Core-Collapse Supernova and Long-Soft GRB Science Opportunities

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Overview:

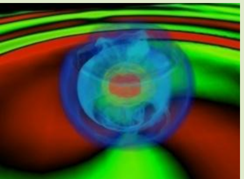
– 20 Minutes to convince you that Stellar Collapse, Core-Collapse Supernovae, and Long-Soft GRBs are exciting Science Targets for ET –

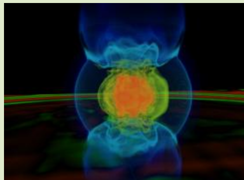
-> Gravity Bombs: The most energetic explosive events in the universe

- Core-Collapse Supernovae
- Accretion-induced collapse of white dwarfs to neutron stars.
- Long-Soft Gamma-Ray Bursts

-> Science to be done with ET GW observations:

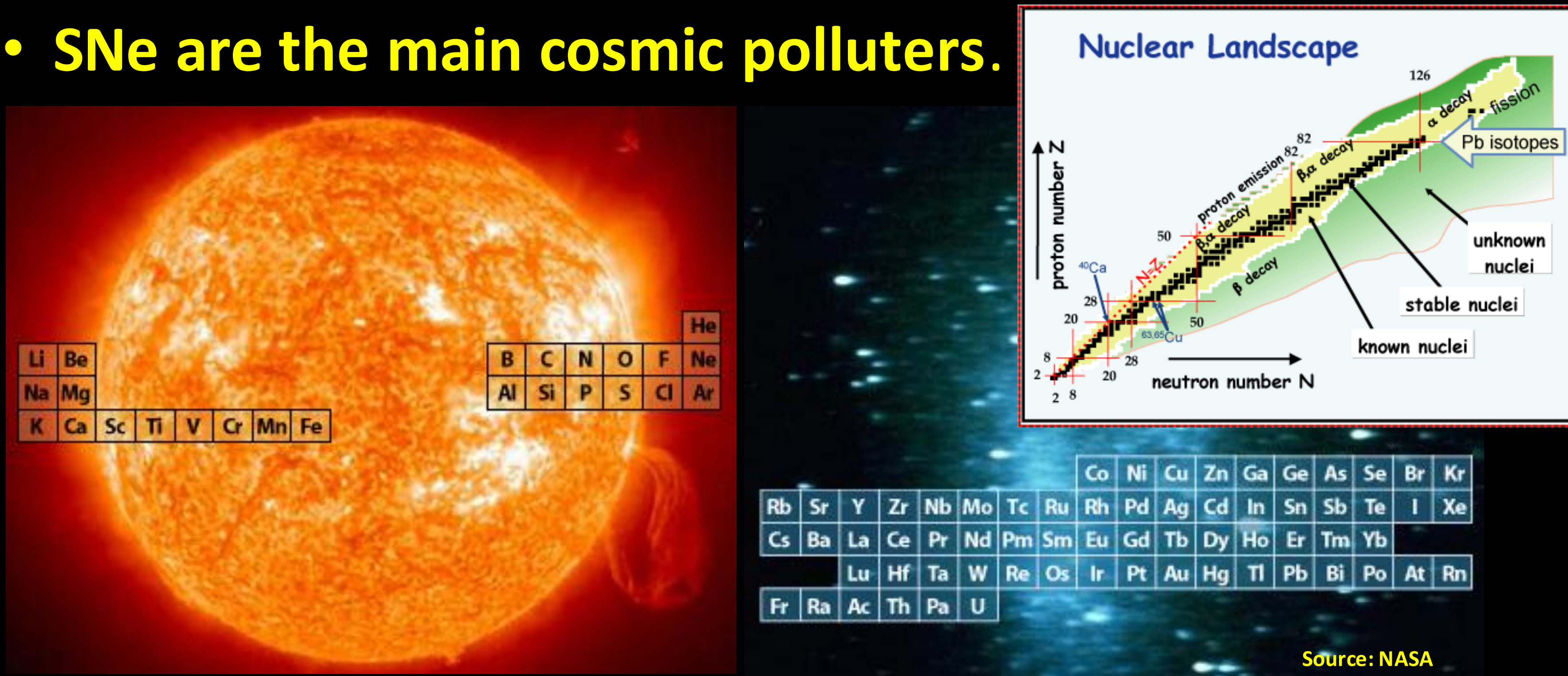
- The mechanism of core-collapse supernova explosions.
- Catching Unnovae – witnessing black hole formation.
- Seeing the unseen – observing EM silent/obscured CCSNe and AICs.
- The precollapse spin of massive stars.
- Equation of state (EOS), composition, and structural properties of hot nuclear matter.





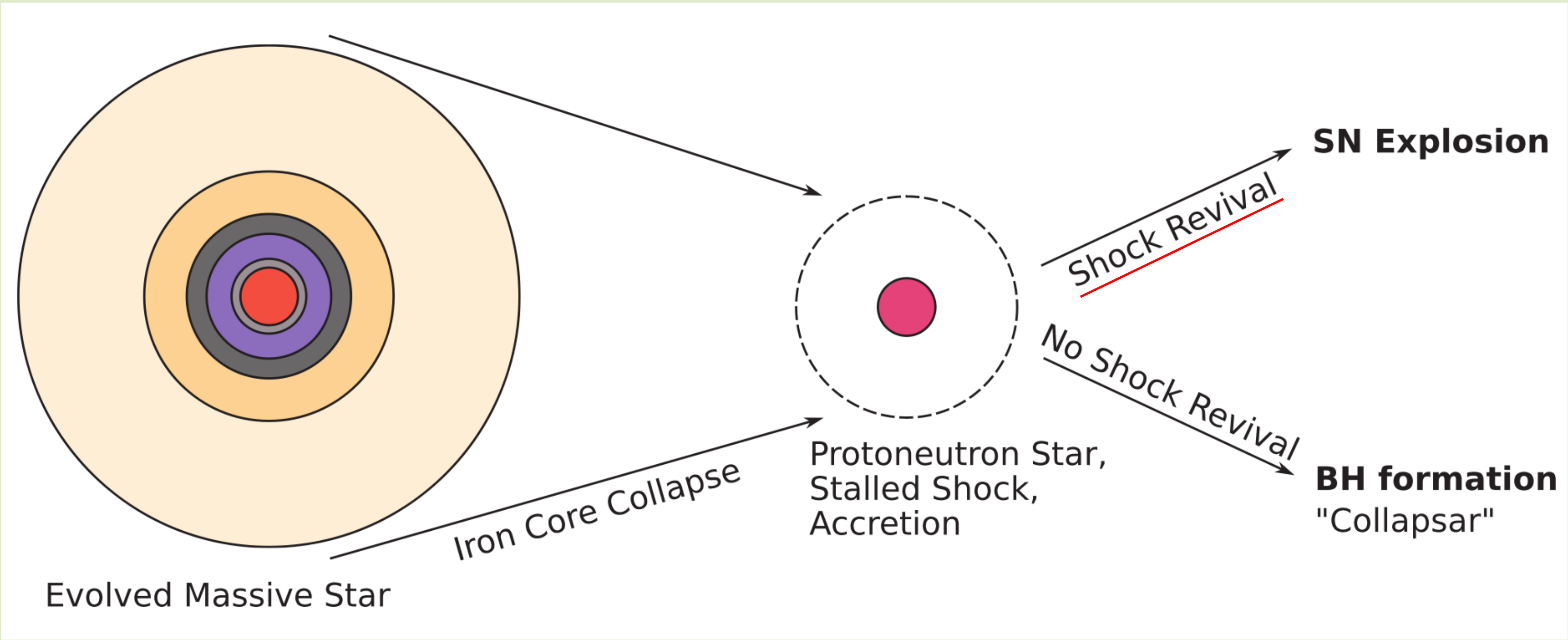
Why do we care about Supernovae?

- **SNe are the main cosmic polluters.**



- Dynamical impact on galaxy evolution.
- Stellar collapse:
  The making of neutron stars and black holes.
- Cosmic standard candles.

Core-Collapse Supernovae



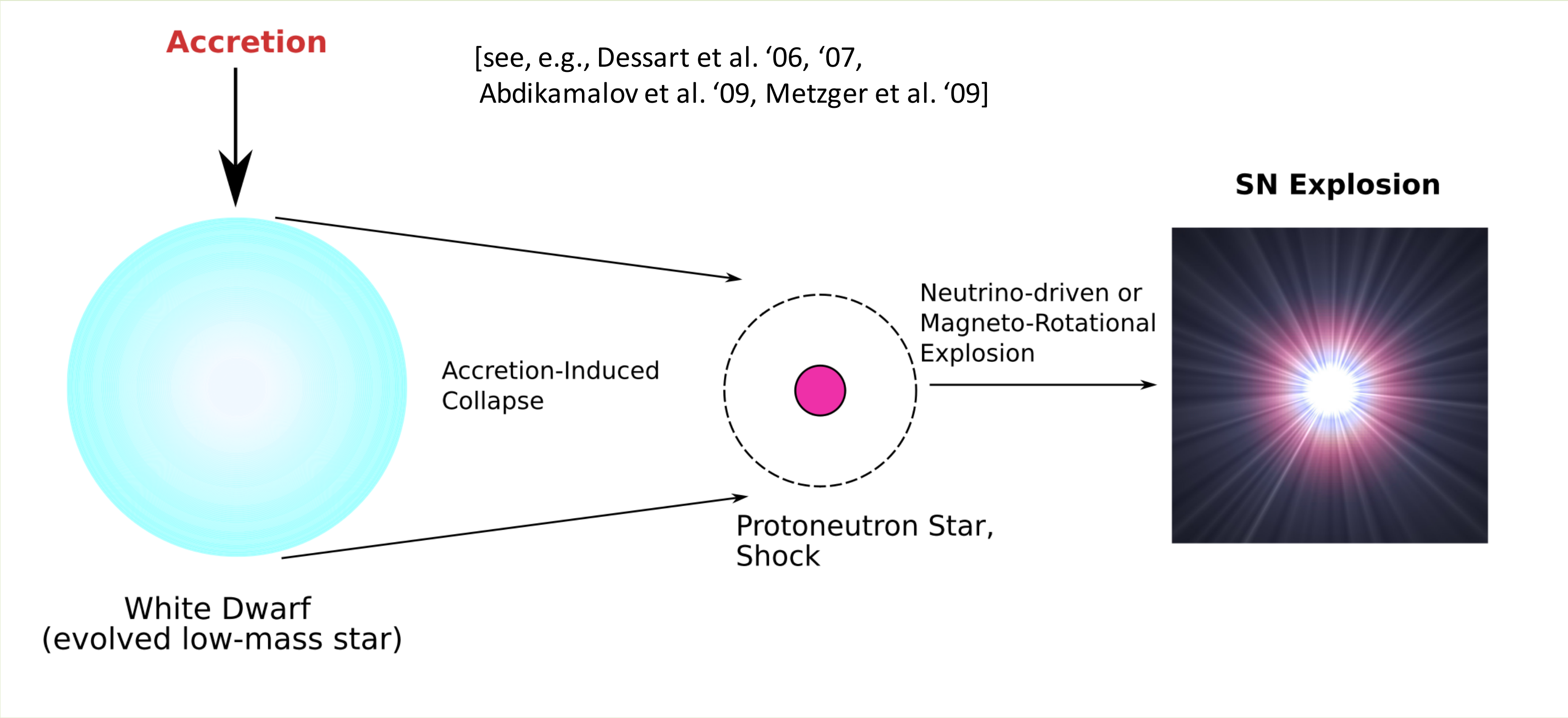
- **Energy reservoir:**
  few x 10^{53} erg (100 [B]ethe)
- **Explosion energy**:
  ~1 B

- Time frame for explosion:
  ~0.3 – 1.5 s after bounce.
- BH formation at baryonic
  PNS mass $\geq$ 1.8 – 2.5 M_{SUN}.

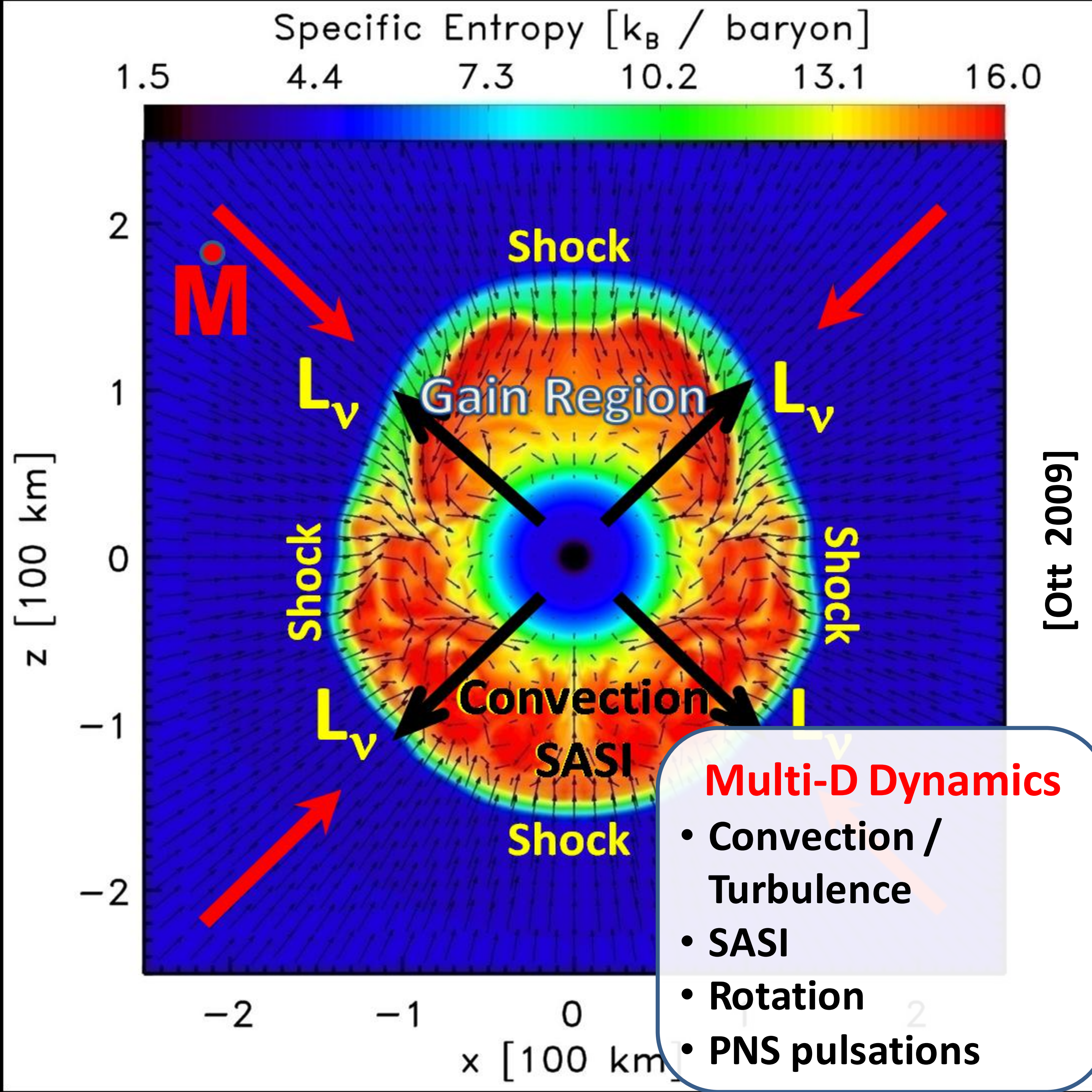
The Supernova Problem:

What is the mechanism of shock revival?

Variation of the Theme: AIC



- Collapse of accreting, probably rapidly rotating White Dwarf.
- Neutrino-driven or magneto-rotational explosion
- Explosion probably weak, subluminous, little Nickel-56.
- Potential birth site of magnetars.

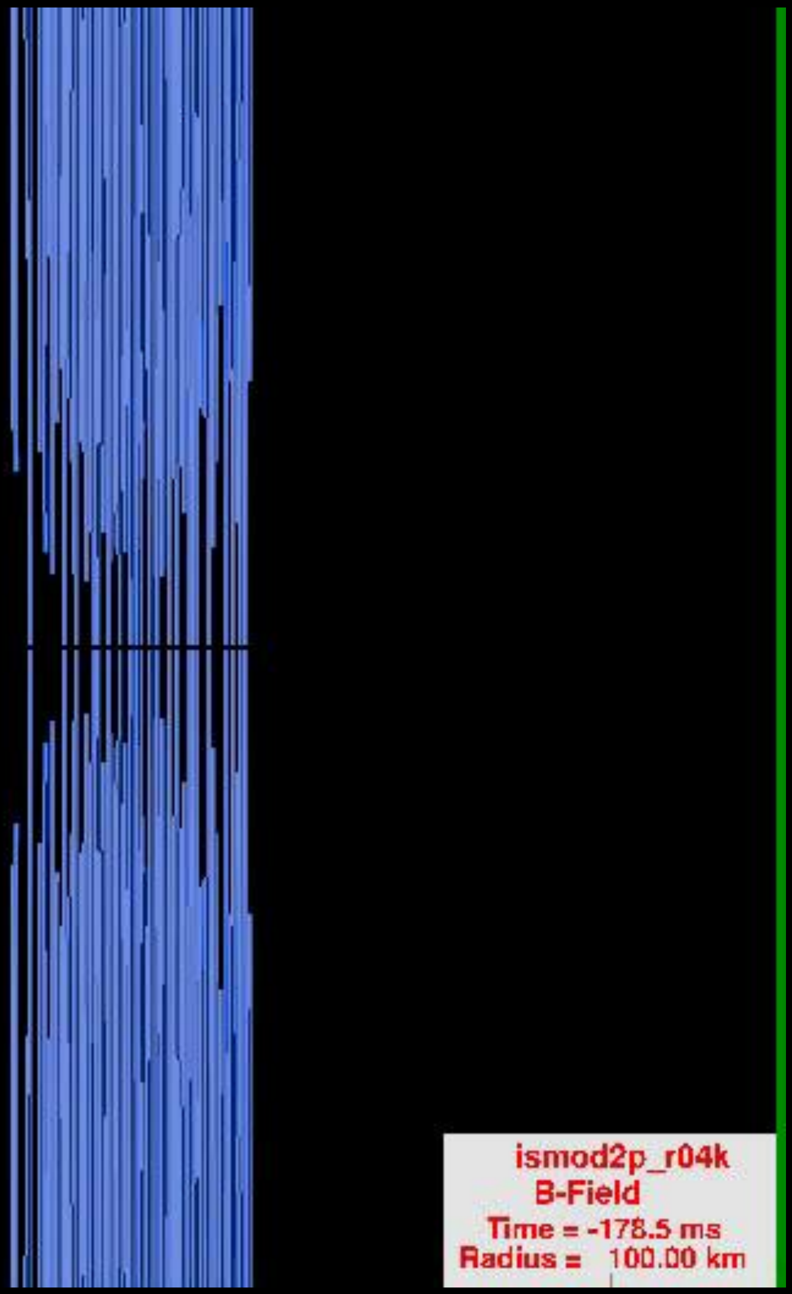


Multi-D Dynamics

- Convection / Turbulence
- SASI
- Rotation
- PNS pulsations

Newtonian
Radiation-MHD
Simulations with
VULCAN/2D

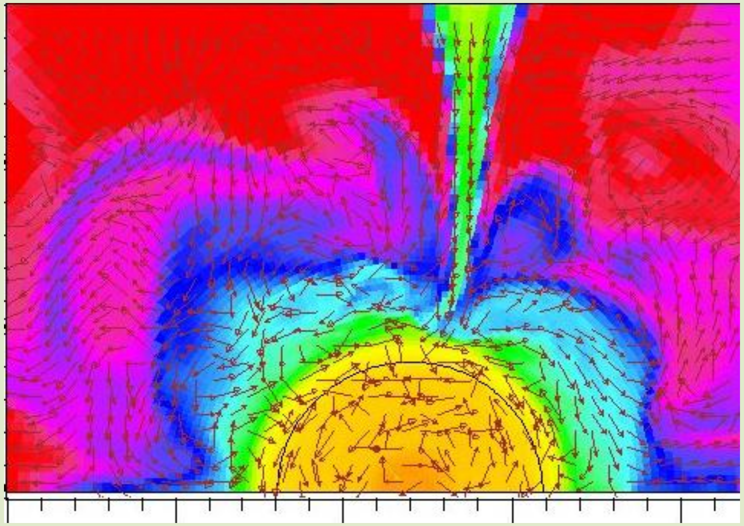
Magnetic field lines in
M15B11UP2A1H of
Burrows, Dessart,
Livne, Ott, Murphy '07.

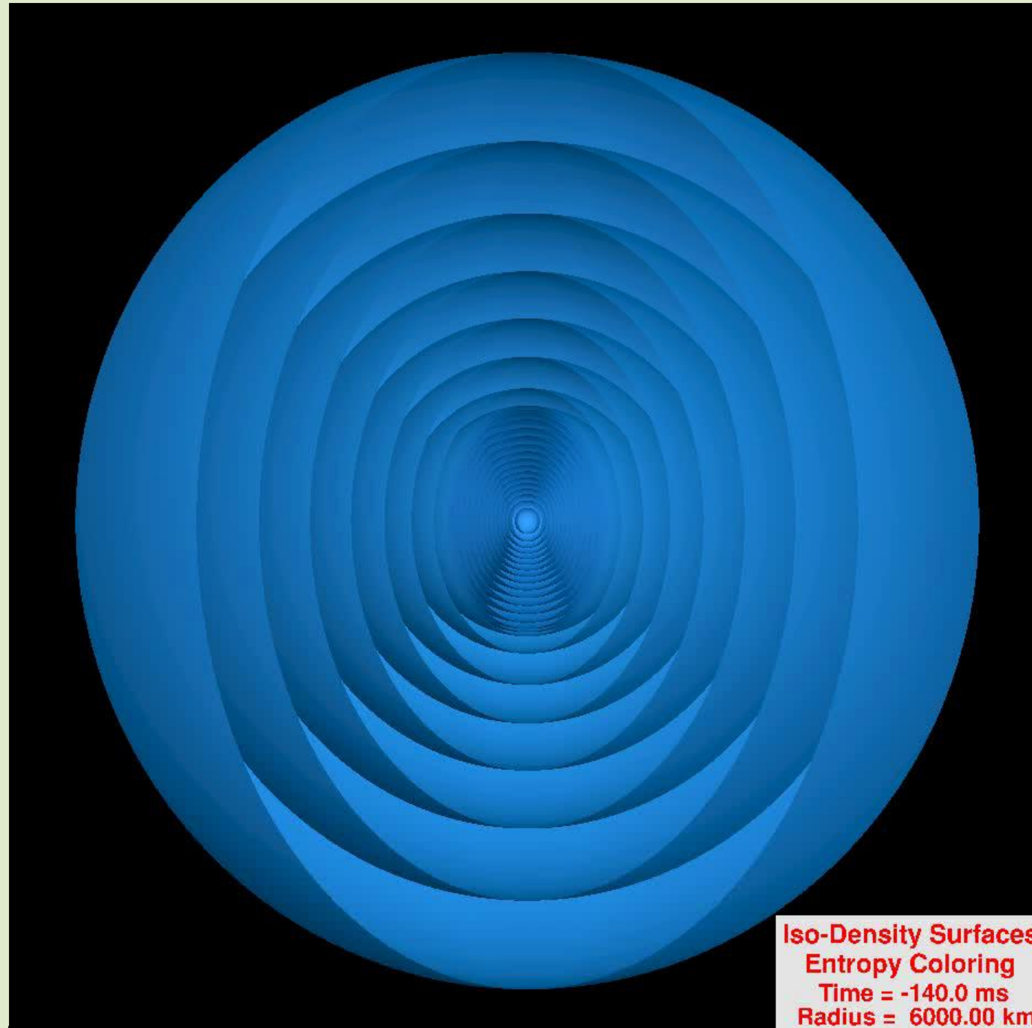


Acoustic Mechanism

[Burrows, Livne, Dessart, **Ott**, Murphy 2006, 2007b/c, **Ott** et al. 2006]

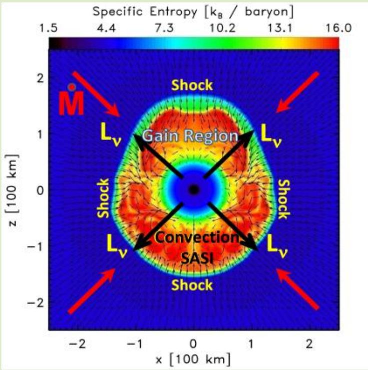
- SASI-modulated supersonic **accretion streams** and SASI generated **turbulence** excite lowest-order (l=1) g-mode in the PNS. f ≈ 300 Hz.

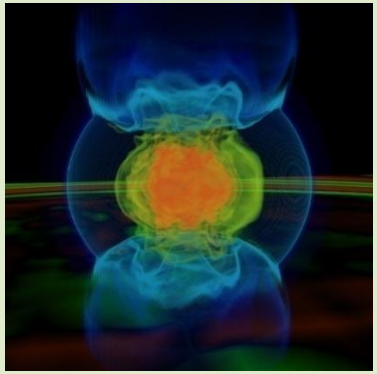


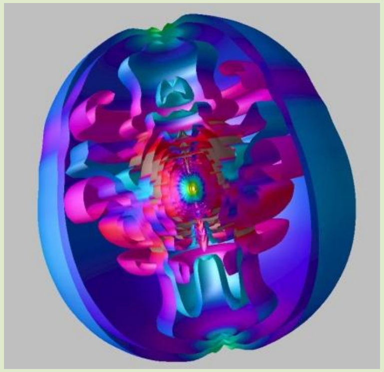


- g-modes reach large amplitudes ~500 ms —1 s after bounce.
- Damping by strong sound waves that steepen into shocks; deposit energy in the stalled shock.
- ~1 B explosions at late times.
- (1) hard to simulate; unconfirmed, (2) possible parametric instability, limiting mode amplitudes. [Weinberg & Quatert'08]

SN Mechanisms and Their Multi-D Features





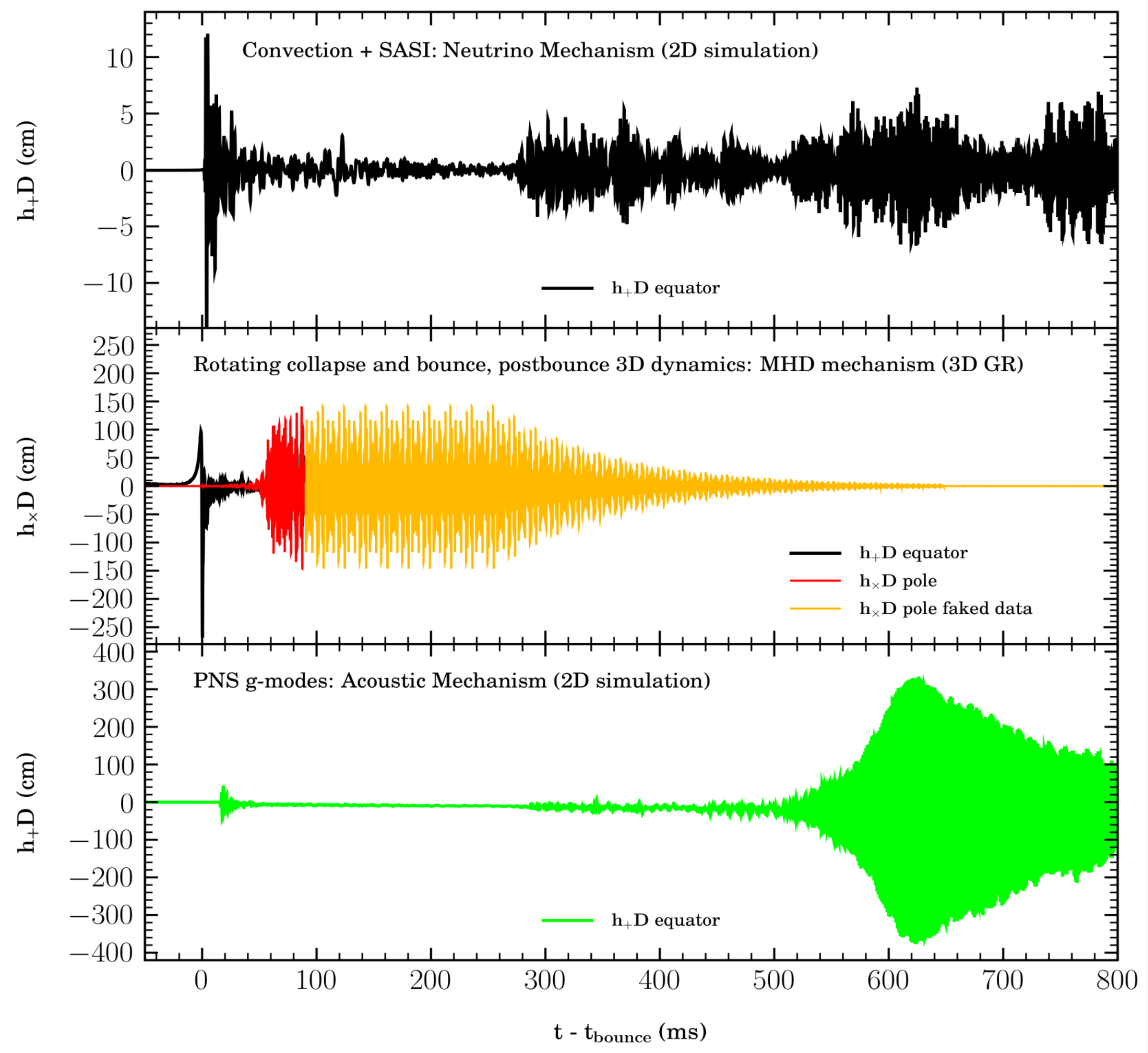


[Ott 2009, CQG 26, 204015]

Dominant Multi-D Processes

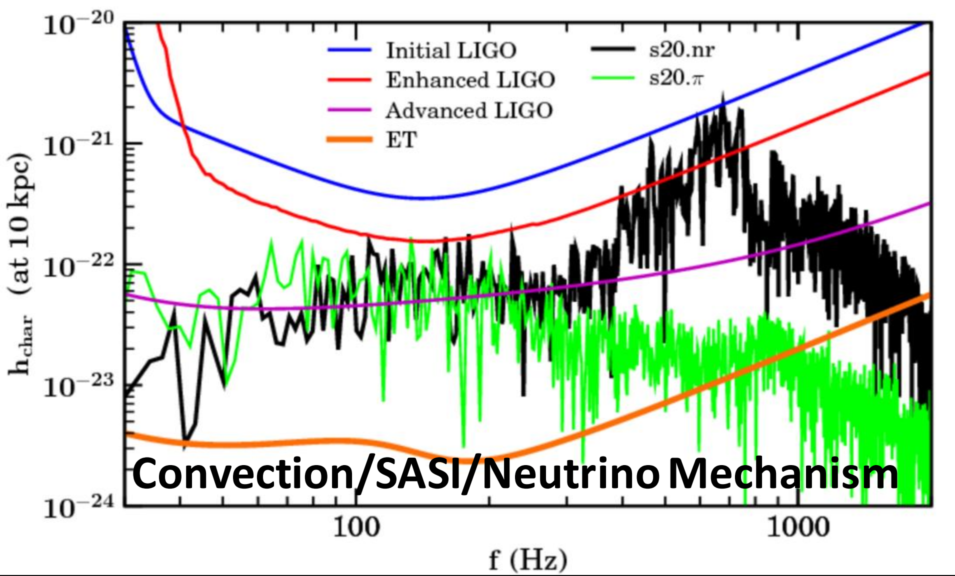
Mechanism		Dominant Multi-D Processes
Neutrino Mechanism	→	Convection and SASI
MHD-Jet Mechanism	→	Rotation
Acoustic Mechanism	→	Protoneutron Star Pulsations

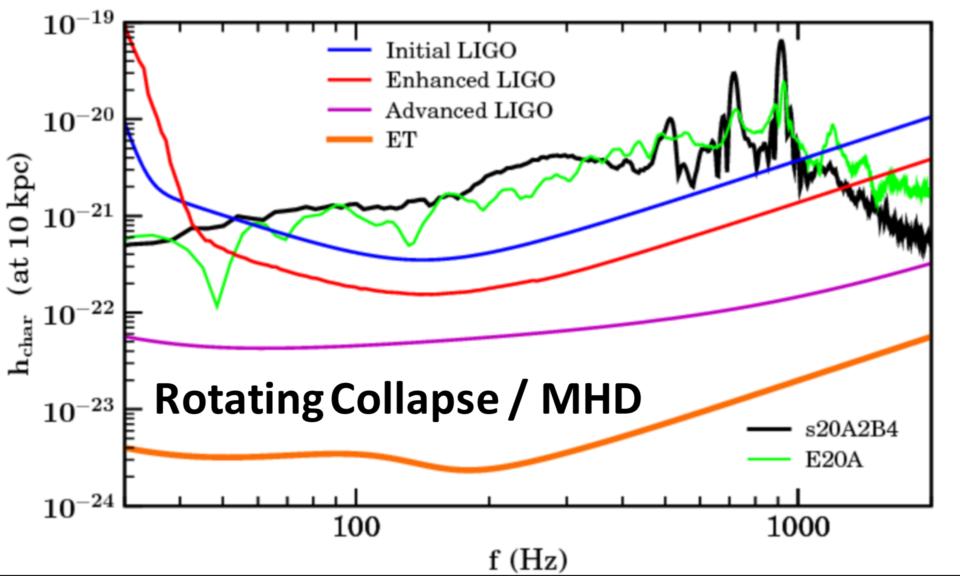
Model GW Signals from Core-Collapse Supernovae



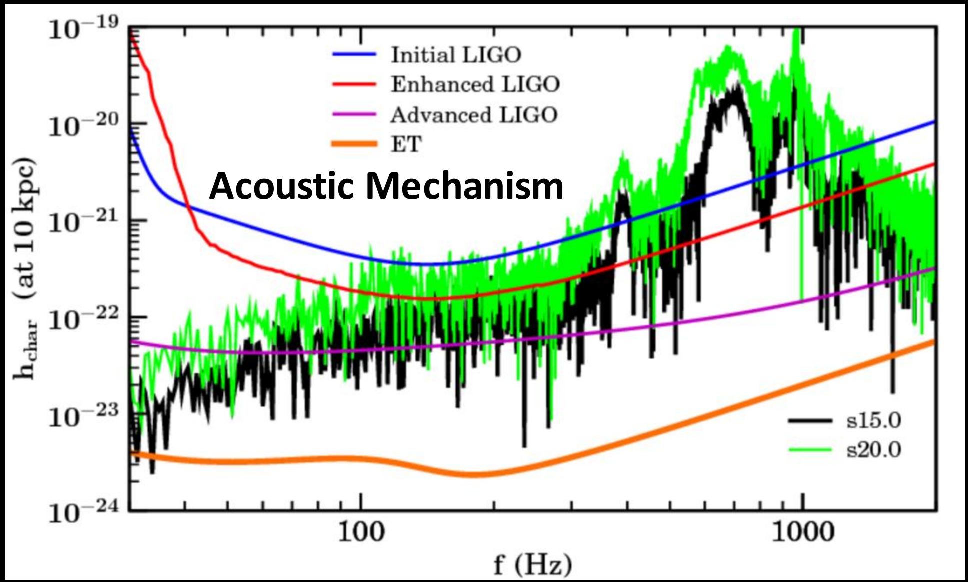
[Ott 2009]

Characteristic Strain Spectra
at 10 kpc

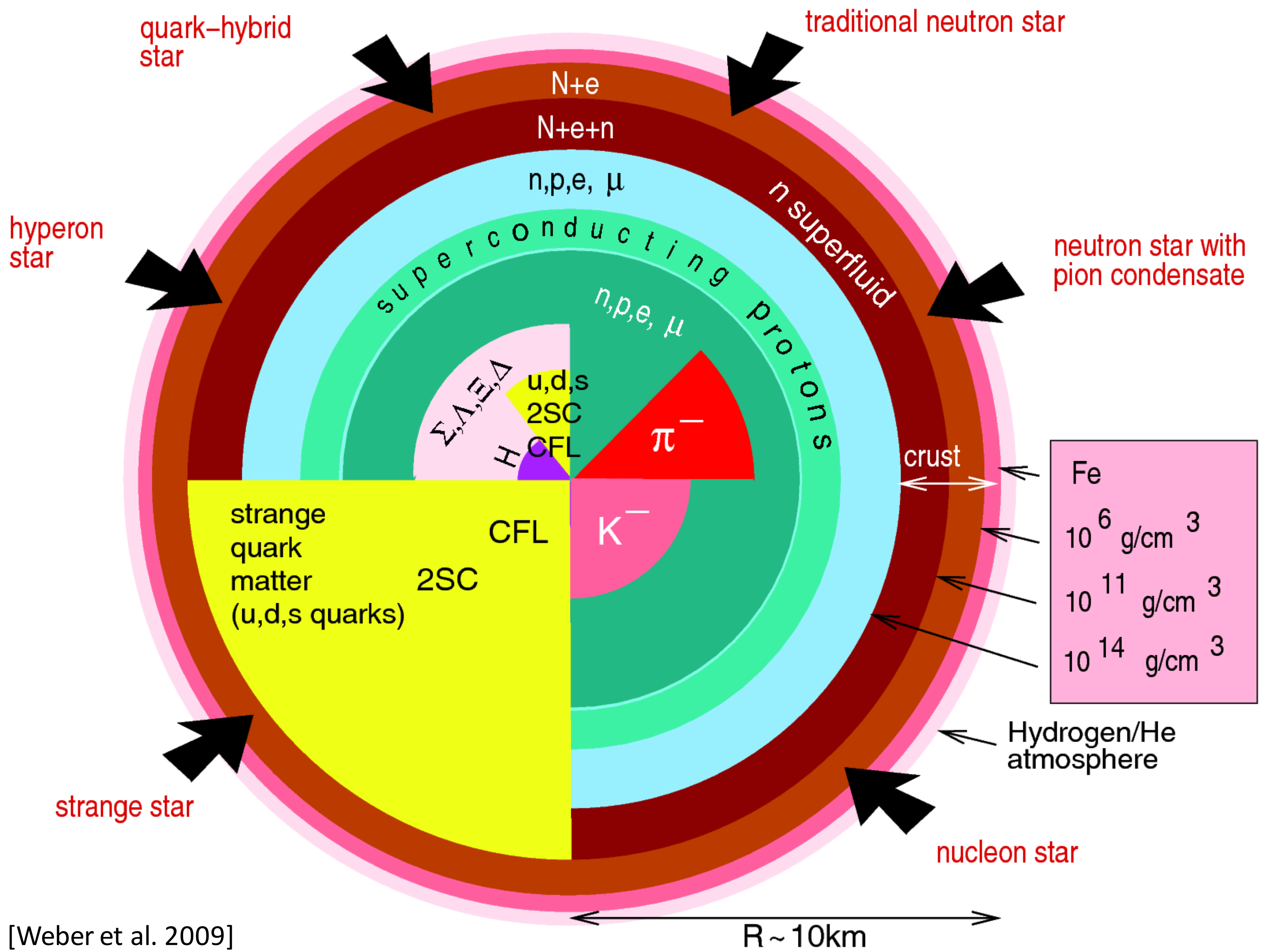




Important:
Emission frequencies contain encoded information on (Proto-)NS structure and rotation.

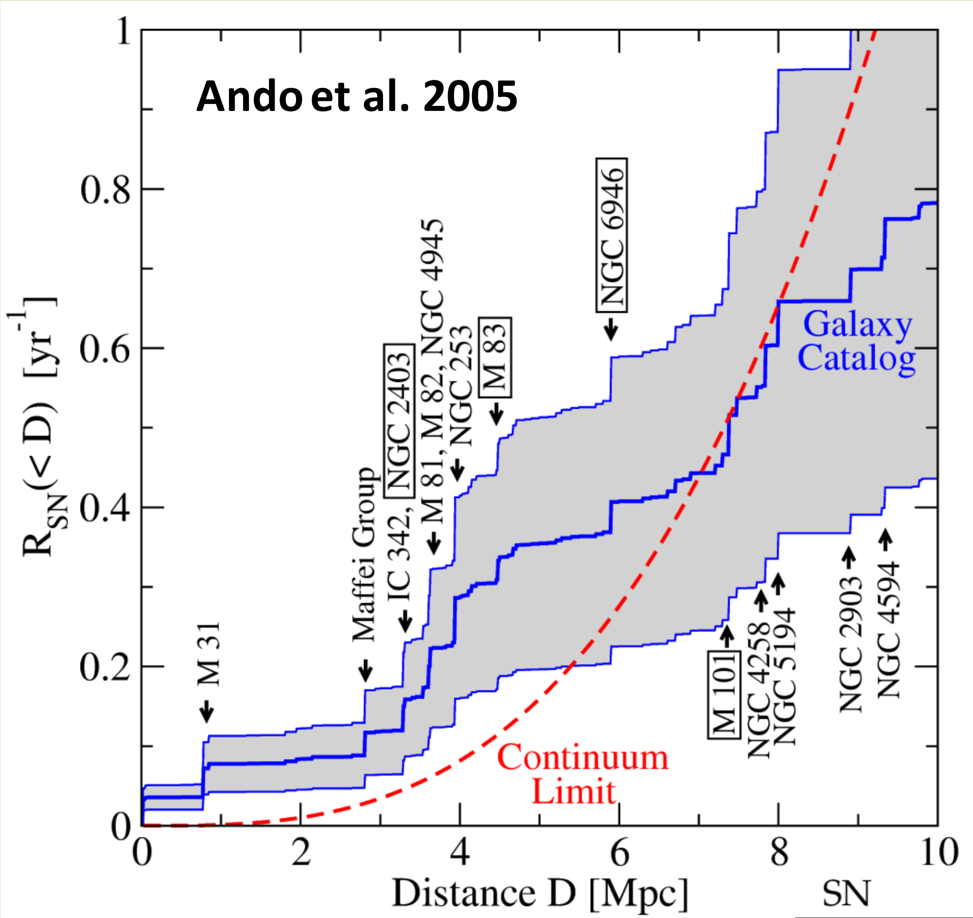


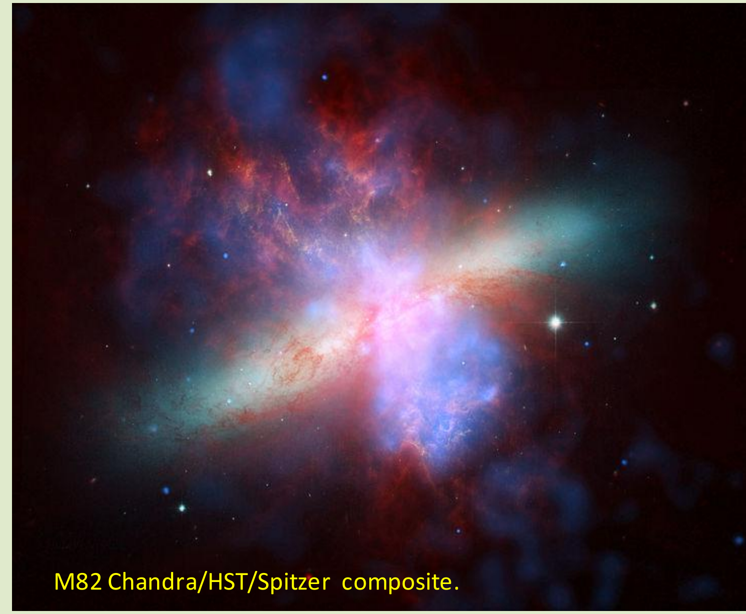
Neutron Star Structure



[Weber et al. 2009]

Nearby Core-Collapse Supernovae




M82 Chandra/HST/Spitzer composite.

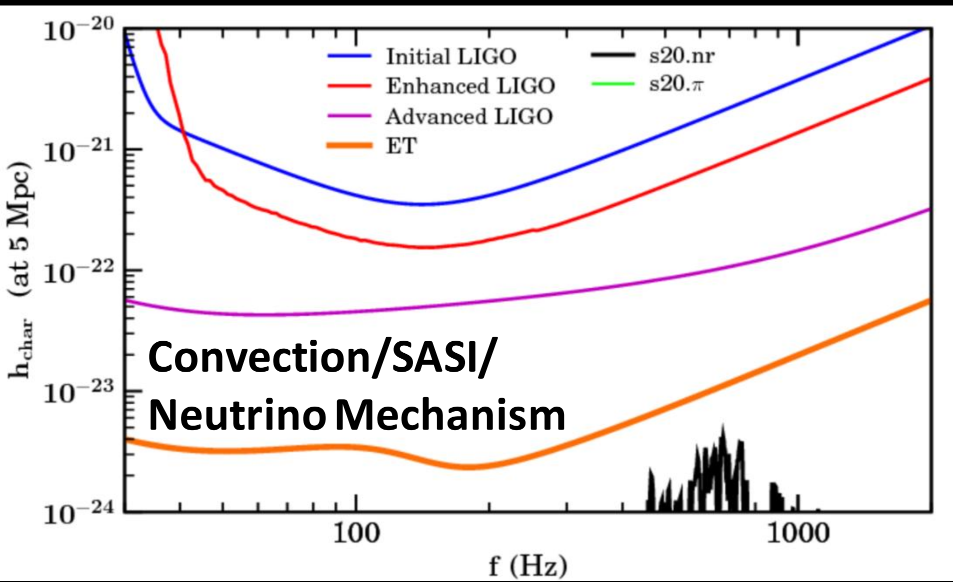
Core-collapse SNe within 5 Mpc since the beginning of LIGO operations:

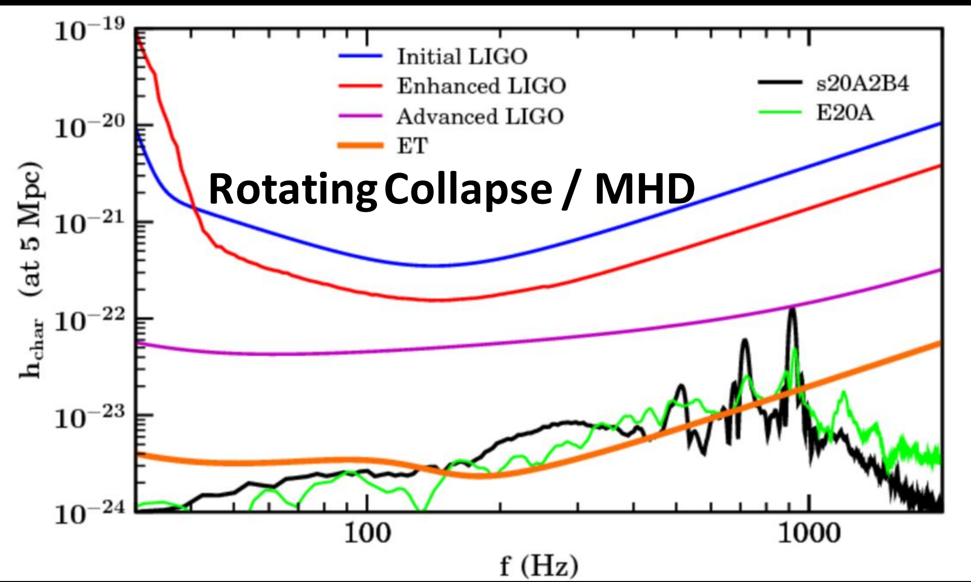
SN	Host Galaxy	Date	Type	Distance
2008iz[1]	M 82	20090515 [2]	II	∼ 3.5 [3]
2008bk	NGC 7793	20080325 [4]	II-P	∼ 3.9 [5]
2005af	NGC 4945	20050208 [6]	II-P	∼ 3.6 [5]
2004dj	NGC 2403	20040731 [7]	II-P	∼ 3.3 [5]
2004am	M 82	20040305 [8]	II-P	∼ 3.5 [3]
2002kg	NGC 2403	20021026 [9]	IIn	∼ 3.3 [5]

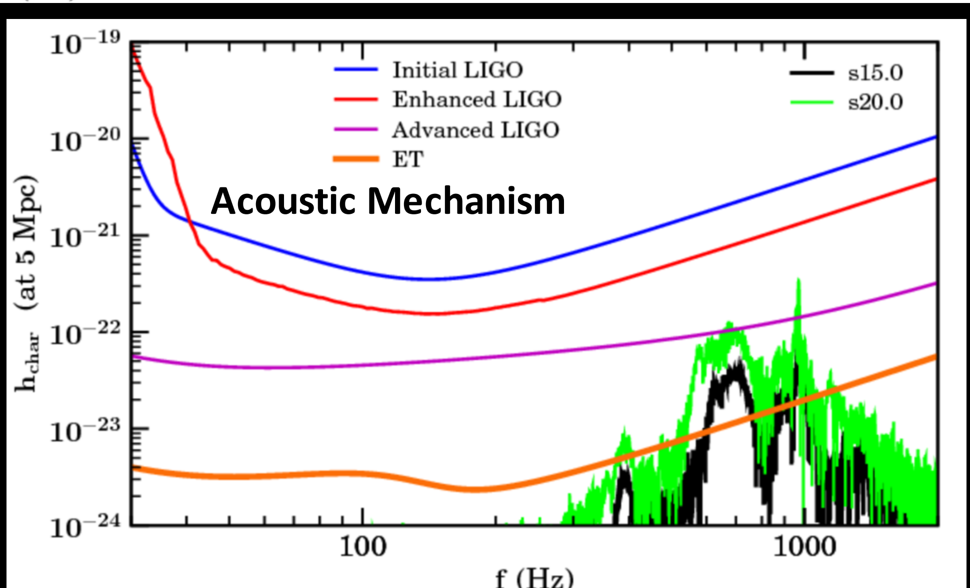
[1] Radio supernova, not observed in the optical. Explosion in late January 2008.


M31 (Andromeda) Spitzer.

Characteristic Strain Spectra
at 5 Mpc: ~0.5 to 1 CCSNe / year







Unnovae

- Core collapse events that do not lead to explosion.
- May be common in stars of $M > 25\text{-}35\ M_{Sun}$.
- EM signature: Disappearing star.
- BUT: strong **GW signature** and **neutrino signature.**
- LSST and other high-cadence EM surveys will be looking for unnovae.
- ET: sensitive to extragalactic unnovae that may be missed by surveys.

- ET:
  (1) Sensitive to extragalactic un-novae potentially missed by surveys.

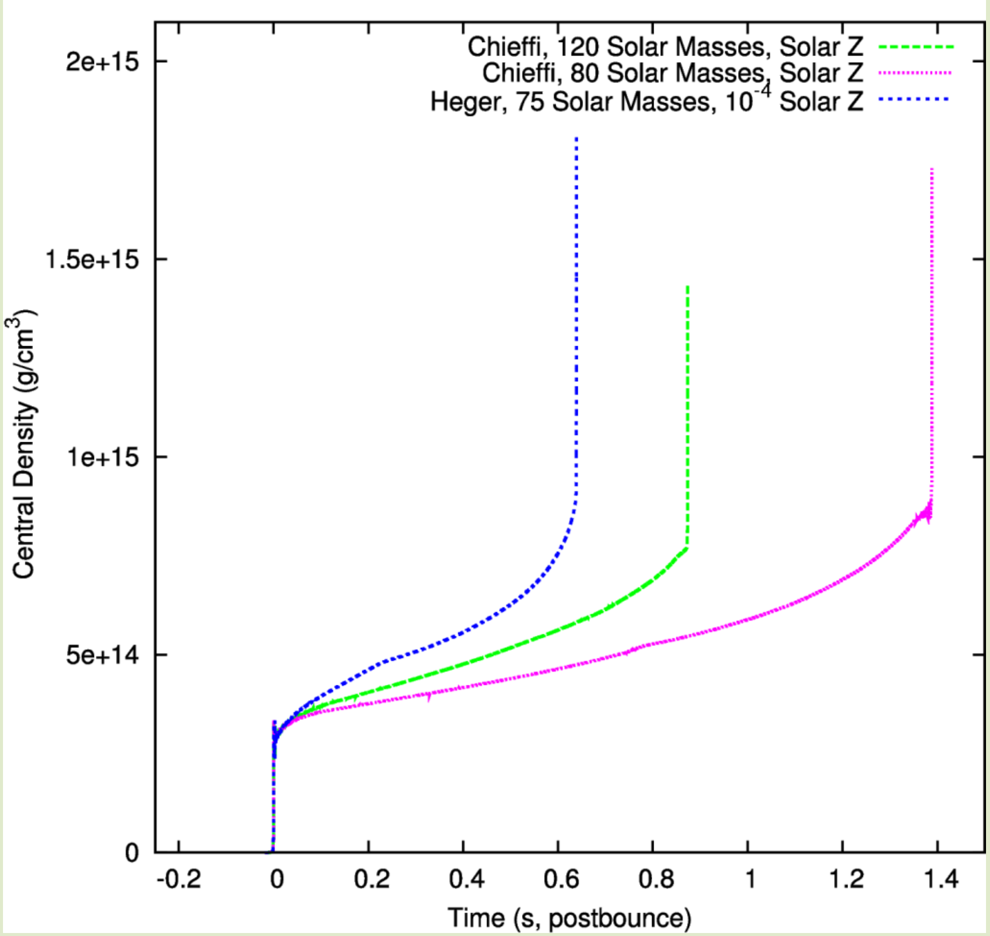
  (2) Can complement data on unnovae: e.g., mass of star, mass of PNS at BH formation.

Failing CCSNe & BH Formation

1) There is no direct/prompt BH formation.

2) Route 1 to a BH: ***Collapsar Type I*** [Heger et al. 2003]

- Explosion fails.
- **No EM signal, only GWs and neutrinos.**
- BH forms on accretion timescale. τ_{BH} determined by
  (1) Stiffness of the nuclear EOS.
  (2) Accretion rate
  <- progenitor structure.

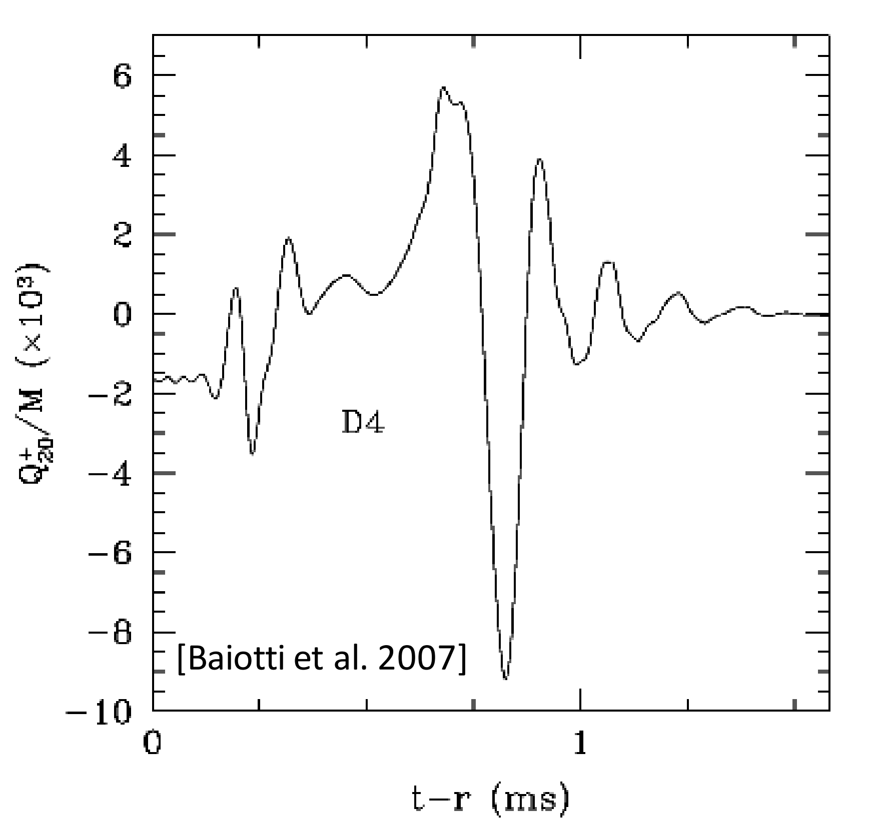


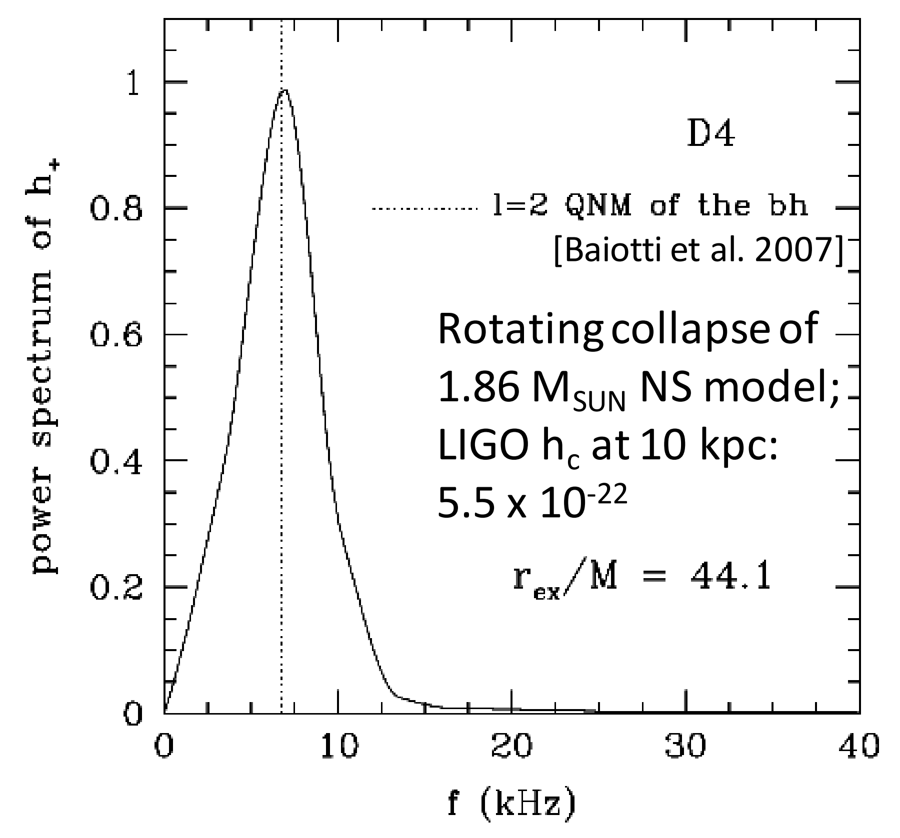
3) Route 2 to a BH:
Collapsar Type II

- Weak explosion, subsequent fall-back accretion.
  [Zhang & Woosley 2008]

Probing BH Formation with GWs

- Nonspherical collapse of a (Proto-)NS to a BH





- Emission dominated by BH QNM as BH rings down to Kerr.

$$f_{200} = 14.4\left(\frac{M}{M_\odot}\right)^{-1}\left(1 - 0.165(1-j)^{0.355}\right)\,\mathrm{kHz}\,,$$

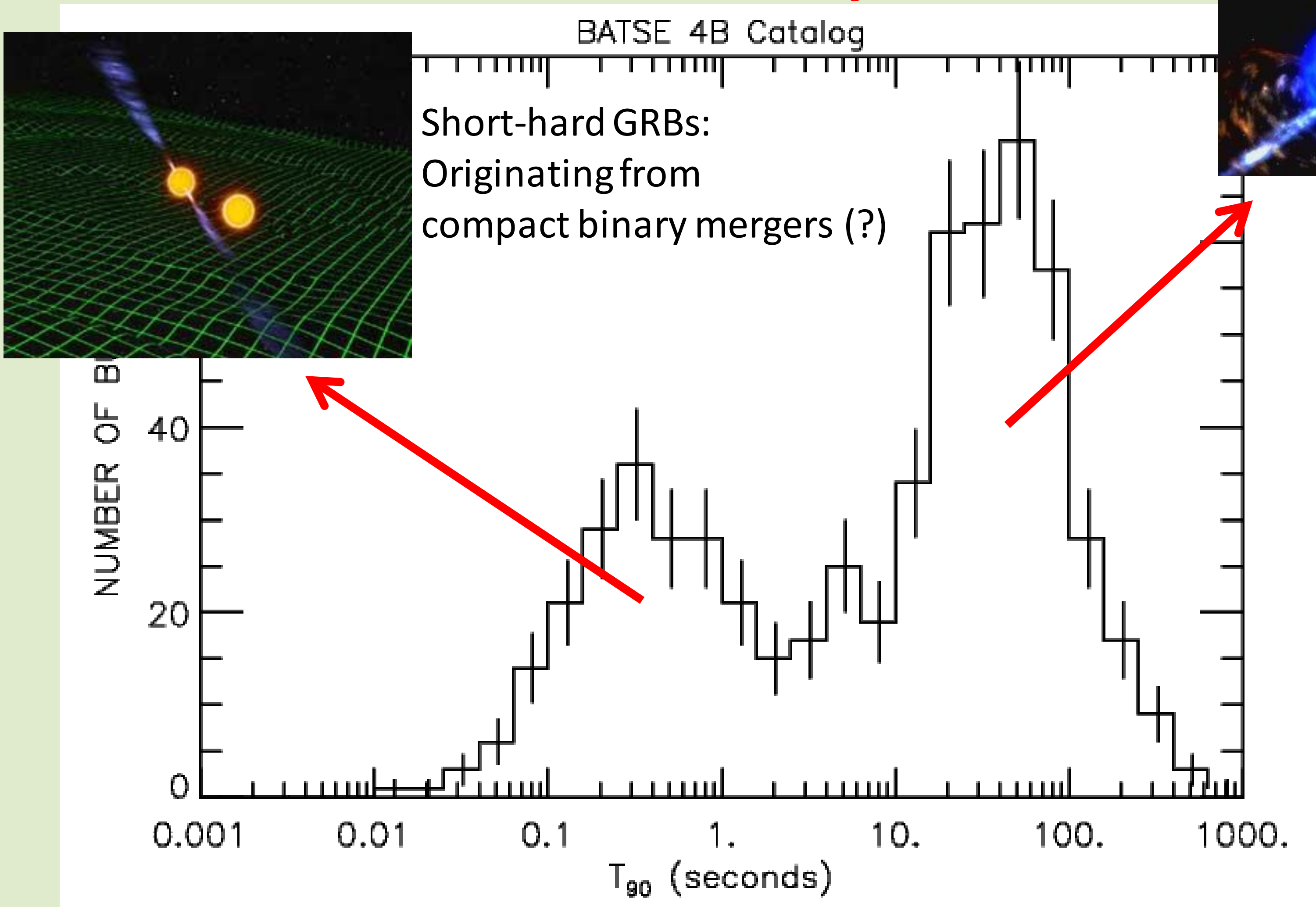
$$f_{220} = 49.4\left(\frac{M}{M_\odot}\right)^{-1}\left(1 - 0.759(1-j)^{0.1292}\right)\,\mathrm{kHz}$$

$M_{NS} = 2\ M_{SUN}$ -> $f_{QNM} \sim 6$ KHz; decreases as BH accretes more matter.

[see discussion in Ott 2009]

Gamma-Ray Bursts

Short-hard GRBs:
Originating from
compact binary mergers (?)

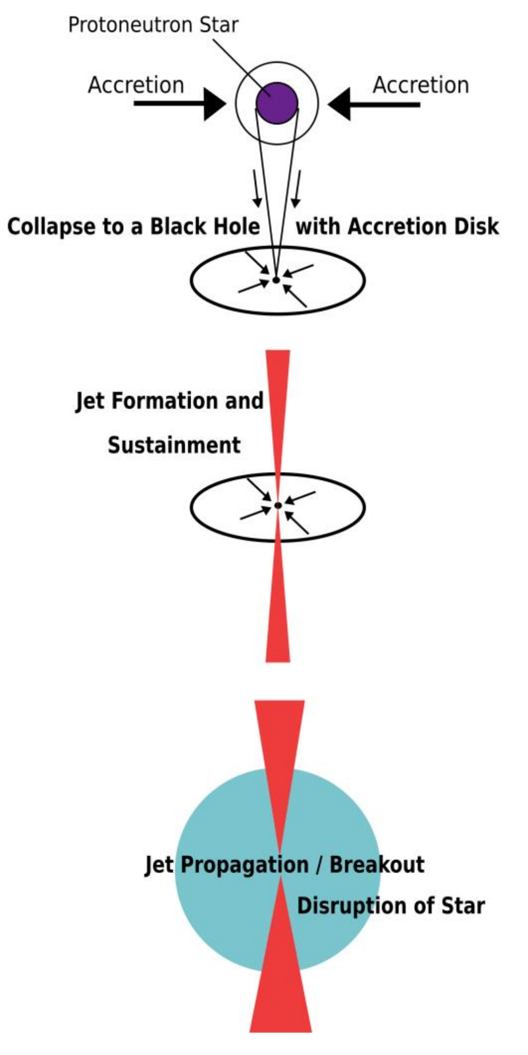


Observations:
long-soft GRBs
related to
core-collapse
SNe

- (At least) 2 classes of GRBs: Short hard ($T_{90} < 2$ s), long soft ($T_{90} > 2$s)

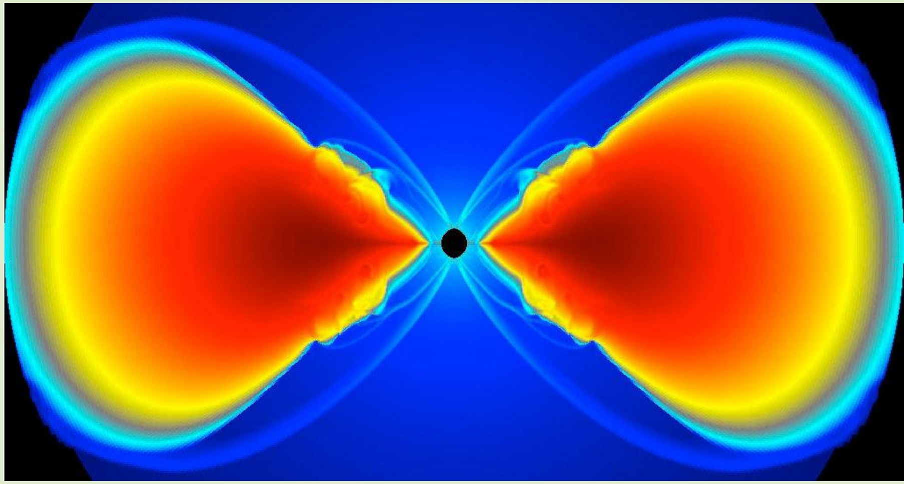
Long-Soft Gamma-Ray Bursts

- **Highly-beamed EM emission**, most likely aligned with axis of rotation. Energies comparable to SN explosion.
- **Ultimate source of energy: Gravitational collapse**. Mediators: **Rapid rotation** & **MHD** effects
- ~1% of massive stars sufficiently rapidly rotating to make a long-soft GRB. (But: Not all can make GRBs, not all GRBs pointed towards us.)
  -> **GRBs extremely rare in the local universe;**
  closest GRB at ~40 Mpc.
- Variety of theoretical long-soft GRB models; some that are favored:
  - Collapsar type I (no SN explosion; star blown up by GRB)
  - MHD Hypernova + Collapsar (explosion before BH)
  - MHD Hypernova + Millisecond Magnetar



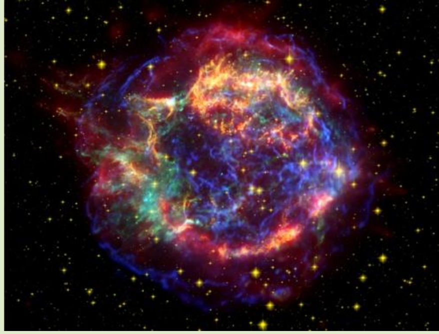
GWs from Long-Soft GRBs

[credit: J. McKinney]



- **pre-BH-formation GW signature identical to rapidly rotating core-collapse supernova.**
- BH-torus system crucial for Collapsar-type L-S GRB. Torus will persist for duration of central engine operation.
- **GWs:**
  Torus will be unstable to nonaxisymmetric perturbations.
  - multiple local density maxima ("clumping", fragmentation), spiral density waves redistributing angular momentum. Episodic destruction of torus?
  - GWs: elliptical polarization, frequency: 2 x ISCO frequency, set by BH mass (~2 – 5+ (?) M_{Sun}) and spin. **So far only back of the envelope estimates**.
- **Collapsar vs. Magnetar smoking GW gun**:
  BH formation signal and/or shut-off of signal from NS dynamics before/during GRB electromagnetic emission [see Corsi & Meszaros 2009].

Summary



- GW observations are crucial for our understanding of stellar collapse and related explosive phenomena.

Einstein Telescope:

- Potential to answer pressing astrophysical questions with GWs:
  - **Mechanisms of Core-Collapse Supernovae.**
  - **Central Engines and Progenitors of Long-Soft GRBs**.
- **Astrophysics Reach:** adv. LIGO needs to get lucky to see a CCSN. ET is virtually guaranteed to see at least 0.5 CCSNe per year.
- **Determine/constrain physical parameters of collapsing and exploding stars.**
- **Add to the multi-messenger mix & find unnovae and weak explosions hard (or impossible) to see in EM.**
- **Additional major pay-off beyond Astrophysics**: Constrain nuclear physics at high density and energy.