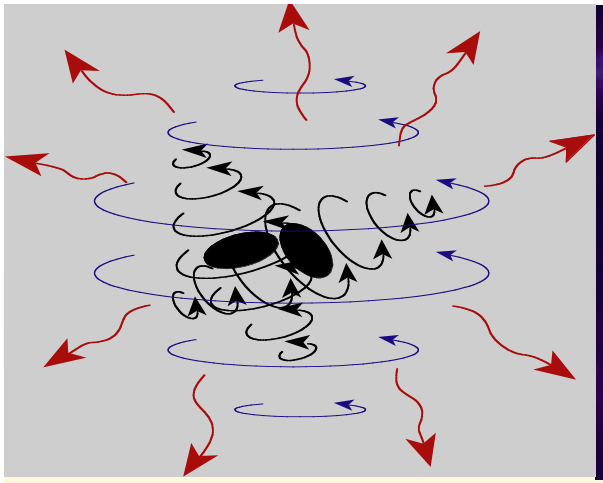
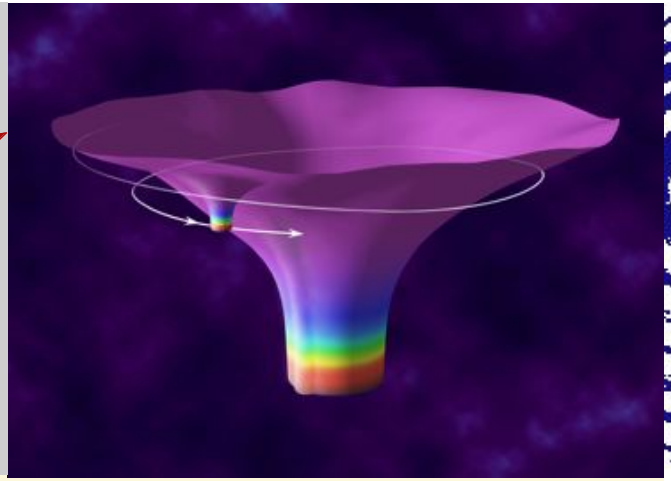
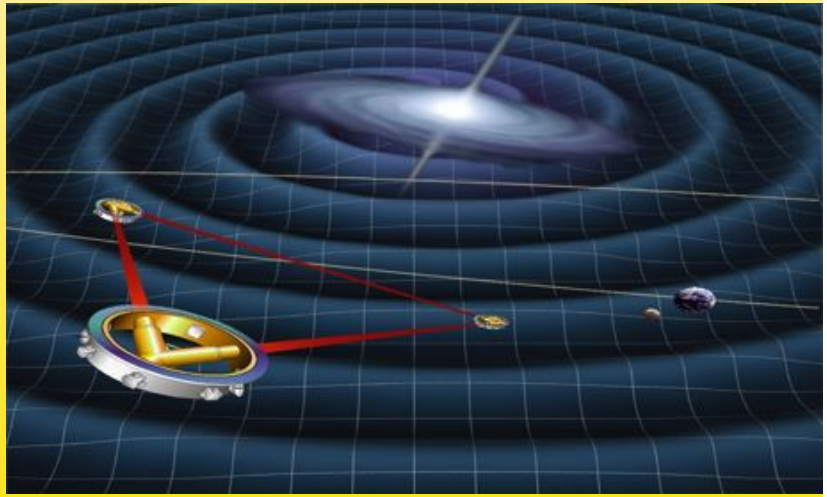



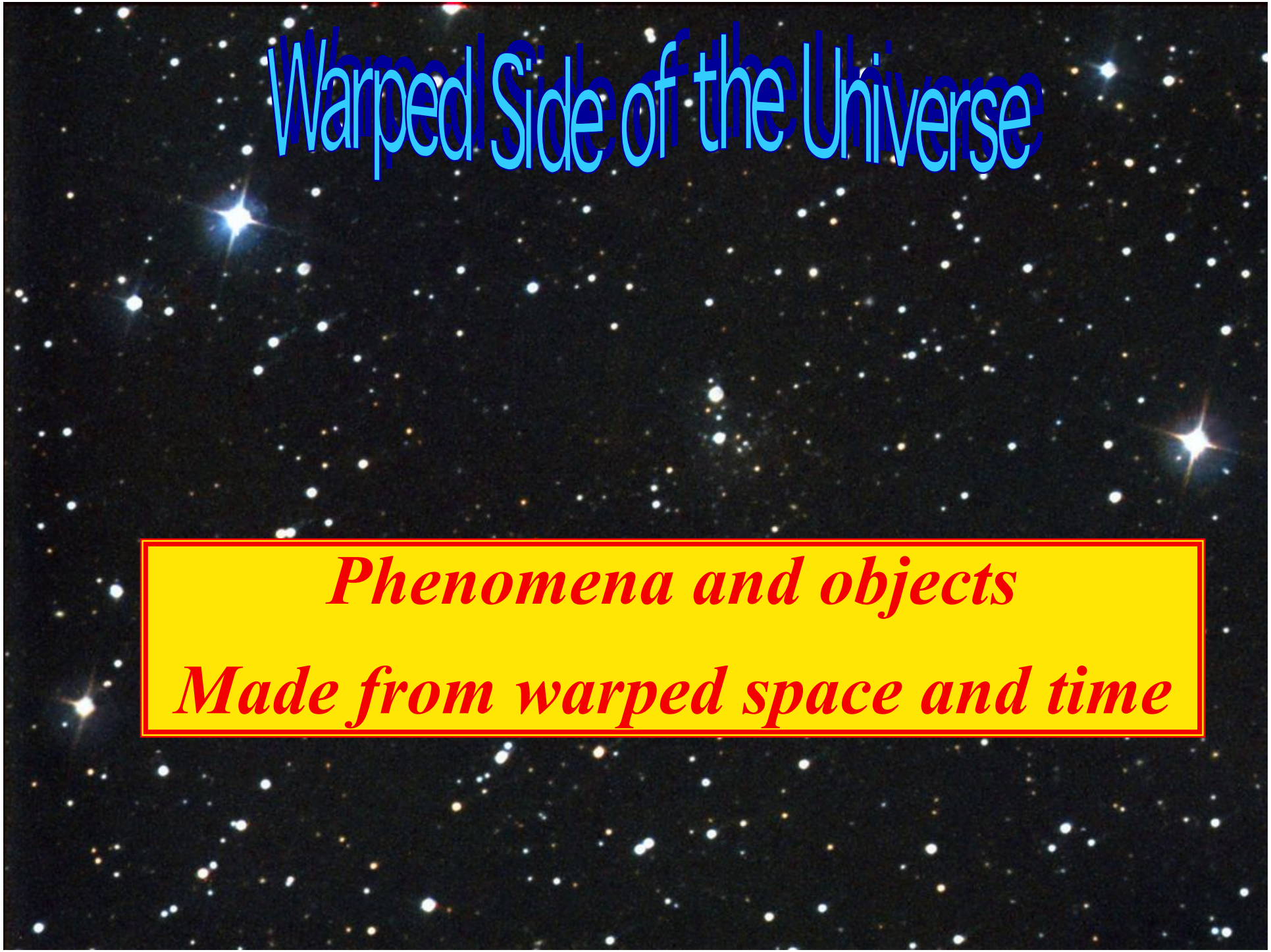

The Warped Side of the Universe:

From the Big Bang to Black Holes & Gravitational Waves

Kip Thorne

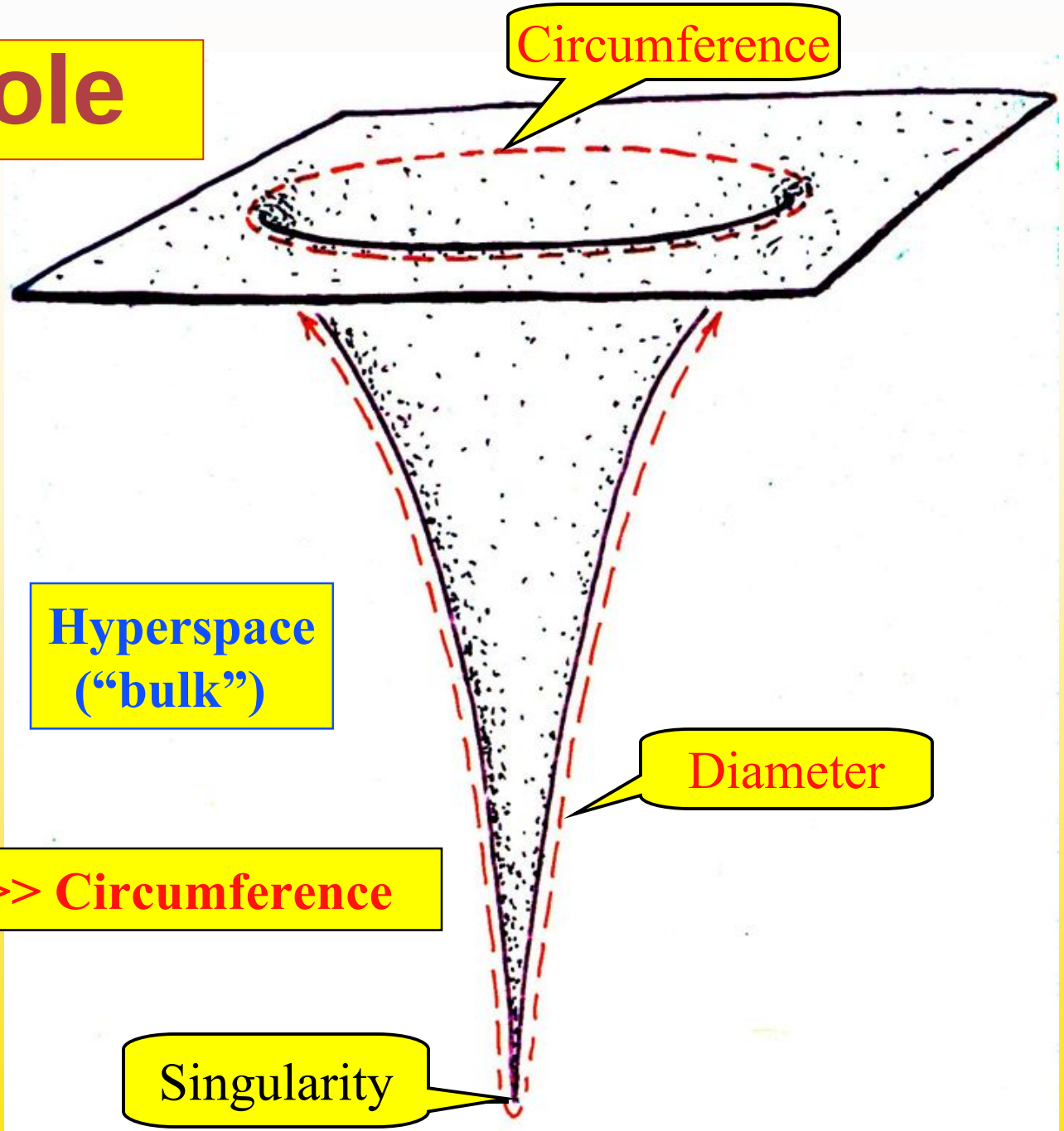



Lyncean Group, and Caltech Alumni Association, San Diego, 7 April 2010

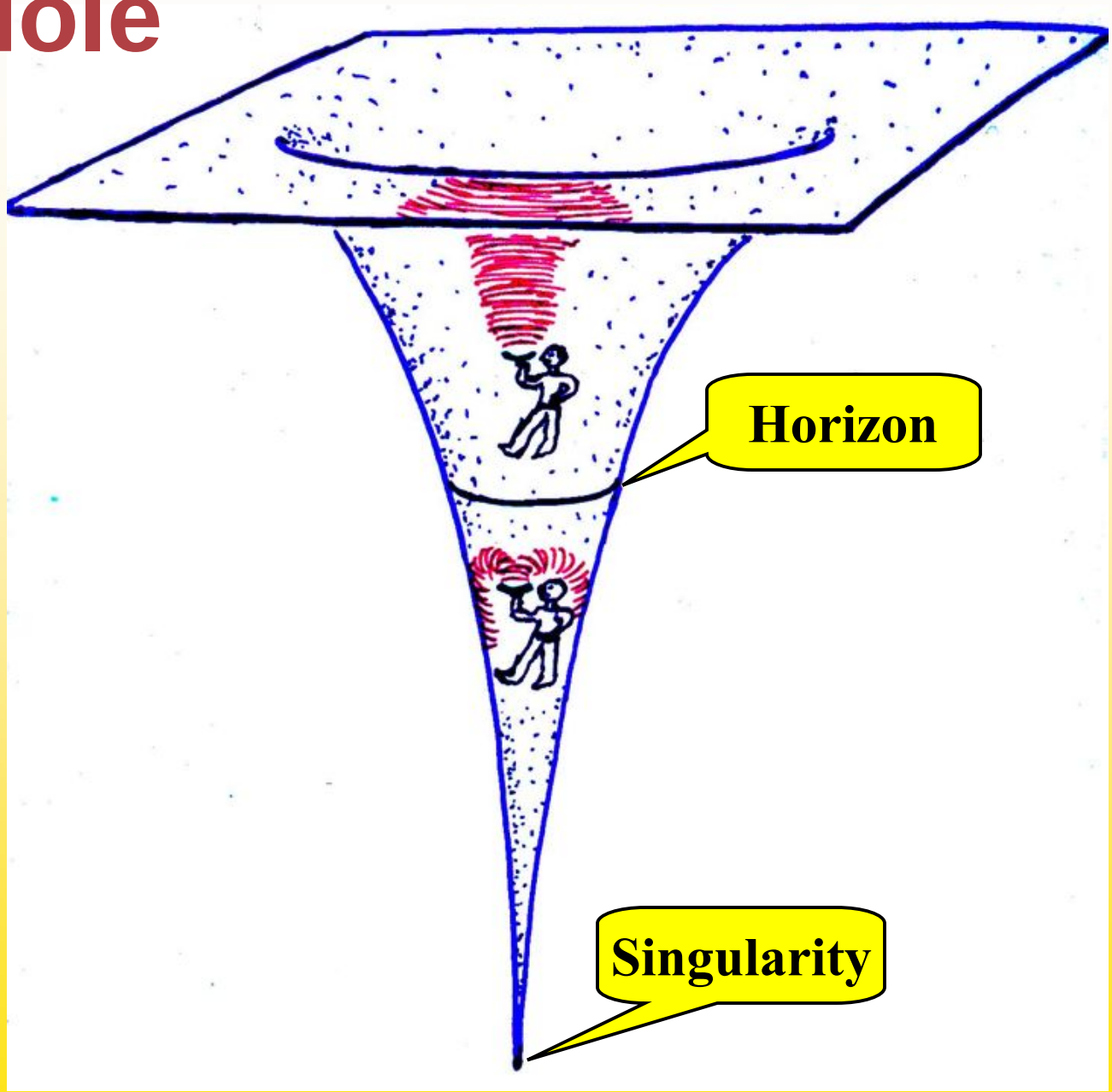

Warped Side of the Universe
Phenomena and objects
Made from warped space and time

Black Hole

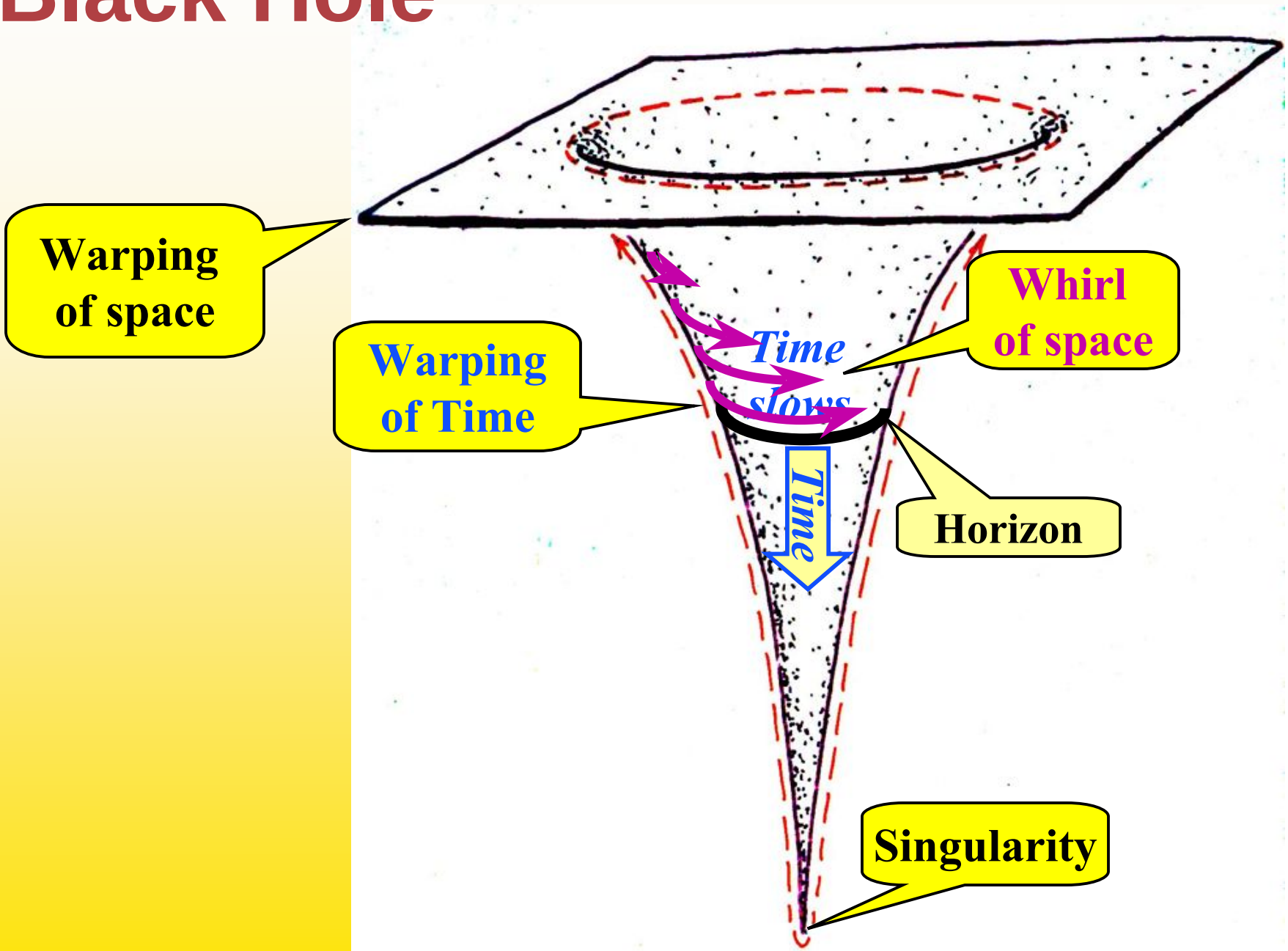
Black Hole


Circumference
Hyperspace
("bulk")
Diameter
Diameter >> Circumference
Singularity

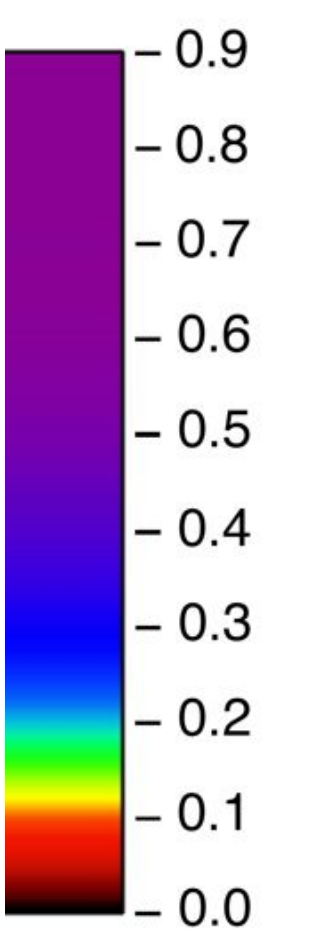
Black Hole



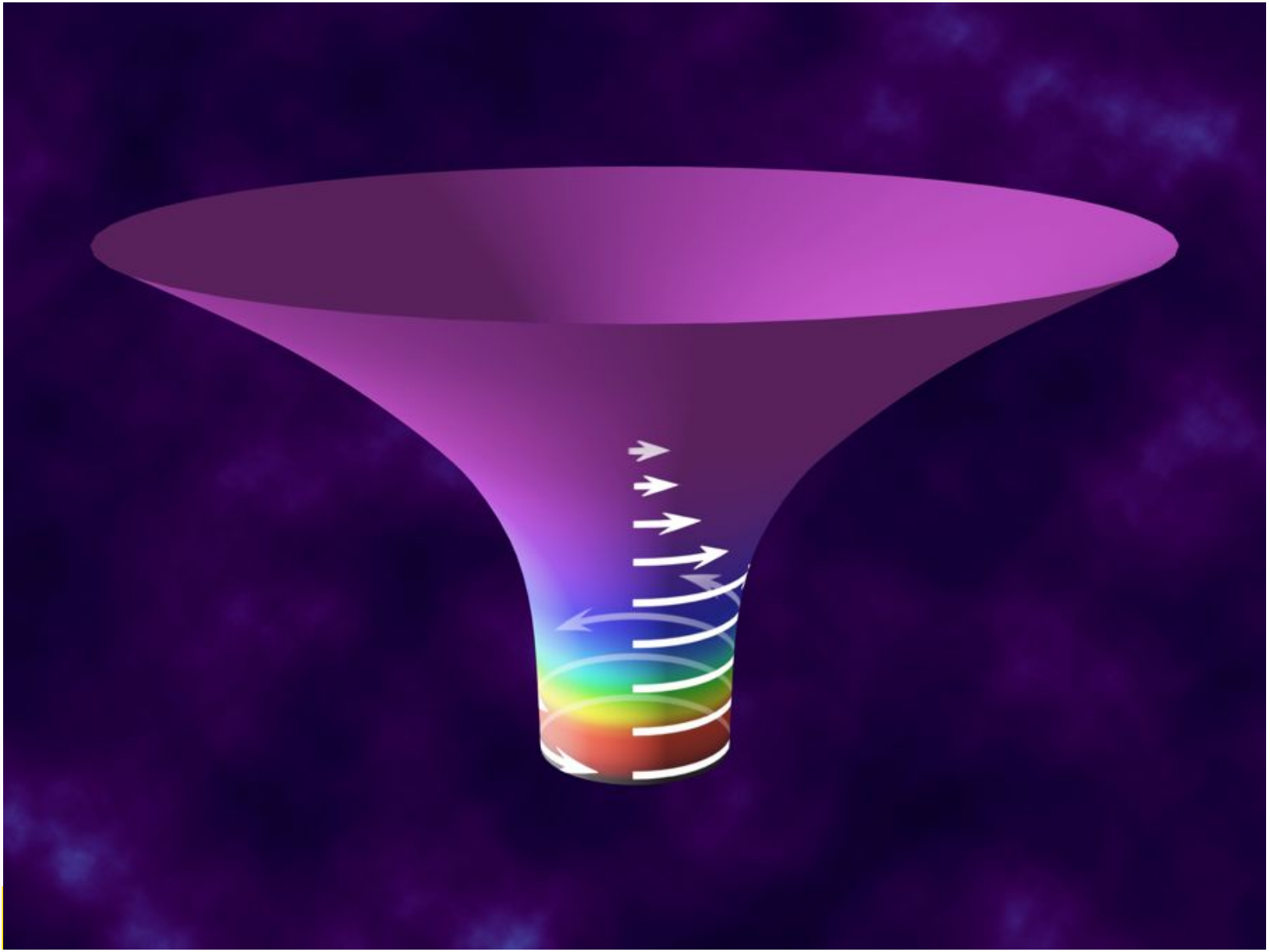
Black Hole


Warping of space
Warping of Time
Time slows
Whirl of space
Time
Horizon
Singularity

Map for Fast Spinning Hole



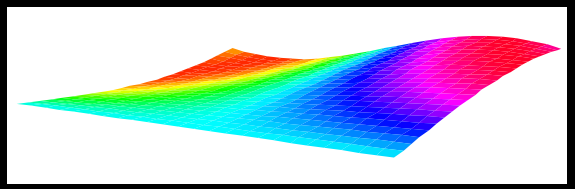
Rate of Time flow



Warped Side of the Universe

Other Examples

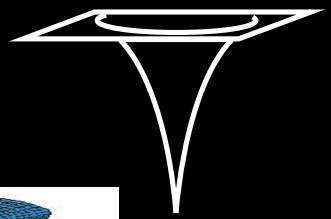
- *The Big Bang Singularity*



- *Our Universe as a Brane in a higher-dimensional bulk*
- *Cosmic String*

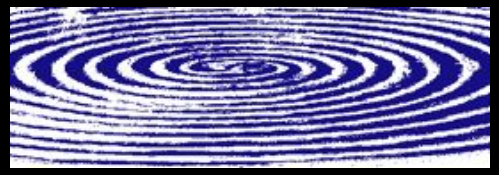
$C/R = 2\pi(1-4G\mu/c^2)$

- *Singularity inside a black hole*



- *Naked Singularity*

- *Gravitational Waves*



Warped Side of the Universe

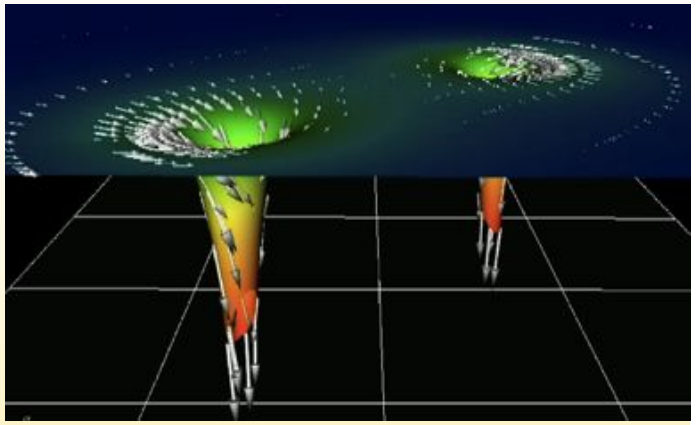
Other Examples

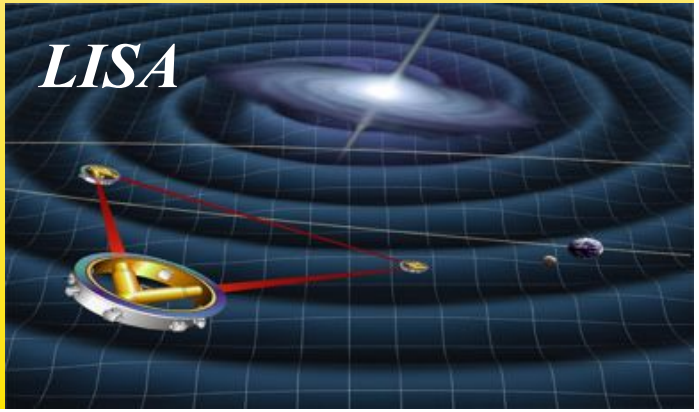
WHICH ARE REAL?

WHAT ELSE?

Probing the Warped Side: Tools

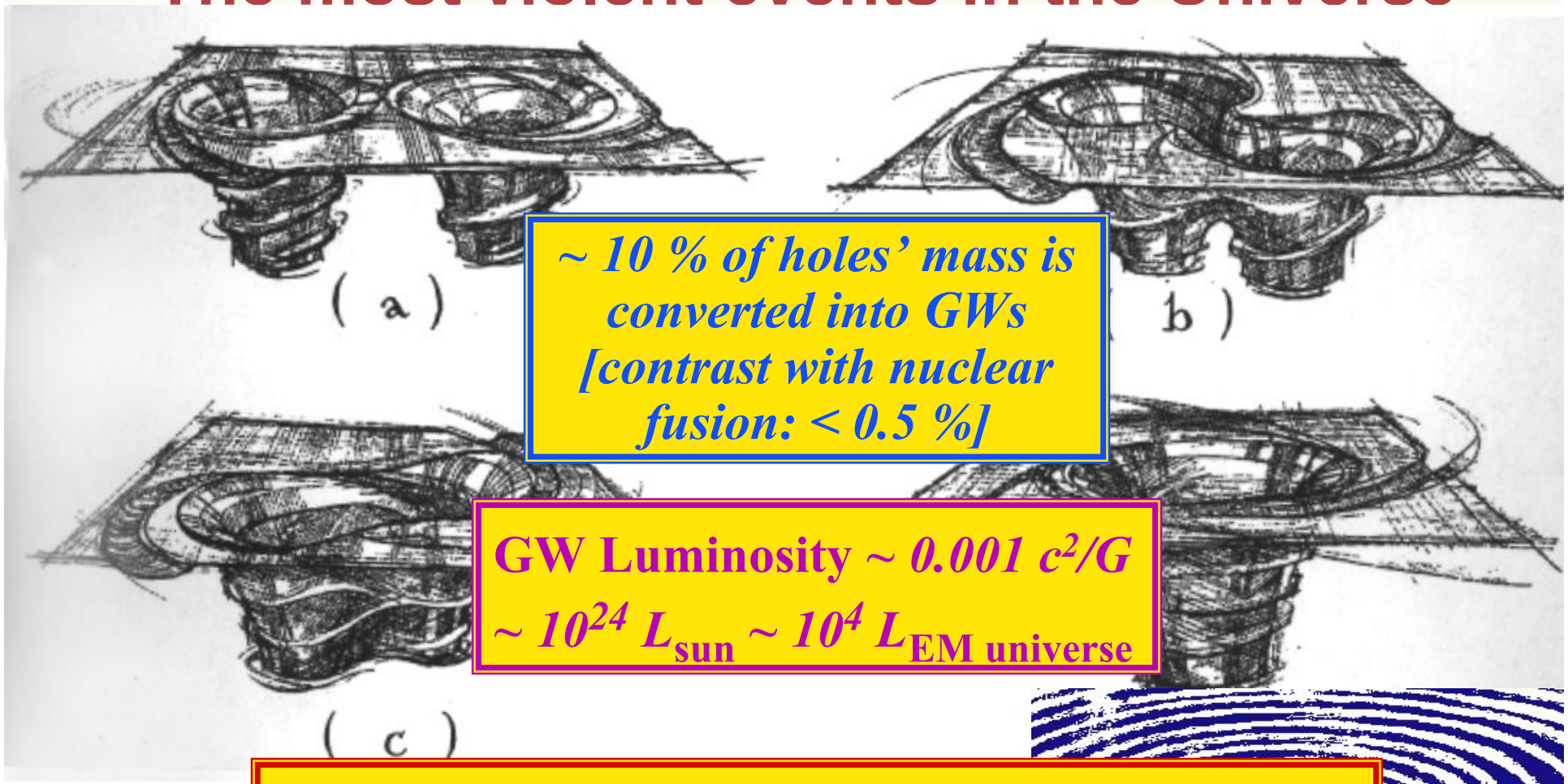
- What kinds of objects ***might*** exist?
  - » General Relativity Theory
    - – Progress has slowed…
  - » ***Numerical Relativity***
    - – Exciting new era…
    - – Part 1
- What kinds of objects ***do*** exist?
  - » Electromagnetic observations
    - –Limited information
  - » ***Gravitational-Wave observations***
    - –Ideal tool for probing the . Warped Side
    - –Part 2





Part 1
Numerical Relativity

The "Holy Grail": Collisions of Black Holes - The most violent events in the Universe



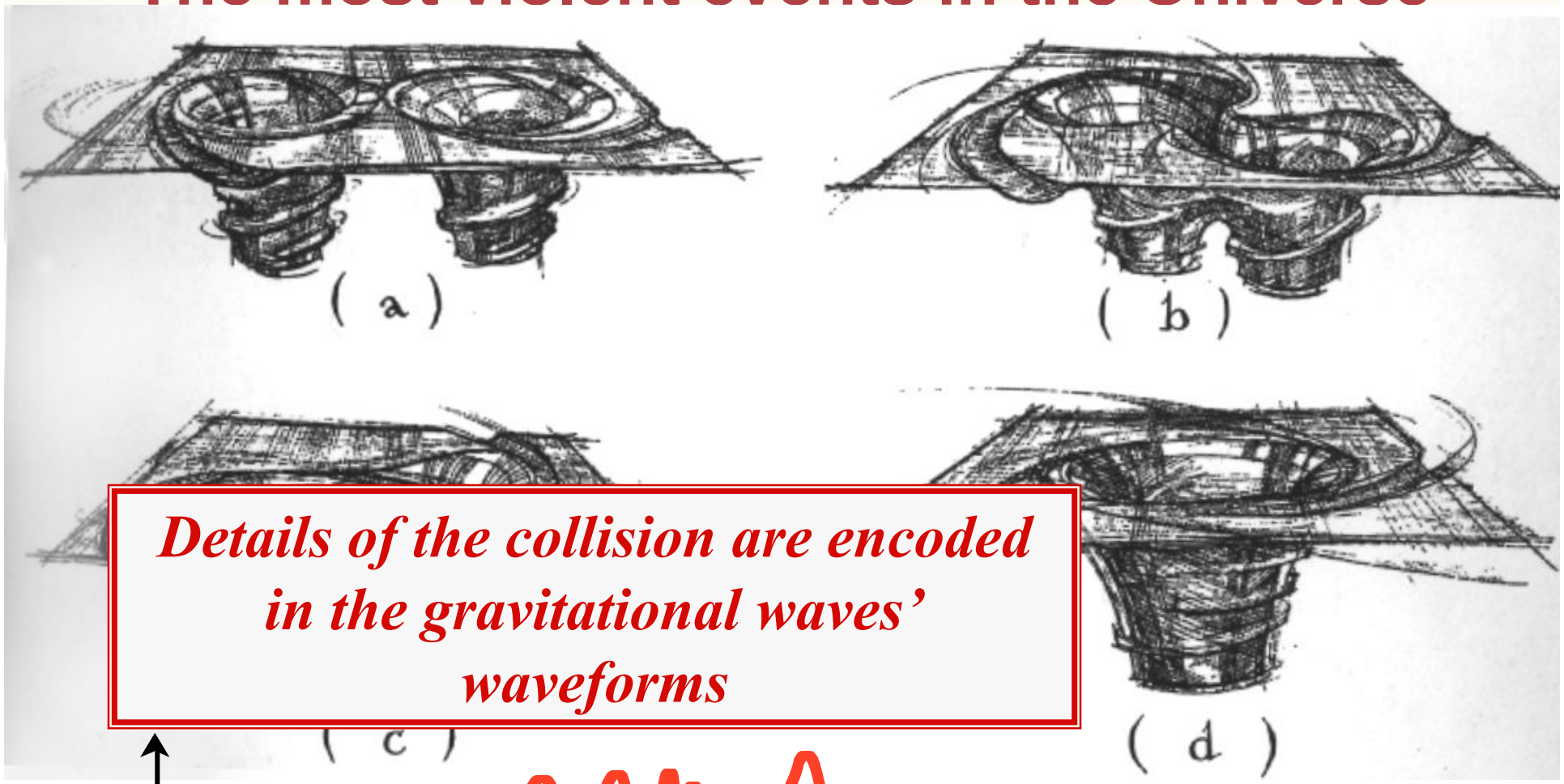
~ 10 % of holes' mass is converted into GWs [contrast with nuclear fusion: < 0.5 %]

GW Luminosity ~ *0.001 c^2/G*
~ 10^{24} L_{sun} ~ 10^4 $L_{EM\ universe}$

No Electromagnetic Waves emitted whatsoever

- only Gravitational Waves -

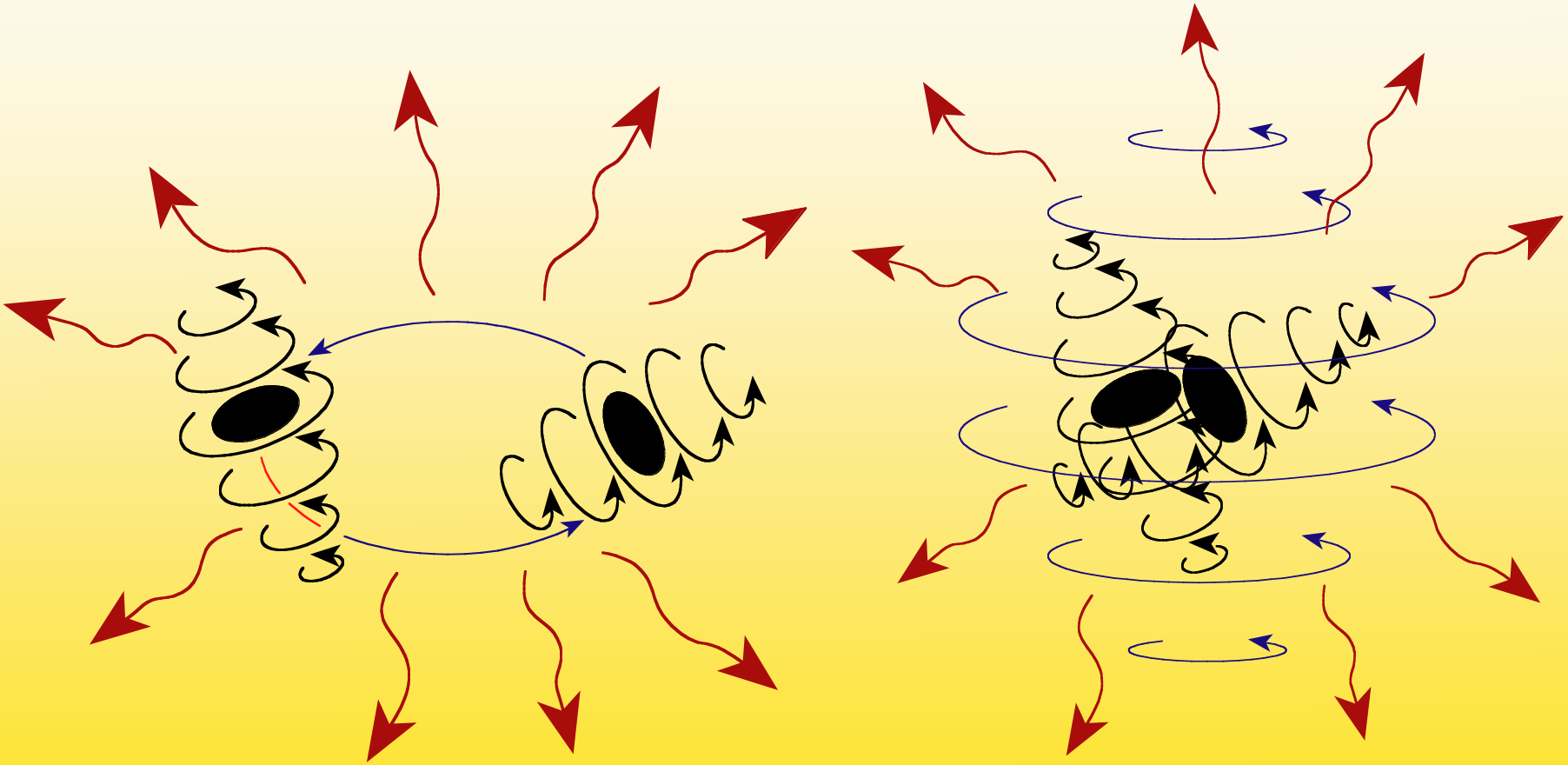
Collisions of Black Holes:
The most violent events in the Universe



Details of the collision are encoded in the gravitational waves' waveforms

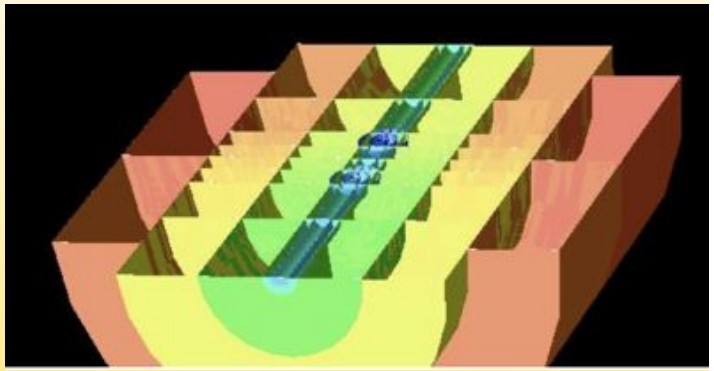
Why are Black-Hole Collisions Interesting?

Wild vibrations of warped spacetime

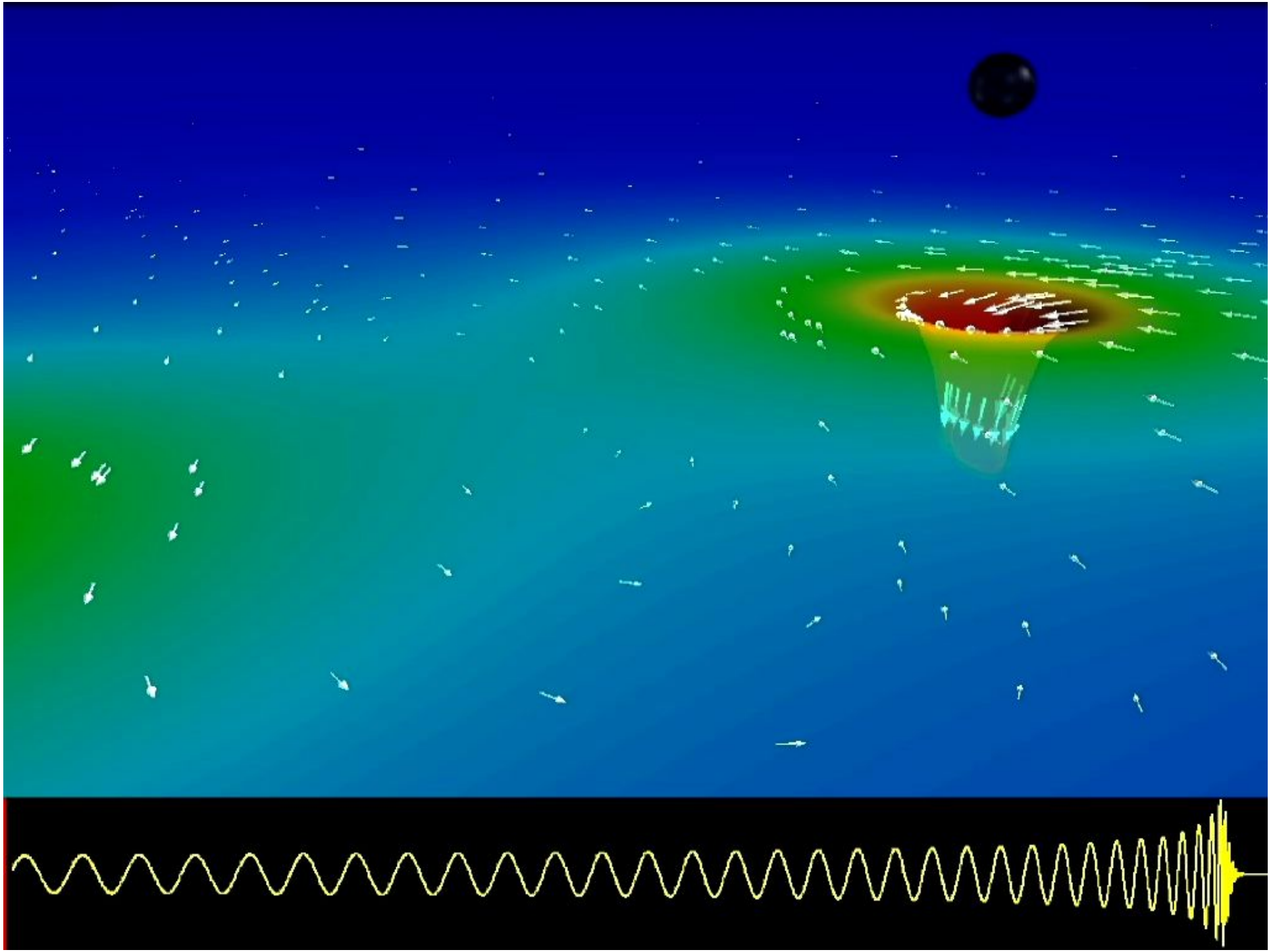


Numerical Simulations of Black Hole Binaries

- Evolve the geometry of space and the warping of time.
  - » Techniques under development since 1970s; only recently matured
  - » Caltech/Cornell team: 2001 - spectral methods [vs finite difference] exponential convergence

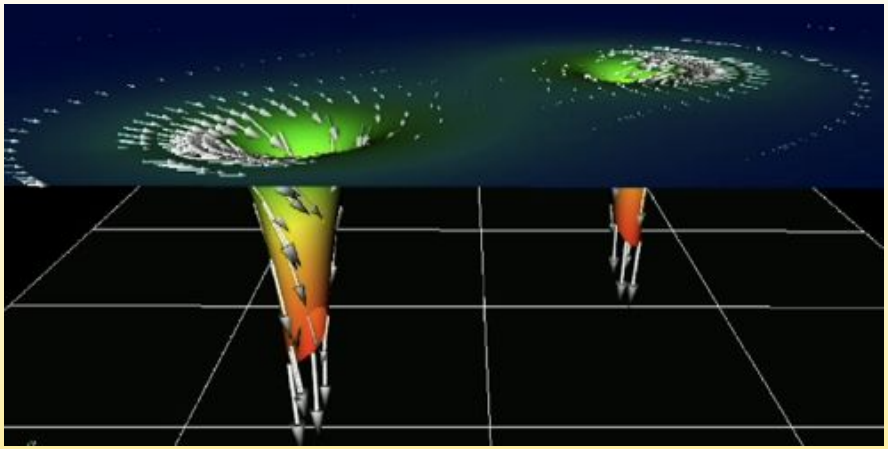


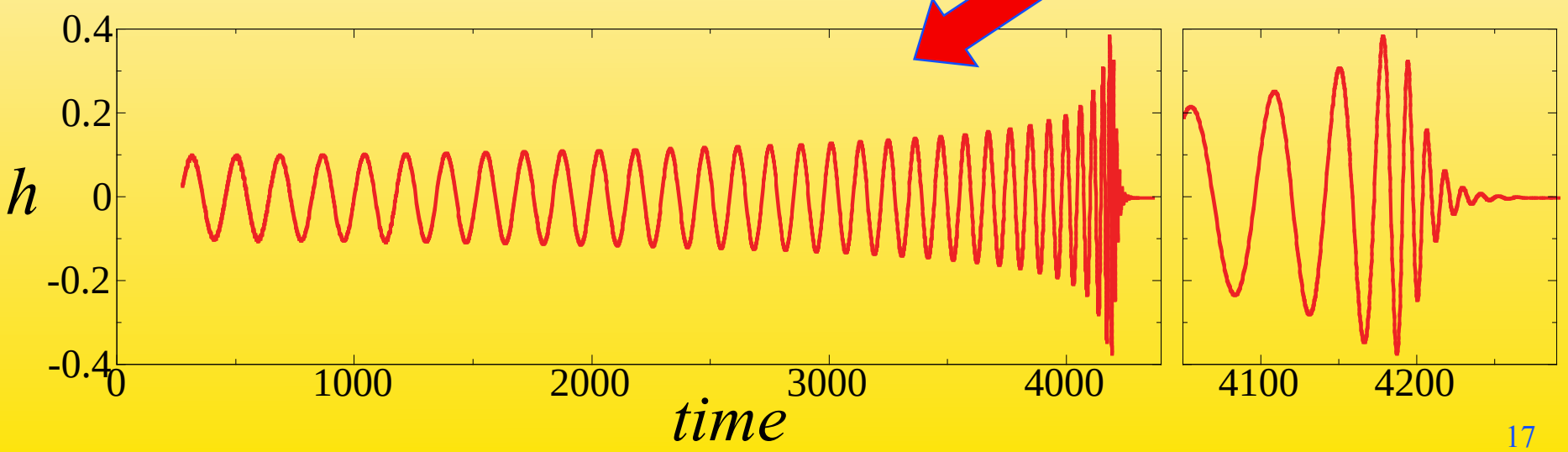
- Example: Identical black holes, not spinning
  - »**Caltech/Cornell:** Kidder, Lindblom, Pfeiffer, Scheel, Teukolsky
  - »10,000 cpu-hours on a 264 cpu cluster



“Rosetta Stone”

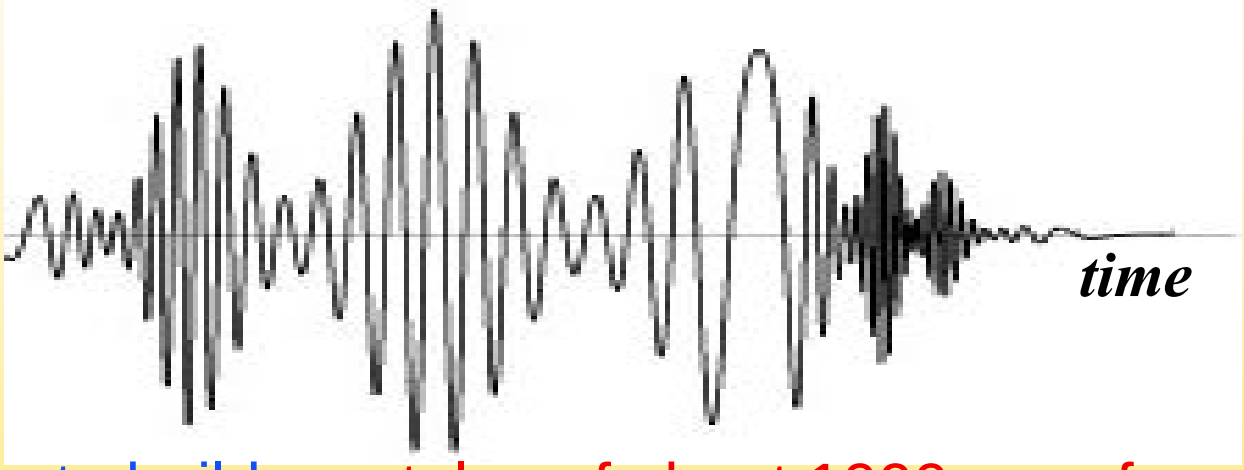
Numerical simulations and theory provide “rosetta stone” for interpreting observed Gravitational Waveforms





“Rosetta Stone”

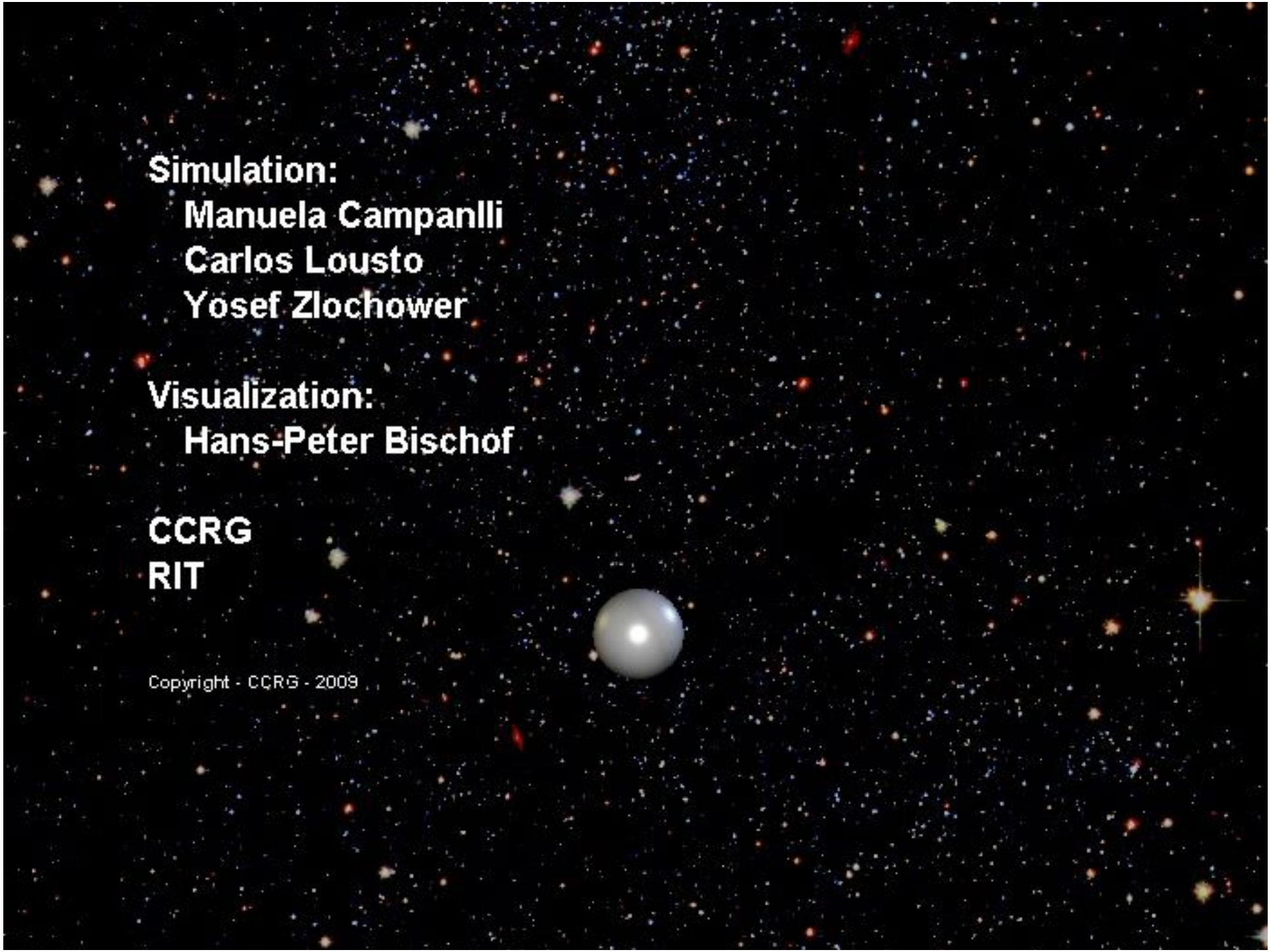
- For generic binaries, waveforms are much more complex
  - » Noncircular orbits; different sized holes, spinning, random orientations



- We are beginning to build a catalog of about 1000 waveforms for use in LIGO!s searches for gravitational waves (new computer cluster … NSF/Fairchild funded; 50 million cpu-hours)
- We are also exploring the rich & complex dynamics of warped spacetime that produces these waveforms. Simple example:

What we are learning from Simulations

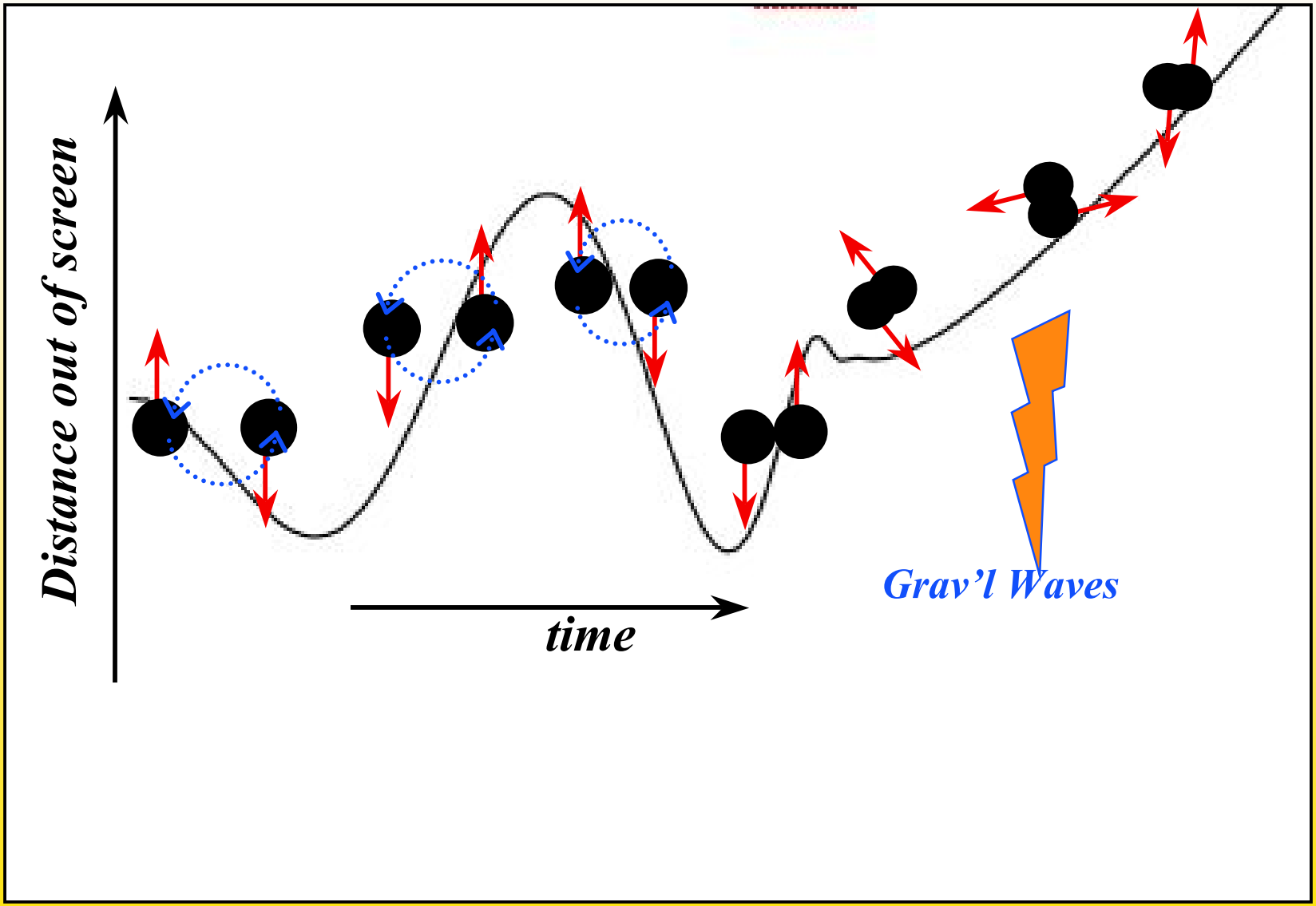
- ***Example: Holes spinning on their sides***


Simulation:
Manuela Campanlli
Carlos Lousto
Yosef Zlochower
Visualization:
Hans-Peter Bischof
CCRG
RIT
Copyright - CCRG - 2009

Analogous to 2 Vortices in a Fluid

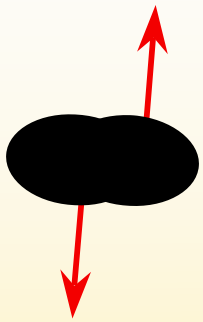
Explanation of Bobbing and Kick

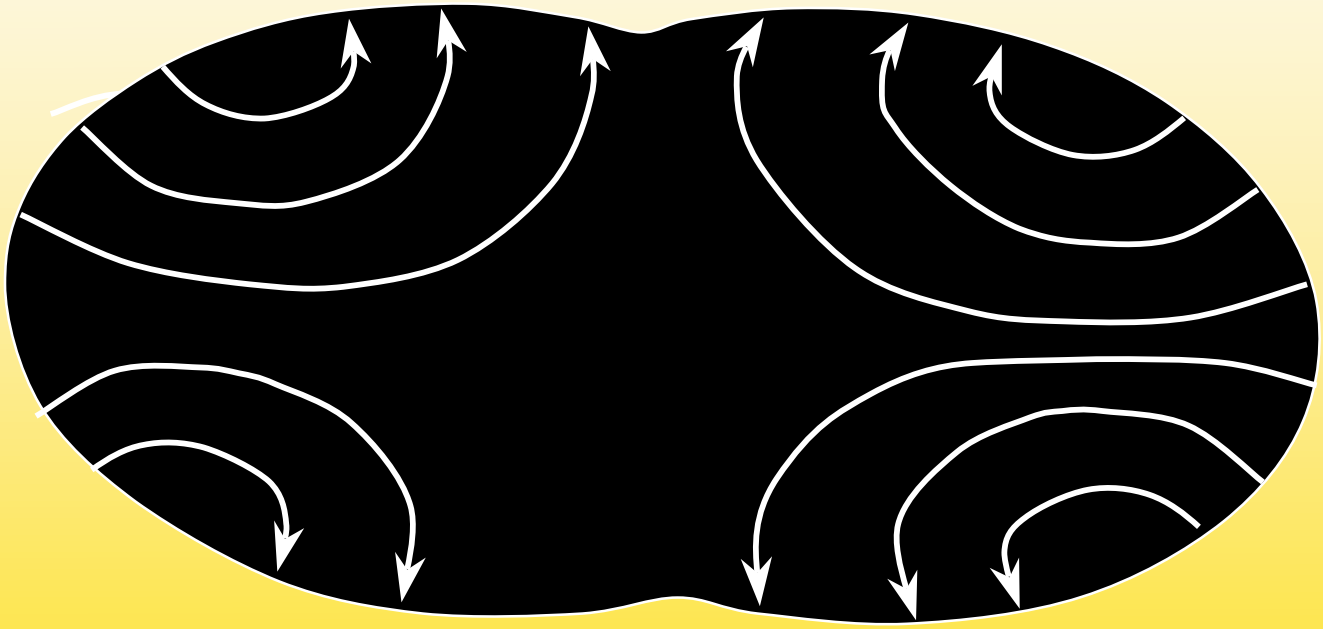
[Yanbei Chen, Kip, …]



Motion of Space *in Horizon*

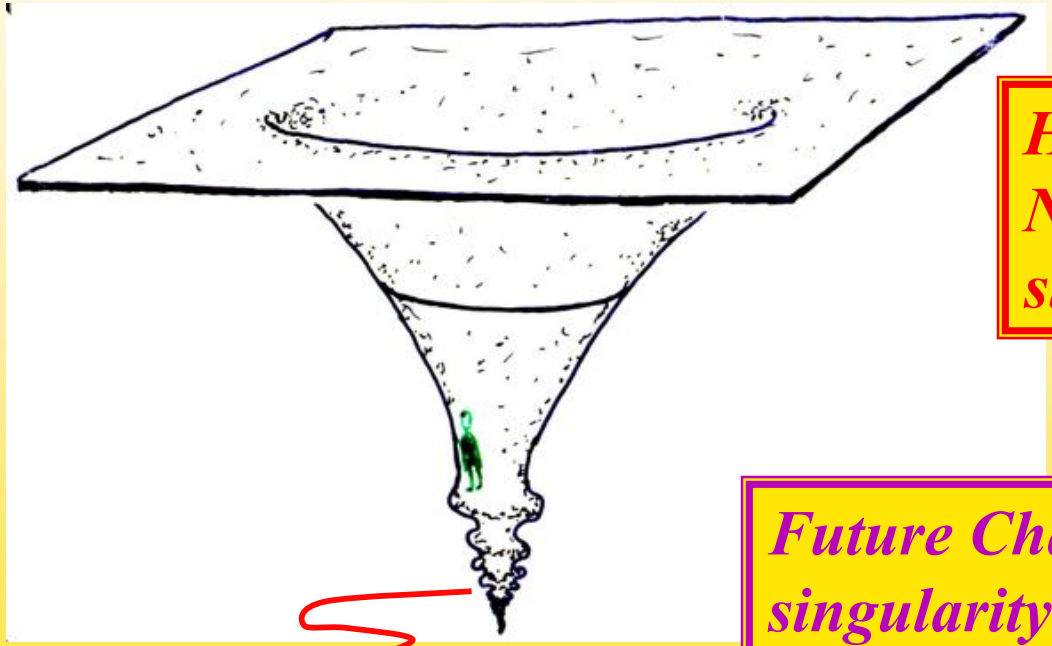
as seen in a reference frame that rotates with the merged hole





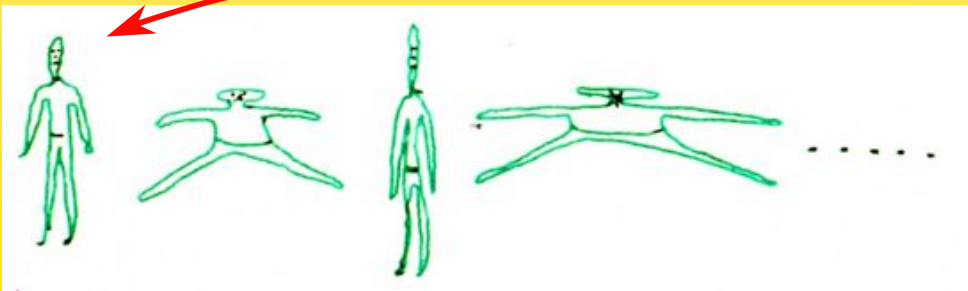
Singularity Inside a Black Hole

- Dynamics of spacetime near **singularity**
  - » Approximate analytic calculations suggested (1971):



Has been confirmed by Numerical Relativity simulations [Garfinkle]

Future Challenge: How does singularity evolve as hole ages?



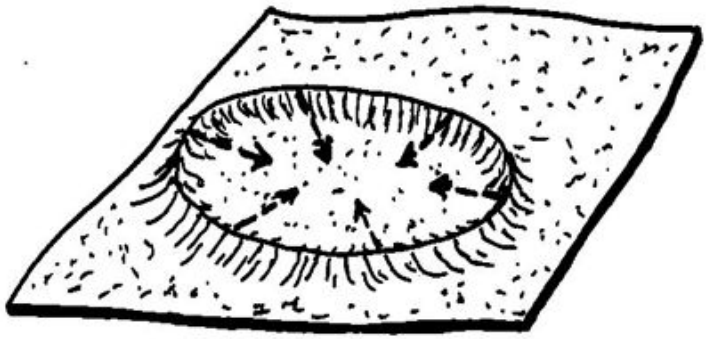
Chaotic pattern of stretch and squeeze

Naked Singularities?

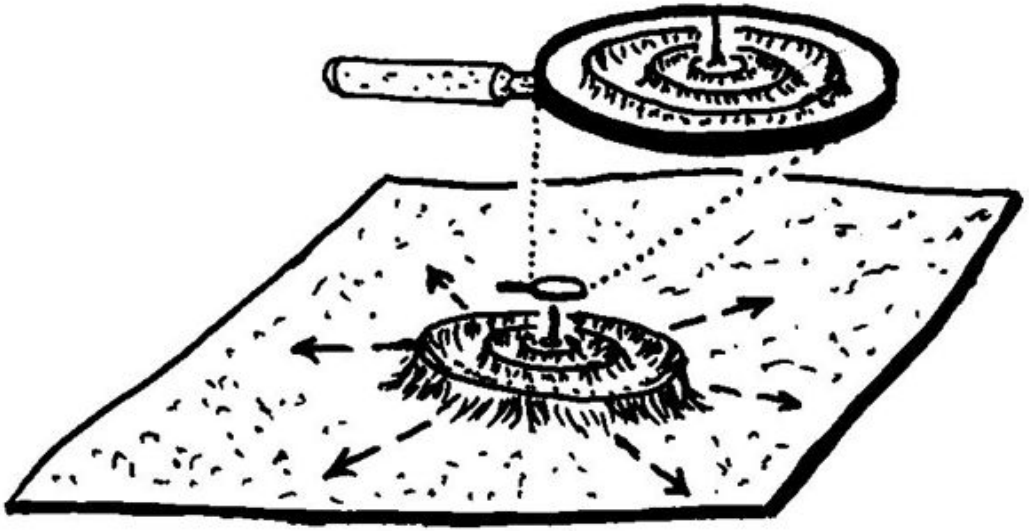
- **Cosmic Censorship Conjecture [Penrose 1968]**
  - » All singularities (except the big bang) are hidden inside black holes.

Numerical Simulations

Matt Choptuik ~ 1994 - (U Texas -> UBC)



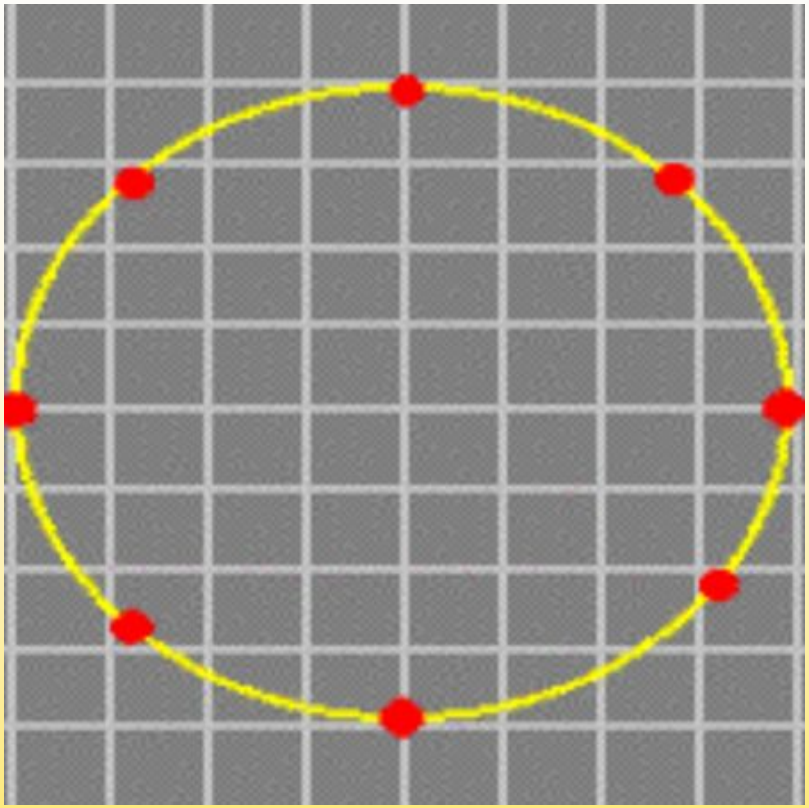
Imploding Waves



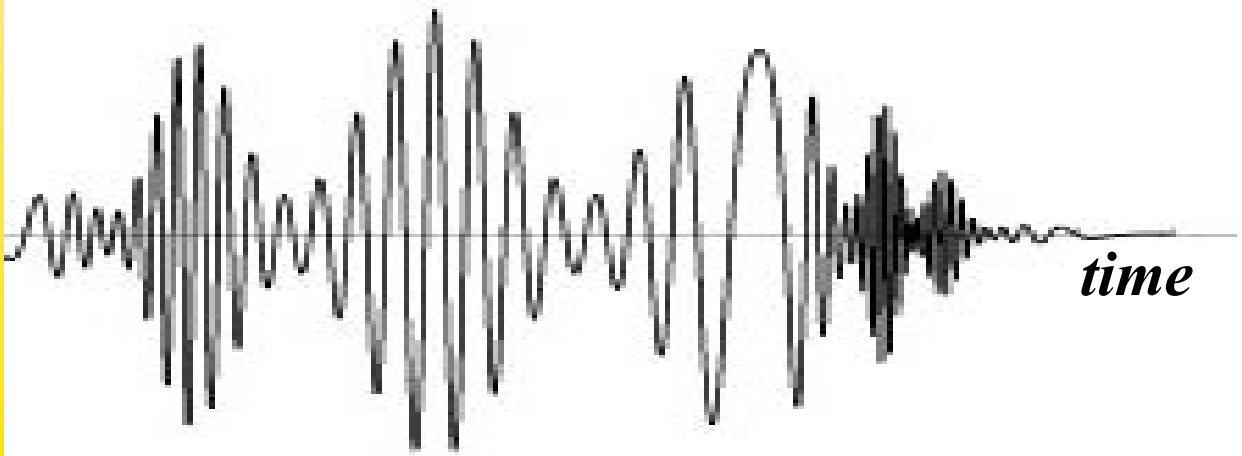
Naked Singularity

Part 2
Gravitational Wave Observations Probe the Warped Side of Universe

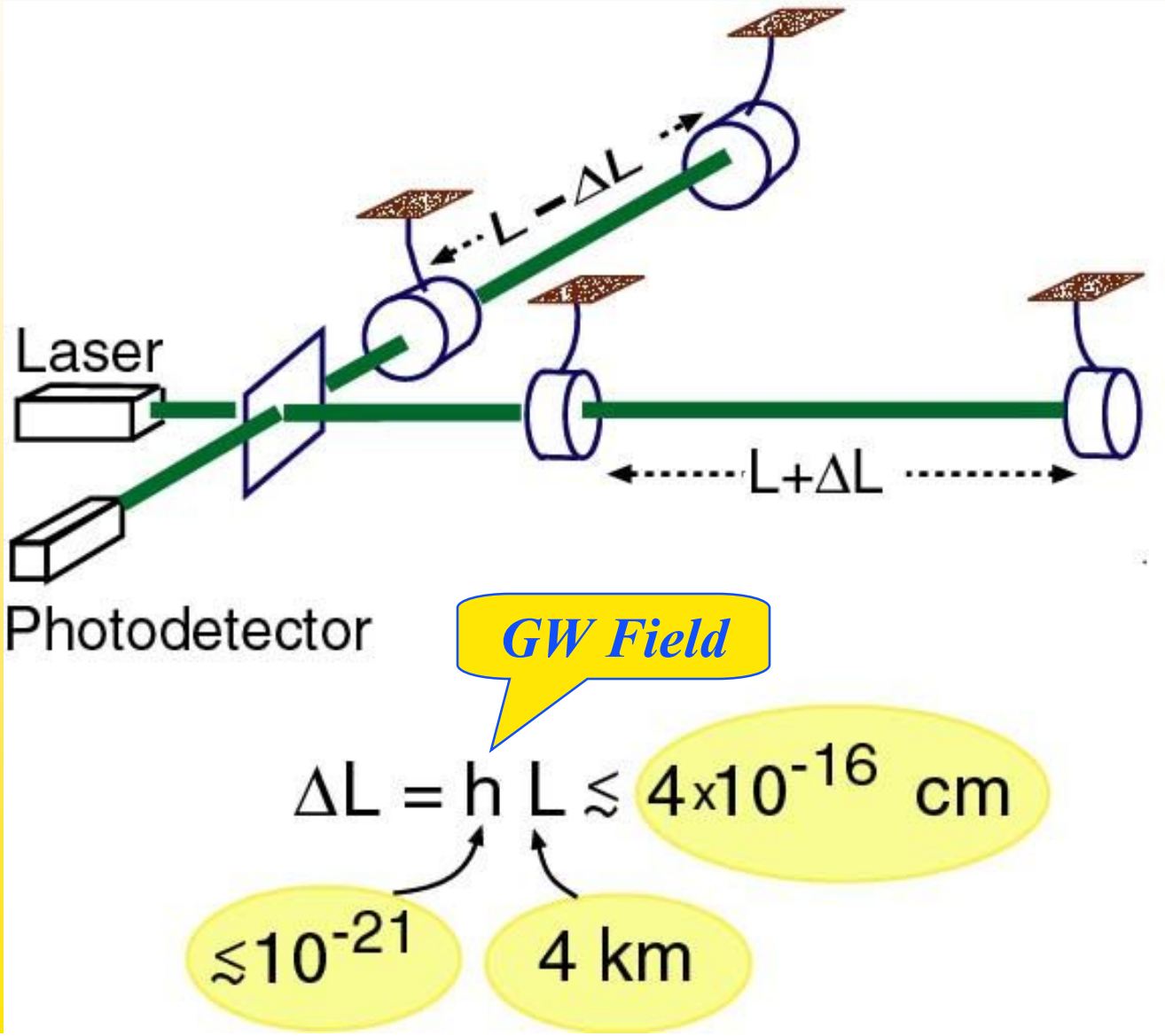
Motivation



$\Delta L/L = h(t)$



Laser Interferometer Gravitational-Wave Detector - "GW Interferometer"



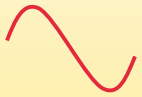
How Small is 10^{-16} Centimeters?

One centimeter ~ 1/2 inch

÷100

Human hair ~ 100 microns

÷100



Wavelength of light ~ 1 micron

÷10,000

Atomic diameter 10^{-8} cm

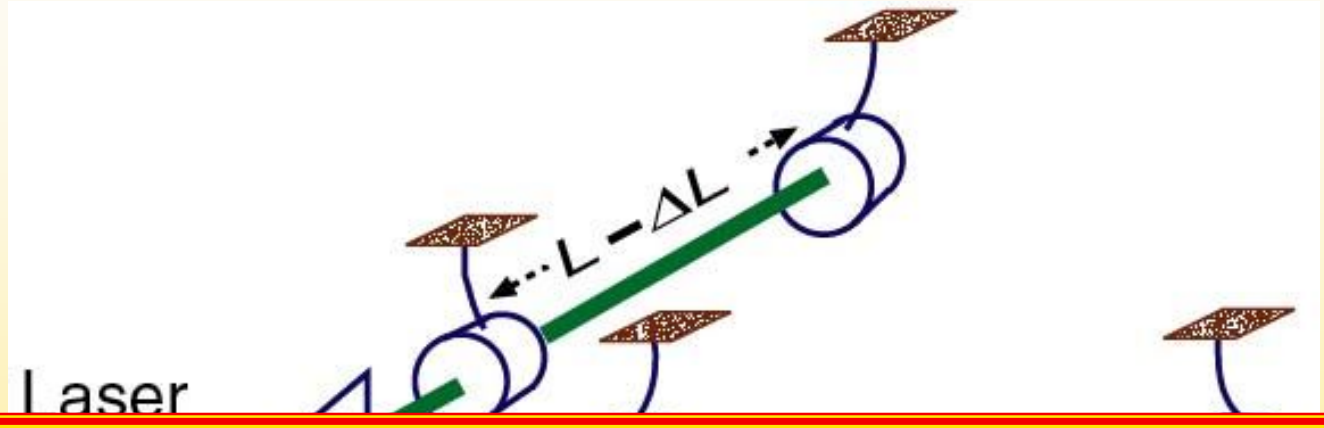
÷100,000

Nuclear diameter 10^{-13} cm

÷1,000

LIGO sensitivity 10^{-16} cm

Laser Interferometer Gravitational-Wave Detector - "GW Interferometer"



Isn't it OUTRAGEOUS to claim one can measure mirror displacements ~1000 times smaller than the nucleus of an atom?

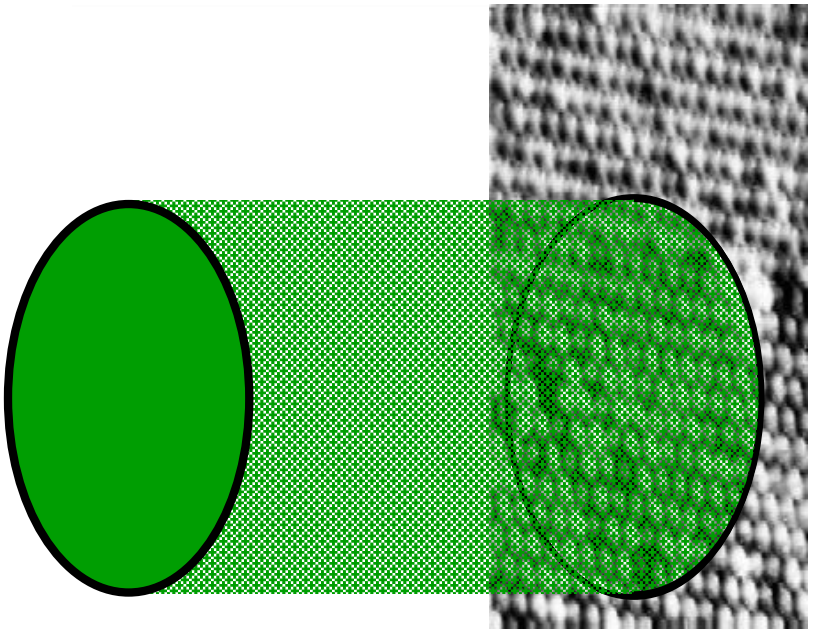
$$\Delta L = h\,L \lesssim 4\times10^{-16}\ \text{cm}$$

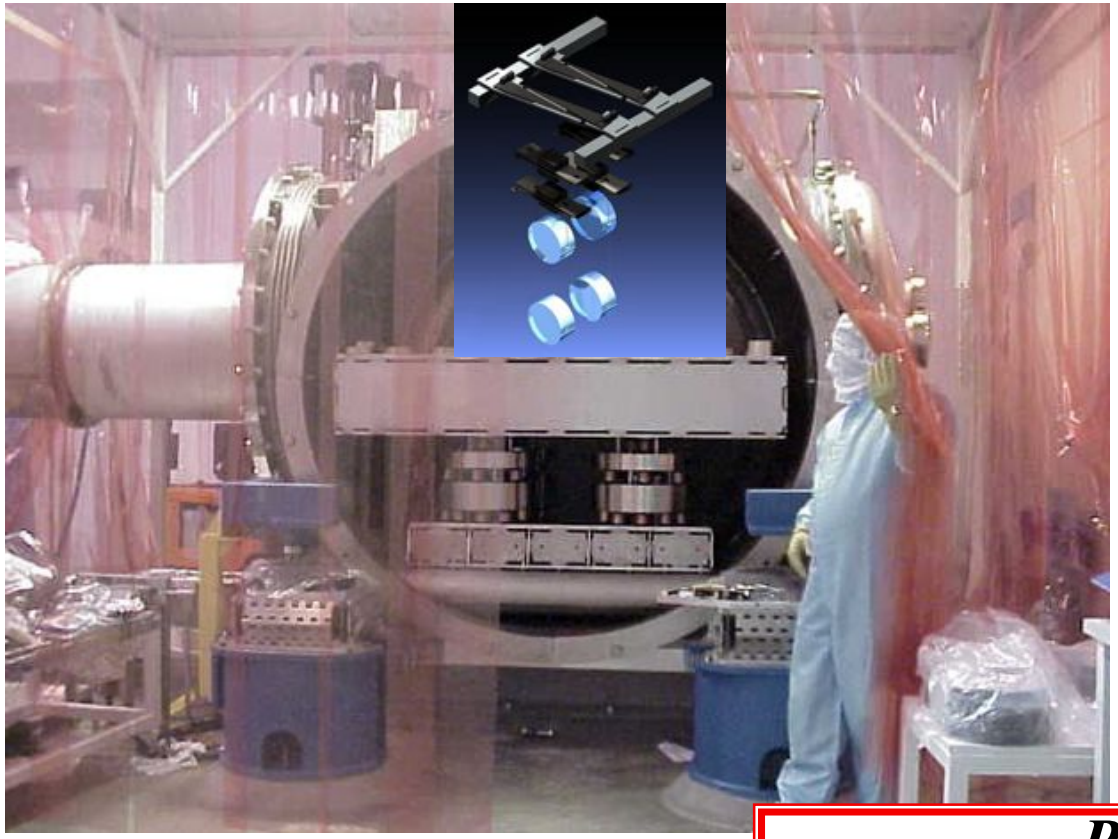
$\lesssim 10^{-21}$ 4 km

Keys to Success

Thermal Noise:

Average over space and time





Seismic Noise:

Isolate from environment

Photon Shot Noise:

Use lots of photons: ~ 10^{20} in 0.01 second

LIGO: Laser Interferometer Gravitational Wave Observatory

Began as MIT/Caltech collaboration [Weiss; Drever, Kip]

Now: Collaboration of ~650 scientists at ~50 institutions in 8 nations [J. Marx, Director; D. Rietze, Spokesman]

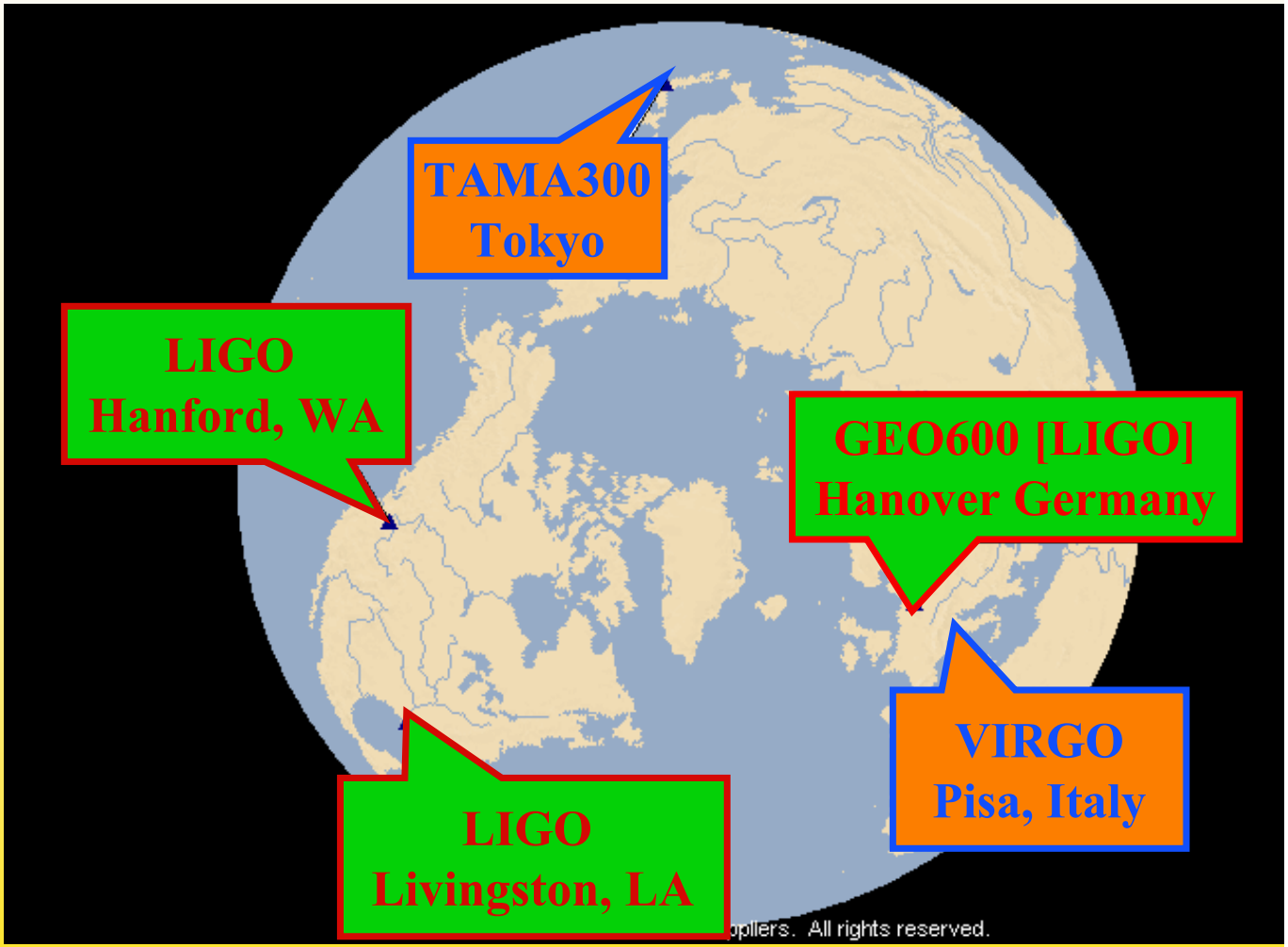
LIGO

USA, UK, Germany, Australia, India, Japan, Russia, Spain

Earth-Based GW Interferometers

Network Required for:

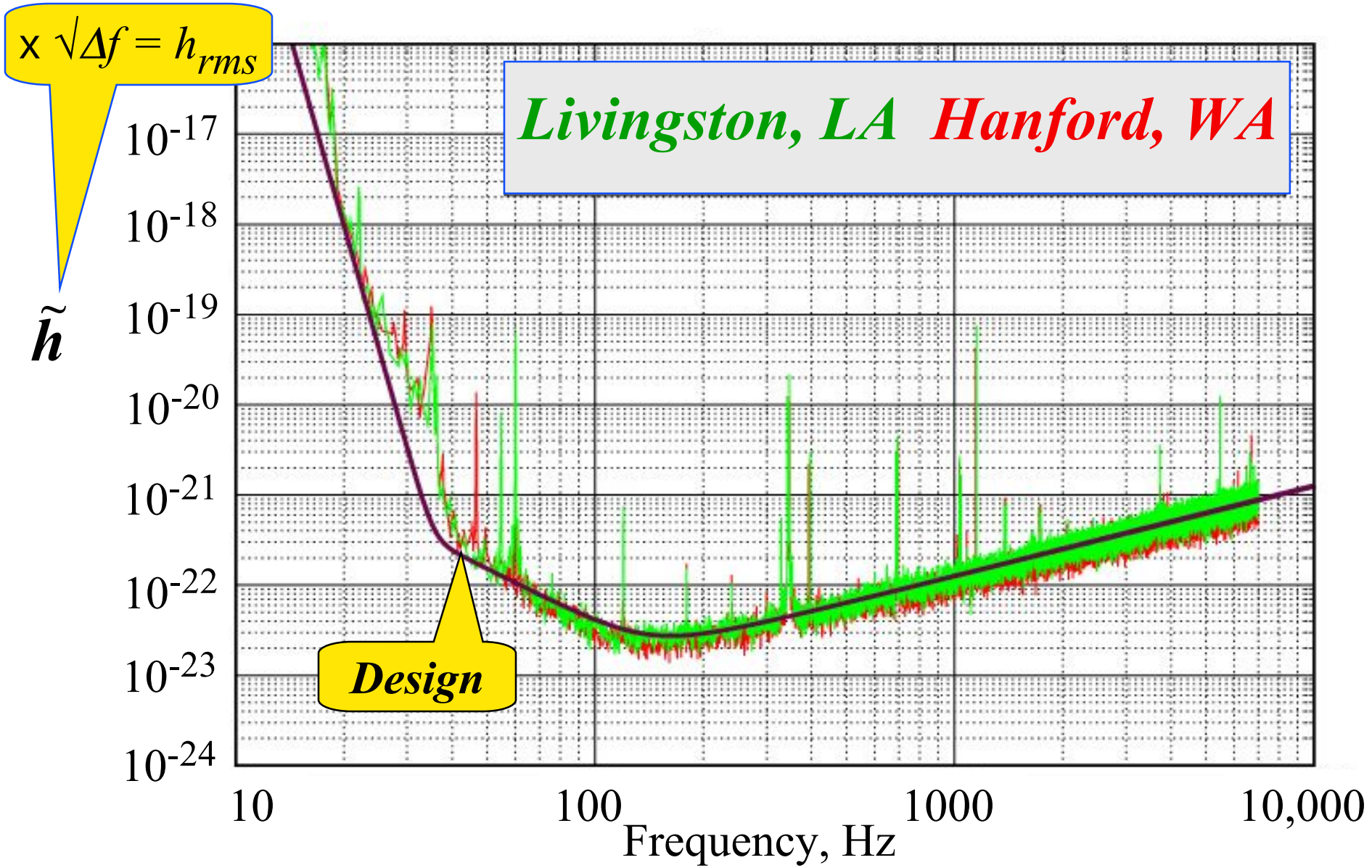
- » **Detection Confidence**
- » **Waveform Extraction**
- » **Direction by Triangulation**



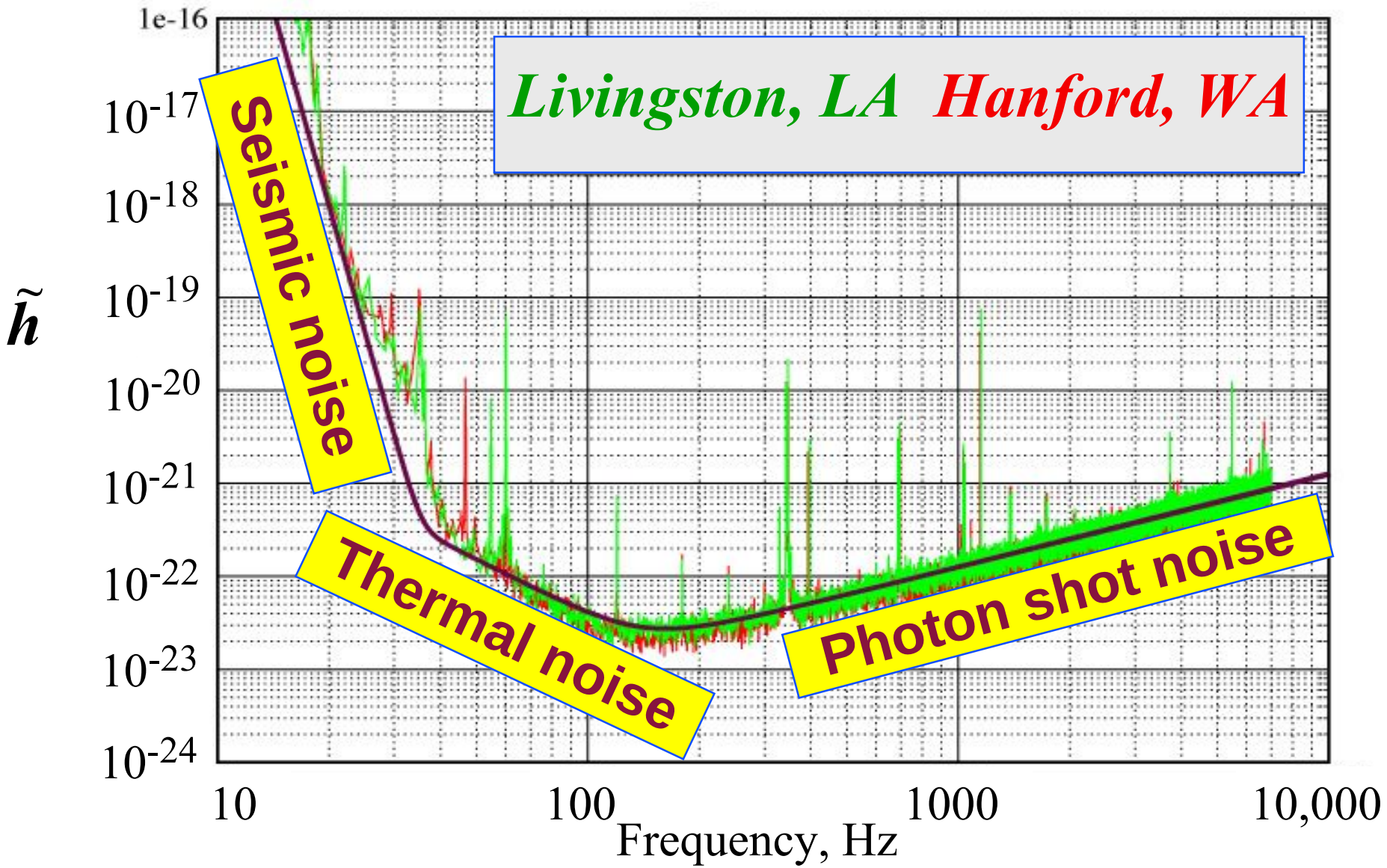
LIGO Timeline

- 1971-94 R&D
- 1989: Construction proposal (to NSF). Two Stage Strategy:
  - » Initial Interferometers: sensitivity where plausible to see GWs
  - » Advanced: sensitivity where high probability to see many GWs
- 1995-2000: Construction
- 2001-2005: Initial Interferometers Installed & Commissioned
- 2005-2007: Initial GW Search
- 2008-2010: Advanced Interferometer components built; prepared for installation. Initial interferometers souped up ("Enhanced LIGO"), searching with them until October.
- 2010-2015: Advanced Interferometers Installed & Commissioned; GW searches begin.

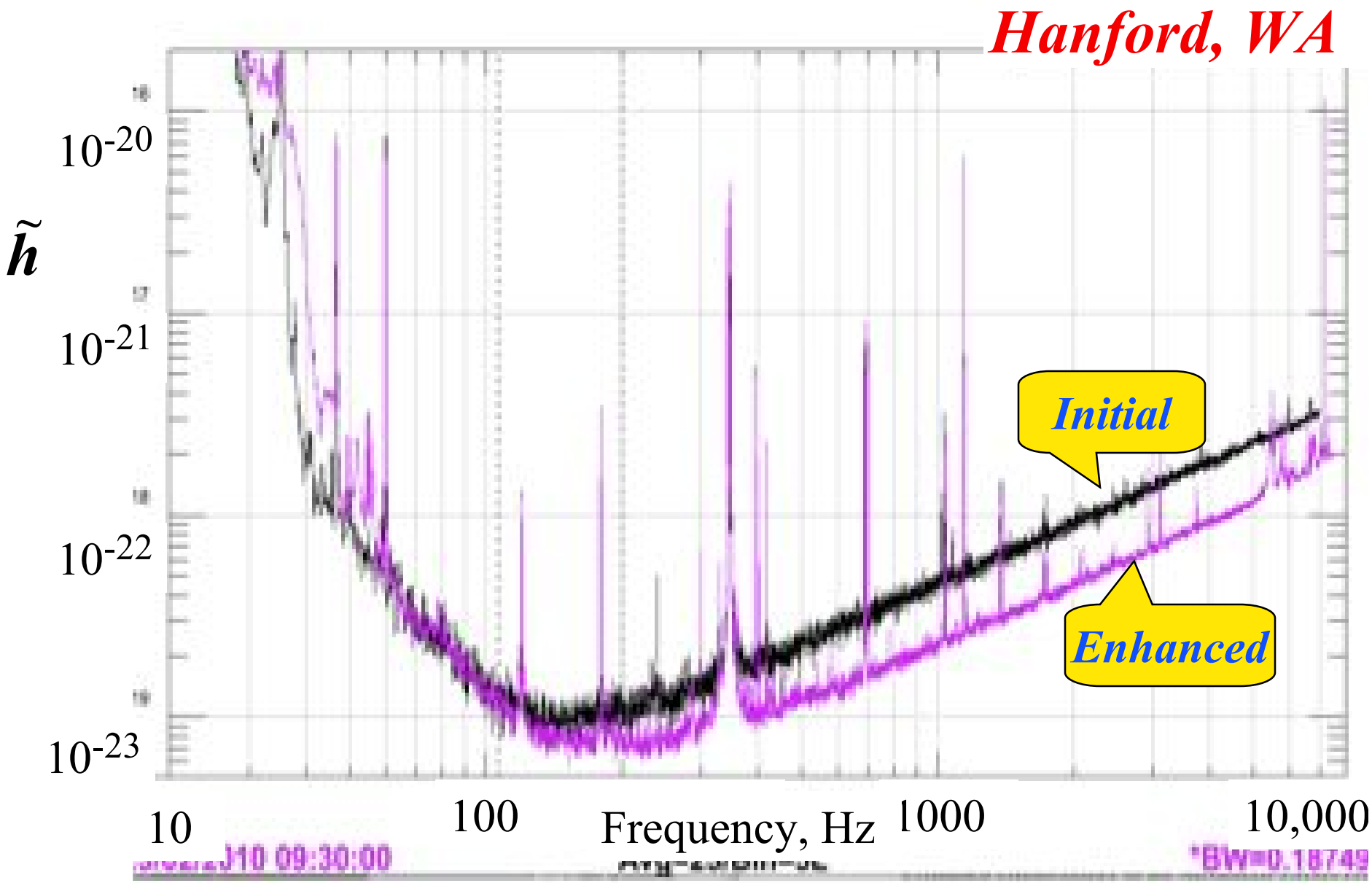
Initial Interferometers! Noise (2005-07)



Initial Interferometers! Noise (2005-07)



Enhanced Interferometers! Noise (2009-10)

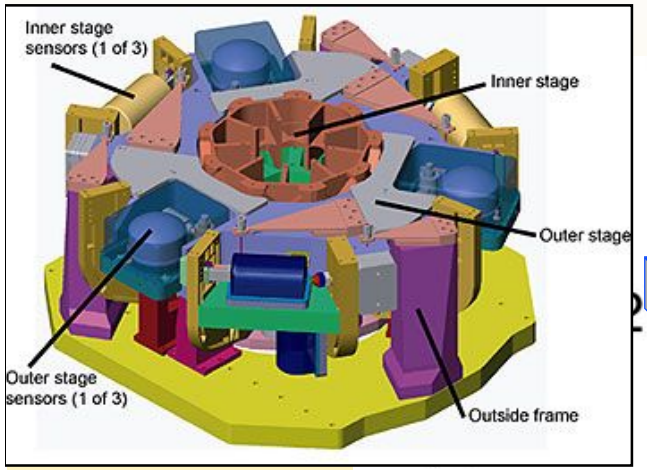


2005-2007, 2009-10 GW Searches

Nothing seen yet

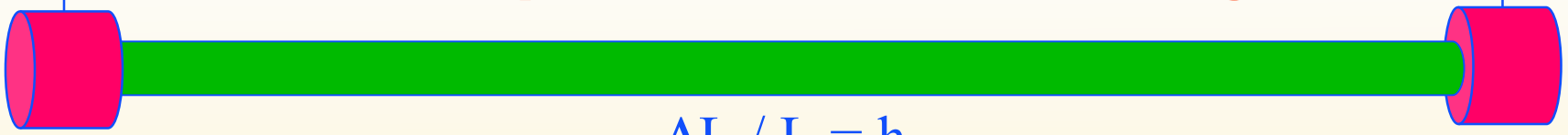
Interesting limits (later)

From Initial Interferometers to Advanced



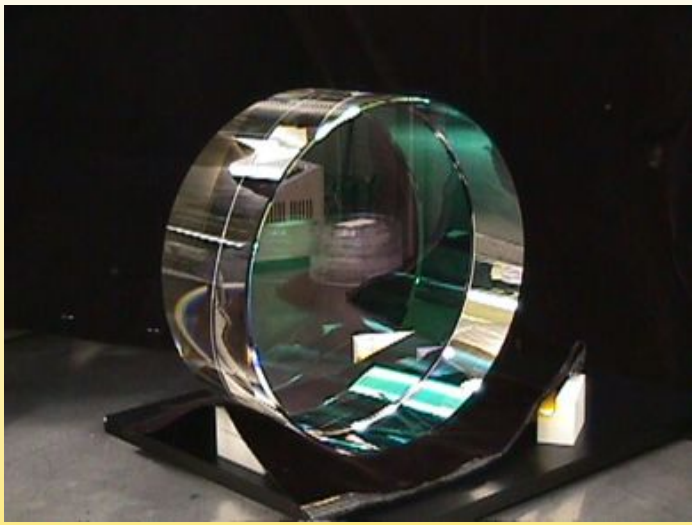
ACTIVE VIBRATION ISOLATION
Seismic wall: 40 Hz→10 Hz

Advanced LIGO Interferometers
The Experimental Challenge



$\Delta L / L = h$

- **Monitor motions of 40 kg mirrors to:**
  - » **$\Delta L \sim 10^{-17}$ cm**
  - » **~ 1/2 width of Schrödinger wave function of center of mass**



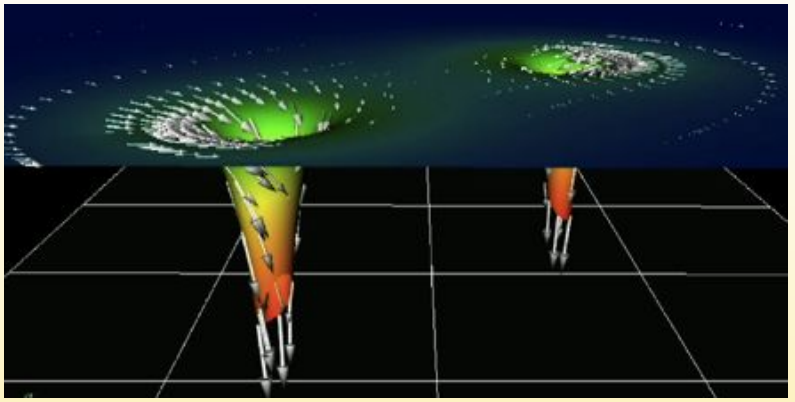
For the first time humans will see human-sized objects behave quantum mechanically!

Quantum Nondemolition (QND) Technology to deal with this [Branch of Quantum Information Science]

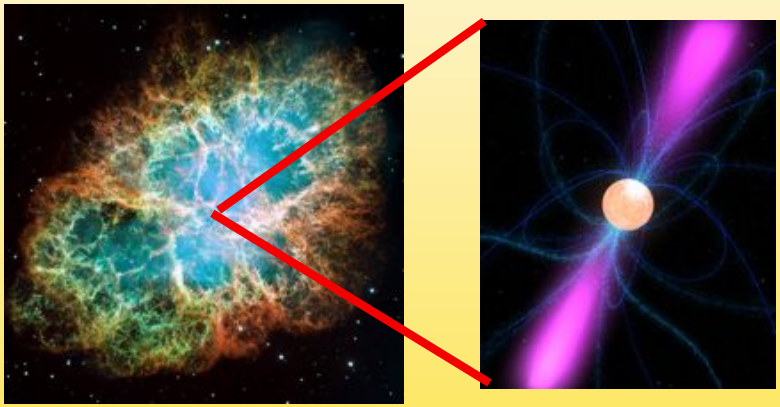
Yanbei Chen's talk to Lyncean Group, May 2009

2005-07 Initial LIGO Search: A few Results from ~1/2 Data

- **Black Hole Binaries:** <1/860 yrs in Milky Way type galaxy



- **Crab Pulsar:** <7% of spindown energy goes to GWs



- **GWs from big bang:**
  GW energy in LIGO band
  < 1/100,000 of energy to close the universe

Advanced LIGO Science [2015…]

- Will see 15 times farther into the universe than Initial LIGO
  - » 15 x 15 x 15 = 3000 more sources
- Black-hole binaries: see to 3 billion light years (1/5 of way to edge of observable universe)
  - » Predicted rate: ~ 1/month to 1/day
- Other sources we expect to see:
  - » Supernova explosions (births of neutron stars)
  - » Pulsars (spinning neutron stars)
  - » Black holes tearing neutron stars apart
  - » Neutron-star binaries … inspiral, collision, merger
  - » Central engines for “gamma ray bursts”
  - » …

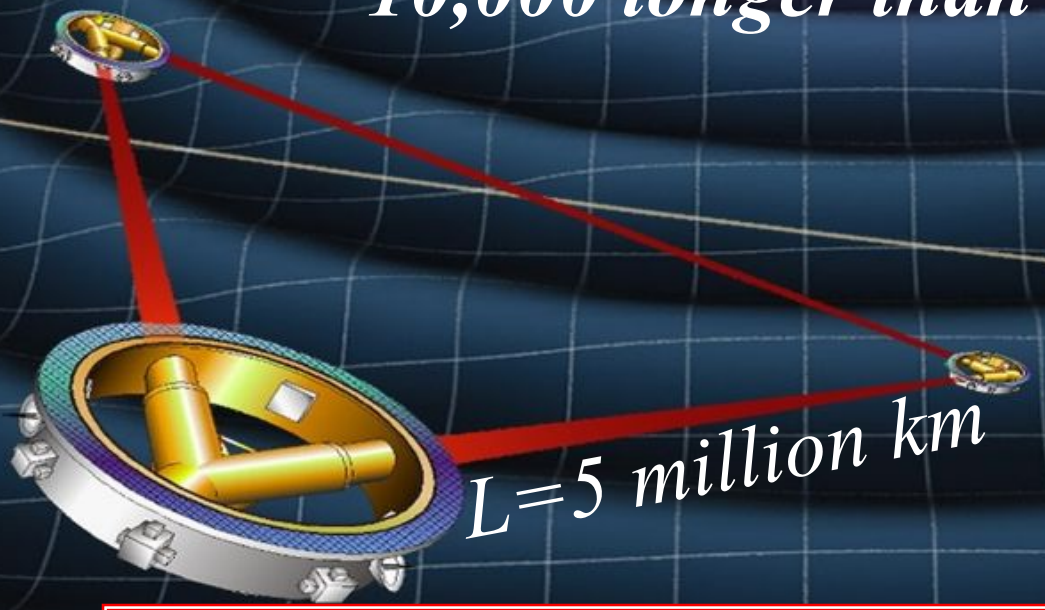
Third-Generation GW Interferometers

- Design study underway in Europe for Einstein Telescope
  - » To operate in 2020s
  - » Tentative goal: reduce noise below Advanced LIGO by factor 10 to 30
  - » See all merging black hole binaries in our entire universe with masses below about 300 suns.
    and many many other phenomena on warped side
- LIGO!s third generation should be similar

LISA

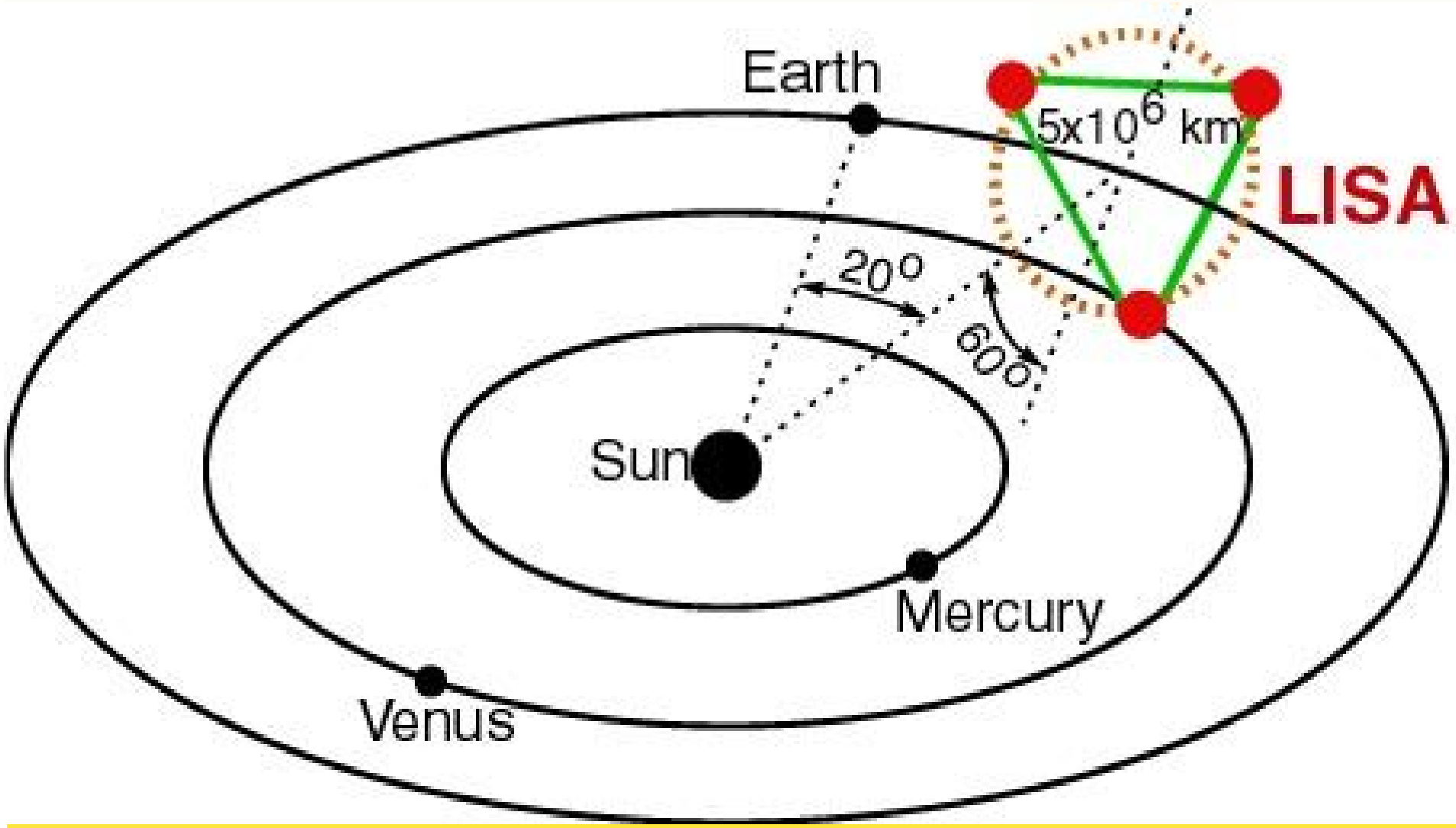
Laser Interferometer Space Antenna

GW wavelengths
10,000 longer than LIGO



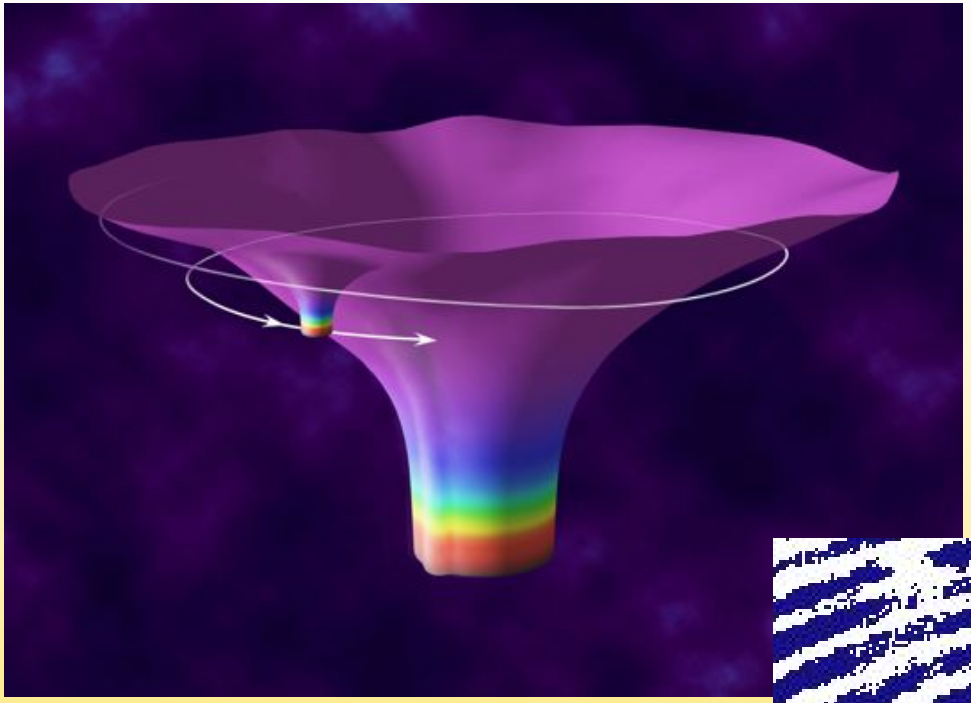
Supermassive holes, ~10^5 - 10^7 Msun
throughout universe. S/N ~ 10 to 10,000

LISA: Joint ESA/NASA Mission



- **Technology test flight: 2012**
- **Launch: 2018 or later**

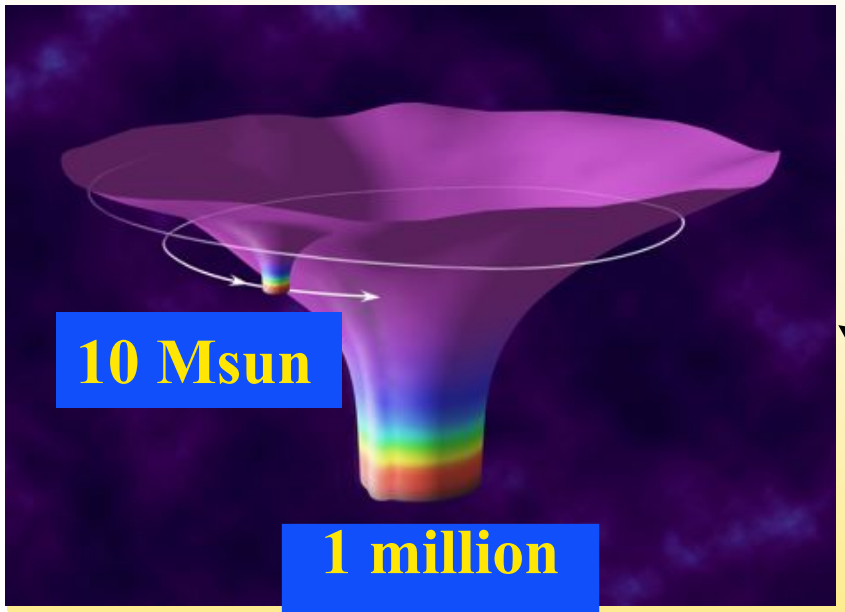
Mapping a Quiescent Black Hole



Full Map is encoded in the waves

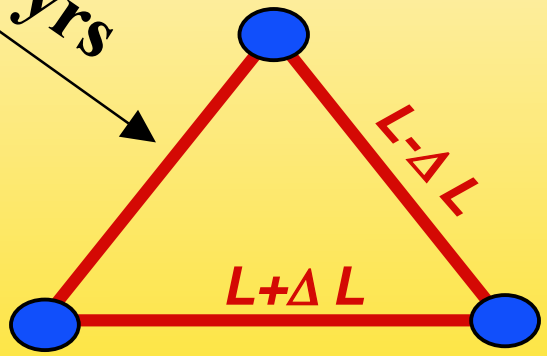
Some Numbers for LISA

5 million km = 20 light sec



Final Year:
100,000 orbits with
Circumference <
4 x (Horizon circumference)

3 billion light yrs



$h \sim 10^{-20}$

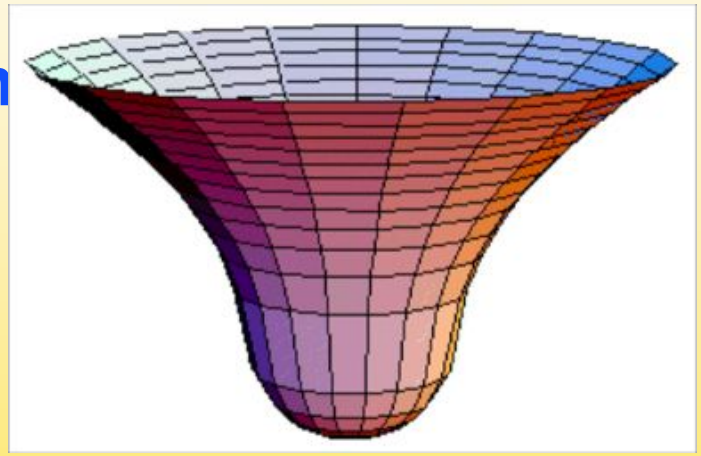
L=5 million km

$\Delta L = 10^{-8}$ cm

What if the Map is Not that of a Black Hole?

May have discovered a new type of "inhabitant" of dark side of the universe. Two long-shot possibilities:

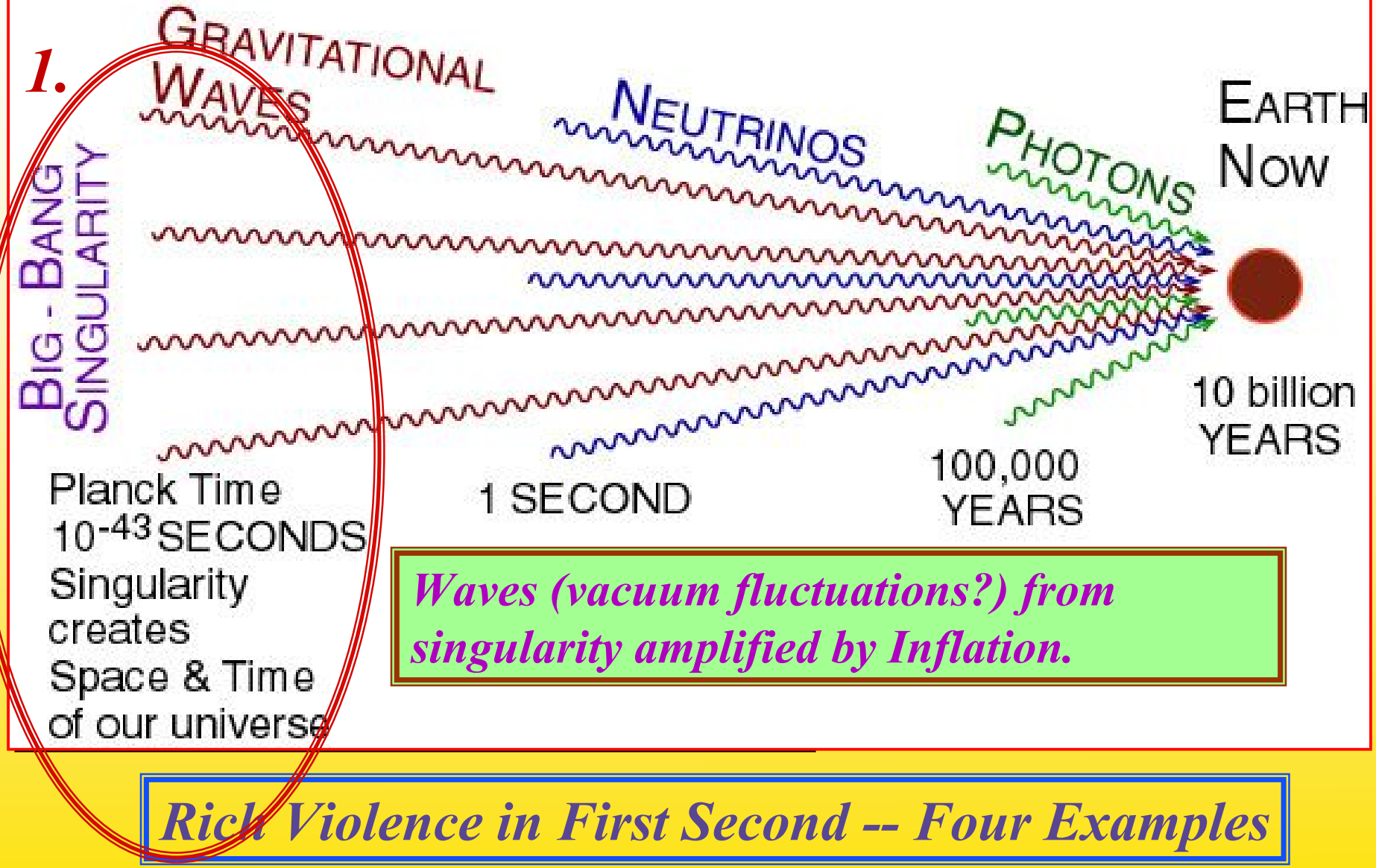
- **Dense objects made from cold, dark matter**
  - » **(Dark ``Stars!!)**
  - » **e.g. boson stars**



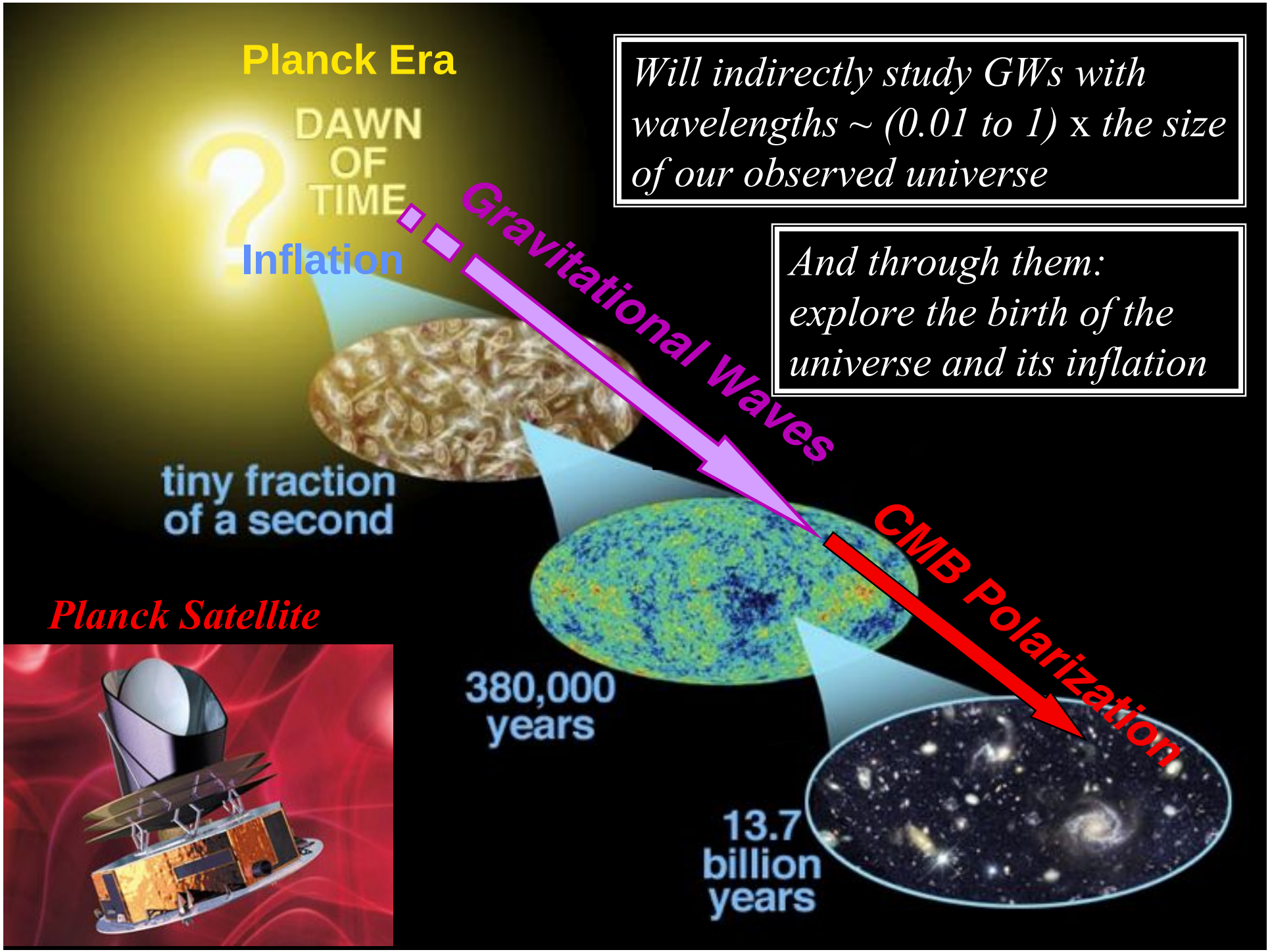
- **Naked Singularities**

Over the Next 40 Years

Probe the Initial Second of Universe's Life

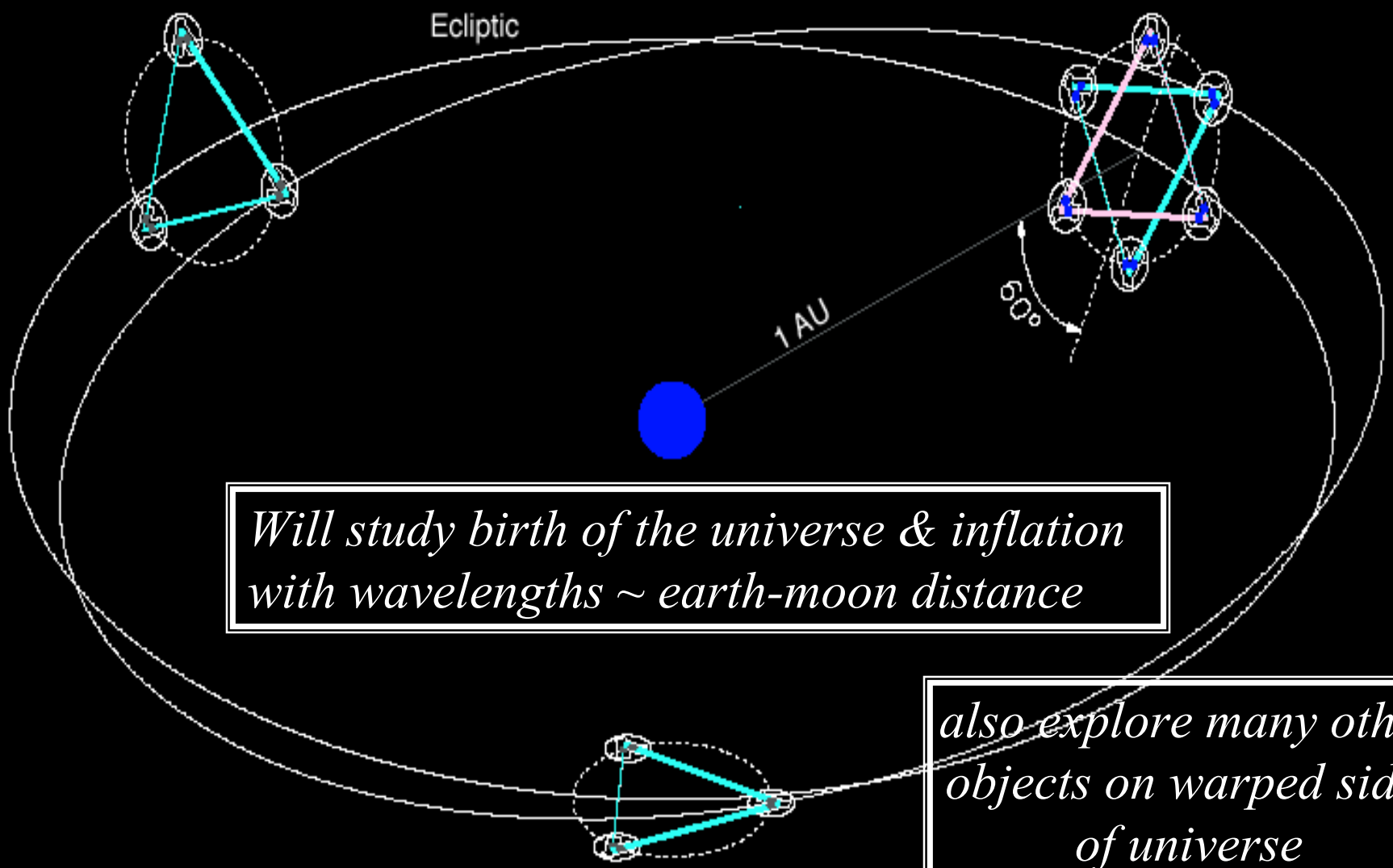


Rich Violence in First Second -- Four Examples


Planck Era
DAWN OF TIME
Inflation
Gravitational Waves
CMB Polarization
tiny fraction of a second
380,000 years
13.7 billion years
Will indirectly study GWs with wavelengths ~ (0.01 to 1) x the size of our observed universe
And through them: explore the birth of the universe and its inflation
Planck Satellite

BBO: Big Bang Observer

Launch ~2030 or later

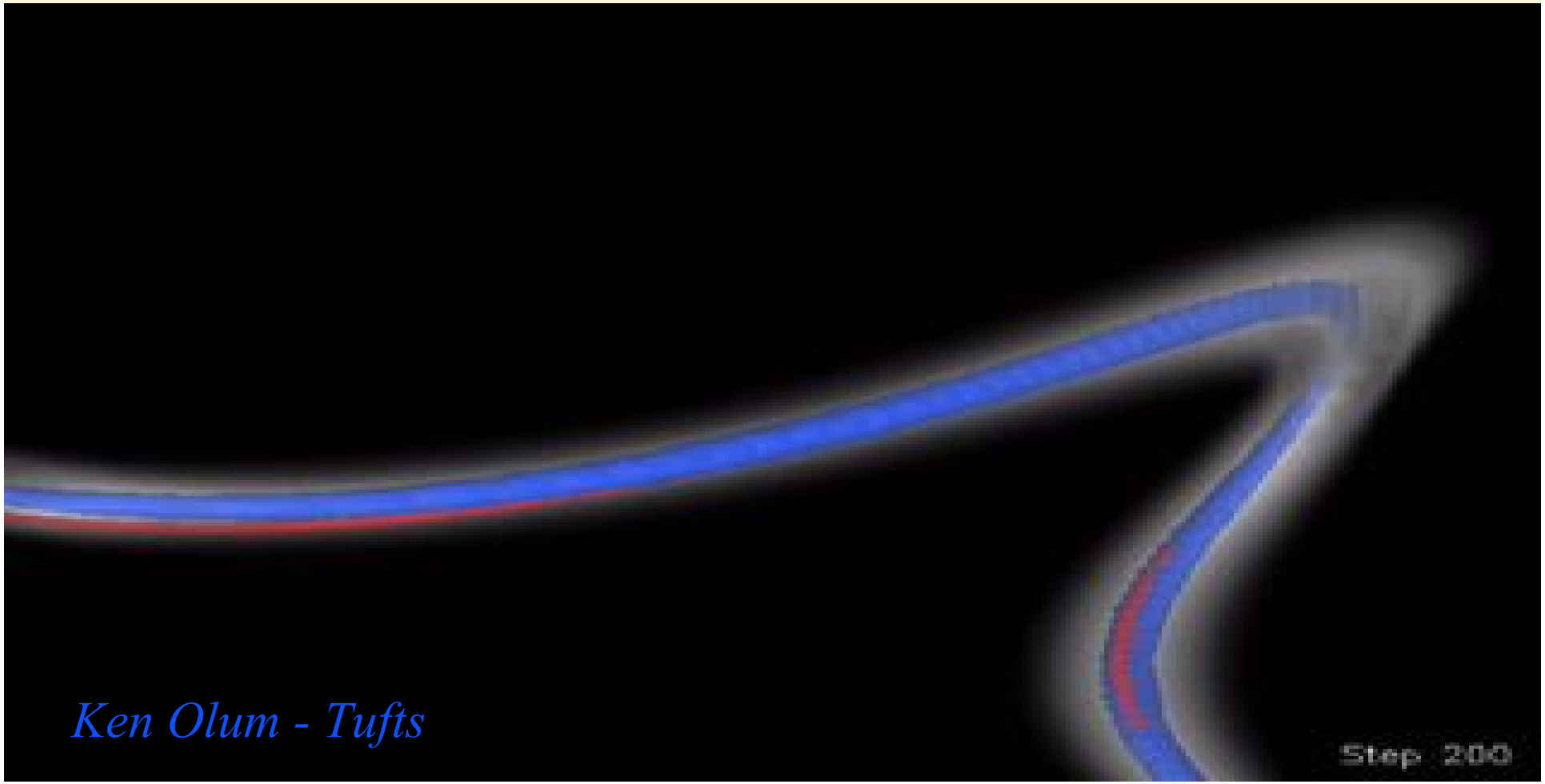


Will study birth of the universe & inflation with wavelengths ~ earth-moon distance

also explore many other objects on warped side of universe

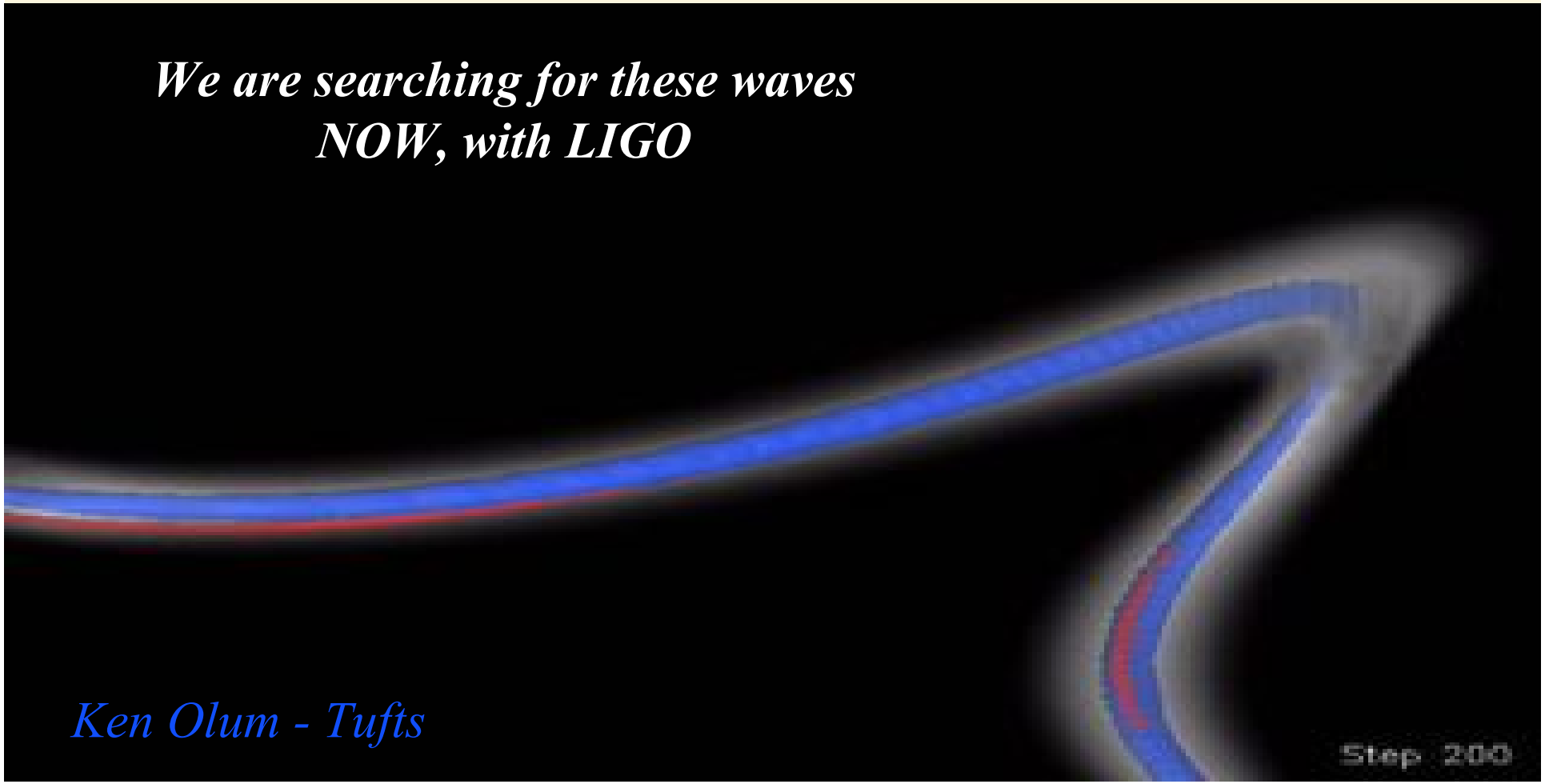
2. Cosmic Strings

- ***Inflation*** enlarges some superstrings to cosmic size
- Kinks, cusps and waves on cosmic strings produce gravitational waves



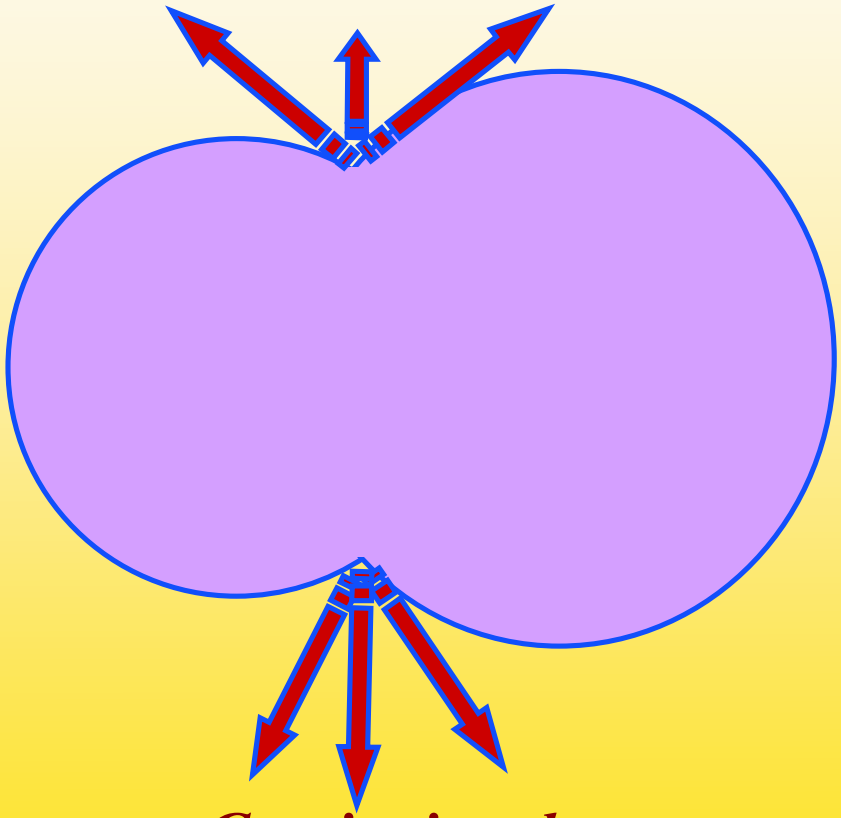
2. Cosmic Strings

- ***Inflation*** enlarges some superstrings to cosmic size
- Kinks, cusps and waves on cosmic strings produce gravitational waves



3. Birth of Fundamental Forces

- At age ~ 10^{-12} seconds [kT~ 1 TeV … LHC energy]:
  - » Phase transition: Electroweak force -> EM + Weak



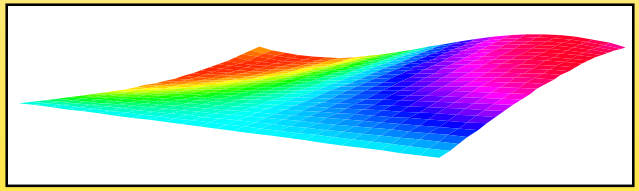
Gravitational Waves

Waves are in LISA's domain

Phase transition at age ~10^{-22} sec [kT ~ 10^{5} TeV] Is in LIGO's domain

4. Our 3-D Universe as a "Brane" in Higher Dimensional Bulk

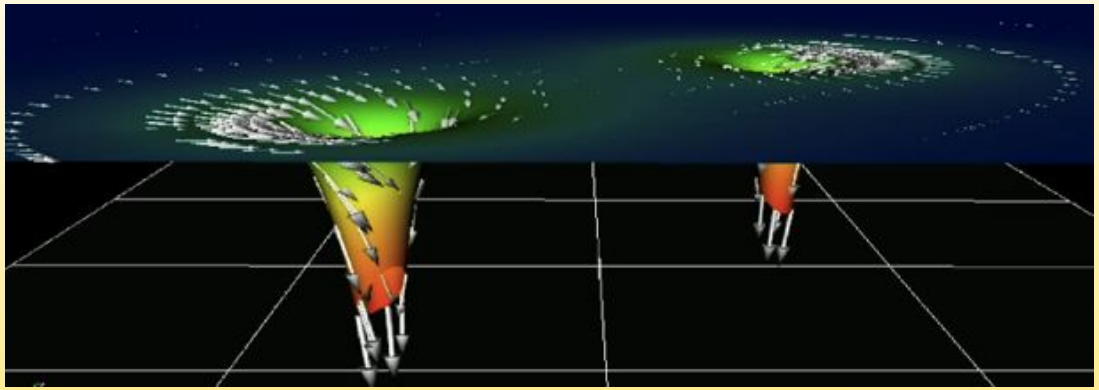
- May have formed wrinkled
- As universe expanded, adjacent regions discovered the wrinkle between them
- Wrinkle began vibrating -- producing gravitational waves - brane smoothed out



Example of the kind of surprise gravitational-waves may bring us

Conclusions

Numerical Relativity and Gravitational Wave Observations are on the threshold of producing a revolution in our knowledge of the Warped Side of our Universe



Gravitational-wave technology is bringing quantum physics into realm of human-sized objects