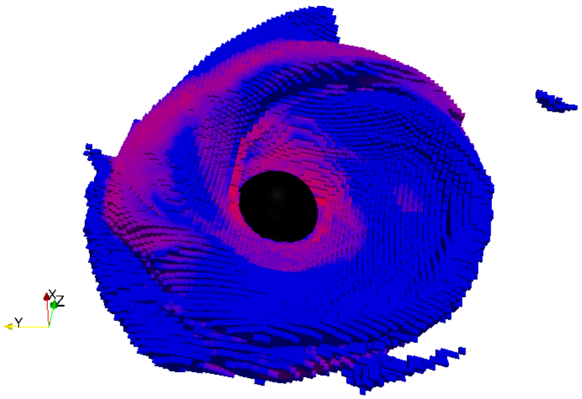
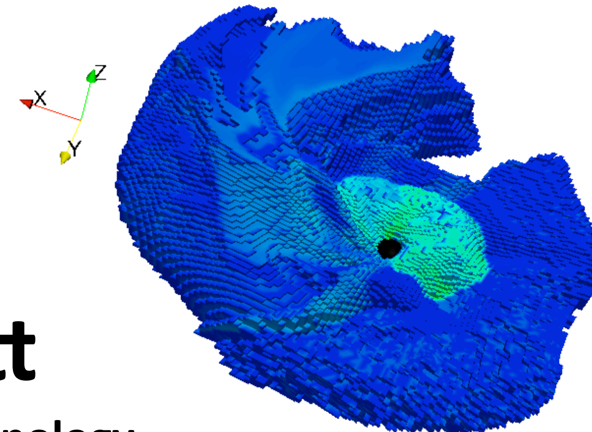
How to Rattle & Shine right

– Microphysics: What, When, Why, How? –





Christian D. Ott

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for the

Simulating eXtreme Spacetimes (SXS) Hydro Team

WSU: Brett Deaton, Fatemeh Nouri, **Matt Duez (team leader)**

Caltech: Jeff Kaplan, Roland Haas, Philipp Mösta, Evan O'Connor (->CITA), Mark Scheel, Béla Szilágyi

Cornell: Curran Muhlberger, Saul Teukolsky, Larry Kidder

CITA: Francois Foucart

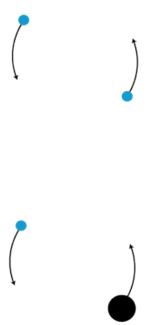
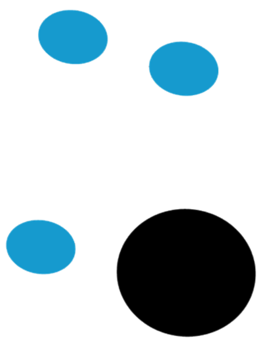
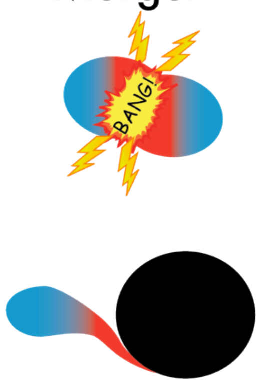
Outline of this Talk

- Overview of microphysical aspects of NS-NS and NS-BH mergers.
- Nuclear EOS and how to include it in your simulations.
- Neutrinos and how to include them in your simulations.
- Some results of BH-NS simulations with nuclear EOS and neutrinos with the Simulating eXtreme Spacetimes (SXS) code **SpEC**.

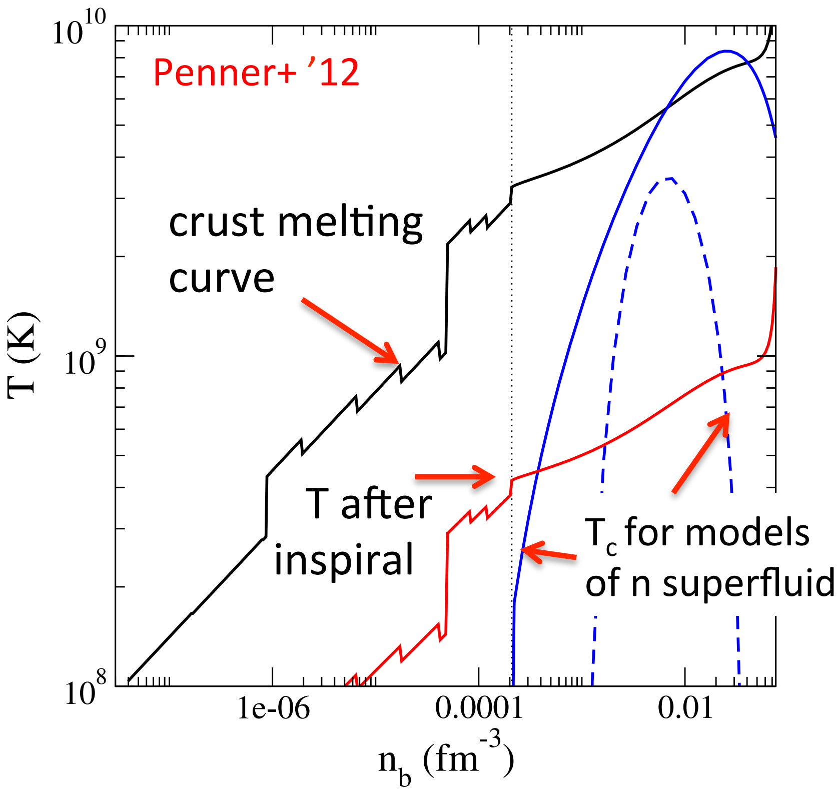
Overview: The What and The When

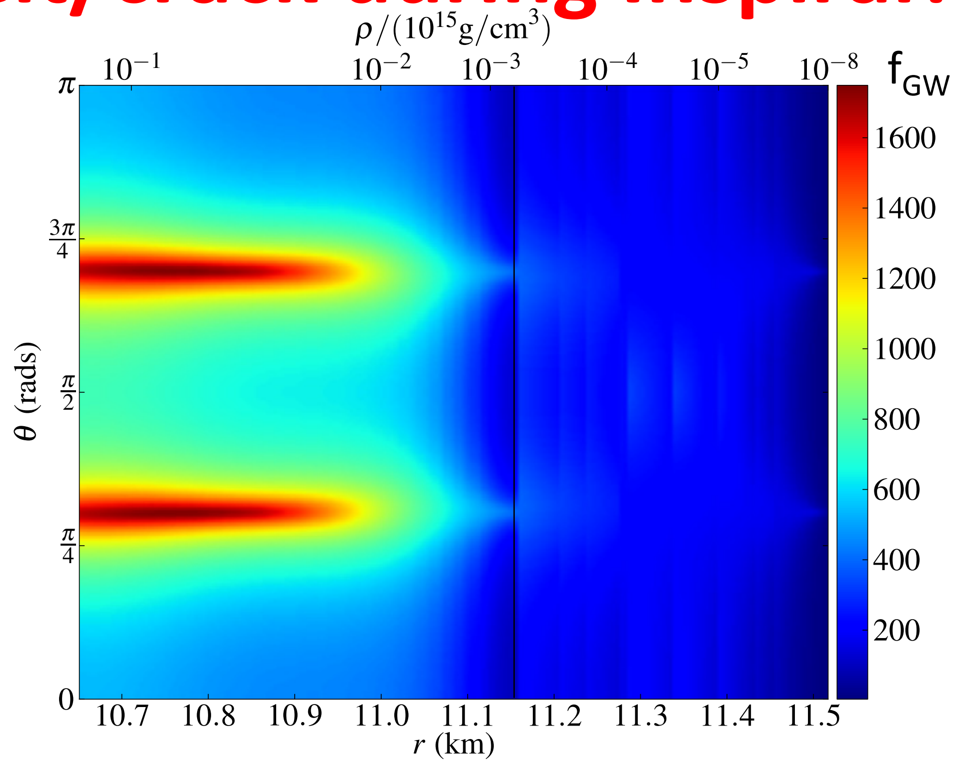
Nuclear Equation of State (EOS) Crust Physics & Superfluidity (SF)

Neutrinos/Neutrino Interactions Nuclear Reactions & Opacities

Inspiral	Late Inspiral	Merger	Postmerger		Late Time (t >~1s)
				GRB?	
Inspiral	Late Inspiral	Merger/Disruption	Postmerger		
	Crust/SF				
	EOS	EOS	EOS	EOS	
		Neutrinos	Neutrinos	Neutrinos	Neutrinos
	see Gail McLaughlin's talk →		Nuclear	Nuclear	Nuclear

Does the Crust fail/melt/crack during Inspiral?





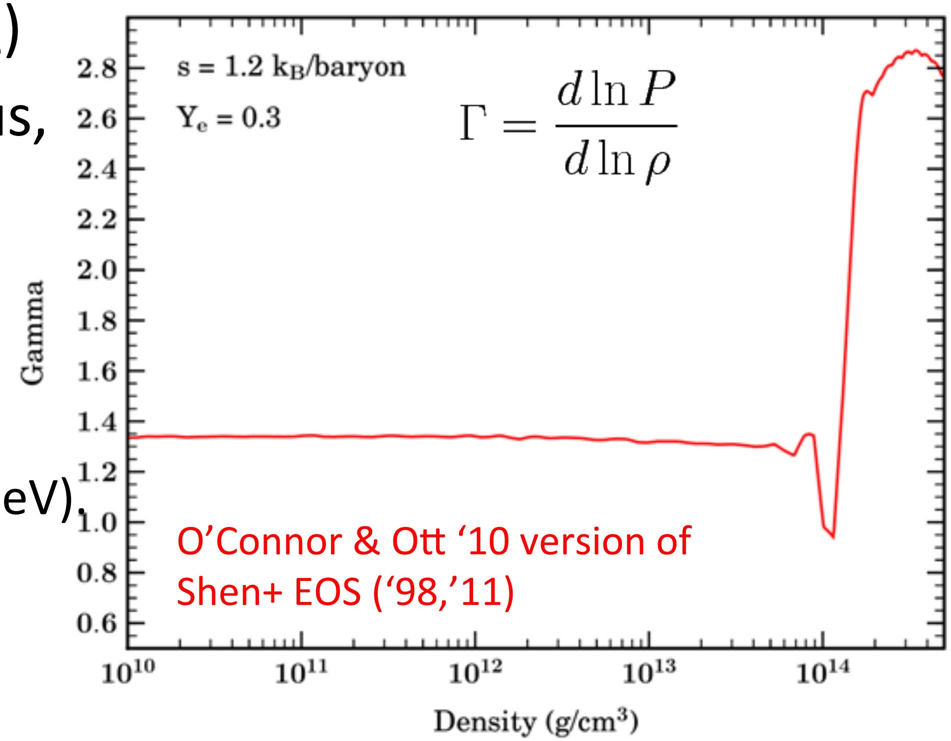
Penner+ '12

- Crust will not melt/fail completely during inspiral, but may fracture (Tsang+ '12 -> see poster, Penner+ '12). Superfluidity will persist.
- Crust: Influence on tidal deformability (Love number) very small.
- Superfluid n, superconducting p: influence on EOS small, but important for crust-core coupling, pulsations, neutrino interactions.

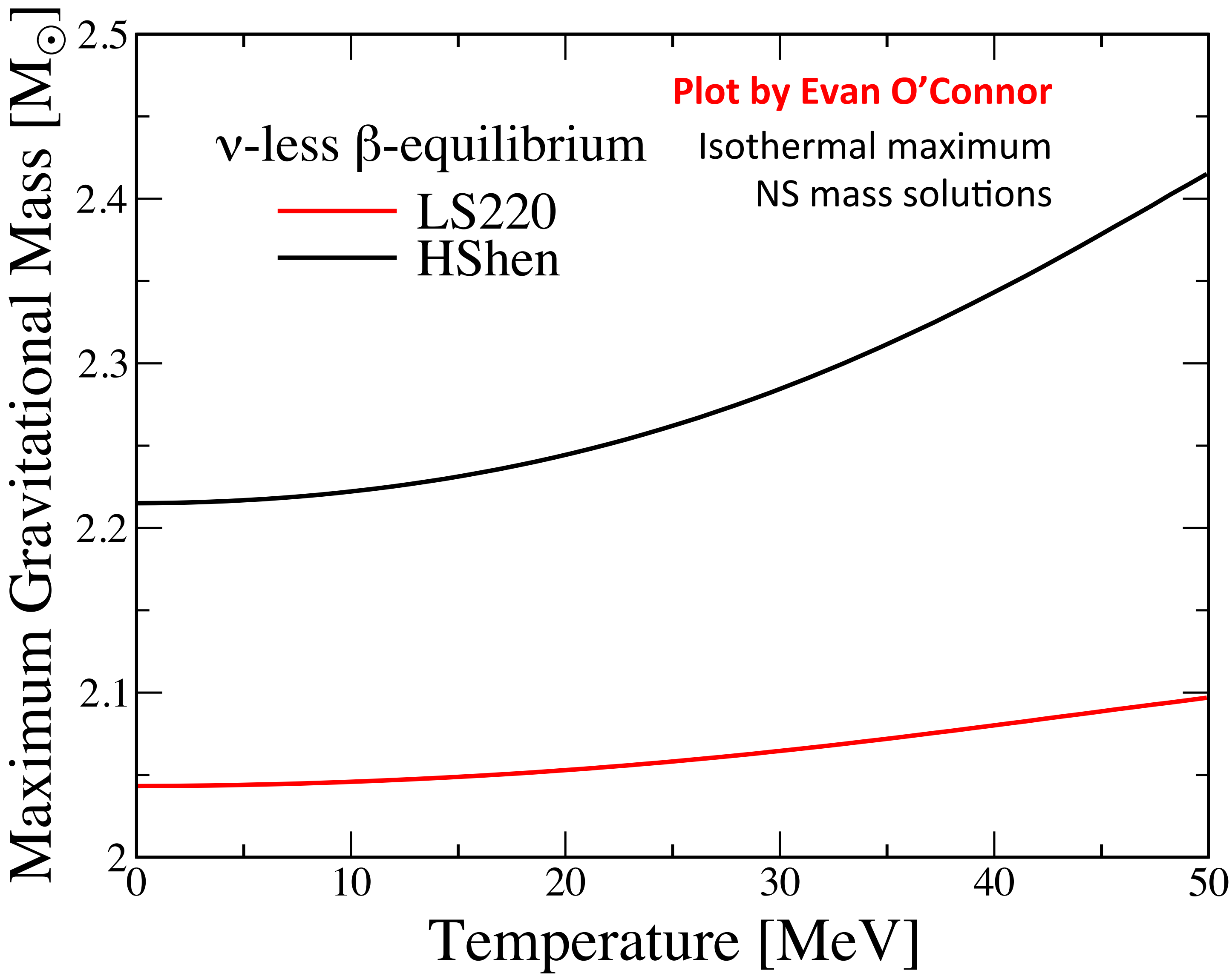
Hot Microphysical Equation of State

(more details in Sanjay Reddy's talk tomorrow)

- Nuclear statistical equilibrium (NSE) at T > 0.5 MeV (~5x10^9 K). Helmholtz Free Energy $F=F(\rho,T,Y_e)$
- Nucleons, alphas, average nucleus, electrons, photons.
- Near nuclear density: EOS "stiffens" due to repulsive core of nuclear force potential.
- $P \propto T^2$ above ρ_{nuc} (relevant if $T \gg 1$ MeV). Complicated $\propto$ T, T^2, T^4 at low ρ.



Temperature Dependence of NS M_{max}



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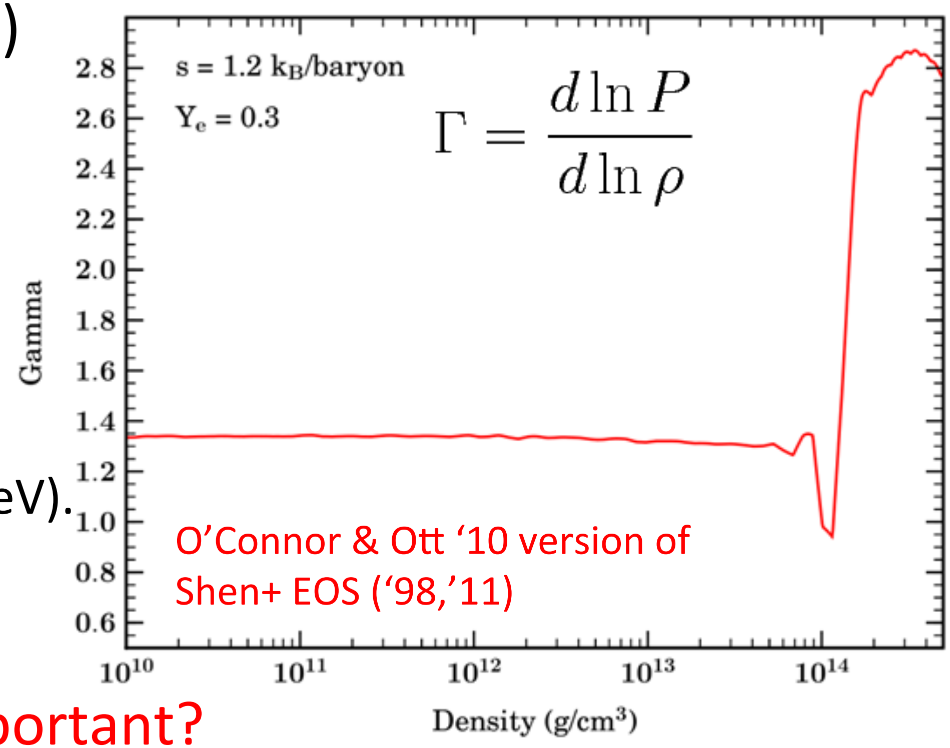


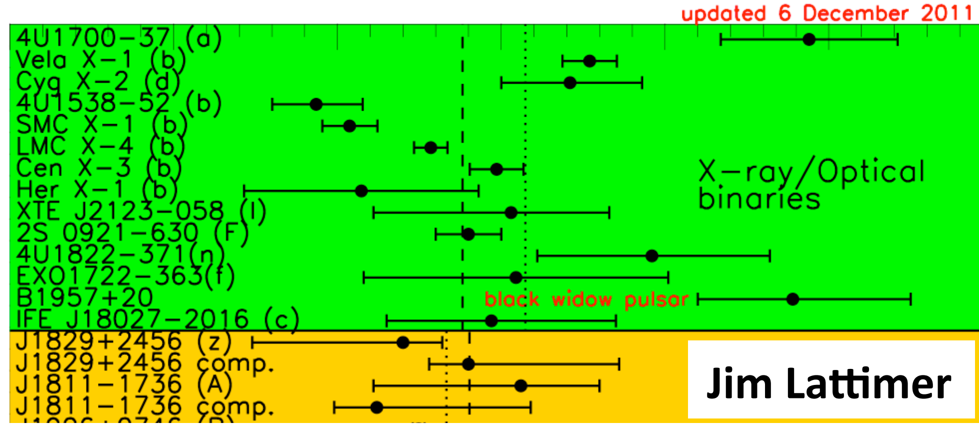
Why is a hot microphysical EOS important?

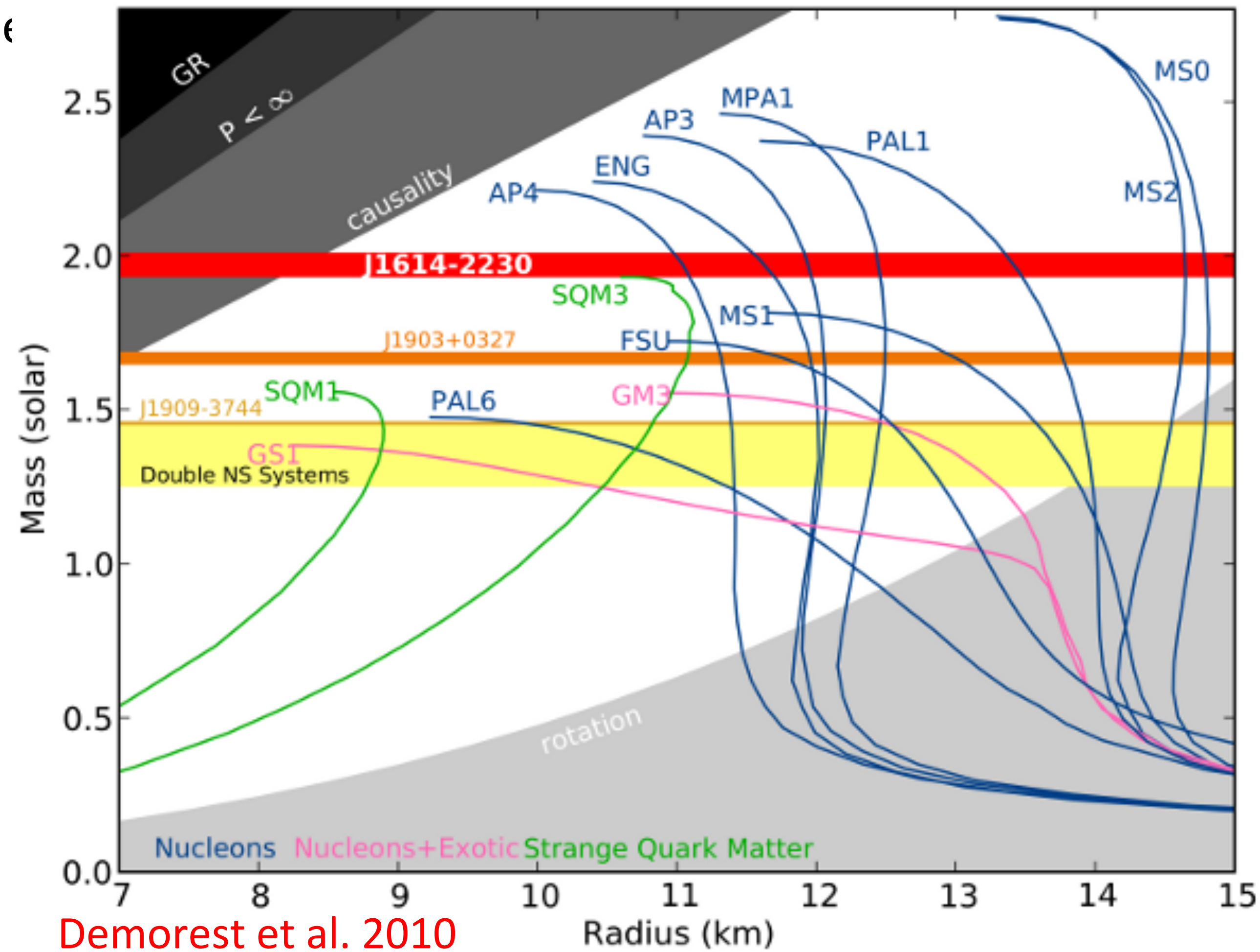
- NS structure/radius, tidal deformability (<- can also get this from cold EOS)
- Structure, dynamics, & survival of merged object or delay to BH formation.
- Thermal support of envelope/disk, disk mass.
- Composition, chemical potentials (-> neutrinos).

Constraints on the Nuclear EOS

Maximum NS Mass:

- Most solid if binary inclination constrained by Shapiro de
- **J1614-2230**
  Demorest et al. 2010:
  1.97 +/- 0.04 M_{Sun}

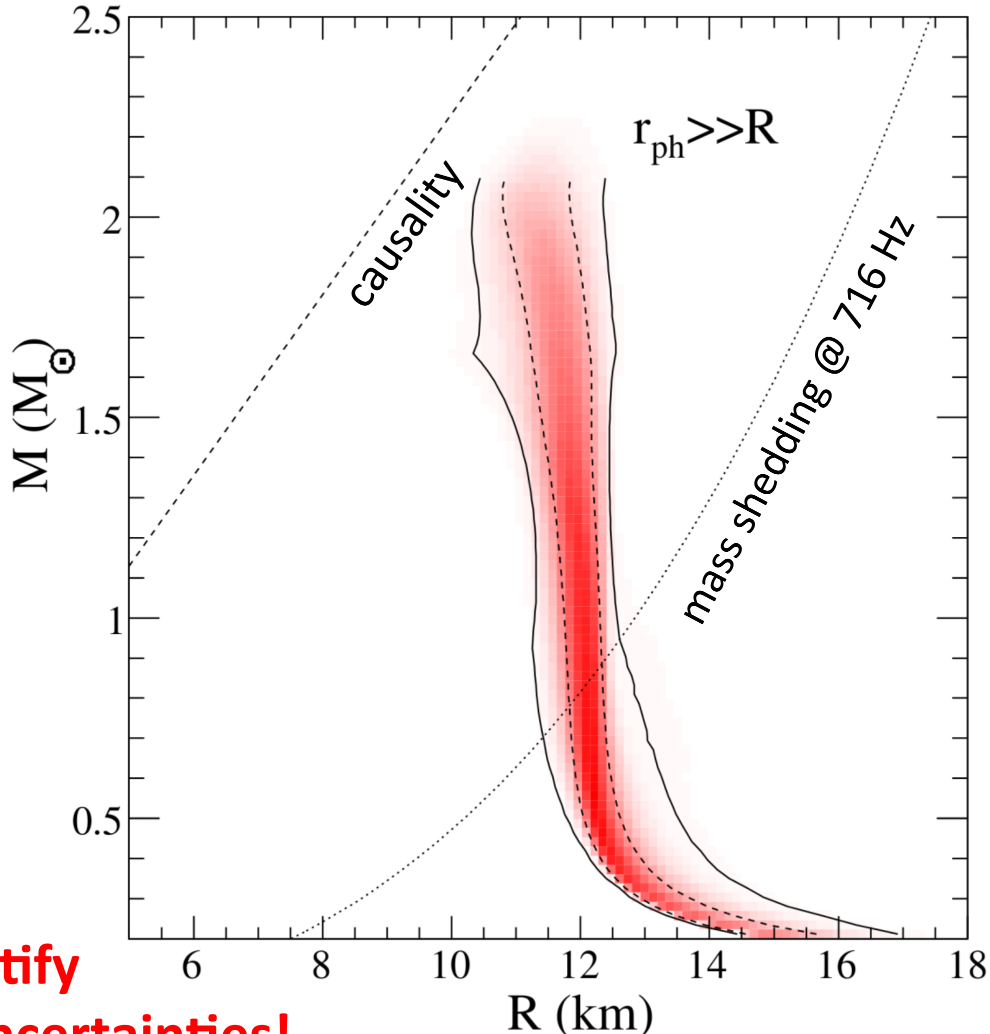




Demorest et al. 2010

Constraints on the Nuclear EOS (3)

- NS Radius Constraints from Type-1 X-Ray Burst Observations + Bayesian inference model: Steiner, Lattimer, Brown '10; Özel et al. '10

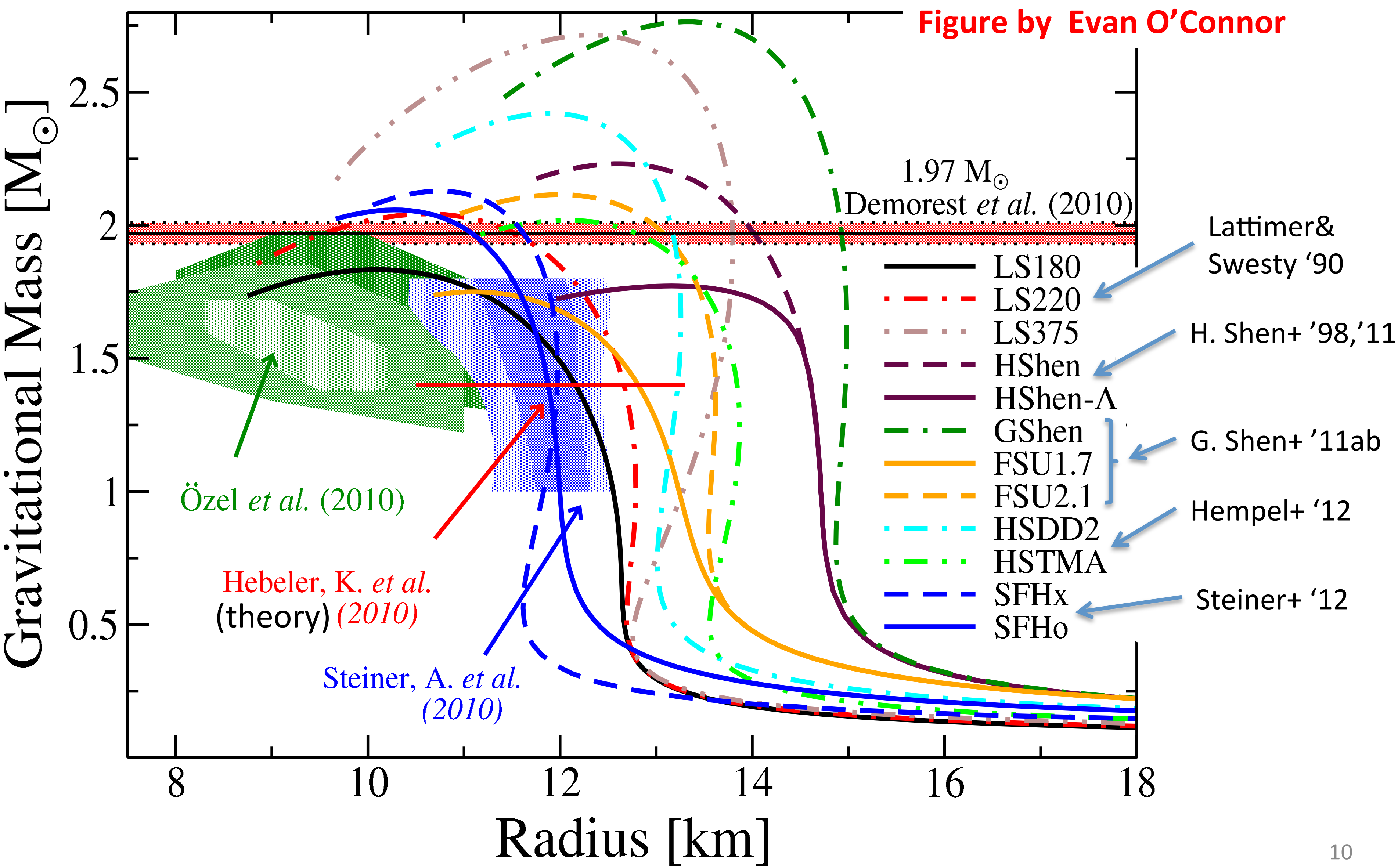


credit: Tony Piro

Warning:
Hard to quantify systematic uncertainties!

Constraints on the Nuclear EOS (4)

- Application to available microphysical finite-temperature EOS:



The How: Including a Nuclear EOS

Cold nuclear EOS: $P = P_{\rm cold}(\rho) + (\Gamma_{\rm th} - 1)\rho\epsilon$

Or: piecewise-polytropic fit + thermal component: **Read+ '09**

$$P = [K\rho^{\Gamma}]_i + (\Gamma_{\rm th} - 1)\rho\epsilon$$

Shibata+ '05, Shibata & Taniguchi '06, Kiuchi+ '09, Baiotti+ '10, Hotokezaka+ '11, Thierfelder+ '11, Kyutoku+'11, Bauswein '10, '12ab, ...

Problem: No compositional information.

No good way to include neutrinos.

Outcome quite sensitive to choice of $\Gamma_{\rm th}$ (Bauswein+ '10).

The How: Including a Nuclear EOS

Cold nuclear EOS: $P = P_{\mathrm{cold}}(\rho) + (\Gamma_{\mathrm{th}} - 1)\rho\epsilon$

Or: piecewise-polytropic fit + thermal component: **Read+ '09**

$$P = [K\rho^{\Gamma}]_i + (\Gamma_{\mathrm{th}} - 1)\rho\epsilon$$

The Real Thing: $P = P(\rho, T, Y_e)$

Pioneered by: Ruffert+ '96, '97, Rosswog+ '99,'00, Ruffert & Janka '01, Rosswog & Davies '02, Rosswog & Ramirez-Ruiz '02, Rosswog & Liebendörfer '03, Rosswog+ '04,'05ab, Oechslin+ '06,'07ab, Bauswein+ '10, Bauswein+ '12ab, Duez+ '10, Sekiguchi+ '11, '12, Rosswog+ '12, ...

The How: Including a Nuclear EOS

Cold nuclear EOS: $P = P_{\rm cold}(\rho) + (\Gamma_{\rm th} - 1)\rho\epsilon$

Or: piecewise-polytropic fit + thermal component: **Read+ '09**

$$P = [K\rho^\Gamma]_i + (\Gamma_{\rm th} - 1)\rho\epsilon$$

The Real Thing: $P = P(\rho, T, Y_e)$

Necessary steps:

- Get nuclear EOS table; add electrons/positrons & photons.
- Ensure correct zero point of specific internal energy for GR calculations.
- Code efficient interpolator (linear interpolation + dense EOS table).
- Test for thermodynamic consistency.
- Inversion routine (Newton-Raphson/Bisection): ε -> T.
- Solve advection equation for Y_e. Set up NSs in neutrinoless β equilibrium.
- Handle non-NSE regime (approximately or fully consistently).

Open-Source EOS Routines and Tables

https://www.stellarcollapse.org/equationofstate

(described in O'Connor & Ott '10)

Open-source EOS driver routines and EOS tables:

- **`EOSMaker`**: Fortran 90 routines that take raw nuclear EOS table and generate complete EOS table in HDF5 format.
- **`EOSDriver`**: Fortran 90 reader/interpolator routines that return thermodynamic variables for calls with (ρ,T,Y_e), (ρ,e,Y_e), and (ρ,s,Y_e).
- C & GPU-enabled versions in preparation.
- Included in the **Einstein Toolkit** (http://einsteintoolkit.org).
- Pre-made EOS tables for the following EOS:
LS180, LS220, LS375, HShen (2011), GShen, Hempel+ and (new!) SFH*.

Open-Source EOS Routines and Tables

https://www.stellarcollapse.org/equationofstate

EOS variant	Table name and link
Lattimer and Swesty EOS, website	
LS EOS, K = 180 MeV	LS180_234r_136t_50y_analmu_20091212_SVNr26.h5.bz2
LS EOS, K = 220 MeV	LS220_234r_136t_50y_analmu_20091212_SVNr26.h5.bz2
LS EOS, K = 375 MeV	LS375_234r_136t_50y_analmu_20091212_SVNr26.h5.bz2
H. Shen et al. EOS, website	
H. Shen EOS (2011, EOS2)	HShenEOS_rho220_temp180_ye65_version2.0_20111026_EOSmaker_svn9.h5.bz2
G. Shen et al. EOS (NL3) G. Shen et al. EOS (FSU), website	
GShen EOS, NL3	GShen_NL3EOS_rho280_temp180_ye52_version1.03_20120730.h5.bz2
GShen EOS, FSU1.7	GShenFSU_1.7EOS_rho280_temp180_ye52_version1.01_20120730.h5.bz2
GShen EOS, FSU2.1	GShenFSU_2.1EOS_rho280_temp180_ye52_version1.01_20120730.h5.bz2
Hempel et al. EOS**, website	
HS EOS, TMA	Hempel_TMA_SCEOS_rho234_temp180_ye60_version1.0_20120730.h5.bz2
HS EOS, TM1	Hempel_TM1_SCEOS_rho234_temp180_ye60_version1.0_20120730.h5.bz2
HS EOS, FSG	Hempel_FSG_SCEOS_rho234_temp180_ye60_version1.0_20120730.h5.bz2
HS EOS, NL3	Hempel_NL3_SCEOS_rho234_temp180_ye60_version1.0_20120730.h5.bz2
HS EOS, DD2	Hempel_DD2_SCEOS_rho234_temp180_ye60_version1.0_20120730.h5.bz2
Steiner et al. EOS**, website	
SFH EOS, SFHo	Hempel_SFHo_SCEOS_rho222_temp180_ye60_version1.0_20120730.h5.bz2
SFH EOS, SFHx	Hempel_SFHx_SCEOS_rho234_temp180_ye60_version1.0_20120730.h5.bz2
**Please be aware that the Hempel et al. and Steiner et al. EOS have light nuclei in addition to neutron, protons, alphas and a characteristic heavy nucleus. These include deutrons, tritons, helions, and 4Li nuclei. There effect the compositions, and therefore neutrino interactions. All eight mass fractions are available in the H5 table, however the EOSdriver routines must be modified to access them.	

Neutrinos!

not shown: anti-neutrinos

http://particlezoo.net/

Neutrino Interactions in NS-NS & NS-BH Mergers

- Charged-current and neutral-current interactions; may deal with three neutrino "species": $\nu_e, \bar{\nu}_e, \nu_x = \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$
- Relevant interactions: e.g., Ruffert+ '96, Rosswog & Liebendörfer '03, Burrows+ '06

Scattering

$$\nu_i + (n,p) \longrightarrow \nu_i + (n,p) \;\propto T^2$$

Open-source implementation of interaction rates: nulib.org

Emission & Absorption

$$\left.\begin{array}{l} e^- + p \longleftrightarrow n + \nu_e \\ e^+ + n \longleftrightarrow p + \bar{\nu}_e \end{array}\right. \propto T^6$$

$$e^- + e^+ \longleftrightarrow \nu_i + \bar{\nu}_i$$

$$\gamma \longrightarrow \nu_i + \bar{\nu}_i \;\propto T^6 - T^9$$

$$(n,p) + (n,p) \longleftrightarrow (n,p) + (n,p) + \nu_i + \bar{\nu}_i$$

-> Neutrino emission becomes strong only at merger!

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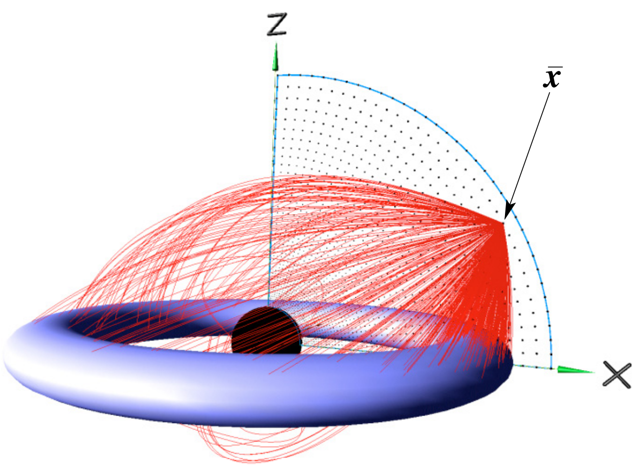

Birkl+ '07

Emission & Absorption

$$\left.\begin{aligned} e^- + p &\longleftrightarrow n + \nu_e \\ e^+ + n &\longleftrightarrow p + \bar{\nu}_e \end{aligned}\right. \;\propto T^6$$

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Neutrino-pair annihilation: $\nu_i + \bar{\nu}_i \longrightarrow e^- + e^+$
Potential important source of pair plasma for GRB fireball!

Neutrino Interactions in NS-NS & NS-BH Mergers

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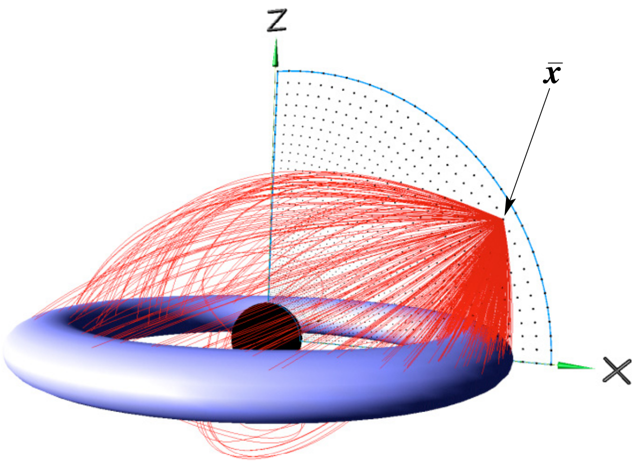


Birkl+ '07

Emission & Absorption

$$\left.\begin{array}{l} e^- + p \longleftrightarrow n + \nu_e \\ e^+ + n \longleftrightarrow p + \bar{\nu}_e \end{array}\right\} \propto T^6$$

Crucial in determining Y_e of disk and unbound material -> important for r-process nucleosynthesis (-> Gail's talk).

Neutrino-pair annihilation: $\nu_i + \bar{\nu}_i \longrightarrow e^- + e^+$
Potential important source of pair plasma for GRB fireball!

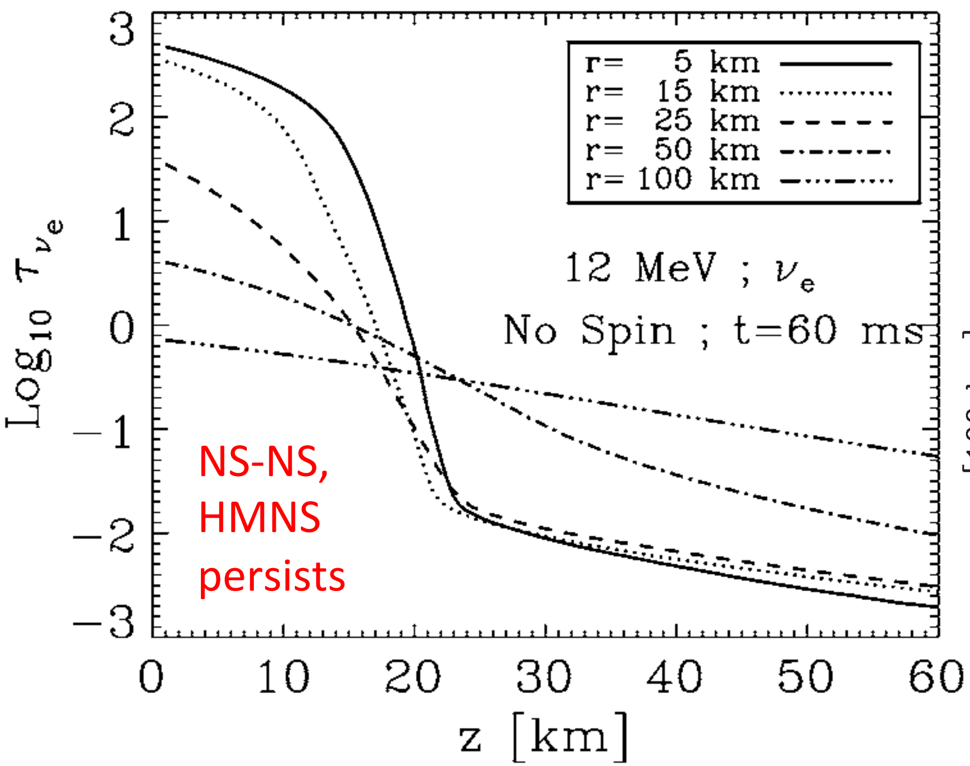
Neutrinos: Why bother?

$$1/\kappa_{\rm total} = \lambda \approx \text{few} \times 10^3 \left(\frac{10^{13}\,\mathrm{g\,cm^{-3}}}{\rho}\right)\left(\frac{10\,\mathrm{Mev}}{T}\right)^2 \mathrm{cm}$$

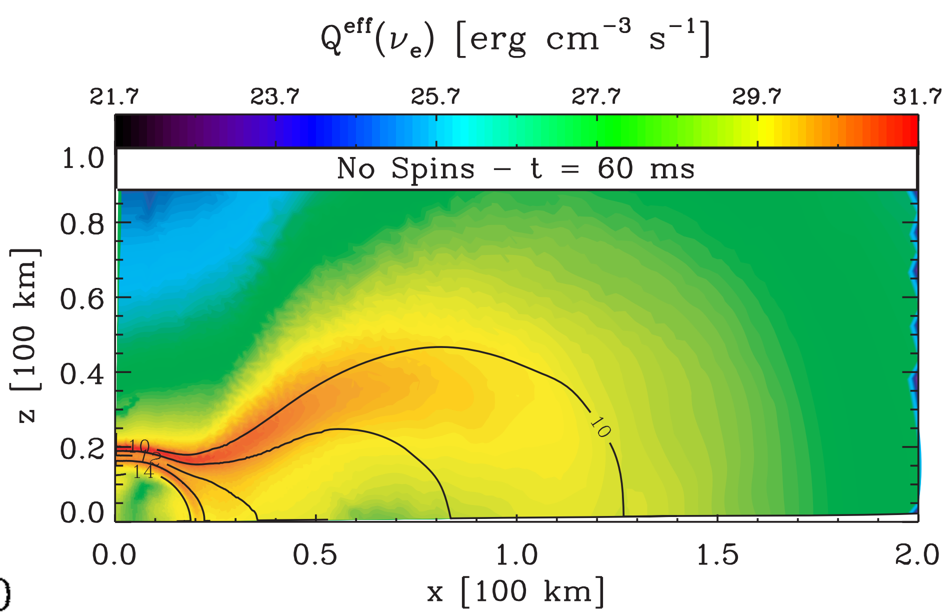
$$t_{\rm diff} \approx \frac{3}{c}\tau\Delta r \qquad \tau(r) \approx \int_r^{\text{far away}} \kappa_{\rm total}\, dr$$

"Neutrinosphere"

$$\tau_\nu \approx 1$$



Dessart, Ott+ '09



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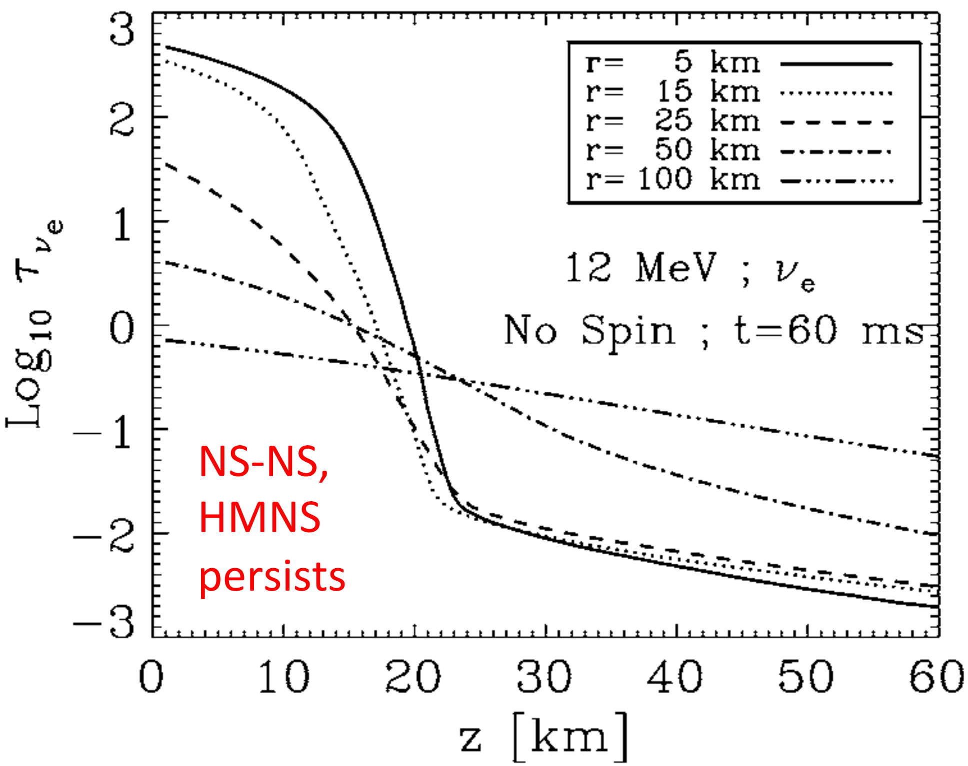
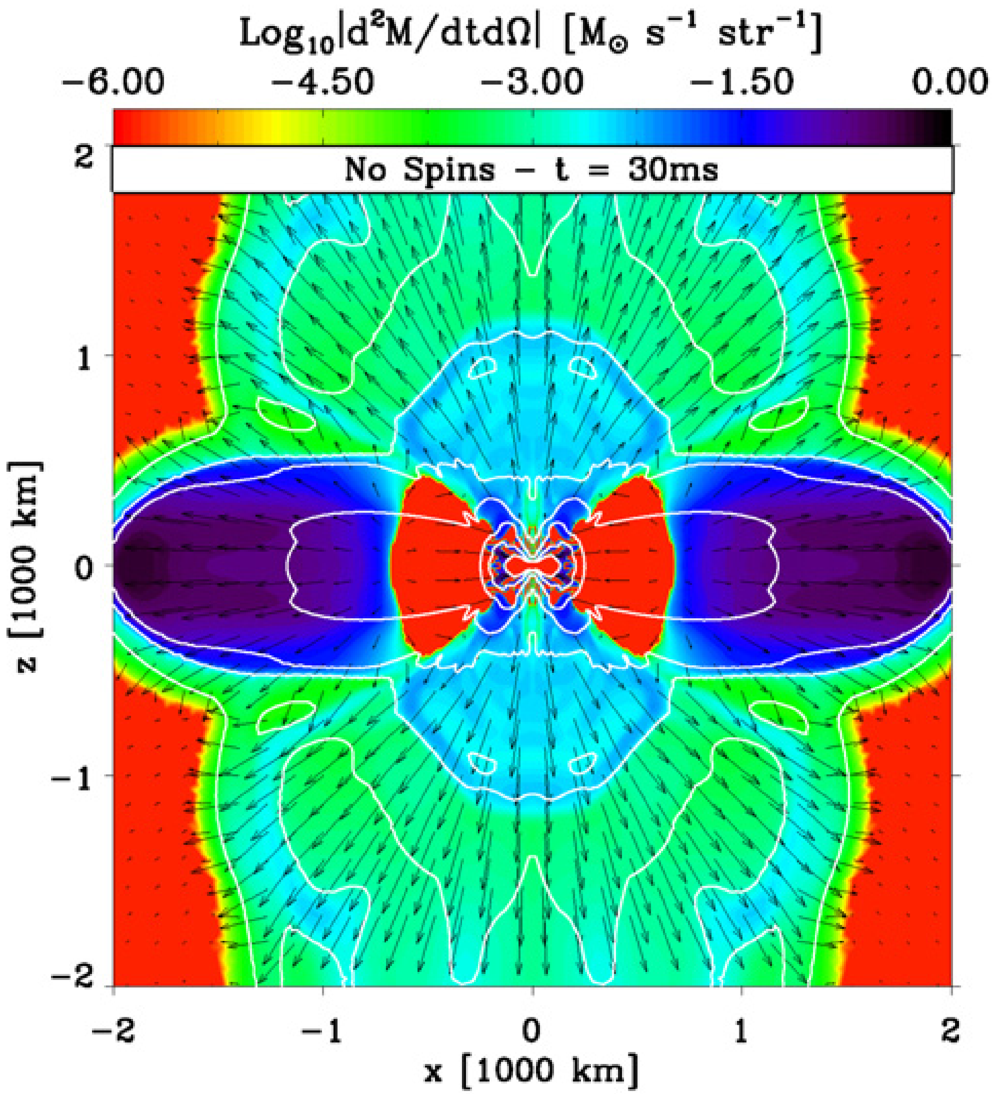


Dessart, Ott+ '09

- Neutrinos important for cooling of inner disk & envelope of HMNS. Cooling timescale: O(10-100) ms
- Pair annihilation
- Nucleosynthesis
- Neutrino signal possibly observable for event at 5 Mpc (Sekiguchi+ 11).

Neutrino-Driven Wind

Dessart, Ott+ '09



- Present, if HMNS survives for > 10-100 ms.
- Energy & momentum deposition: ejection of neutron-rich matter.
- long-term survival of merged object in low-mass NS-NS systems.
- Dessart+ '09 was Newtonian, but included spectral neutrino transport.
  -> need to check in GR.

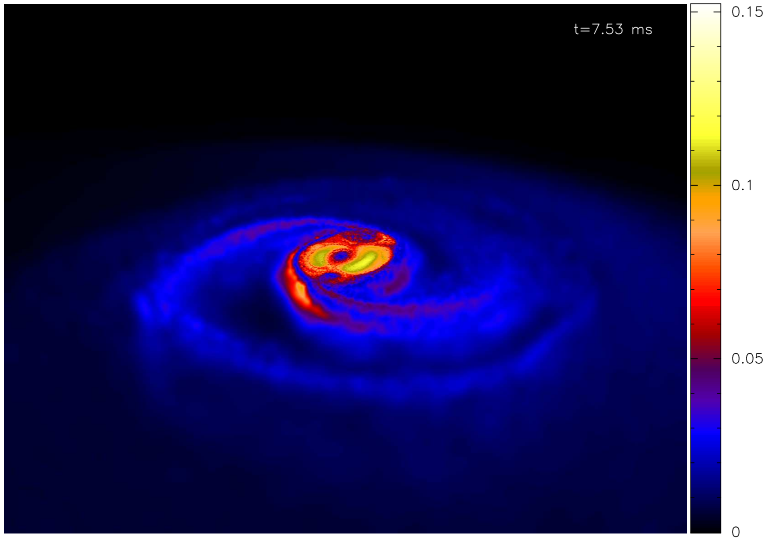
Neutrinos: The How

- Must solve/approximate transport of neutrinos: 6+1 D problem.
- Standard diffusion approximation fails – cannot handle transition to free streaming.

Common approaches (in the NS-NS/NS-BH context):

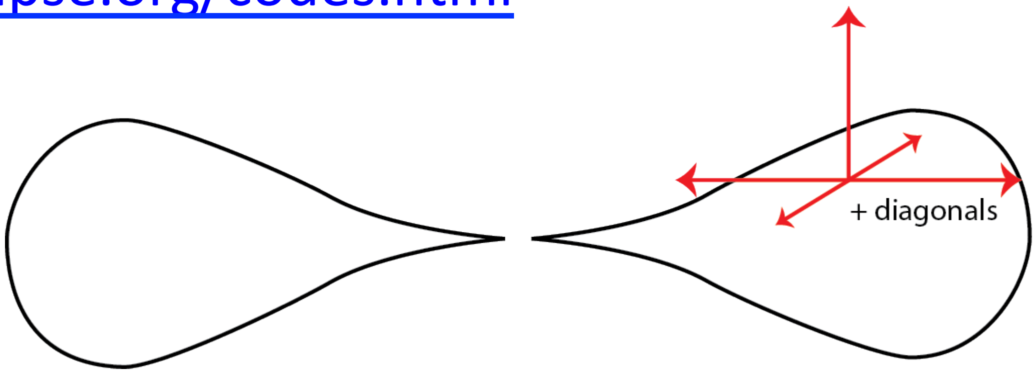
- Energy-averaged, multi-species neutrino "leakage".
  Ruffert+ '96, '97, Ruffert & Janka '01, Rosswog & Liebendörfer '03, Rosswog+ '04,'05ab, Lee & Ramirez-Ruiz+ '04,'05, Sekiguchi+ '11, '12, Rosswog+ '12, ...
- Multi-group flux-limited diffusion.
  Dessart+ '09 (5+1 D post-processing)
- New: GR two-moment schemes with analytic closures based on Thorne's GR moment expansion of the radiation field (Shibata+ '10).
- Ray-tracing for pair annihiliation estimates (see Birkl+ '07 and refs.).

Rosswog+ 12'; Y_e, leakage



Getting Neutrinos into Your Code

- Simplest, yet still state-of-the-art approach: **Neutrino Leakage**
- Open-source implementation: O'Connor & Ott '10 as part of **GR1D** code: http://stellarcollapse.org/codes.html
- Multi-D implementation:
  - Cast rays in multiple directions at points of an auxilliary grid to compute optical depth. Use minimum value.



  - **All other computations are fully local** and can be taken directly from GR1D's leakage routines. Get neutrino energy and number loss rates to be included in hydro update.
  - Possible to include neutrino pressure in optically-thick region.
  - 3D implementation used in stellar collapse (Ott+ '12) soon available as part of the **Einstein Toolkit** (though only radial rays from center).

Simulation of BH-NS Coalescence with Nuclear EOS and Neutrinos

– Preliminary Results –

Duez+ in Preparation

Simulating eXtreme Spacetimes (SXS) Hydro Team

WSU: Brett Deaton, Fatemeh Nouri, **Matt Duez (team leader)**

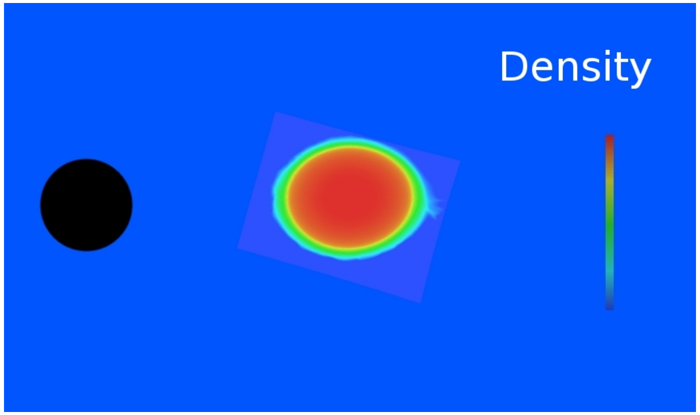
Caltech: Jeff Kaplan, Roland Haas, Philipp Mösta, Evan O'Connor (->CITA), Mark Scheel, Béla Szilágyi

Cornell: Curran Muhlberger, Saul Teukolsky, Larry Kidder

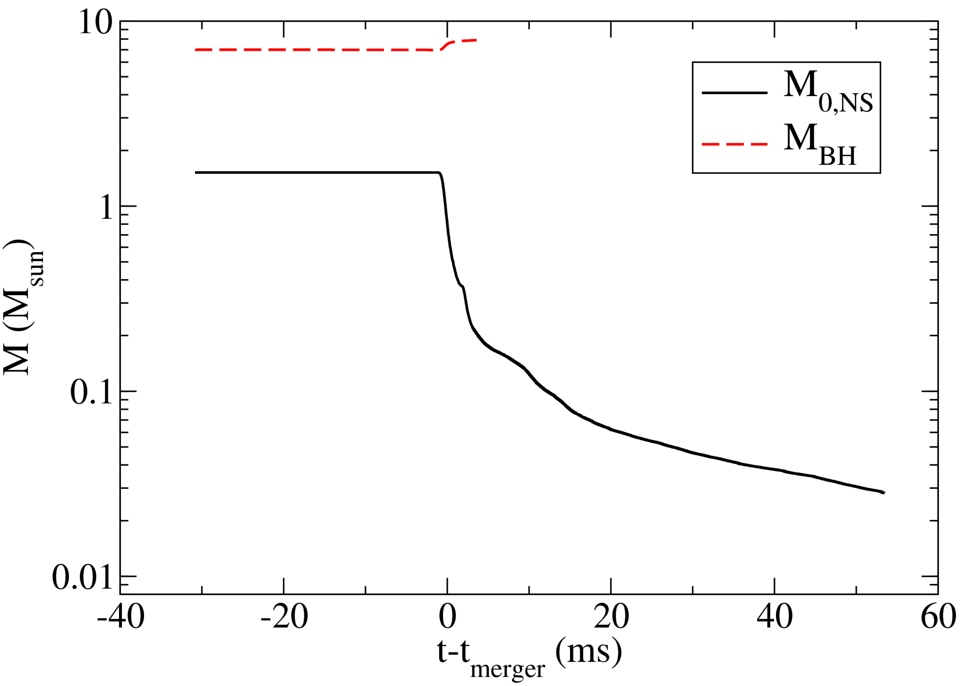
CITA: Francois Foucart

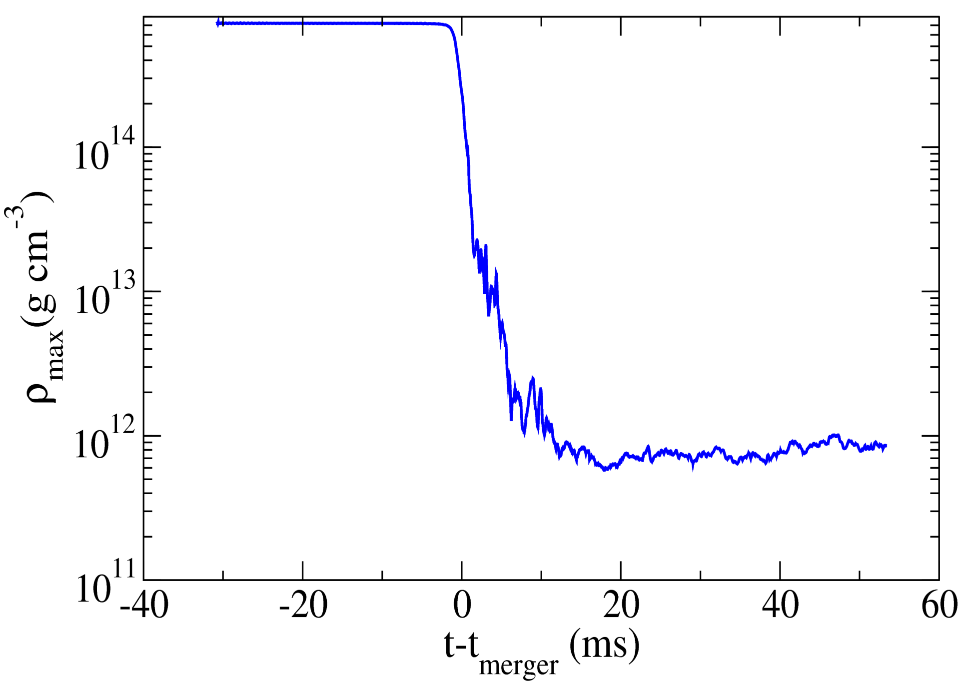
Simulation Setup & Initial Data

- SXS SpEC code (see Lovelace talk for vacuum part):
  - Pseudospectral spacetime evolution.
  - Comoving grid & excision. Pseudospectral grid extends to wave zone.
  - Finite-volume high-resolution shock capturing hydrodynamics.
  - Leakage scheme following O'Connor & Ott '10.
- $M_{NS,grav} = 1.4\ M_{Sun}$, $M_{BH} = 5.6\ M_{Sun}$ (mass ratio 4:1).
- BH spin: $a_* = 0.9$.
- Initial separation corresponding to 6 orbits before disruption.
- Lattimer & Swesty 220 EOS.



SpEC NS-BH Simulations with hot EOS & Neutrinos





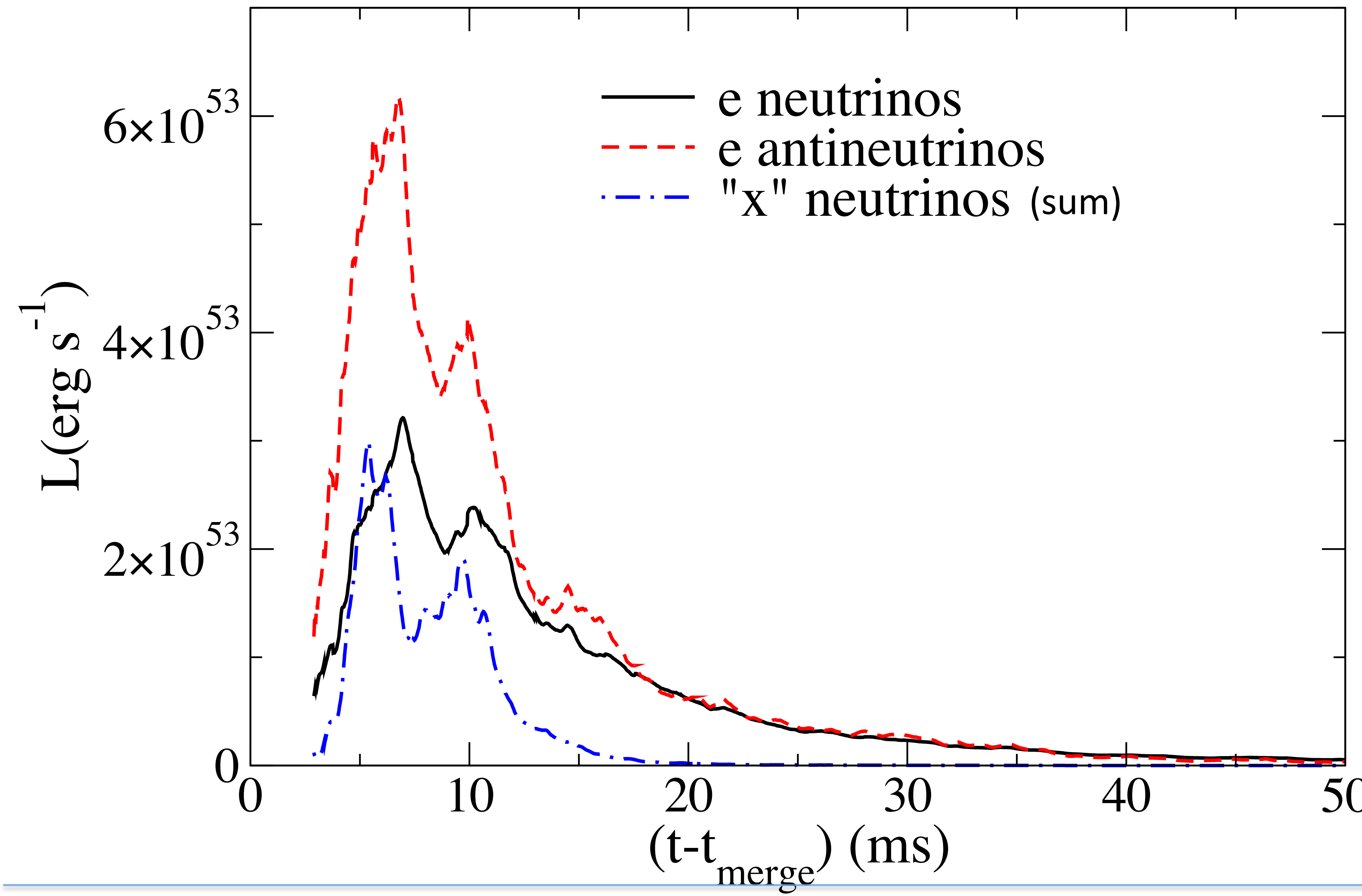
Evolved for 30 ms before and 55 ms after merger.

Spacetime evolution switched off few ms after onset of merger.

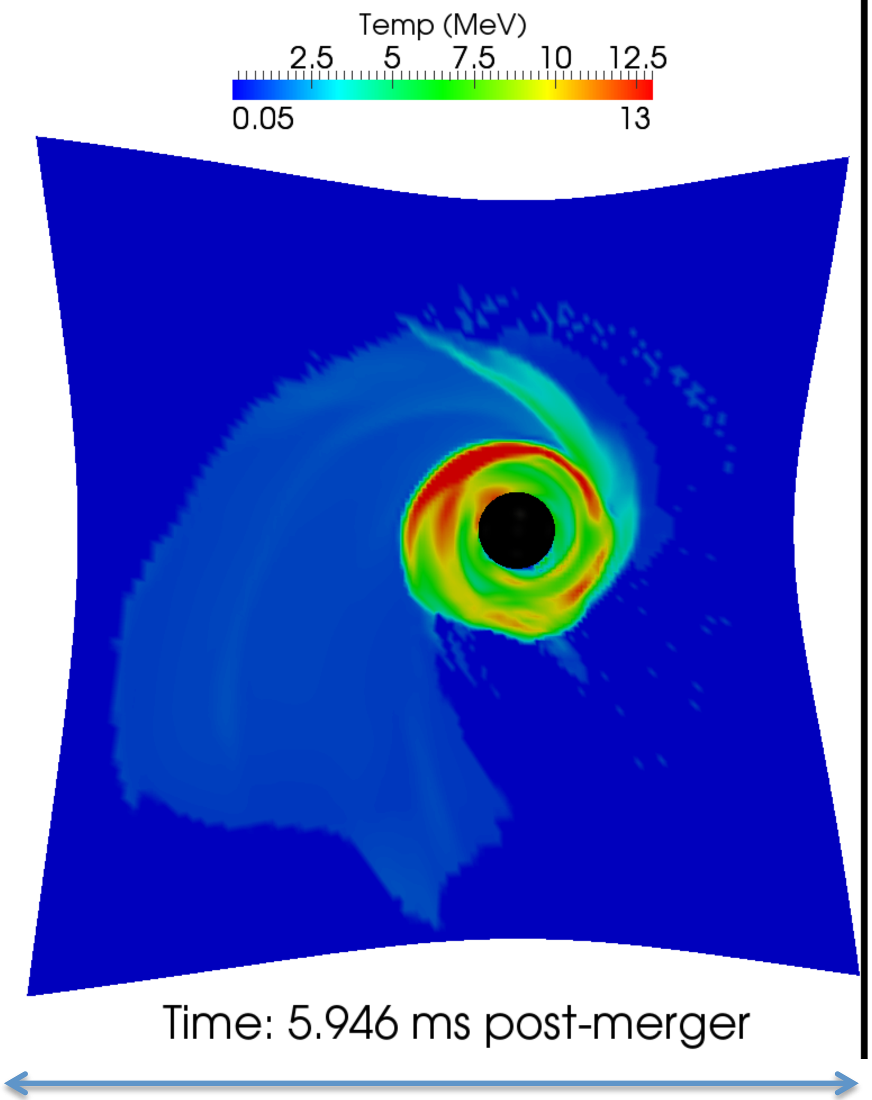
Initial disk mass ~0.1 M_{Sun}

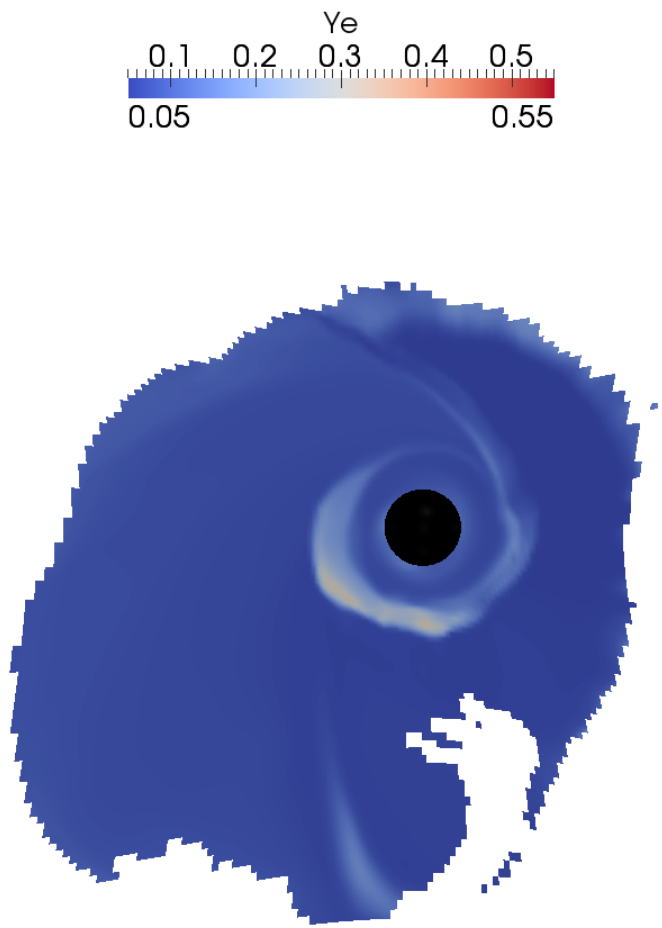
Ejecta mass estimate: ~0.03 M_{Sun} (large uncertainty)

SpEC NS-BH Simulations: Neutrino Luminosities



SpEC NS-BH Simulations with hot EOS & Neutrinos

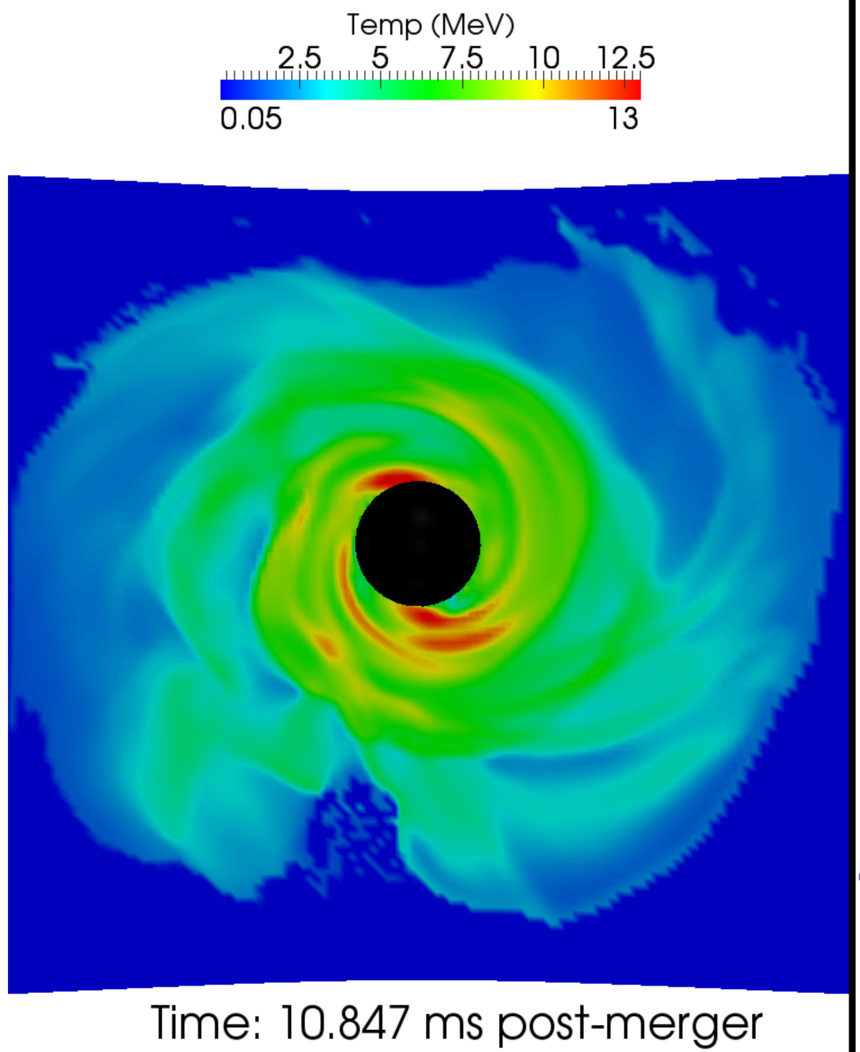




~200 km (with radial stretching)

Figure by Jeff Kaplan.

SpEC NS-BH Simulations with hot EOS & Neutrinos



~150 km (with radial stretching)

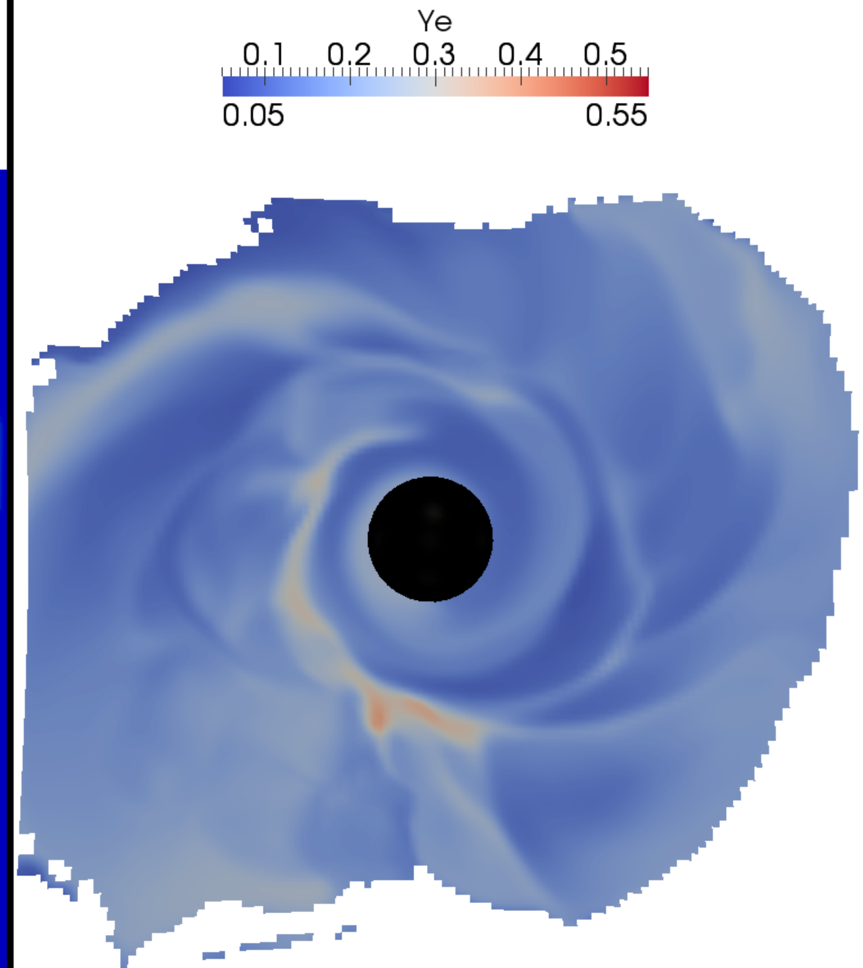
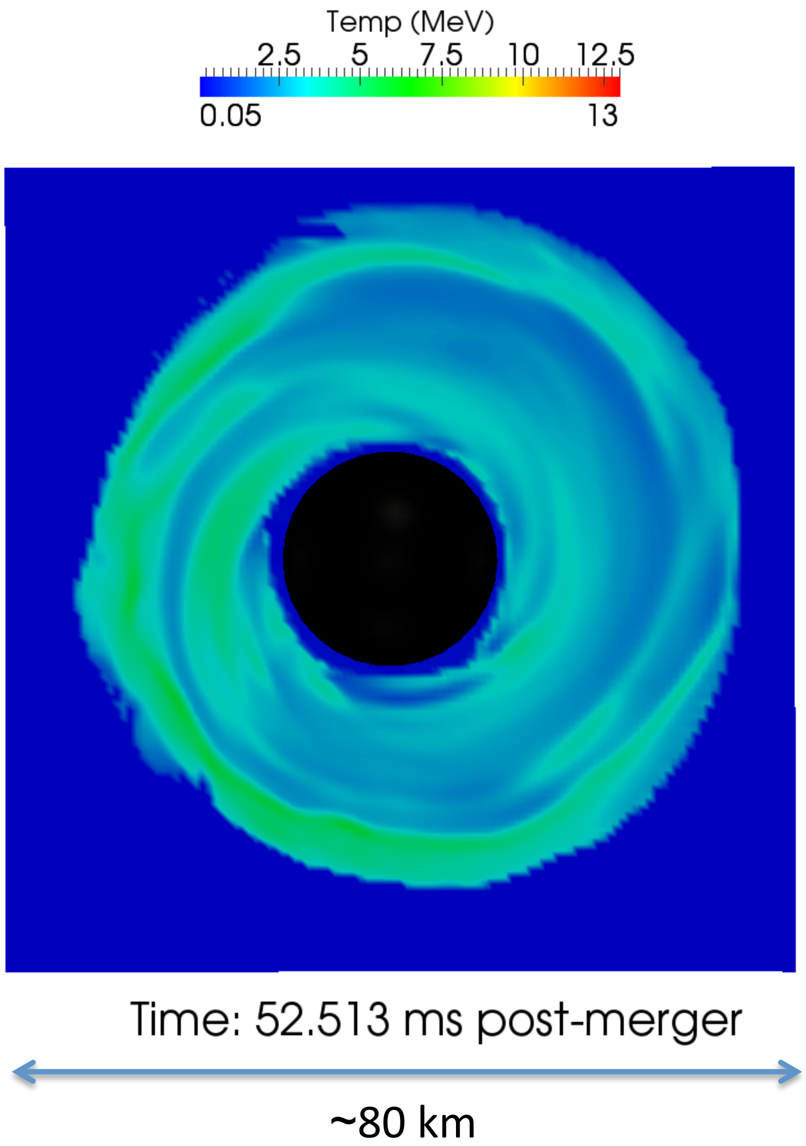


Figure by Jeff Kaplan.

SpEC NS-BH Simulations with hot EOS & Neutrinos



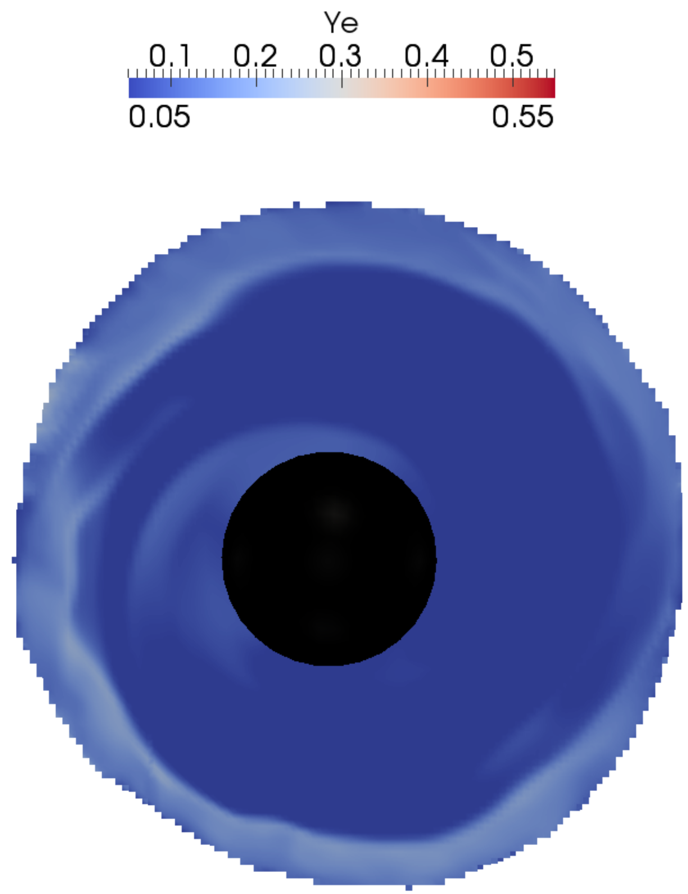


Figure by Jeff Kaplan.

3D Temperature Distribution

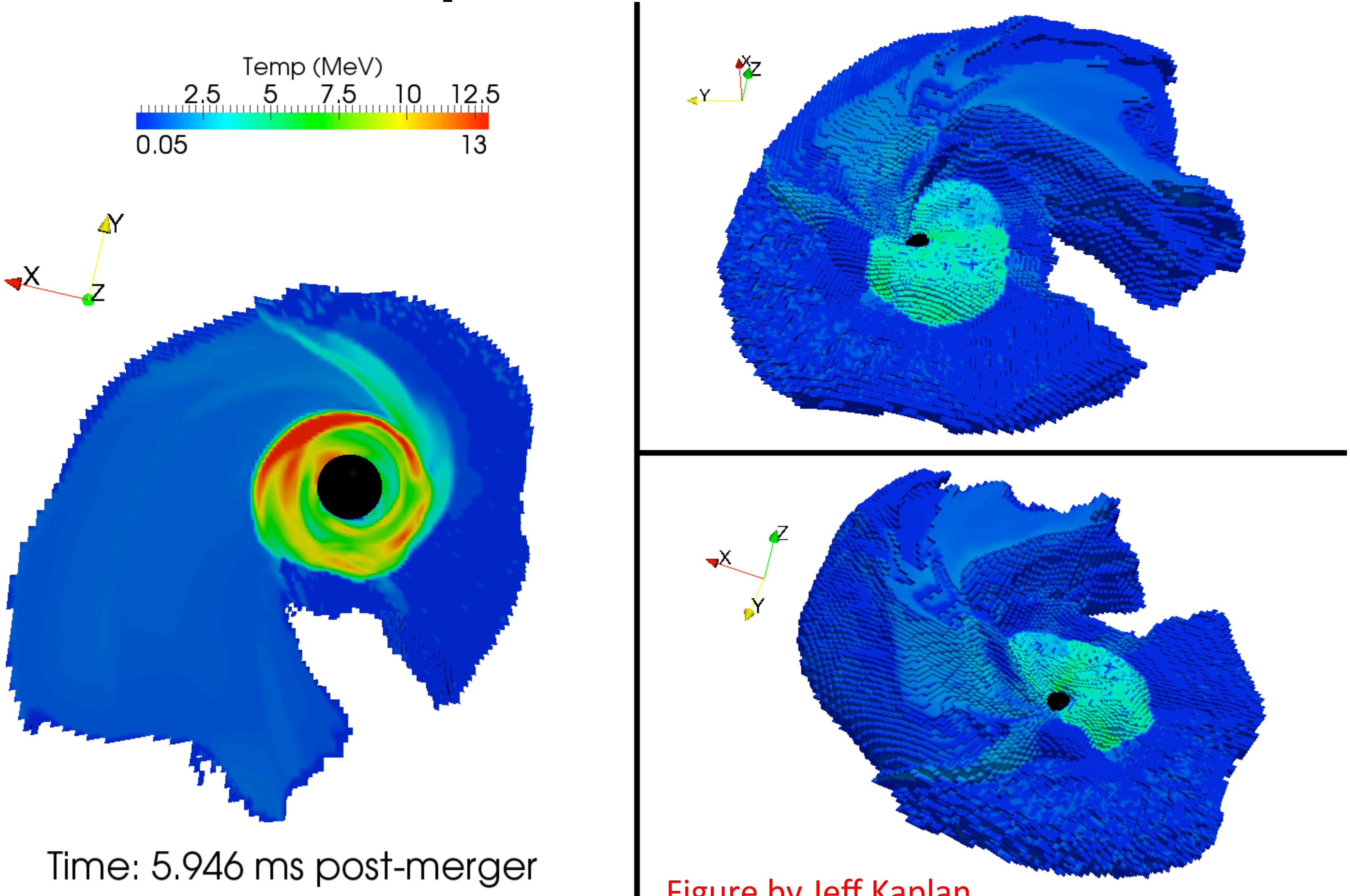


Figure by Jeff Kaplan.

3D Temperature Distribution

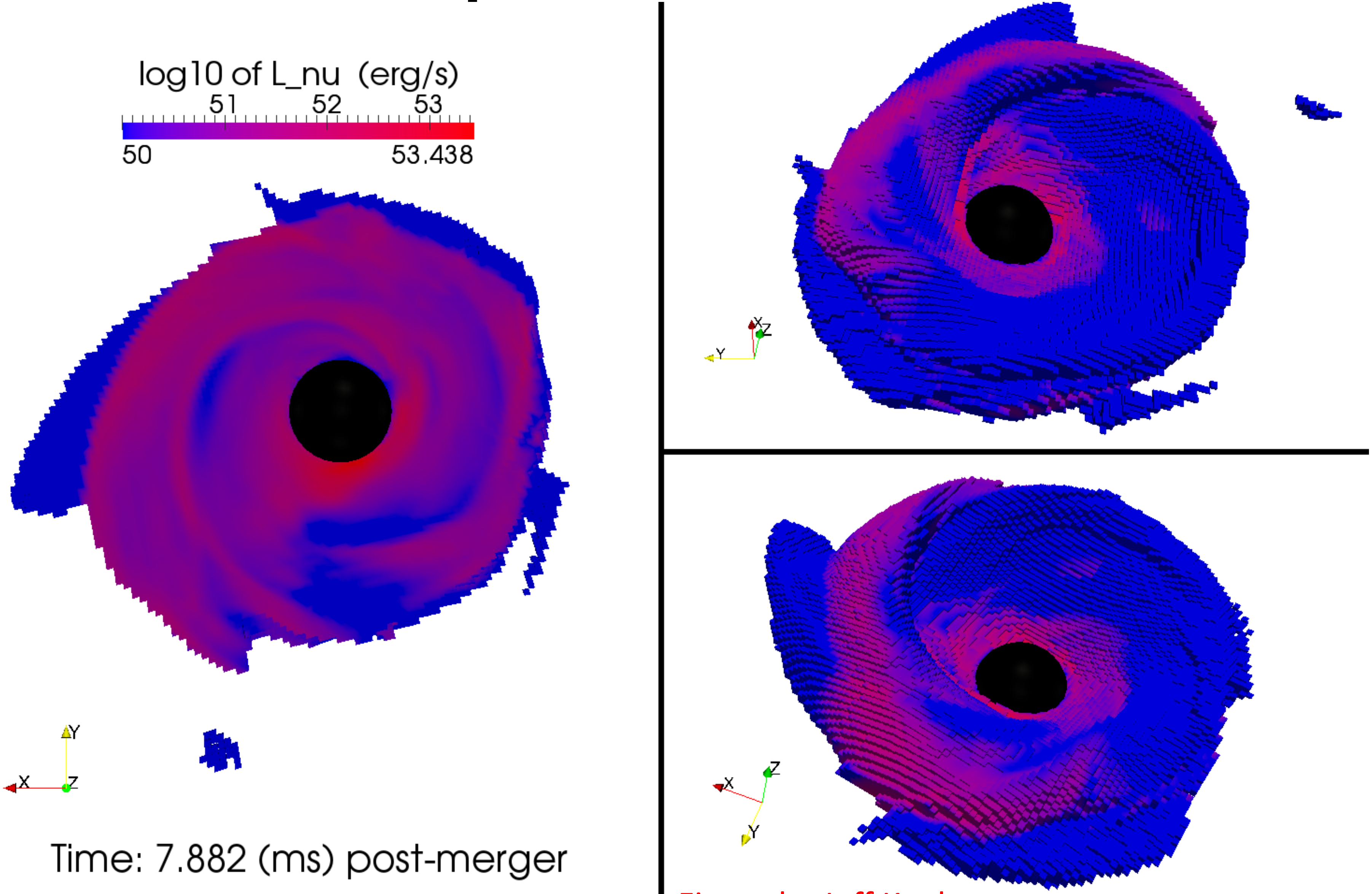
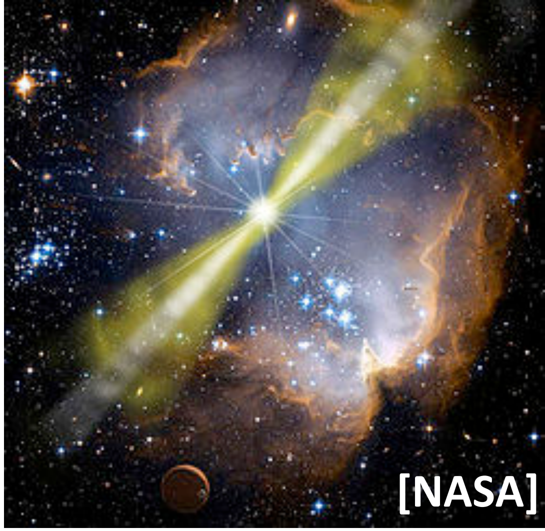


Figure by Jeff Kaplan.

Summary



- **Numerical Relativists:**
  Please stop using polytropes!

- It's (relatively) easy to use more realistic hot nuclear EOS. Open-source code & EOS tables available from **stellarcollapse.org**.

- Including neutrinos is crucial for disk dynamics, nucleosynthesis, and evolution towards GRB. Open-source neutrino leakage scheme available at **stellarcollapse.org**.

- Next step beyond leakage:
  Energy-dependent neutrino transport in GR merger simulations (e.g., two-moment approx by Shibata+ '11).

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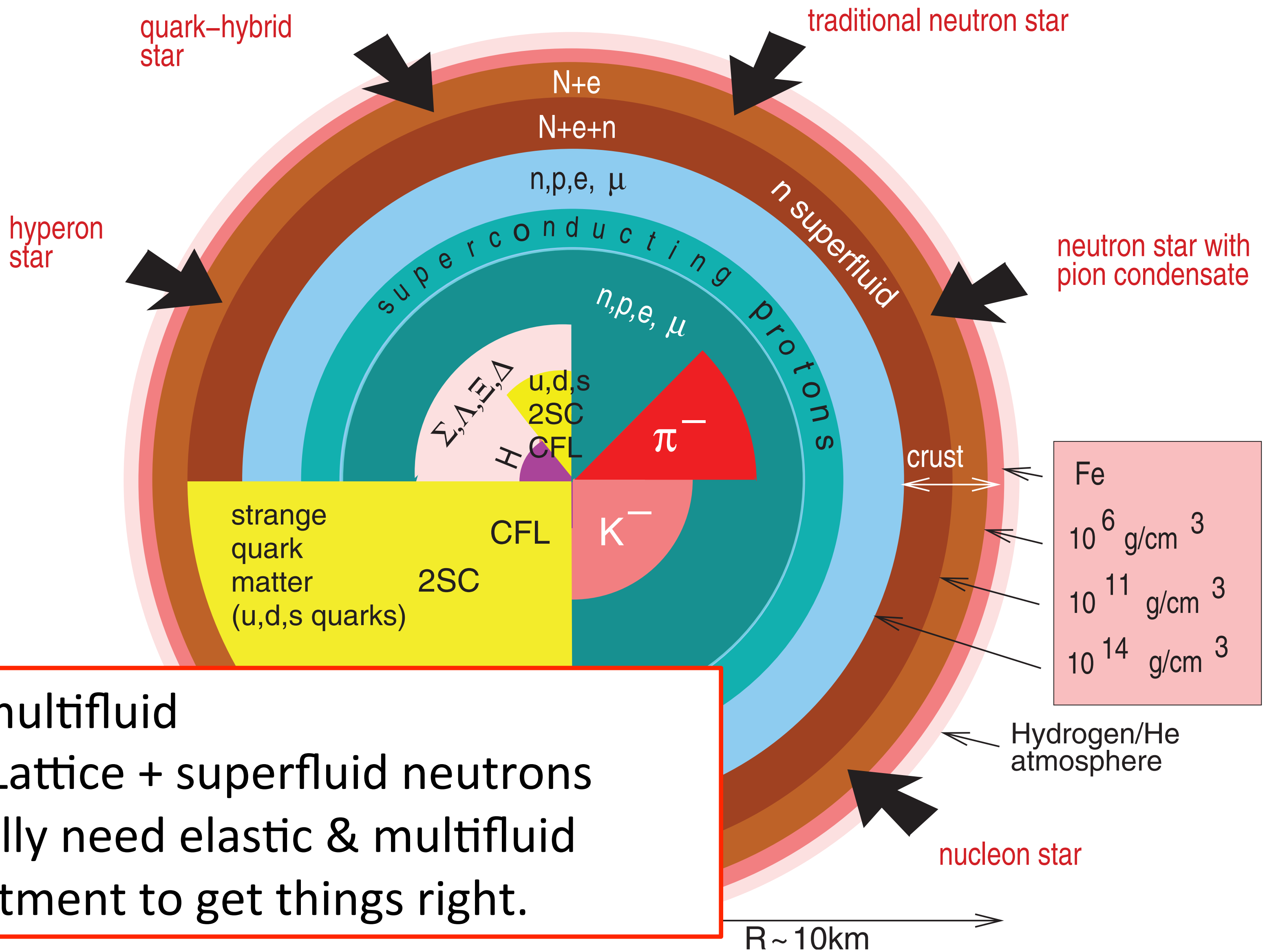
http://www.aps.org/units/ggr/

Now is a great time to join to help us gain
APS division status by 2015,
the centennial of General Relativity!

Supplemental Slides

Neutron Star Structure and Crust

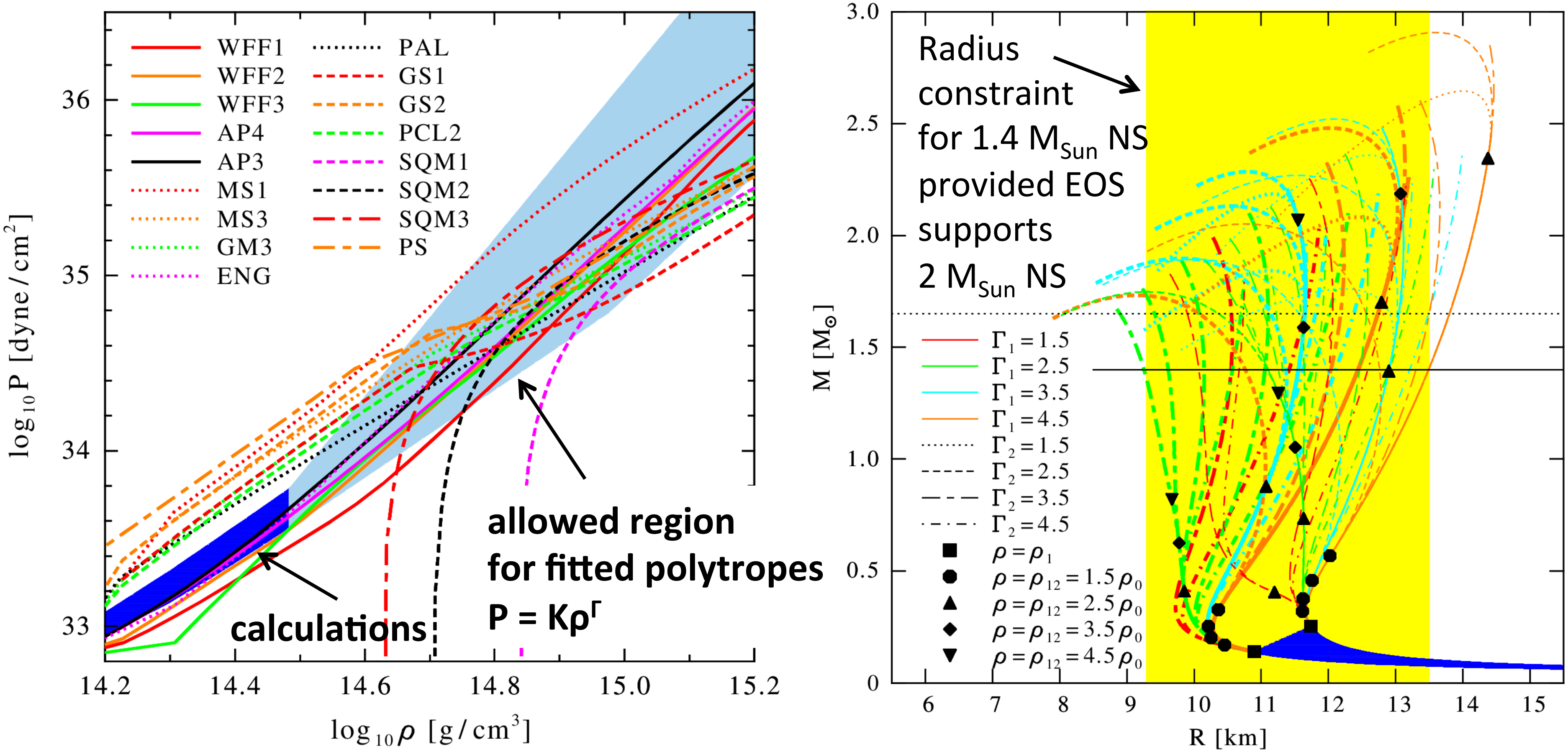


credit:
F. Weber

Core: multifluid
Crust: Lattice + superfluid neutrons
-> ideally need elastic & multifluid treatment to get things right.

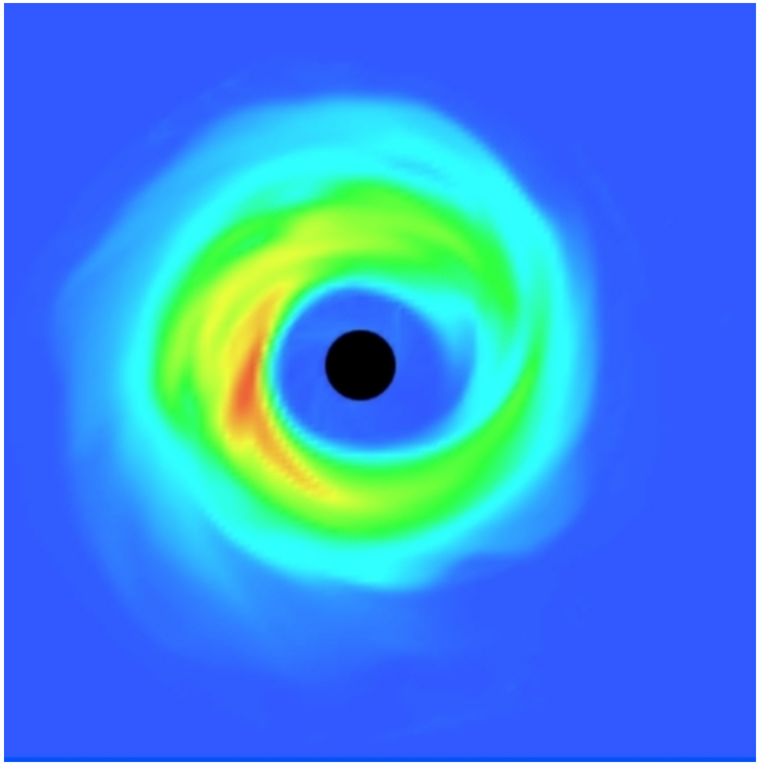
Constraints on the Nuclear EOS (2)

- Hebeler, Lattimer, Pethick, Schwenk '10, PRL

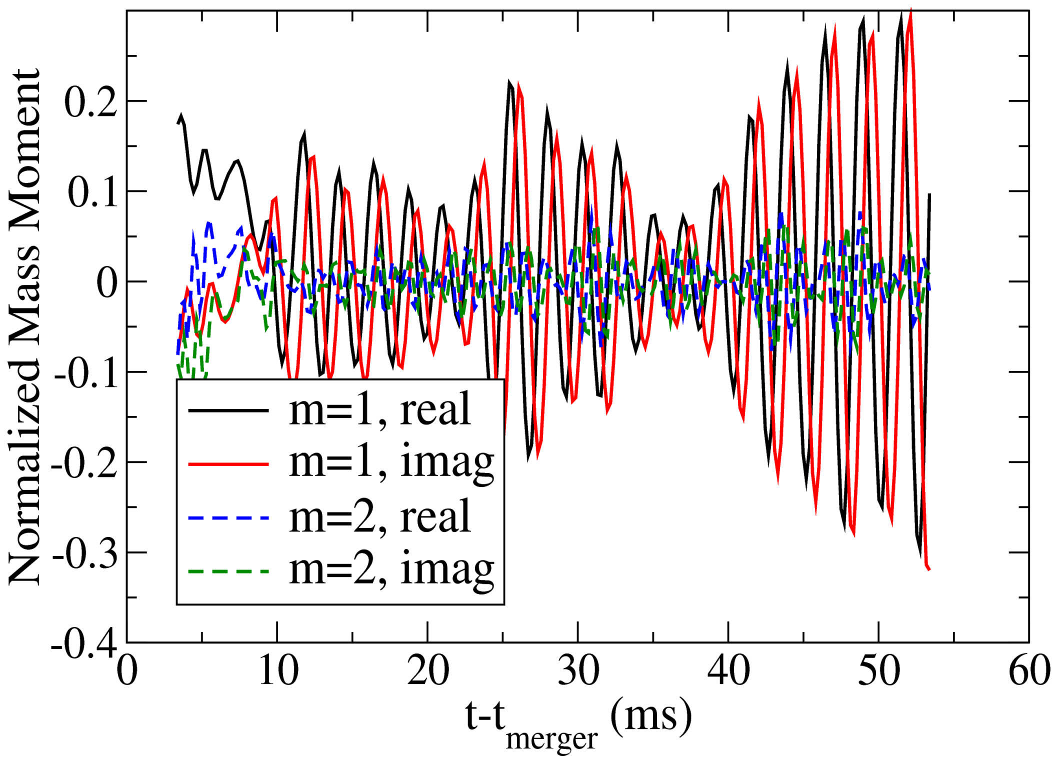


- Detailed EOS calculations with 3-nucleon interactions below nuclear density -> solid theoretical constraints on EOS and NS radii.

SpEC NS-BH Simulations with hot EOS & Neutrinos



Density in disk phase.



Postmerger disks is strongly non-axisymmetric, dominant m=1 mode.