The 0.1 – few KHz GW Window:
Studying the Physics and Dynamics of Matter at Extreme Densities and Energies

Christian David Ott

cott@tapir.caltech.edu

TAPIR, California Institute of Technology, Pasadena, CA, USA

& Niels Bohr Institute, Copenhagen, Denmark

In collaboration with and inspired by

Benjamin J. Owen and Richard O'Shaughnessy

Pennsylvania State University, State College, PA

G0900620-v1

Overview:

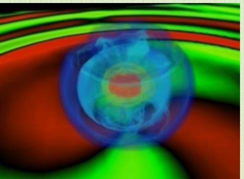
- 25 Minutes to convince you to invest in high-f sensitivity -

-> Constraining unknown Astrophysics:

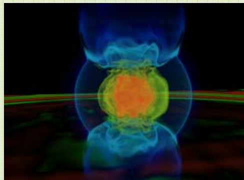
- Massive Star Collapse: **Formation of NSs and BHs**; **Core-Collapse Supernovae** & long-soft Gamma-Ray Bursts
- Binary mergers and the progenitors of short-hard GRBs.
- **Internal structure and composition of NSs**.

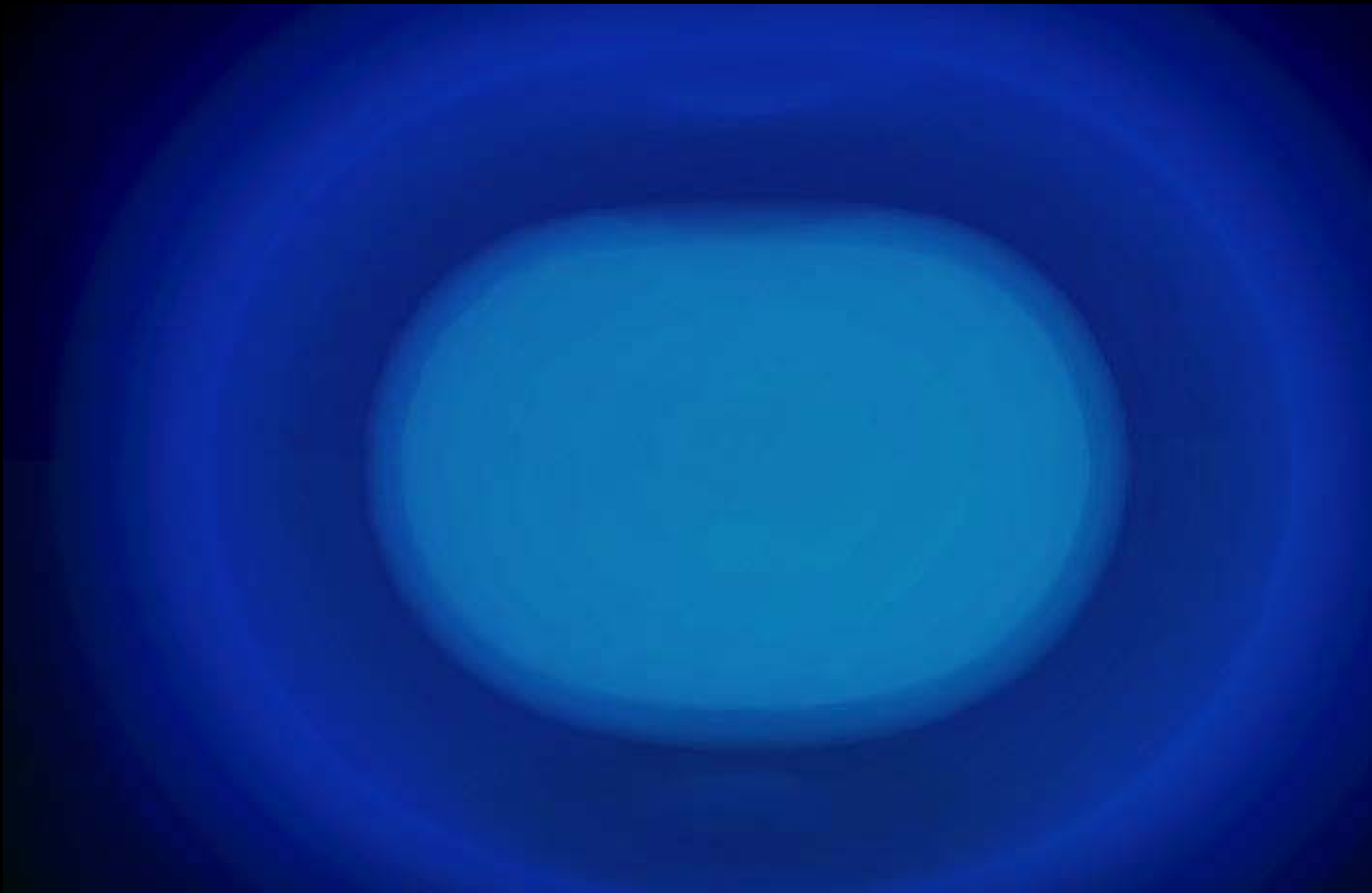
-> Constraining unknown Nuclear / Elementary Particle Physics:

- Equation of state (EOS), composition, and structural properties of hot and cold nuclear matter.

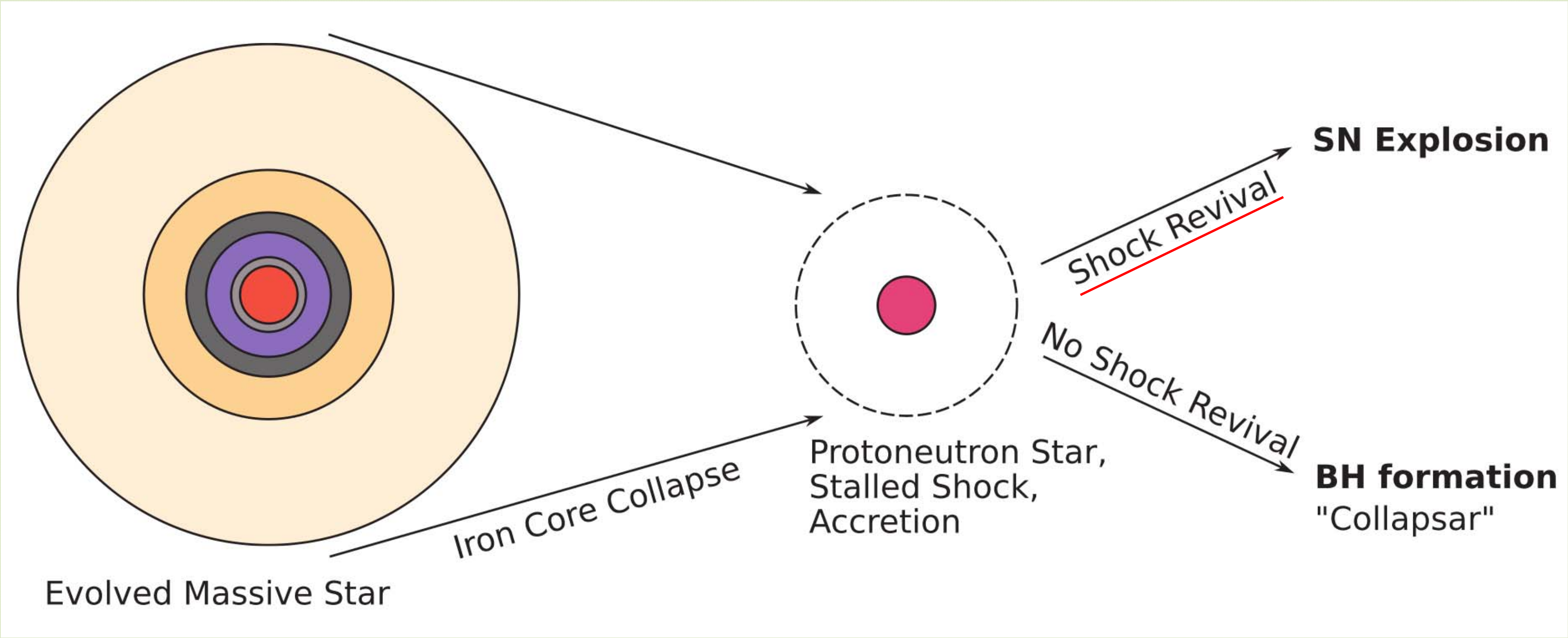


G0900620-v1





Core-Collapse Supernovae



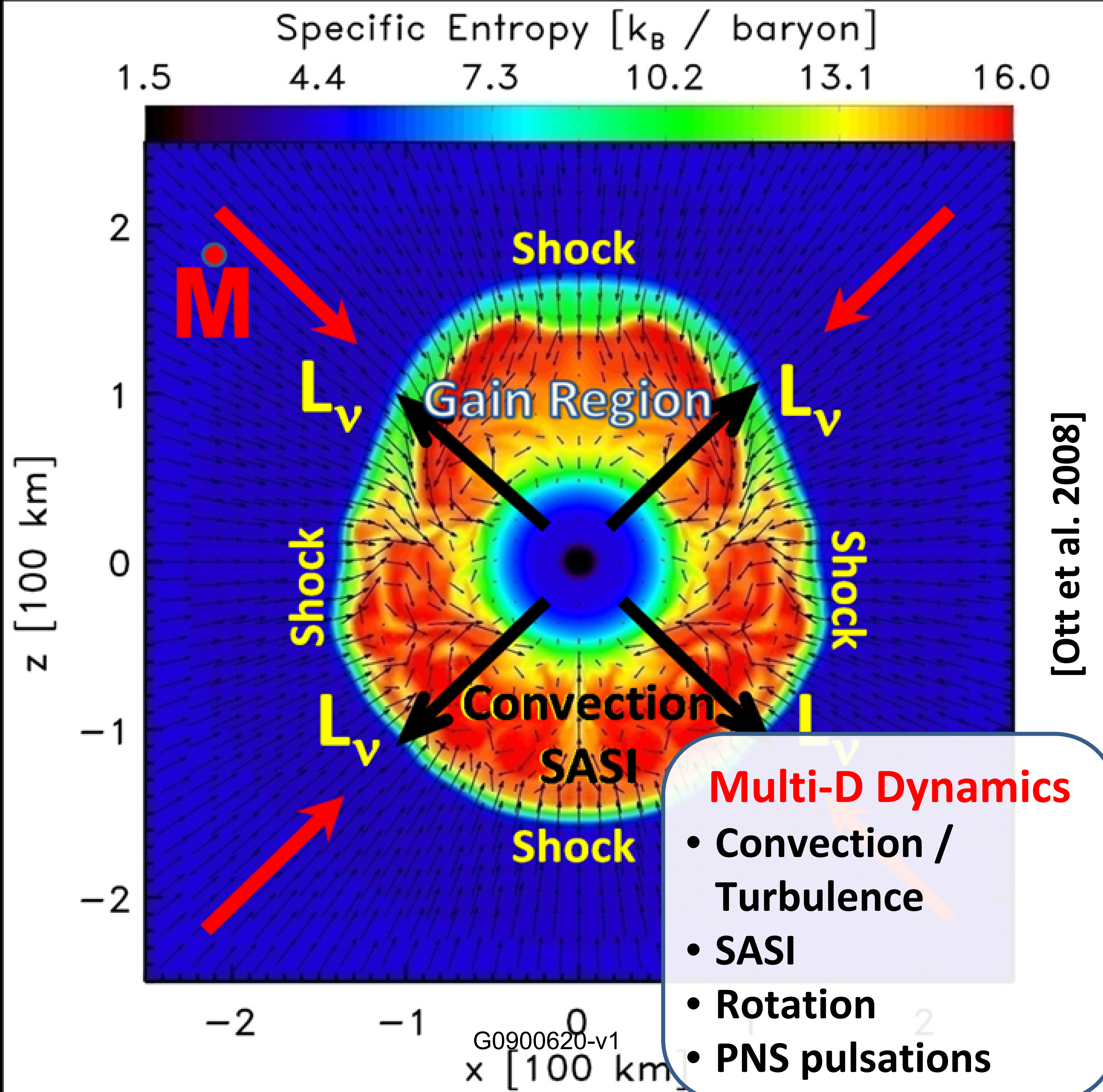
- **Energy reservoir:** **few x 10^{53} erg (100 [B]ethe)**
- **Explosion energy**: **~1 B**

- 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?

G0900620-v1

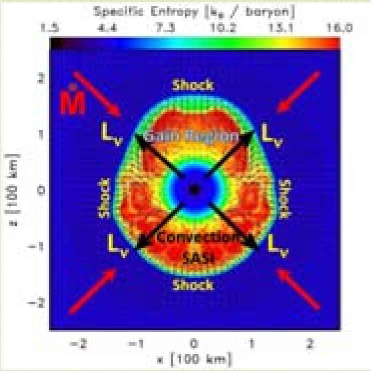


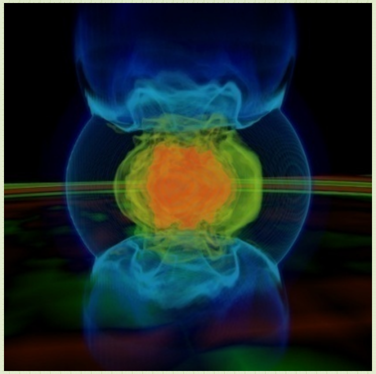
Multi-D Dynamics

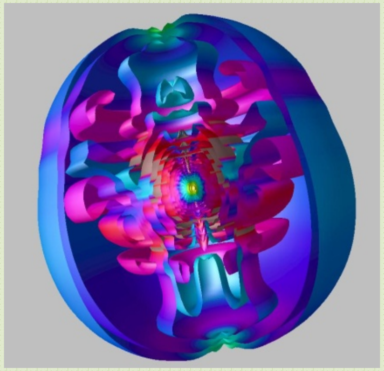
- Convection / Turbulence
- SASI
- Rotation
- PNS pulsations

SN Mechanisms and Their Multi-D Features

[Ott 2009]







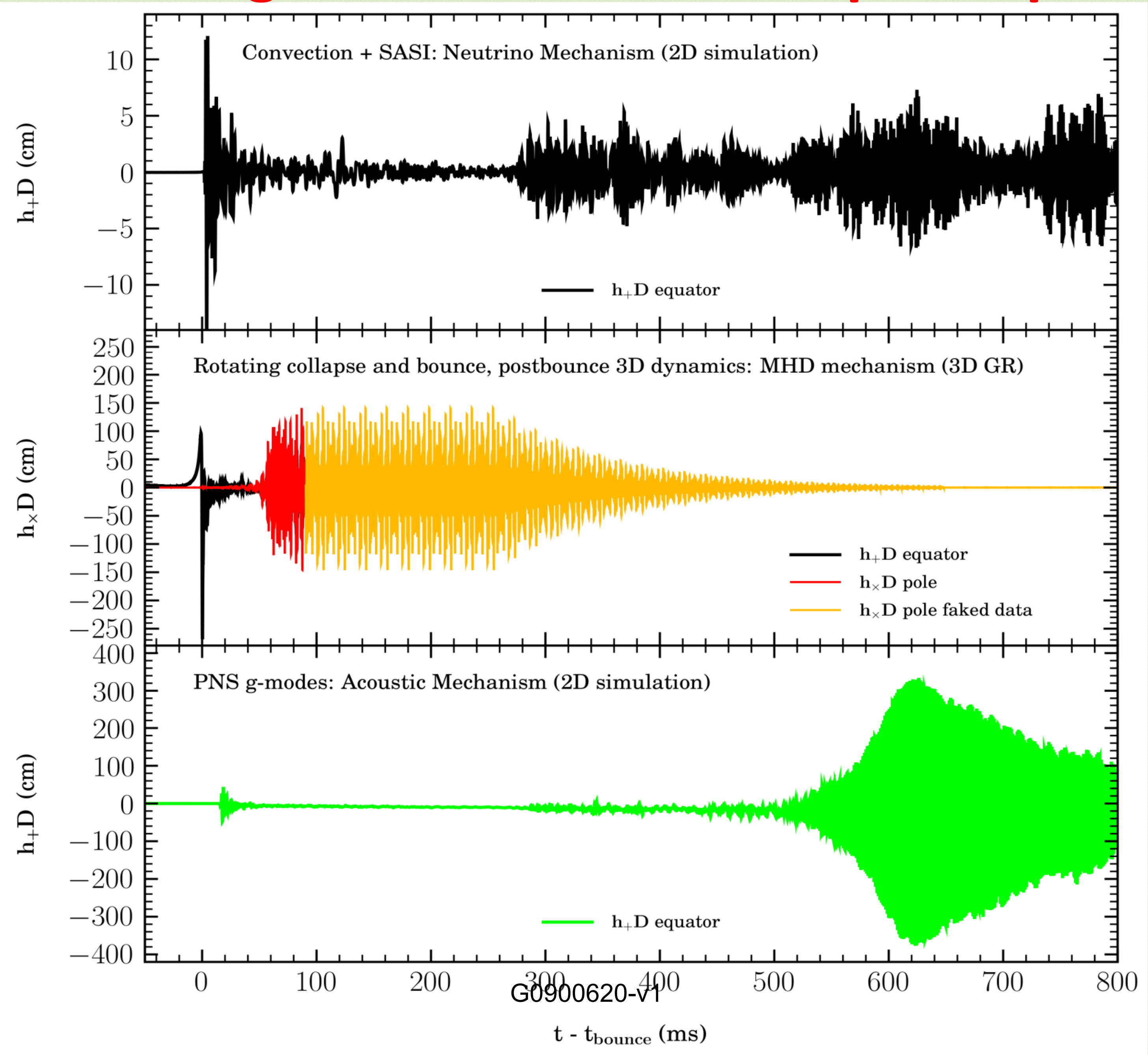
Dominant Multi-D Processes

Neutrino Mechanism	→	Convection and SASI
MHD-Jet Mechanism	→	Rotation
Acoustic Mechanism	→	Protoneutron Star Pulsations

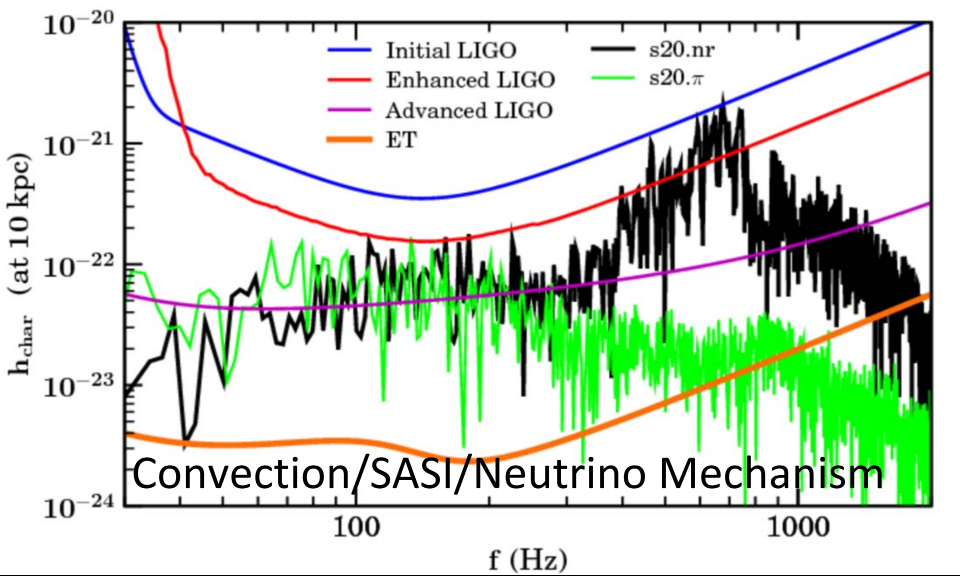
G0900620-v1

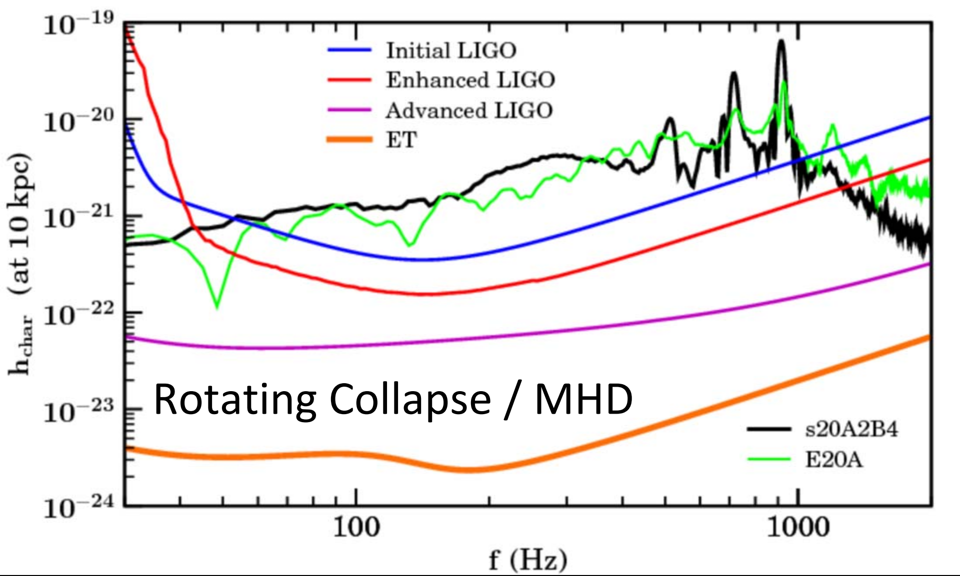
Model GW Signals from Core-Collapse Supernovae

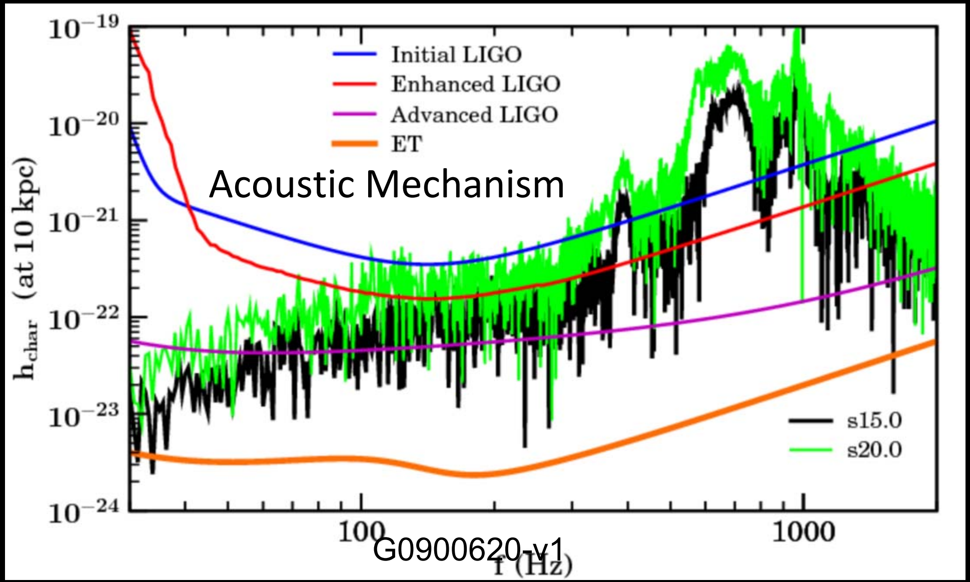
[Ott 2009]



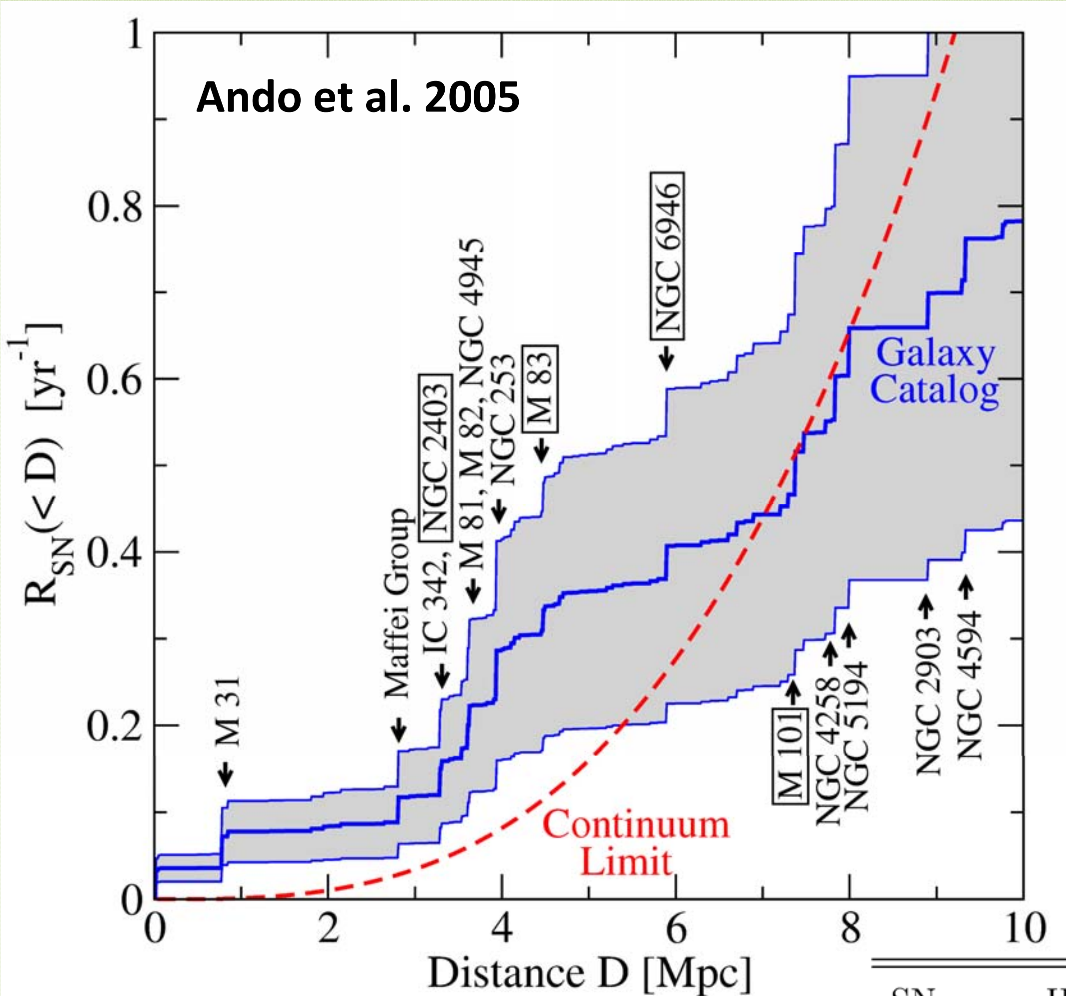
Characteristic Strain Spectra
at 10 kpc

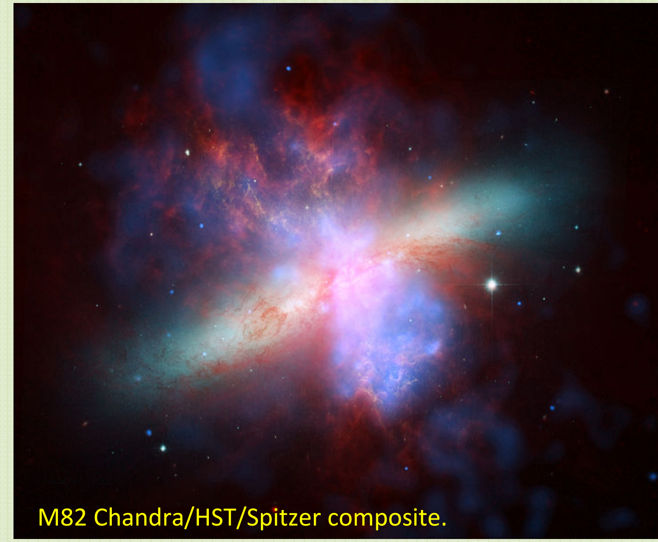






Core-Collapse Supernova Rates





M82 Chandra/HST/Spitzer composite.

M31 (Andromeda) Spitzer.

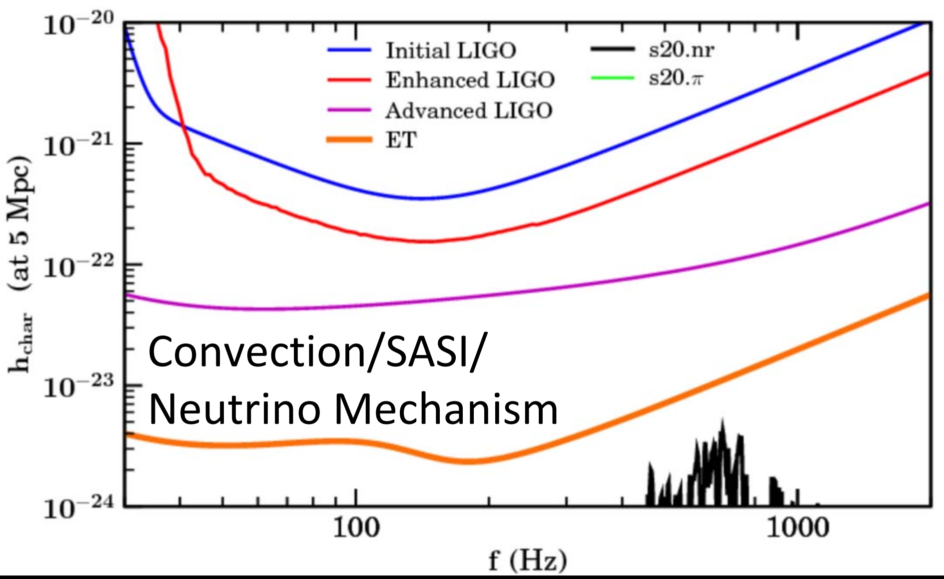
Core-collapse SNe within 5 Mpc since the beginning of LIGO operations:

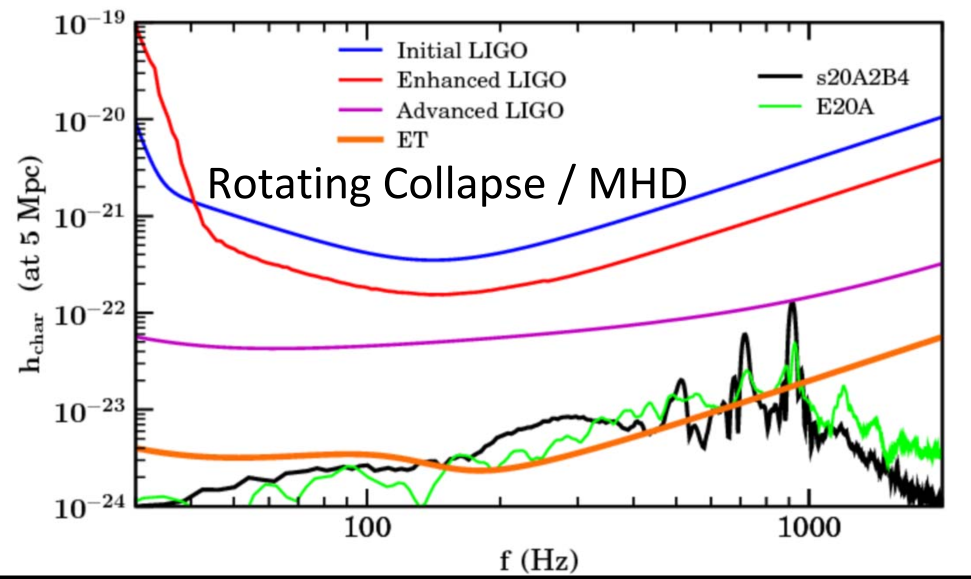
[Ott 2009]

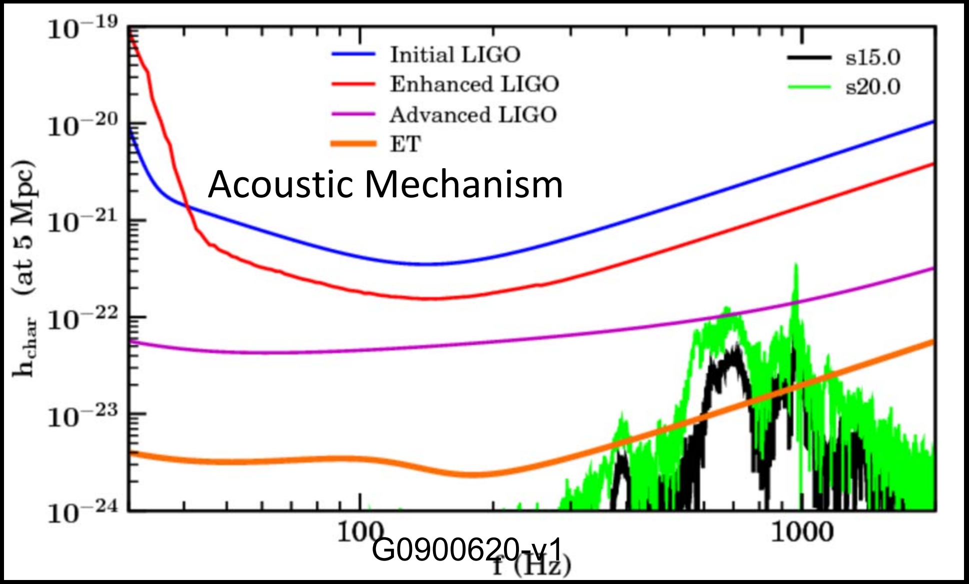
SN	Host Galaxy	Date	Type	Distance
2008bk	NGC 7793	20080325 [132]	II-P	$\sim$ 3.9 [133]
2005af	NGC 4945	20050208 [134]	II-P	$\sim$ 3.6 [133]
2004dj	NGC 2403	20040731 [135]	II-P	$\sim$ 3.3 [133]
2004am	M 82	20040305 [136]	II-P	$\sim$ 3.5 [137]
2002kg	NGC 2403	20021026 [138]	IIn	$\sim$ 3.3 [133]

G0900620-v1

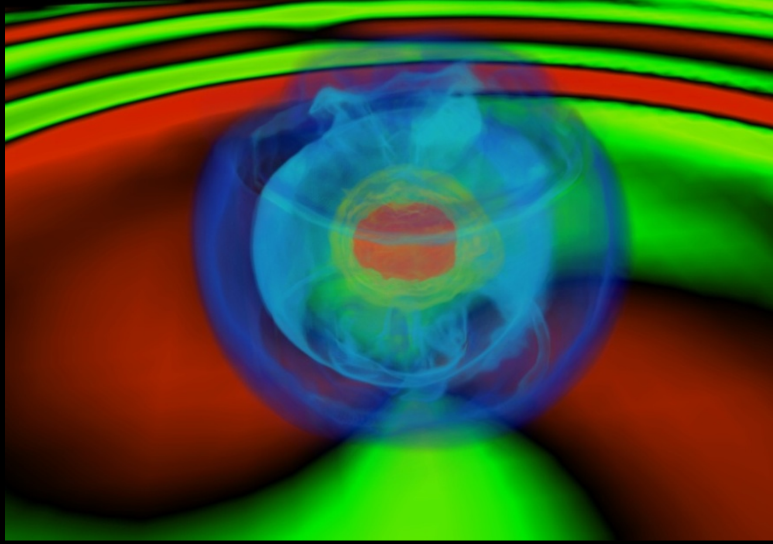
Characteristic Strain Spectra
at 5 Mpc: ~0.5 CC-SNe / year







Summary I: SN Physics with GWs

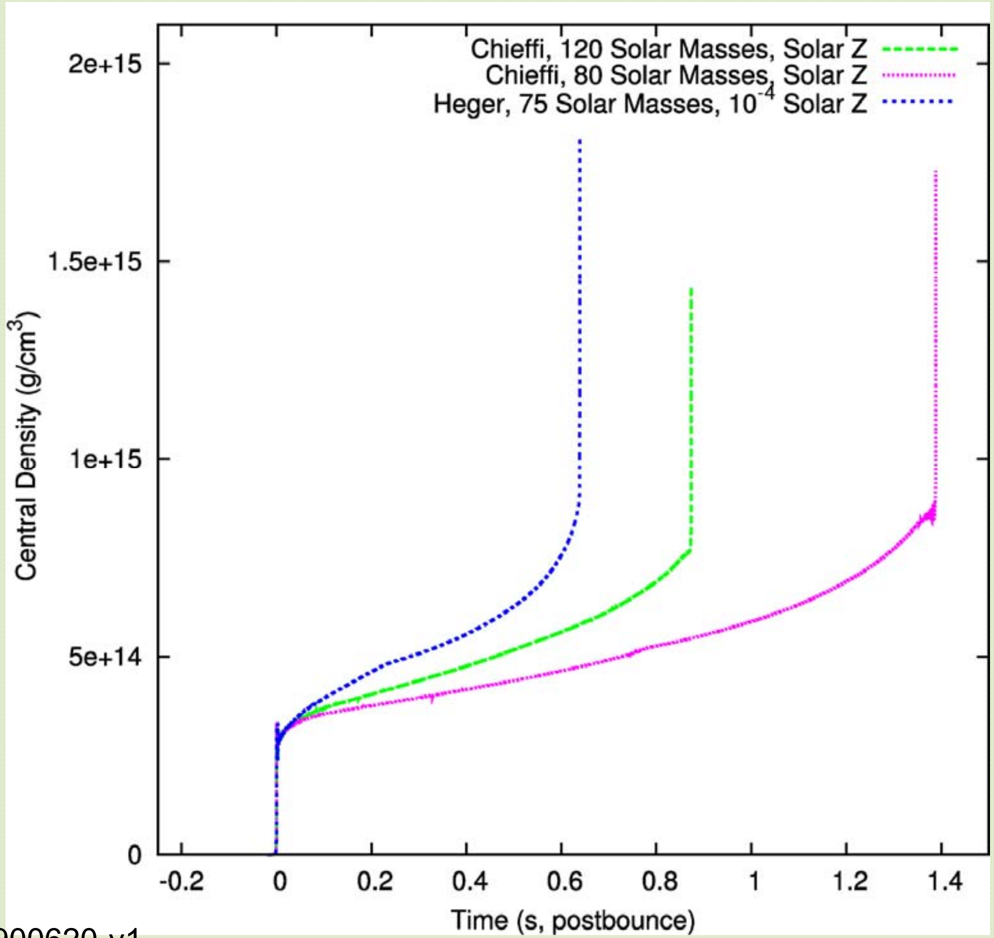


- Baade & Zwicky 1934:
  SN powered by liberation of gravitational energy in collapse of a massive star's core to a neutron star.
- Theoretical efforts every since -> multiple proposed (more or less viable) mediating explosion mechanisms.
- **Only** GWs and neutrinos can carry direct information from SN engine.
- GW signatures of various mechanisms are distinct -> **use GWs to constrain the explosion mechanism**.

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.



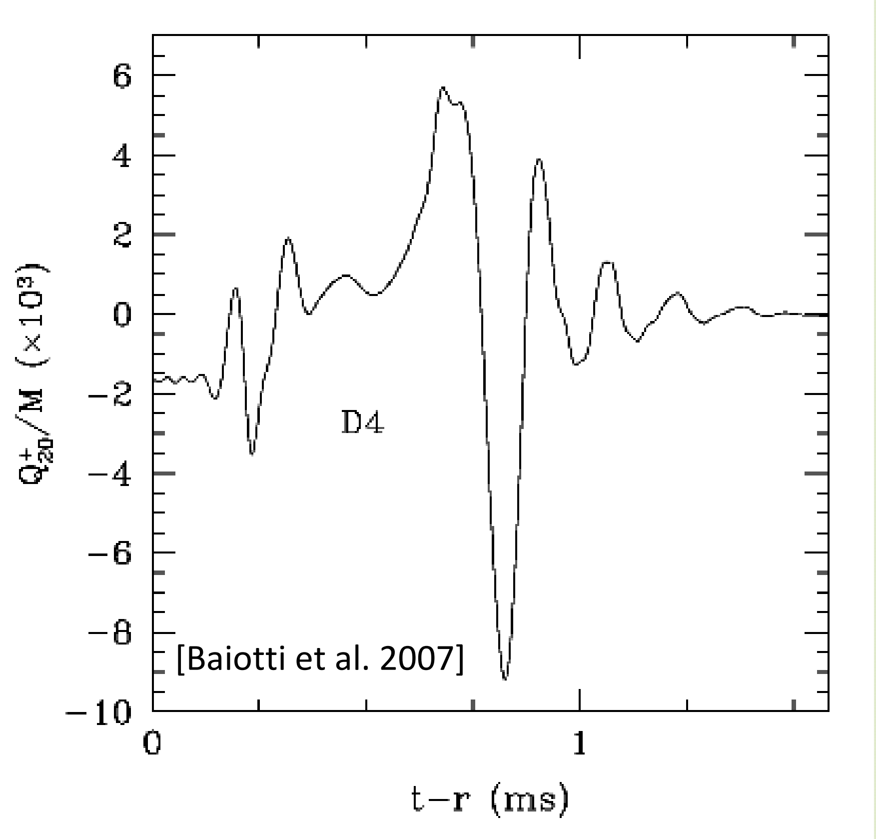
3) Route 2 to a BH: ***Collapsar Type II***

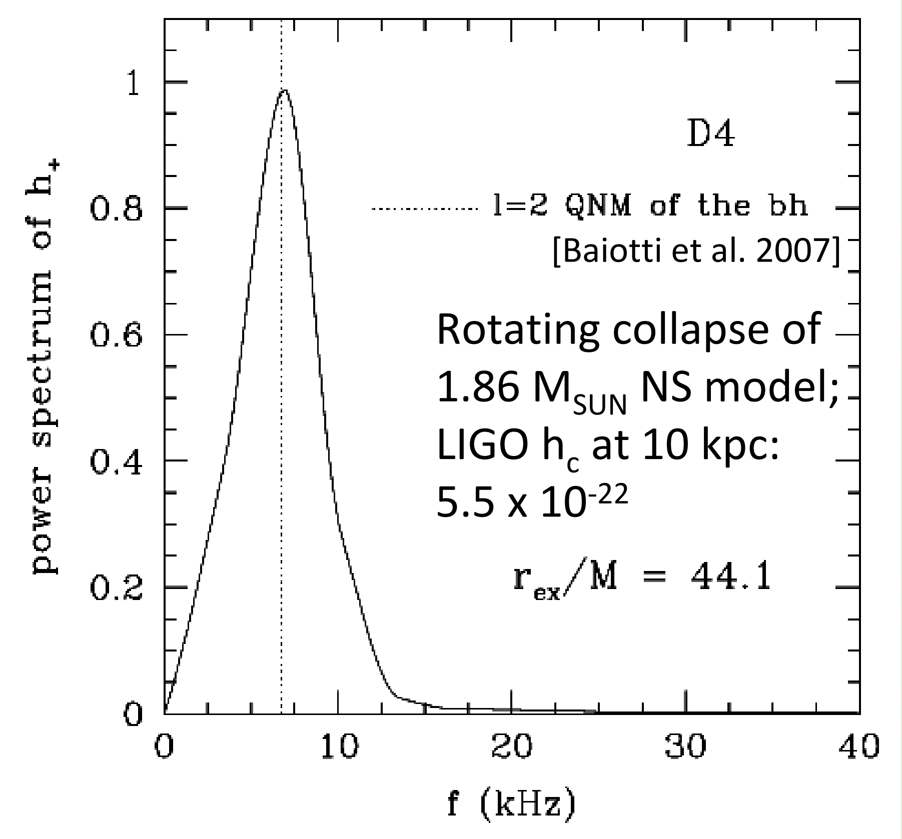
- Weak explosion, subsequent fall-back accretion. [Zhang & Woosley 2008]

G0900620-v1

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.

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

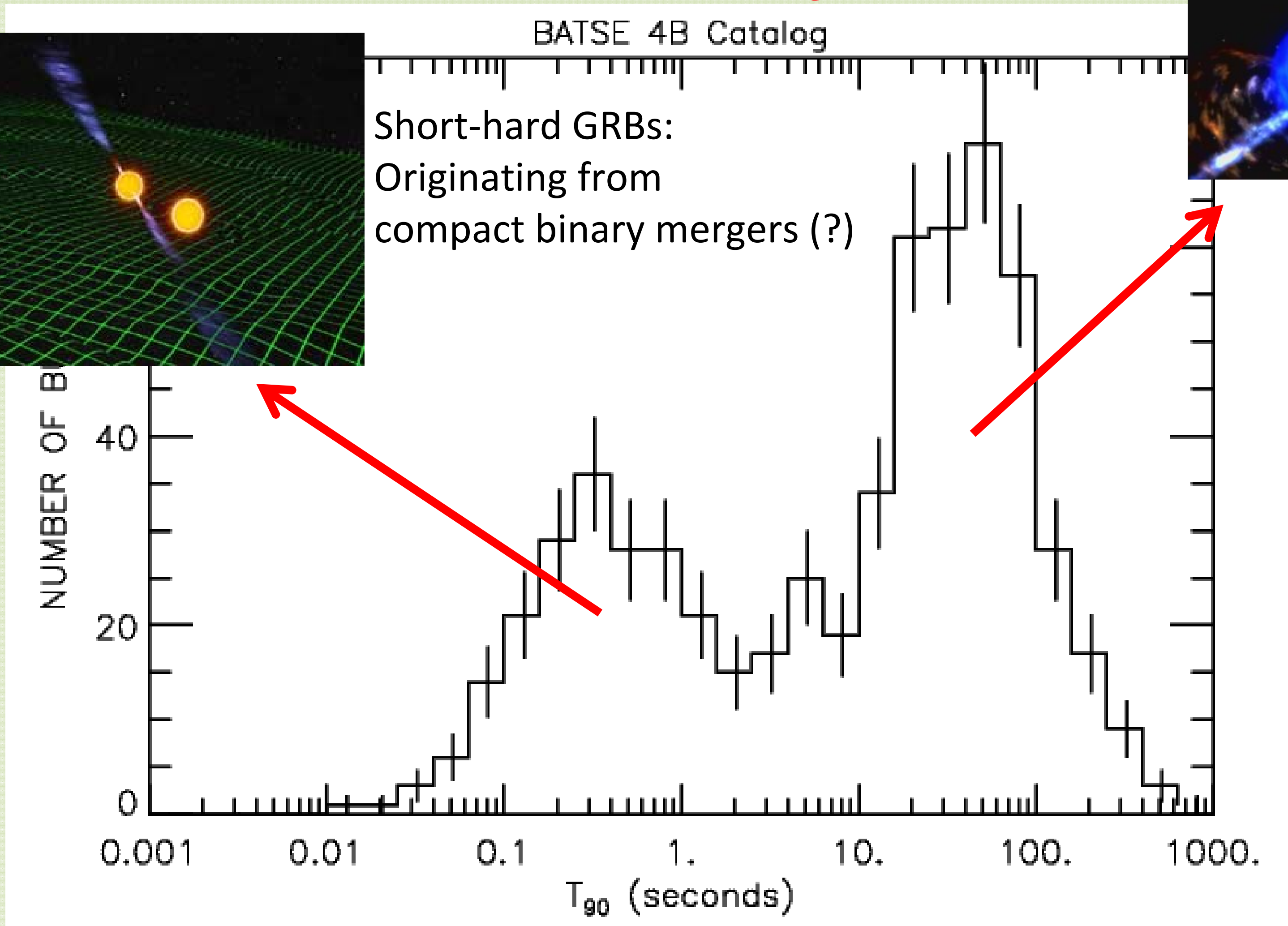
$$f_{220} = 49.4\left(\frac{M}{M_\odot}\right)^{-1}\left(1 - 0.759(1-j)^{0.1292}\right)\,\mathrm{kHz}$$

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

[see discussion in Ott 2009]

G0900620-v1

Gamma-Ray Bursts



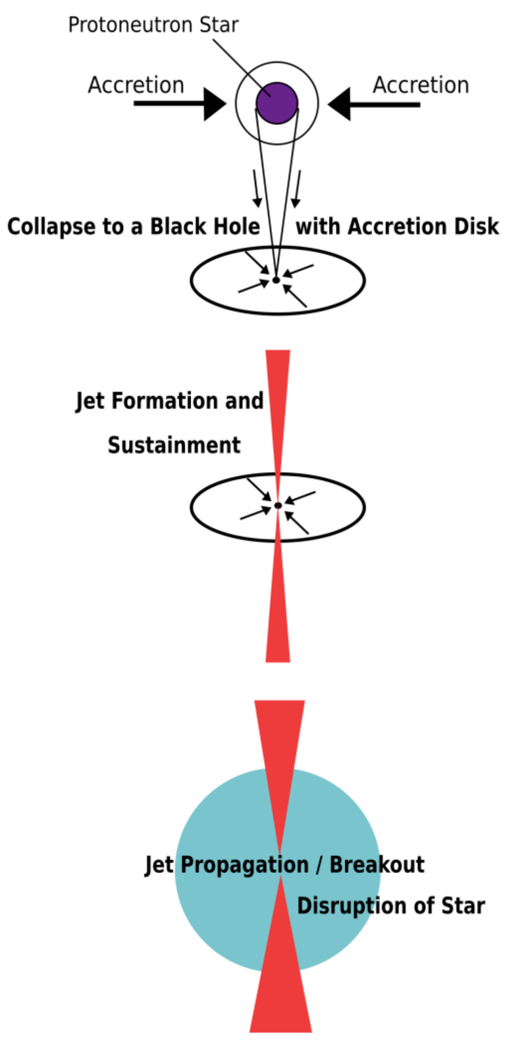
Short-hard GRBs:
Originating from
compact binary mergers (?)

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} > 2s)

Long-Soft Gamma-Ray Bursts

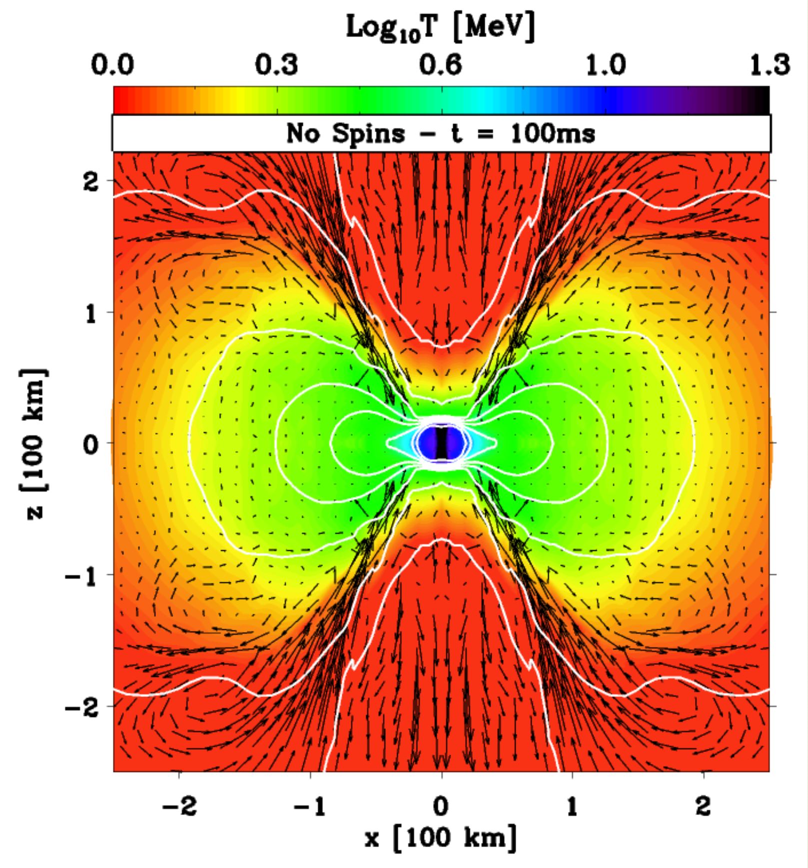
- **Highly-beamed EM emission**, most likely aligned with axis of rotation. Energies comparable to SN explosion.
- **Ultimate source of energy: Gravitational collapse**. Mediators: **Rapid rotation** & **MHD** effects
- ~1% of massive stars sufficiently rapidly rotating to make a long-soft GRB. (But: 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
- **GW emission**:
  Same overall characteristics as in core-collapse SNe.
  – **Collapsar vs. Magnetar smoking gun**: BH formation signal and/or shut-off of signal from NS dynamics before/during GRB electromagnetic emission.



G0900620-v1

Short-Hard GRBs

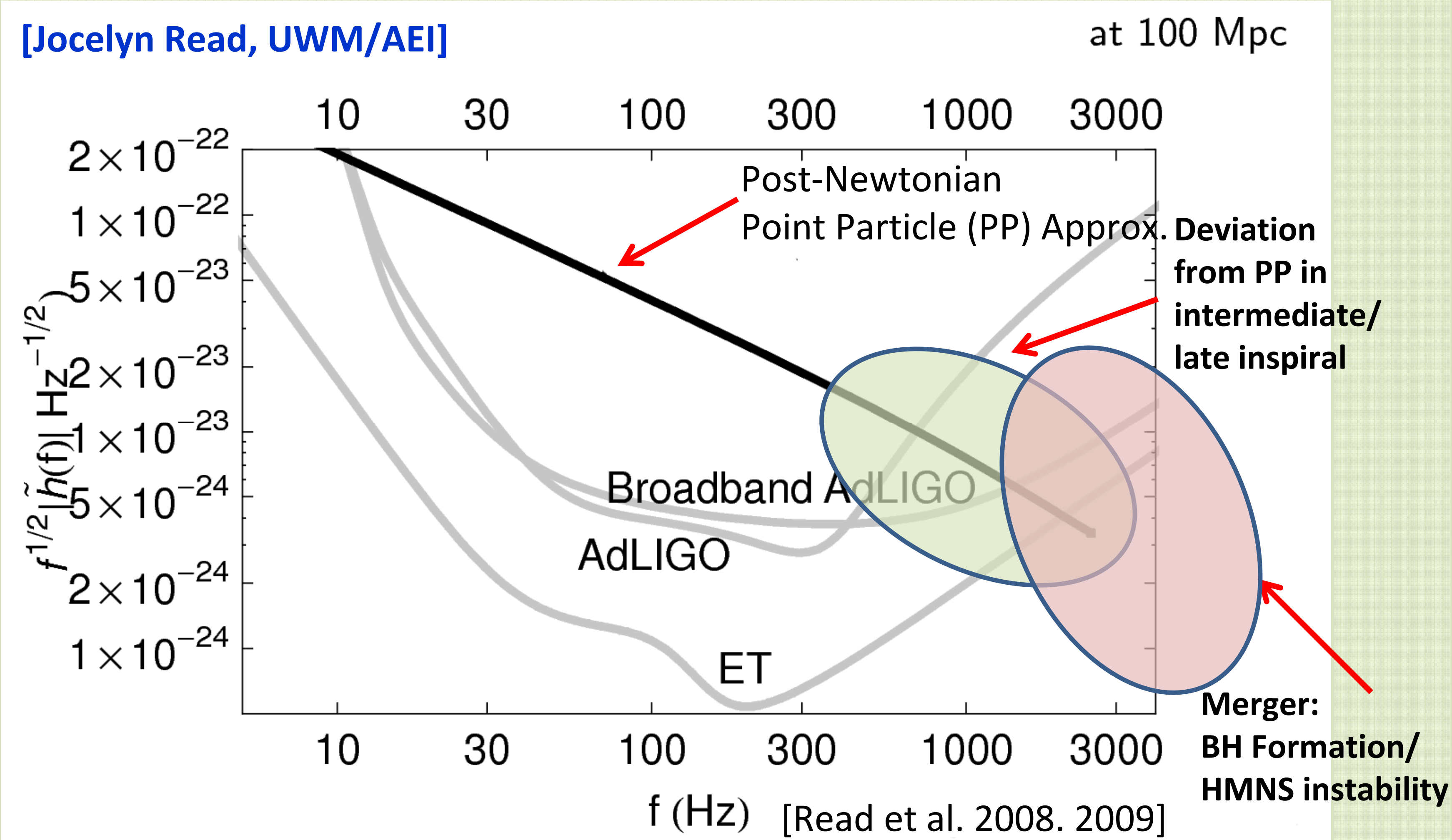
- Energetics: $10^{48} – 10^{50}$ erg, need BH with ~0.01 M_{SUN} disk.
- Powered by **rotation + MHD** and/or **neutrino pair annihilation** (but: inefficient [Dessart, Ott et al. 2009])
- Formation scenarios:
  – **Coalescence & Merger of NS – NS system.**
  Formation of hypermassive NS
  (may survive for many dynamical times)
  – **Coalescence of BH – NS system.**
  Required: Tidal disruption of NS to have sufficient disk material.



G0900620-v1

[Dessart et al 2009]

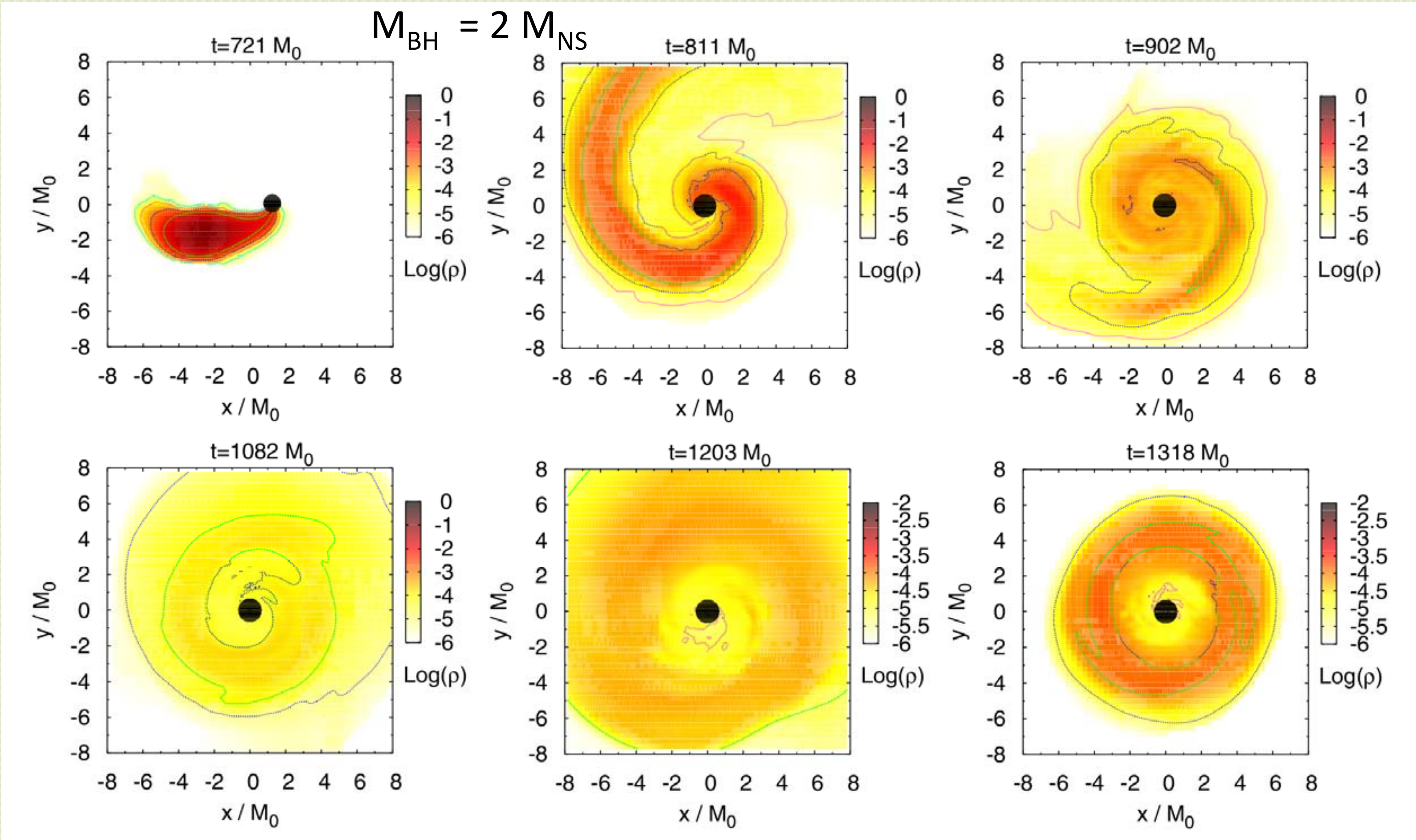
NS-NS Coalescence and Merger



- **Finite size effects**: Tidal deformation, effect on phase of GW signal. [Flanagan & Hinderer '08]
- **Merger**: GW burst from final plunge, HMNS dynamics, BH formation: f ~ few KHz.
- **Tidal deformation and "survival time" of HMNS constrain nuclear EOS.**

BH-NS Merger

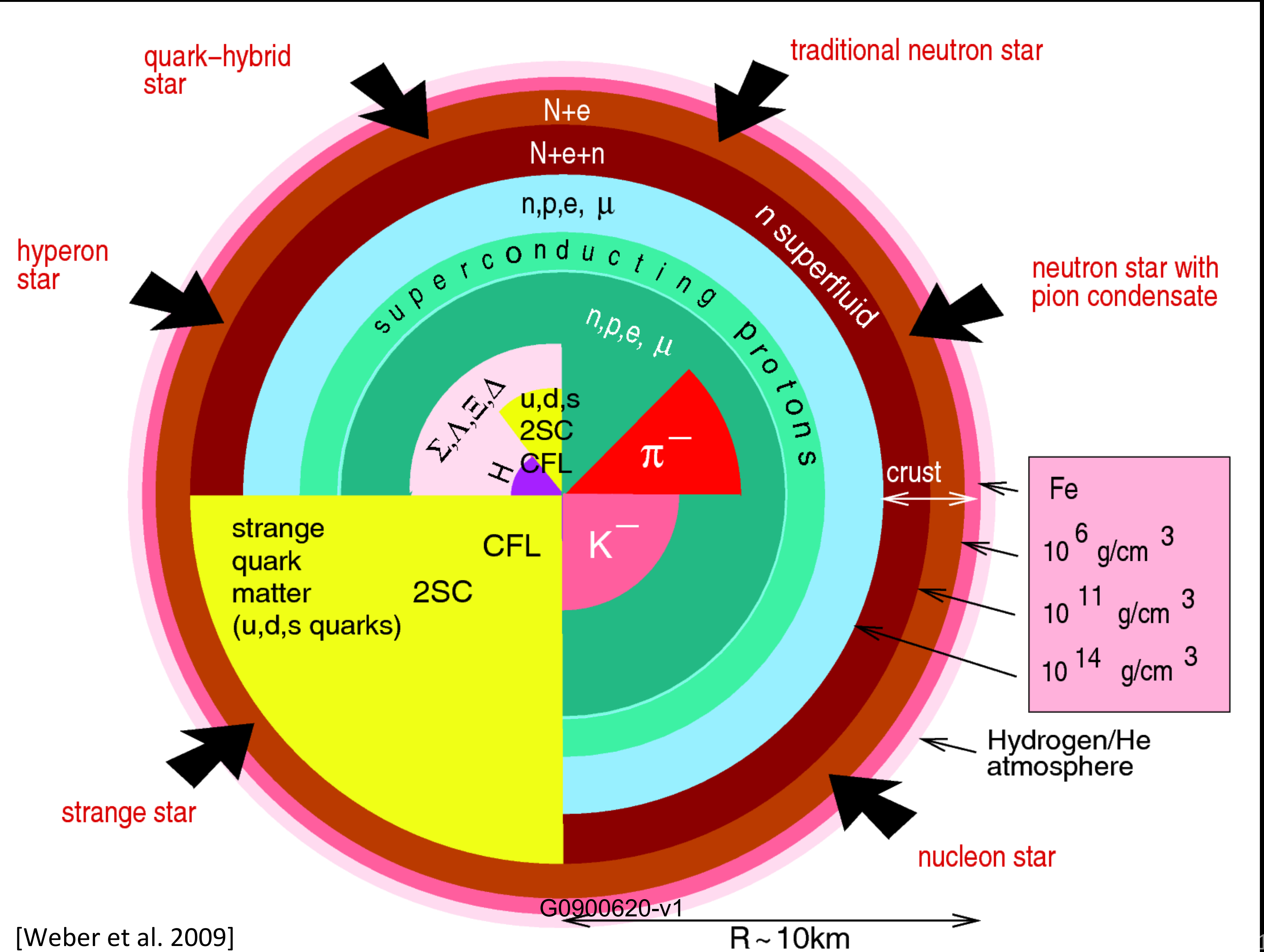
[Shibata et al. 2009]



- As NS-NS: Finite-size effects in late inspiral.
- Tidal disruption of NS necessary for disk formation; likely to happen for $M_{BH} < 4\ M_{SUN}$; $M_{NS} \sim 1.3\text{-}1.6\ M_{SUN}$.
- NS structure / EOS encoded in GW signal / frequency of disruption. f ~ few KHz.

G0900620-v1

Neutron Star Structure



[Weber et al. 2009]

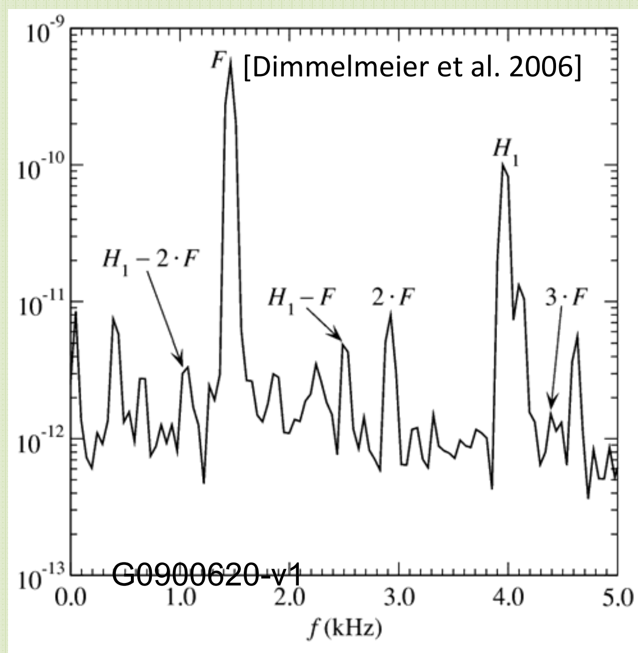
Studying Neutron Stars with GWs

- "Continuous" GWs: **"Mountains" on NSs and r-modes**

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} \qquad h_0 = \frac{(2\pi f)^2}{D} I_{zz}\epsilon \qquad f = \frac{2}{P_{\mathrm{NS}}}$$

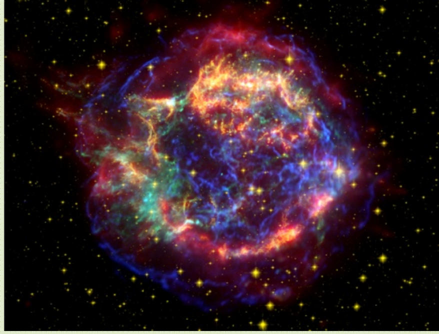
  - Ellipticity $\epsilon \propto$ (breaking strain) x (shear modulus) x (geometry)
    -> set by NS crust & core physics: Normal NS: $\epsilon \sim 10^{-6}$, Quark NS: $\epsilon \sim 10^{-3}$
  - Mountain formation: Accretion (LMXBs), magnetic mountains
  - r-modes; limited by NS viscosity. Present in very young NSs (?)
  - **Strongest emitters: Most rapidly spinning NSs -> $f_{GW} \sim 0.3 – 2$ KHz.**

- Bursts: Excitation of NS pulsational modes (f, p, g, w)
  - Pulsar Glitches
  - Magnetar Quakes: Soft Gamma Ray Repeaters



G0900620-v1

Summary



- Beyond the First Detection **->**
  Gravitational Wave Astronomy

- Potential to answer pressing astrophysical questions with GWs:
  - **Mechanisms of Core-Collapse Supernovae**
  - **Mechanisms and Progenitors of Long-Soft and Short-Hard GRBs**.

- **Characteristic GW frequencies: few 100 Hz – few 1000 Hz**
  Set by dynamical timescales/rotation frequencies of emitting systems

- **Additional major pay-off beyond Astrophysics**:
  Constrain nuclear physics at high density and energy

G0900620-v1