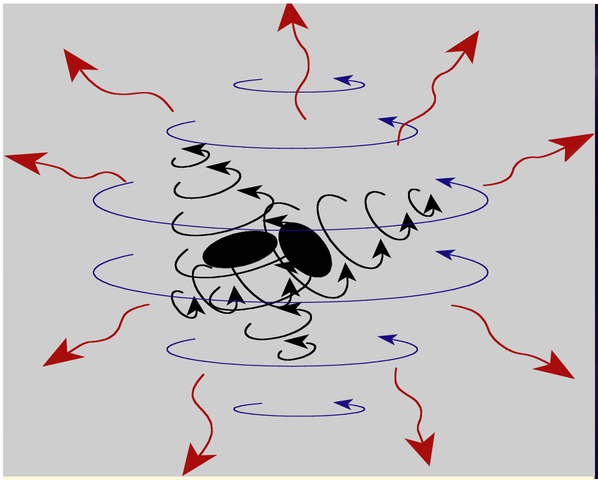
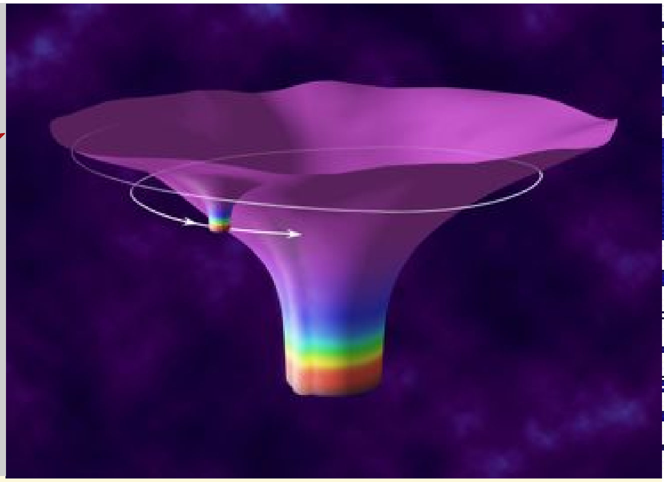
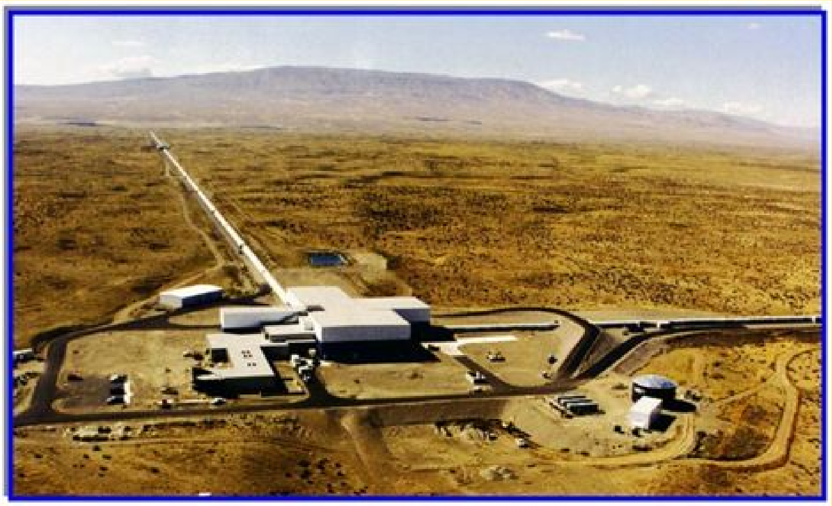
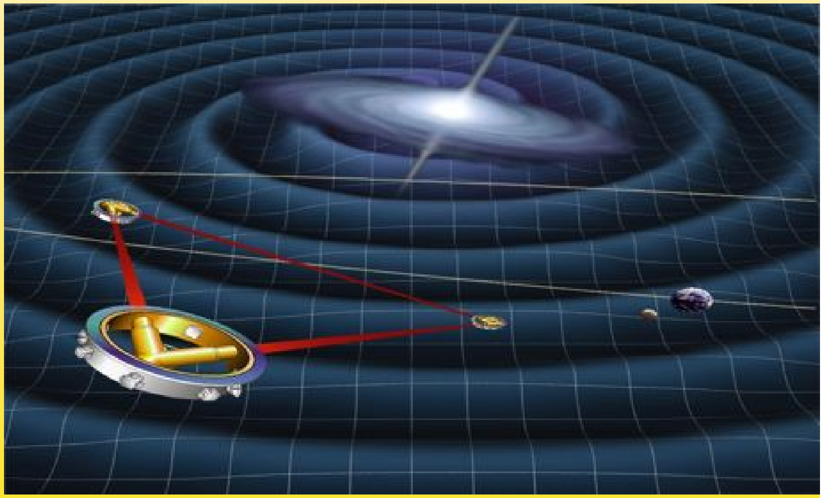




The Warped Side of the Universe

Kip Thorne

Colloquium Ehrenfestii, University of Leiden, 16 Sept 2009

Lorentz Lectures: Gravitational Waves

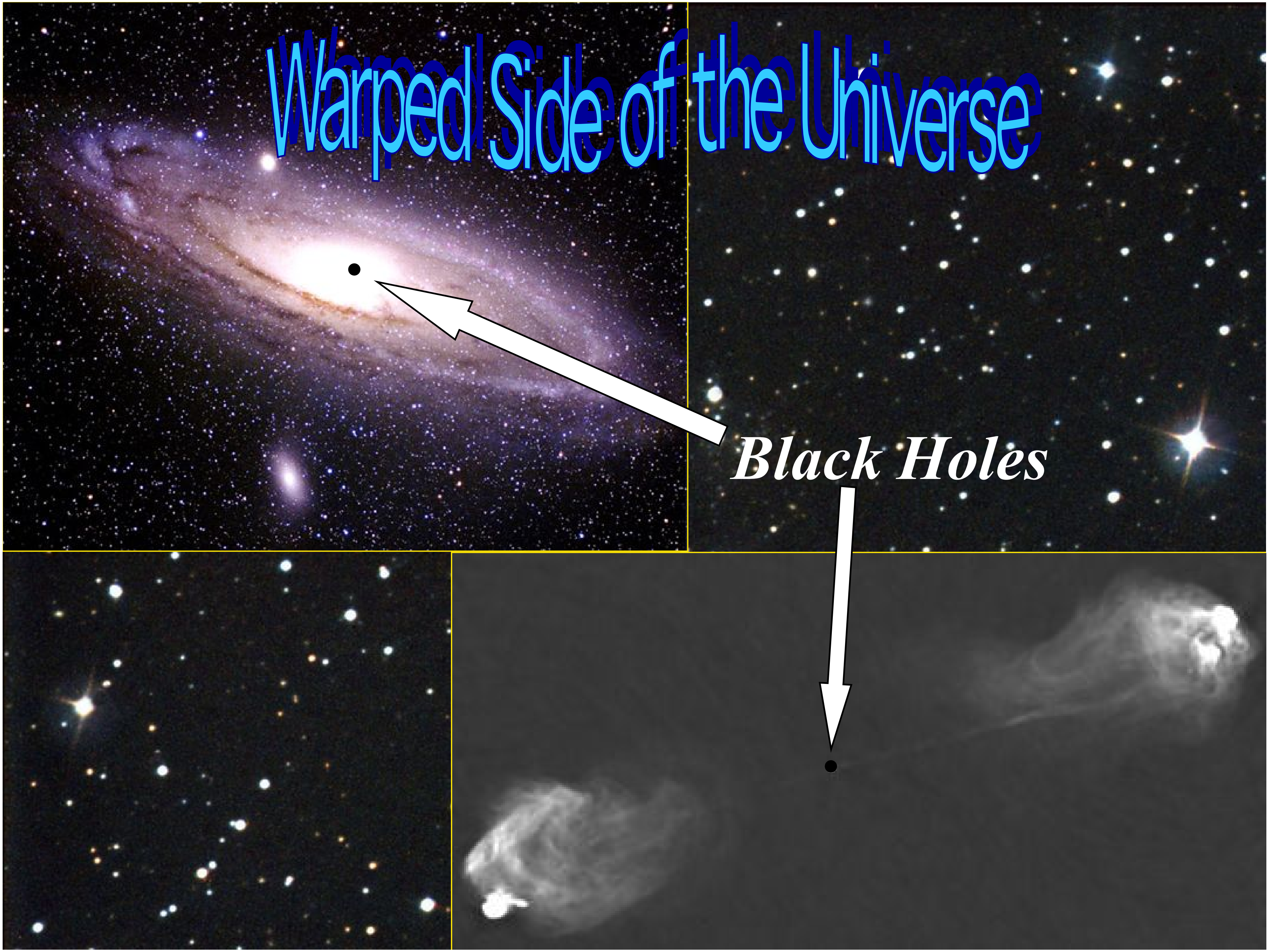
- Understandable without prior knowledge of general relativity
- But knowledge of general relativity will help
- Slides available (pdf) late Thursday nights at

http://www.its.caltech.edu/~kip/LorentzLectures/

Warped Side of the Universe

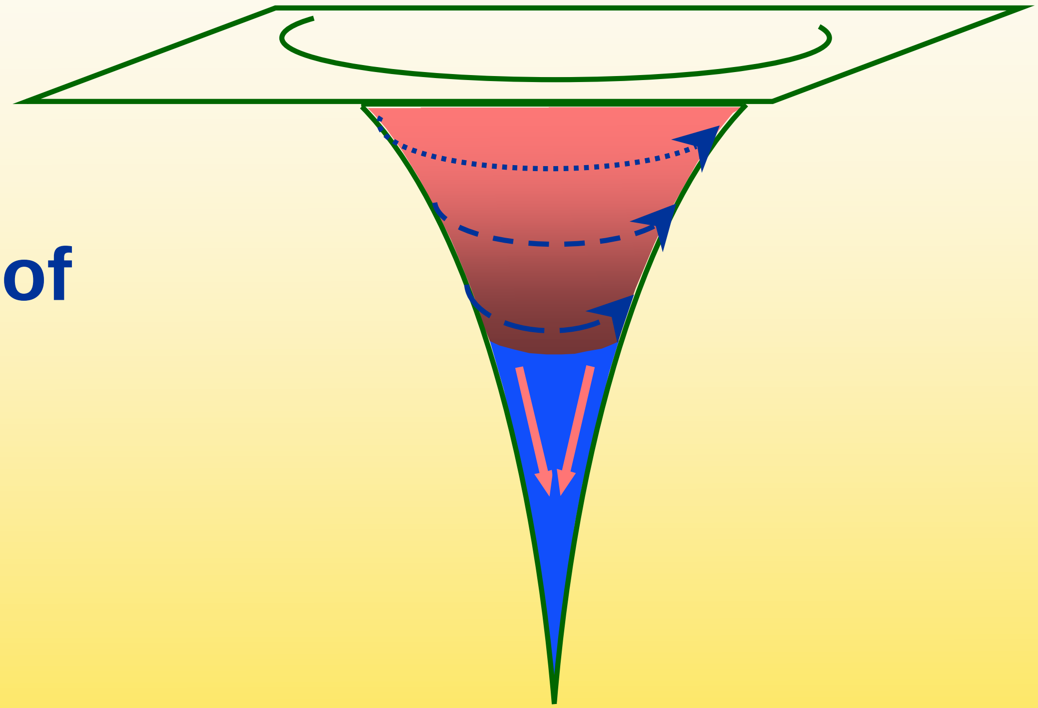
Phenomena and objects

Made from warped space and time


Warped Side of the Universe
Black Holes

Black Hole!s Spacetime Geometry

- **Curvature of Space**
- **Rotational Motion of Space**
- **Warping of Time**

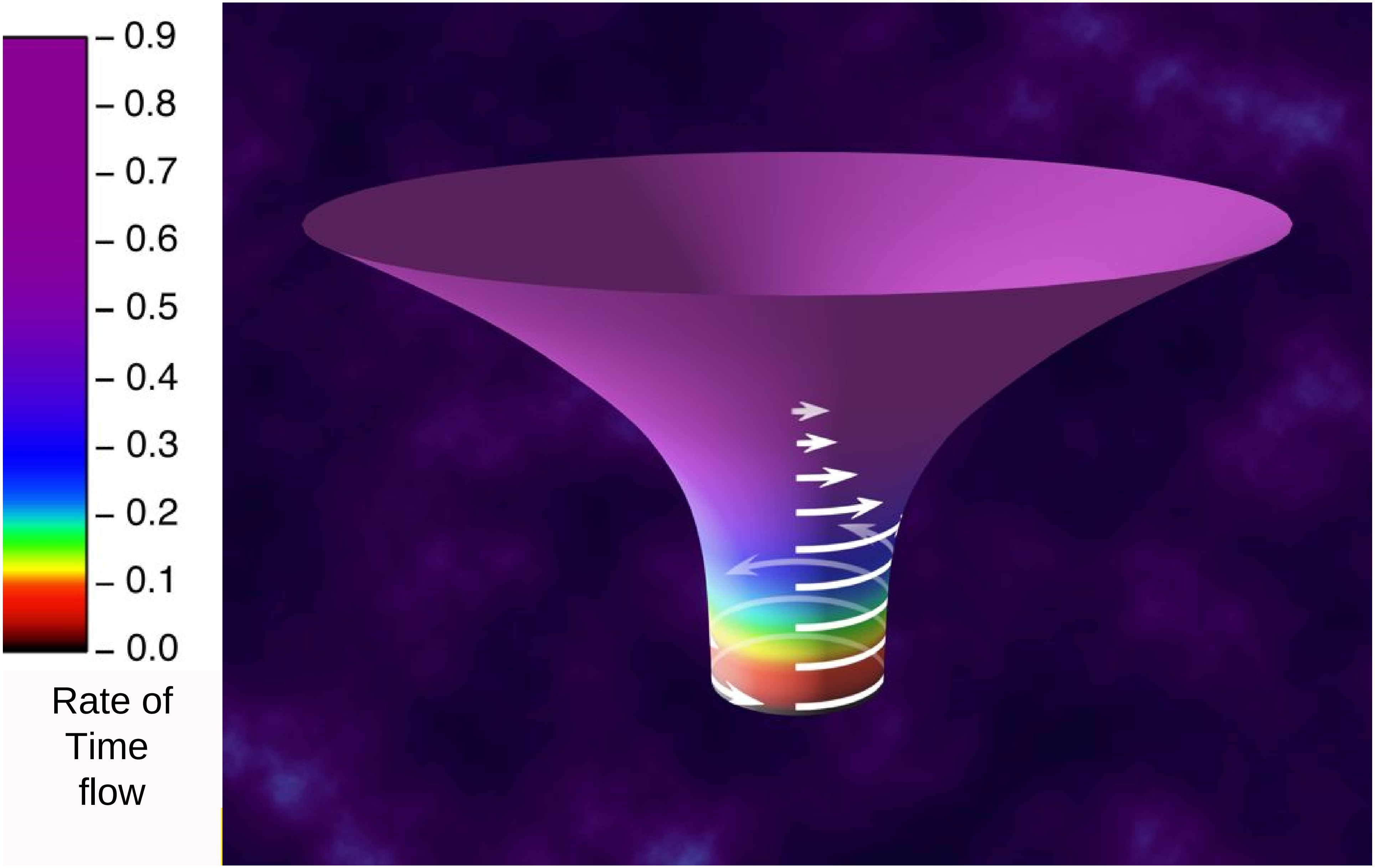


$$ds^2 = g_{rr}dr^2 + g_{\theta\theta}\,d\theta^2 + g_{\phi\phi}\,(d\phi - \omega\, dt)^2 \quad - \alpha^2\, dt^2$$

space curvature	space rotation	time warp
3-metric	***shift*** function	***lapse*** function

Kerr Metric

Map of spacetime geometry for fast spinning hole a/M=0.998

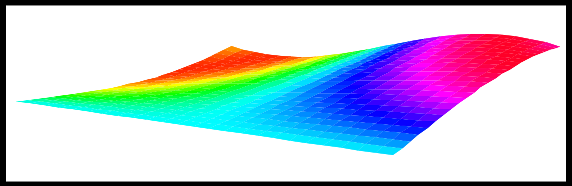


Warped Side of the Universe

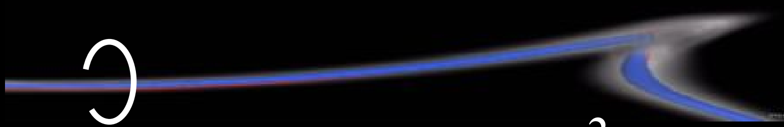
Other Examples

- *The Big Bang Singularity*

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

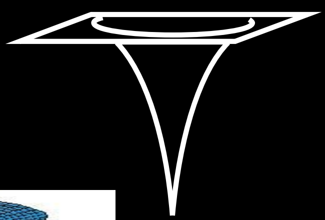


- *Cosmic String*

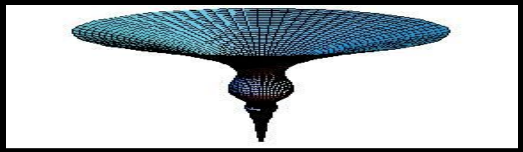


$C/R = 2\pi(1-4G\mu/c^2)$

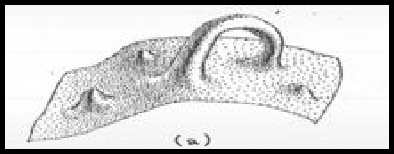
- *Singularity inside a black hole*



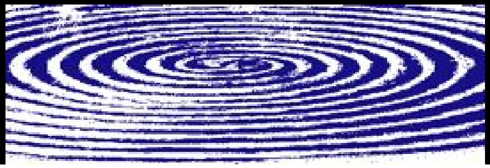
- *Naked Singularity*



- *Wormhole*



- *Gravitational Waves*



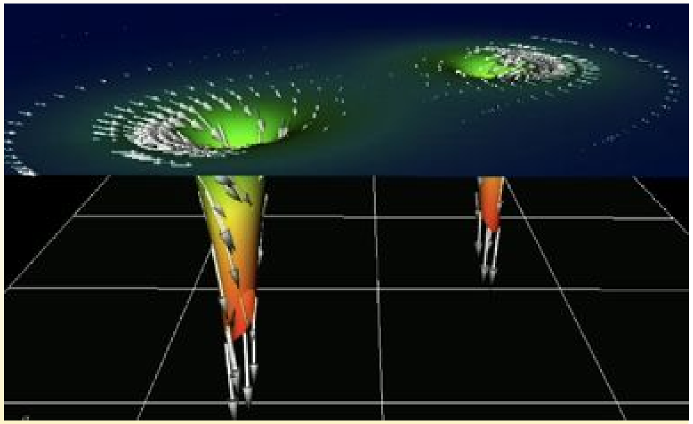
Other Examples

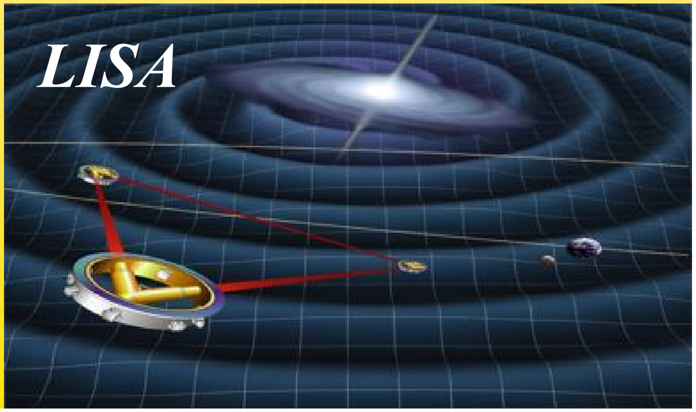
WHICH ARE REAL?

WHAT ELSE?

Probing the Warped Side: Tools

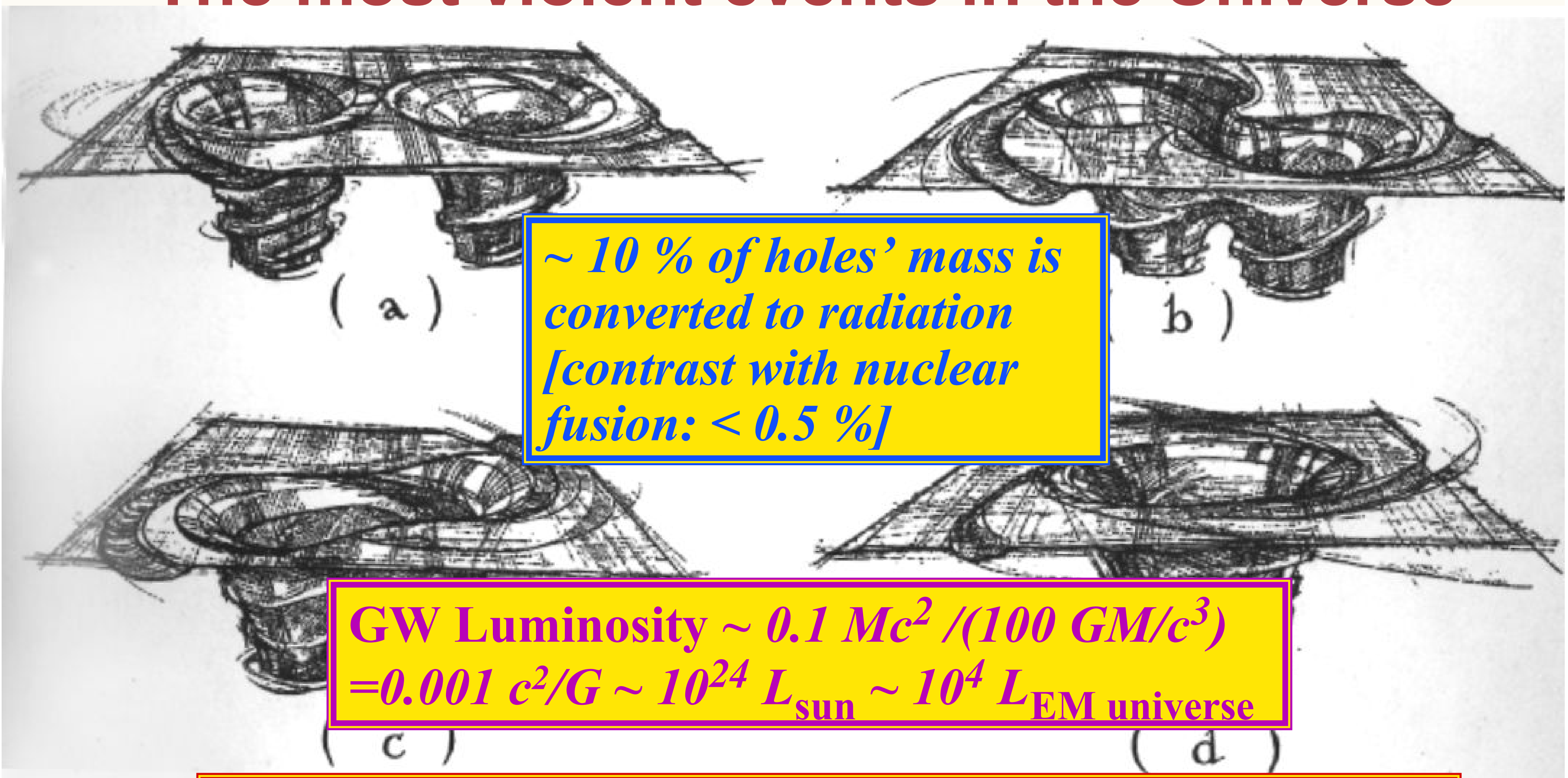
- What kinds of objects ***might*** exist?
  - » General Relativity Theory
    - – Progress has slowed…
  - » ***Numerical Relativity***
    - – Exciting new era…
    - – Part 1 of Colloquium
- What kinds of objects ***do*** exist?
  - » Electromagnetic observations
    - –Limited information
  - » ***Gravitational-Wave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





Part 1
Numerical Relativity

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

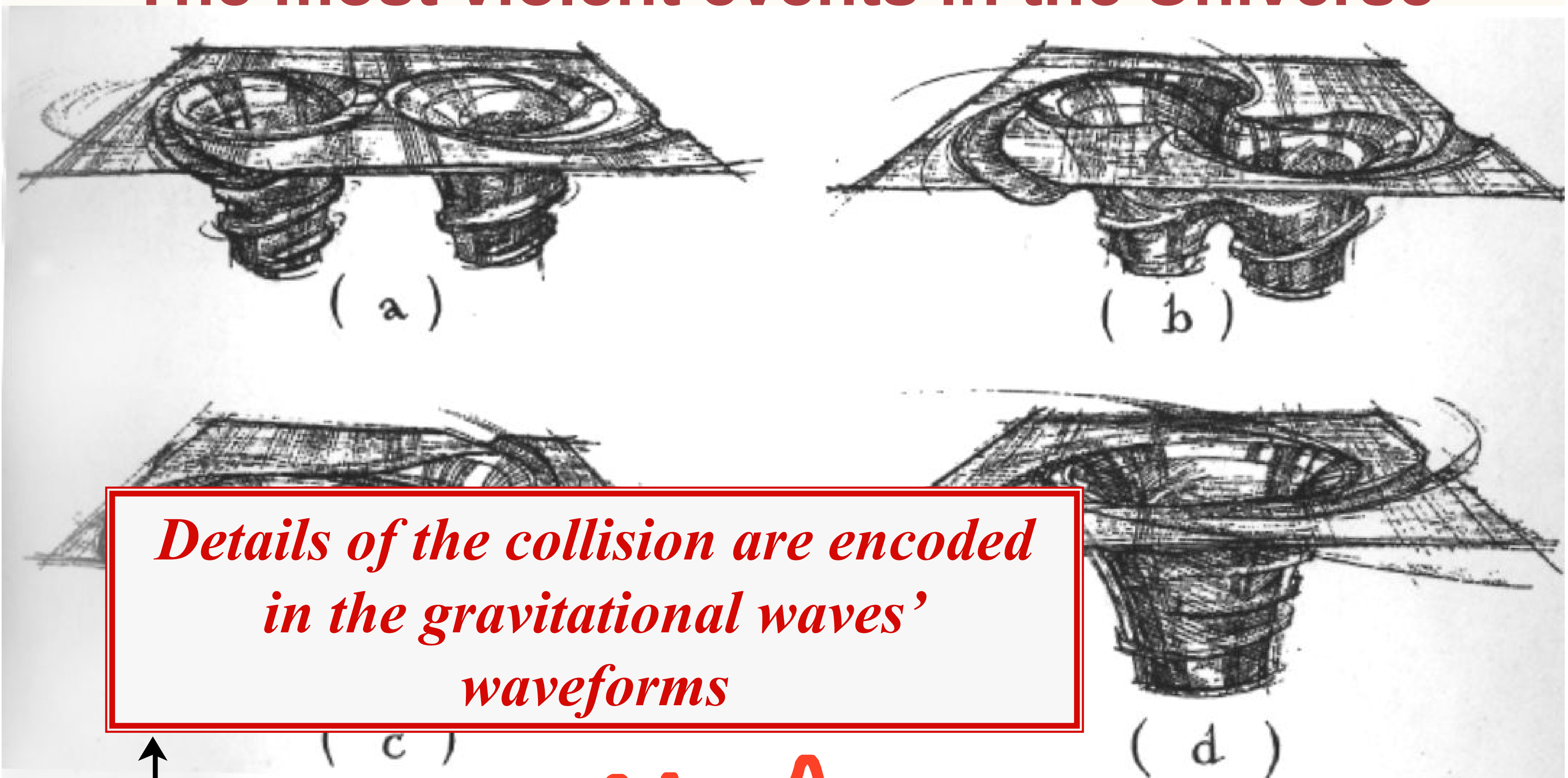


~ 10 % of holes' mass is converted to radiation [contrast with nuclear fusion: < 0.5 %]

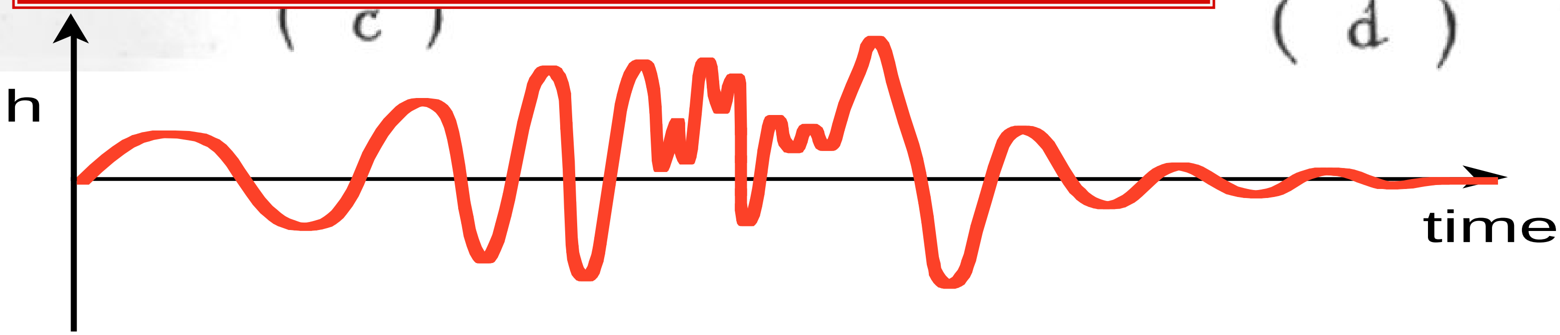
GW Luminosity $\sim 0.1\, Mc^2 / (100\, GM/c^3)$
$= 0.001\, c^2/G \sim 10^{24}\, L_{sun} \sim 10^4\, L_{EM\ universe}$

No Electromagnetic Waves emitted whatsoever
- except from, e.g. disturbed accretion discs

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

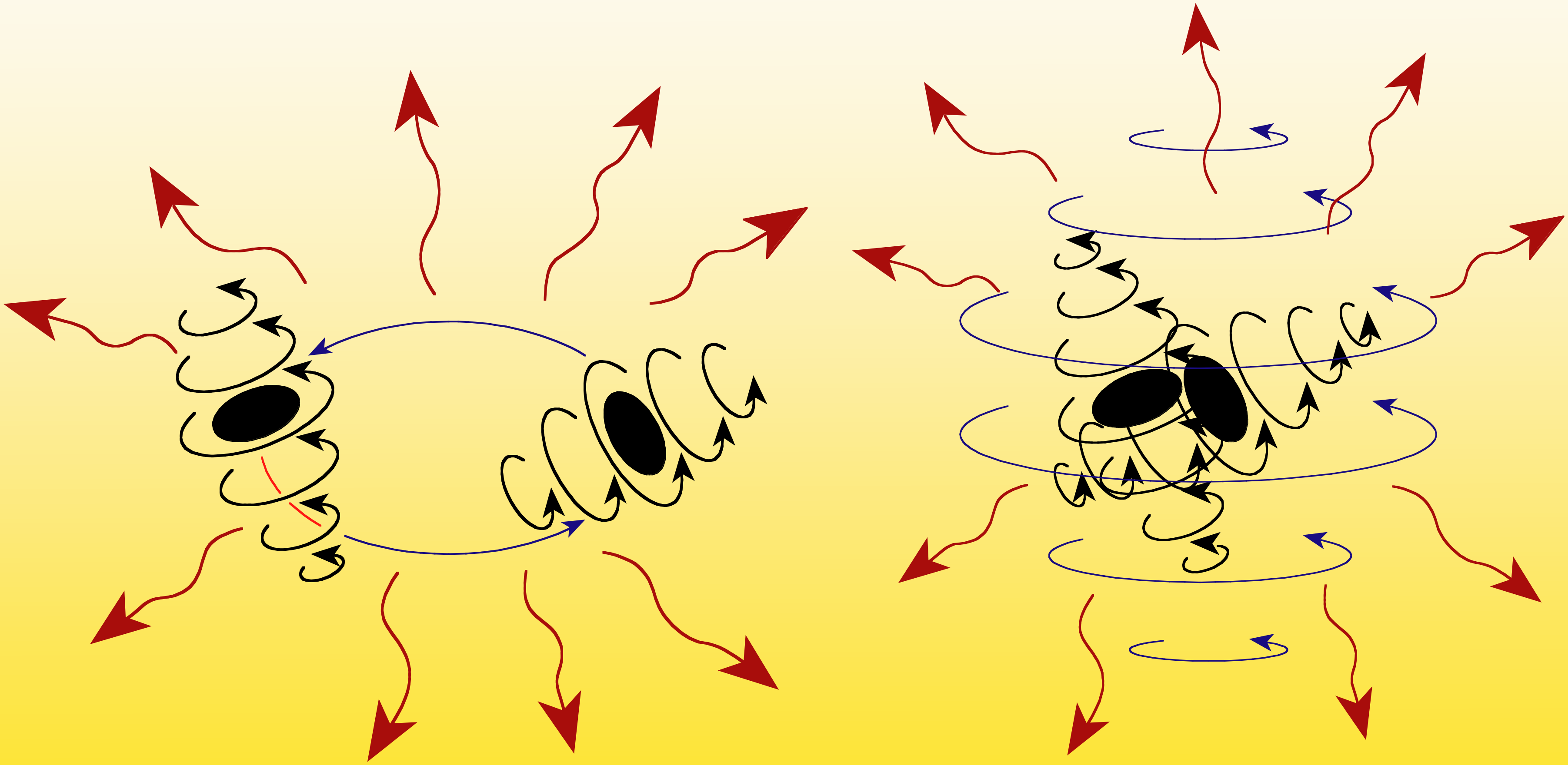


Details of the collision are encoded in the gravitational waves' waveforms



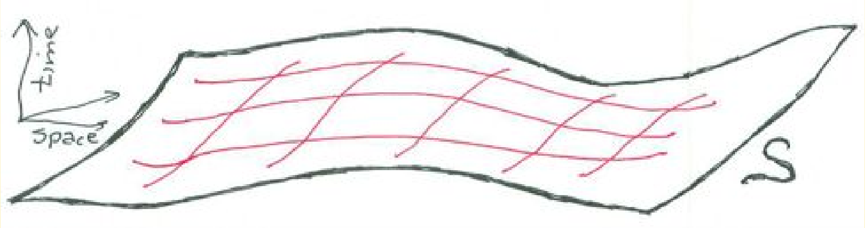
Why are Black-Hole Collisions Interesting?

Wild vibrations of warped spacetime



Numerical Relativity: How is it Done?

- Evolve the geometry of spacetime - not fields in spacetime
- Choose an initial spacelike 3-dimensional surface *S*
  - » Put a coordinates on *S*



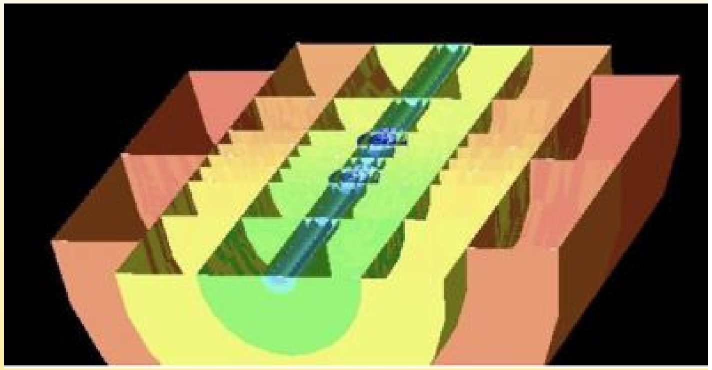
- Specify: *3-metric* g_{ij} and *Extrinsic Curvature* K_{ij} of S
  - » Subject to *constraint equations* [analogues of Div B = 0]
- Lay out coordinates to future by specifying Lapse function α and Shift function β^i
- Integrate 3-metric forward in time via *dynamical equations*
- Build 4-metric of spacetime

$$ds^2 = -\alpha^2\, dt^2 + g_{ij}\,(dx^i - \beta^i\, dt)\,(dx^j - \beta^j dt)$$

Numerical Relativity

Two Mature Approaches

- Finite-difference
  - » Robust, power-law convergence [Astrophysics]
- Spectral
  - » More complicated, less robust - but exponential convergence
  - » Fast; high accuracy [GWs]



Two Major Pitfalls

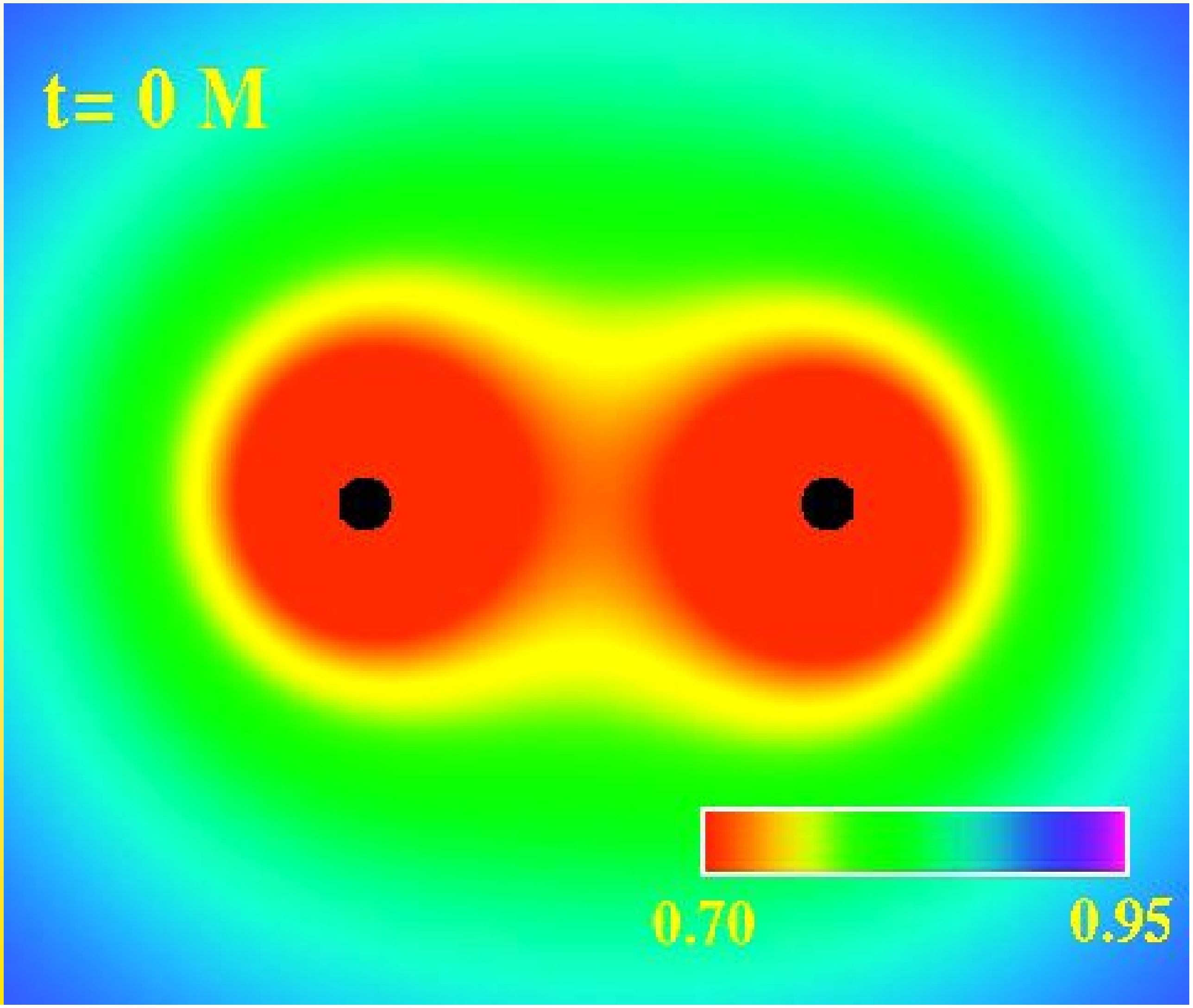
- Constraint-Violation Instabilities:
  - » Slight initial error in constraints (analog of Div **B** = 0) blows up in time
  - » Solved in 2005 after ~ 5 years of struggle
- Coordinates become singular
  - » Only **now** becoming *robustly* solved in spectral code
    Szilagyi, Lindblom, Scheel, PRD & arXiv - submit this weekend

Numerical Relativity Breakthrough

- **The first successful simulations, May 2005:**
  Frans Pretorius (then at Caltech; now Princeton) **finite-difference**

Identical holes, not spinning

Lapse Function



Numerical Relativity Breakthrough

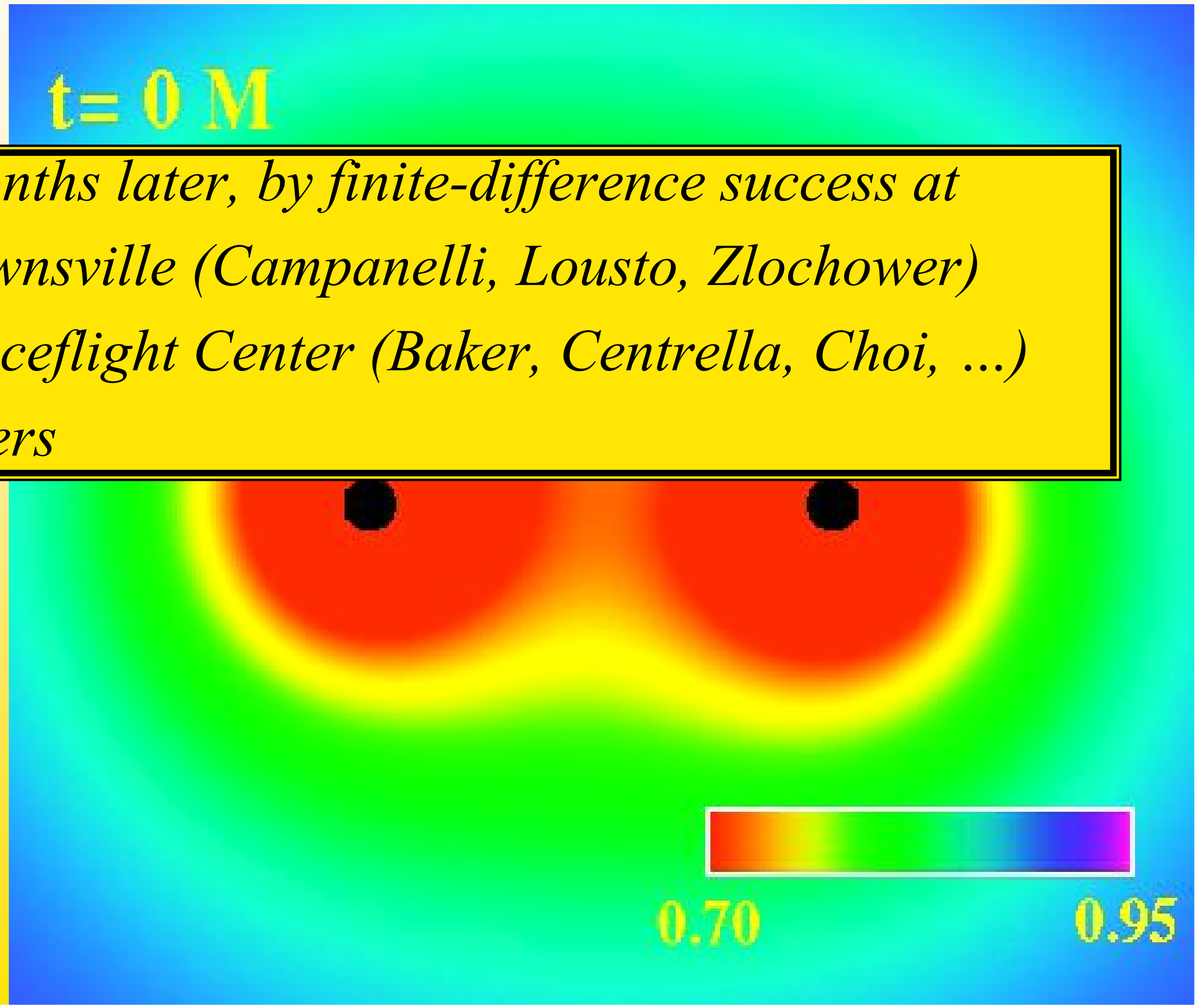
- **The first successful simulations, May 2005:**
  Frans Pretorius (then at Caltech; now Princeton) finite-difference

Ide
not

Followed, 6 months later, by finite-difference success at

- *U Texas Brownsville (Campanelli, Lousto, Zlochower)*
- *Goddard Spaceflight Center (Baker, Centrella, Choi, …)*

Then many others



Lapse Function

Numerical Relativity Groups Today

- Princeton [Pretorius]
- University of British Columbia [Choptuik]
- University of Illinois, Urbana [Shapiro]
- University of Chicago [Khokhlov]
- University of Texas, Austin [Matzner]
- Louisiana State University [Seidel, Pullin, …]
- Goddard Spaceflight Center [Centrella, Baker]
- Rochester Institute of Technology [Campanelli, Lousto]
- Oakland University [Garfinkle]
- Florida Atlantic [Miller, Tichy]
- Albert Einstein Institute [Rezzolla]
- University of Jena [Bruegmann]
- University of Tokyo [Shibata]

Finite Difference

- Cornell/Caltech [Teukolsky, Lindblom, Kidder, Scheel, Pfeiffer] ⟸ *SpEC*

*(**Spectral** Einstein Code)*

- **New Groups this year & last** -
  - » Georgia Tech [Laguna, Shoemaker]
  - » Perimeter Institute / U. Guelph [Lehner]

  Finite Difference

  - » Canadian Institute for Theoretical Astrophysics [Pfeiffer] ⟸ *SpEC*
  - » U. Maryland [Tiglio] ⟸ *SpEC*

Numerical Relativity Groups Today

- Princeton [Pretorius]
- University of British Columbia [Choptuik]
- University of Illinois, Urbana [Shapiro]

2005 - 2009:

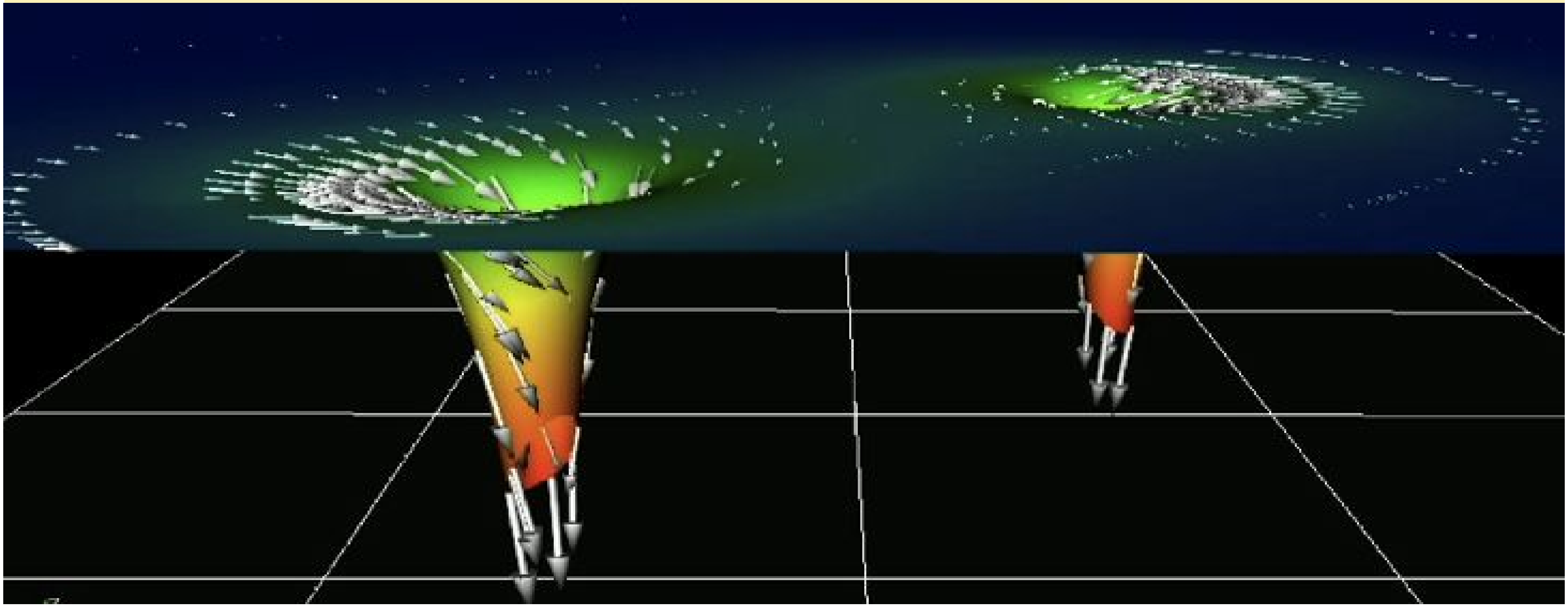
- *Finite Difference groups: astrophysical studies at moderate accuracy*
- *SpEC: solve coordinate problems - make code robust*
  . - embark on GW studies at high accuracy, fast speed;
  . - begin exploring nonlinear dynamics of warped spacetime

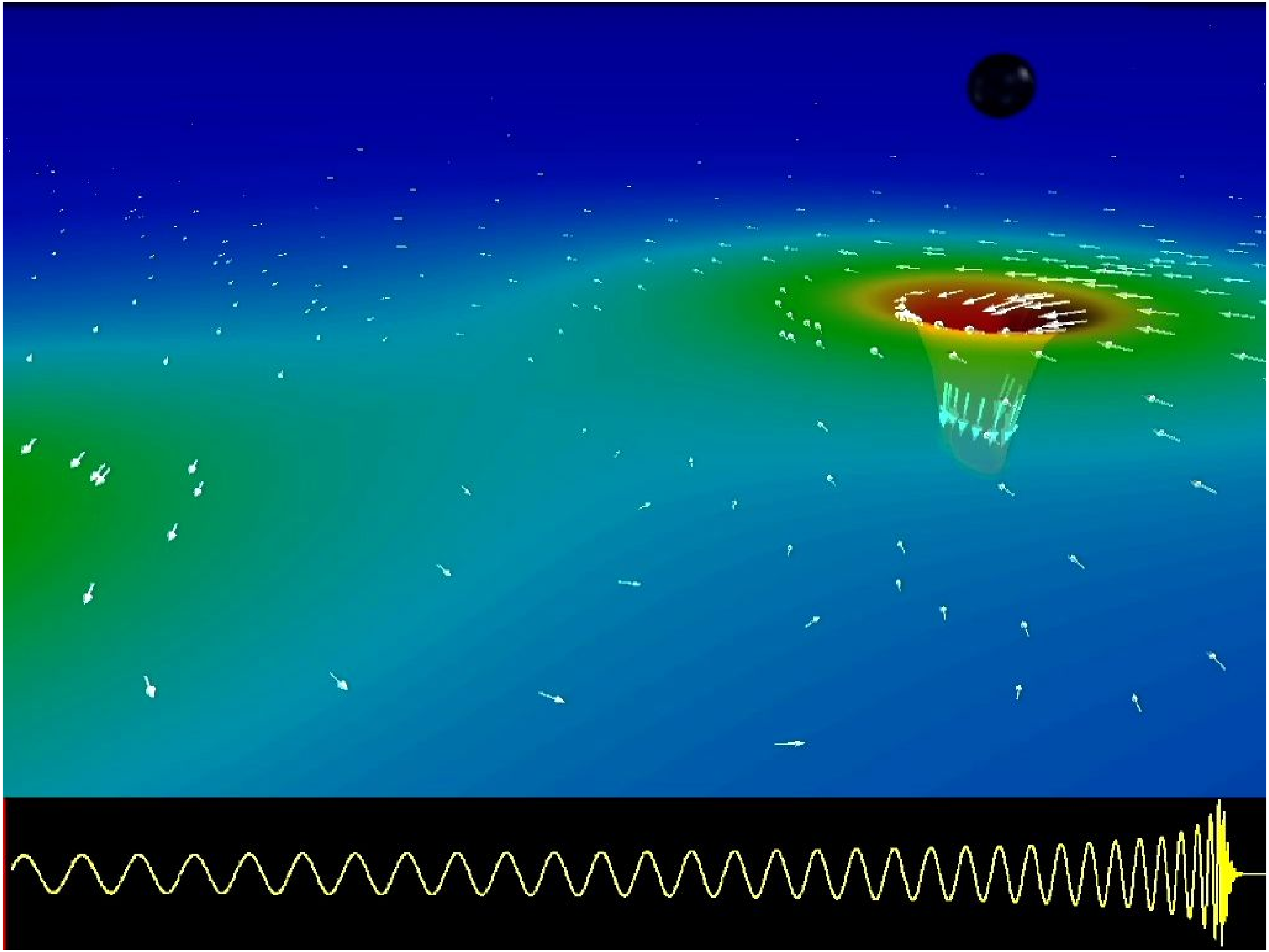
- University of Jena [Bruegmann]
- University of Tokyo [Shibata]
- Cornell/Caltech [Teukolsky, Lindblom, Kidder, Scheel, Pfeiffer] ⇐ *SpEC*
- **New Groups this year & last** -
  - » Georgia Tech [Laguna, Shoemaker]
  - » Perimeter Institute / U. Guelph [Lehner]
  - » Canadian Institute for Theoretical Astrophysics [Pfeiffer] ⇐ *SpEC*
  - » U. Maryland [Tiglio] ⇐ *SpEC*

*(**Spectral** Einstein Code)*

State of the Art Today. SpEC Example:

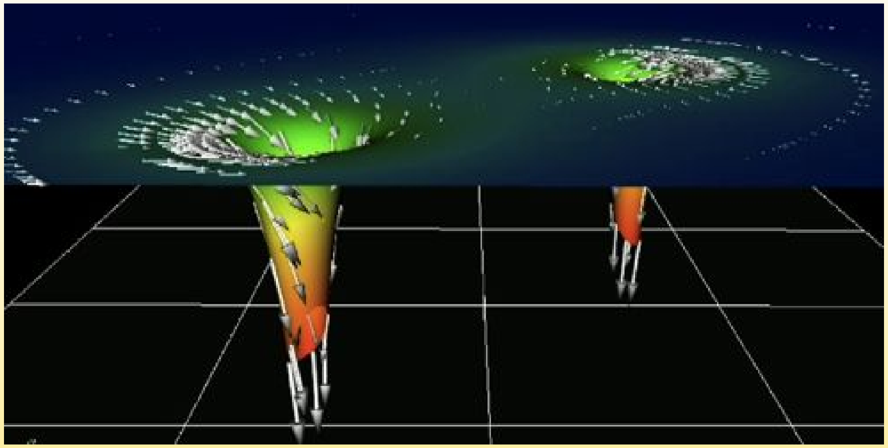
- Identical holes, not spinning
- 16 orbits, collision, merger, and ringdown
- Gravitational waveforms - cumulative phase error ~ 0.01 radians Cornell/Caltech: Kidder, Lindblom Pfeiffer, Scheel, Teukolsky…

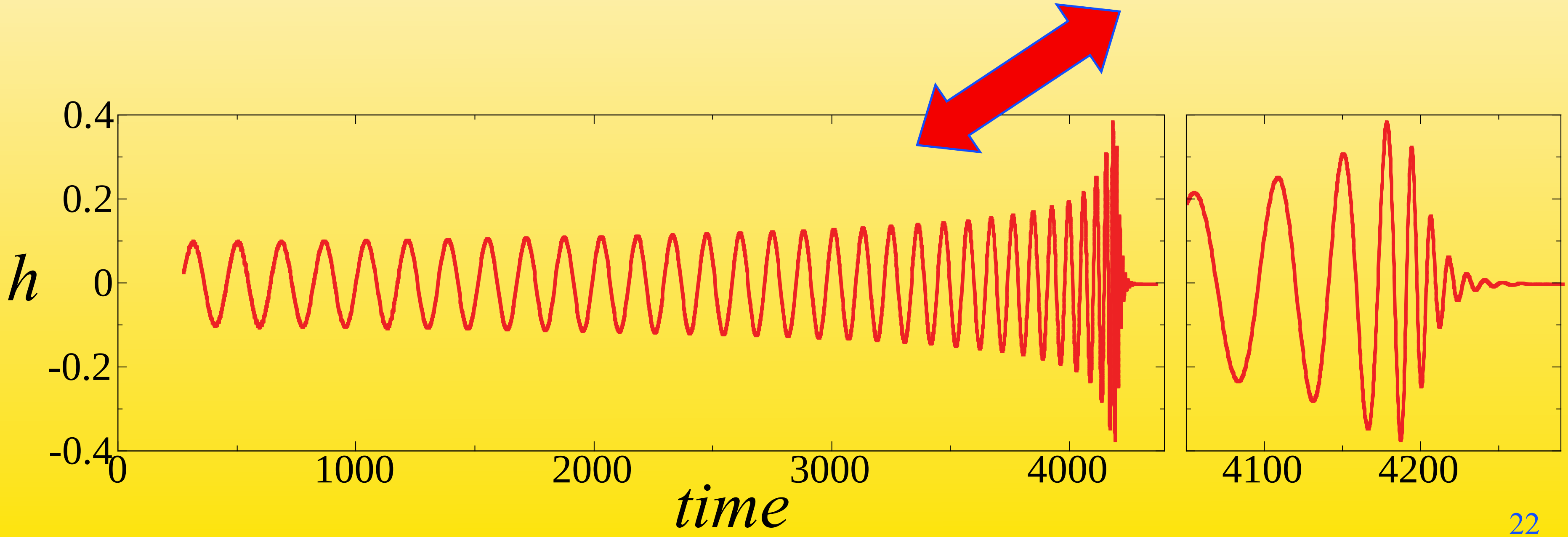




“Rosetta Stone”

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

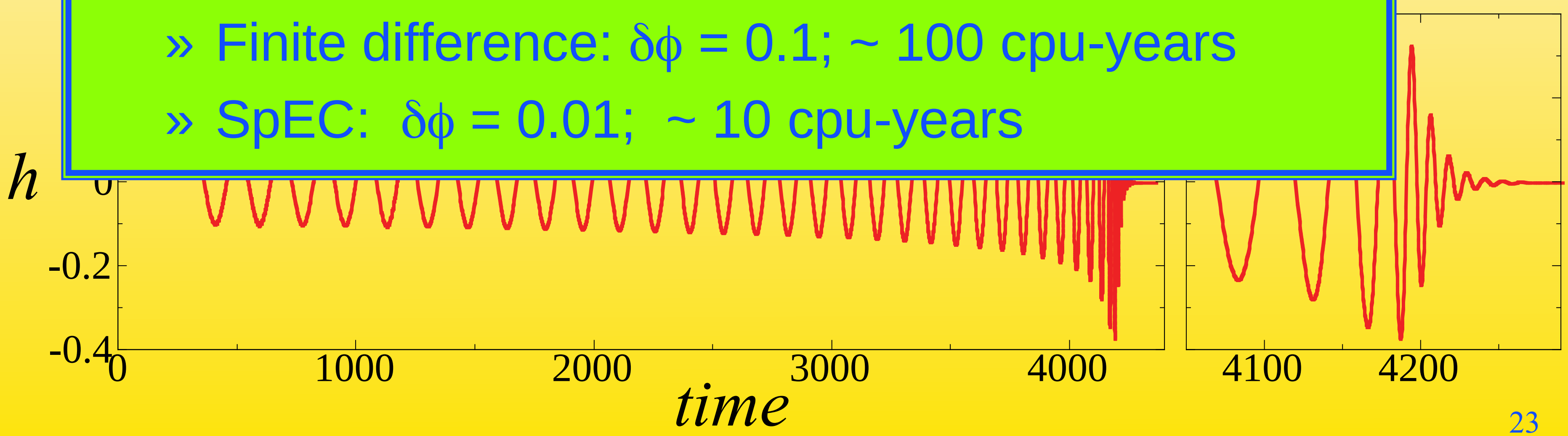




"Rosetta Stone"

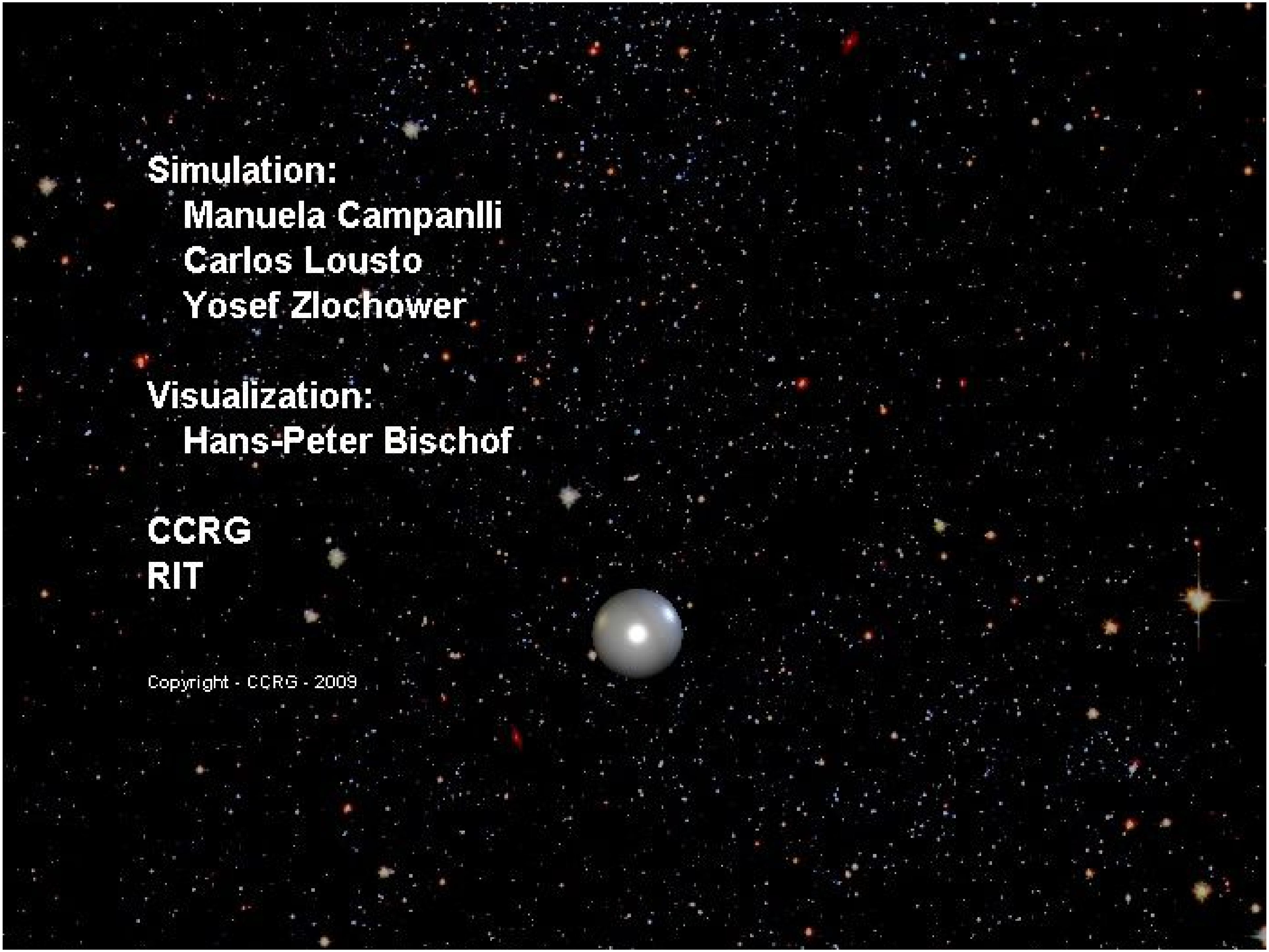
Numerical simulations and theory provide "rosetta stone" for interpreting observed Gravitational Waveforms

- 7 parameters: M_1/M_2, $\boldsymbol{S}_1$, $\boldsymbol{S}_2$
- ~ 500 simulations to underpin GW data analysis
  - » $\delta\phi \sim 0.1$ for searches,
  - » $\delta\phi \sim 0.01$ for information extraction
- For a generic simulation:
  - » Finite difference: $\delta\phi = 0.1$; ~ 100 cpu-years
  - » SpEC: $\delta\phi = 0.01$; ~ 10 cpu-years



Nonlinear Dynamics of Warped Spacetime

- ***Spinning Holes***
  - » Rochester Institute of Technoogy: Campanelli, Lousto, Zlochower
  - » Finite-difference techniques

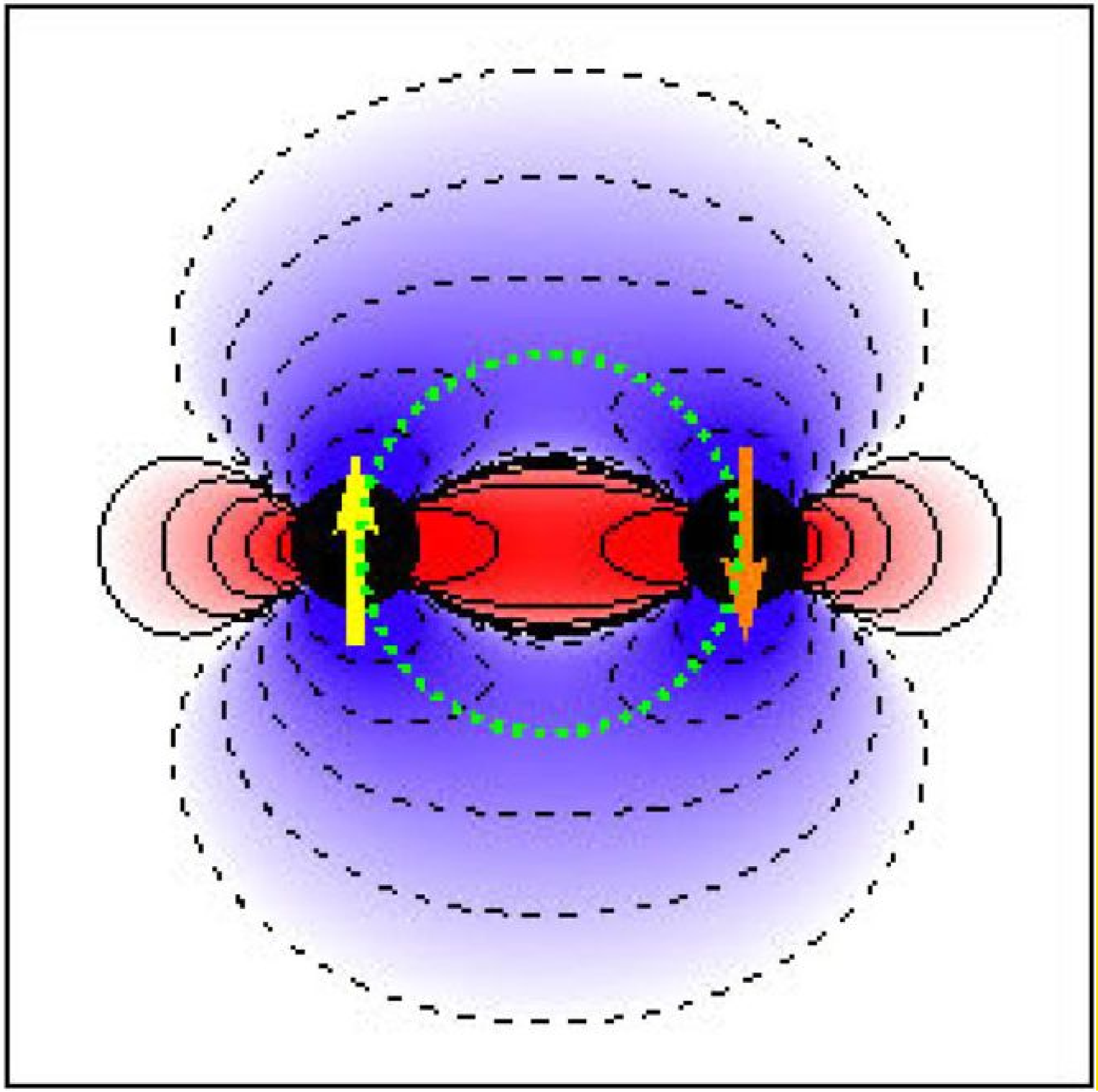

Simulation:
Manuela Campanlli
Carlos Lousto
Yosef Zlochower
Visualization:
Hans-Peter Bischof
CCRG
RIT
Copyright - CCRG - 2009

Analogous to 2 Vortices in a Fluid

from ***Vorticity*** by Asher H. Shapiro (National Comittee on Fluid Mechanics Films, ca 1960)

Nonlinear Dynamics of Warped Spacetime

Explanation (Pretorius): "Frame Dragging" + Spin/Curvature Coupling



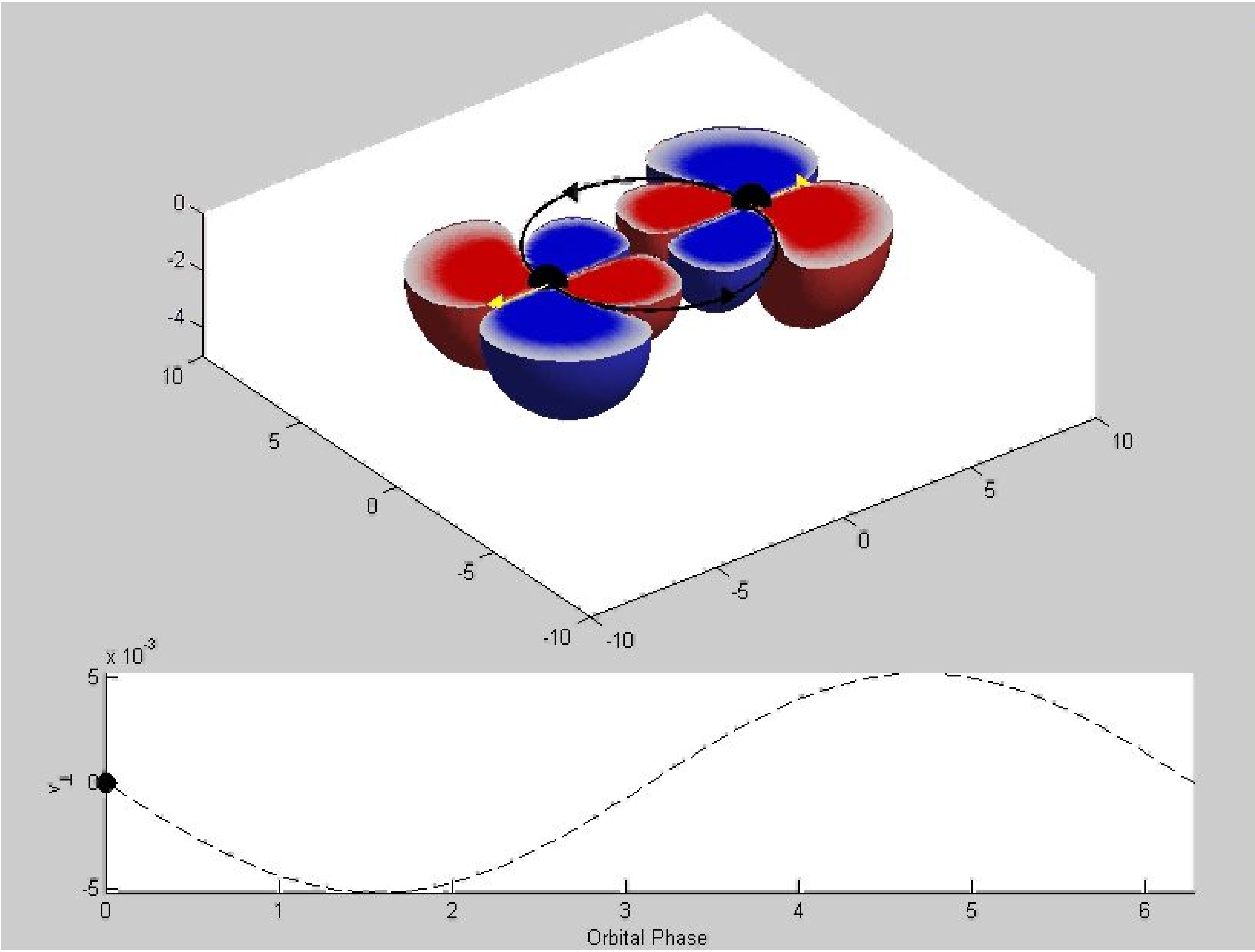
Momentum conservation:

Chen, Keppel, Nichols, Kip

Field momentum:

$$-\frac{1}{4\pi}\vec{g}\times\vec{H}$$

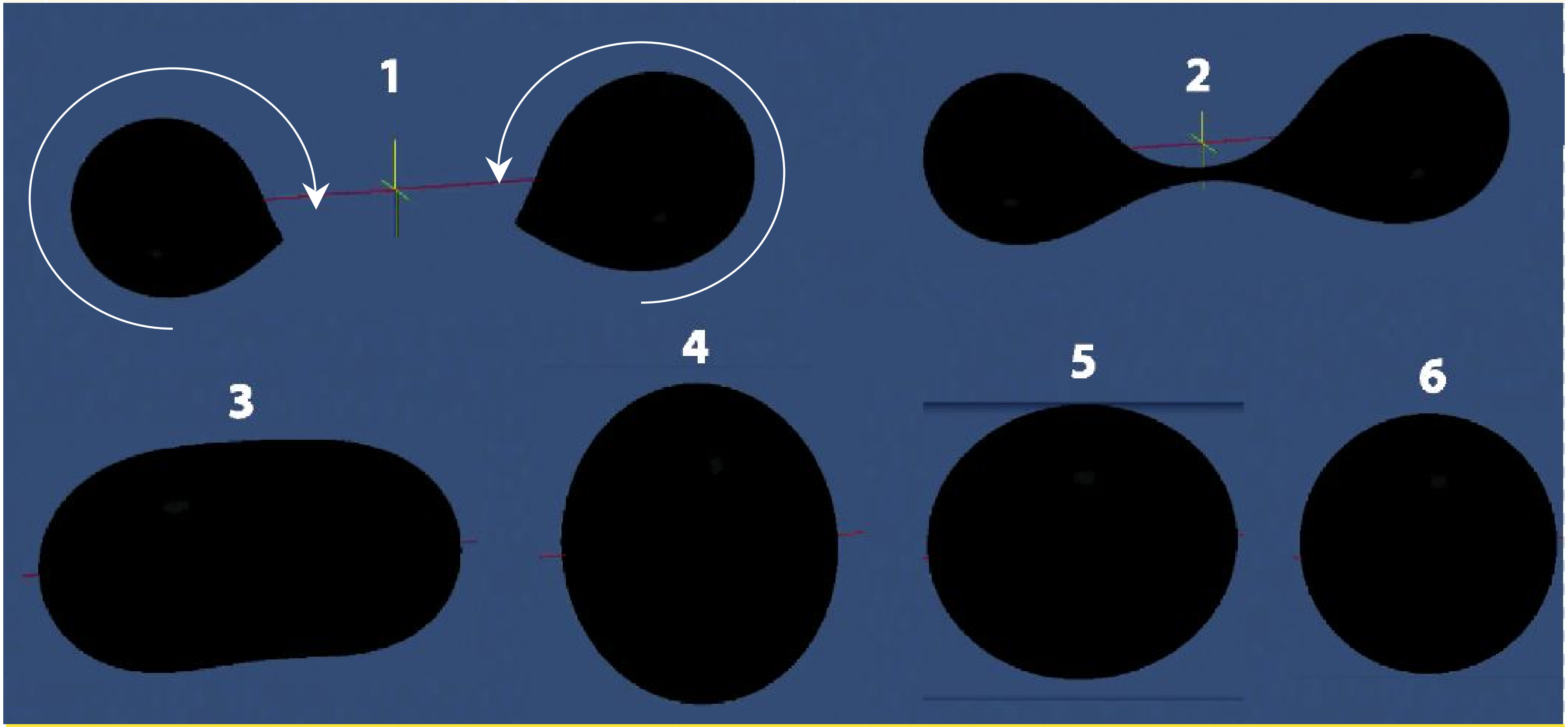
in Post-Newtonian approximation: Chandrasekhar or harmonic gauge



0
-2
-4
10
5
0
-5
-10
-10
-5
0
5
10
x 10^-3
5
0
-5
v_⊥
0
1
2
3
4
5
6
Orbital Phase

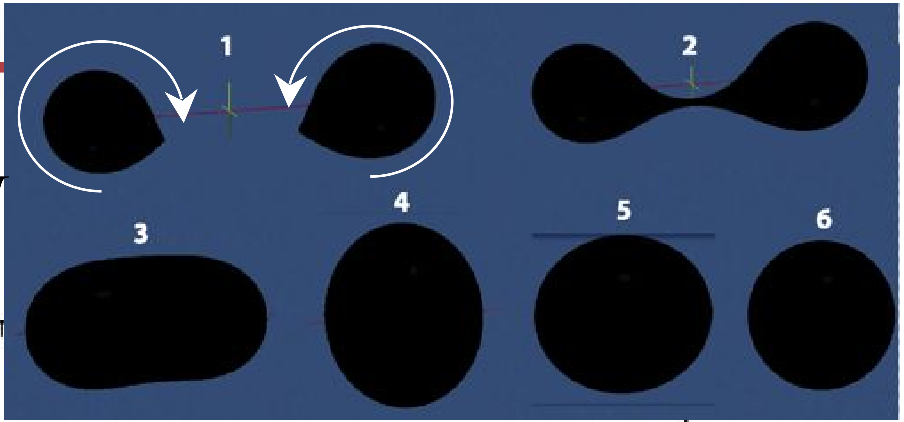
Head-On Collision, Transverse Spin

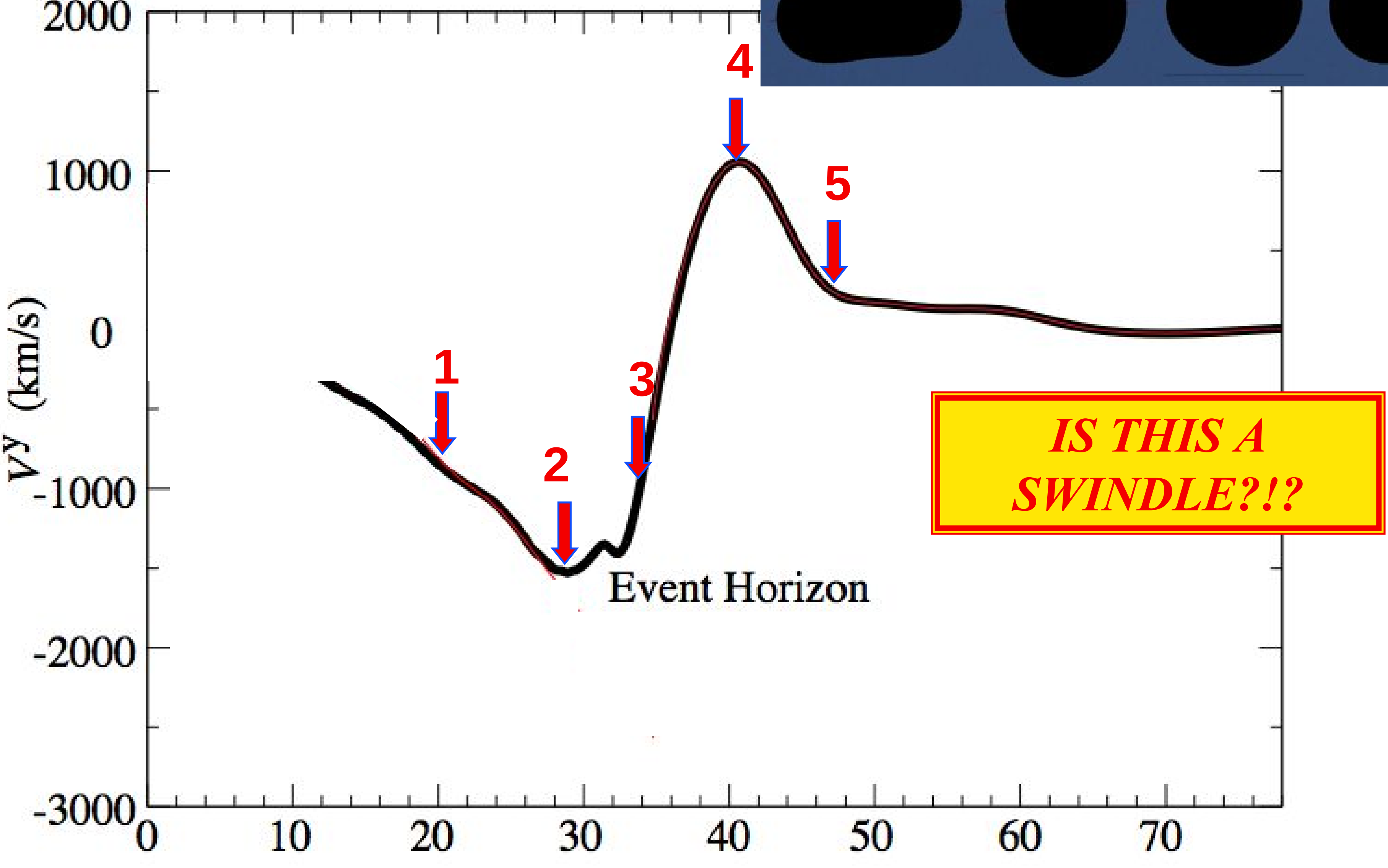
Geoffrey Lovelace, Mark Scheel, Michael Cohen, Jeff Kaplan
[Cornell/Caltech]



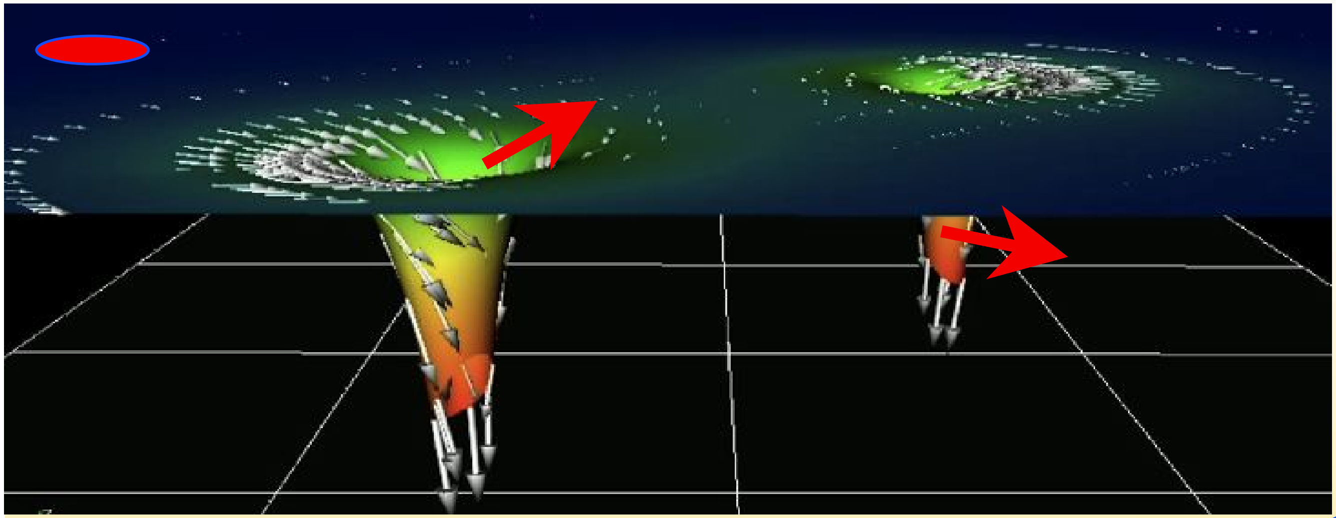
Head-On Collision, T

(Vertical Velocity of horizons) = p_z/M

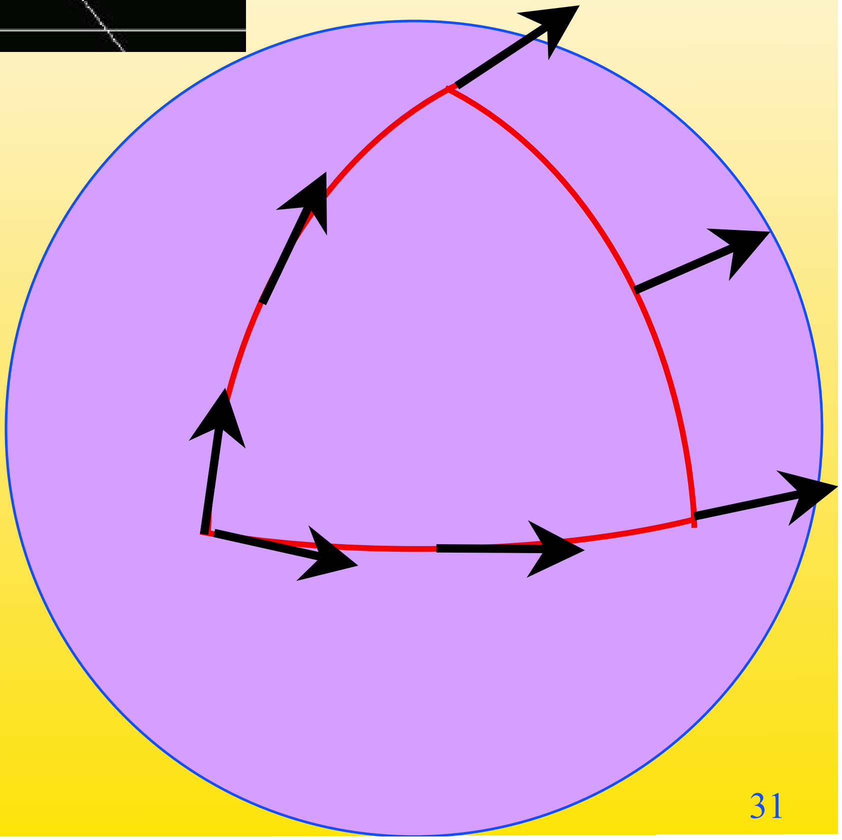




How Define Momentum in Curved Spacetime?



Result of transport depends on path

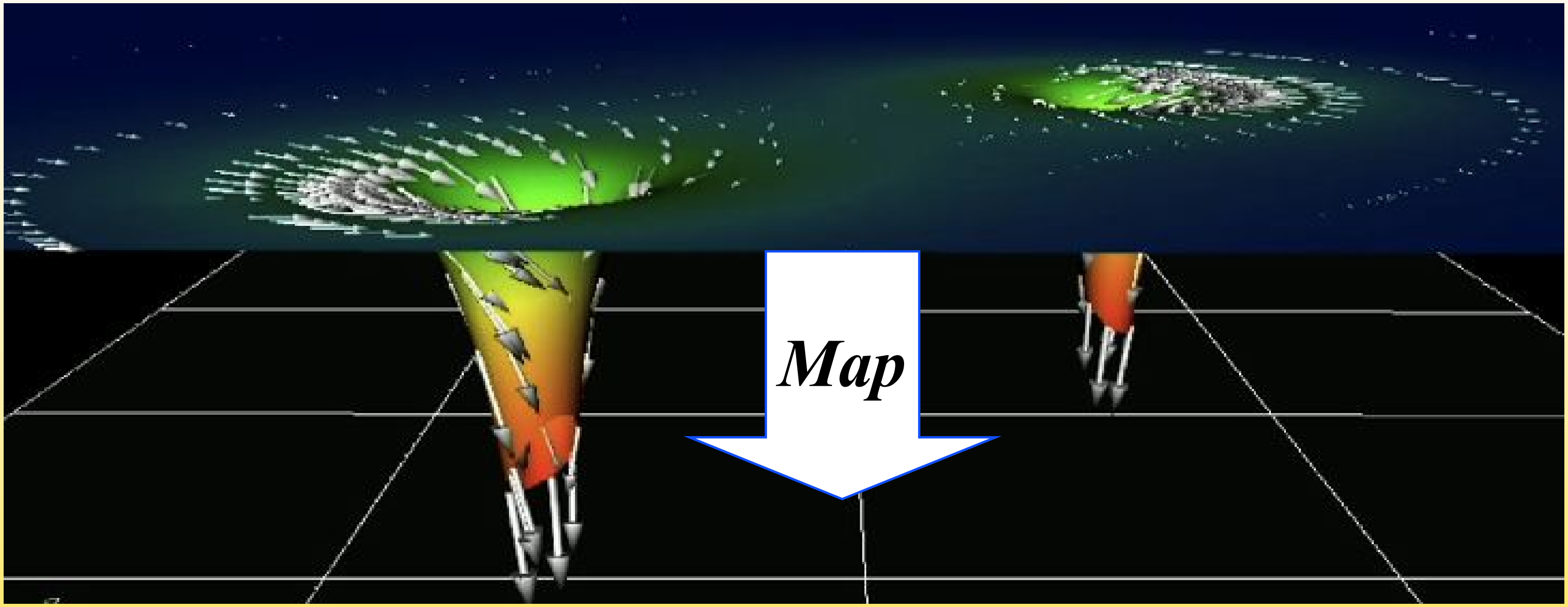


Must transport momentum vectors to a common location before adding them

> ***Momentum conservation arises from translation invariance of spacetime.***
>
> ***BH/BH spacetime has none.***

How Define Momentum in Curved Spacetime?

Rewrite General Relativity Theory as a Nonlinear Field Theory in Flat Spacetime

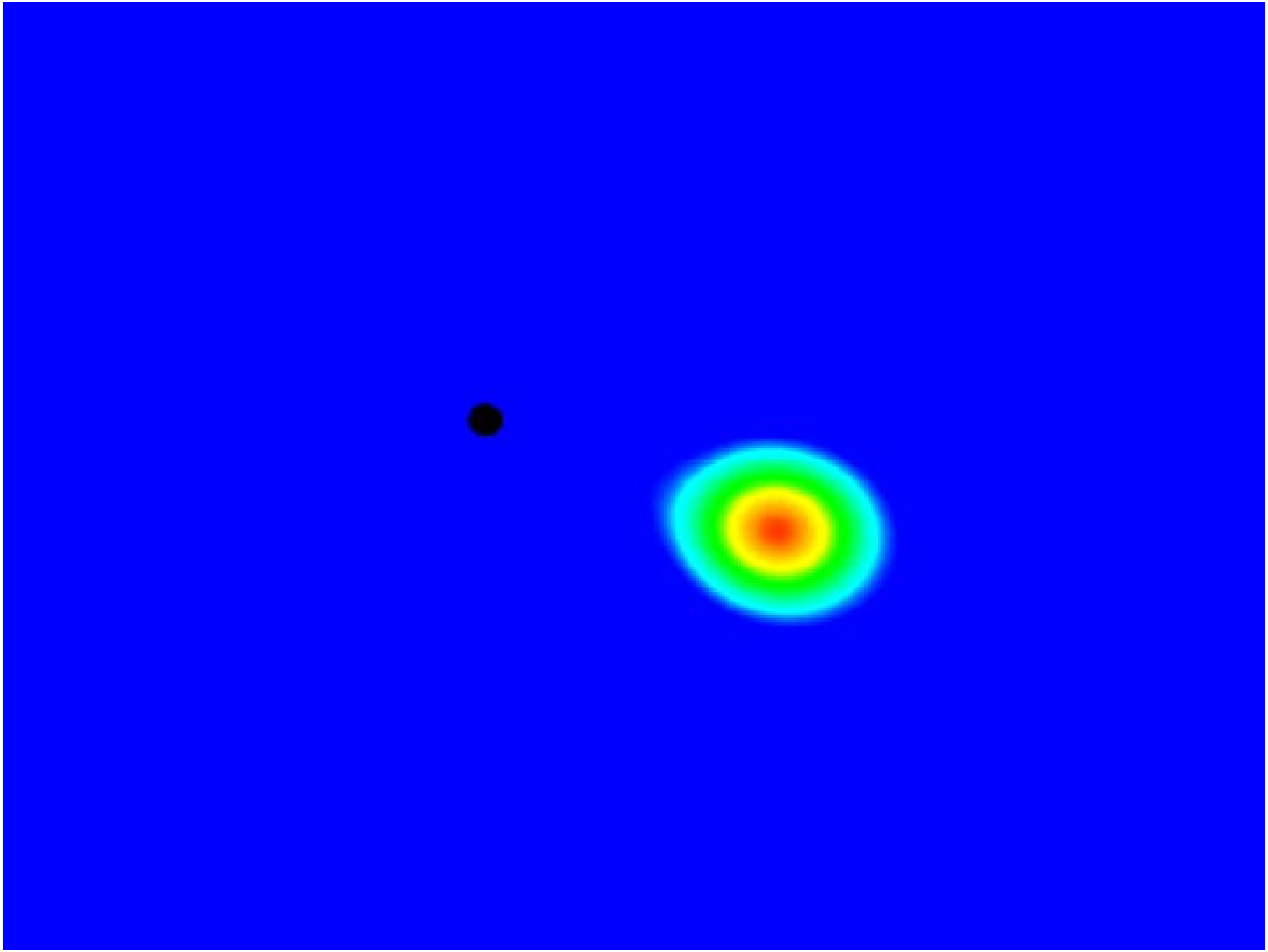


Landau & Lifshitz, Classical Theory of Fields

Mapping is not unique. - Momentum "gauge dependent"

-- but not "very" gauge dependent in this case --

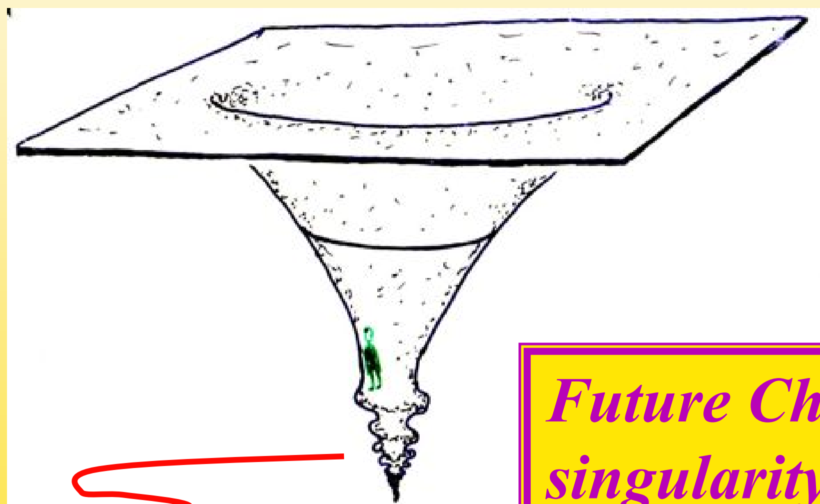
G. Lovelace et al, arXiv:0907.0869



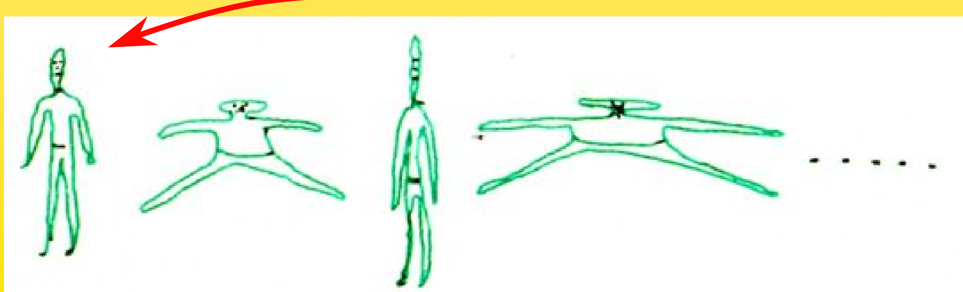
Fundamental Physics Issues

- The dynamics of spacetime near generic singularities
  - » Penrose-Hawking Singularity Theorems (1964 - 72)
  - » Belinsky-Khalatnikov-Lifshitz (BKL) singularity - is it truly generic?

Has been confirmed generic in NR simulations, by David Garfinkle



Future Challenge: How does singularity evolve as hole ages?



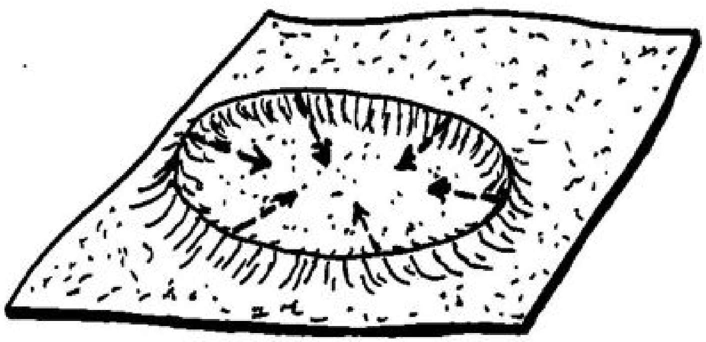
Chaotic pattern of stretch and squeeze

Fundamental Physics Issues

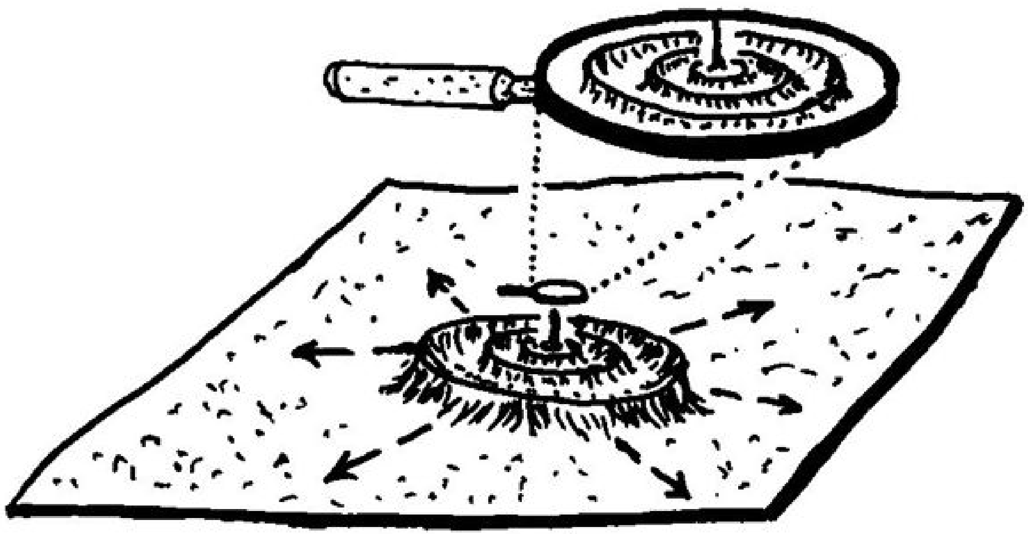
- **Cosmic Censorship Conjecture [Penrose 1968]**
  - » All singularities (except the big bang) are hidden inside black holes.

Numerical Simulations

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



Imploding Scalar Waves



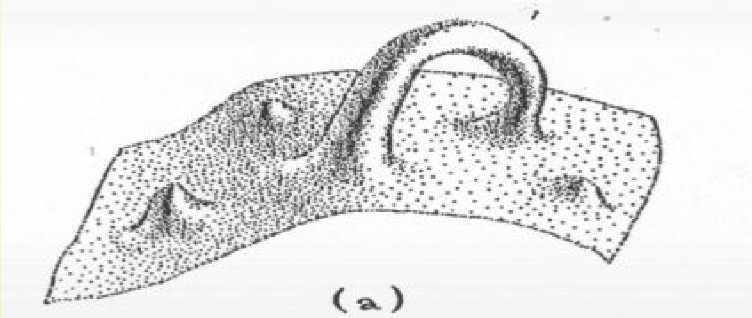
Critical behavior & scaling

Naked Singularity

Fundamental Physics Issues: future

- **Topological Censorship Theorem** [John Friedman et al 1993]:
  - » If the stress-energy tensor always satisfies the null energy condition (NEC), $T_{ab}\, k^a\, k^b \geq 0$ for all null k^a, then information can never travel through a wormhole.

- BUT: null energy condition can be violated, e.g. in Casimir effect and in "squeezed vacuum"

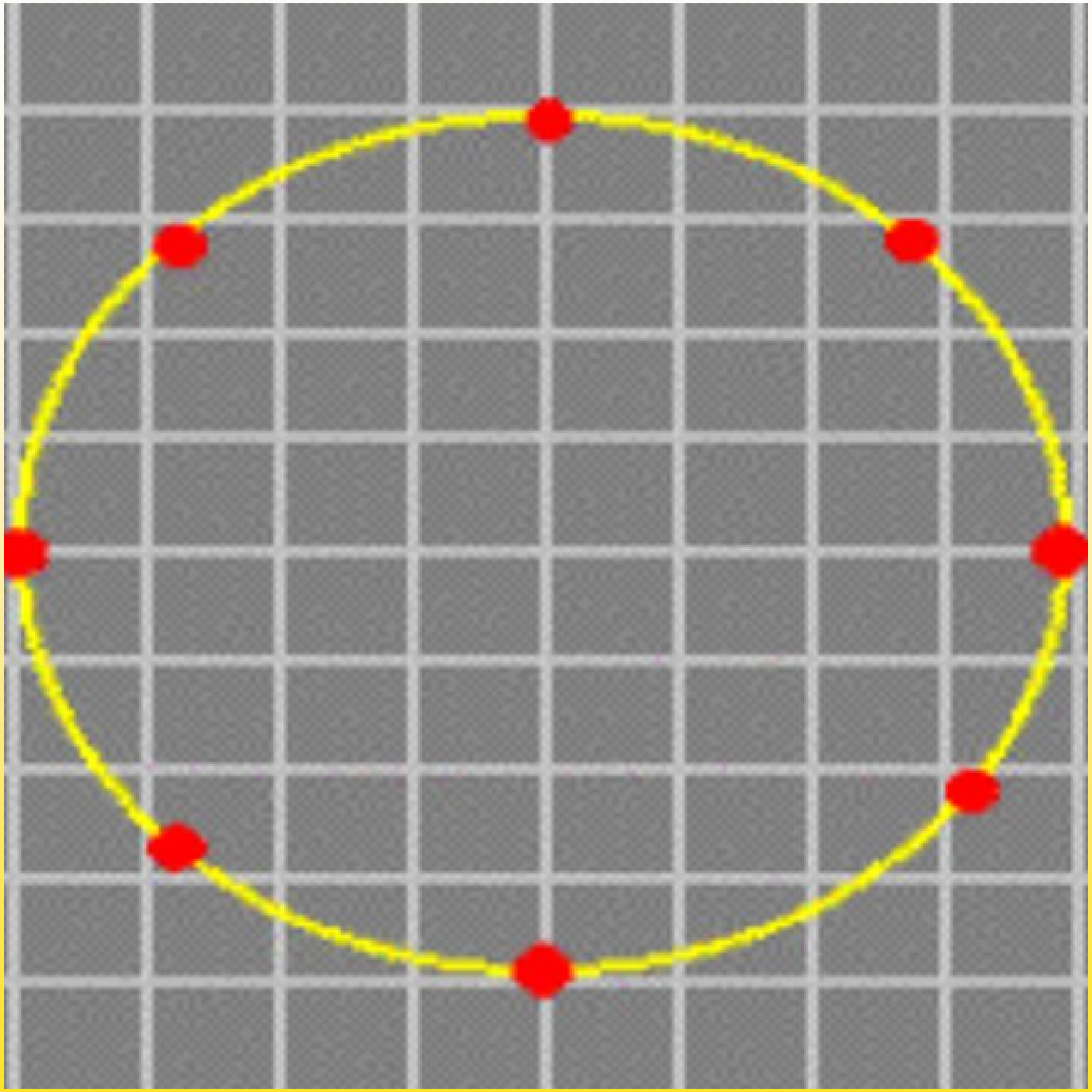


▪*How much violation of NEC is needed to permit travel through a wormhole? [NR]. How much is allowed? [QFT]*

▪*What is the dynamics of the singularity that prevents travel? [NR]*

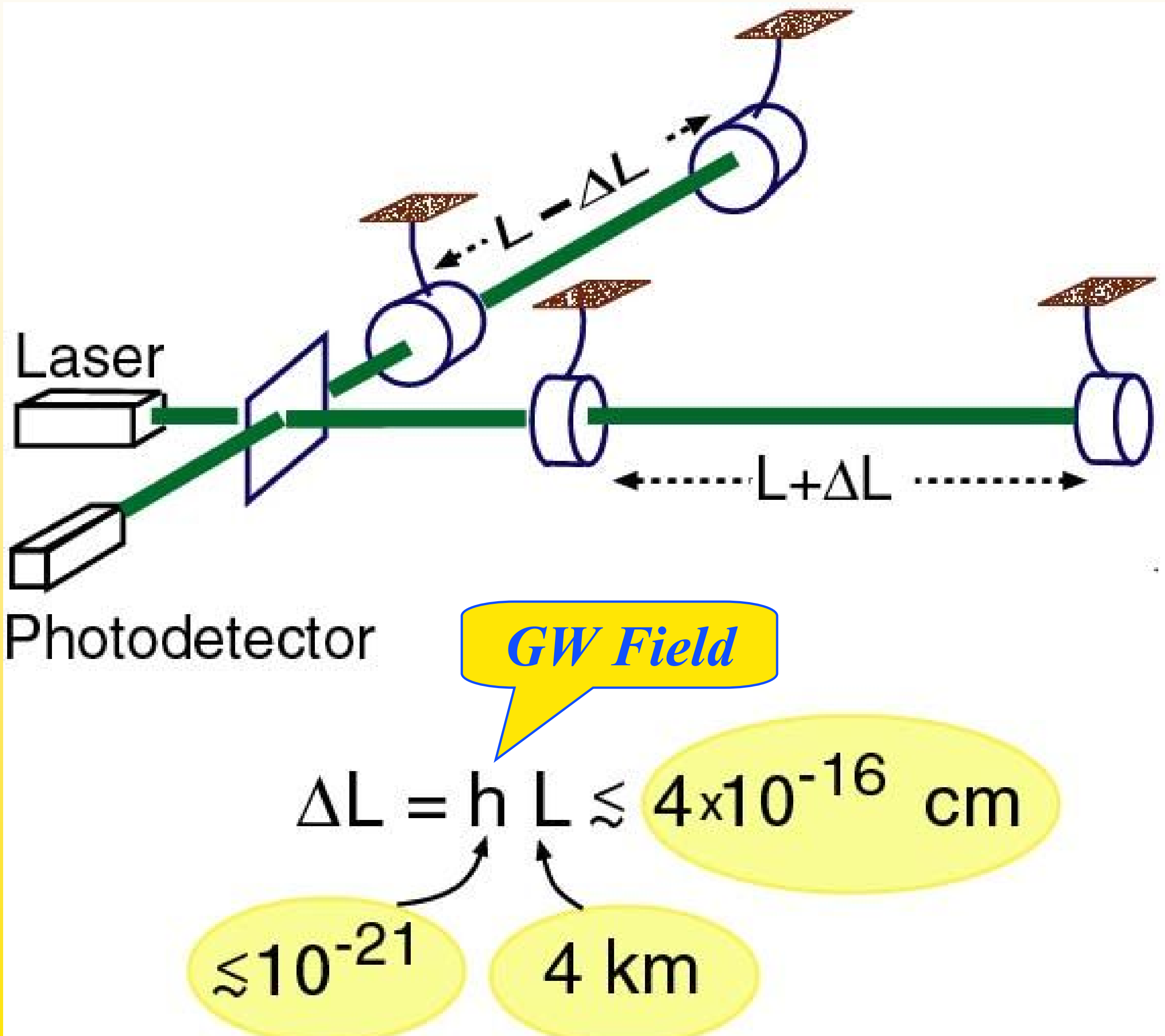
Part 2
Gravitational Wave Observations Probe the Warped Side of Universe

Motivation

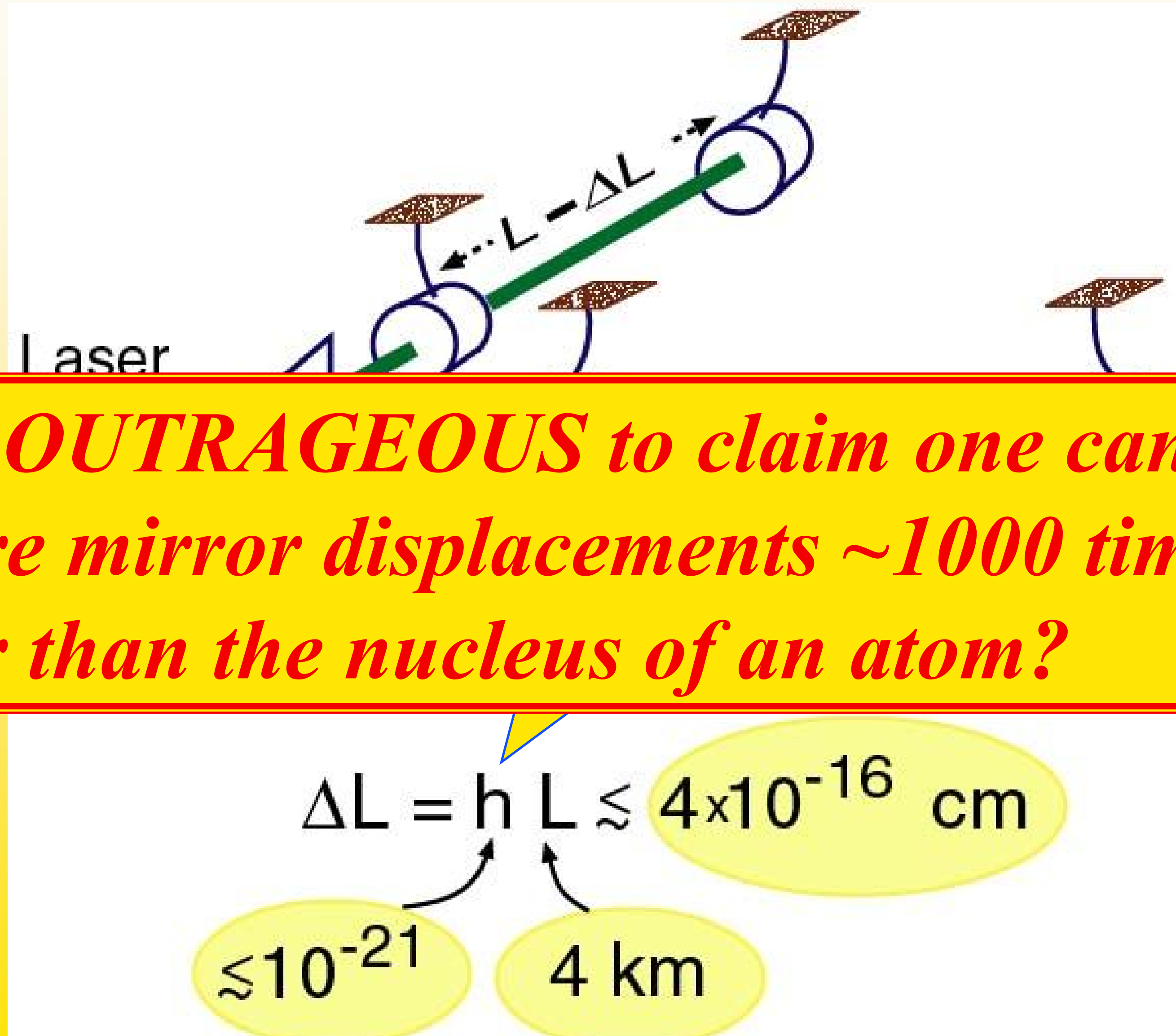


$\Delta L/L = h(t)$

Laser Interferometer Gravitational-Wave Detector - "GW Interferometer"



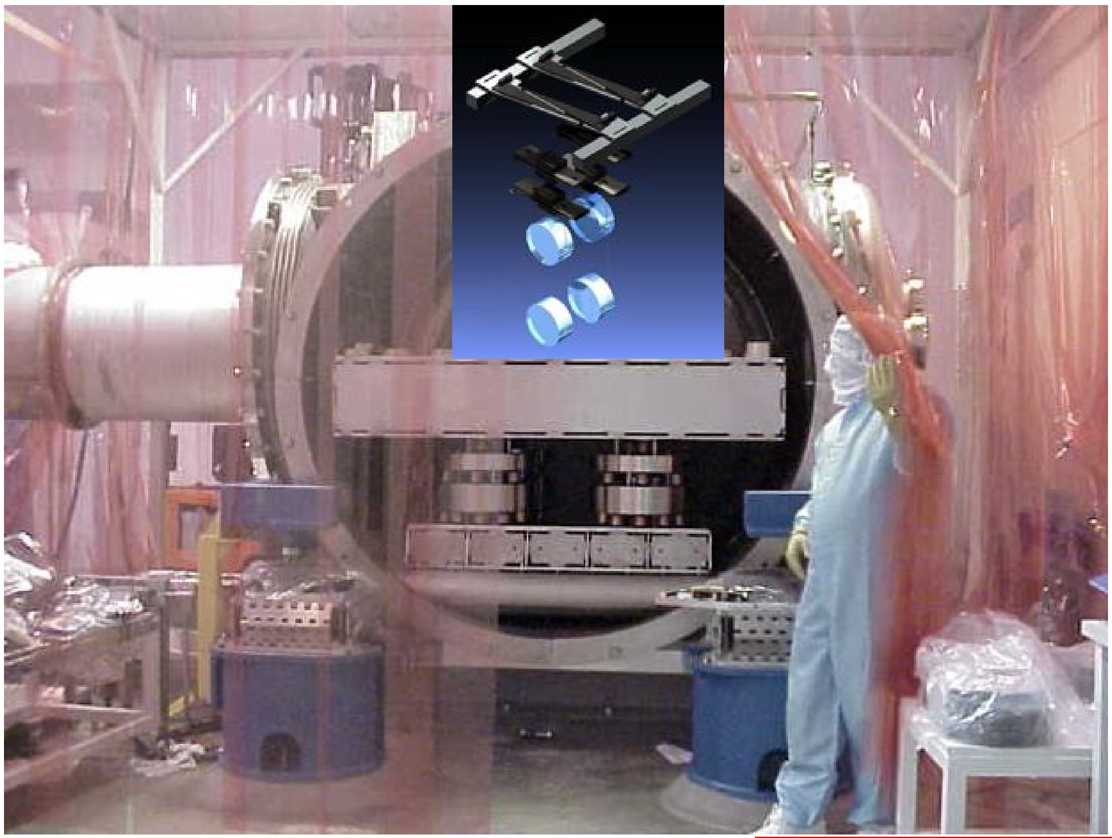
Laser Interferometer Gravitational-Wave Detector - "GW Interferometer"

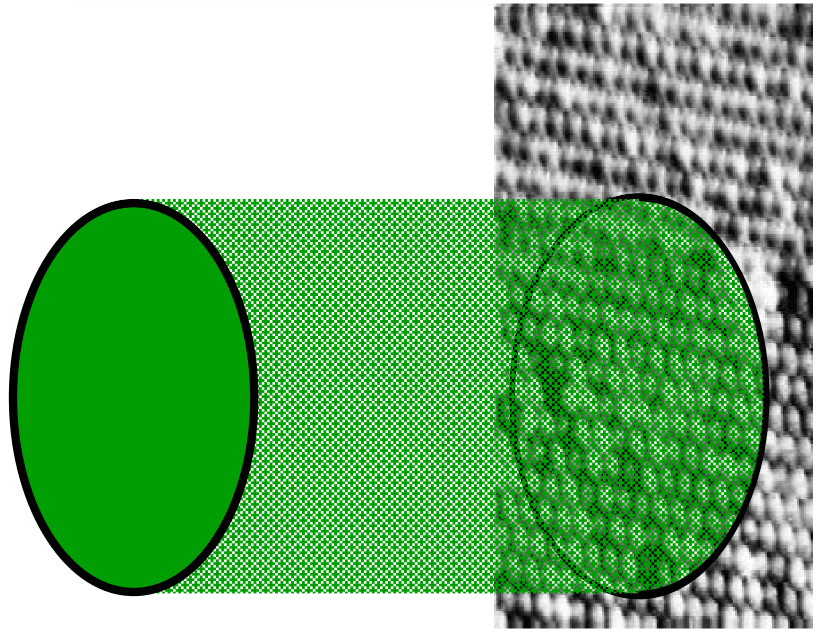


Isn't it OUTRAGEOUS to claim one can measure mirror displacements ~1000 times smaller than the nucleus of an atom?

Keys to Success

Average over space and time





Isolate from environment

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

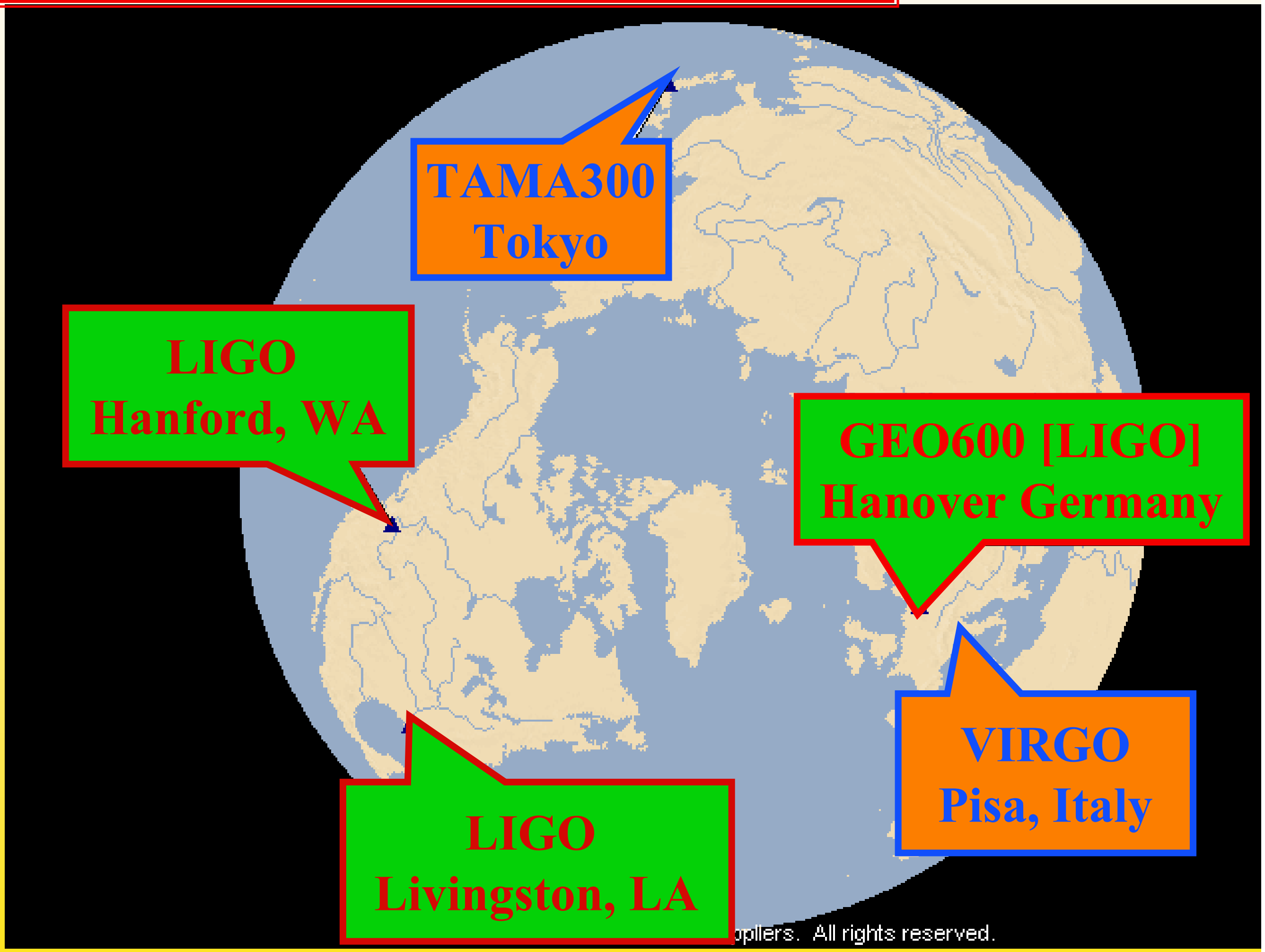
Earth-Based GW Interferometers

Small holes in distant galaxies:

~10 to 100 Msun .   ~ 100 km size

Network Required for:

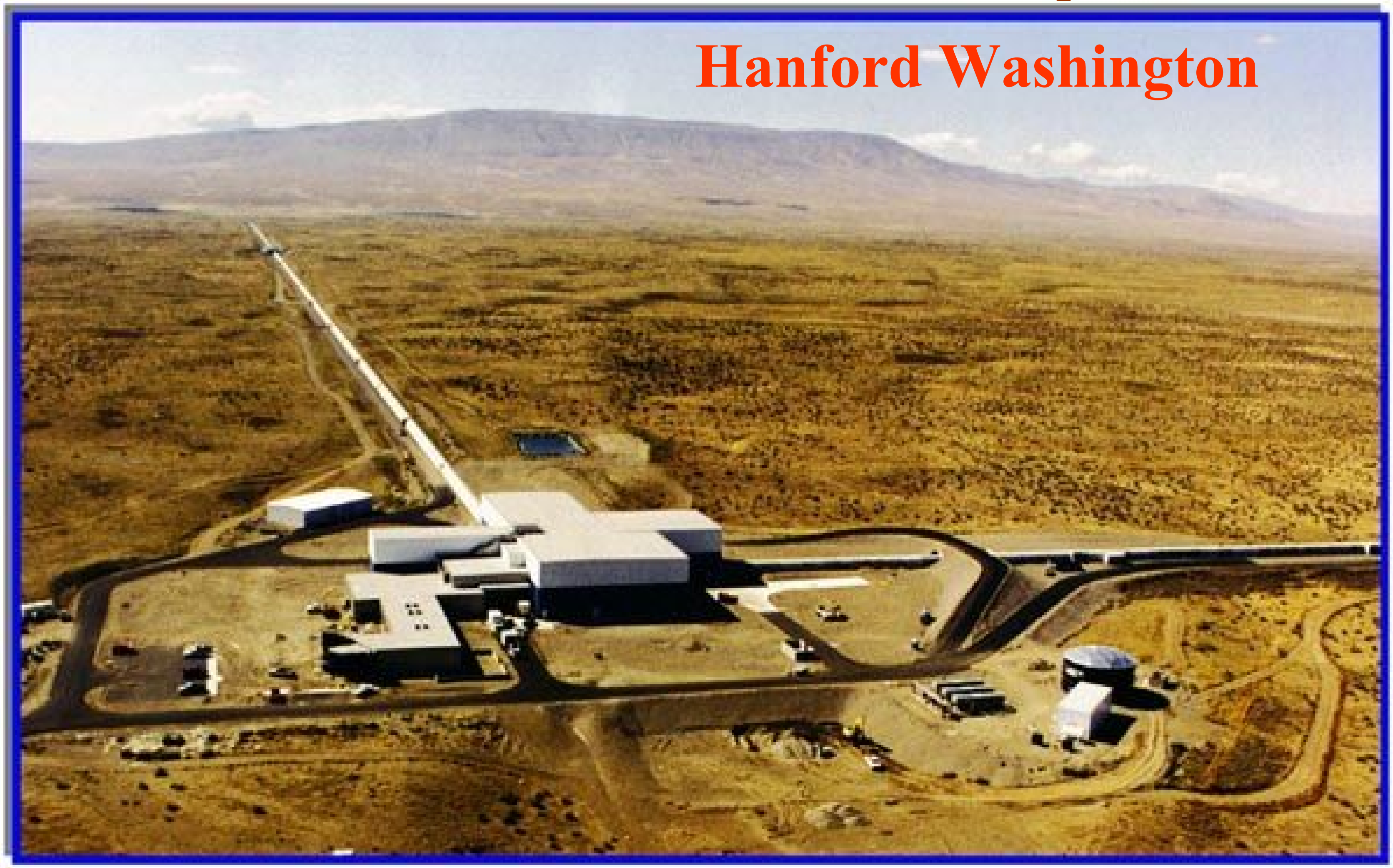
- » Detection Confidence
- » Waveform Extraction
- » Direction by Triangulation



LIGO: **Laser Interferometer Gravitational Wave Observatory**

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

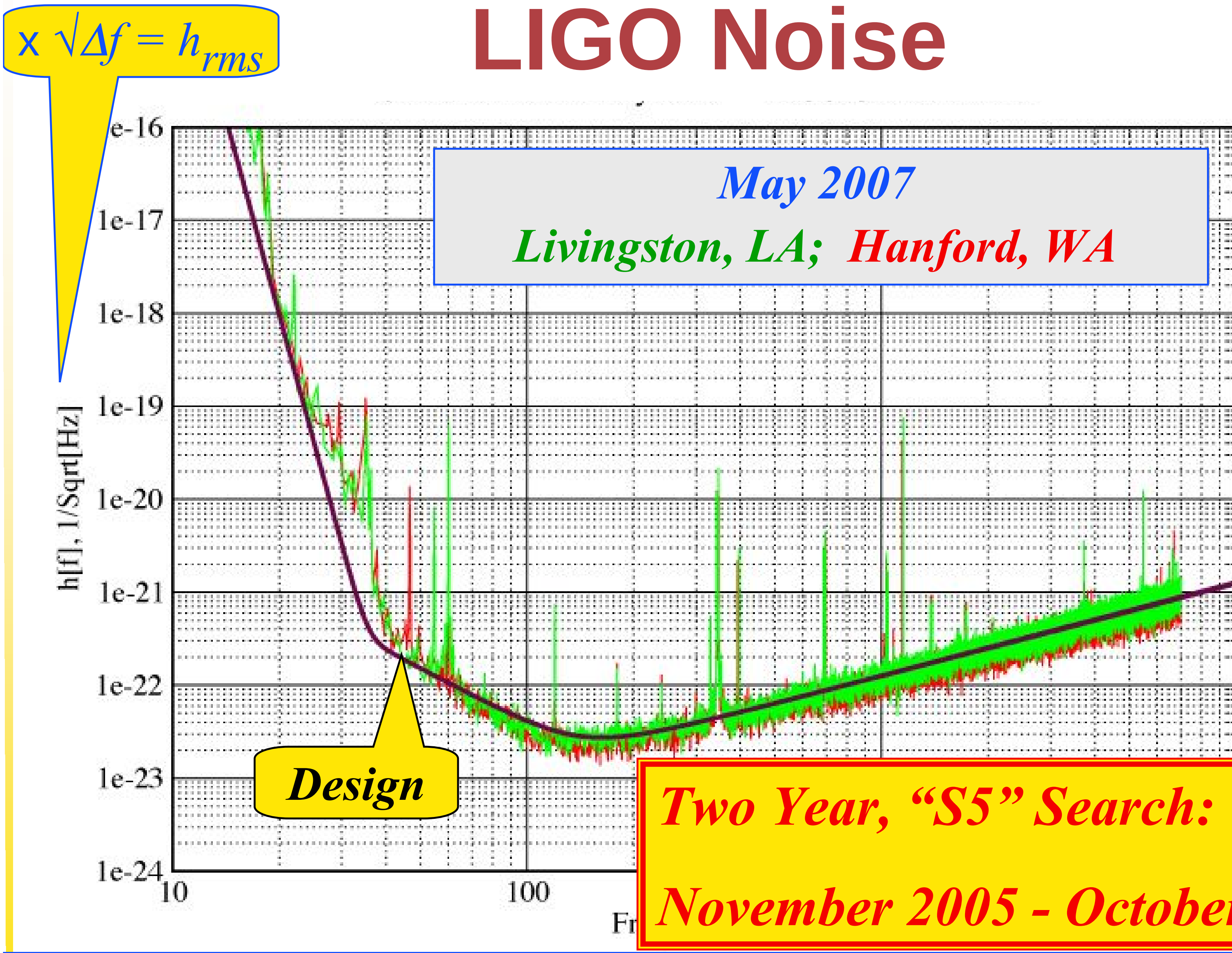
Now: Collaboration of ~500 scientists at ~50 institutions in 8 nations ***[J. Marx, Director; D. Rietze, Spokesman]***



LIGO

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

LIGO Noise



Two Year, "S5" Search:

November 2005 - October 2007

Interesting Limits on Waves from Various Sources; No detections yet

A few S5 Results from ~1/2 of Data

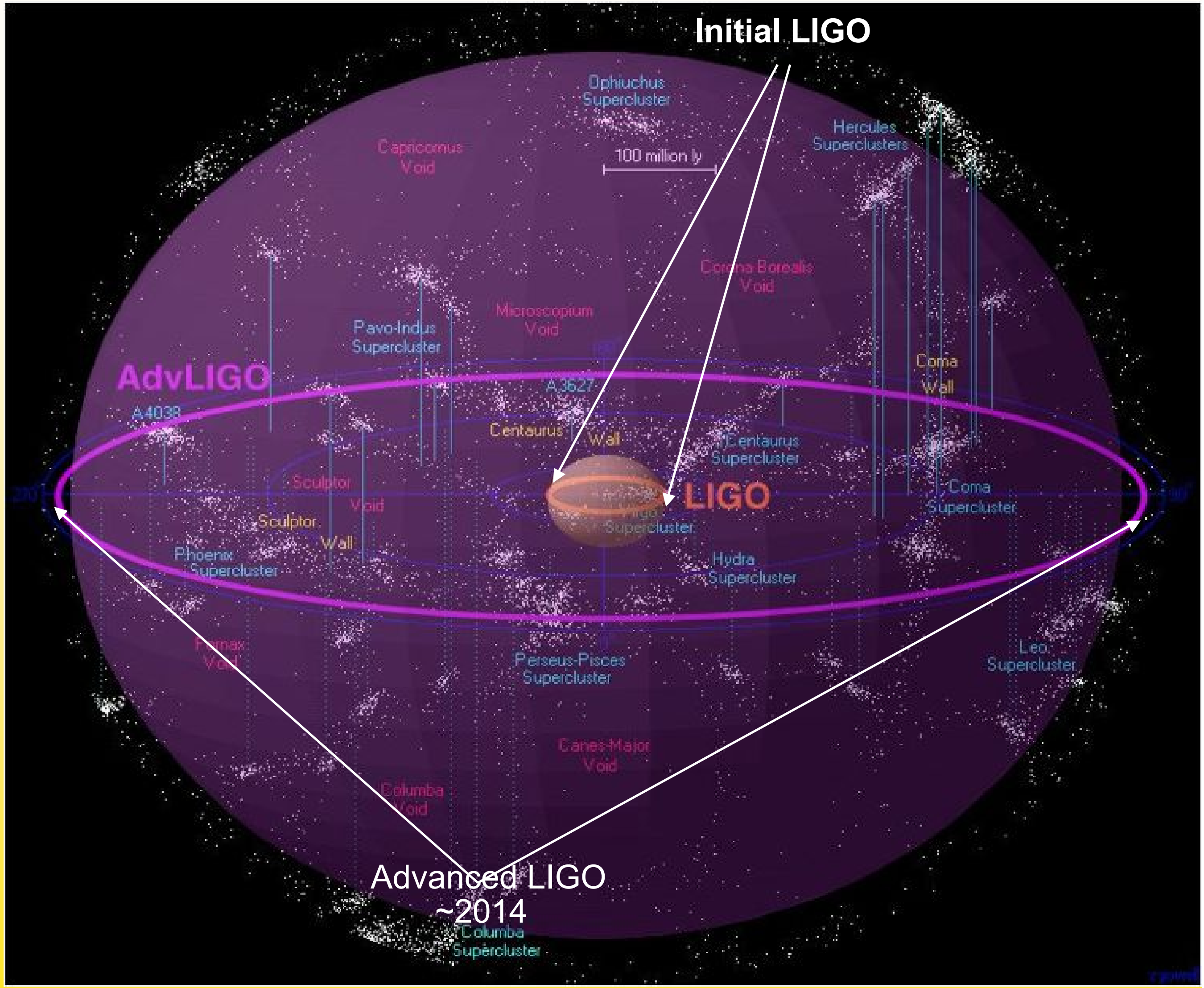
- **BH/BH Binaries with M_{tot} < $35M_{sun}$:** <1/860 yrs in MWEG
- **GRB070201** (coincident with Andromeda) is not a NS/NS or NS/BH in Andromeda
- **Targeted Pulsar Search**
  - » **Crab pulsar:** < 7% of spindown energy goes to GWs
- **Stochastic Background:** $\Omega < 7 \times 10^{-6}$ in 41-178 Hz band (Bayesian 90% confidence)

Future Interferometers in LIGO

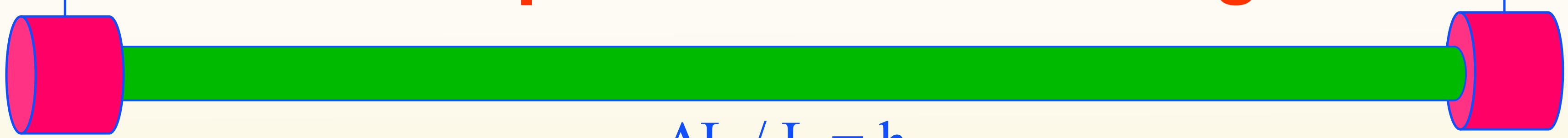
Initial LIGO:
BH/BH ~300 million light years -
≤ 1 BHBH / 10 yrs

Enhanced: 2009-10
~600 million lt yrs
≤ 1 BHBH / yr

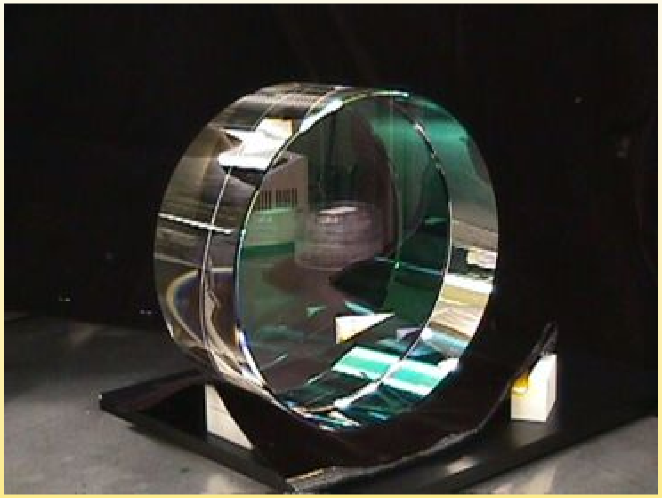
Advanced: 2014-…
~5 billion lt yrs
~1 BHBH/day - mo



Advanced LIGO Interferometers
The Experimental Challenge



$\Delta L / L = h$



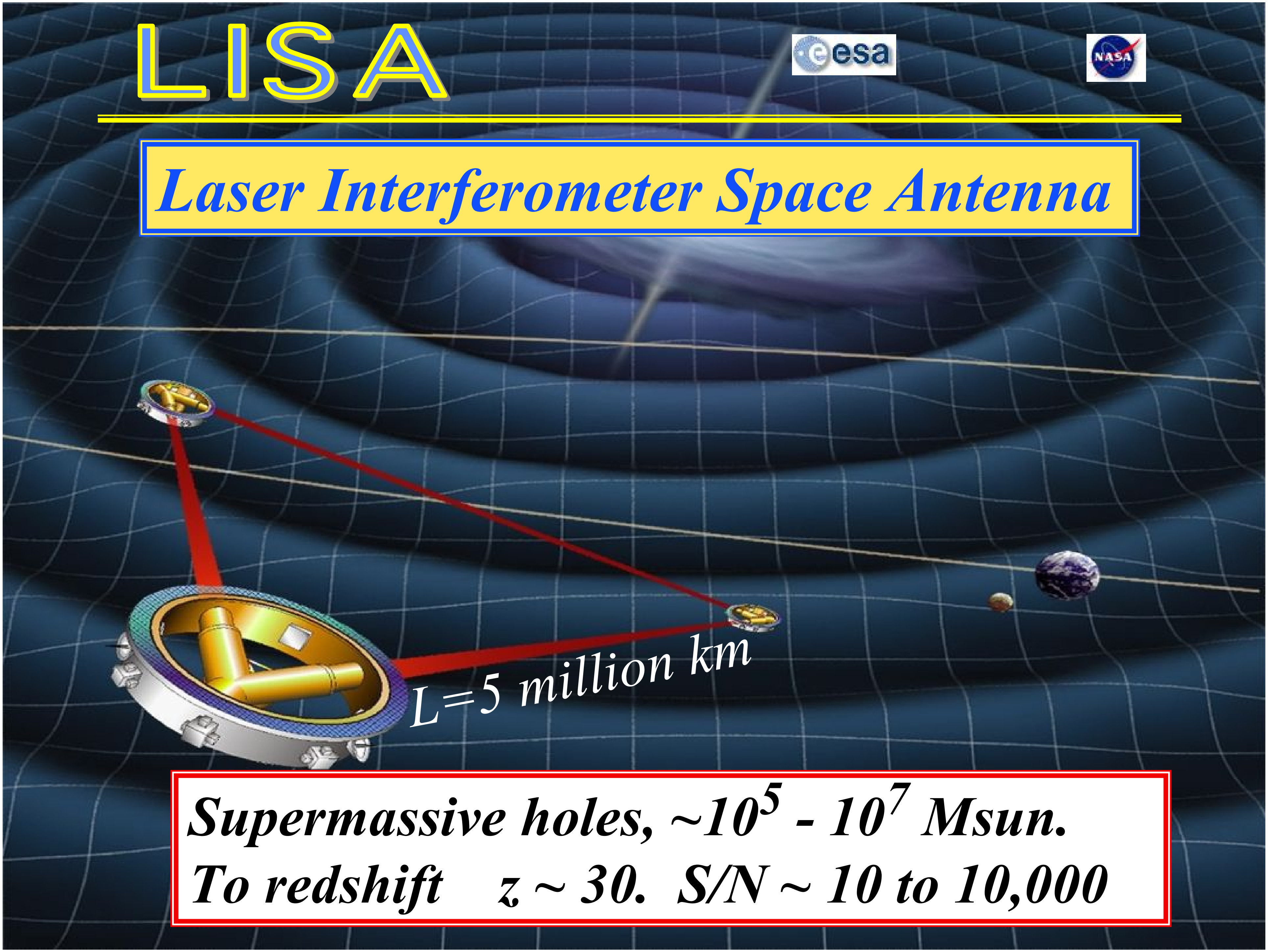
- **Monitor motions of 40 kg mirrors to:**
  - » **$\Delta L \sim 10^{-17}$ cm**
  - » . **~ 10^{-13} wavength of light**
  - » **~ 1/2 width of Schrödinger**
    . **wave function of**
    . **center of mass**

For the first time humans will see human-sized objects behave quantum mechanically!
Quantum Nondemolition (QND) Technology to deal with this

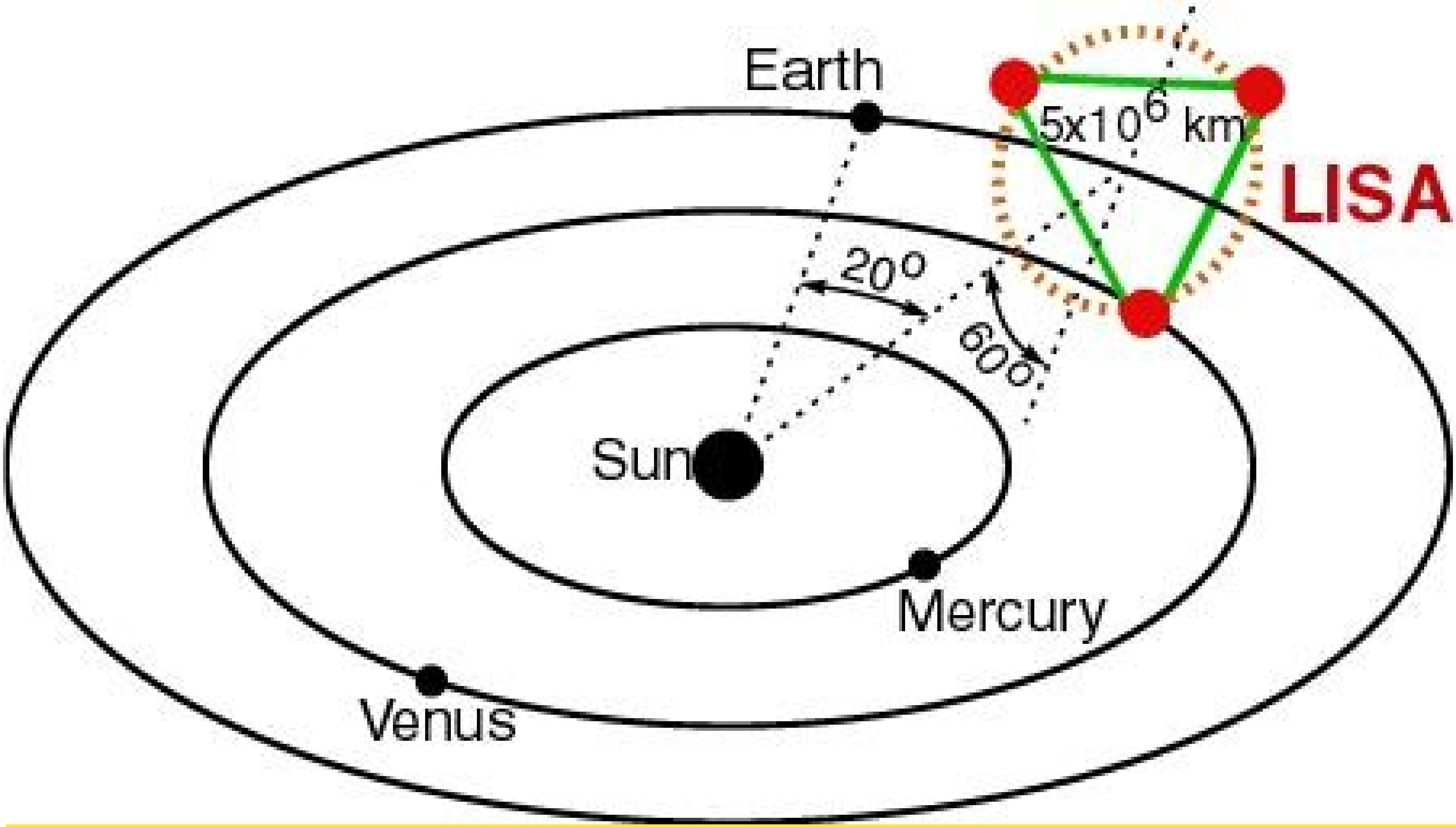
Oct 2 Lorentz Lecture: Advanced LIGO - 2 modes of operation

• GW searches: insensitive to quantum state of mirrors

• Macroscopic QM experiments: maximally sensitive to quantum state

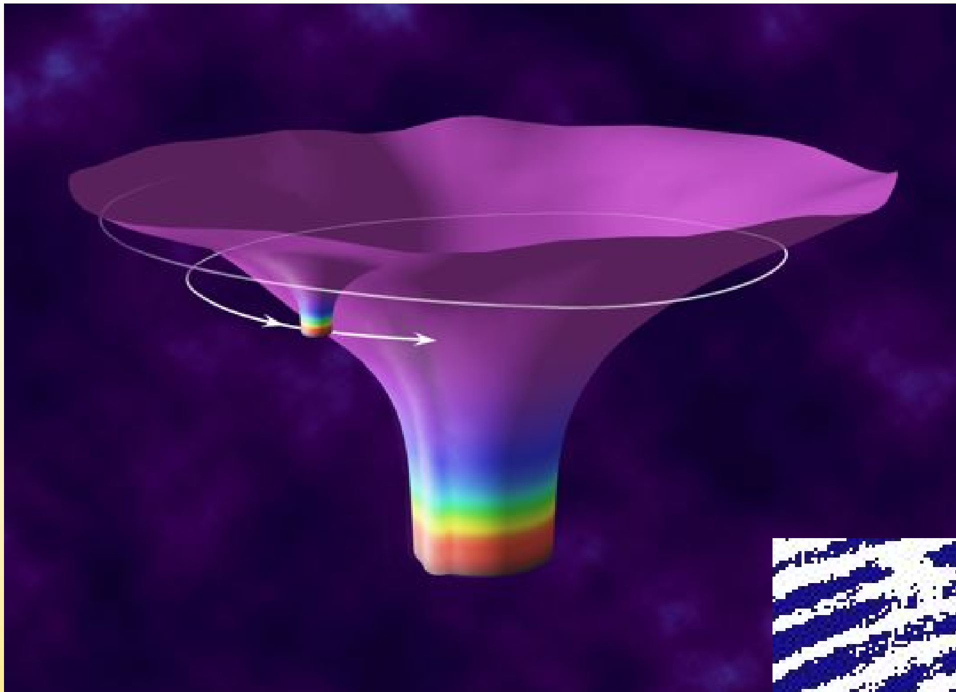

LISA
Laser Interferometer Space Antenna
L=5 million km
Supermassive holes, ~10^5 - 10^7 Msun.
To redshift z ~ 30. S/N ~ 10 to 10,000

LISA: Joint ESA/NASA Mission



- **Launch: about 2018 or later**

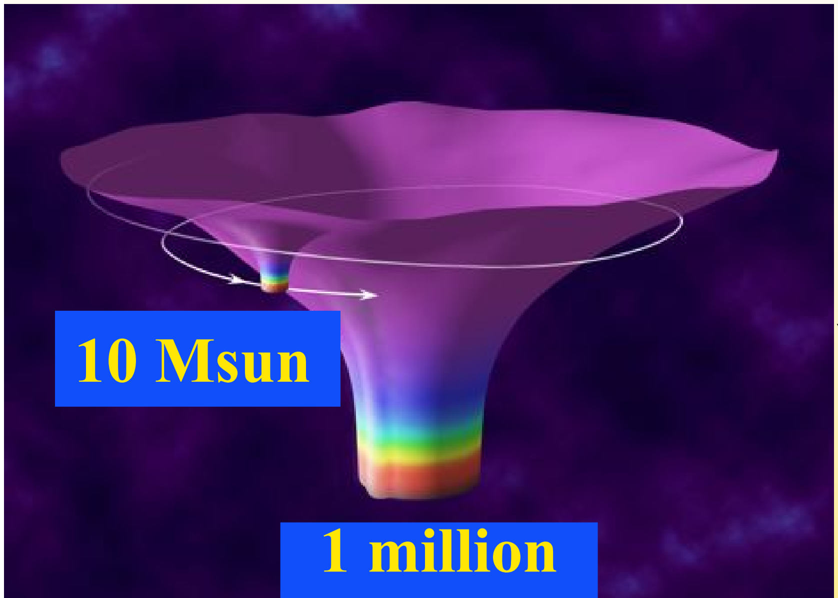
Mapping a Quiescent Black Hole



Full Map is encoded in the waves

Some Numbers for LISA

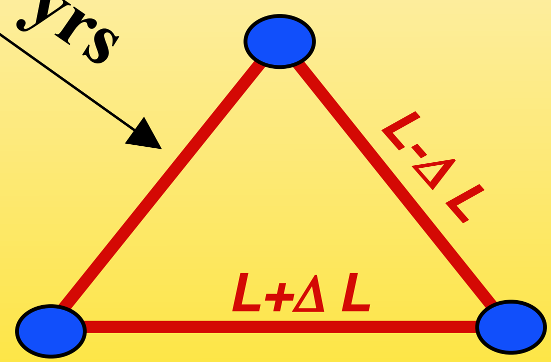
5 million km = 20 light sec



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

3 billion light yrs

$h \sim 10^{-20}$

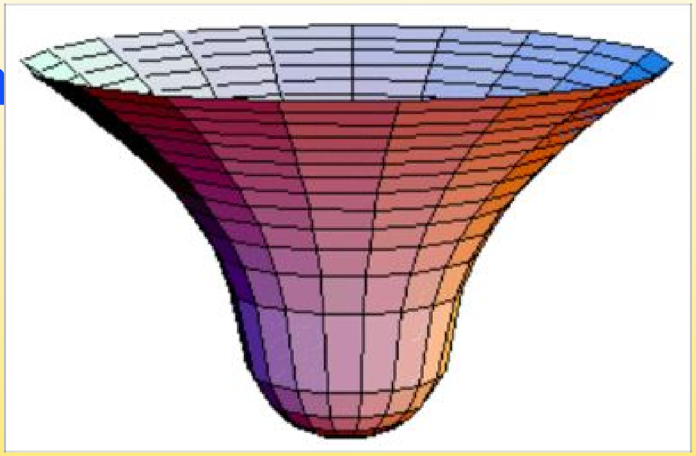


L=5 million km
$\Delta L = 10^{-8}$ cm

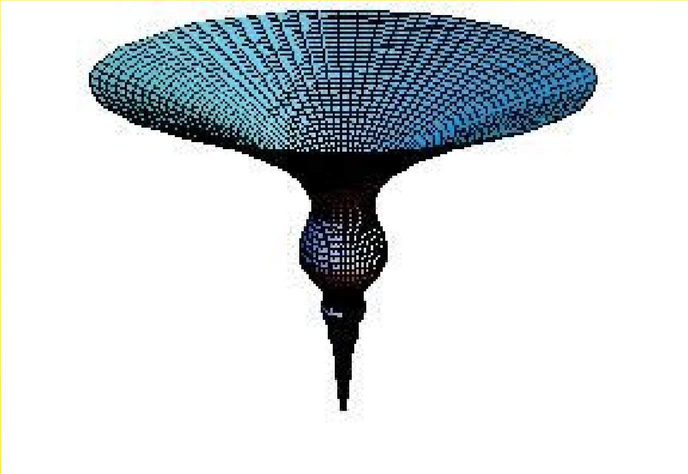
What if the Map is Not that of a Black Hole?

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

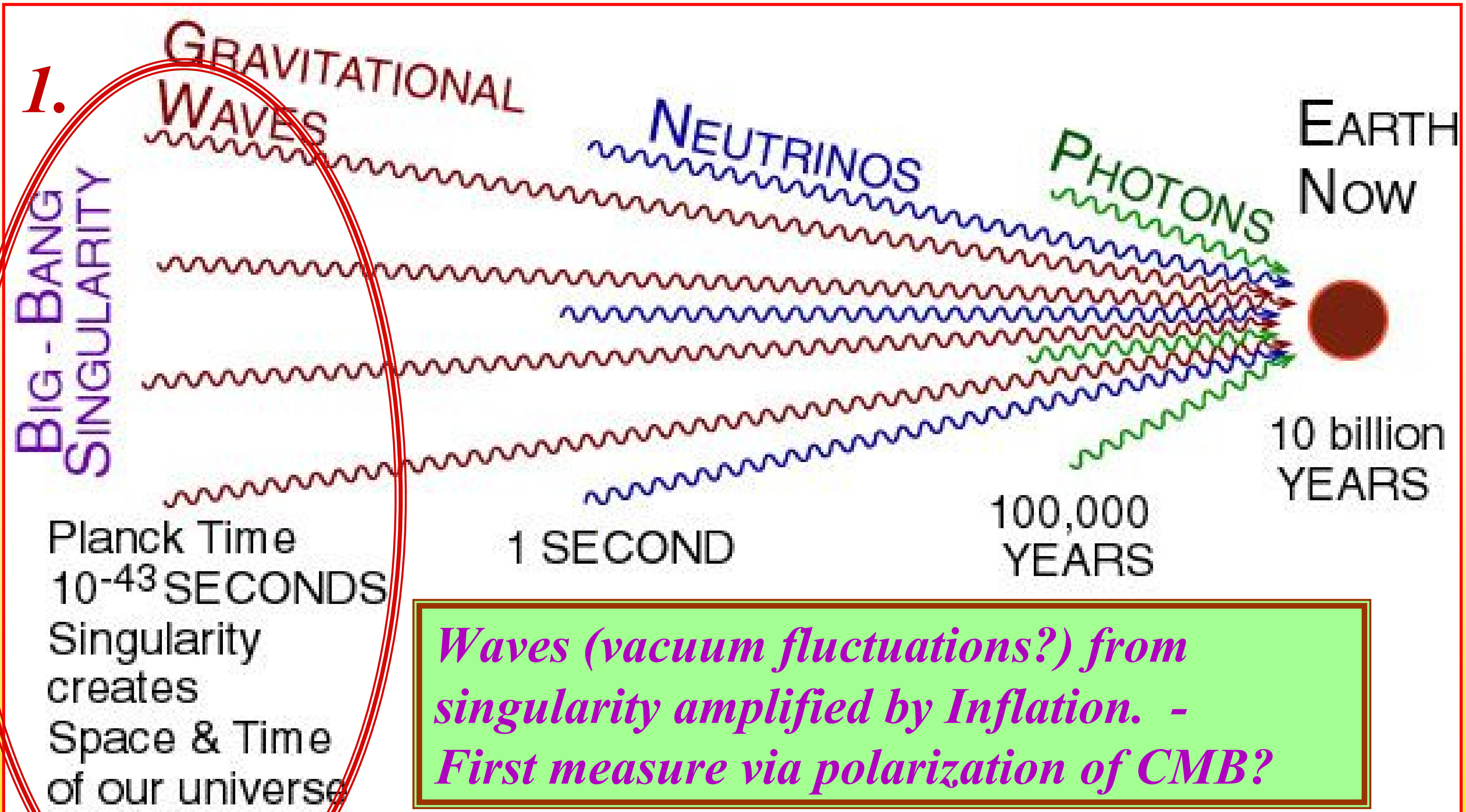


- Naked Singularities



Over the Next 40 Years

Probe the Initial Second of Universe's Life

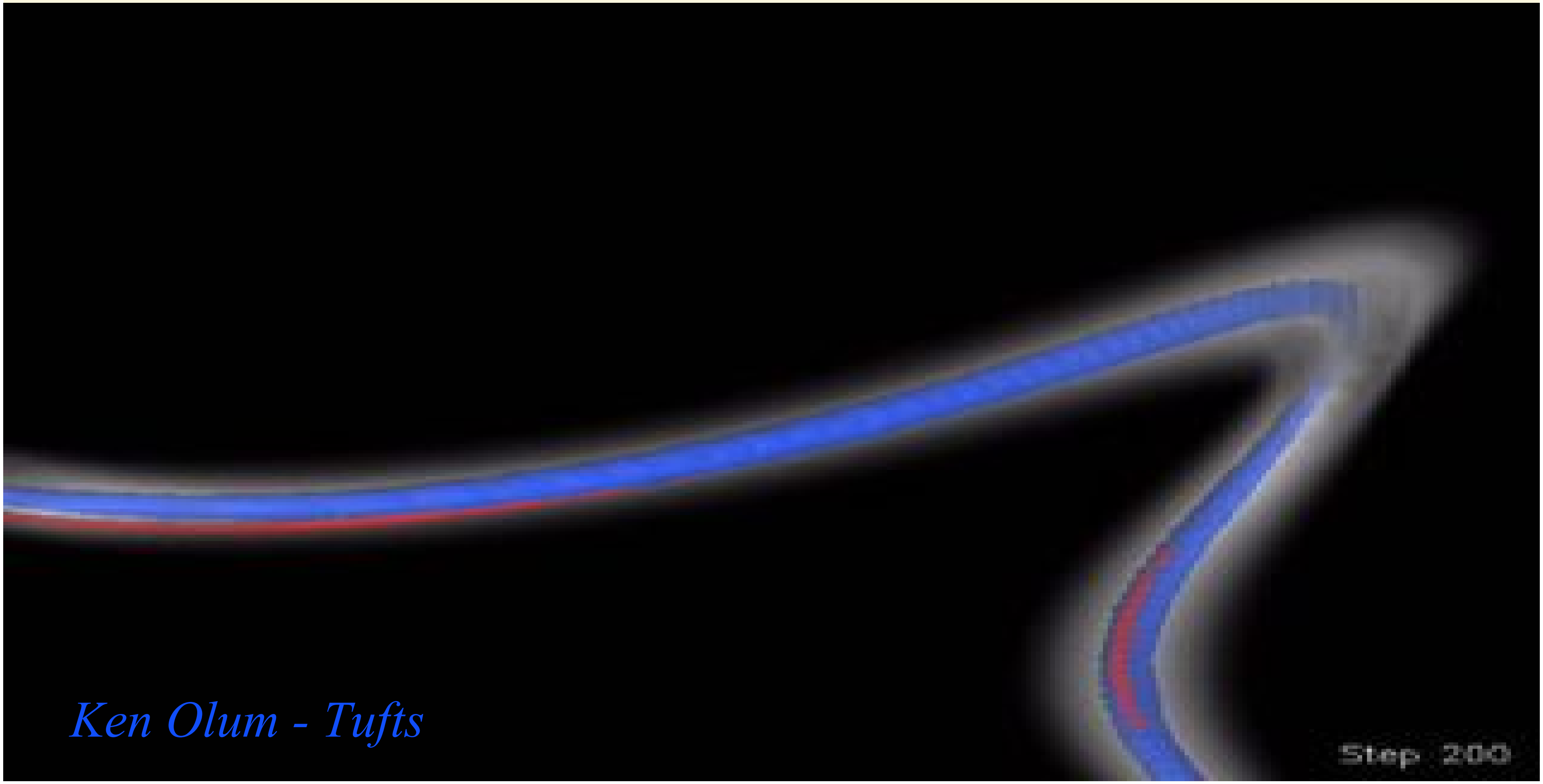


Waves (vacuum fluctuations?) from singularity amplified by Inflation. - First measure via polarization of CMB?

Rich Violence in First Second -- Four Examples

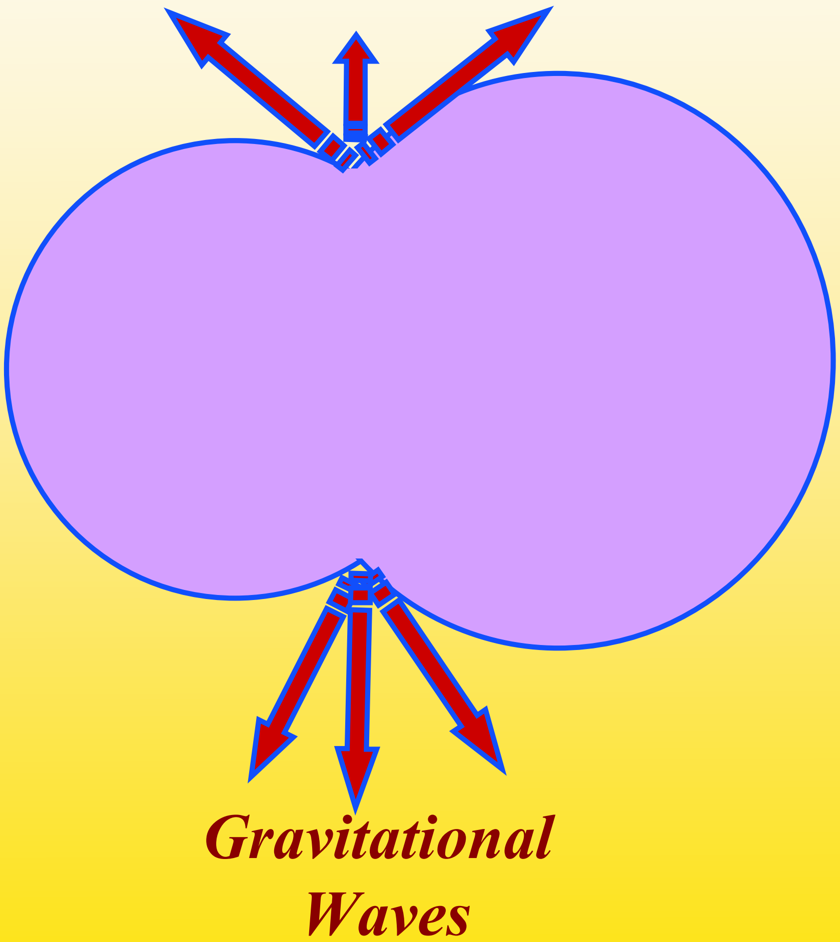
2. Cosmic Strings

- ***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]:**
  - » **Phase transition: Electroweak force -> EM + Weak**

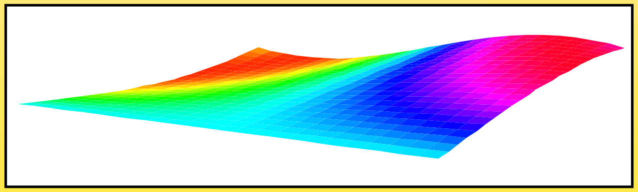


Waves are in LISA's domain

LIGO: Probe physics at age ~ 10^{-22} seconds [kT~10^{5} TeV]

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