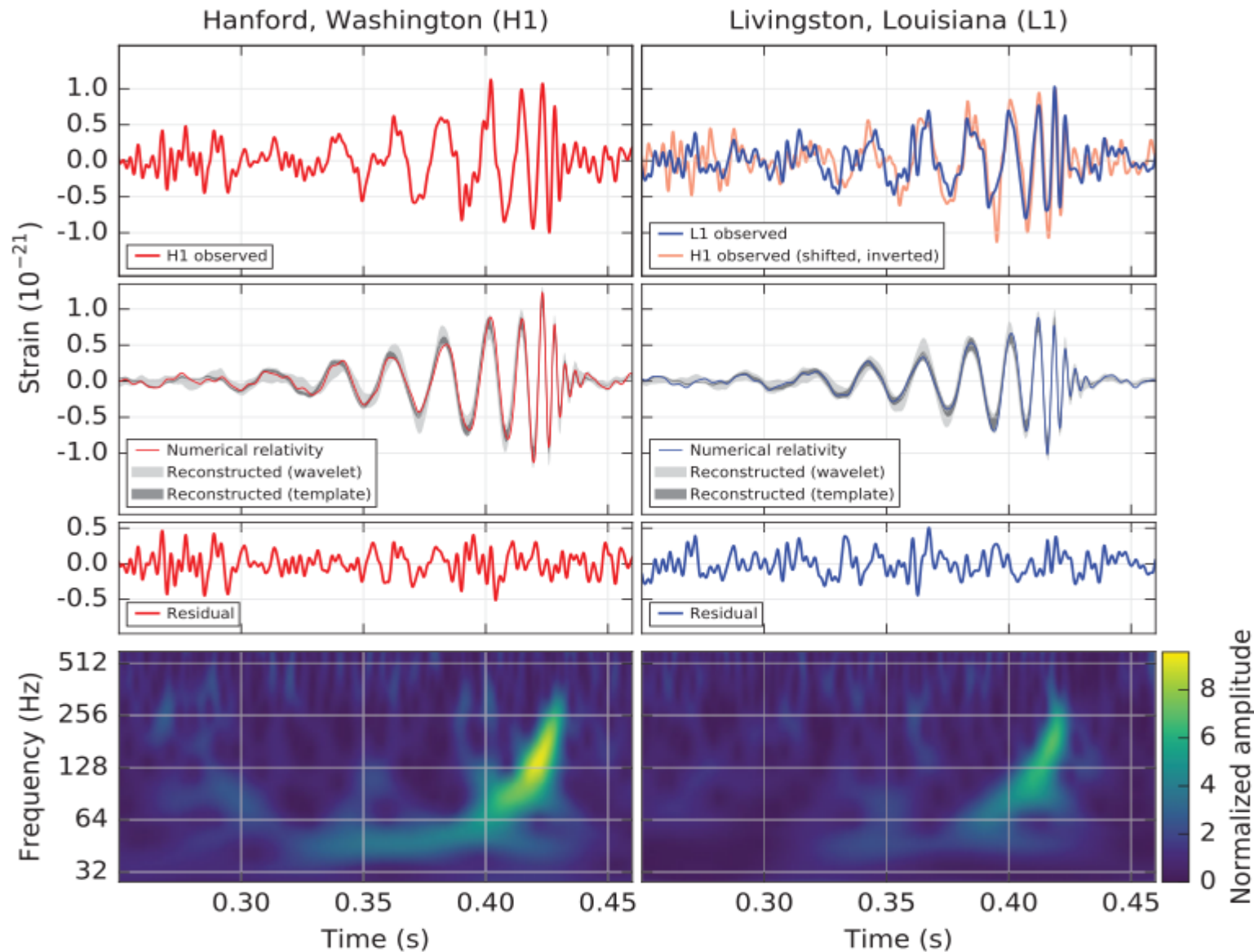
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- GW150914:
    - Marked the birth of gravitational wave astronomy
    - Confirmed general relativity (GR) in the dynamical, strong-field regime
    - Best evidence for the existence of Bhs and binary BHBHs
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- In the next few years aLIGO/Virgo will routinely detect BHNS and NSNS

- BHNS and NSNS have are likely to be accompanied by a wealth of electromagnetic (EM) signals countepart to the GWs, such as kilonovae, short gamma-ray bursts etc. (see also Luciano's talks)

- Coincident detection of GW and EM signals will mark the onset of multimessenger astronomy

BHNS and NSNS binaries are viable sGRB progenitors

Paschalidis, CERN, December 6, 2016

sGRBs in a nutshell

- Flashes of gamma rays of extra-galactic origin

- Instruments: BATSE, Swift, HETE-2, Fermi, Hubble, Liverpool & Faulkes...

- Timescales: $T_{90} \leq 2s$; $<T_{90}> = 0.2s$;

- Gamma ray luminosities: $10^{50} - 10^{52}$ erg/s (10erg = 1 joule)

- Host galaxies: spirals & gas depleted ellipticals $\rightarrow$ (old stars) (Berger 2013)

- Popular model: relativistic jet (fireball); $\Gamma \geq 100$ (Piran 2004)

- Plausible engine: BH + accretion disk (with twin relativistic jets)

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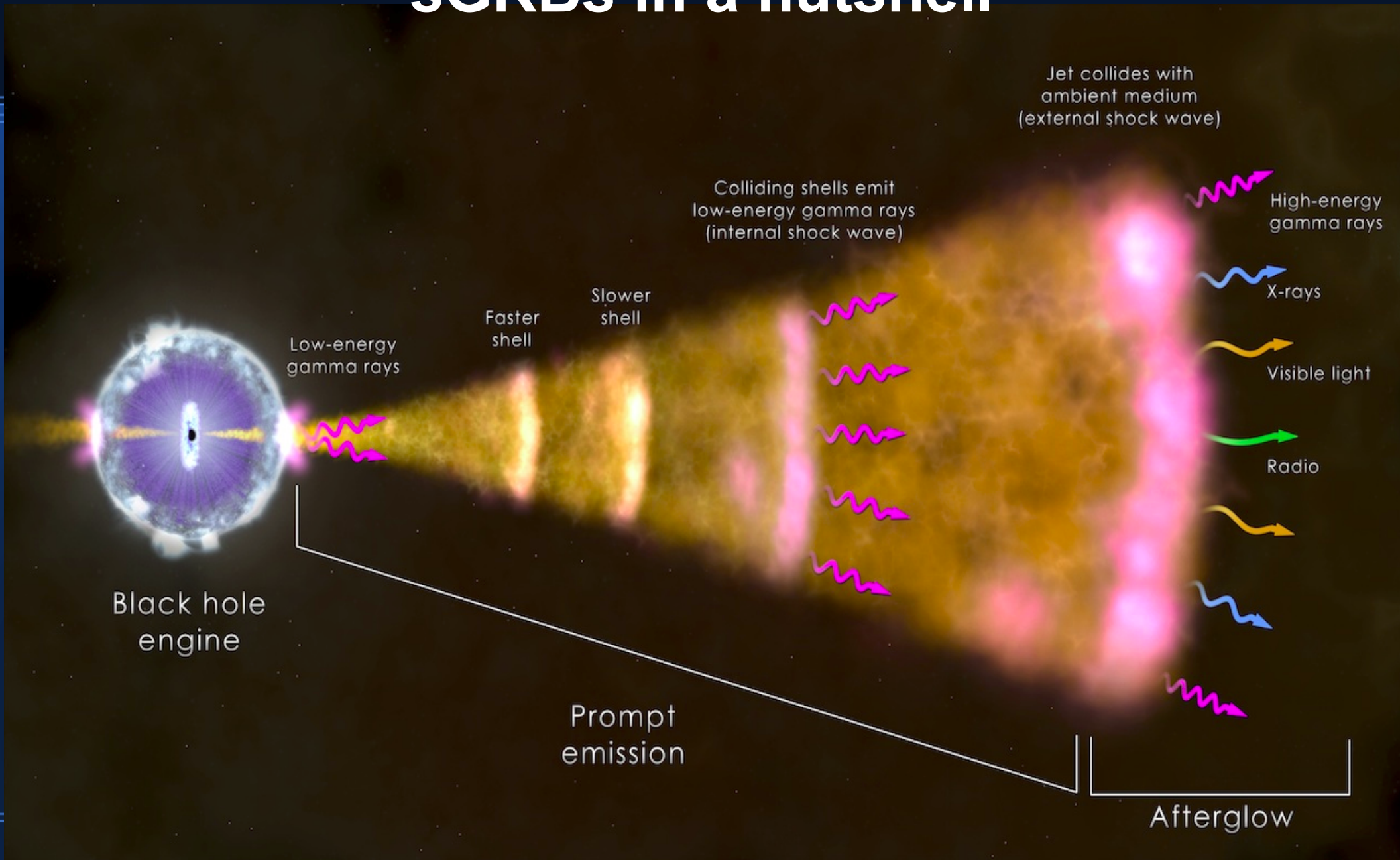
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Motivation for simulating BH-NS and NS-NS mergers as sGRB engines

- Engine behind short-hard Gamma Ray Bursts (sGRBs) is not known!

- NSNS and BHNS mergers: favored progenitors for sGRBs
- But,
    - we do not know how these mergers may power sGRBs
    - it has never been shown theoretically that mergers of compact binaries can launch highly relativistic jets (until recently no jets at all)!

- Through a complete computational/theoretical model of sGRB engines → Infer the progenitor parameters from sGRB → crosscheck with GWs

Motivation for simulating BH-NS and NS-NS mergers as sGRB engines

<u>The theoretical challenge:</u>

Demonstrate from first principles that BH-NS/NS-NS mergers can launch jets (similar to core collapse SN).

Motivation for simulating BH-NS and NS-NS mergers as sGRB engines

The theoretical challenge:

Demonstrate from first principles that BH-NS/NS-NS mergers can launch jets (similar to core collapse SN).

Simulations in full non-linear general relativity (GR), necessary to capture the dynamical inspiral, merger, disk formation and accretion onto the BH and to predict the gravitational wave signature → multimessenger astronomy!
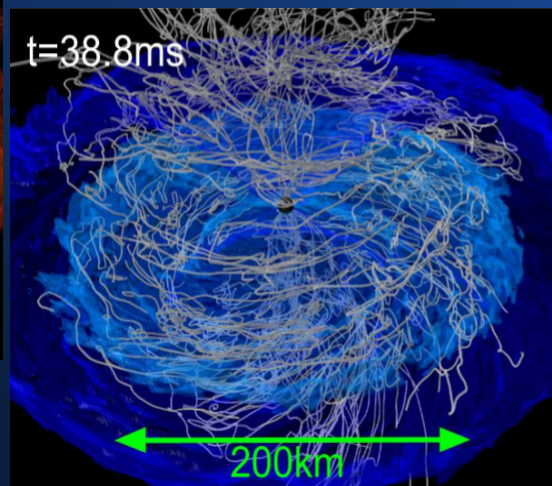
Paschalidis, CERN, December 6, 2016

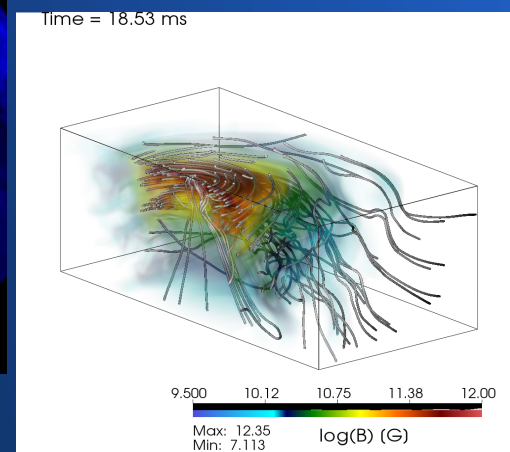# NS-NS mergers → jets?

NS-NS mergers → jets?

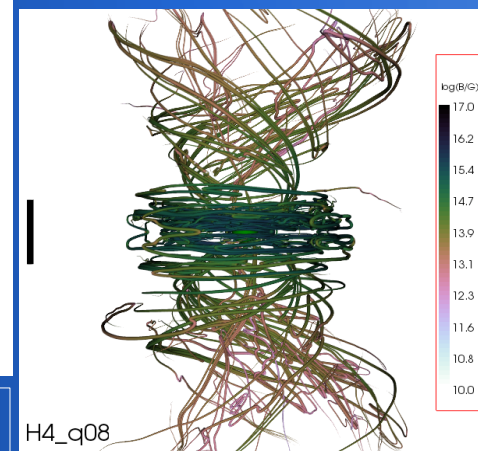- MHD studies in full GR find with initial dipole magnetic fields confined to the NS interiors:
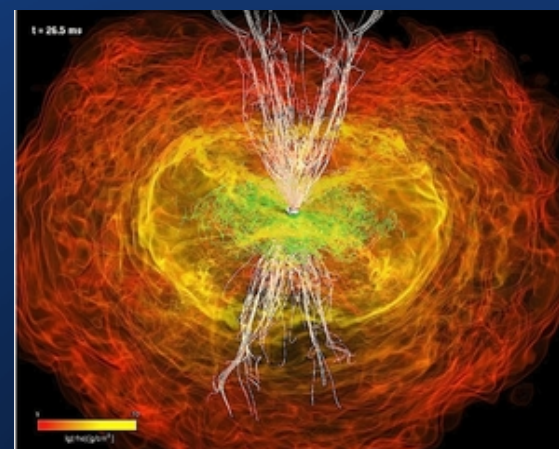
Rezzolla et al. 2011

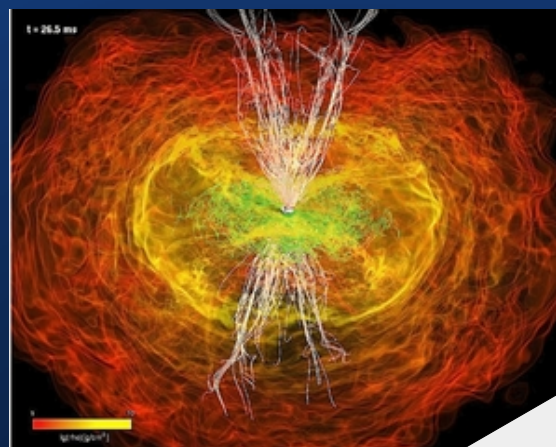Kiuchi et al. 2015

Dionysopoulou & Rezzolla 2016

Kawamura et al. 2016
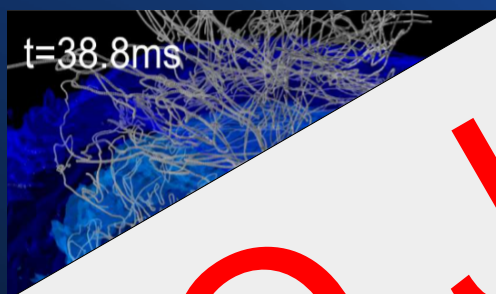
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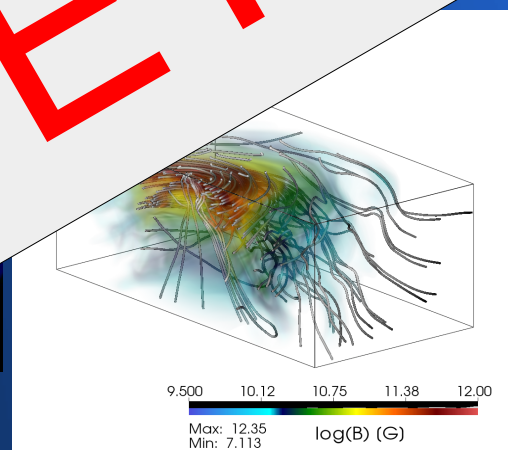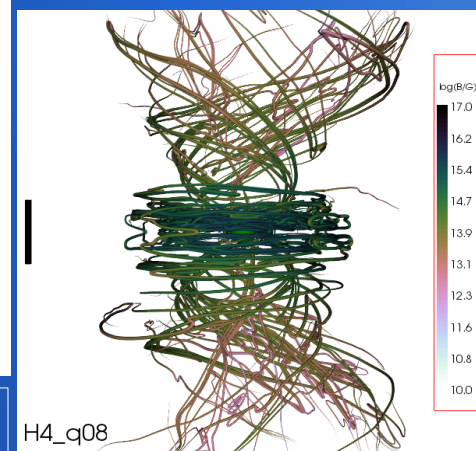- MHD studies in full GR find with initial dipole magnetic [field] confined to the NS interiors:

Rezzolla et al.

t=38.8ms

... et al. 2015

Dionysopoulou & Rezzolla 2016

H4_q08

Kawamura et al. 2016

NO JETS!

NS-NS mergers → jets?

- Ruiz, Lang, Paschalidis, Shapiro, Ap. J. Lett. 824 (2016)

- Perform simulations with magnetized NSNS at reasonably high resolutions

- Initial data same as in Rezzolla et al (2011):

- Initial B field:

  - dipolar (interior + exterior), and interior only
  - Stronger than Rezzolla et al (2011), but still dynamically weak ($320 \leq P_{gas}/P_{mag}$)
  - Strength motivated by expectations of post-merger B-field amplification due to KHI and MRI → $\langle B \rangle \sim 10^{15.3-16}$ G (Price & Rosswog 2006, Zrake & MacFadyen 2013, Kiuchi et al. 2015)

NSNS mergers → incipient jets

t/M = 230

t/M = 467

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2M

15 ms=1000M

t/M = 1691

t/M = 4606
0.5c

9km = 2M

117km = 26M

26M

26M

Paschalidis, CERN, December 6, 2016

NSNS mergers → incipient jets

t/M = 665

Paschalidis, CERN, December 6, 2016
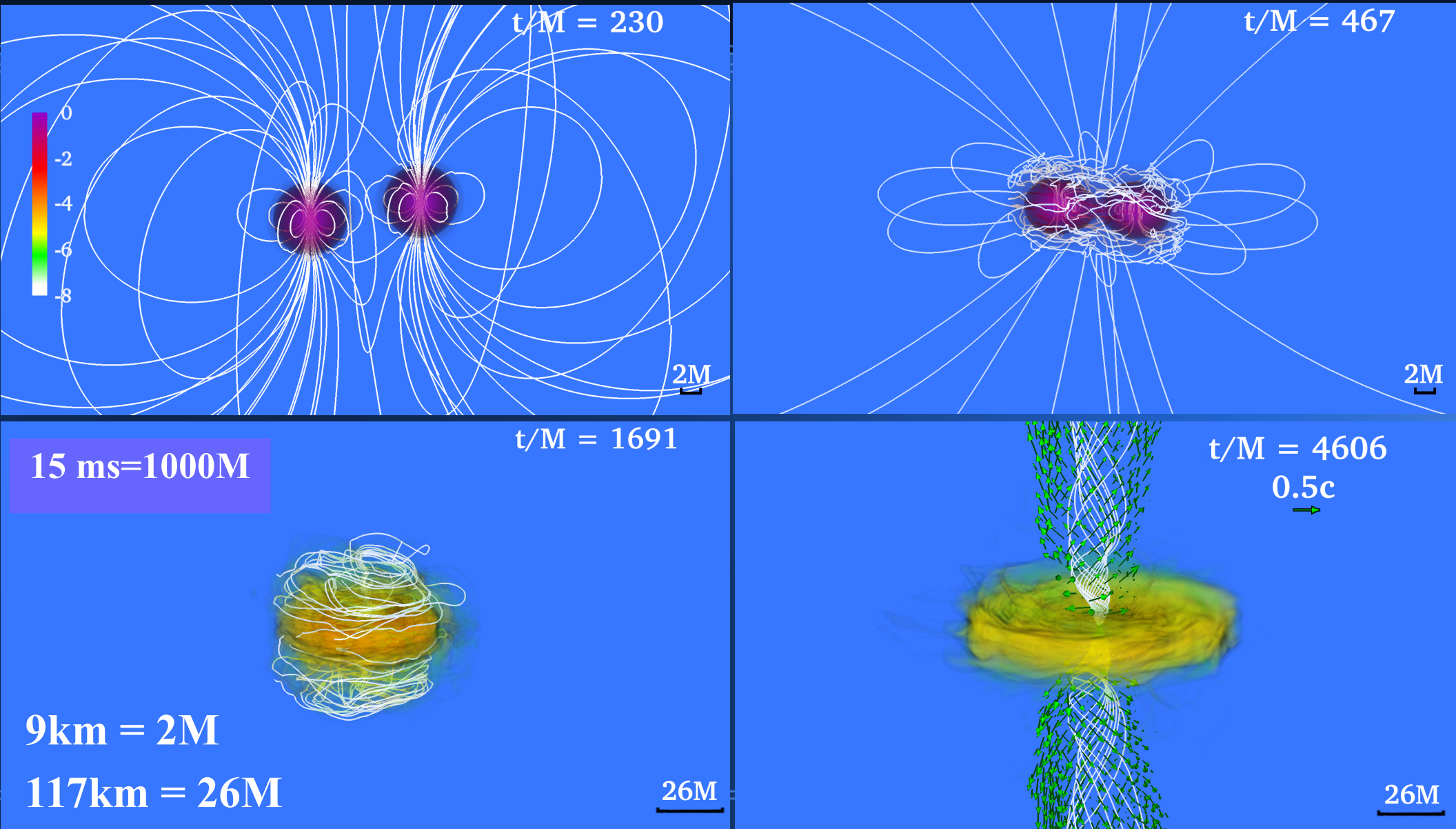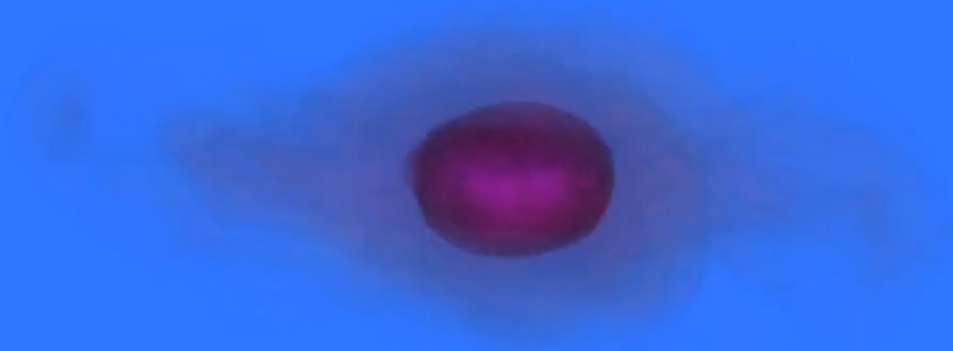
BH-NS mergers → jets?

Previous works with purely interior dipole magnetic fields (BH spin // L_{obr}):

- Chawla, Anderson, Besselman et al. (2010) → No jet

- Etienne, Liu, Paschalidis, Shapiro (2012) → No jet

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- Kiuchi, Sekiguchi, Kyotoku, Shibata, Taniguchi, Wada (2014) → No jet

BH-NS mergers → No jets?

An incipient jet emerges

Paschalidis, Ruiz, Shapiro Ap. J. Lett. 806 (2015)
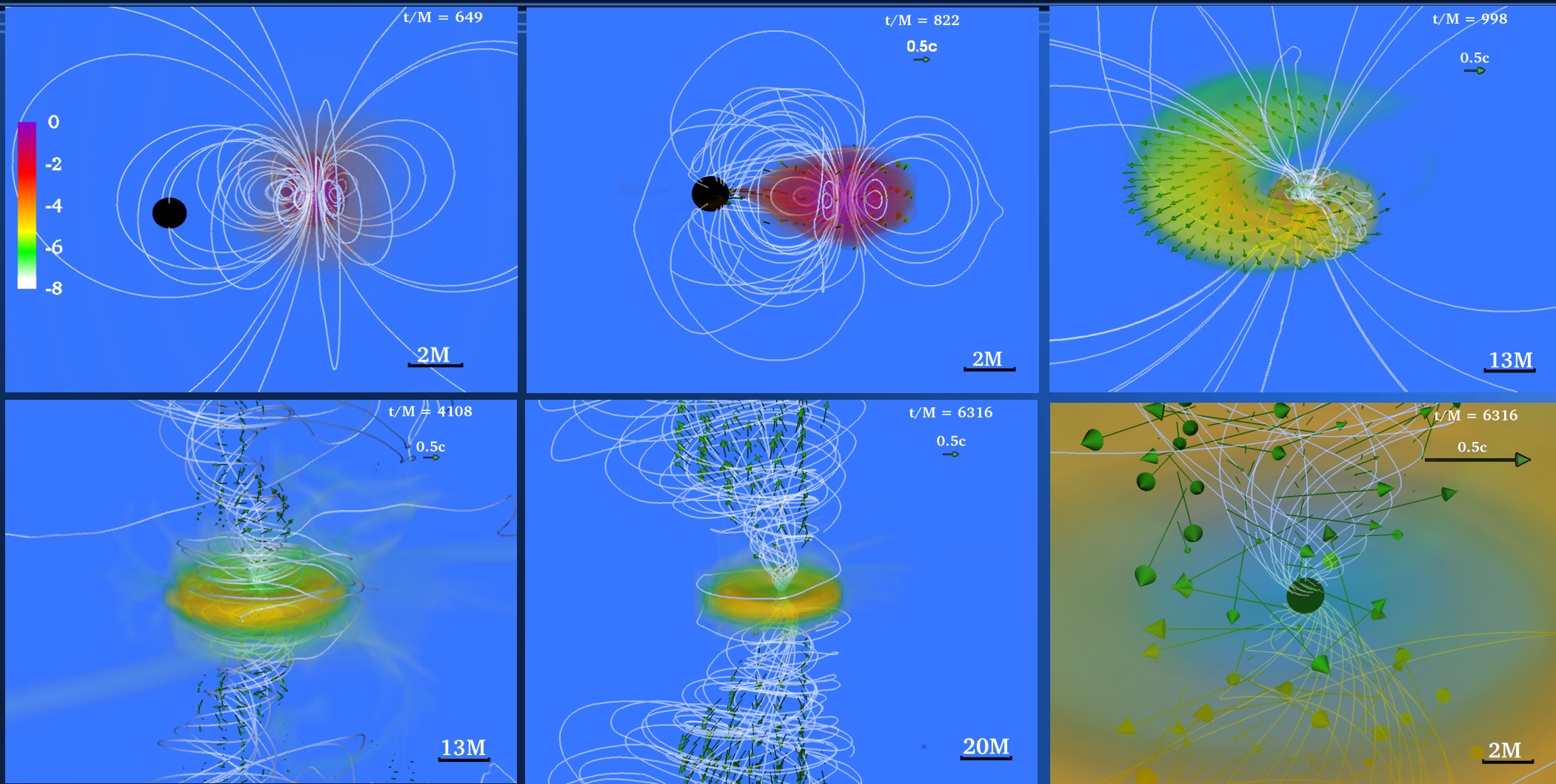
An incipient jet emerges

- $\dfrac{B^2}{8\pi\rho c^2} \sim 100$ ~ terminal Lorentz factor (Vlahakis & Konigl 2003)

- Disk lifetime: $t_{disk} \sim \dfrac{M_{disk}}{\dot{M}} \sim O(0.1\,s)$ consistent with short sGRB $<T_{90}>$

- Outgoing EM luminosity: $L_{EM} \sim 10^{51}\,erg/s$ ~ consistent with typical sGRB

- BHNS and NSNS mergers are viable sGRB engines!

- Delay time between peak GW amplitude and jet launching > 50 ms

Coincident detection of BHNS-generated GW signal and a sGRB can rule out a large number of (cold) nuclear EOS for $M_{NS} < 2M_{sun}$

BHNS mergers → BH+disk?   Not trivial!

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- Why is it difficult to create an accretion disk following merger of a quasicircular BH-NS?

- To have an appreciable disk, the NS must be tidally disrupted **outside** the (effective) innermost circular orbit (ISCO)

BHNS mergers → BH+disk?   Not trivial!

- Key parameters determining the interplay between ISCO and tidal disruption radius:

- $q = M_{BH}/M_{NS}$ and NS compaction, $C = GM_{NS}/R_{NS}c^2 \rightarrow$ tidal disruption radius

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$$a_{tidal} = a_{g,NS} \Rightarrow r_{tidal} = 2\left(\frac{q}{10}\right)^{-2/3}\left(\frac{C}{0.2}\right)^{-1} r_{g,BH}, \qquad r_{g,BH} = \frac{GM_{BH}}{c^2}$$

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- BH spin → ISCO $r_{g,BH} \leqslant r_{ISCO} \leqslant 6\, r_{g,BH}$

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- BH spin → ISCO $\quad r_{g,BH} \leqslant r_{ISCO} \leqslant 6\, r_{g,BH}$

- For a given BH spin and mass ratio, there exists a critical compaction, such that following NS disruption no mass is left outside the BH to form a disk.

Probing the nuclear EOS with GW+sGRB observations

- Let us assume that we have a BHNS GW signal and an associated sGRB

- The inspiral GW signal will provide the NS mass, the BH mass and spin

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- Numerical relativity hydrodynamic simulations using the inferred binary parameters (plus their uncertainties) can be run for all plausible nuclear EOSs to determine which EOSs result in a disk-less BH remnant.

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Probing the nuclear EOS with GW+sGRB observations

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- EOSs forming such a remnant are ruled out by the existence of a sGRB!

- Equivalently, a large No. of numerical relativity hydrodynamic simulations adopting plausible EOSs can be run a priori to determine the critical compaction for a disk-less BH remnant for given binary parameters.

Probing the nuclear EOS with GW+sGRB observations

- Foucart (2012) compiled the results from many numerical relativity BHNS simulations and derived a fitting formula for disk mass predictions

$$\frac{M_{disk}}{M_{NS}} = 0.415\, q^{1/3}\left(1 - 2\,C\right) - 0.148\, q\, C\, \frac{R_{ISCO}}{M_{BH}}$$

- Critical compaction for $M_{disk} = 0$

$$C_{NS,crit} = \left(2 + 2.14\, q^{2/3}\, \frac{R_{ISCO}}{M_{BH}}\right)^{-1}$$

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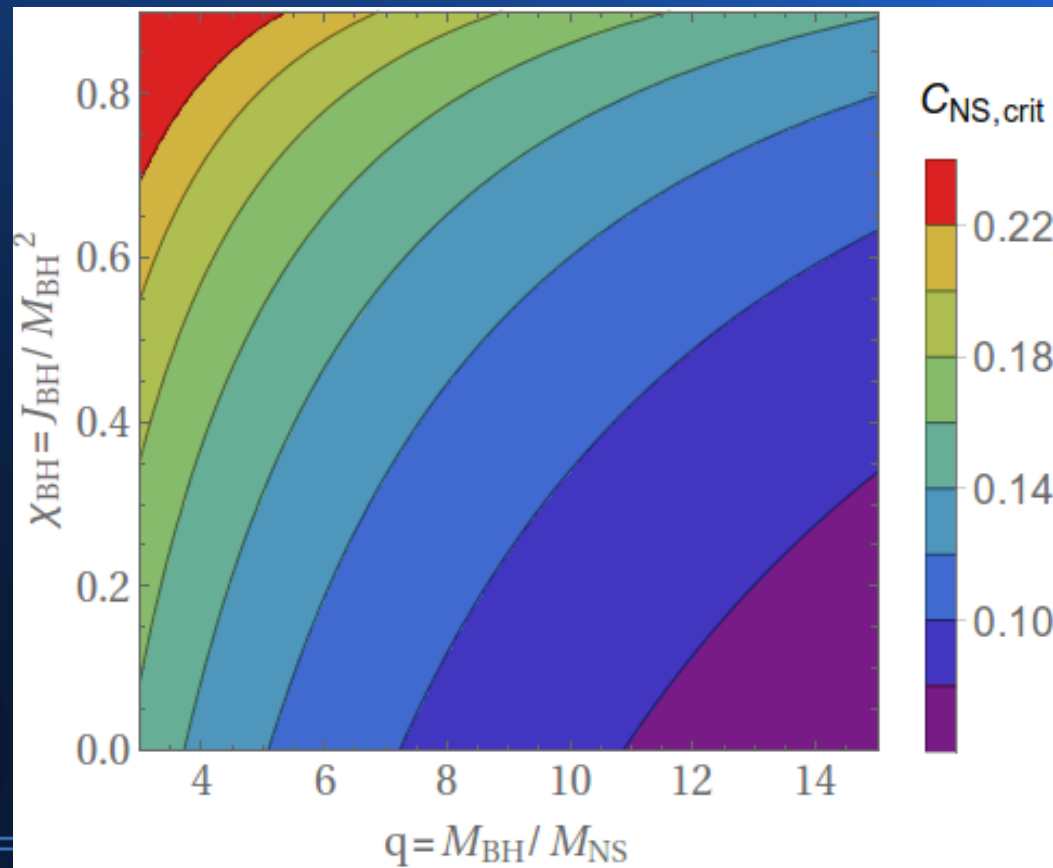- Critical compaction for $M_{disk} = 0$

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- Small q and large BH spin (small R_{ISCO}) increase the $C_{NS,crit}$
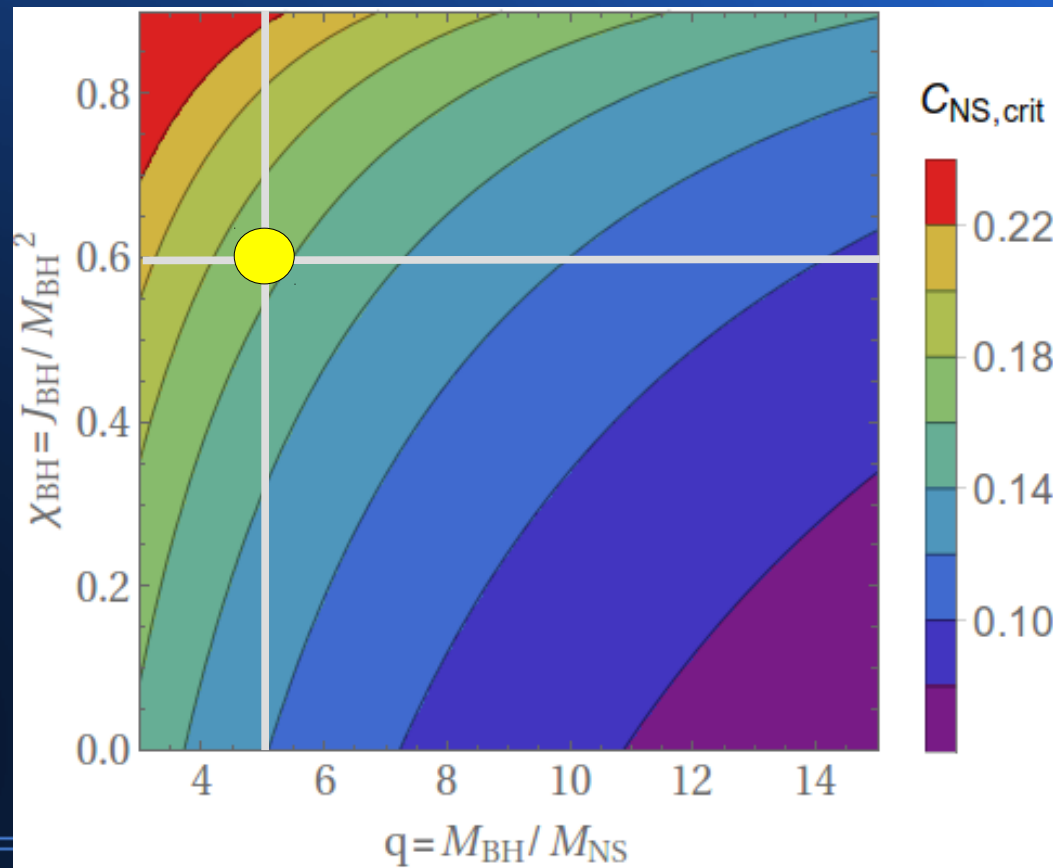
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Probing the nuclear EOS with GW+sGRB observations

$$q = 5, \chi_{BH} = 0.6$$

Probing the nuclear EOS with GW+sGRB observations

- Advantages:

  - Practically model independent

  - Only two assumptions: I) GR, II) No disk → no sGRB

  - Orbital parameters will be known from early inspiral – no need for finite size effects

  - Pure hydrodynamic simulations suffice: no need for complex physics, such as magnetic fields and neutrino transport

- Disadvantage:

  - if true EOS is soft (small NS radii), detection of a simultaneous sGRB + GW BHNS signal may never be realized

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- Pannarale & Ohm (2014) proposed a similar method, but assuming a finite, non-zero $M_{thres} = 0.03 M_{sun}$ for no sGRB → model dependent

NSNS mergers form hypermassive NSs that generically undergo a one-arm (m=1) instability

GWs generated by the m=1 instability can constrain the finite-temperature nuclear EOS for $M_{NS} > 2M_{sun}$

One-arm instability

- Shearing stellar instability (Corvino et al. 2010) → requires differential rotation

- Discovered by Centrella et al. (2001) in Newtonian hydrodynamic simulations of soft polytropic (Γ=1.3), differentially rotating stars

One-arm spiral instability

- Possible mechanism: (resonant excitation?) → corotation radius (Ou & Tohline 2006, Watts et al. 2003)

- Has been observed in Newtonian and GR core collapse simulations (Ott et al 2005, Ott et al. 2006, Kuroda et al. 2014)

- In over 15 years of NS-NS merger simulations, it has never been reported to occur in NS-NS mergers, until recently.

Eccentric NSNS mergers with NS spin

- Initial data (Paschalidis et al. 2015, East, Paschalidis et al. 2016 a, b):

    - adopt (phenom.) piecewise polytropic EOSs with a range of stiffness

    - Set two ($1.35 M_\odot$) stars 200km away, on a marginally unbound orbit determined by a periapse distance r_p

    - Perform hydrodynamics simulations in full general relativity

Eccentric NSNS mergers with spin 0.025

t=3.90 ms
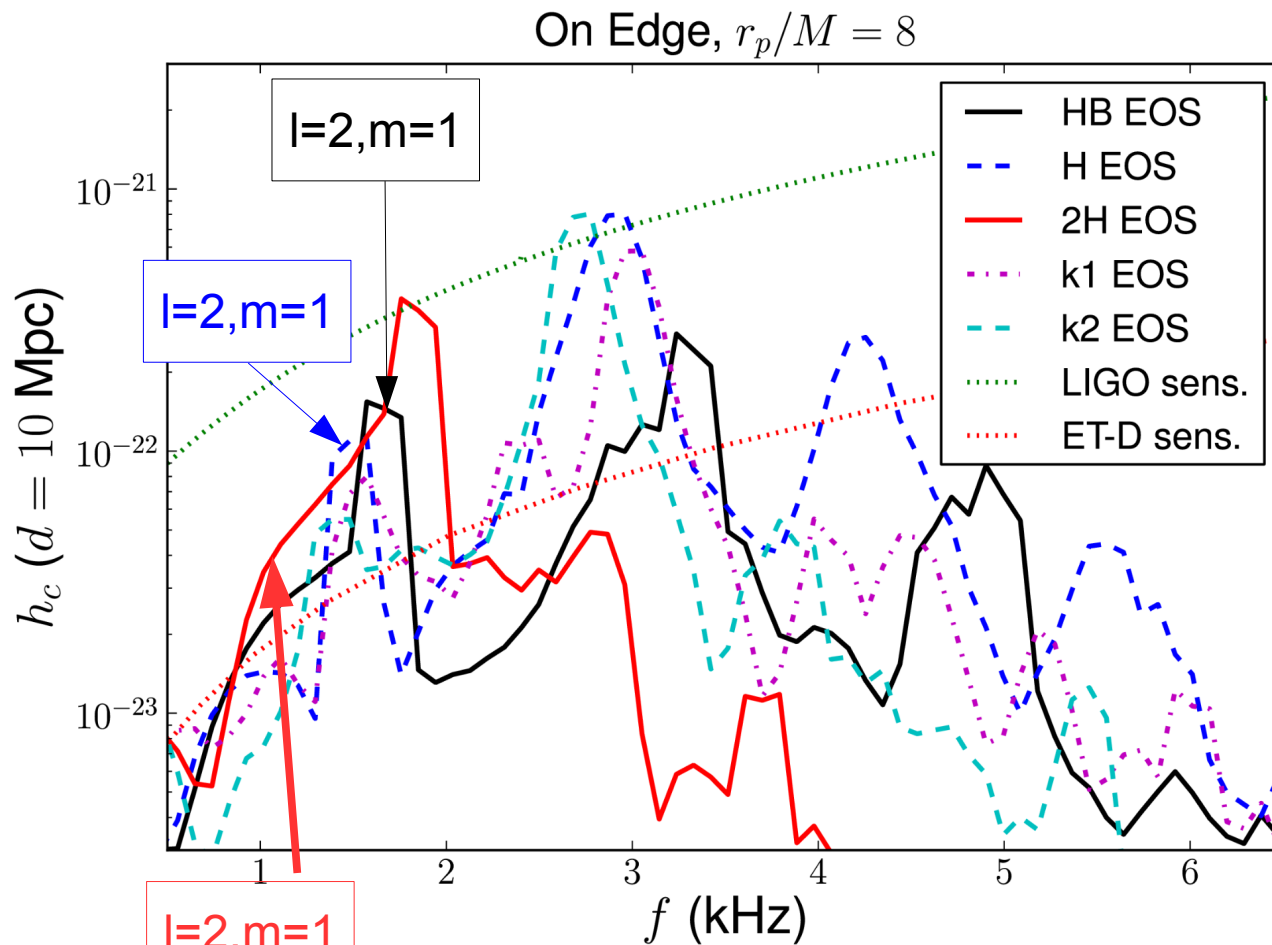
1.00e+12 gr/cm^3   1.00e+15
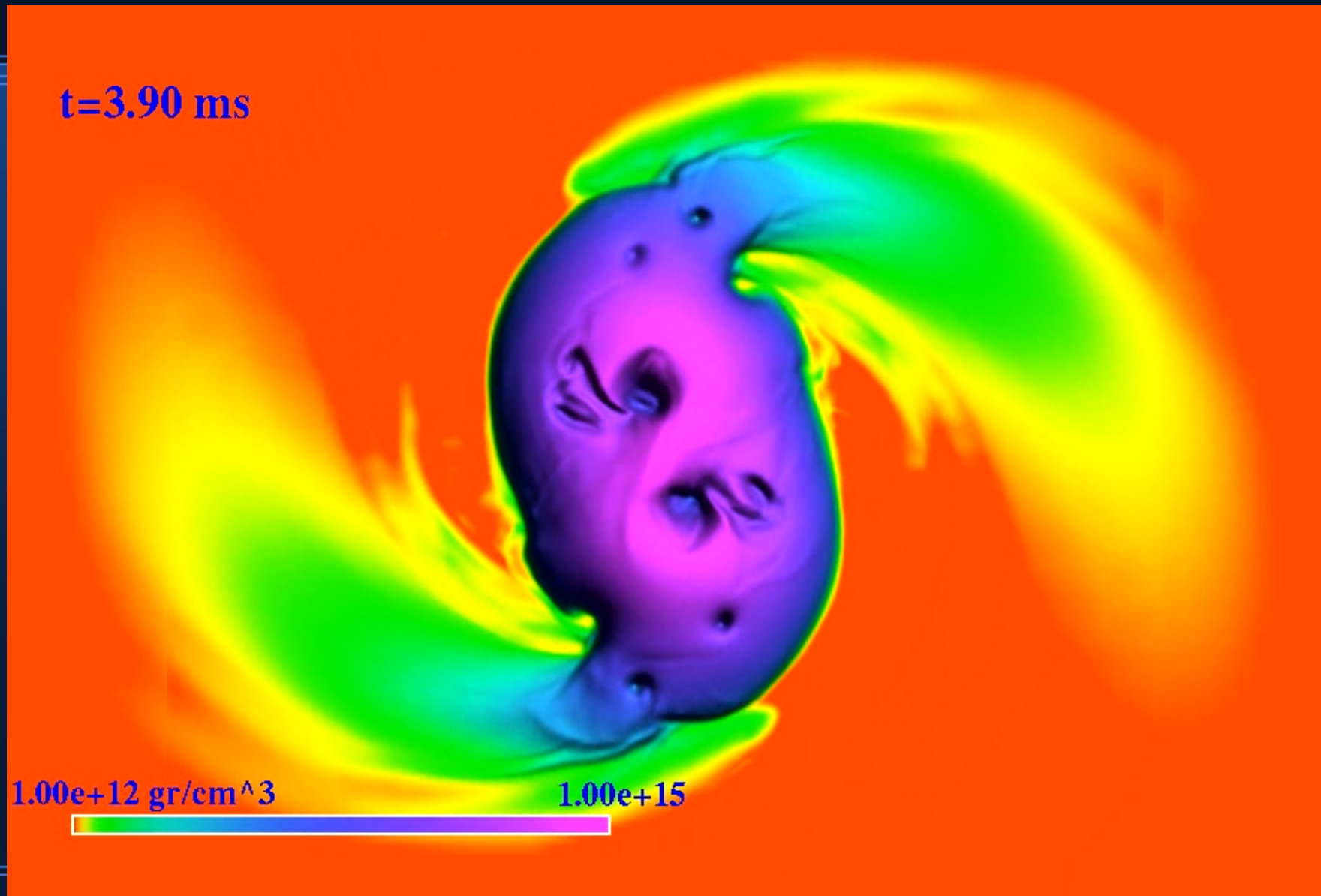
Significance

- Why should we care about this instability?

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- Instability → Signal!

Gravitational Waves: Characteristic strain at 10Mpc, rp=8M for 10ms

On Edge, $r_p/M = 8$

Legend:
- HB EOS
- H EOS
- 2H EOS
- k1 EOS
- k2 EOS
- LIGO sens.
- ET-D sens.

l=2,m=1

$h_c \ (d = 10 \ \text{Mpc})$

f (kHz)

But, GW frequency and amplitude roughly constant with time, and hypermassive neutron star lifetime may be

$$J/\dot{J}_{GW} = 1-3s$$

Thus, h_c may be amplified by 100.

Gravitational Waves II: Characteristic strain at 10Mpc, 2H EOS q=0.9 for >10ms

On Edge, $r_p = 8.0$, EOS=2H, $q = 0.9$

Legend:
- 10.0 ms
- 41.0 ms
- LIGO sens.
- LIGO Hi-Freq
- ET-D sens.

h_c ($d = 10$ Mpc) vs f (kHz)
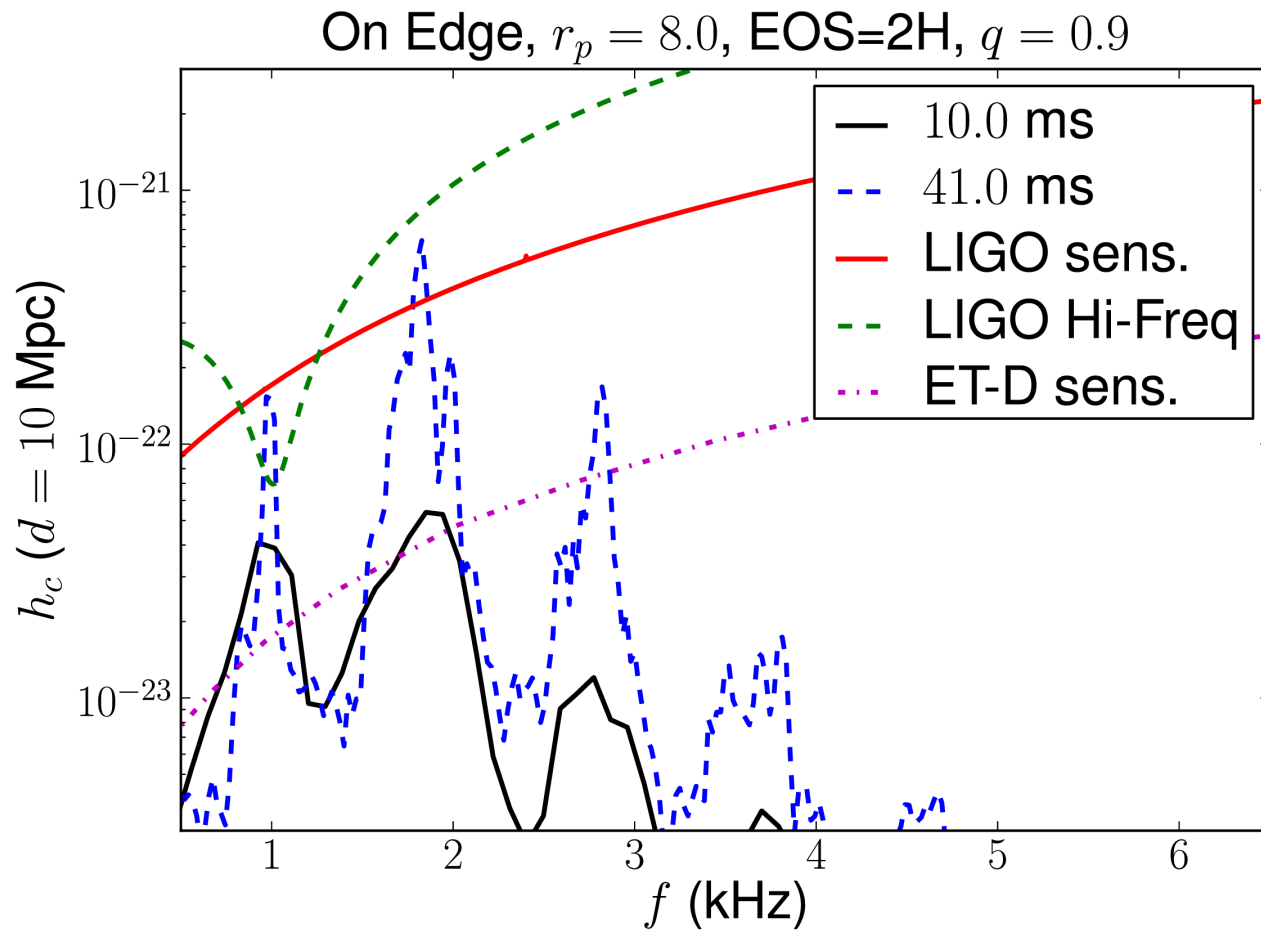
Almost perfect monochromatic source

Correlation of GW 2,1 mode frequency with EOS

The stiffer the EOS, the lower the 2,1 GW mode frequency ($f_{GW,21}$) for a given total mass

Run multiple NSNS simulations varying total mass, and EOS to develop a fitting formula correlating the EOS with $f_{GW,21}$ (much like l=2,m=2 mode see Roberto's & Luciano's talk)

Gravitational Waves: detectability

- A figure of merit for detectability is the GW signal-to-noise (SNR) ratio

- East et al. (2016)

$$SNR_{LIGO} \approx 5.6 \left(\frac{T_{m=1}}{400\,ms} \right)^{1/2} \left(\frac{r}{10\,Mpc} \right)^{-1} \qquad SNR_{ET} \approx 5.0 \left(\frac{T_{m=1}}{400\,ms} \right)^{1/2} \left(\frac{r}{100\,Mpc} \right)^{-1}$$

$$J / \dot{J}_{GW} = 1 - 3\,s$$

- But magnetic fields, neutrinos play a role on these timescales

SUMMARY

- BHNS and NSNS binaries are viable sGRB progenitors

- Even one coincident detection of GW signal and a sGRB from a BHNS inspiral and merger can potentially rule out a large number of (cold) nuclear EOSa

- NSNS mergers form hypermassive NSs that generically undergo a $m=1$ instability and GWs generated can constrain the finite-temperature nuclear EOS

- Numerical relativity is crucial for GW science and constraining the NS EOS

Paschalidis, CERN, December 6, 2016

Probing the nuclear EOS with GW+sGRB observations

- sGRBs with determined redshifts lies at $r > 460\, Mpc = 1.42 \times 10^{22}\, km$

- The NSNS aLIGO horizon is $r_{NSNS} \lesssim 400\, Mpc$

- The BHNS ($M_{BH} = 10 M_{sun}$, $M_{NS} = 1.4 M_{sun}$) aLIGO horizon is $r_{NSNS} \lesssim 900\, Mpc$

- It is a matter of time until we detect GWs from a inspiralling and merging BHNS binary

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- If sGRBs are indeed associated with BHNS mergers, then it is plausible that we will detect a GW BHNS inspiral signal accompanied by a sGRB.

Probing the nuclear EOS with GW+sGRB observations

$$q = 7 \pm 2, \chi_{BH} = 0.5 \pm 0.1$$
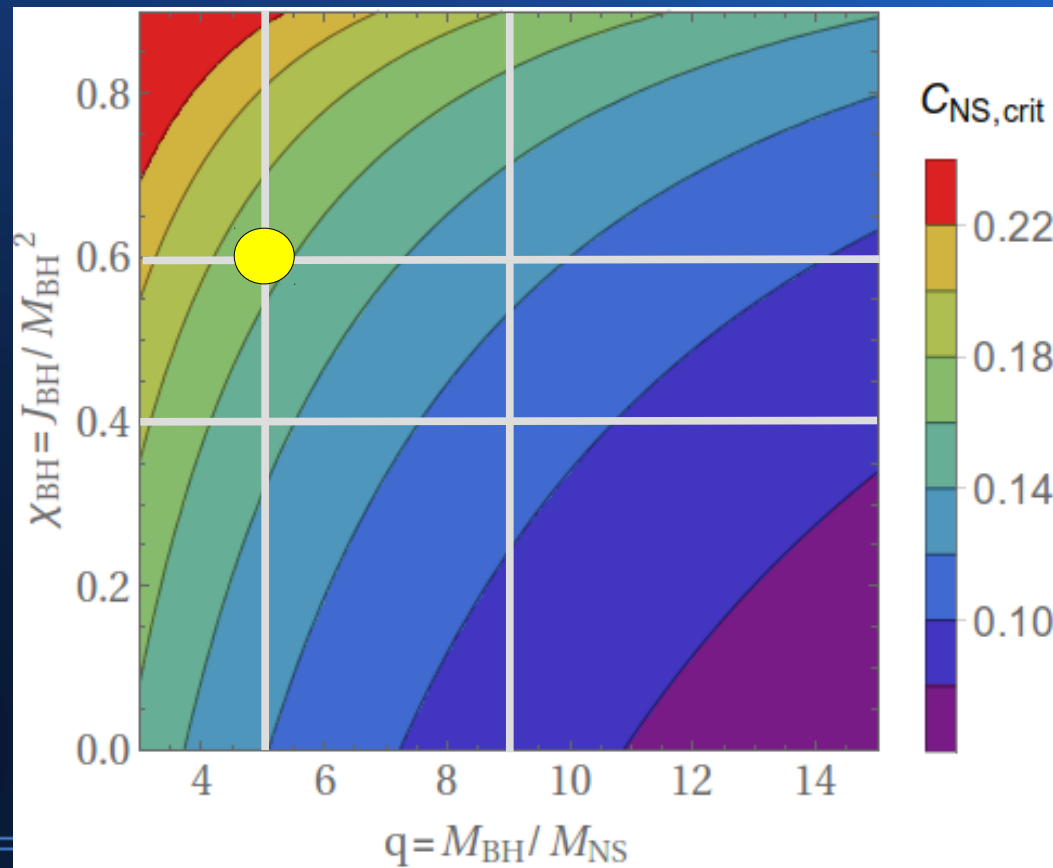
What is a hypermassive neutron star (HMNS)?

- NSs can be non-rotating, uniformly rotating or differentially rotating. The amount of rotation determines how much mass the NS can support.

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- For a given equation of state:

  The maximum mass that can be supported by a non-spinning NS is know as the Tolman-Oppenheimer-Volkoff (TOV or OV) limit denoted by M_{TOV}

  The maximum mass that can be supported by a NS when allowing for maximal uniform rotation is know as the supramassive limit (M_{SUP})

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  The maximum mass that can be supported by a NS when allowing for maximal uniform rotation is know as the supramassive limit (M_{SUP})

- A NS with mass M_{NS} satisfying $M_{TOV} < M_{NS} < M_{SUP}$ is called supramassive

- A NS with mass M_{NS} satisfying $M_{SUP} < M_{NS}$ is called hypermassive

One-arm instability vs EOS

- East, Paschalidis & Pretorius (2016) focusing on eccentric mergers consider 6 equations of state with fixed total mass at 2.7Msun, and spins 0.05, 0.075, rp=8M

B EOS $\quad M_{TOV} = 2.06\, M_\odot \rightarrow$ Forms BH $\rightarrow$ No one-arm instability

HB EOS $\quad M_{TOV} = 2.12\, M_\odot \rightarrow$ Toroidal HMNSs $\rightarrow$ Develop m=1 inst.

H EOS $\quad M_{TOV} = 2.25\, M_\odot \rightarrow$ Ellipsoidal HMNSs $\rightarrow$ Develop m=1 inst.

2H EOS $\quad M_{TOV} = 2.83\, M_\odot \rightarrow$ Ellipsoidal HMNSs $\rightarrow$ "Develop" m=1 inst.

Γ=3, k_1 $\quad M_{TOV} = 2.06\, M_\odot \rightarrow$ Double core HMNSs $\rightarrow$ Develop m=1 inst.

Γ=3, k_2 $\quad M_{TOV} = 2.22\, M_\odot \rightarrow$ Double core HMNSs $\rightarrow$ Develop m=1 inst.

One-arm instability vs EOS

- East, Paschalidis & Pretorius (2016) focusing on eccentric mergers consider 6 equations of state with fixed total mass at 2.7Msun, and spins 0.05, 0.075, rp=8M

  B EOS $\boxed{M_{TOV} = 2.06\,M_\odot}$ $\rightarrow$ Forms BH $\rightarrow$ No one-arm instability

  HB EOS $\boxed{M_{TOV} = 2.12\,M_\odot}$ $\rightarrow$ Toroidal HMNSs $\rightarrow$ Develop m=1 inst.

  H EOS $\boxed{M_{TOV} = 2.25\,M_\odot}$ $\rightarrow$ Ellipsoidal HMNSs $\rightarrow$ Develop m=1 inst.

  2H EOS $\boxed{M_{TOV} = 2.83\,M_\odot}$ $\rightarrow$ Ellipsoidal HMNSs $\rightarrow$ "Develop" m=1 inst.

  Γ=3, k_1 $\boxed{M_{TOV} = 2.06\,M_\odot}$ $\rightarrow$ Double core HMNSs $\rightarrow$ Develop m=1 inst.

  Γ=3, k_2 $\boxed{M_{TOV} = 2.22\,M_\odot}$ $\rightarrow$ Double core HMNSs $\rightarrow$ Develop m=1 inst.

- m=1 instability does not depend on the background about which it develops

- m=1 instability should be generic in nature.

Eccentric NS-NS mergers (azimuthal modes)

- In all cases where the instability appears

$$J_{merger} / M^2 \approx 0.9 - 1.0$$

- This is precisely the regime of interest for quasi-circular NSNS mergers!

- Does the instability arise in quasi-circular NSNS mergers?

One-arm instability in quasicircular mergers

- D. Radice et al. (2016) → hydro simulations in full GR with piecewise polytropic EOS (MS1b) and equal-mass, irrotational NSNS
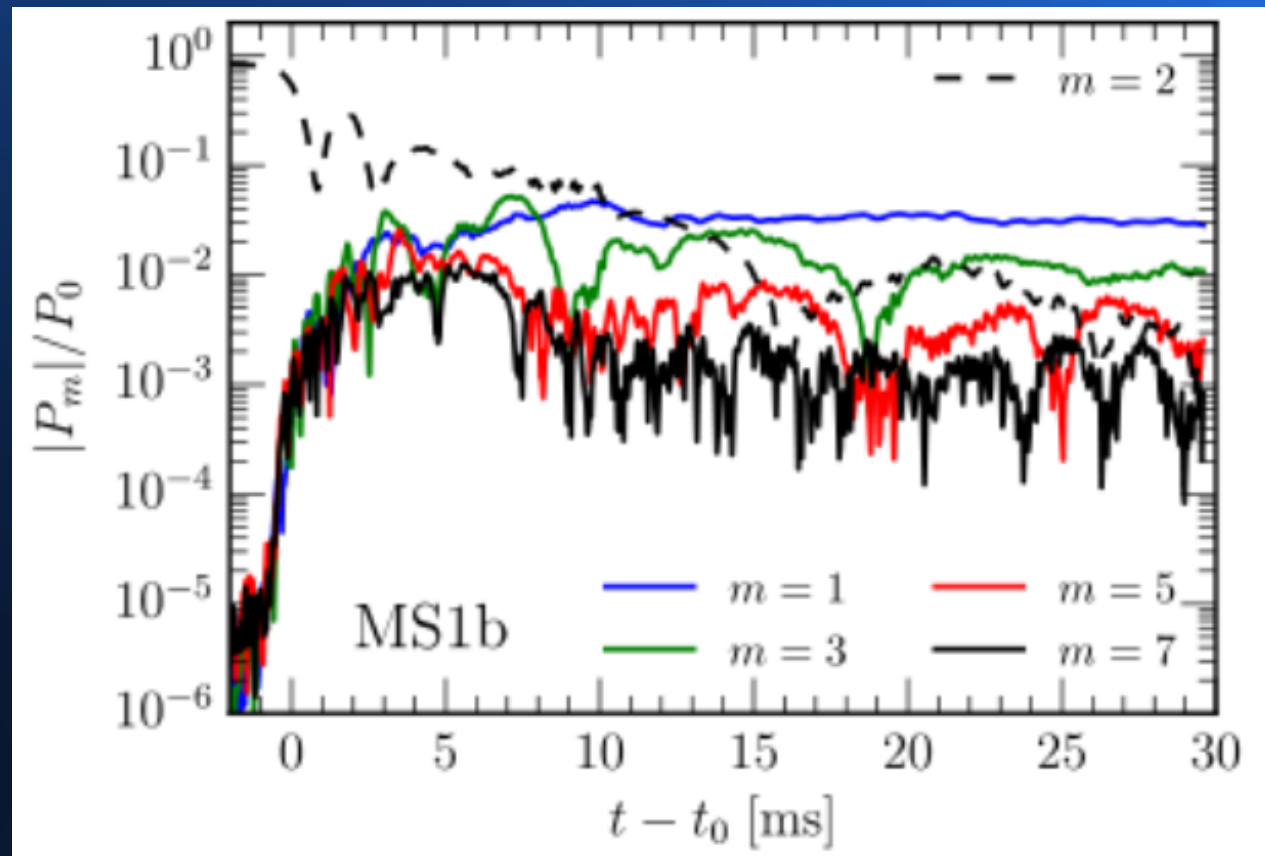
One-arm instability in quasicircular mergers

- Lehner et al. (2016) $\rightarrow$ hydro simulations in full GR with realistic EOS (MS1b) treating equal-mass and unequal mass, irrotational NSNS

- They find that the one-arm instability operates for realistic EOSs and that the larger the binary mass ratio the easier the m=1 density mode dominates following merger.

Gravitational Waves: detectability

- A figure of merit for detectability is the GW signal-to-noise (SNR) ratio

- East et al. (2016)

$$SNR_{LIGO} \approx 2.8 \left(\frac{T_{m=1}}{100\,ms} \right)^{1/2} \left(\frac{r}{10\,Mpc} \right)^{-1}$$

$$SNR_{ET} \approx 2.5 \left(\frac{T_{m=1}}{100\,ms} \right)^{1/2} \left(\frac{r}{100\,Mpc} \right)^{-1}$$

- Radice et al. (2016)

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$$SNR_{LIGO} \approx 6.0 \left(\frac{T_{m=1}}{100\,ms} \right)^{1/2} \left(\frac{r}{10\,Mpc} \right)^{-1}$$

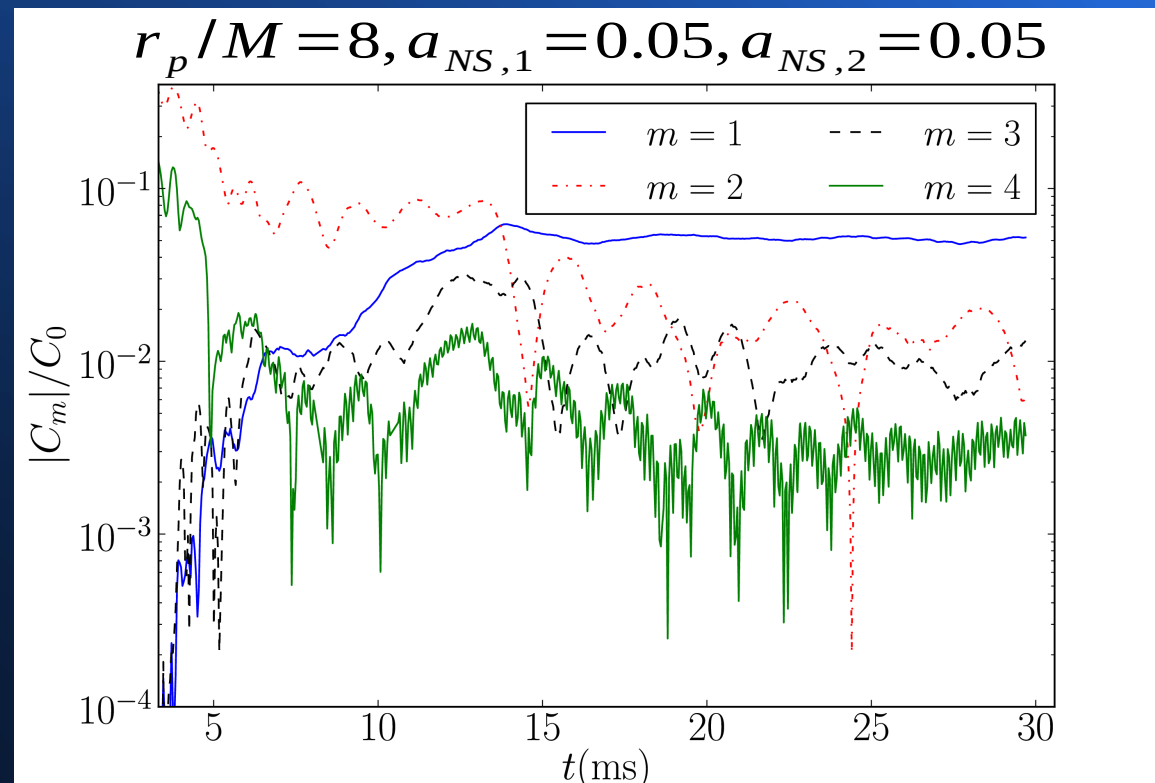$$SNR_{ET} \approx 6.0 \left(\frac{T_{m=1}}{100\,ms} \right)^{1/2} \left(\frac{r}{100\,Mpc} \right)^{-1}$$

Eccentric NSNS mergers (azimuthal modes)

- Volume azimuthal mode decomposition of the rest-mass density in a center-of-mass frame

$$C_m = \int \rho \, e^{im\varphi} \, d^3 x$$

- If axisymmetric $\quad C_m = 0, m > 0$

Eccentric NSNS mergers (azimuthal modes)

Numerical relativity: equations

- Equations:

$$G_{\mu\nu} = 8\pi\, T_{\mu\nu}$$

→ Einstein →

10, 2nd-order highly
Non-linear partial differential
equations (PDEs)

Numerical relativity: equations

- Equations:

$$G_{\mu\nu} = 8\pi\, T_{\mu\nu}$$ → Einstein

$$\nabla_\alpha\left(T^{\alpha\beta} + R^{\alpha\beta}\right) = 0$$

$$\nabla_\alpha R^{\alpha\beta} = -G^\alpha$$

energy-momentum & radiation

8 PDEs

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Maxwell

8 PDEs

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Maxwell

$$\nabla_\alpha \left(\rho_0 u^\alpha \right) = 0$$ → Baryon conservation → 1 PDE

Numerical relativity: equations

- Equations:

$$G_{\mu\nu} = 8\pi\,T_{\mu\nu}$$

$$\nabla_\alpha\left(T^{\alpha\beta} + R^{\alpha\beta}\right) = 0$$

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$$\nabla_\mu F^{\mu\nu} = -J^\nu$$

$$\nabla_\mu{}^* F^{\mu\nu} = 0$$

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

Need to solve a total of > 27 coupled non-linear PDEs in 3+1 dimensions!

Numerical relativity: unique challenges

- Black hole singularities → blow ups both in MHD and gravity sectors

- Coordinates: meaningless, only gauge invariant quantities are meaningful
  → extracting physics not trivial

Single BH accretion → jets!

- For ~15 years fixed-spacetime GRMHD accretion flows → jets

- What is the problem with BH-NS?

Single BH accretion → jets!

- For ~15 years fixed-spacetime GRMHD accretion flows → jets

- What is the problem with BH-NS?

- Fixed-spacetime GRMHD accretion does NOT always launch jets

BH-NS mergers → jets?

- **What is the problem?**

THE INFLUENCE OF MAGNETIC FIELD GEOMETRY ON THE EVOLUTION OF BLACK HOLE ACCRETION FLOWS: SIMILAR DISKS, DRASTICALLY DIFFERENT JETS

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- Initially toroidal B-fields (confined in the disk) → no jets
- Accretion of a net poloidal magnetic flux is essential to support of strong jets

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- Initially toroidal B-fields (confined in the disk) → no jets

- Accretion of a net poloidal magnetic flux is essential to support of strong jets

- The conclusions apply to B-fields initially confined in the disk

Paschalidis, CERN, December 6, 2016

BH-NS mergers → jets?

- How can we get a consistent, large scale, vertical field in a BH-NS merger, since the interior B-field inevitably becomes predominantly toroidal?

- What special initial B-field configuration prior to tidal disruption → jets?

BH-NS mergers → jets?

- How can we get a consistent, large scale, vertical field in a BH-NS merger, since the interior B-field inevitably becomes predominantly toroidal?

- What special initial B-field configuration prior to tidal disruption → jets?

- Recall: pulsars suggest that NSs are likely endowed with dipole B-fields extending from the stellar interior out to the exterior.

- Could an initial dipole field give rise to conditions that favor jet formation?

BH-NS mergers → jets?

- A common result of all mag. BHNS simulations until Fall 2014 (Etienne,Liu Paschalidis, Shapiro (2012), Etienne,Paschalidis, Shapiro (2013):
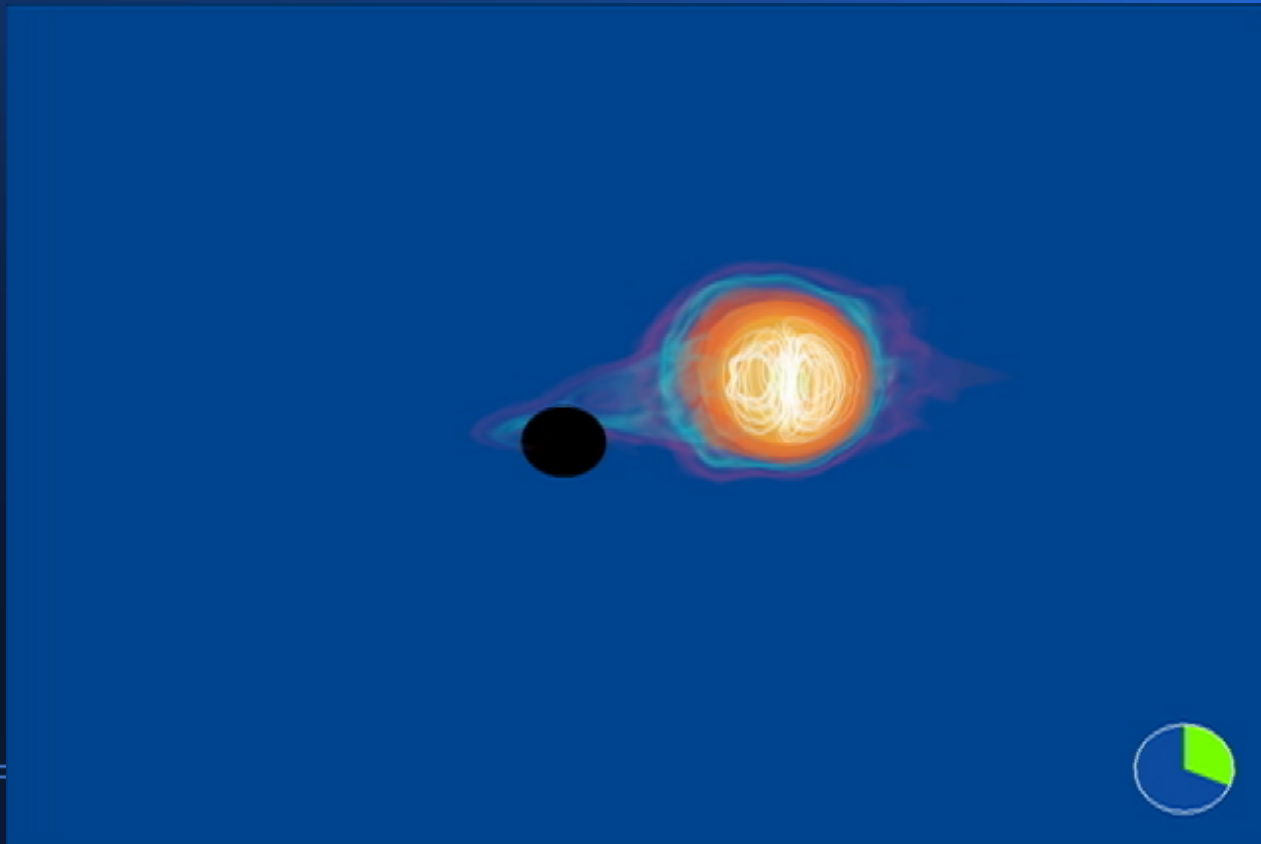
BH-NS mergers → No jets?

- Same outcome in recent very high resolution MHD simulations in full general relativity by Kiuchi et al 2015

BH–NS → no jets!!!!!????????

Paschalidis, CERN, December 6, 2016
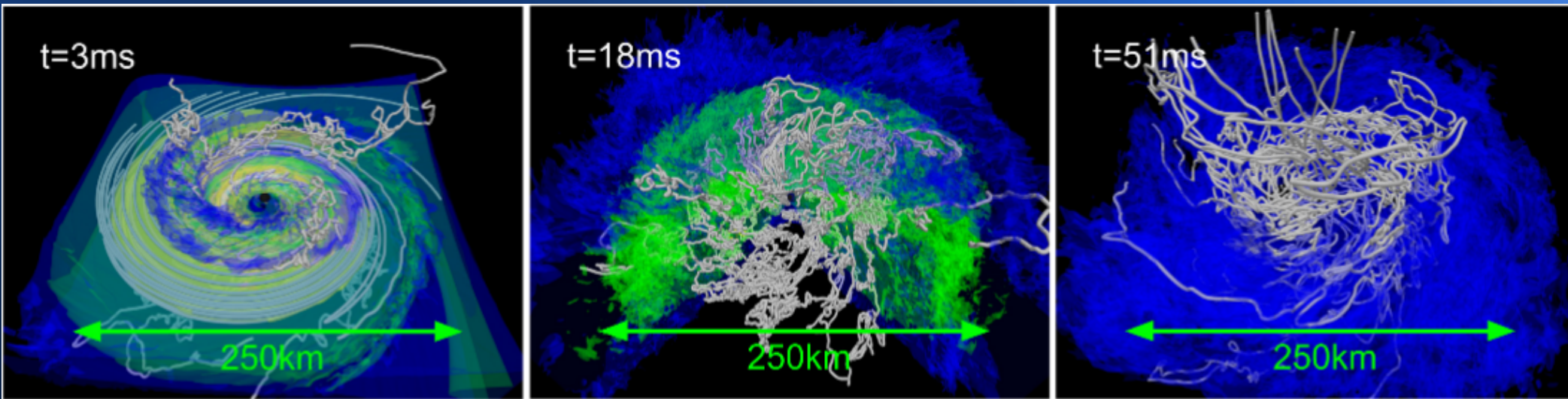
# BH-NS mergers → jets?

- Seed interior+exterior B-field

- <u>Problem:</u> How to evolve exterior force-free (B-field energy density dominated) with ideal MHD code?

- <u>Solution:</u> Mimic force-free exterior at t=0, by considering B-field pressure dominated
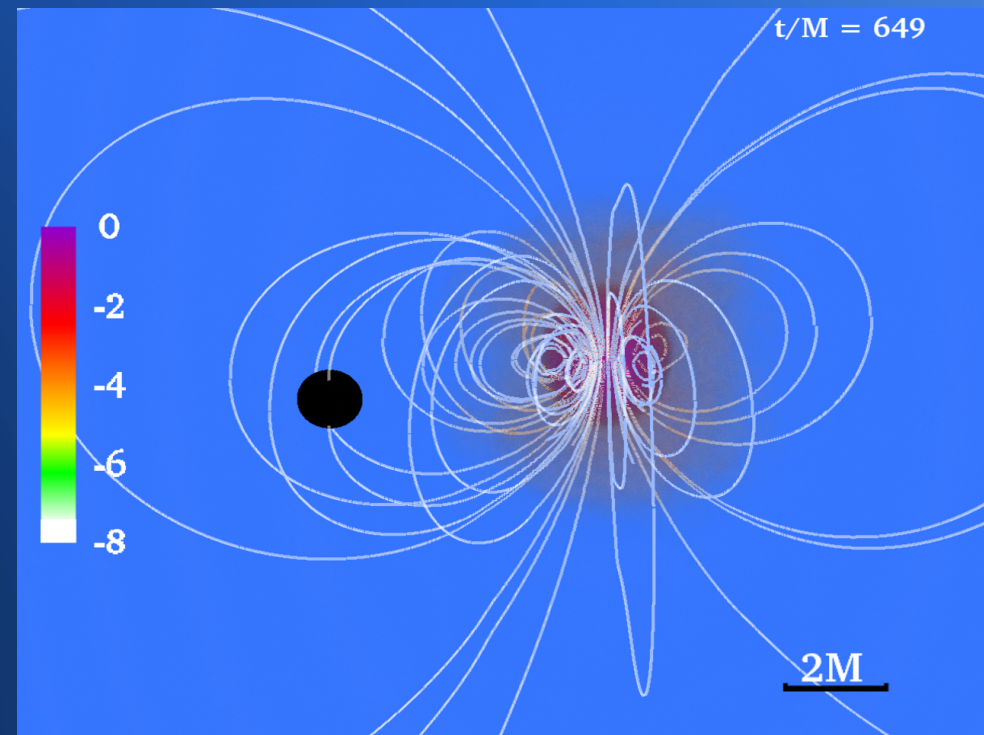
BH-NS mergers → jets?

- Perform simulations with a NS initially endowed with a dynamically weak dipolar magnetic field $P_{gas}/P_{mag} \geqslant 20$ (VP et al 2014)

- Metric and fluid initial data: q=3:1; a/M=0.75; n=1 polytropic NS
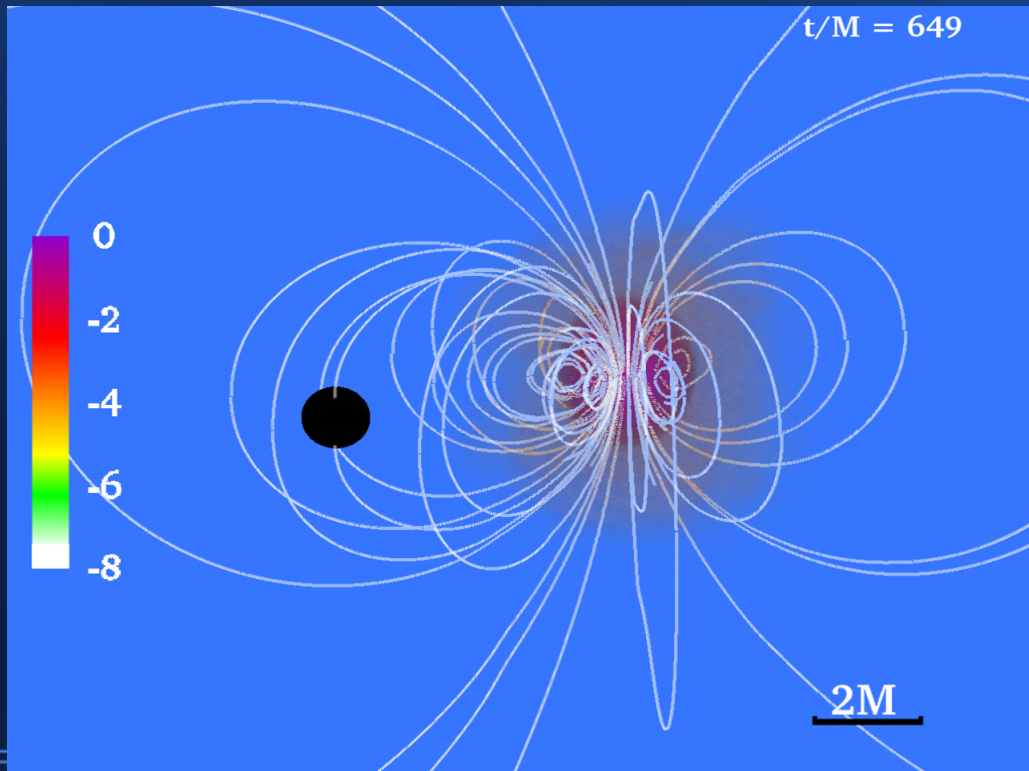
NS: expected to have a low-density force-free (B-energy-density-dominated) exterior magnetosphere.

Set initial exterior atmospheric rest-mass density such that

$$\beta = \frac{P_{gas}}{P_{mag}} = 0.1, 0.05, 0.01$$