ET OSB - Div. 7:
Transient GW sources

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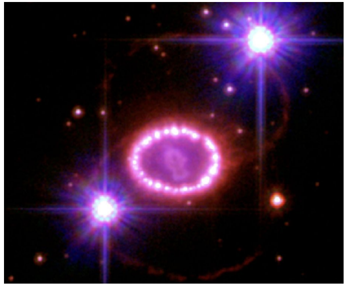
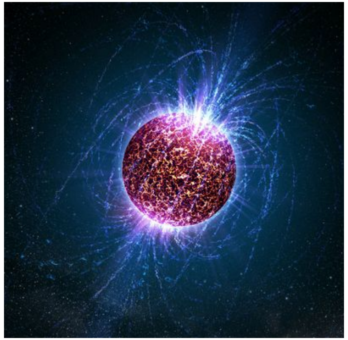
Transient GW sources (non CBC)

- **Collapse of stellar cores**:
    - Core collapse supernovae
    - Direct black hole formation (failed SNe)
    - Long GRBs/hypernovae - SLSN
- **Magnetar transient activity:**
    - Short/long bursts
    - Giant flares
    - Newly born magnetars
    - Fast radio bursts

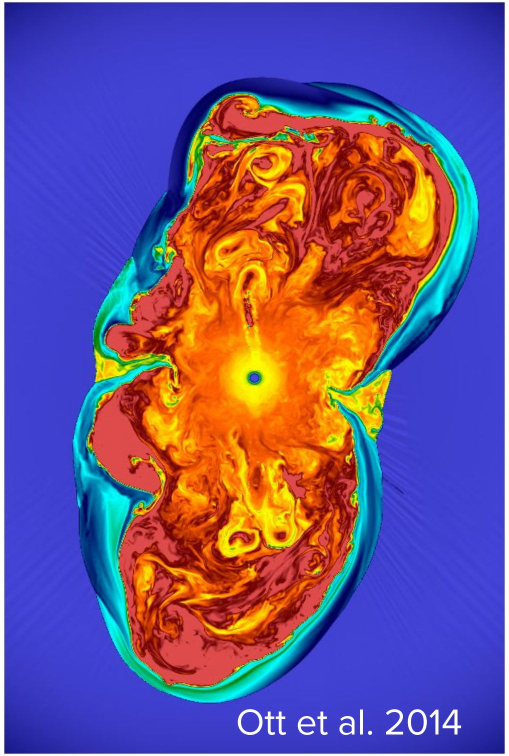
SGRs and AXPs

- **Neutron star glitches**
- ~~**Cosmic string bursts**~~ → Div2 (Cosmology)





SNe from core collapse (CC-SNe)



All” star with mass in the range ~8-100 Msun terminate their life with a core collapse to NS or BH.

Multi-D hydrodynamic instabilities play a crucial role to produce successful explosion. How this occurs is the key question in supernova theory.

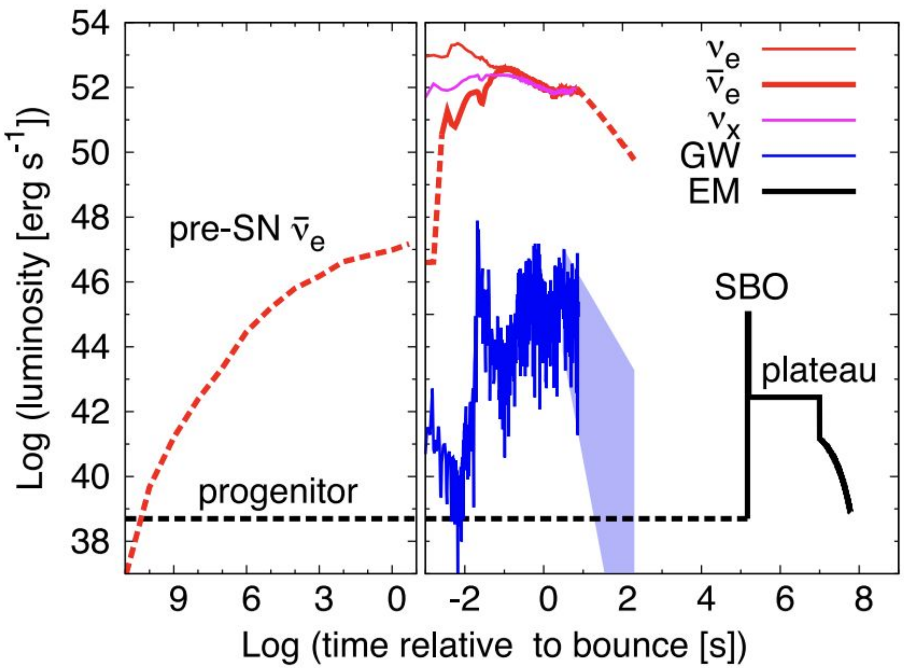
Instabilities are the origin for GW emission. PNS dynamics is responsible for most of the GW.
GW are predicted to be stronger for fast rotators (1% of CC ?)

GW detection will give unique information about the mechanism that produces the explosion and the formation of the compact object.

https://wiki.ligo.org/LSC/2017SupernovaeWorkshop

Multi-messenger of CC-SN

Nakamura et al. 2016   MNRAS 461, 3



The most frequent SN typeare from slow rotating core collapse producing ordinary NS (eg. 1987A)

For galactic SNe we can expect coincident neutrino detections

EM signal is expected even for distant galaxies with delay of few hours / few days

- Different probes need to fit in a coherent physical interpretation
- Crucial for detection / confirmation

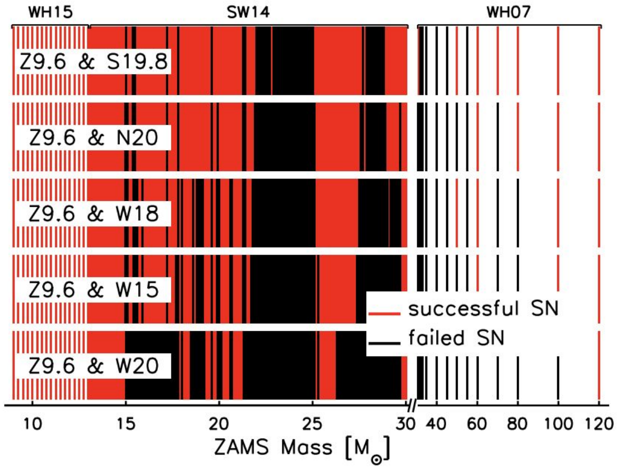
Link to Div 4 and 5

Failed SNe / Unnovae

Predicted by core collapse models
Many uncertainties in the modelling

Not yet conclusive observational evidence

Kresse et al. 2021 ApJ 909, 169



"Landscapes of explodability" for our five different engine models

eg. Adams et al. 2017 MNRAS 469, 1445, Neustadt et al. 2021 arXiv210403318N

1 candidate in 11 yr monitoring of 27 galaxies

If accepted, fraction of failed SNe f=0.16 (range 0 - 0.4 of CC)

Magnetars

NS with strong magnetic field (10^{13} - 10^{15} Gauss)

Transient hard-X and soft-gamma ray emission

Short bursts: 10^{39} - 10^{41} erg/s for 0.1 -1 s
Outbursts: 10^{41} - 10^{43} erg/s for 1 - 40 s
Giant Flares: 10^{44} - 10^{47} erg/s for ~ 0.1 s

Anomalous X-ray Pulsars (AXP)
Soft Gamma-ray Repeaters (SGR)

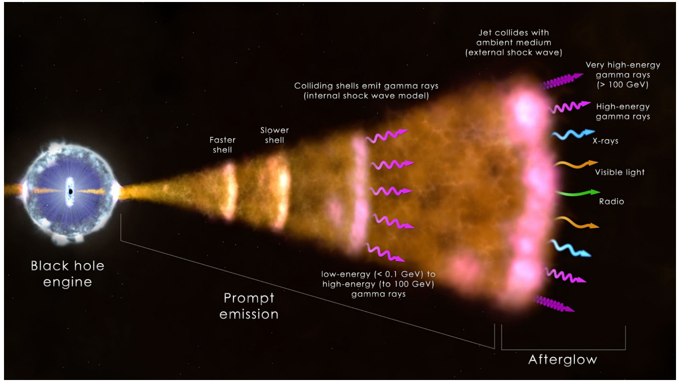
Magnetic flares are likely accompanied by star oscillation and hence GW emission …
…. giant flares are rare ~ 1/100 yr per magnetar
2 dozen known Galactic magnetars

Likely formed by core collapse of rapidly rotating stars

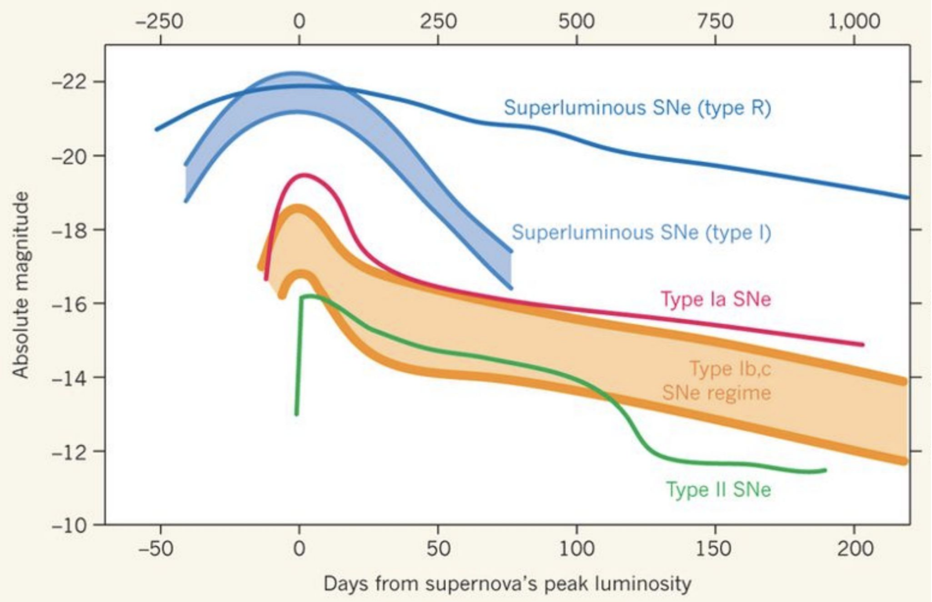
Long GRB / SLSN

LGRB are associate to highly energetic SN Ic (Hypernovae)

Long GRB are linked to the core collapse of rapidly rotating massive stars to a black hole or a magnetar.
MacFadyen & Woosley 1999

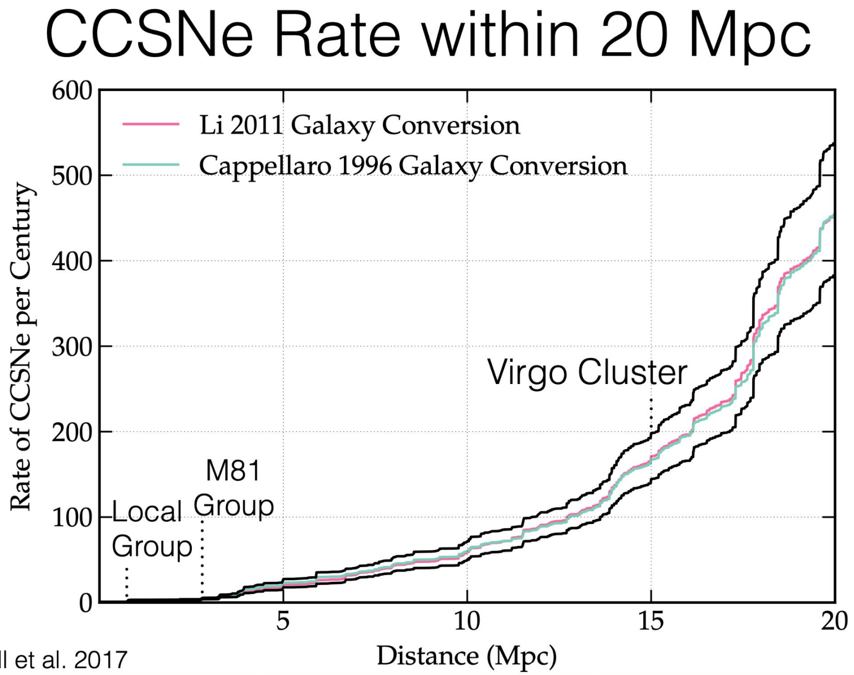


Gal-Yam 2012 Science 337, 927



SLSN luminosity likely powered by magnetar

CC SN rate



Gill et al. 2017

Core collapse /century in the Milky Way

3.2 [-2.6,+7.3] Adams et al. 2013

ApJ 778, 164

1.6+/-0.5 Rozwadowska et al. 2021

NewA 2021.8301498

Local Universe

1 CC/yr in 10-15 Mpc

SNe / Magnetar connection

SNIc-BL are 1% of CC-SNe *Li et al. 2011*

LGRB 1 - 1/40 SNIc-BL (beaming 10-100) *Guetta & Della Valle 2016, Graham & Schady 2016*

SLSN ~ 1/1000 CC *Quimby et al. 2013*

> 99% of core collapse SNe do not show sign of magnetar

The statistics in the Galaxy seems to require that 40% of NS are born as magnetars *Beniamini et al. 2019 MNRAS 487, 1426*

A problem or an opportunity ?

Statistics of potential GW sources

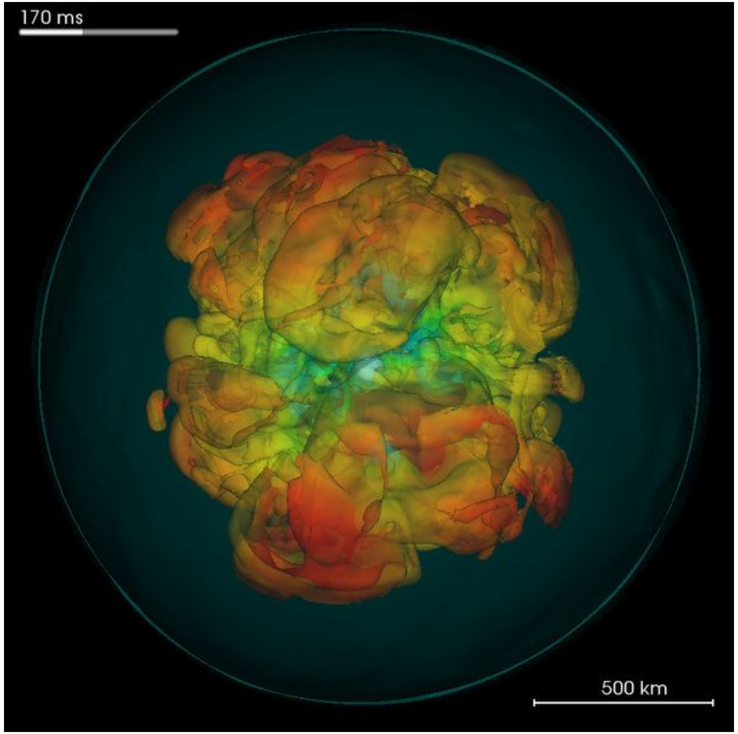
Goal 1: Estimate event rates as a function of distance for CCSNe

- **Local universe non homogeneous**: number of events do not increase linearly with observed volume.
- Dependence for **different populations and environments** (e.g. metallicity).
- **Neutrino-driven explosions** vs **magnetorotational explosions** (LGRB/hypernovae - SLSN) vs **progenitors of magnetars** vs **unnovae.**

Goal 2: Estimate event rates for magnetar / NS transient events

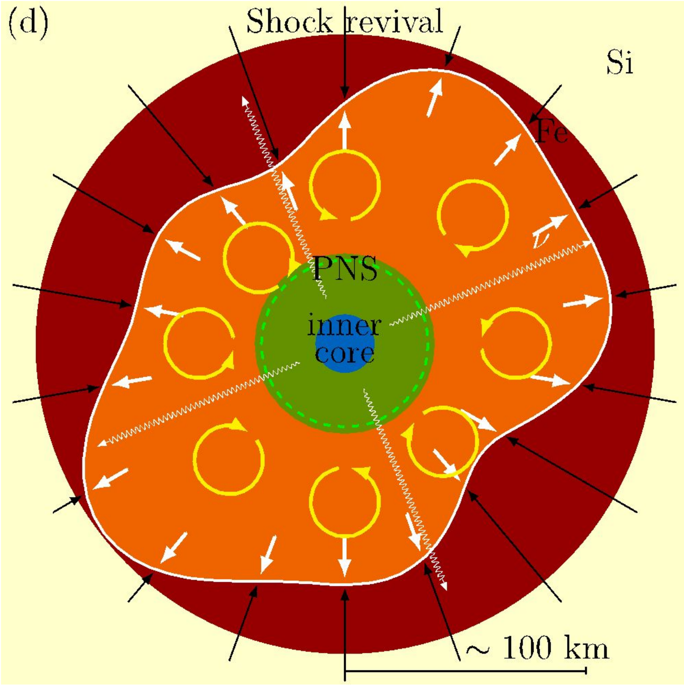
Link with Div. 3 - Population studies

GW source modelling



Collapse of massive stars - neutrino-driven explosions

- Collapse of iron cores in massive stars (~8-100 M_{sun})
- **Slow rotating progenitors** (~99%)
- **Neutrino-driven mechanism**
  - Iron core collapse
  - Hot accreating proto-neutron star + stalled shock
  - ~10^{53} erg emitted in neutrinos ➔ post-shock energy deposition
  - ~10^{51} erg Supernova explosions or BH formation (unnovae)



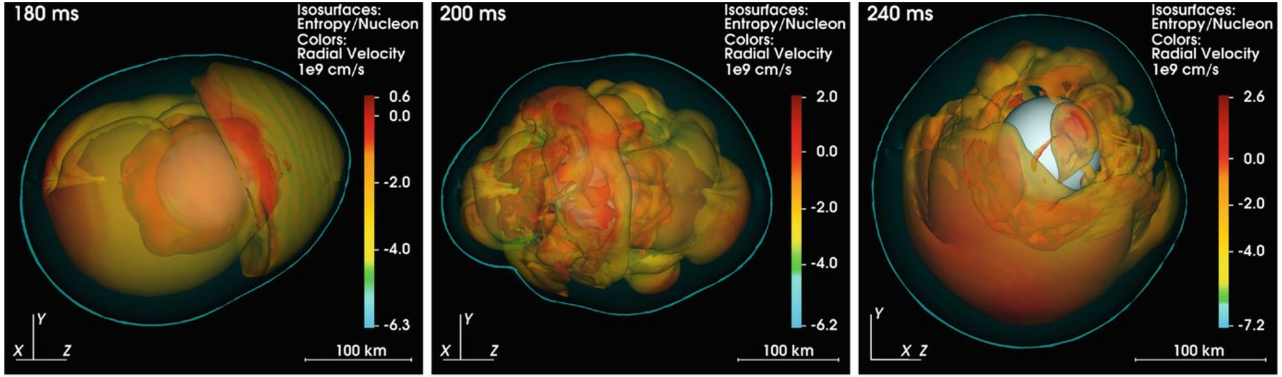
Cerdá-Durán & Elias-Rosa 2018

Review papers:
CCSNe: Janka 2007, 2012, 2017, Burrows 2013, Kotake 2016, Müller 2020
Neutrinos: Janka 2017, Müller 2019
GWs: Kotake 2013, 2017

Collapse of massive stars - neutrino-driven explosions

Uncertainties and challenges

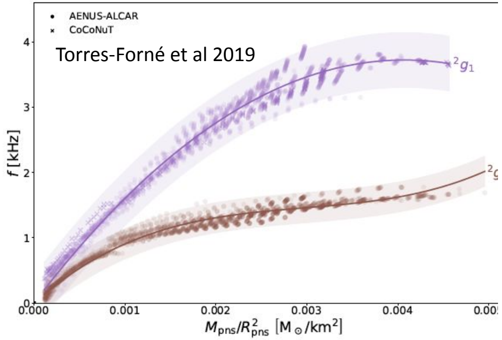
- **Stellar evolution models**
  - Dependence on mass, rotation, metallicity and binarity
  - Rotation and magnetic fields (multi-D effects)
  - Binaries: mass transfer and envelope stripping
  - Stellar winds and metallicity dependence
  - Models for convection
  - Multi-D structure due to convective burning shells
- **3D CCSN simulations**
  - Still discrepancies between groups (no gold standard)
  - Most simulations in the verge between explosion or BH formation (physical reality?)
  - Missing ingredients? (neutrino reaction corrections, pre-SN perturbations, turbulence, slow rotation)
  - Numerical effects (grid resolution, spherical vs Cartesian coordinates, discretization methods)

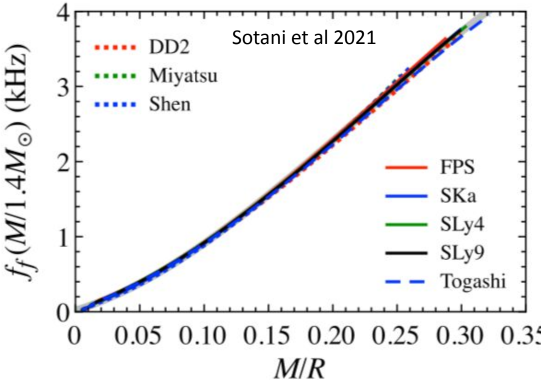


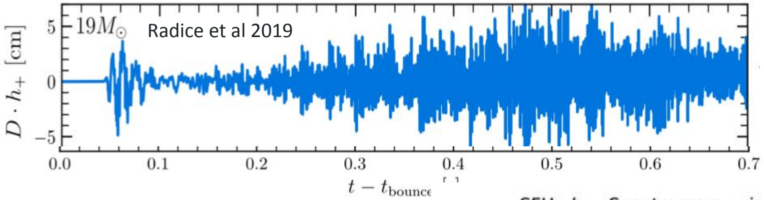
Melson et al 2015

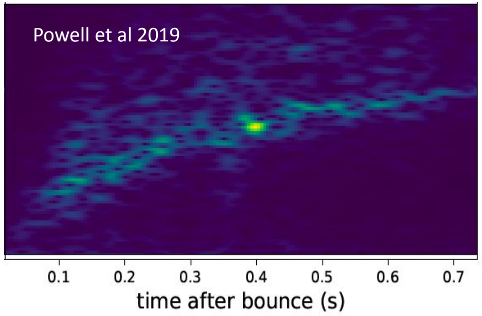
Collapse of massive stars - neutrino-driven explosions

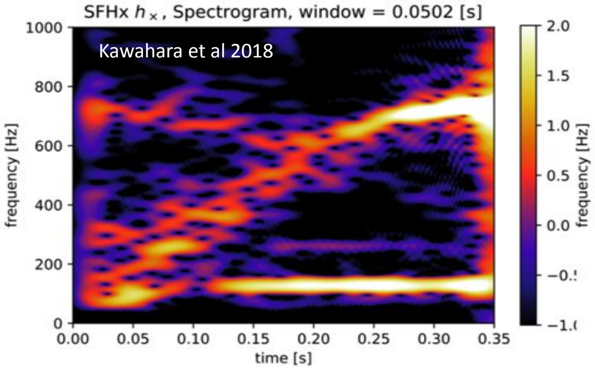
- **GW emission mechanism**: Perturbations induced on the proto-neutron
- **Highly stochastic**
- **Main features**:
  - **g/f-modes**
  - **SASI**









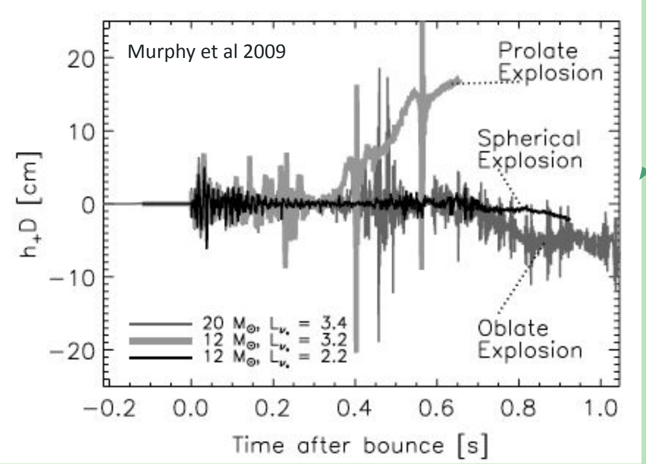


- **Universal relations** between g/f-mode frequencies and PNS properties
  ➜ Asteroseismology possible

- **Challenges**
  - Theoretical understanding of modes
  - Universality in 3D simulations
  - Universal relations for other modes (SASI ...)

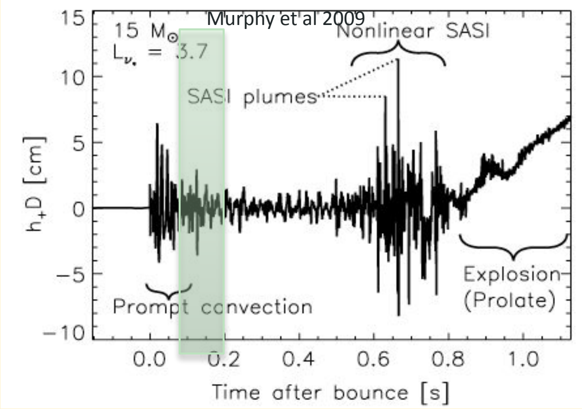
Collapse of massive stars - neutrino-driven explosions

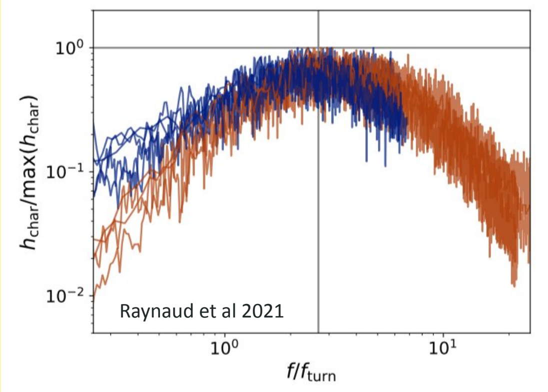
Secondary features:



GW memory (1-10 Hz)

Prompt convection (50-100 Hz)

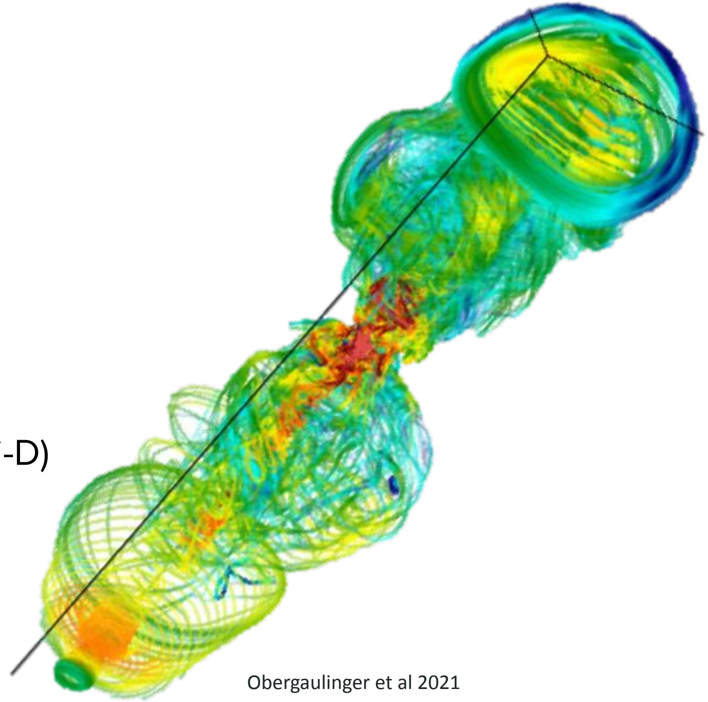




Long-term (10-50 s) PNS convection (100 -1000 Hz)

Collapse of massive stars - magnetorrotational explosions

- **Fast rotating progenitors** (~1%)
- Rapid magnetic field amplification (MRI, dynamos)
- Magneto-rotational explosions ➔ more energetic
- Linked to long GRB and hypernovae



Obergaulinger et al 2021

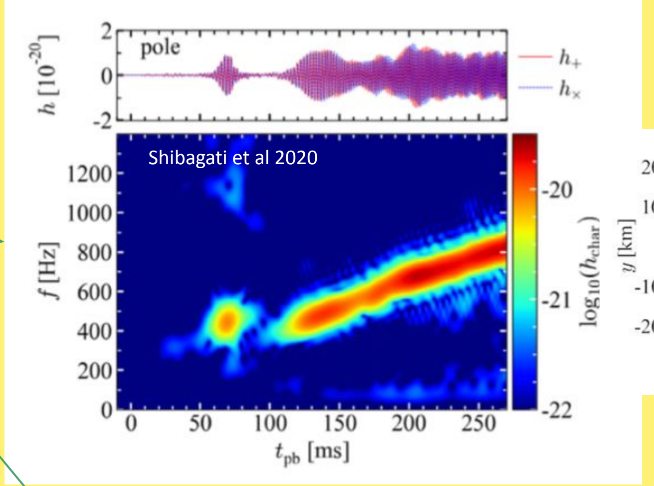
Uncertainties and challenges

- Stellar evolution with rotation and magnetic fields (multi-D)
- MRI, turbulence and dynamos ➔ numerical resolution!!
- Conditions for jet formation
- Origin of magnetars

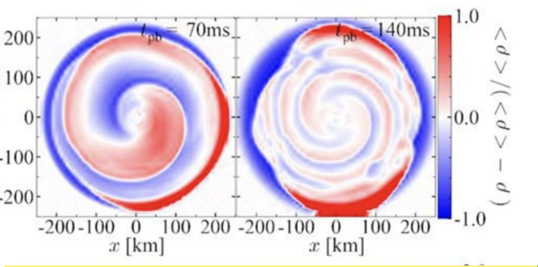
Collapse of massive stars - magnetorrotational explosions

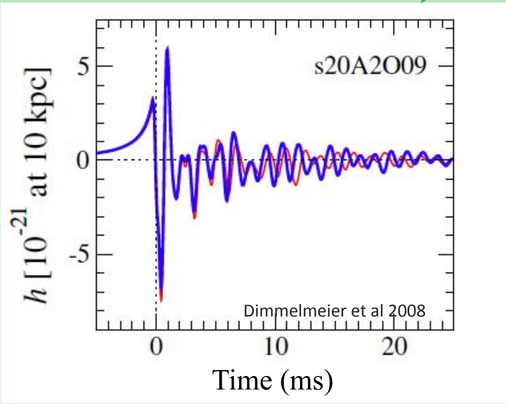
Gravitational waves:

- Same sources as neutrino-driven explosions (~strain x 10)
- Additional features:



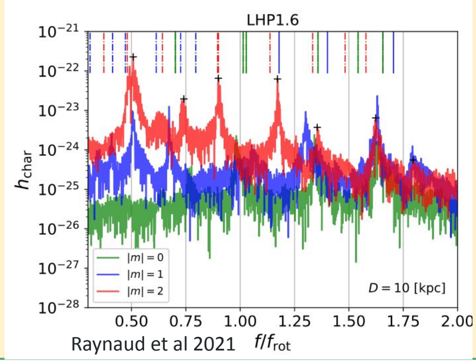
Bar-mode instability (400-1000 Hz)



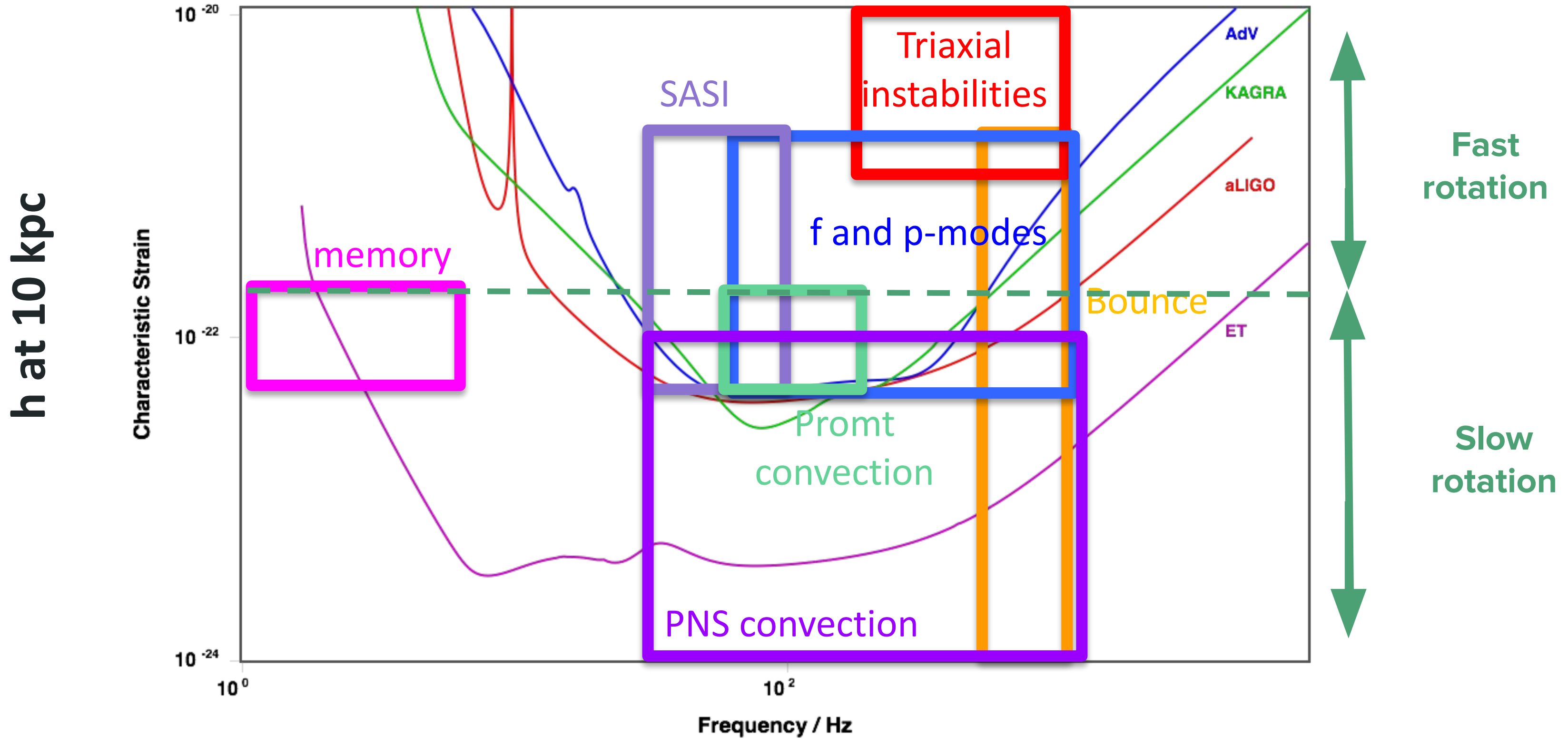


Bounce signal (600-800 Hz) (frequency and amplitude related to PNS properties)

Inertial modes in the long term evolution (10-50 s)



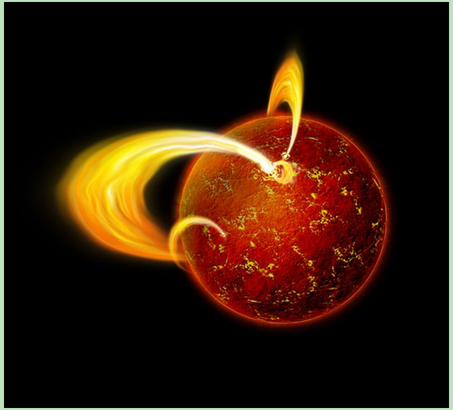
Collapse of massive stars - GW summary



Magnetars

Bursts (10^{36}-10^{43}erg/s) **& Giant flares** (10^{44}-10^{47} erg/s)

- Crust-quake or magnetospheric instabilities
- Torsional modes excited (QPOs, no GWs)
- Excitation of f-modes?
- Theoretical models (Levin & van Hoven 2011, Zink et al 2012, Ciolfi & Rezzolla 2012): **efficiency ~10^{-10} - 10^{-6}**
- **Many uncertainties**



Transients in newborn millisecond magnetars

- BNS mergers and CCSNe
- Spin-flip, bar-mode and r-mode instabilities

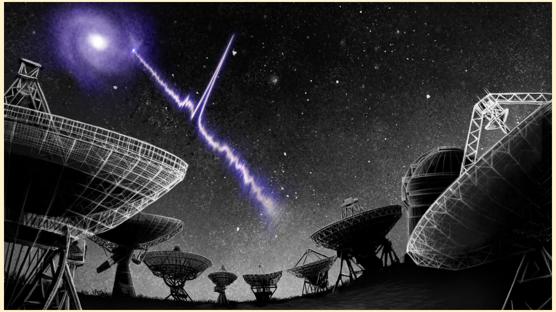
(Dall'Osso et al 2018, 2021, Sarin & Lasky 2021)

- Horizon distances of order 10 Mpc for ET

FRBs and neutron star glitches

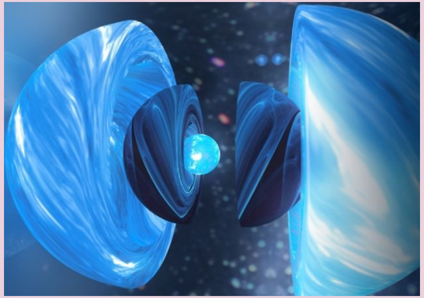
Fast Radio Bursts (FRBs)

- Bursts of coherent radio emission (~ 1 ms)
- Some repeaters
- Possible recent observation of a FRB from a magnetar
- Theoretical models:
  - Close magnetosphere (Katz 2016, Lu et al 2020
  - Shock- deceleration (Beloborodov 2017, Metzger et al 2019)
- GWs? (same uncertainties as magnetar flares)



Neutron star glitches

- Sudden readjustment of a spin-down lag between the superfluid core and the crust (see e.g. Haskell & Melatos 2015)
- Model depends on complex physics (superfluidity, vortex pinning ...)
- Gravitational waves emission:
  - Superfluid vortex avalanches (Warszawski & Melatos 2012): h $\sim 10^{-25}$ at 10 kpc
  - Coupling to f-modes (Ho et al 2020)
- h$\sim 10^{-24}$ - 10^{-25} at 10 kpc



GW source modelling - goals

Goal 1: collect available waveforms (catalogues)

Goal 2: rank waveforms in terms of physical realism / identify uncertainties

Goal 3: identify universal relations for inference ↔ div. 6: Nuclear physics

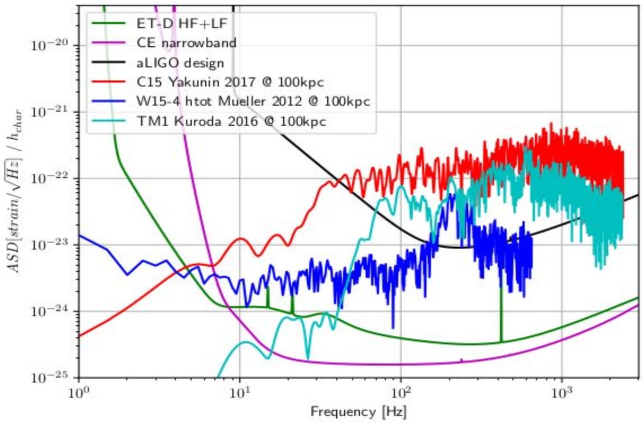
Examples:

- CCSN: Scarcity of waveforms from 3D simulations
- Magnetars/FRBs: Very few studies, with very different results.

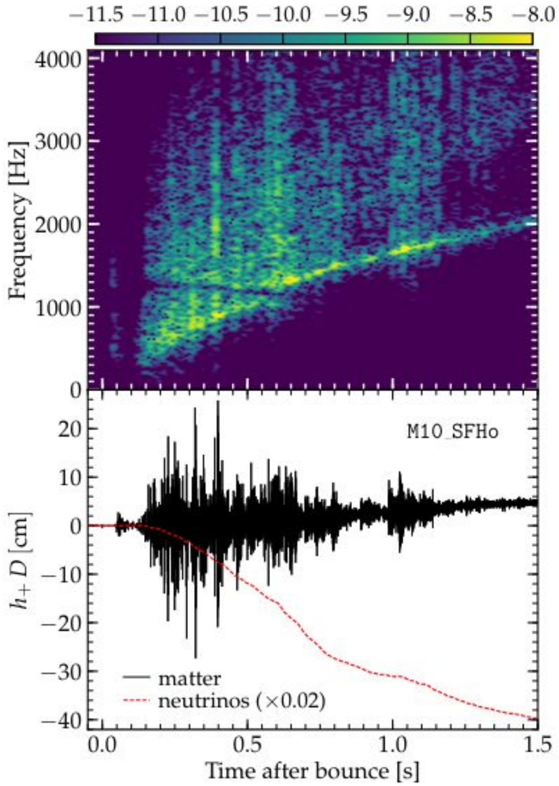
GW detection

Goal 1: Development of dedicated detection pipelines

- **Template-based searches not possible**.
- Current burst **methods too generic** given the complexity of the waveform.
- CCSN signals are broadband: use of ET large band sensitivity.



Kalogera et al, 2019



Morozova et al, 2018

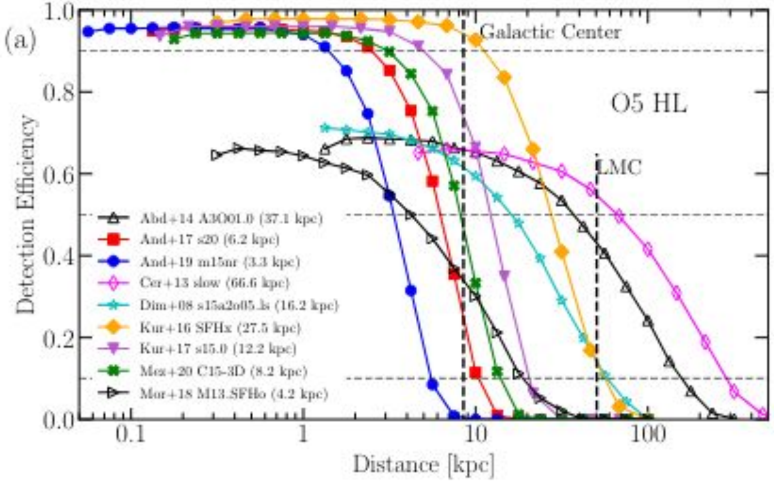
GW detection

Goal 1: Development of dedicated detection pipelines

- Use **properties of sources** (e.g bounce, raising g-modes, SASI in CCSNe).
- Assume known sky position?
- Machine learning algorithms?
- Needs **coordination with div. 10** (data analysis)

➜ room for improvement: we need to stimulate the development of improved detection techniques.

Coherent waveburst detection capability for LIGO @ design sensitivity



Szczepanczyk et al, 2021

GW detection

Goal 2: Development of detection strategies triggered by other multimessenger observations (neutrinos, EM)

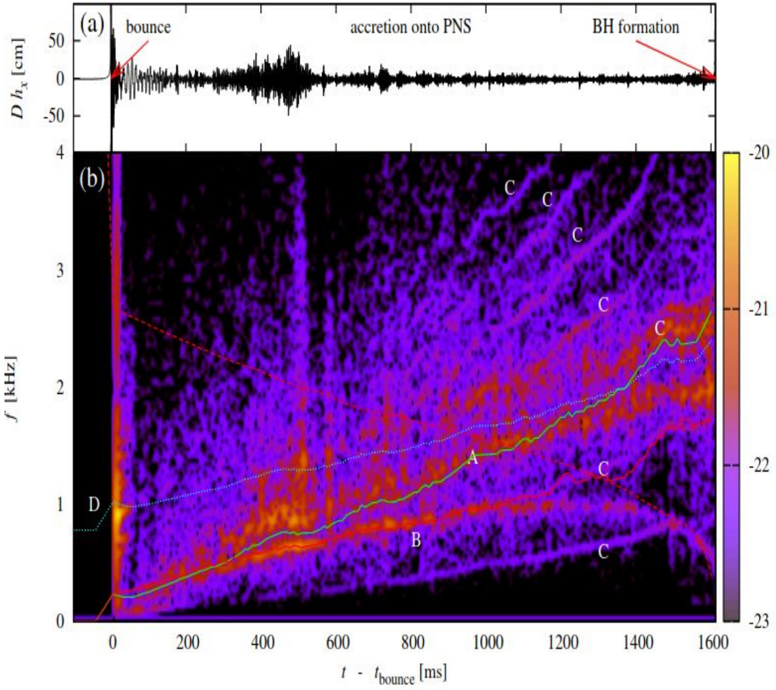
- CCSN
  - Neutrinos detectors (SuperK/hyperK/DUNE/IceCube/KM3net …): real time neutrino monitors : larger horizon than GW detectors? Better sky position accuracy (<5deg)
  - Joint GW/neutrino searches : increase significance (ex: Halim et al 2021)
  - Search for neutrino modulation of GW signal?
- Magnetars / pulsar glitches
  - Observational data are crucial to develop targeted pipelines digging into the noise. Ex: GW signal frequency might be related to QPO in magnetar giant flares
  - Galactic pulsar data
- Needs **coordination with div. 4** (multimessenger observations) and **div. 5** (synergies other GW observatories)

Inference

Goal 3: What can we infer from the source for a GW event from CCSN?

- **Properties** of the progenitor: mass, rotation of the core (β=T/|W|), ...
- **Properties** of the inner structure or the progenitor star, PNS, schock radius
- **Constraints on the EOS** of nuclear matter at high temperatures.
- Explosion mechanism (υ-driven, MHD, SASI, ...)

Cerda-Duran et al 2018

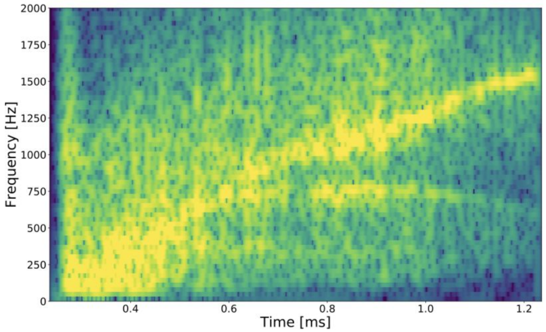


Inference

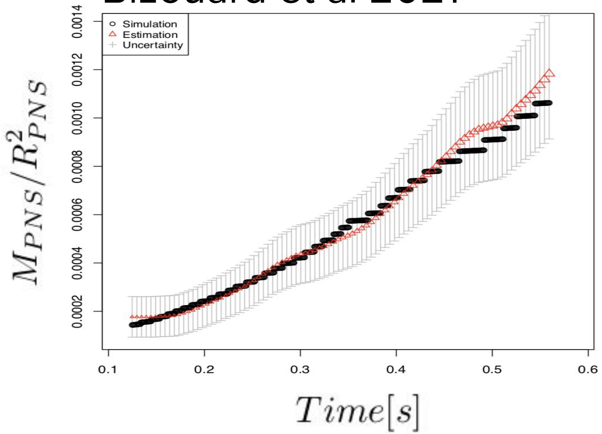
Goal 3: How can we infer information form CCSN?

- Waveform “agnostic” reconstruction
- Methods based on waveforms catalog (Template Bank, Principal Component Analysis, Neural network)
    - **Classification** (which explosion mechanism, glitch vs GW,...)
    - **Extract physical parameters** (core rotation, progenitor mass, EOS, etc)
- Other methods: PNS asteroseismology, ...
    - **Extract time evolution of the physical parameters** (MPNS, RPNS, RSchock, ...) using universal relations for PNS oscillation modes (Torres-Forne et al, 2018)
- Needs for waveforms & coordination with **div. 10**

Torres-Forne et al 2018



Bizouard et al 2021



Summary & challenges

- Many challenges
  - More accurate modelling and more observations will drive GW data analysis developments
  - Population studies (rates, properties, …)
- Many interfaces:
  - EM/neutrino observations
  - Nuclear matter
  - Numerical simulation / waveforms
  - Data analysis techniques R&D
- Organisation:
  - Make sure experts include "ET case" in their performance studies → need to know ET configuration.
  - Continue to contact experts in each domain (modelling, signal detection/extraction and joint observations)
  - Regular meetings & workshops