LIGO

ADVANCED LIGO SCIENCE

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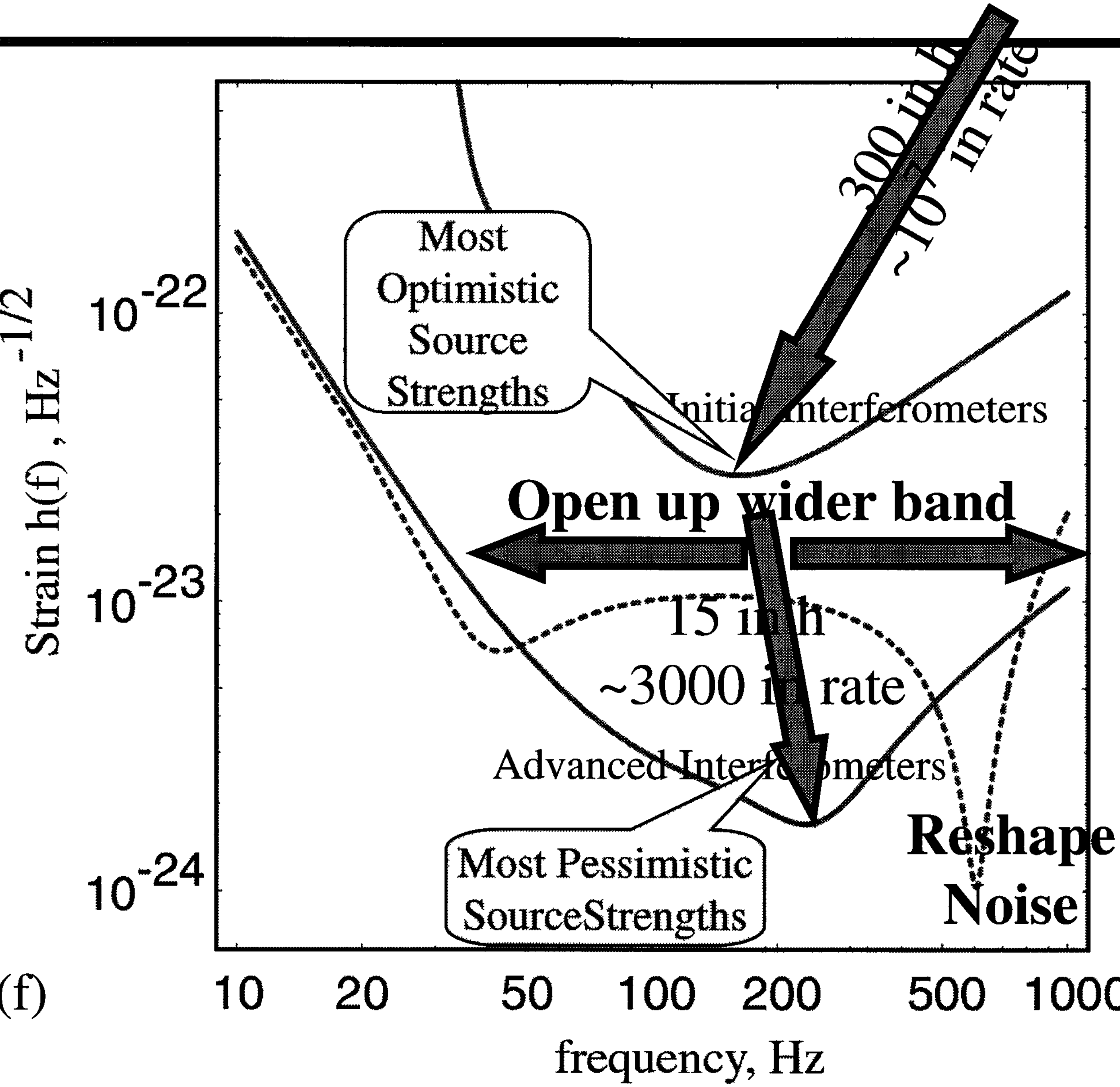
NSF Advanced R&D Panel - 29 January 2001

LIGO-G010430-00-R

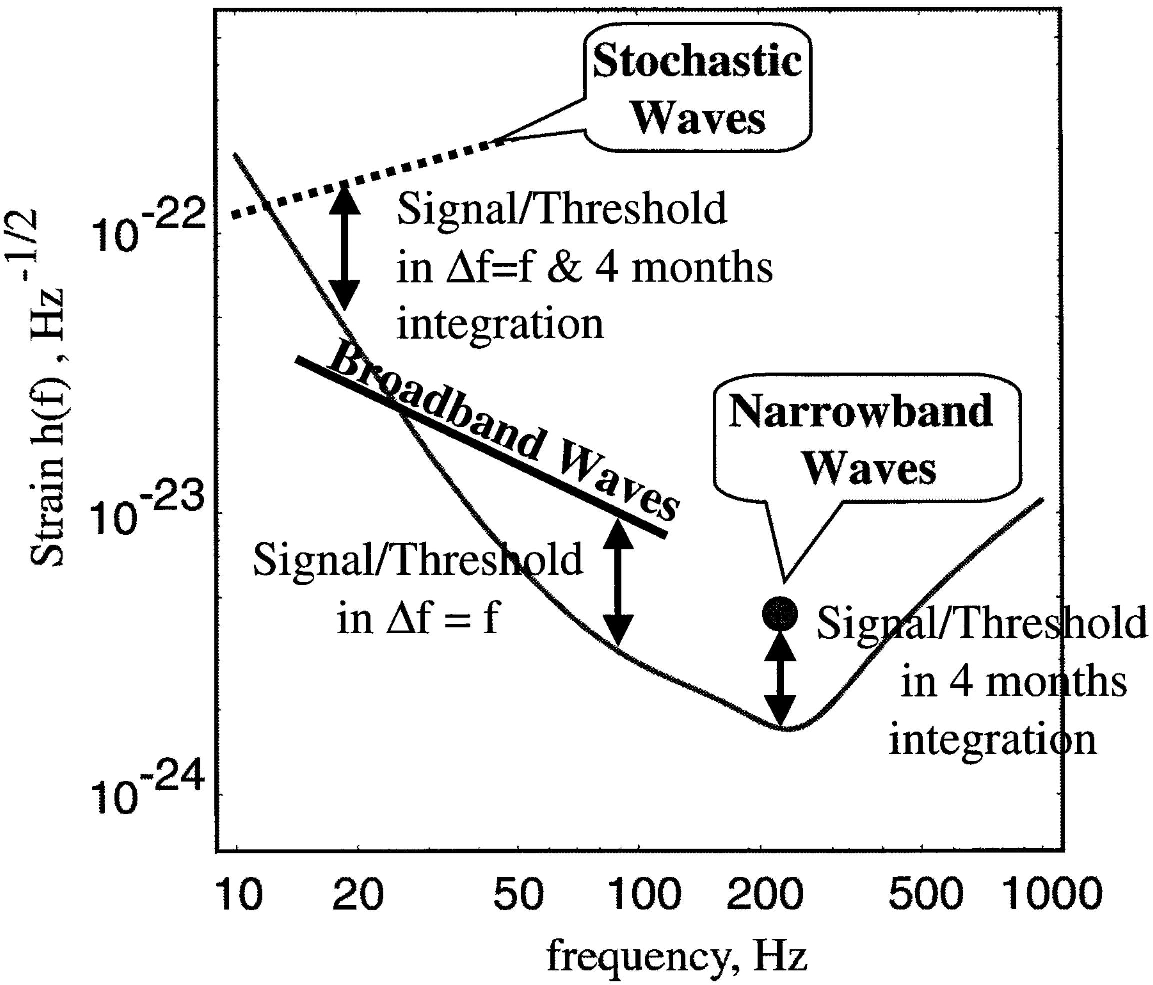
LIGO From Initial Interferometers to Advanced



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

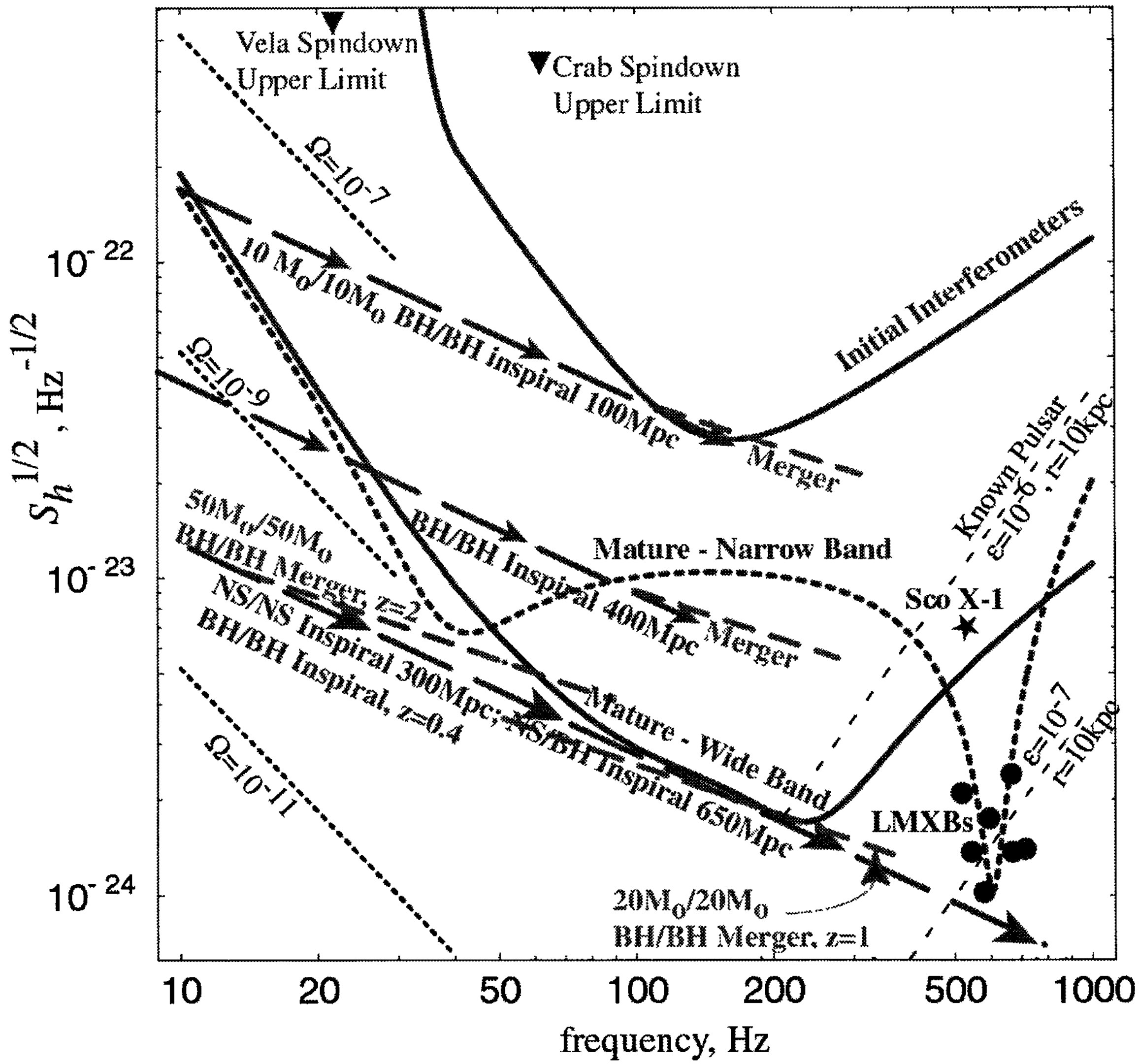
Conventions on Source/Sensitivity Plots

- **Advanced Interferometer:**
  - » sapphire test masses
  - » (If silica, event rate reduced by ~ 2)
- **Data Analysis:**
  - » Assume the best search algorithm now known
- **Threshold:**
  - » Set so false alarm probability = 1%



Overview of Sources

- **Neutron Star & Black Hole Binaries**
  - » inspiral
  - » merger
- **Spinning NS's**
  - » LMXBs
  - » known pulsars
  - » previously unknown
- **Stochastic background**
  - » big bang
  - » early universe



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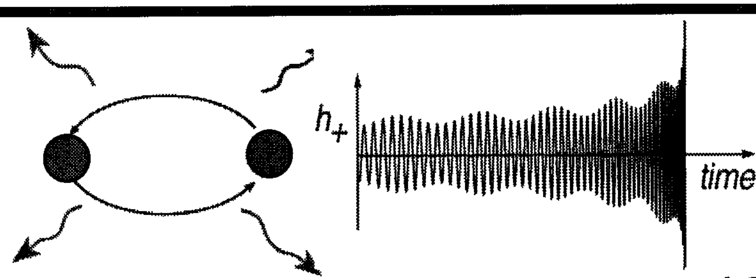
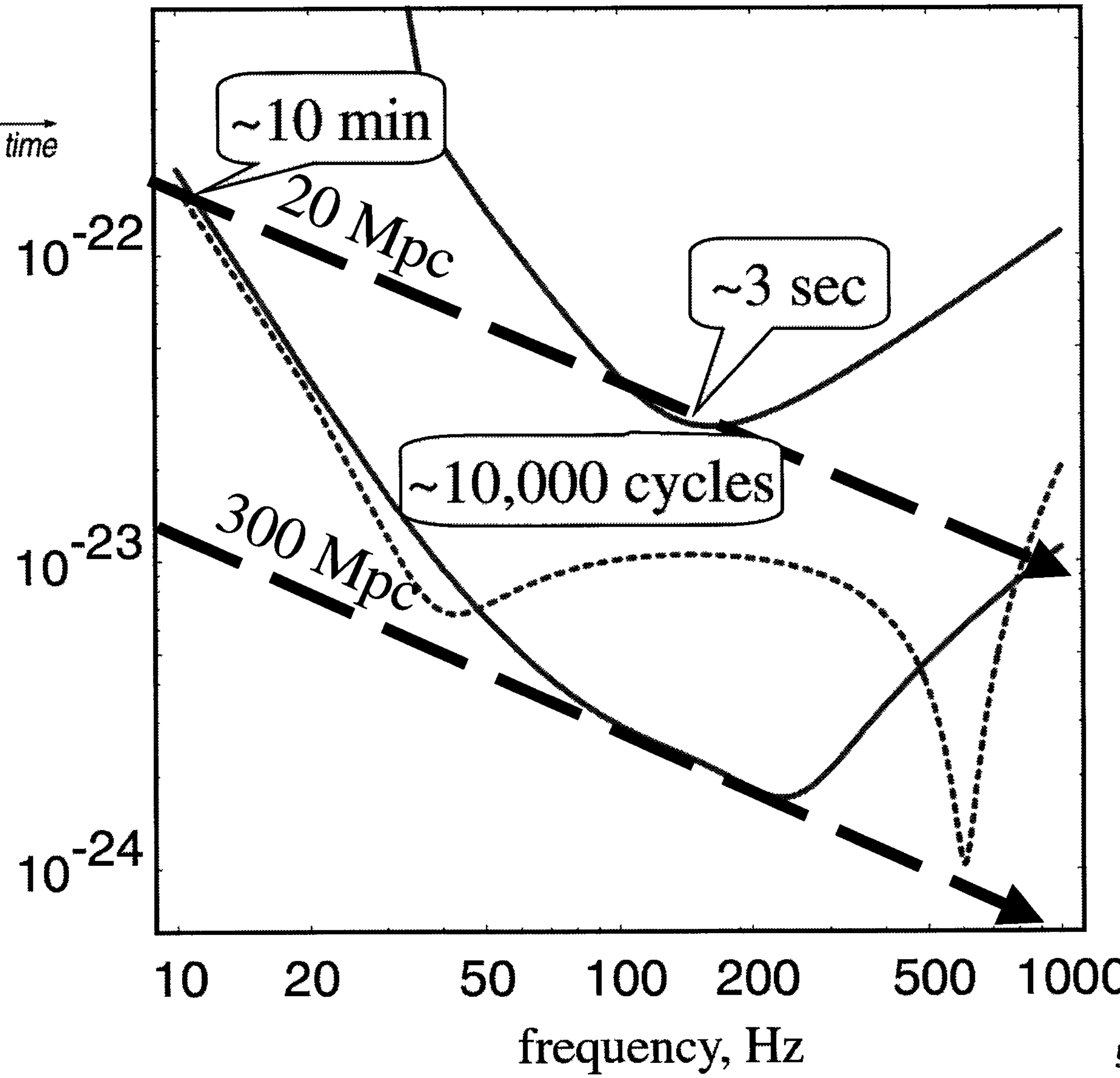
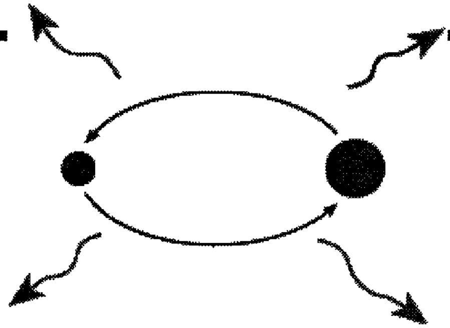
Neutron Star / Neutron Star Inspiral (our most reliably understood source)

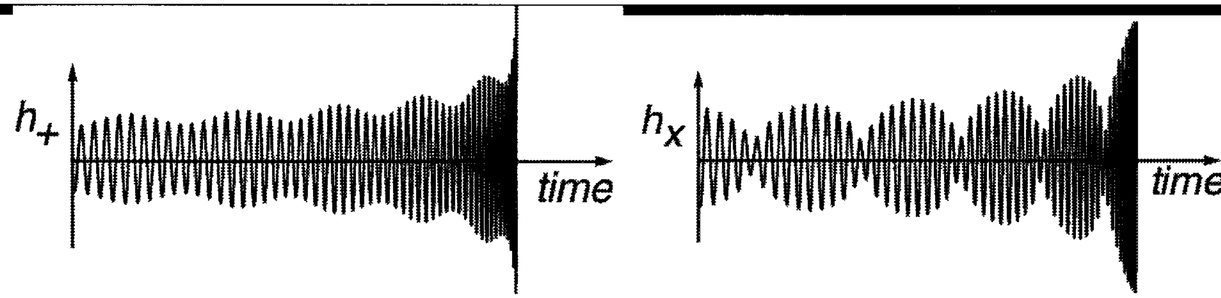


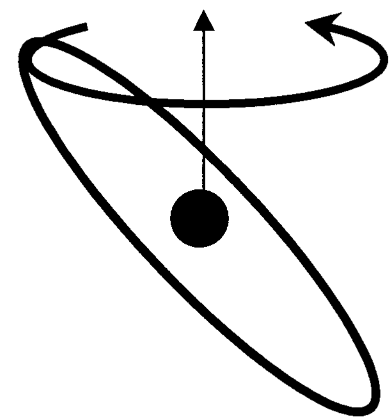
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor astro-ph/0012038
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to 1 / 3yrs
- **Advanced IFOs -**
  - » Range: 300Mpc
  - » 1 / yr to 2 / day



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)***
    - – $M_{\mathbf{chirp}} = \mu^{3/5} M^{2/5}$ to ~10^{-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}***

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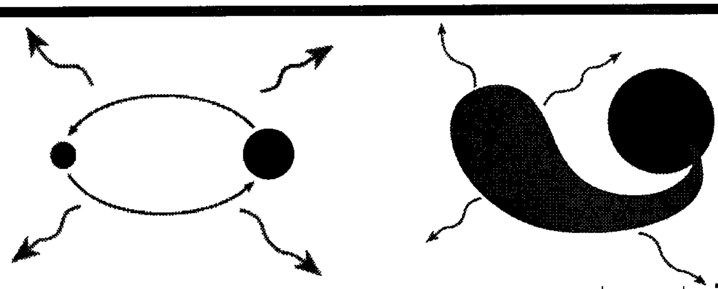
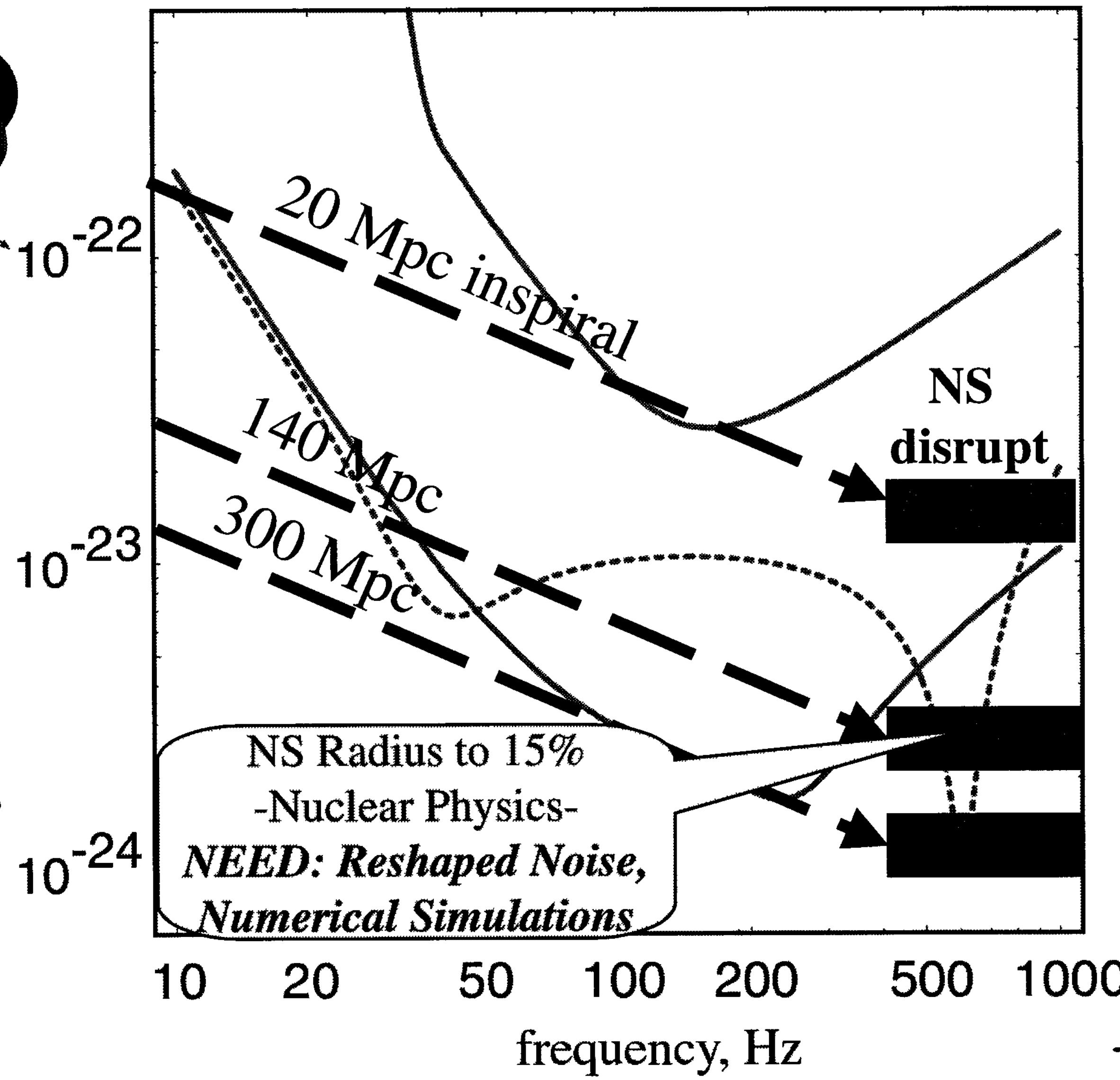
Neutron Star / Black Hole Inspiral and NS Tidal Disruption

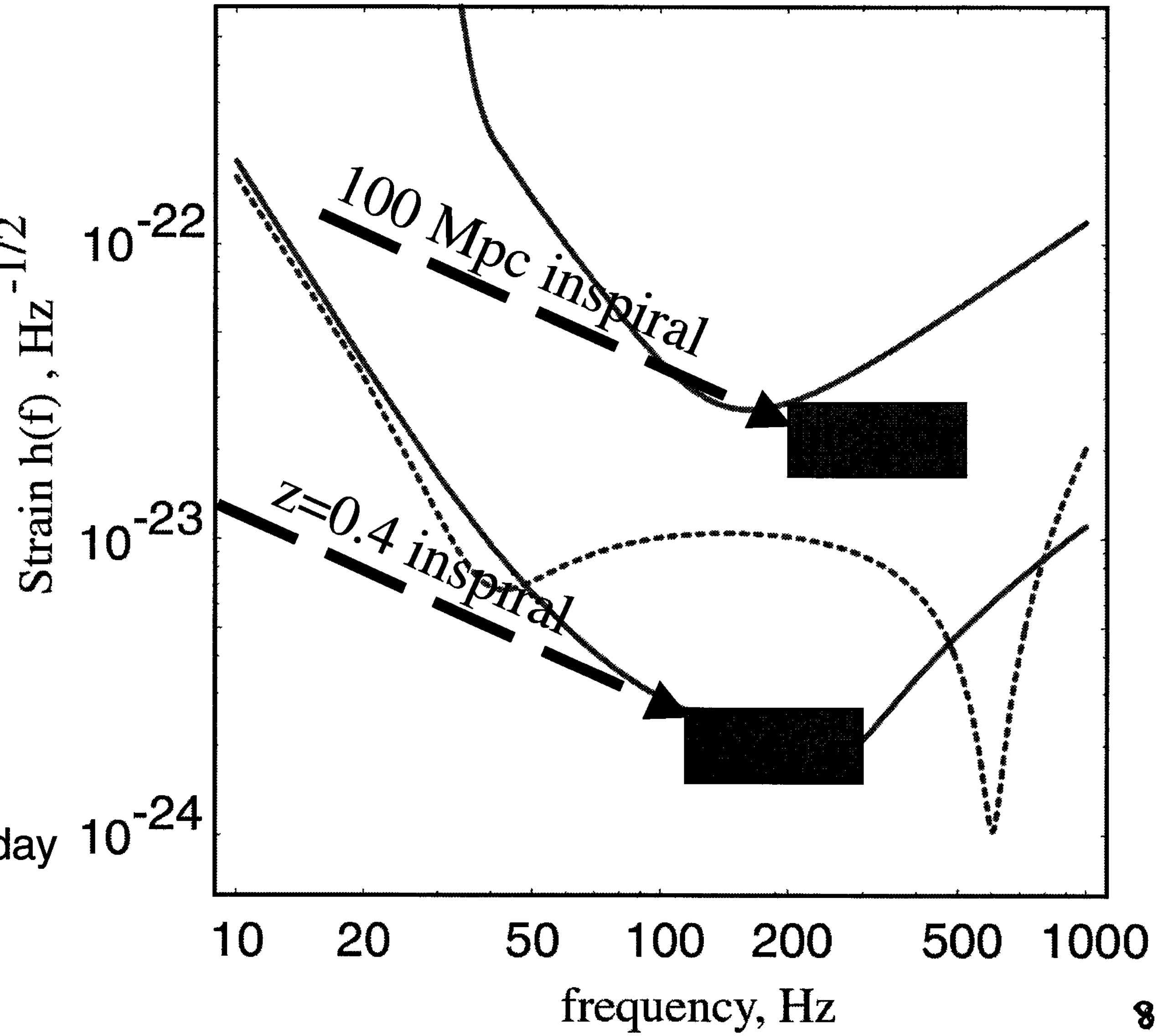


- **1.4Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » ≲ 1 / 2500 yrs to 1 / 2yrs
- **Advanced IFOs**
  - » Range: 300Mpc
  - » ≲ 1 / yr to 4 / day

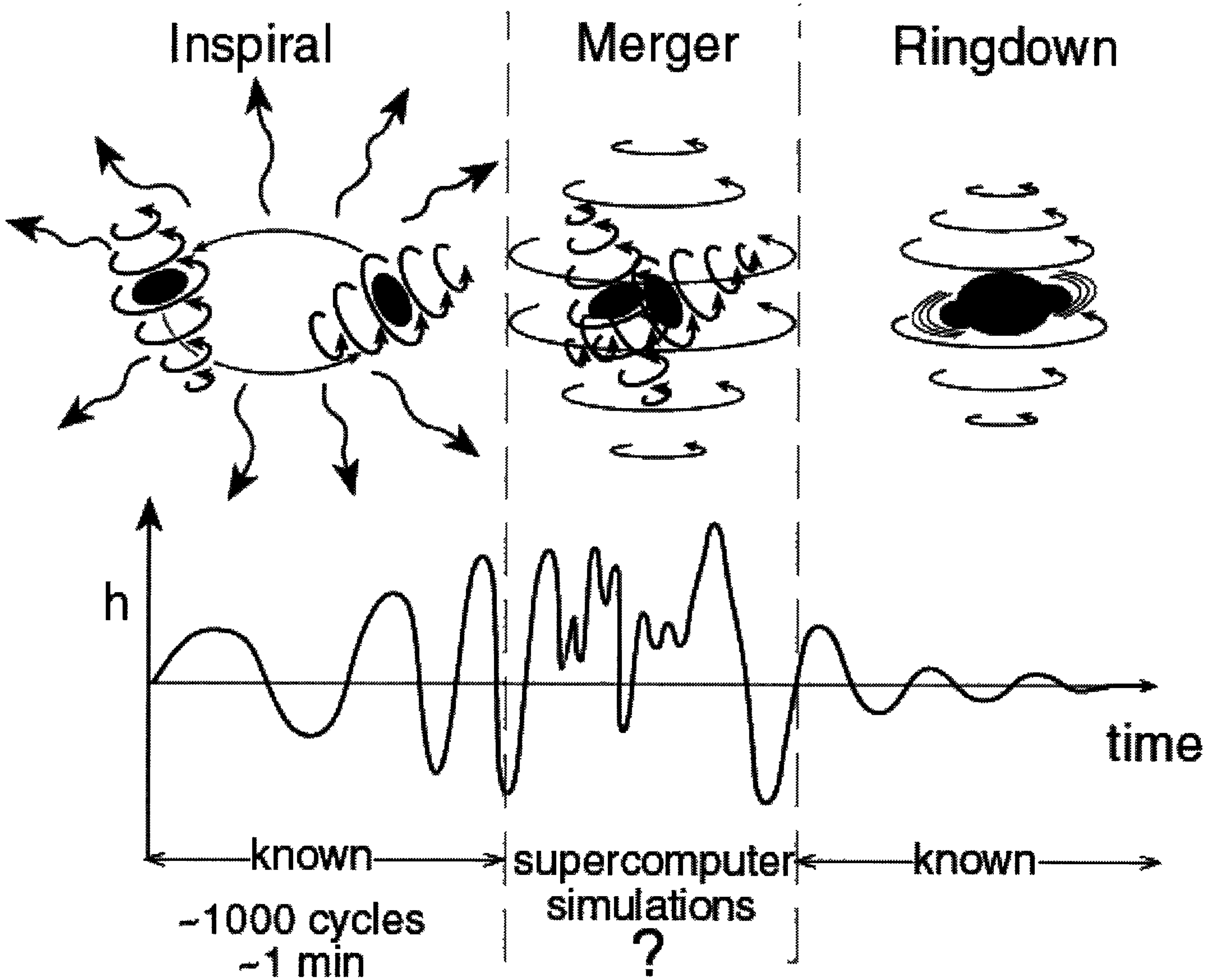


Black Hole / Black Hole Inspiral and Merger

- **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

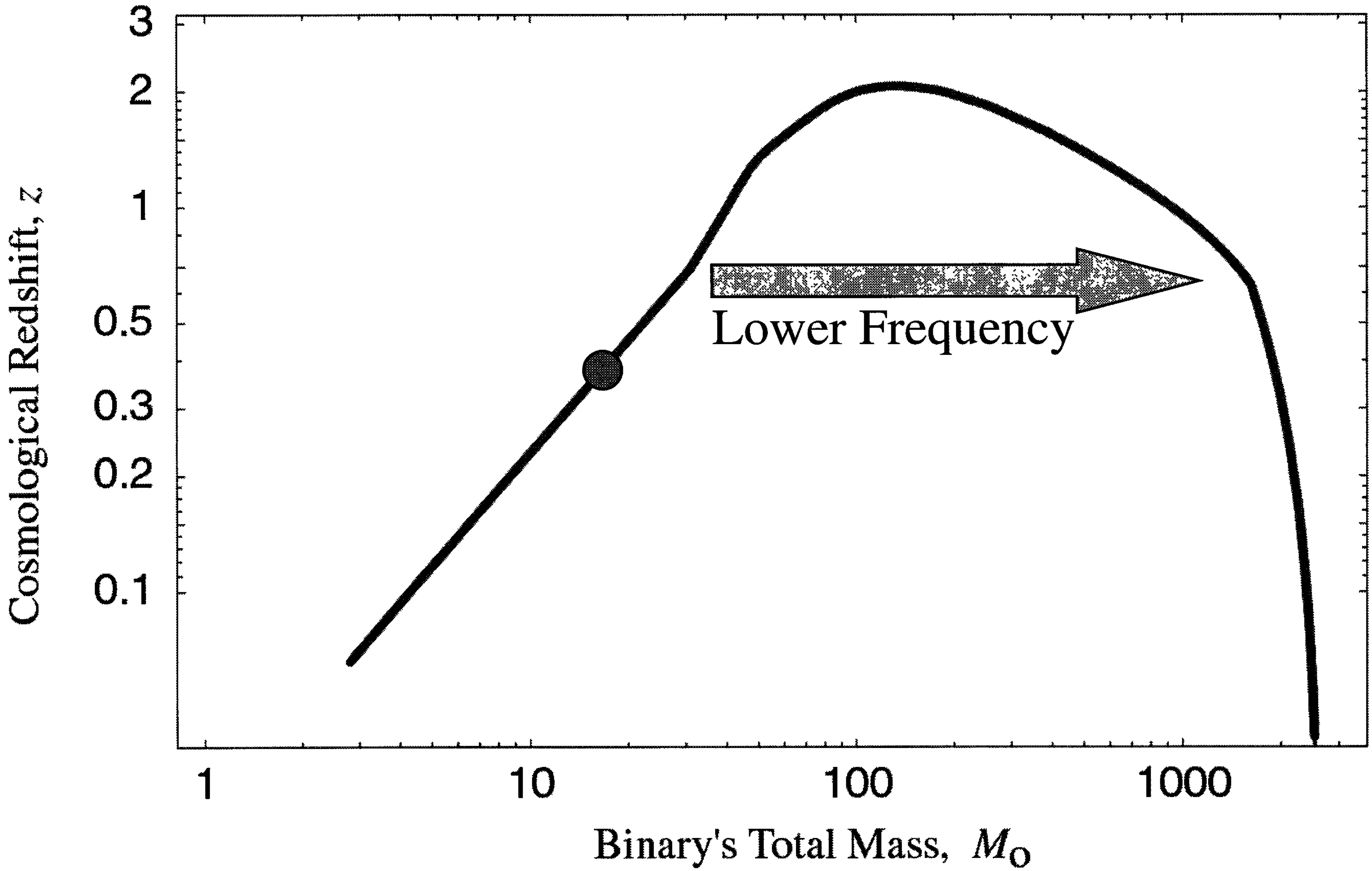


BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



Numerical Relativity Simulations Are Badly Needed!

Massive BH/BH Mergers with Fast Spins



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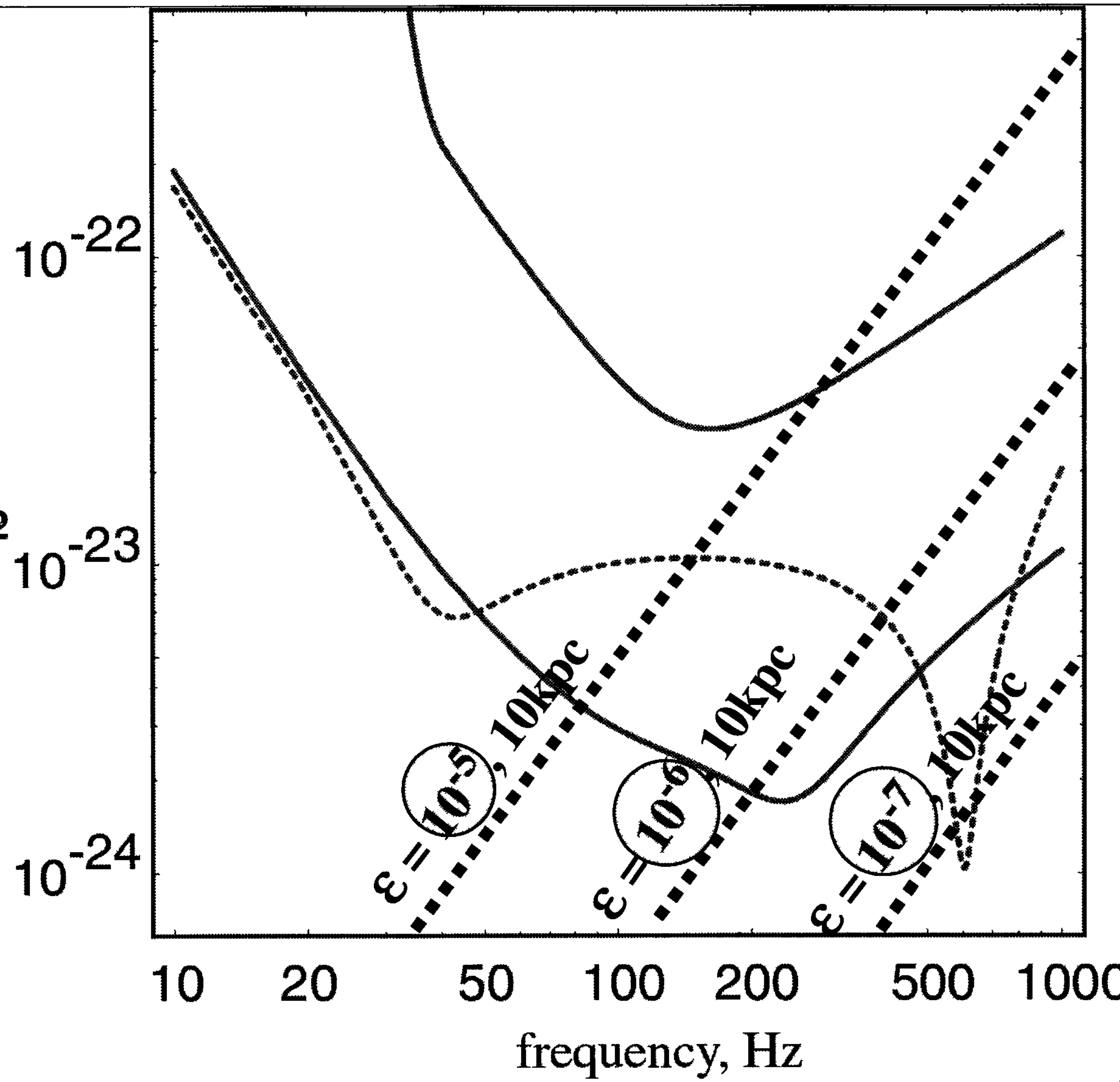
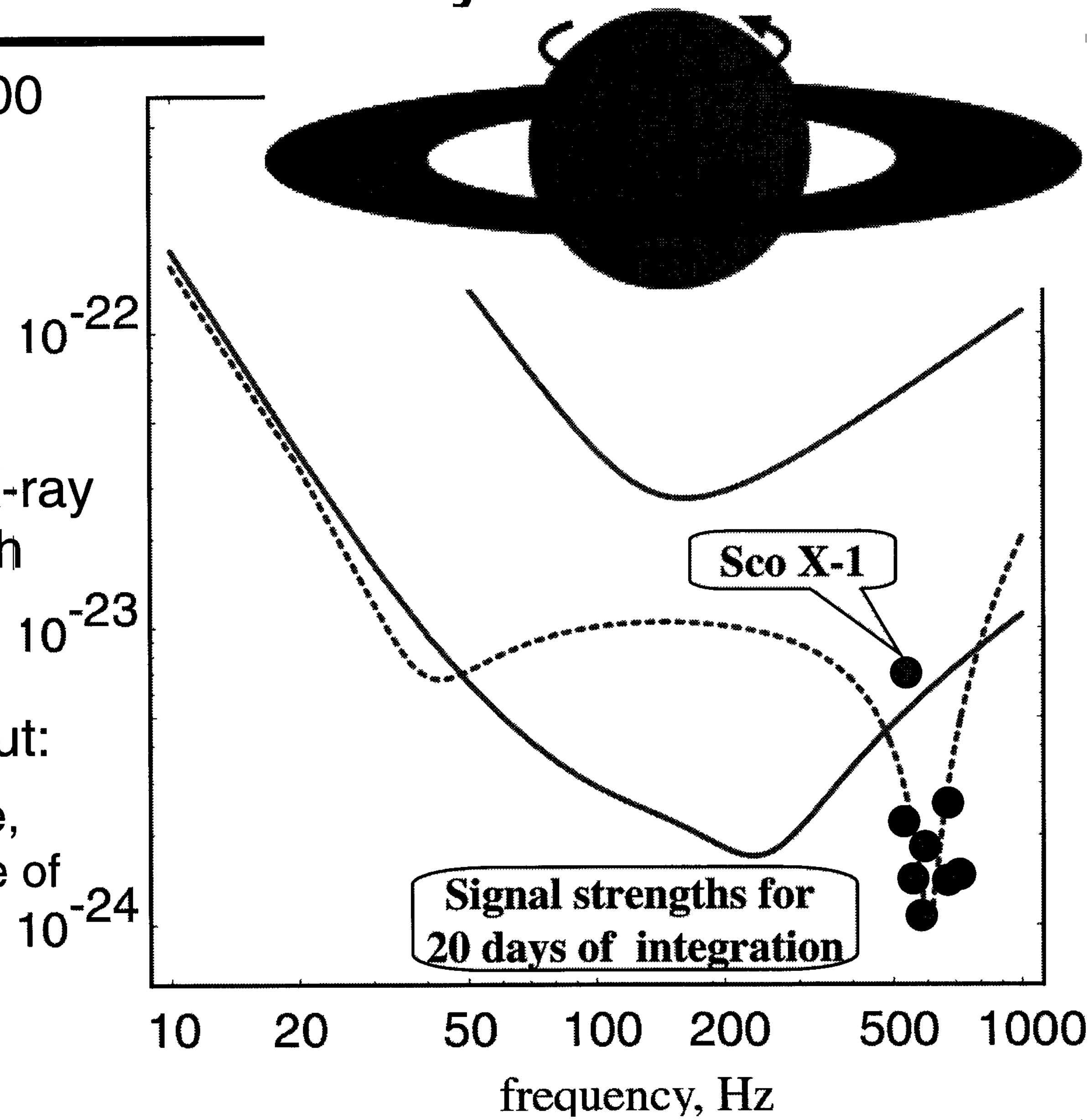
Spinning NS's: Pulsars

- NS Ellipticity:
  - » Crust strength ⇒ $\varepsilon \lesssim 10^{-6}$; possibly 10^{-5}
- Known Pulsars:
  - » Detectable by Narrow-Band IFO if
  - » $\varepsilon \gtrsim 2\times10^{-8}$ (f/1000Hz)^{2} x (distance/10kpc)
- Unknown NS's - All sky search:
  - » Sensitivity ~5 to 15 worse



Spinning Neutron Stars: Low-Mass X-Ray Binaries

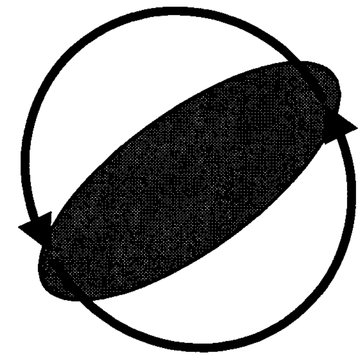
- Rotation rates ~250 to 700 revolutions / sec
  - » Why not faster?
  - » **Bildsten**: Spin-up torque balanced by GW emission torque
- If so, and steady state: X-ray luminosity ⇒ GW strength
- Combined GW & EM obs's ⇒ information about:
  - » crust strength & structure, temperature dependence of viscosity,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



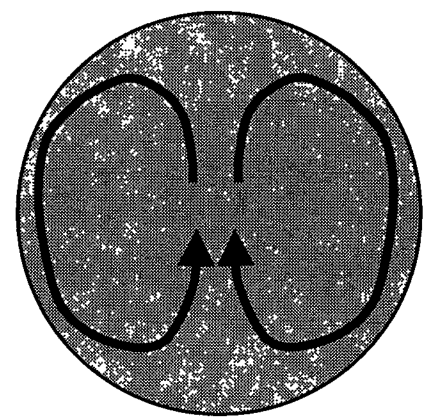
NS Birth:
Tumbling Bar; Convection

- **Born in:**
  - » Supernovae
  - » Accretion-Induced Collapse of White Dwarf

- **If very fast spin:**
  - » Centrifugal hangup
  - » **Tumbling bar** - episodic? (for a few sec or min)
  - » Detectable to ~100Mpc ***if modeling has given us enough waveform information***

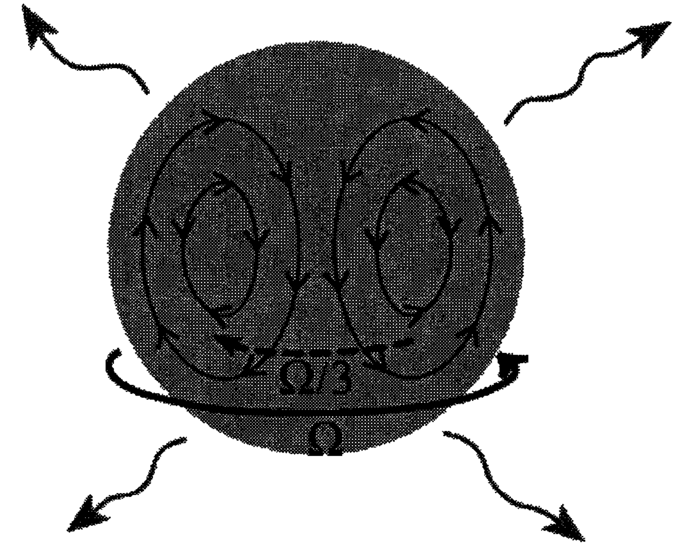


- **If slow spin:**
  - » **Convection** in first ~1 sec.
  - » Detectable only in our Galaxy (~1/30yrs)
  - » GW / neutrino correlations!



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



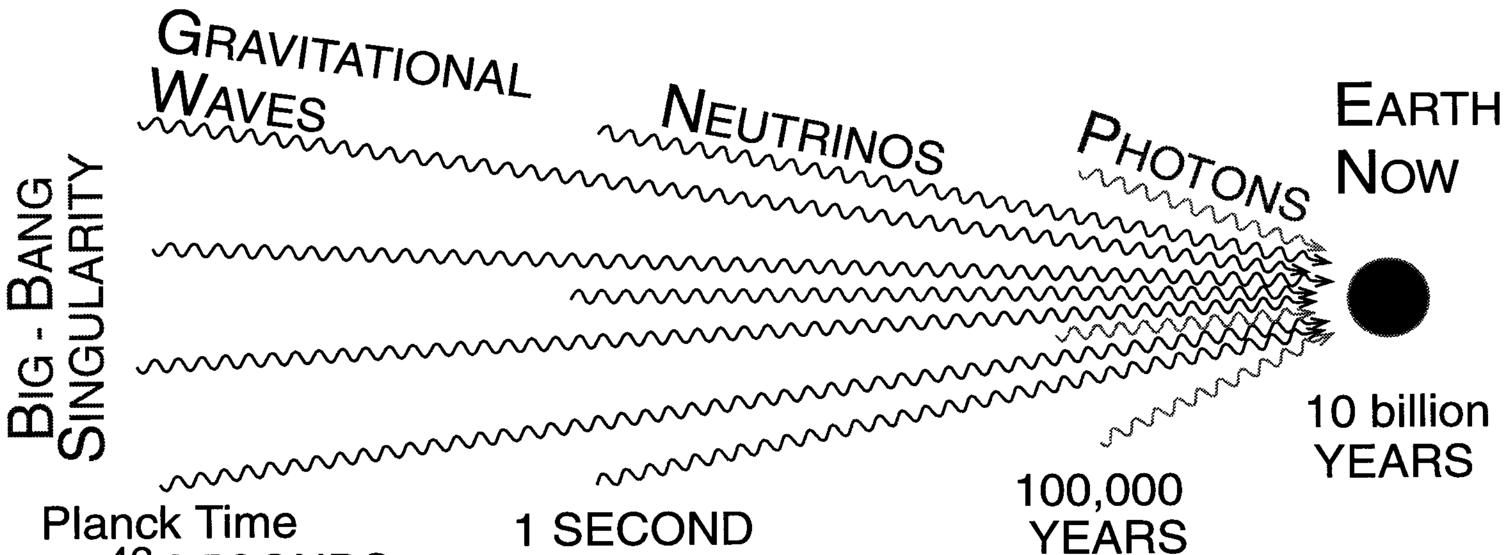
- **Physics complexities: What stops the growth of sloshing & at what amplitude?**
  - » Crust formation in presence of sloshing?
  - » Coupling of R-modes to other modes?
  - » Wave breaking & shock formation?
  - » Magnetic-field torques?
  - » ....

Depending on this,GW's may be detectable in Virgo (supernova rate several per year)

GW's carry information about these

Stochastic Background from Very Early Universe

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

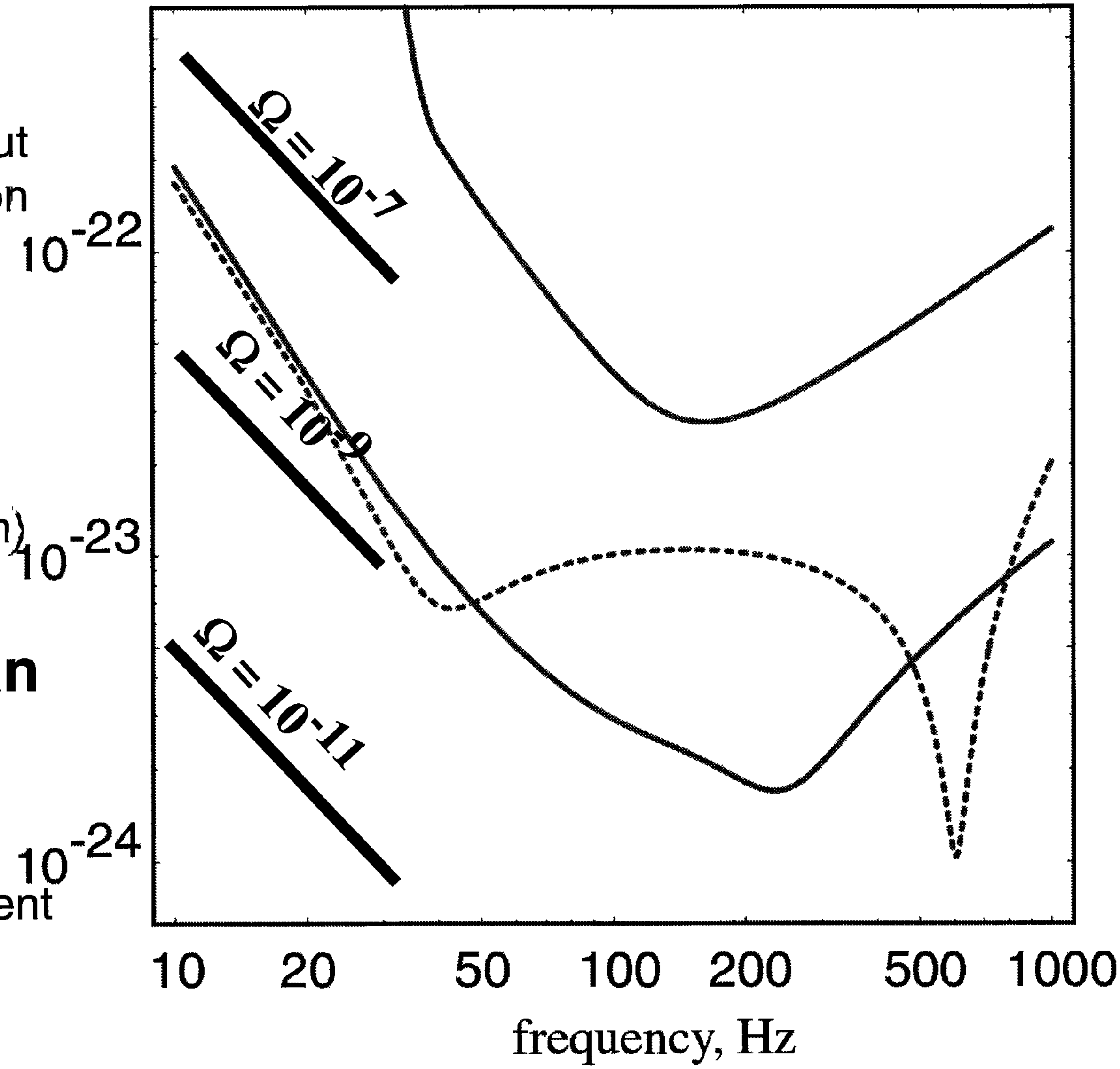


Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe

- **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
- **Advanced IFOs can detect**
  - » $\boldsymbol{\Omega \gtrsim 5\text{x}10^{-9}}$
  - » much better than current 10^{-5} limit



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

- Waves from standard inflation: ~10^{-15}: much too weak
- BUT: Crude string models of big bang suggest waves ***might be strong enough*** for detection by Advanced LIGO
- 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:**
    - **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**
- Example of hitherto ***UNKNOWN SOURCE*** ***-- the most interesting and likely kind of source!***