Big Questions in Astrophysics

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Plan of Talk

- Learning from ~10-1000 Hz gravitational waves
- I will set the stage for several topics (dense matter, dark matter, H_0, dark energy, BH populations) that will be discussed more fully by others
- I will also talk about what we could learn if we luck into a Galactic supernova!

Part 1: Neutron stars, dense matter

See also the talks by Bose and Siegel
and the panel with Mukherjee and Kashyap

Why Study Neutron Stars?

Frontiers in particle, nuclear, condensed matter, plasma, hydro, QED, and general relativity

Core composition is unknown:
Nucleons?
Hyperons?
Quark matter?
Phase transitions?

Let's dive into NS!

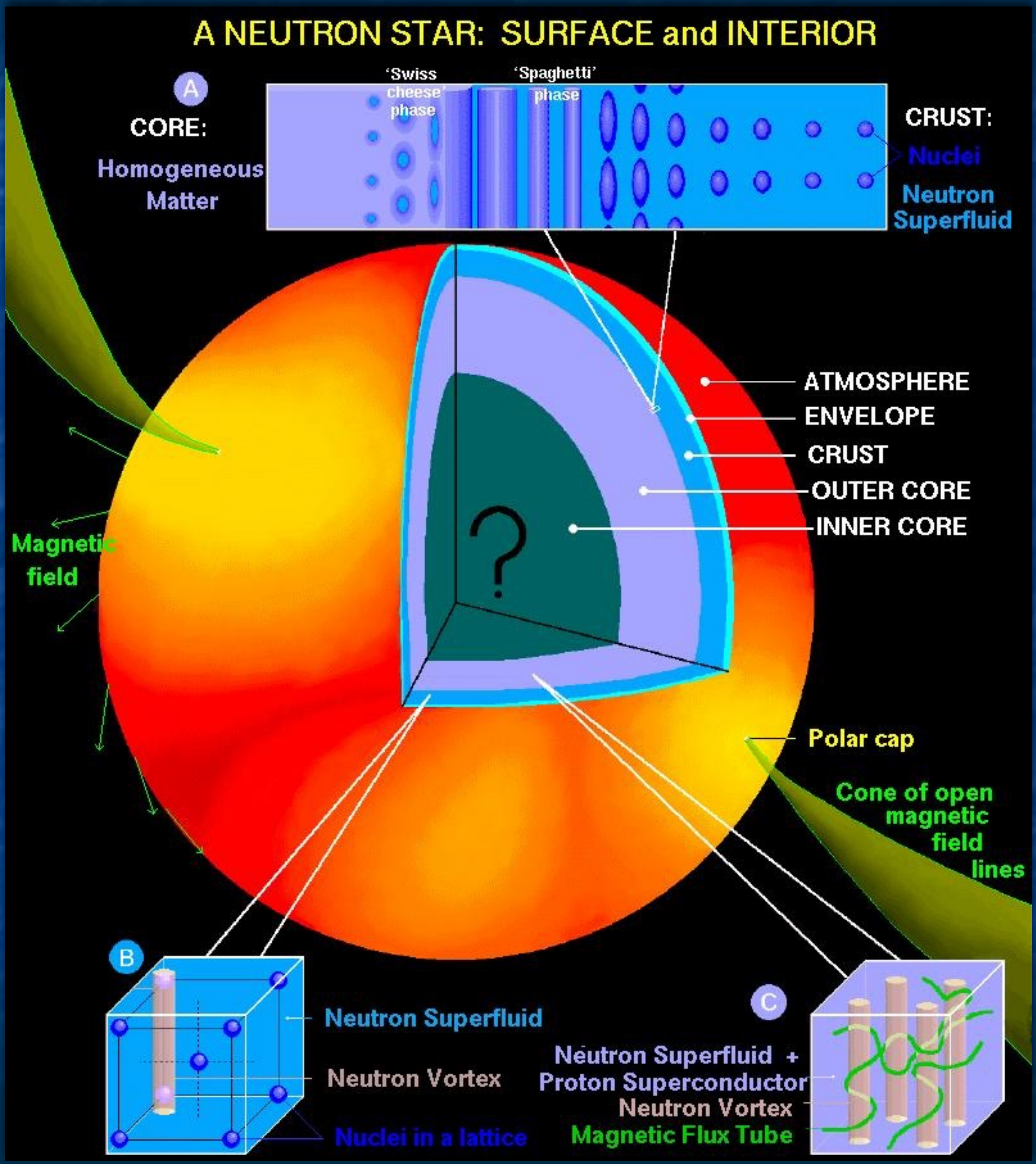


Figure: Dany Page

http://www.astroscu.unam.mx/neutrones/NS-picture/NStar/NStar-I.gif

EOS vs. Composition

- There is excitement about the *composition* of NS core matter...but most things we can observe depend only on the equation of state, $P(\varepsilon)$
- We will thus mainly discuss observations that relate only to the EOS
- With everything: please be an informed consumer! These are mostly indirect measurements, so you have to know what assumptions are being made

Non-GW Information

- Some nuclear theory (e.g., chiral EFT; perturbative QCD less likely to help)
- High masses of some neutron stars
- NICER measurements of radius
- Future: moment of inertia of PSR J0737-3039A

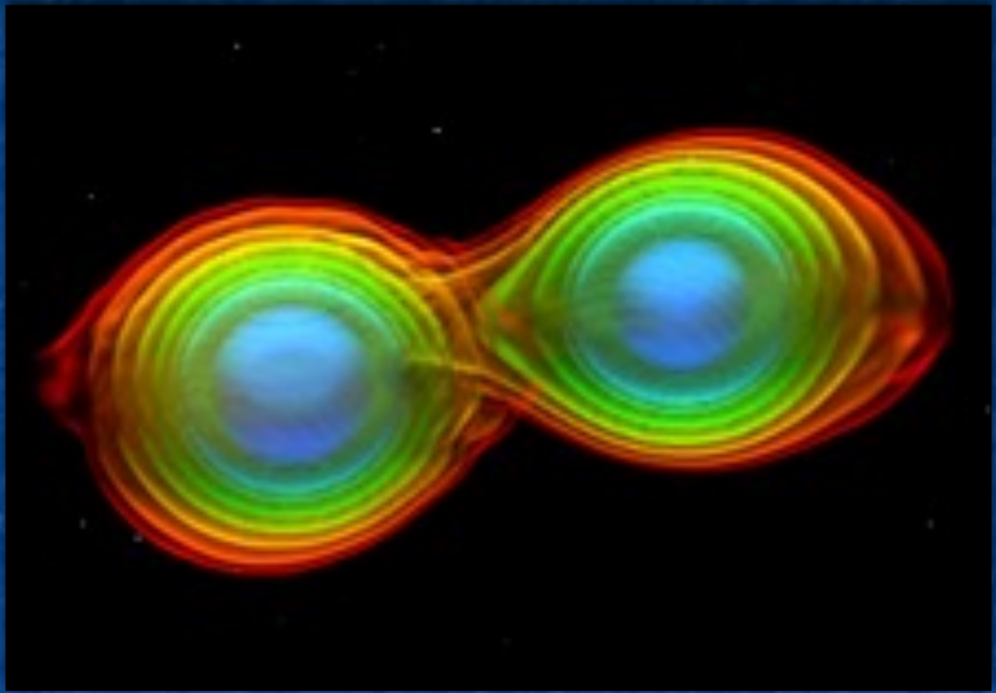
Gravitational Waves and NS

- GW come from mass motions, so bulk of NS is involved
- GW can tell us about cold matter (NS pre-merger) or hot (post-merger, SN)
- Various quantities matter for different GW observations; all depend on the EOS, so this gives us self-consistency checks

Both images from Wikipedia

NS tides from GW

- Tides take energy from orbit
  Changes waveform
- A bigger NS will be deformed more
- Thus measurement of tidal deformability Λ gives insight into structure
- For GW170817, no clear evidence for deformation
  Suggests $R_{1.4}$<13.5 km
  Eliminates hardest EOS



Simulation: T. Dietrich et al. (Albert Einstein Institute)

Information from pre-, post-merger oscillations?

Part 2: Dark matter

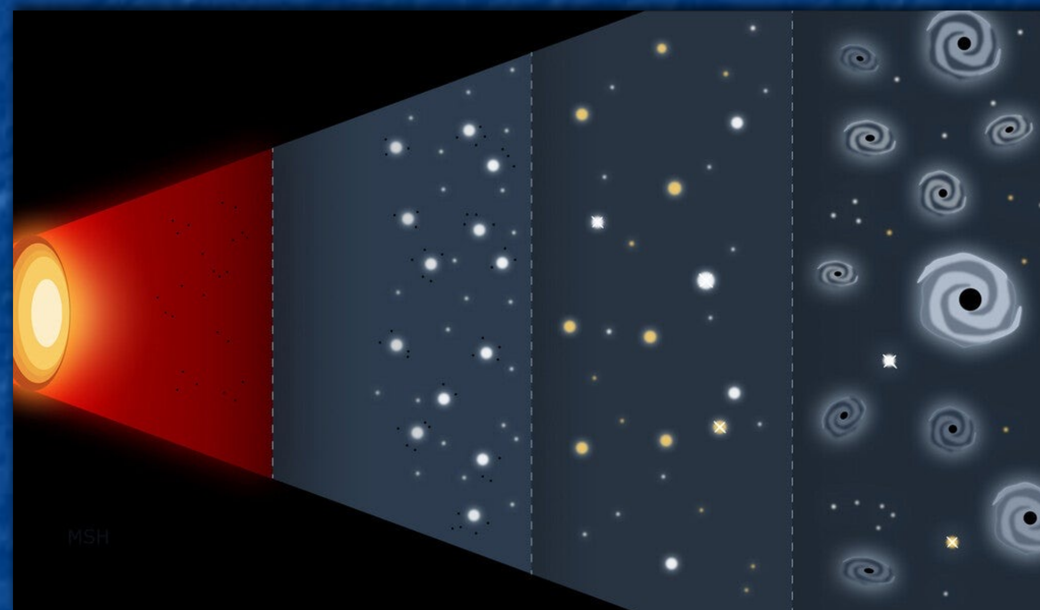
See also the talks by Dasgupta, Miller, and Suyama and panel including Mukherjee and Kashyap

Dark Matter

- Observations require cold (at least not hot) dark matter or non-Newtonian gravity
- Most think it is dark matter
- But no candidate has been confirmed

PBH as Dark Matter

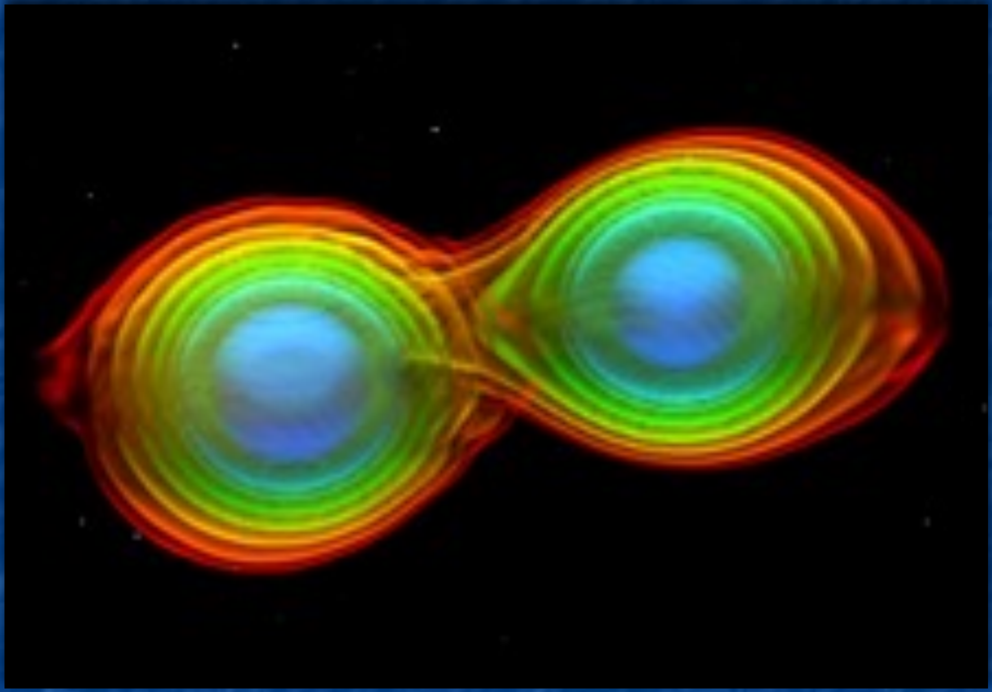
- Primordial black holes would be CDM
- Need to form before BBN (so <<1 sec)
- Possibilities run over the whole mass range; only asteroid-mass could be all of DM
- But GW observations of $M<0.5\ M_{sun}$ compact objects would be definitive



Yale illustration

Clouds of DM: Tides

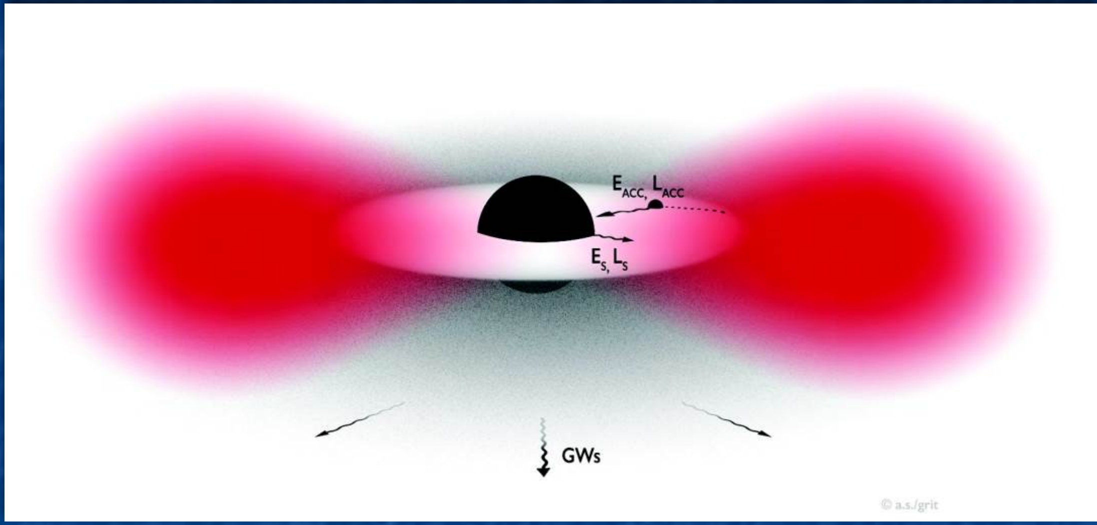
- When mass contracts or collapses, DM can be pulled in
- Produces enhanced density around BH
- Responds tidally; could change GW waveform



Tim Dietrich

Superradiance

- For a class of very light DM particles (axion-like particles, ALPs), for BH of a matching mass, the BH spin energy goes into the cloud of ALPs, and the BH spins down
- Evidence would be low spin in some mass range
- But need to decouple from formation mechanisms



Classical and Quantum Gravity

Part 3: Cosmography, Dark energy

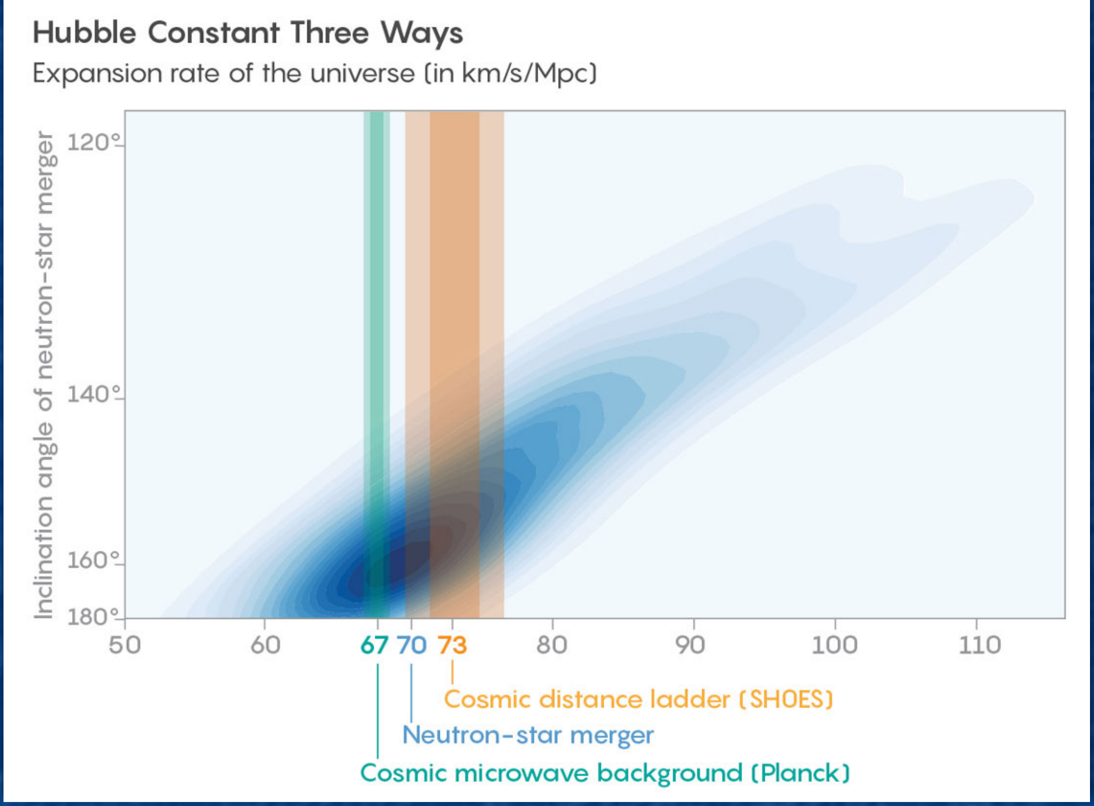
See also the talks by Roy Chowdhary and Ghosh, and panel with Adhikari and Jana

Cosmography

- The measurement of the universe has given us some of the most profound revelations in the history of science
- How can black holes help?
- We will talk about two possibilities:
  1. Measurement of the Hubble parameter
  2. Characterization of dark energy

Hubble Parameter

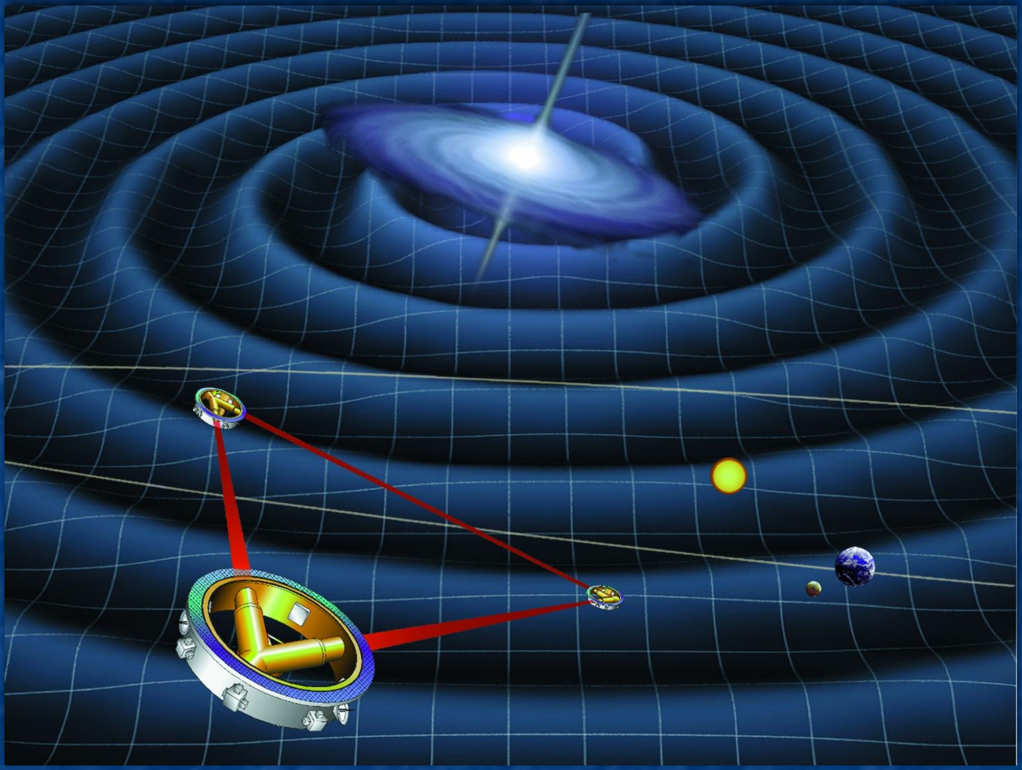
- Speed vs. distance
- Tension in methods?
- From GW, best is if there is EM as well
  BH-NS
- But even without, can use BH-BH combined with structure
- If tension, could lead to major new physics



Quanta magazine

Dark Energy

- Need more precise and distant measurements
- Prime method: SNe Ia
- But EM + LISA(-like) GW would be critical ***if*** host is identified
  Alternatively, next-gen ground-based GW
- Weak lensing?



LISA, from Wikipedia

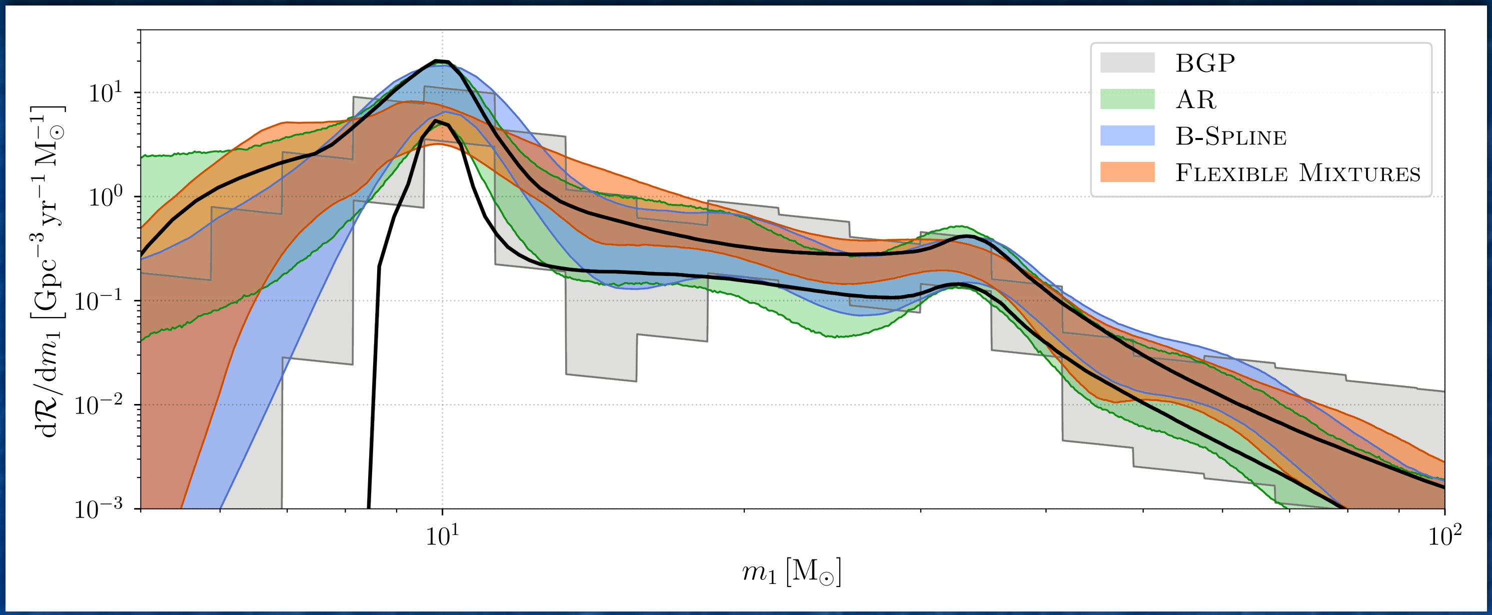
Part 4: Black hole populations

See also the talks by Chatterjee and Vijaykumar, and panel with Hannuksela, Misra, and Resmi

Where we stand, 2025

- ~200 announced LVK BH-BH events
- And yet there is still no clarity about what formation mechanism is most important
- Why? As events have rolled in, people have become more creative
- Worse to be falsified than unfalsifiable!
- How can we actually understand more?

Mass gaps?



LVK O4a

- Still debatable. Gap between NS, BH may not exist. If it does, we learn about CC SN and formation.
- Upper mass gap should exist for isolated binaries; if it is there then isolated channel could be dominant
  Details depend on, e.g., $^{12}C(\alpha,\gamma)^{16}O$ rate; nuc. phys?

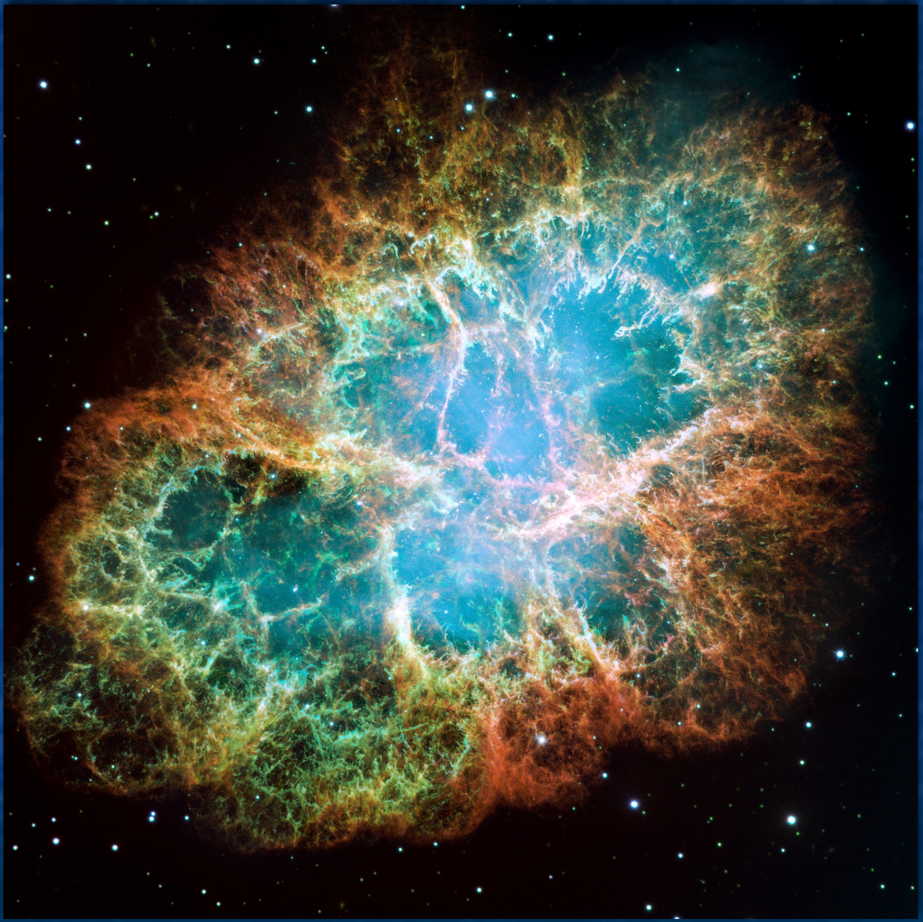
Part 5: Supernovae

See also the talk by Bhalerao

Background on Supernovae

- Core collapse of massive star at roughly M_{Ch}
- Collapse, neutronization, neutrino trapping, core bounce, shock that stalls and is revived... 3D, GR, turbulent, requiring neutrino transport of all 3 species
- Fantastically complicated... and clearly multimessenger

Crab Nebula: Wikipedia



Dense matter from SN EM?

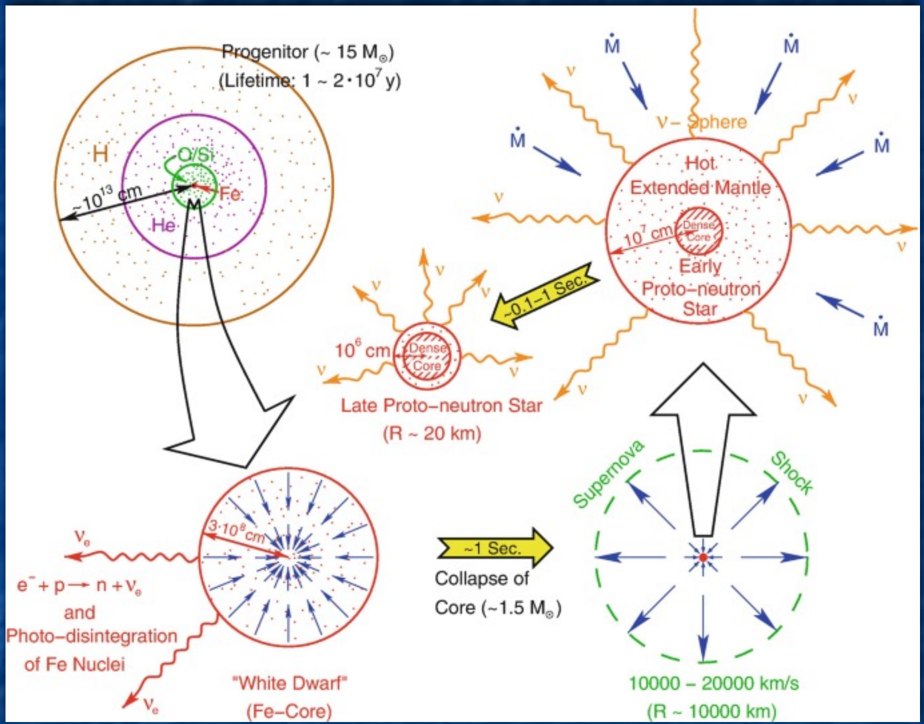
- Not much unambiguous info?
- EM carries only a small fraction of the total energy (~10^{51} ergs kinetic, less in prompt photons)
- EM is also delayed by minutes to hours from collapse, reducing information
- Perhaps a point of discussion? What can we learn?

Dense matter from SN neutrinos

- The SN has to be close; SN 1987A (d=50 kpc) gave us 19 neutrinos. Super-K is ~100x the volume, but still even at M31 we'd only have ~10 neutrinos.
- Let's be optimists: in Milky Way, <10 kpc! Then, ~10^5 neutrinos in Super-K, 0.4 nsec time resolution
- What could we learn?

SN neutrinos, part 2

Janka 2017



- Three phases of ν emission:
  Initial p+e → n+ν
  Shock releases trapped n
  Thermalized ν diffuse out
- Each tells us something different; the last will probably be the most informative about dense matter

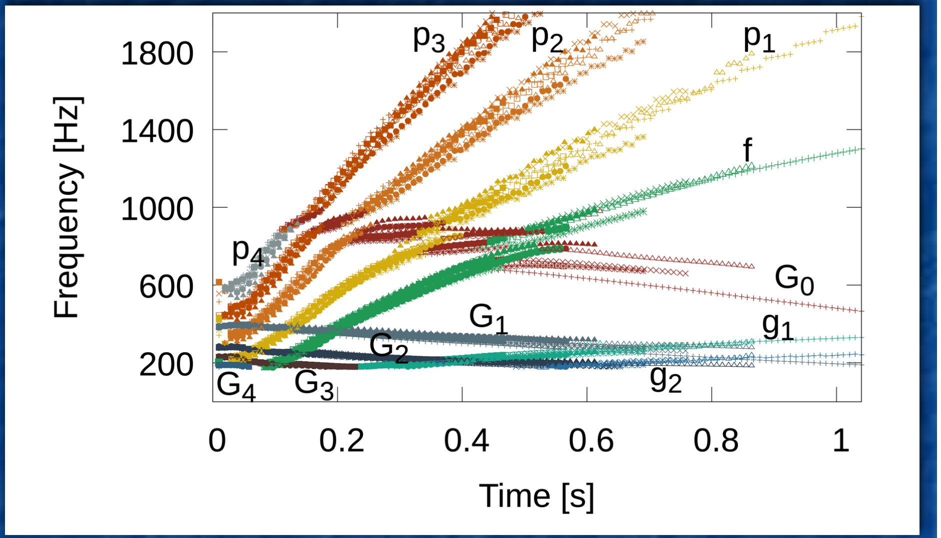
Dense matter from SN GW

- If spherically symmetric, no GW
- Initial (late 1980s) hopes were for large asymmetry, but now we think only ~10^{-10} to 10^{-8} of energy emerges in GW
- Probably need SN within 2 kpc or less even for Advanced LIGO
- Betelgeuse, are you listening?
- Another possibility: hadron-quark transition

SN GW, part 2

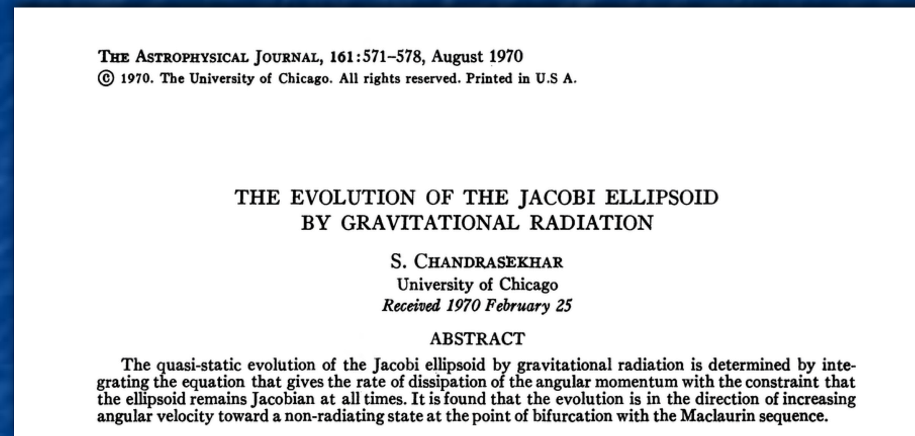
- SN sims indicate that most GW are emitted during PNS
  Mainly oscillations; g, f mode
  Affected by rotation
  Broad-band spike at bounce
- Time evol of freq can be informative about transport
- If hadron-quark transition happens, GW might be tens of times larger

Rodriguez+ 2023



GW from rapidly rotating SN?

- It is now thought that massive star cores usually don’t rotate rapidly
- But if they do, then during collapse the core could become ellipsoidal and emit a *lot* of GW!
- Evolution is uncertain; solid body or differential rotation?
- If solid-body, signal could be seen to Mpc


THE ASTROPHYSICAL JOURNAL, 161:571–578, August 1970
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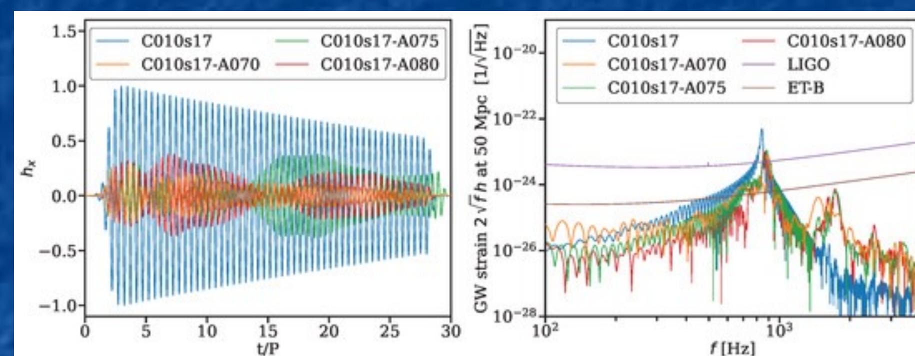
THE EVOLUTION OF THE JACOBI ELLIPSOID
BY GRAVITATIONAL RADIATION

S. CHANDRASEKHAR
University of Chicago
Received 1970 February 25

ABSTRACT

The quasi-static evolution of the Jacobi ellipsoid by gravitational radiation is determined by integrating the equation that gives the rate of dissipation of the angular momentum with the constraint that the ellipsoid remains Jacobian at all times. It is found that the evolution is in the direction of increasing angular velocity toward a non-radiating state at the point of bifurcation with the Maclaurin sequence.



Luo+ 2024

Conclusions

- GW touch on many frontier aspects of astrophysics, particle physics, and cosmology
- Which of these is most informed will depend on luck as well as on the diligence of those who construct instruments and analyze data!