Expected Science from deciHz Gravitational Waves

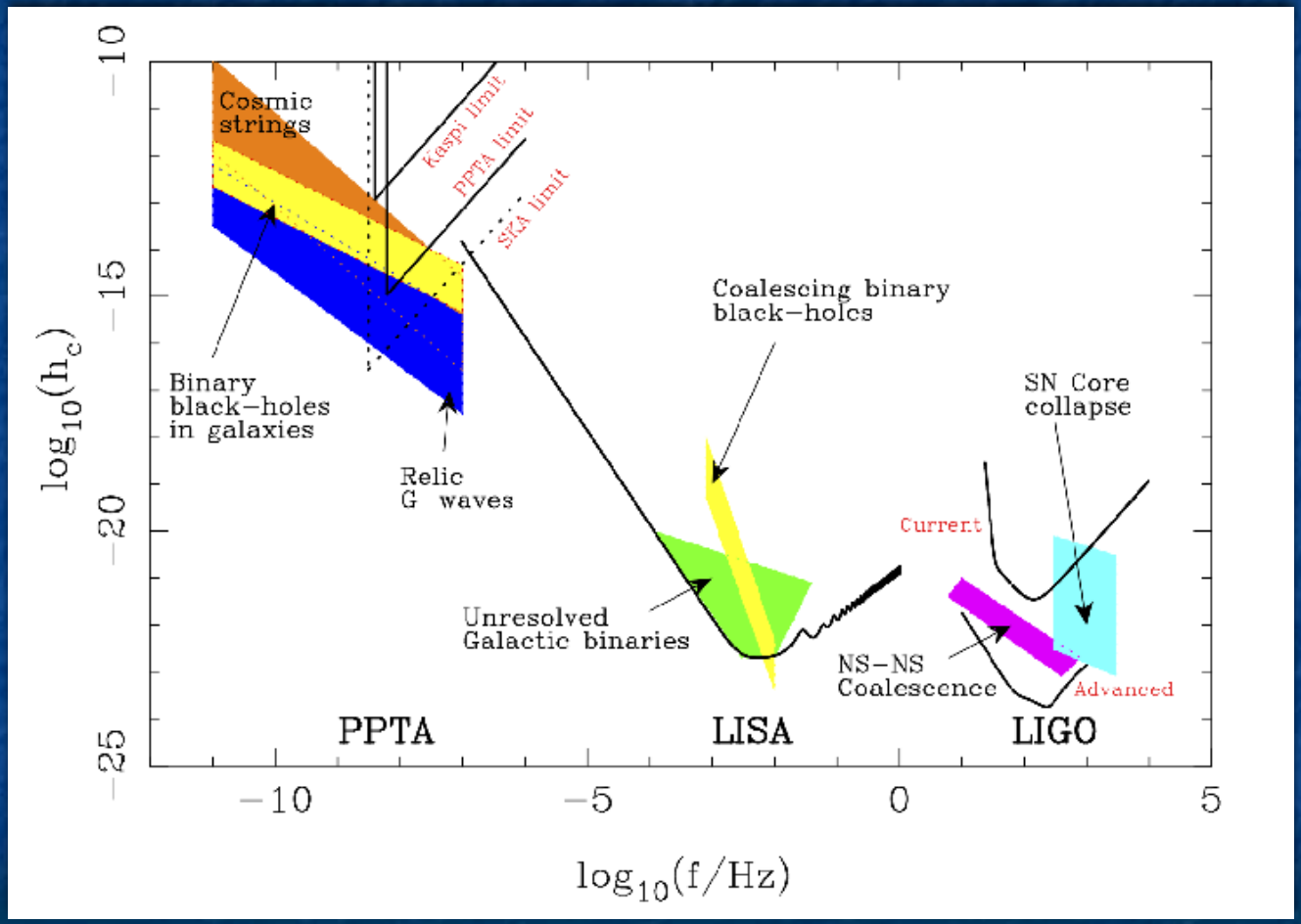
Cole Miller

University of Maryland

Plan of Talk

- I will focus on the science that we anticipate from deciHz (few x 10^{-2} to few x 10^{-1} Hz) gravitational waves, particularly science that is difficult to accomplish otherwise:
  Localization ~ 10^{-3} to 10^{-2} deg^2
  Lead time to merger: multimessenger
  BH mass range ~10^2-10^4 M_{sun}
  Eccentricity of orbits
  Environmental and -PN tests of GR
  Primordial background?
- Please ask questions at any time!

Landscape of GW



Thrane and Romano 2013

Scales and Dependences

$$T_{\rm insp} \approx 0.2\ {\rm yr} \left(\frac{\mathcal{M}}{10\ M_\odot}\right)^{-5/3} \left(\frac{f_{\rm GW}}{0.1\ {\rm Hz}}\right)^{-8/3} (1-e^2)^{7/2}$$

$$\text{where } \mathcal{M} = \eta^{3/5} M_{\rm tot},\ \eta \equiv m_1 m_2 / M_{\rm tot}^2$$

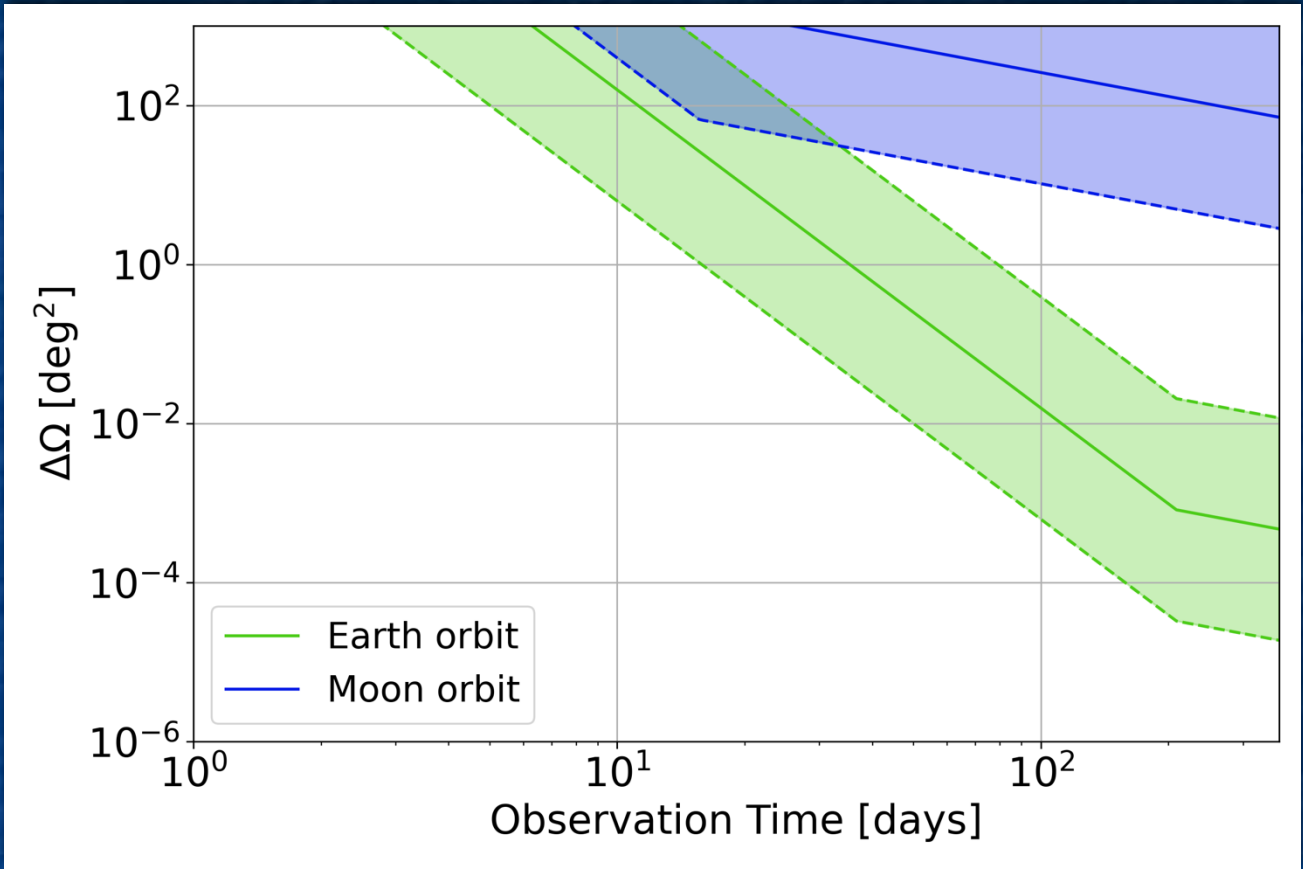
$$\text{Eccentricity } e \ll 1 \propto f^{-19/18} \approx f^{-1}$$

$$f_{\rm ISCO} \approx 0.44\ {\rm Hz}\ (M/10^4\ M_\odot)^{-1}$$

$$f_{\rm max,WD} \sim 0.01 - 1\ {\rm Hz}$$

Conclusions: deciHz (1) is favorable for follow-up, (2) is favorable for eccentricity, (3) gives access to IMBH, (4) gives access to white dwarfs

Localization



From Ajith+ 2025 LGWA white paper, but general scaling applies to other designs. Earth modulation means ~10^{-3} deg^2 in ~1 yr

Benefits of Localization

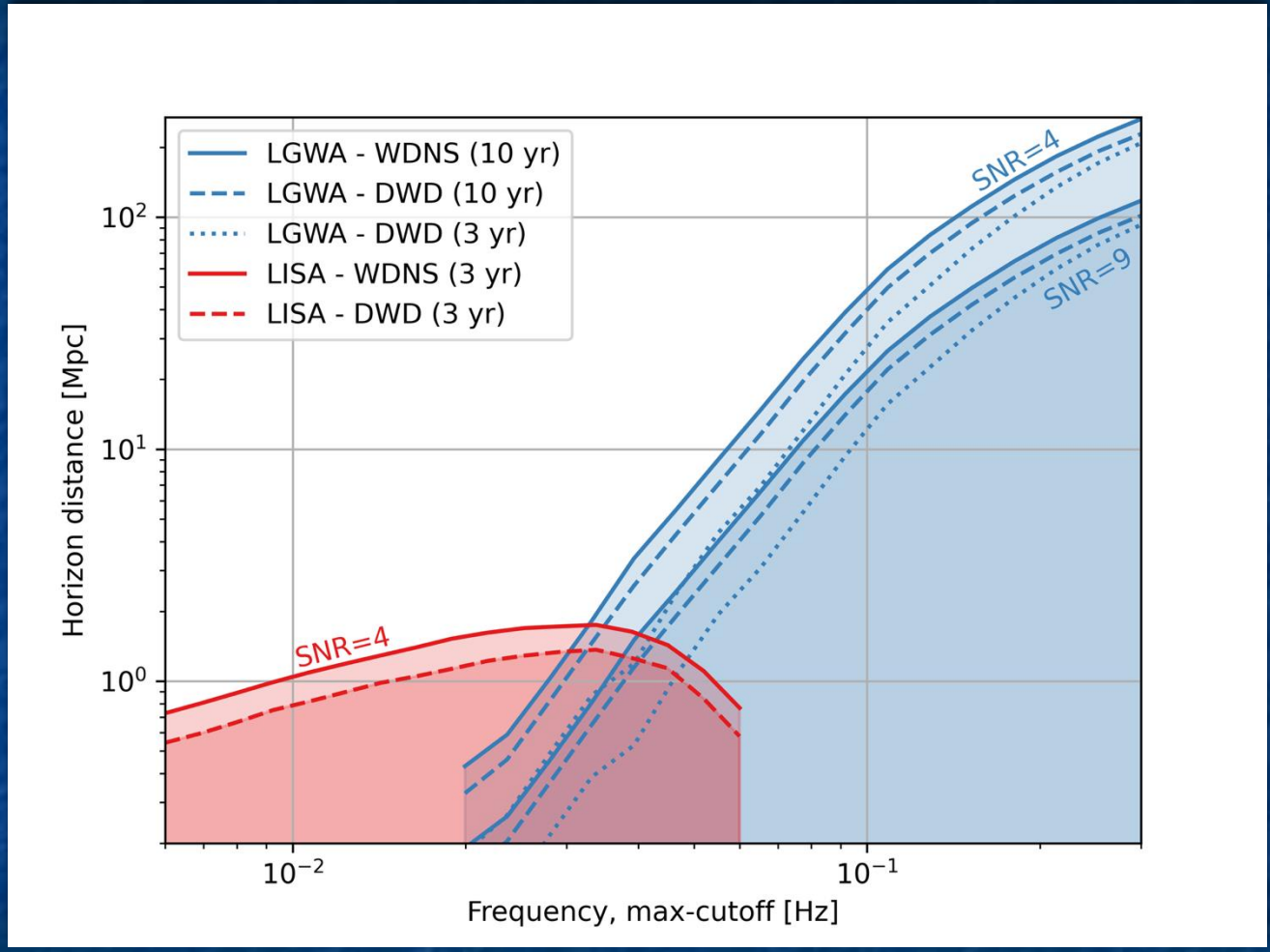
- Suppose detectability to $100 d_{100}$ Mpc.
- Number density of Milky Way Equivalent Galaxies (MWEGs) is ~0.01 Mpc^{-3}, so out to d_{100} you have ~40000 d_{100}^3 galaxies.
- Localization to $\Delta\wedge$ reduces number by factor $\Delta\Omega/4\pi$; signal to noise SNR by another 3/SNR
- $\Delta\Omega=10^{-3}$ deg^2, SNR=8 means you have 1 MWEG in volume out to d_{100}=13, i.e., 1.3 Gpc

Thus limitation is sensitivity, not localization. If detect, then could easily do precise dark siren cosmology, SNe Ia progenitors, etc.

Multimessenger: DWD, SNe Ia

- SNe Ia are critical for cosmography
  H_0, dark energy, tests of cosmology
- Single-degenerate? Star donates to WD
- Double-degenerate? DWD merger
- Current sentiment favors DWD
- If so, they will be deciHz GW sources
- What could we learn?

Example DWD Horizon



Ajith+ 2025; again for LGWA but could adjust for other designs.

Stats for DWD

- Estimated SNe Ia rate is 2.7 ± 0.7 yr^{-1} within 20 Mpc
- If all are DWD, previous plot indicates guarantee of detection at SNR=9 within a few years
  Maybe post-merger osc? Yoshida 2021
- *Any* detection, followed by supernova, would verify that this is a SNe Ia channel
- Will we get a supernova?

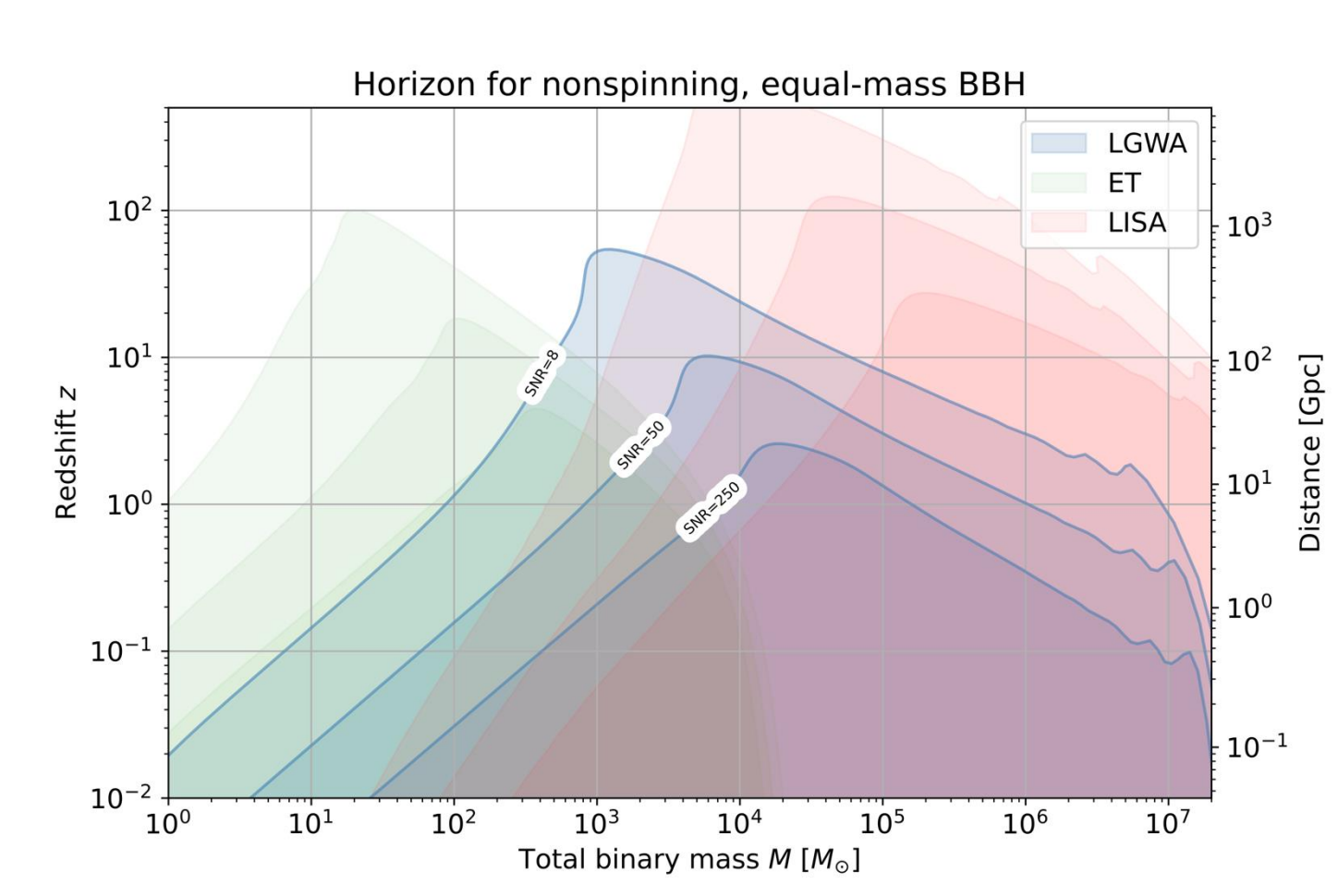
Prompt supernova or not?

- Theoretical opinions differ about interval between DWD merger and SNe Ia
- $M>M_{Ch}$ not essential; what *is* necessary is runaway nuclear burning (fusion rate increases with temperature faster than cooling rate)
- Does merger lead to immediate instability?
- Or does the remnant need to lose rotational support (could take Myrs)?

Multimessenger Signatures

- Would see GW signal a few years in advance, know merger time precisely, and identify host galaxy easily
- If SN Ia soon after merger, clarifies mechanism
- If not, still few x 10^{50} erg energy released on merger; easy to see at 20 Mpc
- Thus multimessenger, and would tell us about mechanism (helping cosmology!)

BH Mass Range



Ajith+ 2025; again for specific design but same principles apply

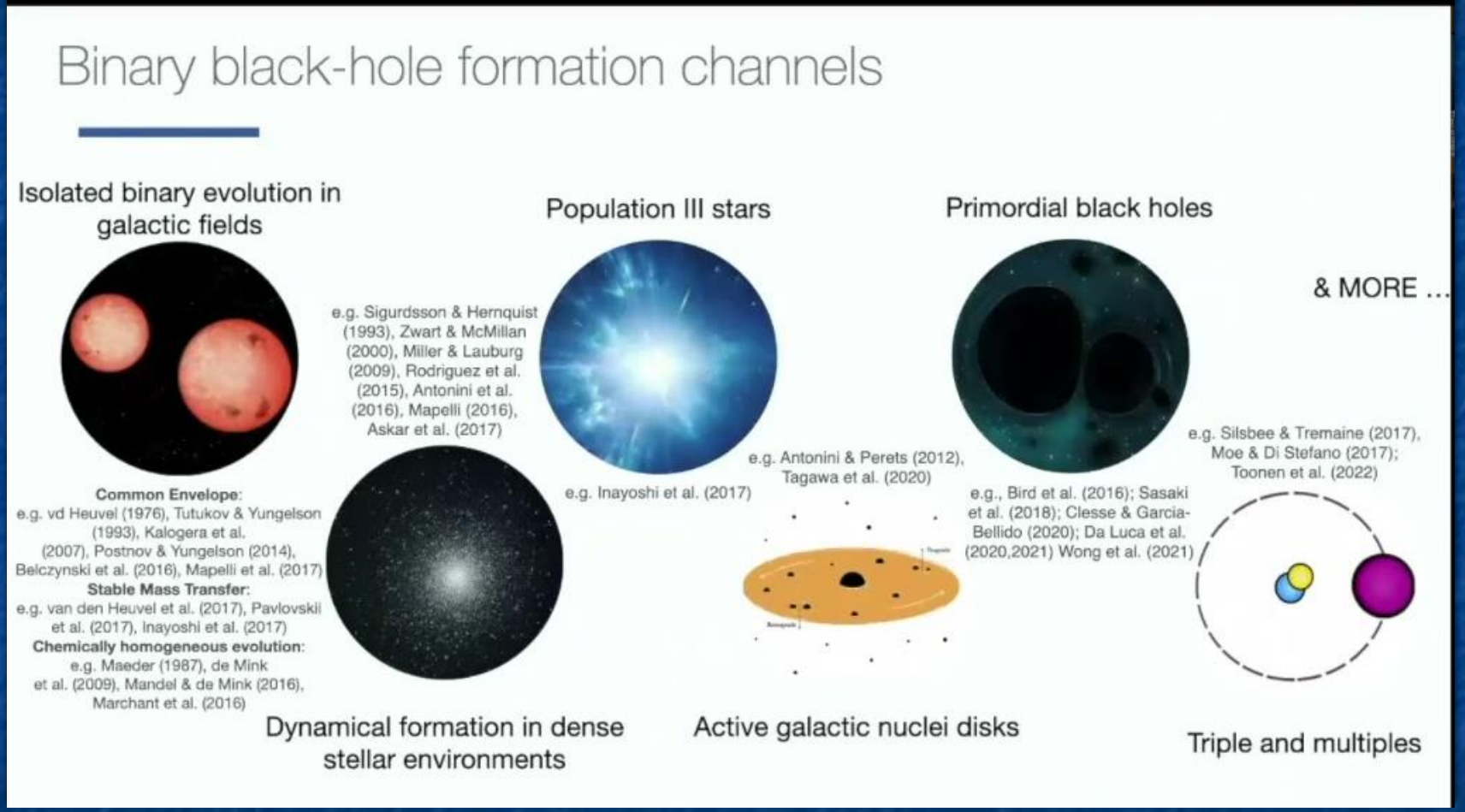
Benefits of mass range?

- From previous plot, unless deciHz detector is more sensitive, ET or LISA will win at most binary masses
- However, the localization for deciHz will tell us far more about the environment
- Lower freq ~0.01 Hz is best for localization; could see M_{chirp}~100 M_{sun} to >1 Gpc. Clear ID of host galaxy, major boost in precision of cosmography

Dark Siren Cosmography

- Some comments on cosmography:
- We need to be aware that EM astronomers are improving their methods, too! GW is not the only game in town
- To get the luminosity distance we will need to know the binary orientation; this requires excellent polarization measurements (or other methods?)

Formation of BBH



From talk by Tassos Fragos

Isolated vs. Dynamical

Isolated: tidal effects circularize, kicks small, low e at ~0.1 Hz

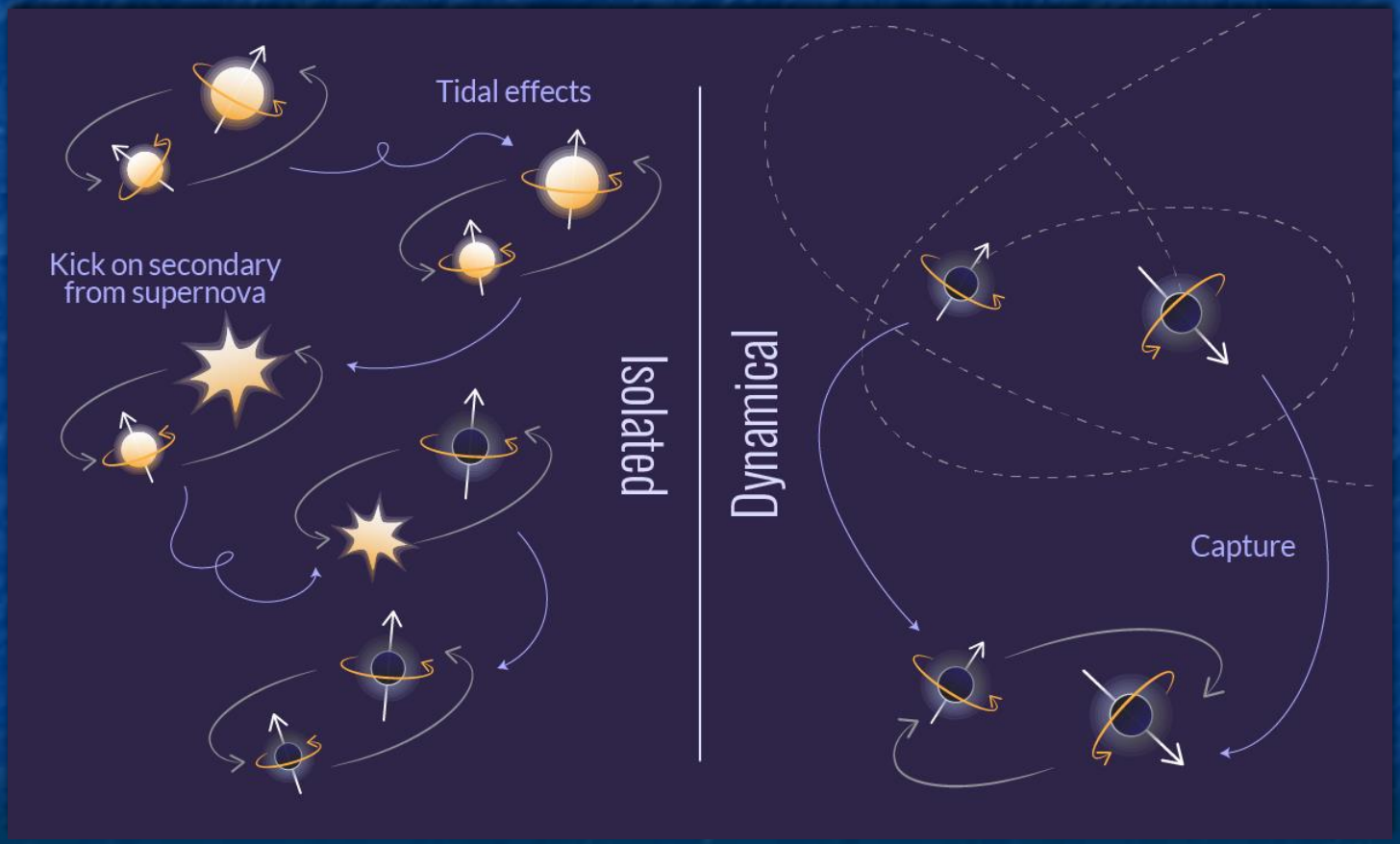


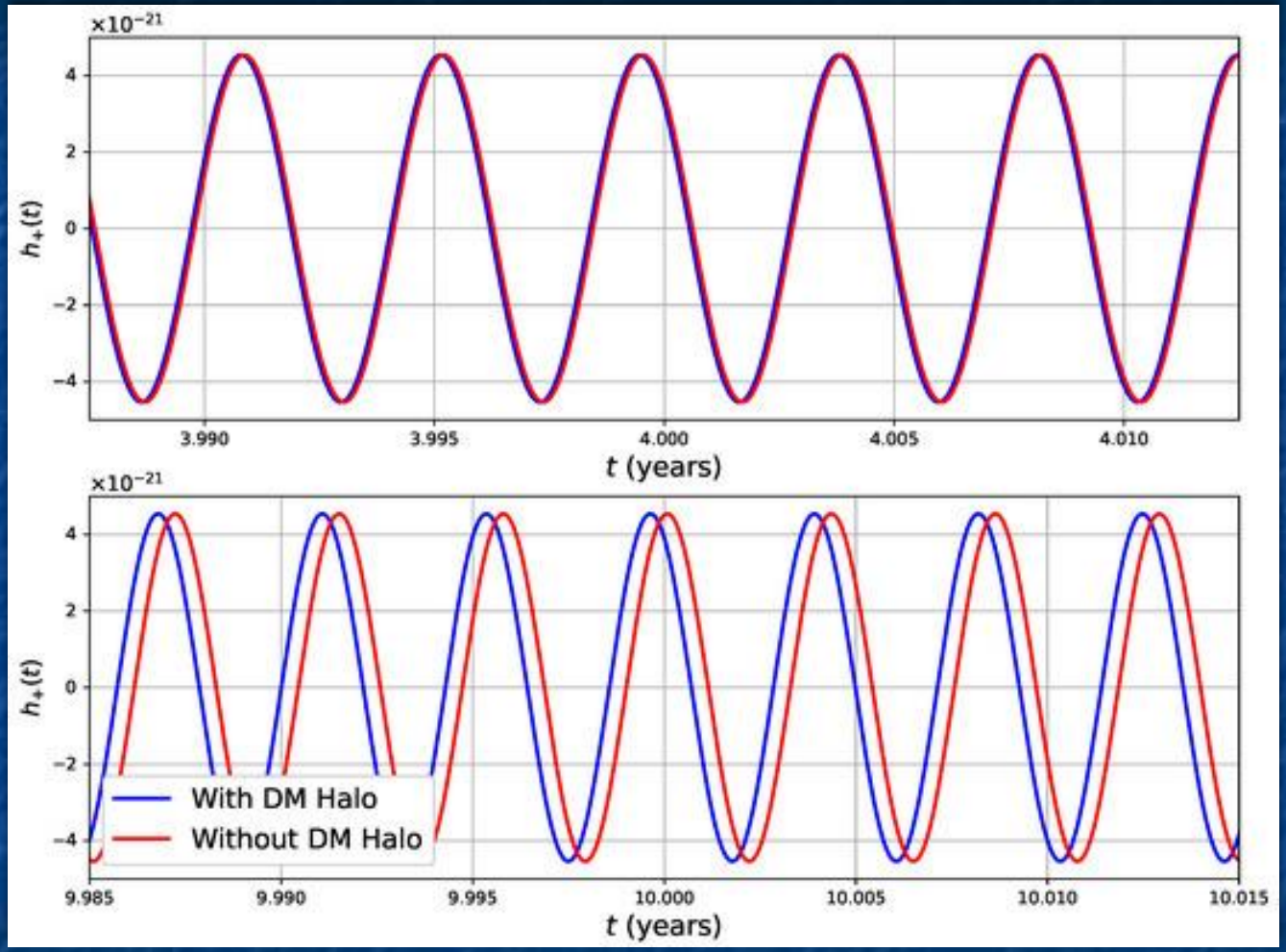
Image by Shanika Galaudage

Dynamical: higher frac of close passes, higher e at ~0.1 Hz

Eccentricity and BBH Formation

- Frustratingly, all proposed pathways to BBH are judged by their advocates to be able to explain all BBH events(!!!)
- A possible distinguishing feature is eccentricity; much easier for dynamical pathways than for isolated binary or disk
- Hints of $e>0$ from LVK but not definite
- $e \sim f^{-1}$ means that eccentricity would be vastly easier to see at lower frequencies

Waveform Effects



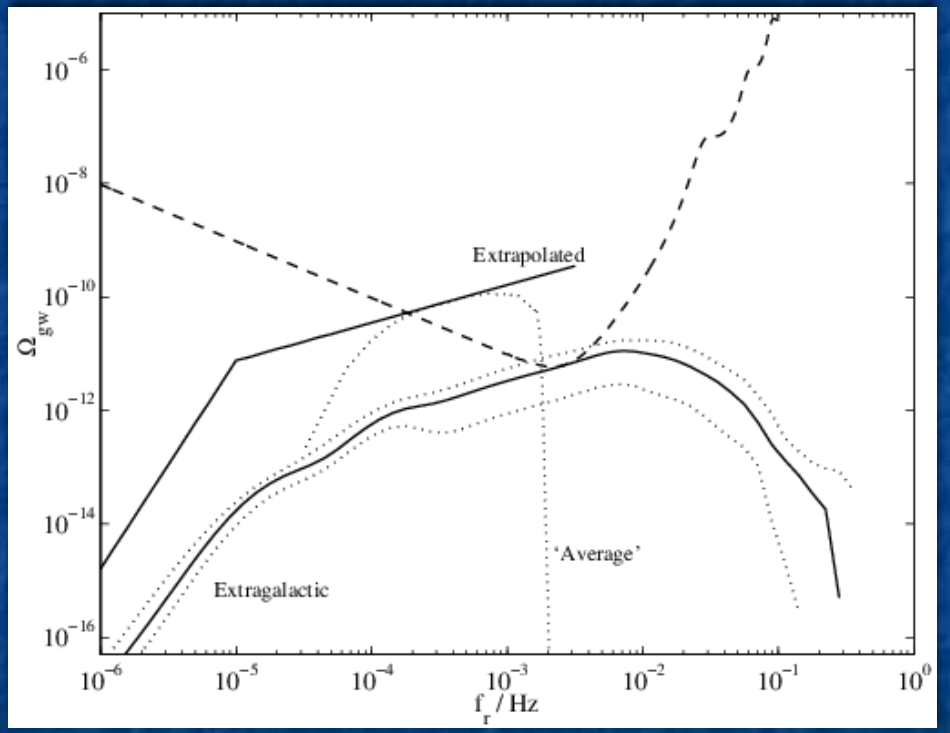
Montalvo+ 2024. This is for a dark matter spike but applies to any change in waveform

Environmental and -PN effects

- At lower frequencies, binaries orbit for far more cycles than at higher ($T_{insp} \sim f_{GW}^{-8/3}$)
- Thus some effects will be much easier to see at low frequencies:
  Dark matter, gas, or tertiary objects
  Pre-Newtonian ("-PN") deviations from GR
  (also helps +PN in concert with ET, CE)
  Tides on white dwarfs
  Precession of misaligned spins (2D spins!)
- All are part of discovery space

Primordial Background?

- No compelling reason to think that there is a detectable background, but...
- deciHz: best combo of possible high signal, resolvable foreground Cutler+Harms 2006
- BNS, BBH resolvable
- Best chance of seeing primordial background?

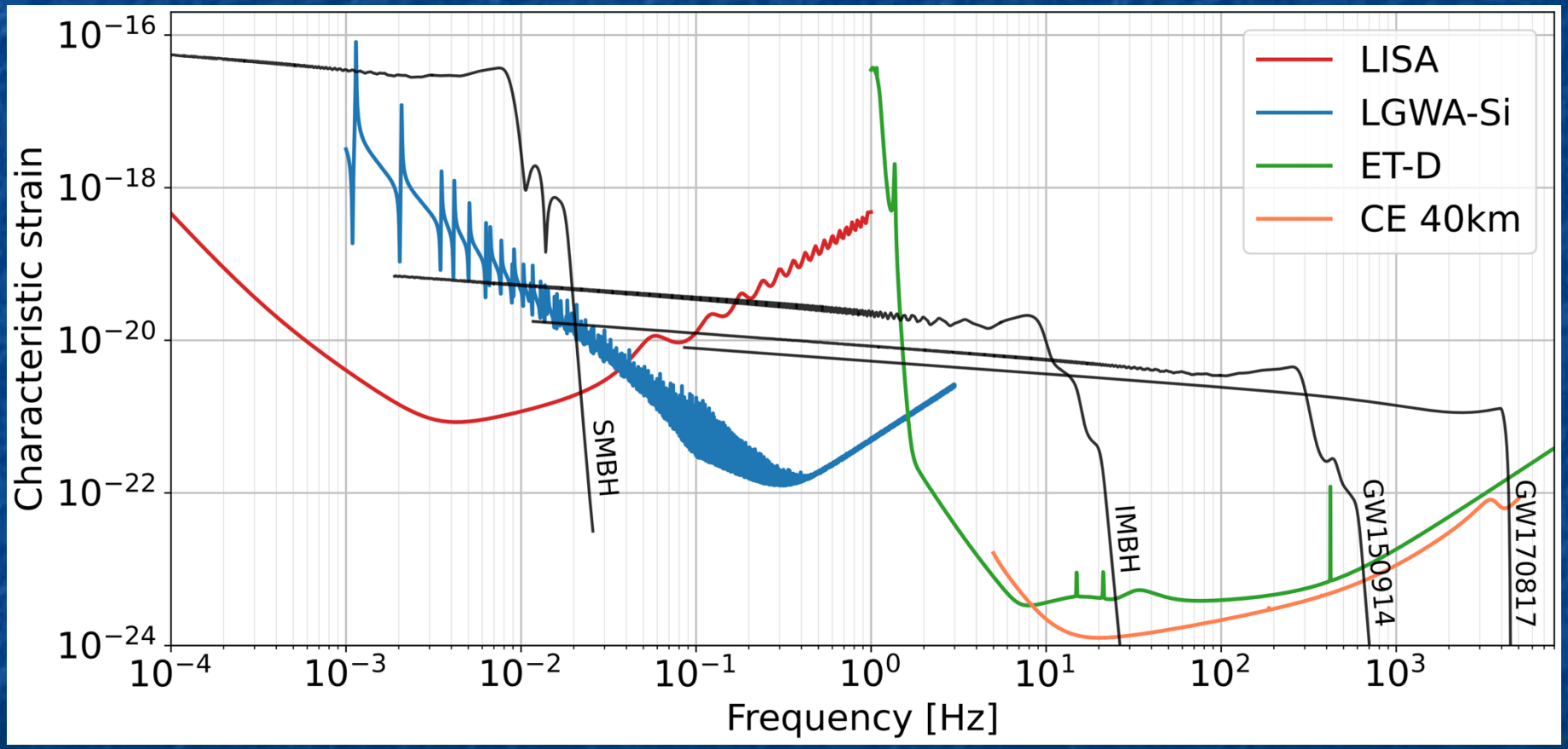


Farmer and Phinney 2003

Summary

- The deciHz band isn't just a new band; there are multiple highly interesting sources and opportunities
- Sensitivity and localization are key; good polarization measurements would add an important dimension
- I look forward to developments!

Example deciHz+other



Ajith+ 2025