Core-Collapse Supernova Theory

University of Arizona
Core-Collapse Simulations

Adam Burrows, Rolf Walder, Christian Ott, Eli Livne, Itamar Lichtenstadt, Jeremiah Murphy, Todd Thompson

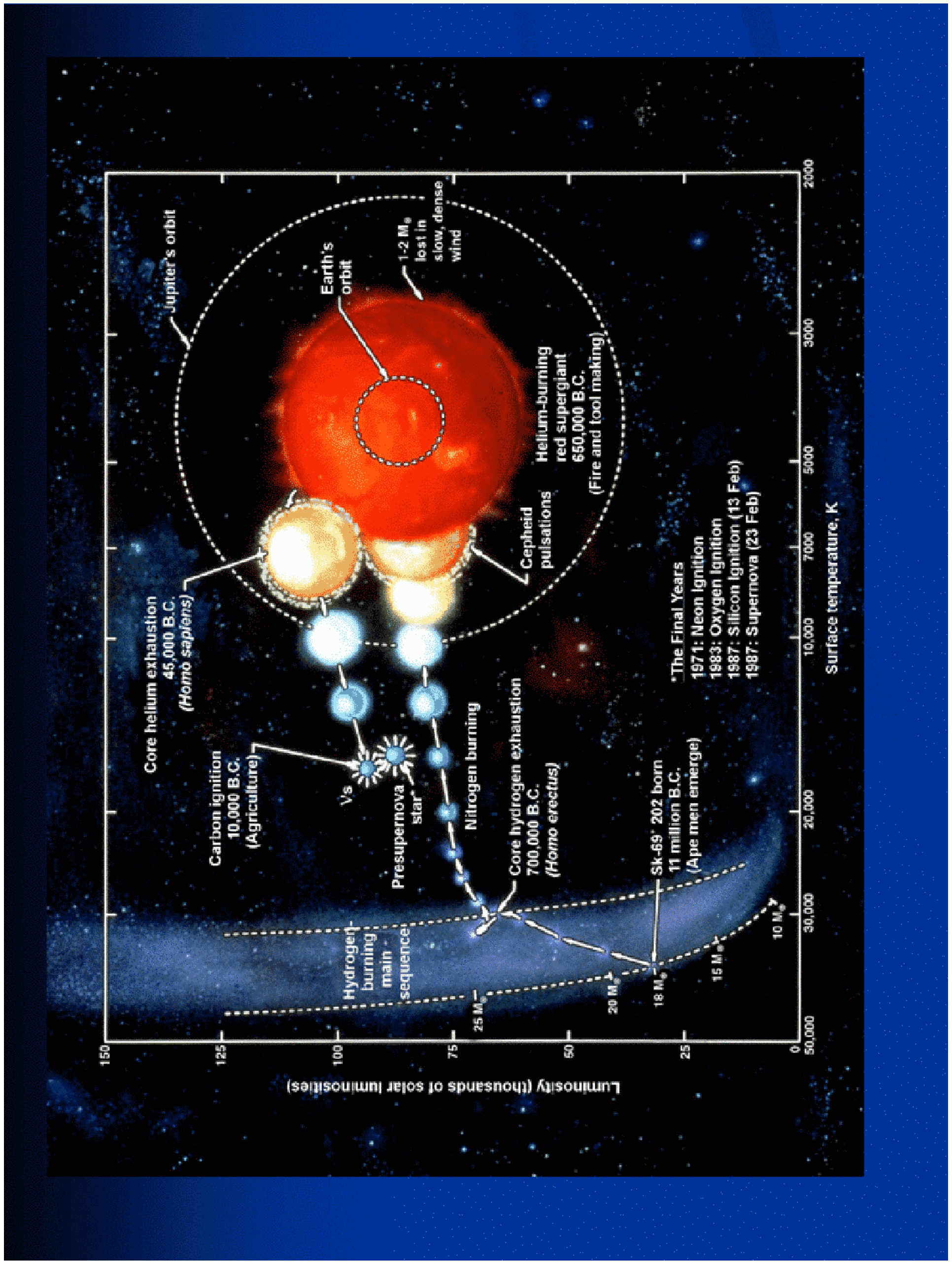
Friday, February 18, 2005

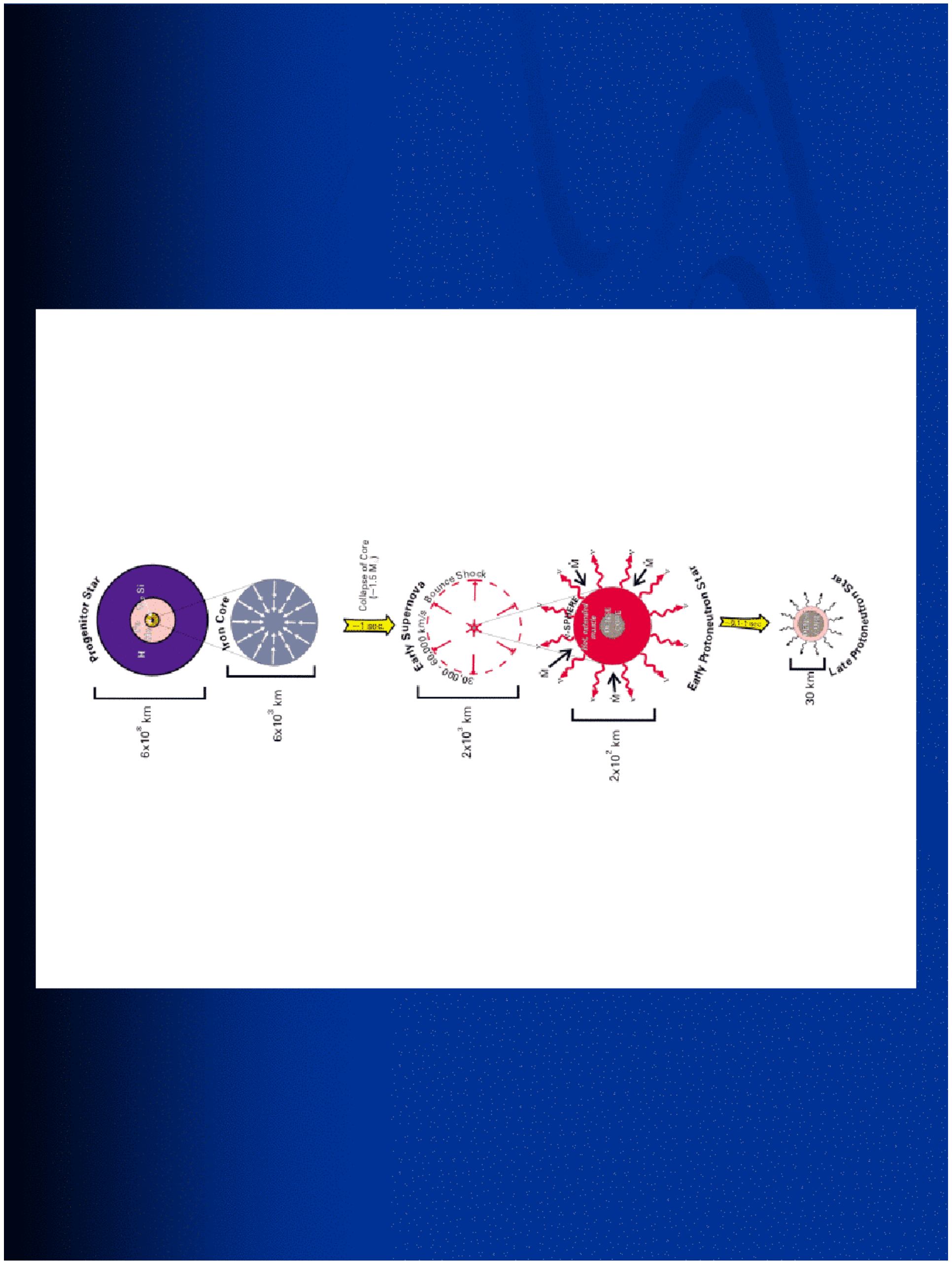
Outline

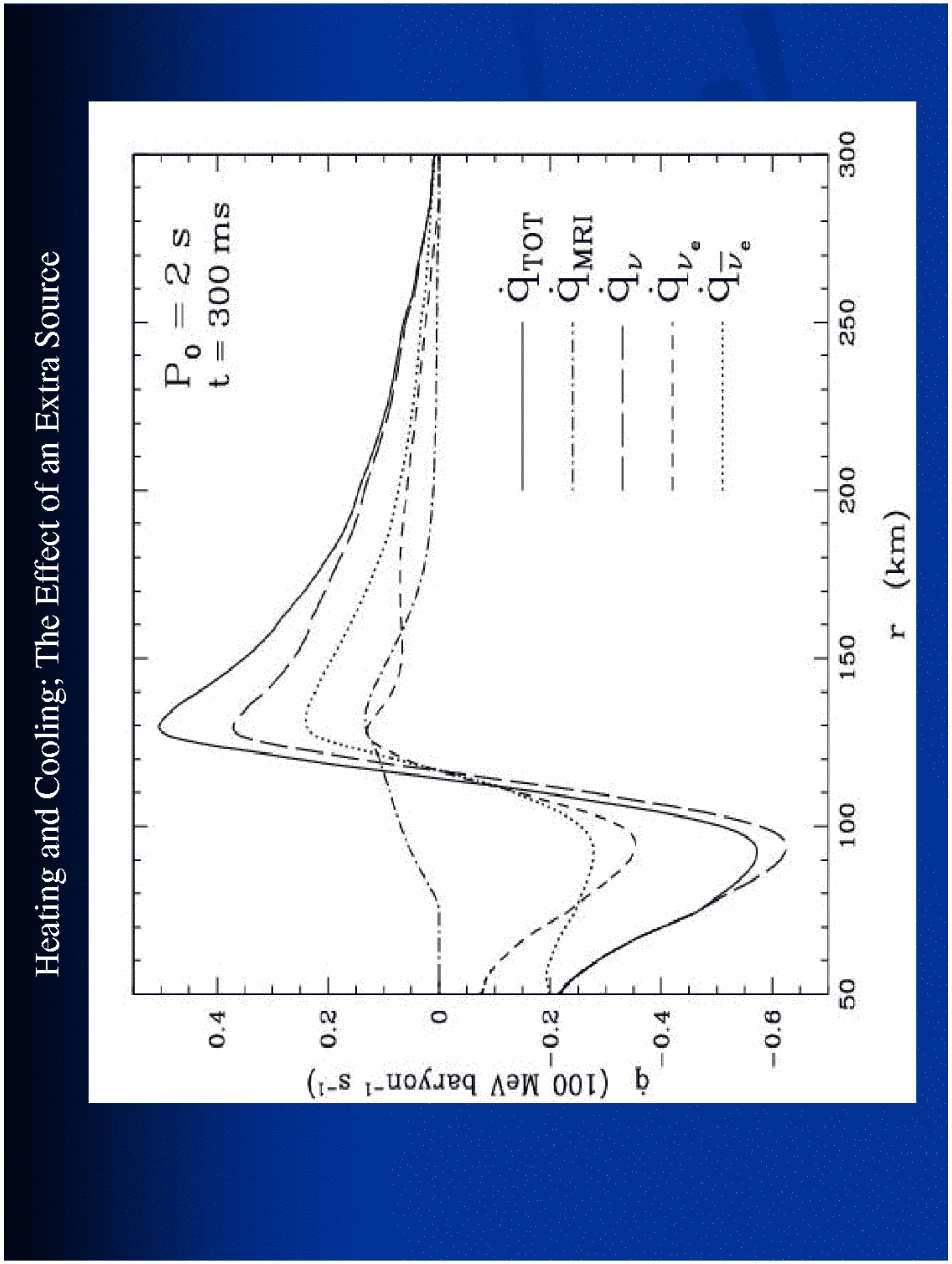
- Basic scenario of Core-Collapse Supernovae
- Rotation? Multi-D effects
- VULCAN/2D: 2D Radiation/hydrodynamics, (with rotation)
- 2D Flux, heating Anisotropy, with and without rotation
- 2D MGFLD Radiation/hydrodynamics results
- Gravitational radiation; Pulsar kicks
- Mixed-Frame 2D Radiation/Hydrodynamics
- Future theoretical work

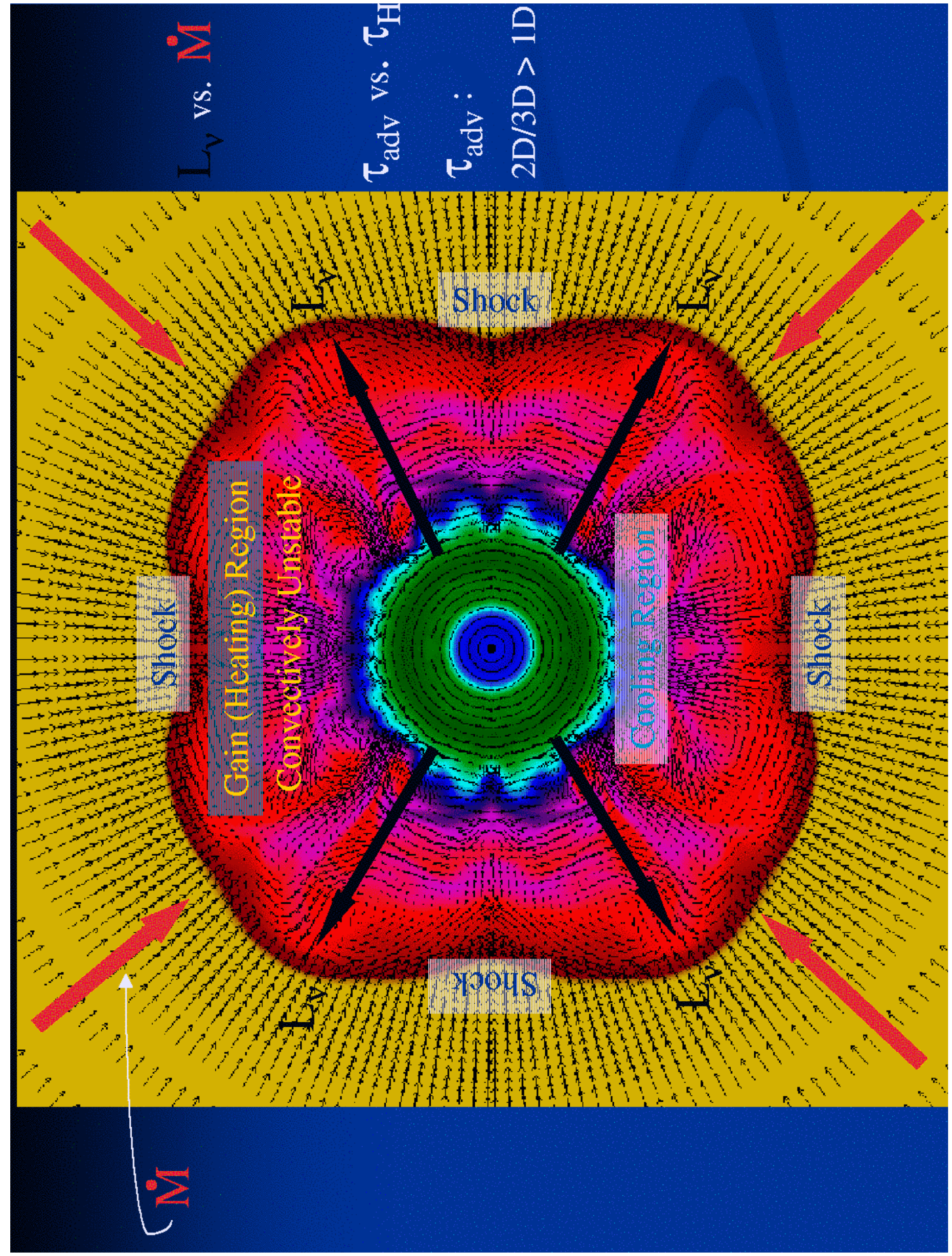

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.


Onion Skin Structure: The Mote in the Eye of the Storm
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.


Jupiter's orbit
Earth's orbit
1-2 M☉ lost in slow, dense wind
Core helium exhaustion 45,000 B.C. (Homo sapiens)
Helium-burning red supergiant 650,000 B.C. (Fire and tool making)
Cepheid pulsations
Carbon ignition 10,000 B.C. (Agriculture)
Vs
Presupernova star
Nitrogen burning
Core hydrogen exhaustion 700,000 B.C. (Homo erectus)
Sk-69° 202 born 11 million B.C. (Ape men emerge)
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)
Hydrogen-burning main sequence
25 M☉
20 M☉
18 M☉
15 M☉
10 M☉
Surface temperature, K
Luminosity (thousands of solar luminosities)


Progenitor Star
Iron Core
Early Supernova
Bounce Shock
Early Protoneutron Star
Late Protoneutron Star
30 km


Heating and Cooling; The Effect of an Extra Source
$P_0 = 2$ s
t = 300 ms
$\dot{q}_{TOT}$
$\dot{q}_{MRI}$
$\dot{q}_{\nu}$
$\dot{q}_{\nu_e}$
$\dot{q}_{\bar{\nu}_e}$
r (km)
$\dot{q}$ (100 MeV baryon^{-1} s^{-1})


L_ν vs. $\dot{M}$
τ_{adv} vs. τ_H
τ_{adv} :
2D/3D > 1D
Shock
Shock
Shock
Shock
Gain (Heating) Region
Convectively Unstable
Cooling Region
L_ν
L_ν
L_ν
L_ν
$\dot{M}$

Explosion Mechanism?

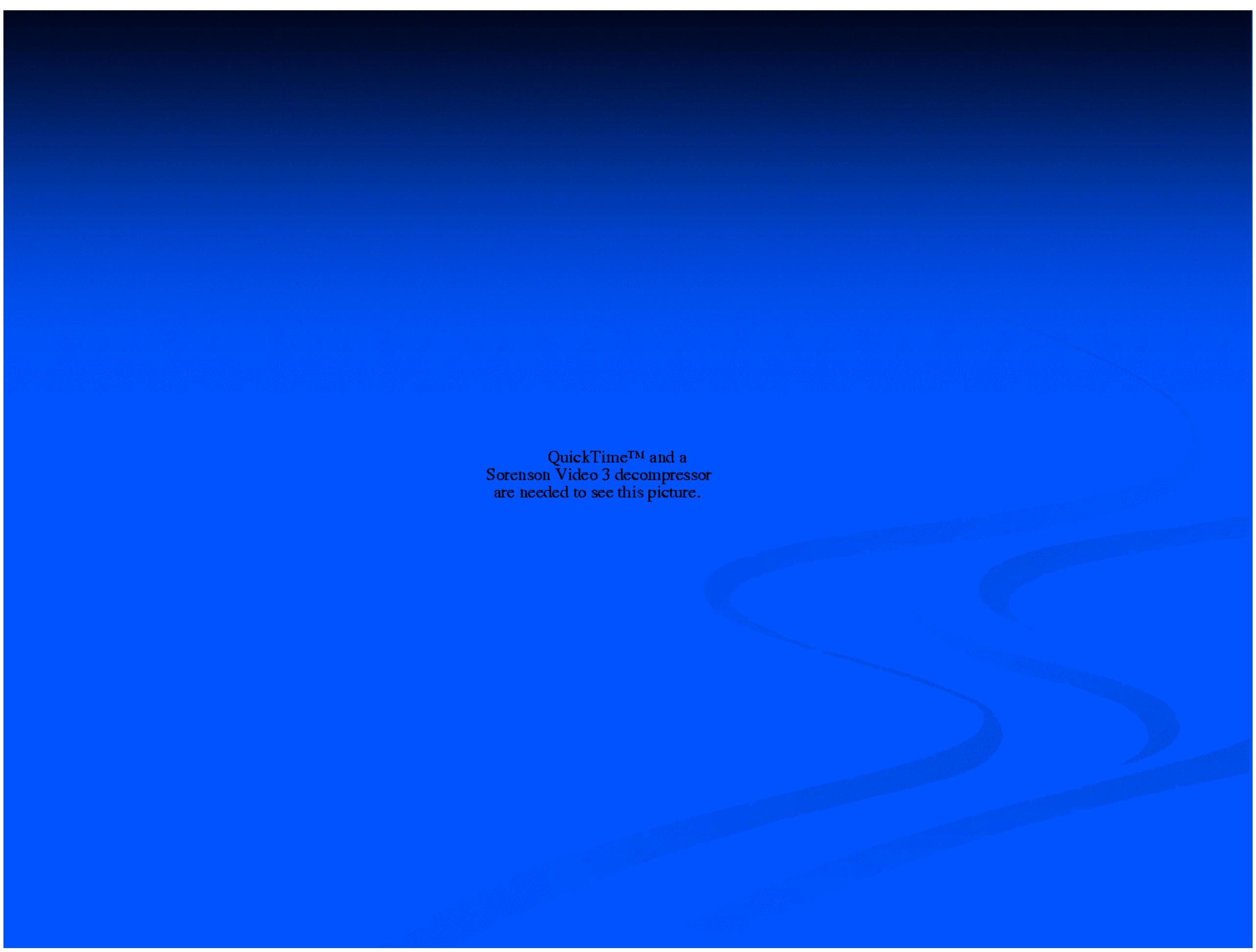
- Explosion driven by neutrino heating of shocked mantle after bounce shock stalls: delay? (Radiation pressure unimportant to mechanism)
- Neutrino-driven explosion is a ~10% phenomenon, not a ~1% phenomenon
- Bounce shock always fizzles: "Direct" hydro mechanism aborts: killed by neutrino losses and photodissociation of heavy nuclei
- Delay is good: Neutron star mass and Ejecta Y_e (nucleosynthesis)
- Explosion condition: L_ν (heating) vs. Mass accretion; "$\tau_H < \tau_{adv}$"
- We know what would facilitate neutrino-driven explosions
- General relativity, EOS, neutrino-matter coupling details not very important at the 10-20% level (feedbacks), but ….

Explosion Mechanism? II

- All groups get the same results in 1D: fizzle. $\tau_H > \tau_{adv}$.
- Multi-D instabilities/convection and radiation hydrodynamics important; 2D/3D may be crucial ⟶ $\tau_H < \tau_{adv}$ (?)
- Also, can core instabilities boost driving neutrino luminosity? Doubly-diffusive instabilities, mixing, eddy digging?
- Rotation's role and final spin period(s): Angular momentum transport? Eddington-Sweet-type mixing instabilites?
- B-fields, MRI?
- Viscous heating and angular momentum transport?
- Vortical-Acoustic instability? l = 1 modes?

Rotation?

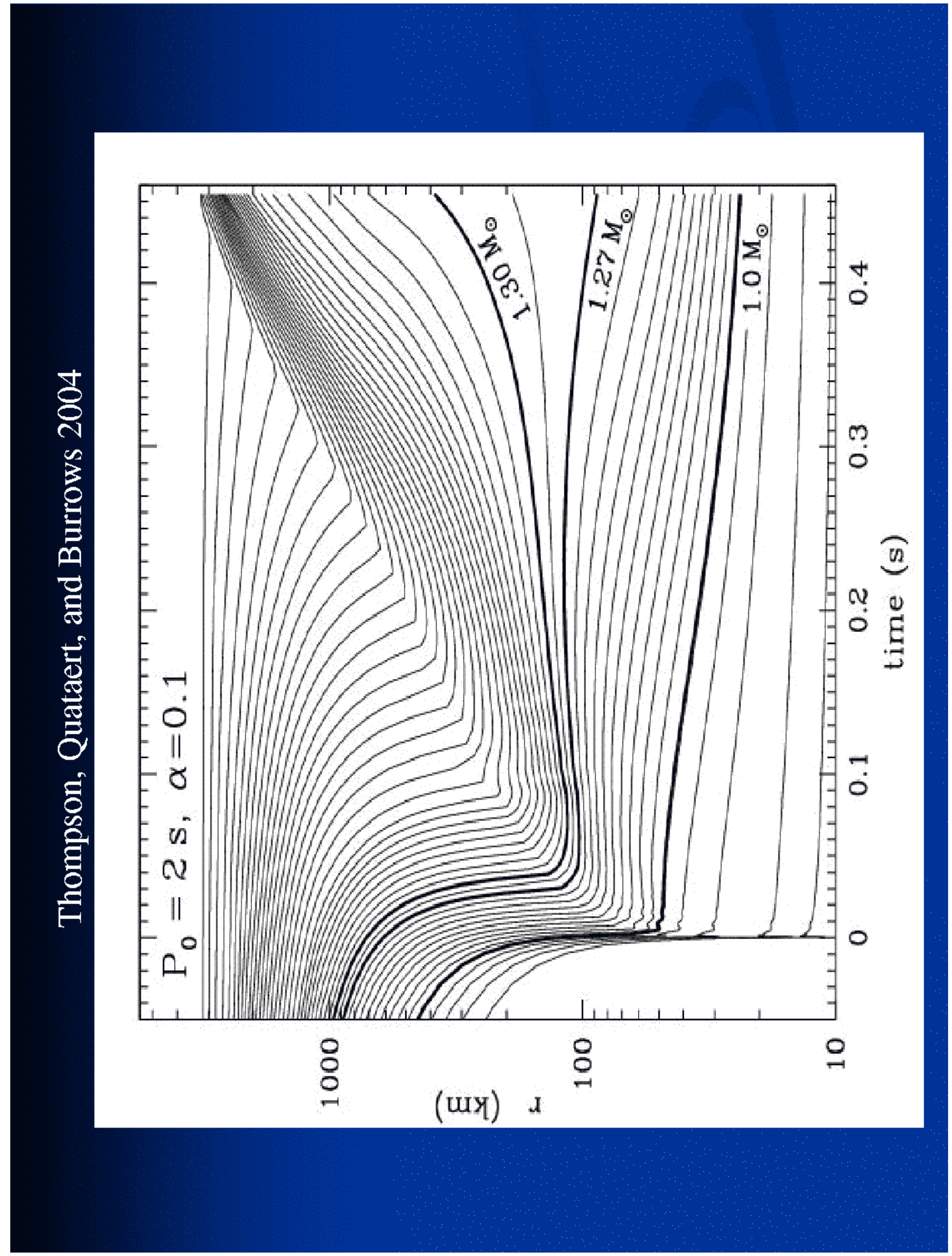
- Produces bi-polar explosions (SN1987A morphology; Type Ic polarization; rough correlation of pulsar spin axis with proper motion)
- Naturally amplified by collapse
- Centrifugal support (lower effective gravity)
- Enlarges gain region
- Generates funnels at poles!
- For rapid rotation, neutrino flux anisotropy: greater at poles?
- GRB connection
- How to shed angular momentum and rotational KE: pulsars?
- B-fields?
- Extra parameter(s)
- New generation of simulations required




QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.


QuickTime™ and a
Photo decompressor
are needed to see this picture.
11 Solar Masses
Rapid Rotation

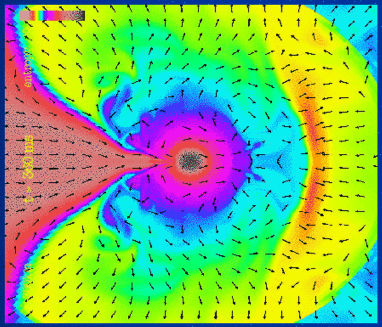

20 Solar Masses
Modest Rotation
Torus Formation
QuickTime™ and a
Photo decompressor
are needed to see this picture.


Thompson, Quataert, and Burrows 2004
P0 = 2 s, α=0.1
1.30 M⊙
1.27 M⊙
1.0 M⊙
r (km)
1000
100
10
time (s)
0
0.1
0.2
0.3
0.4

QuickTime™ and a
Video decompressor
are needed to see this picture.

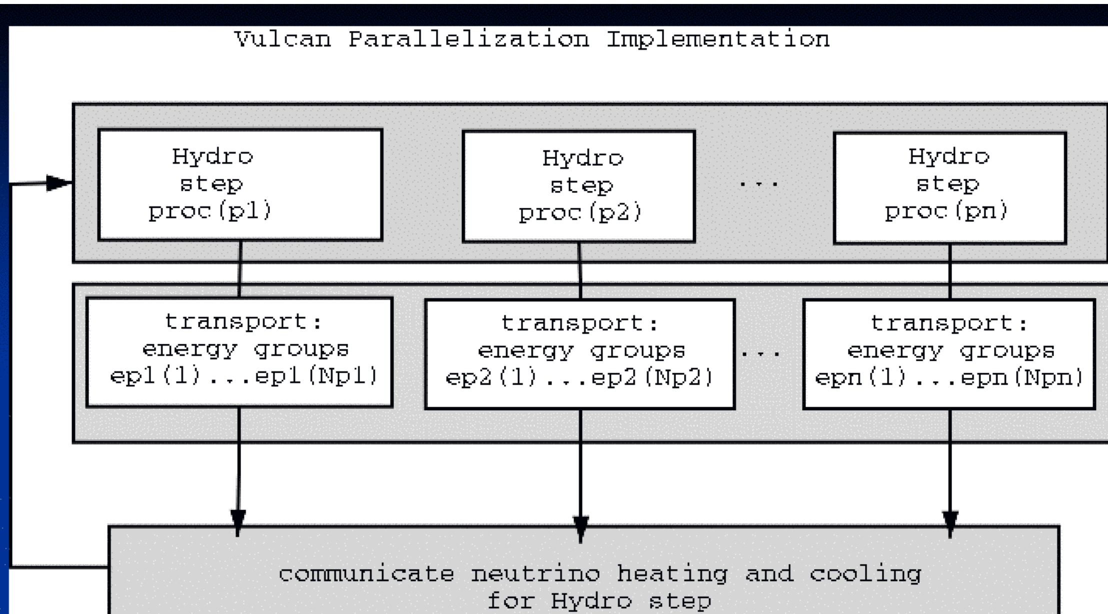
Blondin et al.

QuickTime™ and a
Photo decompressor
are needed to see this picture.

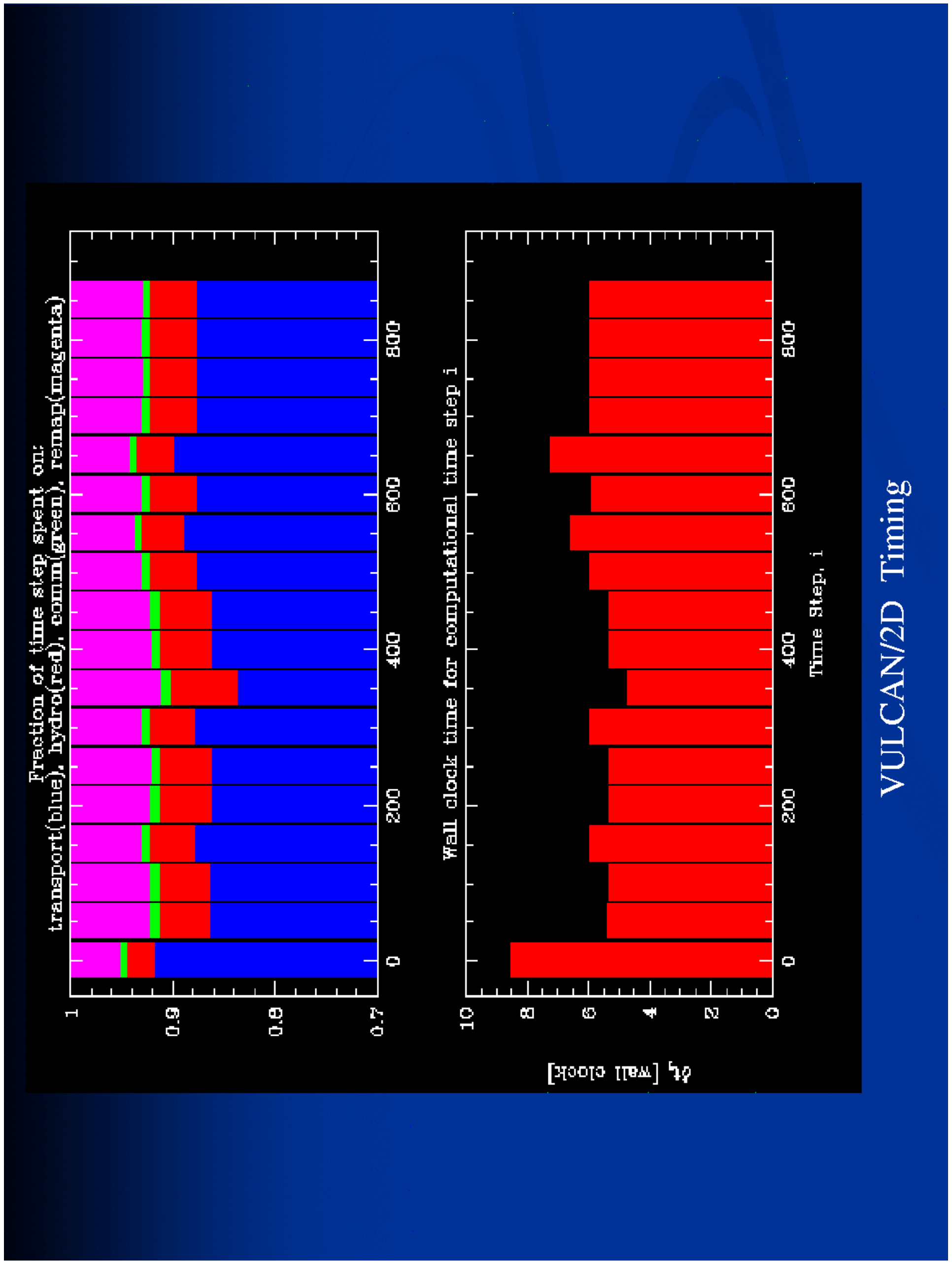


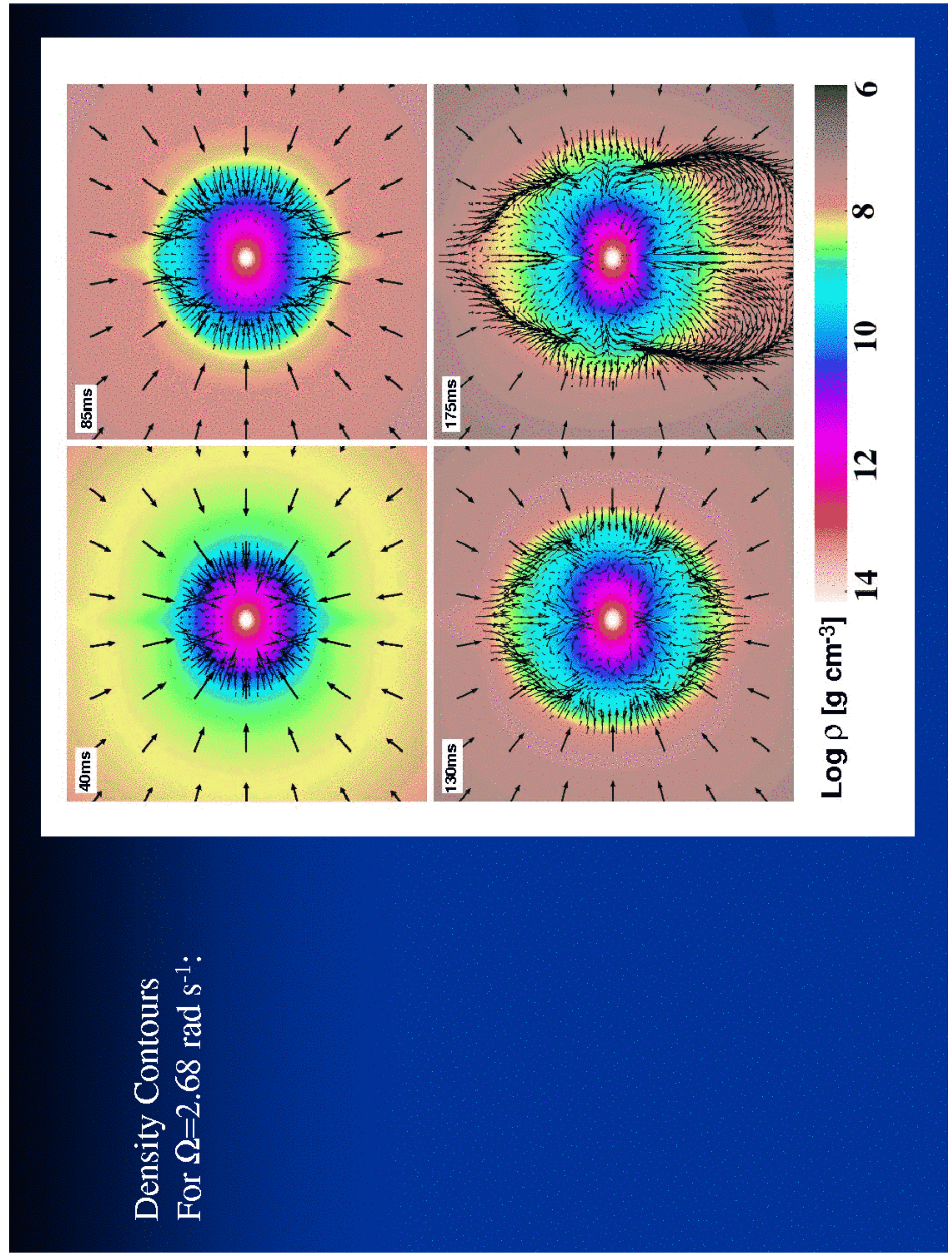
VULCAN/2D Multi-Group,Multi-Angle, Time-dependent Boltzmann/Hydro (6D)

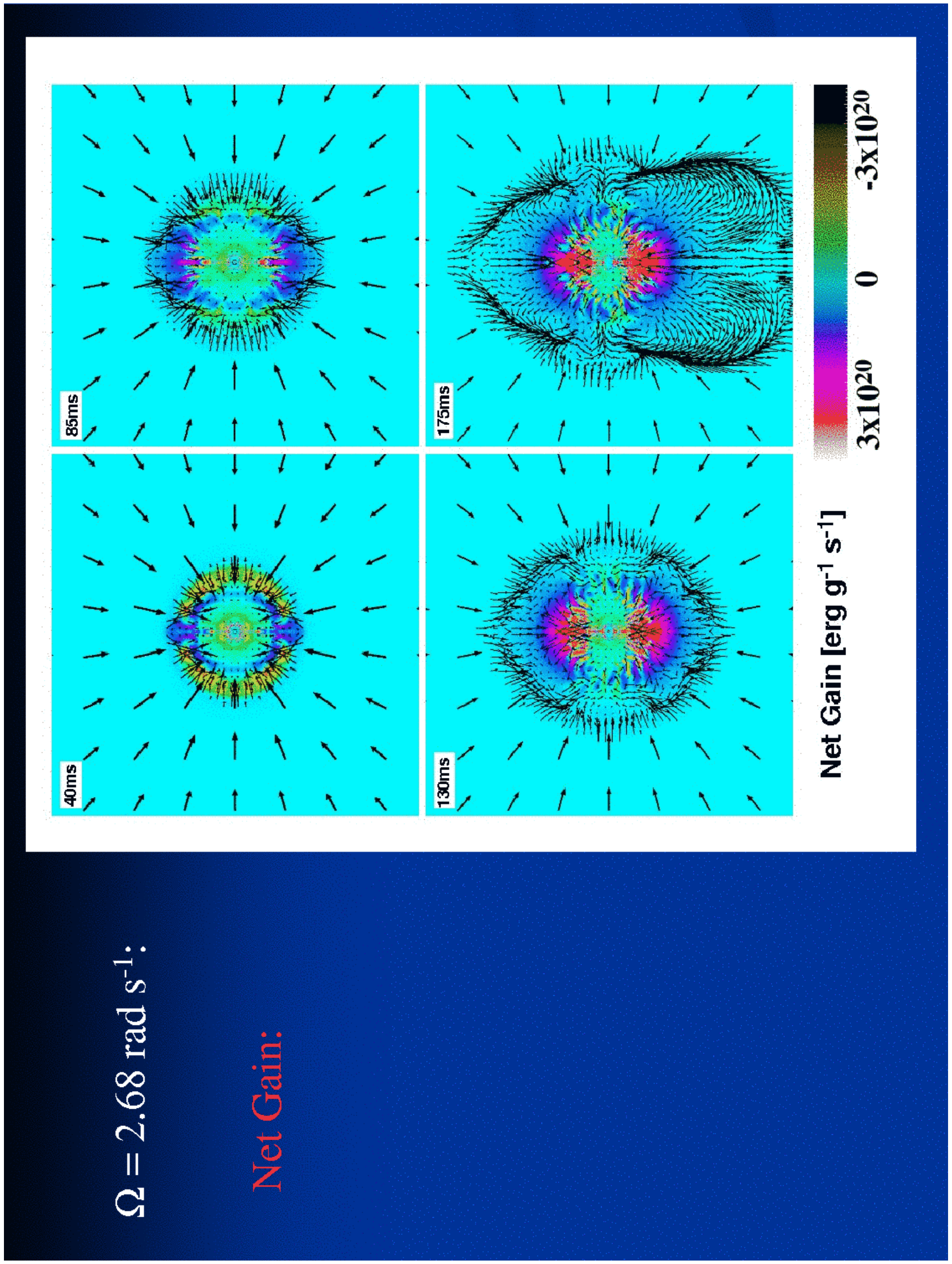
- Arbitrary Eulerian-Lagrangian (ALE); remapping
- 6 - dimensional (1(time) + 2(space) + 2(angles) + 1(energy-group))
- Moving Mesh (FE)
- 2D multi-group, multi-angle, S_n (~150 angles), time-dependent, implicit transport (still slow)
- Axially-symmetric; Rotation
- Flux-conservative; smooth matching to diffusion limit
- Velocity-dependent terms: convective can be included if desired (DI/dt), but not yet Doppler/Aberration terms: will be handled explicitly
- Energy redistribution: explicit (done in 1D, not yet 2-D)
- Has a 2D MGFLD, rotating version
- New Implicit Hydro version
- Livne, Burrows et al. (2004), Ap.J., 609, 277
- Walder et al. (2004), Ap.J., submitted
- Burrows et al. (2005), in preparation

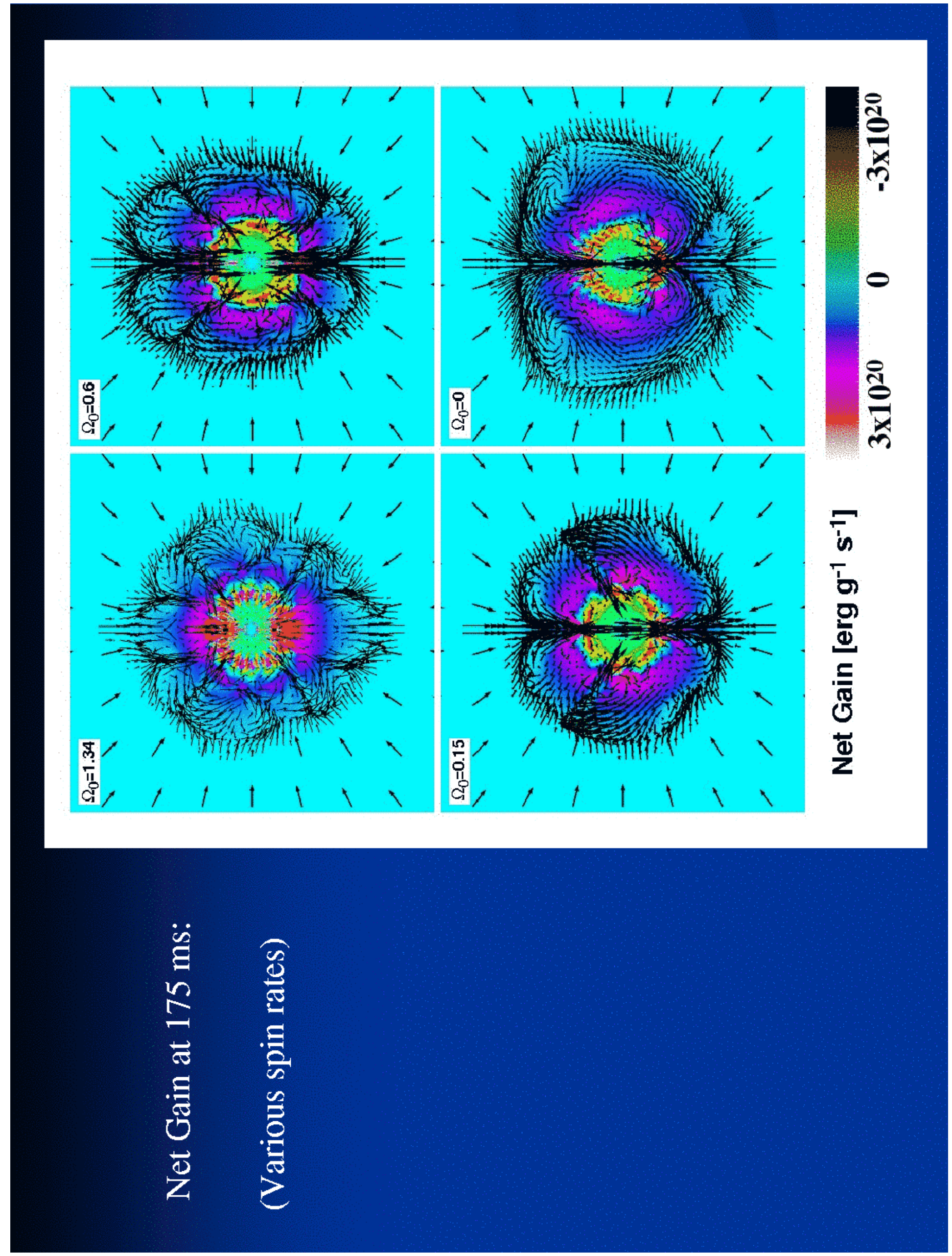


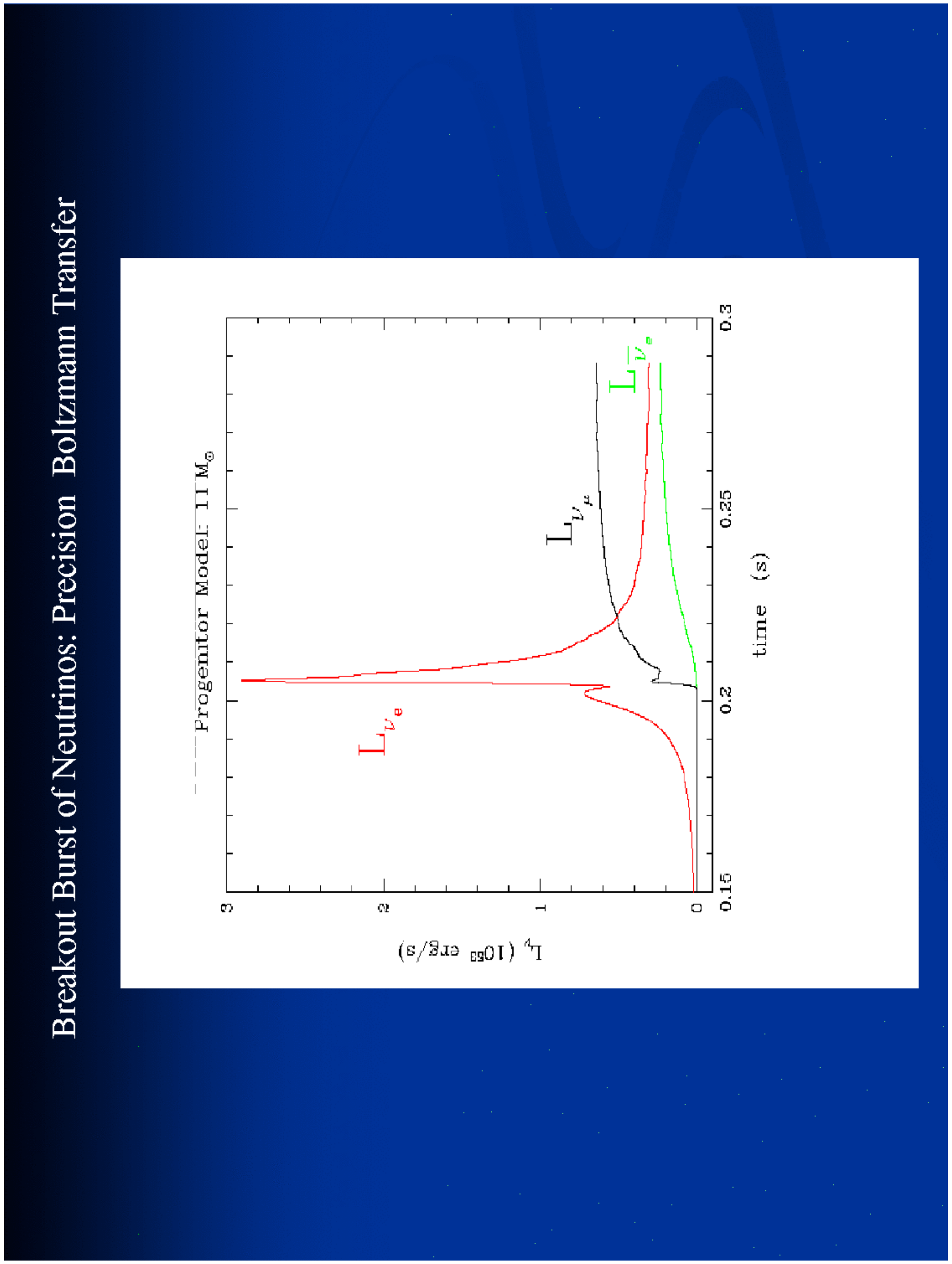
VULCAN/2D
Numerical
Paradigm


VULCAN/2D Timing
Fraction of time step spent on:
transport(blue), hydro(red), comm(green), remap(magenta)
Wall clock time for computational time step i
Time Step, i
δt_i [wall clock]
0
200
400
600
800
1
0.9
0.8
0.7
10
8
6
4
2
0

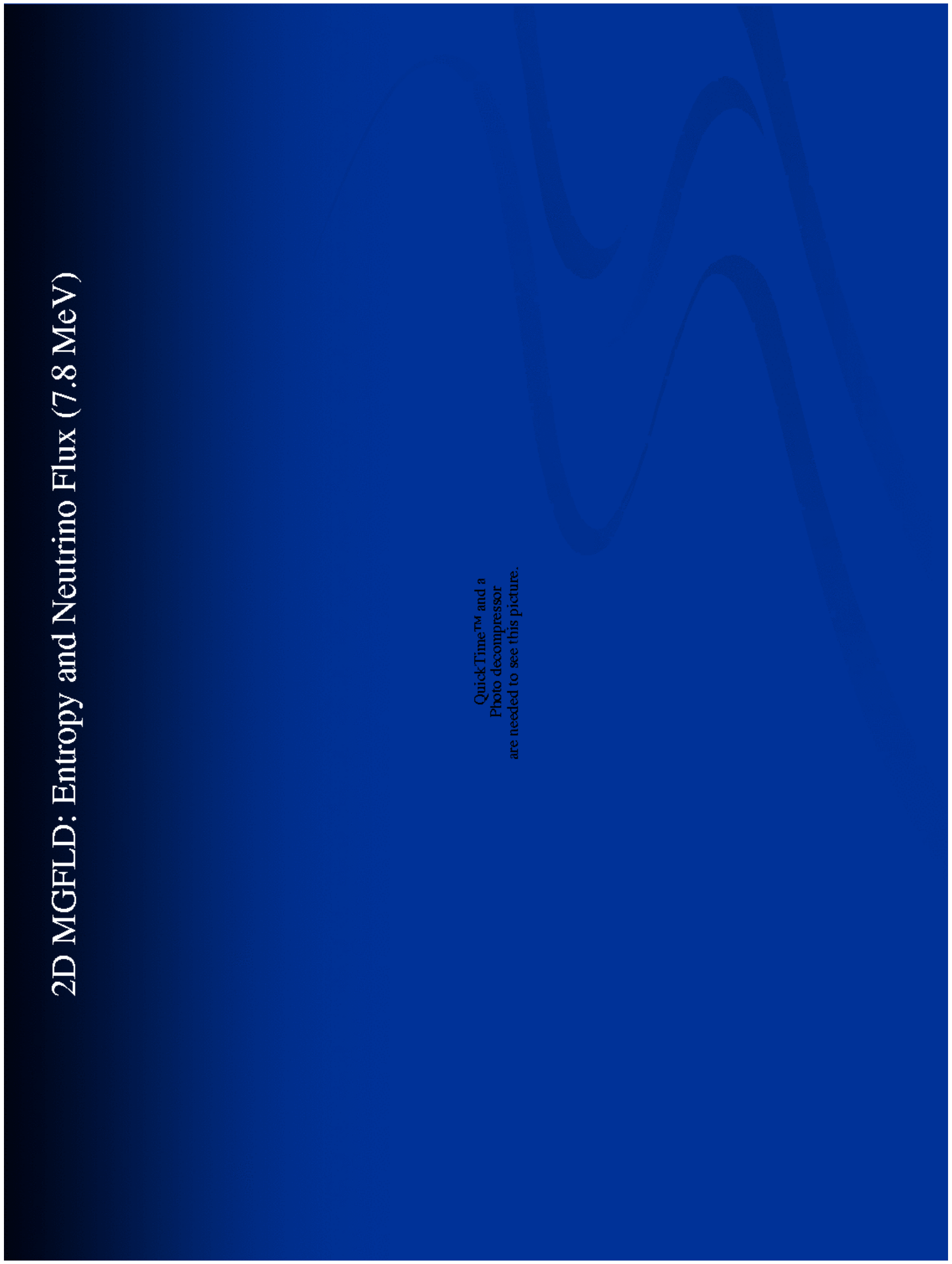

Density Contours
For Ω=2.68 rad s-1:
40ms
85ms
130ms
175ms
Log ρ [g cm-3]
6
8
10
12
14


Ω = 2.68 rad s-1:
Net Gain:
40ms
85ms
130ms
175ms
Net Gain [erg g-1 s-1]
3x1020
0
-3x1020


Net Gain at 175 ms:
(Various spin rates)
Ω0=1.34
Ω0=0.6
Ω0=0.15
Ω0=0
Net Gain [erg g-1 s-1]
3x1020
0
-3x1020

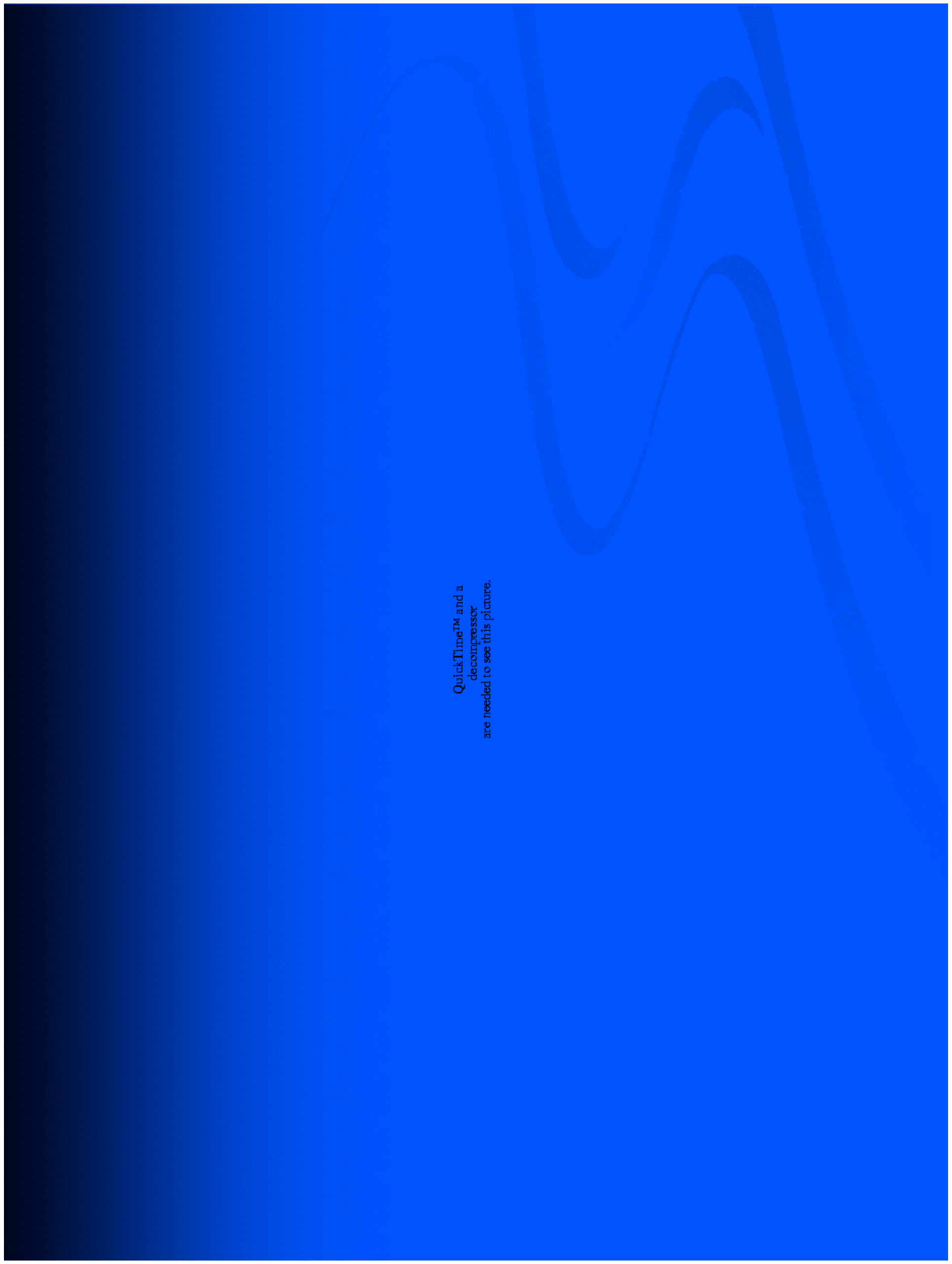

Breakout Burst of Neutrinos: Precision Boltzmann Transfer
Progenitor Model: 11 $M_\odot$
L_{ν_e}
L_{ν_μ}
$L_{\bar{\nu}_e}$
time (s)
L_ν (10^{53} erg/s)
0.15
0.2
0.25
0.3
0
1
2
3


QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

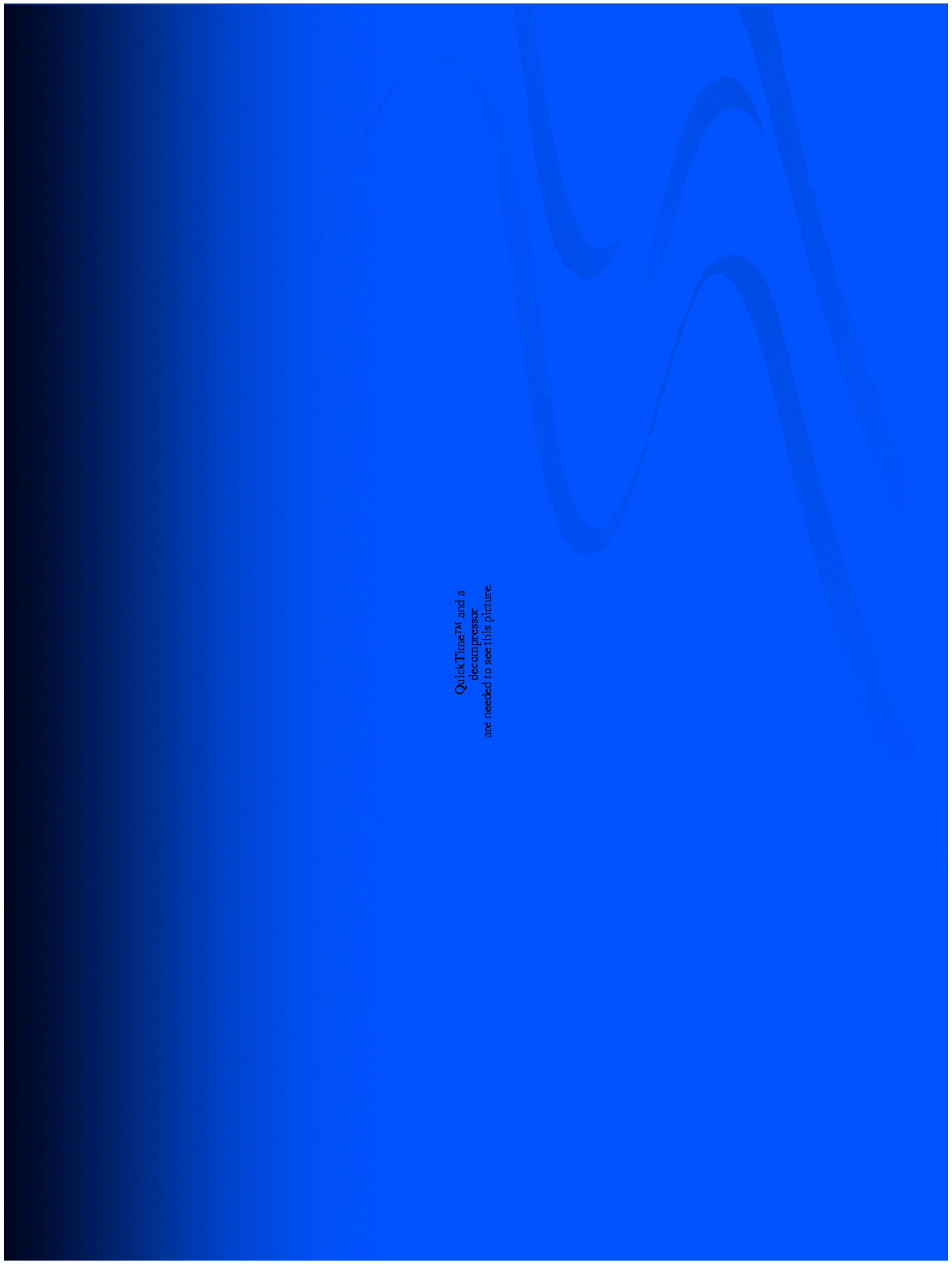

2D MGFLD: Entropy and Neutrino Flux (7.8 MeV)
QuickTime™ and a
Photo decompressor
are needed to see this picture.


2D MGFLD: Neutrino Energy Density and Flux (7.8 MeV)
QuickTime™ and a
Photo decompressor
are needed to see this picture.

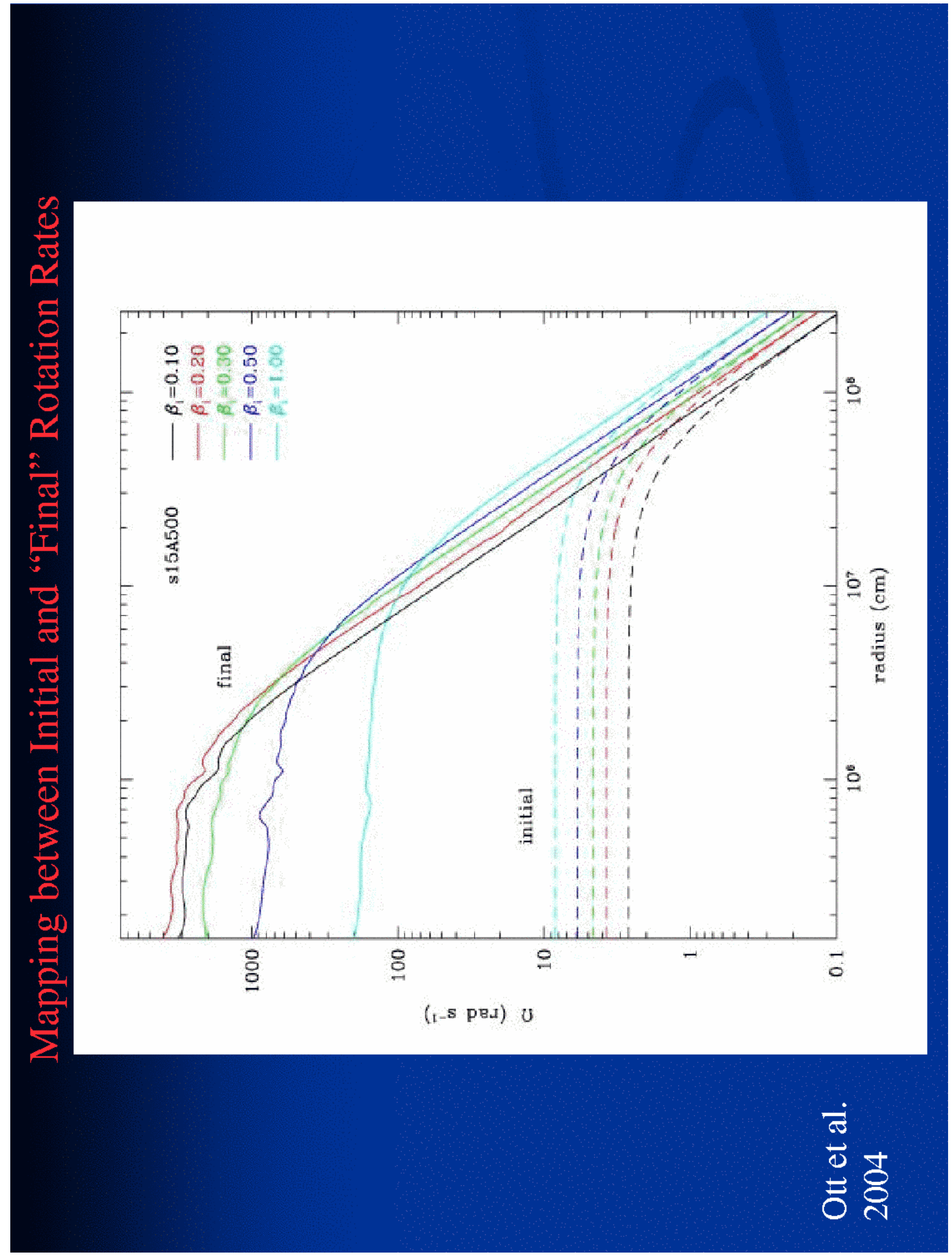

2D MGFLD Rotating Collapse, Bounce, and Convection
QuickTime™ and a
Photo decompressor
are needed to see this picture.

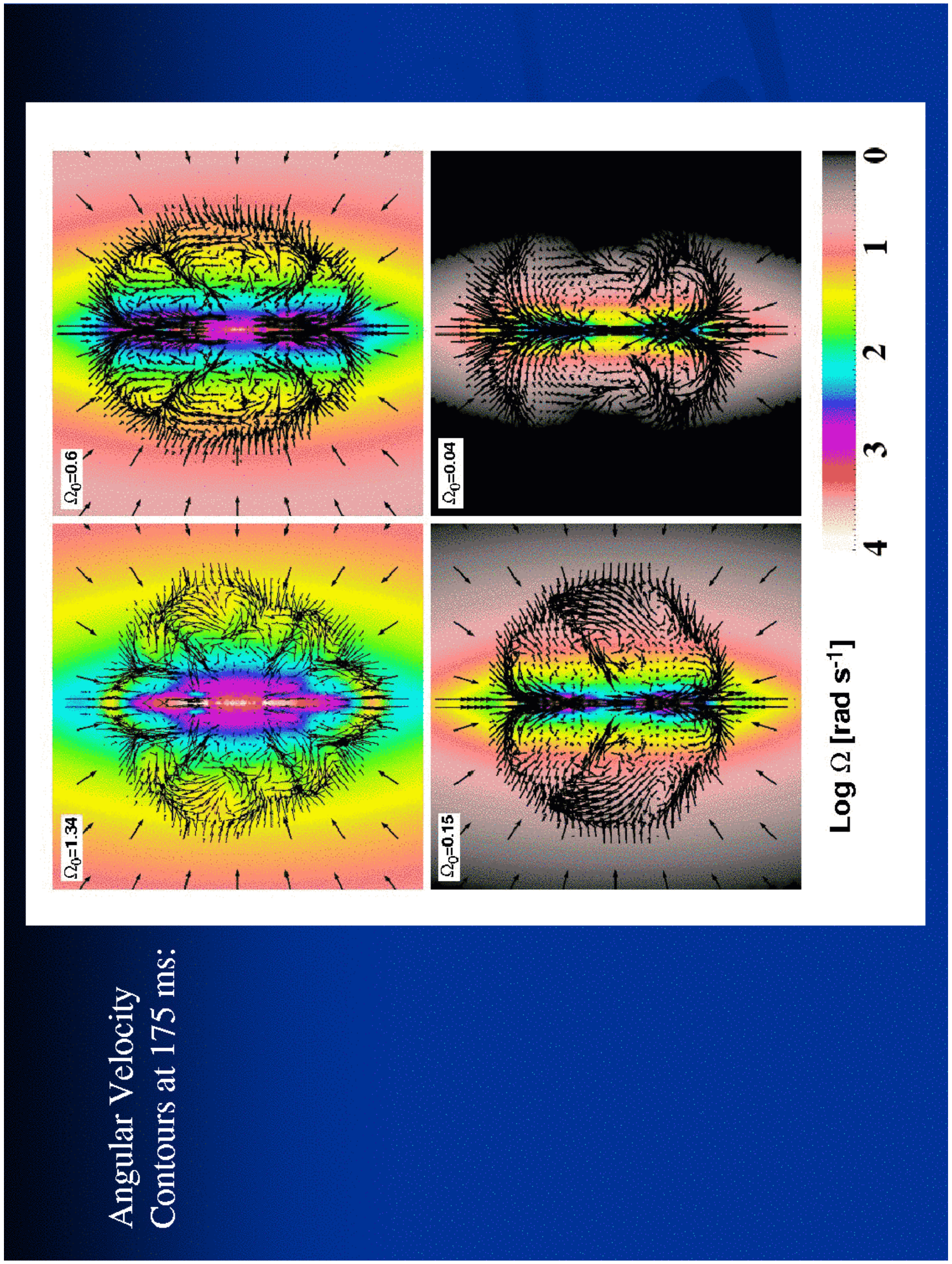

QuickTime™ and a
decompressor
are needed to see this picture.


$\Omega_0 = 2.68$ rad s^{-1}:
Net Gain
QuickTime™ and a Photo decompressor are needed to see this picture.

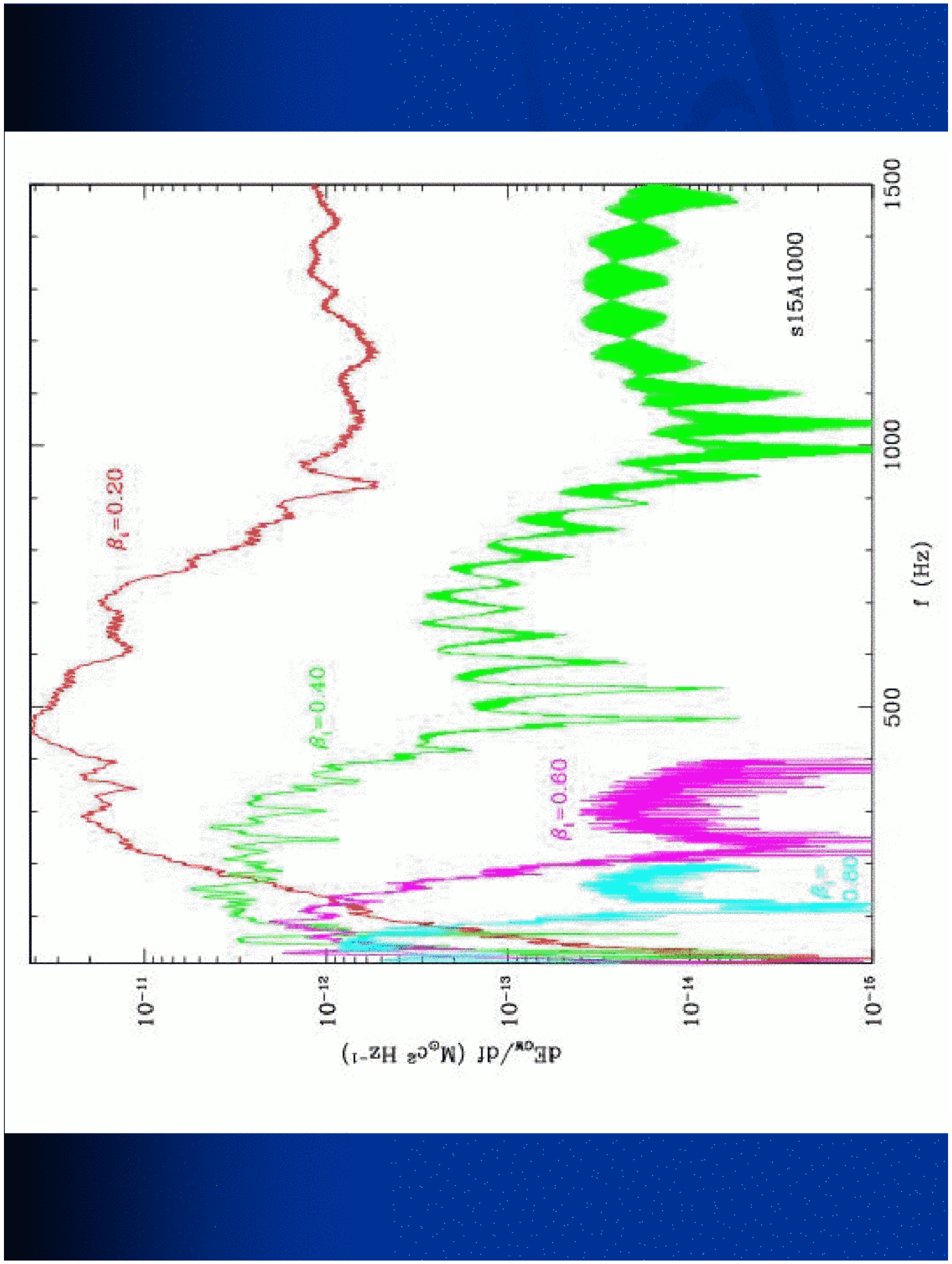

QuickTime™ and a decompressor are needed to see this picture.

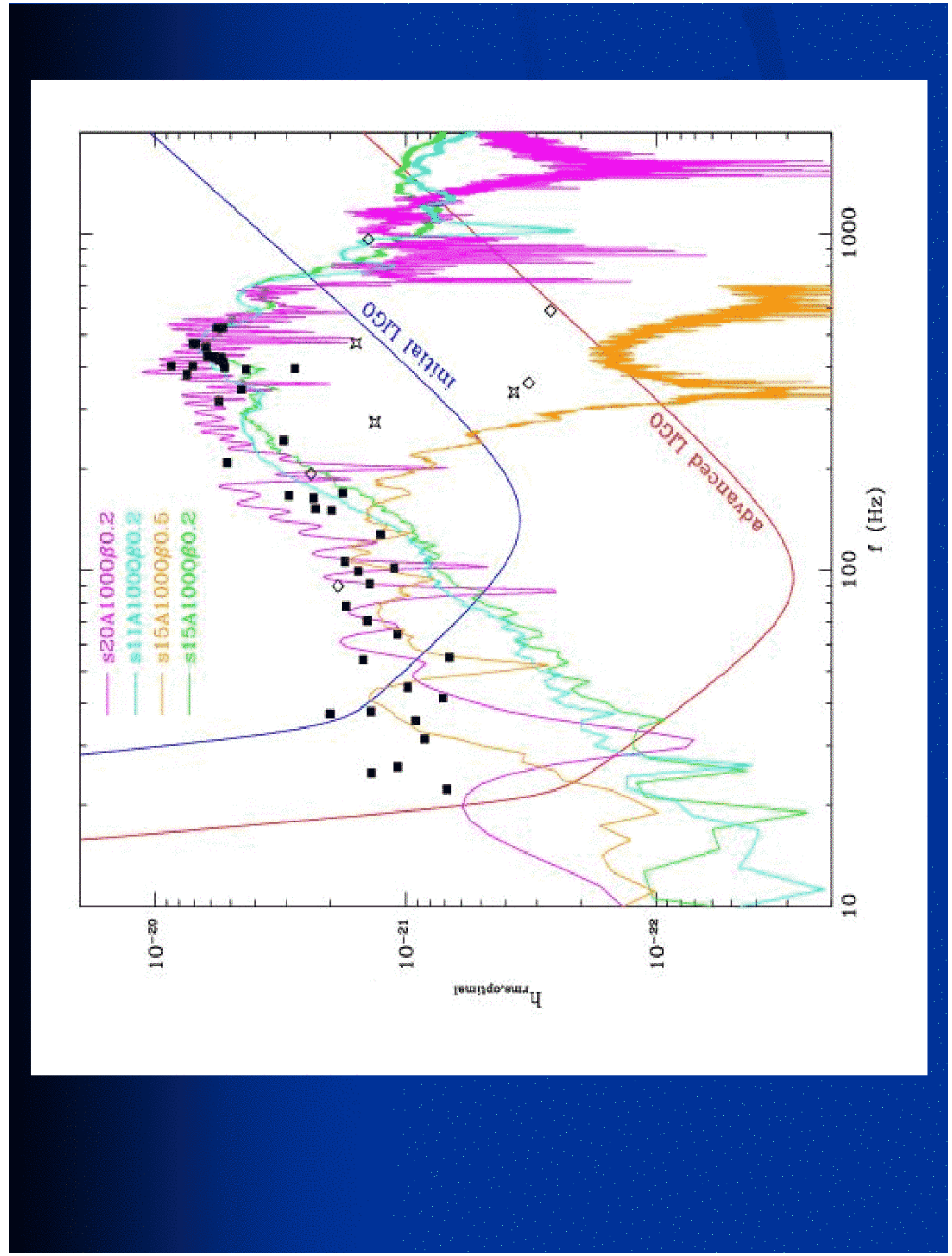

QuickTime™ and a
decompressor
are needed to see this picture.


Mapping between Initial and “Final” Rotation Rates
s15A500
final
initial
β_i=0.10
β_i=0.20
β_i=0.30
β_i=0.50
β_i=1.00
Ω (rad s⁻¹)
radius (cm)
Ott et al.
2004

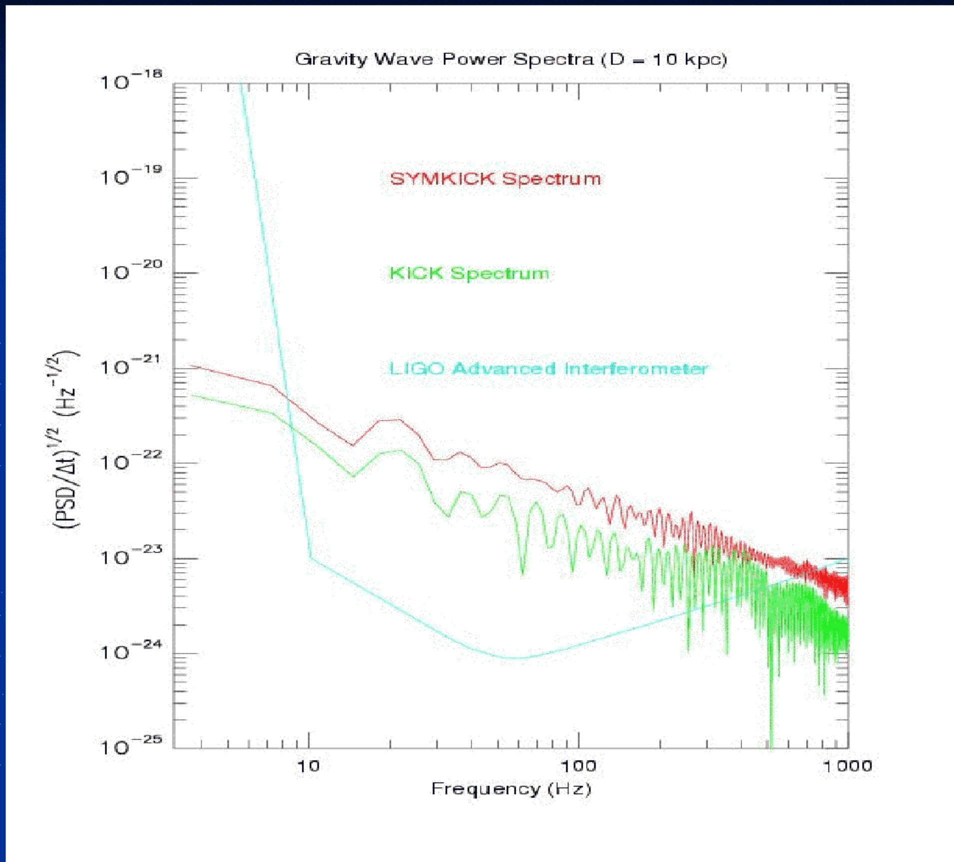

Angular Velocity
Contours at 175 ms:
Ω_0=1.34
Ω_0=0.6
Ω_0=0.15
Ω_0=0.04
Log Ω [rad s^{-1}]
0
1
2
3
4


QuickTime™ and a
Photo decompressor
are needed to see this picture.
Ou et al. 2005


s15A1000
f (Hz)
dE_GW/df (M⊙c² Hz⁻¹)
β_i=0.20
β_i=0.40
β_i=0.60
β_i=0.80


s20A1000β0.2
s11A1000β0.2
s15A1000β0.5
s15A1000β0.2
initial LIGO
advanced LIGO
f (Hz)
h_rms,optimal

Gravitational Waves off Neutrinos



Mixed-Frame Transport in 21/2-D

- σ_0, κ_0, η_0 in Comoving frame (continuum opacities)
- I(ν,**n**) in Laboratory frame (generalization of MK82)
- Lorentz transformation to O(v/c)
- Anisotropic scattering
- 0th and 1st moment equations
- 21/2-D Cylindrical and Spherical coordinates
- Eddington tensor: 5 independent components

(Hubeny and Burrows 2005)

Mixed-Frame Transport (cont.)

- Angular momentum, momentum, and neutrino viscosity
- Implicit transport
- ALI: Two-stepped solution method
- Preconditioning: Angle-averaged source function ($S_2 \rightarrow S_n$)
- Discontinuous Finite Element (DFE)
- Topological ordering: upwind to downwind
- Feautrier technique

Mixed-Frame Transport Equations

(A generalization of Mihalas & Klein (1982), taking into account anisotropic scattering and the energy dependence of the scattering rate.)

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \mathbf{n}\cdot\nabla\right) I(\nu,\mathbf{n}) = \eta^{\rm th}(\nu,\mathbf{n}) + \eta^{\rm sc}(\nu,\mathbf{n}) - [\kappa(\nu,\mathbf{n}) + \sigma(\nu,\mathbf{n})]\, I(\nu,\mathbf{n}) \qquad (1)$$

$$\kappa(\nu,\mathbf{n}) = \kappa_0(\nu) - \frac{\mathbf{n}\cdot\mathbf{v}}{c}\left[\kappa_0(\nu) + \nu\frac{\partial\kappa_0}{\partial\nu}\right] \qquad (2)$$

$$\sigma(\nu,\mathbf{n}) - \sigma_0(\nu) - \frac{\mathbf{n}\cdot\mathbf{v}}{c}\left[\sigma_0(\nu) + \nu\frac{\partial\sigma_0}{\partial\nu}\right] \qquad (3)$$

$$\eta^{\rm th}(\nu,\mathbf{n}) = \eta_0^{\rm th}(\nu) + \frac{\mathbf{n}\cdot\mathbf{v}}{c}\left[2\eta_0^{\rm th}(\nu) - \nu\frac{\partial\eta_0^{\rm th}}{\partial\nu}\right] \qquad (4)$$

$$g_0(\mathbf{n}_0', \mathbf{n}_0) = 1 + \delta\,\mathbf{n}_0'\cdot\mathbf{n}_0 \qquad (5)$$

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \mathbf{n}\cdot\nabla\right) I(\nu,\mathbf{n}) = r_{00}(\nu,\mathbf{n}) + r_{01}(\nu,\mathbf{n}) + r_{10}(\nu,\mathbf{n}) + r_{11}(\nu,\mathbf{n})\,, \qquad (6)$$

where the subscripts refer to terms which are 0-th or 1-st order in v/c and δ, respectively.

In cylindrical coordinates:

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \cos\theta\frac{\partial I_\nu}{\partial z} + \frac{\sin\theta\,\cos\psi}{r}\frac{\partial}{\partial r}(rI_\nu) - \frac{\sin\theta}{r}\frac{\partial}{\partial\psi}(\sin\psi\, I_\nu) = r_{00} + r_{01} + r_{10} + r_{11} \qquad (7)$$

$$r_{00} = \eta_0^{\rm th} - (\kappa_0 + \sigma_0)\, I(\nu, \mathbf{n}) + \sigma_0 J \,, \tag{1}$$

$$r_{01} = \sigma_0\, \delta\, H^j n_j \tag{2}$$

$$\begin{aligned} r_{10} = n_j w^j \left[\eta_0^{\rm th}\left(2 - \frac{\partial \ln \eta_0^{\rm th}}{\partial \ln \nu}\right) + \kappa_0 \left(1 + \frac{\partial \ln \kappa_0}{\partial \ln \nu}\right) I(\nu, \mathbf{n})\right] + \\ + n_j w^j \left[\sigma_0 \left(1 + \frac{\partial \ln \sigma_0}{\partial \ln \nu}\right) I(\nu, \mathbf{n}) + \sigma_0 J \left(2 - \frac{\partial \ln \sigma_0}{\partial \ln \nu} - \frac{\partial \ln J}{\partial \ln \nu}\right)\right] \\ - \sigma_0 w_j H^j \left(1 - \frac{\partial \ln H^j}{\partial \ln \nu}\right) \end{aligned} \tag{3}$$

$$\begin{aligned} r_{11} = -\sigma_0\, \delta \left[n_j w^j J + n_j w_k K^{jk}\left(2 - \frac{\partial \ln K^{jk}}{\partial \ln \nu}\right)\right] \\ -\sigma_0\, \delta\, H^j \left[w_j + n_j n_k w^k \left(1 + \frac{\partial \ln \sigma_0}{\partial \ln \nu} + \frac{\partial \ln H^j}{\partial \ln \nu}\right)\right] \end{aligned} \tag{4}$$

The Moment Equations (cylindrical coordinates):

$$\frac{1}{c}\frac{\partial J}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r H_r) + \frac{\partial H_z}{\partial z} = \eta_0 - \kappa_0 J + \chi_r H_r w_r + \chi_z H_z w_z + \chi_\phi H_\phi w_\phi \tag{1}$$

$$\frac{1}{c}\frac{\partial H_r}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r f_{rr} J) + \frac{\partial}{\partial z}(f_{rz} J) - \frac{1 - f_{rr} - f_{zz}}{r} J = -(\kappa_0 + \sigma_{\rm tr}) H_r + w_r \tilde{\eta}_0 + \xi_r J \tag{2}$$

$$\frac{1}{c}\frac{\partial H_z}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r f_{rz} J) + \frac{\partial}{\partial z}(f_{zz} J) = -(\kappa_0 + \sigma_{\rm tr}) H_z + w_z \tilde{\eta}_0 + \xi_z J \tag{3}$$

$$\frac{1}{c}\frac{\partial H_\phi}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r f_{r\phi} J) + \frac{\partial}{\partial z}(f_{z\phi} J) = -(\kappa_0 - \sigma_{\rm tr}) H_\phi + w_\phi \tilde{\eta}_0 + \xi_\phi J \tag{4}$$

$$\xi_r = \tilde{\sigma}_2 w_r + (\tilde{\kappa}_0 + \tilde{\sigma}_3)(fw)_r + \frac{\sigma_0\, \delta}{3}(\partial f w)_r + + \frac{\partial \ln J}{\partial \ln \nu}\frac{\sigma_0}{3}\left[-w_r + \delta\,(fw)_r\right] \tag{5}$$

$$(fw)_r = f_{rr} w_r + f_{rz} w_z + f_{r\phi} w_\phi \tag{6}$$

$$(fw)_z = f_{rz} w_r + f_{zz} w_z + f_{z\phi} w_\phi \tag{7}$$

$$(fw)_\phi = f_{r\phi} w_r + f_{z\phi} w_z + f_{\phi\phi} w_\phi \tag{8}$$

and

$$(\partial f w)_r = \frac{\partial}{\partial \ln \nu}(fw)_r = \frac{\partial f_{rr}}{\partial \ln \nu} w_r + \frac{\partial f_{rz}}{\partial \ln \nu} w_z + \frac{\partial f_{r\phi}}{\partial \ln \nu} w_\phi \tag{9}$$

$$\chi_\phi = \tilde{\kappa}_0 + \tilde{\sigma}_1 + \sigma_{\rm tr}\frac{\partial \ln H_\phi}{\partial \ln \nu} \tag{10}$$

Core-Collapse Supernovae: The Future

- Collapse/Explosion instabilities and rotation: Multi-D
- Instabilities are generic
- Neutrino-driven?
- "Vortical-acoustic" instability, l=1?
- Multi-D radiation hydrodynamics
- Is there an important role for Rotation?
- Is there a role for Magnetic fields? Pulsar fields?
- Viscosity? viscous heating and angular momentum transport
- Equation of state?
- Neutrino rates?
- Systematics with progenitor of observables/diagnostics?
- GRB/SN connection
- Pulsar kicks; black hole formation

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Neutrino-Driven Convection and Core-Collapse Supernovae: Burrows et al. 1995


Computational Nuclear Astrophysics
Core-Collapse Supernovae (Grid-based & Statistical methods)
Thermonuclear Supernovae (Type Ia)
Gamma-Ray Bursts
X-ray Bursts
Stellar Convection simulations (2D/3D)
World-class Nuclear Data Archive
1-,2-,3-D Radiation/Hydrodynamics
Astrophysical Flame Physics
Collaboratory- Vertically Integrated Nuclear Astrophysics: Stellar Evolution -Nucleosynthesis - Supernova Explosions - Light Curves


Codes and Capabilities
2D/3D Anelastic hydro; spectral methods (+MHD) (Glatzmaier)
VULCAN/2D Boltzmann/hydro (6D) (TOPS)
Implicit Stellar Evolution (Kepler)
2D/3D Stellar Evolution
3D Hydro/diffusion for core collapse (SPH)
2D/3D Thermonuclear combustion (APDEC)
FLASH 2D/3D Hydro code
3D Monte Carlo radiation transport
3D Special-relativistic hydro (GRBs)
Nuclear Network solver(s)
Visualization infrastructure at Arizona (Hariri)

Main Computers and Platforms

- NERSC/seaborg
- ORNL/cheetah, eagle
- Beowulfs at LANL, UCSC, U.Arizona
- ASCI Q (LANL)

Major Accomplishments

- First 3D Simulation of Core-Collapse Supernova (Diffusion)
- First 2D Boltzmann Rad/Hydro Simulation in Core Collapse: Multi-group, multi-angle
- First Full Core-Collapse Simulation with 2D MGFLD
- First 3D Relativistic GRB Jet Calculation
- First Fully-Resolved 3D Rayleigh-Taylor Nuclear Burning Study in Type Ia Supernova Context and 3D Simulation of Onset of Ignition
- First 1600-Species Nuclear Network Calculation for X-Ray Bursts
- Assembly of the World's Most Comprehensive Nuclear Reaction Database
- 3D Stellar Convection simulations: sun, massive stars

Color Map: Ye

Vectors: Flux

Multi-Group

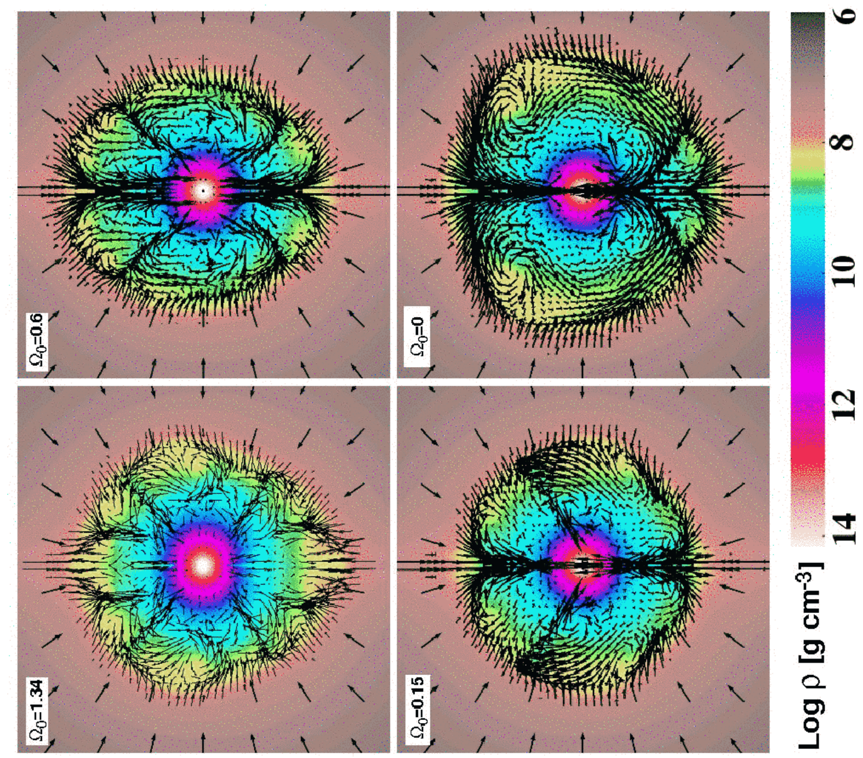
Multi-Angle

Boltzmann

Transport

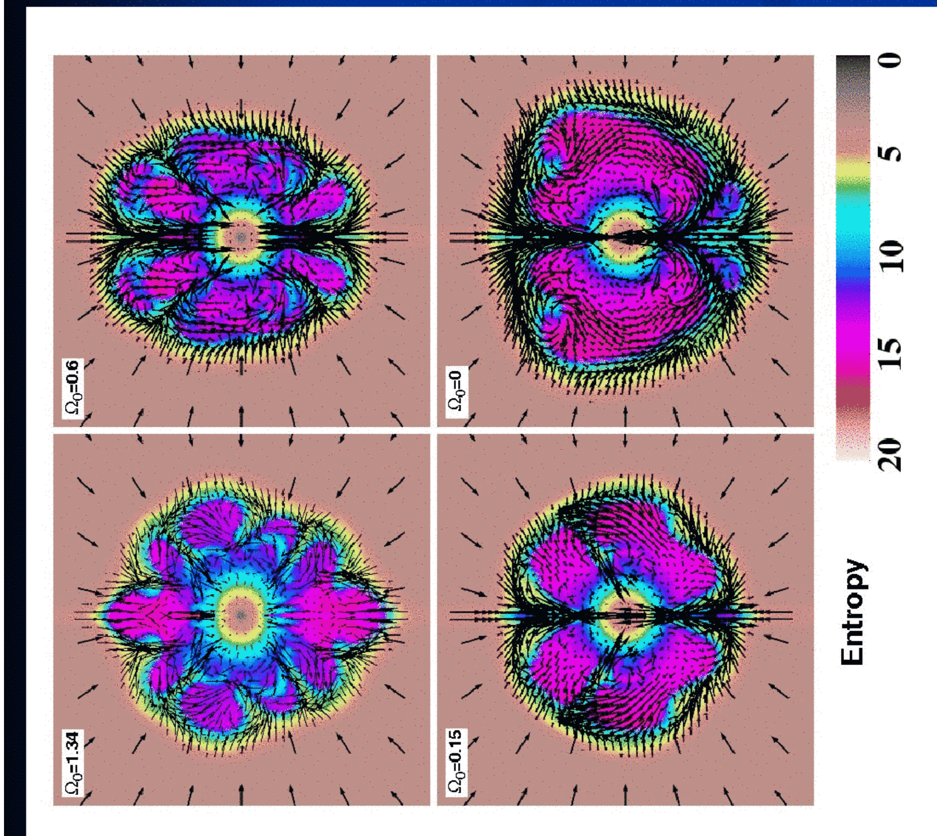
Livne, Burrows, et al. 2004, Ap.J. in press

QuickTime™ and a Photo decompressor are needed to see this picture.



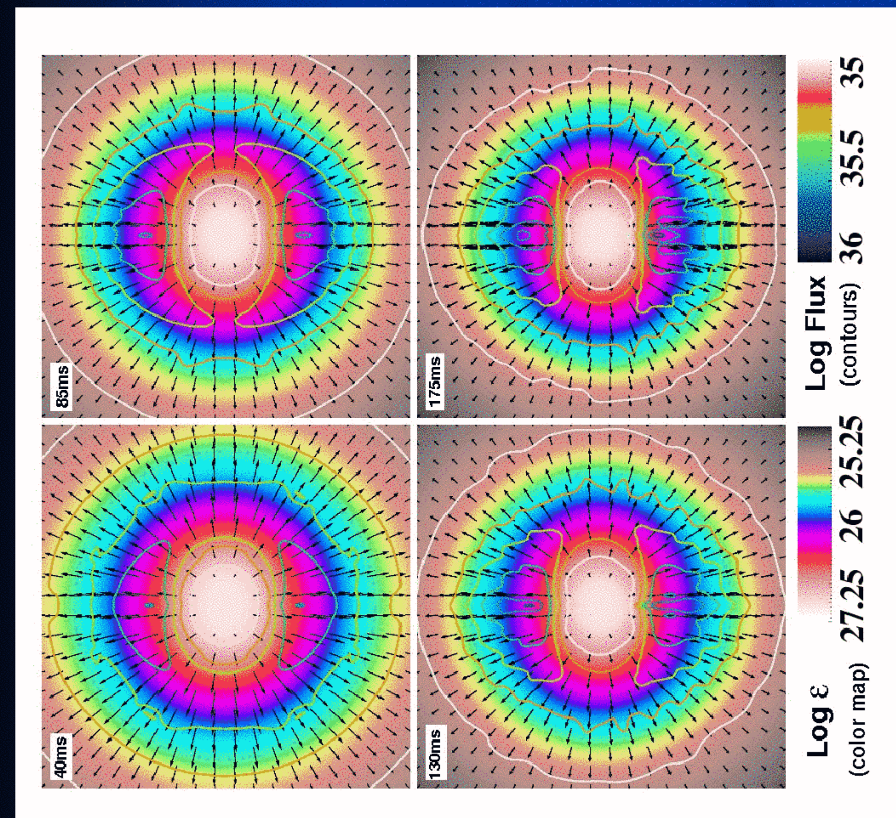
Densities for Various Ω's at 175 ms:

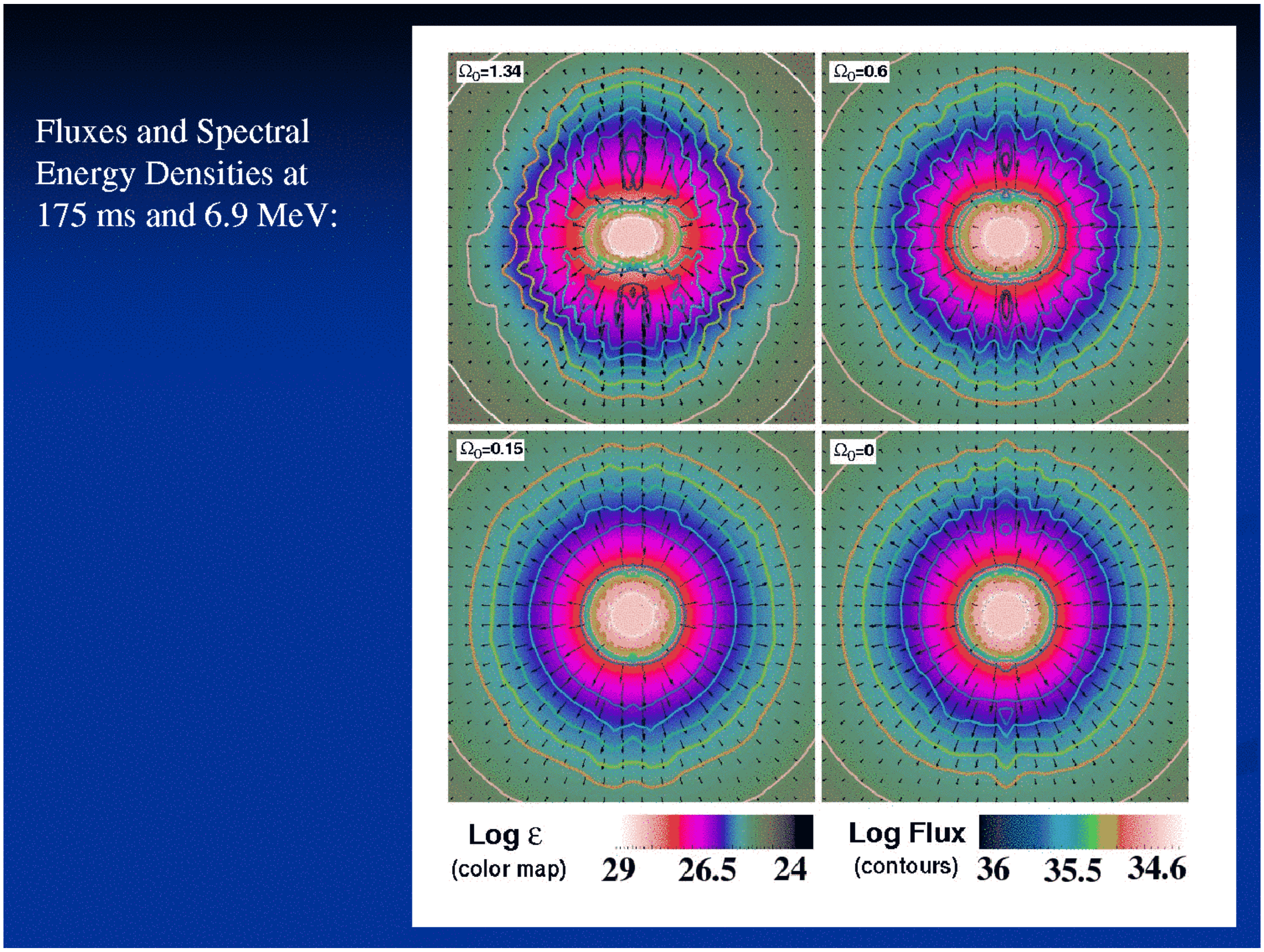
Entropy at 175 ms:

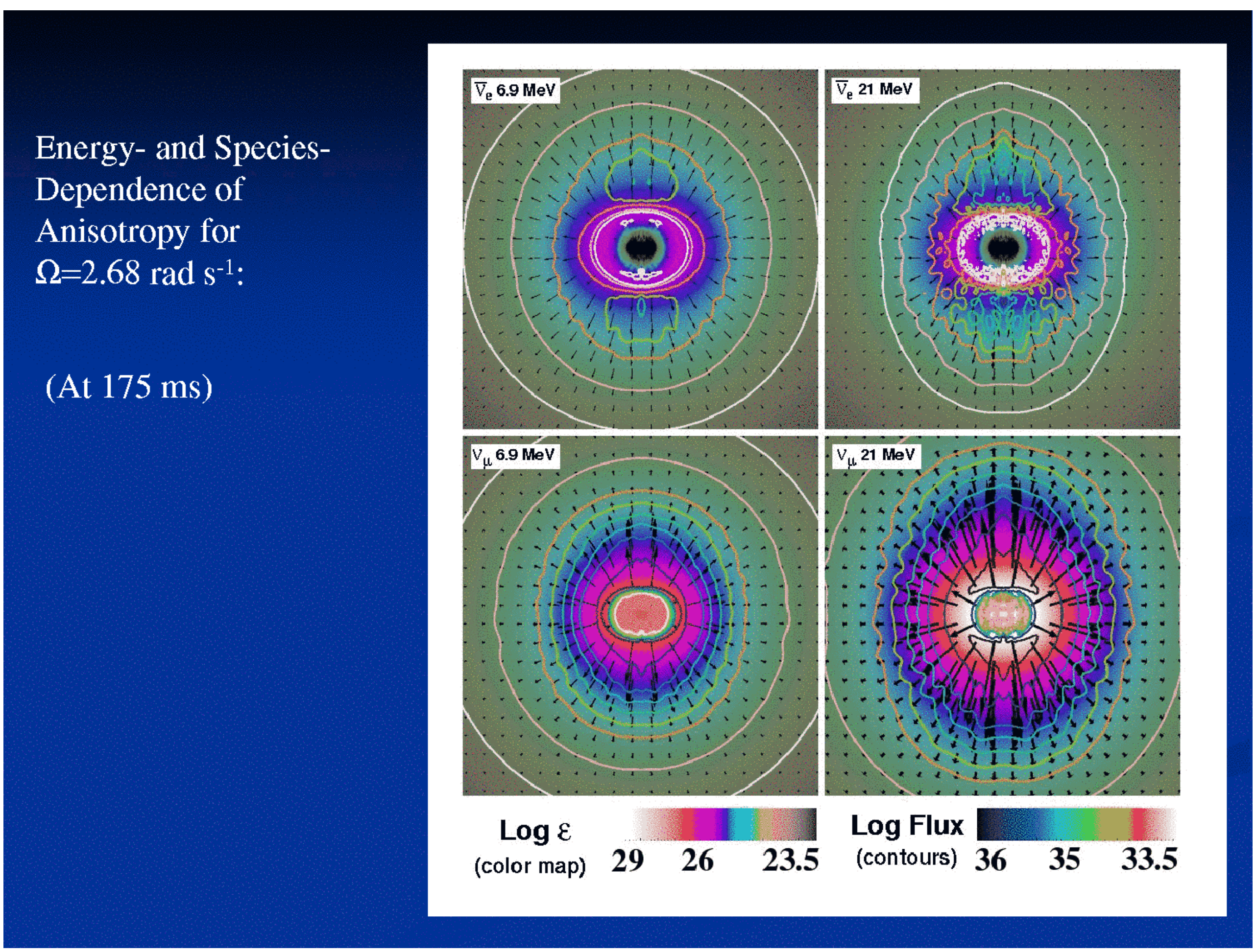


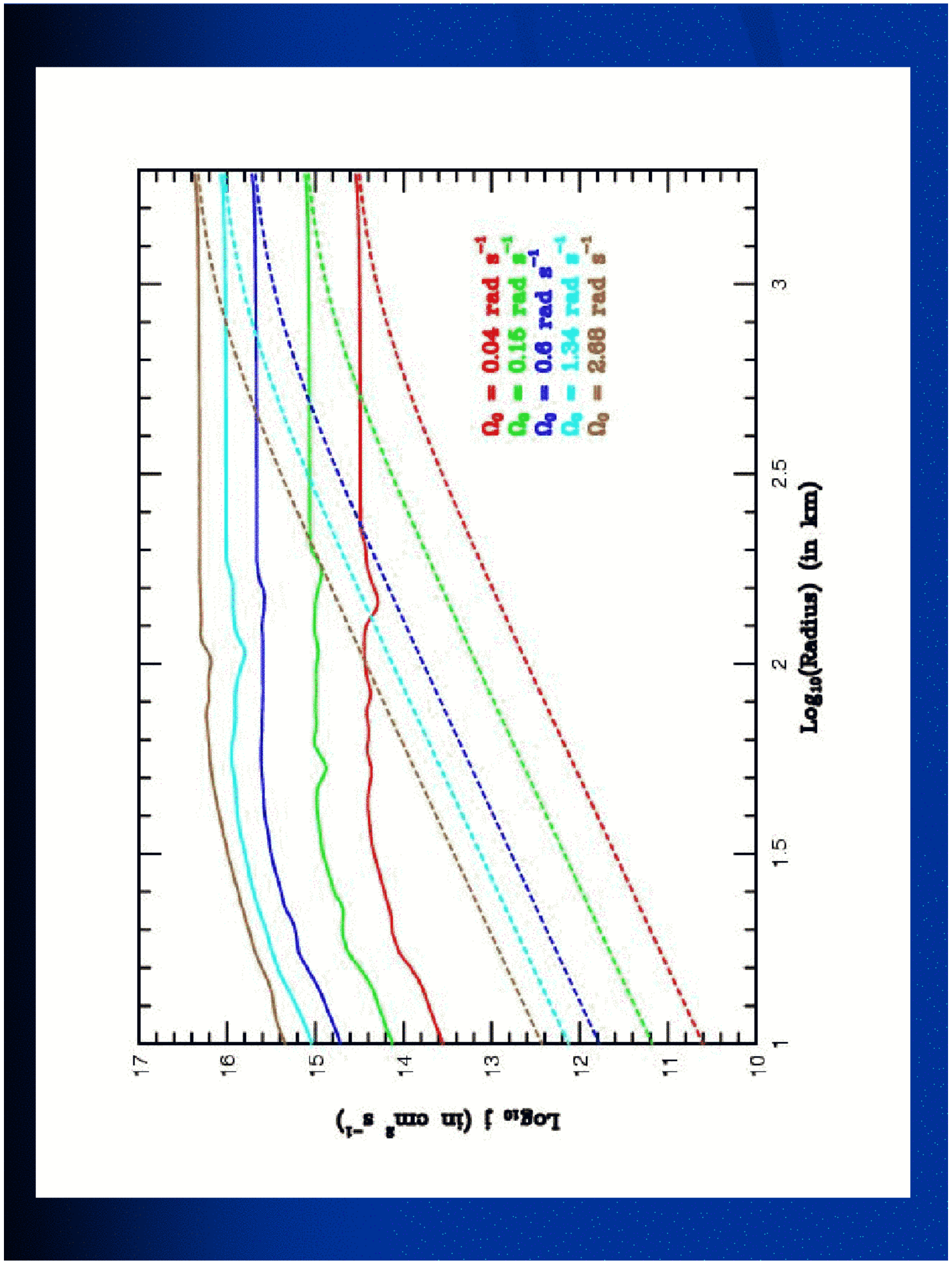
Electron Neutrinos
At 6.89 MeV:

$\Omega_0 = 2.68$ rad s^{-1}




Fluxes and Spectral Energy Densities at 175 ms and 6.9 MeV:
Ω_0=1.34
Ω_0=0.6
Ω_0=0.15
Ω_0=0
Log ε (color map)
29 26.5 24
Log Flux (contours)
36 35.5 34.6


Energy- and Species-Dependence of Anisotropy for Ω=2.68 rad s^{-1}:
(At 175 ms)
$\bar{\nu}_e$ 6.9 MeV
$\bar{\nu}_e$ 21 MeV
ν_μ 6.9 MeV
ν_μ 21 MeV
Log ε (color map)
29 26 23.5
Log Flux (contours)
36 35 33.5

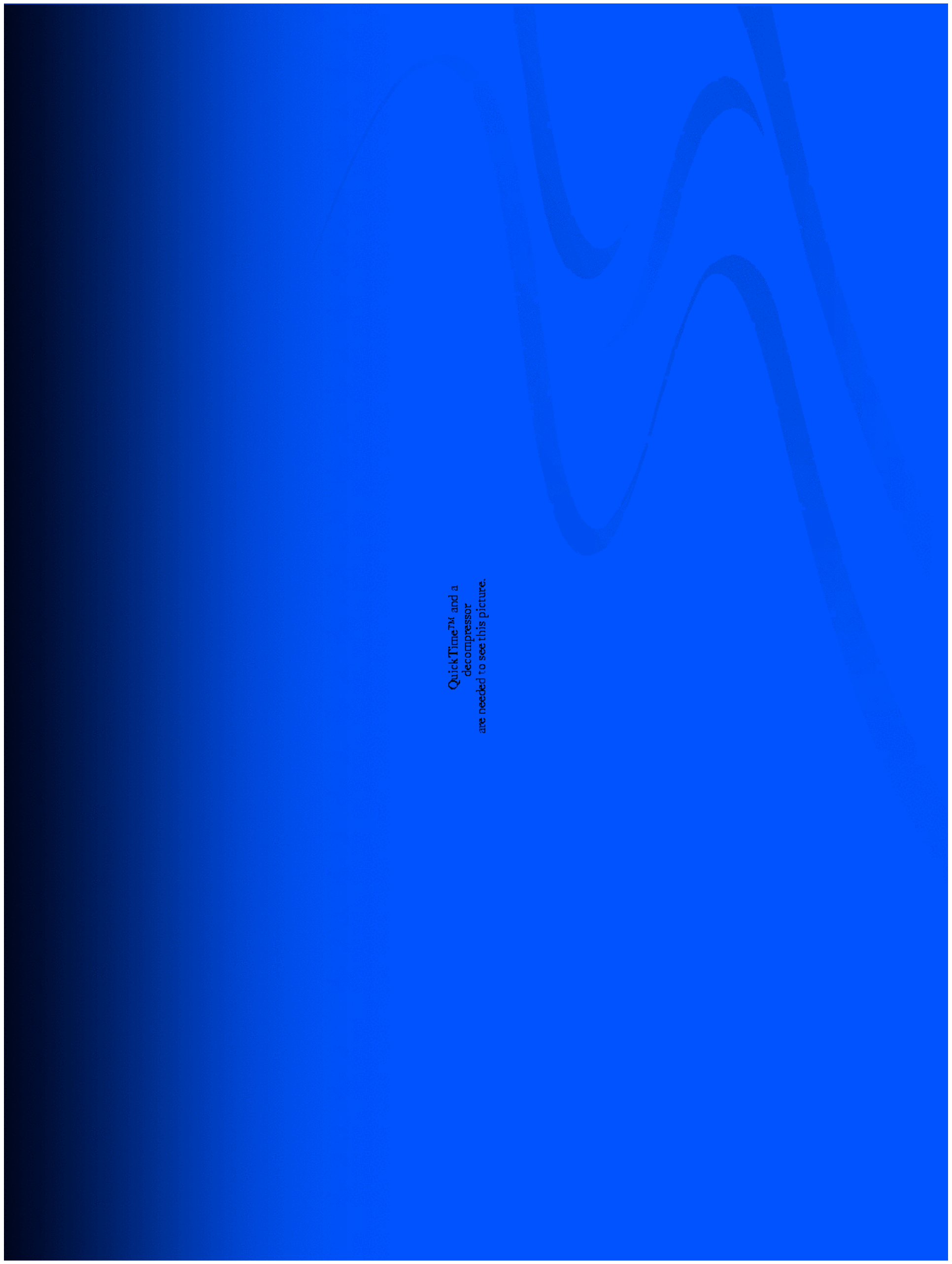


Ω_0 = 0.04 rad s^{-1}
Ω_0 = 0.15 rad s^{-1}
Ω_0 = 0.6 rad s^{-1}
Ω_0 = 1.34 rad s^{-1}
Ω_0 = 2.68 rad s^{-1}
Log_{10}(Radius) (in km)
Log_{10} j (in cm^2 s^{-1})
1
1.5
2
2.5
3
10
11
12
13
14
15
16
17

QuickTime™ and a
Photo decompressor
are needed to see this picture.
20 Solar Masses
Modest Rotation
Torus Formation

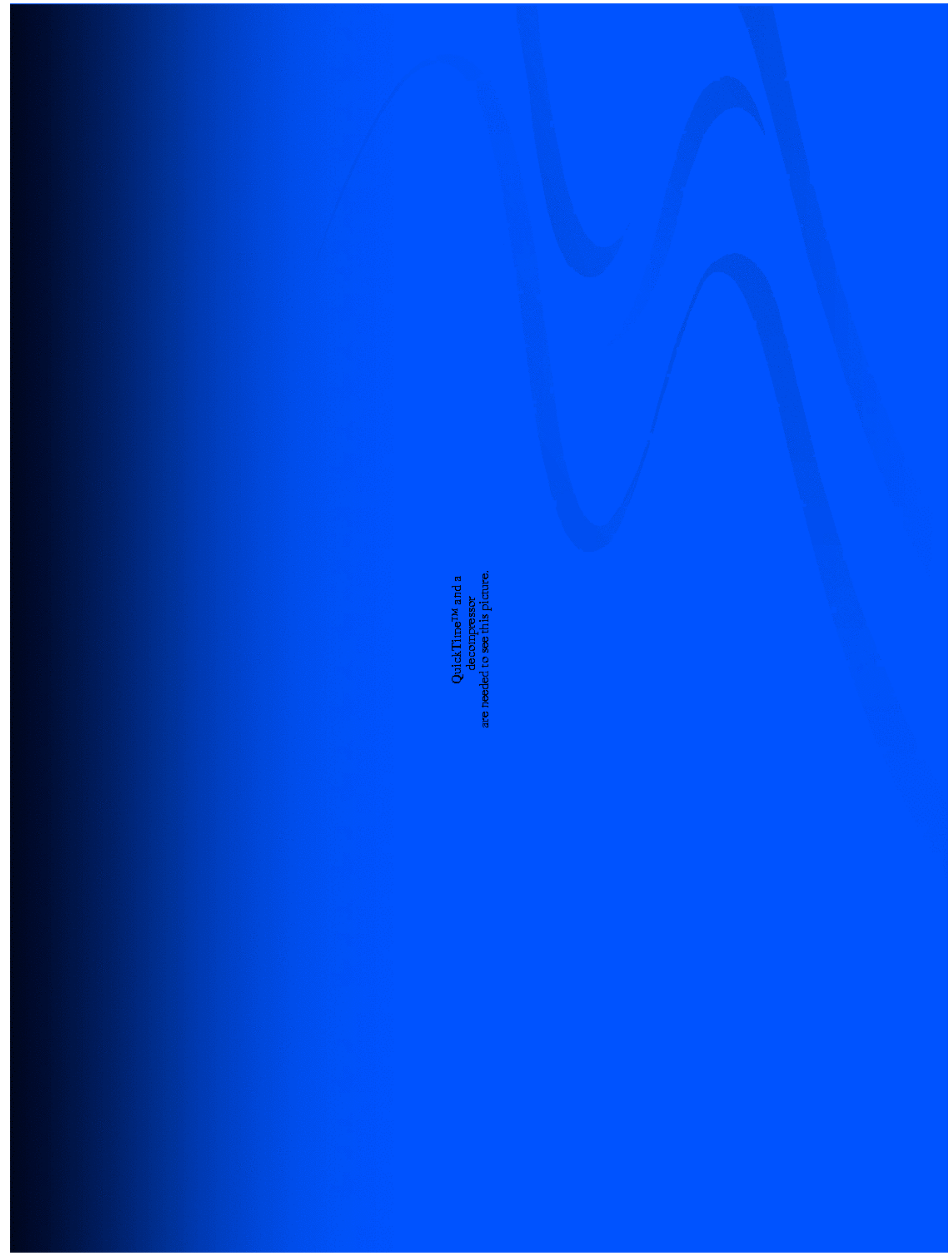

2D MGFLD Rotating Collapse, Bounce, and Convection
QuickTime™ and a
Photo decompressor
are needed to see this picture.

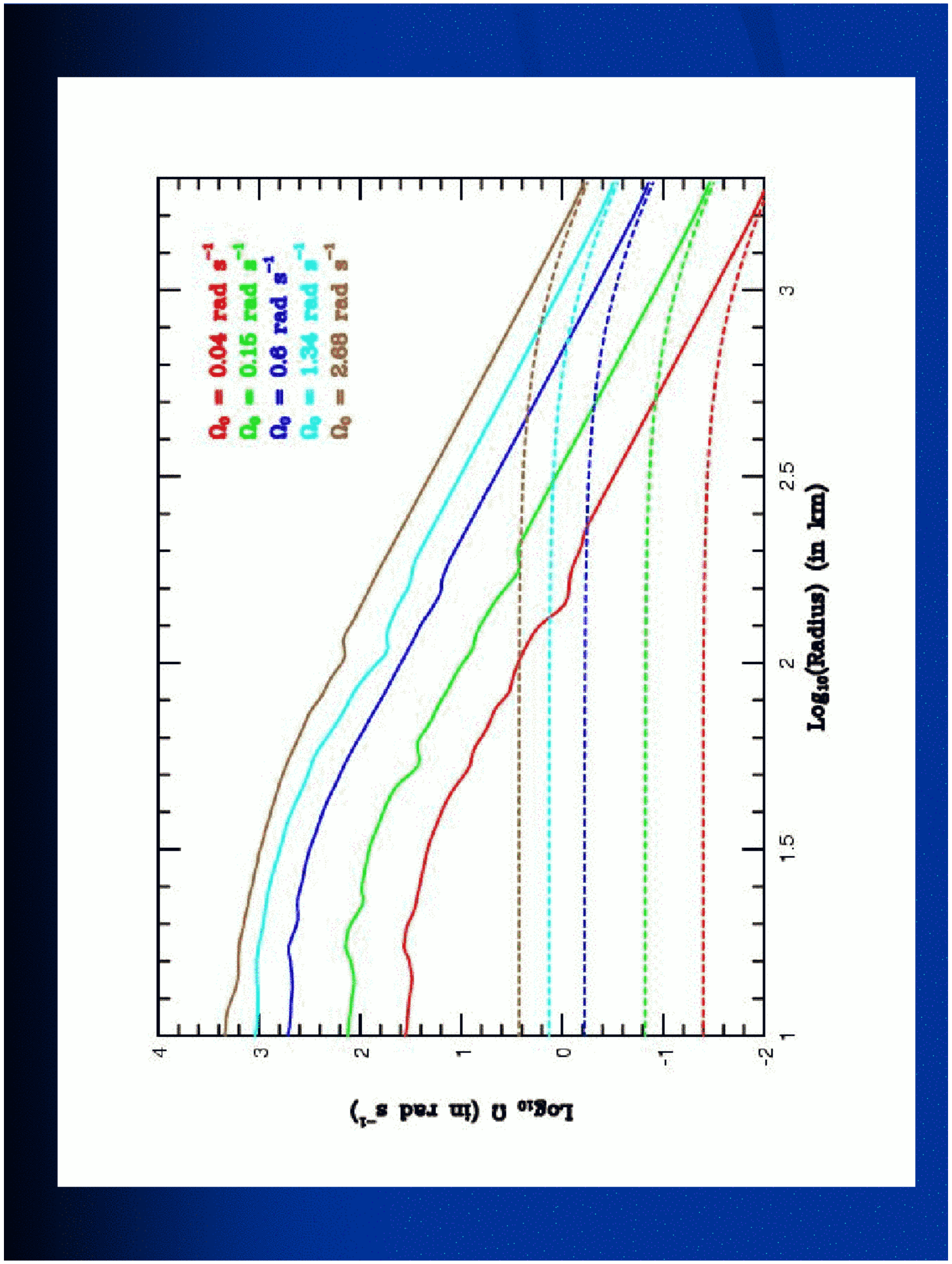

2D MGFLD Rotating Collapse, Bounce, and Convection
QuickTime™ and a
Photo decompressor
are needed to see this picture.

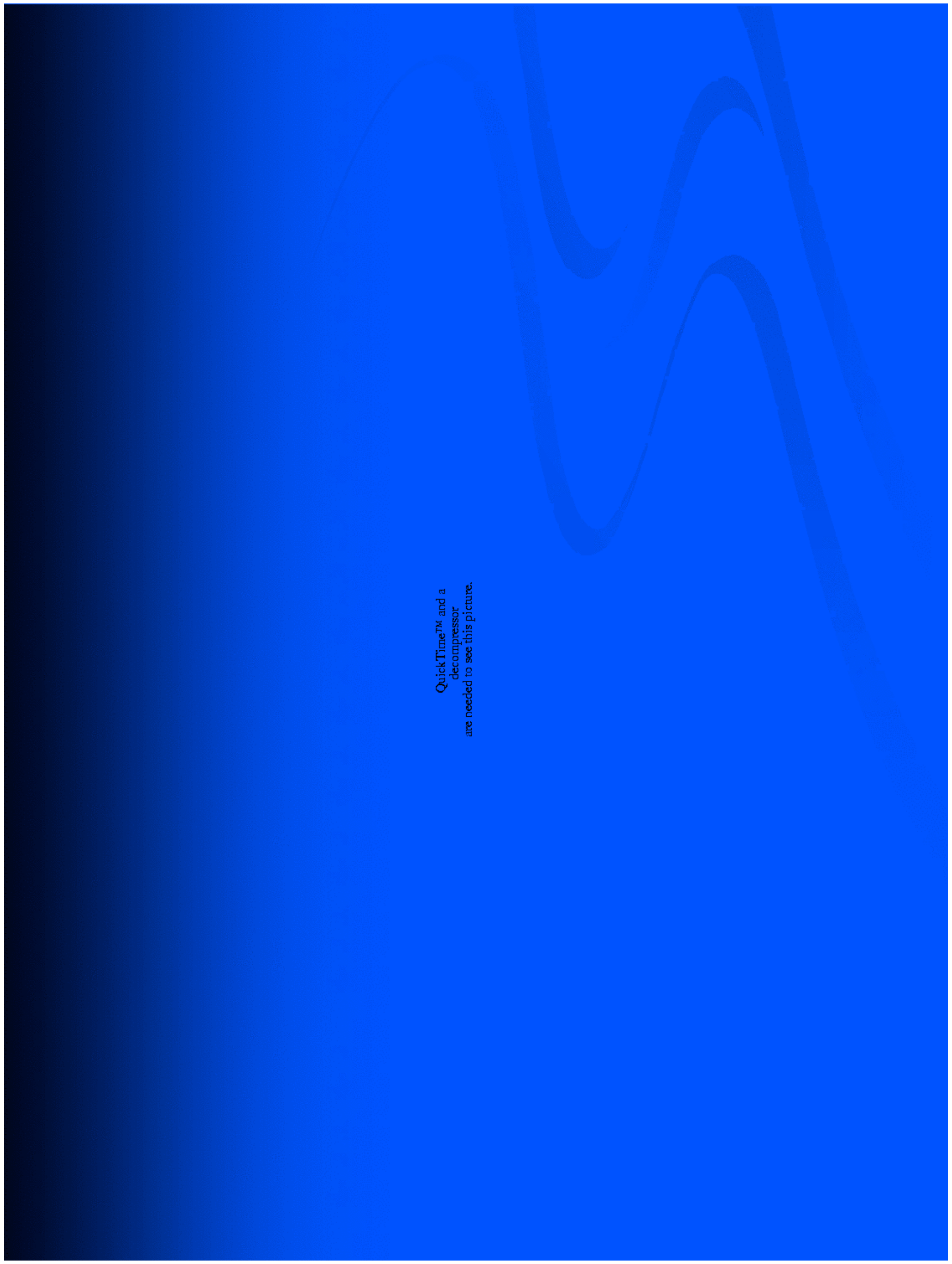

QuickTime™ and a
decompressor
are needed to see this picture.

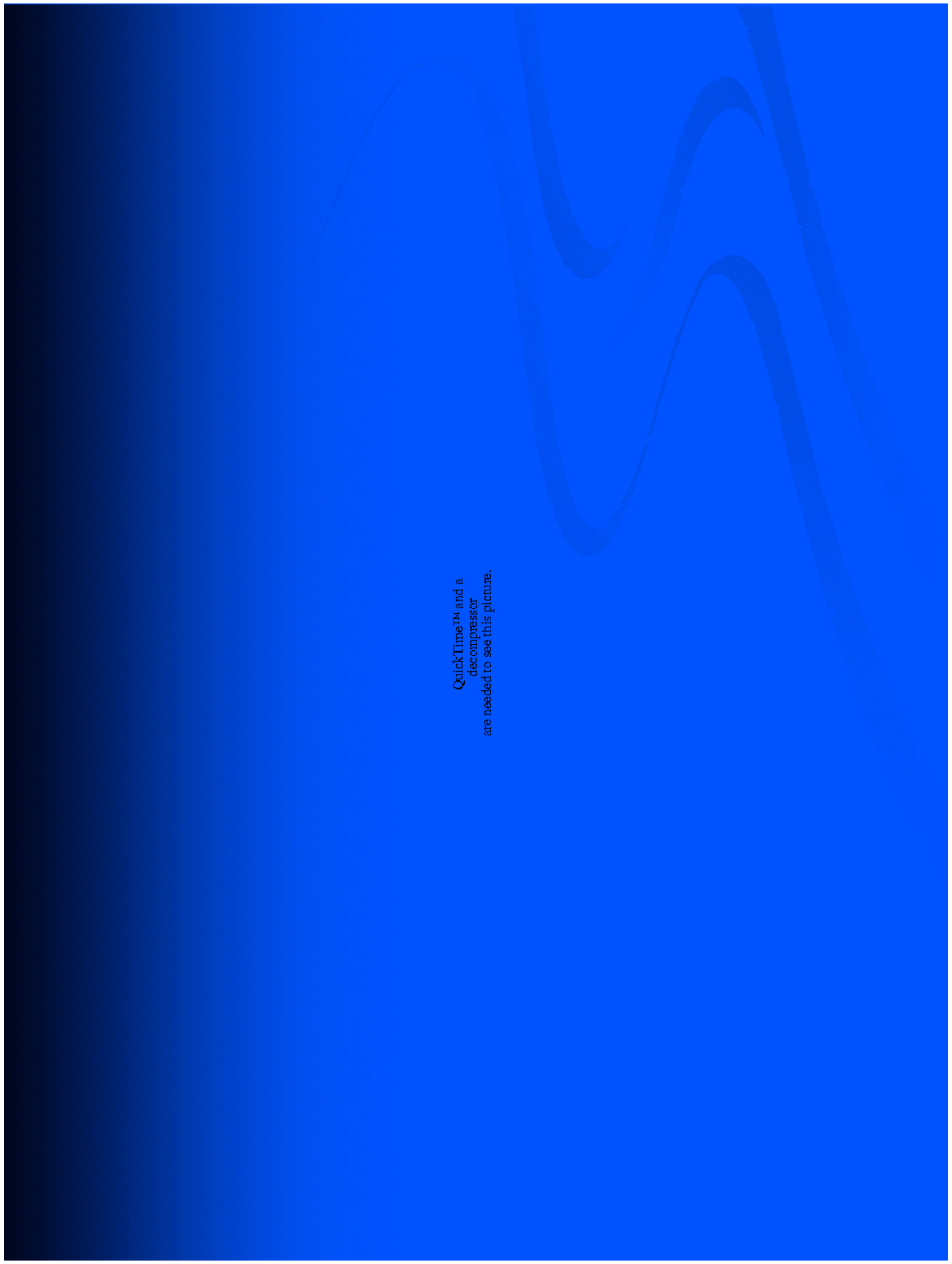

QuickTime™ and a
decompressor
are needed to see this picture.


QuickTime™ and a
decompressor
are needed to see this picture.


QuickTime™ and a
decompressor
are needed to see this picture.


Ω0 = 0.04 rad s-1
Ω0 = 0.15 rad s-1
Ω0 = 0.6 rad s-1
Ω0 = 1.34 rad s-1
Ω0 = 2.68 rad s-1
Log10(Radius) (in km)
Log10 Ω (in rad s-1)


QuickTime™ and a
decompressor
are needed to see this picture.


QuickTime™ and a
decompressor
are needed to see this picture.


QuickTime™ and a
decompressor
are needed to see this picture.