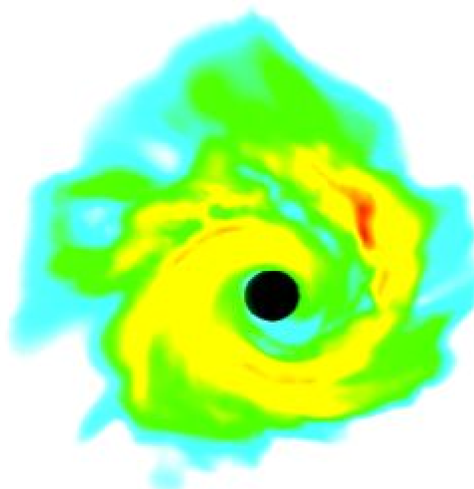
Title: Unsolved Problems in Modelin Neutron Star-Neutron Star and Black Hole Neutron Star Binary Mergers

Date: Jun 23, 2011 09:00 AM

URL: http://pirsa.org/11060031

Abstract: Black hole-neutron star (BHNS) binary mergers areimportant gravitational wave sources and (possibly) gamma ray burst progenitors. Fully relativisticsimulations have only recently begun to try to capture neutron star physics beyond the polytrope approximation. In this talk we discuss the numerical challenges of replacing polytropes with realistic neutron stars--particularly those relating to sharper neutron star surface features and to the effects of neutrino radiation--and we present the current status of simulations by the (Caltech-Cornell-CITA-WSU) SXS collaboration and how they are dealing with these issues.

Unsolved Problems in modeling neutron star-neutron star and black hole-neutron star binary mergers



By Matt Duez, WSU
A member of the CCCW SXS collaboration

MICRA 2011

This Talk

- review of the phenomenon
- Problem 1: accurate inspirals

  + the neutron star surface
- Problem 2: BHNS parameter space

  uncharted territory
- Problem 3: Neutrino transport

  leakage and beyond
- Problem 4: magnetic field issues

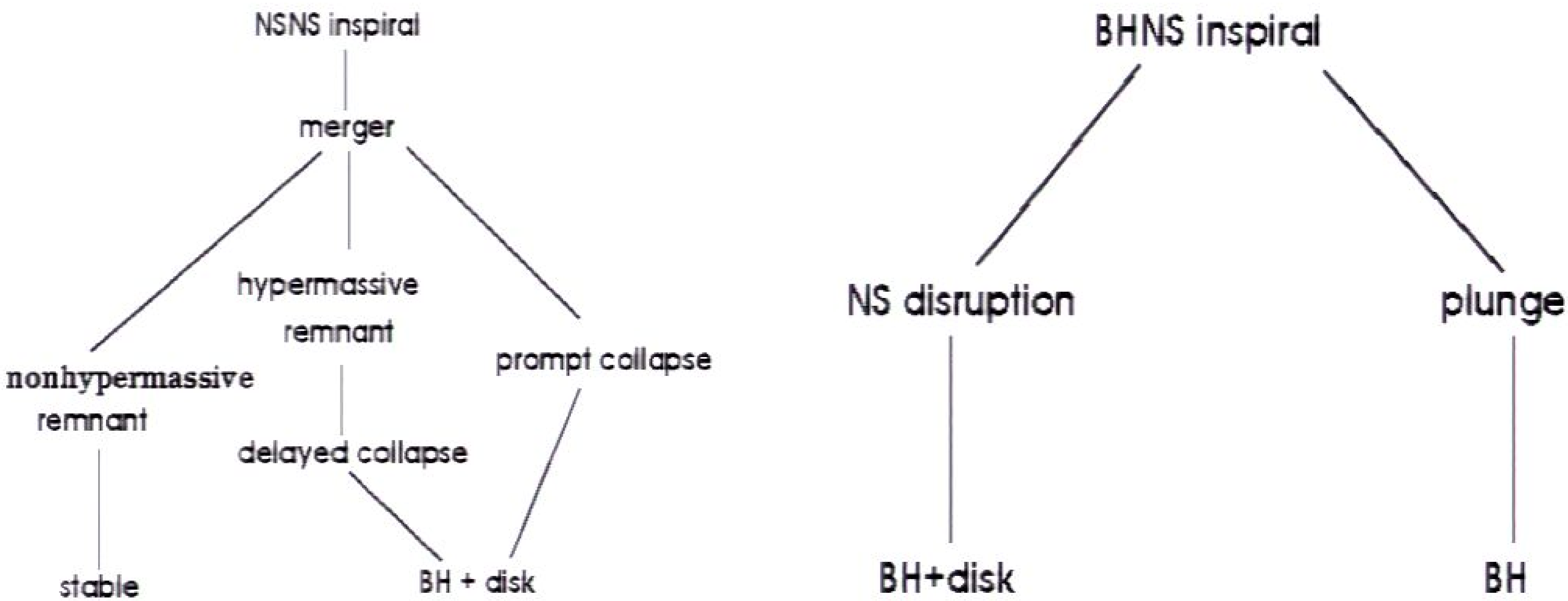
  magnetospheres, MRI turbulence

Throughout this talk, "*ea*" will mean "*et al*"

What we want to get out of simulations

- Gravitational waves
  - Need long inspirals, accurate bulk evolution, accurate metric evolution/wave extraction
- Test sGRB viability
  - Need to verify massive disk, baryon poor region
  - Need MHD and/or neutrino radiation for energy extraction
- Ejecta effects (r-process source, afterglow emission)
  - Need to track/characterize outflows with reasonable accuracy

Basic stages



Effects that don't seem to carry over from Newtonian sims. (for circ. orbit):

— unbounded ejecta

— core survival/multiple mass transfer events

Evolving the nuclear fluid

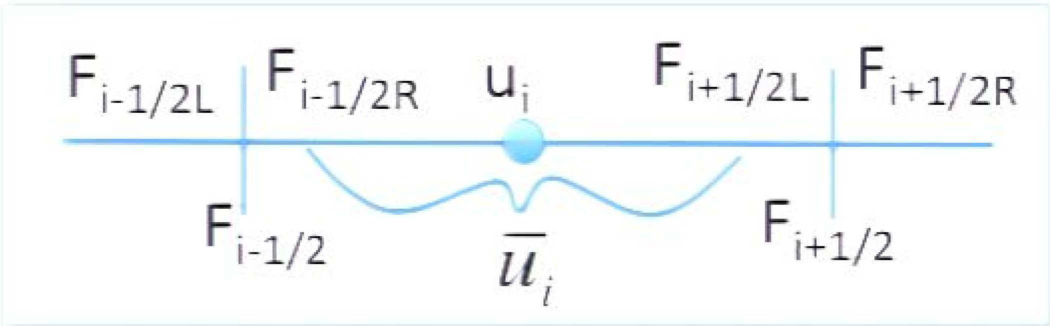
- Conservative form

$$\partial_t u = -\partial_x F + S, \qquad u = \rho, E, \vec{S}, \rho Y_e$$

$$\partial_t \overline{u} = [F_{i-1/2} - F_{i+1/2}]/\Delta x + \overline{S}$$

$$F_{i+1/2} = \Re(F_{i+1/2L}, F_{i+1/2R}, u_{i+1/2L}, u_{i+1/2R})$$

- Choices:
  - FD vs FV
  - Reconstruction($u_{R,L}$): how and what
  - Riemann Solver($\Re$)



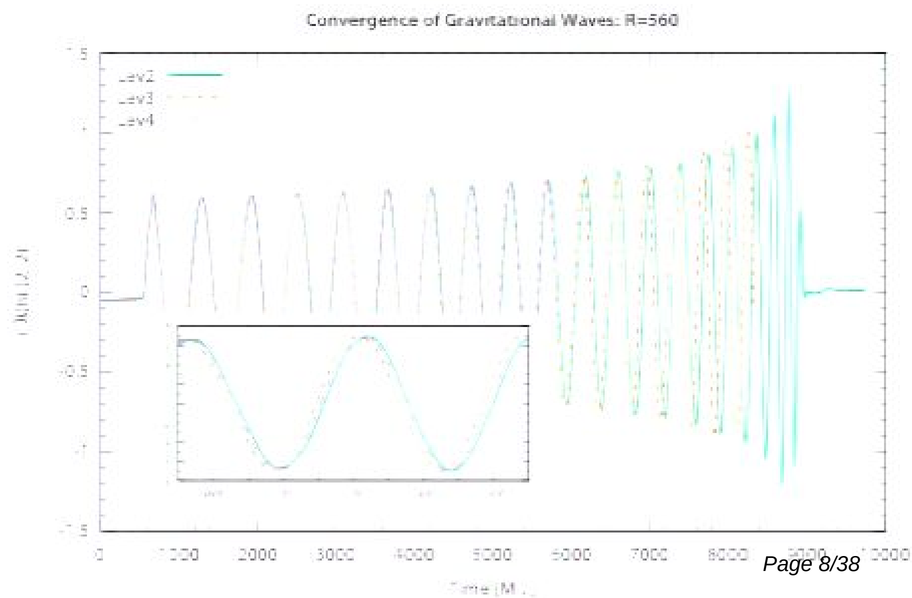
- Alternatives:
  - SPH, PS, DG

SpEC: the Spectral Einstein Code

- SpEC
  - http://www.black-holes.org/SpEC.html
  - Core written by Kidder, Scheel, Pfeiffer
  - Pseudospectral $g_{\mu\upsilon}$ evolution → extreme accuracy for smooth $g_{\mu\upsilon}$
  - Generalized harmonic formalism, BH excision, comoving coords.
  - Matter evolved on a separate FD/FV grid
  - BHNS binaries: see Duez, Foucart *ea* (08-11)
- New work: Neutron star-neutron star binaries (Kaplan)

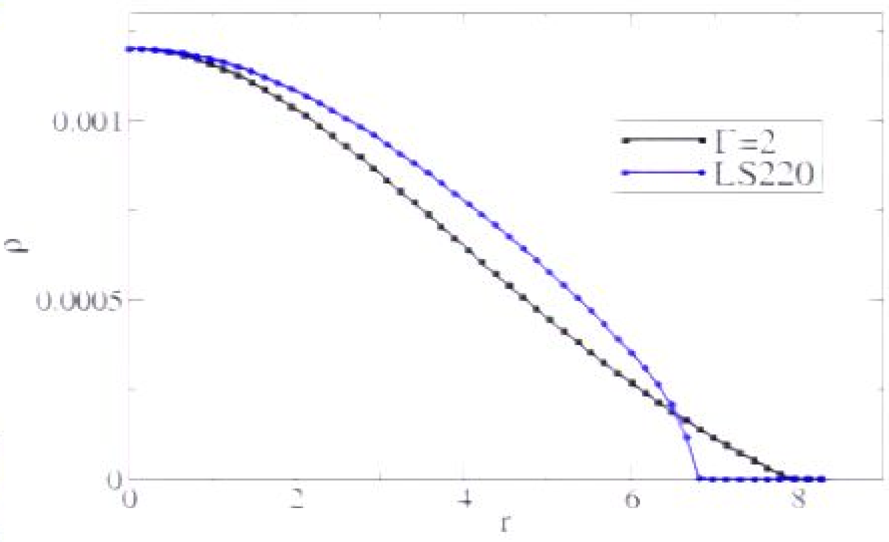
Problem 1: accurate inspirals

- Can EoS be constrained from inspiral?
  - BHNS: only stiffest EoS for AdvLIGO (Pannarale *ea* 11)
    yes if include merger (Lackey *ea*, Kyutoku *ea* 10)
  - NSNS: only stiff/low-M NS for early insp. (Hinderer *ea* 10)
    larger late inspiral tidal effects (Read *ea* 09)
- Longest inspirals to date
  - NSNS: Baiotti *ea* (10,11):
    10 orbits, ½-rad phase error
    EOB calibration
  - BHNS: Muhlberger *ea*:
    9 orbits



Neutron star surface errors

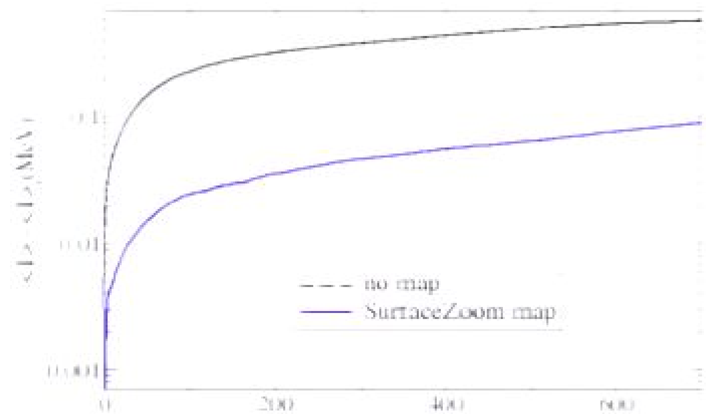
- Main source of hydro error for inspirals
- Drop to 1st order; $c_s \rightarrow 0$ shocks
- Problem worse for realistic NS
  - Nasty ρ(r) profile
  - Neutrino emission very sensitive to T
- Nonsmoothness in EoS tables destroys convergence of initial data (and, hence, of evolution)
  - We (or nuc. phys. people) need to smooth the tables



Improving the NS evolution

Steepness issue

- Solution: Concentrate grid near surface
- Surface tracking? Moving meshes?



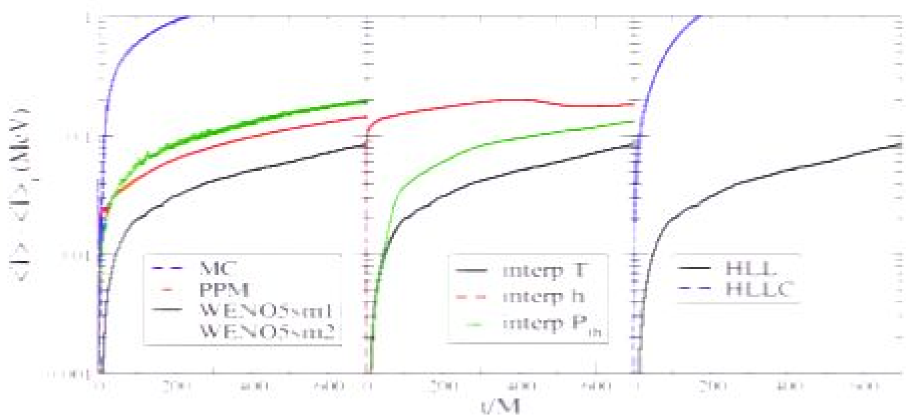
HRSC options

- Have some effect

Actual discontinuity

- Subcell modeling?

  Anti-diffusive fluxes? Ghost fluid?

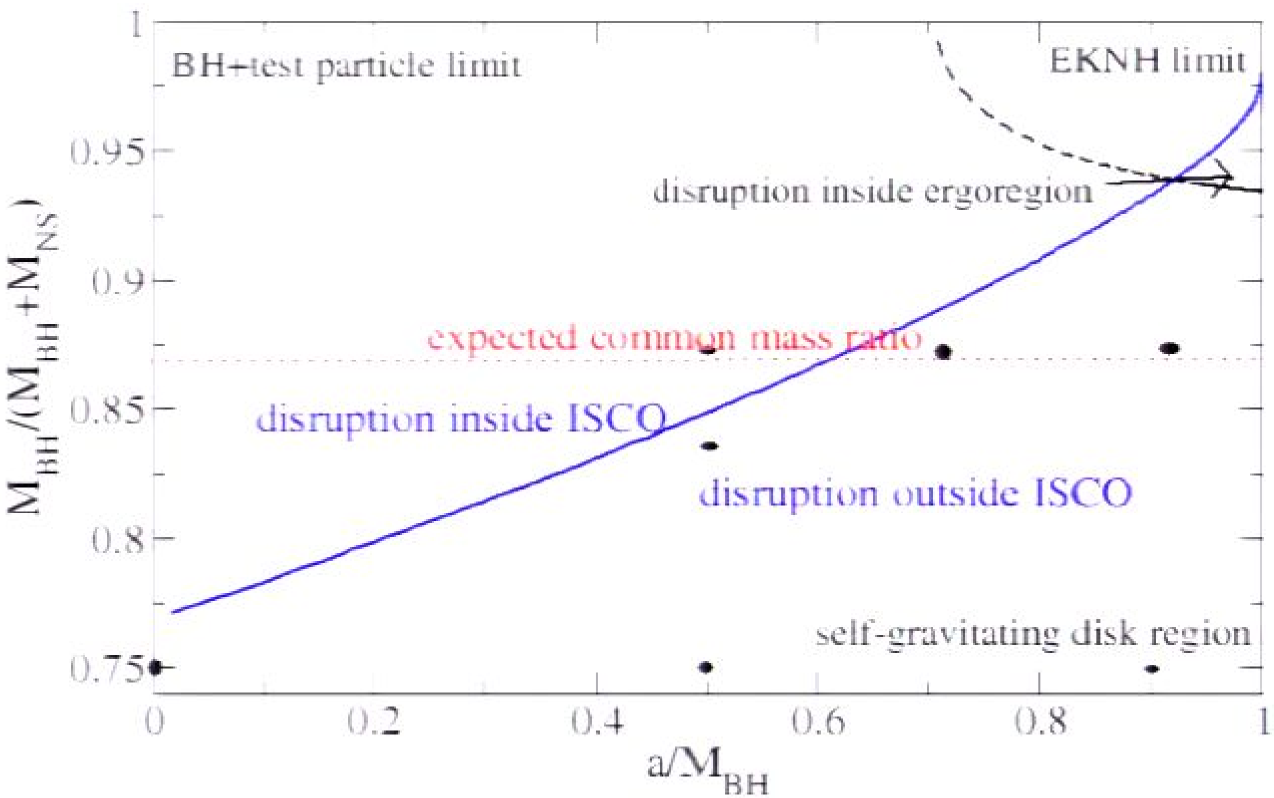


Other numerical techniques/grids may do better

- Multipatch HRSC (Zink *ea* 08)
- Discontinuous Galerkin (Radice & Rezzolla 11)—see talk

Problem 2: BHNS parameter space

- Define $q=M_{BH}/M_{NS}$, $s=|S_{BH}|/M_{BH}^2$
- Parameters: q, R_{NS}, $\mathbf{S}_{BH}$ (s & misalignment), e (clusters)

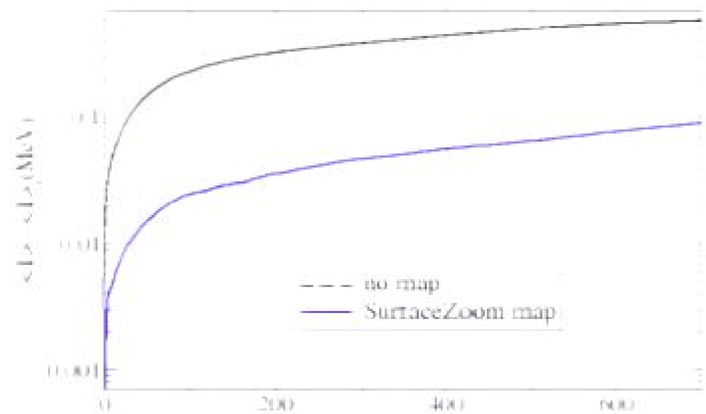


q vs. s space
for aligned BH,
~14km NS

Improving the NS evolution

Steepness issue

- Solution: Concentrate grid near surface
- Surface tracking? Moving meshes?

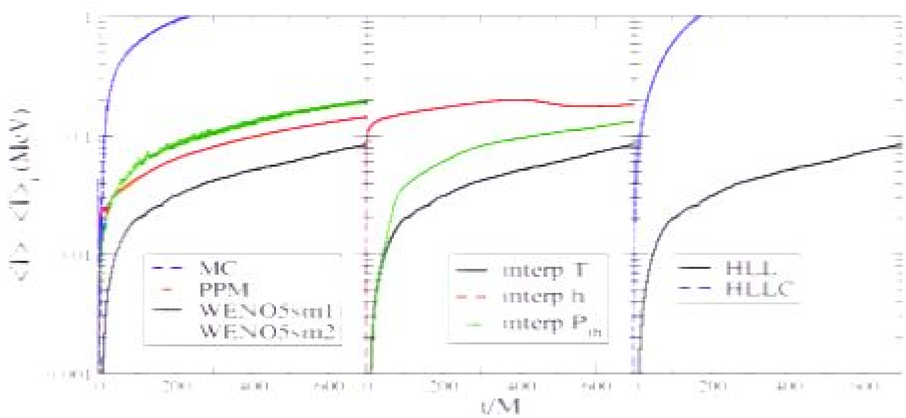


HRSC options

- Have some effect

Actual discontinuity

- Subcell modeling?
  Anti-diffusive fluxes? Ghost fluid?

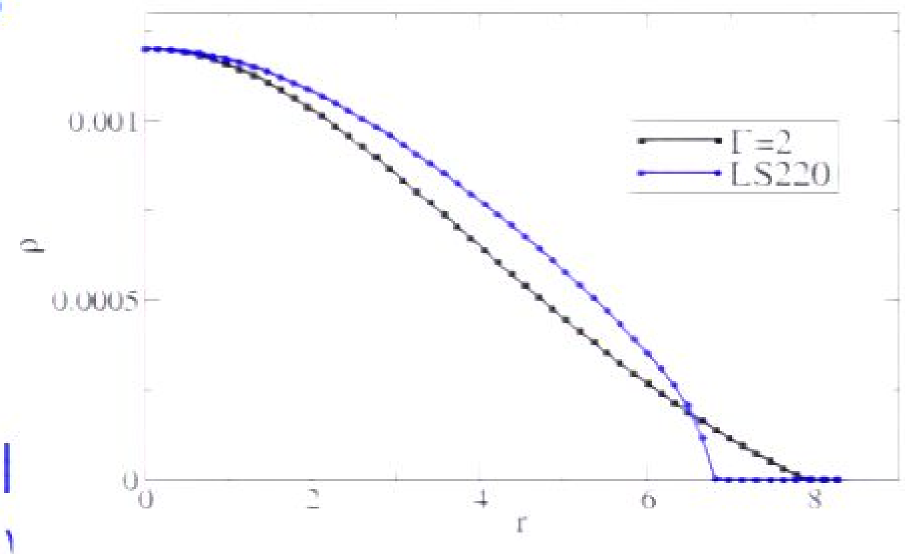


Other numerical techniques/grids may do better

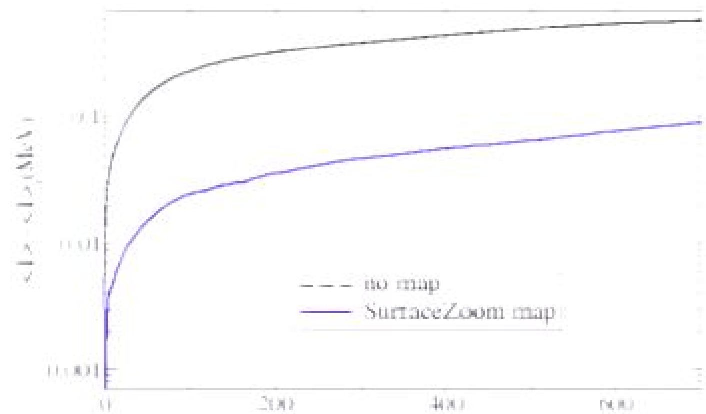
- Multipatch HRSC (Zink *ea* 08)
- Discontinuous Galerkin
  (Radice & Rezzolla 11)—see talk

Neutron star surface errors

- Main source of hydro error for inspirals
- Drop to 1st order; $c_s \rightarrow 0$ shocks
- Problem worse for realistic NS
  - Nasty $\rho(r)$ profile
  - Neutrino emission very sensitive to T
- Nonsmoothness in EoS tables destroys convergence of initial data (and, hence, of evolution)
  - We (or nuc. phys. people) need to smooth the tables



Improving the NS evolution



Steepness issue

- Solution: Concentrate grid near surface
- Surface tracking? Moving meshes?

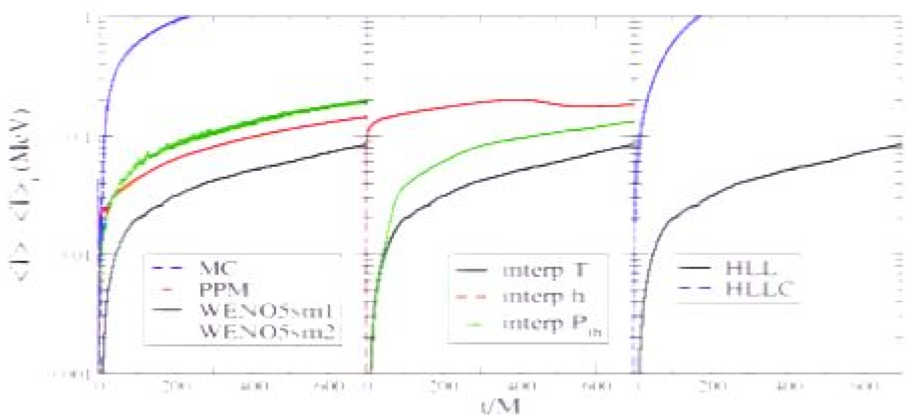
HRSC options

- Have some effect

Actual discontinuity

- Subcell modeling?

  Anti-diffusive fluxes? Ghost fluid?

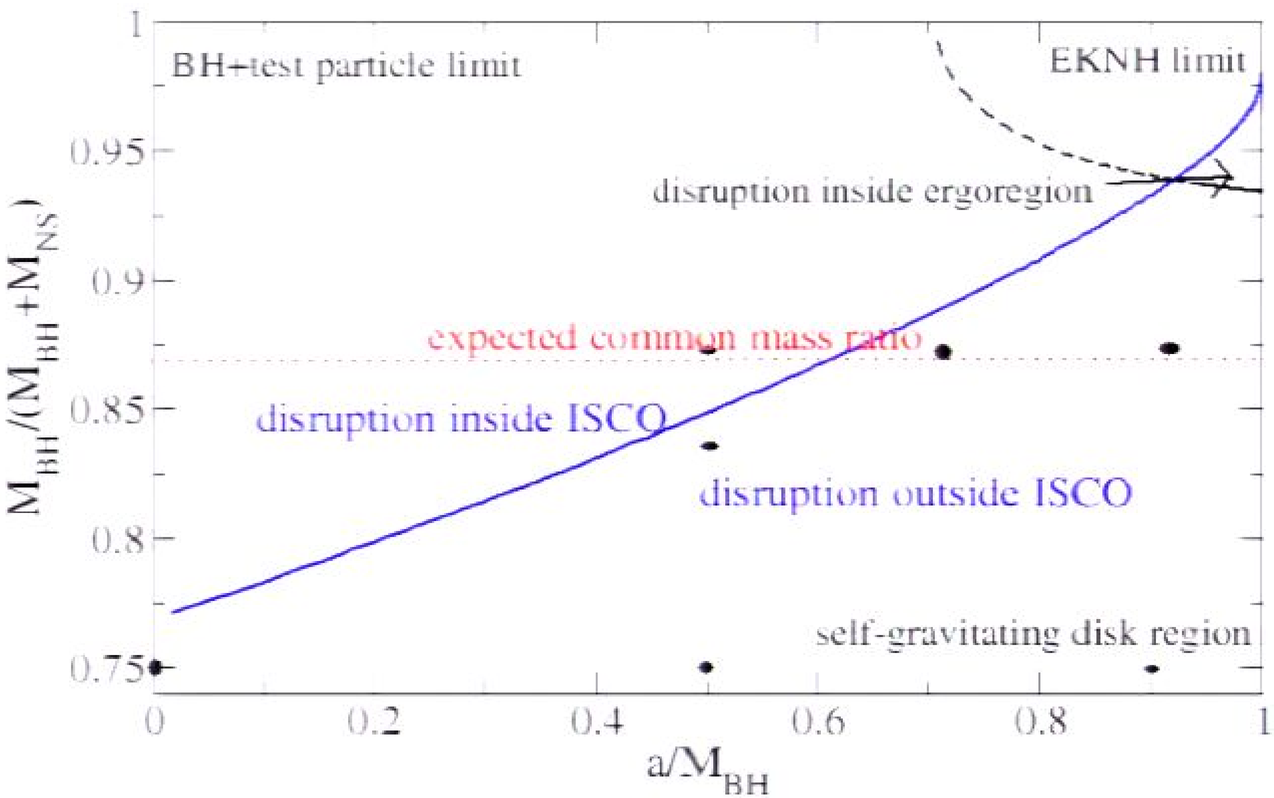


Other numerical techniques/grids may do better

- Multipatch HRSC (Zink *ea* 08)
- Discontinuous Galerkin (Radice & Rezzolla 11)—see talk

Problem 2: BHNS parameter space

- Define $q=M_{BH}/M_{NS}$, $s=|S_{BH}|/M_{BH}^2$
- Parameters: q, R_{NS}, $\mathbf{S}_{BH}$ (s & misalignment), e (clusters)

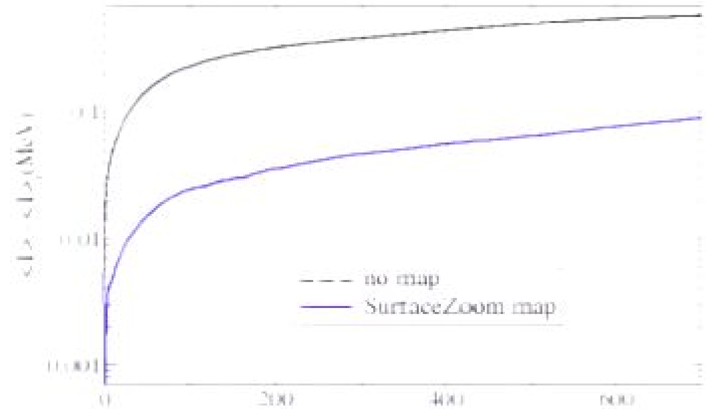


q vs. s space for aligned BH, ~14km NS

Improving the NS evolution

Steepness issue

- Solution: Concentrate grid near surface
- Surface tracking? Moving meshes?



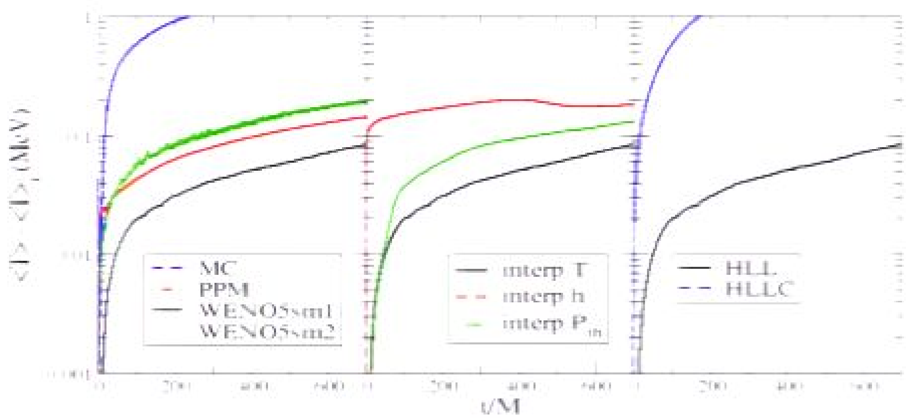
HRSC options

- Have some effect

Actual discontinuity

- Subcell modeling?

  Anti-diffusive fluxes? Ghost fluid?

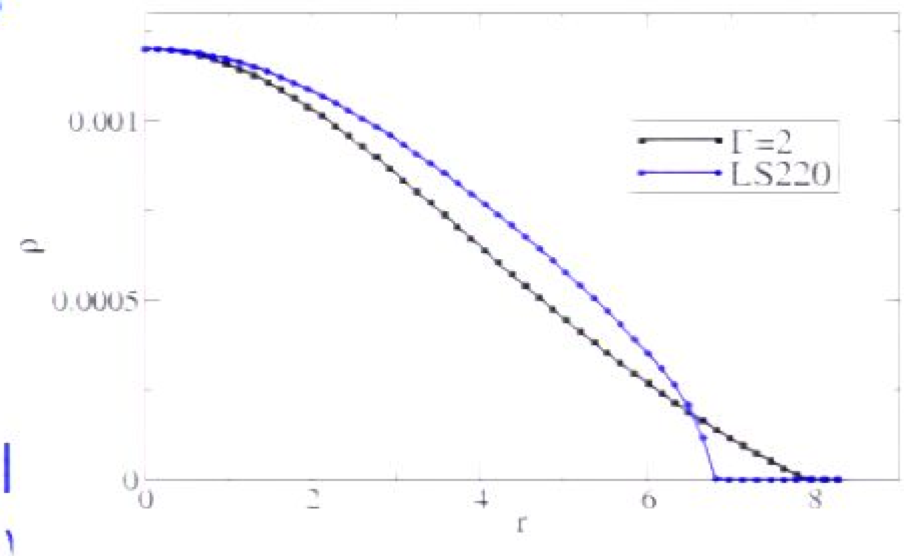


Other numerical techniques/grids may do better

- Multipatch HRSC (Zink *ea* 08)
- Discontinuous Galerkin (Radice & Rezzolla 11)—see talk

Neutron star surface errors

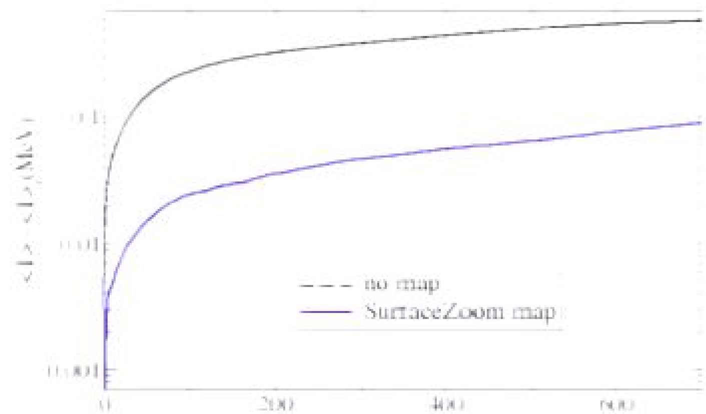
- Main source of hydro error for inspirals
- Drop to 1st order; $c_s \rightarrow 0$ shocks
- Problem worse for realistic NS
  - Nasty ρ(r) profile
  - Neutrino emission very sensitive to T
- Nonsmoothness in EoS tables destroys convergence of initial data (and, hence, of evolution)
  - We (or nuc. phys. people) need to smooth the tables



Improving the NS evolution

Steepness issue

- Solution: Concentrate grid near surface
- Surface tracking? Moving meshes?



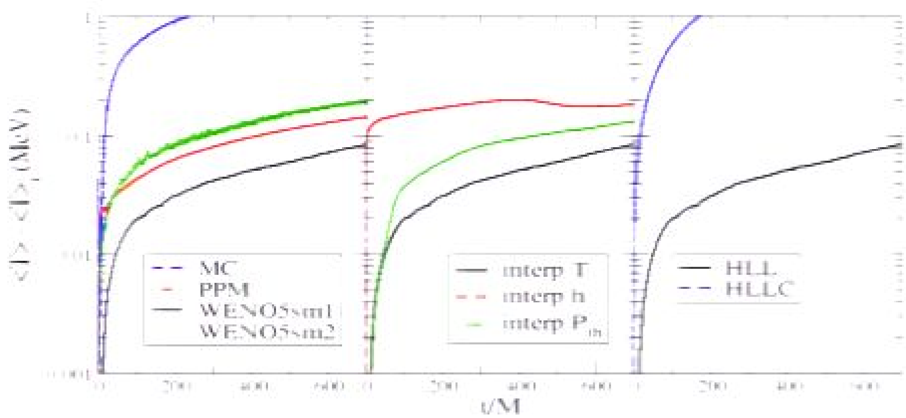
HRSC options

- Have some effect

Actual discontinuity

- Subcell modeling?

  Anti-diffusive fluxes? Ghost fluid?

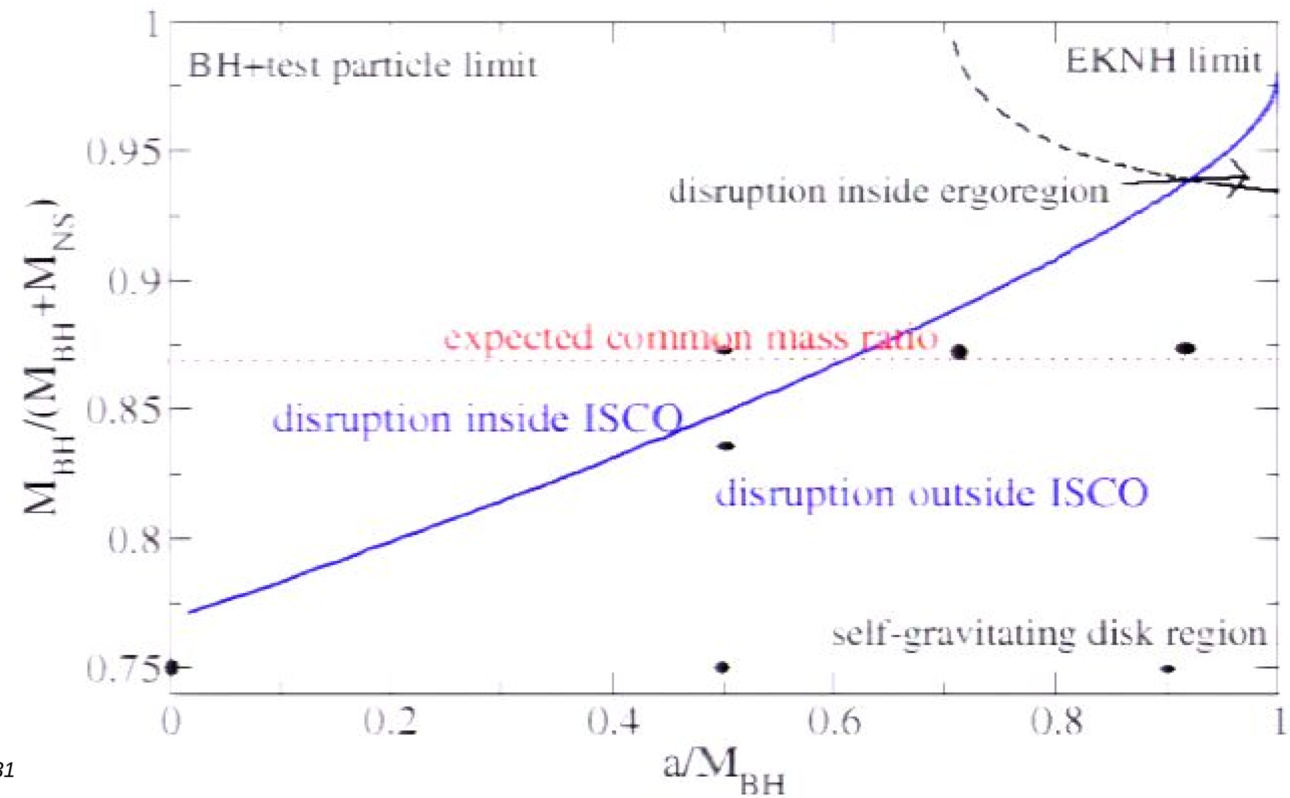


Other numerical techniques/grids may do better

- Multipatch HRSC (Zink *ea* 08)
- Discontinuous Galerkin (Radice & Rezzolla 11)—see talk

Problem 2: BHNS parameter space

- Define $q=M_{BH}/M_{NS}$, $s=|S_{BH}|/M_{BH}^2$
- Parameters: q, R_{NS}, $\mathbf{S}_{BH}$ (s & misalignment), e (clusters)

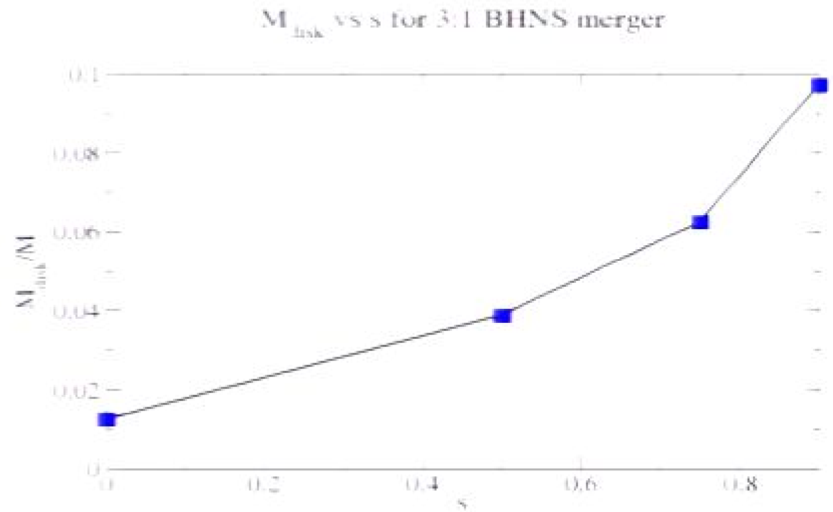


q vs. s space for aligned BH, ~14km NS

Low-q, high-s region

- For q=3, high s,

  can get very massive disks



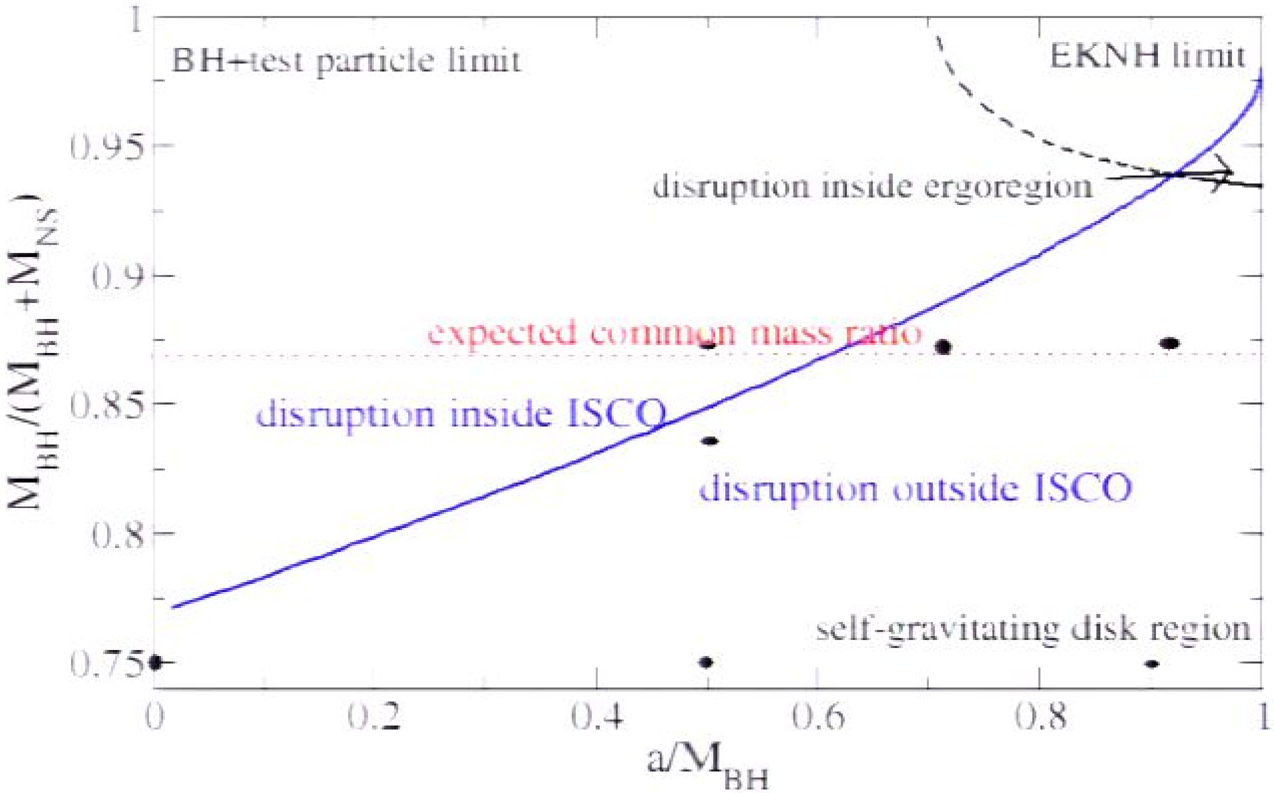
- Disk self-gravity effects
  - Runaway instability—doesn't happen (Montero *ea* 10)
  - Spirals/clumping/fragmentation—not seen
  - Papaloizou-Pringle instability (m=1)

    Korobkin *ea* (11), Kiuchi *ea* (11)

    → disk & BH wobble → strong GW signal

Problem 2: BHNS parameter space

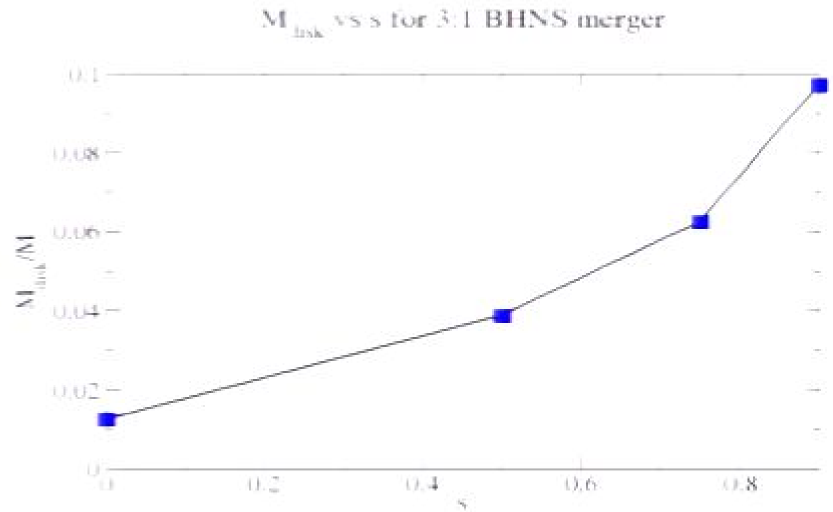
- Define $q = M_{BH}/M_{NS}$, $s = |S_{BH}|/M_{BH}^2$
- Parameters: q, R_{NS}, $\mathbf{S}_{BH}$ (s & misalignment), e (clusters)



q vs. s space for aligned BH, ~14km NS

Low-q, high-s region

- For q=3, high s,
  can get very massive disks

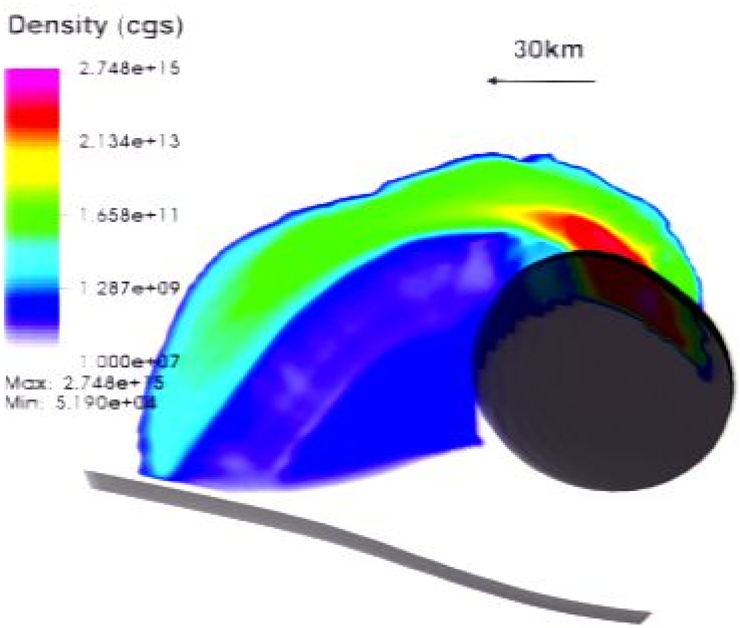


- Disk self-gravity effects
  - Runaway instability—doesn't happen (Montero *ea* 10)
  - Spirals/clumping/fragmentation—not seen
  - Papaloizou-Pringle instability (m=1)
    Korobkin *ea* (11), Kiuchi *ea* (11)
    → disk & BH wobble → strong GW signal

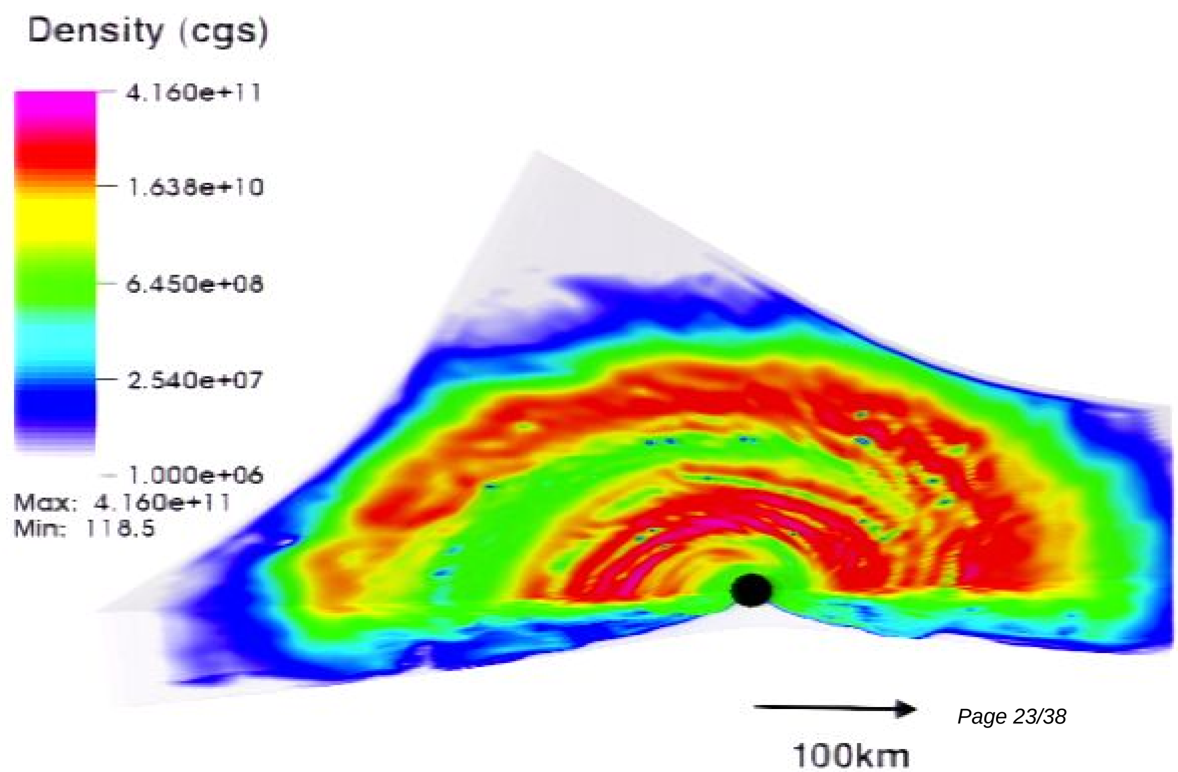
Realistic-q, high-s region

- SXS effort led by Foucart (see his poster)
- Studying q=5,7
- Massive, extended disk for q=7 if s≥0.7, C=0.14

q=7, s=0.5

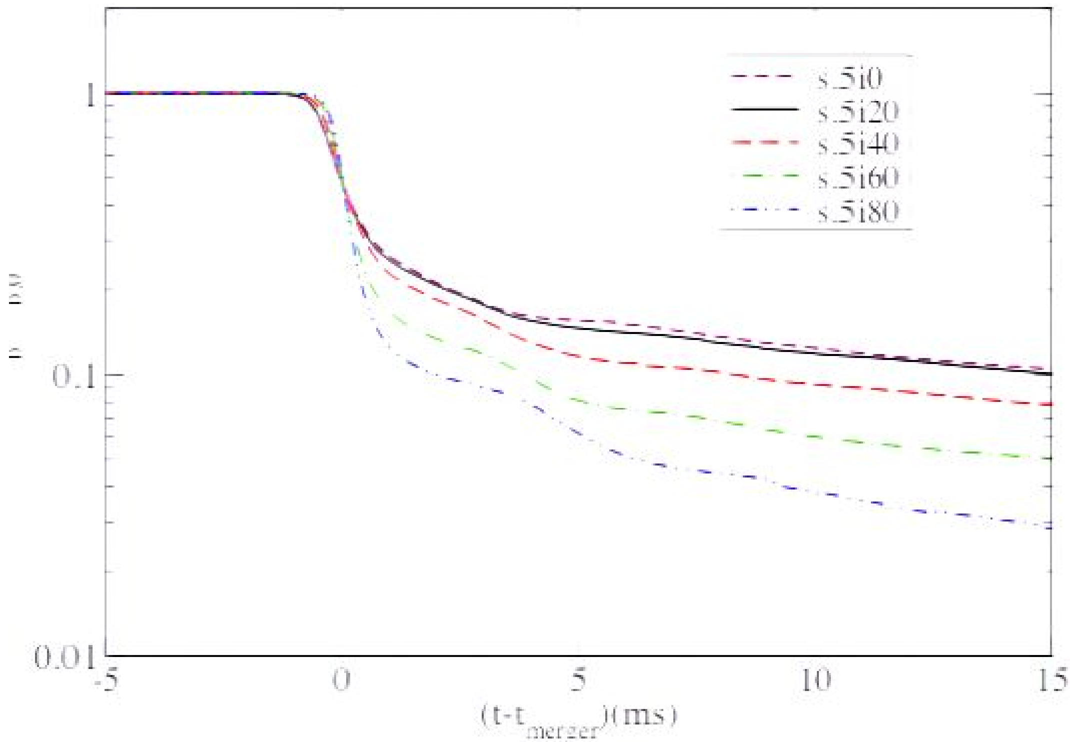


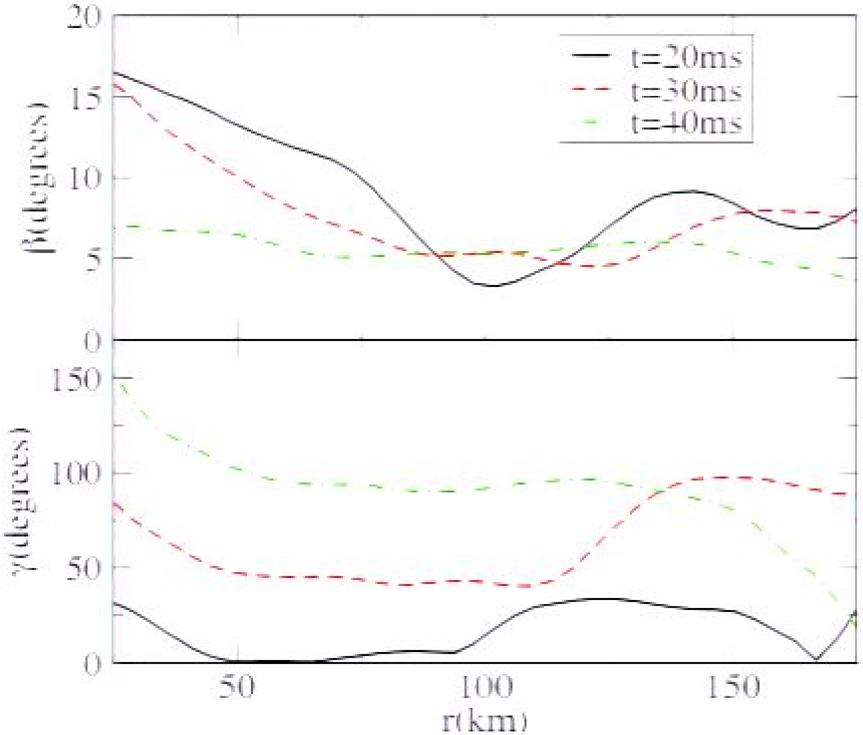
q=7, s=0.7



Misaligned $\mathbf{S}_{BH}$

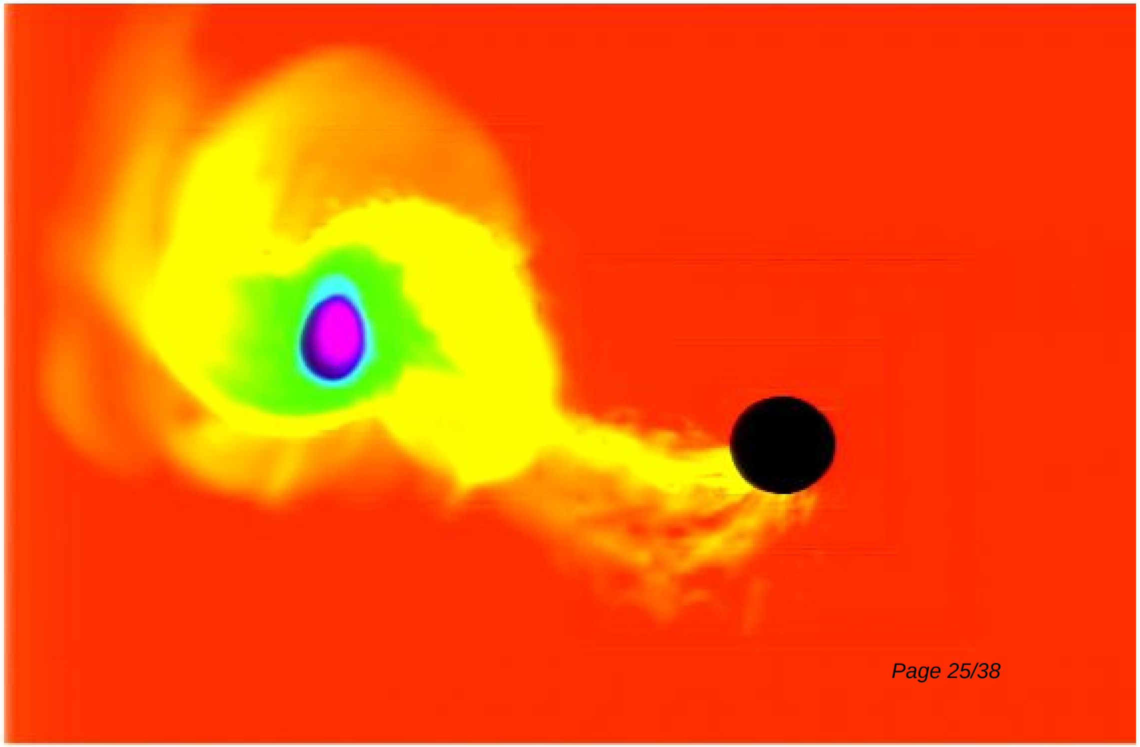
- Foucart *ea* (11)
- Modestly reduced-mass, tilted disks





Eccentricity

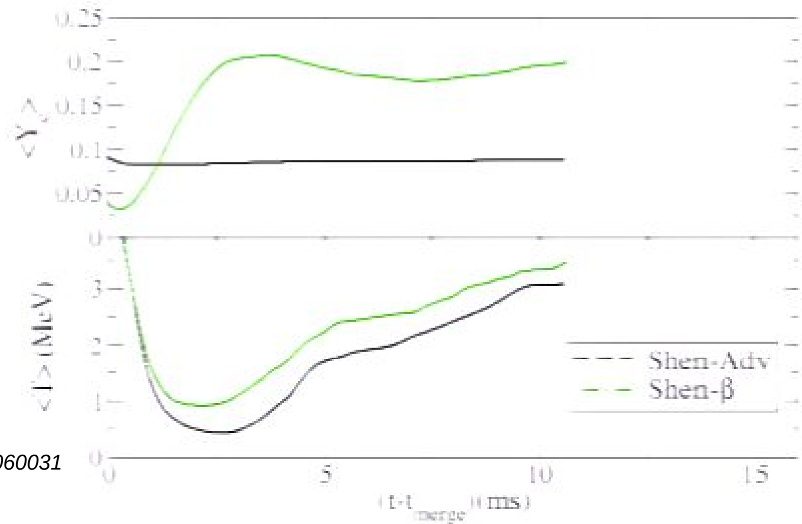
- NSNS/BHNS collisions in clusters may contribute significantly to sGRB rate (Lee *ea* 10)
- Sims: Newtonian: Lee *ea* 10; GR: Stephens *ea* 11
- Features:
  - Large M_{disk} even for a=0
  - Unbounded ejecta
  - Core survival
  - zoom-whirl behavior



from Stephens *ea* 11

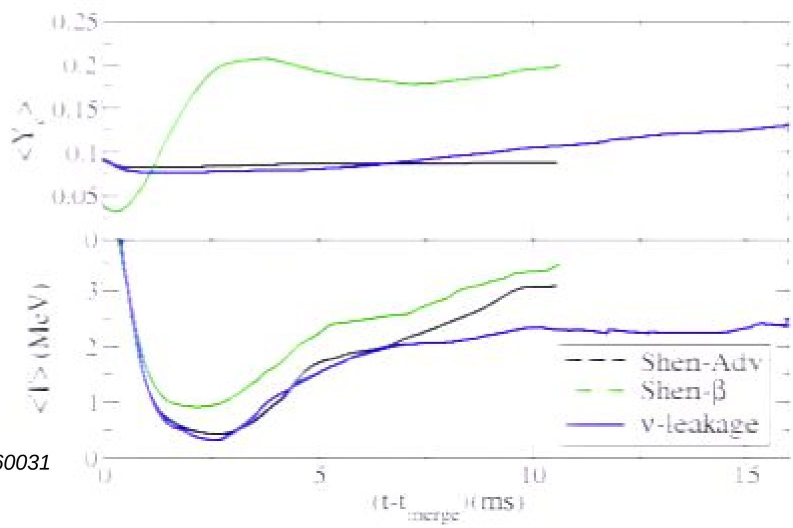
Problem 3: neutrino transport

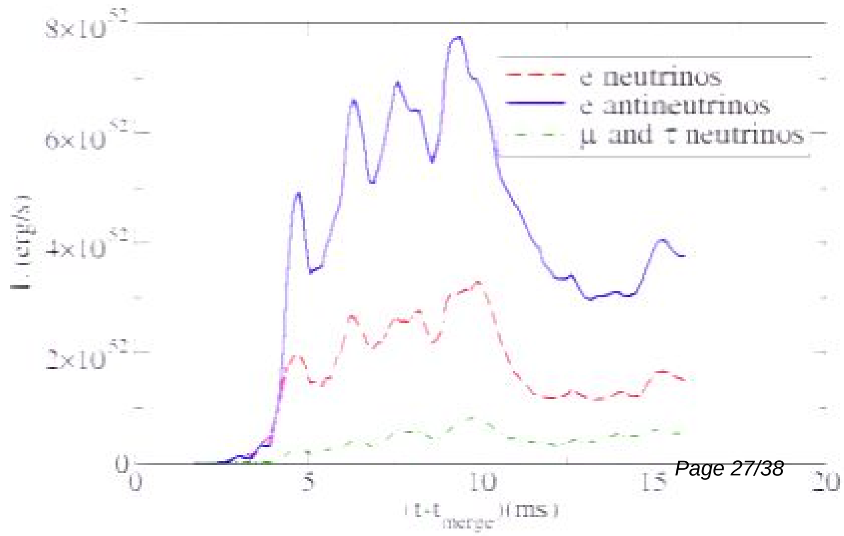
- Neutrinos
  - Cool/heat gas (→wind?)
  - Changes Y_e (→convection?)
  - Radiation pressure
  - $\nu\bar{\nu}$ annihilation energy
- Last year at MICRA 2010
  - My q=3, s=0.5 BHNS merger with Shen EoS
  - Y_e=advected or assumed μ_ν=0 β-equilibrium



Problem 3: neutrino transport

- Neutrinos
  - Cool/heat gas (→wind?)
  - Changes Y_e (→convection?)
  - Radiation pressure
  - $\nu\bar{\nu}$ annihilation energy
- This year at MICRA 2011
  - My q=3, s=0.5 BHNS merger with Shen EoS
  - Y_e from neutrino leakage evolution





Getting our feet wet: Neutrino leakage

- Cooling & leptonization, no heating or transport
- GR: O'Connor and Ott (10), Sekiguchi (10)

$$\text{In rest frame, } \frac{dE}{dt} = -Q, \qquad \frac{dn_e}{dt} = -R$$

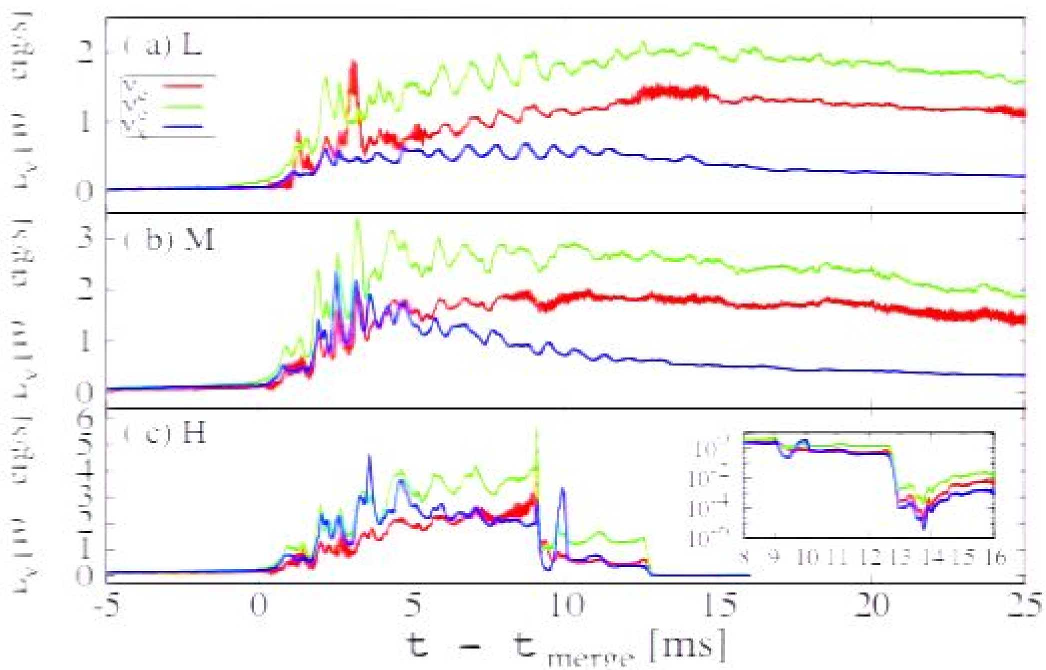
$$\rightarrow \nabla \cdot \vec{T}_{\text{fluid}} = -Q\vec{u}, \qquad \nabla \cdot (nY_e\vec{u}) = -R$$

$$R = \begin{cases} R_{\text{local}} & \text{for } \tau_\nu \ll 1 \\ n_\nu / T_\nu^{\text{diff}} & \text{for } \tau_\nu \gg 1 \quad (T_\nu^{\text{diff}} \sim \lambda_\nu \tau_\nu^2 / c) \end{cases}$$

$$\text{Must estimate } \tau_\nu = \min \int dl / \lambda_\nu$$

Neutrinos from NSNS merger

- Sekiguchi *ea* (11)



from Sekiguchi 11

- Antineutrino dominated
- Detectable out to 10Mpc
- Cooling driven HMNS collapse for low M?

Next steps

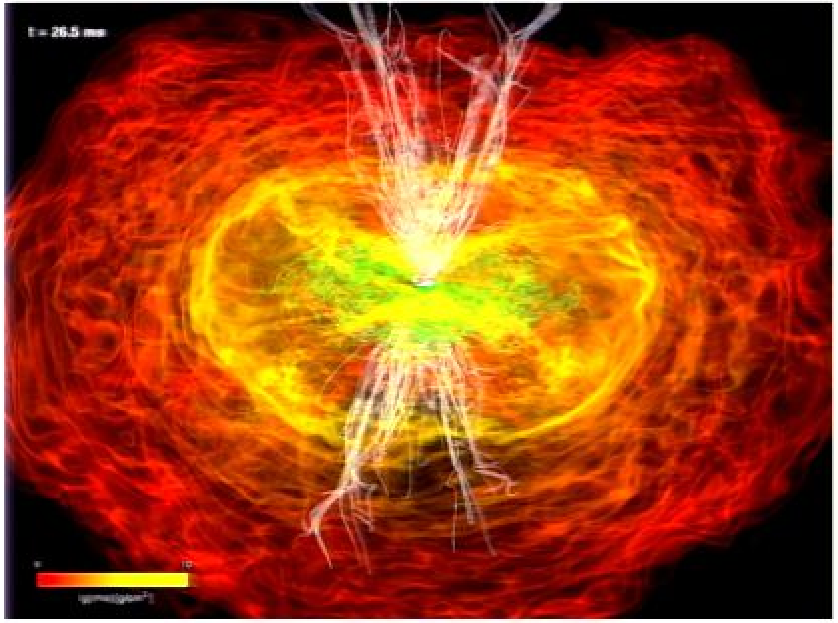
- Grey diffusion
  - Farris *ea* (08)
- Truncated moment transport
  - Shibata *ea* (11)
- Monte Carlo 6D transport
  - Abdikamalov *ea*

- Questions:
  - What do we need to avoid missing any qualitative effect?
  - What can we afford?

Problem 4: MHD issues

- Important progress:
  - BHNS merger with MHD (Chawla *ea* 10)
  - Magnetic winding → EM signal from HMNS (Shibata *ea* 11)
  - The "missing link" (Rezzolla *ea* 11): NSNS→sGRB

  B amplification to 10^{15}G in axial jet, unbounded outflow



from Rezzolla *ea* (11)

Magnetospheres

- $B^2/\rho >> 1 \quad \Rightarrow \quad$ force-free limit
  $\rho_c \mathbf{E} + \mathbf{J}_c \times \mathbf{B} = 0$
- Important for
  - Blandford-Znajek effect
  - NSNS magnetospheres interaction
    →sGRB presignal? (Hansen & Lyutikov 01)
- Standard MHD codes fail in this regime
- Solution: evolve force-free equations
  - Palenzuela *al* (10,11) FF code applied to binary BH, BZ effect
  - New: coupled to MHD code inside NS

Trouble ahead: the MRI

- $$\lambda_{\rm MRI} \sim v_A/\Omega = \frac{P_{\rm orb} B}{2\pi\sqrt{4\pi\rho}}$$

  disk: $P_{\rm orb} \sim 10^{-2}\,{\rm s},\ \rho \sim 10^{11}\,{\rm g\ cm^{-3}},\ {\rm B} \sim 10^{13}\,{\rm G}$

  $$\Rightarrow \lambda_{\rm MRI} \sim 10^{4}\,{\rm cm}$$

  HMNS: $P_{\rm orb} \sim 10^{-3}\,{\rm s},\ \rho \sim 10^{14}\,{\rm g\ cm^{-3}},\ {\rm B} \sim 10^{13}\,{\rm G}$

  $$\Rightarrow \lambda_{\rm MRI} \sim 10^{2}\,{\rm cm} \sim 10^{-4} R!$$

- I don't see how AMR helps.
- Solutions:
  - Crank up **B** (c.f. Duez *ea* 06)
  - Local MRI subgrid model calibrated to shearing box sims

    Kato & Yoshhizowa (95), Ogilvie (03), Pessah *ea* (06)

    test local vs global sims: Sorathia *ea* (10,11)

Magnetospheres

- $B^2/\rho >> 1 \quad \Rightarrow \quad$ force-free limit

  $\rho_c \mathbf{E} + \mathbf{J}_c \times \mathbf{B} = 0$
- Important for
  - Blandford-Znajek effect
  - NSNS magnetospheres interaction

    →sGRB presignal? (Hansen & Lyutikov 01)
- Standard MHD codes fail in this regime
- Solution: evolve force-free equations
  - Palenzuela *al* (10,11) FF code applied to binary BH, BZ effect
  - New: coupled to MHD code inside NS

Trouble ahead: the MRI

- $$\lambda_{\rm MRI} \sim v_{\rm A}/\Omega = \frac{P_{\rm orb} B}{2\pi\sqrt{4\pi\rho}}$$

  disk: $P_{\rm orb} \sim 10^{-2}{\rm s},\ \ \rho \sim 10^{11}{\rm g\ cm^{-3}},\ \ {\rm B} \sim 10^{13}{\rm G}$

  $\Rightarrow \lambda_{\rm MRI} \sim 10^{4}{\rm cm}$

  HMNS: $P_{\rm orb} \sim 10^{-3}{\rm s},\ \ \rho \sim 10^{14}{\rm g\ cm^{-3}},\ \ {\rm B} \sim 10^{13}{\rm G}$

  $\Rightarrow \lambda_{\rm MRI} \sim 10^{2}{\rm cm} \sim 10^{-4} R!$

- I don’t see how AMR helps.
- Solutions:
  - Crank up **B** (c.f. Duez *ea* 06)
  - Local MRI subgrid model calibrated to shearing box sims

    Kato & Yoshhizowa (95), Ogilvie (03), Pessah *ea* (06)

    test local vs global sims: Sorathia *ea* (10,11)

Other fluid instability issues

- KH instability B-field amplification
  - Discrepancy between SPH & Whisky simulations
- Turbulence
  - How to identify/characterize it?
  - How well do we evolve it?
  - Is numerical dissipation/reconnection adequate?
- Radiation
  - L_ν might approach ν Eddington limit
  - How will radiation affect disk turbulence/inflow/jet?

Conclusions

- Lots of papers (esp. letters) this past year
- NSNS/BHNS a hot topic
- Challenges ahead
  - EoS tables
  - Hydro accuracy
  - Cases to study
  - Neutrino transport approximations
  - Multi-scale motion: instabilities and turbulence

Other fluid instability issues

- KH instability B-field amplification
  - Discrepancy between SPH & Whisky simulations
- Turbulence
  - How to identify/characterize it?
  - How well do we evolve it?
  - Is numerical dissipation/reconnection adequate?
- Radiation
  - L_ν might approach ν Eddington limit
  - How will radiation affect disk turbulence/inflow/jet?