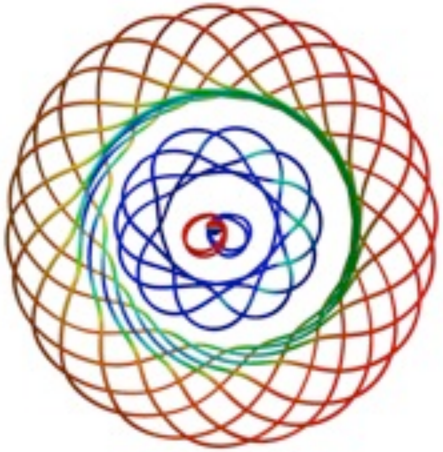
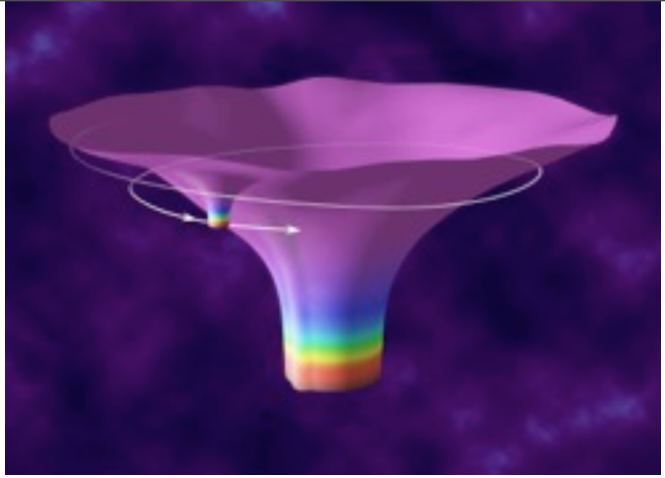
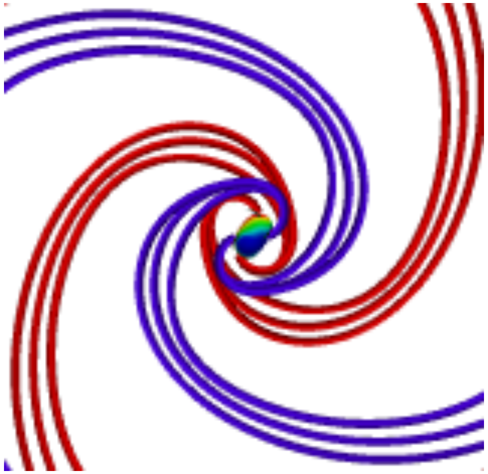
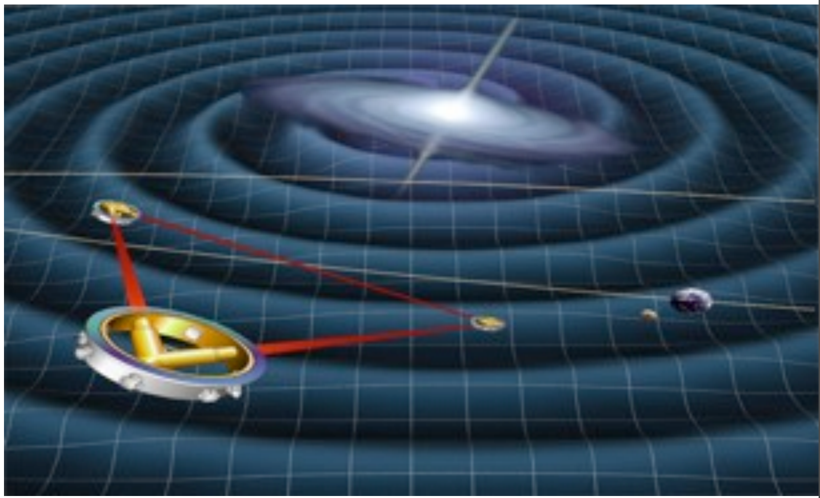




Black Hole Research: A New Golden Age

Kip Thorne

7th International Conference on Gravitation and Cosmology

Goa, India, 15 December 2011

First Golden Age of Black-Hole Research
1963 - 1977

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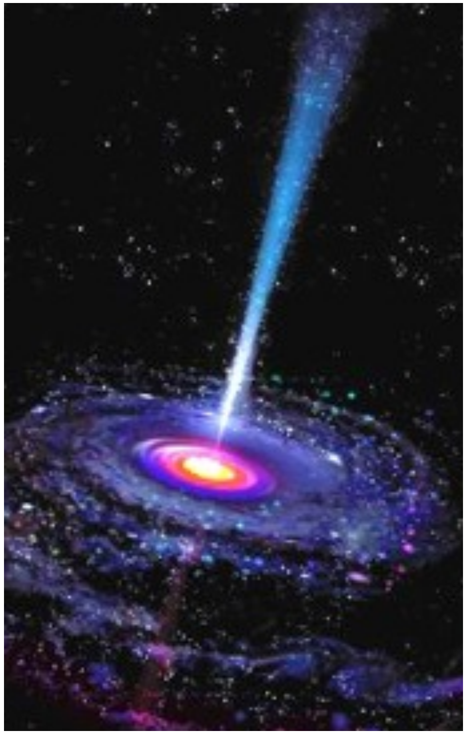

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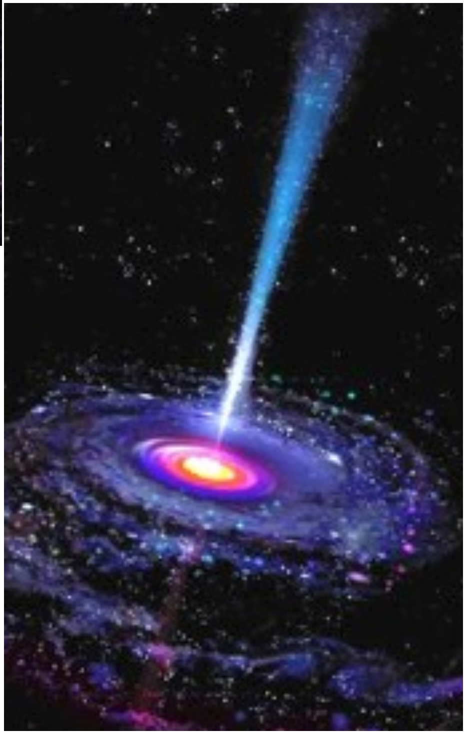

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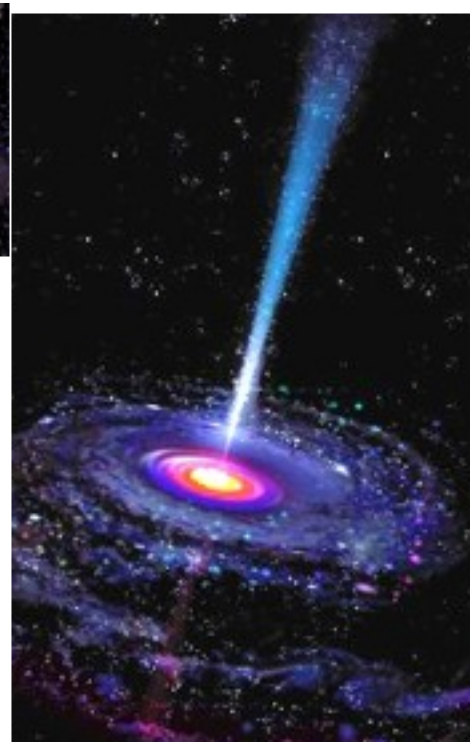

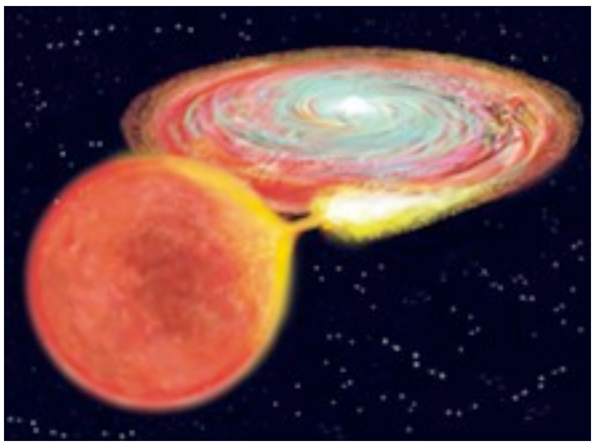

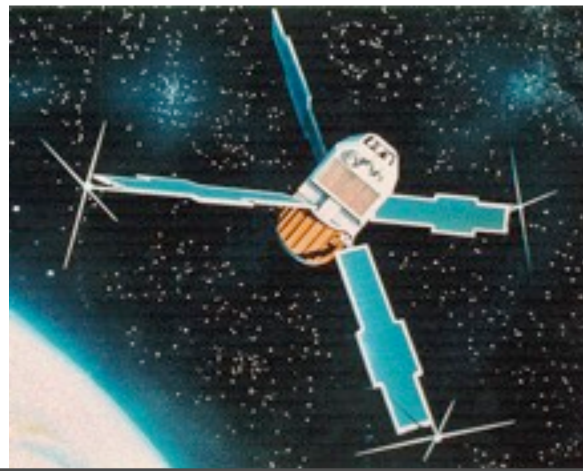

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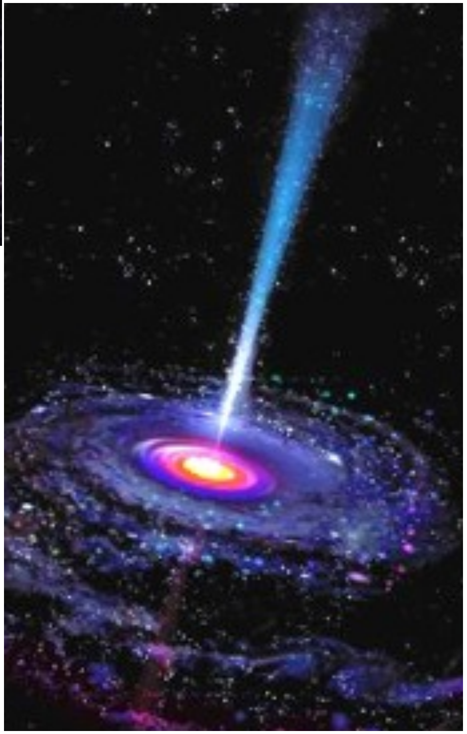

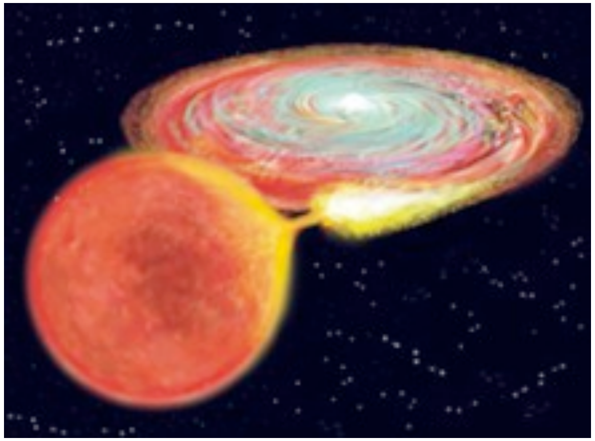

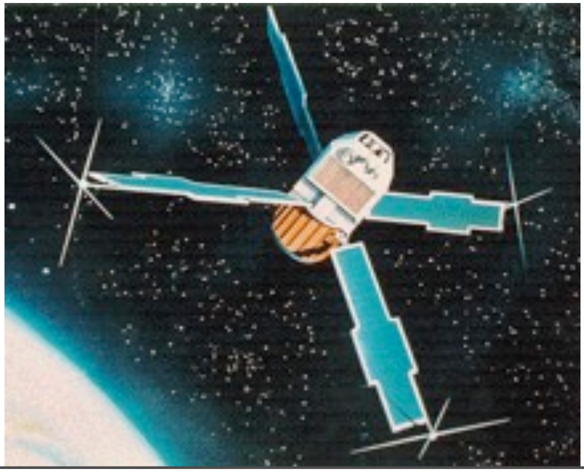

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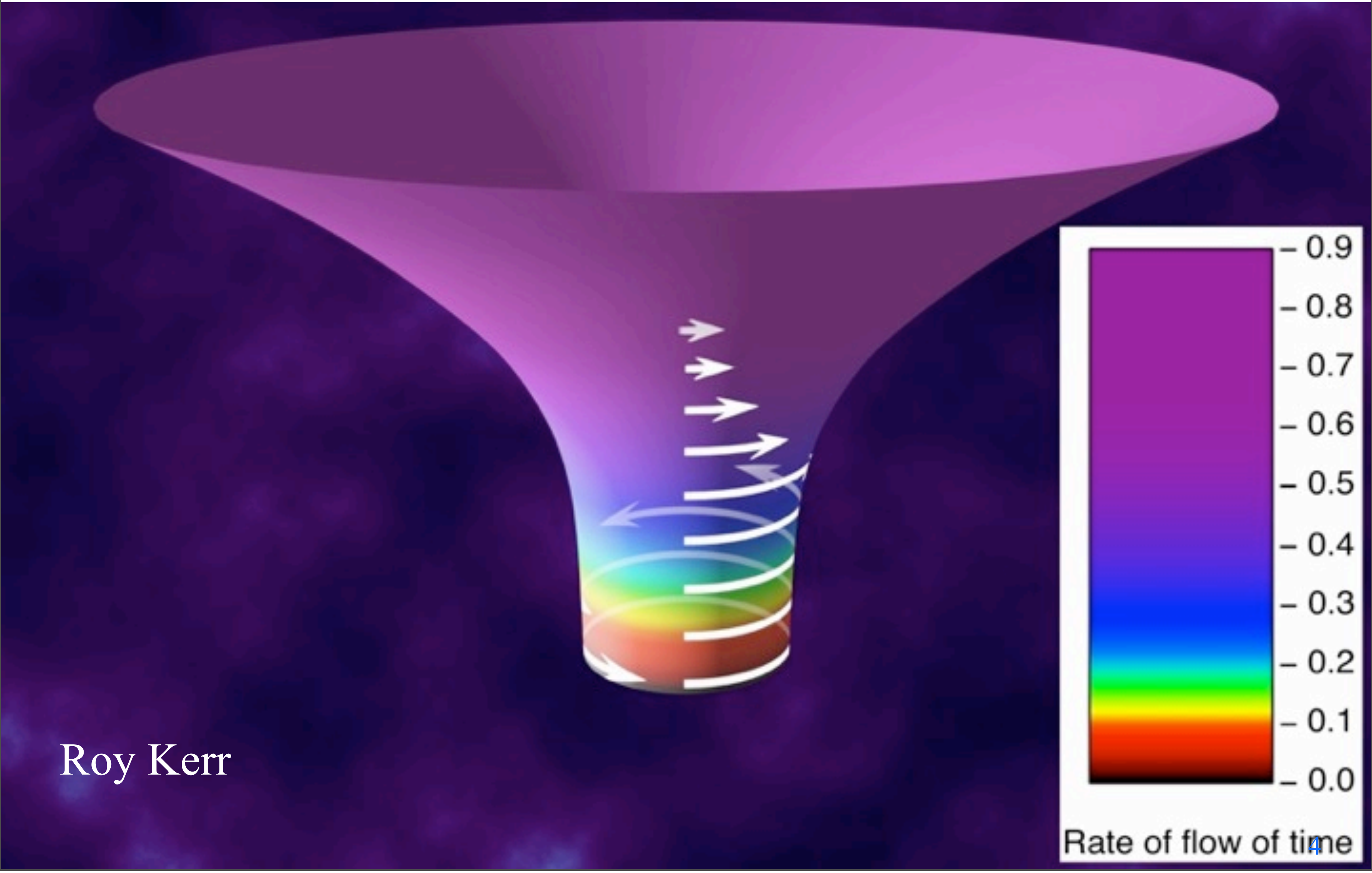
- Black hole thermodynamics (Hawking, Bekenstein)
  - Hawking radiation; temperature $T \sim \kappa$, entropy $S \sim A$

Quiescent Black Hole: Embedding Diagram



Roy Kerr

Black Hole Status in 2009

Object	Understood?	Observed?

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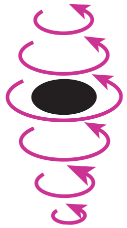
Quiescent Black Hole		**Yes**	**No**

Black Hole Status in 2009

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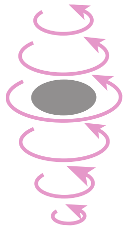
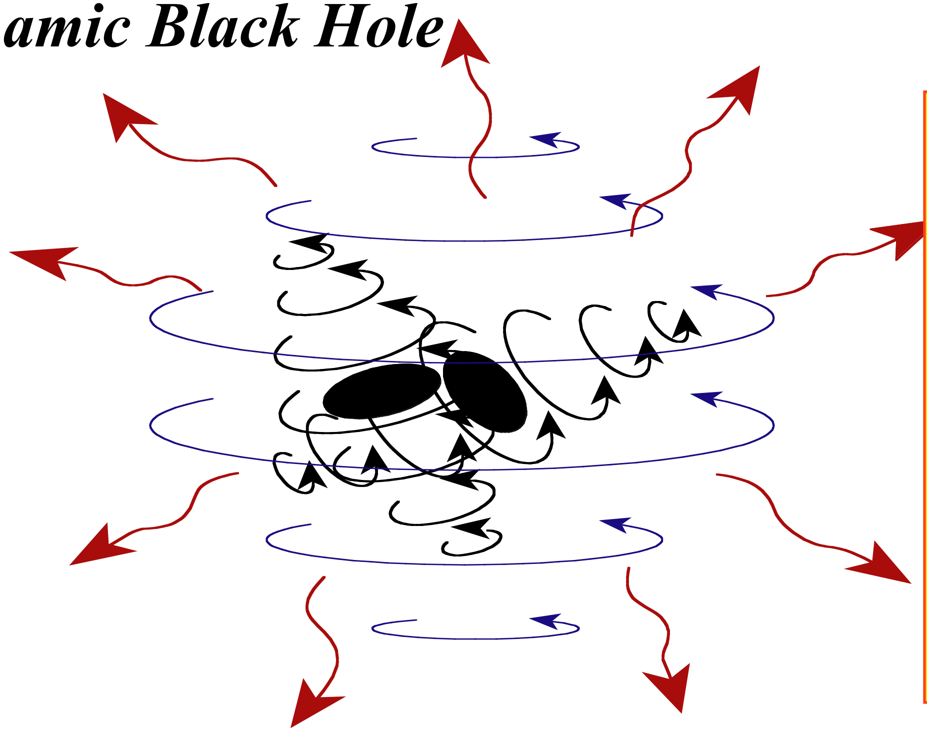
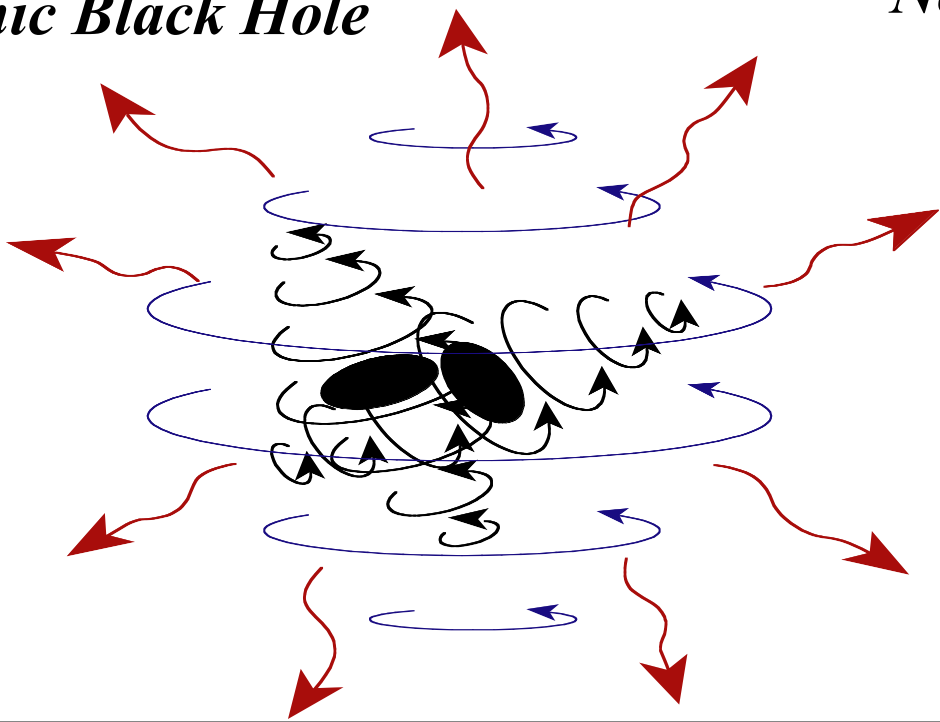
Quiescent Black Hole 	Yes	No
Wildly dynamic Black Hole	*No* *	*No*



* except for some very important theorems:
* Penrose: singularity at center
* Hawking: Area Increase

Black Hole Status in 2009

	Understood?	Observed?
	Yes	**No**
Wildly dynamic Black Hole	***No*** *	***No***



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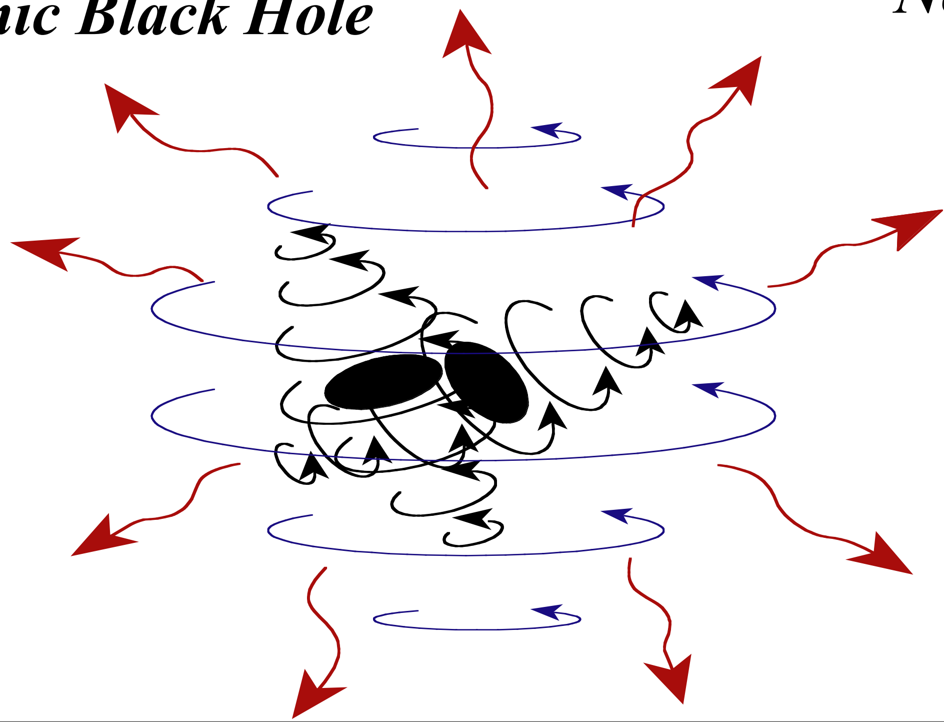

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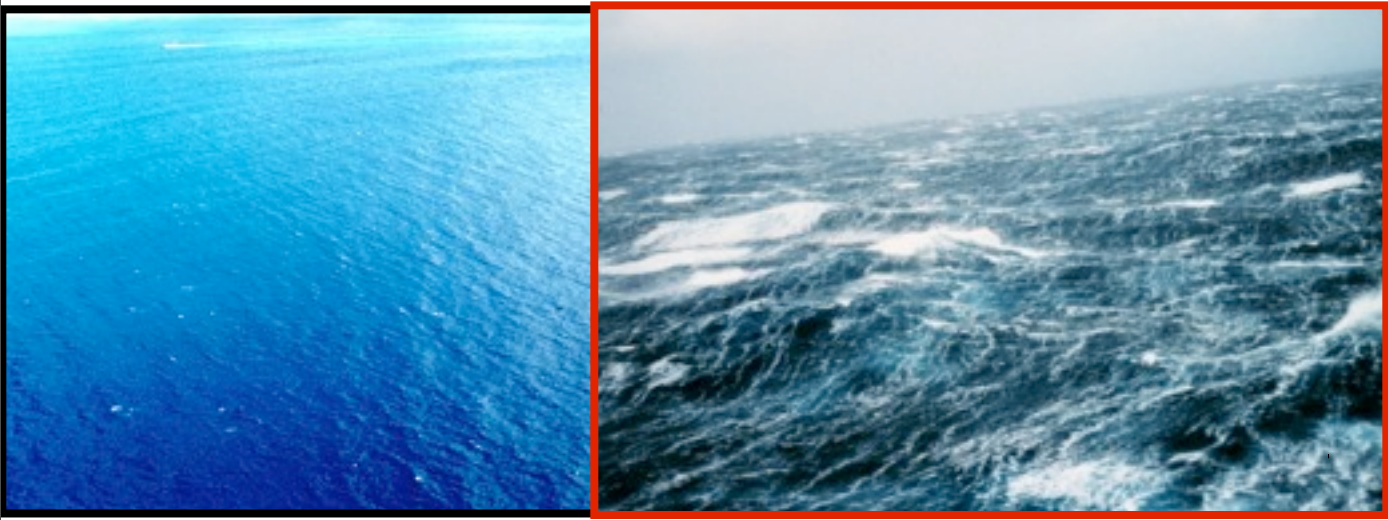

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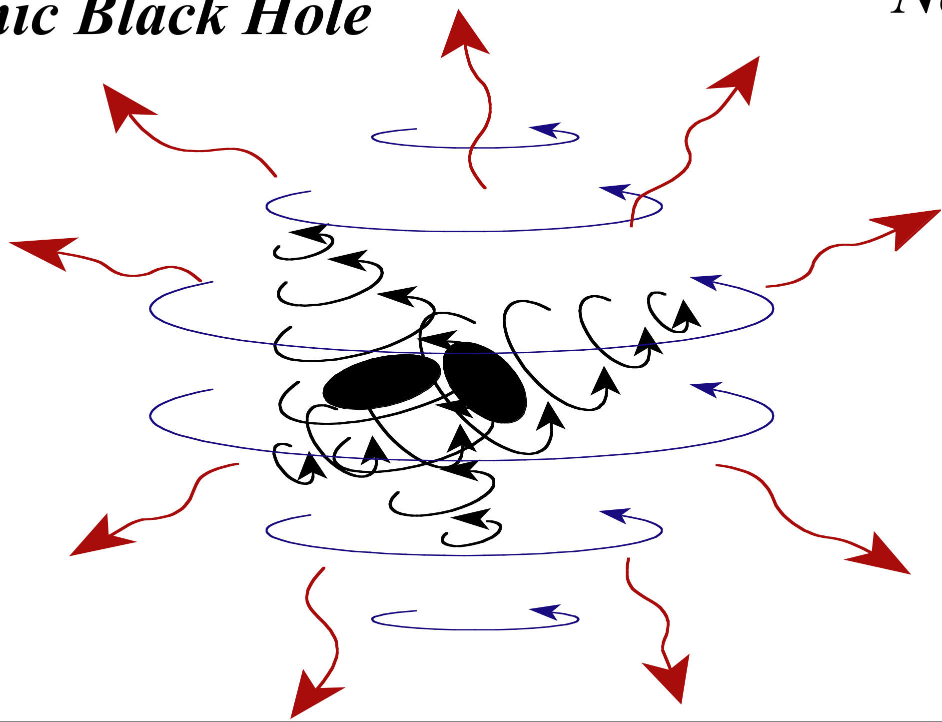

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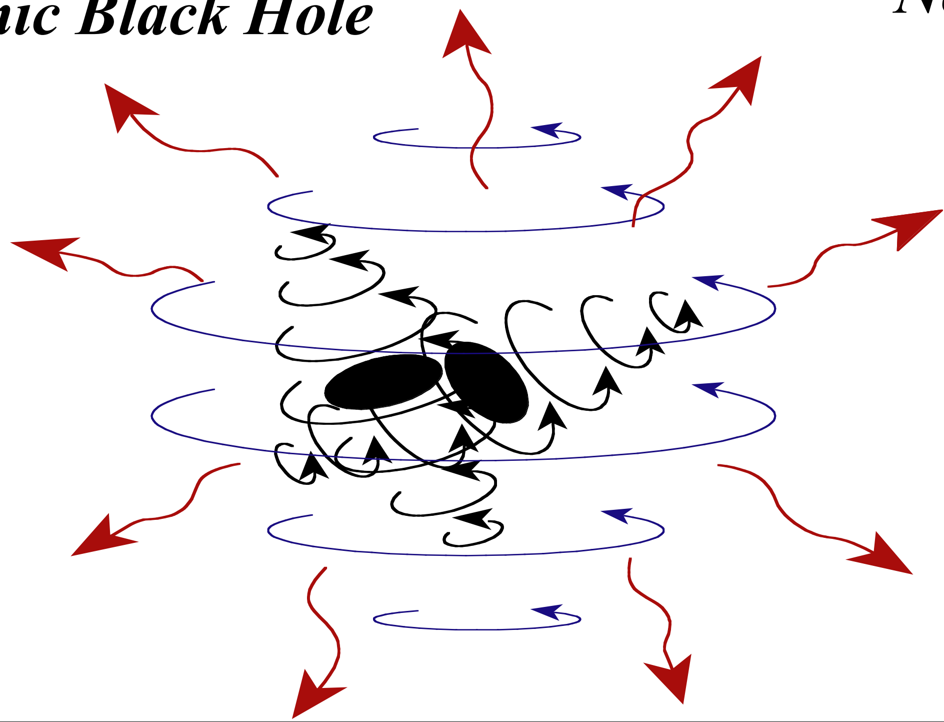

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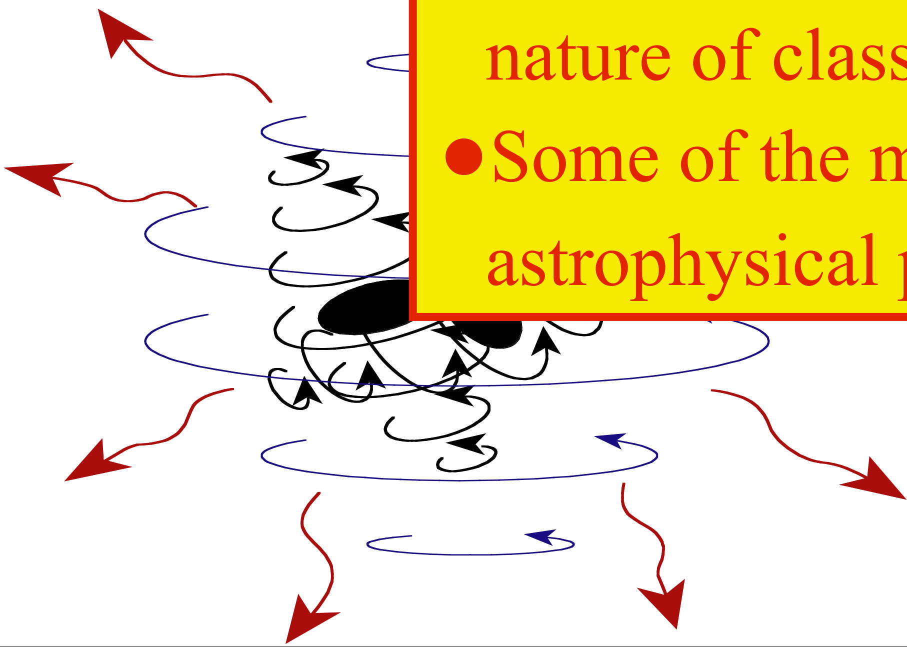

- Some of the deepest issues in nature of classical spacetime
- Some of the most interesting astrophysical phenomena

A New Golden Age: 2010 - ??

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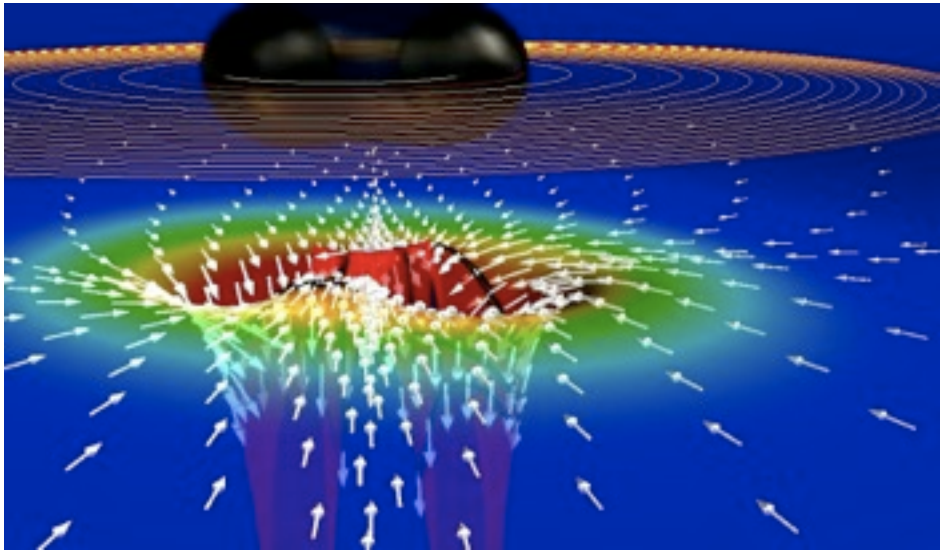
- Driven by ***Numerical Simulations*** of Colliding Black Holes



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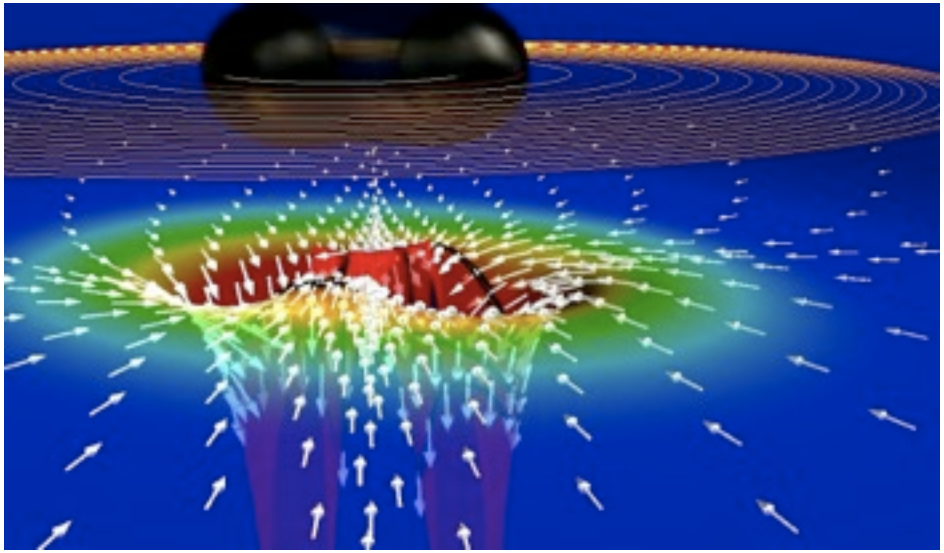

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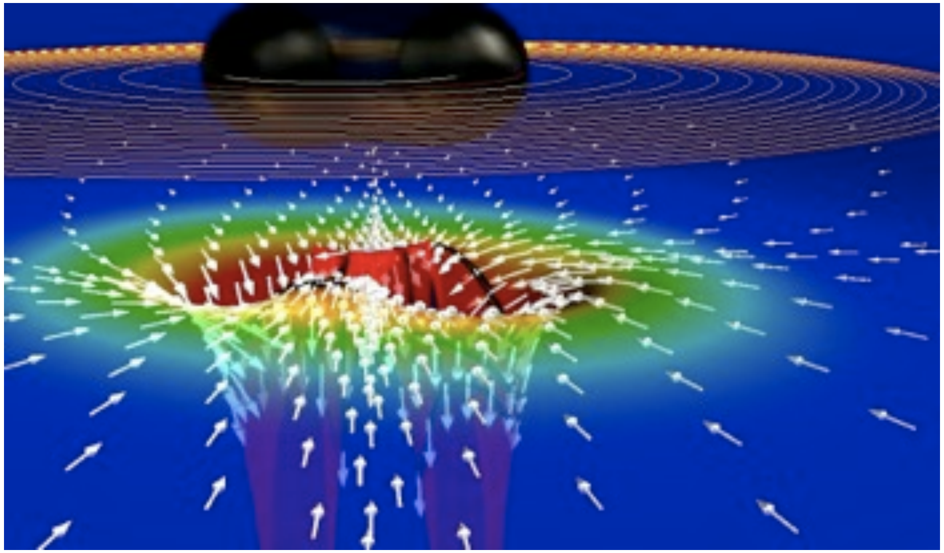

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Also:
Research into quantum black holes
- connections to string theory, LHC physics, ...

I will not discuss

Numerical Simulations
(numerical relativity)

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- Under development since 1960s

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(numerical relativity)

- **Under development since 1960s**
- **Big success in past several years**
  - » ***beginning to teach us about the "nonlinear dynamics" of curved spacetime***

- John Wheeler's GEOMETRODYNAMICS

Numerical Relativity: How is it Done?

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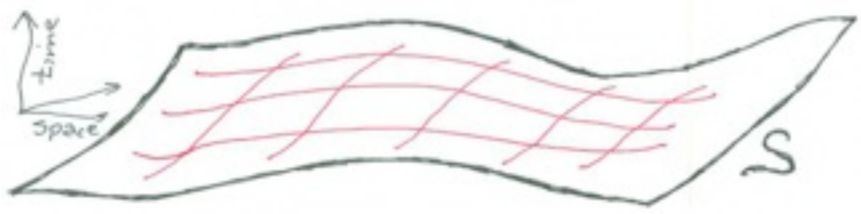

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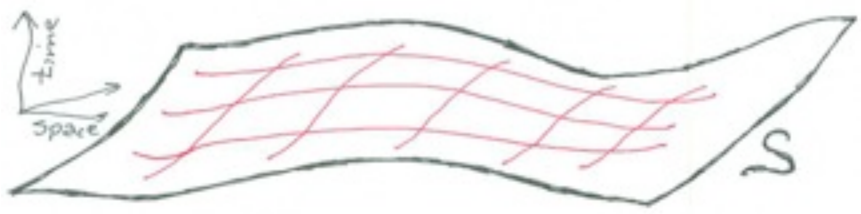

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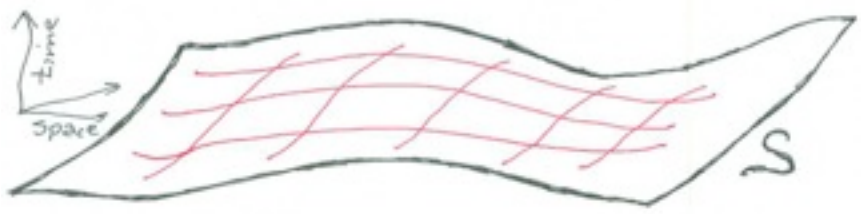

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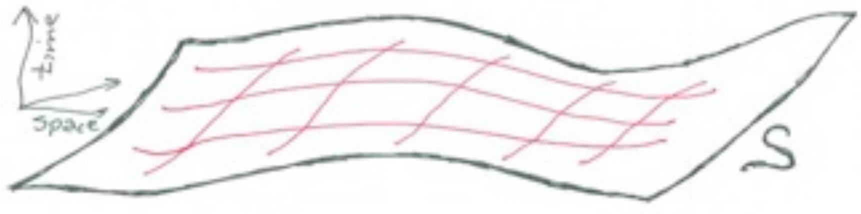

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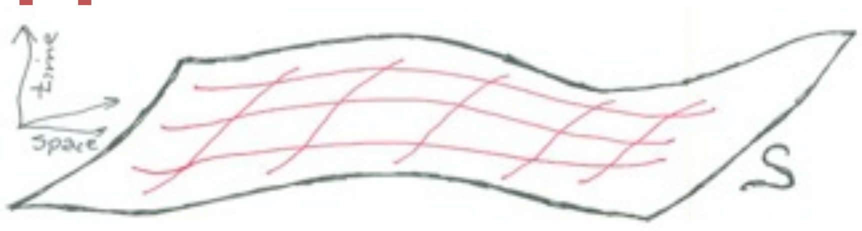
$$ds^2 = -\alpha^2\, dt^2 + g_{ij}\,(dx^i - \beta^i\, dt)\,(dx^j - \beta^j dt)$$

Two Mature Approaches



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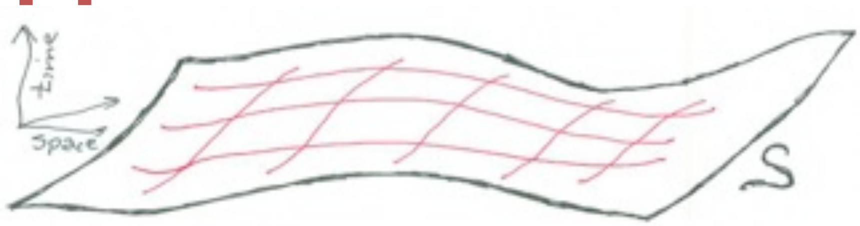

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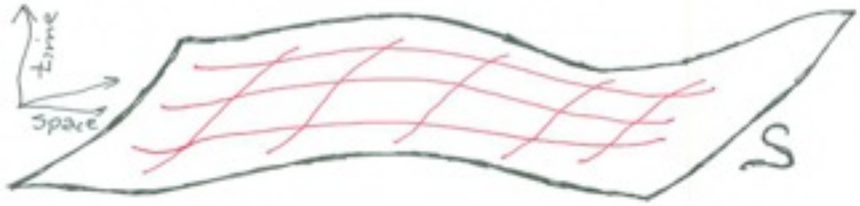

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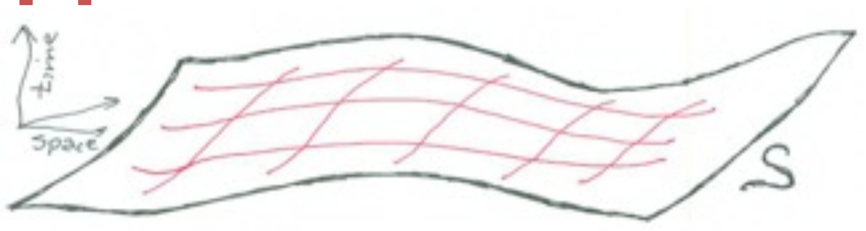

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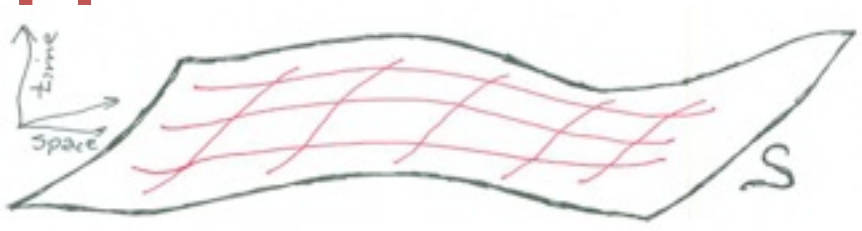

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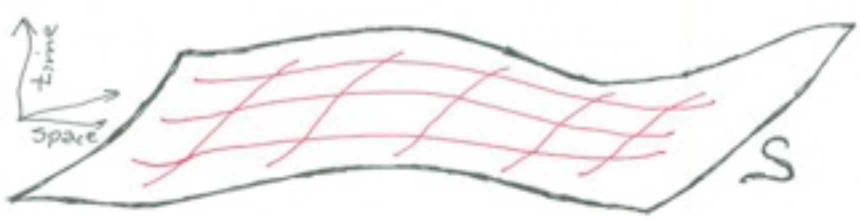

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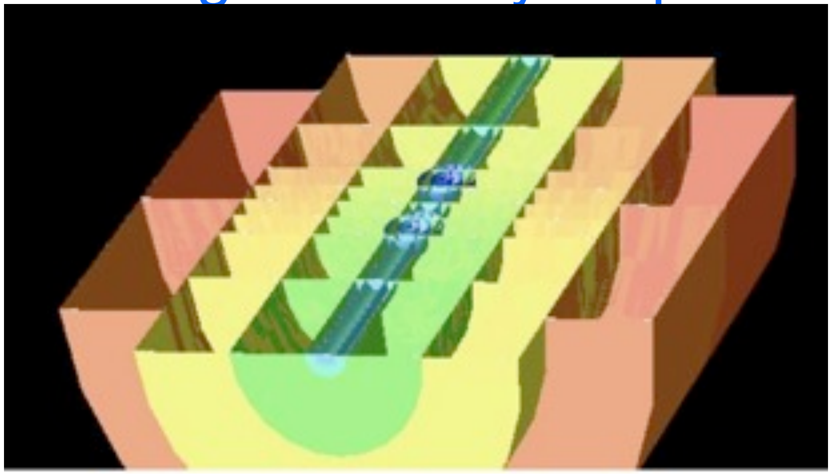
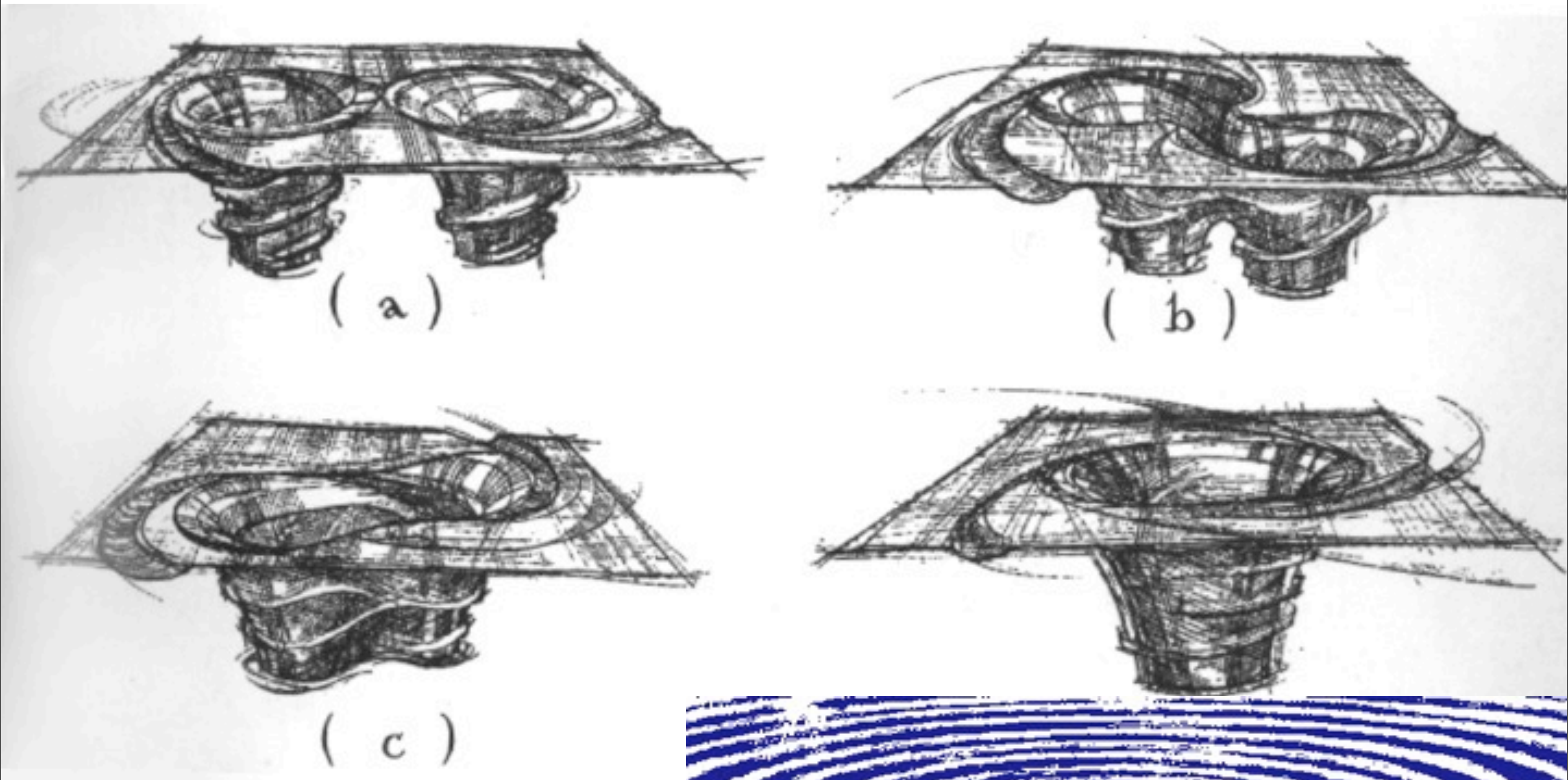
  - » Explore geometrodynamics
  - » Gravitational waveforms - very high accuracy; huge numbers.

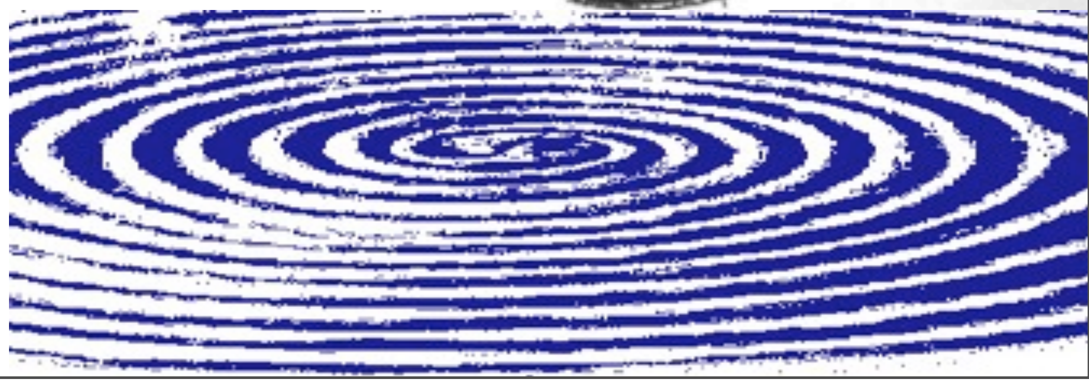


Numerical Relativity Research Groups

- ***Simulating Generic Black-Hole Binaries:***
  - » Princeton (Pretorius),
  - » Rochester Institute of Technology (Campanelli, ...),
  - » Goddard Spaceflight Center (Centrella, ...),
  - » U. Illinois (Shapiro, ...),
  - » Albert Einstein Instititute & LSU (Rezolla, Pollney, ...),
  - » U. Jena (Bruegmann, ...),
  - » Georgia Tech (Laguna, ...),
  - » U. Texas (Matzner, ...),
  - » Perimeter/Guelph (Lehner, ...)
  - » U. Maryland (Tiglio, ...),
  - » Florida Atlantic U. (Tichy, ...),
  - » Barcelona (Sperhake, ...),
  - » Cornell/Caltech/CITA (Teukolsky, Kidder, Scheel, Pfeiffer, Szilagyi), ...

Black Hole / Black Hole Collisions:
The most violent events in the Universe





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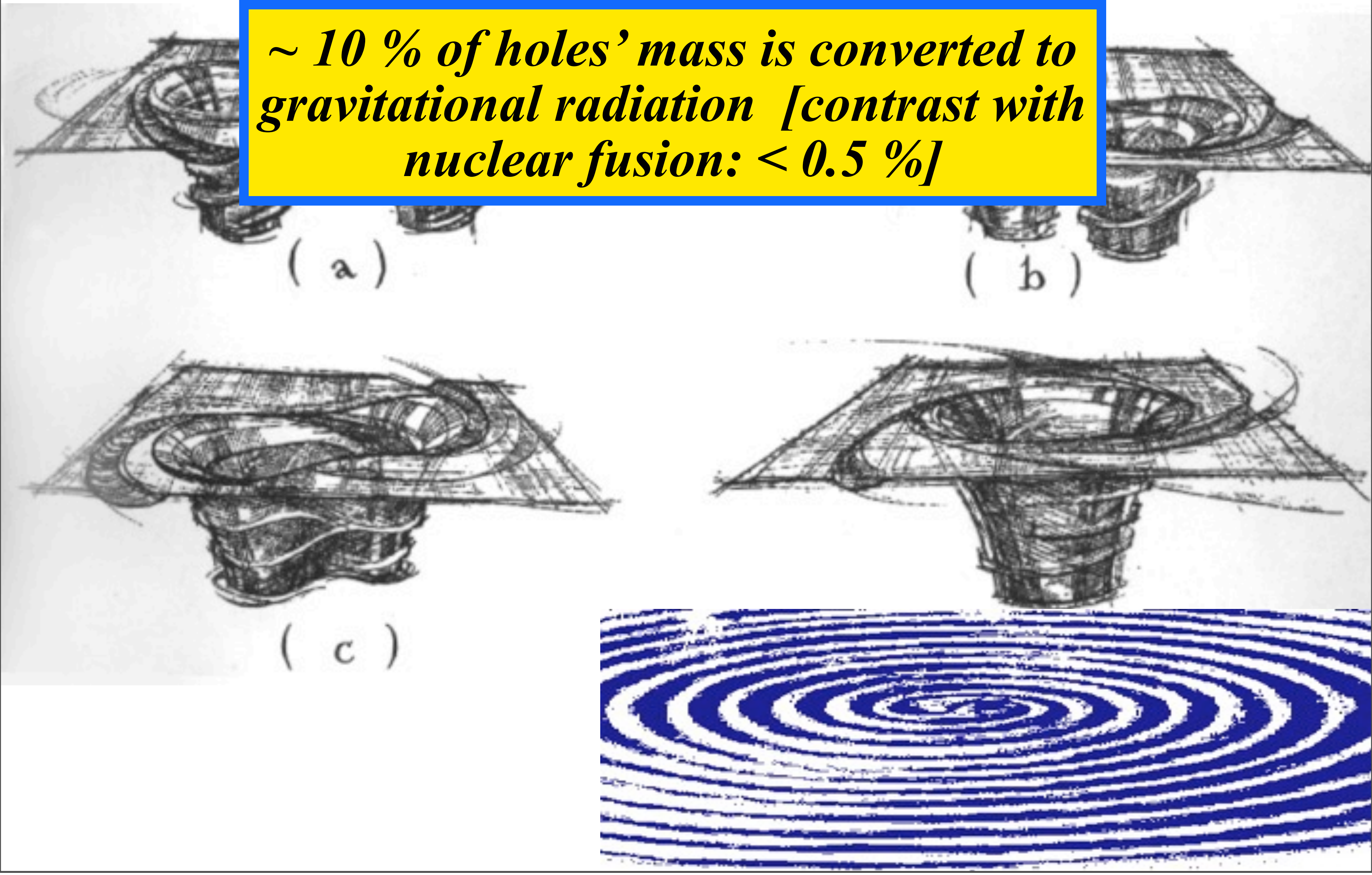
~ 10 % of holes' mass is converted to gravitational radiation [contrast with nuclear fusion: < 0.5 %]



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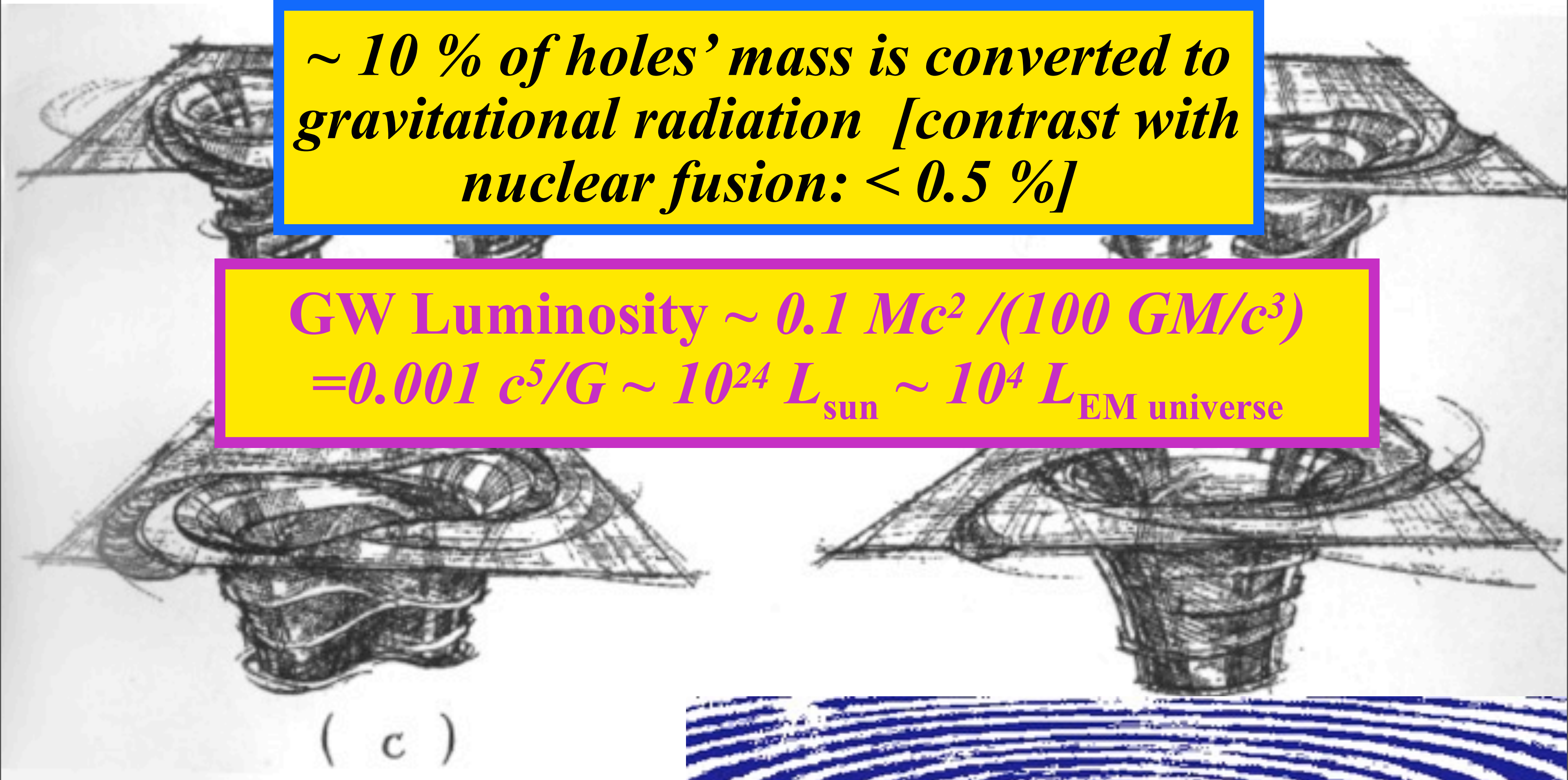

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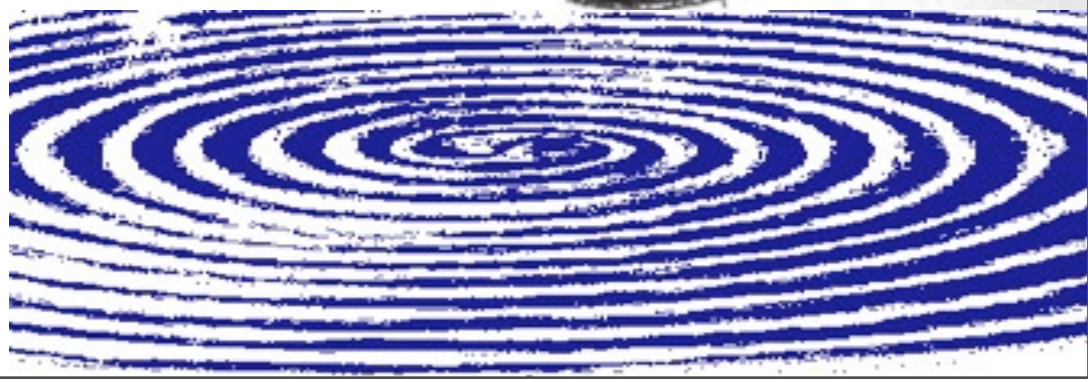
GW Luminosity ~ *$0.1\, Mc^2 /(100\, GM/c^3)$*
$=0.001\, c^5/G \sim 10^{24}\, L_{\rm sun} \sim 10^4\, L_{\rm EM\ universe}$



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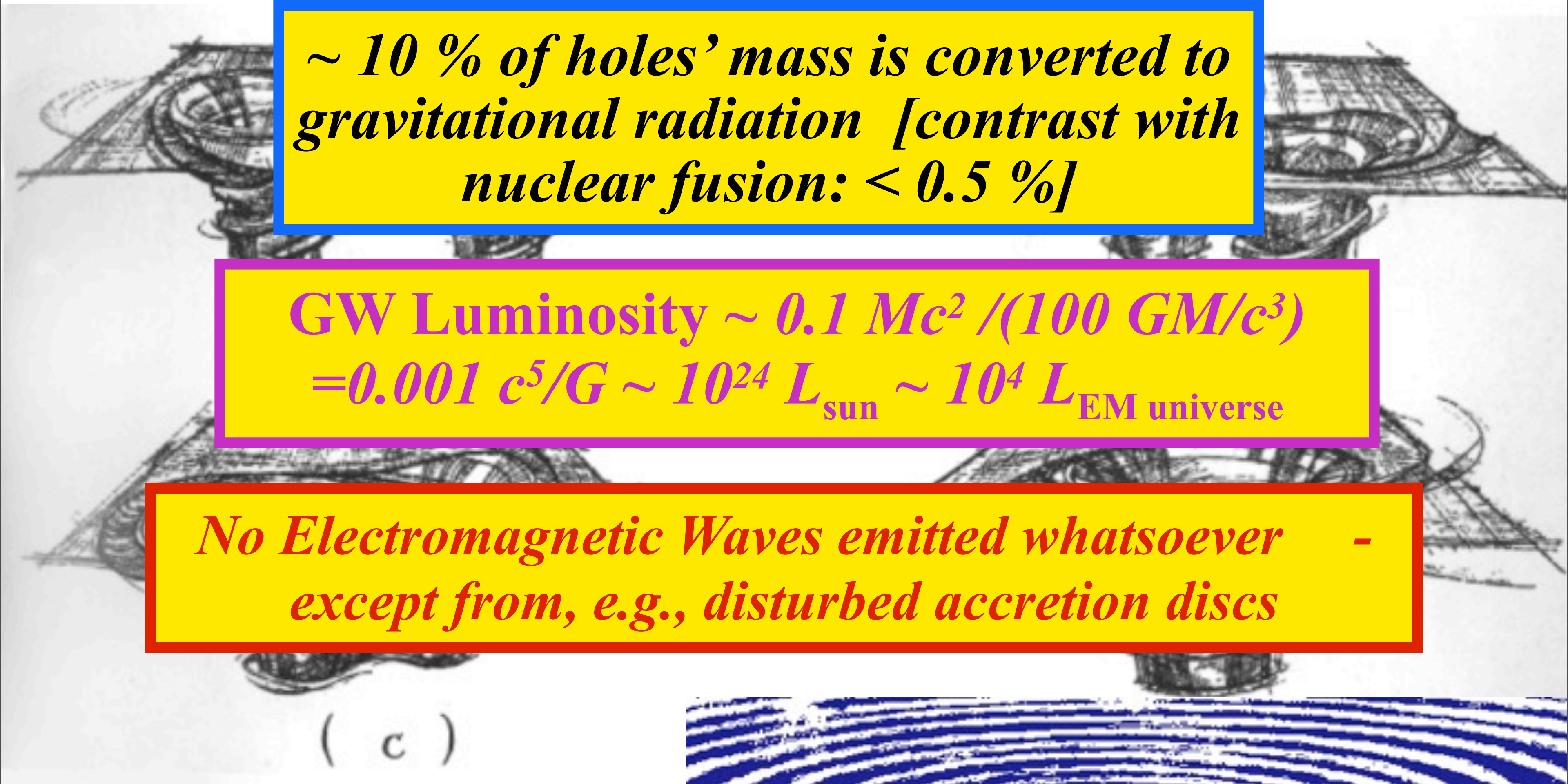

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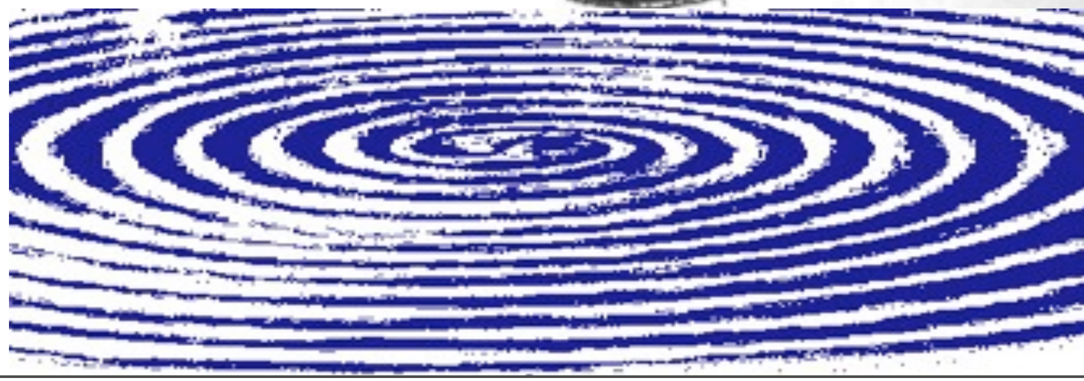
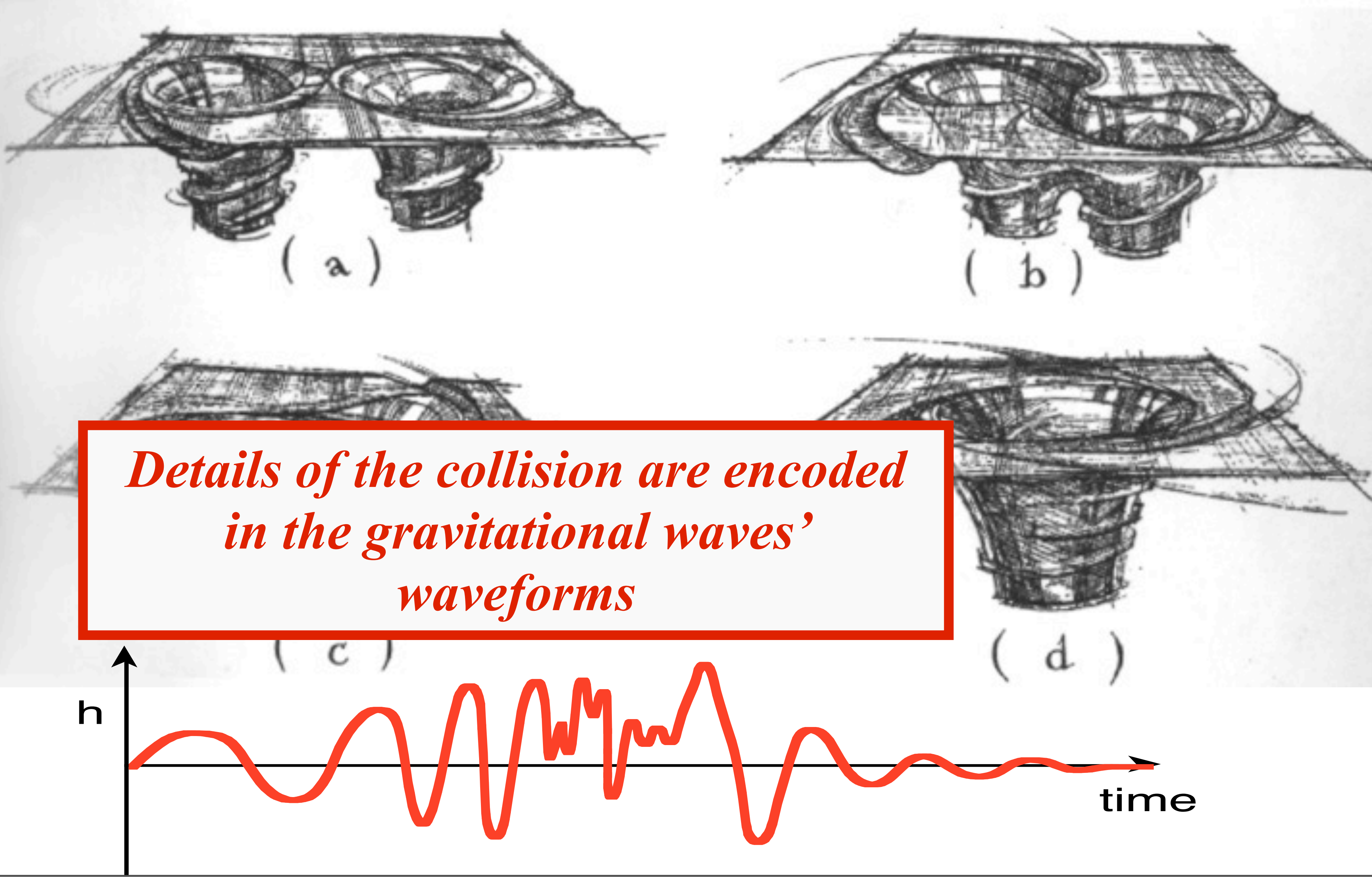
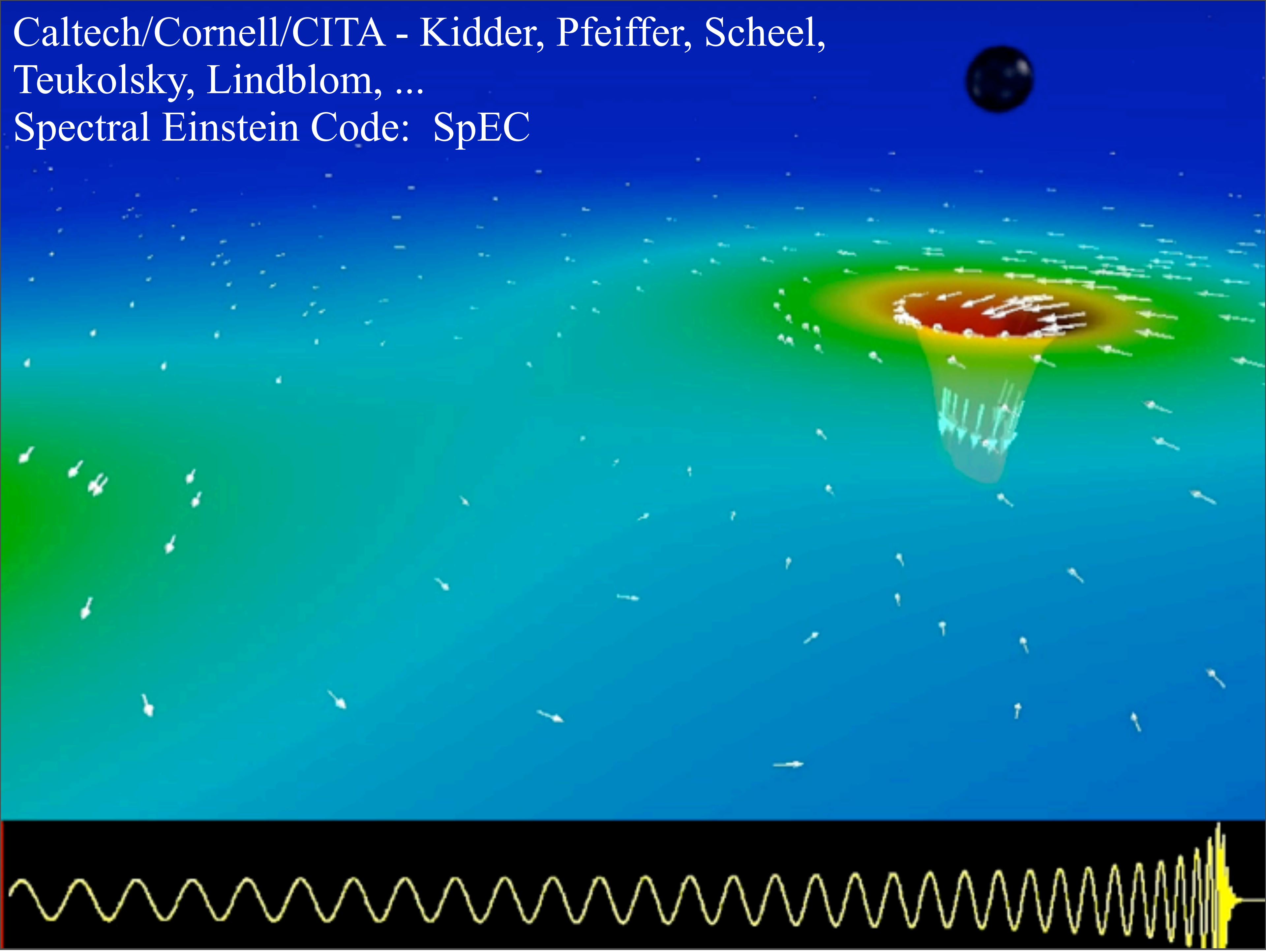
No Electromagnetic Waves emitted whatsoever - except from, e.g., disturbed accretion discs



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



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


Caltech/Cornell/CITA - Kidder, Pfeiffer, Scheel,
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Spectral Einstein Code: SpEC

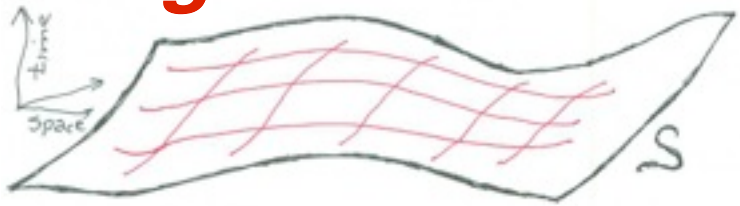
A New Way to Visualize the Curvature of Spacetime

Rob Owen, Jeandrew Brink, Yanbei Chen, Jeff Kaplan, Geoffrey Lovelace, Keith Matthews, David Nichols, Mark Scheel, Fan Zhang, Aaron Zimmerman, and Kip Thorne

Caltech, Cornell, and NiTheP (South Africa)

Physical Review Letters , **106,** 151101 (2011)

Tidal Field & Frame-Drag Field



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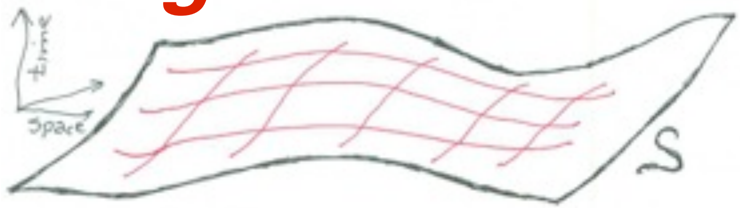
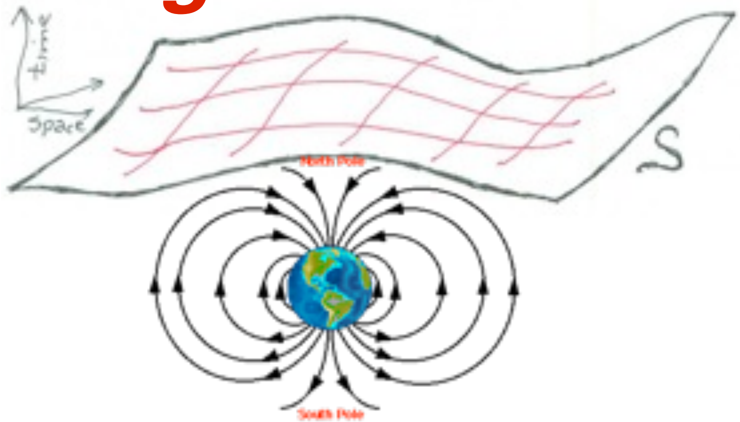


- Slice spacetime into space plus time

Tidal Field* & *Frame-Drag Field



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- EM field tensor ***F*** → Electric field and magnetic field; visualize with field lines

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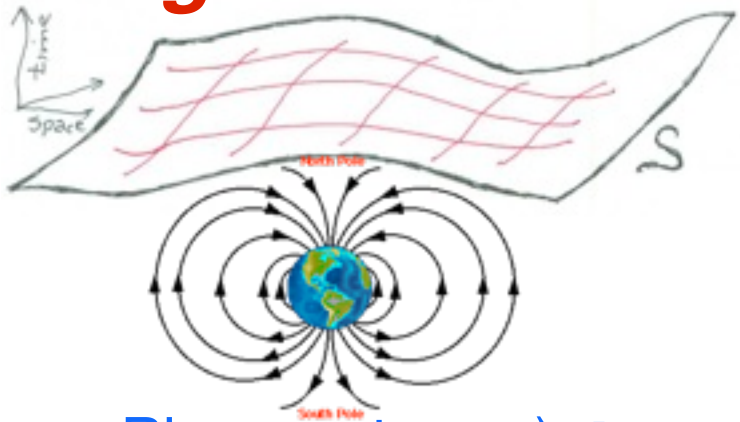
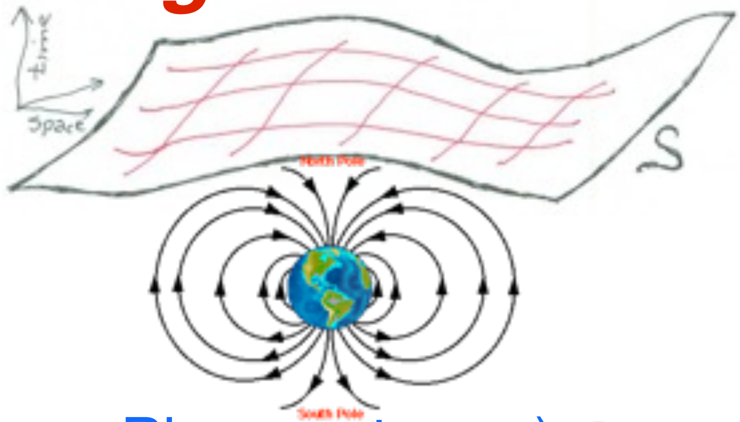


- Weyl curvature tensor (in vacuum, same as Riemann tensor) ➔ **"electric" part** $\mathcal{E}_{jk}$ and **"magnetic" part** $\mathcal{B}_{jk}$

$$\mathcal{E}_{jk} = C_{0j0k} \qquad \mathcal{B}_{jk} = \frac{1}{2}\epsilon_{jpq}C^{pq}{}_{k0}$$

Symmetric, Trace-Free (STF) tensors

Tidal Field & Frame-Drag Field



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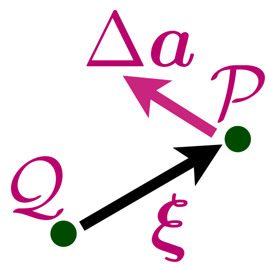
- $\mathcal{E}_{jk}$ describes **tidal accelerations** $\Delta a_j = -\mathcal{E}_{jk}\,\xi^k$



We call $\mathcal{E}_{jk}$ the ***tidal field***

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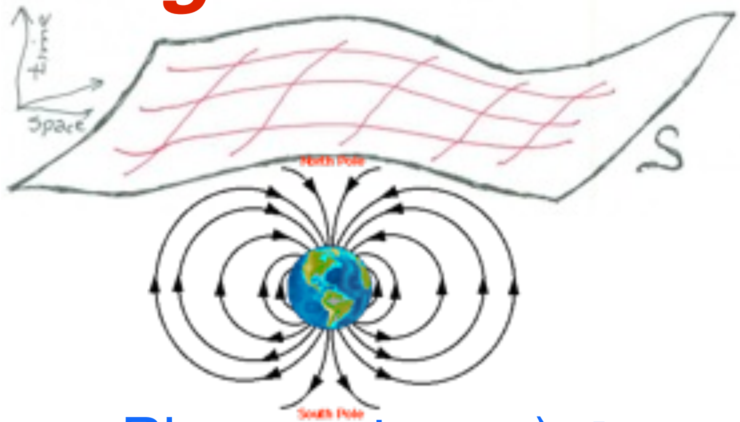

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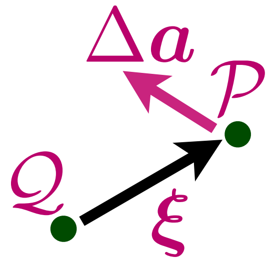

We call $\mathcal{E}_{jk}$ the ***tidal field***

- $\mathcal{B}_{jk}$ describes **differential frame dragging**: Gyroscope at P precesses relative to inertial frames at Q with angular velocity

$$\Delta\Omega_j = \mathcal{B}_{jk}\xi^k$$

We call $\mathcal{B}_{jk}$ the ***frame-drag field***

Tendex Lines and their Tendicities

- Any **STF tensor** is completely characterized by **three orthogonal eigenvectors**, and their **eigenvalues**.

- For the tidal field , the **integral curve of an eigenvector *n*** is called its *Tendex Line*; its **eigenvalue** is its *Tendicity*

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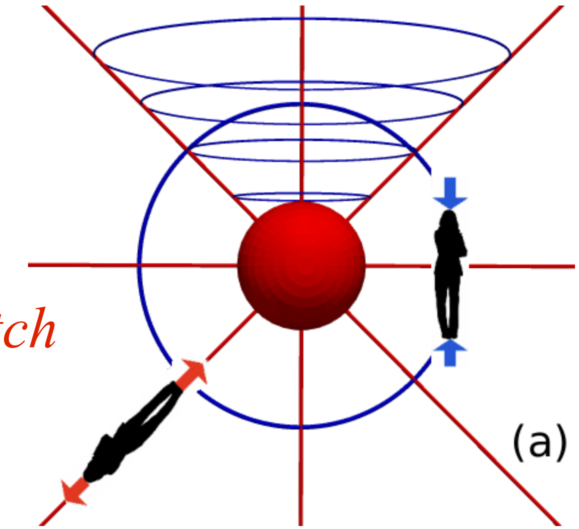
- Example: Tidal field above the Earth or outside a Nonrotating BH
  - » *eigenvector fields* $\mathbf{e}_{\hat{r}}, \ \mathbf{e}_{\hat{\theta}}, \ \mathbf{e}_{\hat{\phi}}$

Three sets of tendex lines, each with its own tendicity



$\mathcal{E}_{\hat{r}\hat{r}} < 0$ *tidal stretch*

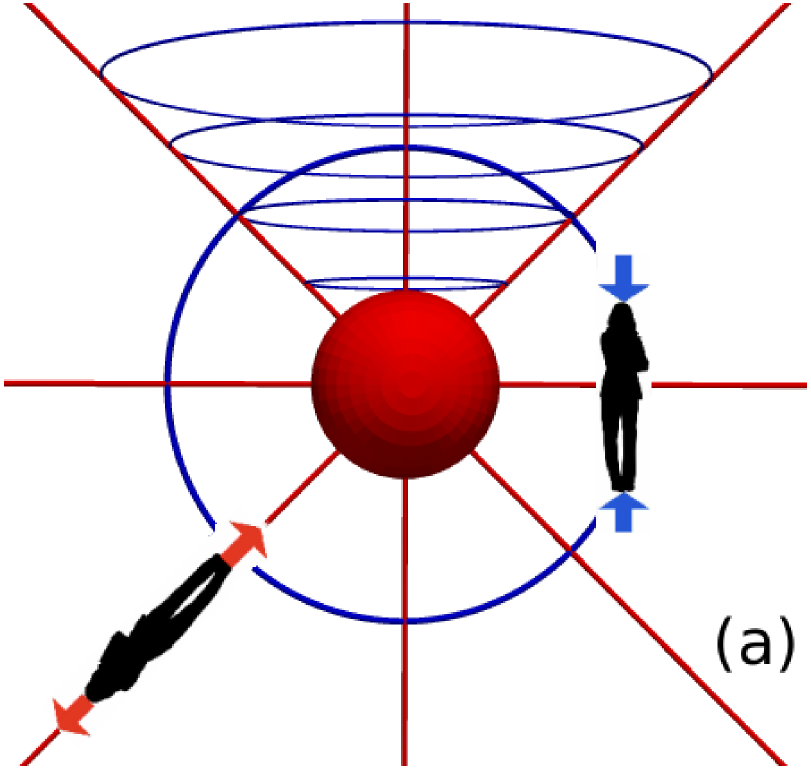
negative tendicity

$\mathcal{E}_{\hat{\theta}\hat{\theta}} > 0$ *tidal squeeze*

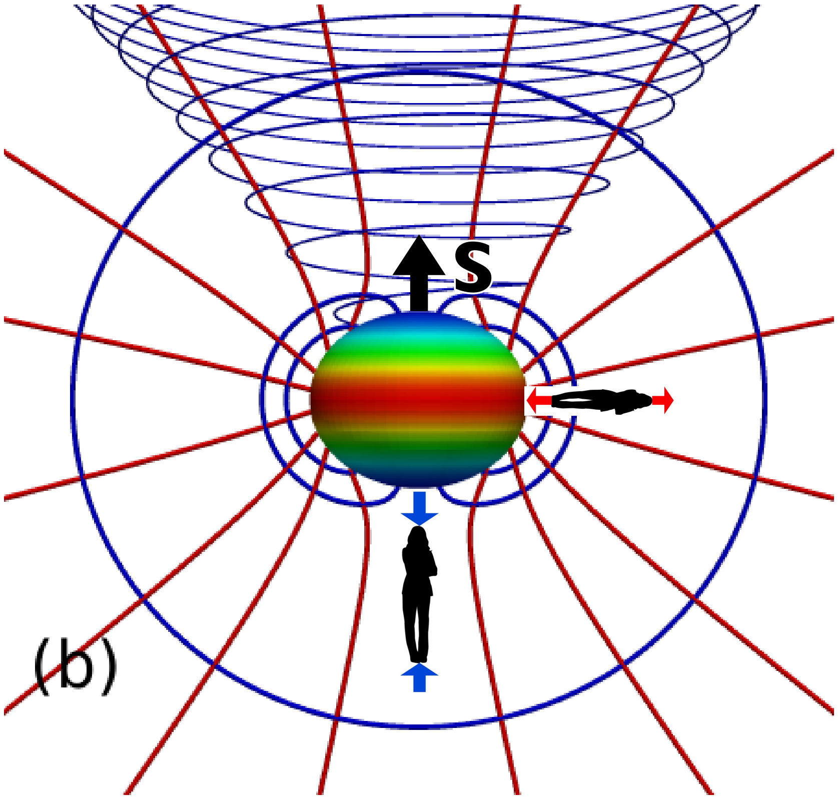
positive tendicity

Tendexes around Black Holes

Non-Spinning Black Hole



Fast Spinning Black Hole, a=0.95



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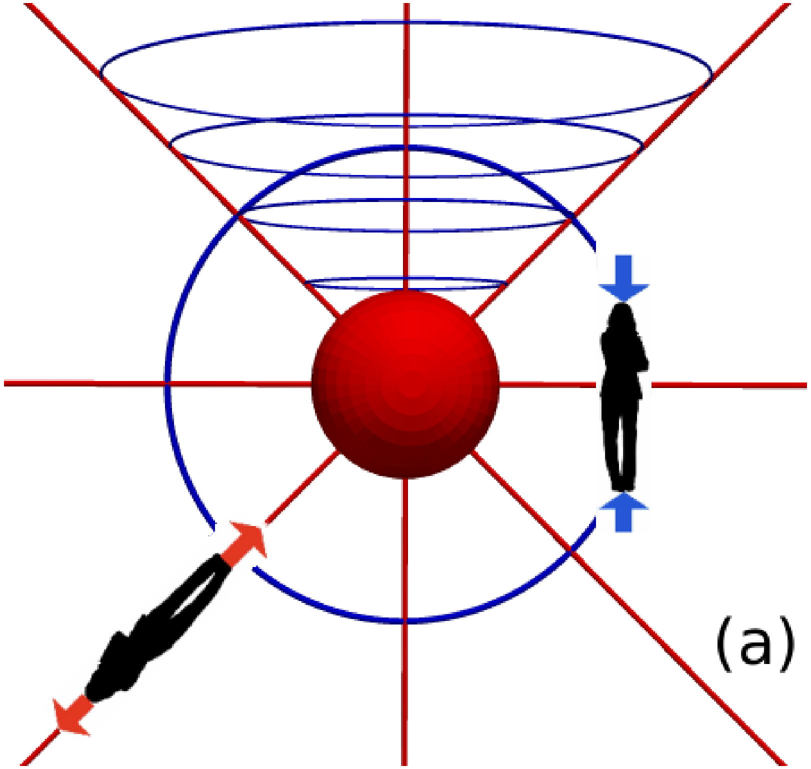

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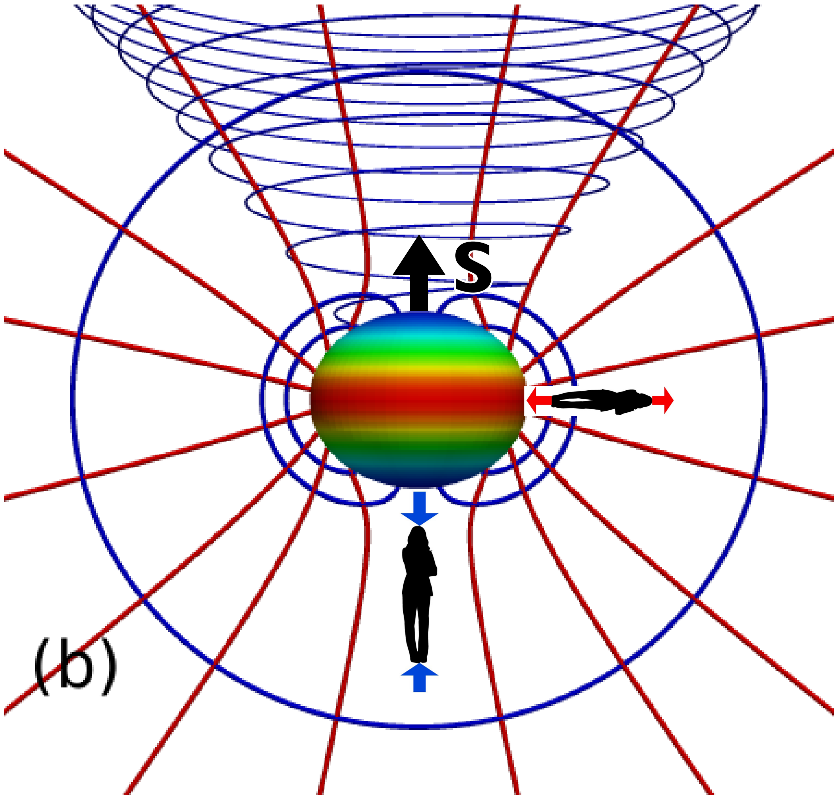

Horizon Tendex:
region of large tendicity

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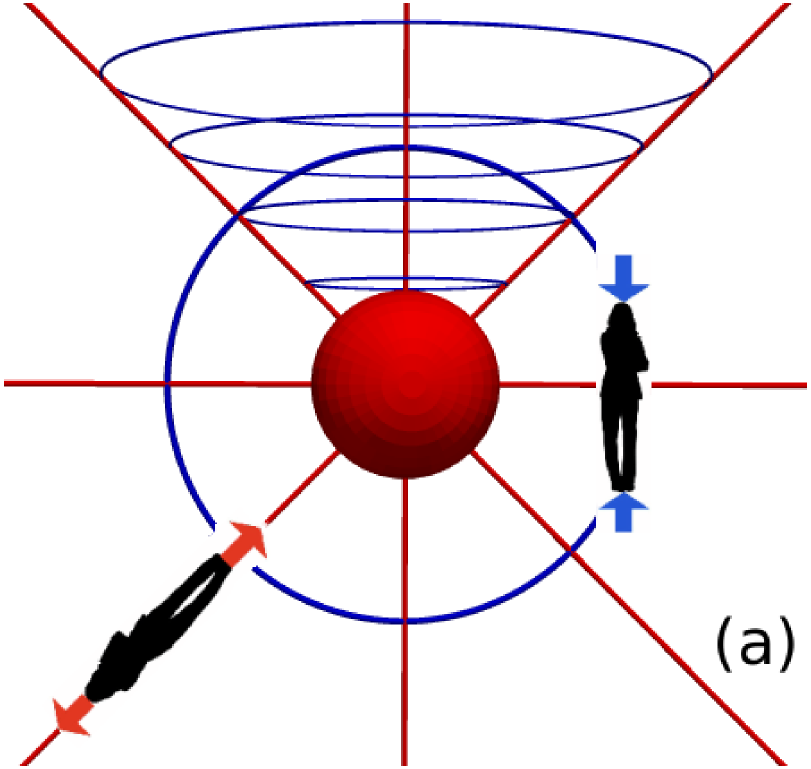

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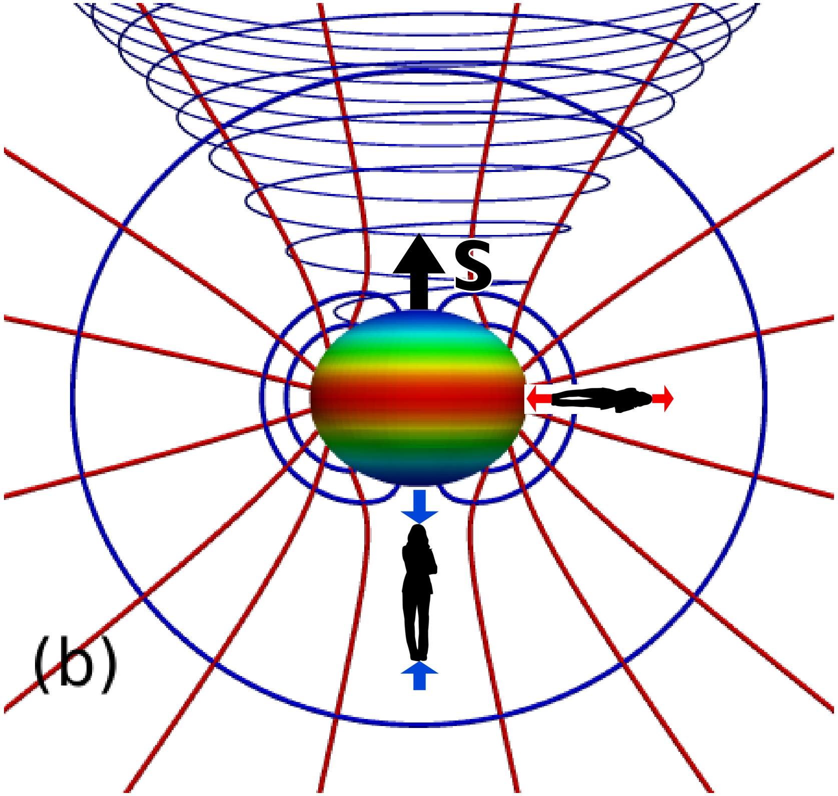

Horizon Tendicity: $\mathcal{E}_{NN}$

Blue: positive tendicity

Green: near zero

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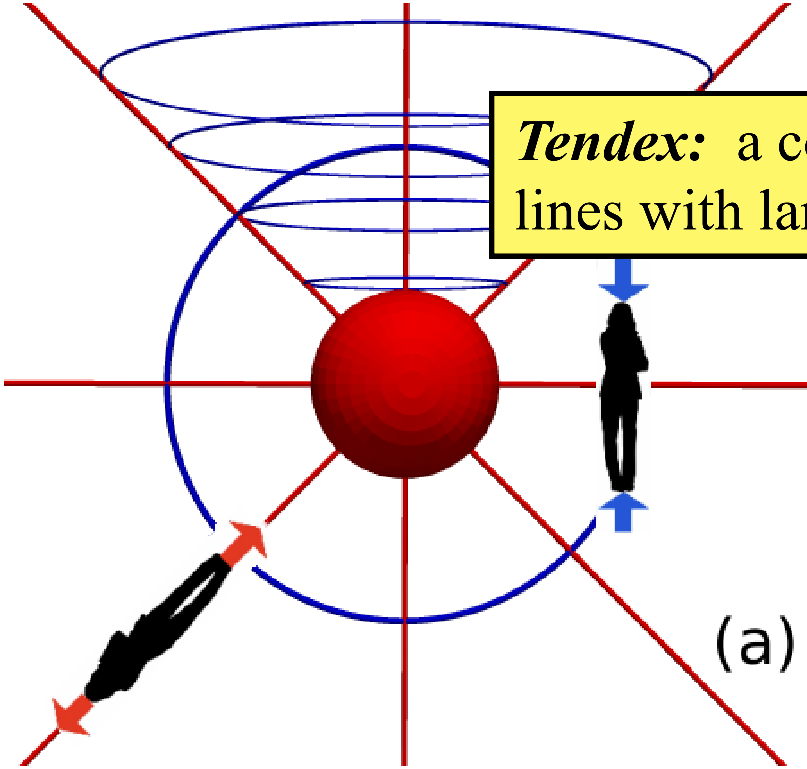
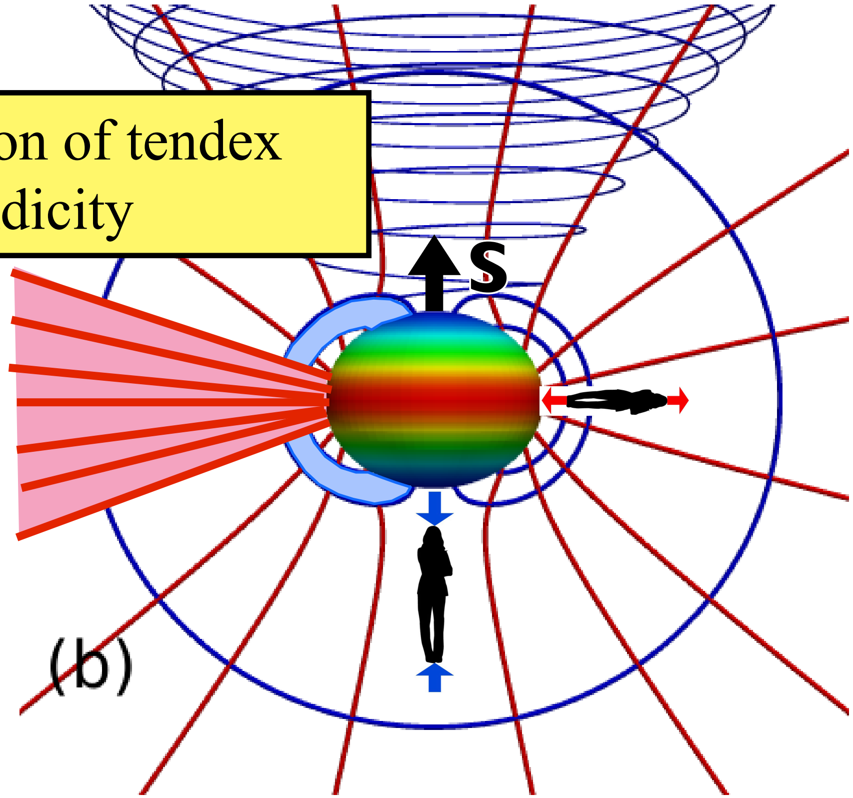


Tendex: a collection of tendex lines with large tendicity



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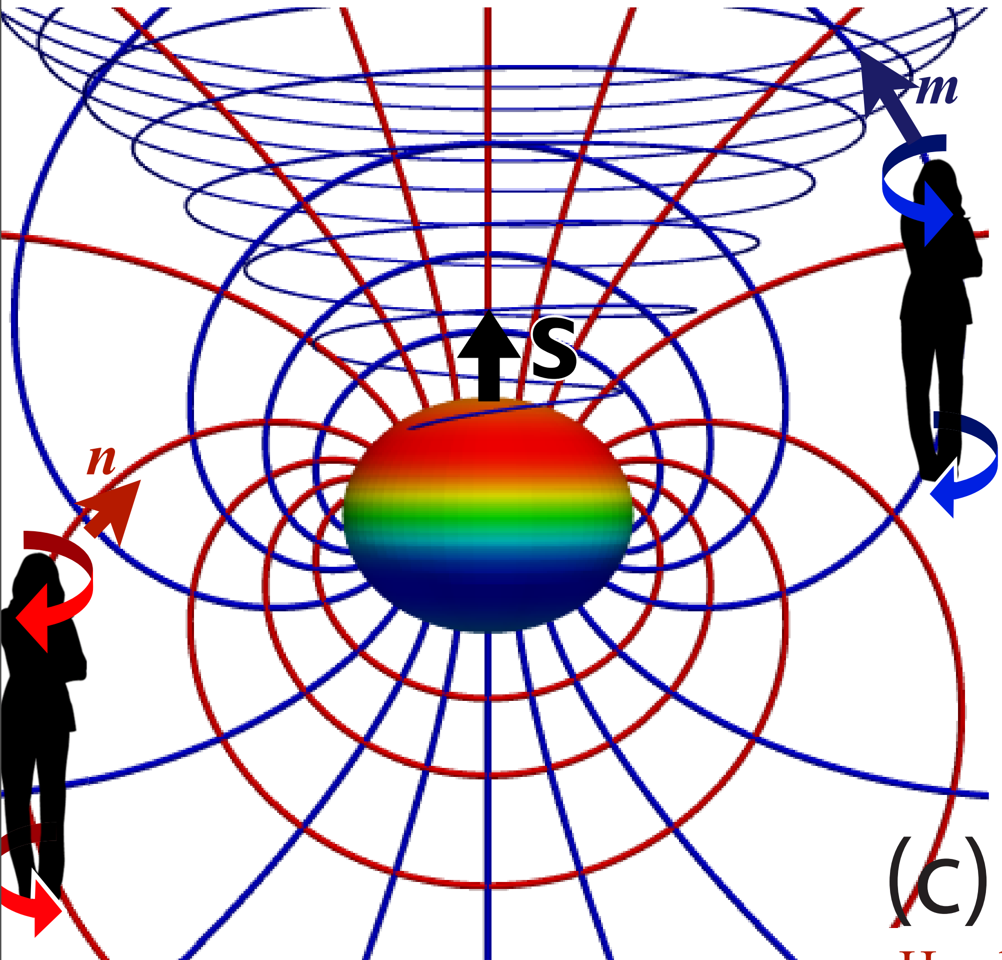

positive-vorticity vortex lines $\mathcal{B}_{mm} > 0$

- Head sees feet dragged clockwise
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negative-vorticity vortex lines $\mathcal{B}_{nn} < 0$

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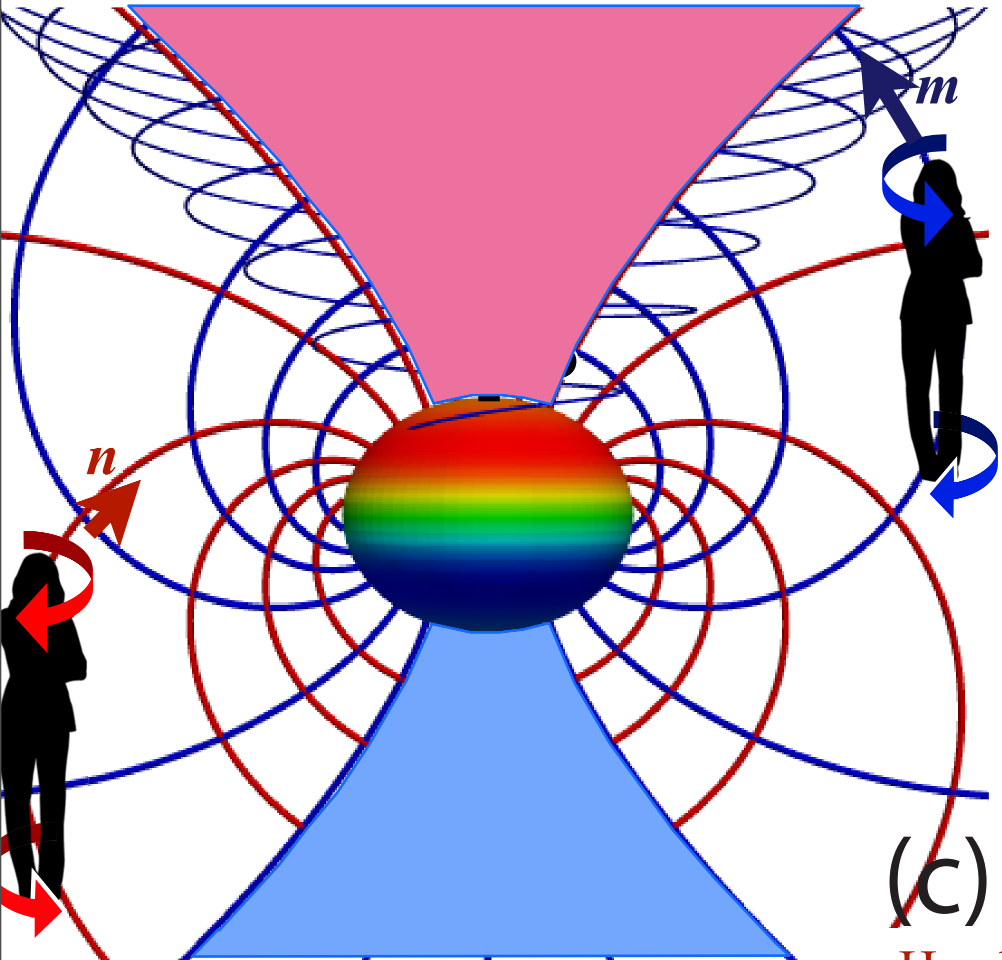

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(c)

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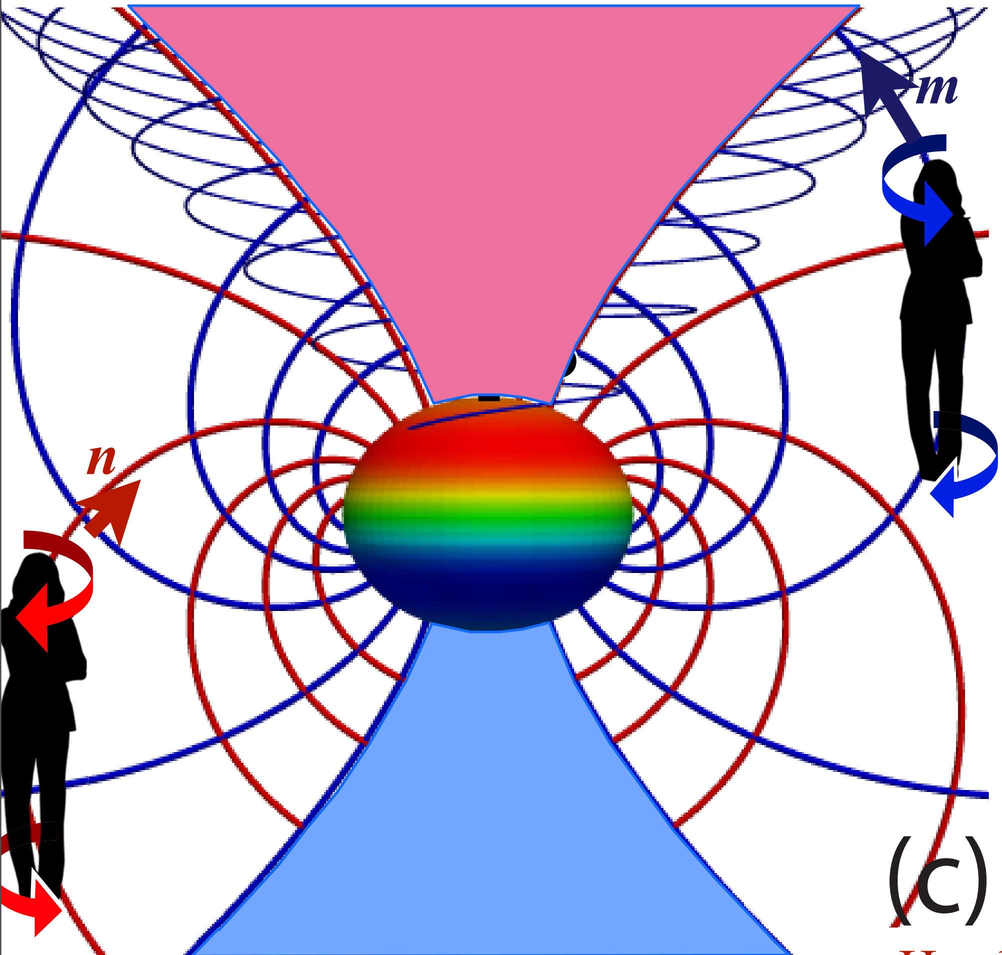

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Horizon vorticity: $\mathcal{B}_{NN}$

Horizon Vortex: region of large vorticity

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Head-On Collision with Transverse Spin

Keith Matthews, Geoffrey Lovelace, Mark Scheel

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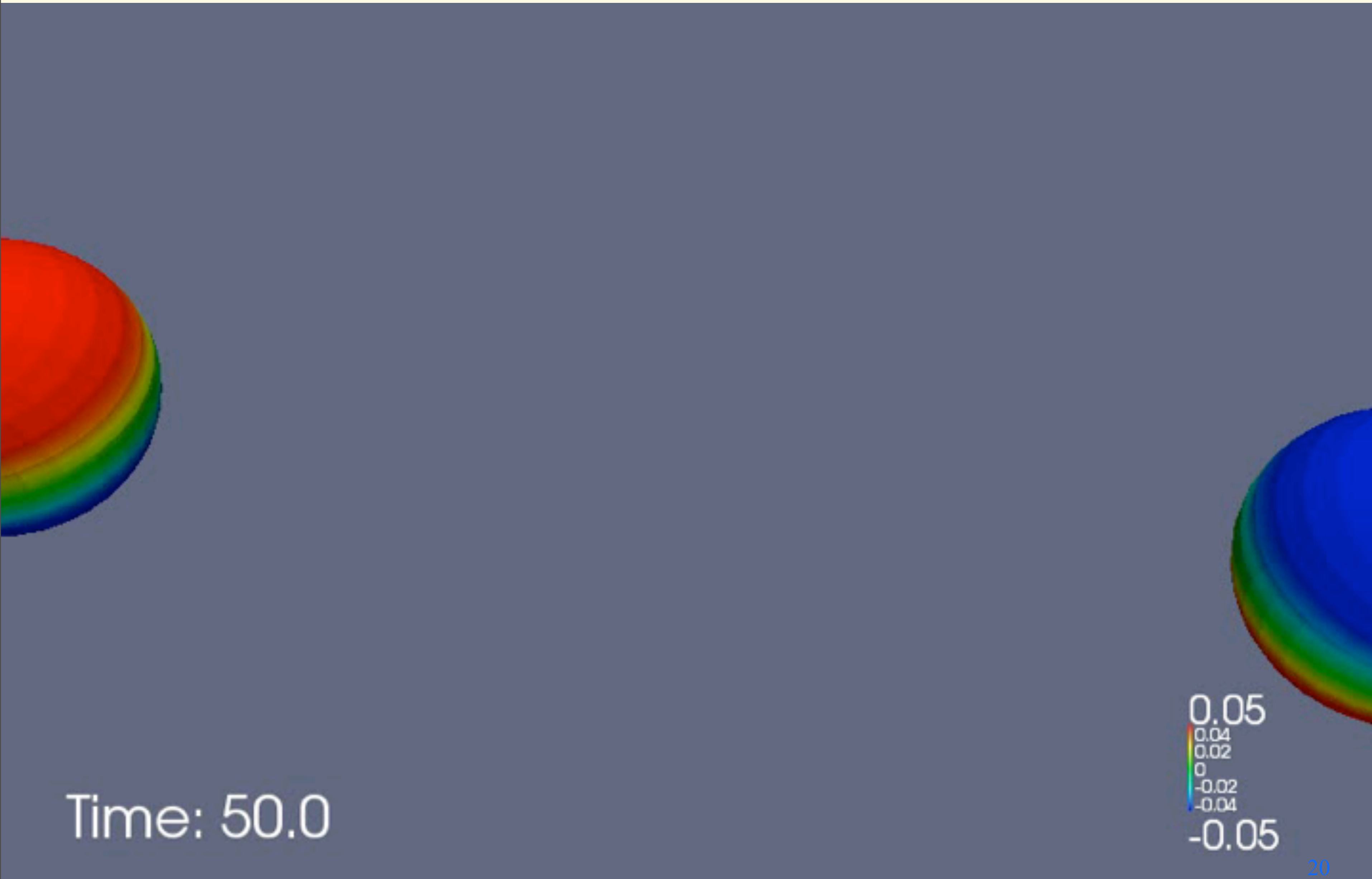

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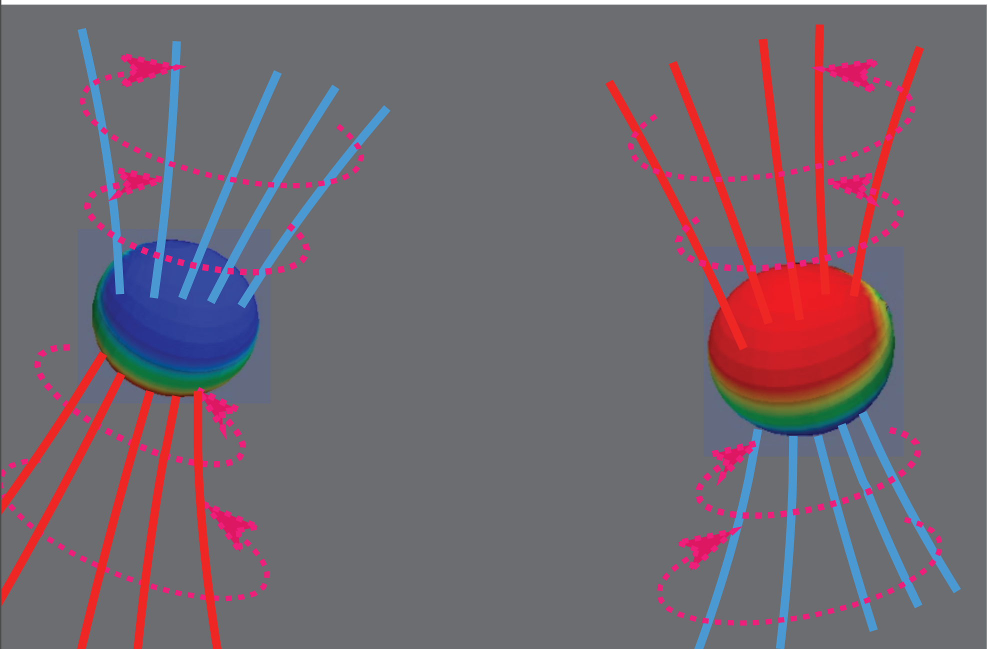

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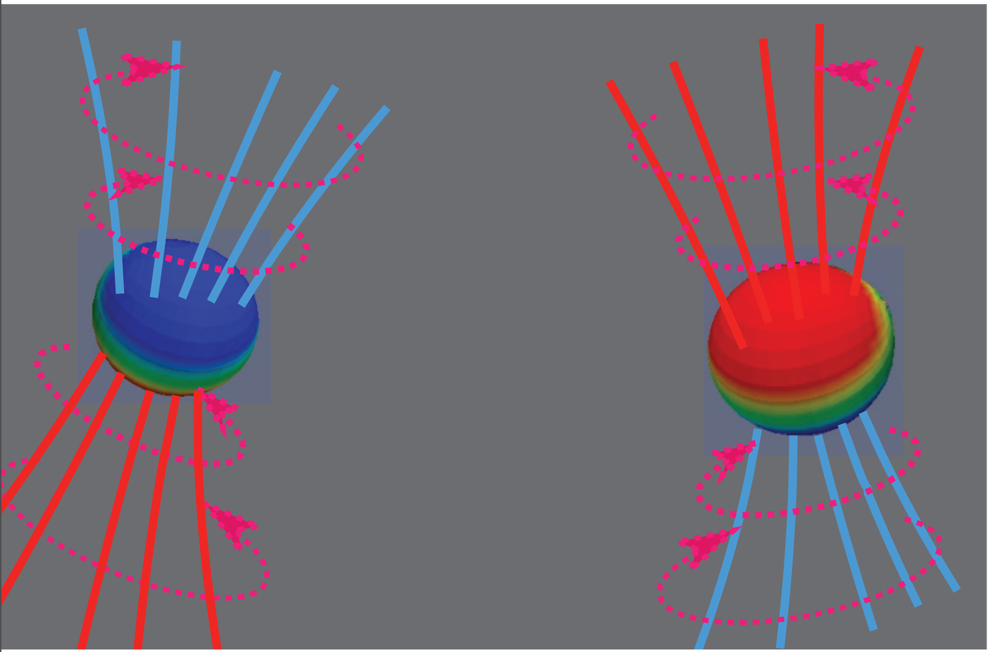

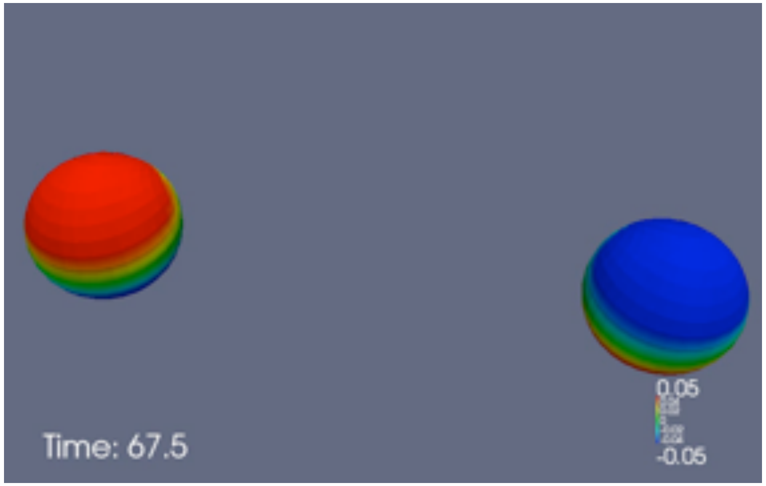

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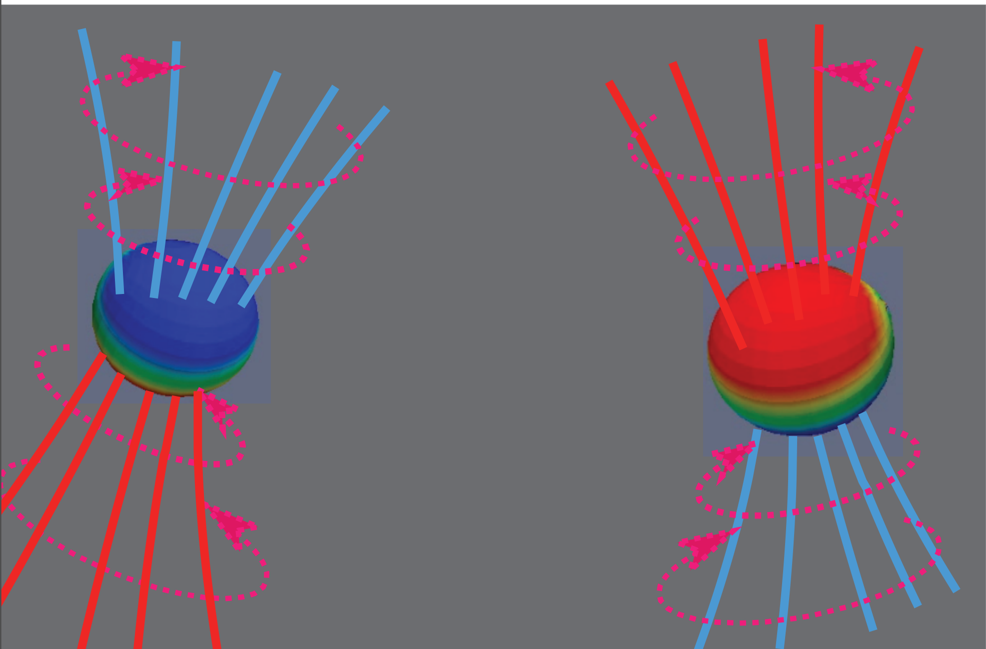
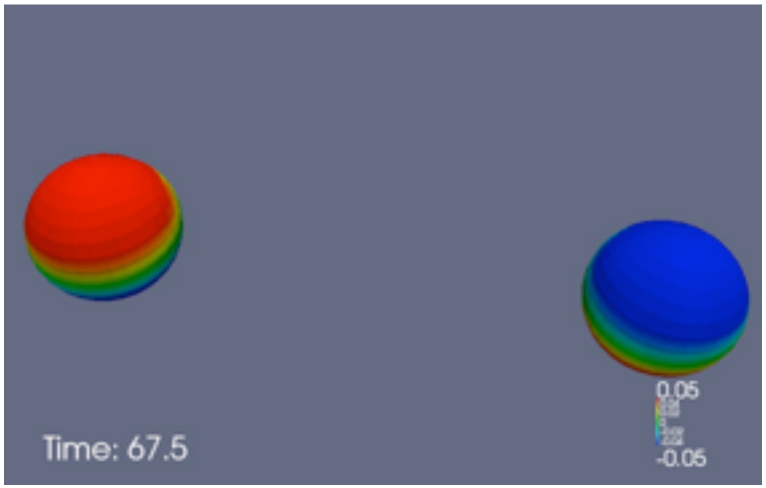
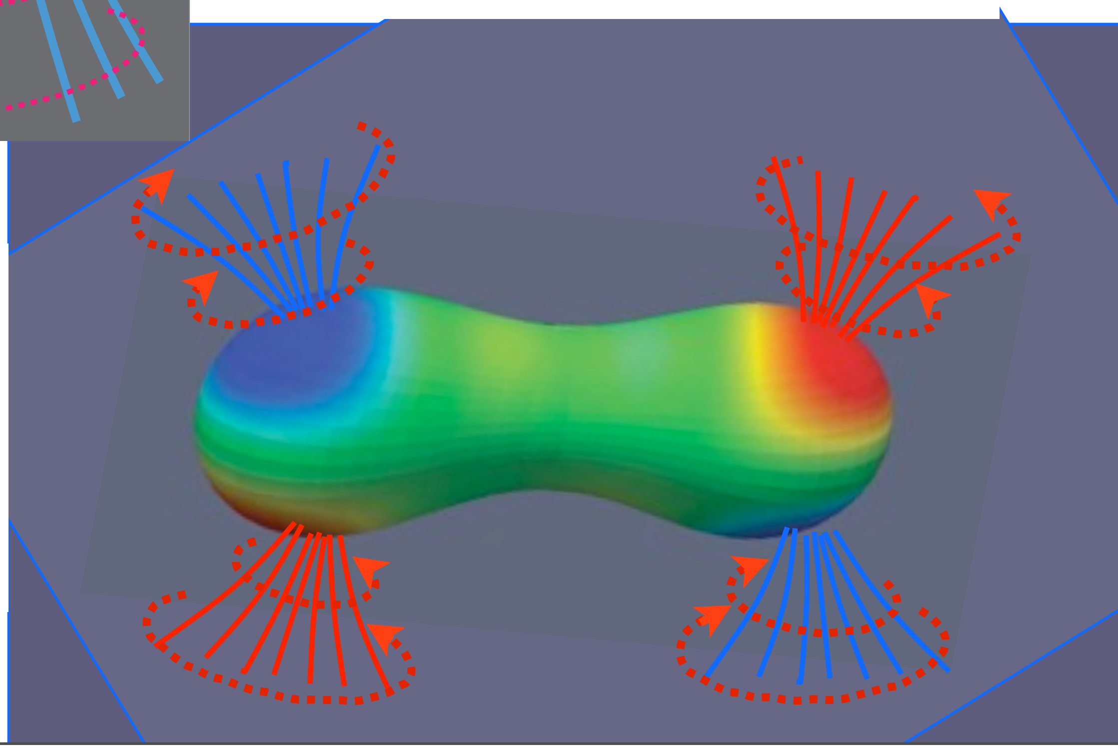
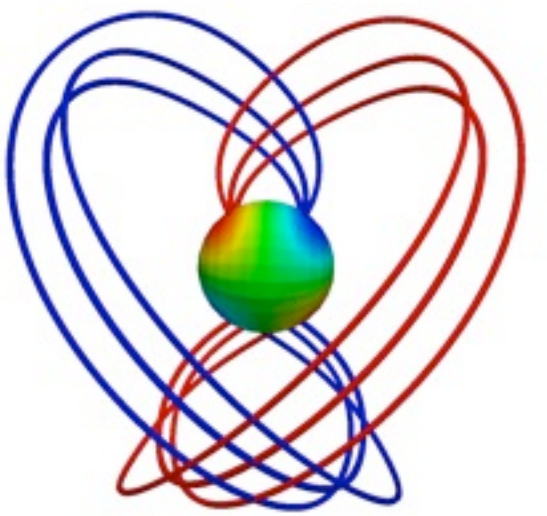




Vortexes robustly retain their individuality



Sloshing Ejects Vortexes



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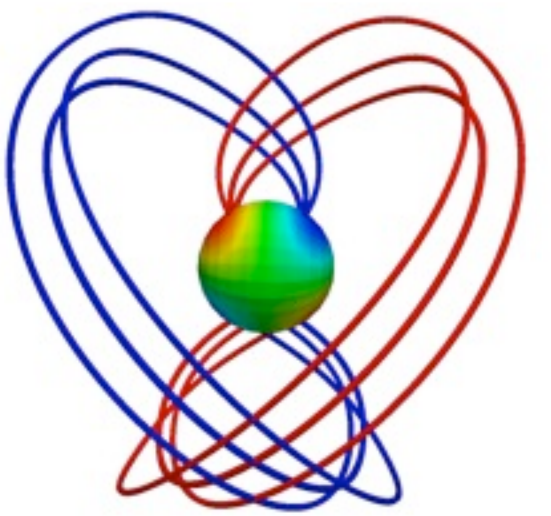

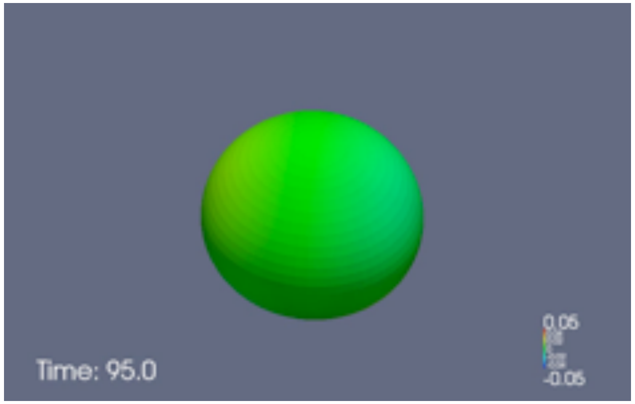

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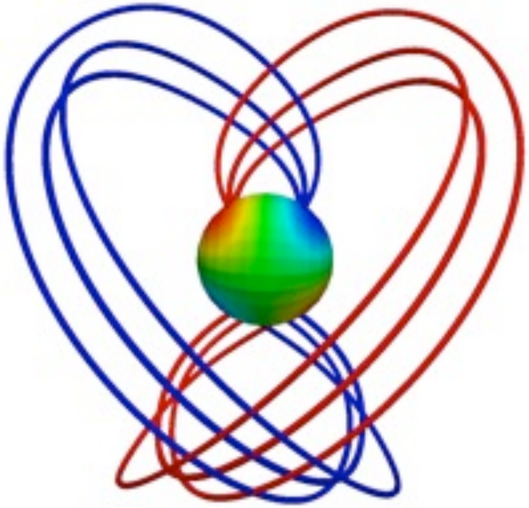
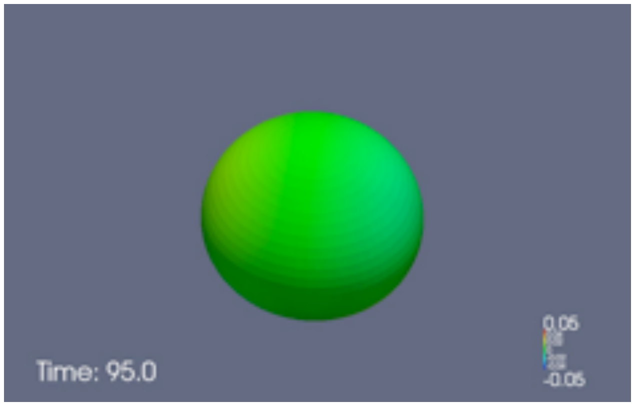
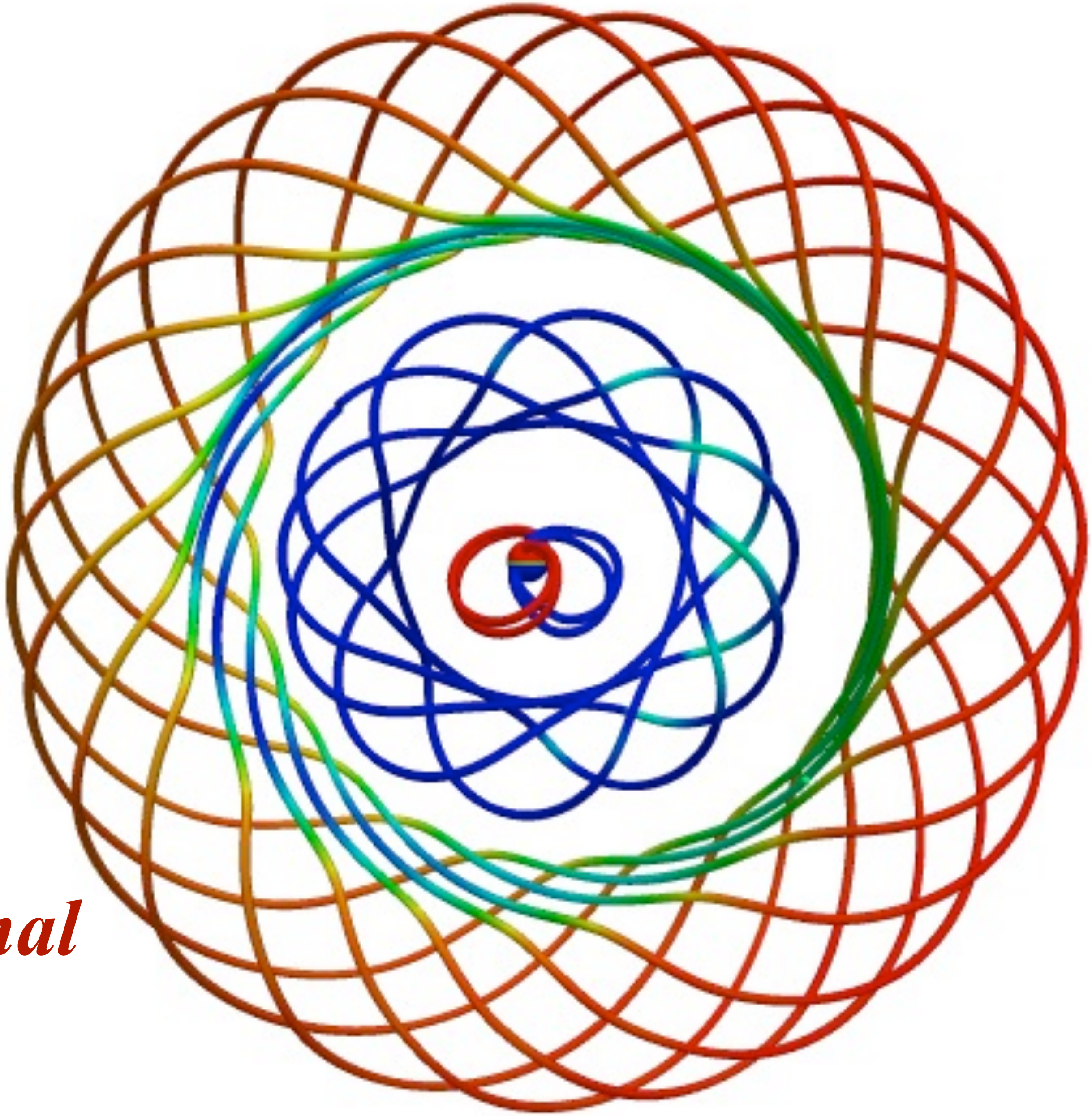
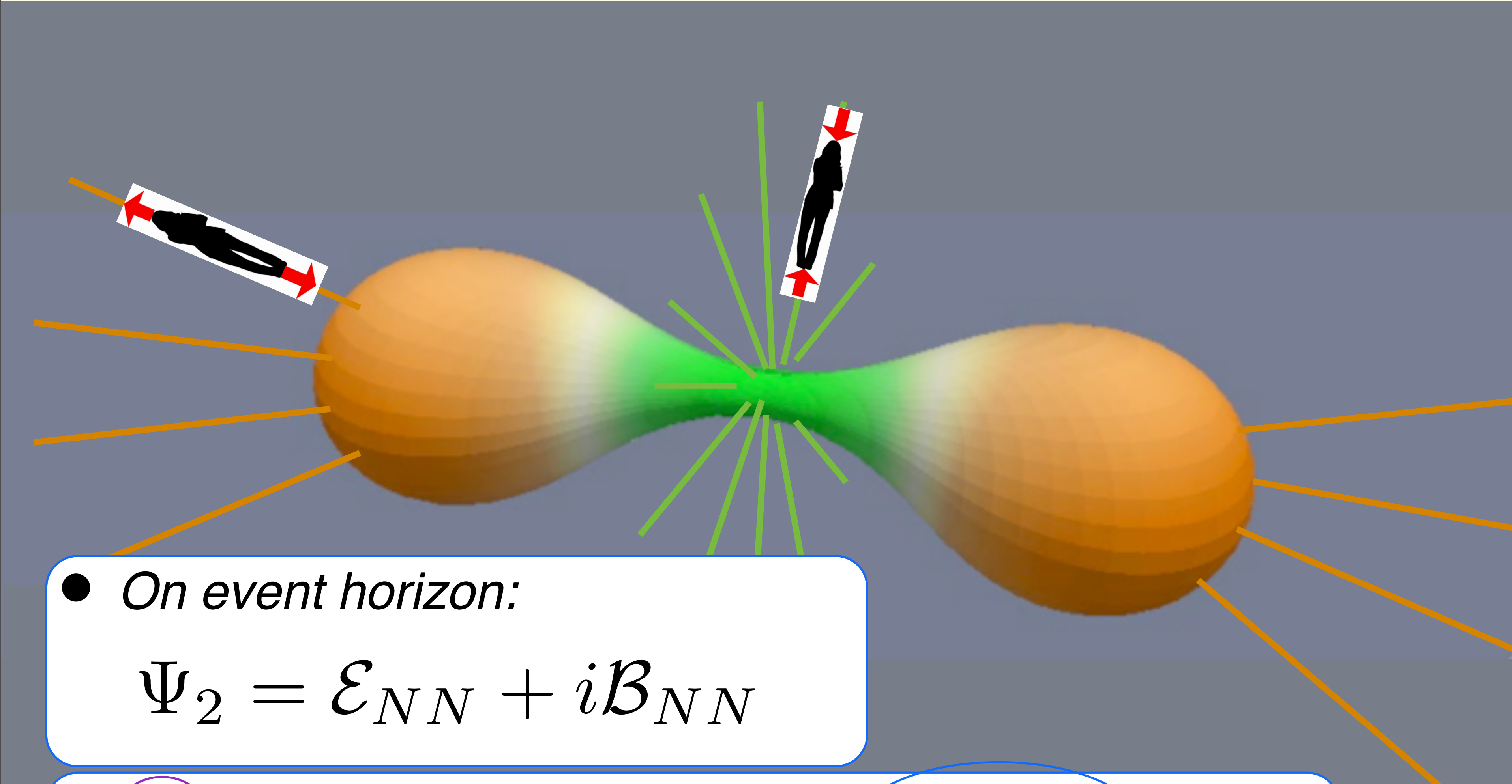






gravitational waves

Horizon Tendicity and Vorticity



- *On event horizon:*

$$\Psi_2 = \mathcal{E}_{NN} + i\mathcal{B}_{NN}$$

$$\mathcal{K} = \mathcal{R} + i\chi = -\Psi_2 + \mu\rho - \lambda\sigma$$

Complex curvature

numerically small

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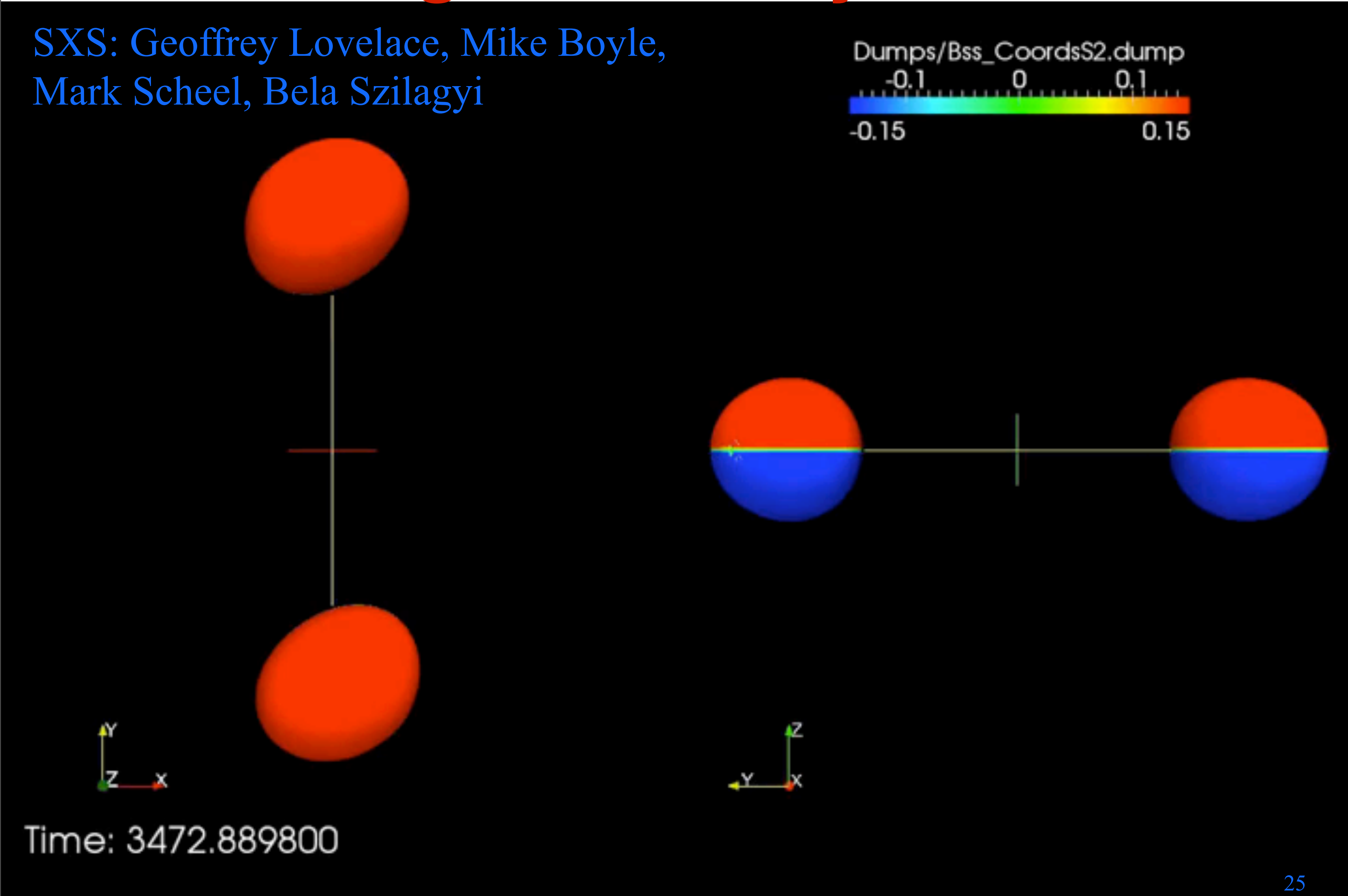

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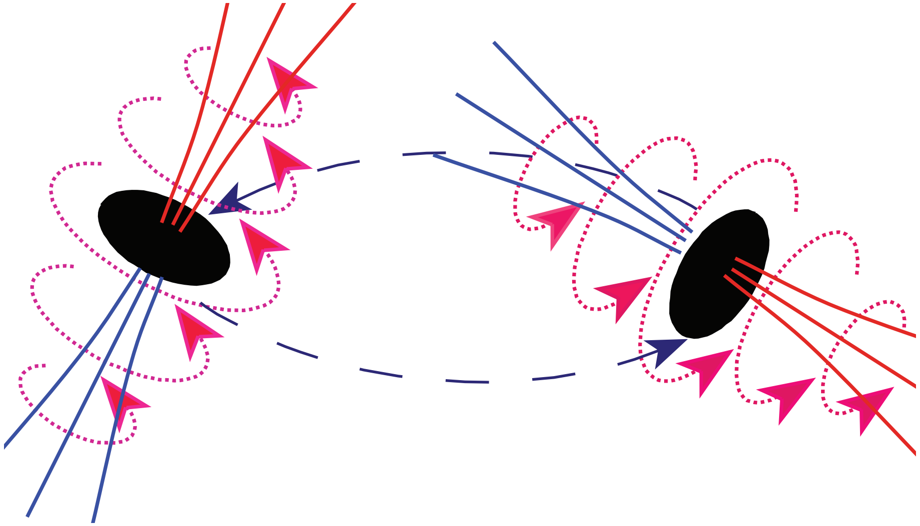
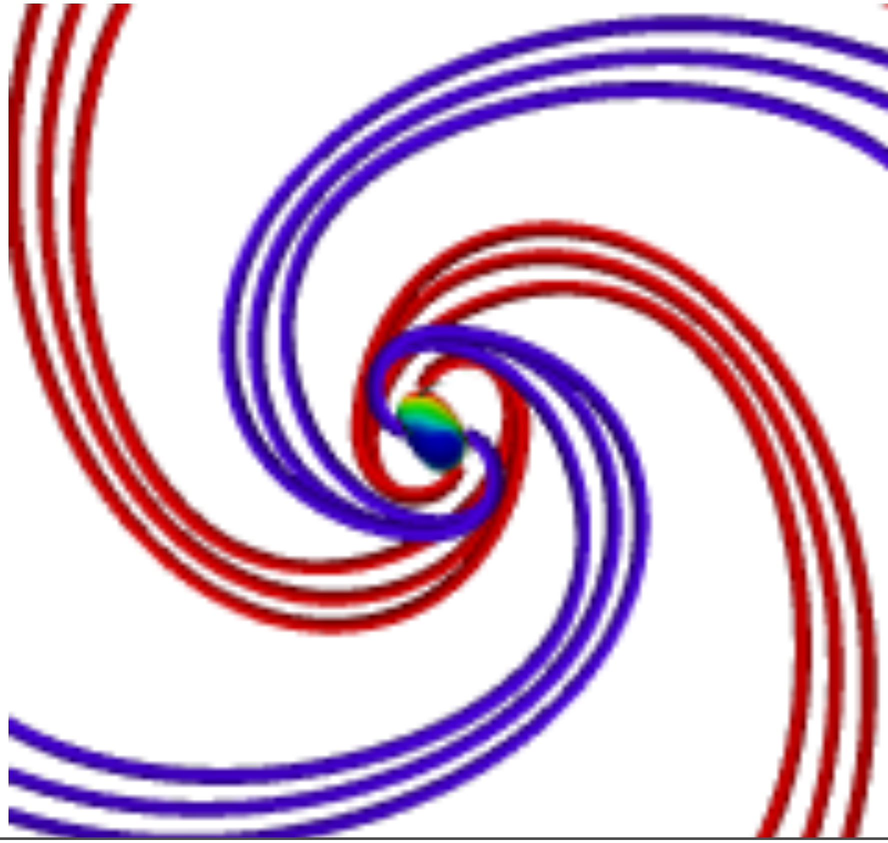
Generic Orbiting Collision





Pulsations of a Nonrotating Hole [l=m=2 “odd-parity normal modes”]

First Golden Age:

Regge & Wheeler
Chandrasekhar & Detweiler

$\omega = (0.747 - i\, 0.178)/2M$

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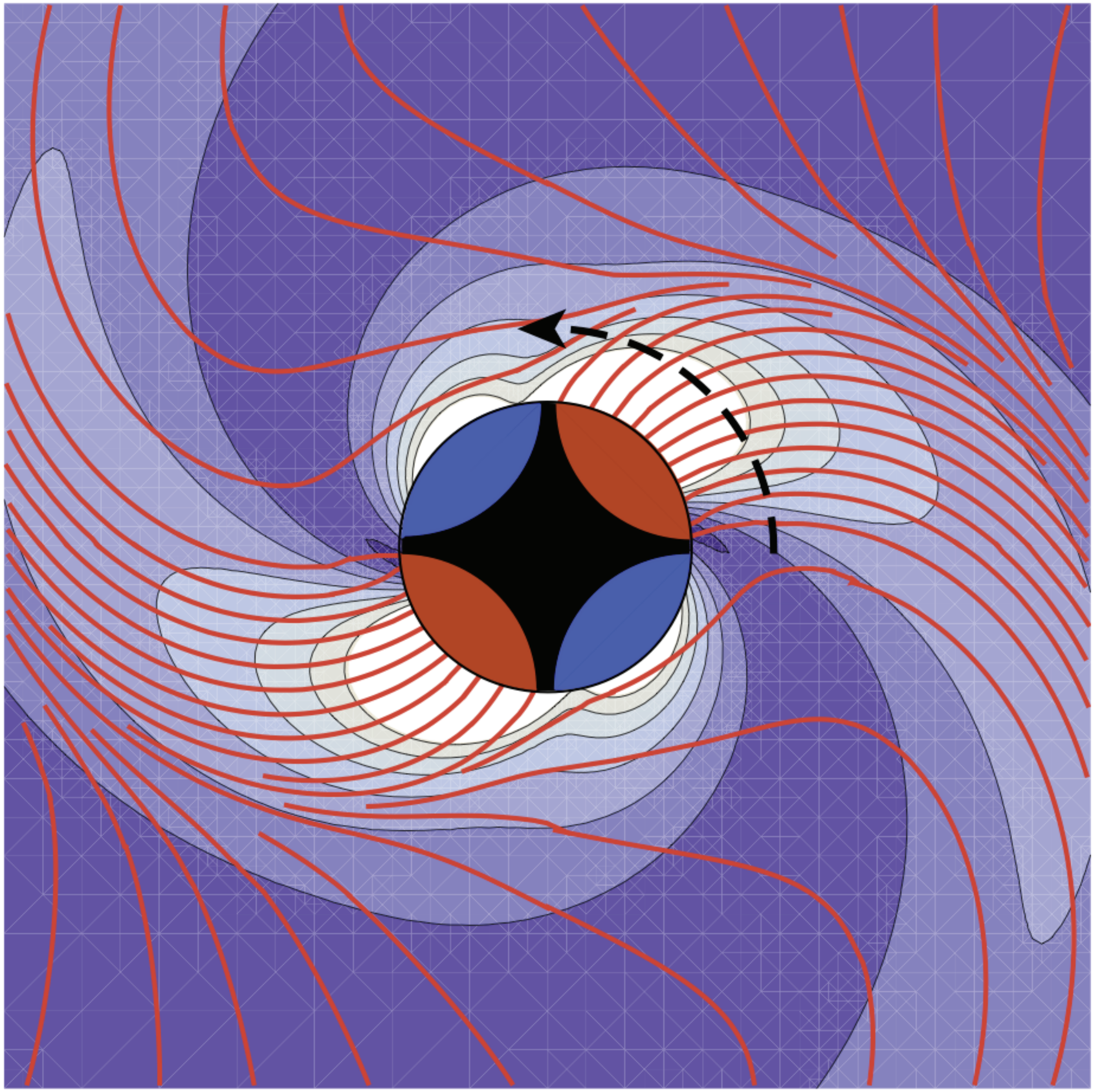

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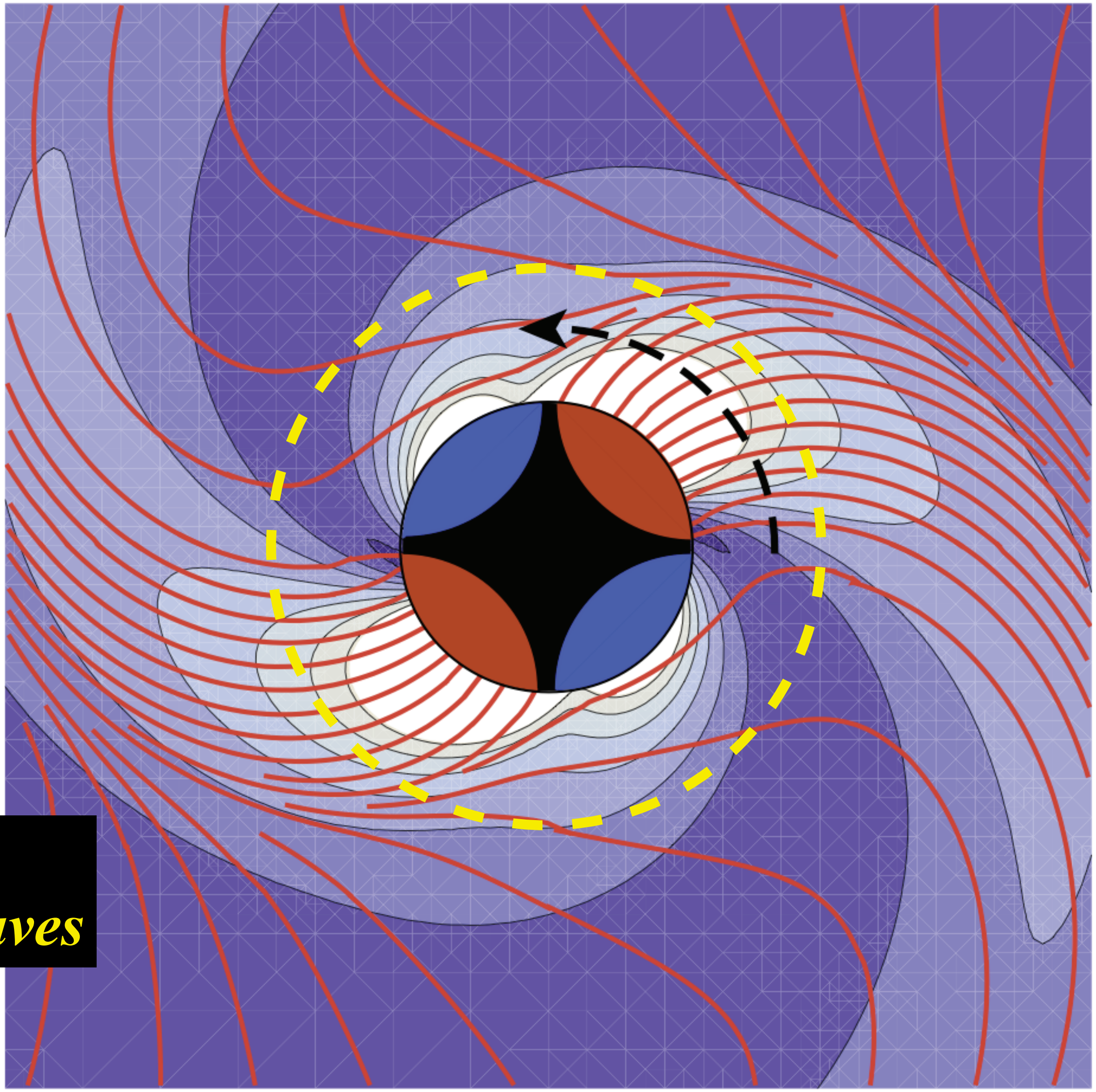

Near-hole vortexes generate gravitational waves

Pulsations of a Nonrotating Hole [l=m=2 "odd-parity normal modes"]

Old Golden Age:

Regge & Wheeler,
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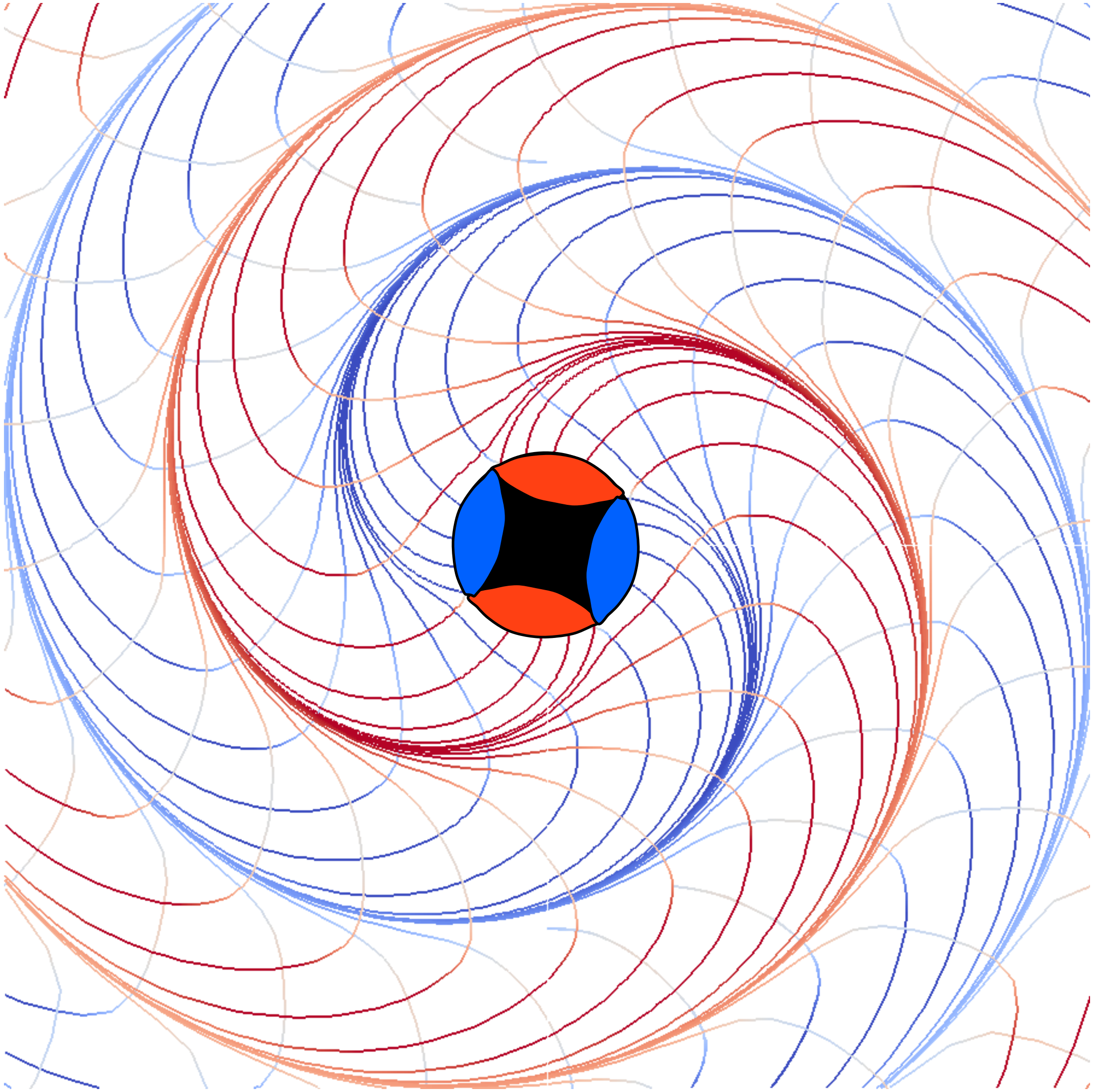
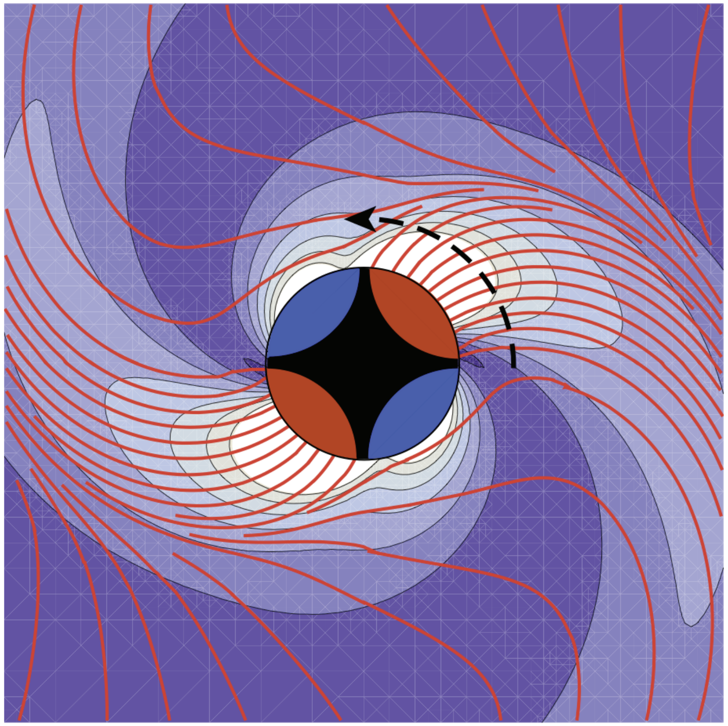
l=m=2 "even-parity" normal modes: same, but vortex lines ➔ tendex lines for perturbation of Weyl tensor



Gravitational Wave Generation



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In local Lorentz frame

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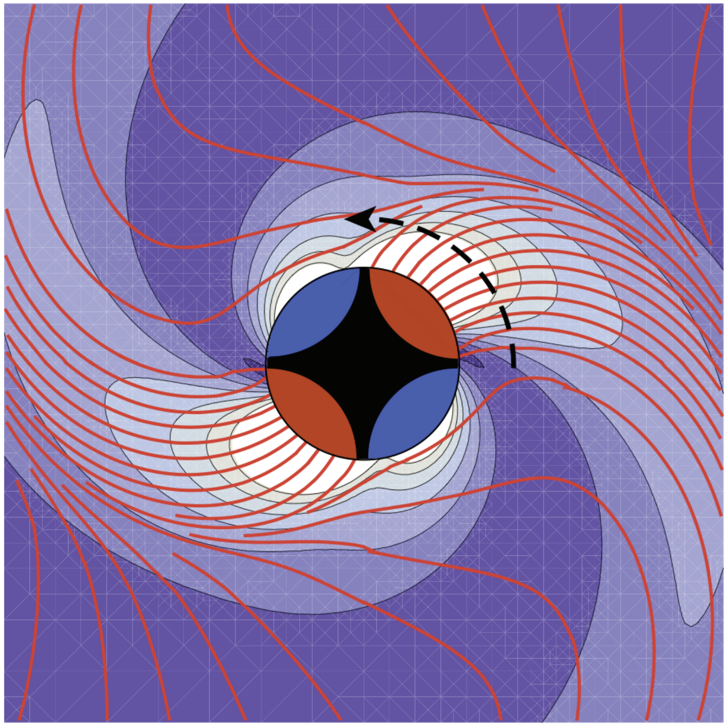

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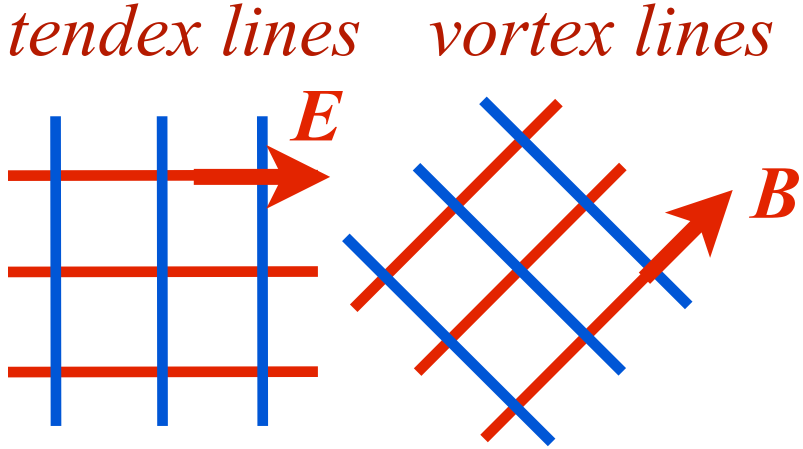
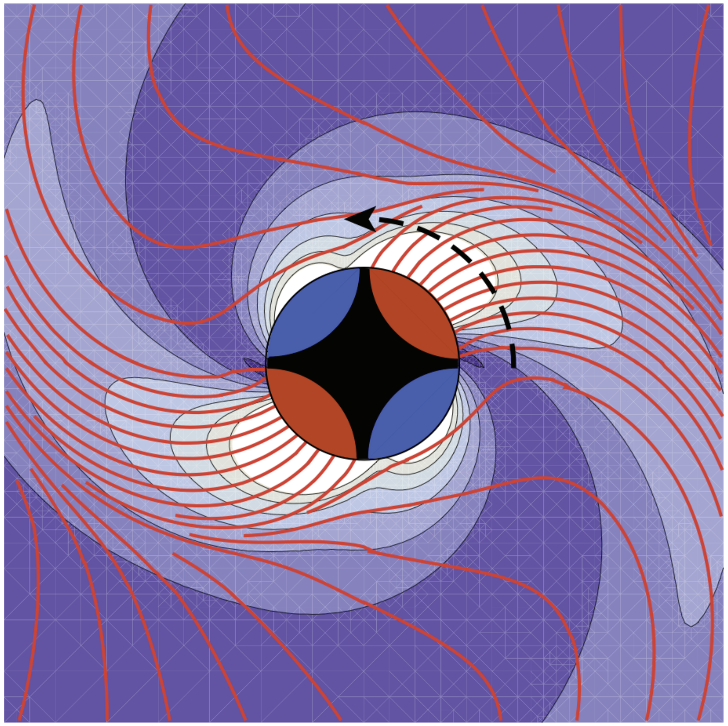
Plane Gravitational Wave



***E*×*B* is direction of wave propagation**

Gravitational Wave Generation



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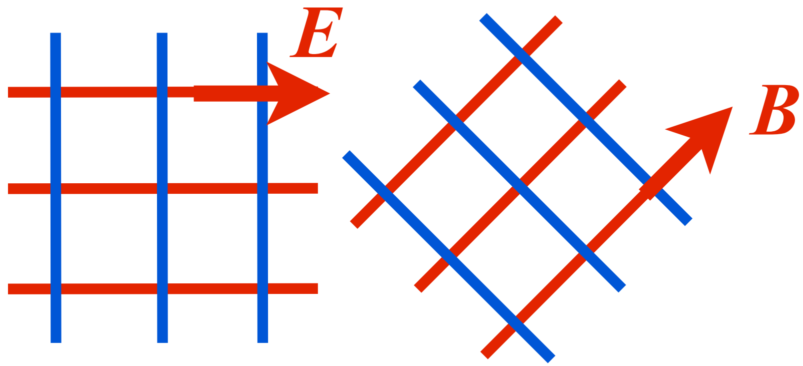
Plane Gravitational Wave

tendex lines *vortex lines*



E*×*B is direction of wave propagation

Vortex/Tendex Research

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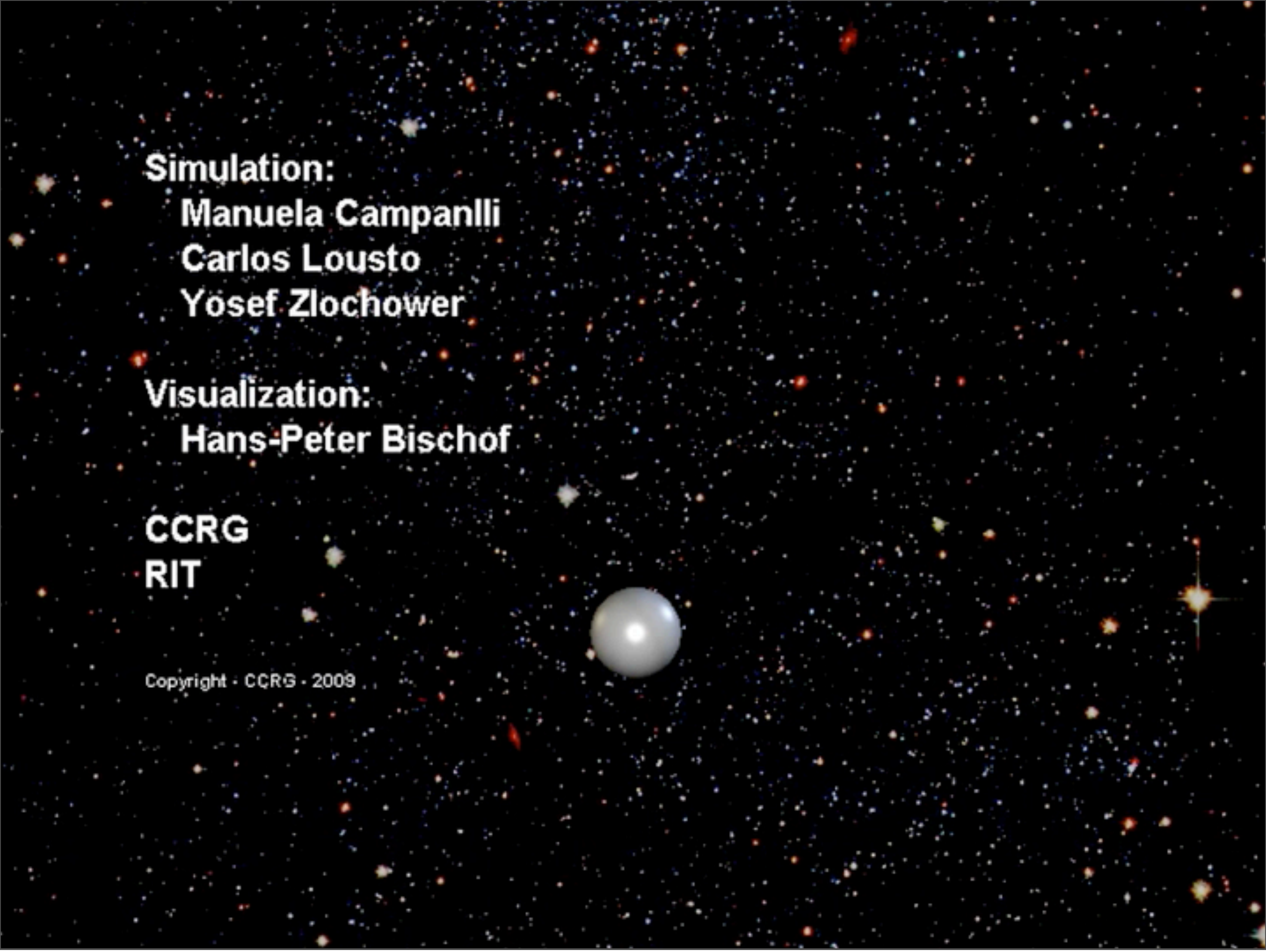
  - » **Why** do vortexes and tendexes usually retain identity instead of diffusing and annihilating
  - » What is mechanism for exchange of vorticity in head-on, transverse-spin collisions?

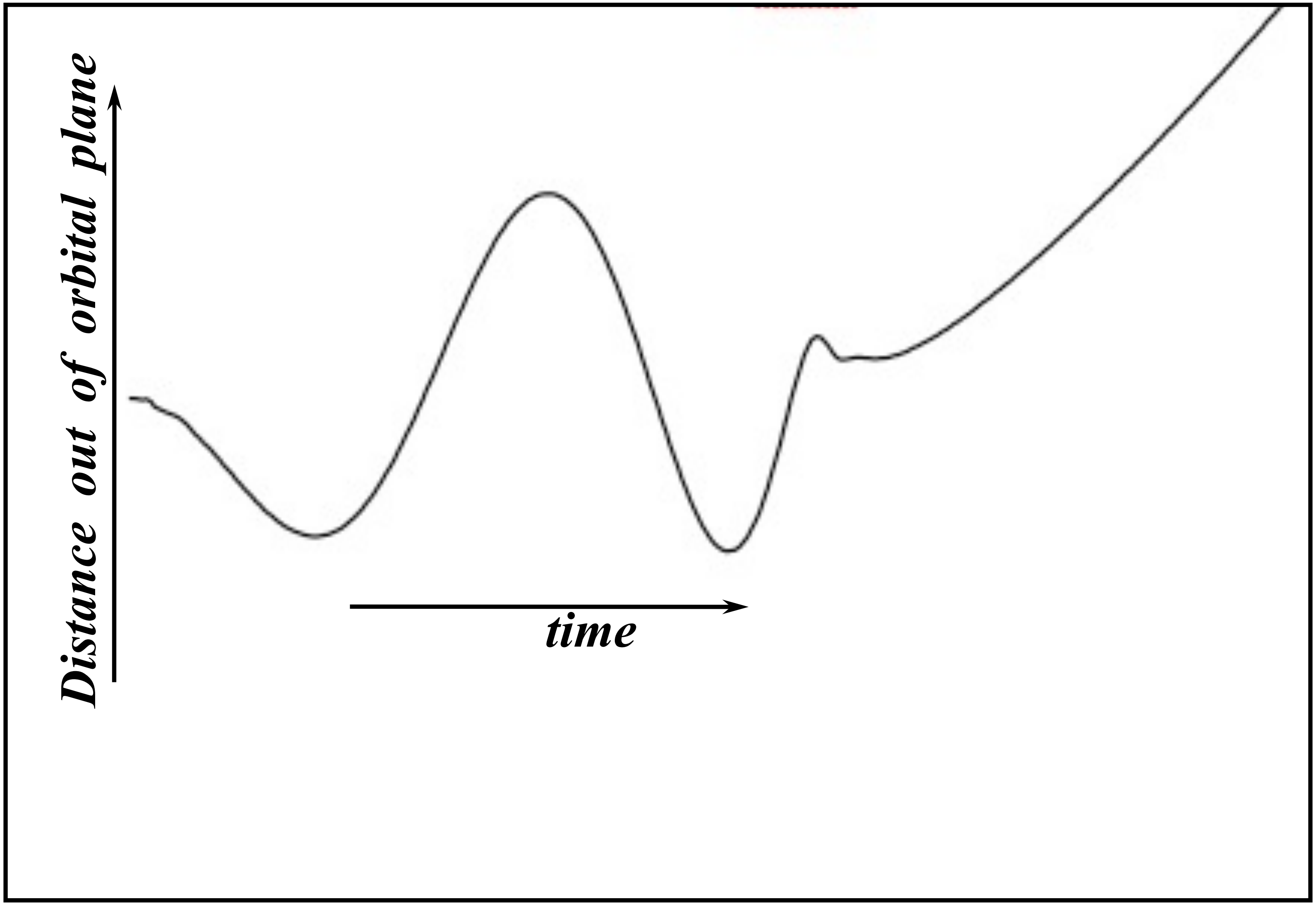
“Extreme-Kick” Collision of Black Holes

Rochester Institute of Technology:
Campanelli, Lousto, Zlochower


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

Explanation of Bobbing

[Pretorius]



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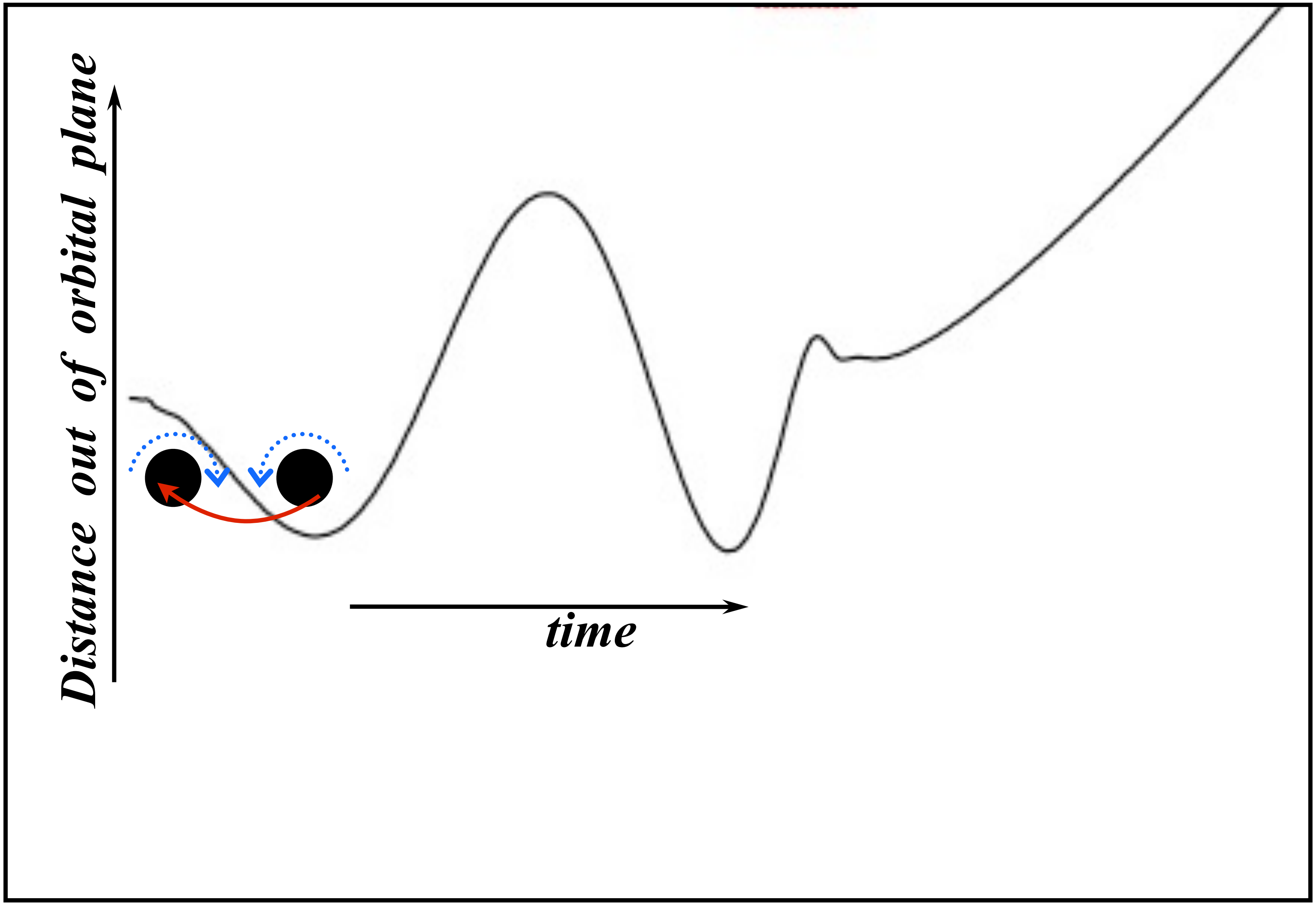

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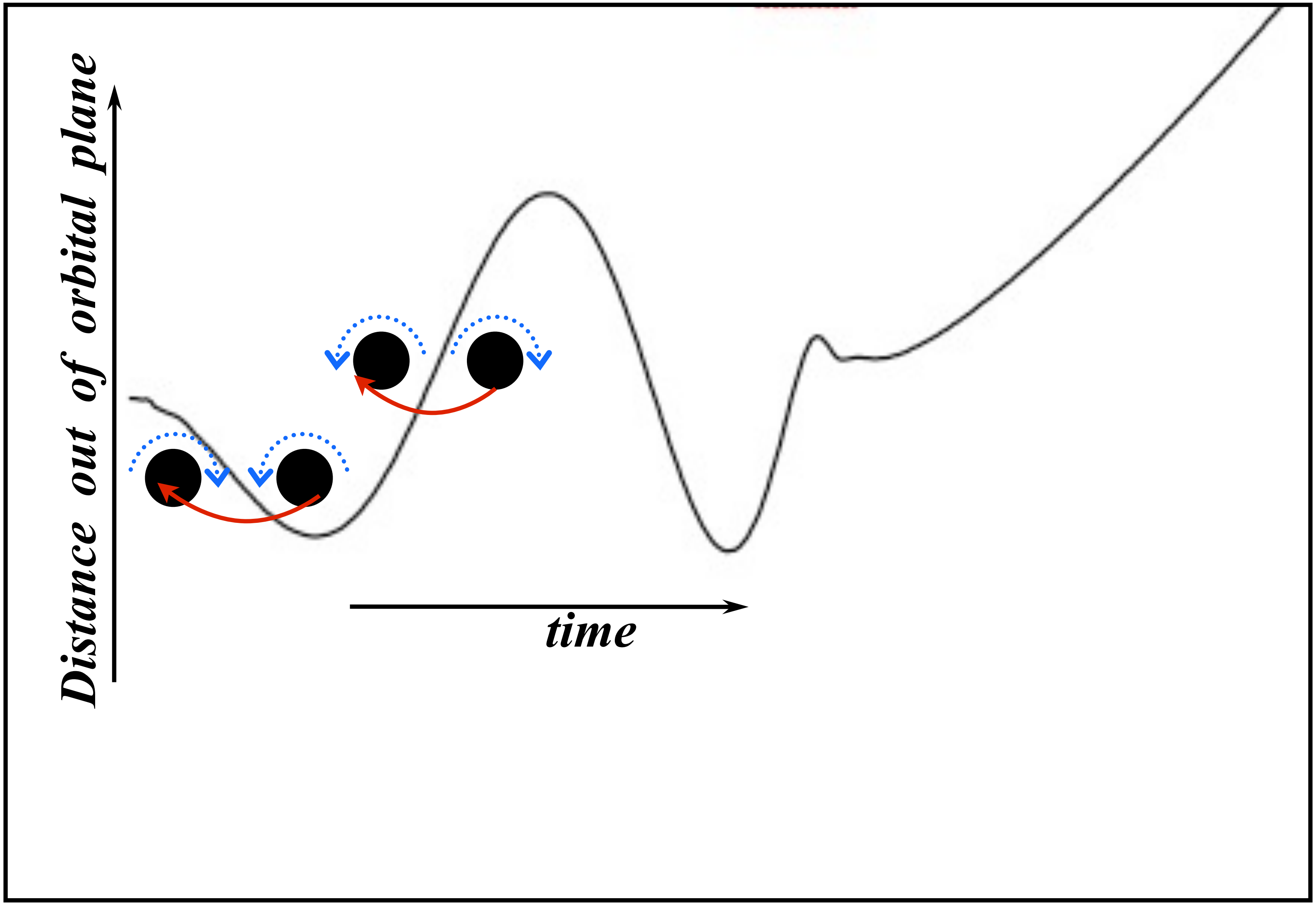

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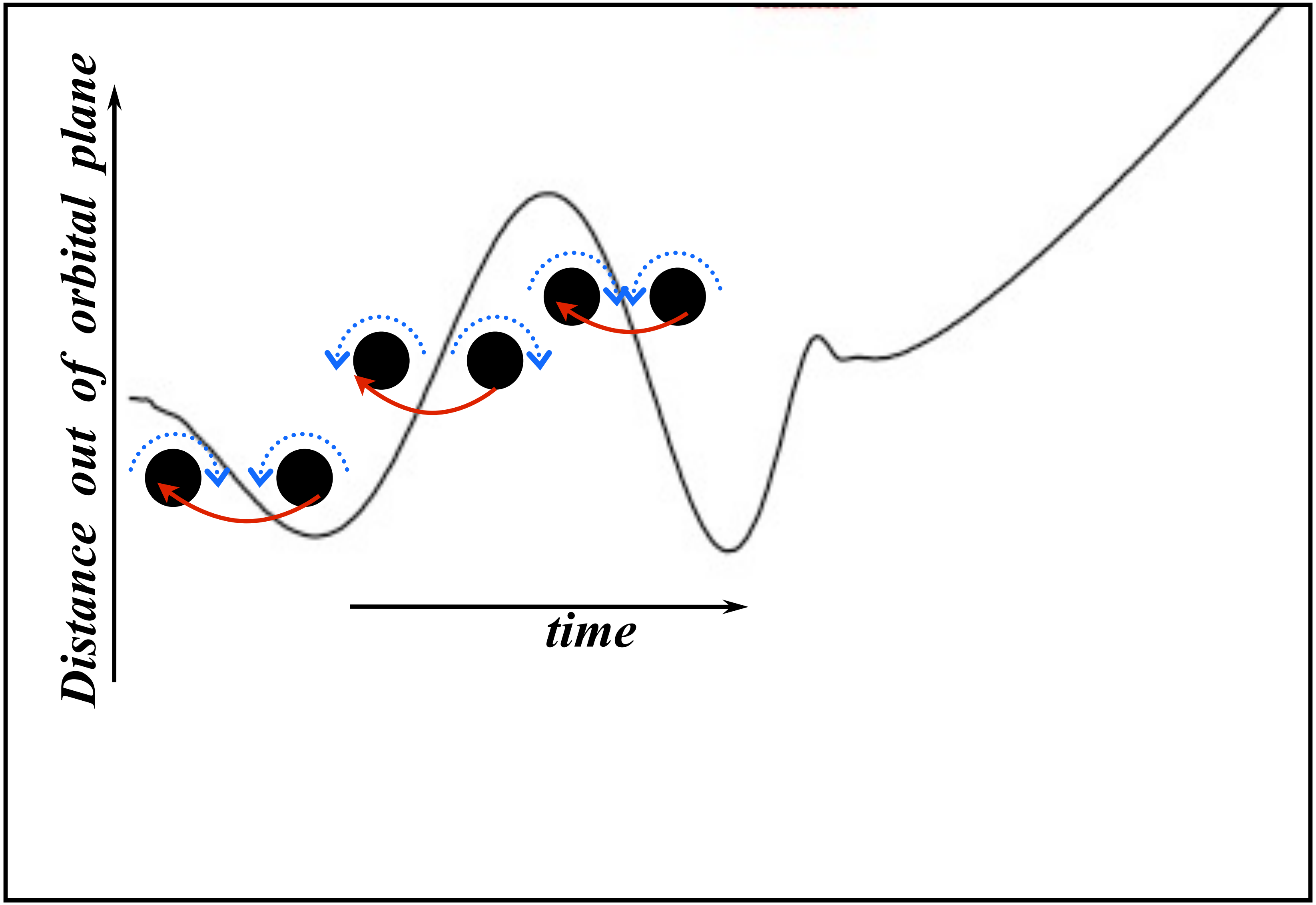

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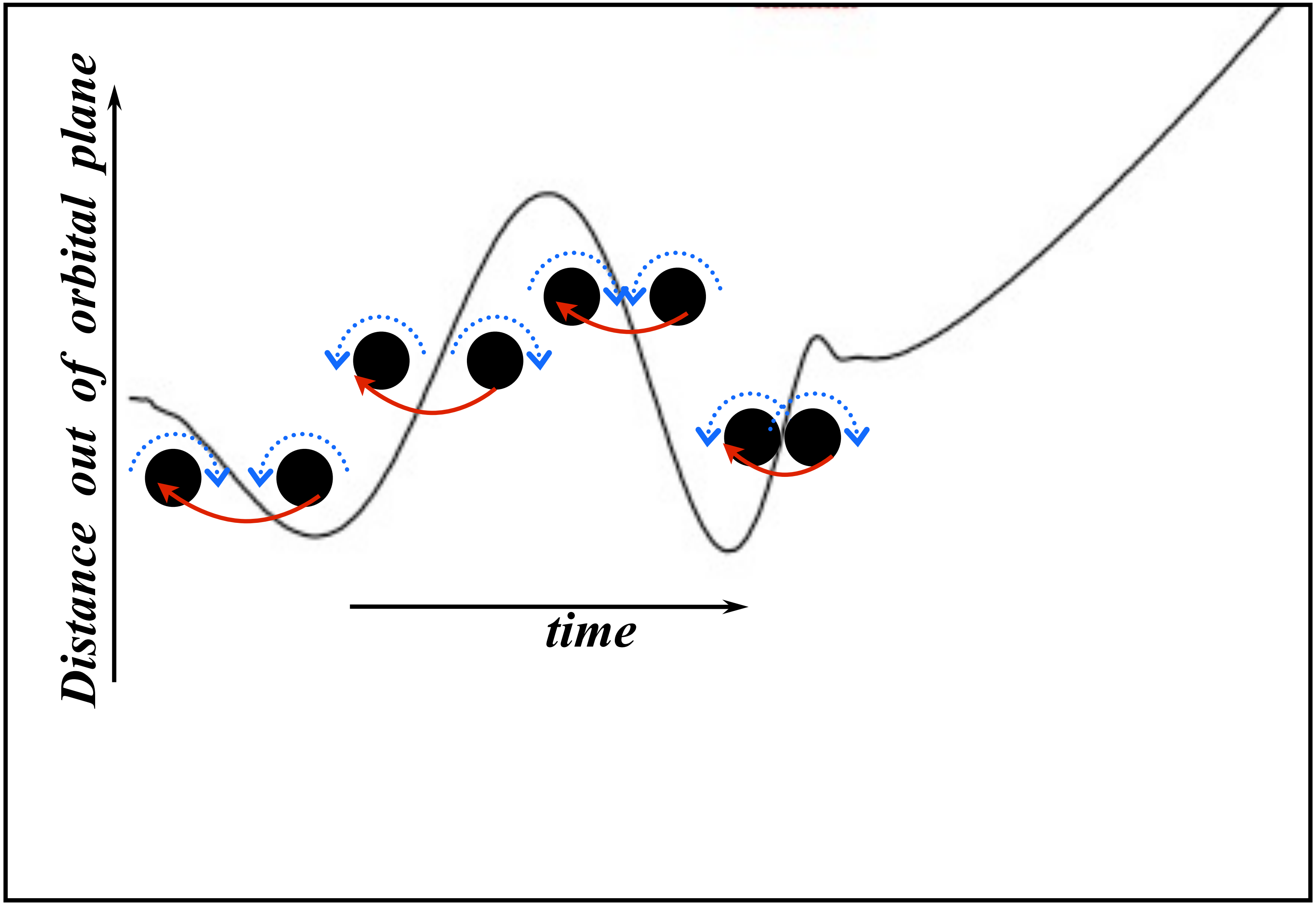

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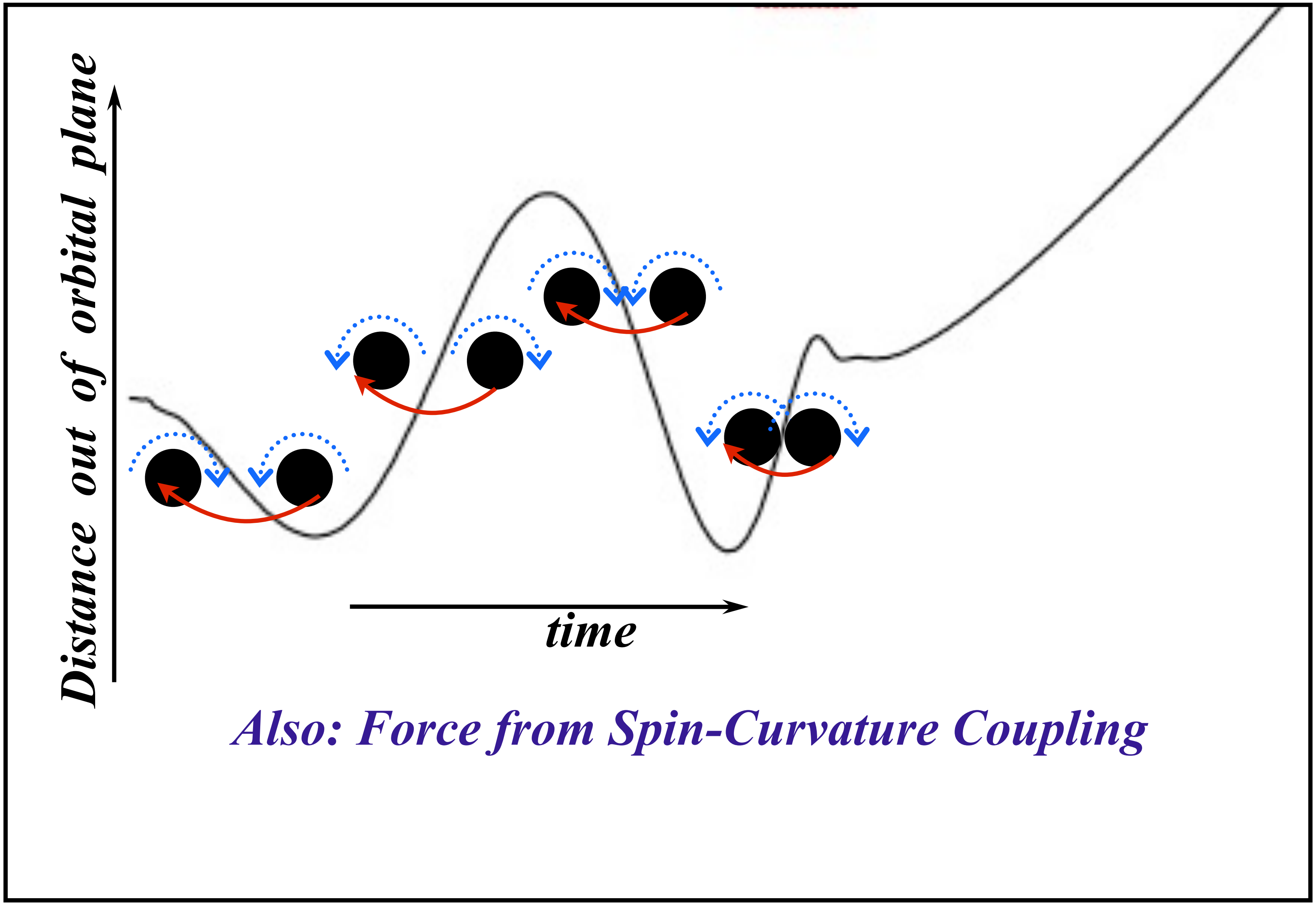

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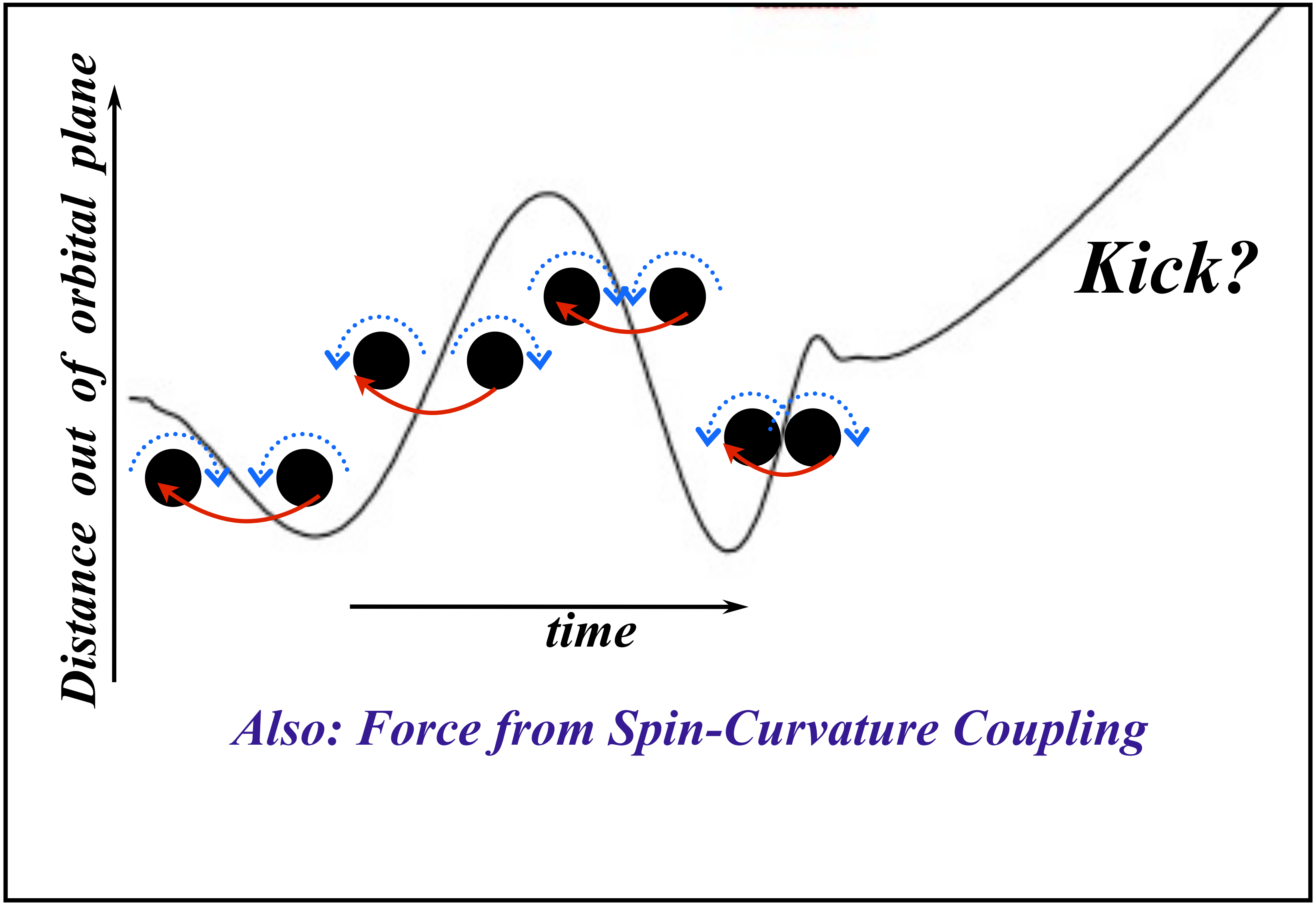

Analogous to 2 Vortexes in a Fluid

From film ***Vorticity*** by **Ascher H. Shapiro** (Educational Services Inc, 1961)

Analogous to 2 Vortexes in a Fluid

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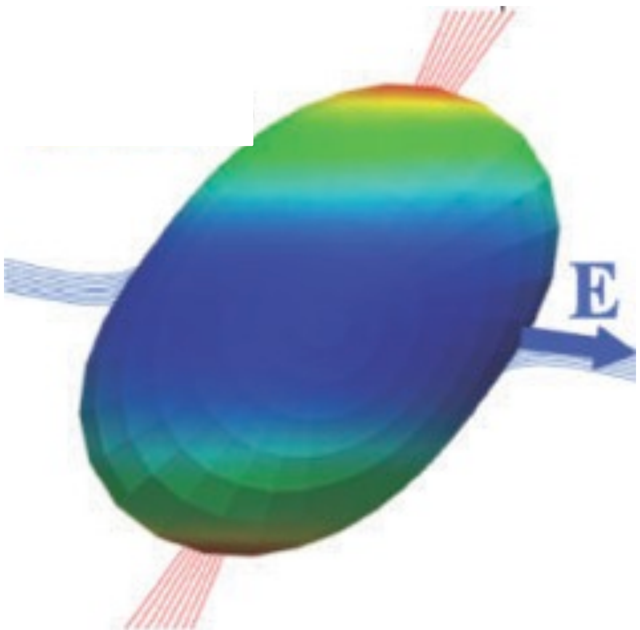
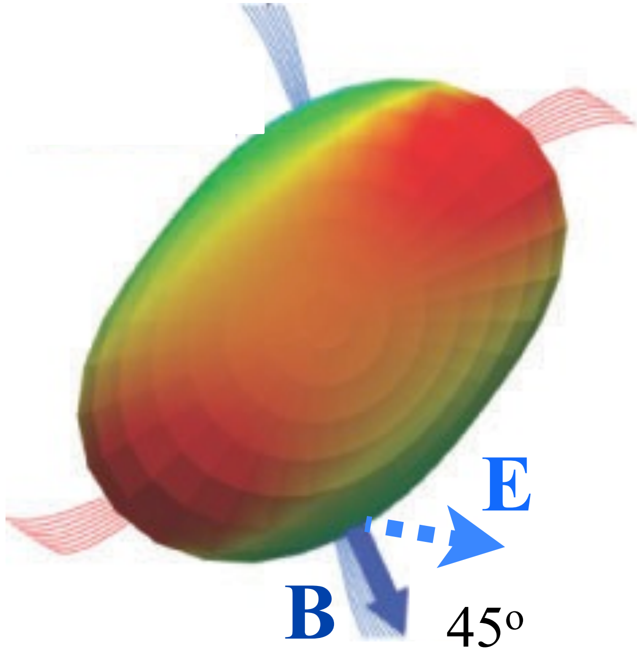
What causes the Kick?

Immediately After Merger

Near-Hole Tendexes ***Near-Hole Vortexes***





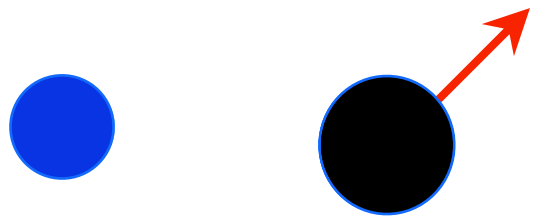
For waves going into screen: Waves from vortexes ADD to those from tendexes

For waves going out of screen: Waves CANCEL

Merged hole is kicked out of screen

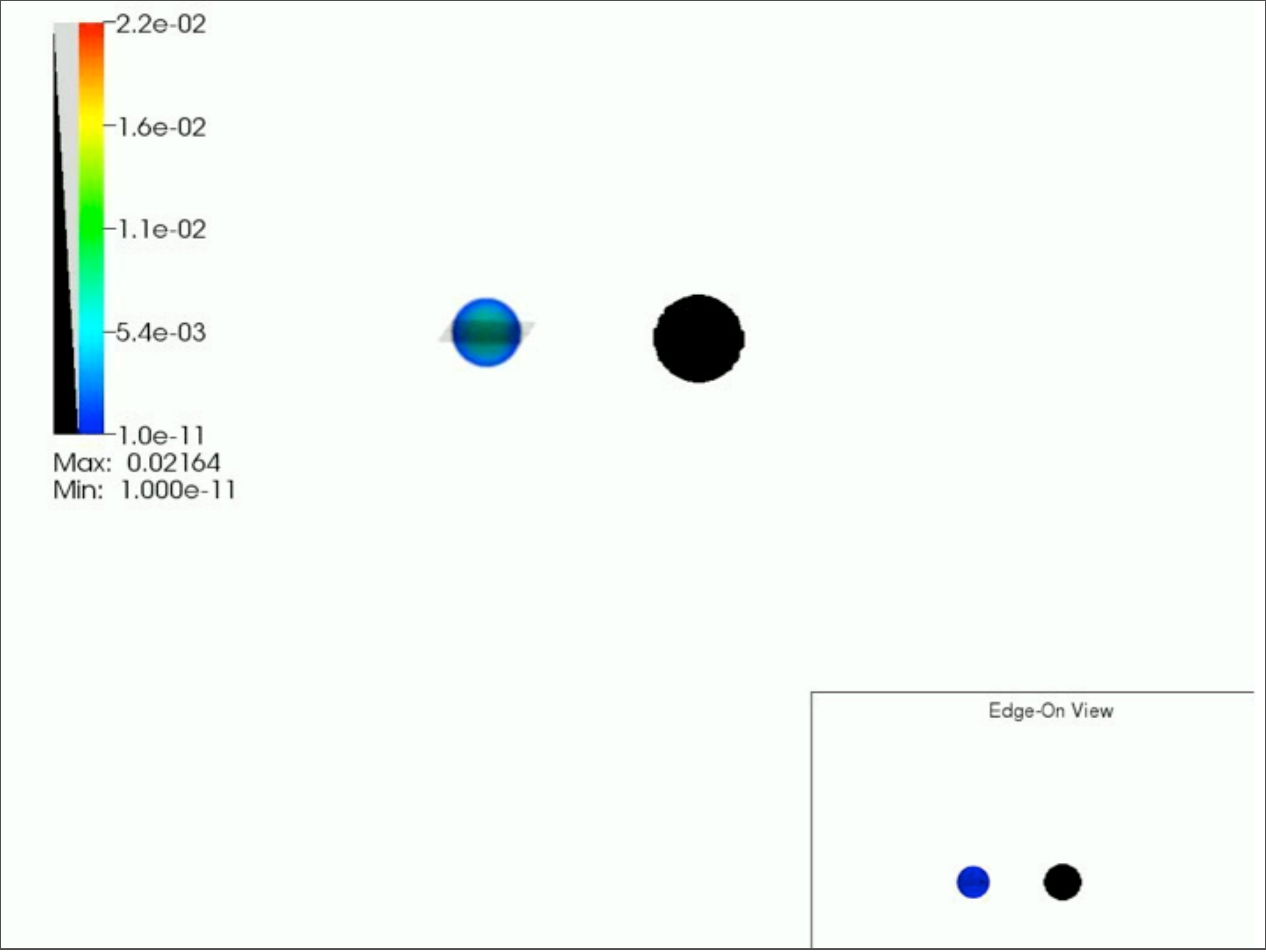
Black Hole Rips a Neutron Star Apart

- Francois Foucart, Mathew Duez, Larry Kidder, Saul Teukolsky (Cornell)



Black hole 3 times heavier than neutron star

Black hole spins at 0.5 maximum rate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1.6e-02
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Max: 0.02164
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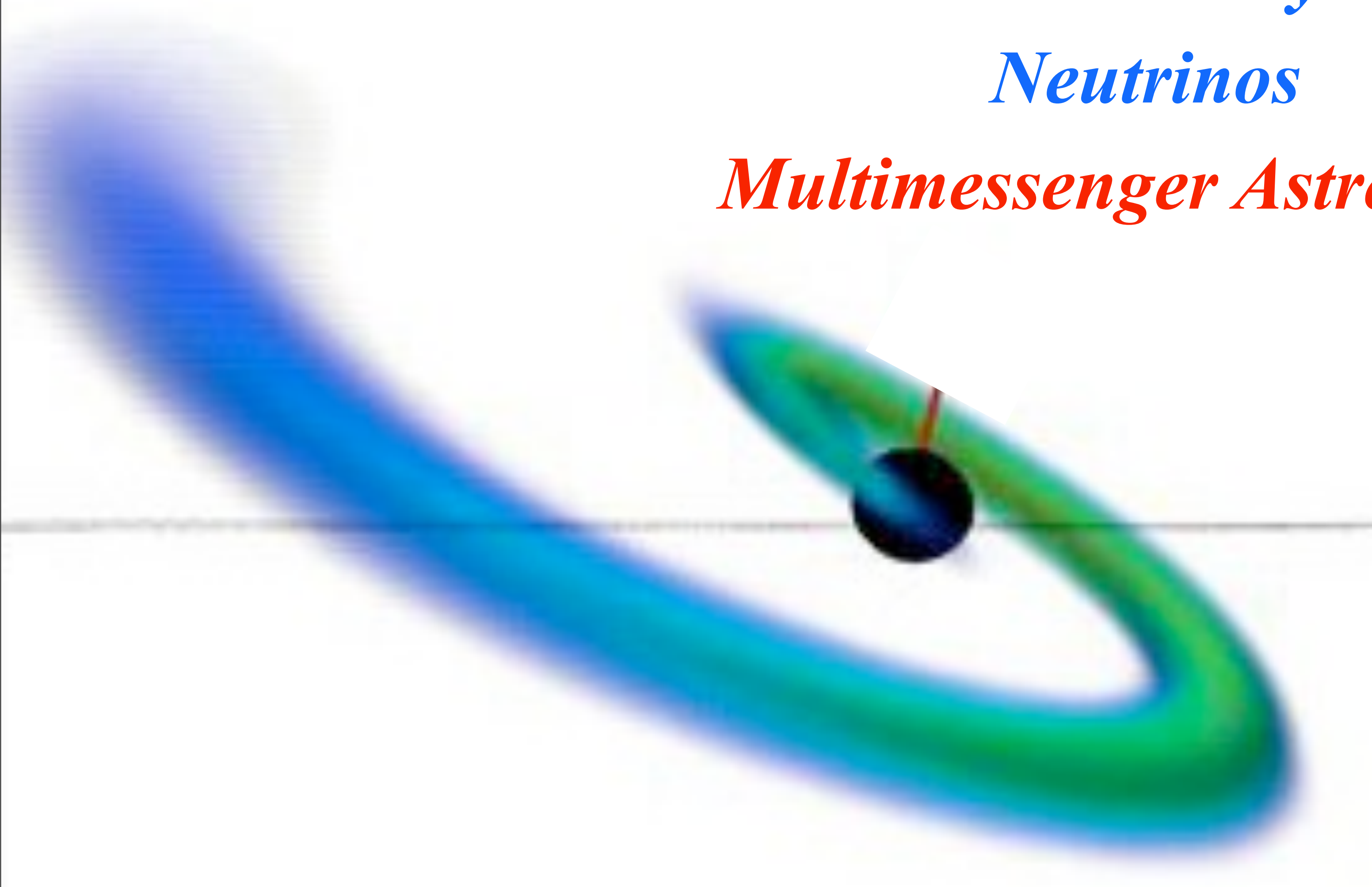
Edge-On View

Gravitational Waves

Gamma Rays

Neutrinos

Multimessenger Astronomy



Gravitational Waves
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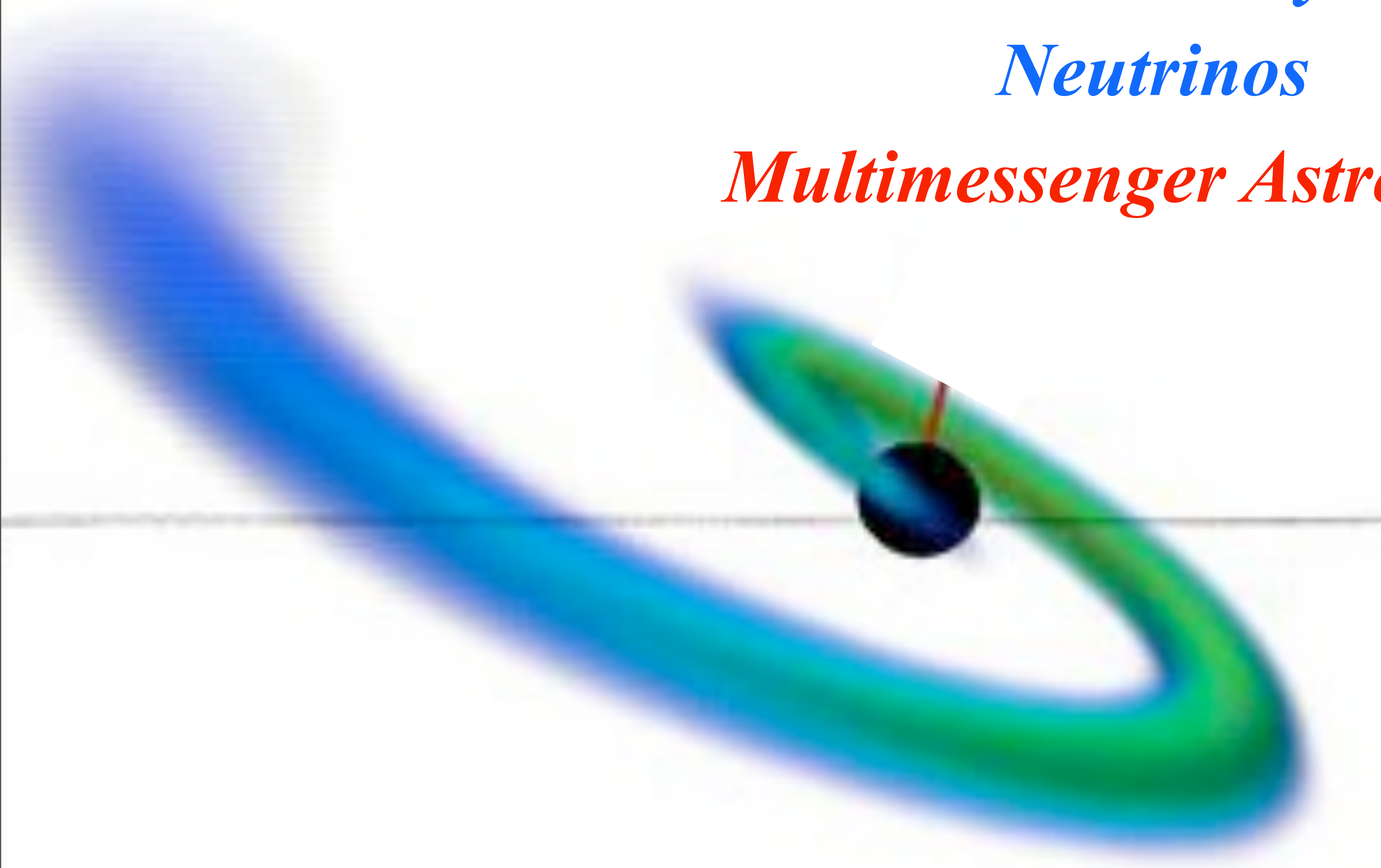

Masaru Shibata - Sunday: BH/NS Binaries

Black String in 4+1 Dimensions: Gregory/LaFlamme Instability

- Luis Lehner & Frans Pretorius,
  Phys Rev Lett **105**, 101102 (2010)
  - » self-similar cascade: smaller holes connected by thinner strings
  - » spacetime singularity in finite proper time
  - » violation of cosmic censorship

Lehner's Lecture - Saturday

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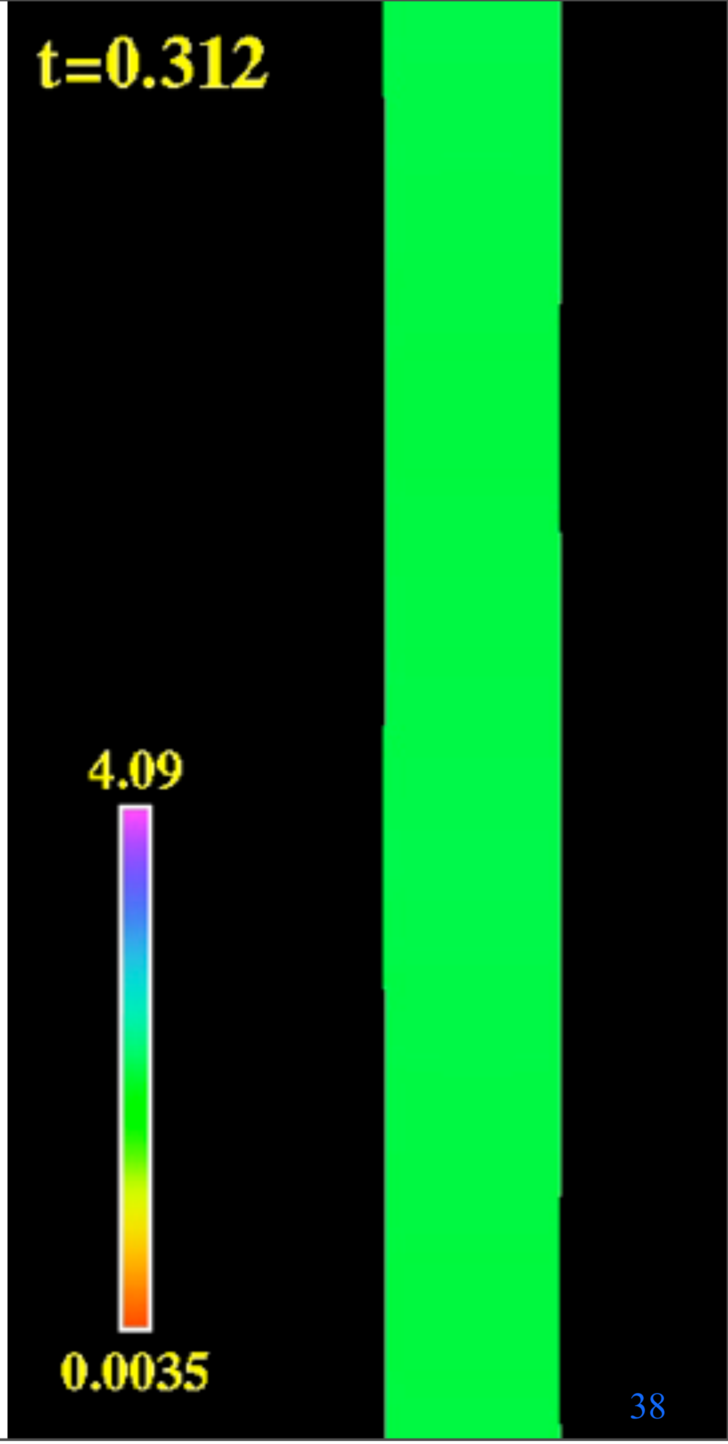

Gravitational Wave Observations of BHs

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Ground-based Interferometers	Wave Frequencies	Black holes:
	10 Hz to 10,000 Hz “high-frequencies”	2 to one thousand solar masses

Gravitational Wave Observations of BHs

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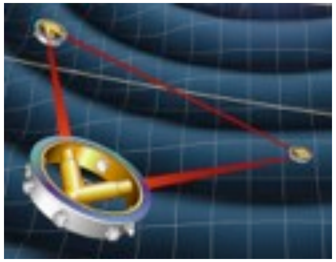
Space-based Interferometers 	Wave Periods 10 sec to 3 hours “low-frequencies”	Black holes: 10 thousand to 10 million solar masses

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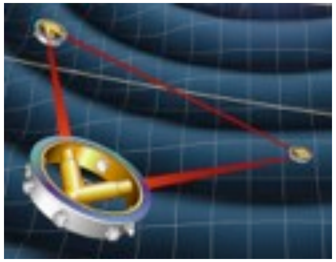
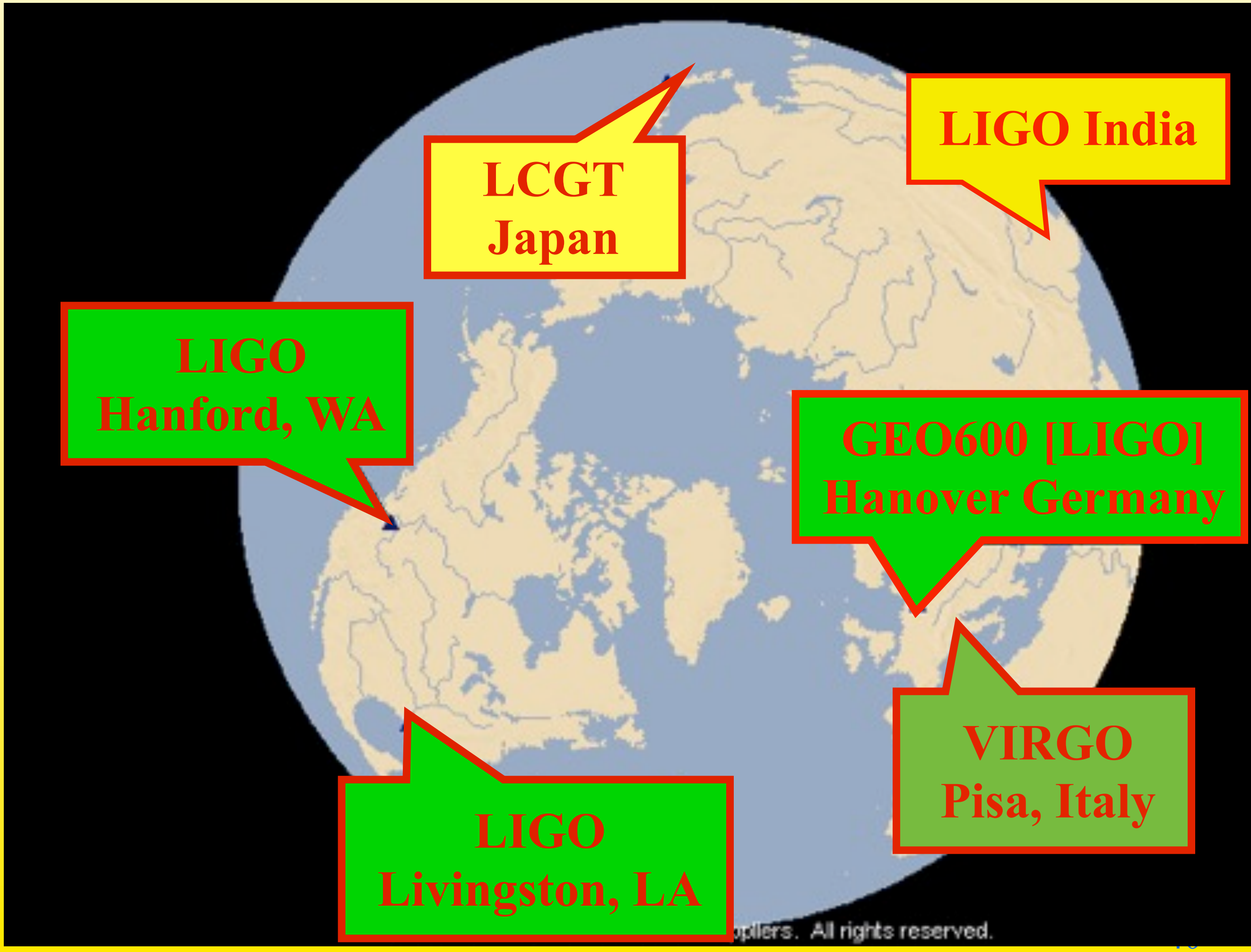
Space-based Interferometers 	Wave Periods 10 sec to 3 hours "low-frequencies"	Black holes: 10 thousand to 10 million solar masses
Pulsar Timing 	Wave Periods A month to 30 years "very low frequencies"	Black holes: 100 million to 10 billion solar masses

Earth-Based GW Interferometers

Small black holes in distant galaxies:

Masses: ~10 to 1000 Suns . ~ 10 to 1000 km size

Stan Whitcomb's Lecture Sunday



Earth-Based GW Interferometers

Small black holes in distant galaxies:

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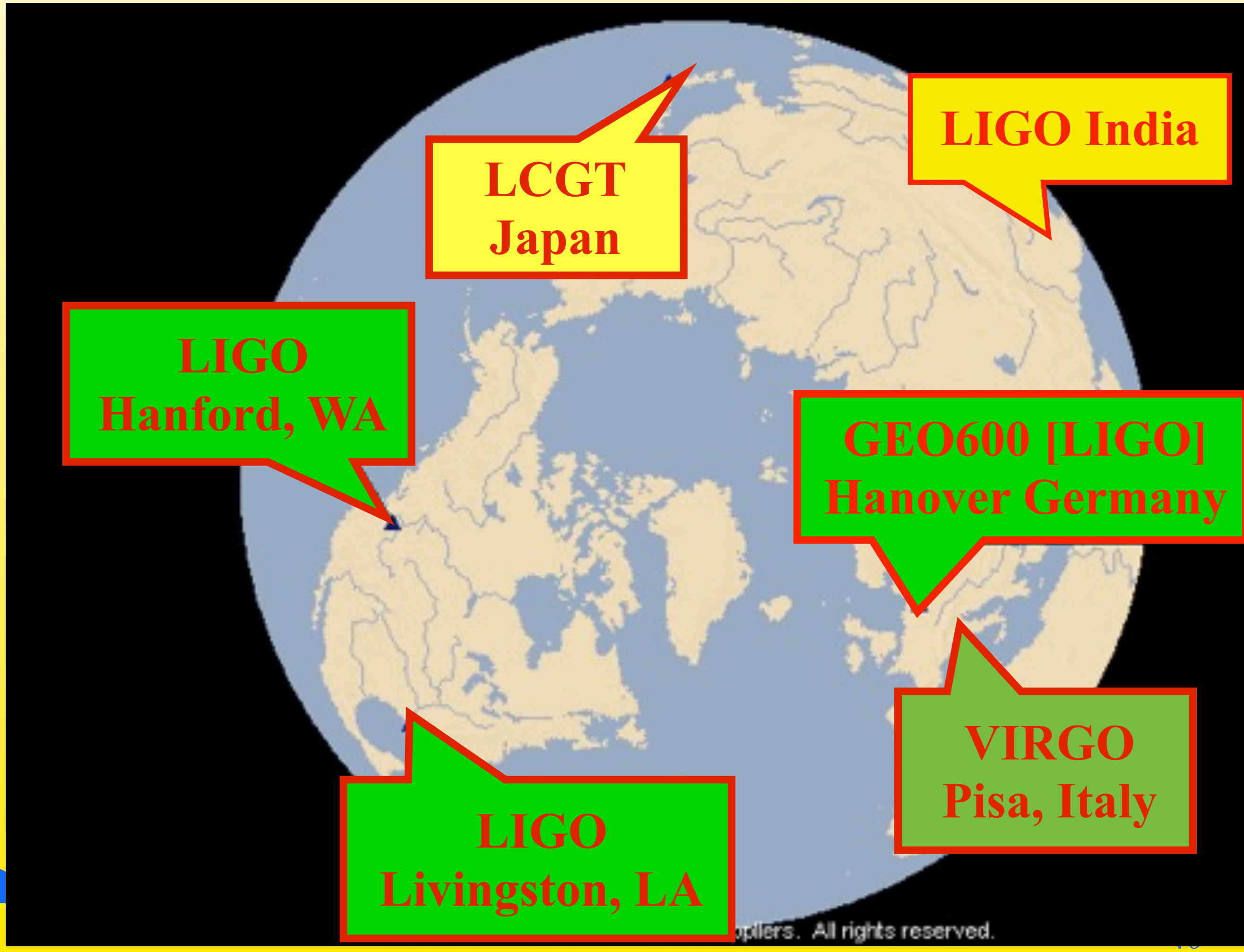
Stan Whitcomb's Lecture Sunday

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



LIGO: **Laser Interferometer Gravitational Wave Observatory**

Collaboration of 800 scientists at 75 institutions in 13 nations

USA, UK, Germany, India, Australia, Spain, Canada, China, Hungary, Japan, Korea, Poland, Russia

[David Reitze, Director; Gabriella Gonzalez, Spokesperson]

Sequence of Interferometers in LIGO

100 million
light years

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- 1989 Proposal for LIGO: 2-step strategy:
  - » ***Initial interferometers*** *- plausible but not likely to see GWs*

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- Initial interferometers, 2005-10:
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  - » *none seen yet*
- Advanced interferometers: installation began October 2010. Searches near design sensitivity 2017 - … LIGO-India 2020- ...
  - » *BH/BH out to 4 billion light years: ~3/yr - 1/day*
  - » *Many other sources.*

Bernard Schutz, Saturday
GW Astronomy

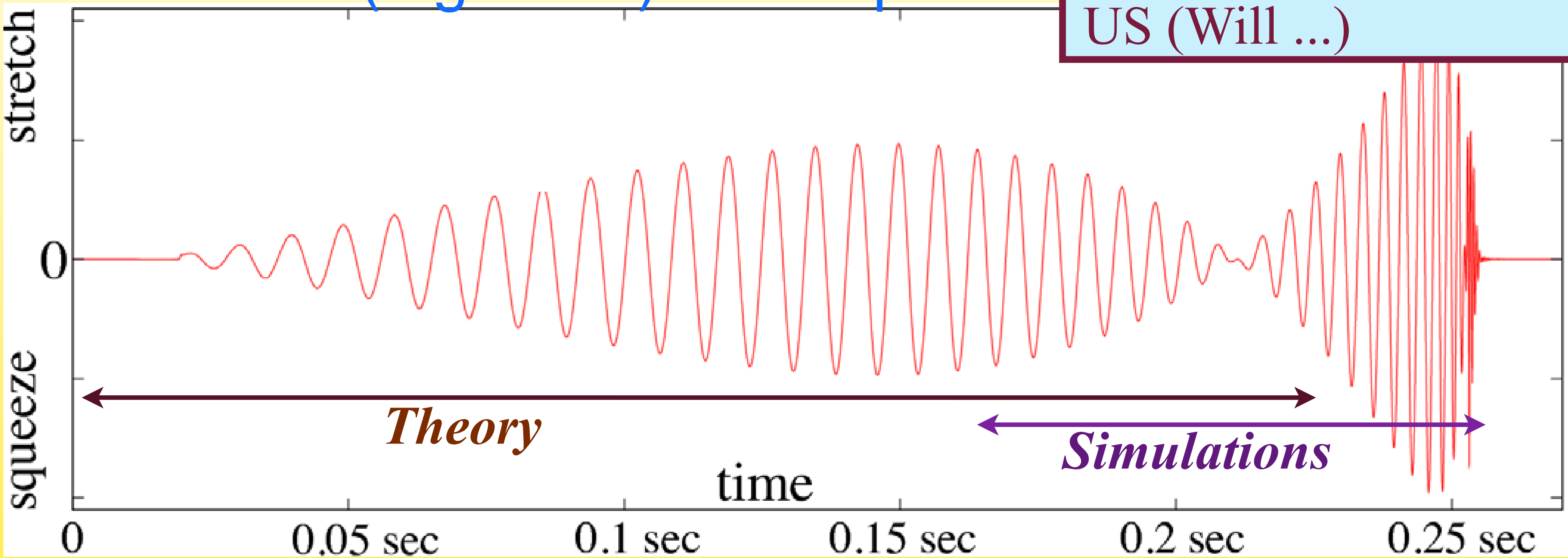
Gravitational Waveforms

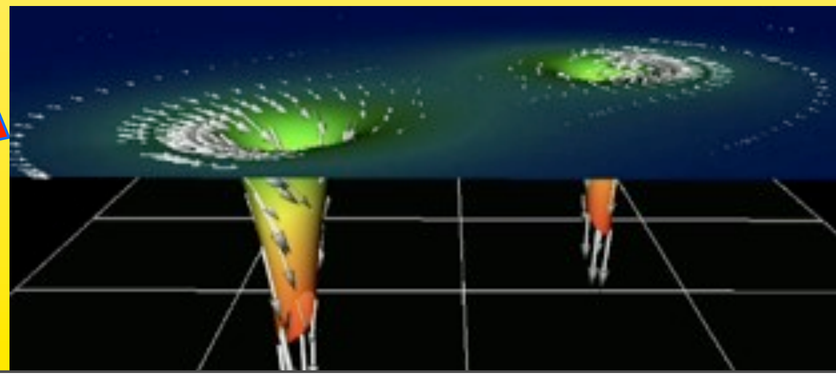
Dictionary: Post-Newtonian Theory

Plus Numerical simulations

➙ Formula (e.g. EOB) for templates

India (Iyer, ...) +
France (Blanchet, ...) +
US (Will ...)





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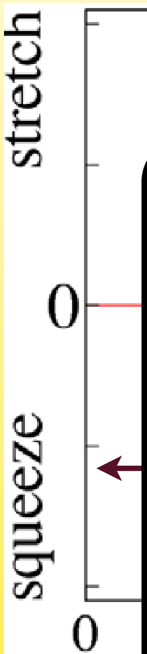
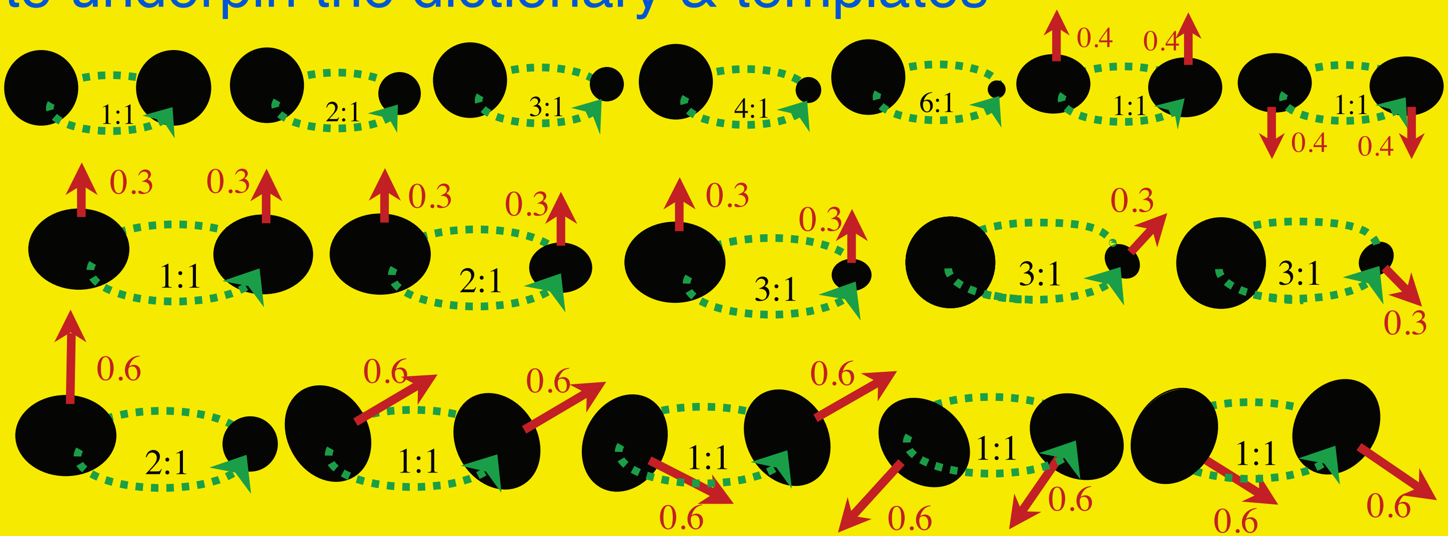
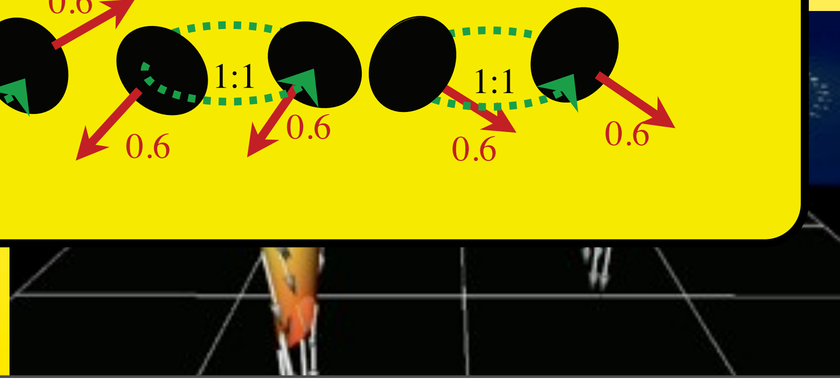
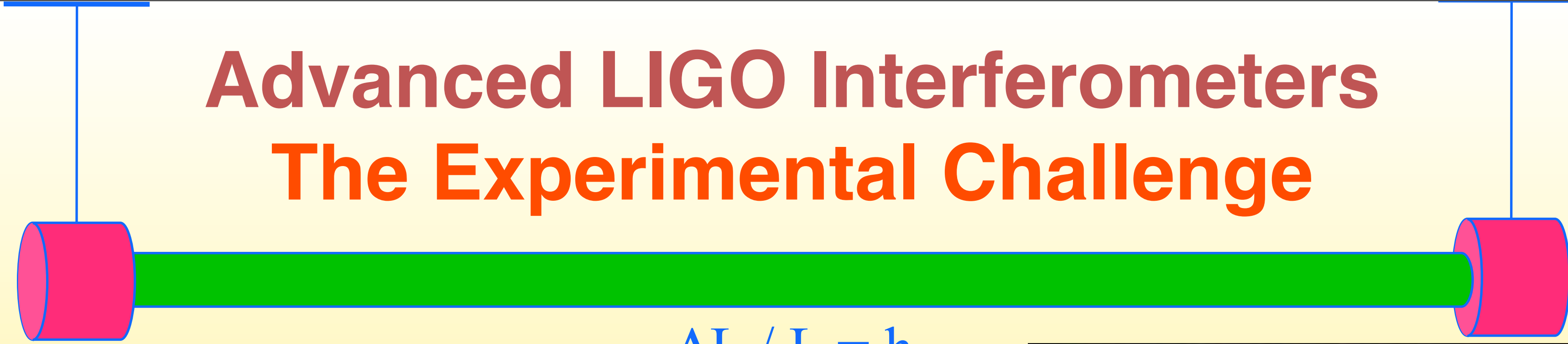


- NR/AR Collaboration: Now carrying out ~1000 simulations to underpin the dictionary & templates

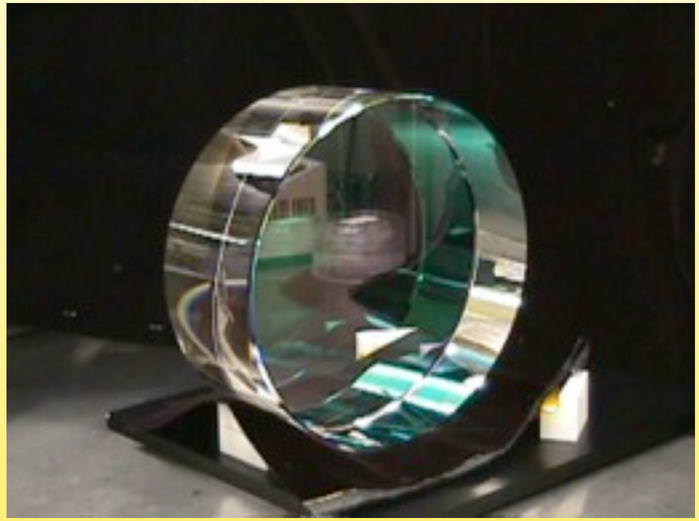




Advanced LIGO Interferometers
The Experimental Challenge



$\Delta L / L = h$



- **Monitor motions of 40 kg mirrors to:**
  - » $\Delta L \sim 10^{-17}$ cm
  - » ~ size where mirror behaves quantum mechanically

Advanced LIGO Interferometers
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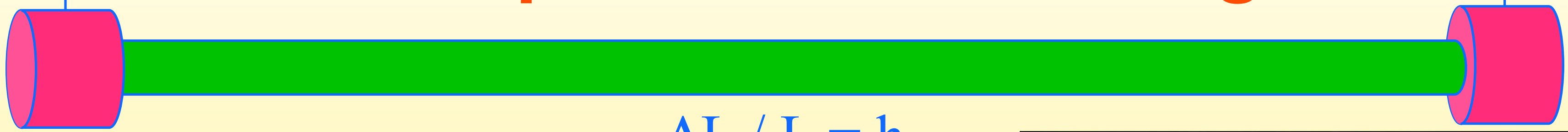

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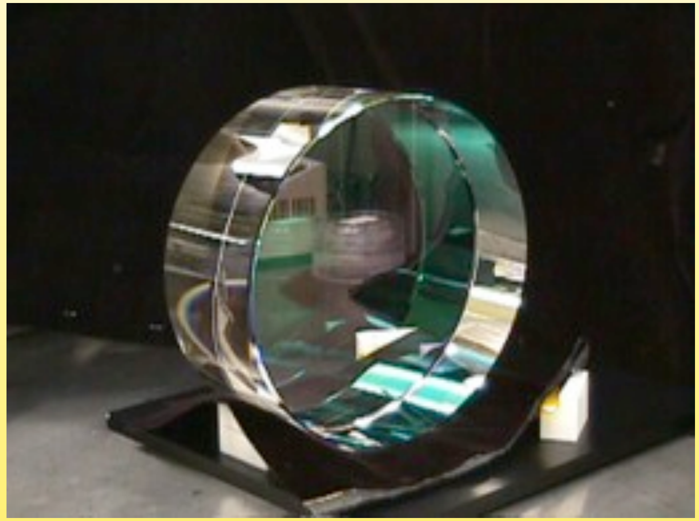


- **Monitor motions of 40 kg mirrors to:**
  - » $\Delta L \sim 10^{-17}$ cm
  - » ~ size where mirror behaves quantum mechanically

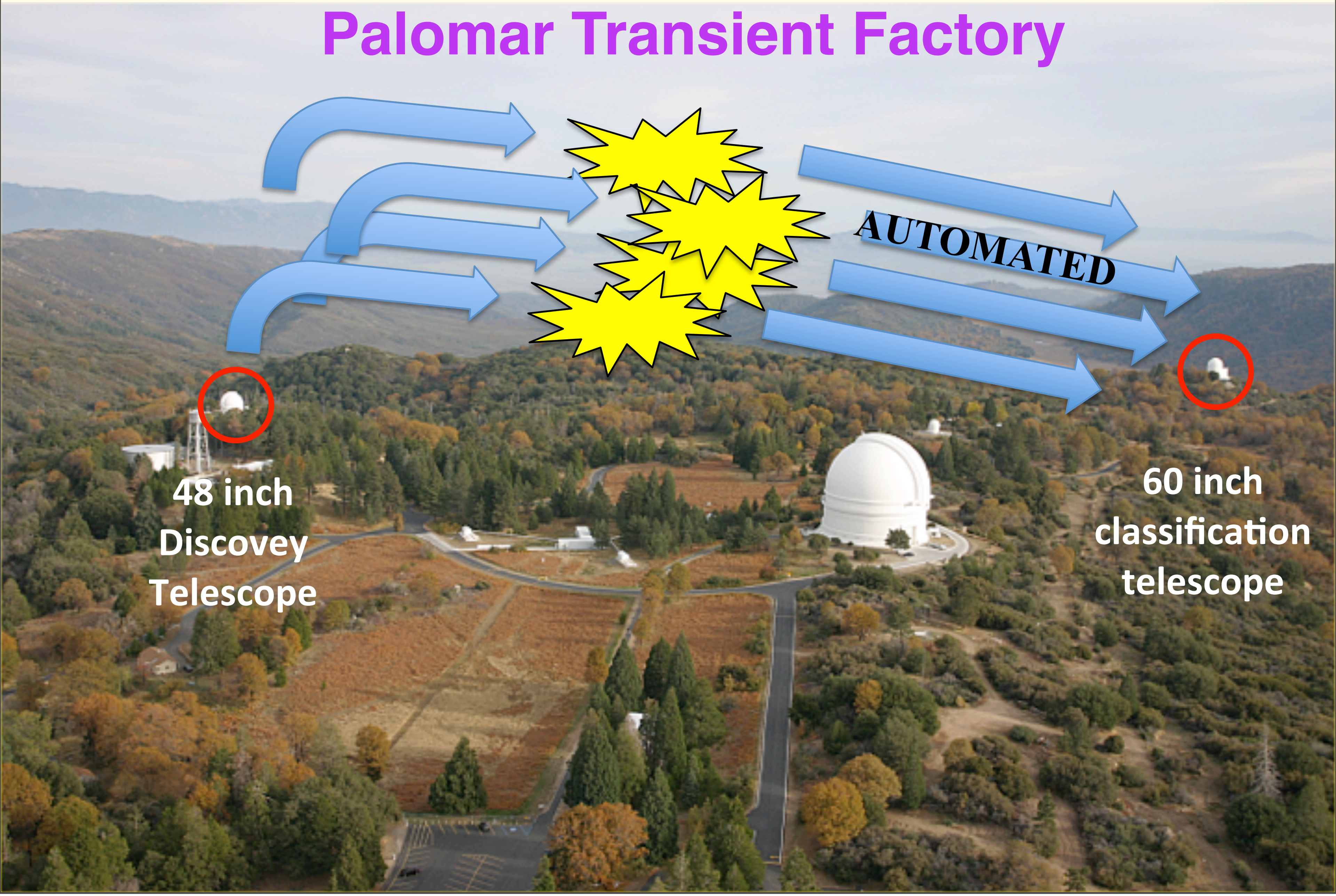
For the first time humans will see human-sized objects behave quantum mechanically!

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

Preparation for Multimessenger Astronomy:

Palomar Transient Factory

Preparation for Multimessenger Astronomy:



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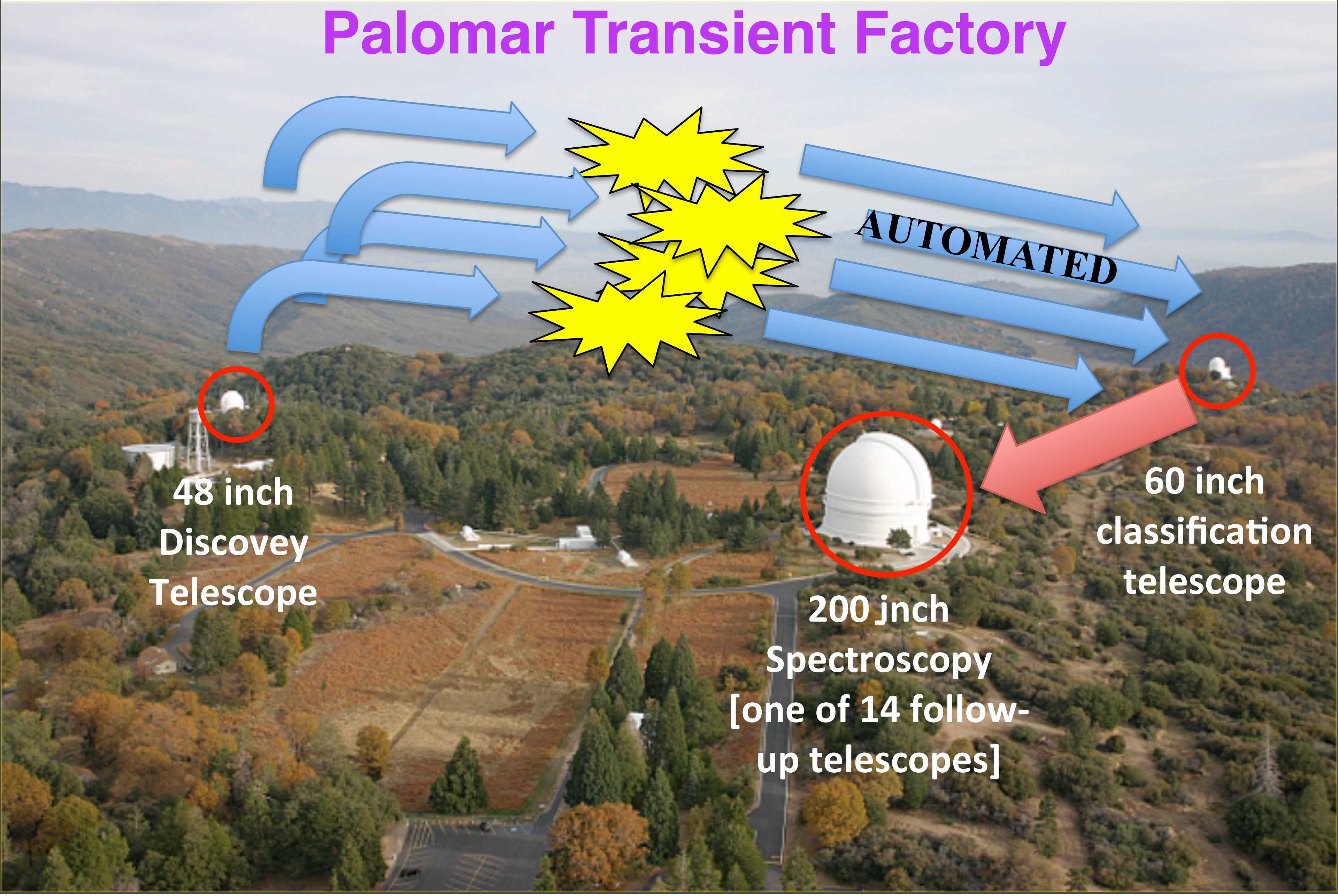
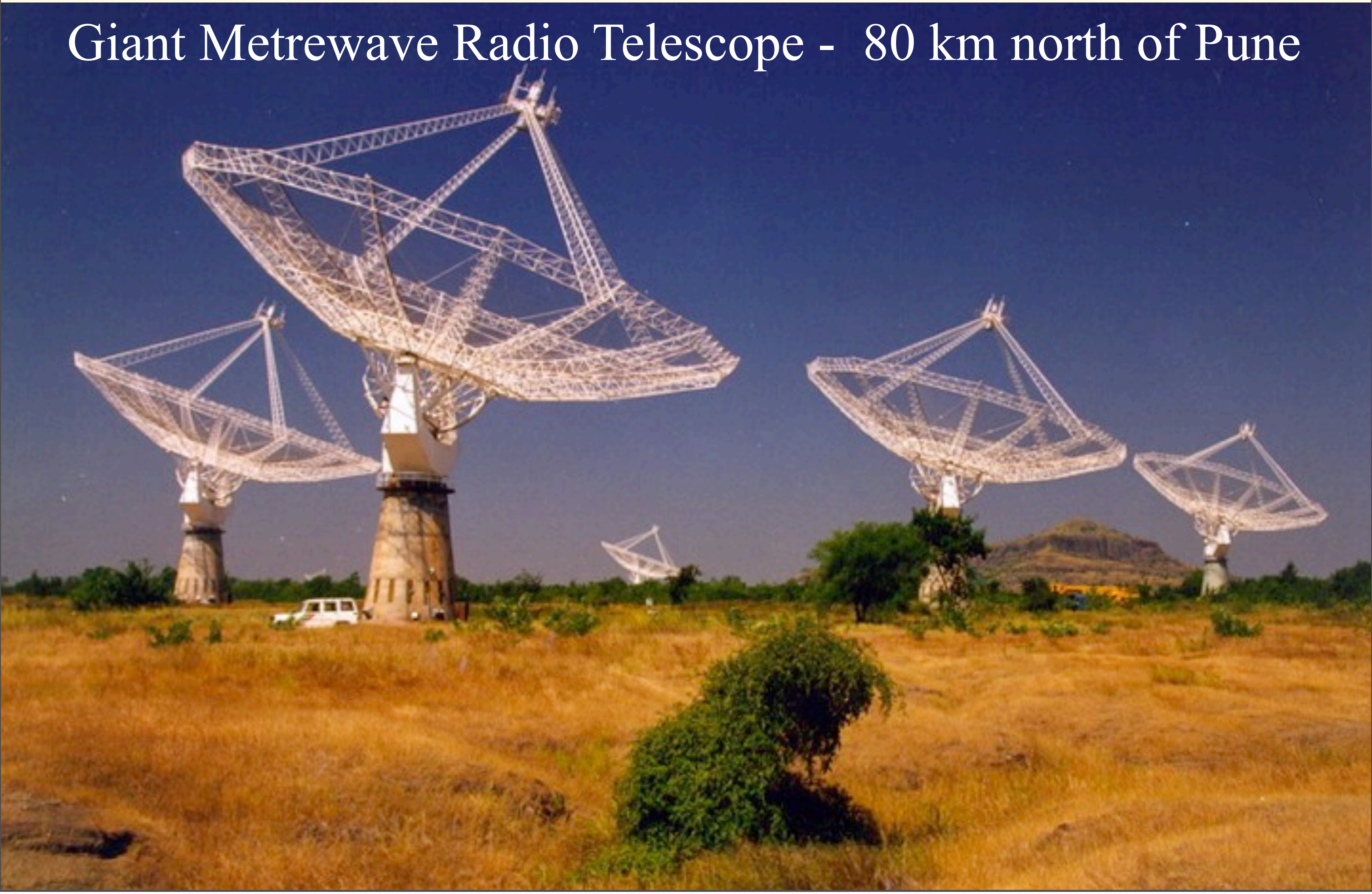


Multimessenger Astronomy



Giant Metrewave Radio Telescope - 80 km north of Pune

Problem:
Good Enough GW Angular Resolution for Multi-Messenger Astronomy

Whitcomb Talk - Sunday

Problem:
Good Enough GW Angular Resolution for Multi-Messenger Astronomy

SOLUTION:
LIGO-INDIA

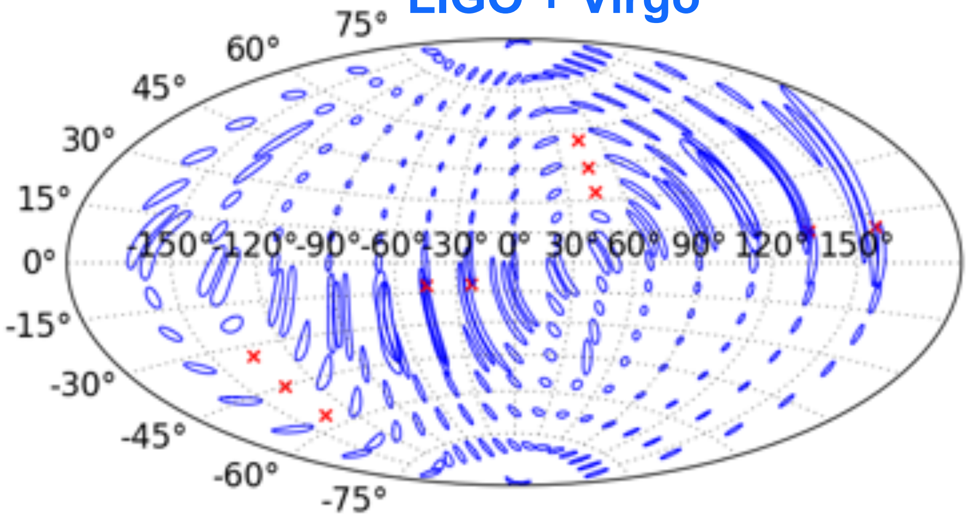
IndIGO *- consortium of 10 Indian National Institutions*

Whitcomb Talk - Sunday

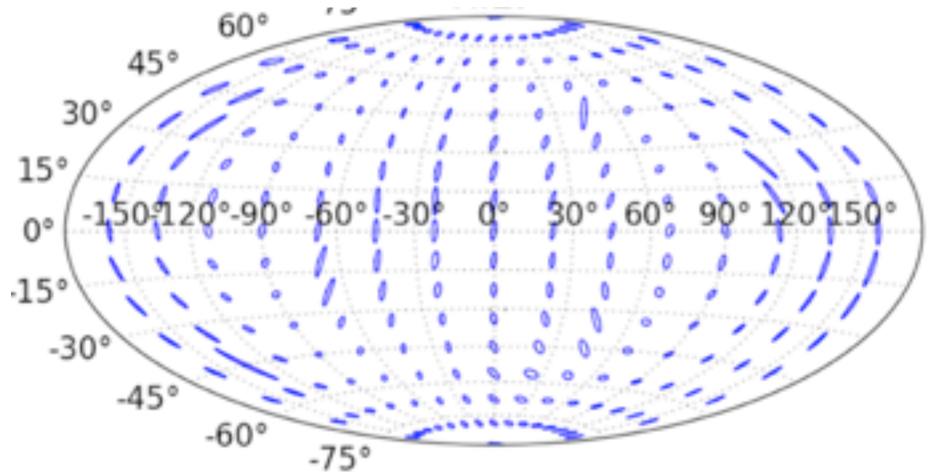
What LIGO-India Brings to Network

Determination of source sky position: NS-NS

LIGO + Virgo



With LIGO-India



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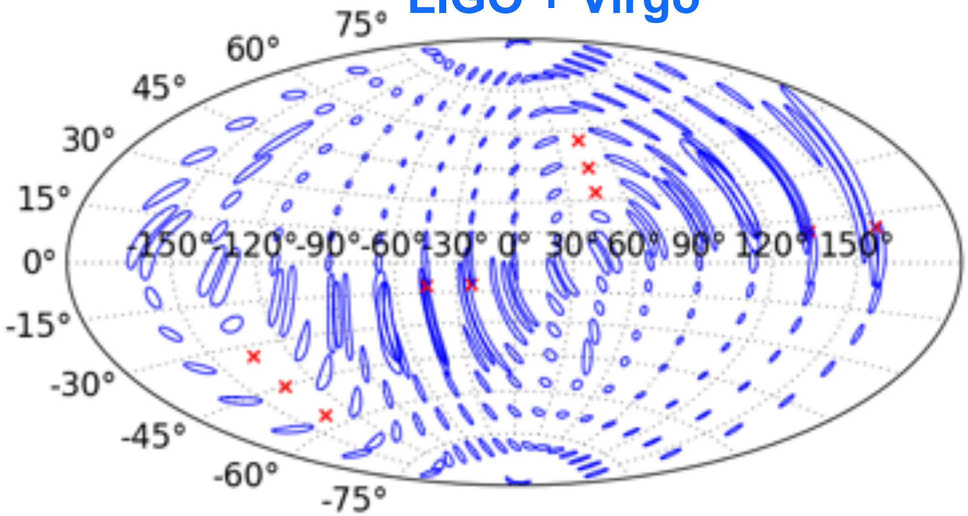

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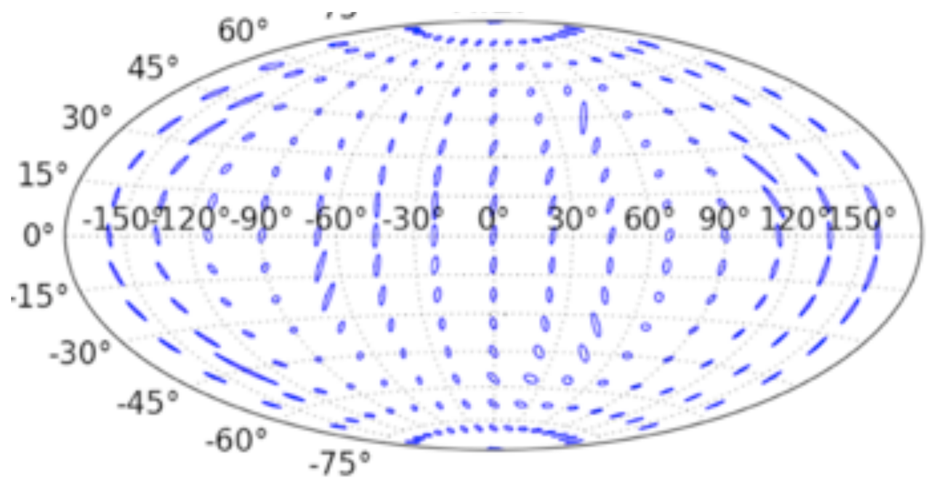

- North/South uncertainty greatly reduced

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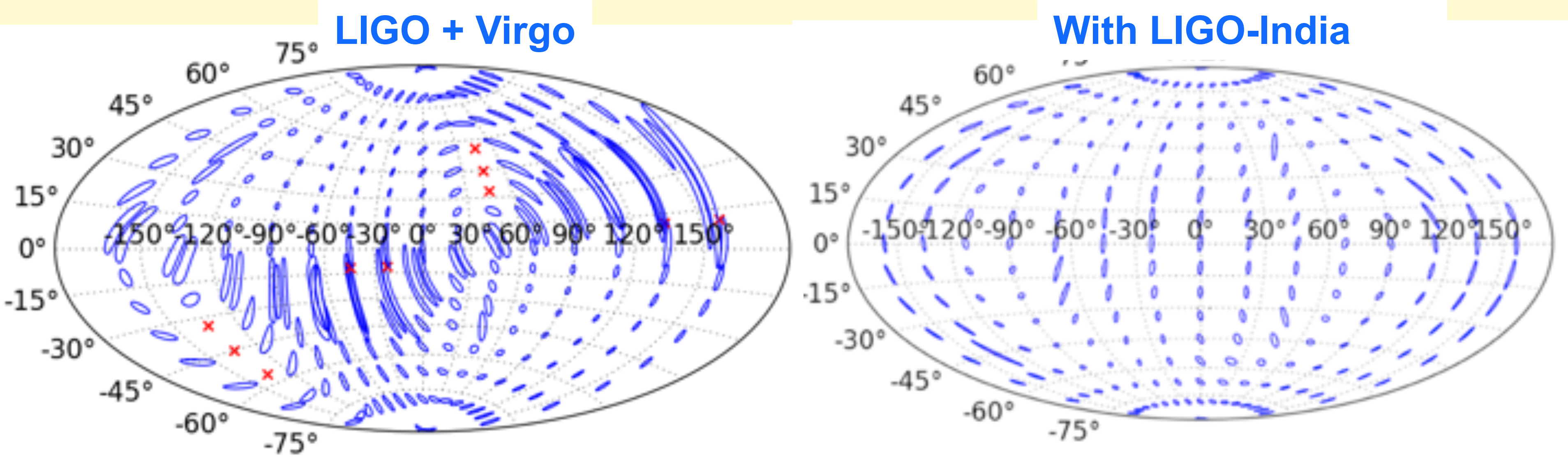

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- Average improvement in angular resolution: a factor 3.5

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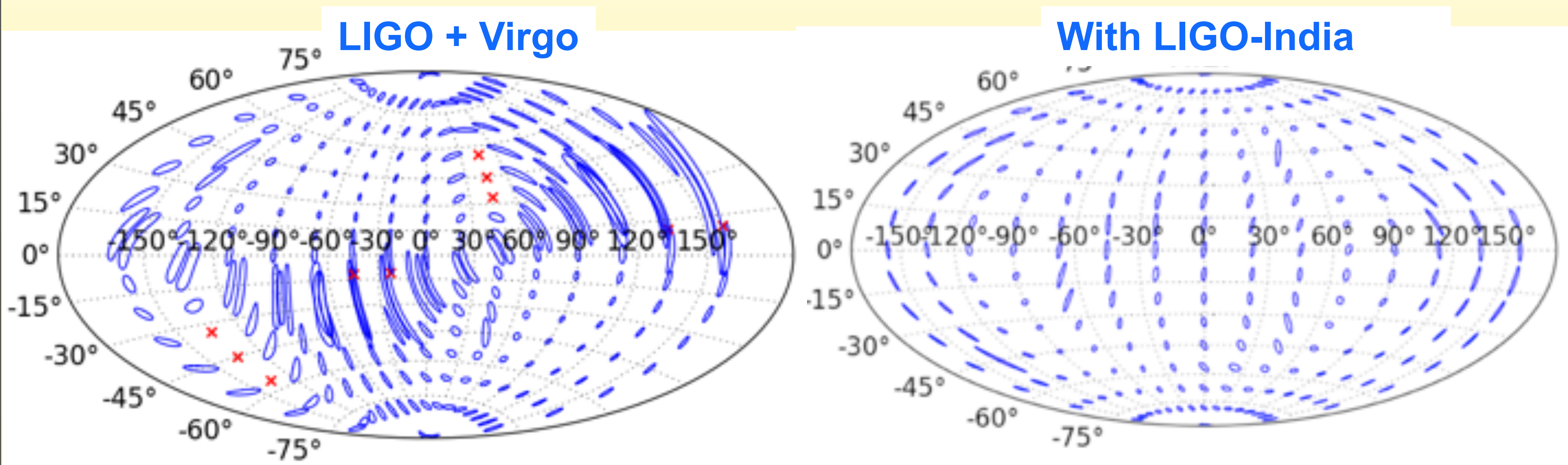

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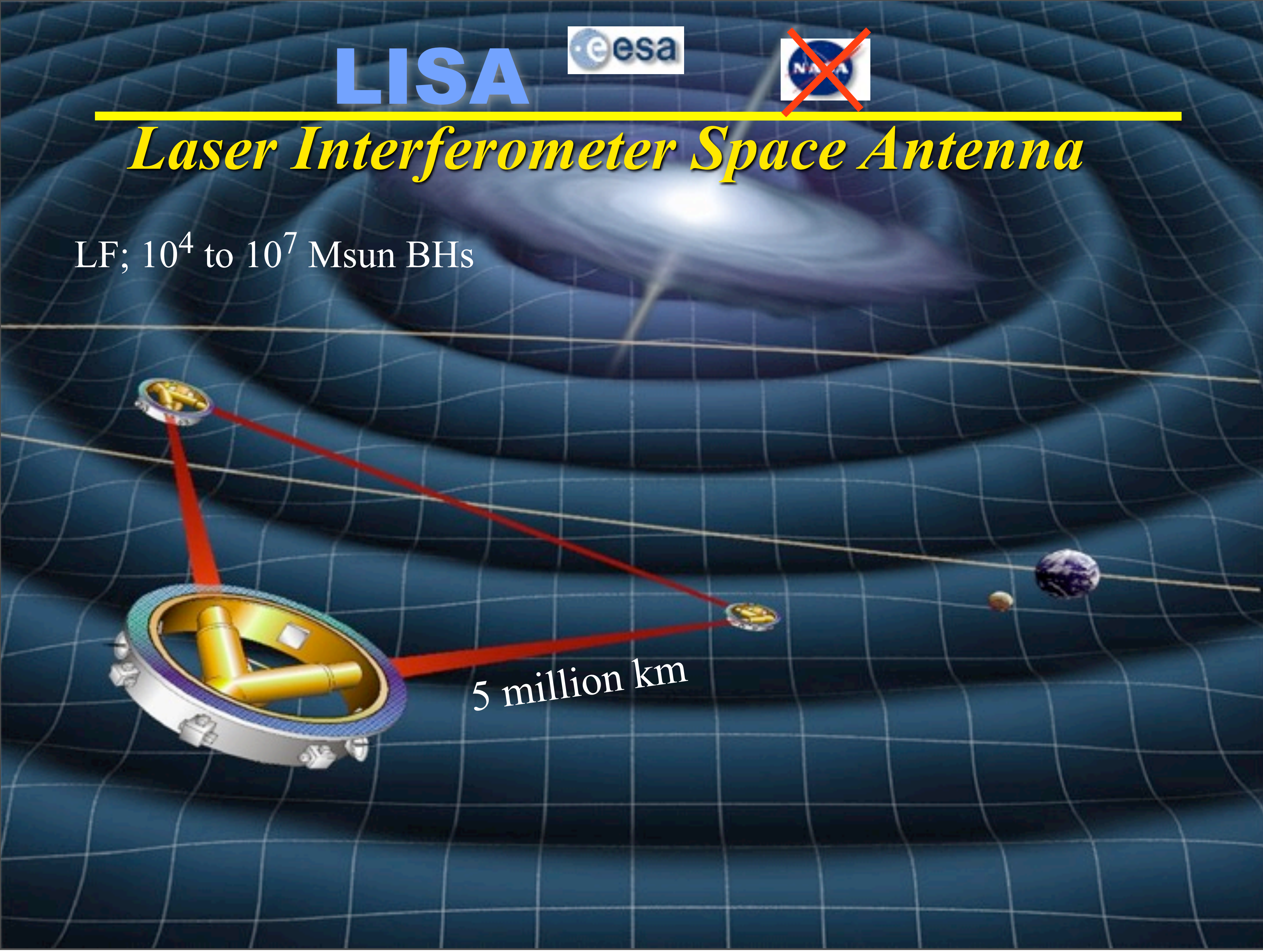
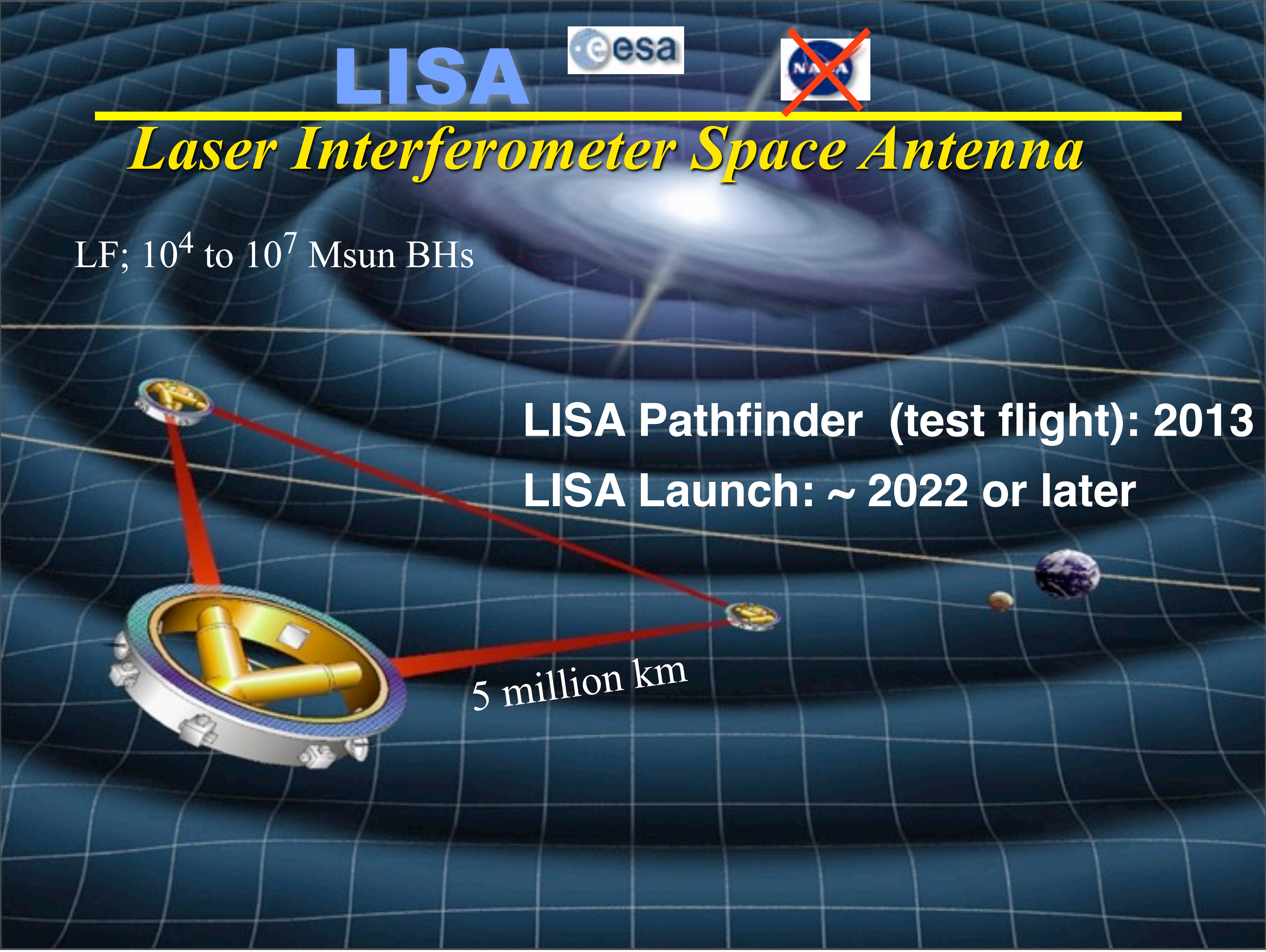
28 deg² reduced to 8 deg² (for half of sky, 90% confidence)



Monday 2 January 12


LISA
esa
Laser Interferometer Space Antenna
LF; 10^4 to 10^7 Msun BHs
LISA Pathfinder (test flight): 2013
LISA Launch: ~ 2022 or later
5 million km

LISA

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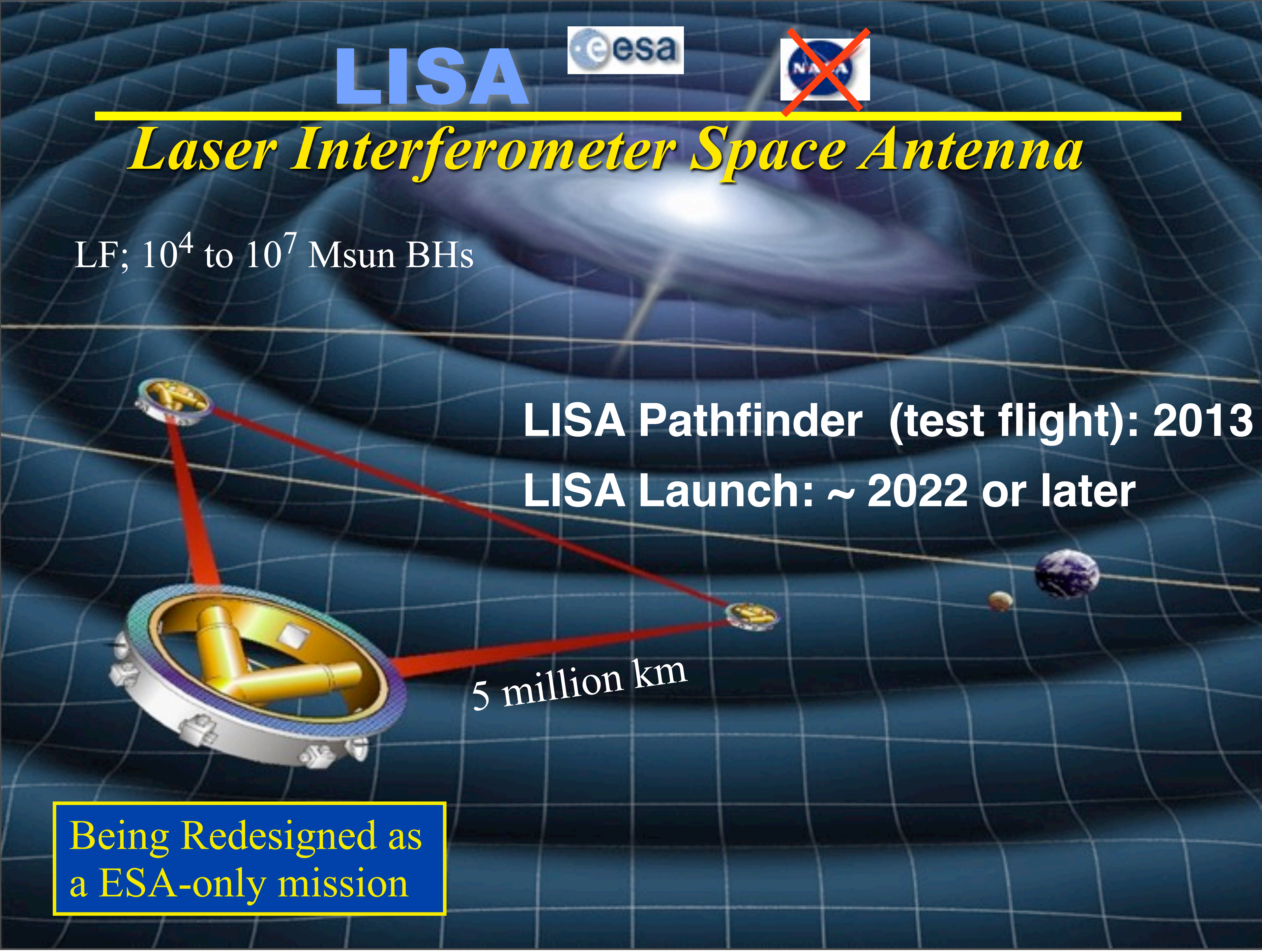
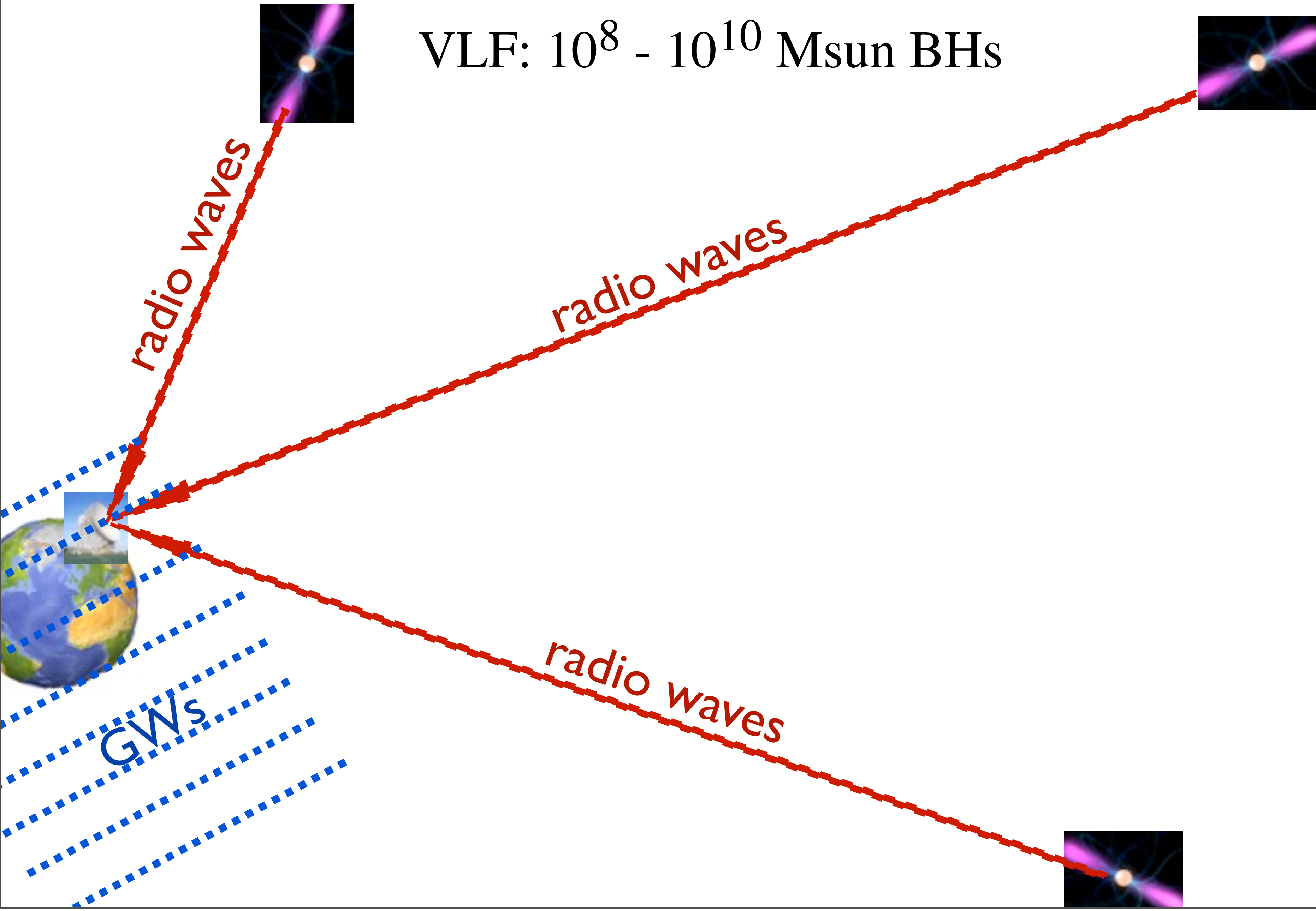


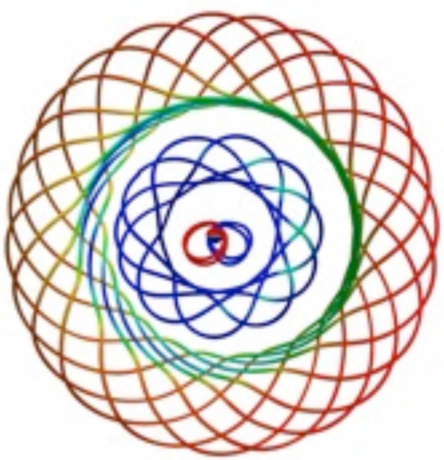
Being Redesigned as a ESA-only mission

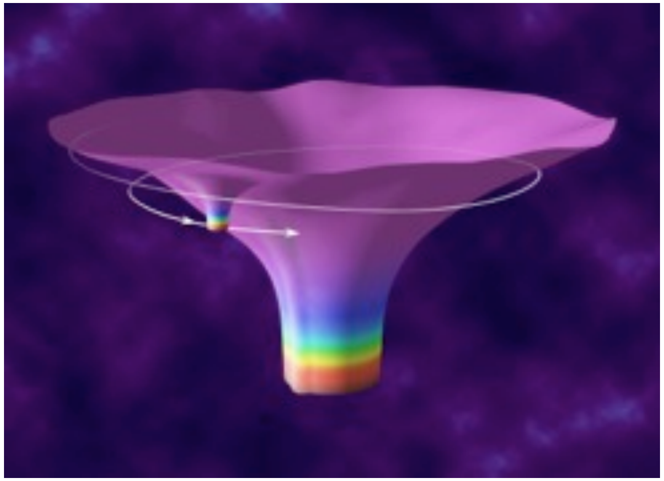
Pulsar Timing Array

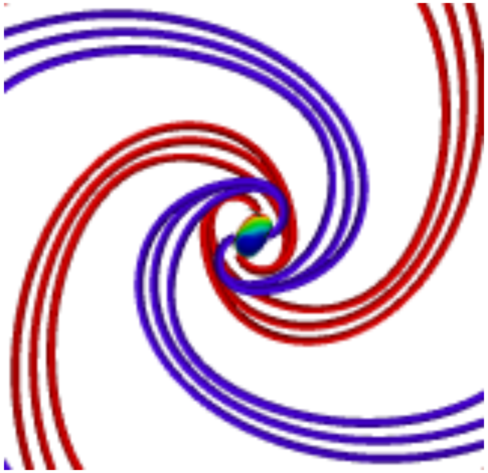
VLF: 10^8 - 10^{10} Msun BHs



Conclusion







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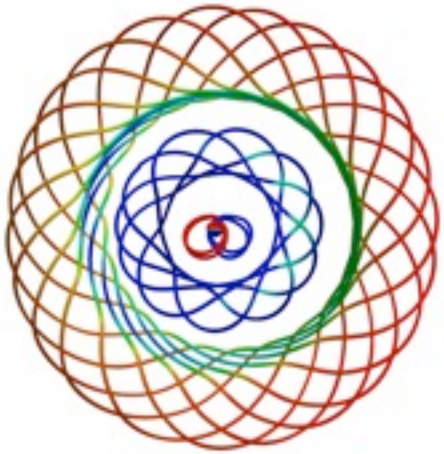
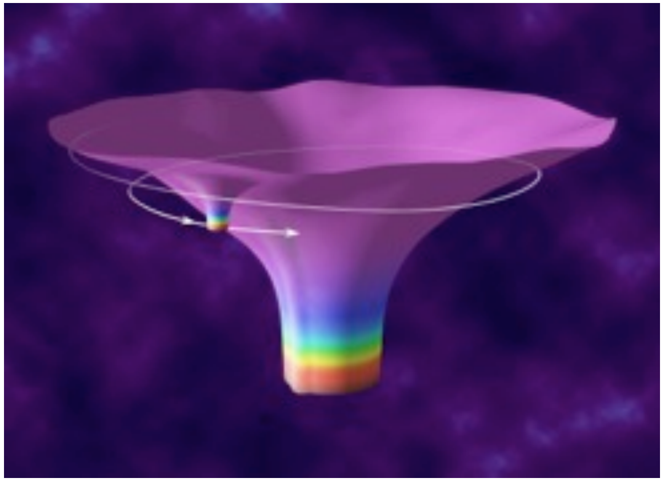
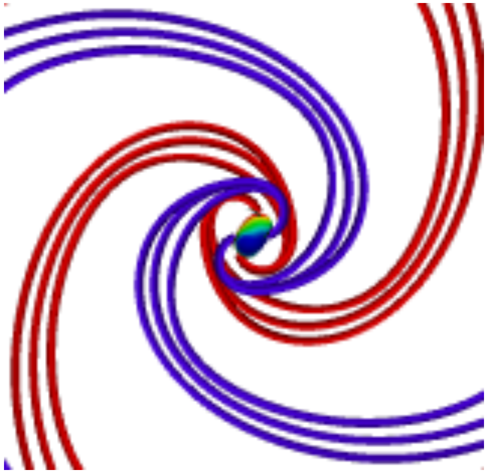
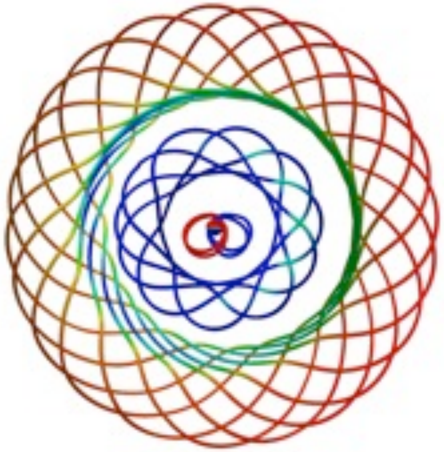


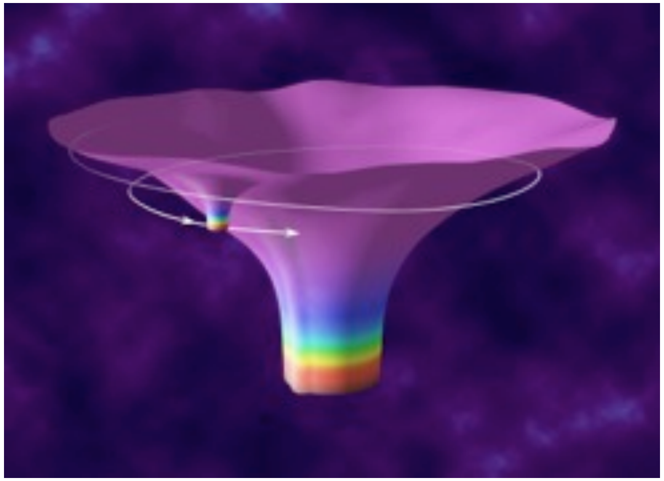


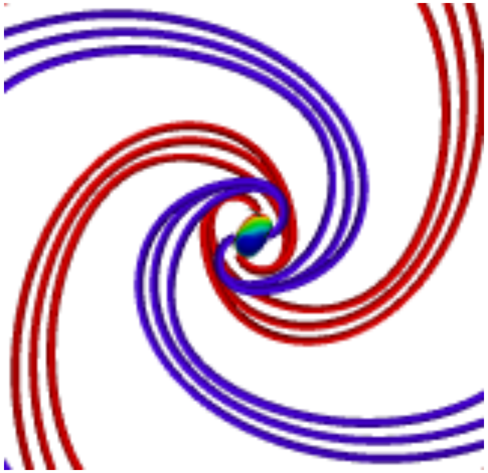


- Highly dynamical Black Holes show an amazing richness of structure and behaviors

Conclusion

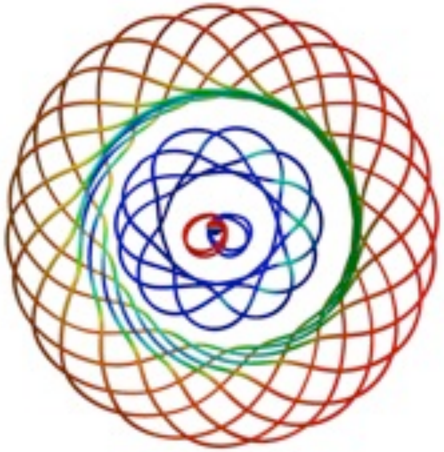


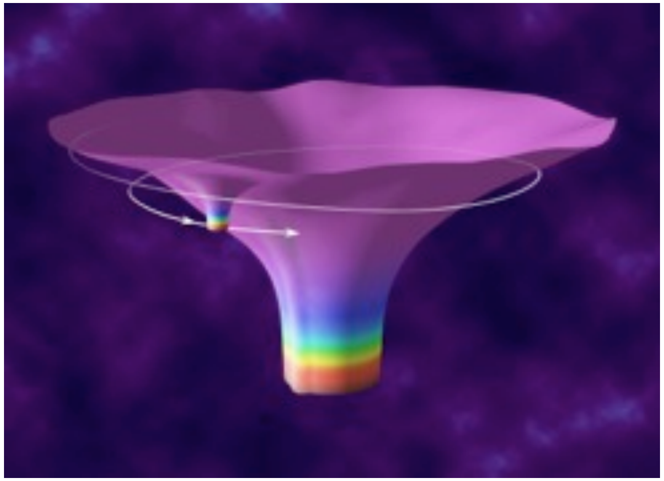


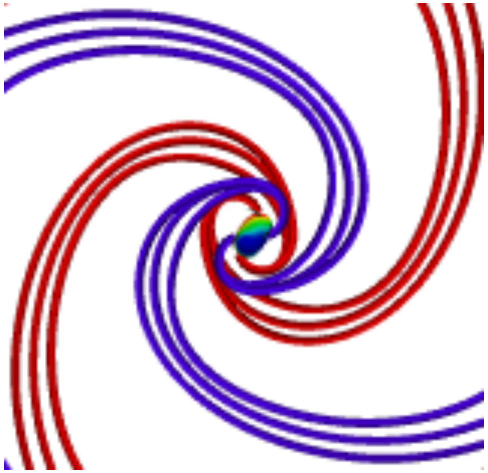


- Highly dynamical Black Holes show an amazing richness of structure and behaviors
- Numerical Relativity has become a powerful tool for probing this richness

Conclusion

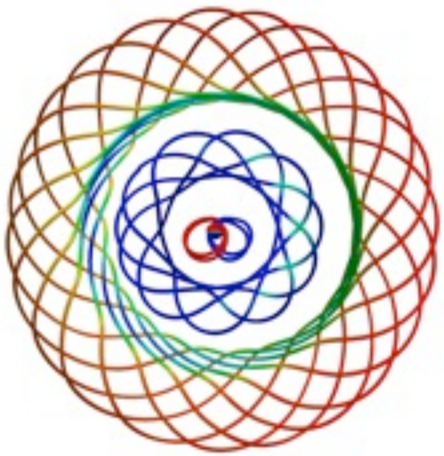


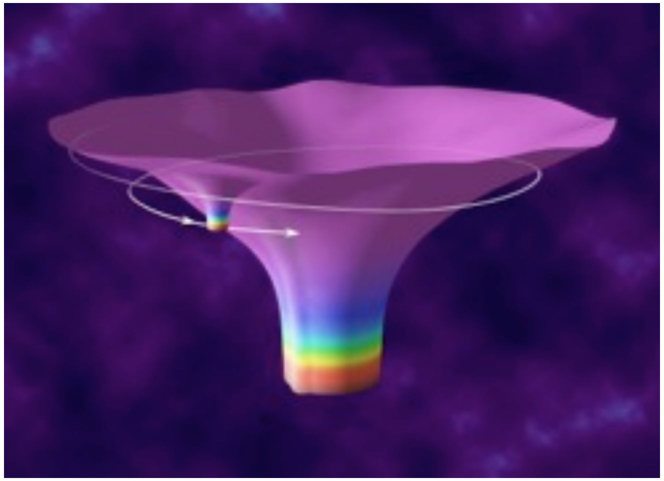


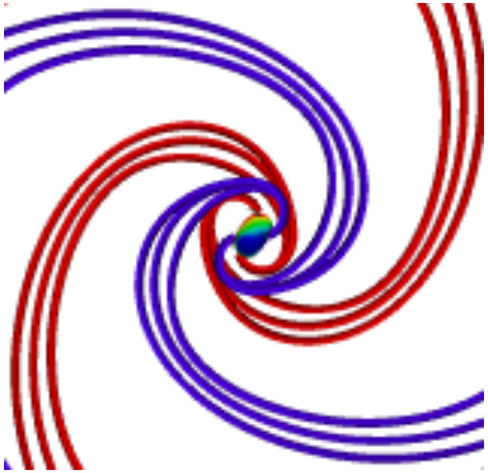


- Highly dynamical Black Holes show an amazing richness of structure and behaviors
- Numerical Relativity has become a powerful tool for probing this richness
- Gravitational Waves will bring this rich physics into the realm of observations

Conclusion







- Highly dynamical Black Holes show an amazing richness of structure and behaviors
- Numerical Relativity has become a powerful tool for probing this richness
- Gravitational Waves will bring this rich physics into the realm of observations
- A new golden age of black hole research