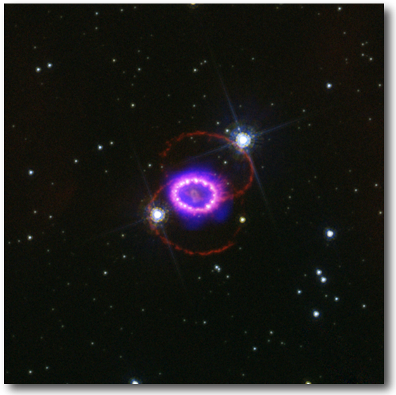
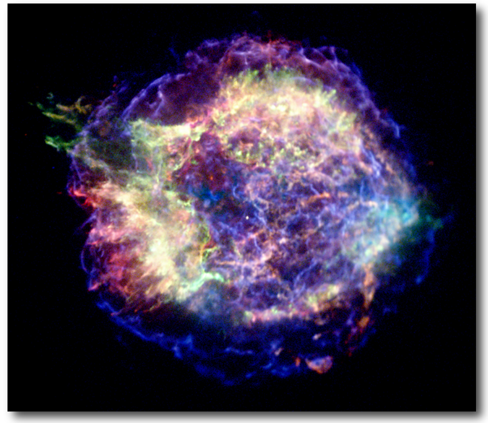
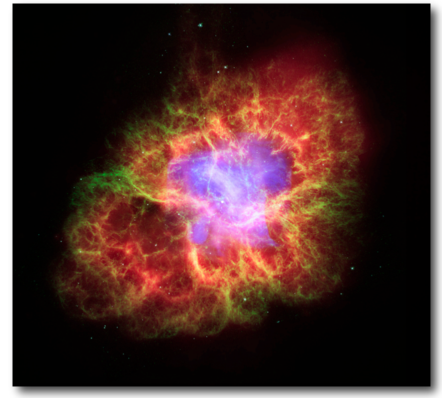
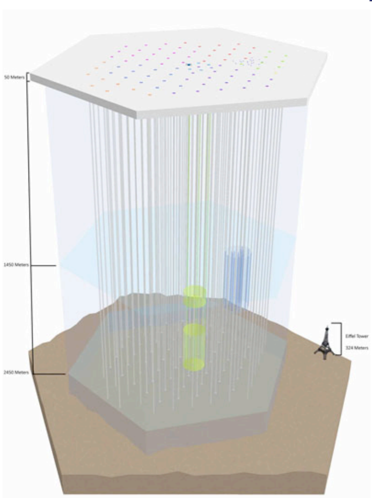
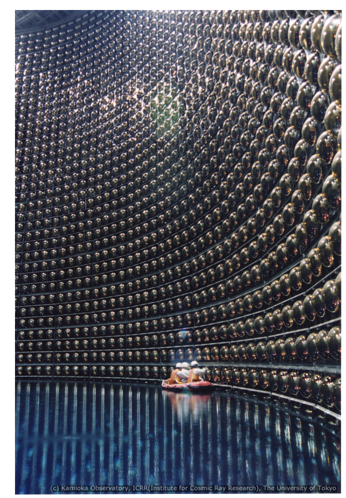
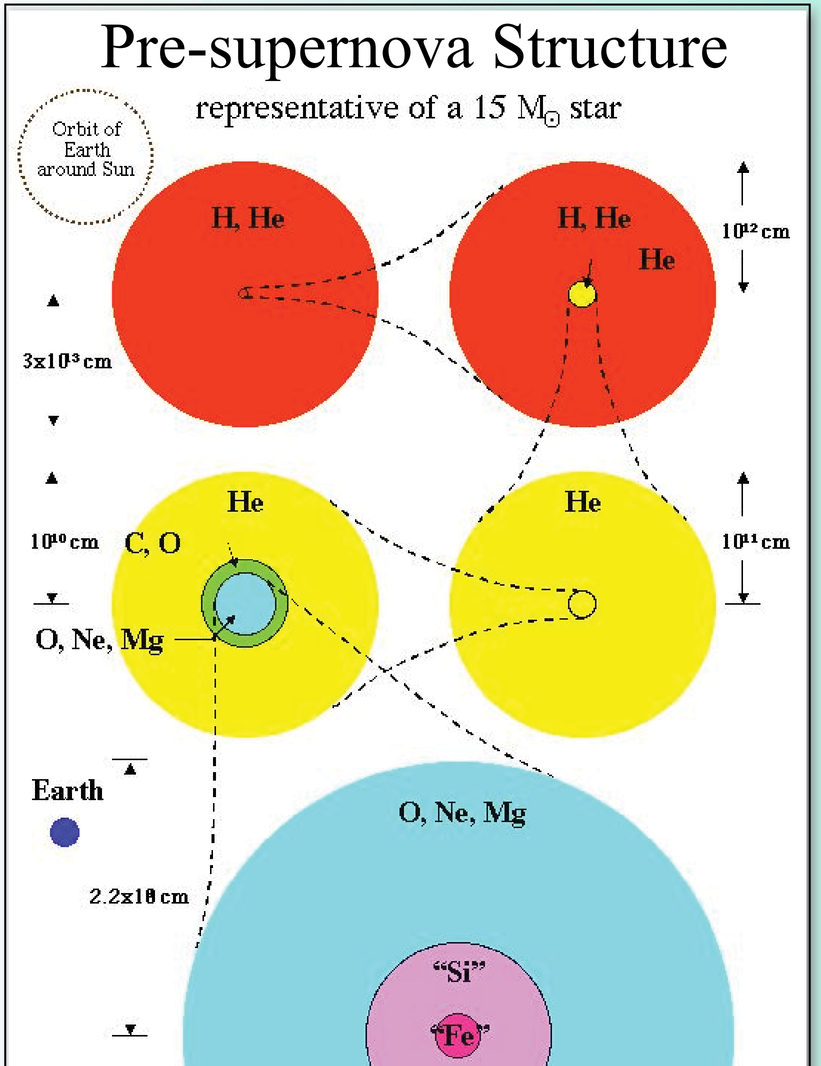




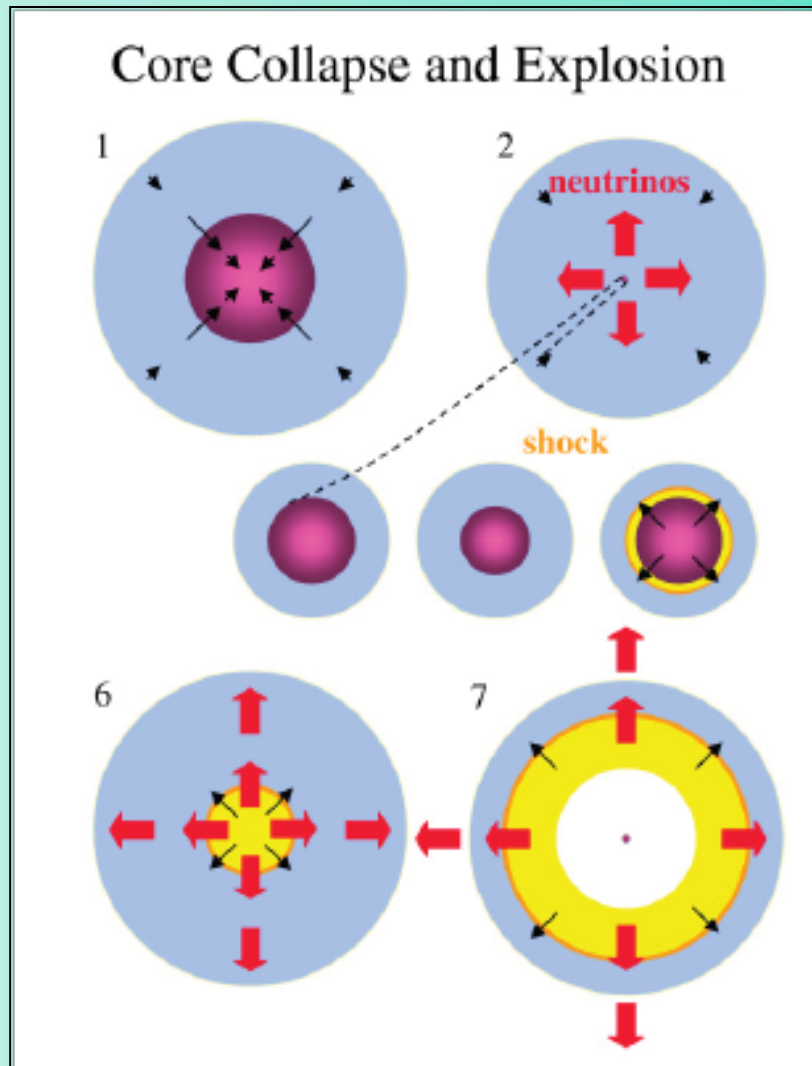
Toward Realistic 3D Core Collapse Supernova Modeling: Near-Term Expectations and Longer-Term Plans and Challenges



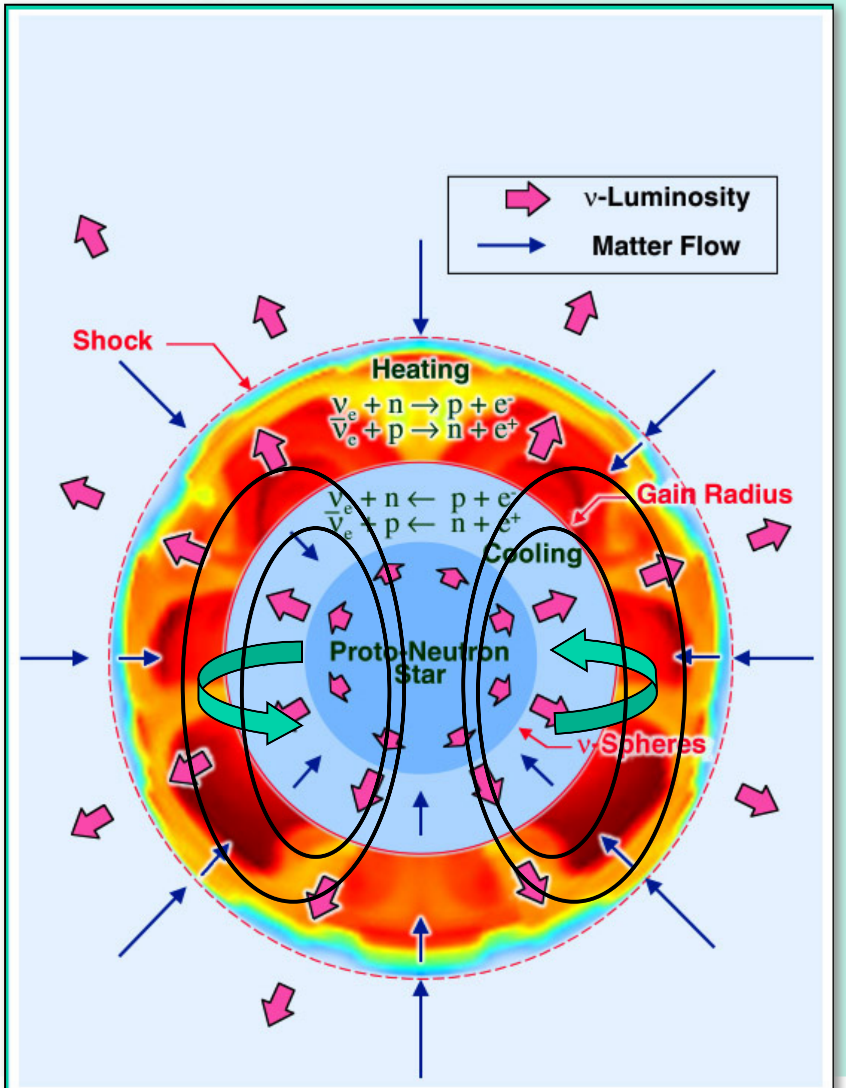


Core Collapse Supernova Paradigm





How is the supernova shock wave revived?

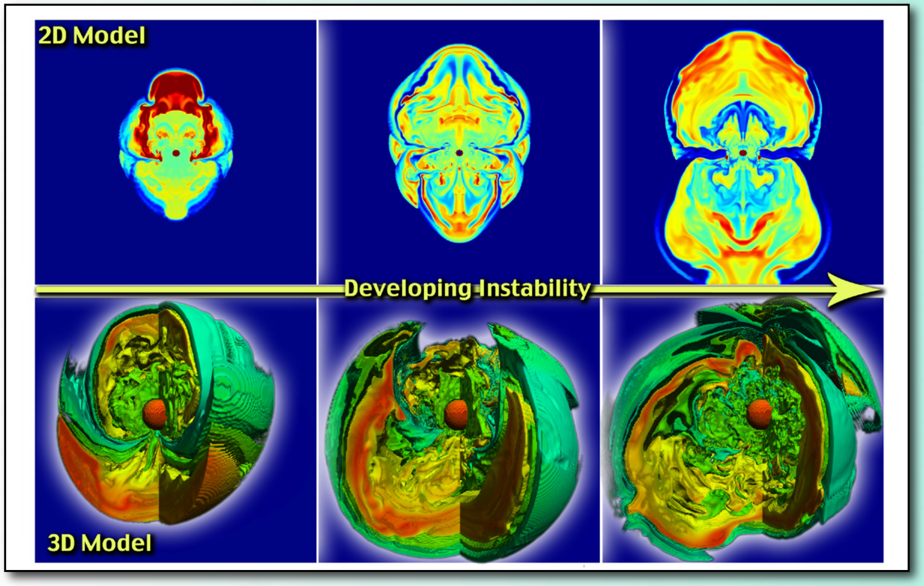


The most fundamental question in supernova theory

- Gravity
- Neutrino Heating
- Convection
- Shock Instability
- Nuclear Burning
- Rotation
- Magnetic Fields

New Ingredient

Stationary Accretion Shock Instability (SASI)

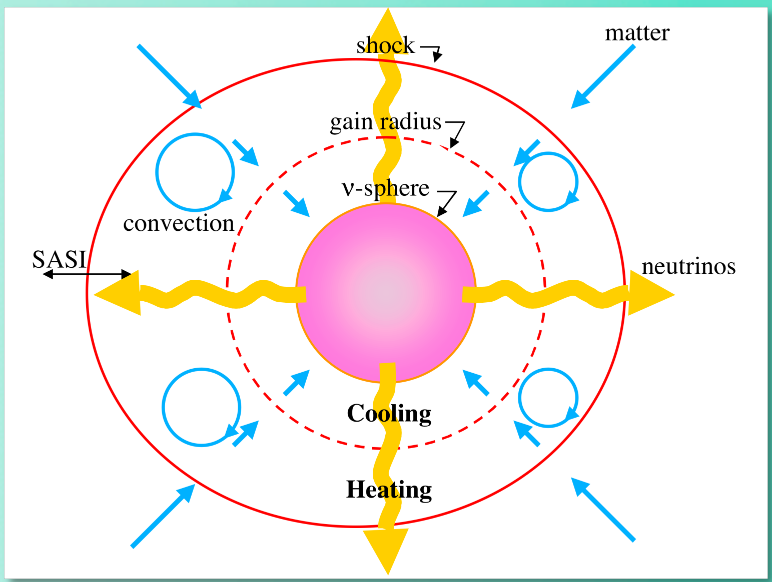


Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)

Shock wave unstable to non-radial perturbations.

SASI has *axisymmetric and nonaxisymmetric* modes that are both linearly unstable!

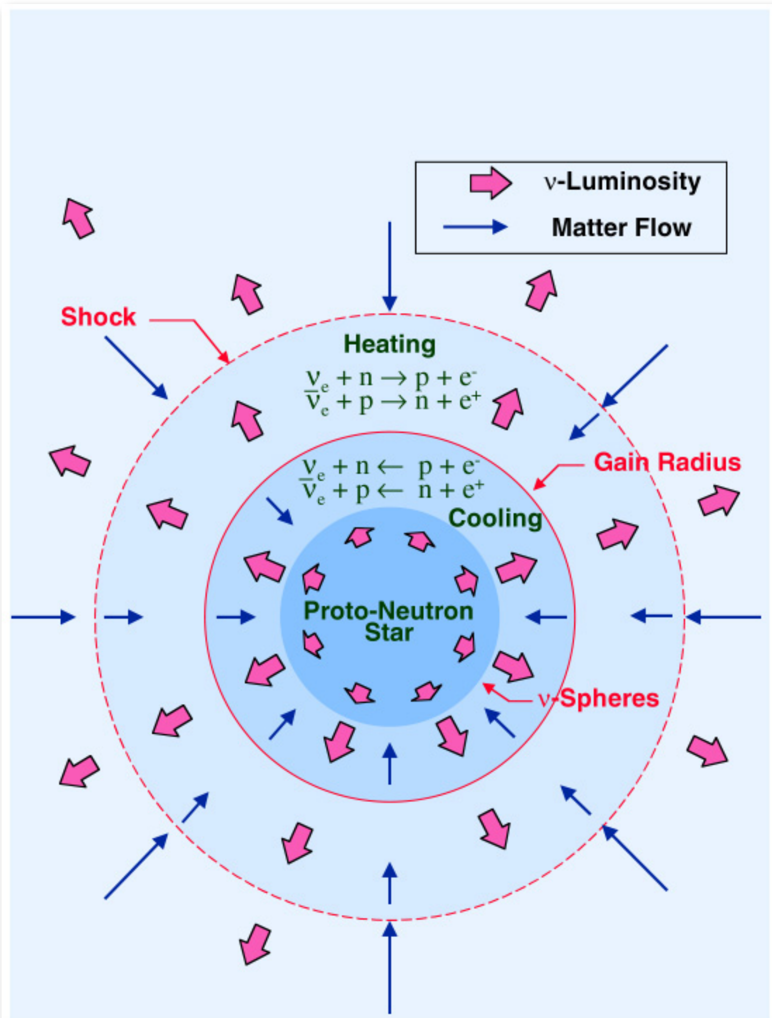
- Blondin and Mezzacappa, *Ap.J.* **642**, 401 (2006)
- Blondin and Shaw, *Ap.J.* **656**, 366 (2007)
- Blondin and Mezzacappa, *Nature* **445**, 58 (2007)



- Decreases advection velocity in gain region.
- Increases time in the gain region.
- Moves shock toward silicon/oxygen layers.
- Generates convection.

⇒ Marek and Janka, *Ap.J.* **694**, 664 (2009)

The Heart of the Matter



Neutrino heating depends on neutrino luminosities, spectra, and angular distributions.

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\langle E_{\nu_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle + \frac{X_p}{\lambda_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\langle E_{\bar{\nu}_e}^2\rangle\langle\frac{1}{\bar{\mathcal{F}}}\rangle$$

Neutrino heating is sensitive to all three (most sensitive to neutrino spectra).

⇨ *Must compute neutrino distributions.*

$$f(t,r,\theta,\phi,E,\theta_p,\phi_p)$$

Multifrequency
Multiangle

$$E_R(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, f$$

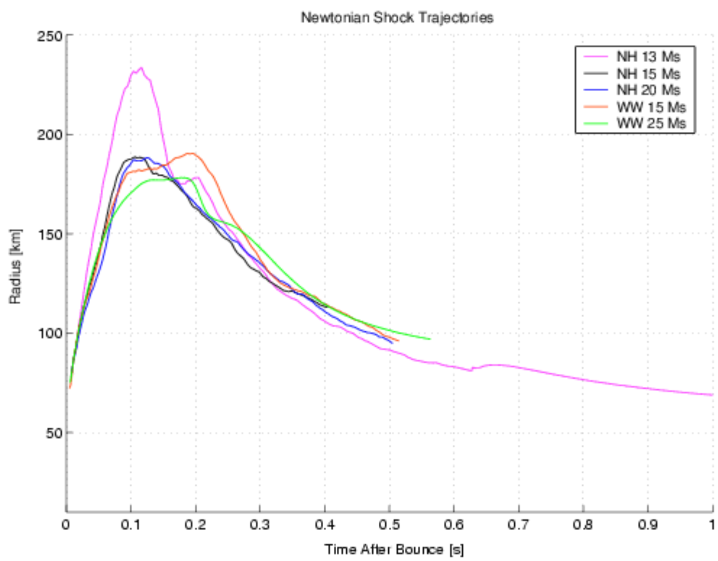
Multifrequency
(*Parameterize Isotropy*)

$$E_R(t,r,\theta,\phi) = \int dE\, d\theta_p\, d\phi_p\, f$$

Gray
(*Parameterize Isotropy and Spectra*)

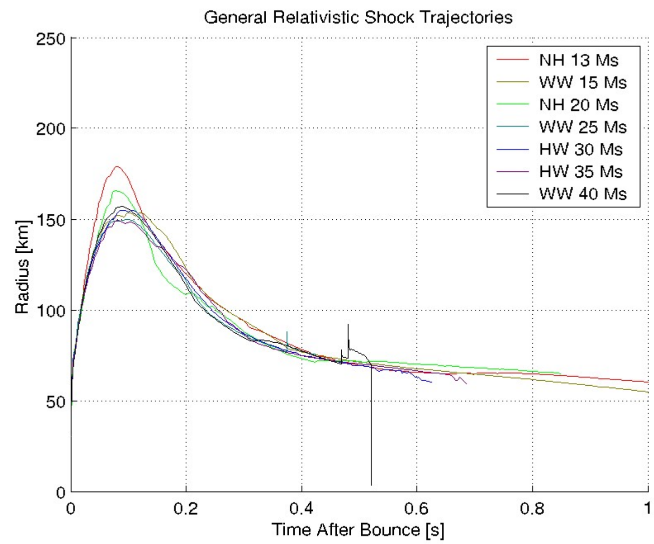
Completed: Spherical Models with Boltzmann Transport

Newtonian



Mezzacappa et al., PRL, **86**, 1935 (2001)

General Relativistic



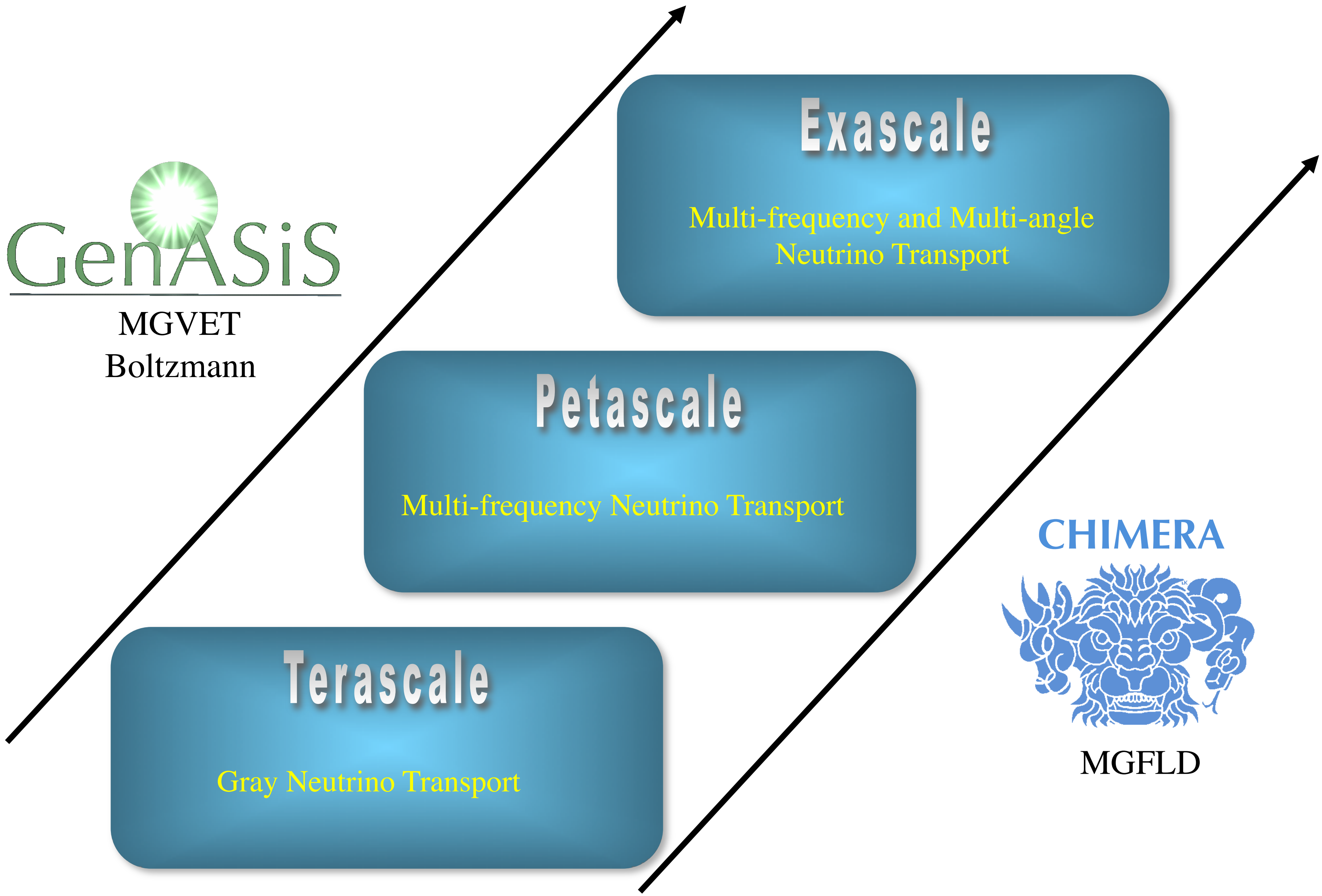
Liebendoerfer et al., PRD, **63**, 103004 (2001)

The simulation of core collapse supernovae with fully general relativistic, multi-angle, multi-frequency, Boltzmann neutrino transport has been achieved for spherically symmetric cases.

⇨ What's missing?

- Better weak interaction physics?
- Better EOS?
- Neutrino mixing?
- Multi-D effects.

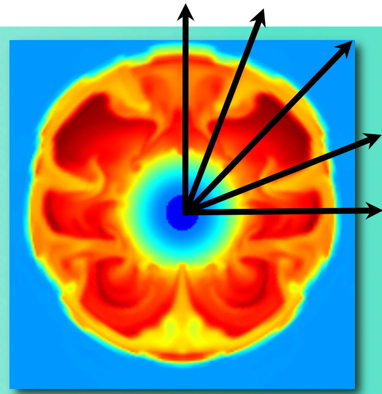
Agile-BOLTZTRAN


GenASiS
MGVET
Boltzmann
Exascale
Multi-frequency and Multi-angle Neutrino Transport
Petascale
Multi-frequency Neutrino Transport
Terascale
Gray Neutrino Transport
CHIMERA
MGFLD

Ongoing 2D Multi-Physics Supernova Models

<u>Simulation Building Blocks</u>

- *“RbR-Plus” MGFLD Neutrino Transport*
  - *O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)*
- *2D PPM Hydrodynamics*
  - *GR time dilation, effective gravitational potential, adaptive radial grid*
- *Lattimer-Swesty EOS*
  - *180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)*
- *Nuclear (Alpha) Network*
  - *14 alpha nuclei between helium and zinc*
- *2D Effective Gravitational Potential*
  - Marek et al. *A&A*, **445**, 273 (2006)
- *Neutrino Emissivities/Opacities*
  - *“Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*

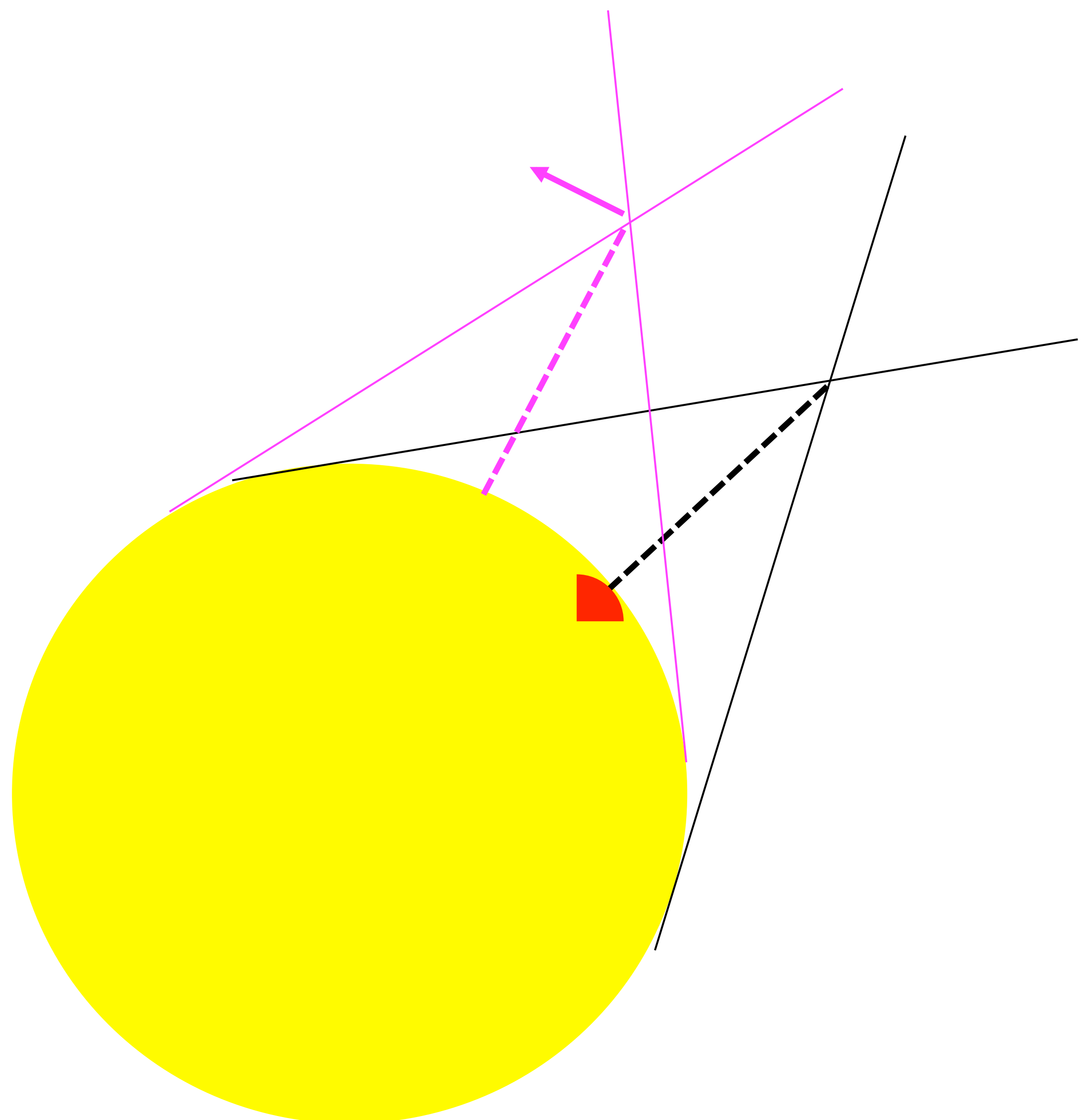


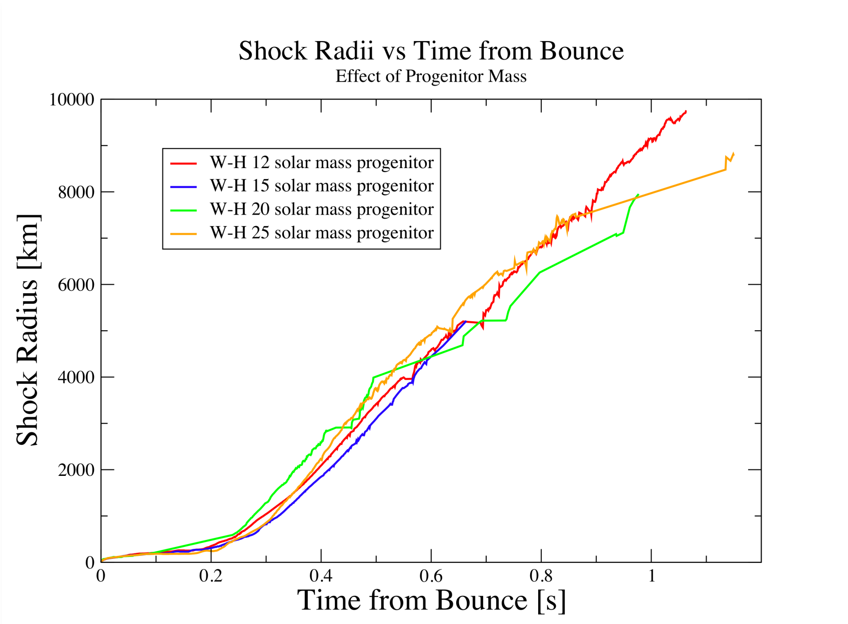
“Ray-by-Ray-Plus” Approximation

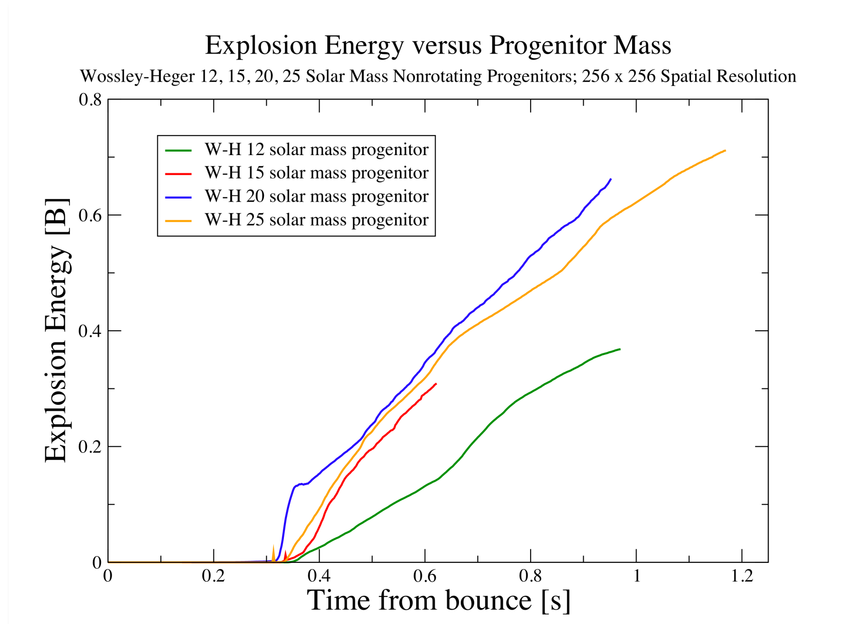
- Solve set of 1D problems.
- Ignore differences in lateral fluxes across 1D problems.

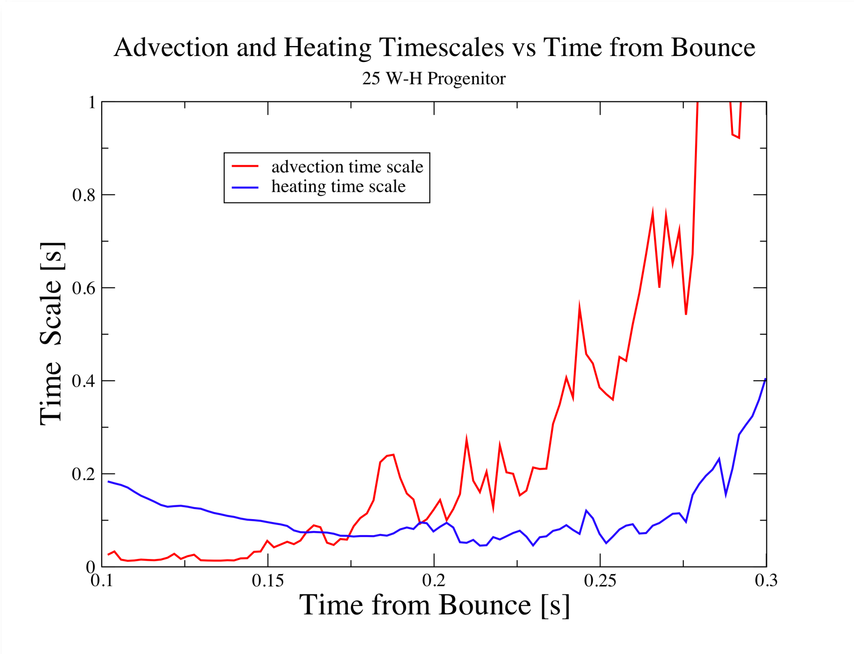
– Buras et al. *A&A*, **447**, 1049 (2003)

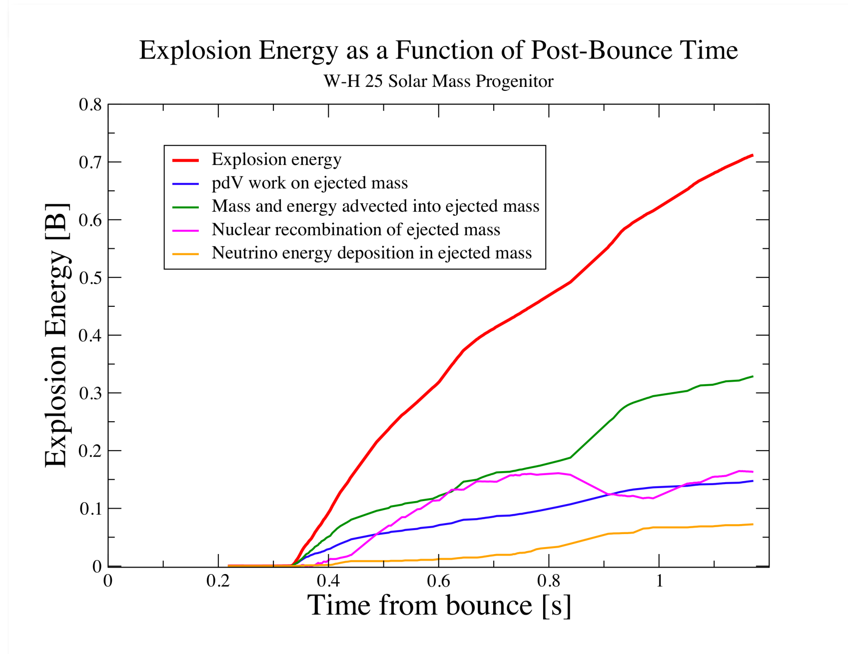
CHIMERA



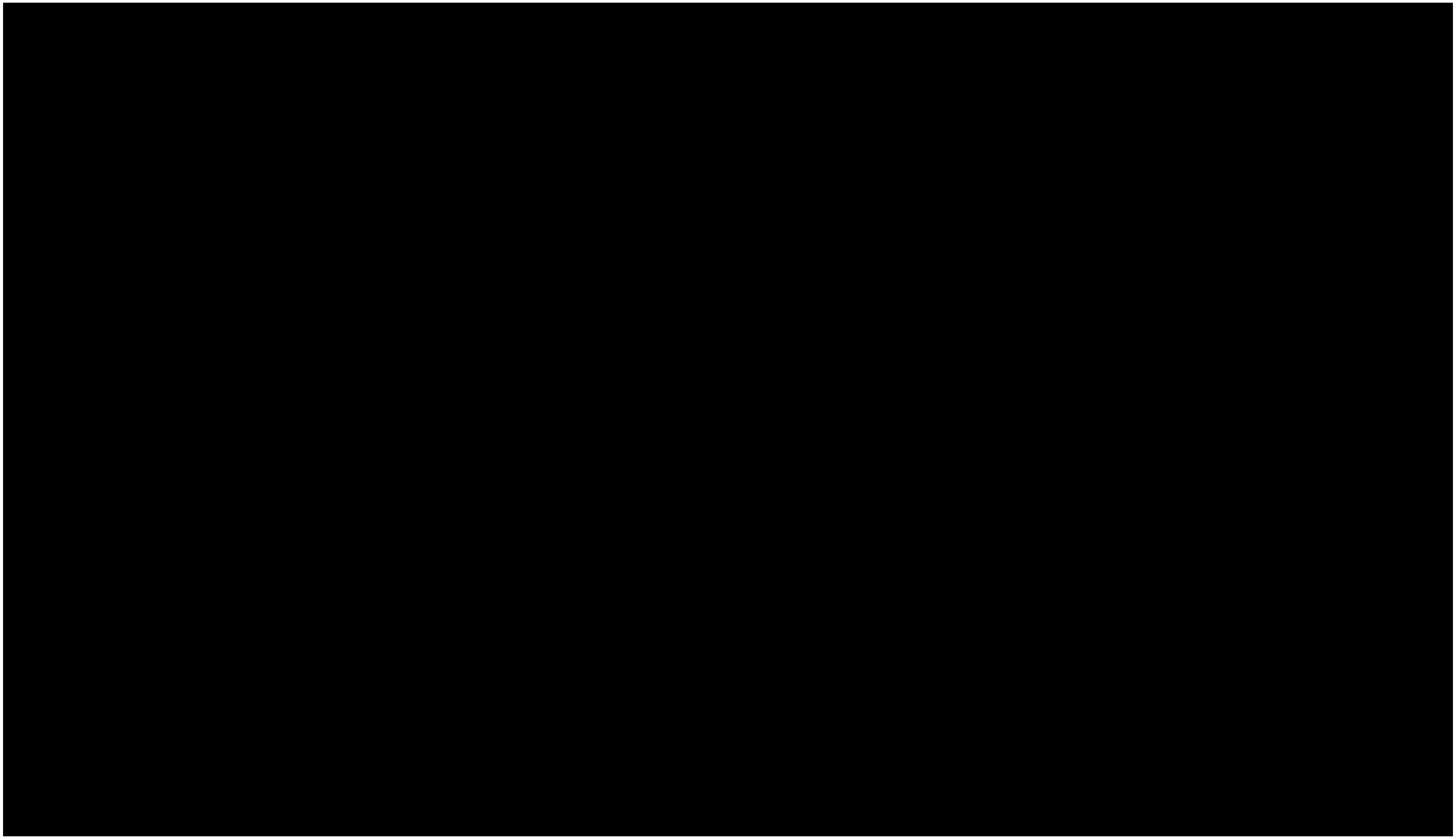


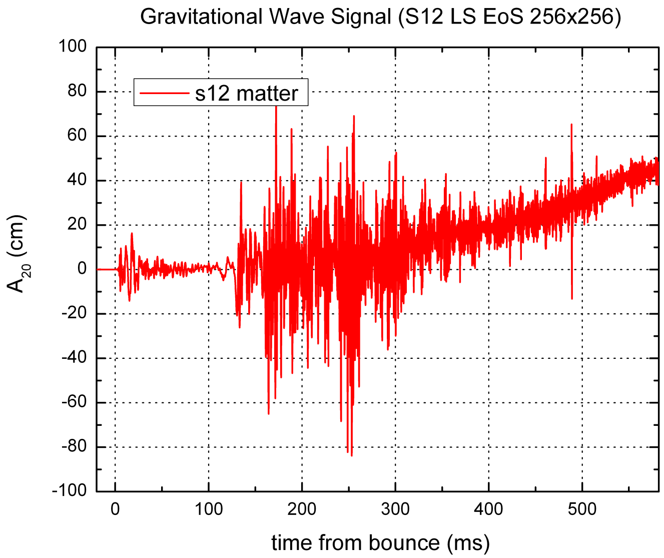


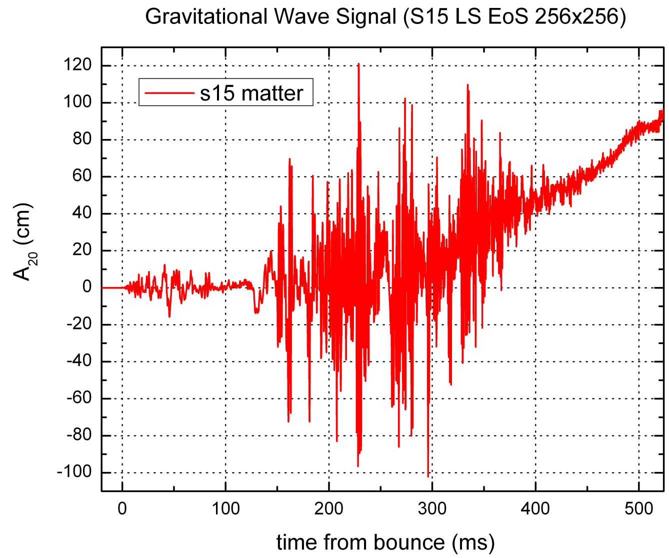


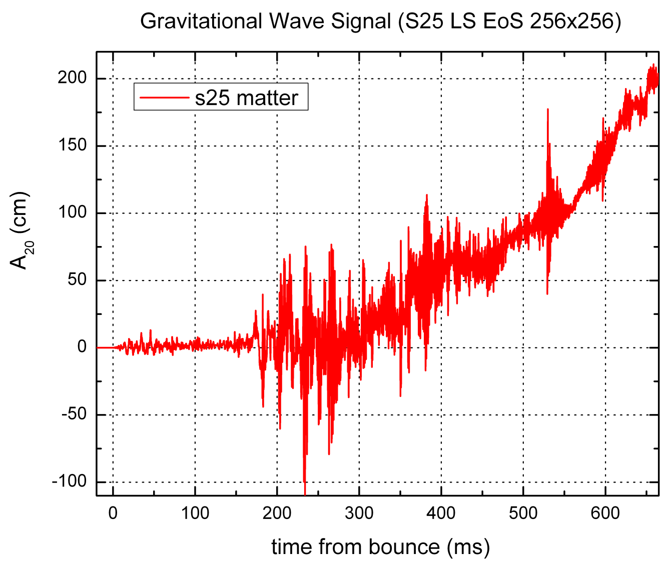


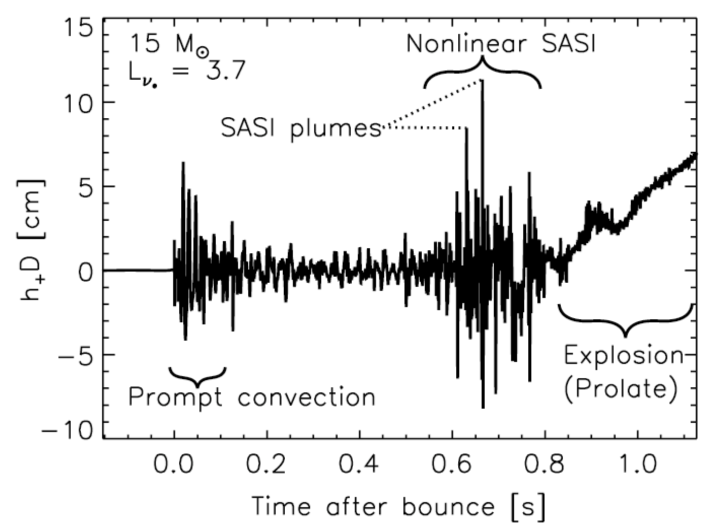
Bruenn et al., *Journ. Phys. Conf. Ser.* **180**, 012018 (2009)





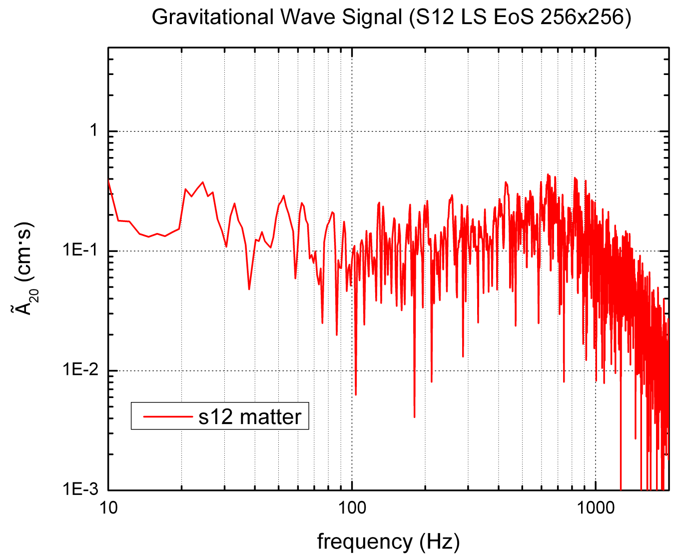


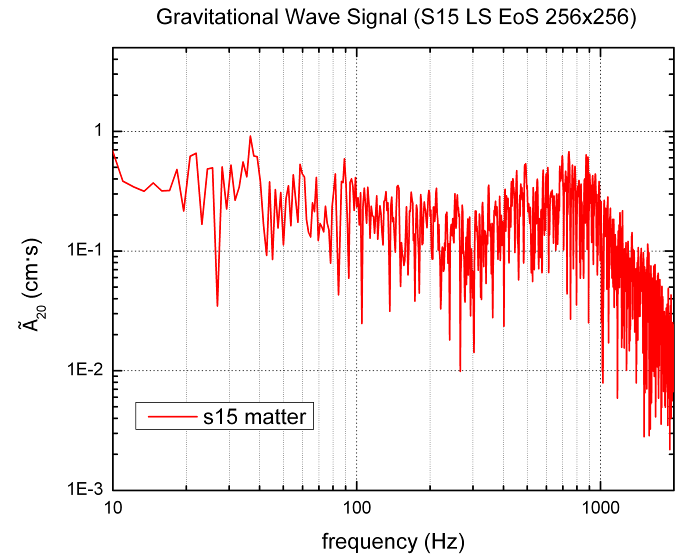


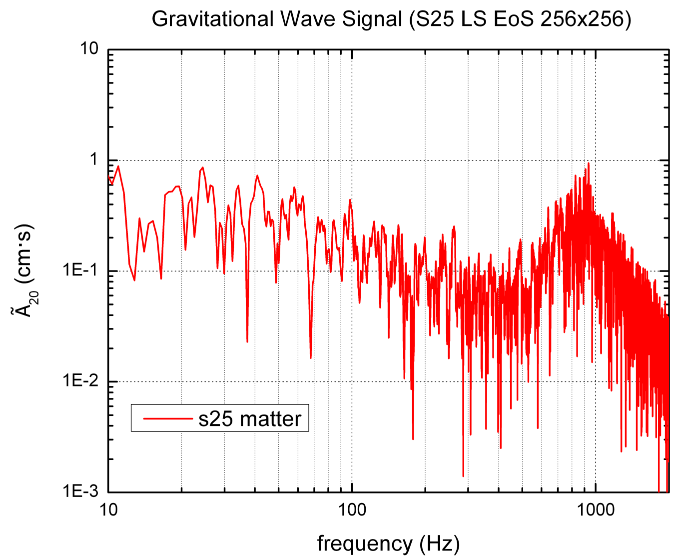


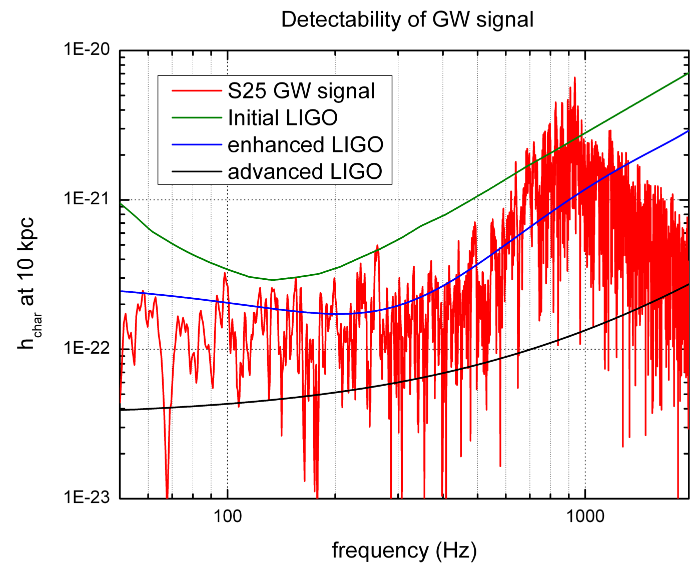
Prediction from parameterized model.
Murphy, Ott, and Burrows, *Ap.J.* **707**, 1173 (2009)

$$h_+ D = \frac{1}{8}\sqrt{\frac{15}{\pi}}(\sin^2\theta)A_{20}$$









Yakunin et al., *Class. Quant. Grav.*, **27,** 194005 (2010)

Ongoing 3D Multi-Physics Simulations

<u>Simulation Building Blocks</u>

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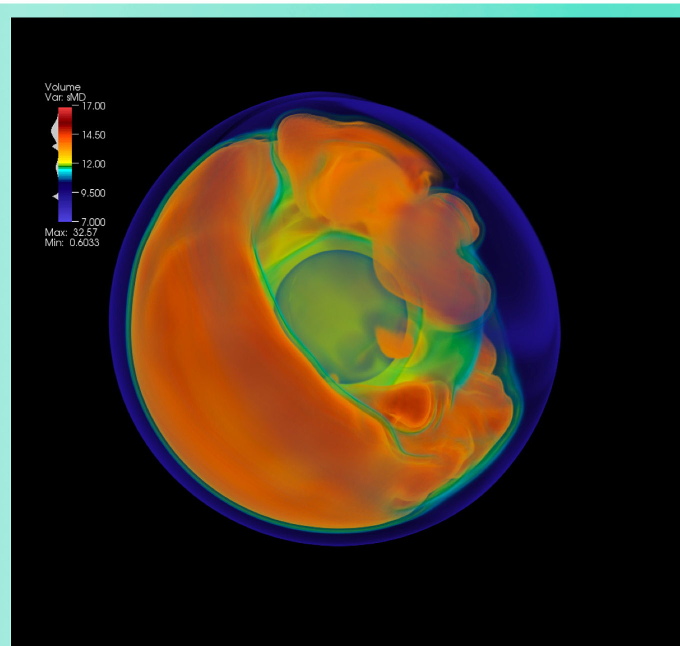
- Marek et al. *A&A*, **445**, 273 (2006)

➲ *Neutrino Emissivities/Opacities*
- *“Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*

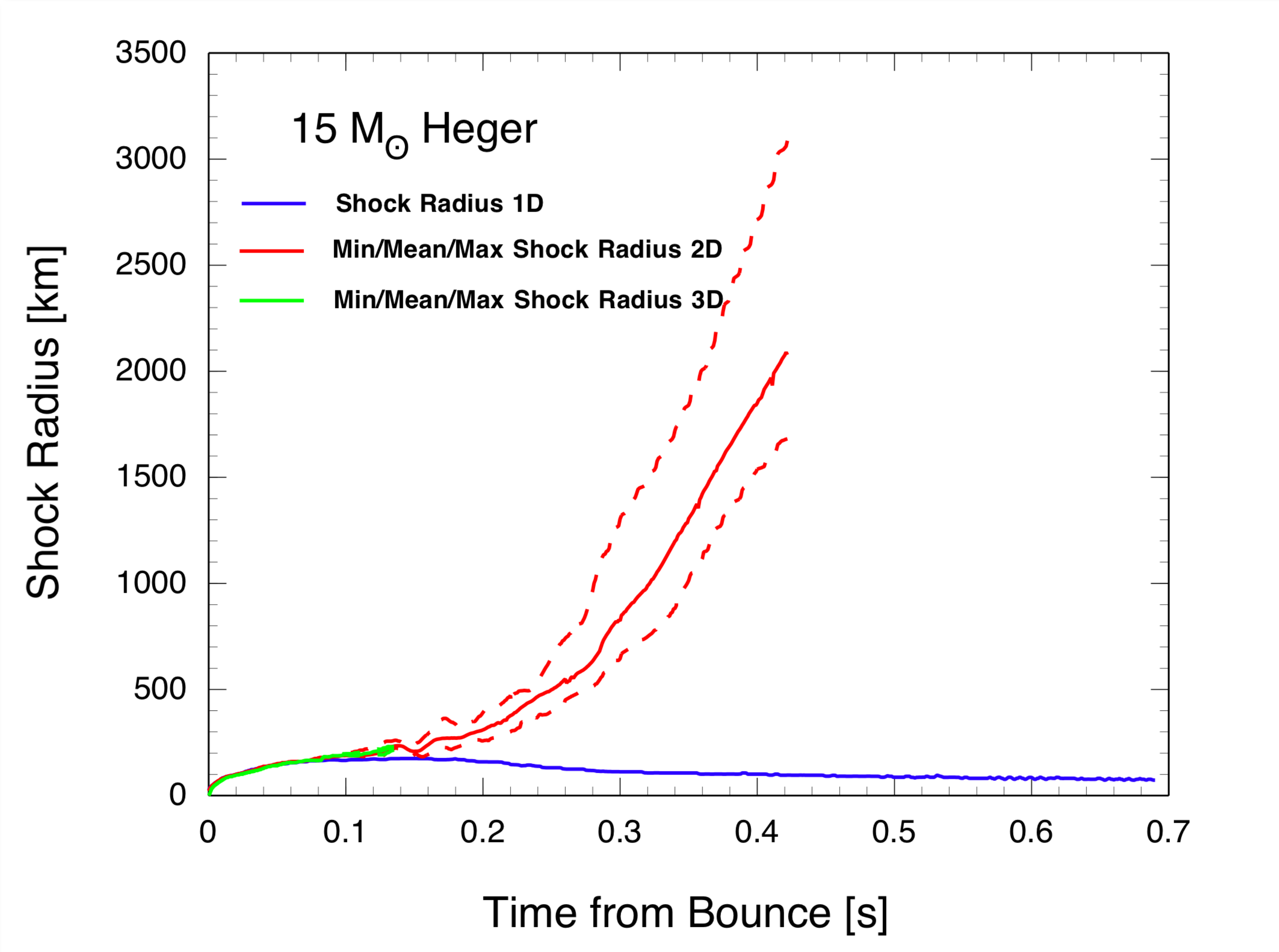


Bruenn et al., *Journ. Phys. Conf. Ser.*, **180** 012018 (2009)

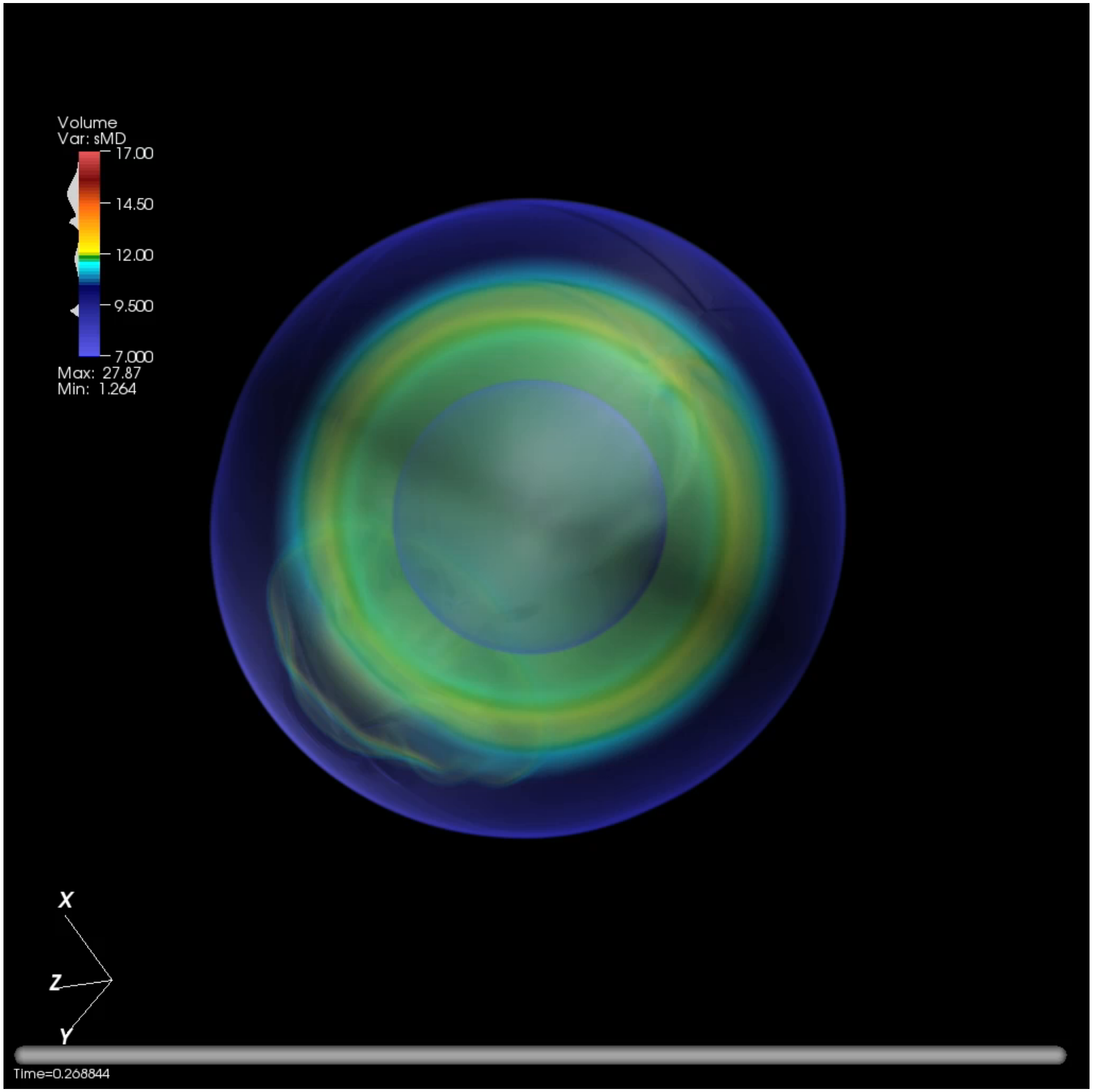
<u>Resolution</u>

512 X 128 X 256 (recently launched)
⇒ ~33,000 processors

~ 200 days/simulation
~ *80M proc-hrs/simulation*



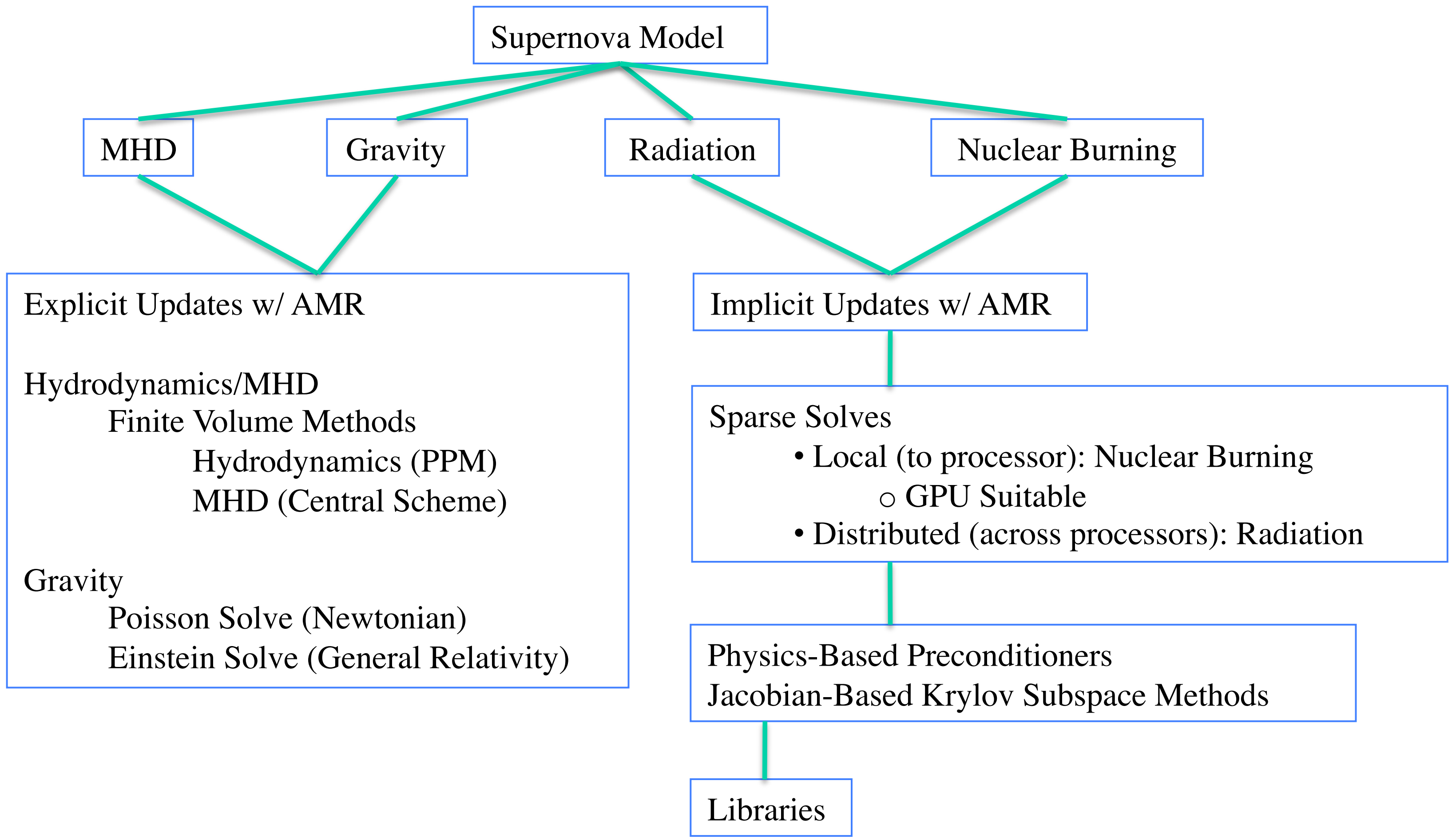
Bruenn et al., *Journ. Phys. Conf. Ser.* **180**, 012018 (2009)


Volume
Var: sMD
17.00
14.50
12.00
9.500
7.000
Max: 27.87
Min: 1.264
X
Z
Y
Time=0.268844

PREVIEWS OF COMING DISTRACTIONS

3D Models: Path Forward						
Code	Neutrino Transport Approach	GR	Network	Platform	Time Frame	Target
CHIMERA	RbR MGFLD	Approximate	Alpha, Full	2 PF	2010	CCSNe
GenASiS	MGVET	BSSN	Alpha, Full	2-20 PF	2012	CCSNe, Hypernovae
GenASiS	Boltzmann	BSSN	Alpha, Full	10 EF	> 2020	CCSNe, Hypernovae

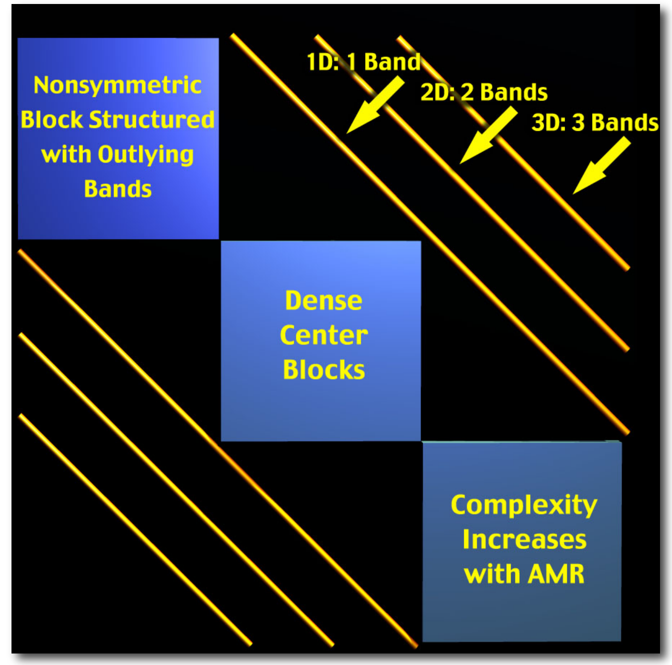
SCIENCE TO SOLVERS MAPPING



The Need for Exascale Resources

Dominated by preconditioning of dense blocks.

$$\text{FLOPS} \sim N_t N_s N_i f N_m^{\,2} \sim 3.5 \times 10^{22} f$$



N_t = number of time steps $\sim 1 \times 10^6$

N_s = number of spatial zones $\sim 512 \times 512 \times 512$

N_i = number of iterations per time step ~ 10

N_m = number of neutrino momentum zones

$f \in [1, N_m] = [1, 5120]$

$$N_m = N_\nu \times N_E \times N_p \times N_a$$

$N_\nu = 4$

N_E = number of neutrino energy groups ~ 20

N_p = number of neutrino polar direction angles ~ 8

N_a = number of neutrino azimuthal direction angles ~ 8

Algorithms critical!

Runtime: ~ $4f$ days per run on a 1 EF machine (at 10% of peak).

The Need for Exascale Resources

Dominated by preconditioning of dense blocks.

$$\text{FLOPS} \sim N_t N_s N_i f N_m^{\ 2} \sim 3.4\times10^{19} f$$

N_t = number of time steps $\sim 1\times10^{6}$

N_s = number of spatial zones $\sim 512\times512\times512$

N_i = number of iterations per time step ~ 10

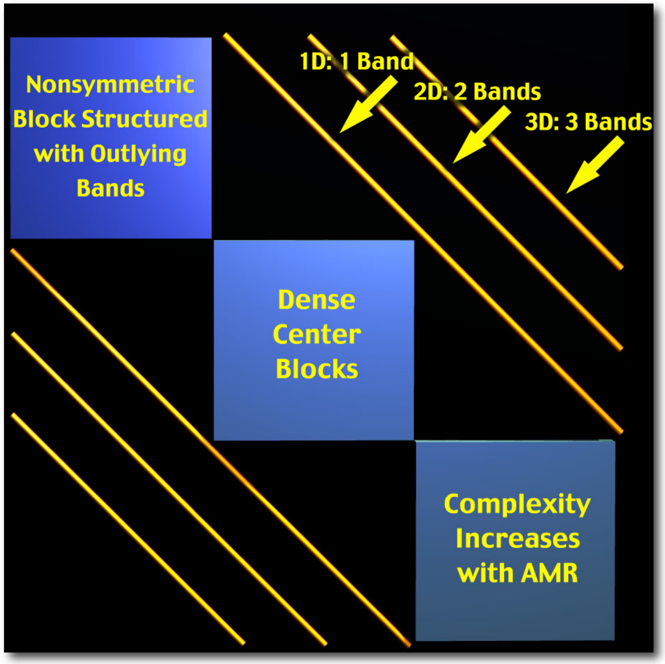
N_m = number of neutrino momentum zones

$f \in [1, N_m] = [1, 160]$

$N_m = N_\nu \times N_E$

$N_\nu = 4\times2$

N_E = number of neutrino energy groups ~ 20



Algorithms critical!

Runtime: ~ *f* hours per run on a 1 EF machine (at 10% of peak).

Other Issues

Half Empty:

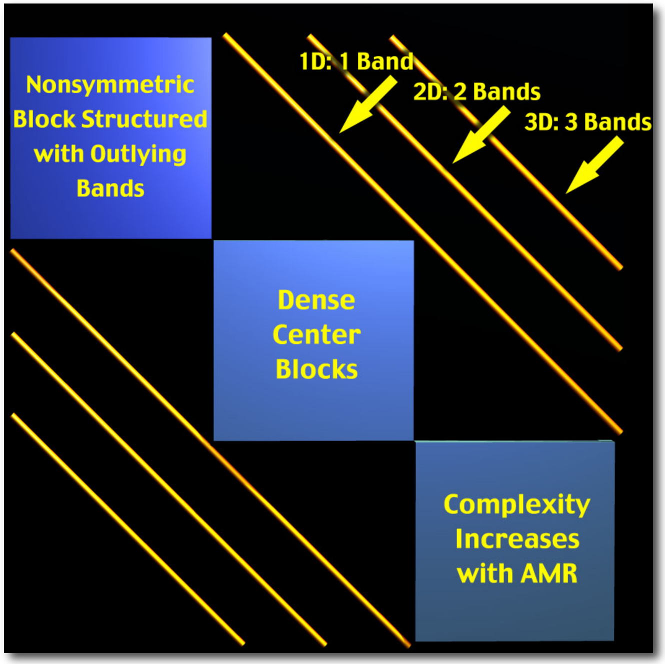
The proposed exaflop platform will likely have 32-64 PB of memory.

⇒ Memory/core will be greatly reduced.
- Problematic for multi-physics applications.
- Will significantly stress current approaches.

E.G.: Memory footprint for Jacobian-based Newton-Krylov approaches to solving 3D neutrino Boltzmann equations will have a footprint ~30 PB *at moderate resolution*.

⇒ *Must run on a significant fraction of the machine.*

- ○ Krylov methods?
- ○ Approaches to AMR?
- ○ Programming models?
- ○ Collective parallel I/O?
- ○ Fault tolerance?
- ○ …



Half Full:

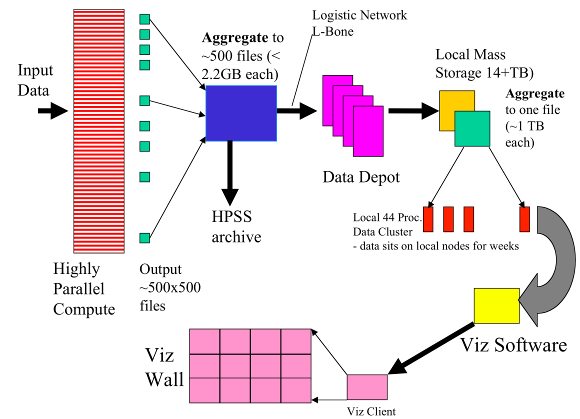
Multi-physics applications offer the dimensionality and richness of physics to make effective use of heterogeneous processors.

Scientific Workflows: A Different Challenge

In "production mode," managing Workflows has become a paramount issue.

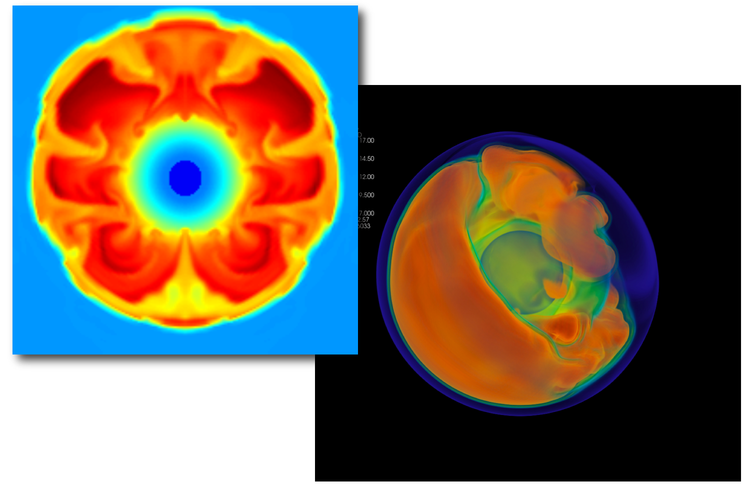
⇨ Ideally, we would like to automate these workflows.

⇨ Data Management and Analysis
⇨ Networking
⇨ Visualization

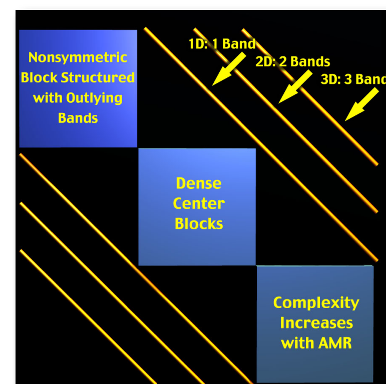


Code	# Variables	Resolution	# Dumps	Data Output	Runtime	Machine
CHIMERA 1.0	~ 200	576X96X192	3000	~50 TB	~ 3 Months	2 PF
CHIMERA 2.0	~ 350	576X96X192	3000	~100 TB	~ 3 Months	20 PF
GenASiS	~ 5000	512X512X512	3000	~30 PB	?	10 EF

Summary and Outlook



- Recent 2D results very promising.
- 3D results in the RbR approximation forthcoming.
- Efforts underway to perform fully 3D (4D including neutrino energy) simulations.
- Robust algorithms have been developed, but these will be challenged by architectural trends.
- Multi-physics applications will be well positioned to exploit heterogeneous processing.



Collaborators

Oak Ridge National Laboratory

The University of Tennessee Knoxville

Budiardja
Cardall
Chertkow
Endeve
Hix
Lentz
Messer
Mezzacappa
Parete-Koon

FAU

Bruenn
Marronetti
Tsatsin
Yakunin

NC State University

Blondin
Mauney

UCSD

Fuller
+

Applied Math/CS Collaborators

- *Closures, Solvers: Hauck, D'Azevedo*
- *Data Management: Klasky and collaborators*
- *Networking: Beck, Rao, and collaborators*
- *Visualization: Ahern, Ma, Meredith, Pugmire, Toedte*
- *Cray Center of Excellence: Levesque, Wichmann*

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National Science Foundation

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