ASTROPHYSICS

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NSF Advanced LIGO Review

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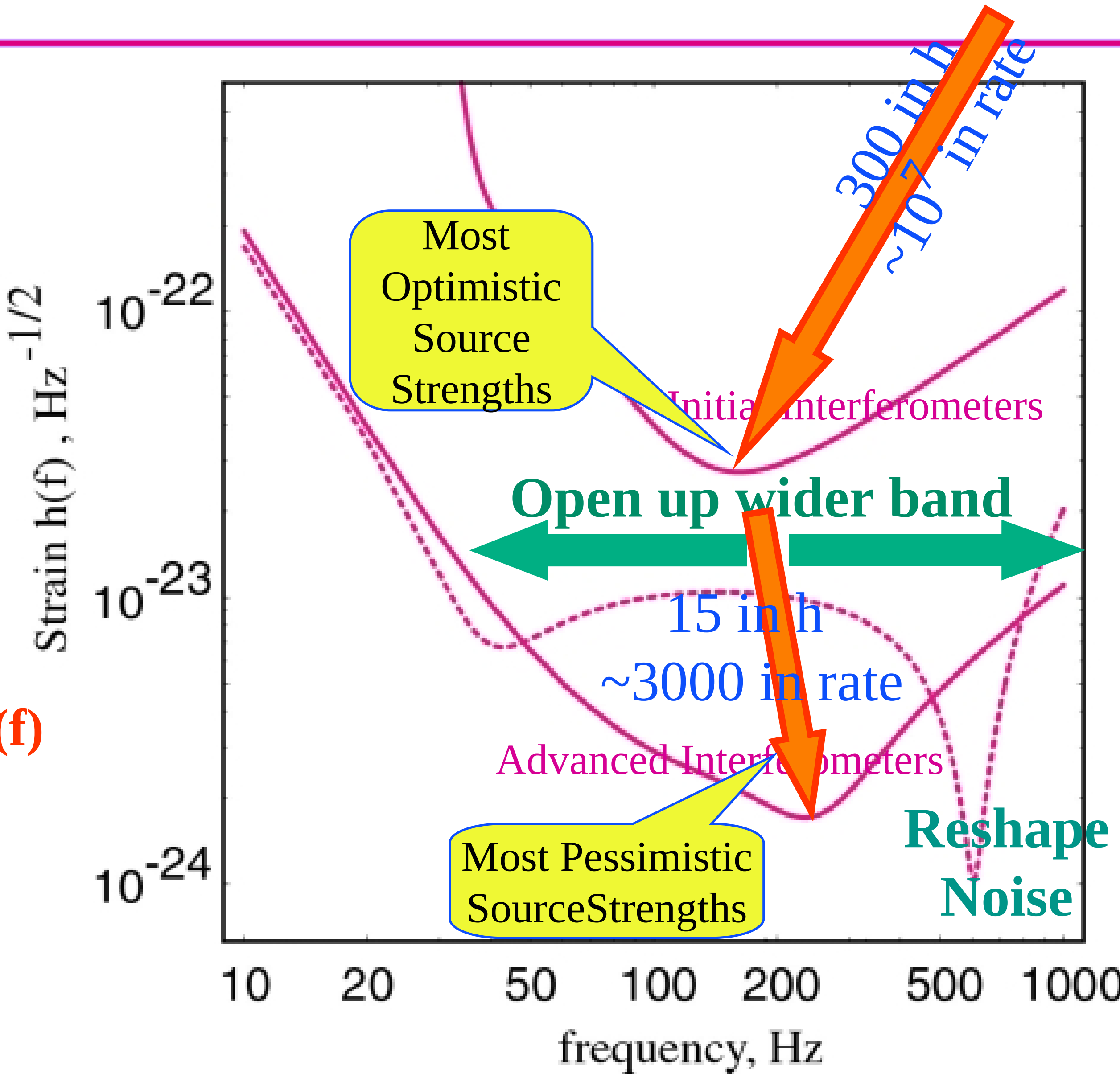
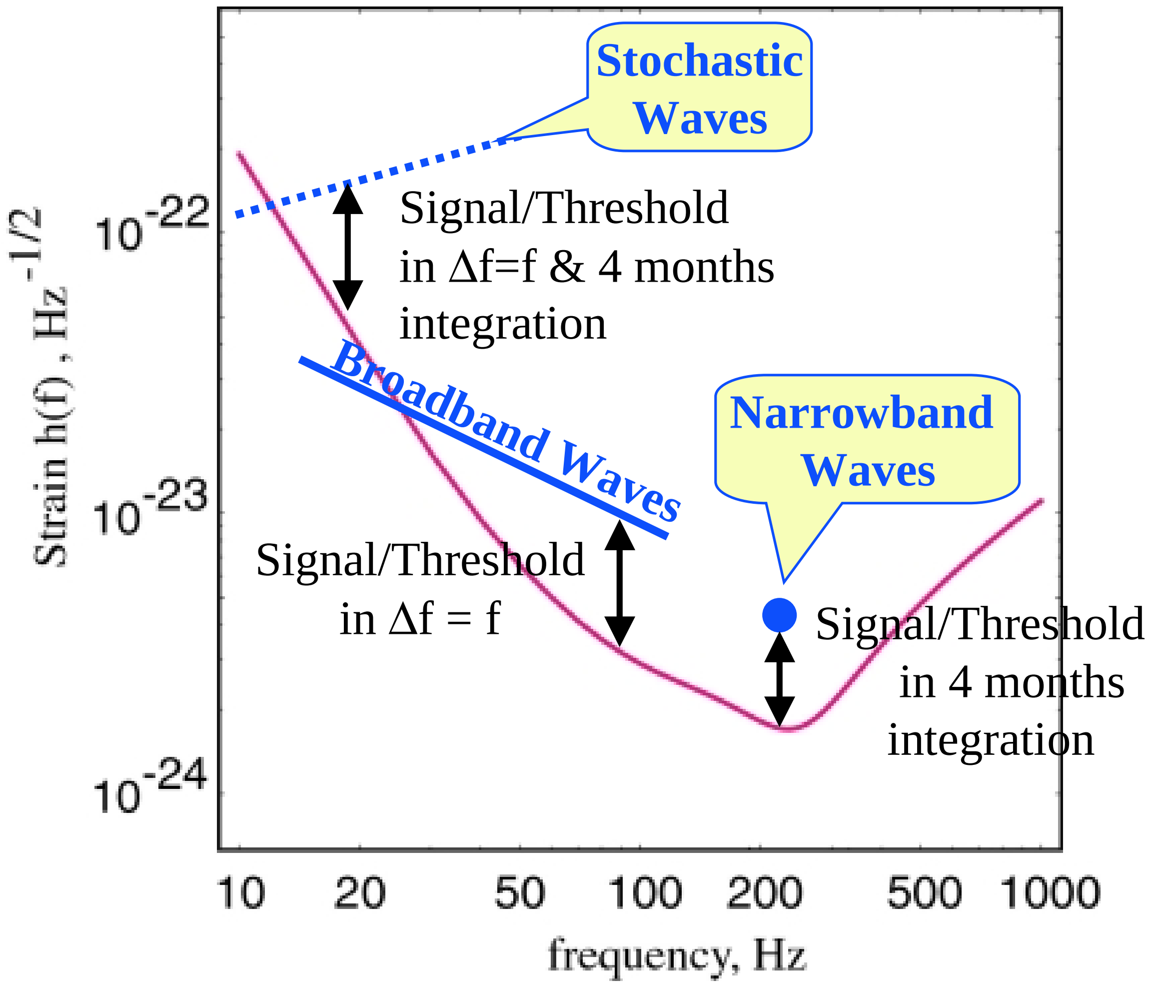
From Initial Interferometers to Advanced



$h_{rms} = h(f)\sqrt{f} \sim 10\, h(f)$

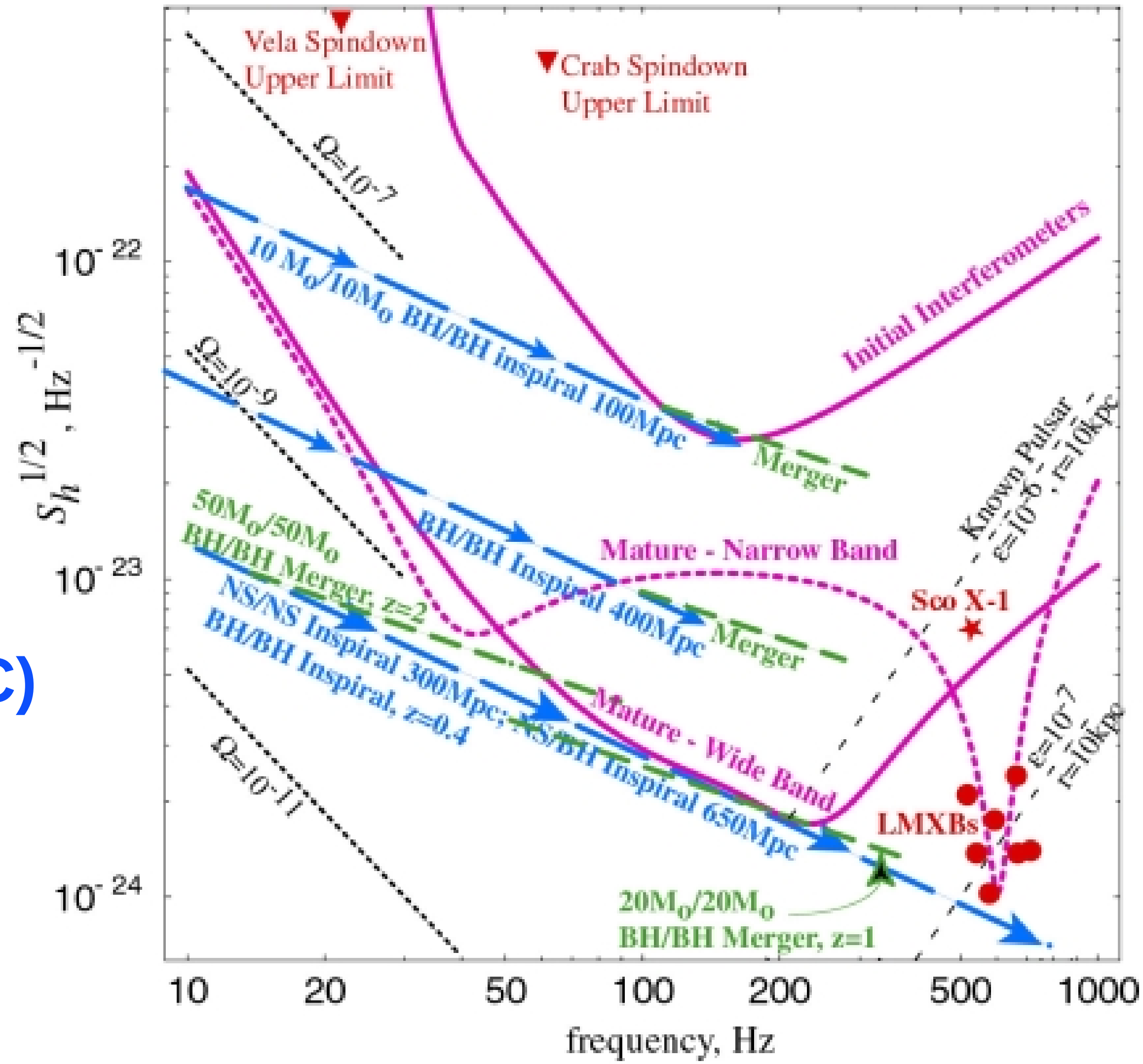
Conventions on Source/Sensitivity Plots

- **Assume the best search algorithm now known**
- **Set Threshold so false alarm probability = 1%**
  - » For rare broadband signals: on tail of Gaussian; increase S/T by ~10% ➔ 0.01% false alarm

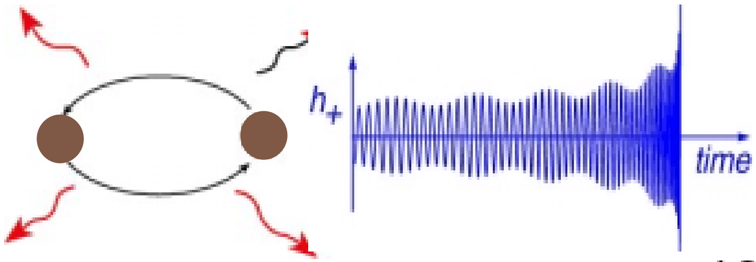


Overview of Sources

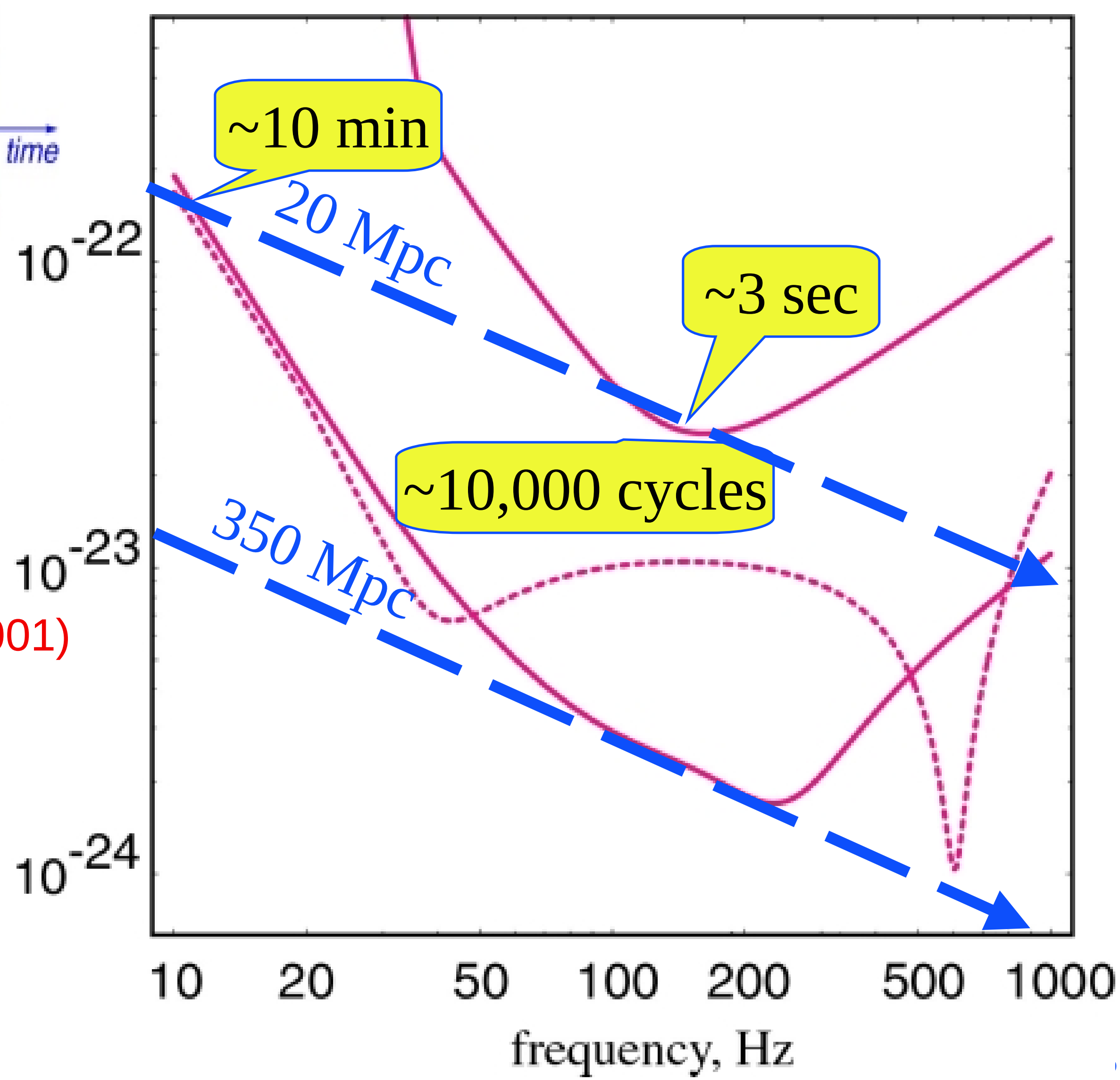
- **Neutron Star & Black Hole Binaries**
  - » inspiral
  - » merger
- **Spinning NS's**
  - » LMXBs
  - » known pulsars
  - » previously unknown
- **NS Birth (SN, AIC)**
  - » tumbling
  - » convection
- **Stochastic background**
  - » big bang
  - » early universe



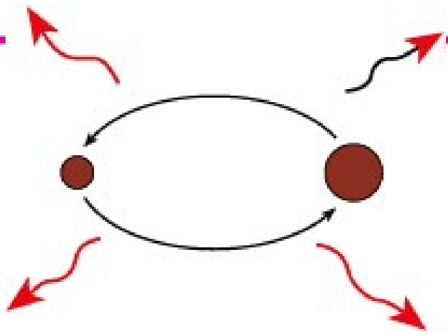
Neutron Star / Neutron Star Inspiral
(our most reliably understood source)

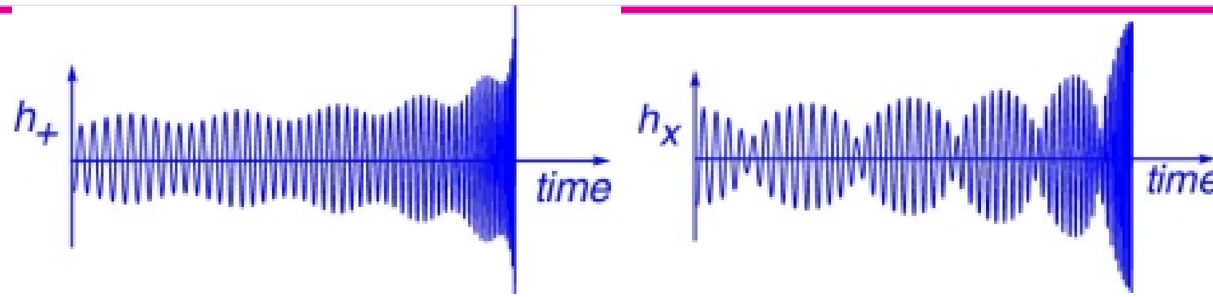


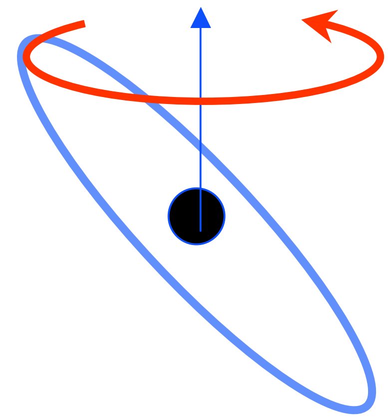
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor *Astrophys J,* 556, 340 (2001)
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 4yrs**
- **Advanced IFOs -**
  - » Range: 350Mpc
  - » **2 / yr to 3 / day**



Science From Observed Inspirals: NS/NS, NS/BH, BH/BH

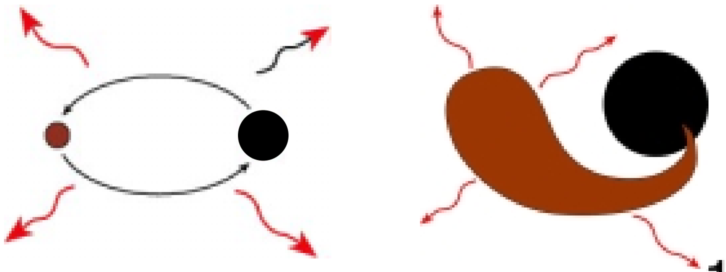




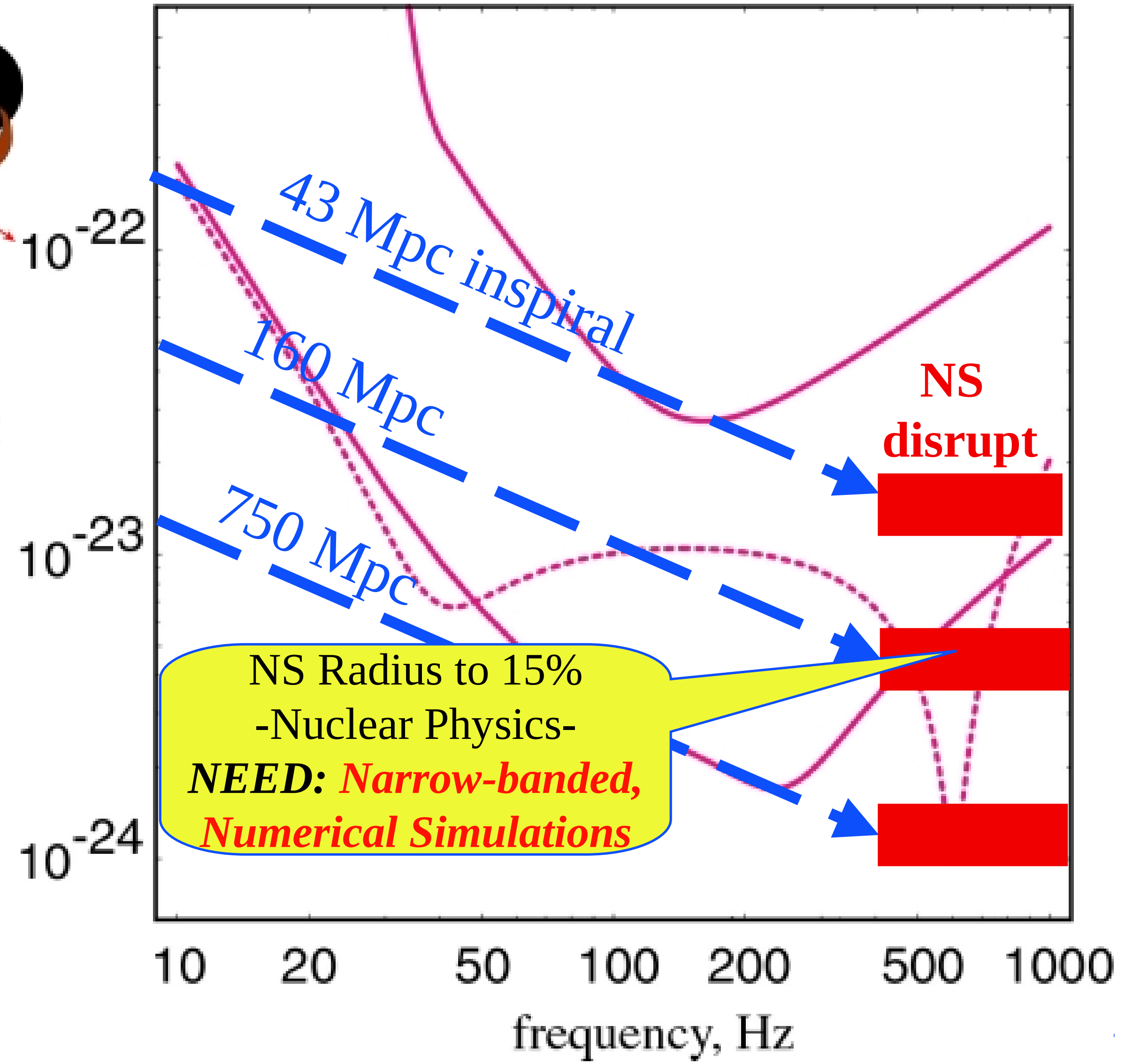


- Relativistic effects are very strong -- e.g.
  - » ***Frame dragging by spins ➔ precession ➔ modulation***
  - » ***Tails of waves modify the inspiral rate***
- Information carried:
  - » ***Masses (a few %), Spins (?few%?), Distance [not redshift!] (~10%), Location on sky (~1 degree)***
    - – $M_{\mathbf{chirp}} = \mu^{\mathbf{3/5}} M^{\mathbf{2/5}}$ to $\sim 10^{\mathbf{-3}}$
- Search for EM counterpart, e.g. γ-burst. If found:
  - » ***Learn the nature of the trigger for that γ-burst***
  - » ***deduce relative speed of light and gw's to ~ 1 sec / 3x10^9 yrs ~ 10^{-17}***

Neutron Star / Black Hole Inspiral and NS Tidal Disruption

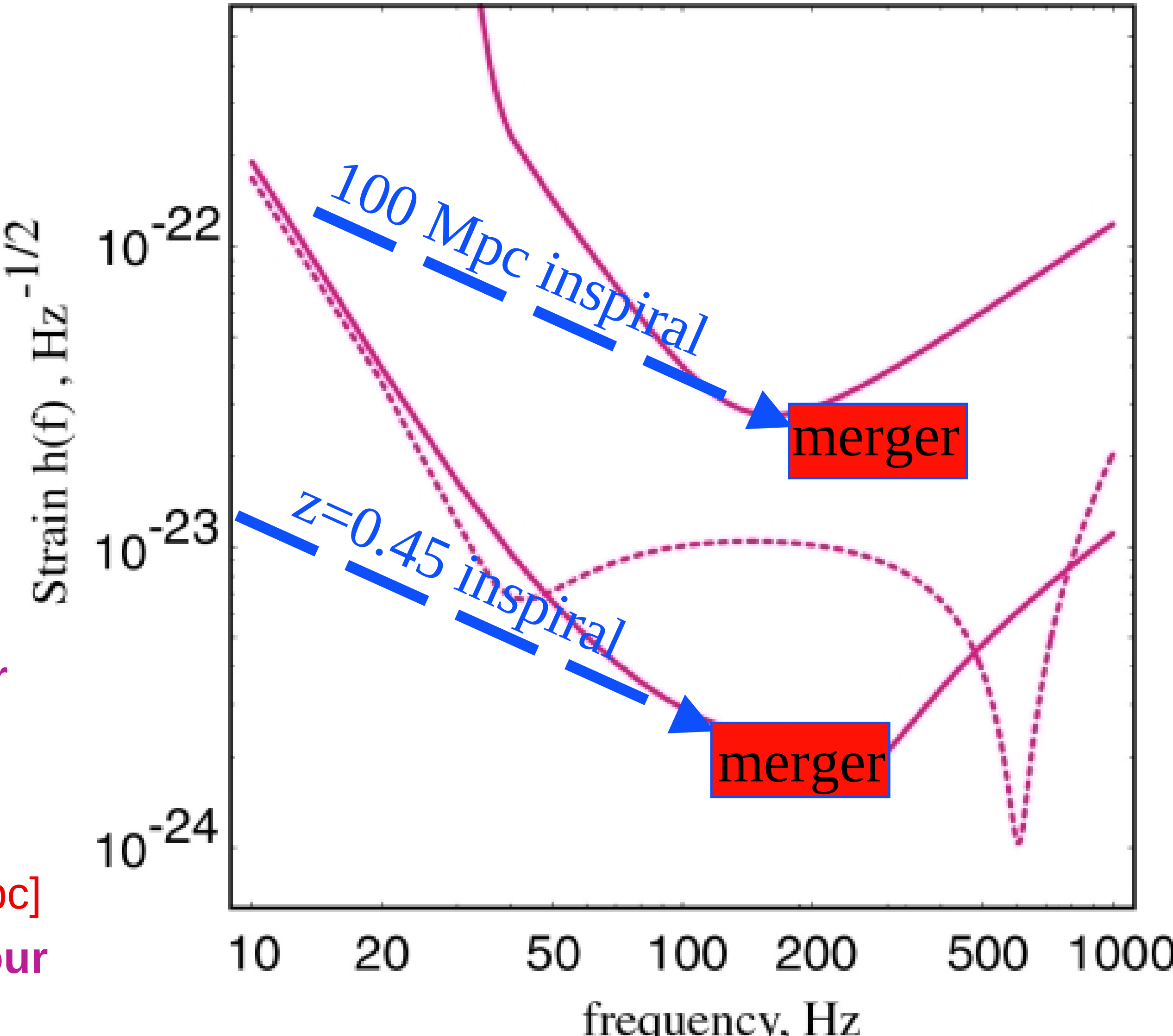


- **1.4Msun / 10 Msun NS/BH Binaries**
- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » 1 / 5000 yrs to **1 / 3yrs**
- **Advanced IFOs**
  - » Range: 750 Mpc
  - » **1 / yr to 4 / day**

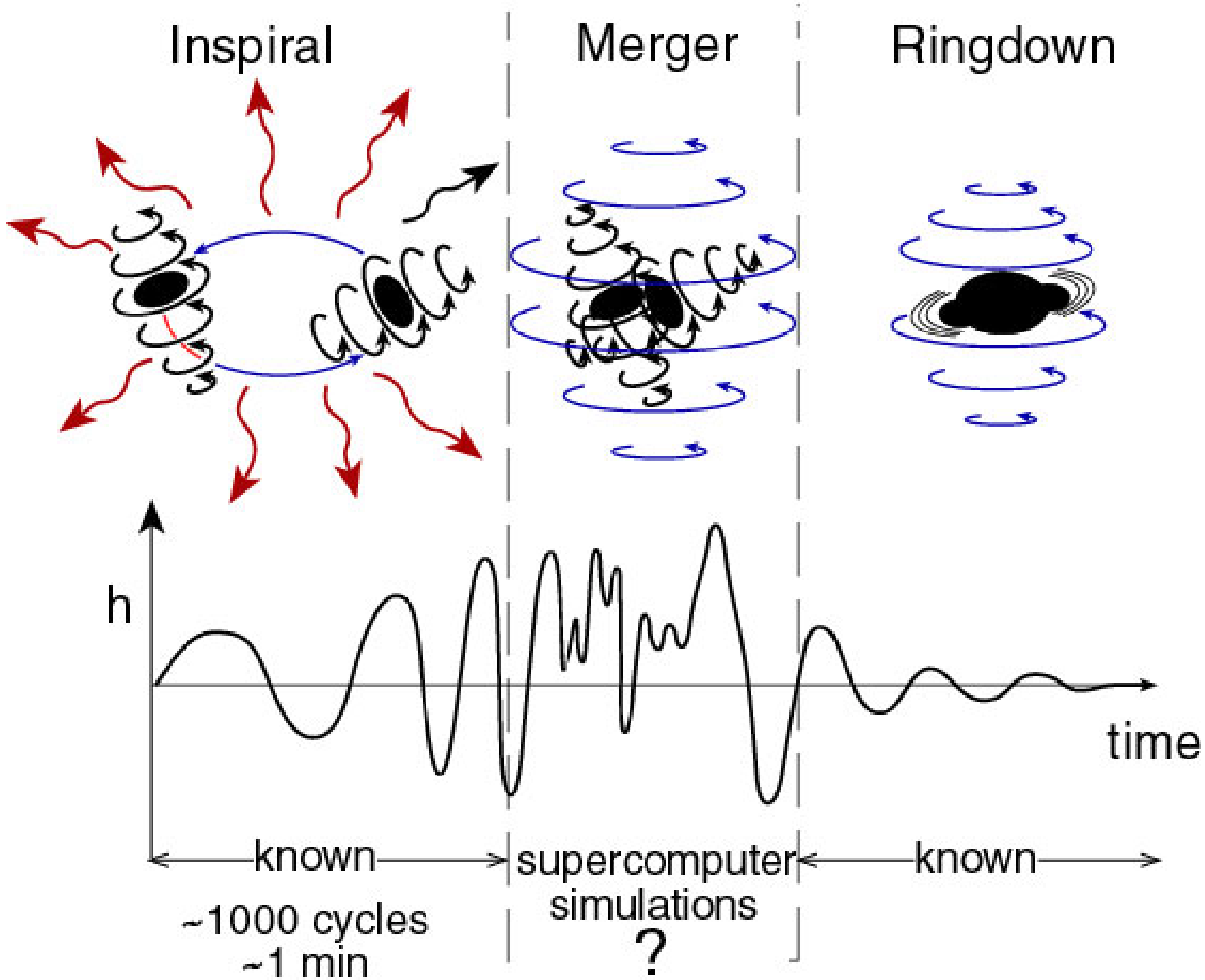


Black Hole / Black Hole Inspiral and Merger

- **10Msun / 10 Msun BH/BH Binaries**
- **Event rates**
  - » Population synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 100 Mpc
  - » ~1 / 250 yrs to **~2 / yr**
- **Advanced IFOs -**
  - » Range: z=0.45 [1.7 Gpc]
  - » **~1/ month to ~1 / hour**



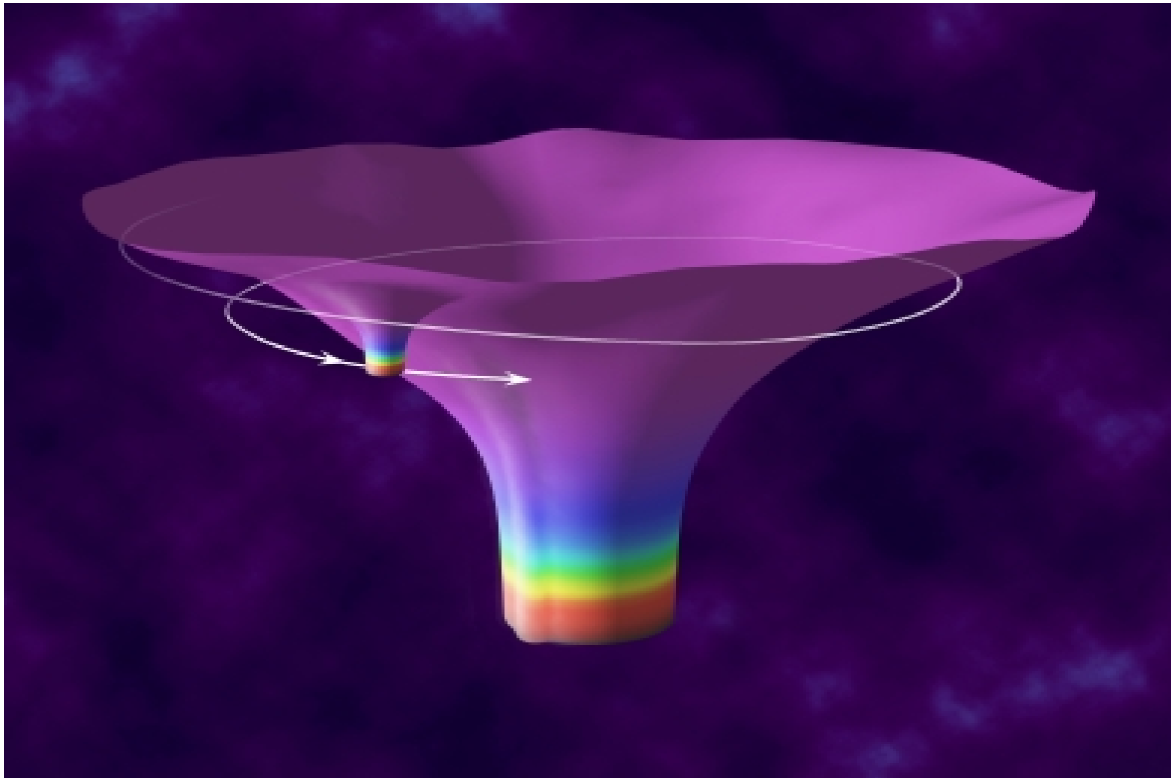
BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



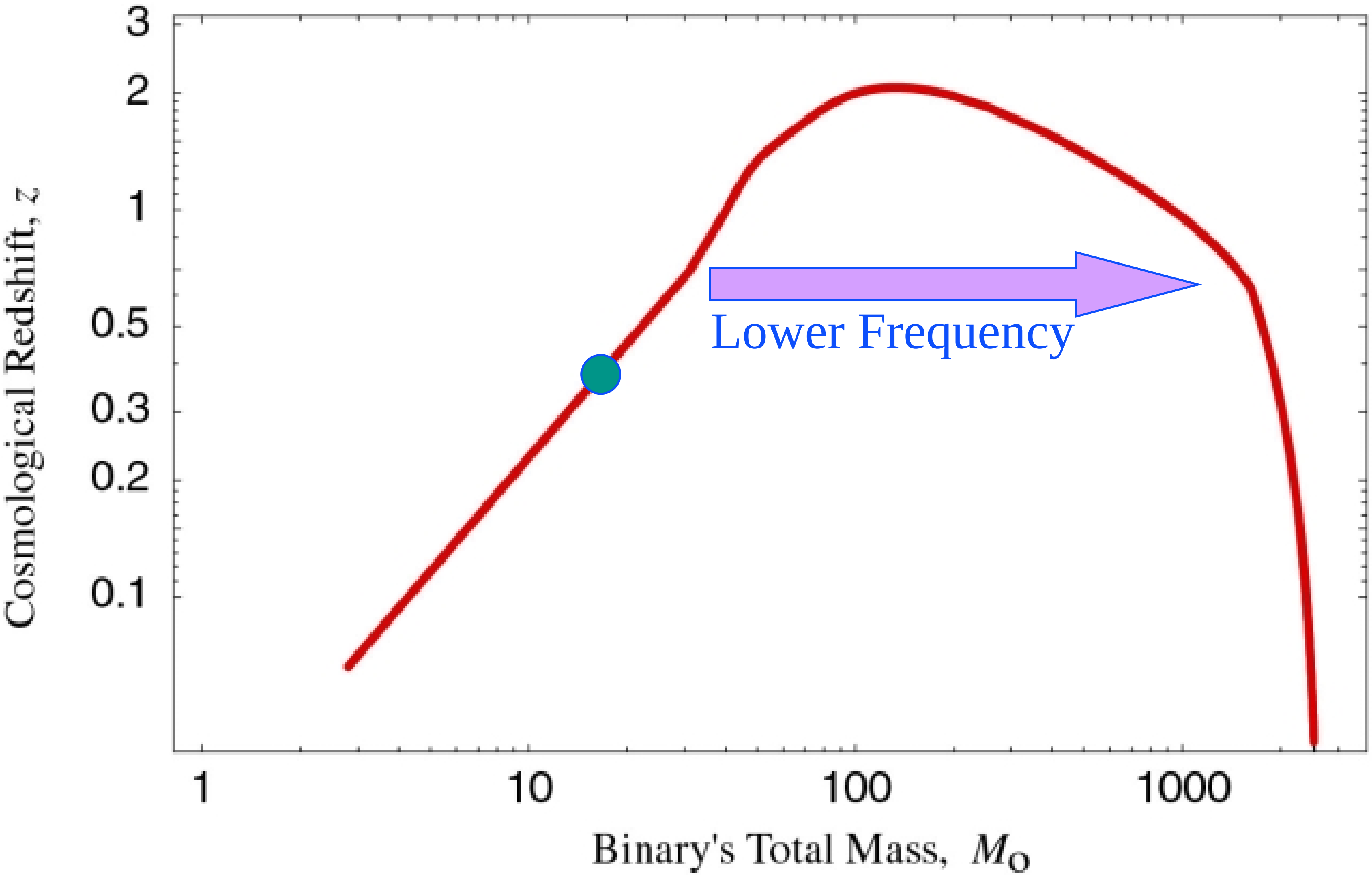
To interpret Observed waves: Compare with Numerical Relativity Simulations

Probing Intermediate Mass BH's with Small BH's

- **In globular clusters: BH-BH capture formation, merger, formation, merger, … in globular clusters ➔ intermediate-mass BH: 100 - 1000 Msun** [Cole Miller]
- **Plunge of few Msun BH into few ~100 Msun BH**
- **Ringdown studies: ~ 10 per year with M/m > 60; more for smaller M/m**

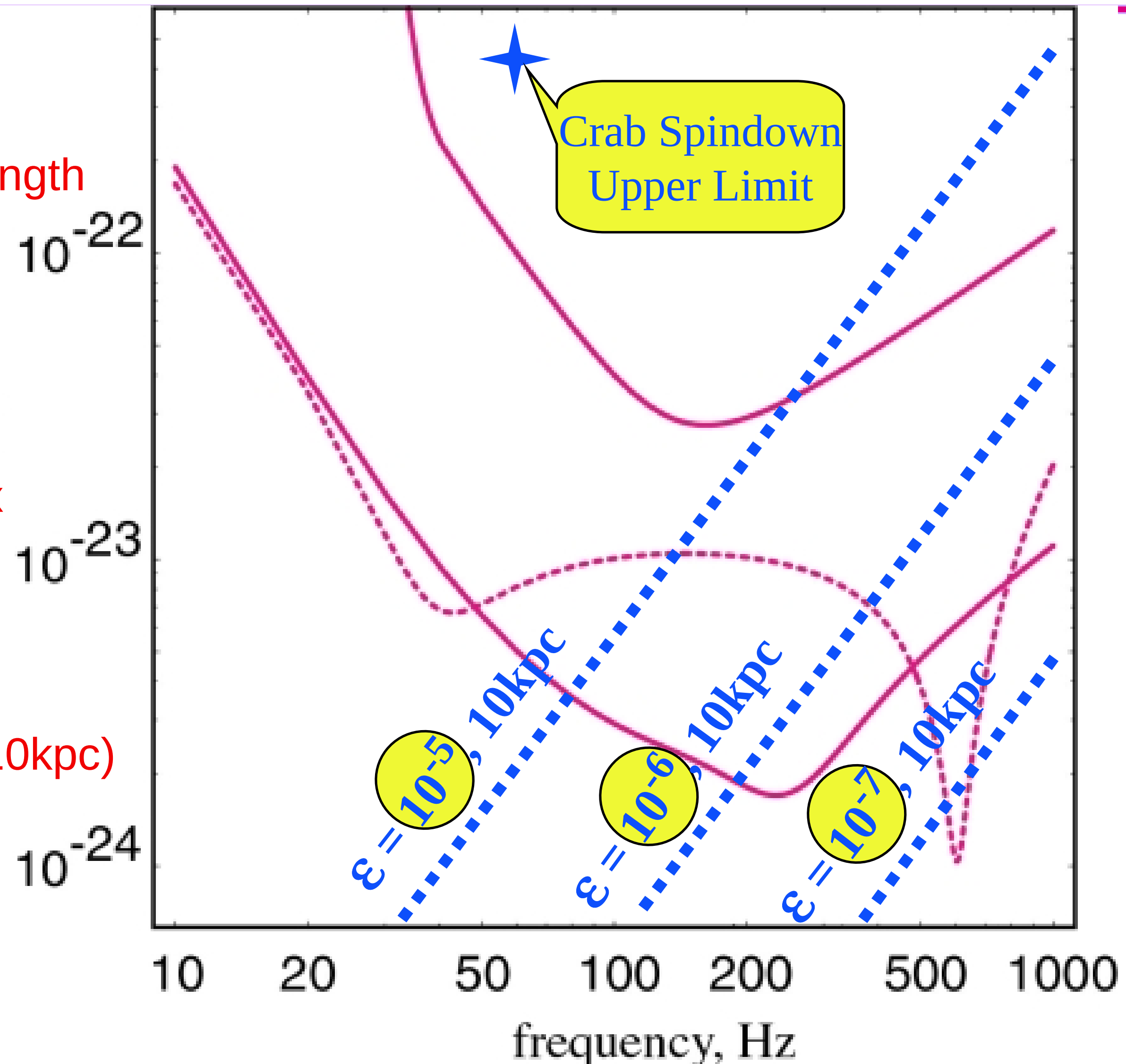


Massive BH/BH Mergers with Fast Spins - Advanced IFOs



Spinning NS's: Pulsars in Our Galaxy

- NS Ellipticity:
  - » Crust strength or B strength
    $\varepsilon \lesssim 10^{-5}$
- Known Pulsars:
  - » First Interferometers:
    $\varepsilon \gtrsim 3\text{x}10^{-6}$ (1000Hz/f) x (distance/10kpc)
  - » Broadband Advanced
    $\varepsilon \gtrsim 5\text{x}10^{-7}$ x (distance/10kpc)

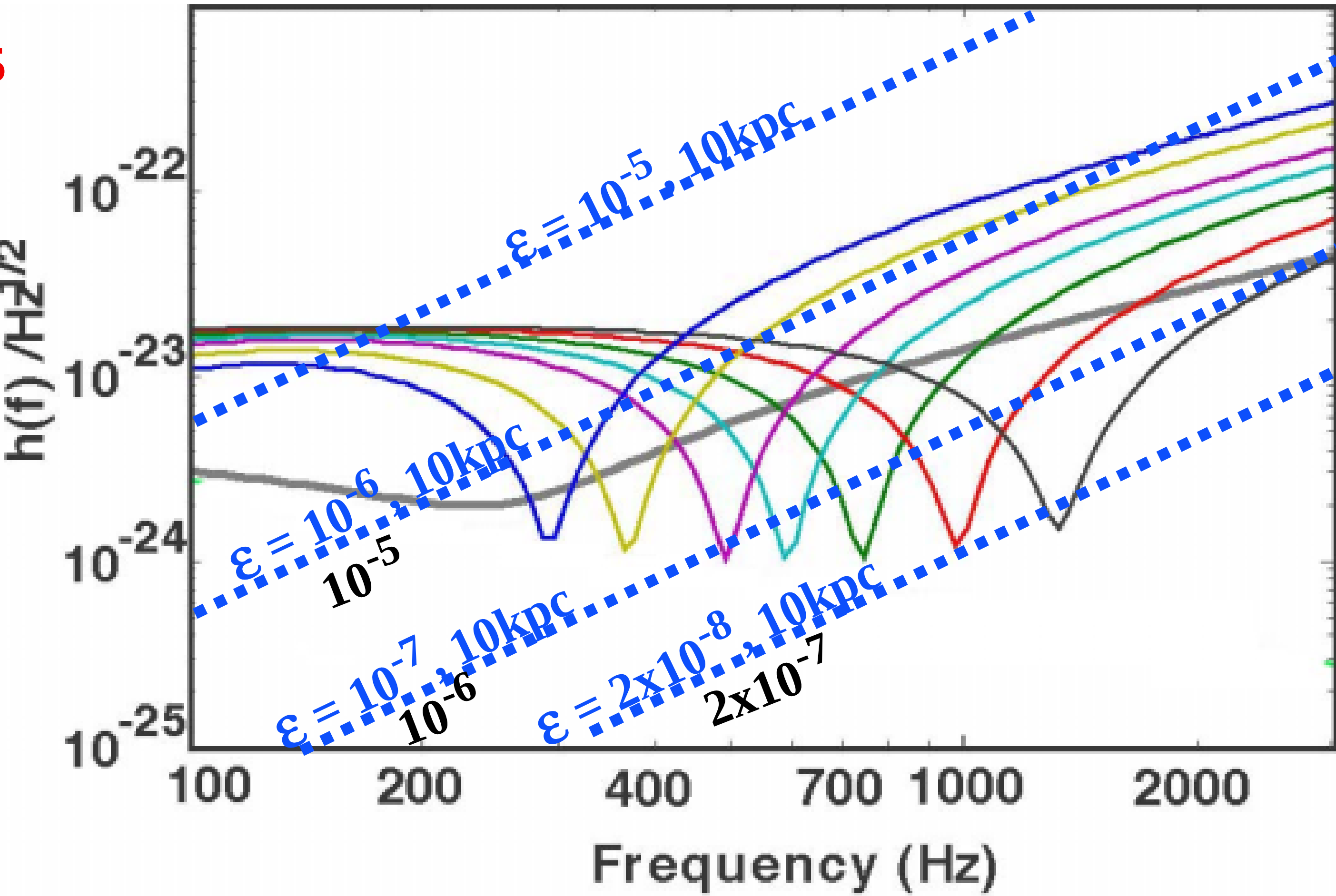


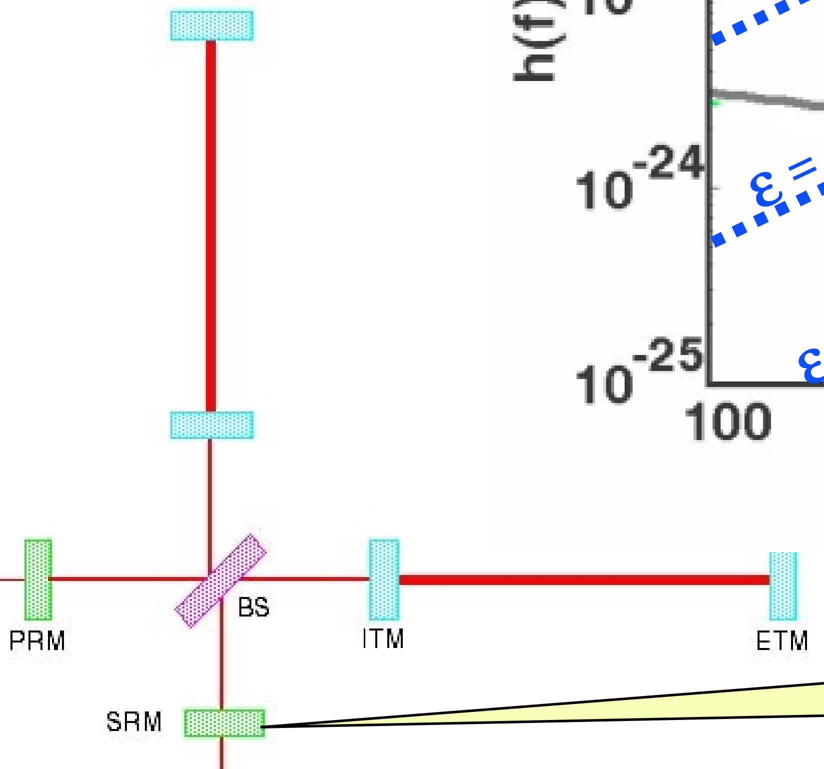
Spinning NS's: Pulsars in Our Galaxy [narrow-banded interferometer]

Plausible: ε≲ 10^-5

Known Pulsars

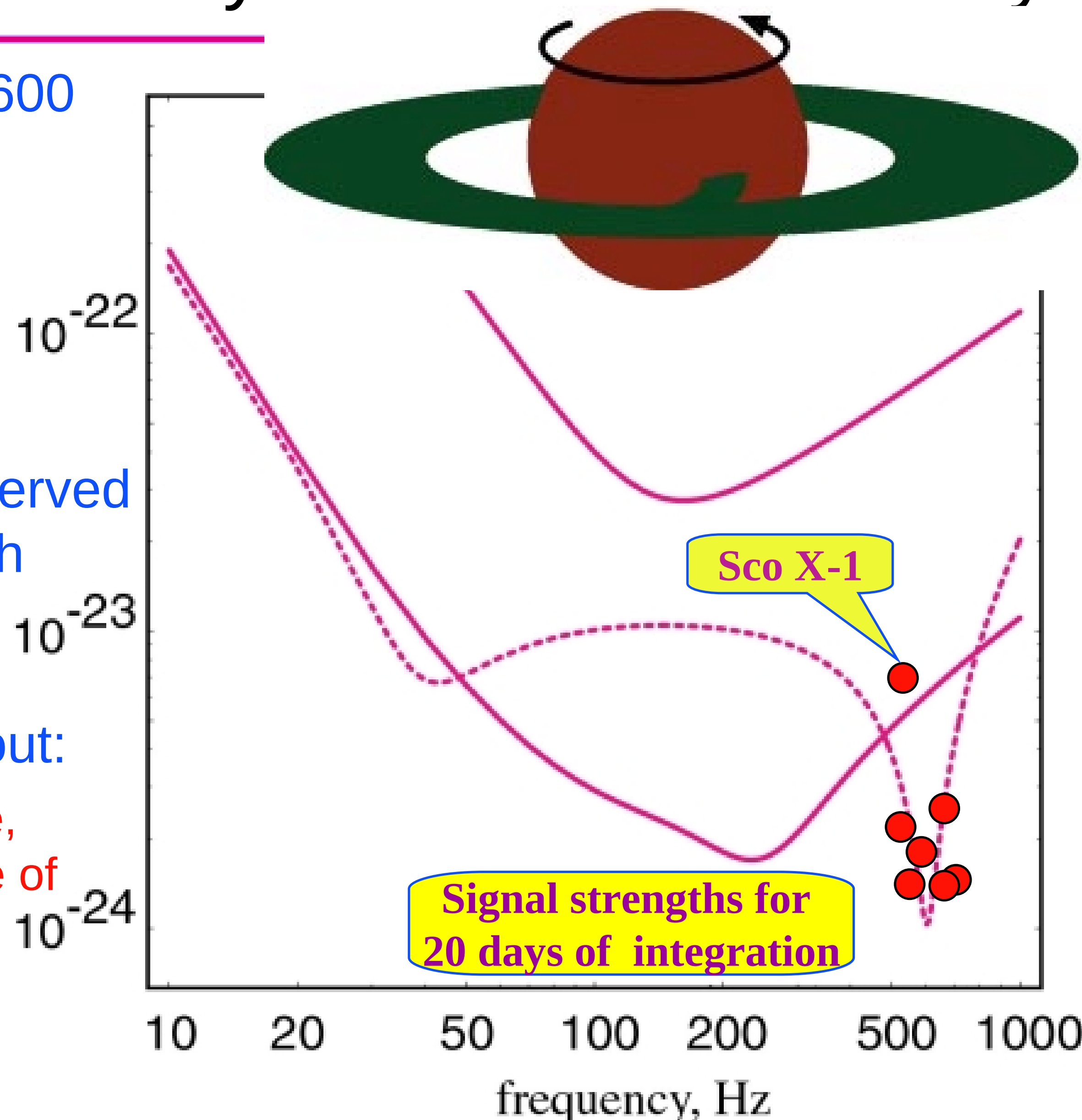
Unknown: All Sky search





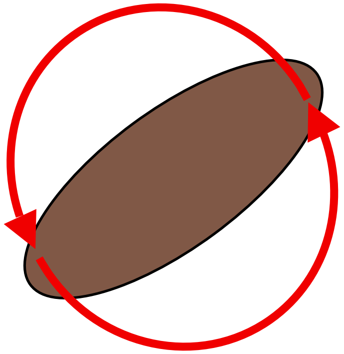
Spinning Neutron Stars: Low-Mass X-Ray Binaries in our Galaxy

- Rotation rates ~250 to ~600 revolutions / sec
  - » Why not faster?
  - » **Bildsten**: Spin-up torque balanced by GW emission torque
- If so, & steady state: observed X-ray flux ➔ GW strength
- Combined GW & EM obs's ➔ information about:
  - » crust strength & structure, temperature dependence of viscosity, ...

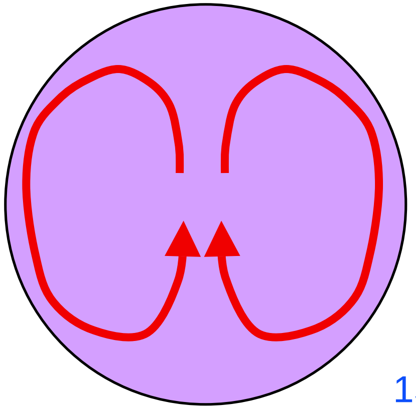


NS Birth:
Tumbling Bar; Convection

- **Born in:**
  - » Supernovae
  - » Accretion-Induced Collapse of White Dwarfs
- **If very fast spin:**
  - » Centrifugal hangup
  - » **Tumbling bar** - episodic? (for a few sec or min)
  - » ***If modeling gives enough waveform information,*** detectable to:
    - – Initial IFOs: ~5Mpc (M81 group, ~1 supernova/3yr)
    - – Advanced IFOs: ~100Mpc (~500 supernovae/yr)



- **If slow spin:**
  - » **Convection** in first ~1 sec.
  - » Advanced IFOs: Detectable only in our Galaxy (~1/30yrs)
  - » GW / neutrino correlations!



Complementarity of LIGO & LISA

LIGO

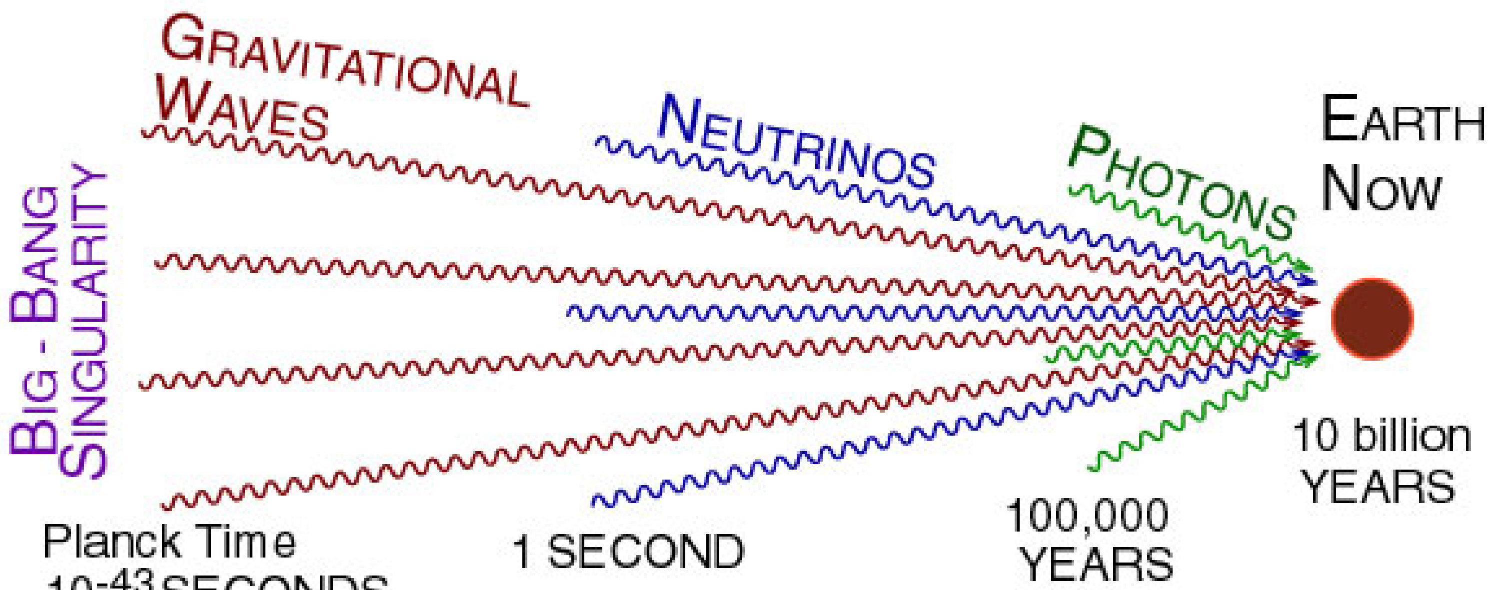
- **High-frequency band: ~10Hz to ~1500Hz (analog of optical astronomy)**
- **Neutron-star studies:**
  - » Tidal disruption by BH
  - » Low Mass X-Ray Binaries
  - » Pulsar Spins
- **Study stellar mass BH's (~3 Msun to ~1000 Msun)**
- **Study merger of NS and BH binaries in distant galaxies**
- **Study early universe at age ~10^{-25} sec (~10^{9} Gev)**

LISA

- **Low-frequency band: ~0.0001 Hz to ~0.1 Hz (analog of radio astronomy)**
- **Cannot study neutron star physics**
- **Study supermassive BH's (~100,000 to 10,000,000 Msun)**
- **Study White dwarf, NS, and BH binaries in our galaxy, long before merger**
- **Study early universe at age ~10^{-12} sec (~100 GeV)**

Stochastic Background from Very Early Universe

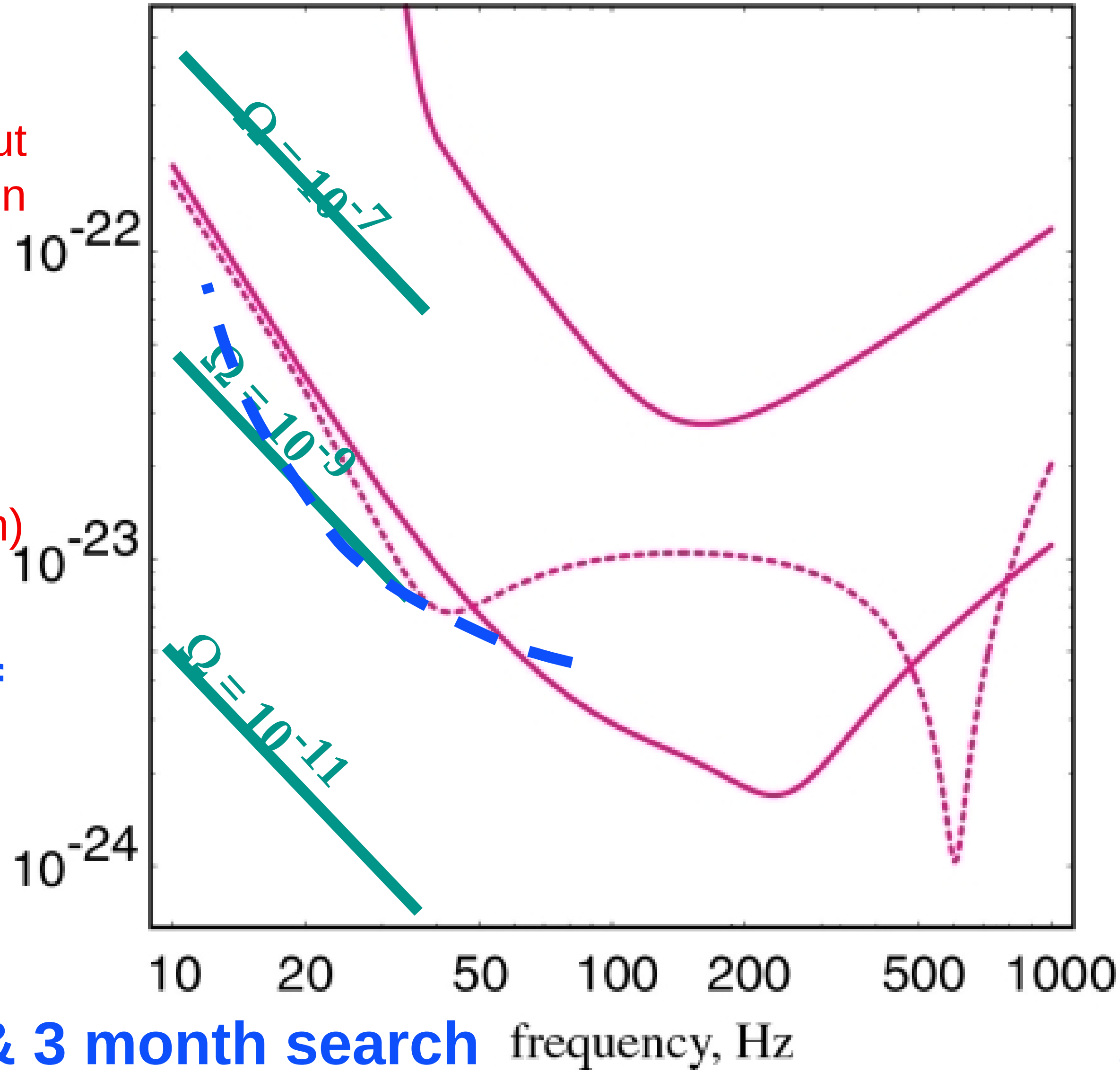
- **GW's are the ideal tool for probing the very early universe -- "messenger" from first one second**



- **Present limit on GWs**
  - » From effect on primordial nucleosynthesis
  - » Ω = (GW energy density)/(closure density) $\lesssim$ $\mathbf{10^{-5}}$

Stochastic Background from Very Early Universe

- **Detect by**
  - » cross correlating output of Hanford & Livingston 4km IFOs
- **Good sensitivity requires**
  - » (GW wavelength) $\gtrsim$ **2x**(detector separation)
  - » f $\lesssim$ 40 Hz
- **Initial IFOs detect if**
  - » **$\Omega \gtrsim 10^{-5}$**
- **Advanced IFOs:**
  - » **$\Omega \gtrsim 1 \times 10^{-9}$ with reduced power & 3 month search**



Grav'l Waves from Very Early Universe. *Unknown Sources*

- Waves from **standard inflation**: $\Omega \sim 10^{-15}$: much too weak
- ***BUT:*** Crude **superstring models** of big bang suggest waves *might be strong enough* for detection by Advanced IFOs
- Bursts from **cosmic strings**: possibly detectable by Initial IFOs
- Energetic processes at (universe age) **~ 10^{-25} sec** and (universe temperature) ~ 10^9 Gev ➔ GWs in LIGO band
  - » **phase transition at 10^9 Gev**
  - » **excitations of our universe as a 3-dimensional "brane" (membrane) in higher dimensions: [C. Hogan]**
    - **Brane forms wrinkled**

    - **When wrinkles "come inside the cosmological horizon", they start to oscillate; oscillation energy goes into gravitational waves**
    - **LIGO probes waves from wrinkles of length ~ 10^{-10} to 10^{-13} mm**
    - **If wave energy equilibrates: possibly detectable by initial IFOs**
- Example of hitherto ***UNKNOWN SOURCE***

Conclusions

- LIGO's Initial Interferometers bring us into the realm where it is plausible to begin detecting cosmic gravitational waves.
- With LIGO's Advanced Interferometers we can be confident of:
  - » detecting waves from a variety of sources
  - » gaining major new insights into the universe, and into the nature and dynamics of spacetime curvature, that cannot be obtained in any other way