LIGO SCIENCE

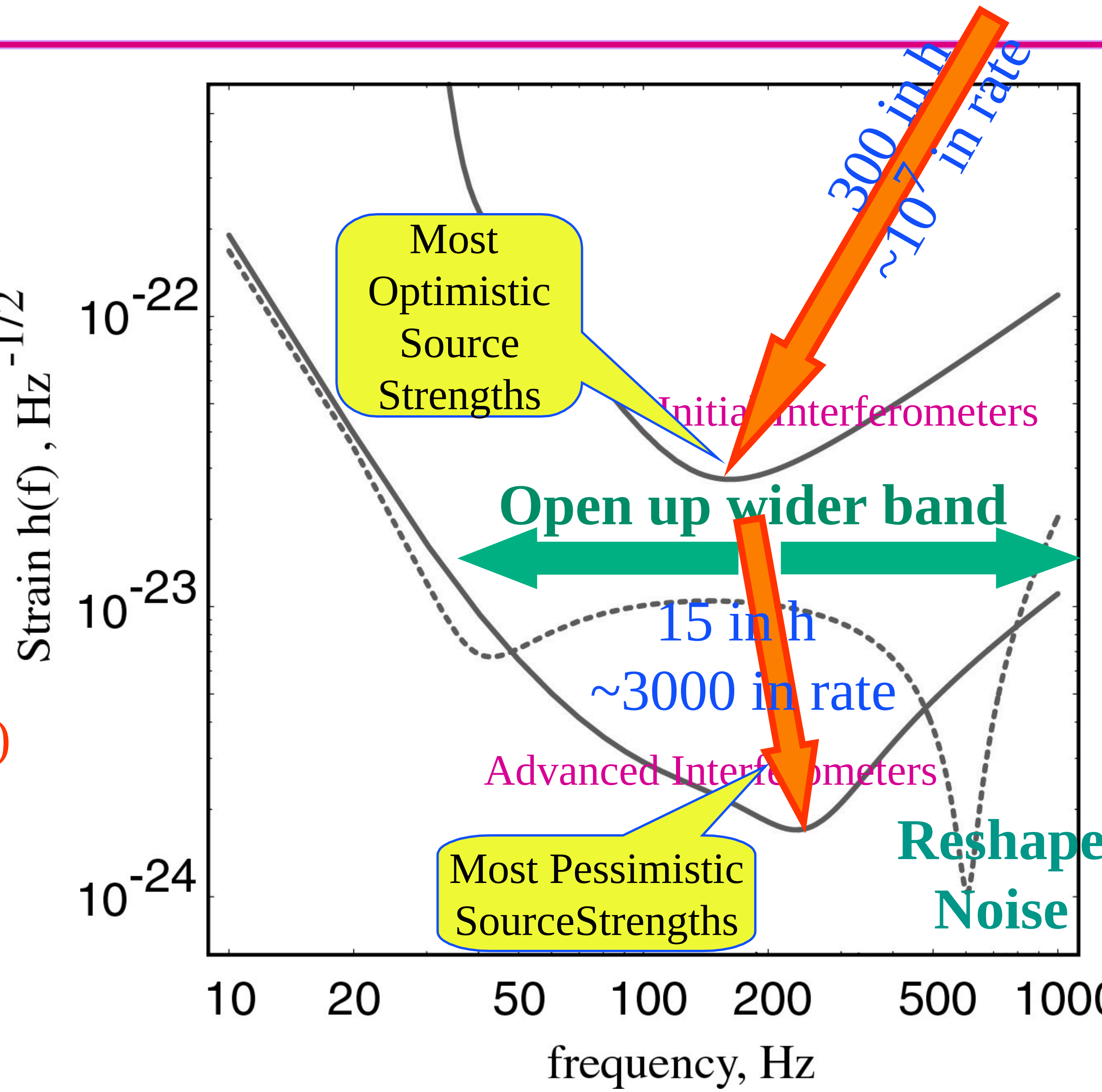
Kip S. Thorne
CaRT, California Institute of Technology

NSF LIGO Operations Panel
Hanford - 26 February 2001

LIGO-G010183-00-M

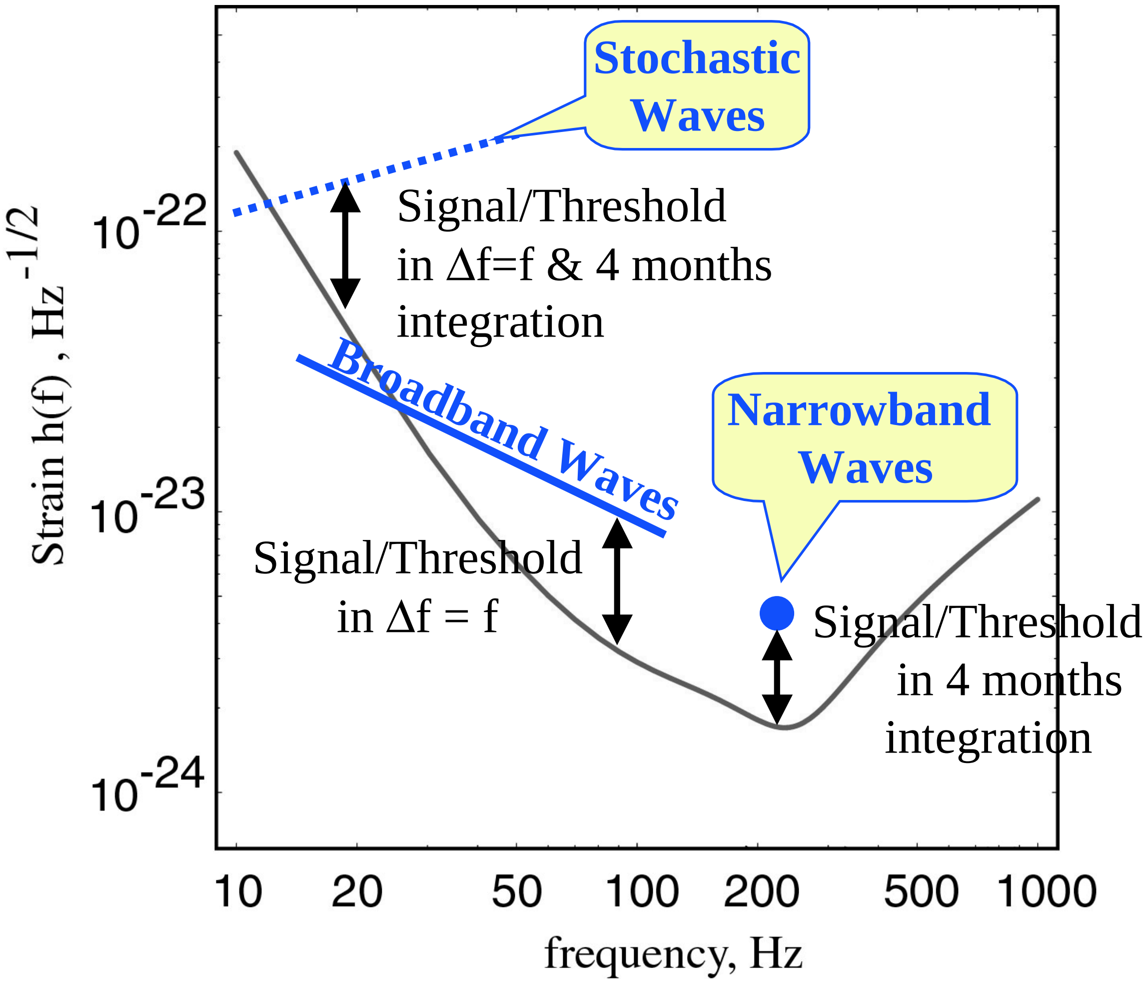
From Initial Interferometers to Advanced

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



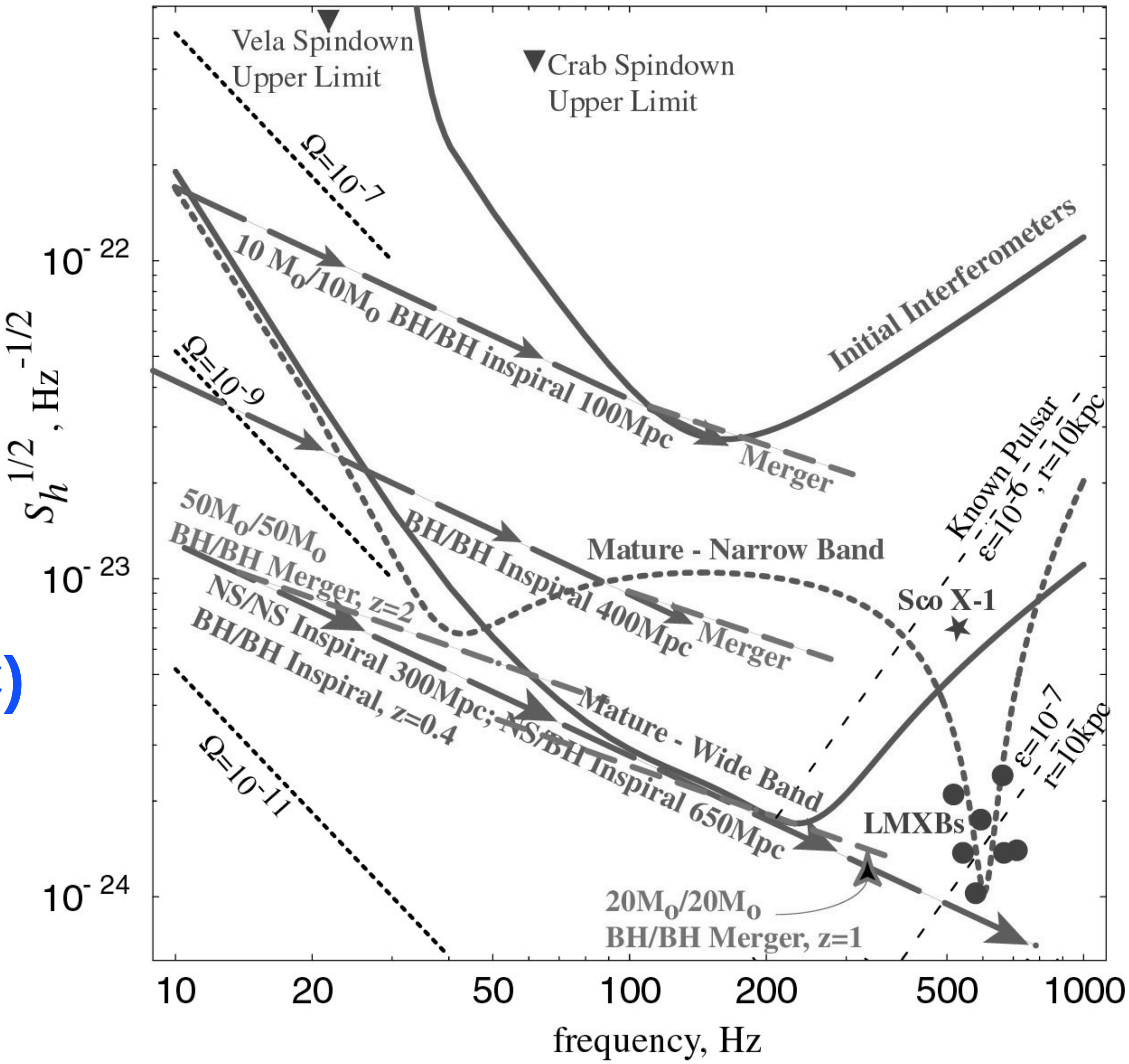
Conventions on Source/Sensitivity Plots

- **Assume the best search algorithm now known**
- **Set Threshold so false alarm probability = 1%**



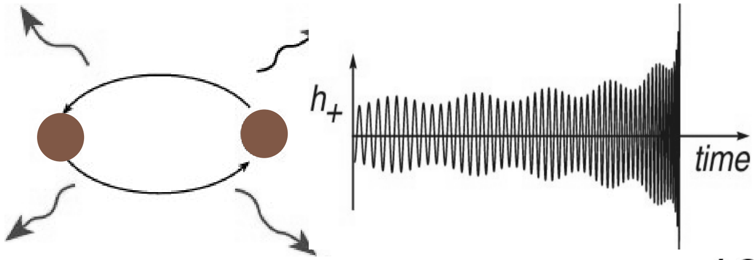
Overview of Sources

- **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

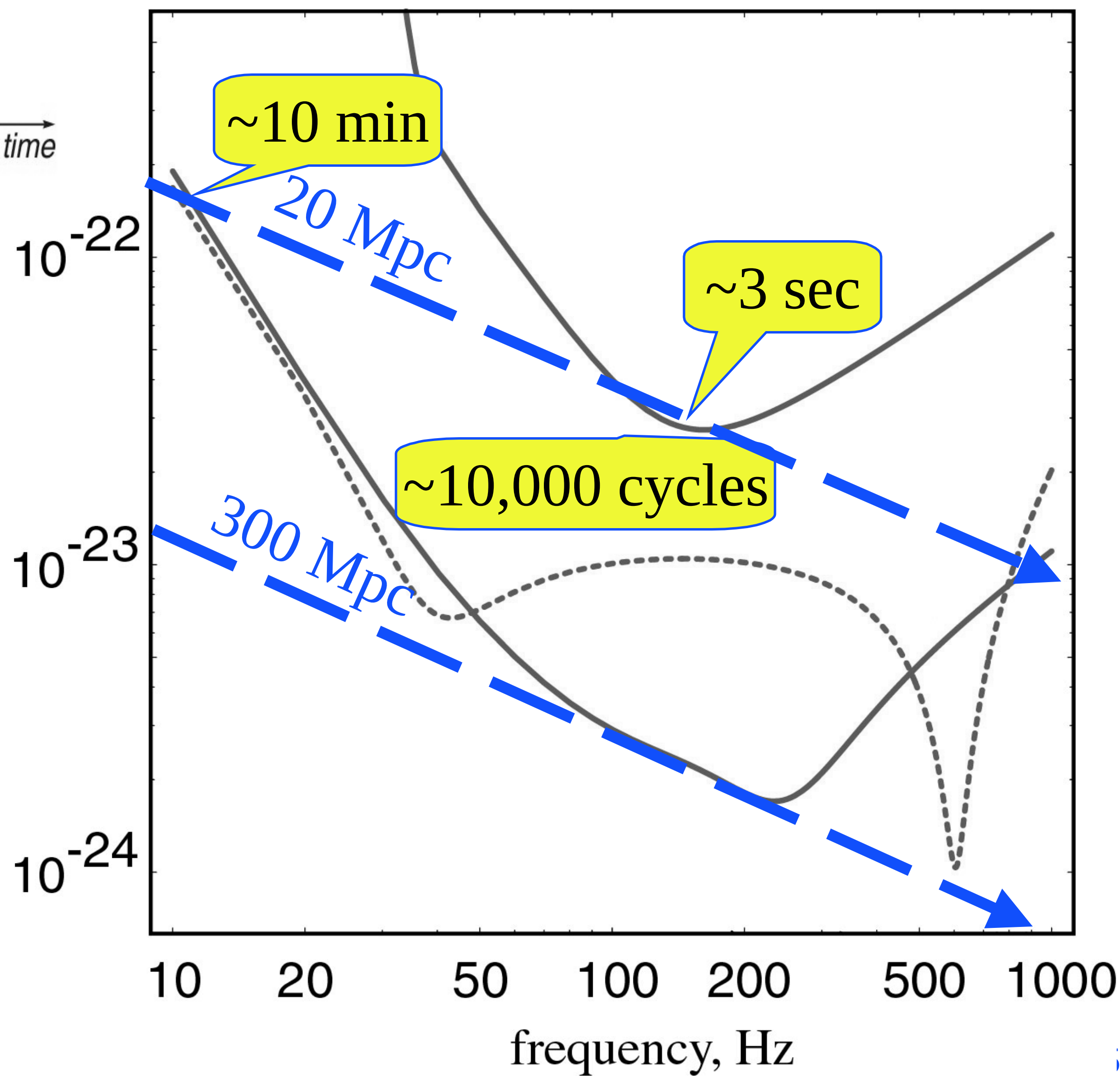


LIGO

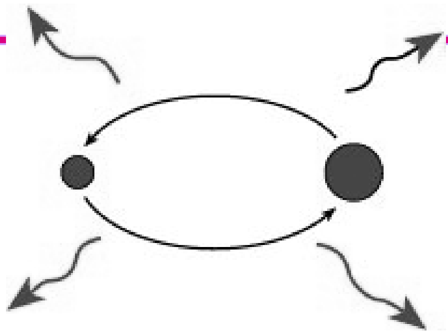
Neutron Star / Neutron Star Inspiral
(our most reliably understood source)

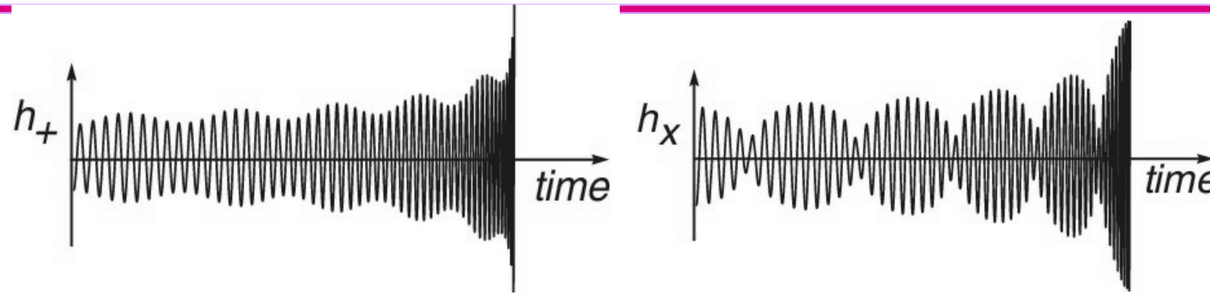


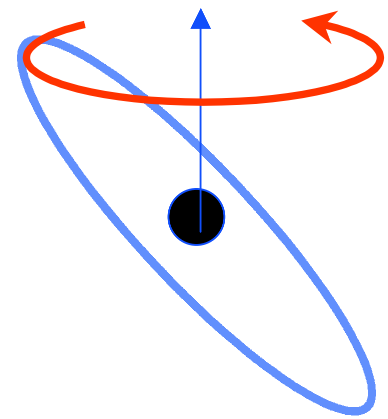
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor astro-ph/0012038
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 3yrs**
- **Advanced IFOs -**
  - » Range: 300Mpc
  - » **1 / yr to 2 / day**



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

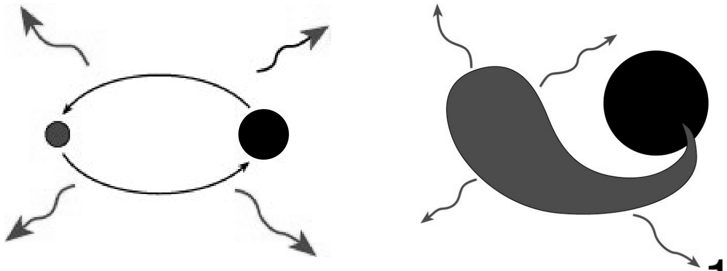




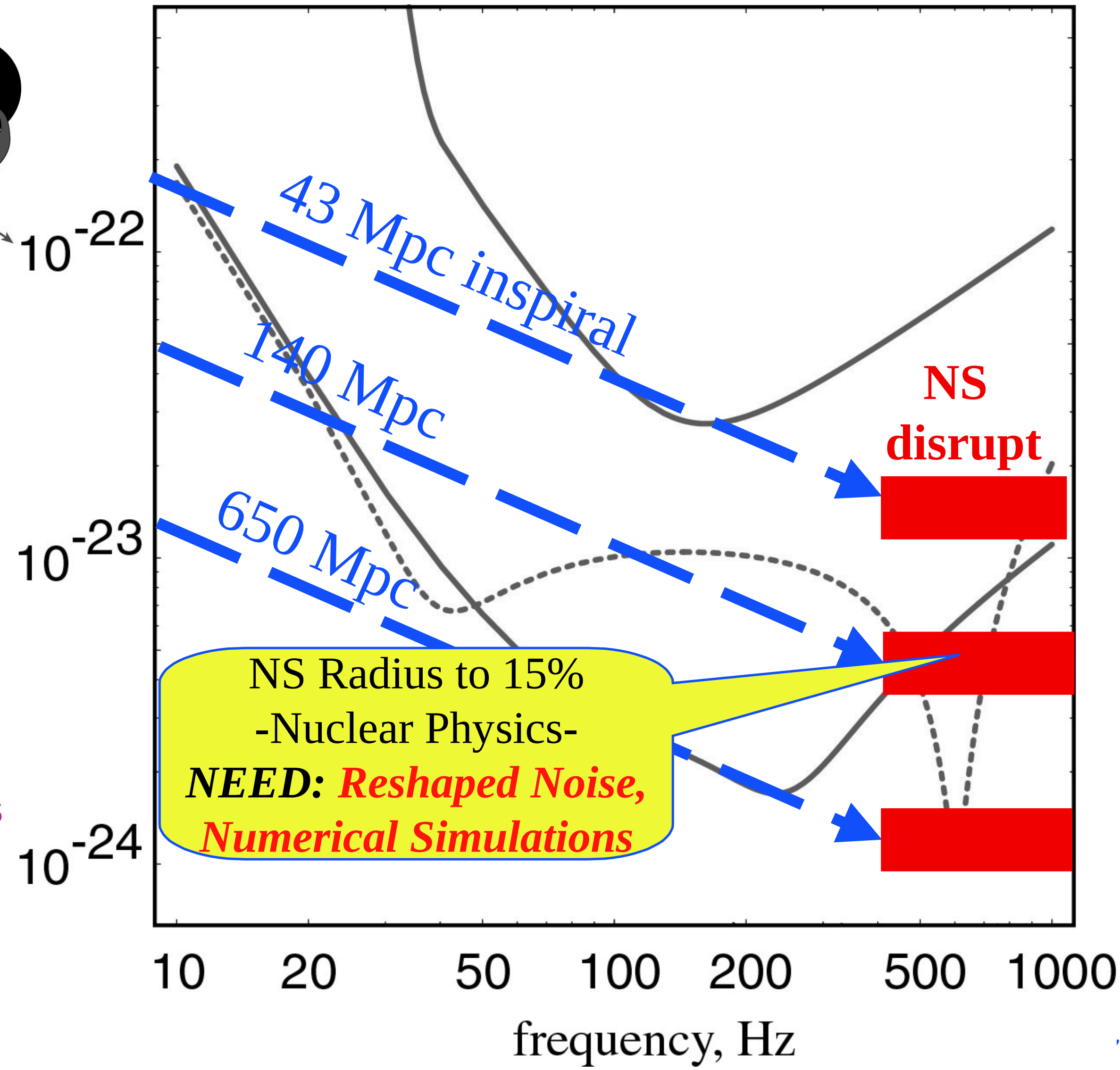


- Relativistic effects are very strong -- e.g.
  - » ***Frame dragging by spins ⇒ precession ⇒ modulation***
  - » ***Tails of waves modify the inspiral rate***
- Information carried:
  - » ***Masses (a few %), Spins (?few%?), Distance [not redshift!] (~10%), Location on sky (~1 degree)***
    - – $M_{\mathbf{chirp}} = \mu^{\mathbf{3/5}} M^{\mathbf{2/5}}$ 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 / 3x10⁹ yrs ~ 10⁻¹⁷***

Neutron Star / Black Hole Inspiral and NS Tidal Disruption

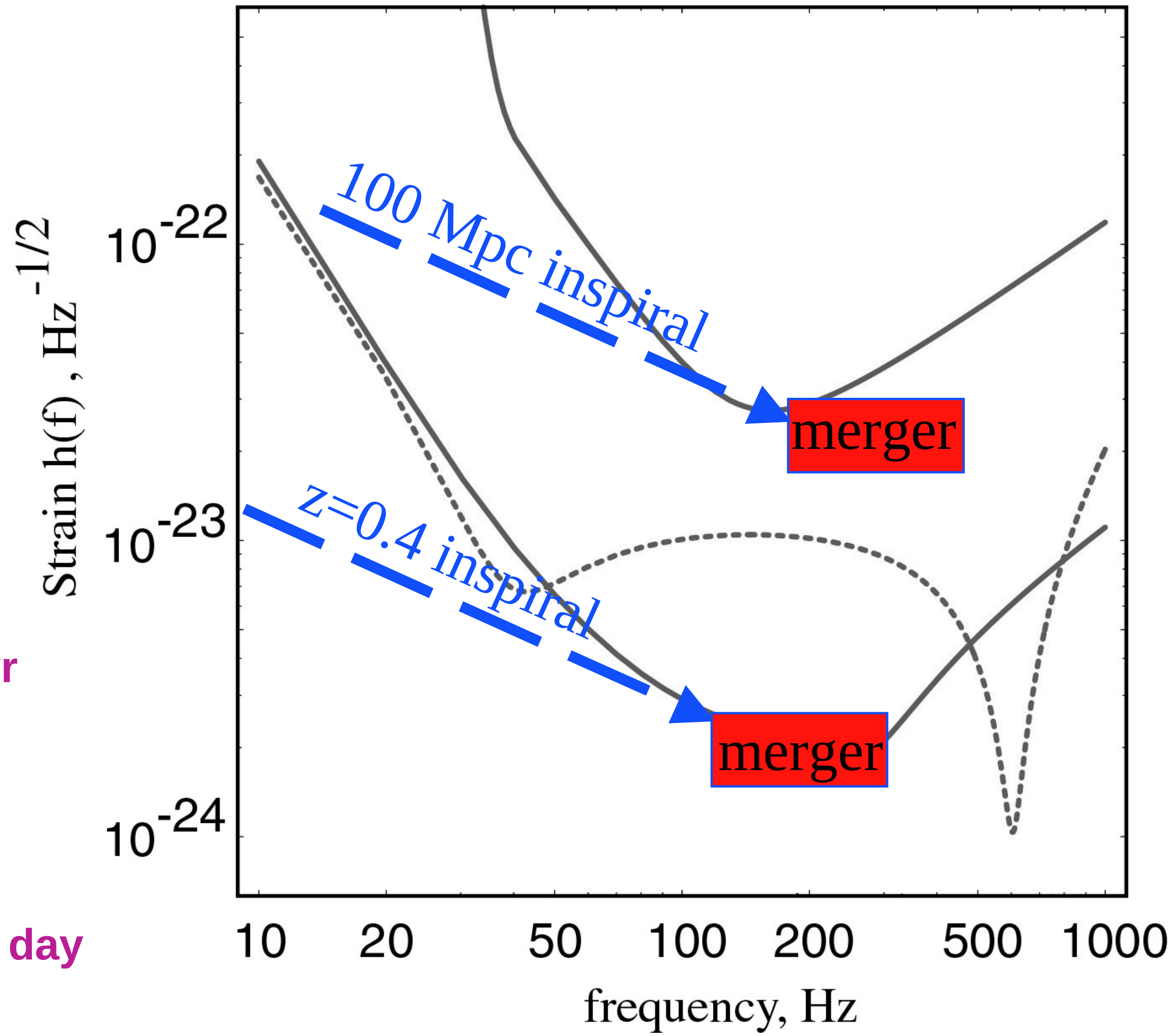


- **1.4Msun / 10 Msun NS/BH Binaries**
- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » ≲1 / 2500 yrs to **1 / 2yrs**
- **Advanced IFOs**
  - » Range: 650 Mpc
  - » **≲1 / yr to 4 / day**

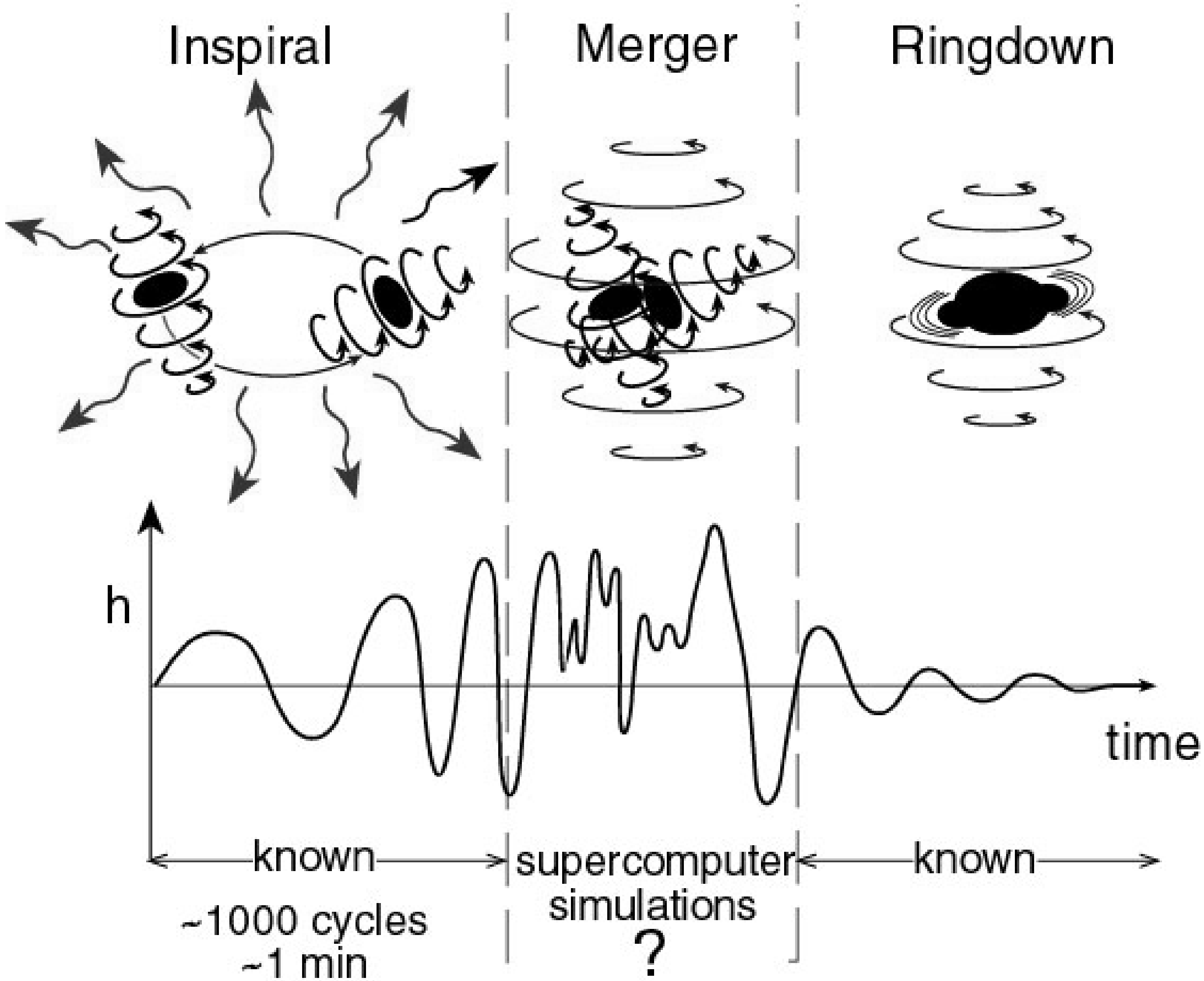


Black Hole / Black Hole Inspiral and Merger

- **10Msun / 10 Msun BH/BH Binaries**
- **Event rates**
  - » Based on population synthesis [Kalogera's summary of literature]
- **Initial IFOs**
  - » Range: 100 Mpc
  - » ≲1 / 300yrs to **~1 / yr**
- **Advanced IFOs -**
  - » Range: z=0.4
  - » **≲2 / month to ~10 / day**

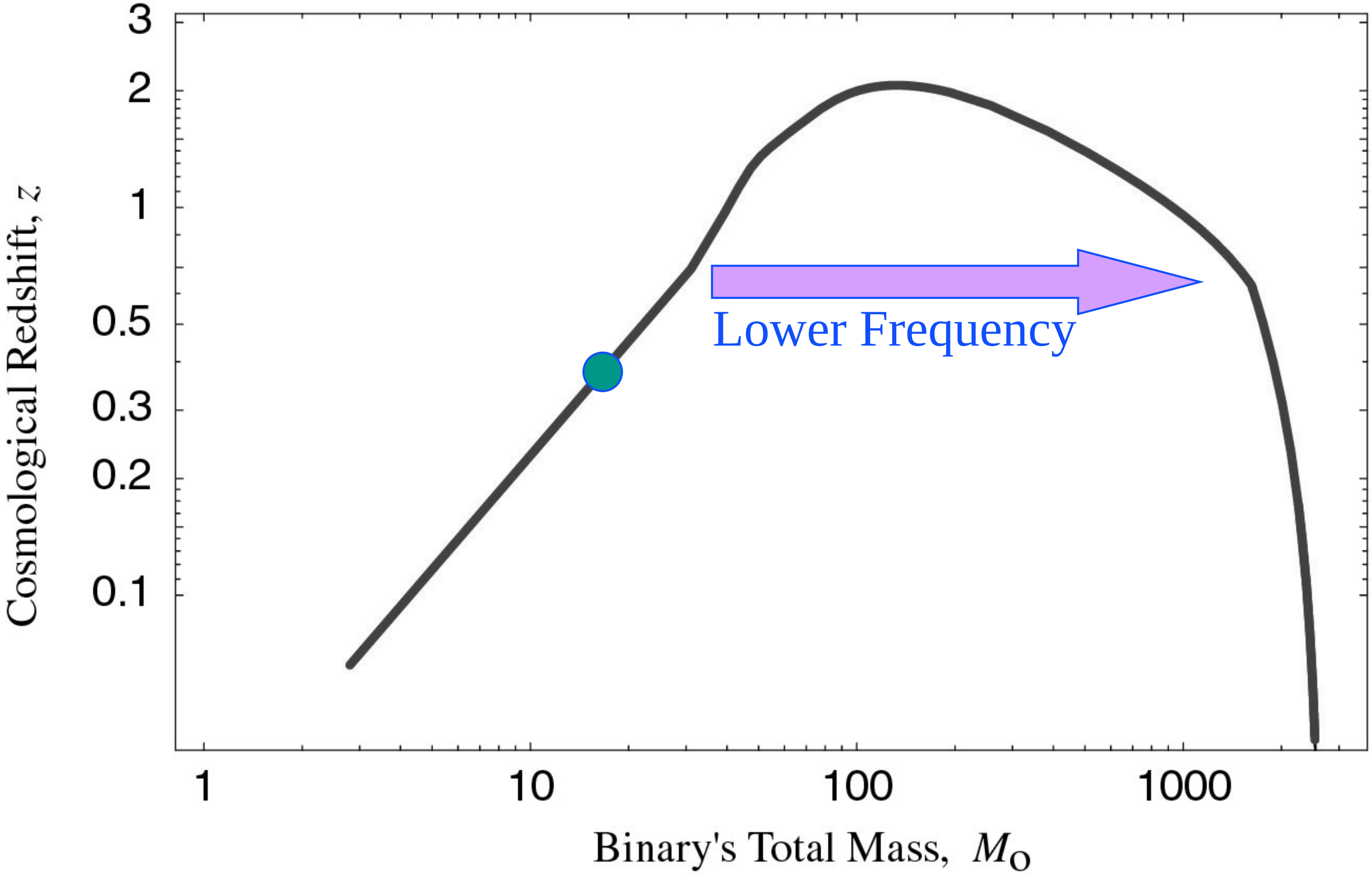


BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



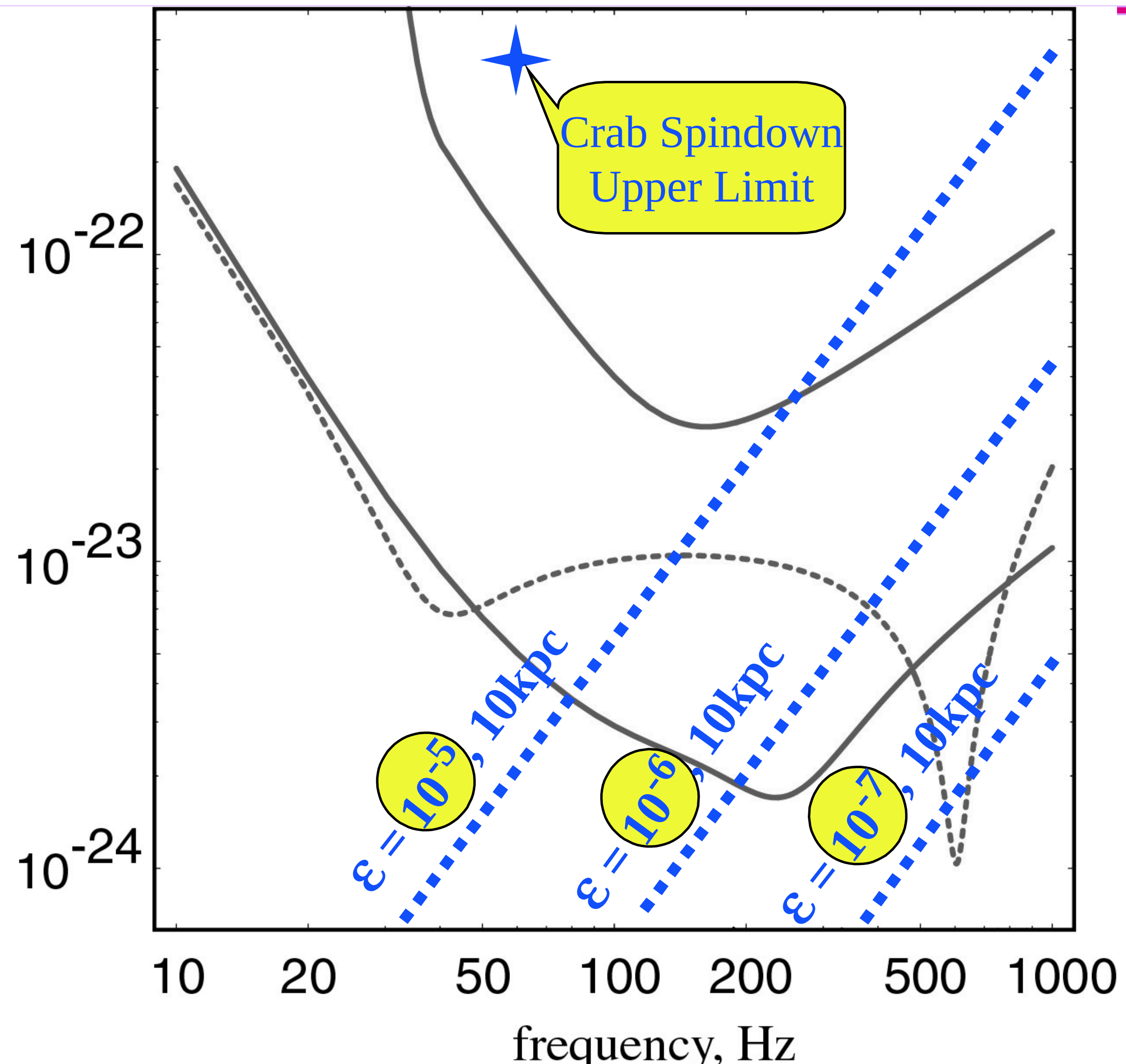
Numerical Relativity Simulations Are Badly Needed!

Massive BH/BH Mergers with Fast Spins - Advanced IFOs



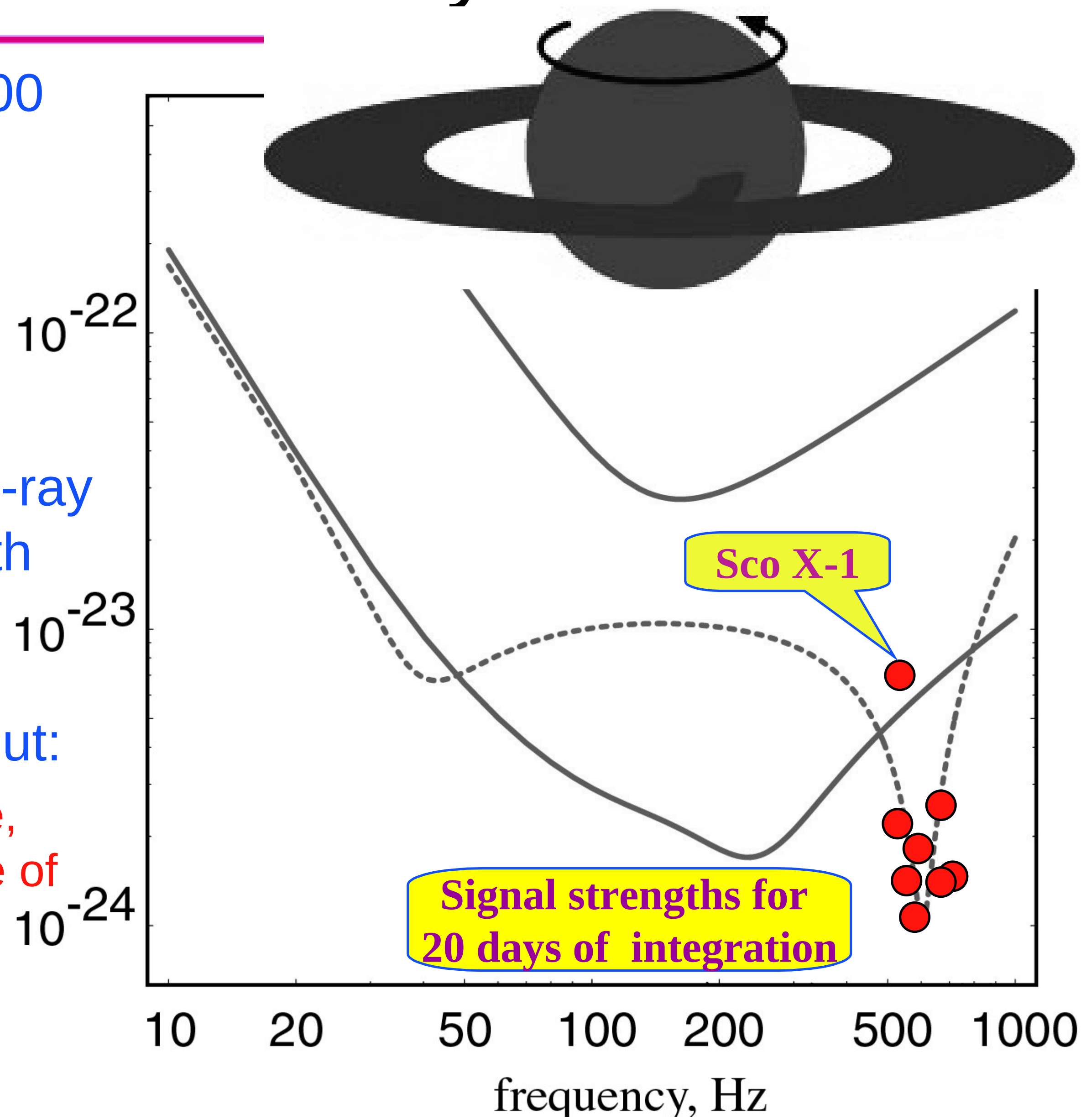
Spinning NS's: Pulsars

- NS Ellipticity:
  - » Crust strength ε
    $\varepsilon \lesssim 10^{-6}$; possibly 10^{-5}
- Known Pulsars:
  - » First Interferometers:
    $\varepsilon \gtrsim 3\text{x}10^{-6}$ (1000Hz/f) x (distance/10kpc)
  - » Narrowband Advancedδ
    $\varepsilon \gtrsim 2\text{x}10^{-8}$ $(1000\text{Hz/f})^2$ x (distance/10kpc)
- Unknown NS's - All sky search:
  - » Sensitivity ~5 to 15 worse



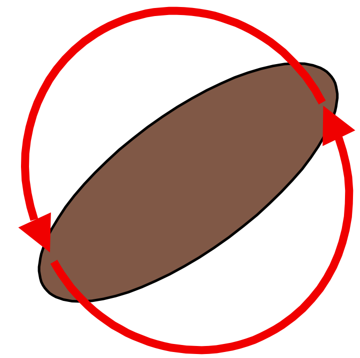
Spinning Neutron Stars: Low-Mass X-Ray Binaries

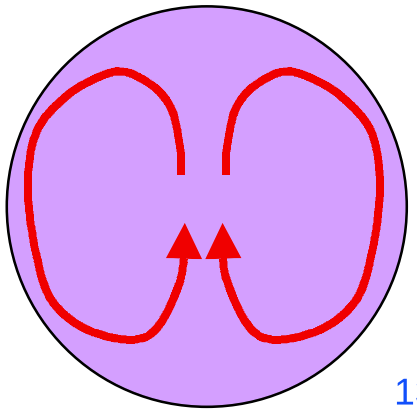
- Rotation rates ~250 to 700 revolutions / sec
  - » Why not faster?
  - » **Bildsten**: Spin-up torque balanced by GW emission torque
- If so, and steady state: X-ray luminosity ⇒ GW strength
- Combined GW & EM obs's ⟹ information about:
  - » crust strength & structure, temperature dependence of viscosity, ...



NS Birth:
Tumbling Bar; Convection

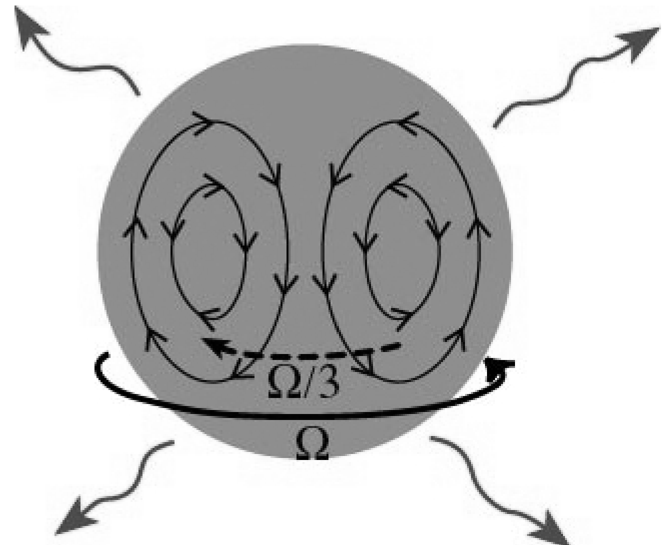
- **Born in:**
  - Supernovae
  - Accretion-Induced Collapse of White Dwarf
- **If very fast spin:**
  - Centrifugal hangup
  - **Tumbling bar -** episodic? (for a few sec or min)
  - ***If modeling gives enough waveform information,*** detectable to:
    - Initial IFOs: ~5Mpc (M81 group, ~1 supernova/3yr)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





Neutron-Star Births: R-Mode Sloshing in First ~1yr of Life

- **NS formed in supernova or accretion-induced collapse of a white dwarf.**
  - » *If* NS born with P_{spin} < 10 msec: ***R-Mode instability:***
  - » Gravitational radiation reaction drives sloshing



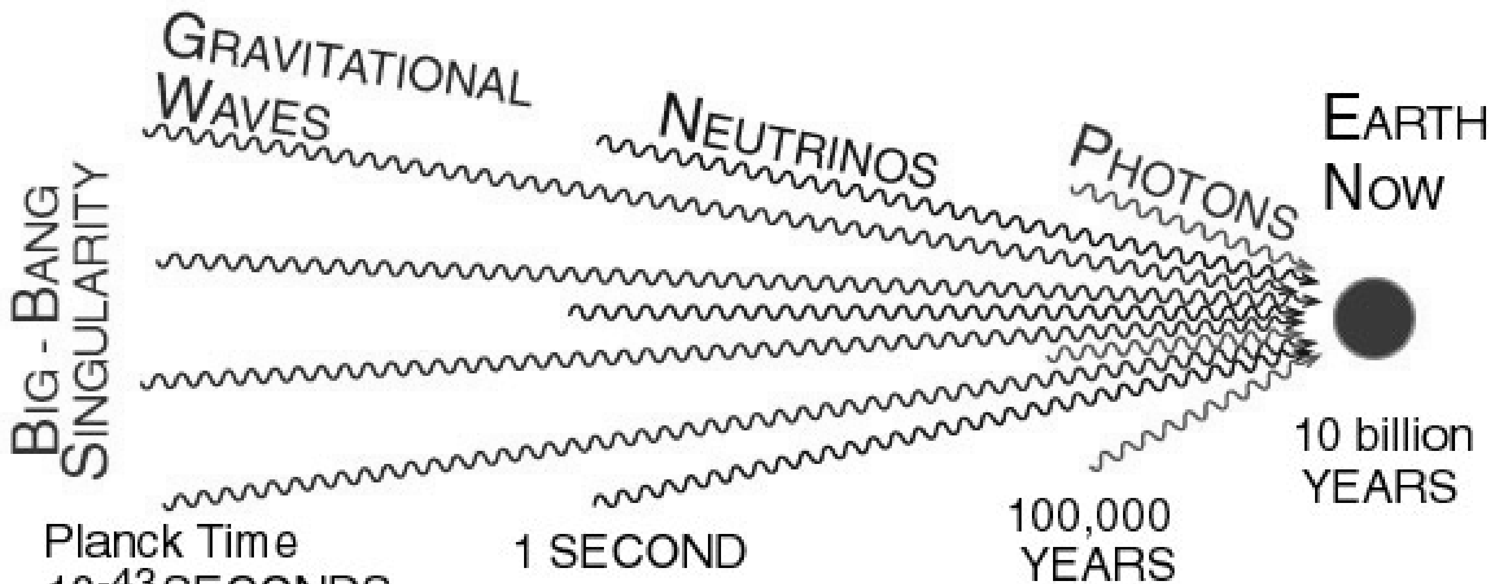
- **Physics complexities: What stops the growth of sloshing & at what amplitude?**
  - » Crust formation in presence of sloshing?
  - » Coupling of R-modes to other modes?
  - » Wave breaking & shock formation?
  - » Magnetic-field torques?
  - » ….

Depending on this, Initial IFOs detect to 1 Mpc (Local Group, ~1 SN/15yr) Advanced IFOs detect to 20 Mpc (Virgo, ~5 SN/yr)

GW's carry information about these

Stochastic Background from Very Early Universe

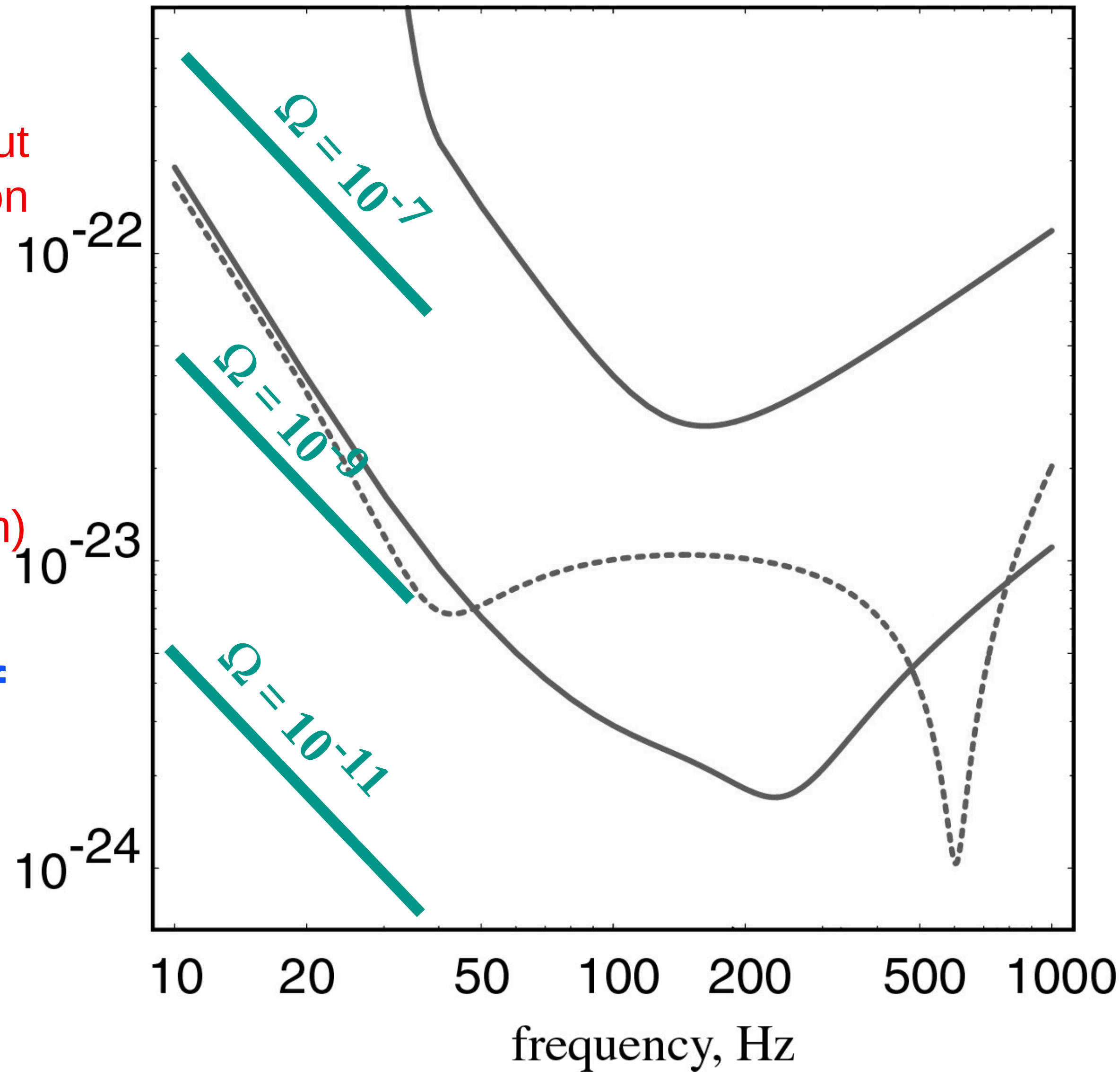
- **GW's are the ideal tool for probing the very early universe**



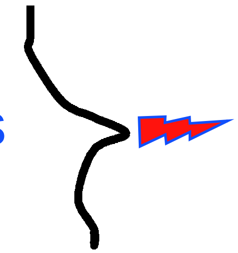
- **Present limit on GWs**
  - » From effect on primordial nucleosynthesis
  - » Ω = (GW energy density)/(closure density) $\lesssim$ **10^{-5}**

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:**
  - » **$\Omega \gtrsim 5\text{x}10^{-9}$**



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 LIGO
- GW bursts from cosmic strings: possibly detectable by Initial IFOs
- Energetic processes at (universe age) ~ 10^{-25} sec and (universe temperature) ~ 10^{9} Gev $\Rightarrow$ GWs in LIGO band
  - » **phase transition at 10^{9} Gev**
  - » **excitations of our universe as a 3-dimensional "brane" (membrane) in higher dimensions:**
    - **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