Gravitational Waves

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Bethe Centenial Symposium on Astrophysics

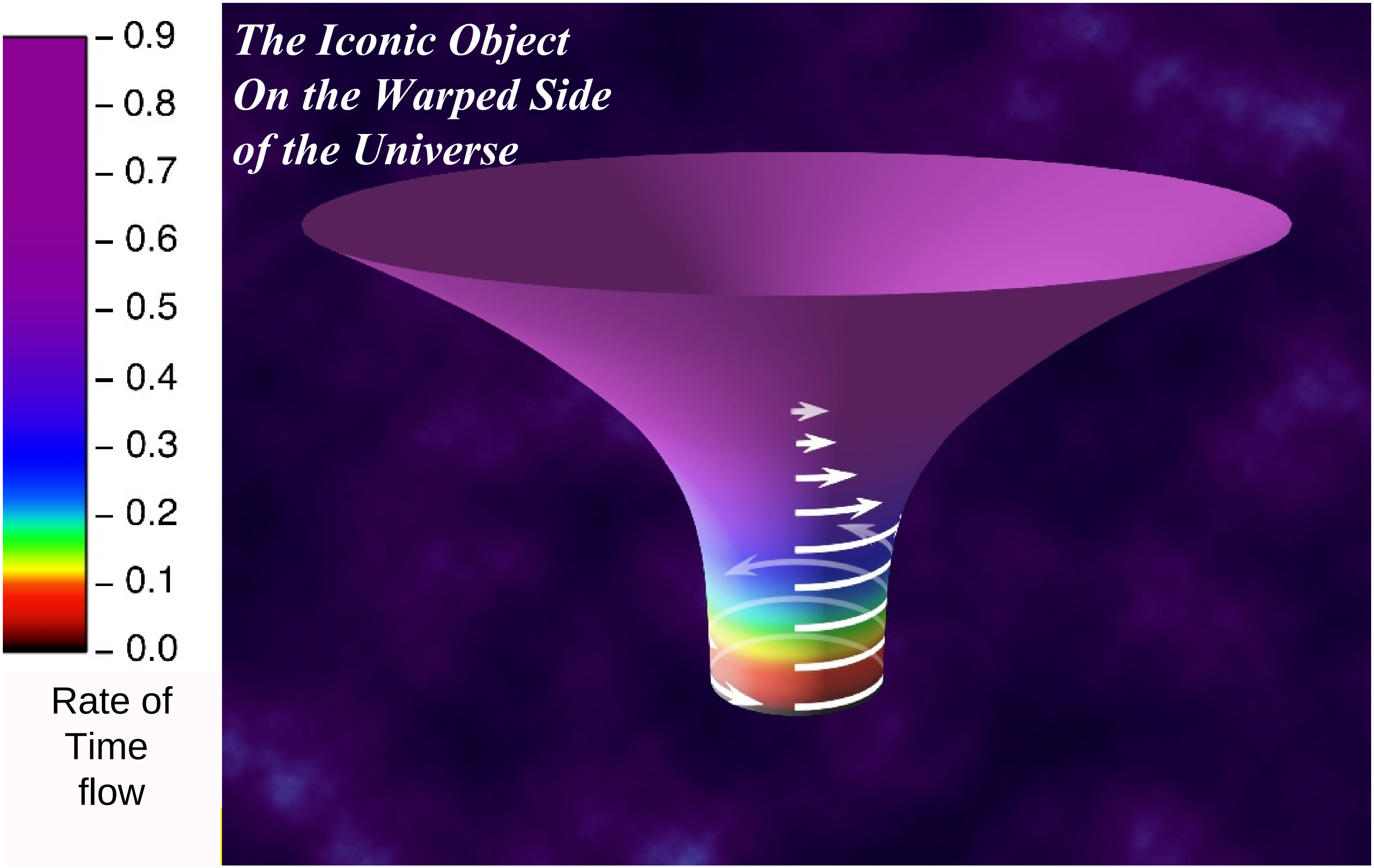
Cornell University

3 June, 2006

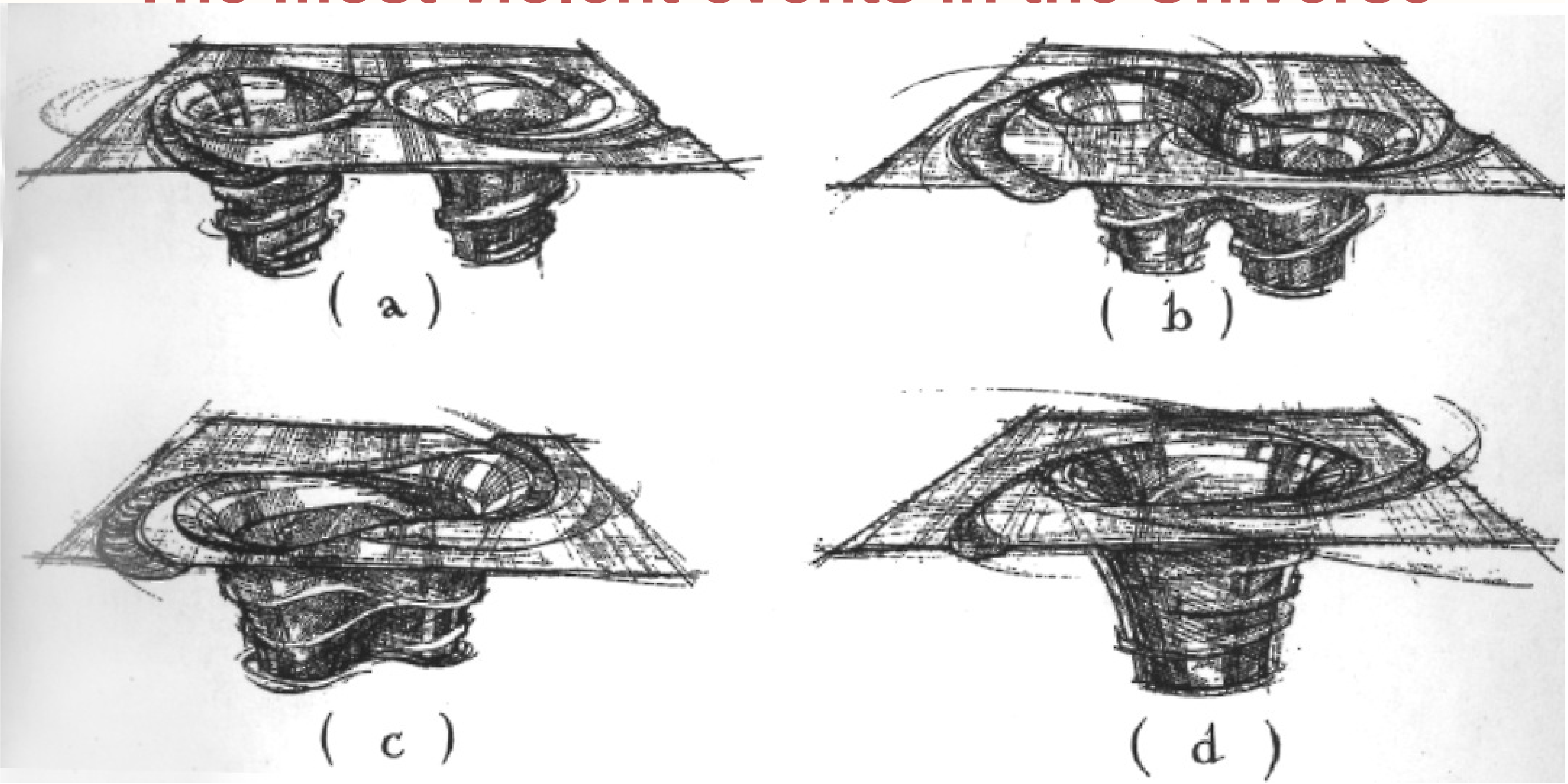
INTRODUCTION

The Warped Side of the Universe
&
Gravitational Waves

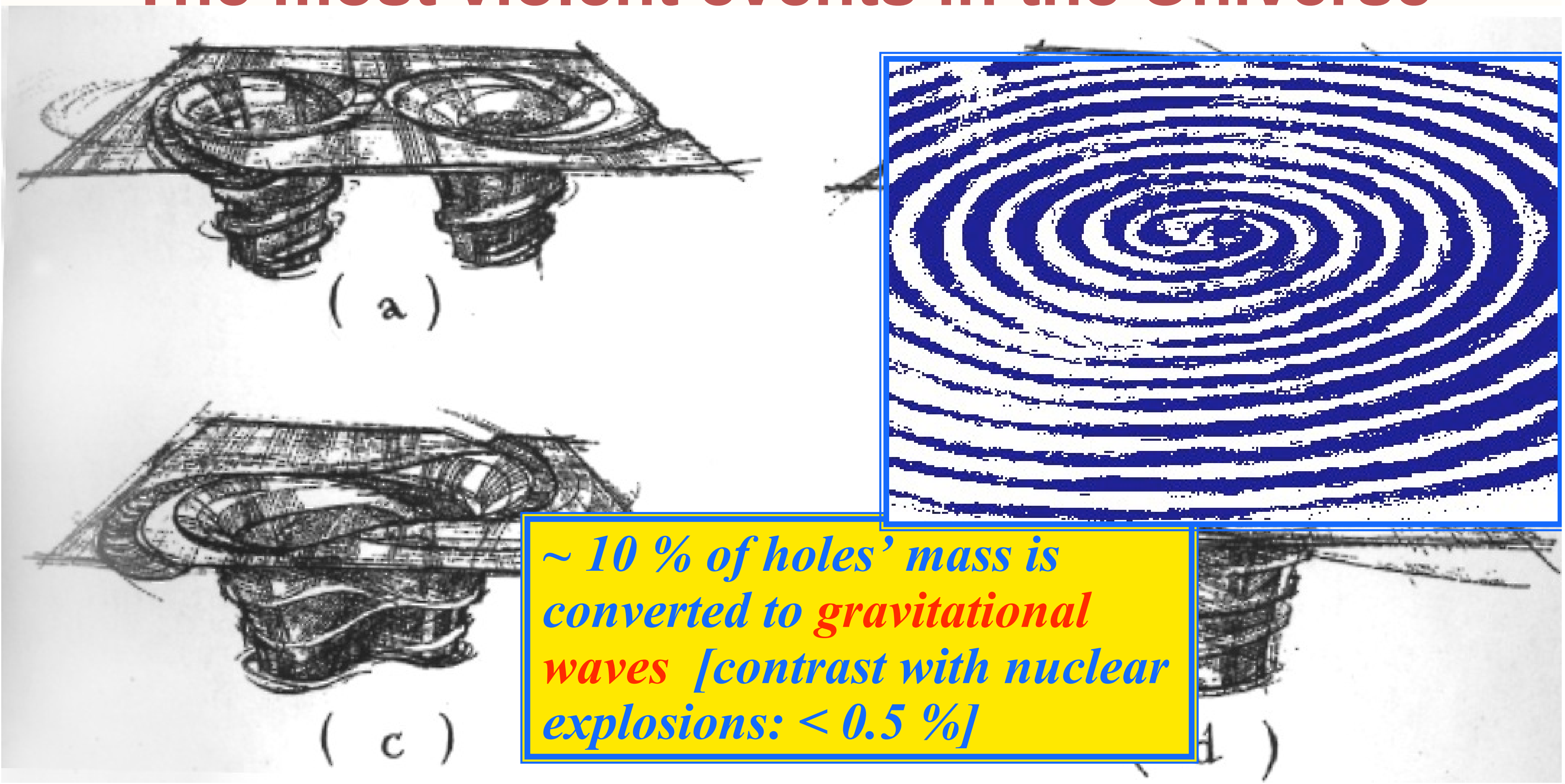
Black Hole: Made of Warped Spacetime



Collisions of Black Holes:
The most violent events in the Universe



Collisions of Black Holes: The most violent events in the Universe



~ 10 % of holes' mass is converted to gravitational waves [contrast with nuclear explosions: < 0.5 %]

Gravitational Waves: The Ideal Observational Tool for Studying the Warped Side of the Universe

Theoretical Explorations of Warped Side of Universe

- How should warped spacetime behave when highly dynamical and nonlinear?
- What other kinds of objects exist in the warped side of the universe?
- ….

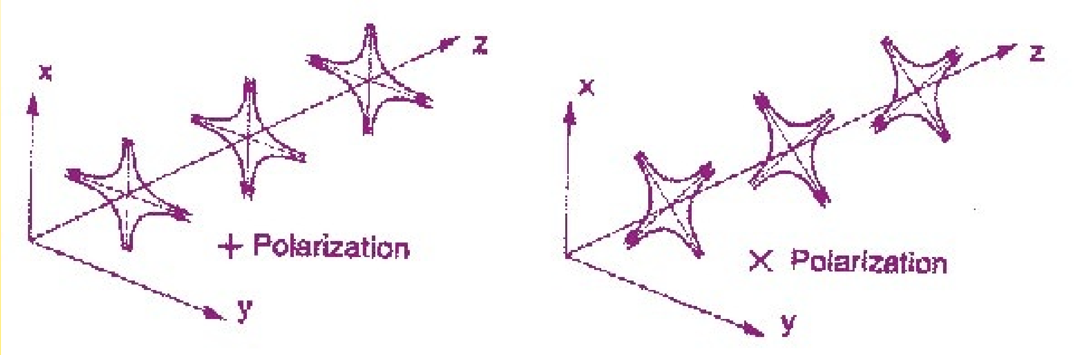
Key Tool:
Numerical Relativity

Gravitational Waves: Theory and Detectors

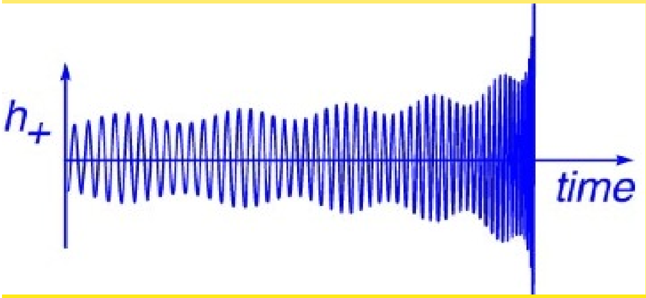
Physical Nature of Gravitational Waves

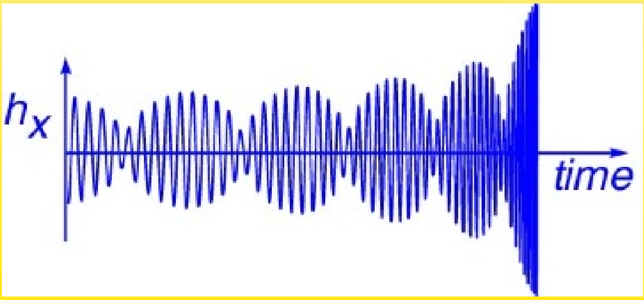
- Ripples of curvature in the fabric of spacetime

- Dominant form of curvature in short detectors:
  - » Oscillatory Stretch and squeeze of space



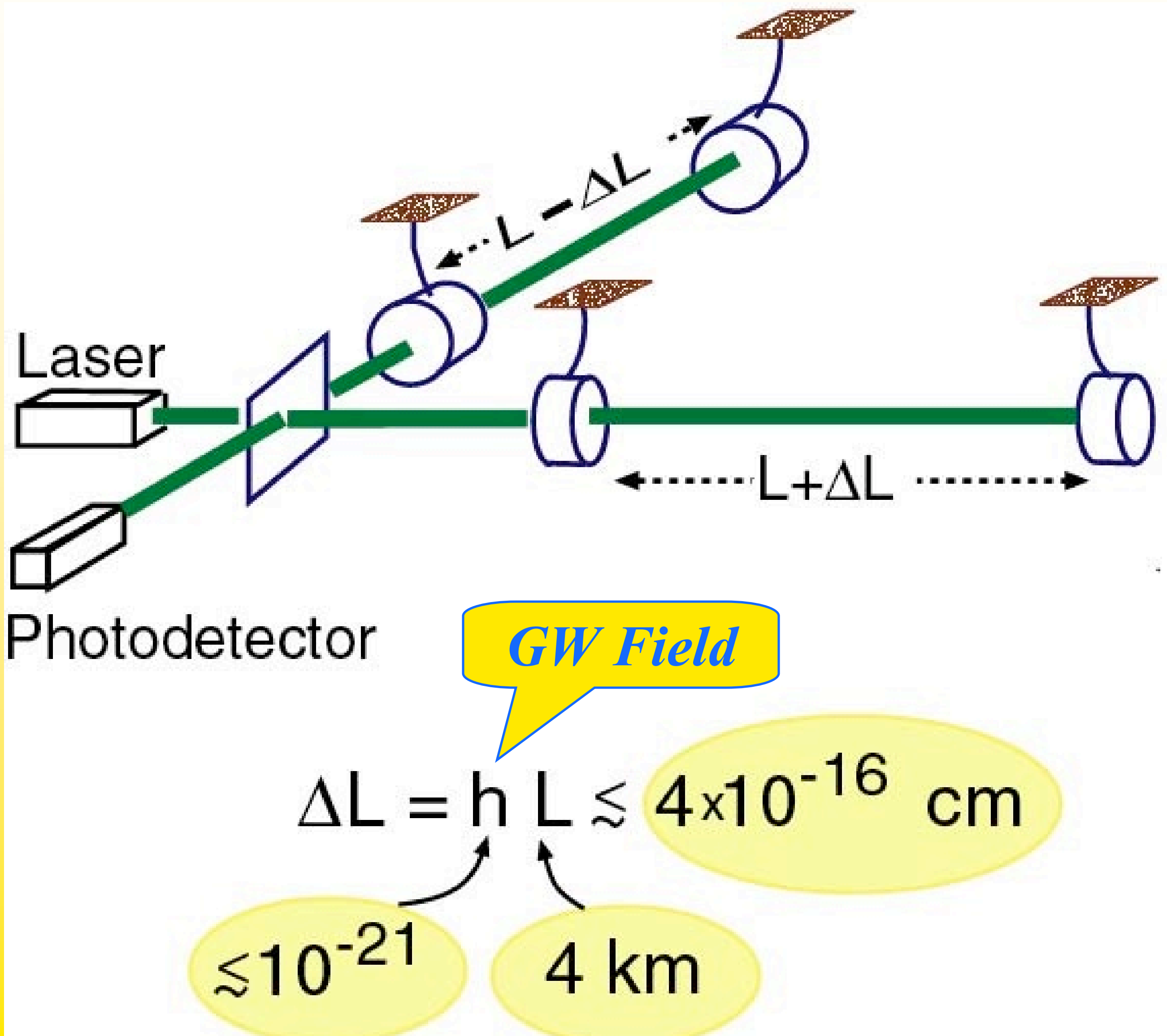
$\Delta L / L = h$





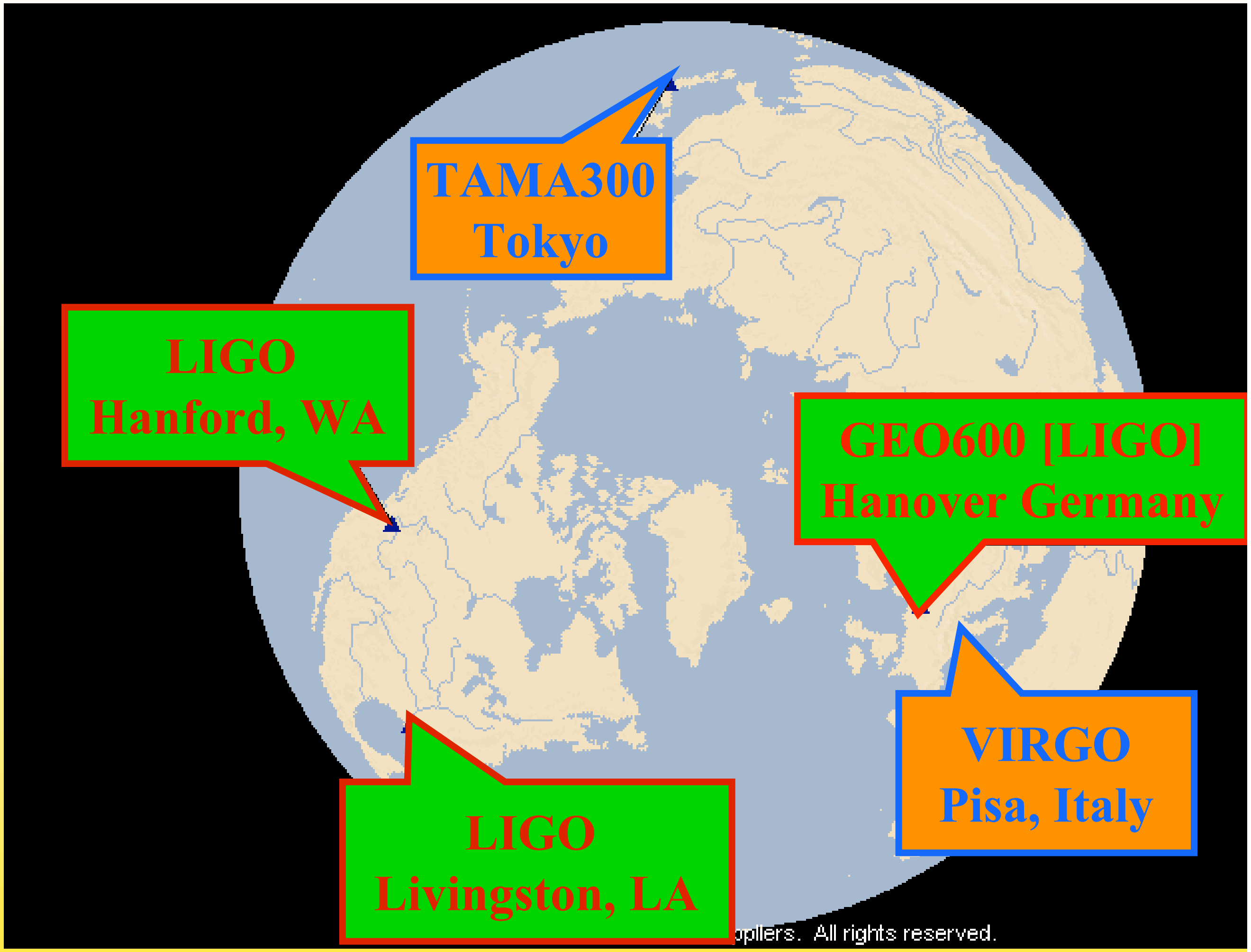
- ***Waveforms carry detailed information about source***

Laser Interferometer Gravitational-Wave Detector



International Network of Interferometric Detectors

- **Network Required for:**
  - » Detection Confidence
  - » Waveform Extraction
  - » Direction by Triangulation



+ "Bar Detectors" : Italy, Switzerland, Louisiana

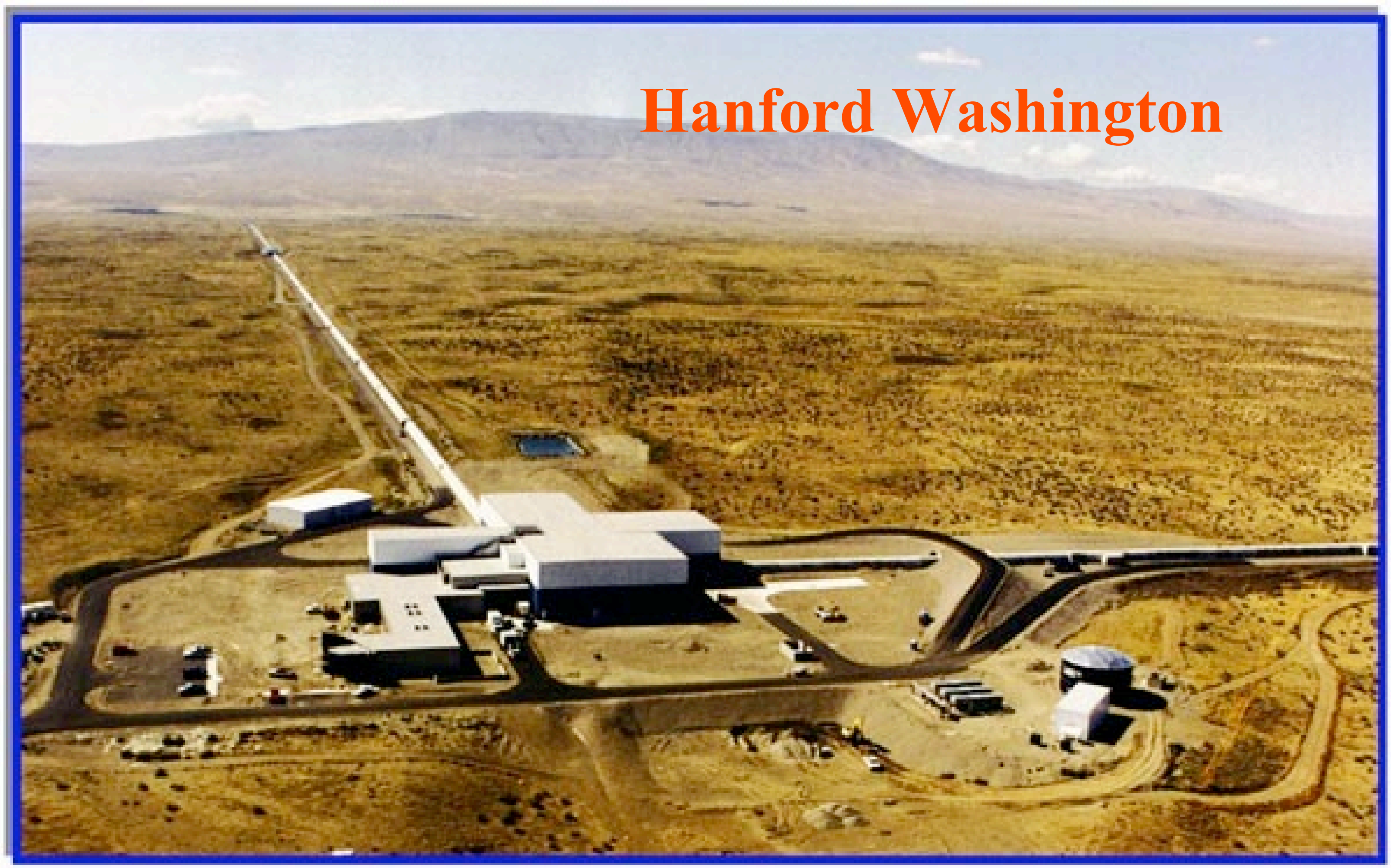
LIGO!s Organization

- **National Science Foundation: Funding & oversight**
- **Directorate: Director - Jay Marx (succeeding Barish); Deputy - Stan Whitcomb; LSC Spokesperson - Peter Saulson**
- **LIGO Laboratory Caltech & MIT**
  - » **Responsible for Facilities; and for Design, Construction, & Operation of Interferometers**
- **LIGO Scientific Collaboration (LSC)**
  - » **Formulates science goals**
  - » **Carries out Interferometer R&D**
  - » **Carries out Gravitational Wave Searches**
  - » **~540 scientists and engineers in ~40 institutions, 8 nations**
    - – **Caltech, California State University, Carleton, Cornell, FermiLab, U. Florida, Goddard, Iowa State, JILA (U. Colorado), LSU, Louisiana Tech, MIT, U. Michigan, Northwestern, U. Oregon, Penn State, Southern U., Stanford, Syracuse, U. Texas-Brownsville, U. Wisconsin-Milwaukee, ACIGA (Australia), GEO600 (Britain & Germany), IUCAA (India), NAOJ-TAMA (Japan), Moscow State U. & IAP-Nizhny Novgorod (Russia), …**

Some Milestones

- 1971: Interferometer invented [Weiss, building on Weber, …]; R&D began
- 1983: LIGO conceived
- 1989: LIGO construction proposed
- 1999: LIGO construction completed

LIGO



4 km

2 km

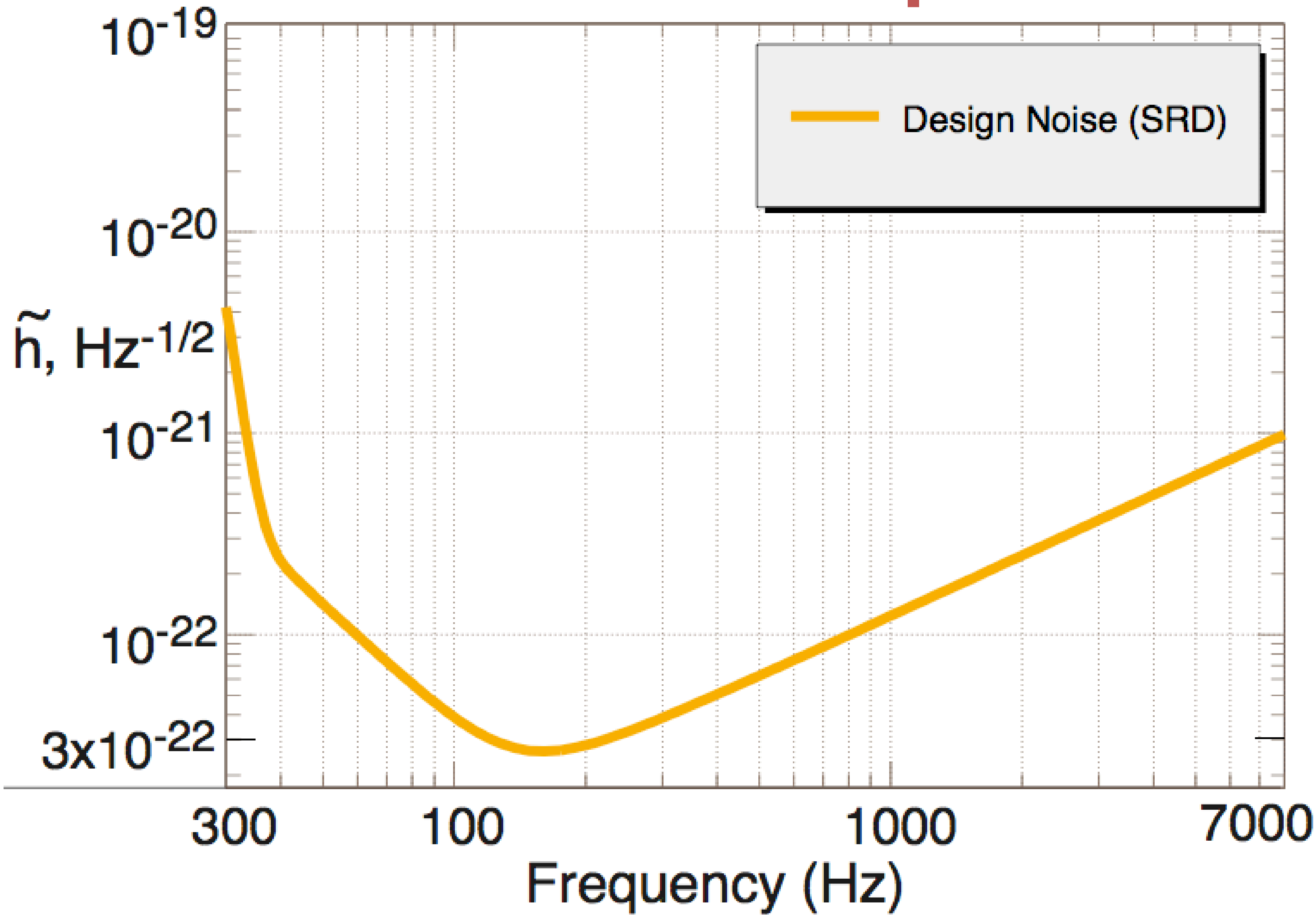
LIGO

4 km

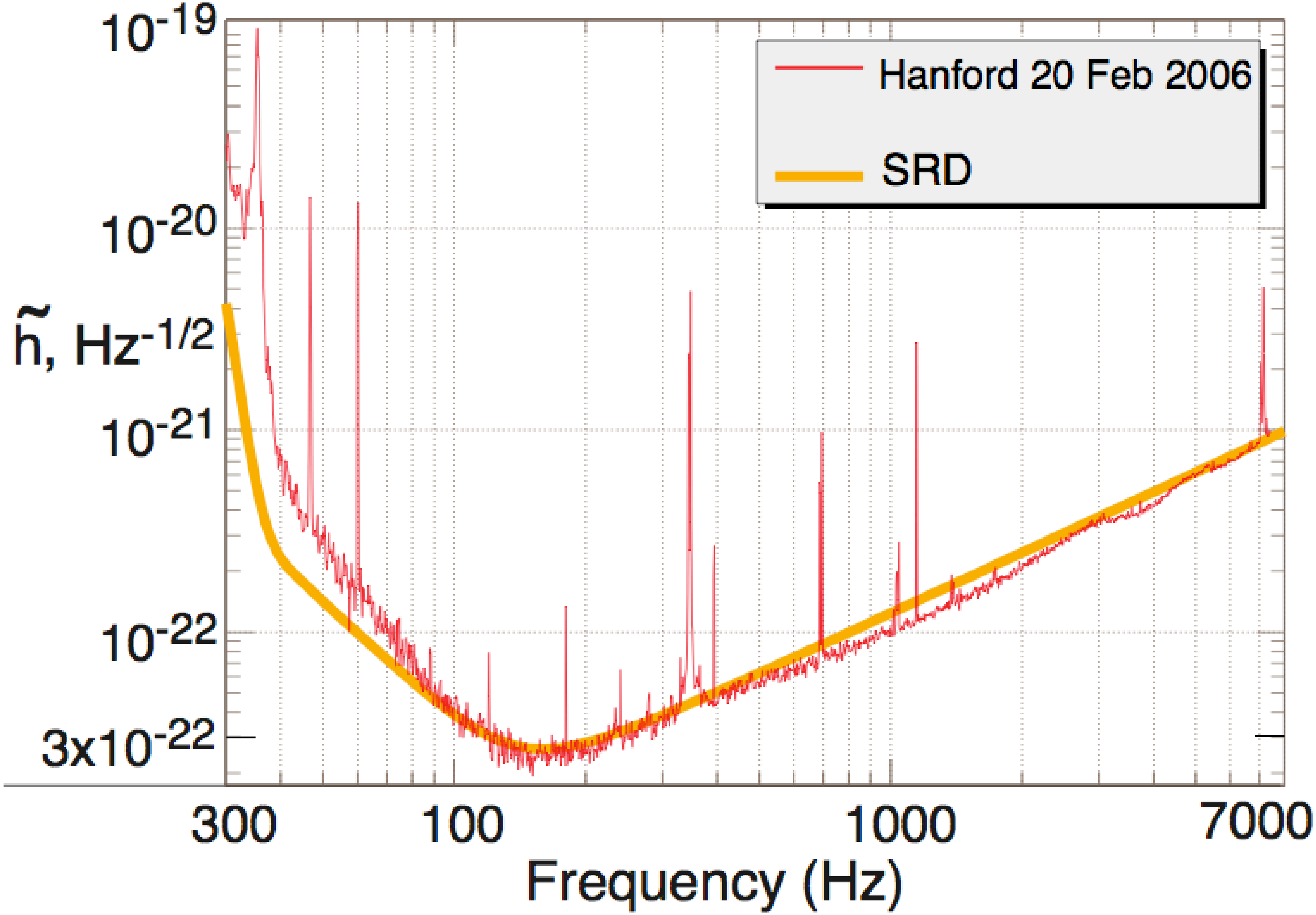
Some Milestones

- **2000-01: First Interferometers Installed**
- **2001-2005: Commisioning of Interferometers; short searches**
- **Nov 2005-2007: Search at design sensitivity- 1 yr of coincident data**

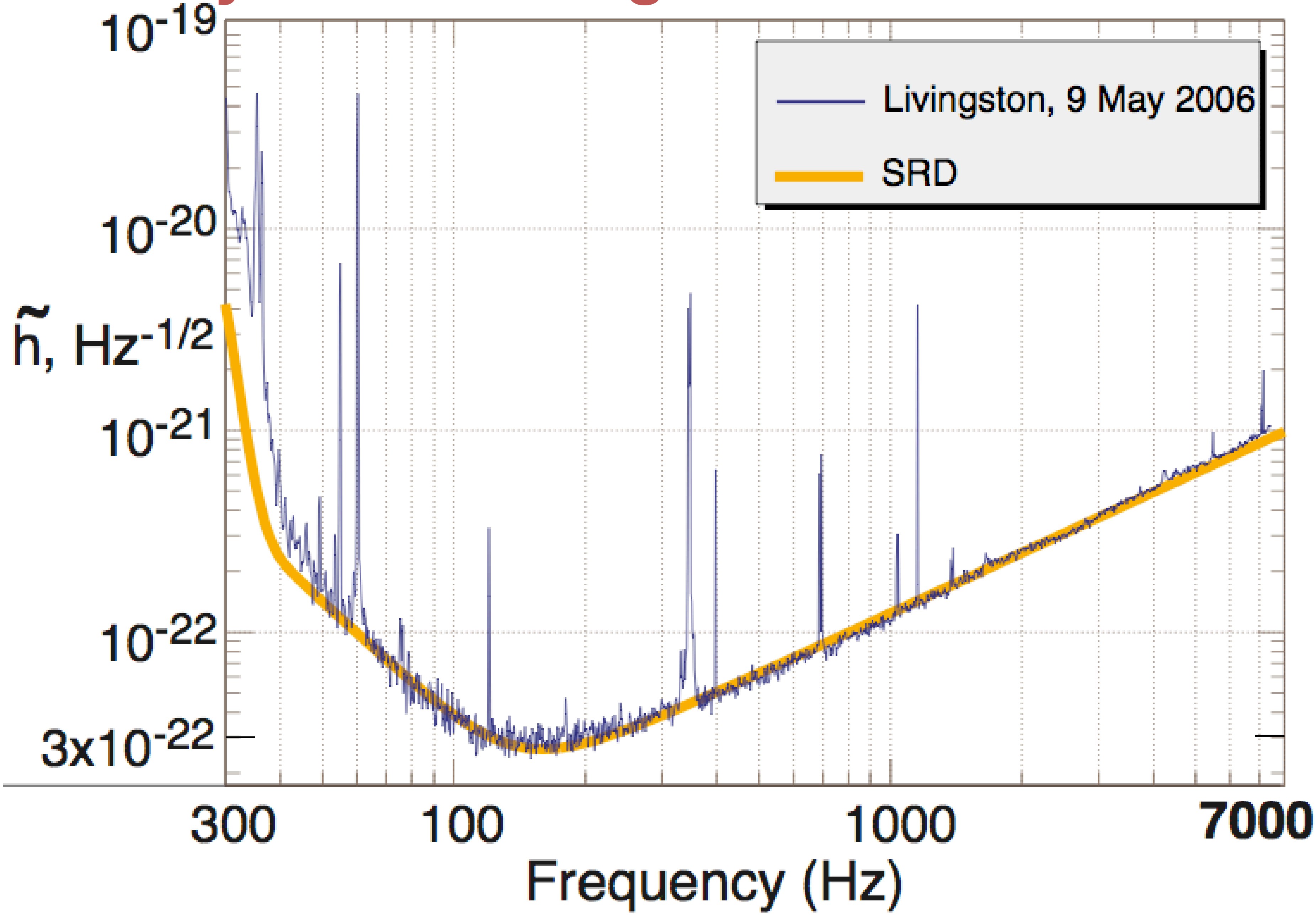
1989 - LIGO Proposal



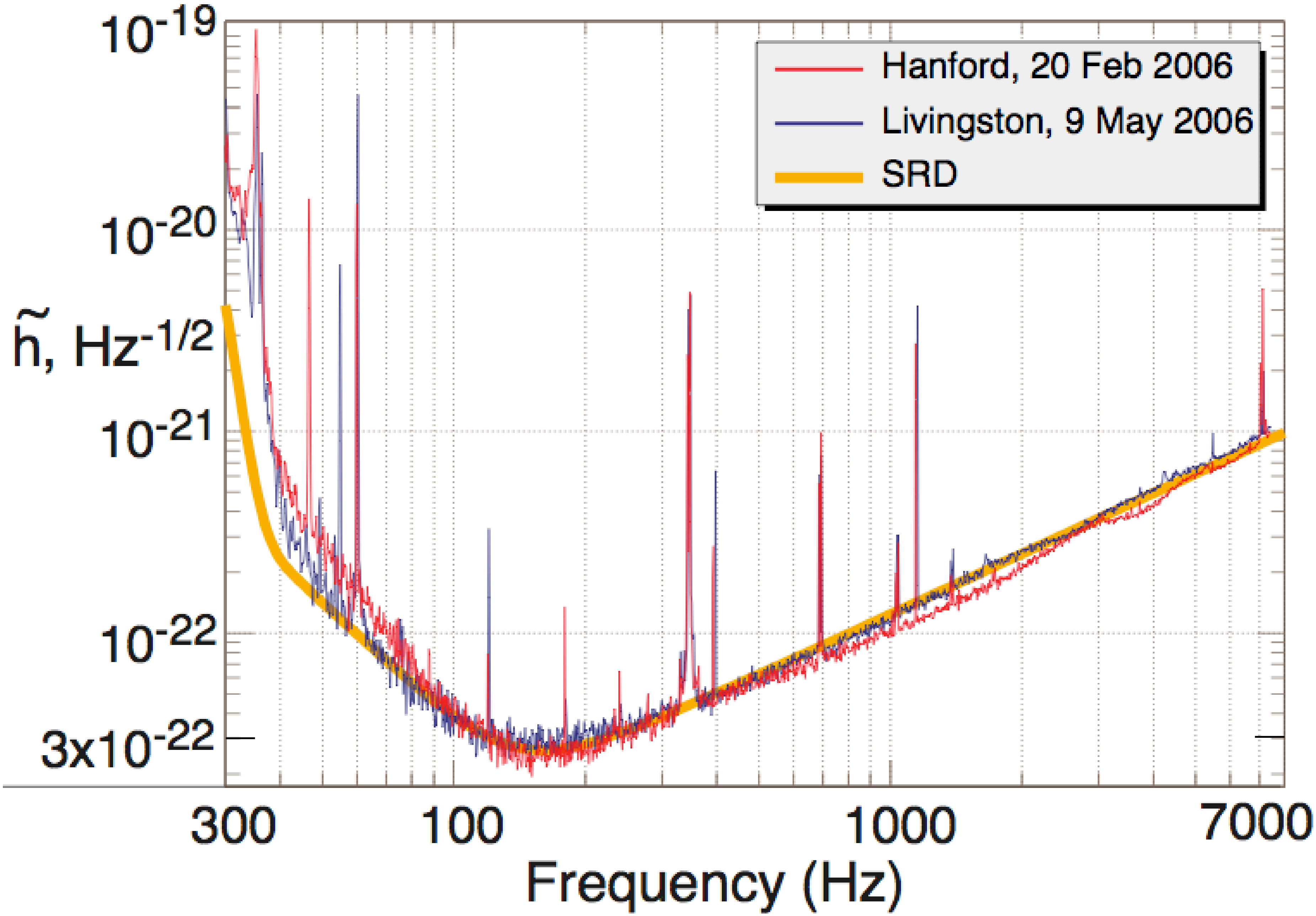
Feb 2006: Hanford Noise Curve



May 2006: Livingston Noise Curve



2006: Both Noise Curves



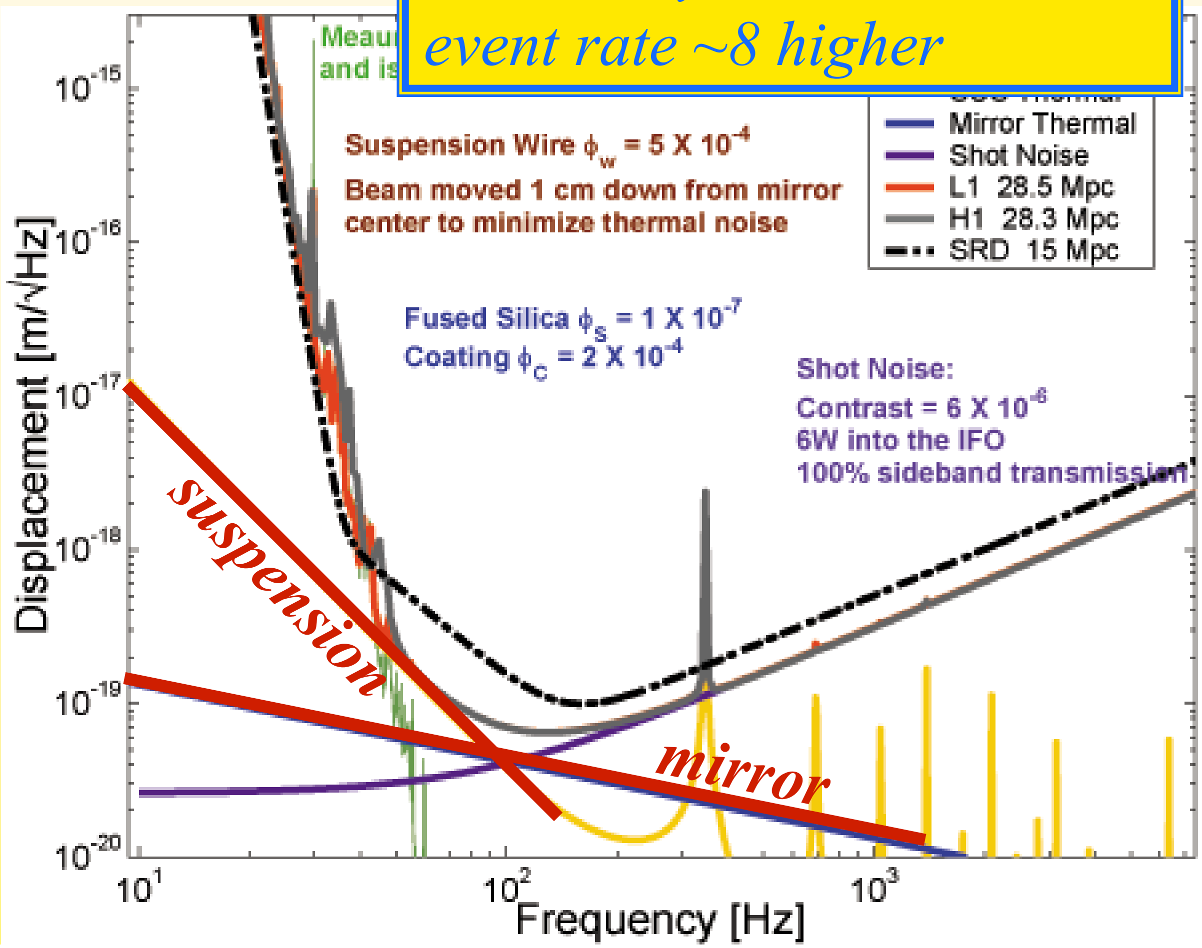
Advanced LIGO Interferometers

- A major upgrade, long planned:
  - » 10 to 15 times better sensitivity than initial LIGO
- Funding start FY 2008
  - » Begin installation early 2011
  - » So what to do with initial LIGO interferometers in meantime?

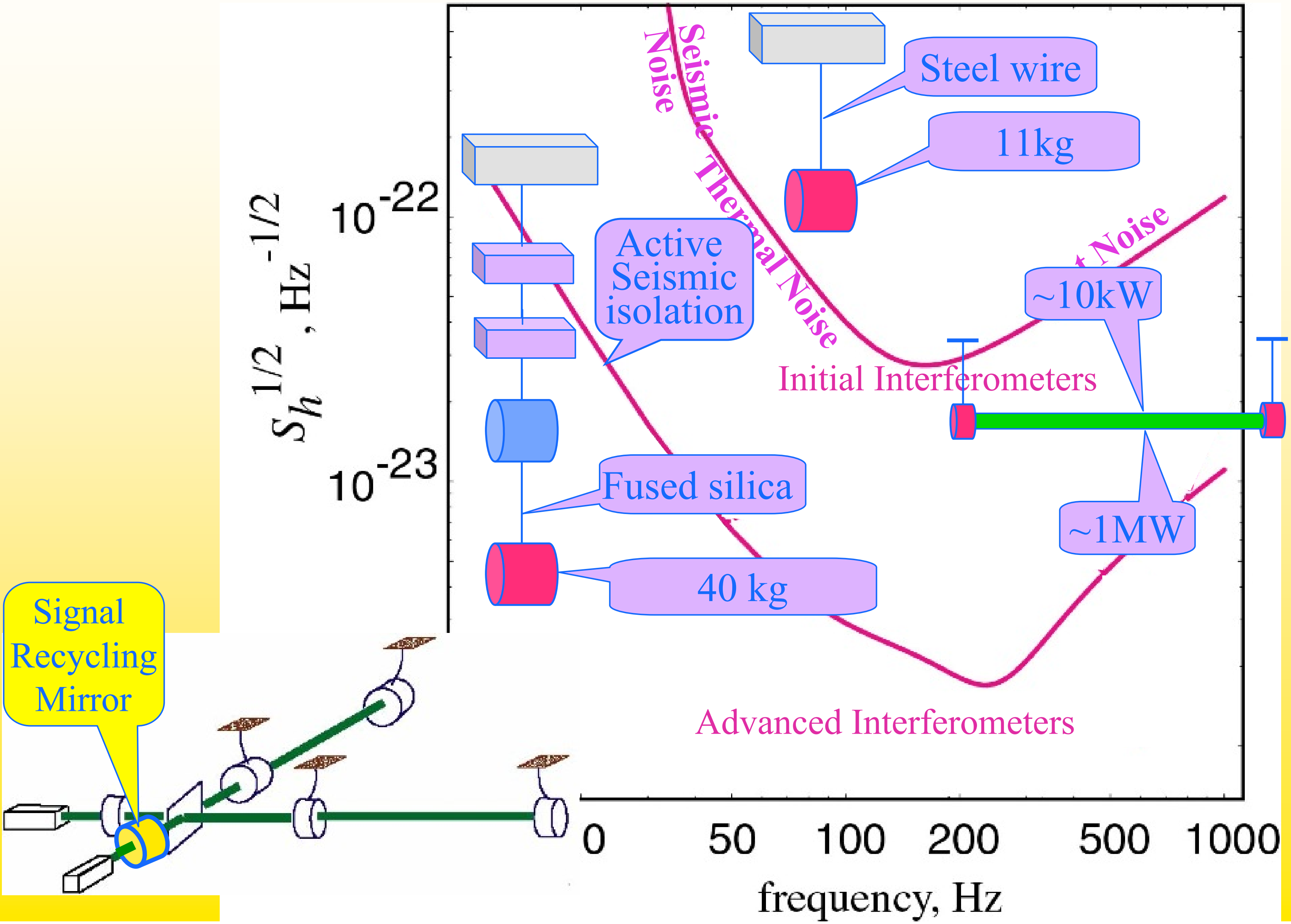
Enhancement of Initial Interferometers

- Instruments very complex
  - » ~ 50 servos, many tightly coupled
  - » Many many noise sources
- Elegant experi-mental probing
  - » Rana Adhikari, PhD thesis
- Thermal noise 2 to 3 lower than design!

2008-2010: Enhance Initial . Interferometers.
Another year-long search @ . sensitivity ~2 better; . event rate ~8 higher



LIGO: From Initial Interferometers to Advanced



Status of Advanced LIGO

- Proposal to NSF: 2003
- Approved by National Science Board
- In OMB Advanced Planning budget:
  - » first funding FY 2008
- Major contributions: US, Germany, UK, Australia
- Procurement and Preparation: 2008-2010
- Begin Installation: early 2011
- First Searches: 2013

NS/NS, BH/NS, BH/BH Binaries Estimated Event Rates

Begin with comparison of rates for BH/NS and NS/NS:

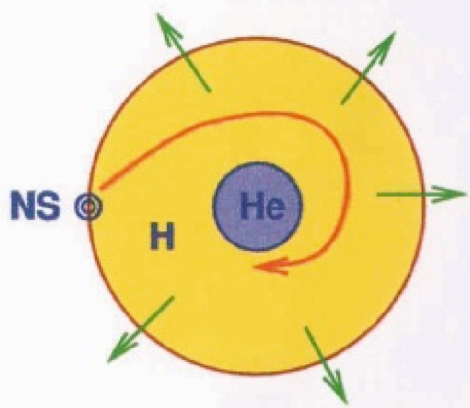
Hans Bethe, Gerald Brown and Chang-Hwan Lee

- January 1996…

Bethe-Brown-Lee

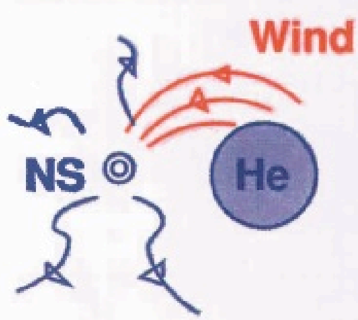
From a Caltech LIGO seminar by Brown

What is Supposed to Happen



Neutron star spirals in. Orbital energy loss is coupled, throug
dynamical friction, to the envelope, which is expelled.

Left with

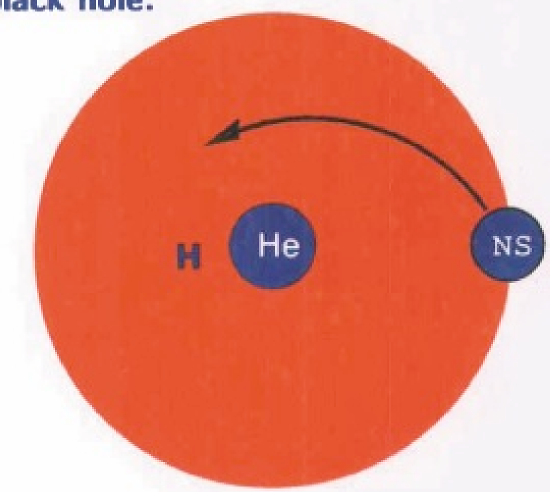


We do see one such object Cyg X-3. But there should be
$\geq$ 100 if this is the usual outcome.

What we believe does happen

H.A. Bethe & G.E.Brown
ApJ 506, 780 (1998)

In the dispersal of the envelope, the neutron star accretes mass $\longrightarrow$ black hole.



Bethe-Brown-Lee

5424

Accretion

$$\dot{E} = \frac{1}{2} C_d G (M_A + M_B) a^{-1} \dot{M}_A \qquad (350)$$

$$E = \frac{1}{2} G M_A M_B a^{-1} \qquad (351)$$

E here is the gravit. energy between A & B. Initially,

$$E_i = \frac{3}{5} G M_{Bi}^2 / a_i \qquad (526)$$

(350) can be integrated, using $M_B a^{-1}$ and M_A as variables. From (351)

$$\dot{E} \sim \frac{M_B}{a} \dot{M}_A + \frac{d}{dt}\left(\frac{M_B}{a}\right) M_A \qquad (527)$$

Neglect $M_A \ll M_B$ in (350), then

$$\dot{M}_A \frac{M_B}{a} (c_d - 1) = M_A \frac{d}{dt}\left(\frac{M_B}{a}\right) \qquad (528)$$

$\therefore$

$$M_A \sim \left(\frac{M_B}{a}\right)^{\frac{1}{c_d - 1}} \sim \left(\frac{M_B}{a}\right)^{0.2} \qquad (529)$$

$$E_f = 2 E_i$$

$$M_{Af} \frac{M_{Bf}}{a_f} = 2.4 \frac{M_{Bi}^2}{a_i} \qquad (530)$$

$$M_{Ai} \left\{\frac{(M_B/a)_f}{(M_B/a)_i}\right\}^{1.2} = 2.4 M_{Bi} \qquad (531)$$

$$\frac{(M_B/a)_f}{(M_B/a)_i} = \left(2.4 \frac{M_{Bi}}{M_{Ai}}\right)^{5/6} = \left(2.4 \frac{16}{1.4}\right)^{5/6} = 27^{5/6} = 15.6 \qquad (5\ldots$$

$$\frac{M_{Af}}{M_{Ai}} = 15.6^{1/5} = 27^{1/6} = 1.73 \qquad (533)$$

Bethe's calculation

THE BOTTOM LINE:

BH/NS rate for LIGO is 20 times higher than NS/NS rate

Compact Binary Inspiral Rates, yr^{-1}

	FROM	Initial LIGO	Enhanced	Advanced
NS/NS	Observed binary pulsars - Kalogera et al	.007 - .04 - .13	.06 - .3 - 1	20 - 1200 - 4000
NS/BH	Bethe/Brown/ Lee	.14 - .8 - 3	1 - 6 - 24	400 - 2400 - 10,000
NS/NS	Short γ burst afterglows: Nakar et al	0.001 - 0.3 ~0.1 γ -GW coincidences	0.01 - 3 ~ 0.8 γ -GW coincidences	2 - 30 ~ 300 γ -GW coincdences
or ***NS/BH***	Short γ burst afterglows: Nakar et al	0.01 - 3 ~0.3 γ -GW coincidences	0.1 - 30 ~2.4 γ -GW coincidences	20 - 1000 ~1000 γ -GW coincidences
BH/BH	Population Synthesis: ~4 times NS/NS			

Examples of Science in Advanced-LIGO Era

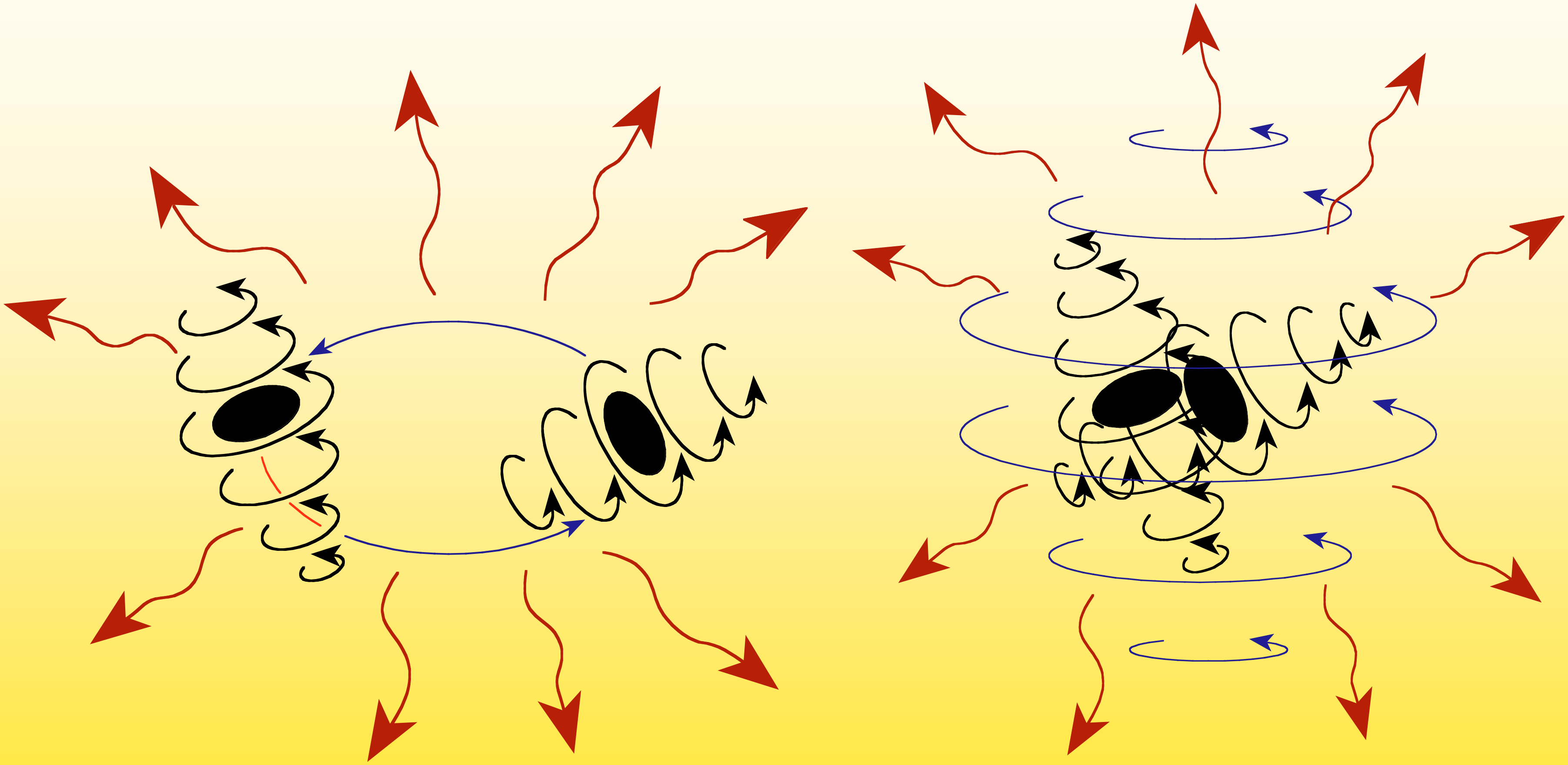
- Survey populations of sources - e.g. BH/BH, BH/NS, NS/NS binaries in universe
  - » BH/BH up to several hundred solar masses; possibly 1000
- Test general relativity in binary inspirals, up to $(v/c)^6$ beyond leading-order radiation reaction [Hulse-Taylor]
- Explore behavior of highly nonlinear, dynamical warped spacetime - in BH/BH mergers
  - » Requires comparison with numerical relativity [NR] simulations
- Study structures of NSs, and NS equation of state, via tidal disruption of NS by BH
  - » Requires comparison with Numerical Simulations
- Study physics of rapidly spinning NSs -
  - » Pulsars
  - » Low Mass X-Ray Binaries [Bildsten]

Examples of Science in Advanced-LIGO Era [Cont.]

- Study triggers of gamma-ray bursts
  - » Hypernovae; NS/BH or NS/NS mergers?
- Compare propagation speed of gamma-rays and gravitational waves, to ~ 1 part in 10^{17}
- Search for speculated waves from very early universe:
  - » Cosmic strings, phase transitions, …
  - » [GW!s only direct probe of first 1 second]

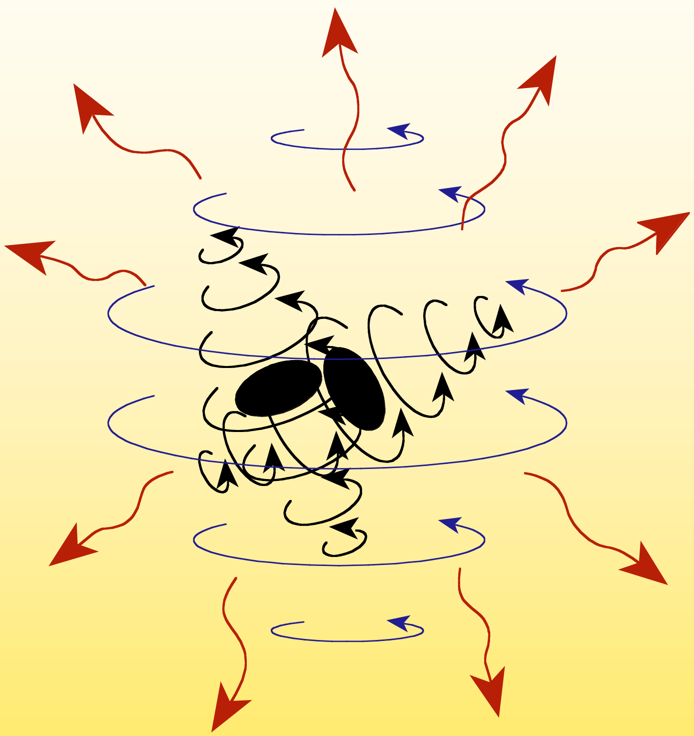
Why are Black-Hole Collisions Interesting?

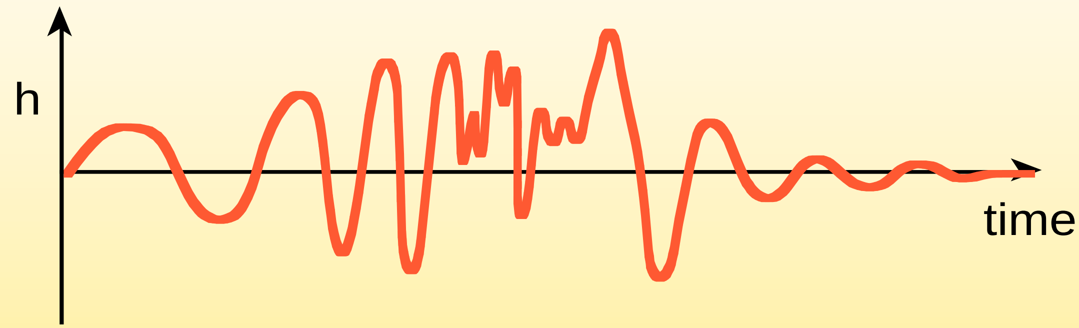
Wild vibrations of warped spacetime



To Interpret Observed Waves: Compare with Computer Simulations

"Numerical Relativity"





Numerical Relativity: a powerful new tool to explore physics on the Warped Side of the Universe

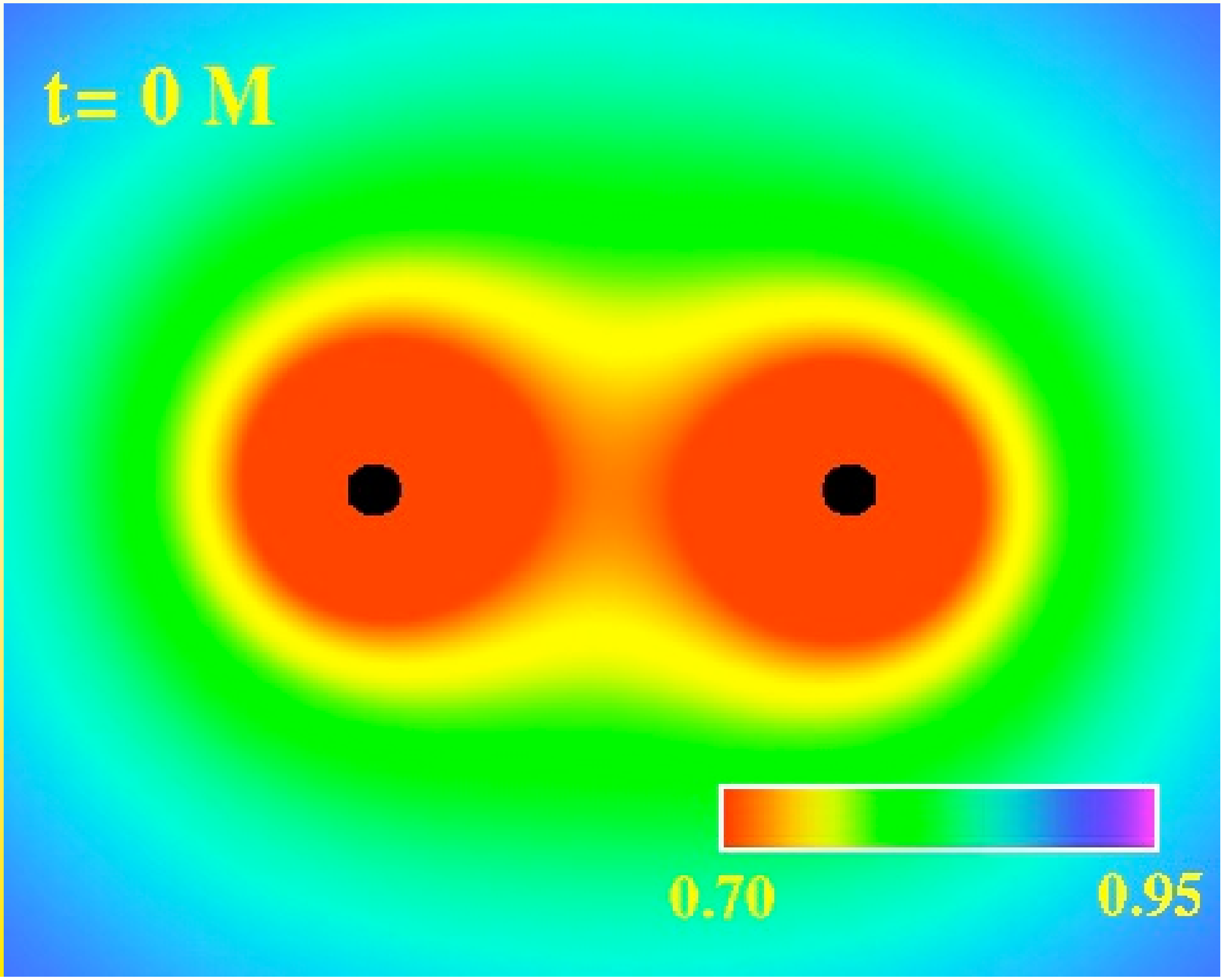
Status of Numerical Relativity

- 1970s: Foundations - DeWitt, Smarr, York, … 1+1 dimensional simulations (BH head on collisions, …)
- 1980s: Transition to 2+1 dimensions; waveform extraction; slicing; …
- 1990s: Transition to 3+1 dimensions
  - » Choptuik: 2+1 -> critical behavior in grav collapse
- 2000 - 2005:
  - » Struggles with constraint violation instabilities, …
- 2005: First long-lasting, robust simulations of binary black holes [Frans Pretorius; …]
- 2006: Other groups doing long, robust simulations [Goddard, UT Brownsville, LSU/AEI, Cornell/Caltech…]

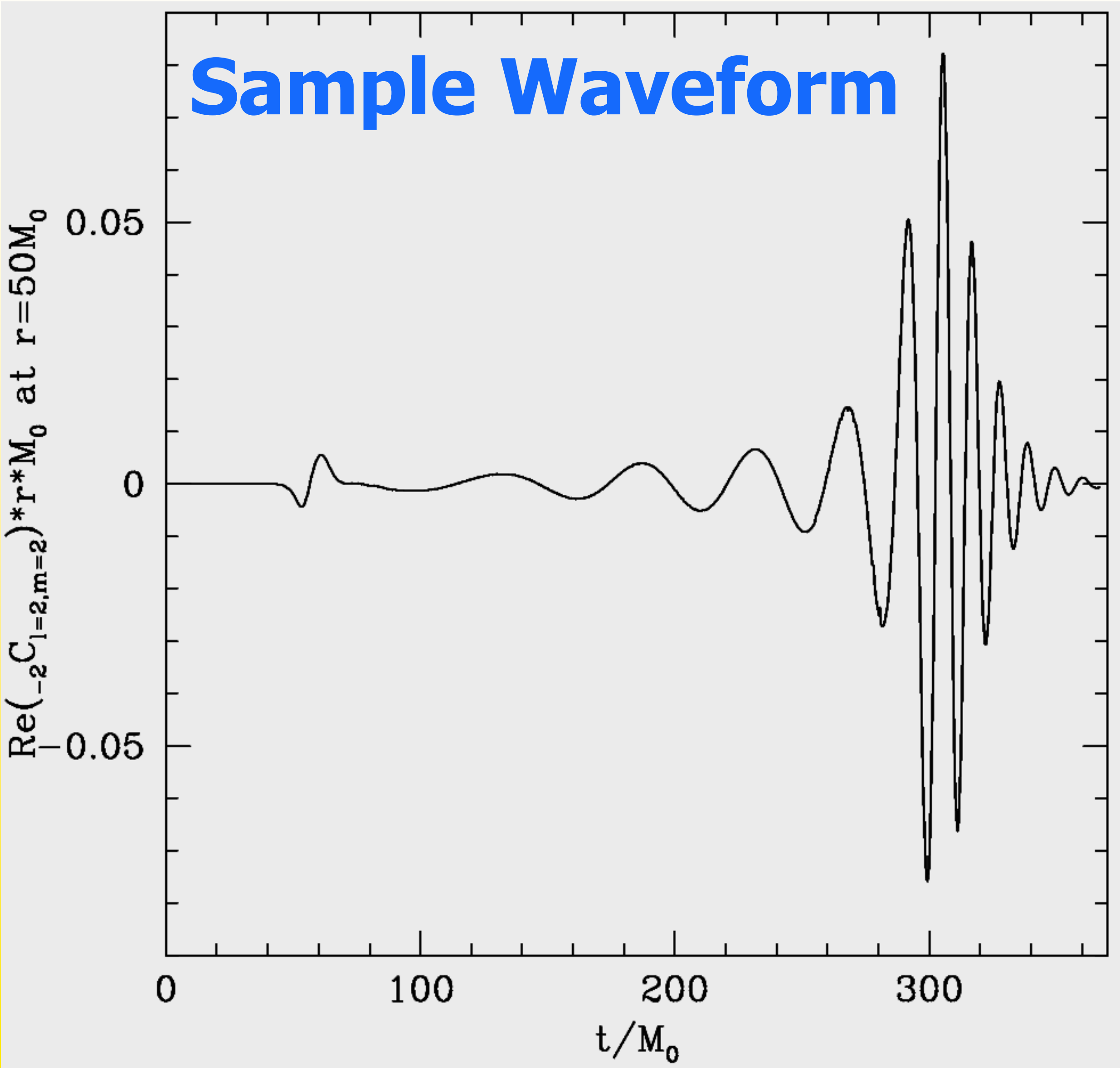
Pretorius! Simulation of Nonspinning Binary Black Hole - 1

Lapse function α, in orbital plane

Initial data:
Pfeiffer & Cook



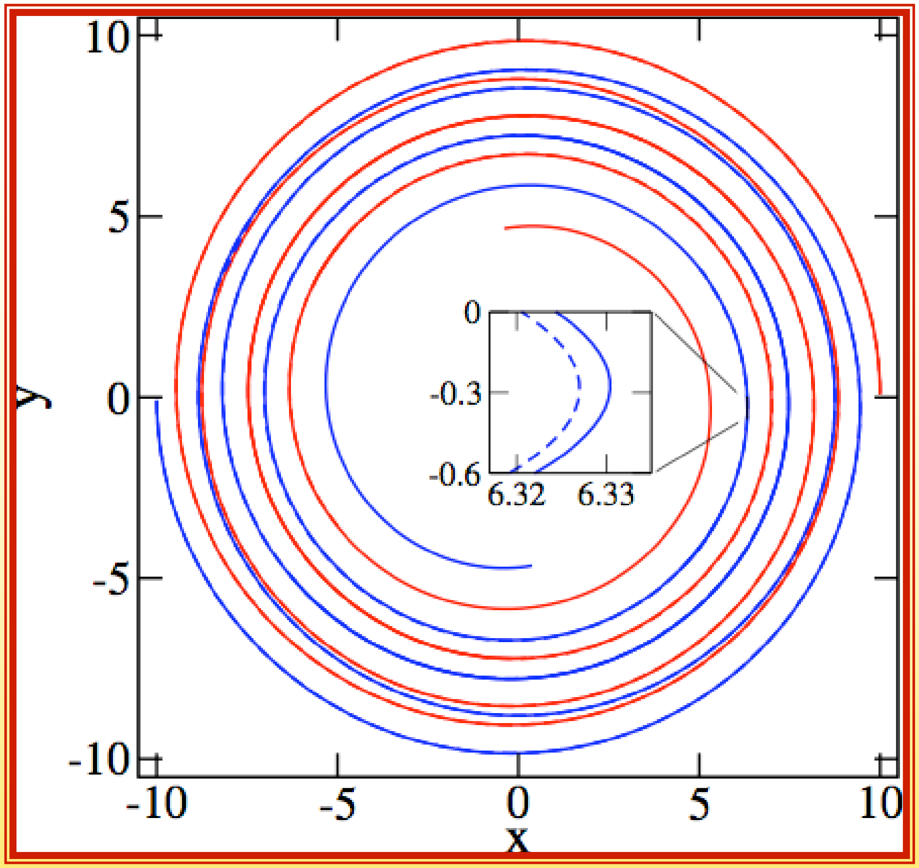
Pretorius! Simulation of Nonspinning Binary Black Hole - 2

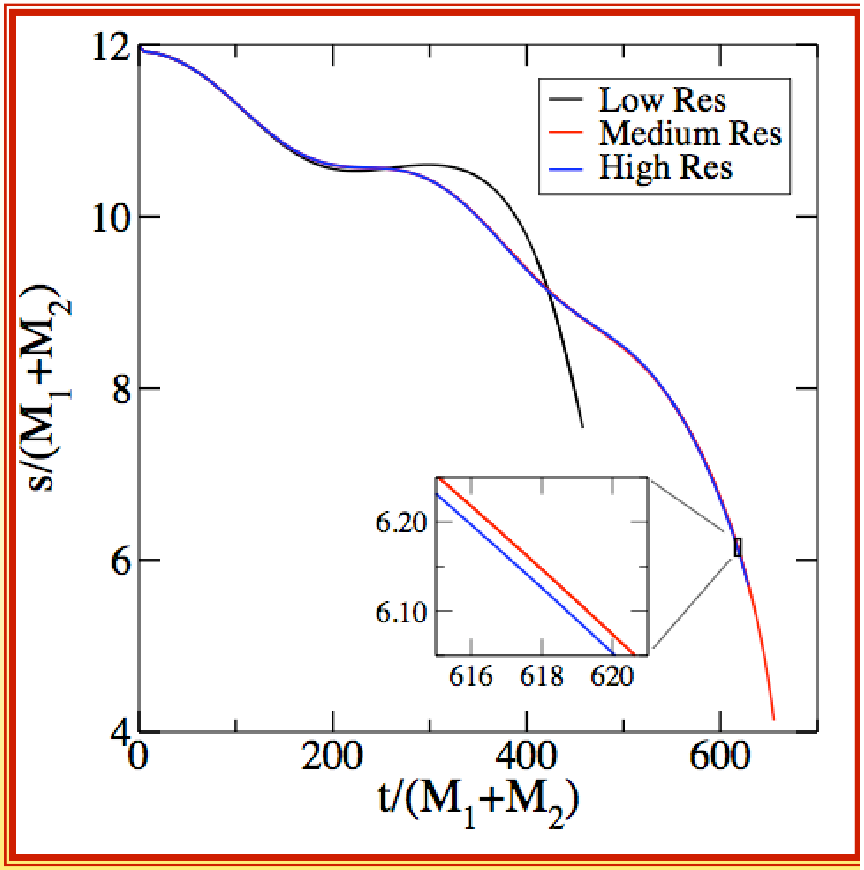


Cornell/Caltech BH/BH Simulations

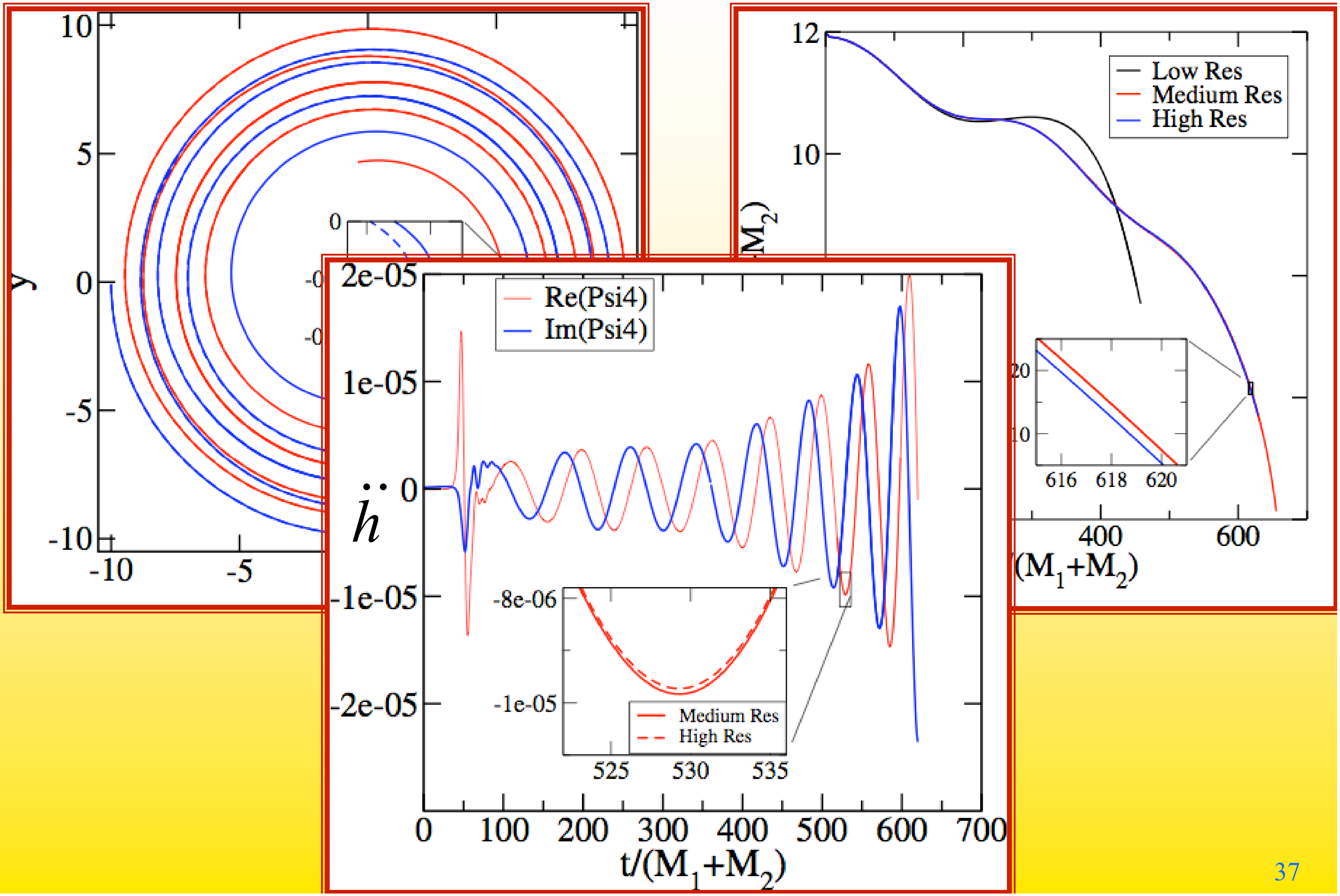
- Program for Simulations of eXtreme Spacetimes: SXS
- Steering Committee
  - » Saul Teukolsky & Larry Kidder (Cornell)
  - » Lee Lindblom, Harald Pfeiffer, & Mark Scheel (Caltech)
- James York (Cornell)
- 4 additional postdocs
- 7 grad students
- Pseudospectral Methods instead of Finite Difference
  - » Exponentially fast convergence

Cornell/Caltech: Orbit & Waves



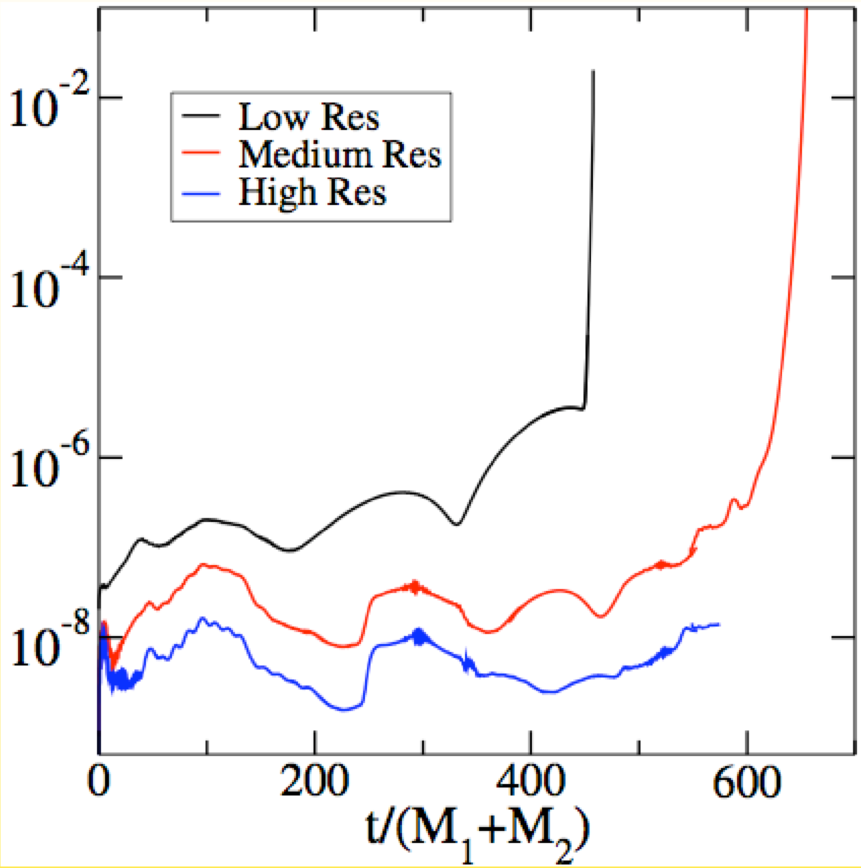


Cornell/Caltech: Orbit & Waves

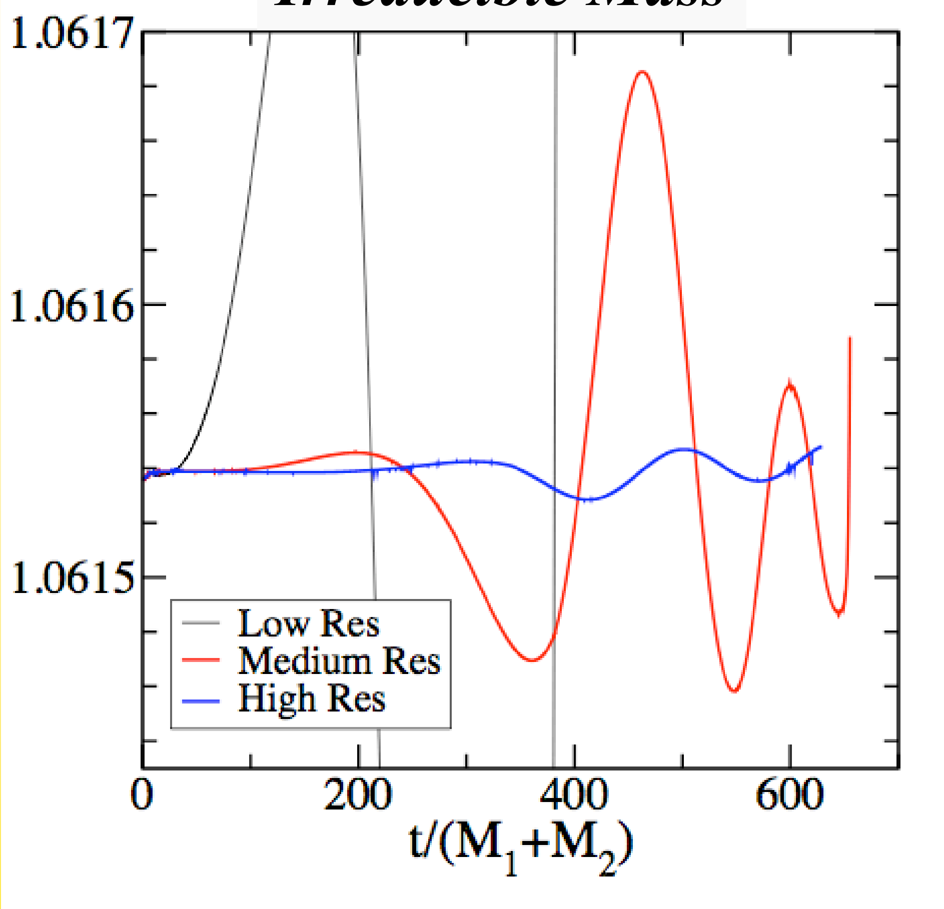


Cornell/Caltech: Accuracy

Constraint Violation

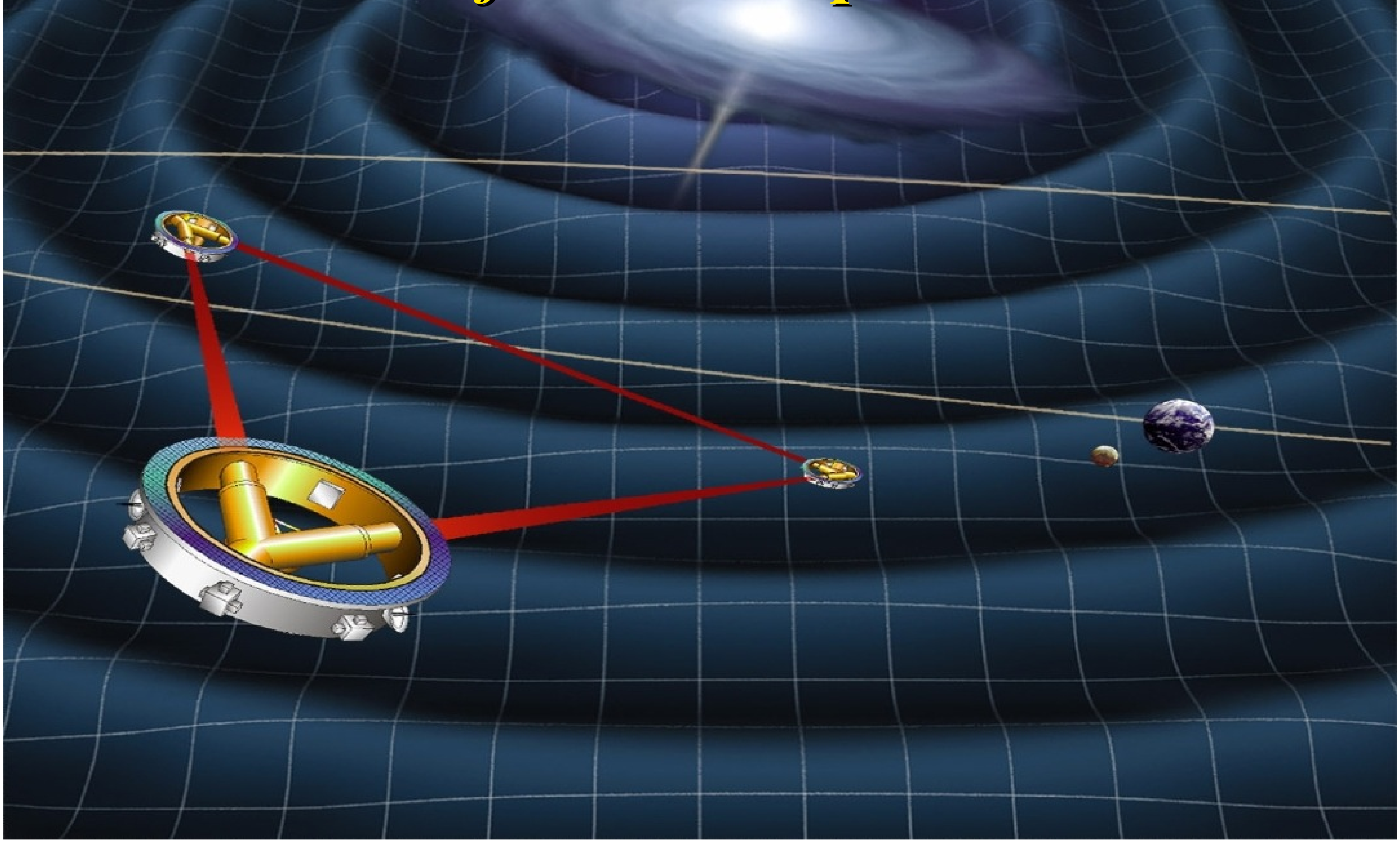


Irreducible Mass

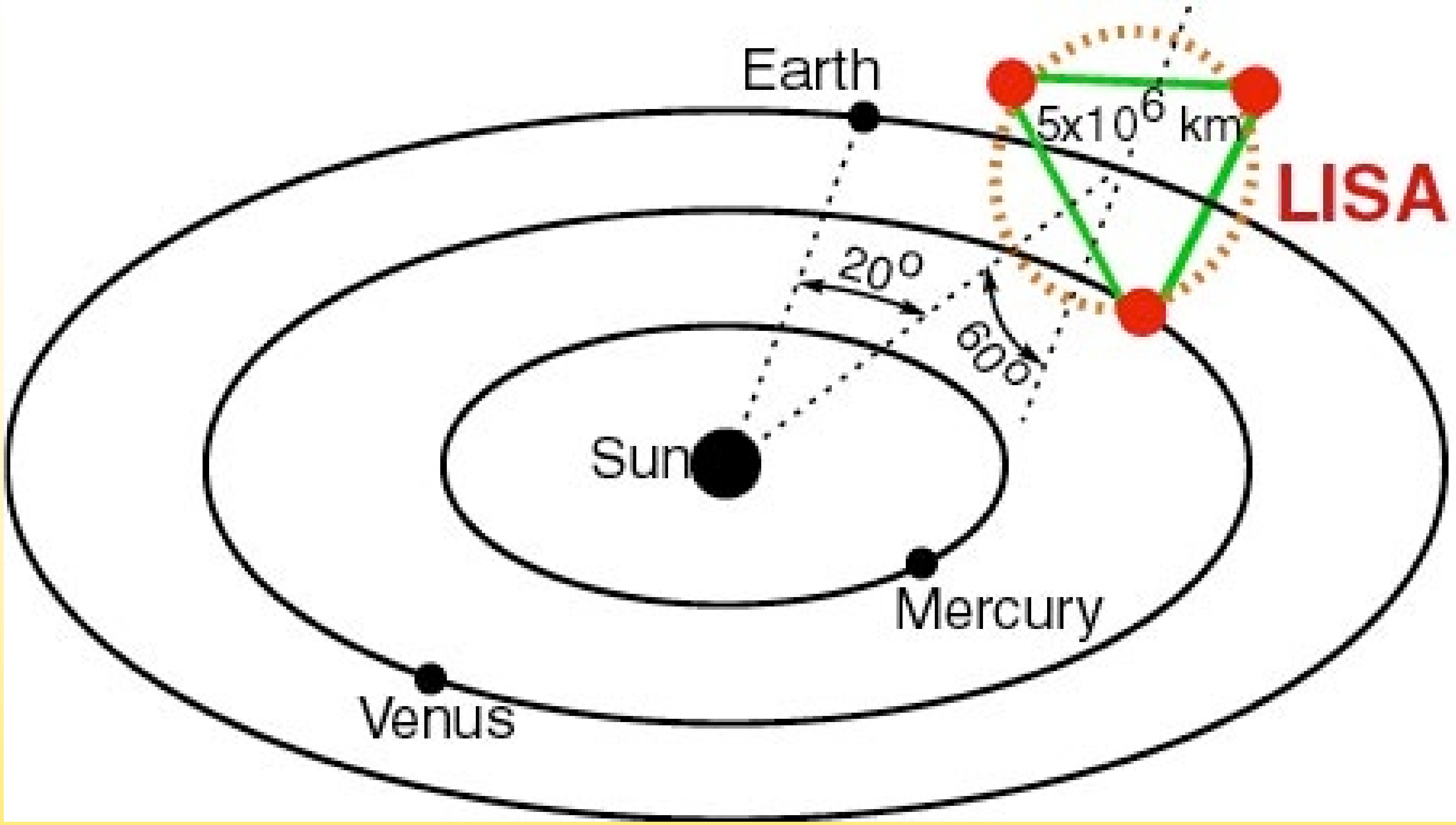


LISA

Laser Interferometer Space Antenna

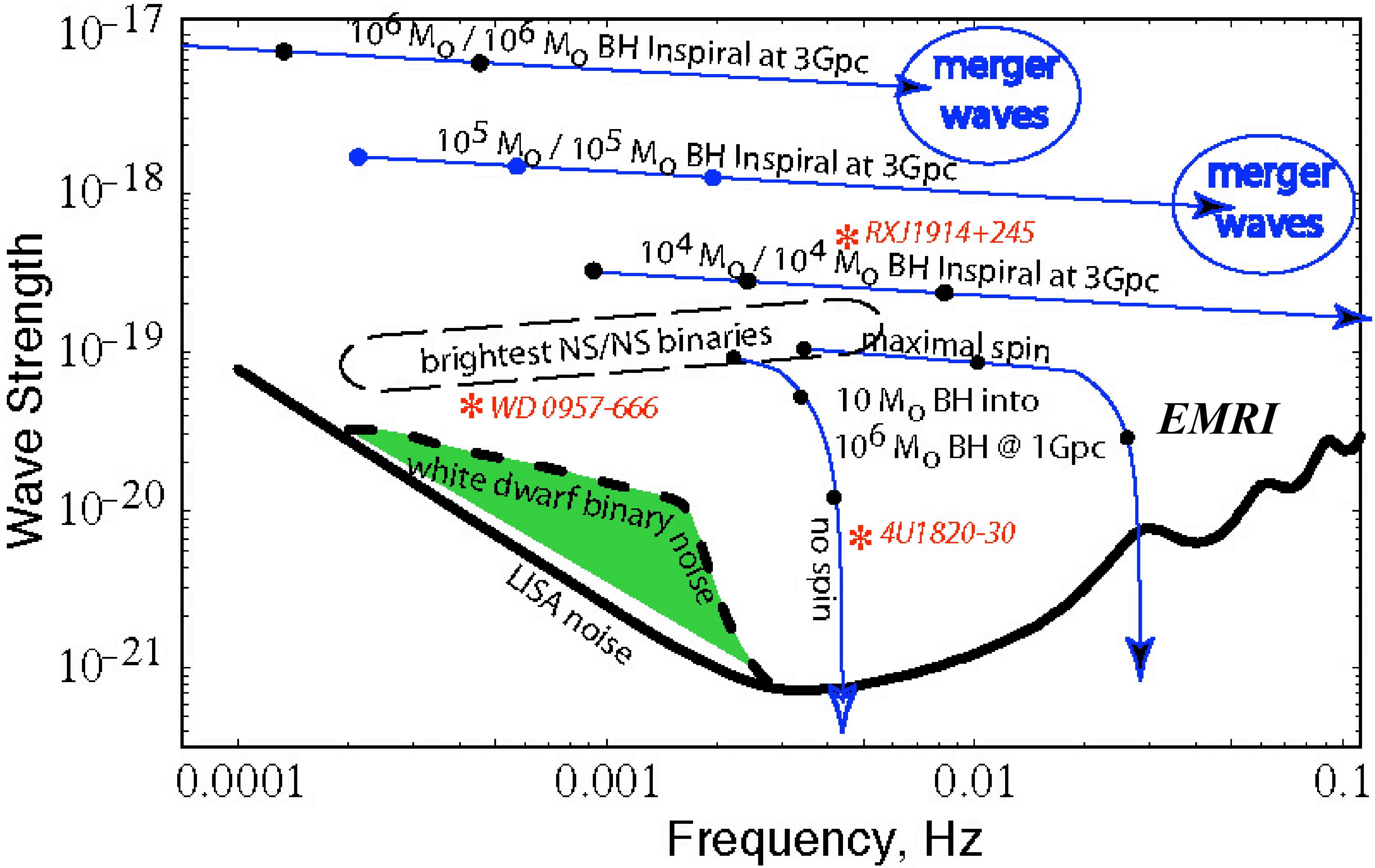


LISA: Joint ESA/NASA Mission

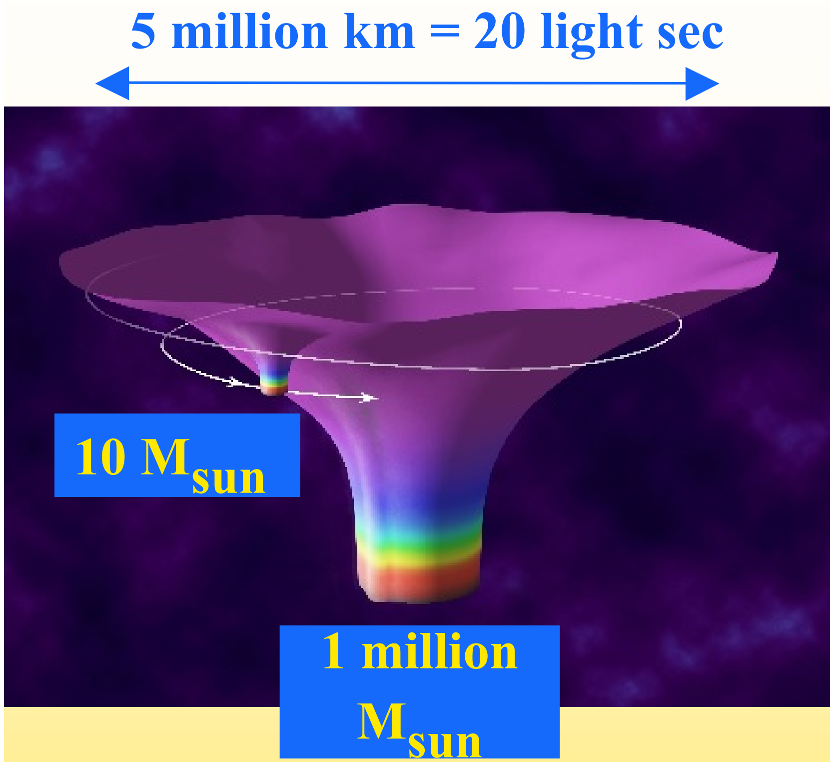


- **Launch: ~2015 *or later***

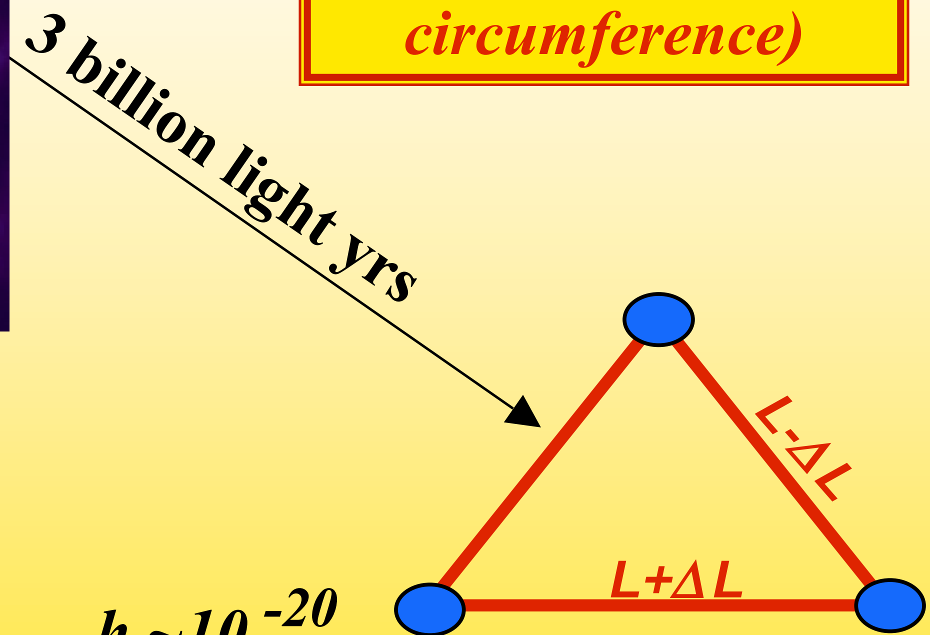
Reminder of LISA Science



Some Numbers for LISA - EMRIs



Final Month: 20,000 orbits with Circumference < 4 x (Horizon circumference)



Map the spacetime metric of the big hole

$h \sim 10^{-20}$

L=5 million km

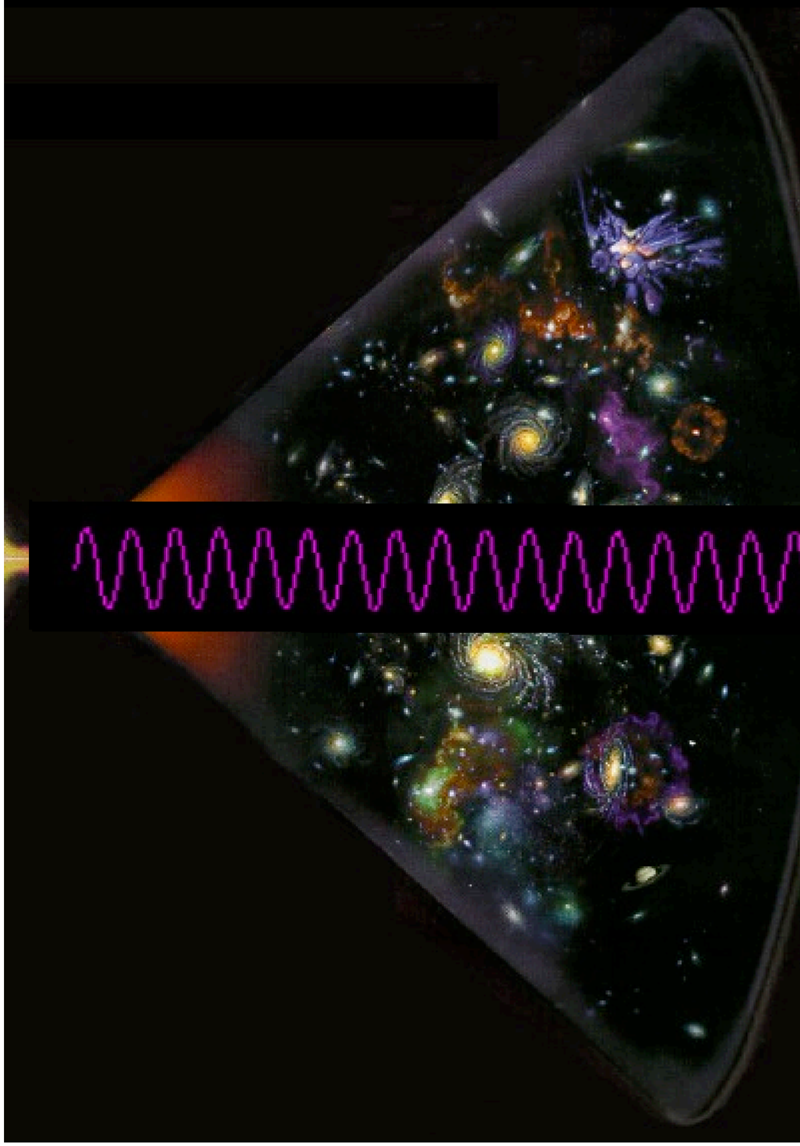
$\Delta L = 10^{-10}$ cm

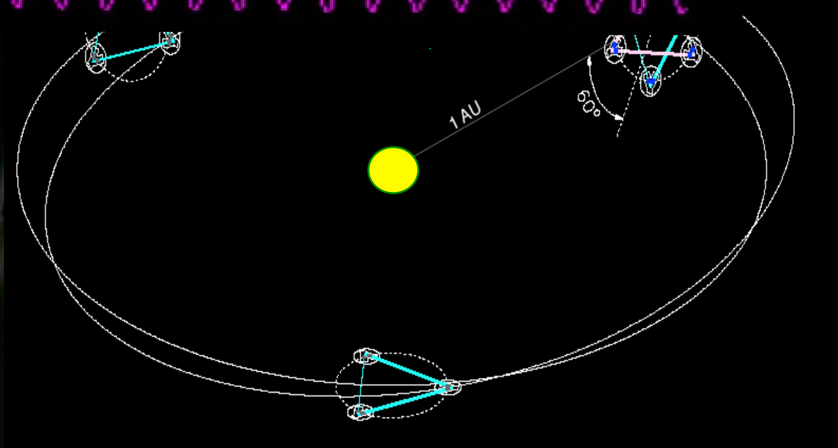
BBO: Big Bang Observer

Based on 2005 study by
BBO Team of 56 - chair: **Sterl Phinney**

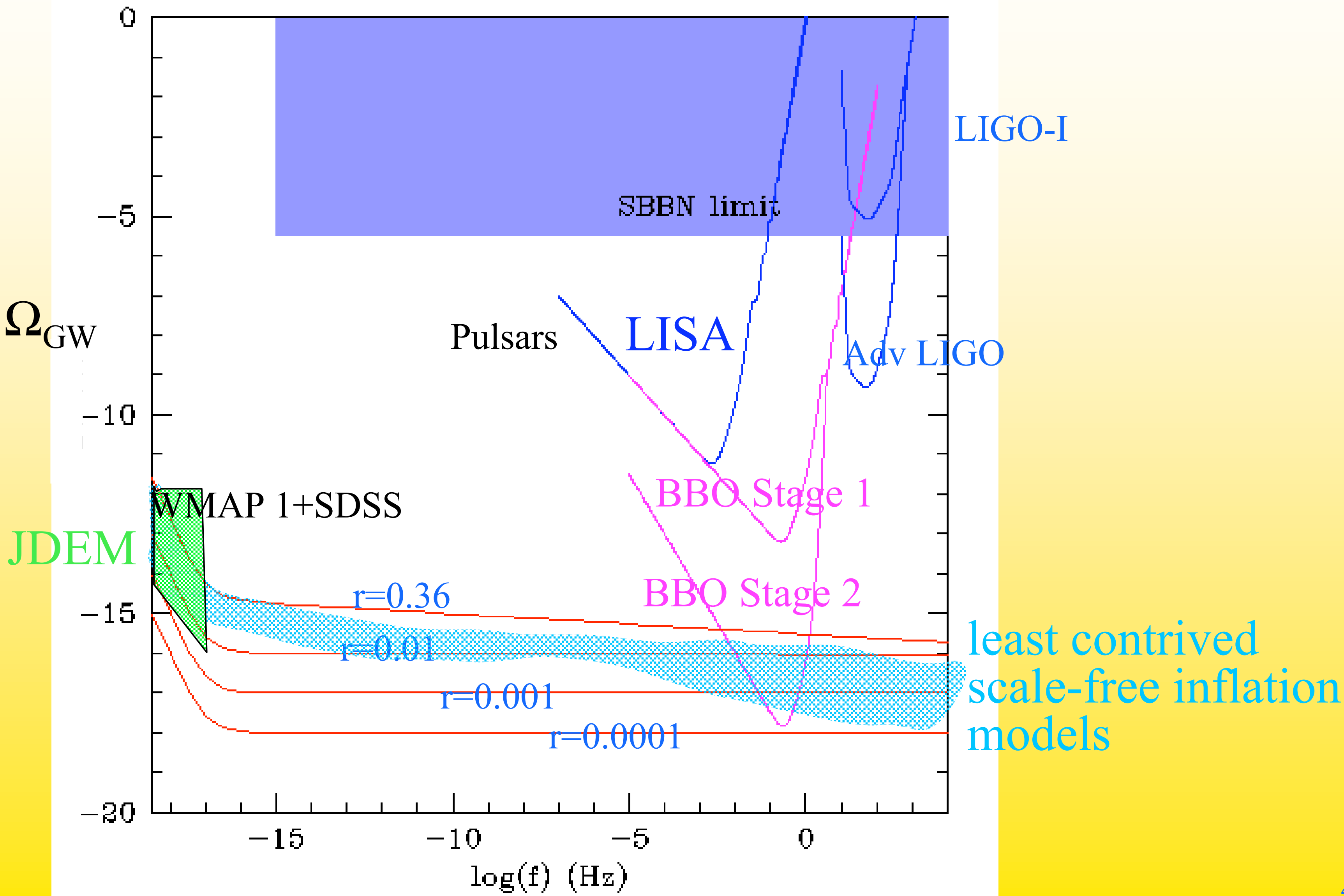
[funding to Caltech, GSFC, JPL, MIT, Montana State, Stanford]

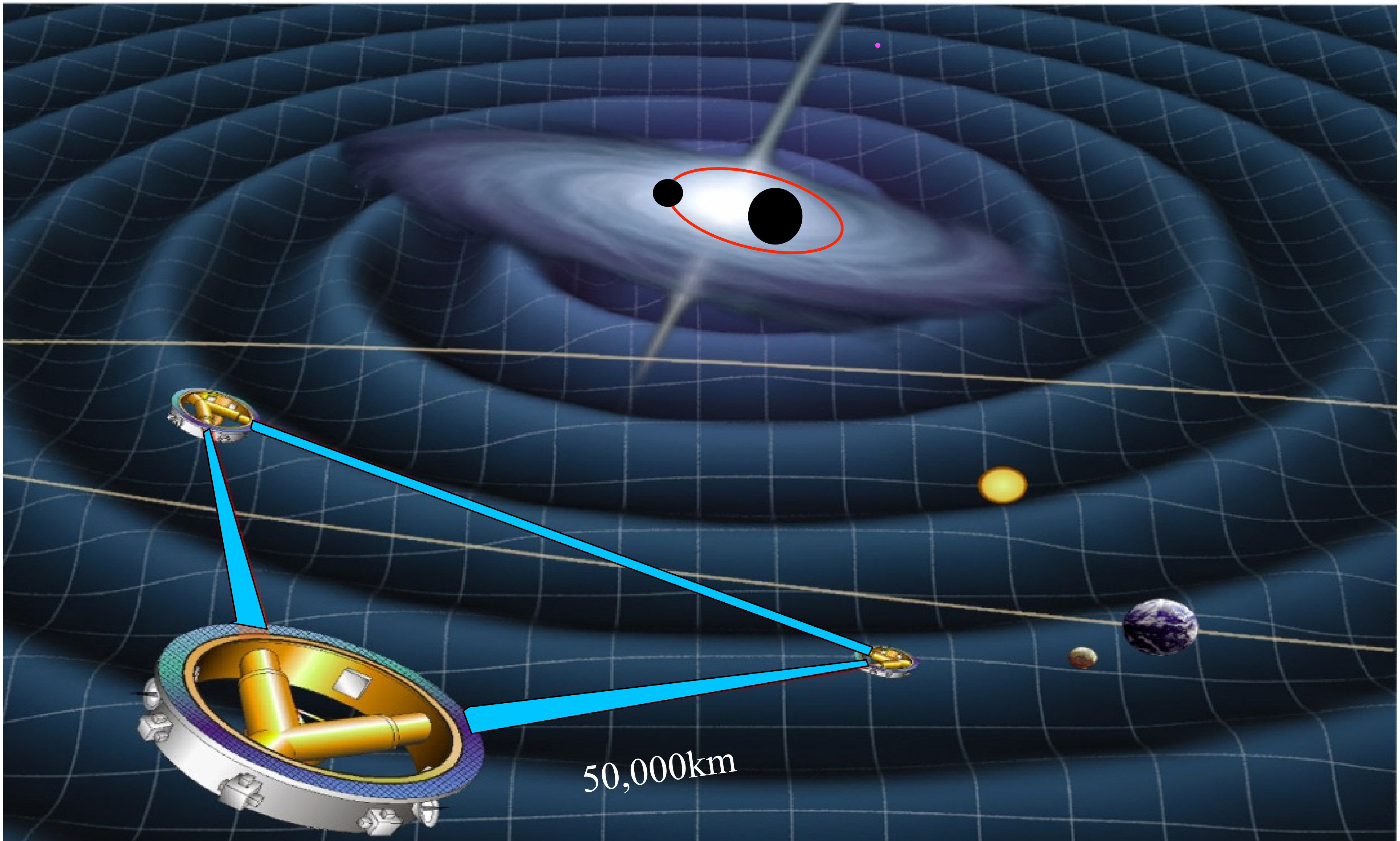
- slides from Phinney





BBO & Stochastic Background





BBO Stage 1: 3 Spacecraft, no solar plasma correction.

Goal: determine nature and number of sources in 0.1-1Hz

Design optimal arm length for Stage 2 correlated pair.

BBO Stage 1: Science

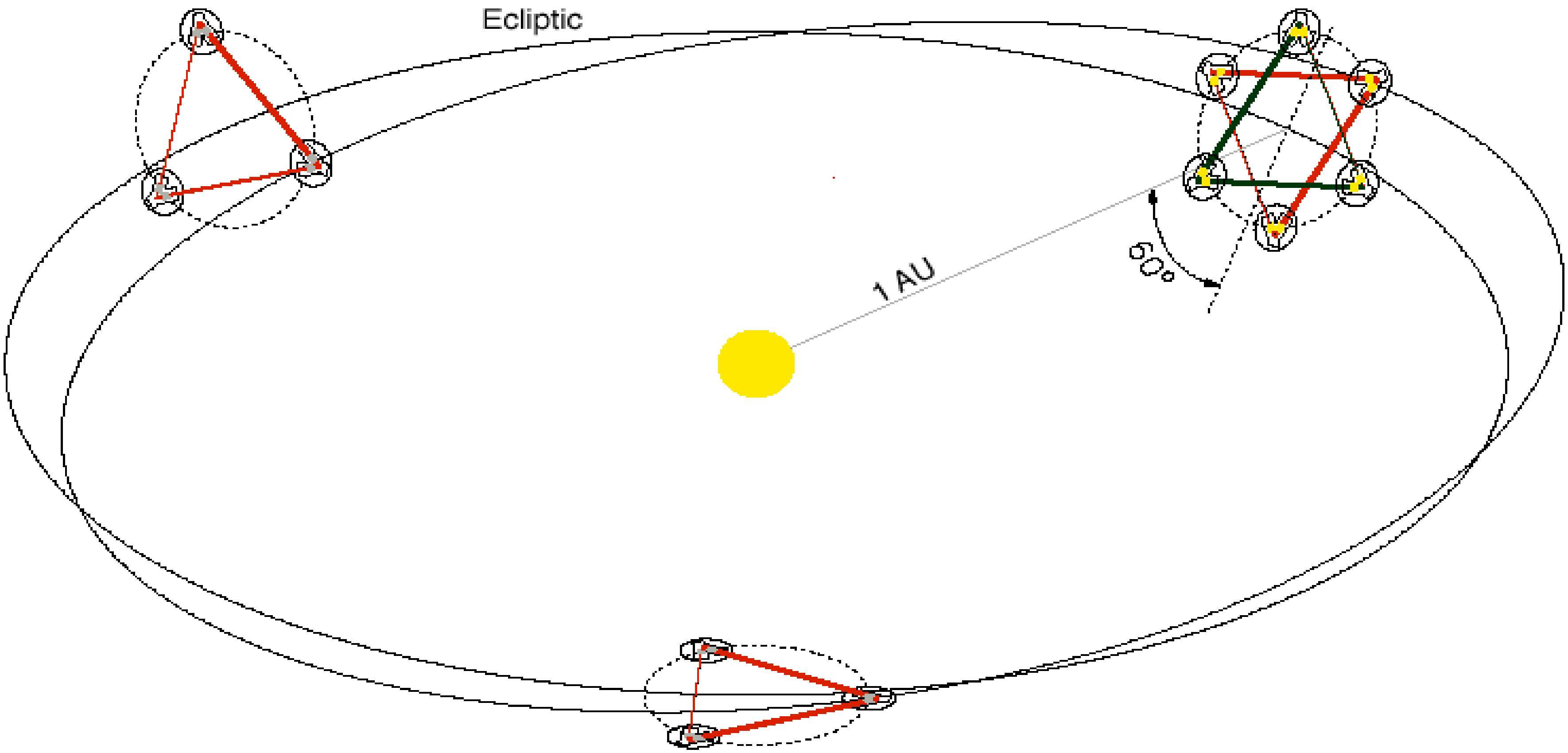
1) Last year of every merging NS-NS, NS-BH, BH-BH of stellar mass at $z<8$. ~1 arcmin positions.

2) Luminosity distances for (1): ~10^4-10^5 sources, accurate to < 1%

3) All mergers of intermediate mass BH at any z.

4) Cosmic/Superstrings over entire range $G\mu/c^2 > 10^{-14}$

BBO Stage 2



- *Triangulate on foreground sources: positions to subarcsecond*
- *Colocated IFOs: Stochastic Background down to $\Omega \sim 10^{-17}$*

Conclusions

- Gravitational wave astronomy has a very bright future
- Gravitational-Wave Observations and Numerical Relativity are both nearing maturity
- May revolutionize our understanding of the warped side of the universe
  - » separately and jointly