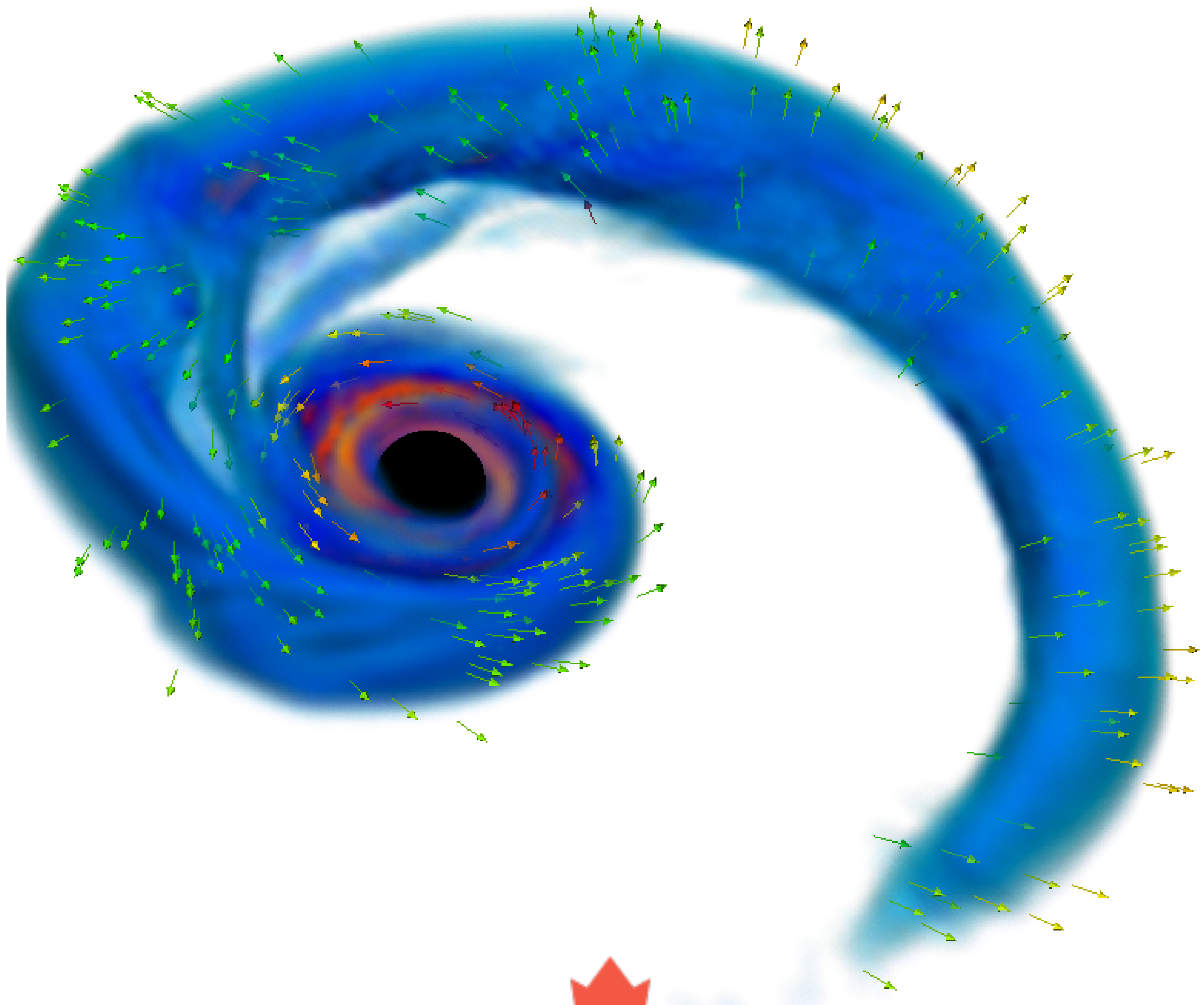
Neutron Star - Black Hole Mergers



Francois Foucart (CITA)

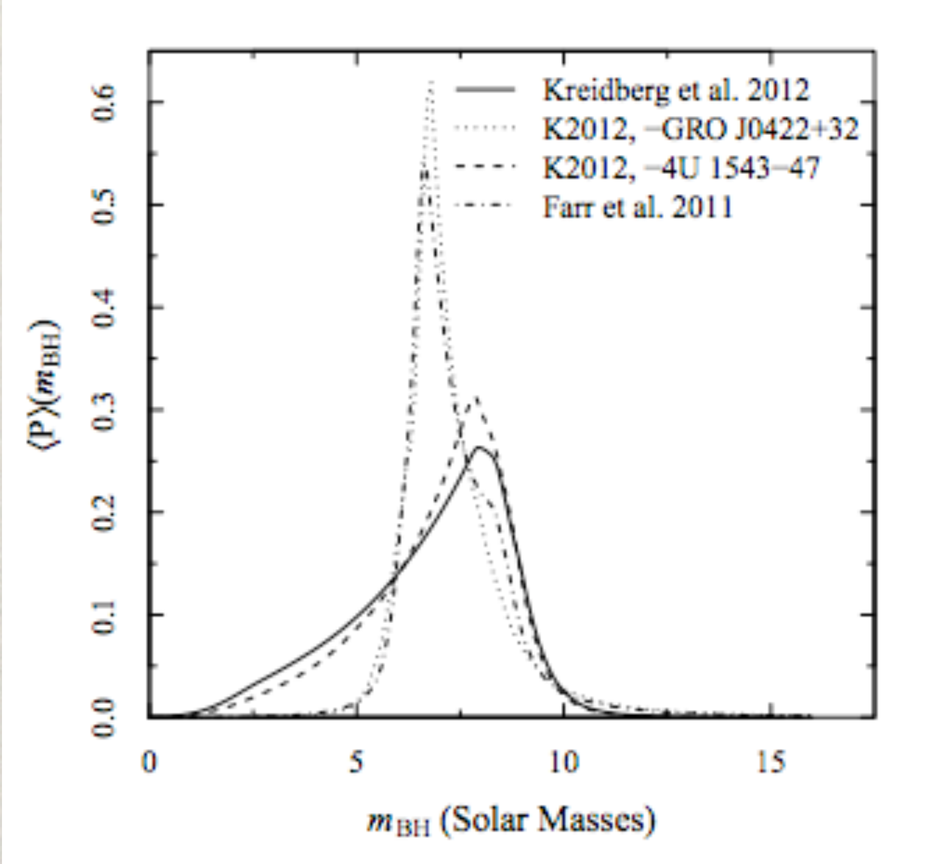
July 11th 2014

Outline

- Status of numerical simulations
  - Merger results from binary parameters
  - Post-Merger evolution
- SpEC Code
  - Overview
  - Neutrinos and B-fields - Future plans and current issues

Parameter Space

- Wider parameter space than NS-NS binaries
  - Arbitrary BH spin
  - M_{BH} ~ 5-10 M_{sun}?
  - Choice of equation of state
  - M_{NS} ~ 1-3 M_{sun}
  - Eccentricity? NS spin?
- ... but generally simpler mergers

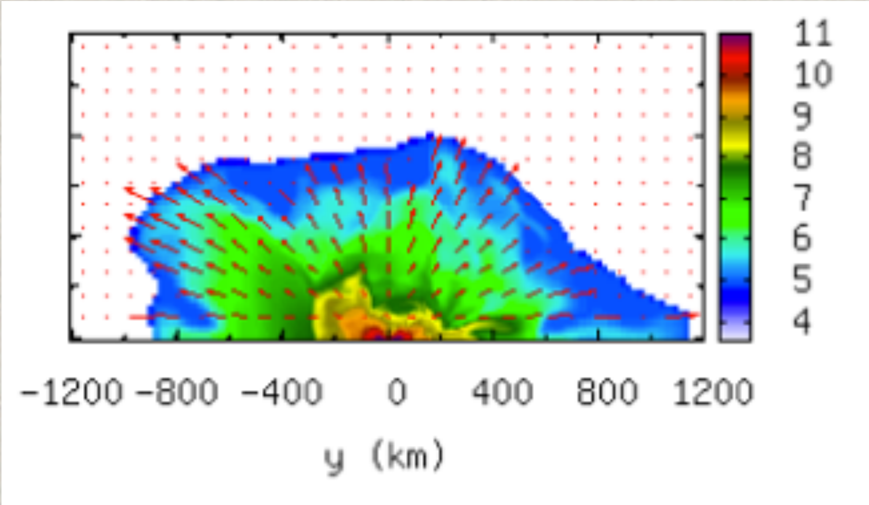


Kreidberg et. al 2012

NSNS vs NSBH

NS-NS

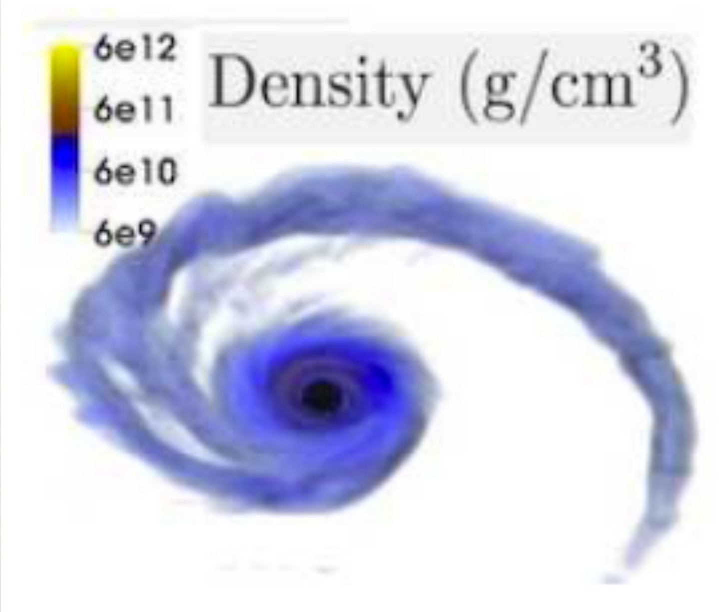
- Reliably produce disks & outflows
- Known to exist, probably more frequent
- Larger tidal effects on GW



Hotokezaka *et al* (2013)

NS-BH

- Cleaner environment
- Massive ejecta / disks
- Kelvin-Helmholtz less important?
- Observed farther away



Foucart *et al* (2014)

Existing GR-Hydro Simulations

Equation of State

- For GW / Disruption : Γ=2 ideal gas (SpEC, UIUC), piecewise polytropes (Kyoto)
- Finite temperature EoS: HShen, LS220 (SpEC)
- New EoS compatible with current nuclear theory / astrophysical constraints
    - FSU1, SFHo - available, but not used yet
    - Hebeler *et al.* 2013 (cold equilibrium)

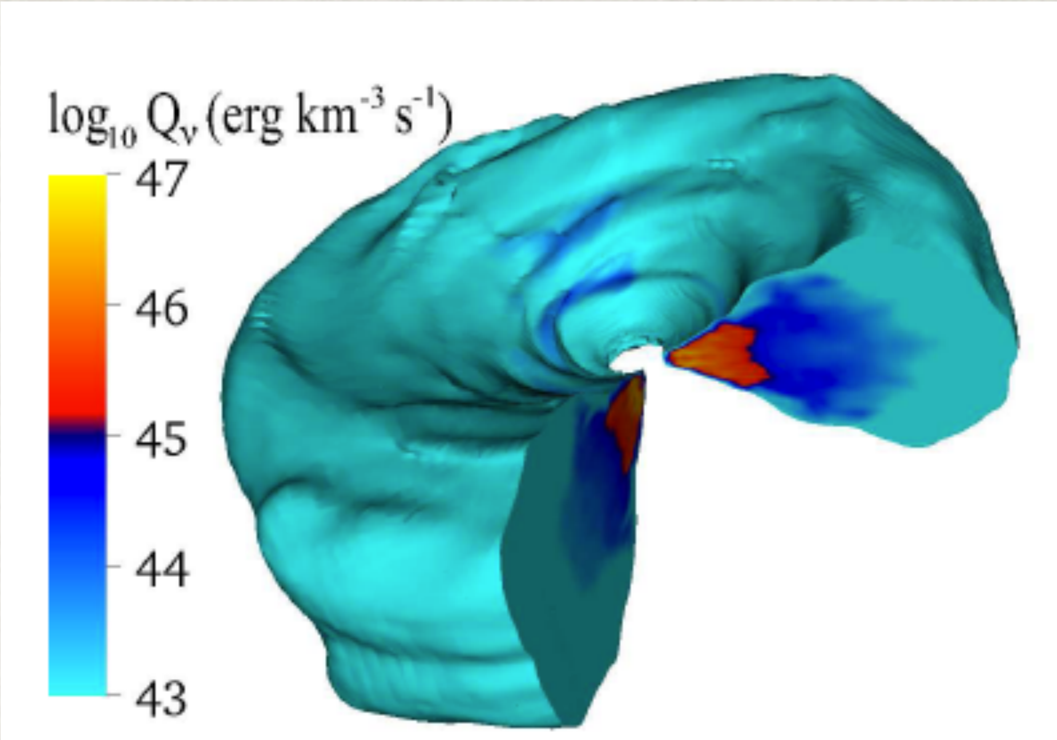
Magnetic Fields

- Chawla *et al* 2010 : q=5, B=10^{12}G
  - Negligible effect of B-field pre-merger
- Etienne *et al* 2011,2012: q=3, B=$10^{16\text{-}17}$G (tilted)
  - GW effect for large B-fields
  - Post-merger field nearly fully toroidal
  - Too expensive to resolve MRI **for aligned spins**
- Paschalidis *et al* 2013: force-free evolutions

Neutrinos

- Deaton *et al* 2013, Foucart *et al* 2014
  - Leakage scheme, with LS220 EoS

…

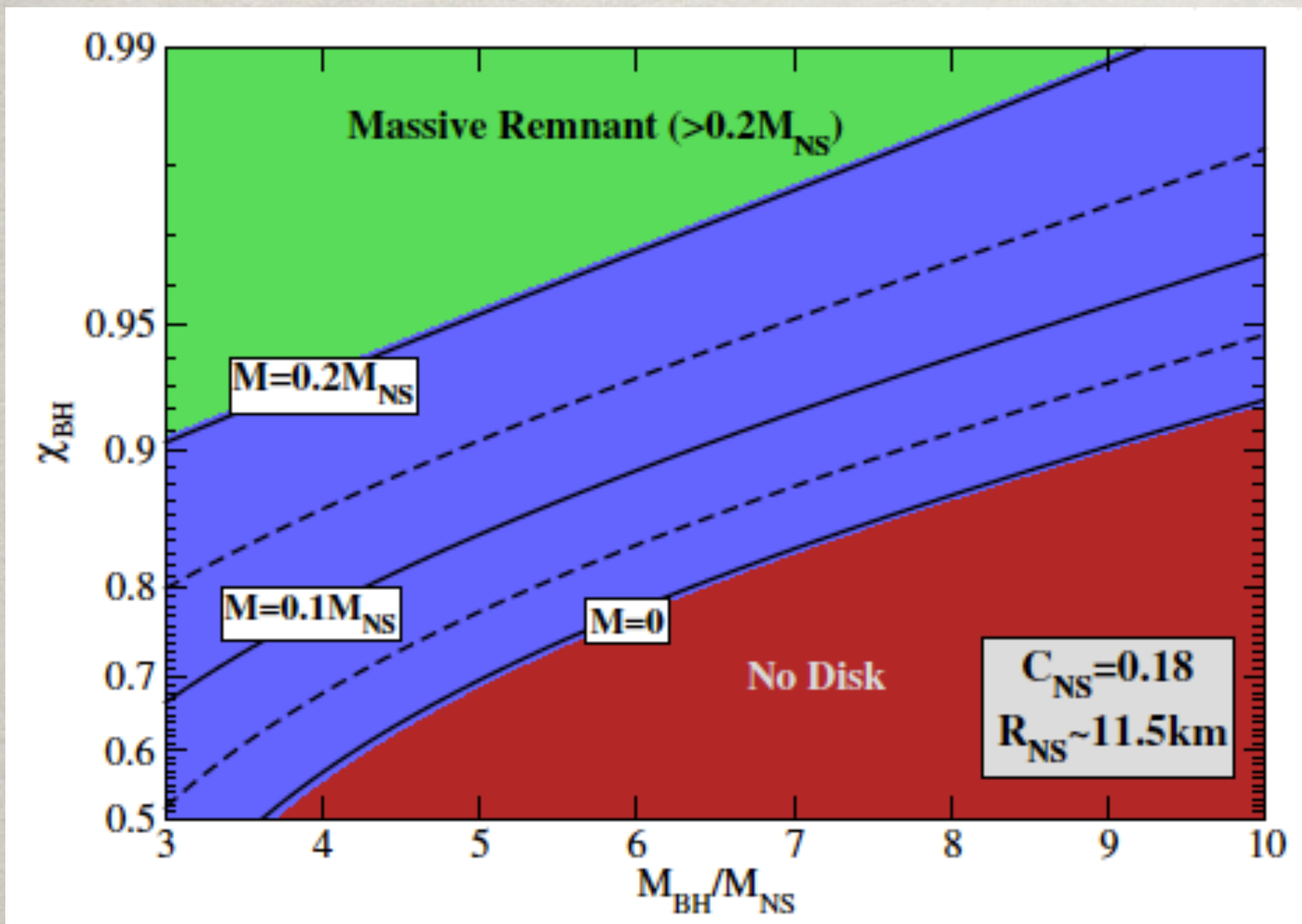


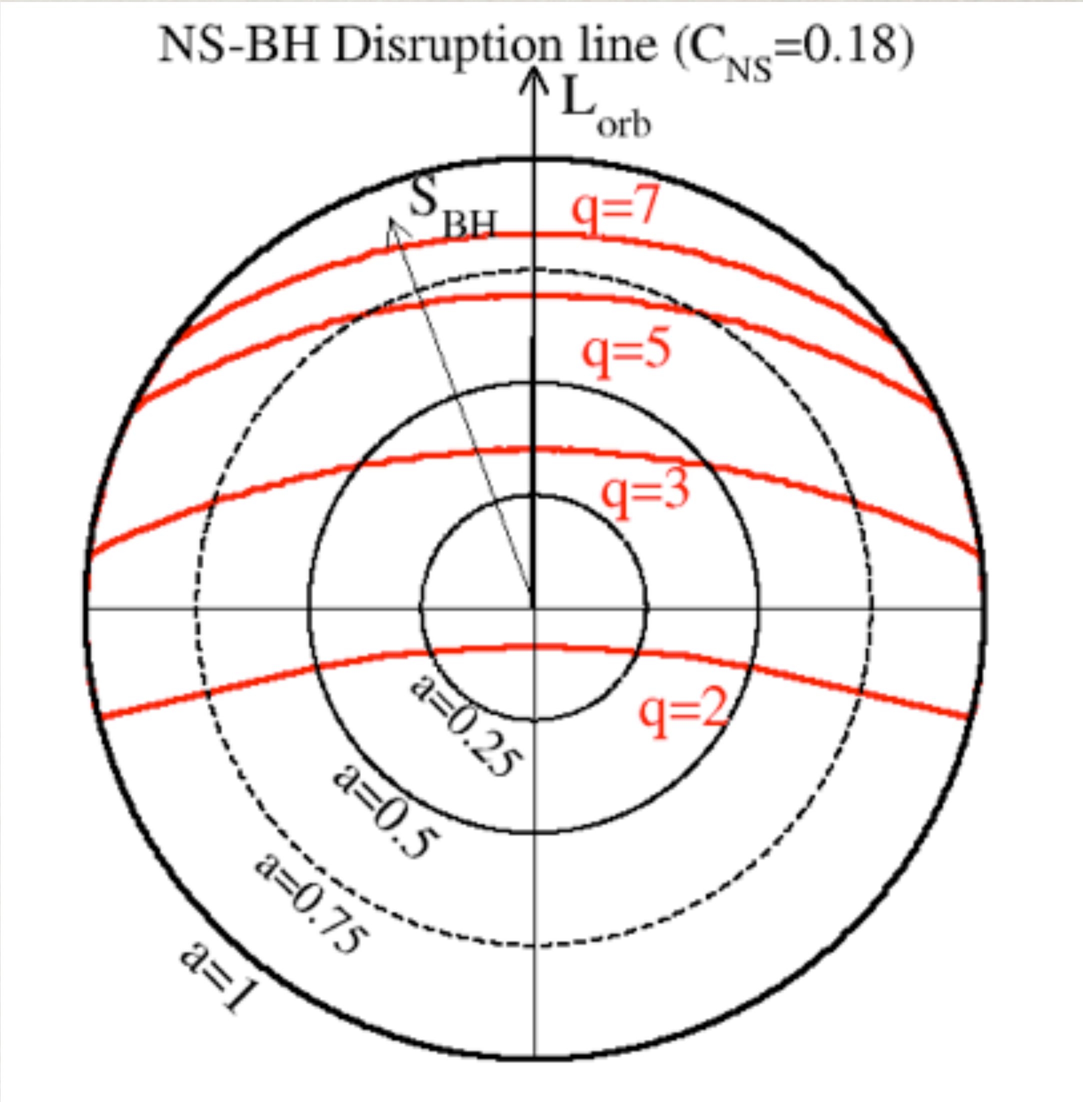
  - and that's it for GR-Hydro simulations (but a lot more done without GR)

Numerical Results

Merger Outcomes

Merger Outcome





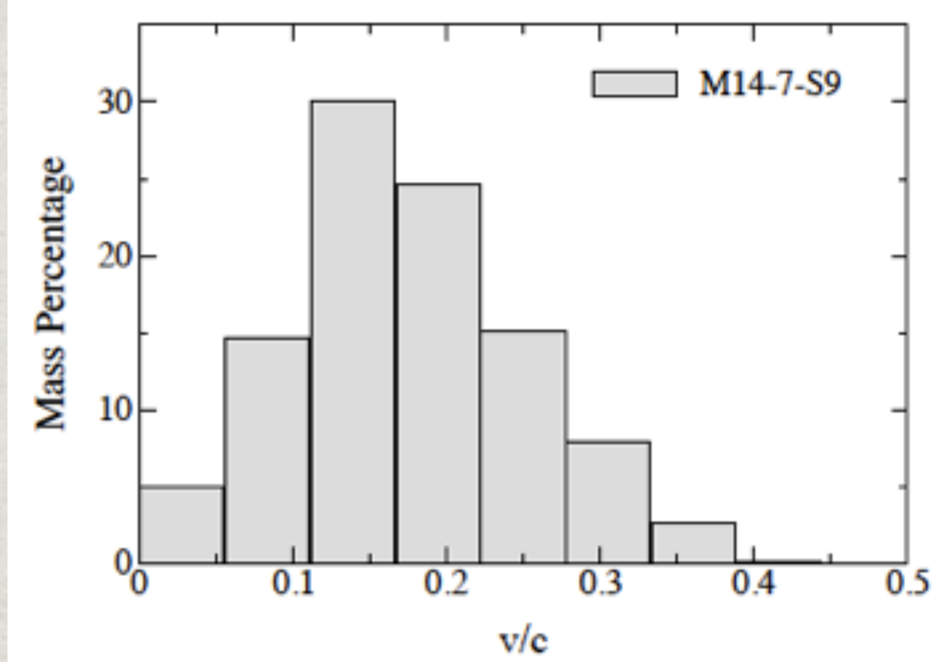
Approximate disruption condition from NR simulations:

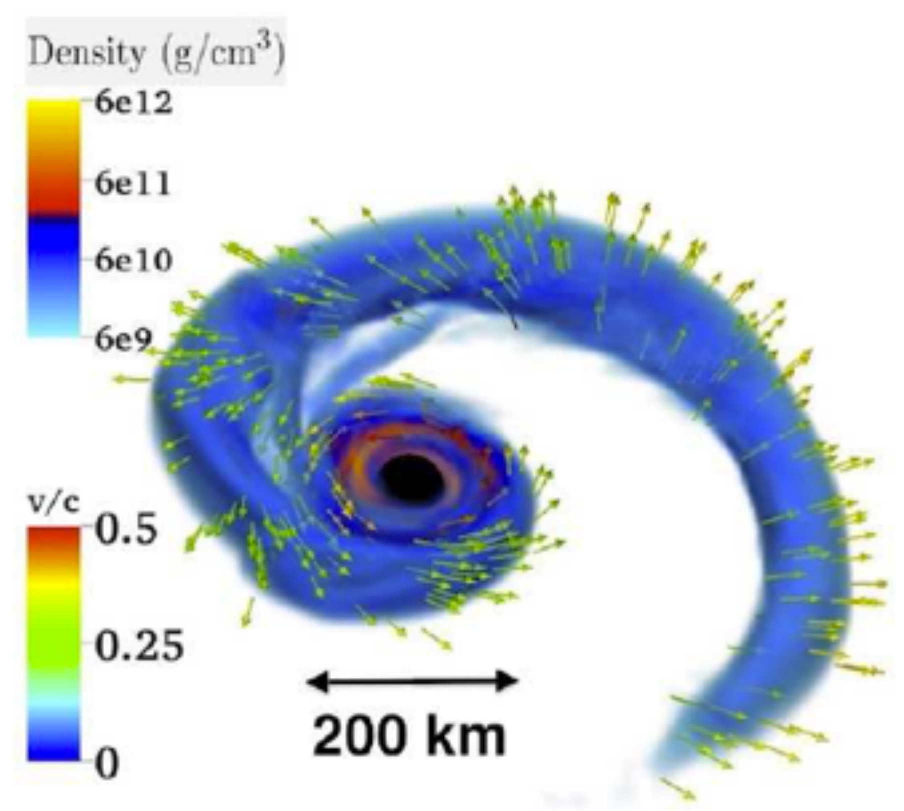
$$C_{\rm NS} \lesssim \left(2 + 2.14 q^{2/3} \frac{R_{\rm ISCO}}{6M_{\rm BH}}\right)^{-1}$$

Foucart 2012, Stone *et al* (2012)

Dynamical Outflows

- Large outflows if NS disrupts
  - $M_{ej} \sim 0.01\text{-}0.25\ M_{sun}$!
  - Cold, low Y_e -> strong r-process
- Asymmetric ejection
  - Large kicks v~100-800 km/s
  - Effect on color/magnitude of kilonova?





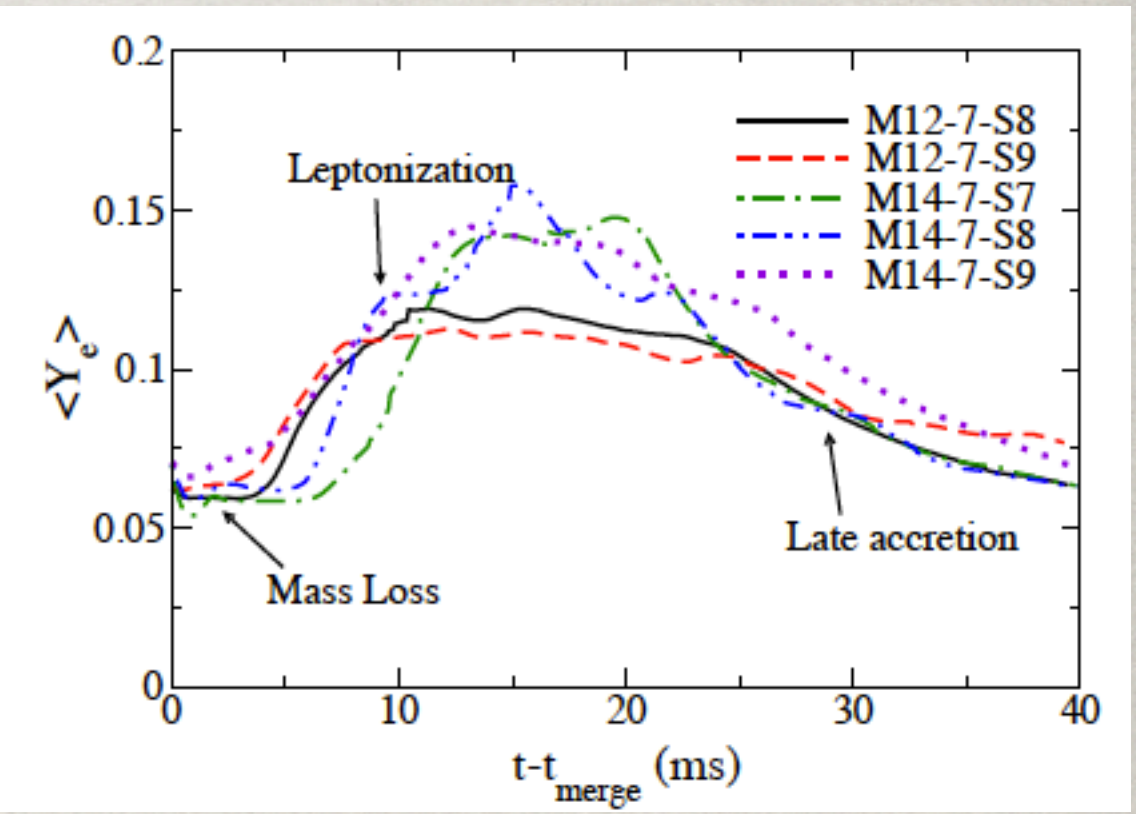
Deaton *et al* (2013), Foucart *et al* (2013,2014), Hotokezaka *et al* (2013)
Kyutoku *et al* (2013), Lovelace *et al* (2013), Tanaka *et al* (2013)

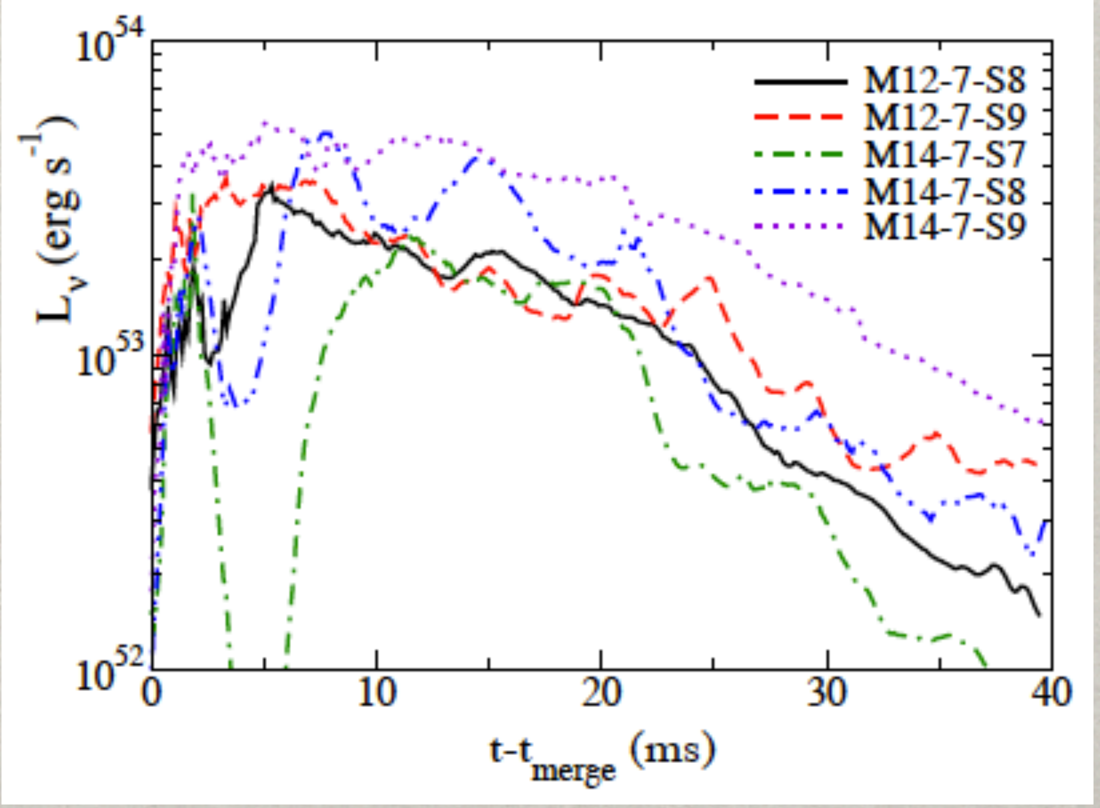
Disk Evolution

- Initial disk properties (for q~5-7)
  - M_{disk}~0.05-0.15M_{sun} T ~ 1-10MeV
    $Y_e < 0.10$ r < 100 km
    H/r ~ 0.2-0.3 $\tau_\nu \sim$ 1-10
- Rapidly evolve to quasi-equilibrium state (in ~10-20ms), at least without MHD...
- Misalignment $\beta < 10^o$ for realistic masses, rapid disk alignment expected
- Instabilities observed in the most massive disks, $M_{disk} > 0.2\ M_{sun}$

Disk Evolution

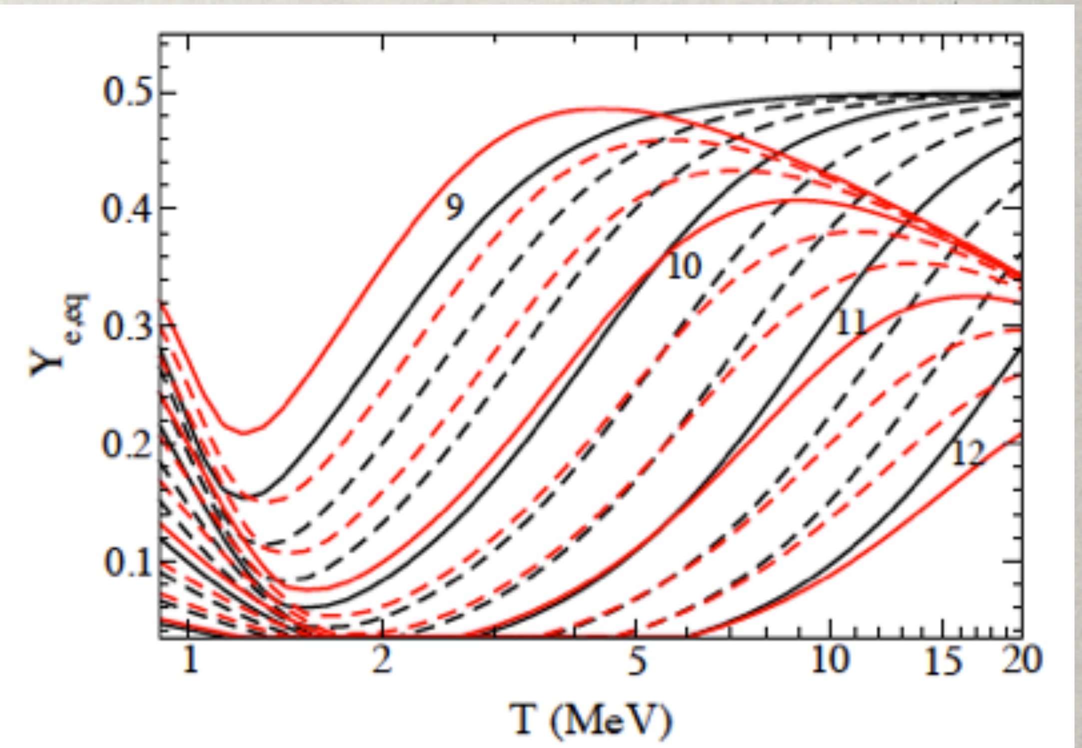
- Importance of neutrino cooling
  - Disk remains compact
  - T ~ 2-3 MeV after ~20ms
  - Non-monotonous Y_e evolution
  - High $L_\nu \sim 10^{53}$ erg/s
- Early evolution affected by fallback
- Late evolution: need MRI

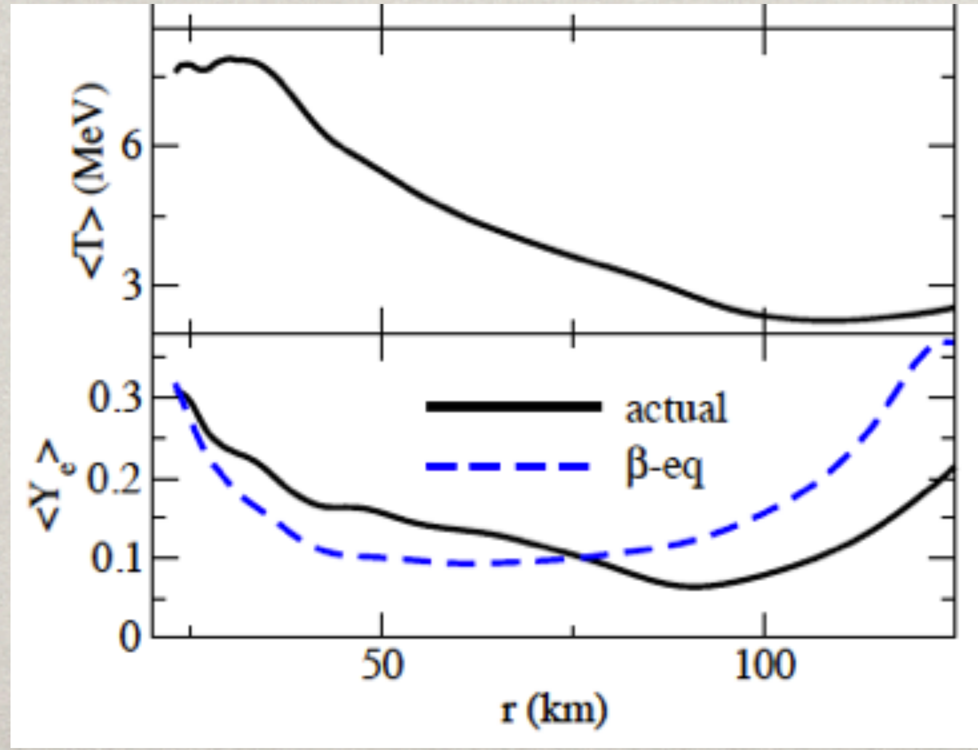




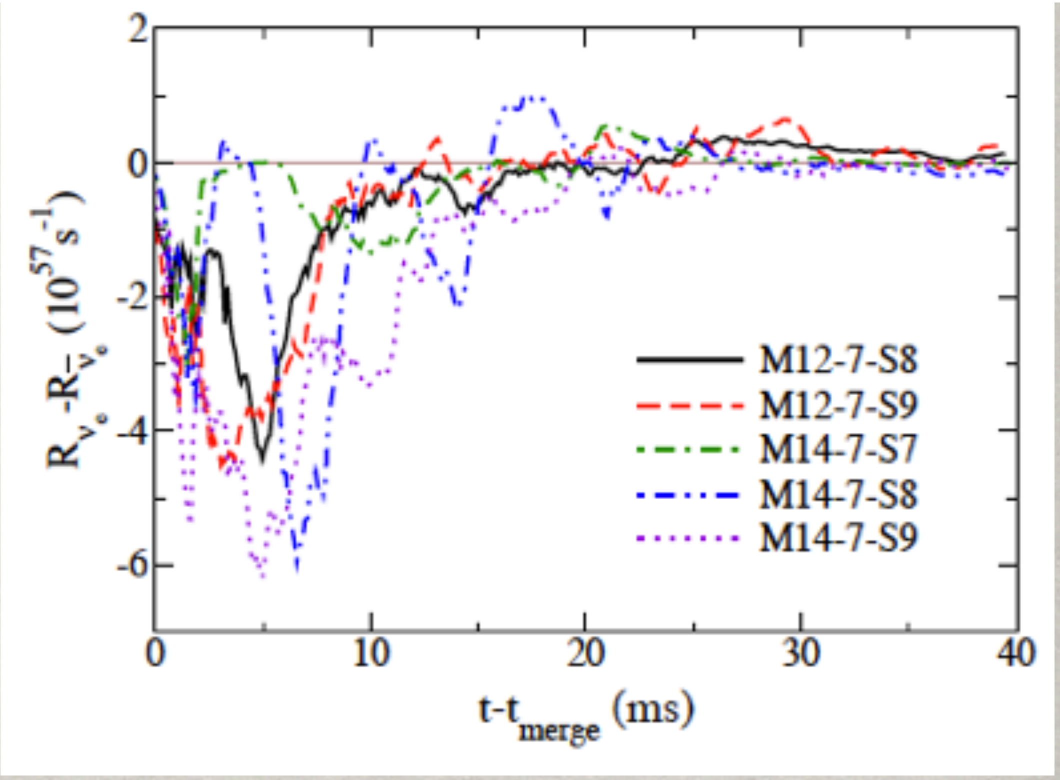
Composition evolution

- Y_e evolution ~equilibrium Y_e
- Variations < disk asymmetries
- Mild differences for massive / optically thick disks





Deaton *et al* (2013) - Massive disk

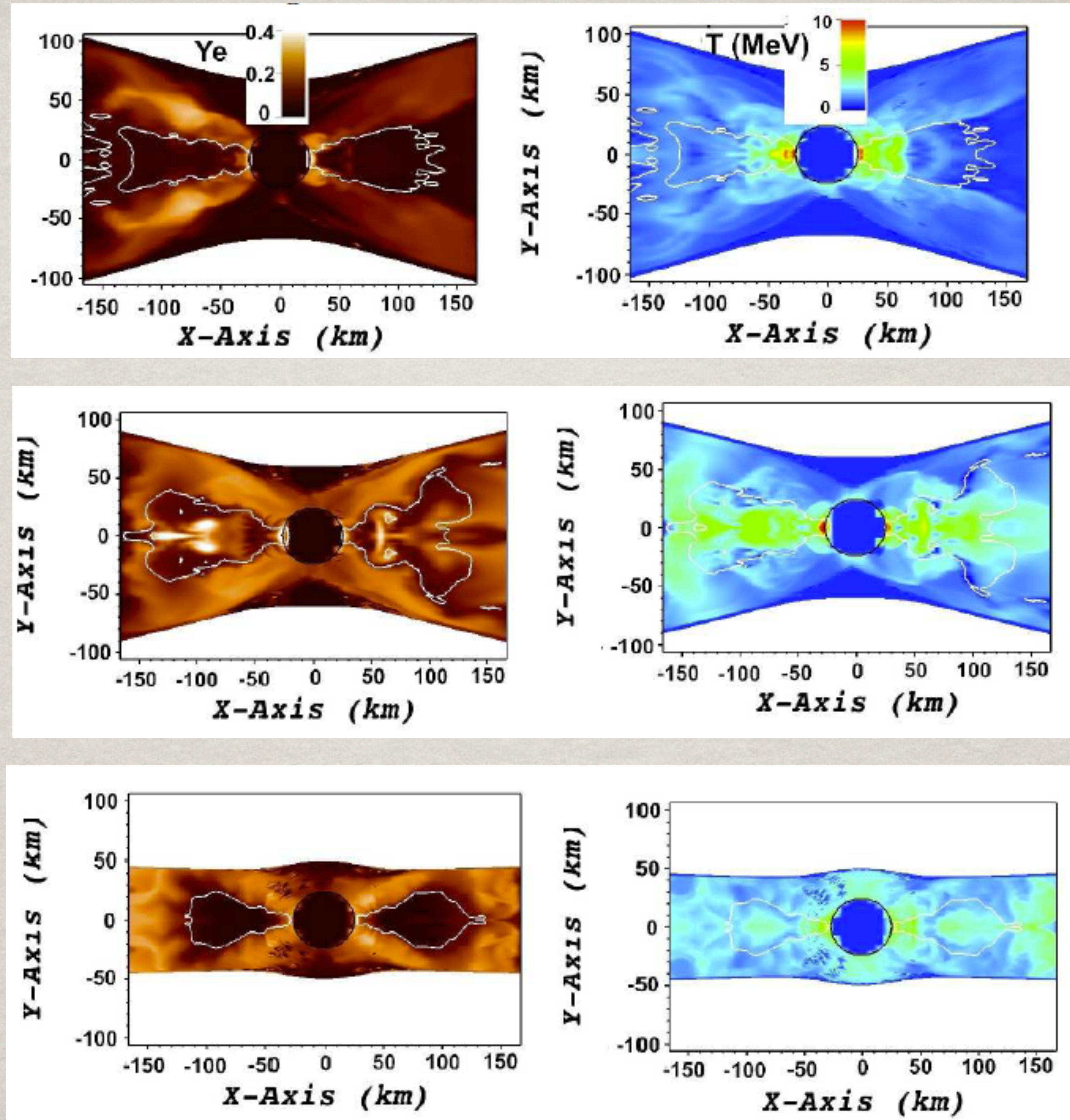


Foucart *et al* (2014)

t=5ms

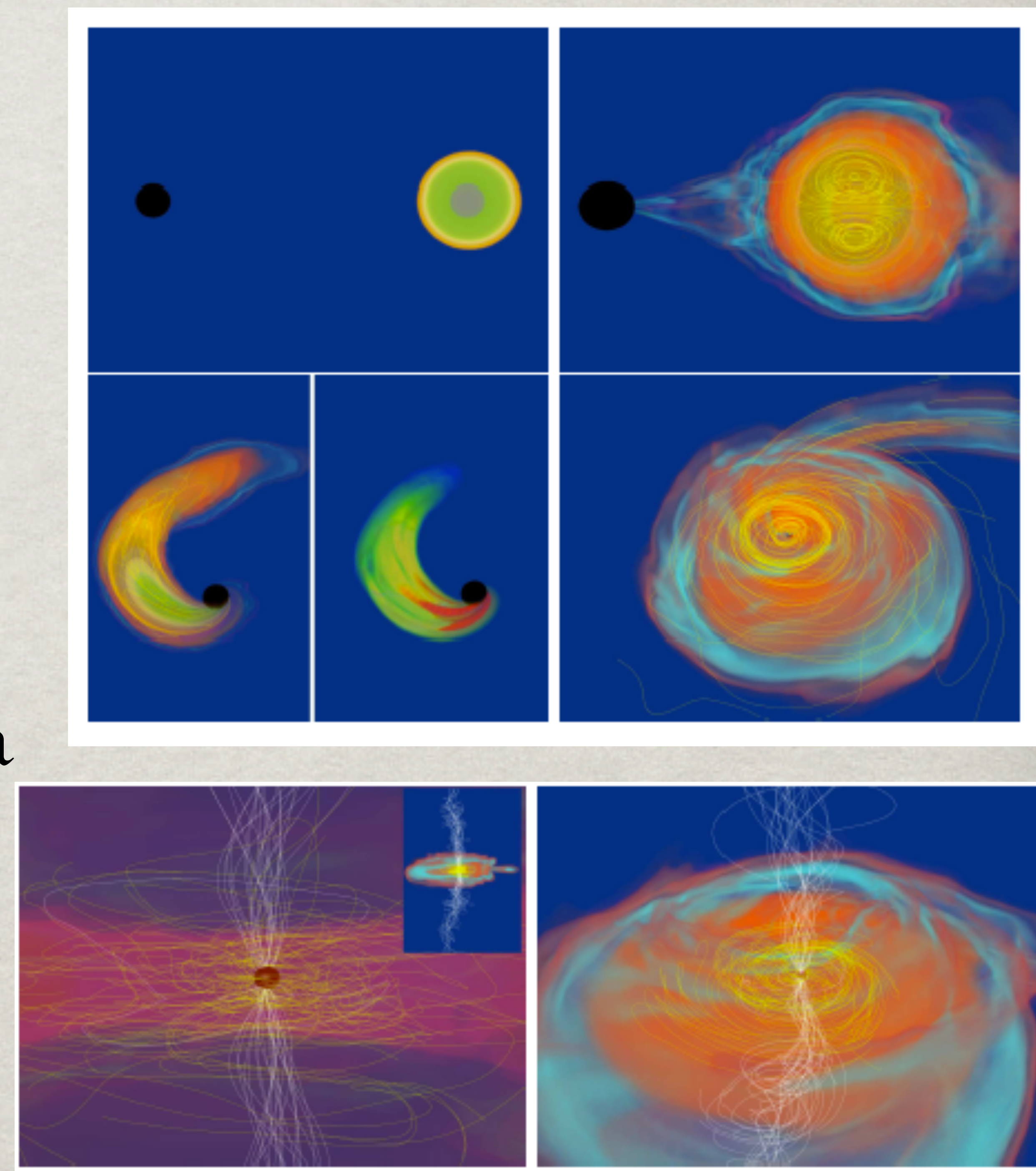
t=10ms

t=40ms



Disk Evolution

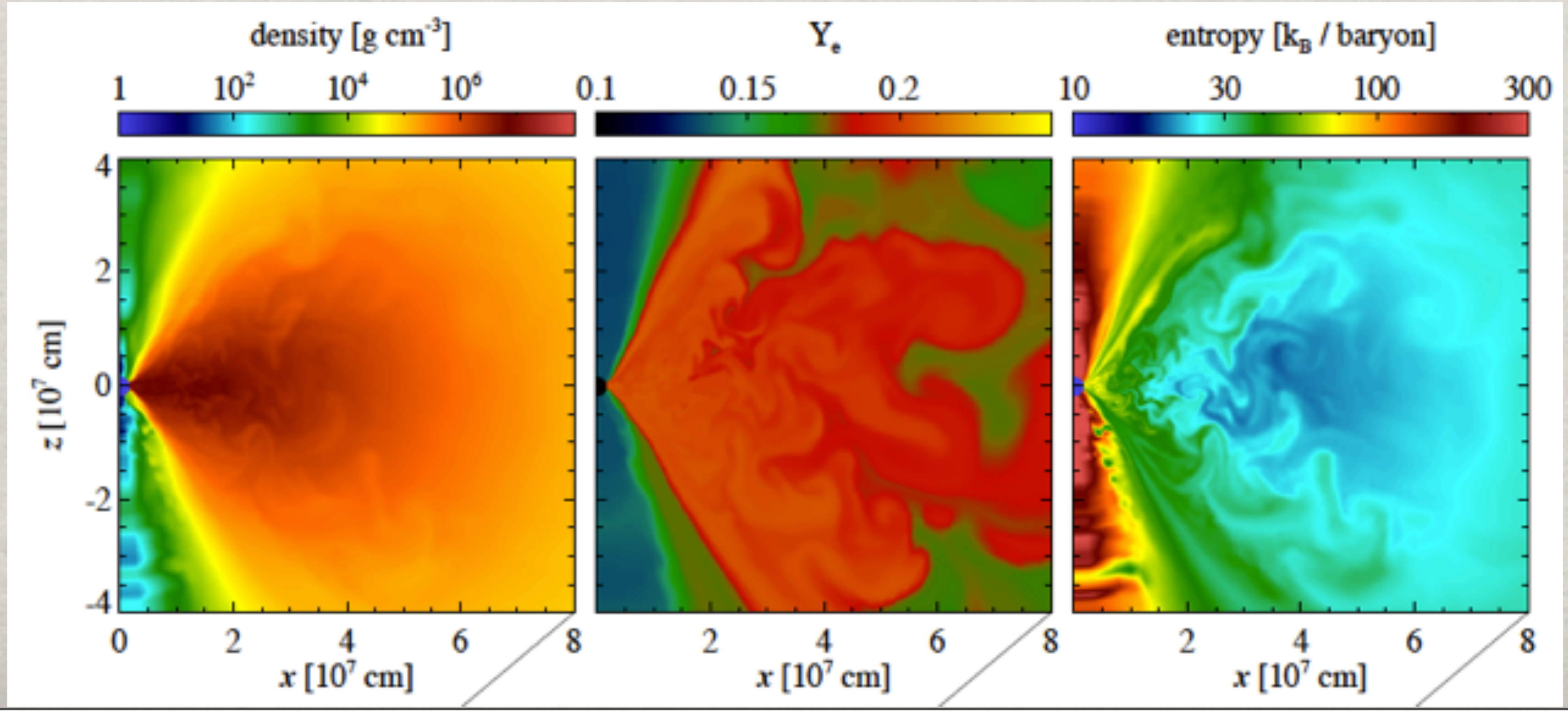
- Post-merger B-field mostly toroidal
- Resolving MRI for realistic field strength very costly
- Outflows seen after seeding a poloidal field post-merger
- Can we grow a coherent poloidal field?



Etienne *et al* (2012)

Disk Evolution

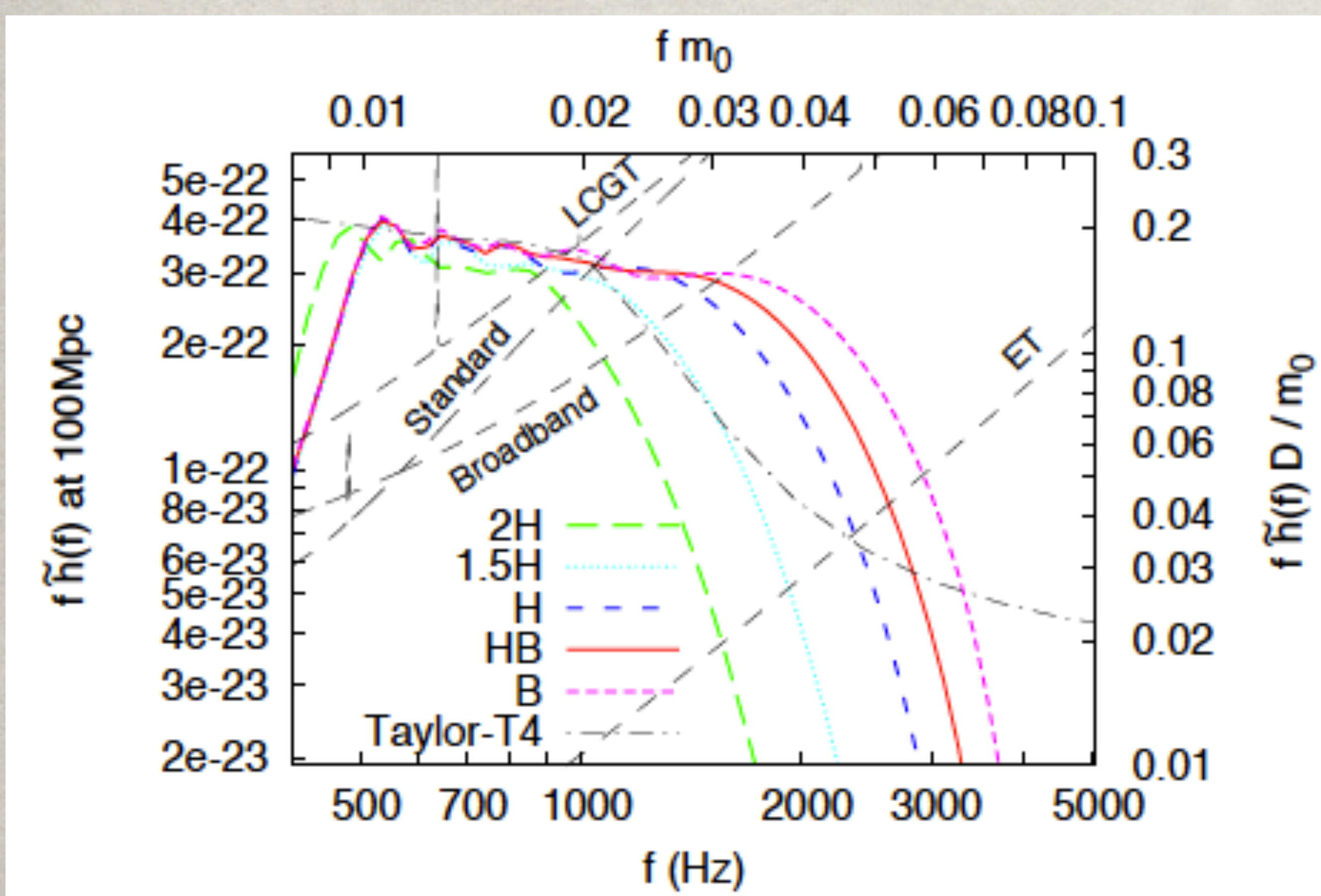
- Long-term evolution: 2D codes (e.g. Lee et al. 2009, Fernandez & Metzger 2013)
    - Models for viscosity, neutrinos, recombination
    - Late time outflow $M_{outflow} \sim 0.1\ M_{disk}$
    - For BH-NS: $M_{outflow} << M_{ejecta}$, with similar Y_e
    - Could be important for NS-NS



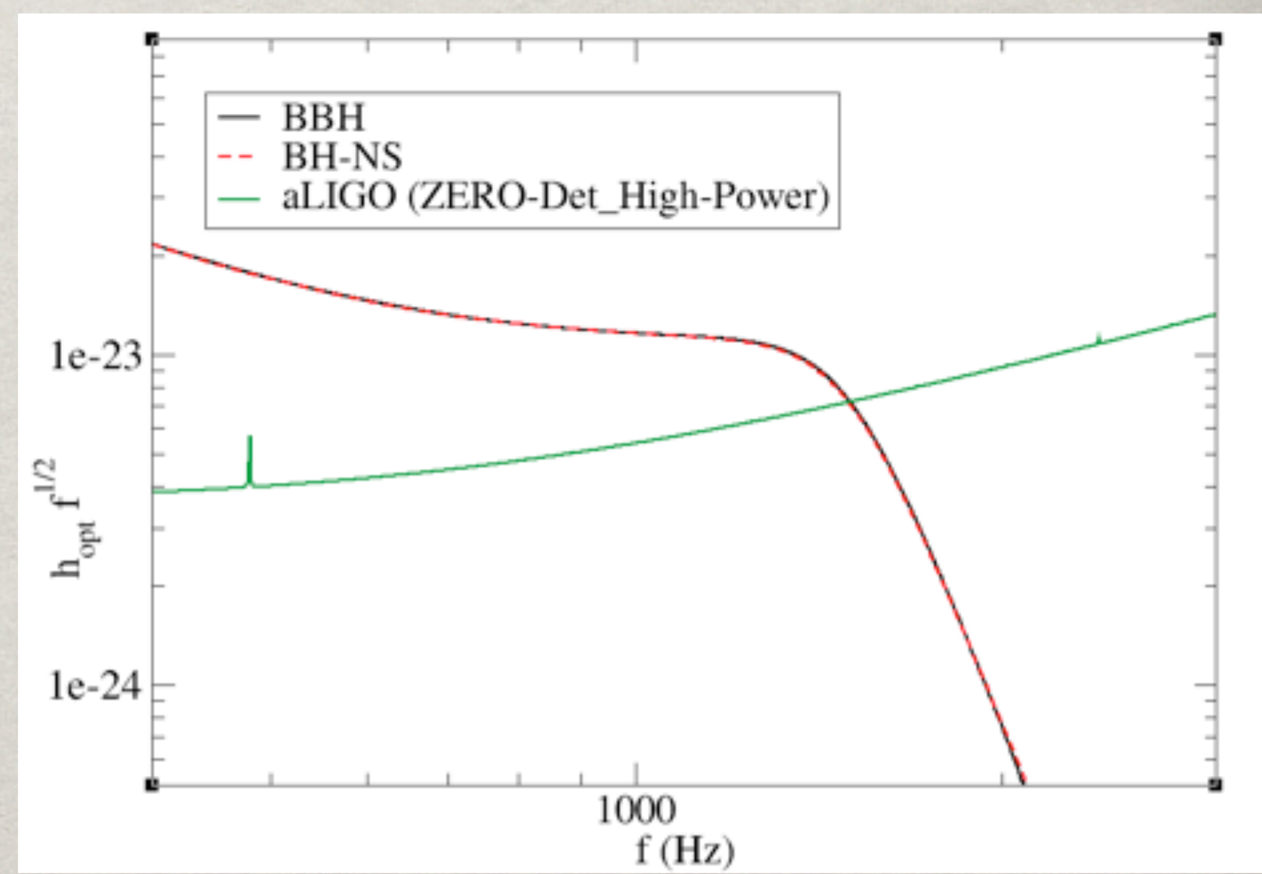
Fernandez & Metzger 2013

Gravitational waves

- Equation of state effects *probably* too hard to detect for realistic M_{BH}
  - Tidal effects smaller than in NS-NS
  - NS disruption at 1-2 kHz



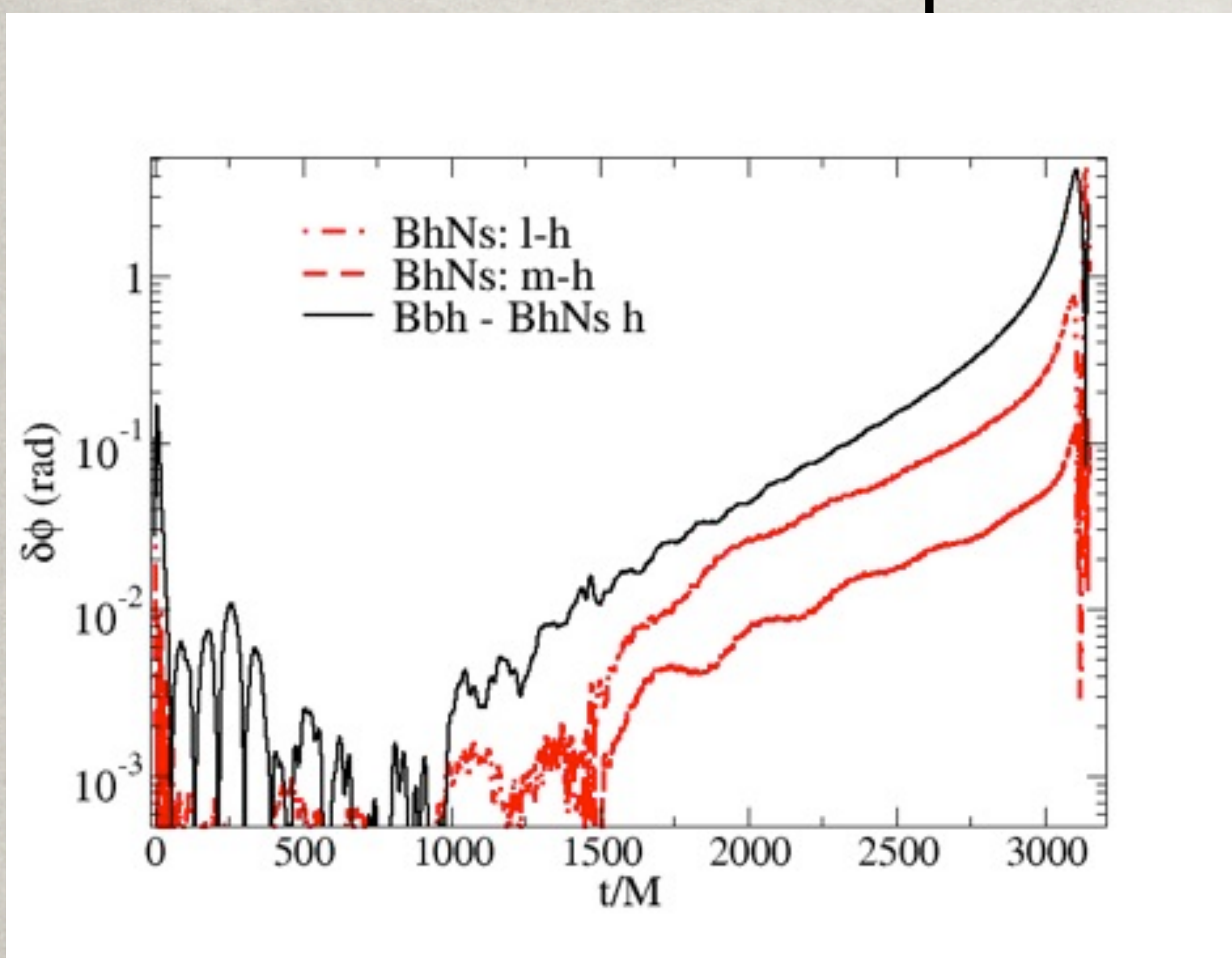
Kyutoku *et al.* 2011



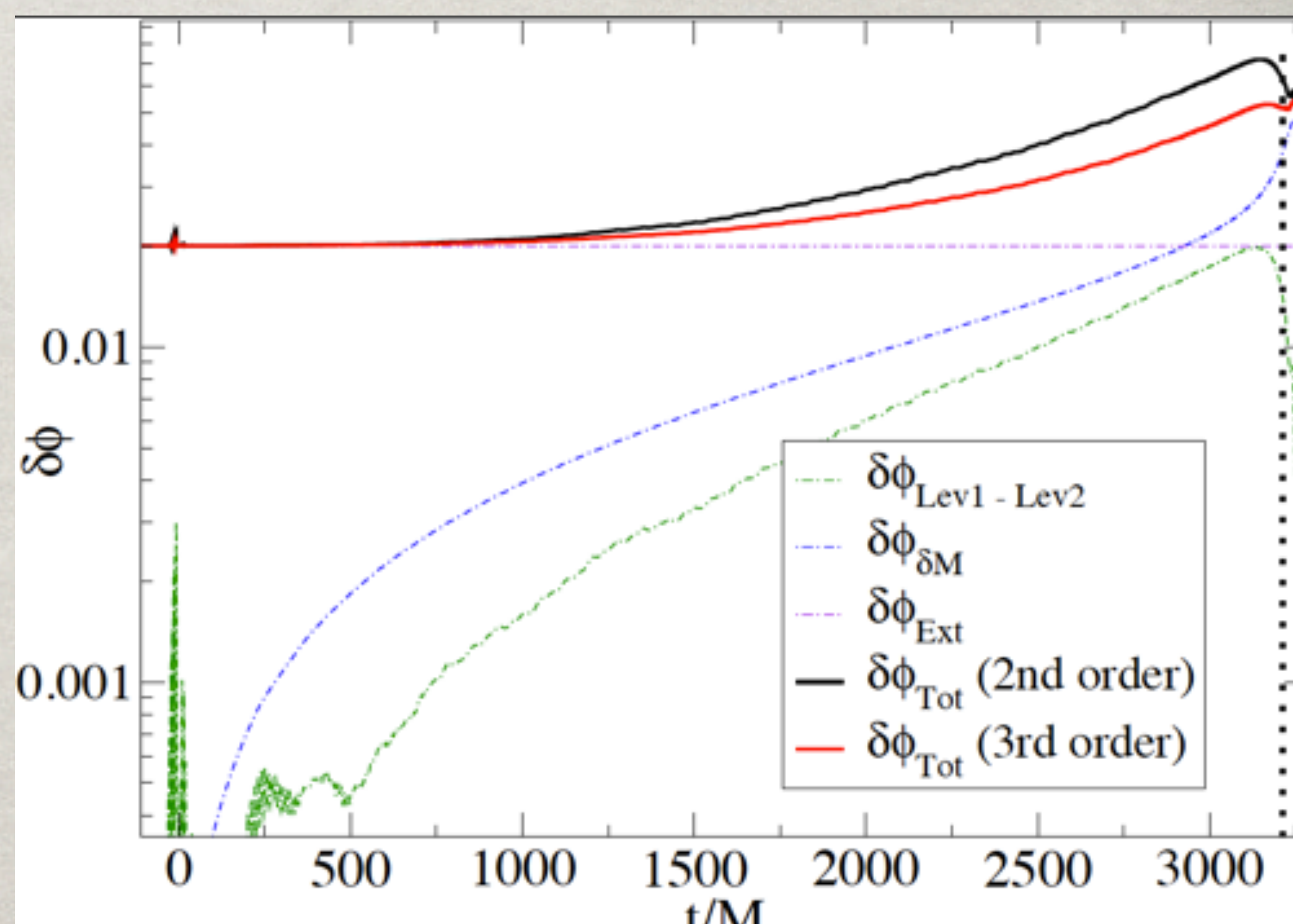
Foucart *et al.* 2013

Gravitational waves

- Can be used to test analytical waveforms
  - Need high order methods (Radice et al. 2013)
  - Potential to resolve tidal effects at <10%
  - Need to improve error estimates



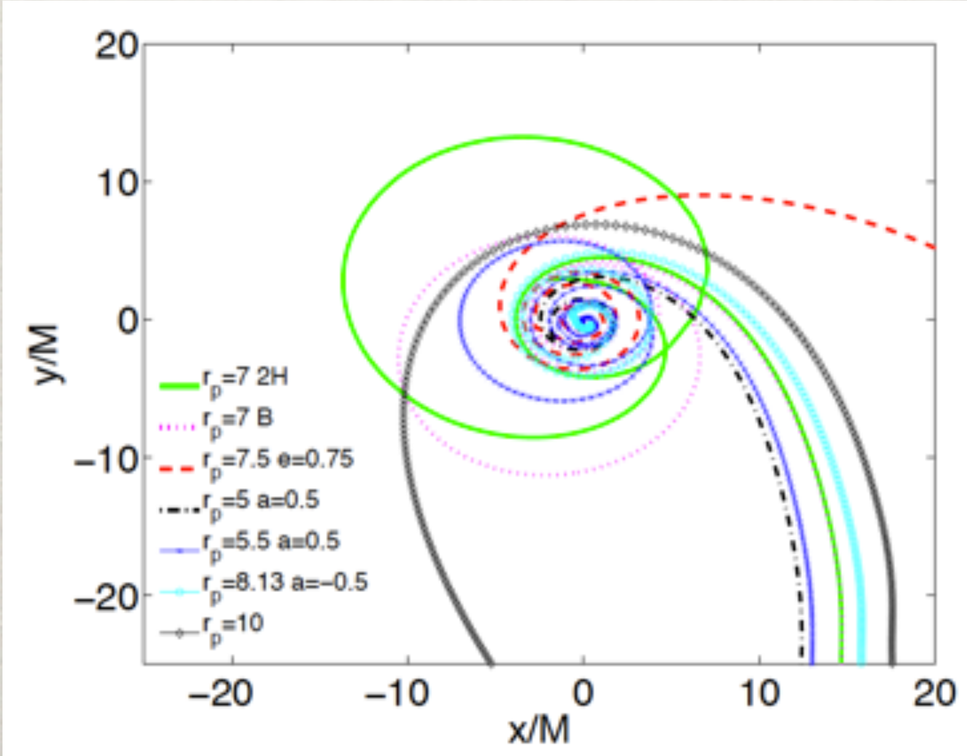
Preliminary : q=2



Preliminary : q=1

Eccentric binaries

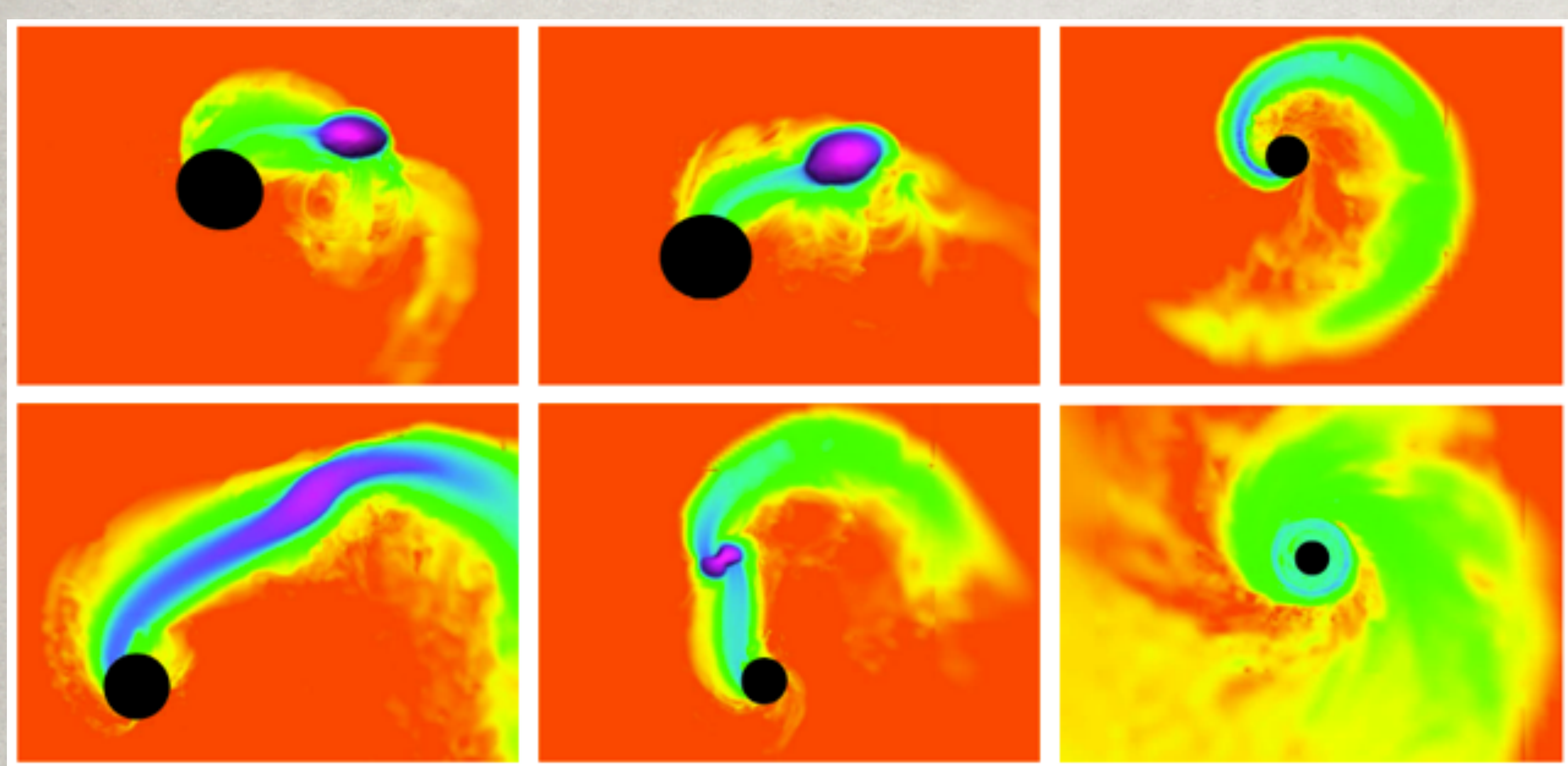
- Rates very controversial
- Currently only detectable through burst searches
- Richer results than circular binaries
  - Massive ejecta / disks
  - Stable mass transfers
  - Mode excitation

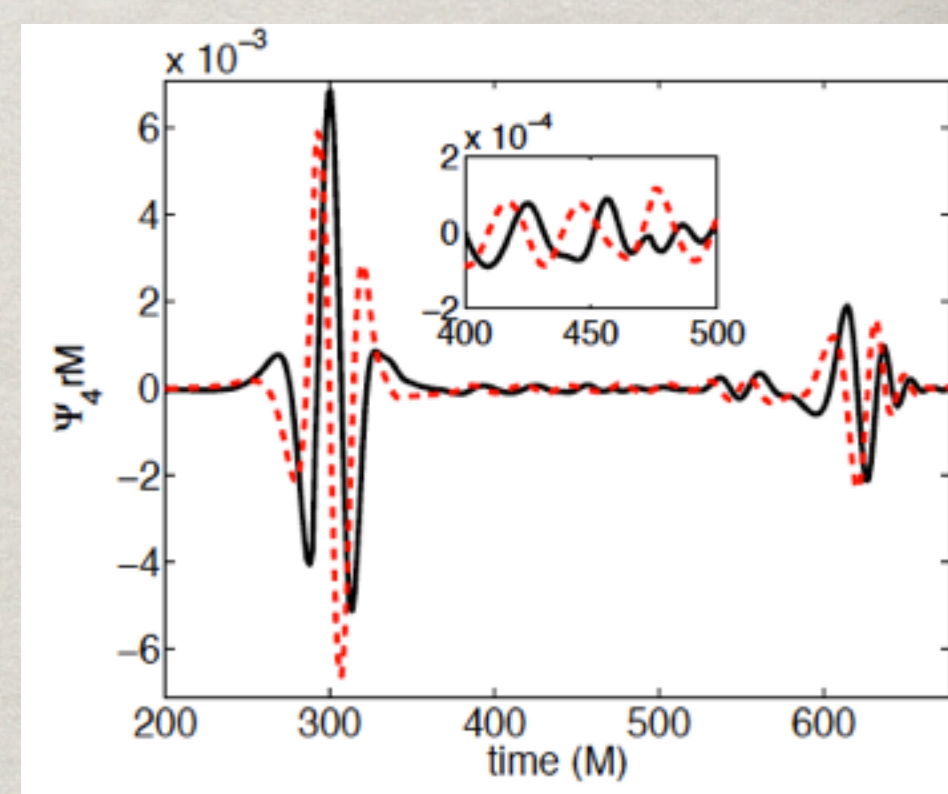


East *et al* 2012

Eccentric binaries

- Numerical simulations (East *et al* 2012)





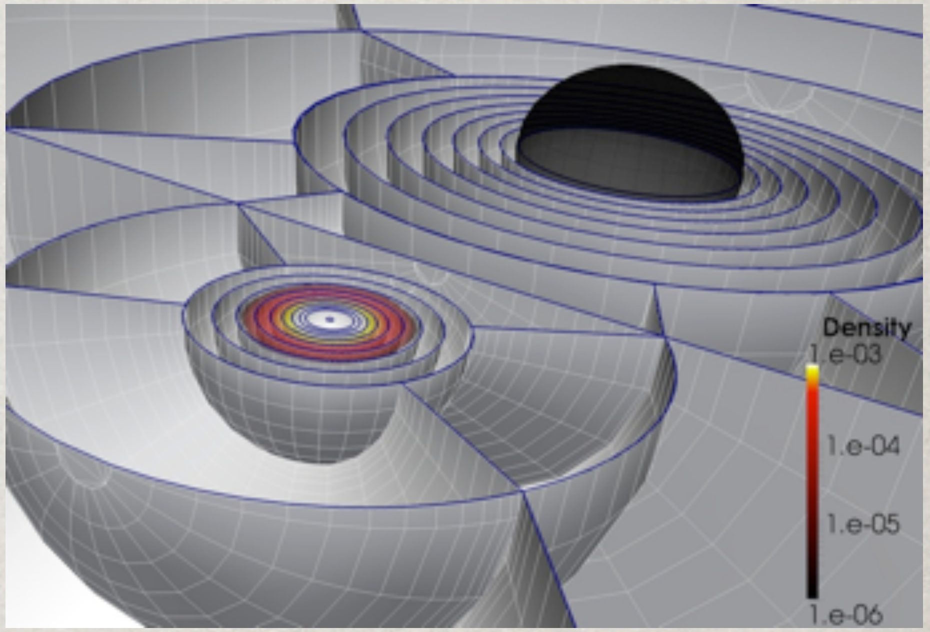
GR-Hydro in SpEC

SpEC-Hydro

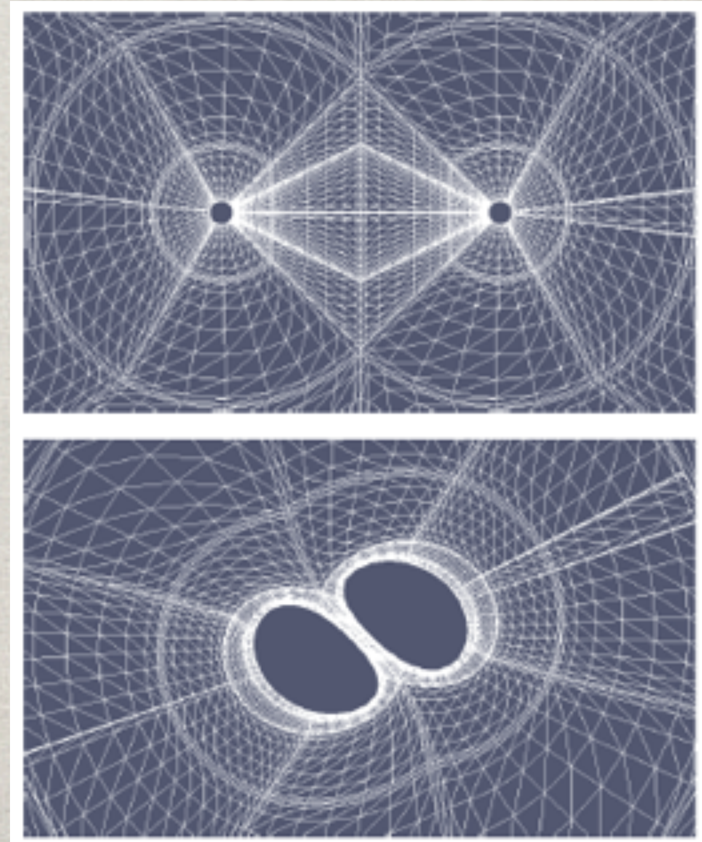
- **Caltech**: R. Haas, J. Lippuner, C. Ott, L. Roberts, B. Szilagyi, M. Scheel
- **CITA**: F. Foucart, E. O'Connor, I. MacDonald, H. Pfeiffer, N. Tacik
- **Cornell**: A. Bohn, K. Henriksson, L. Kidder, C. Muhlberger, S. Teukolsky
- **Fullerton**: G. Lovelace
- **WSU**: W. Brege, B. Deaton, M. Duez, F. Nouri
- ... and many more for BH-BH simulations

SpEC Methods: GR

- Pseudo-spectral methods
  - Spectral AMR
  - Exponential convergence
  - BH excision
- Generalized harmonic formalism
- Comoving grid, complex control system



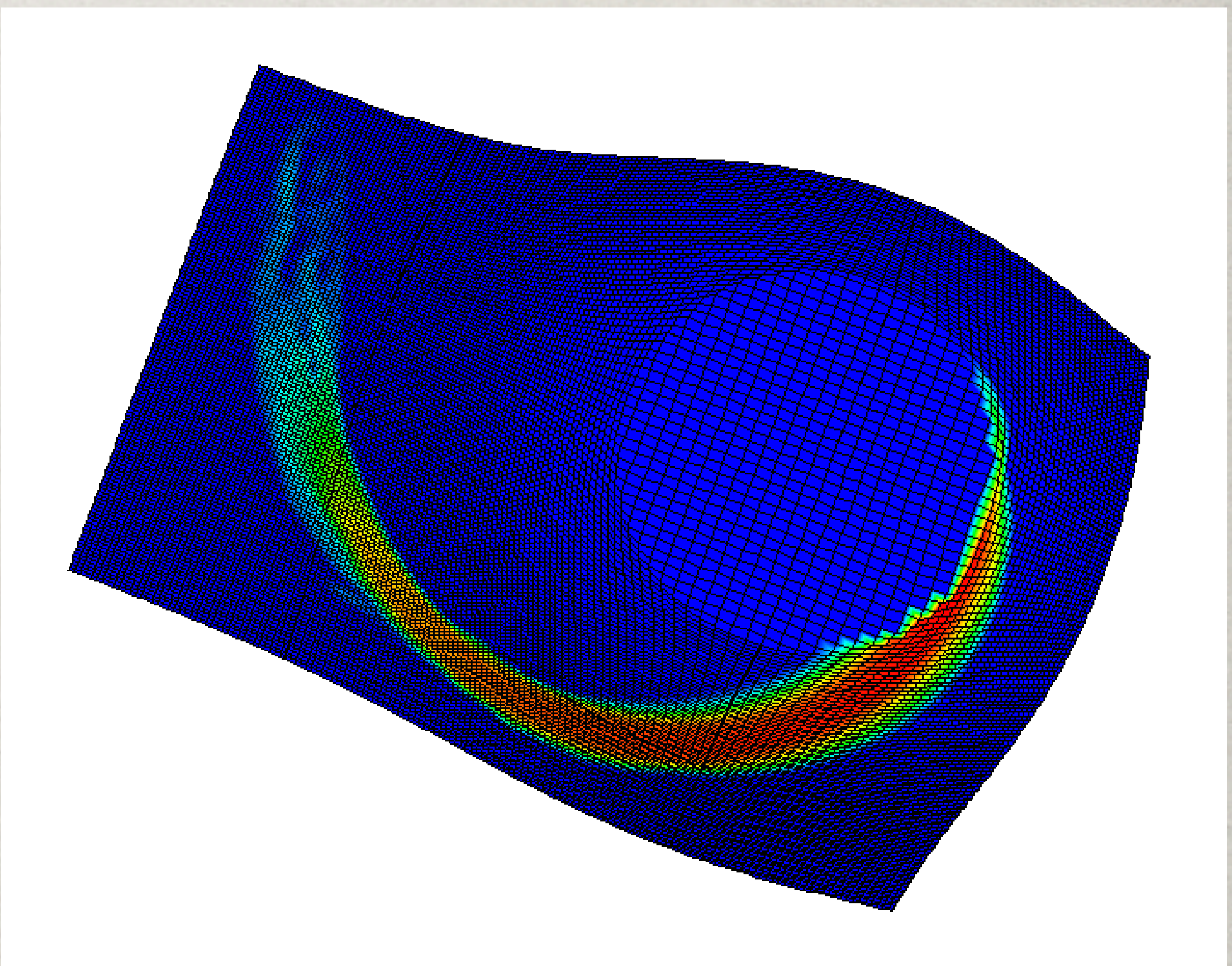
Foucart *et al* 2013



Hemberger *et al* 2012

SpEC Methods: Hydro

- Finite volume
  - WENO5 + HLL
  - MHD / Leakage
  - Nuclear EoS
  - FMR
- Finite difference
  - MP5 + Roe / LF
- Communication GR <-> Hydro grid ; Regrids



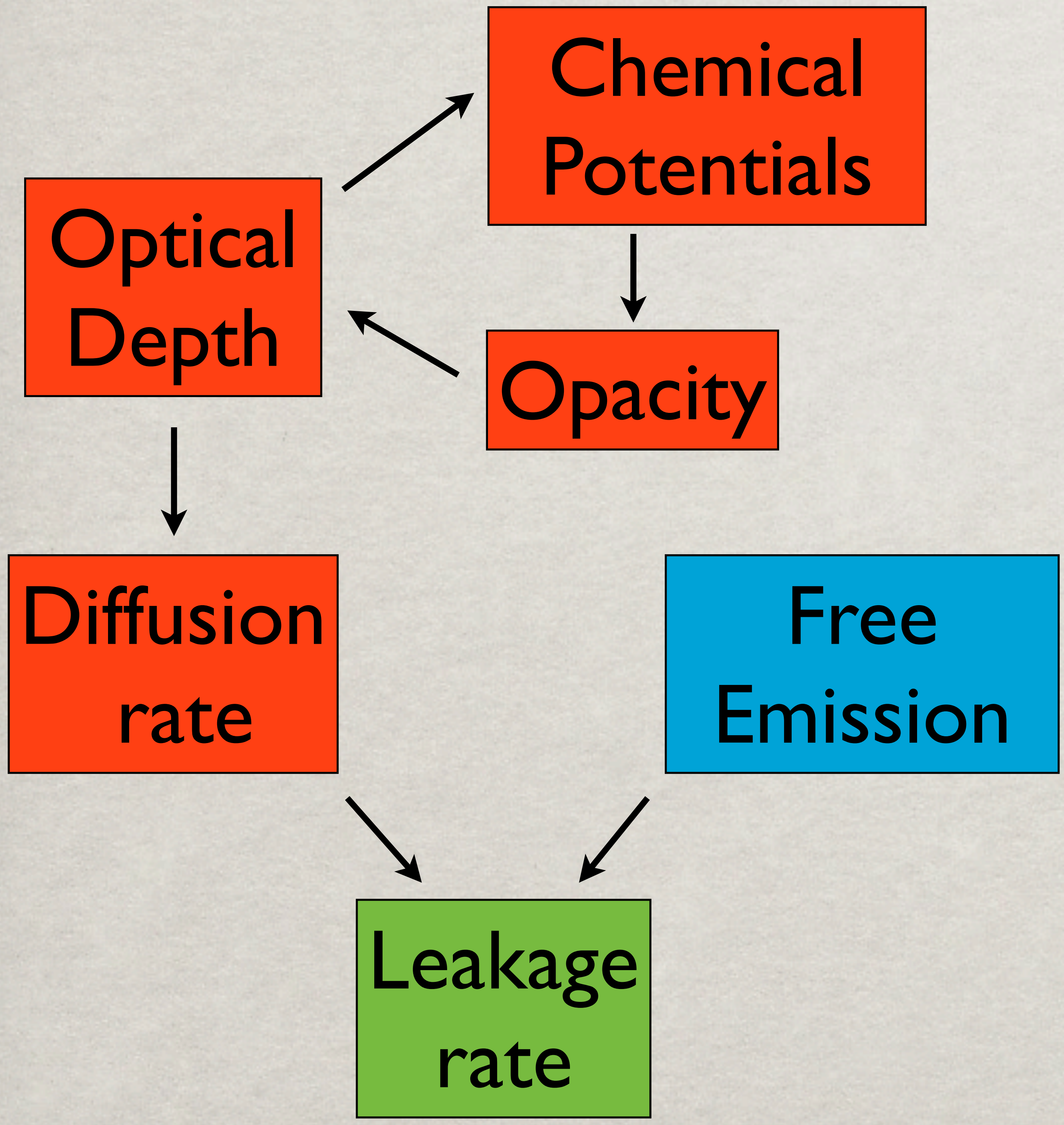
SpEC: Vacuum

- Spectral code allows efficient computation of high accuracy, long waveforms
  - Usually comes at the cost of less robust numerical methods
- Catalog of 179 waveforms publicly available (Mroue *et al* 2013)
- Still working on extending parameter space coverage
  - Precessing binaries
  - Larger mass ratios
  - Extreme spins

GR-Hydro Accuracy

- GW phase: typically ~1-2 rad with FV methods (for ~10 orbits)
- BH properties : ~1% relative error
- Matter : 10-50% error
- Neutrino luminosity: order of magnitude
- Sometimes difficult to assess: non monotonous error, complexity of two-grid method

SpEC Methods: Leakage



$$p + e^- \rightarrow n + \nu_e$$

$$n + e^+ \rightarrow p + \tilde{\nu}_e$$

$$e^+ e^- \rightarrow \nu_i \tilde{\nu}_i$$

$$\tilde{\gamma} \rightarrow \nu_i \tilde{\nu}_i$$

$$NN \rightarrow NN \nu_i \tilde{\nu}_i$$

$$p + \tilde{\nu}_e \rightarrow n + e^+$$

$$n + \nu_e \rightarrow p + e^-$$

$$N + \nu \rightarrow N + \nu$$

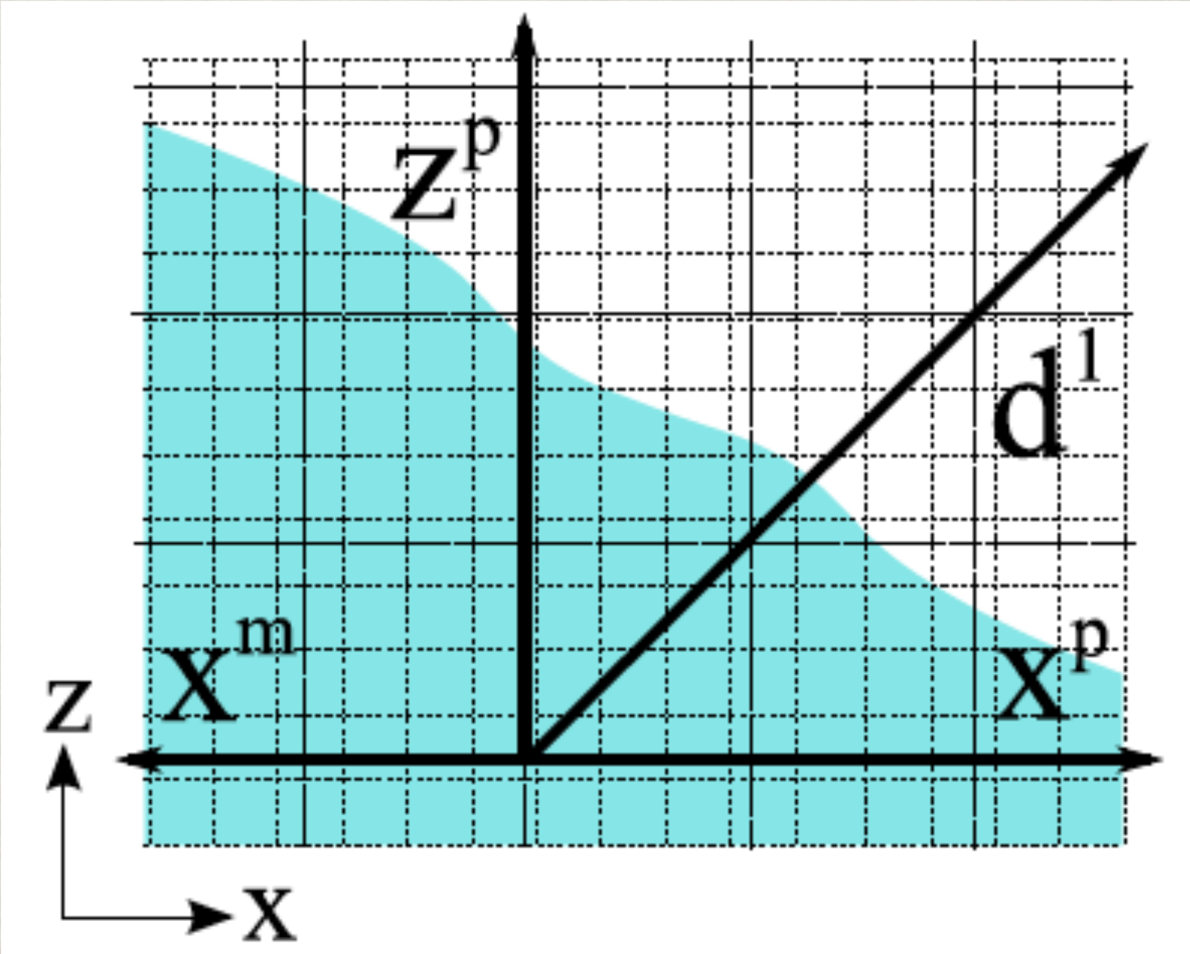
$$X^i + \nu \rightarrow X^i + \nu$$

$$Q_{\rm leak} = \frac{Q_{\rm free} Q_{\rm diff}}{Q_{\rm free} + Q_{\rm diff}}$$

Ruffert 96, Rosswog & Liebendorfer 2003, O'Connor & Ott 2010, Deaton et al. 2013

SpEC Methods: Opacity

- Optical depth:
  1. Approximate τ_ν
  2. Compute cross-sections using guess for potentials $\mu(\tau_\nu)$
  3. Compute τ_ν from line integrals on coarse grid
  4. Iterate until τ_ν converges



Or: Replace (3) by method from Neilsen *et al* 2014

Development: Neutrinos

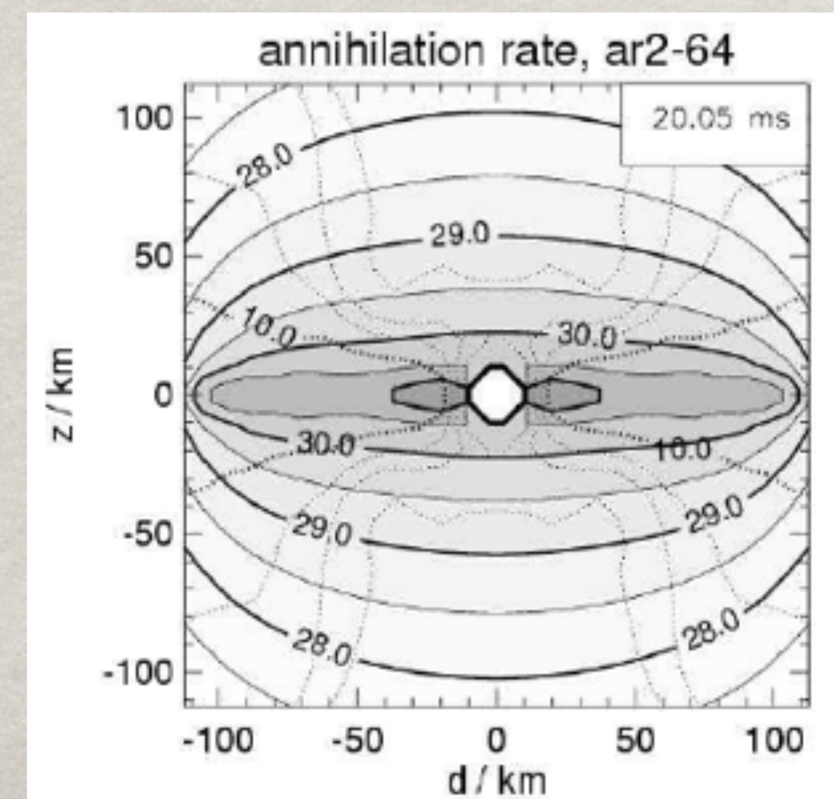
- Current direction: moment formalism
  - Evolve E, F_i for each species
  - Grey scheme or energy dependent?
  - Problematic time step & treatment of high-velocity regions
  - Closure relation? M1 known to fail for crossing beams...
- Otherwise, Monte Carlo?
- What is the effect of the atmosphere?

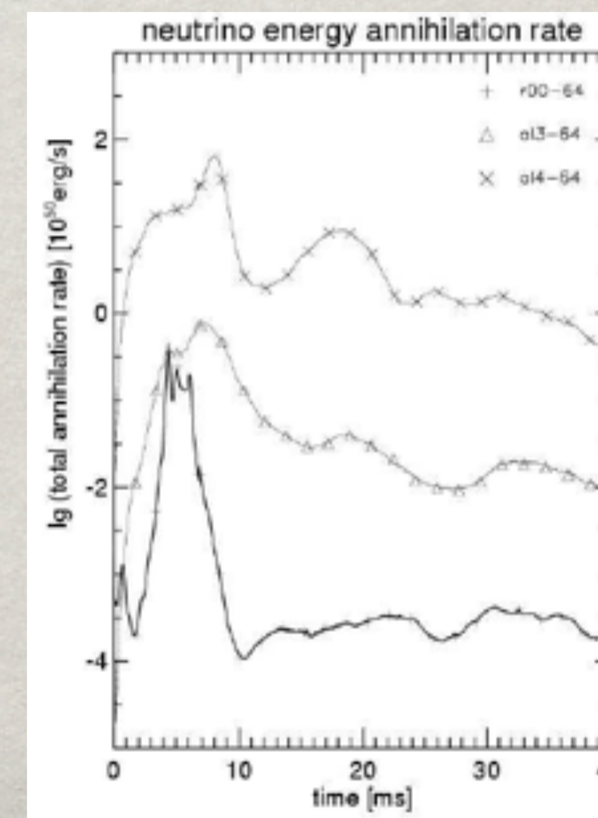
Post-Processing: Neutrino annihilation

- Neutrinos deposit energy in low-density region above disk
  - Estimates of ~a few % of total luminosity
  - Could be $Q_\nu \sim 10^{51}$erg/s after merger!
- Should impact jet formation
  - Baryon loading from e^+-e^- creation?
  - Helps power the outflows?
- Not handled by leakage, M1...

Post-Processing: Neutrino annihilation

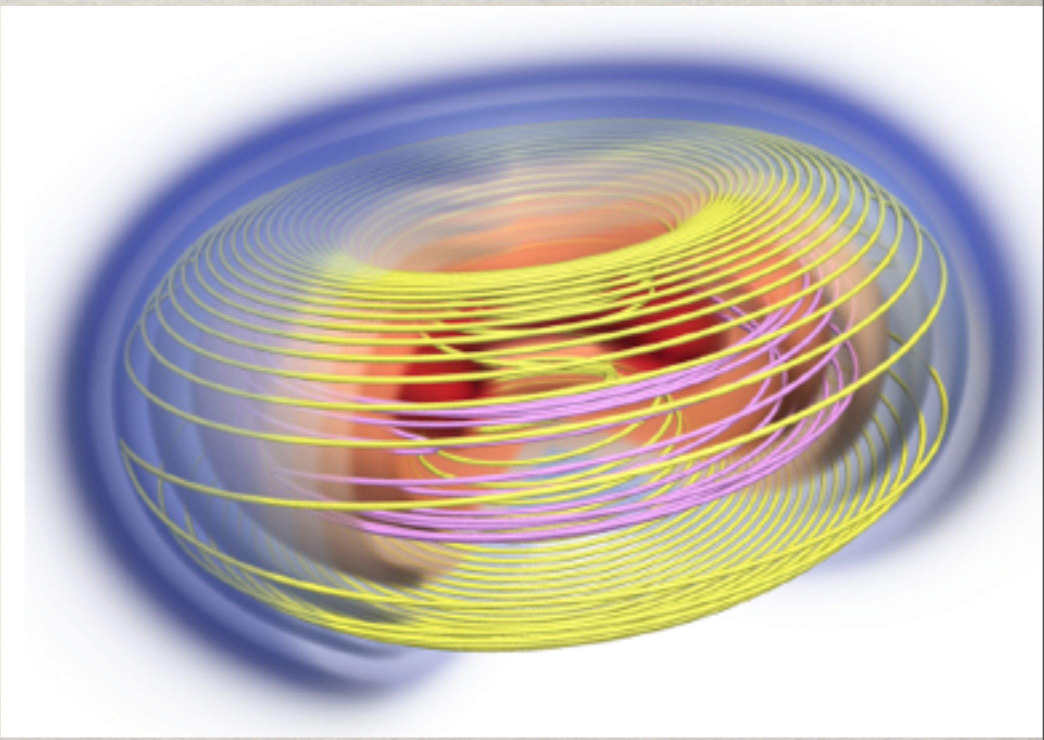
- Post-process with Monte-Carlo integration
  - Use ray-tracing from neutrinosphere (developed for event horizon finder)
  - Estimate annihilation rate
  - Newtonian results (Setiawan *et al* 2006):





SpEC Methods: B-fields

- So far, ideal MHD
- Evolve either B-field or vector potential using constrained transport
  - Can also evolve potential at cell center (but requires dissipation)
- Used to study low T/W instability (Muhlberger et al 2014), NS-BH inspirals, Accretion disk



Issues: B-fields

- Dual grid methods not adapted to MHD techniques
  - Interpolation, close outer boundary
- Influence of excision
- Boundary condition on vector potential
- And of course, the usual resolution issues...

Post-Processing: r-Process

- Use tracer particles to get history of ejecta
- SPH continuation of GR-Hydro simulations?
  - Need fixed metric SPH code
  - Can then follow ejecta over long timescales
- Post-processing with nuclear reaction network