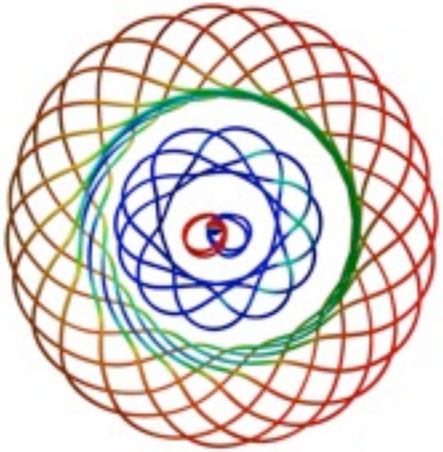
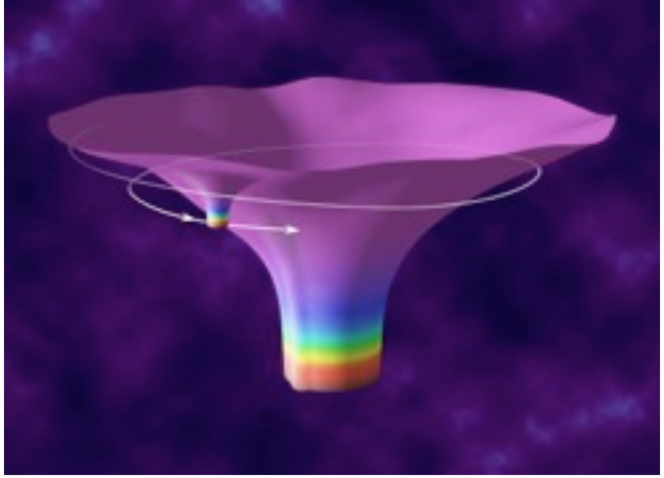
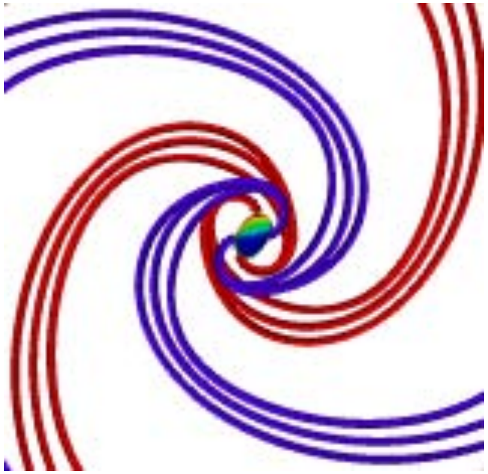
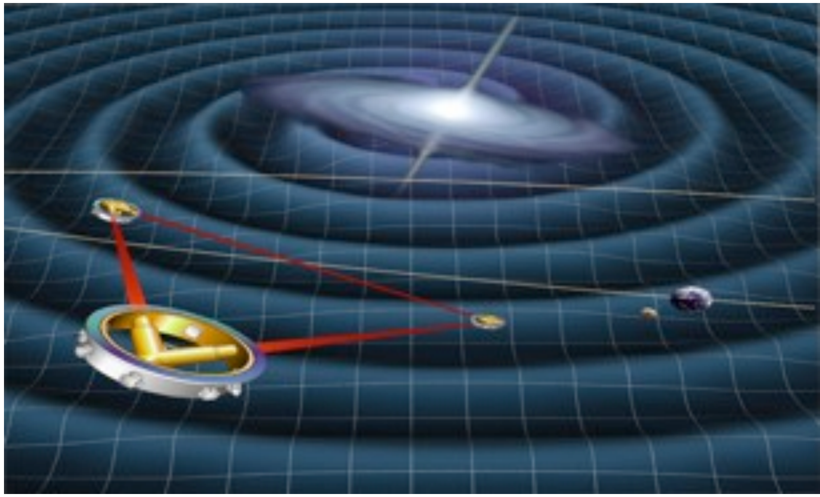
  

Black Holes: A New Golden Age

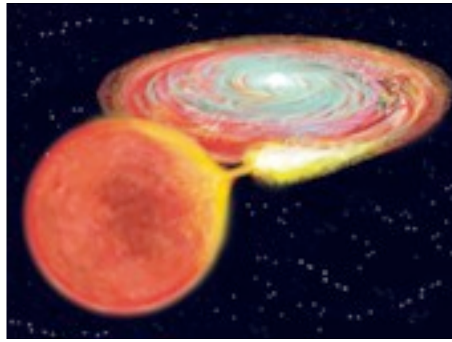
Kip Thorne

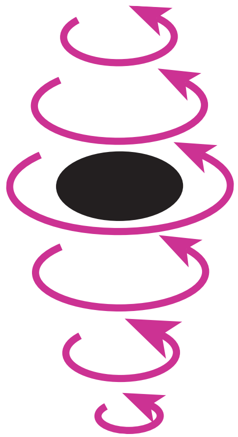
Ginzburg Conference on Physics

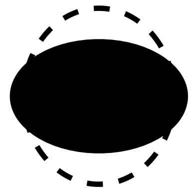
Lebedev Physical Institute, Moscow, 1 June 2012

First Golden Age of Black-Hole Research
1963 - 1977



- Driven by observational discoveries:
  - » quasars, compact X-ray sources
- Theoretical discoveries
  - » singularity at BH center
  - » BHs dynamical: spin, vibrate
  - » laws of BH mechanics
  - » Hawking radiation
  - » BH thermodynamics



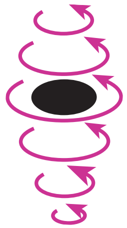


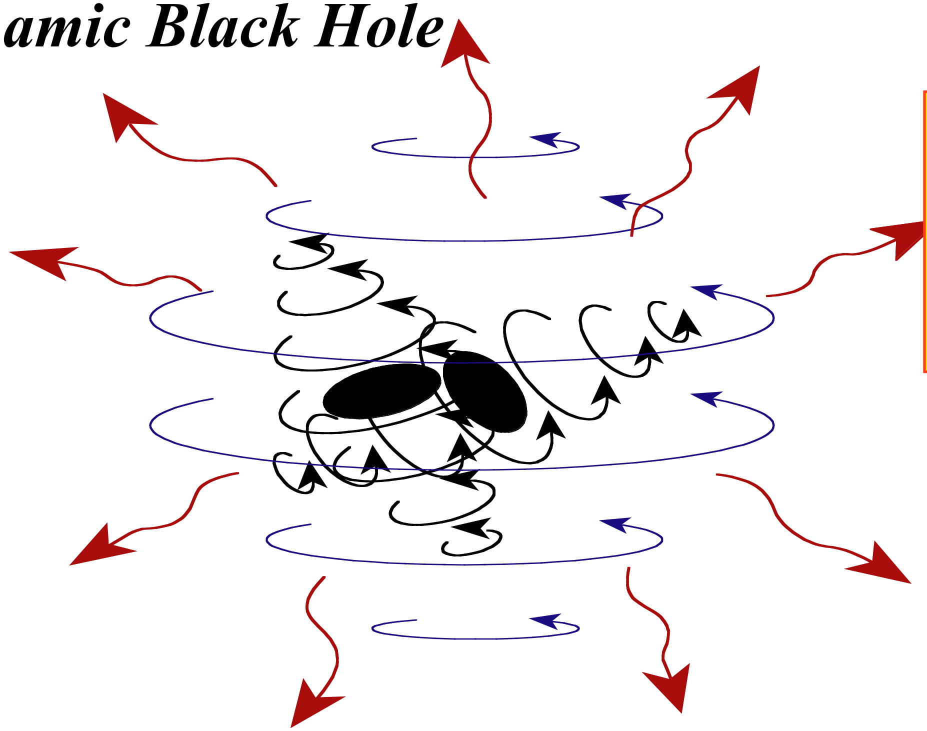
VALERY FROLOV
tomorrow, 11:00 AM

- Bifurcation of BH theory
  - » classical: Astrophysical Black Holes
  - » quantum

Astrophysical Black Hole Status in 2009

Object	Understood?	Observed?
Quiescent Black Hole	**Yes**	**Little**
Wildly dynamic Black Hole	***No*** *	***No***



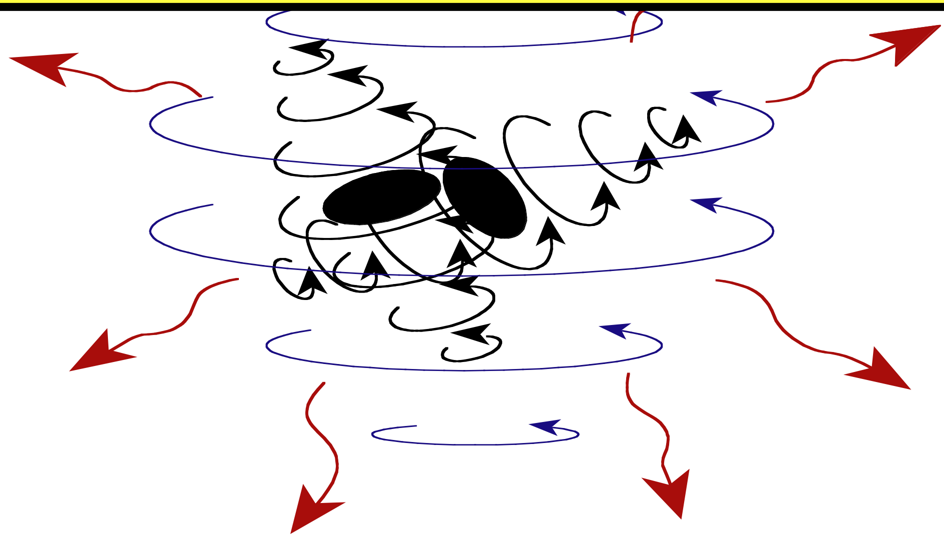


* except for some very important theorems

Black Hole Status in 2006

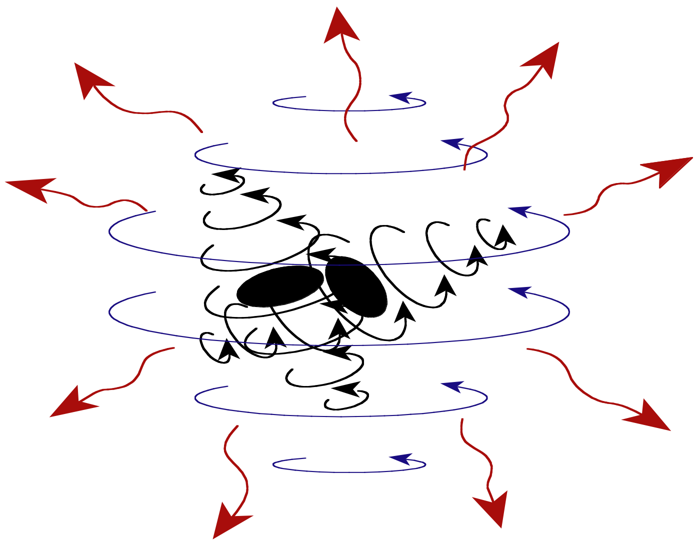


The nonlinear dynamics of curved space-time
John Wheeler's "geometrodynamics"



A New Golden Age: 2007 - ??

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



A dozen research teams in Europe, US, Canada

- Driven by ***Observations*** of Colliding Black Holes via ***Gravitational Waves***

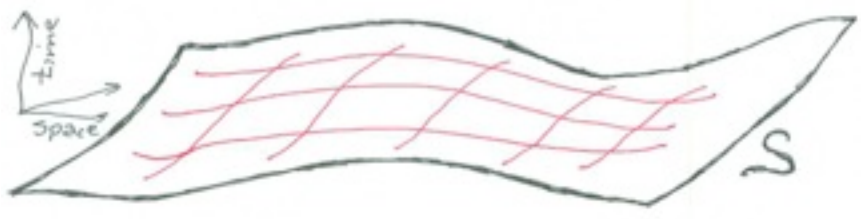
Numerical Simulations
(numerical relativity)

- Under development since 1960s

- Big success in past several years

Numerical Relativity: How is it Done?

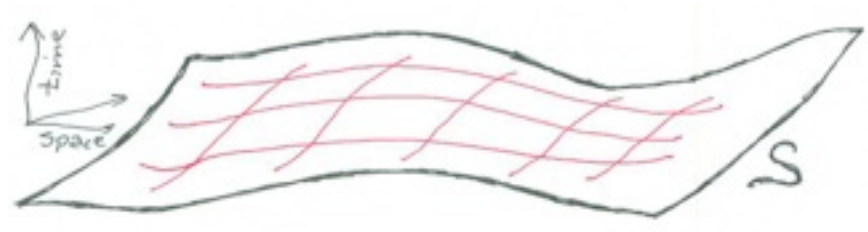
- Evolve the geometry of spacetime - not fields in spacetime
- Choose an initial spacelike 3-dimensional surface *S*
  - » Put a coordinates on *S*



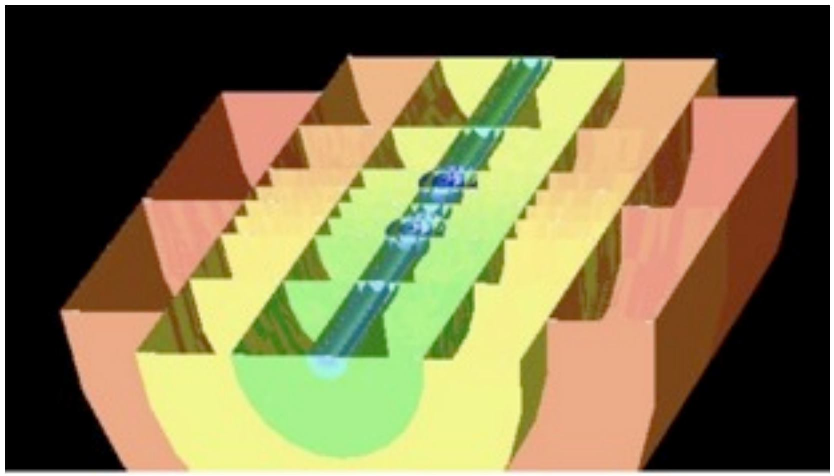
- Specify: *3-metric* g_{ij} and *Extrinsic Curvature* K_{ij} of S
  - » Subject to *constraint equations* [analogues of Div B = 0]
- Lay out coordinates to future by specifying Lapse function α and Shift function β^i
- Integrate 3-metric forward in time via *dynamical equations*

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

Two Mature Approaches



- Finite-difference description of spatial geometry
- Spectral description [Cornell/Caltech/CITA/WSU]
  - » More complicated; was slower to mature
    - but exponential convergence ⇒ High accuracy & speed



Numerical Relativity Research Groups

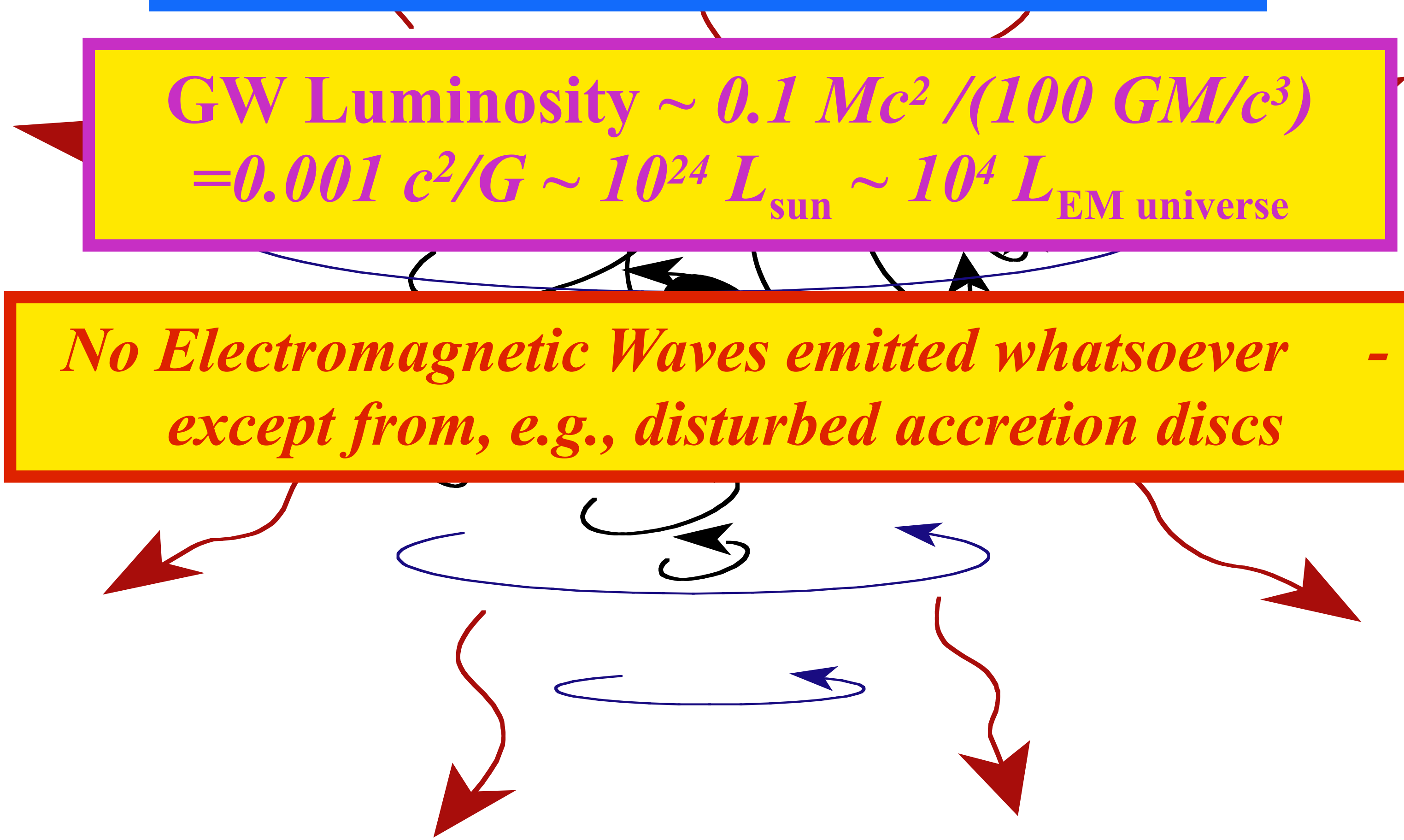
- ***Simulating Generic Black-Hole Binaries:***
  - » Princeton (Pretorius),
  - » Rochester Institute of Technology (Campanelli, ...),
  - » Goddard Spaceflight Center (Centrella, ...),
  - » U. Illinois (Shapiro, ...),
  - » Albert Einstein Instititute & LSU (Pollney, ...),
  - » U. Jena (Bruegmann, ...),
  - » 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

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

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

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



10

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

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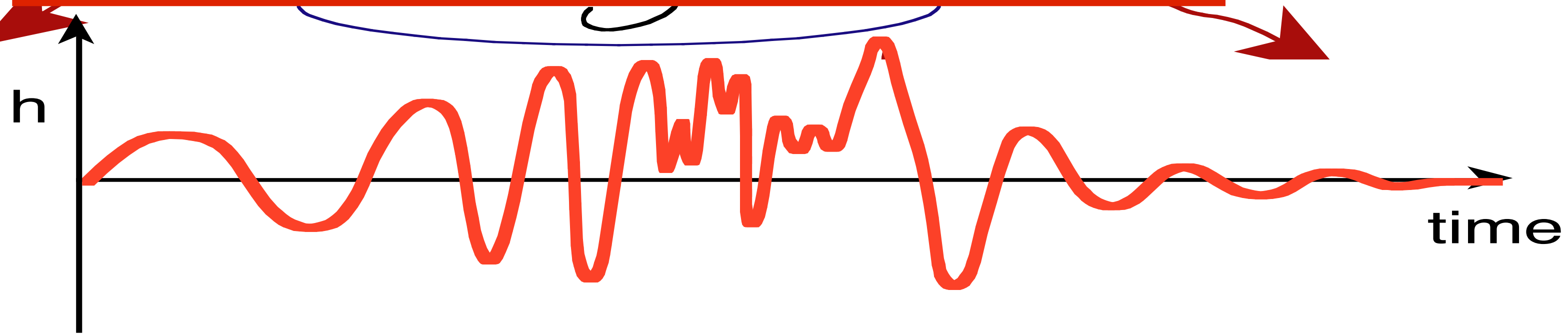
GW Luminosity ~ $0.1\ Mc^2/(100\ GM/c^3)$ $=0.001\ c^2/G \sim 10^{24}\ L_{sun} \sim 10^4\ L_{EM\ universe}$

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



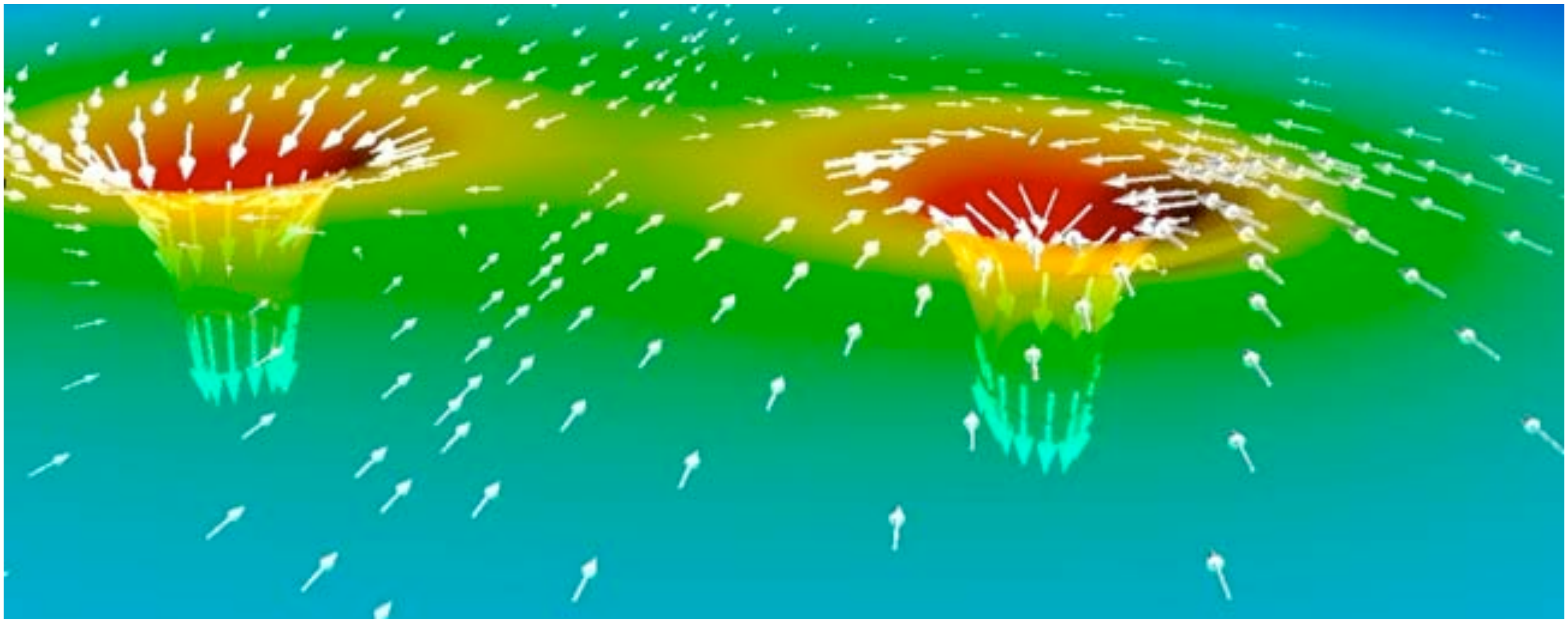
Old Way to Visualize Geometrodynamics

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

color (→ α)

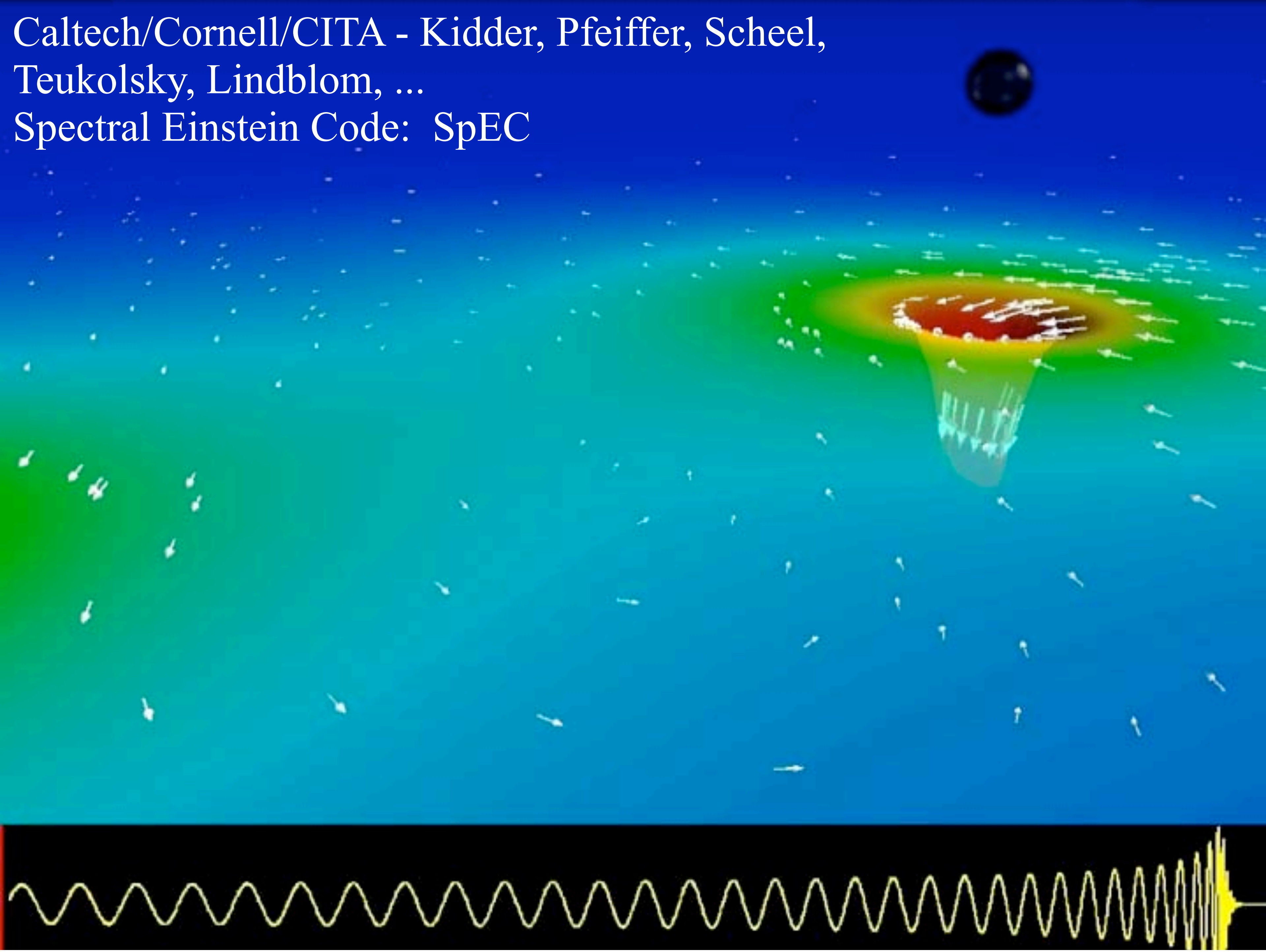
scalar curvature in orbital plane: Shape (→ g_{ij})

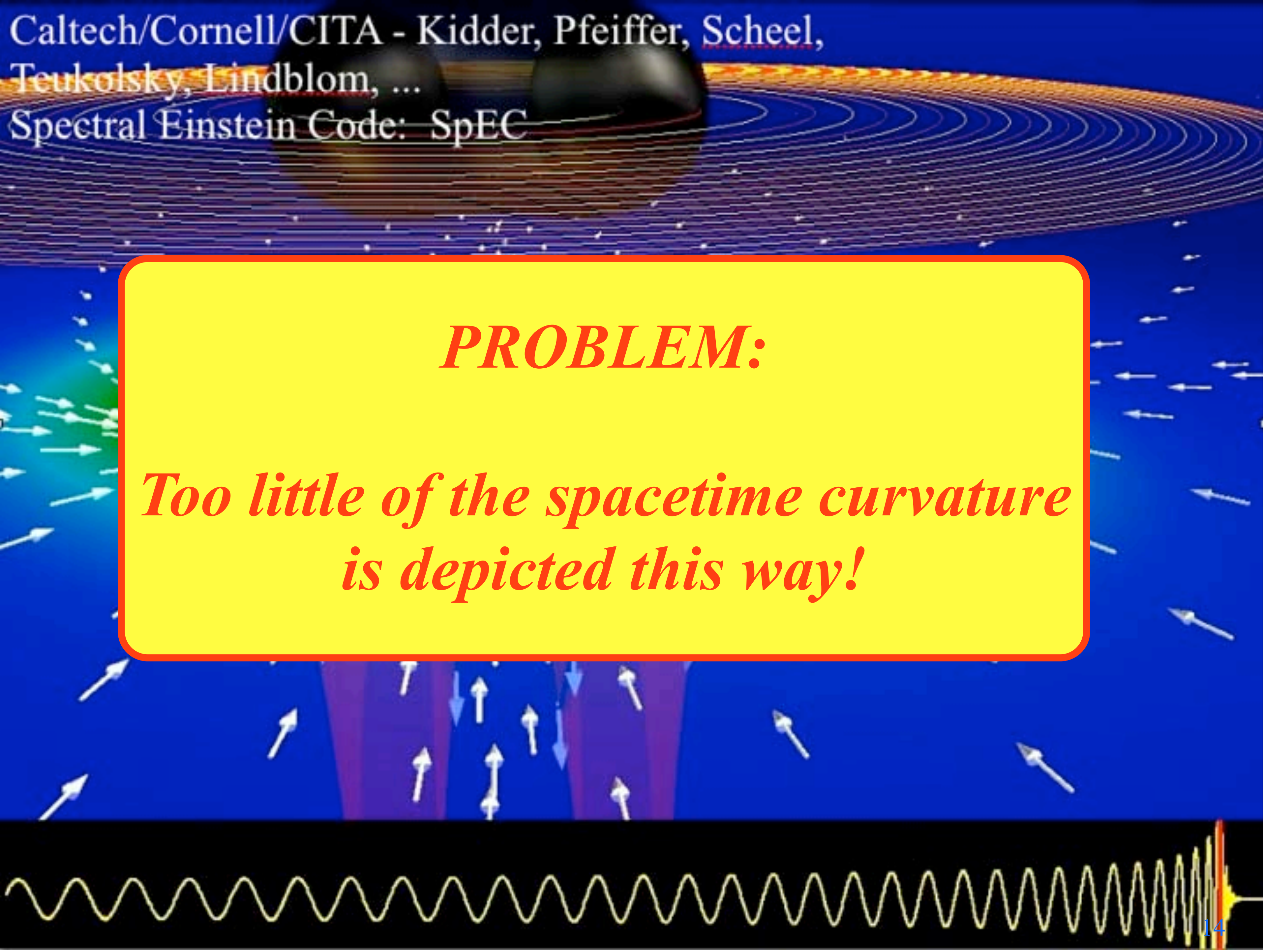
white arrow (→ β^j)



Caltech/Cornell/CITA - Kidder, Pfeiffer, Scheel, Teukolsky, Lindblom, ...

Spectral Einstein Code: SpEC




Caltech/Cornell/CITA - Kidder, Pfeiffer, Scheel,
Teukolsky, Lindblom, ...
Spectral Einstein Code: SpEC
PROBLEM:
Too little of the spacetime curvature
is depicted this way!
14

New Ways to Visualize Curvature of Spacetime

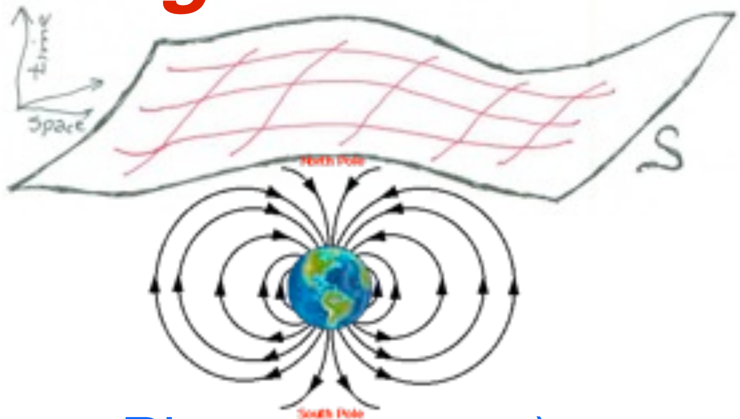
Cornell Caltech

NITheP
South Africa

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

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

Tidal Field & Frame-Drag Field

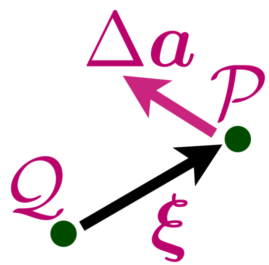


- Slice spacetime into space plus time
- EM field tensor ***F*** ➔ Electric field and magnetic field; visualize with field lines
- Weyl curvature tensor (in vacuum, same as Riemann tensor) ➔ **"electric" part** $\mathcal{E}_{jk}$ and **"magnetic" part** $\mathcal{B}_{jk}$

$$\mathcal{B}_{jk} = \frac{1}{2}\epsilon_{jpq}C^{pq}{}_{k0}$$

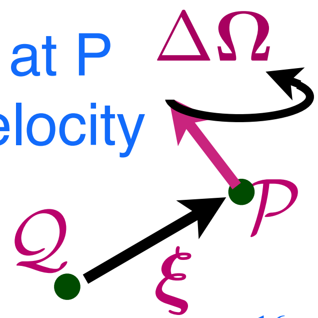
Symmetric, Trace-Free (STF) tensors

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



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***

Visualizing $\mathcal{E}_{ij}$: Tendex Lines and their Tendicities

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

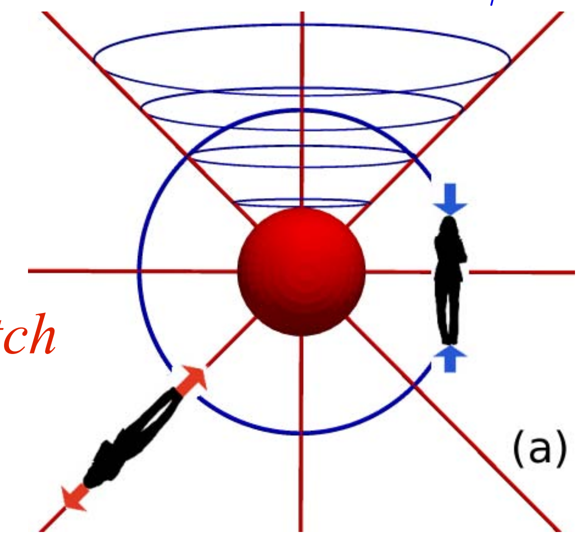
- For the tidal field $\mathcal{E}_{jk}$, the **integral curve of an eigenvector *n*** is called its *Tendex Line*; its **eigenvalue** $\mathcal{E}_{nn}$ is its *Tendicity*

- 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



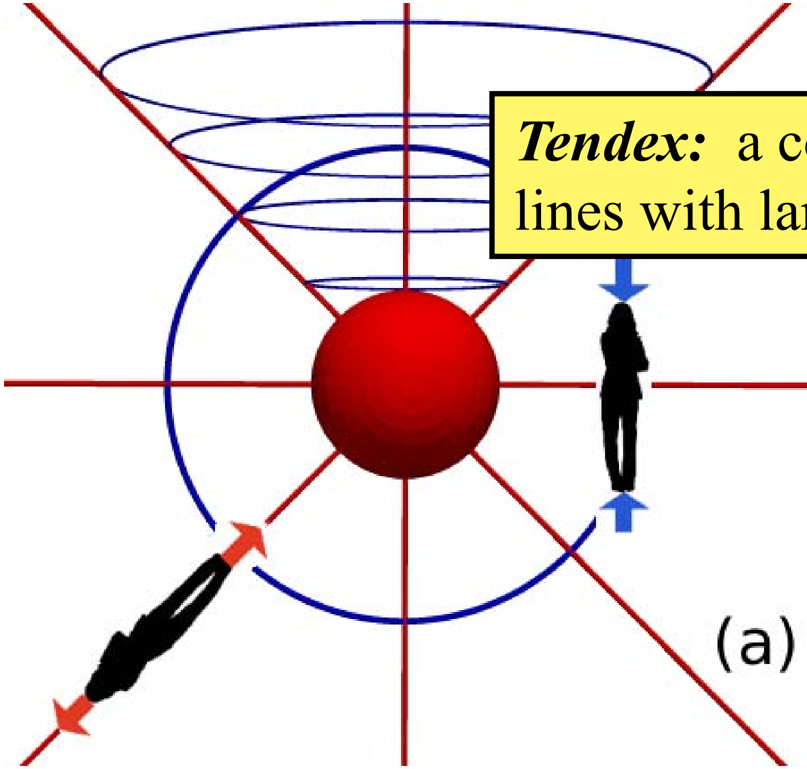
$\mathcal{E}_{\hat{\theta}\hat{\theta}} > 0$ *tidal squeeze*

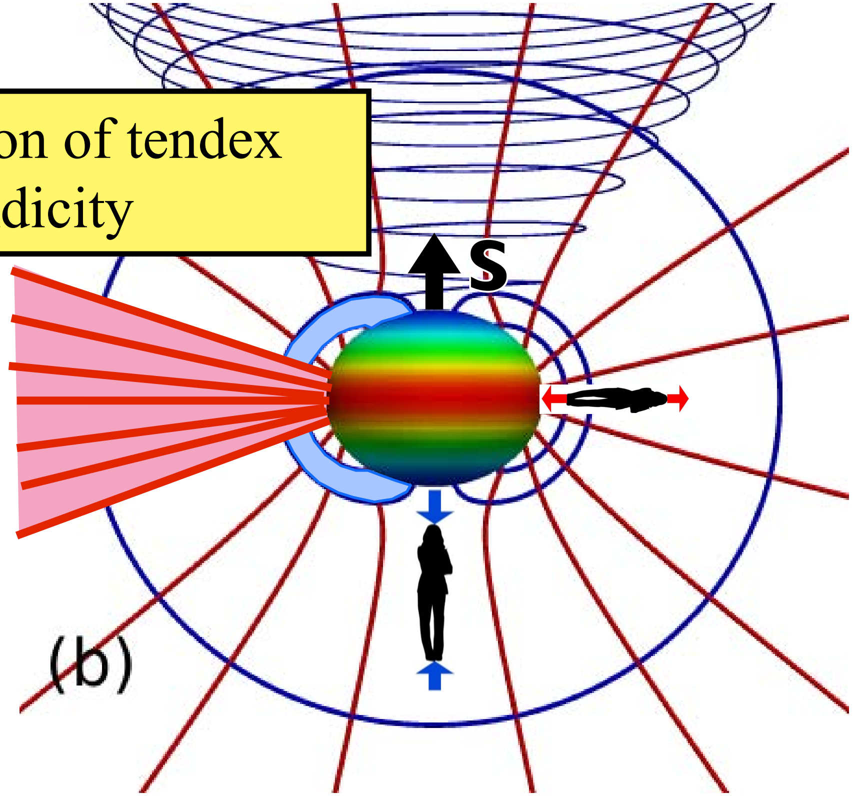
positive tendicity

Tendexes around Black Holes

Non-Spinning Black Hole

Fast Spinning Black Hole, a=0.95





Tendex: a collection of tendex lines with large tendicity

Horizon Tendex:
region of large tendicity

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

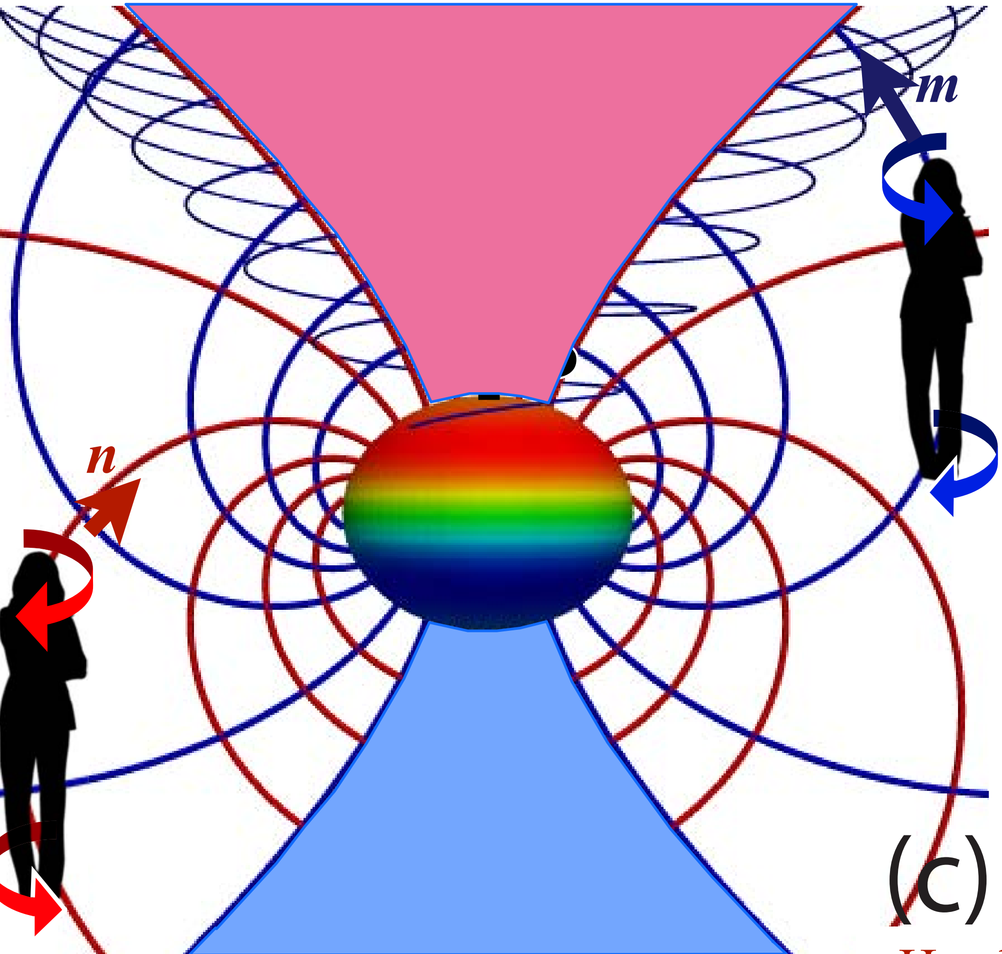
Blue: positive tendicity

Green: near zero

Red: negative tendicity

Vizualizing $\mathcal{B}_{ij}$: Vortex Lines and Their Vorticities

- For the frame-drag field $\mathcal{B}_{jk}$, **integral curve of eigenvector field *n*** is called its *Vortex Line*; its **eigenvalue** $\mathcal{B}_{nn}$ is *Vorticity*



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

- Head sees feet dragged clockwise
- Feet see head dragged clockwise

Vortex: a collection of vortex lines with large vorticity

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

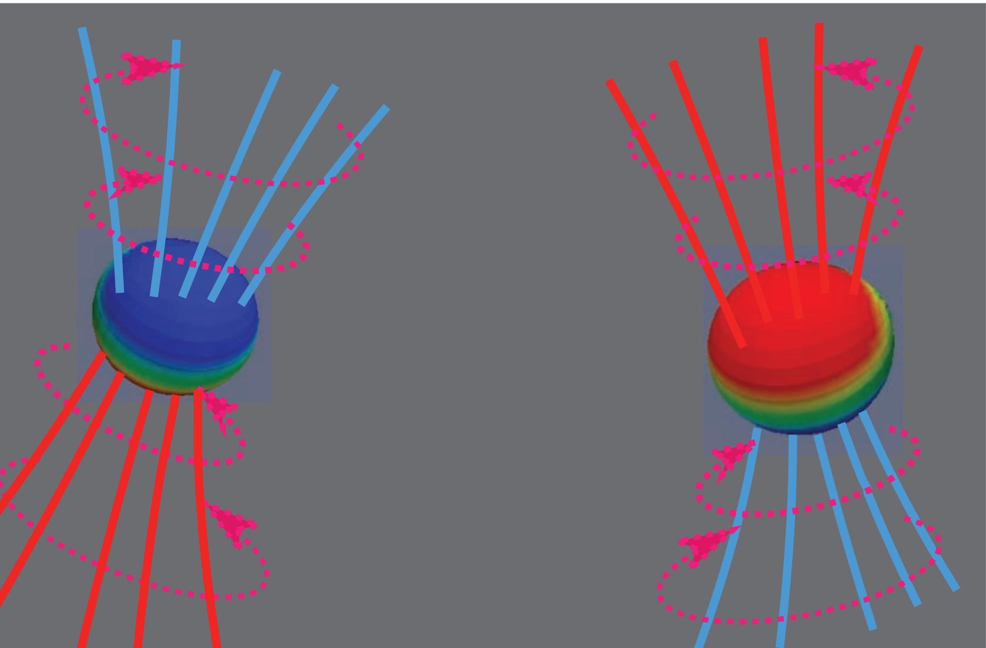
Horizon Vortex: region of large $\mathcal{B}_{NN}$

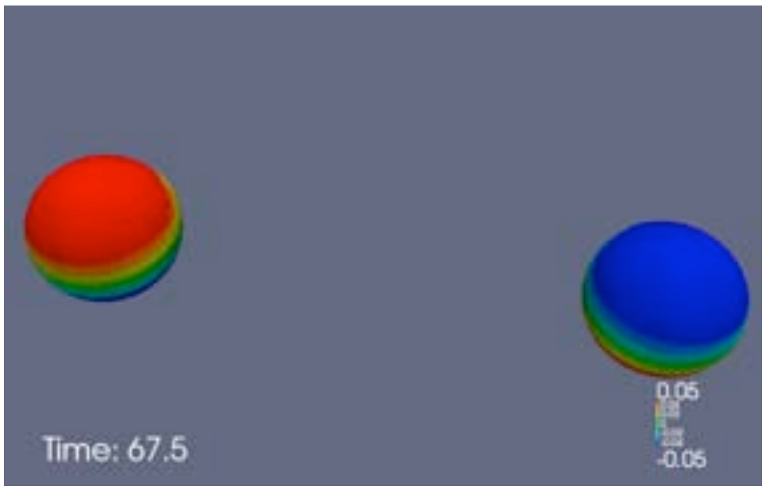
negative-vorticity vortex lines $\mathcal{B}_{nn} < 0$

- Head sees feet dragged counter-clockwise
- Feet see head dragged counter-clockwise

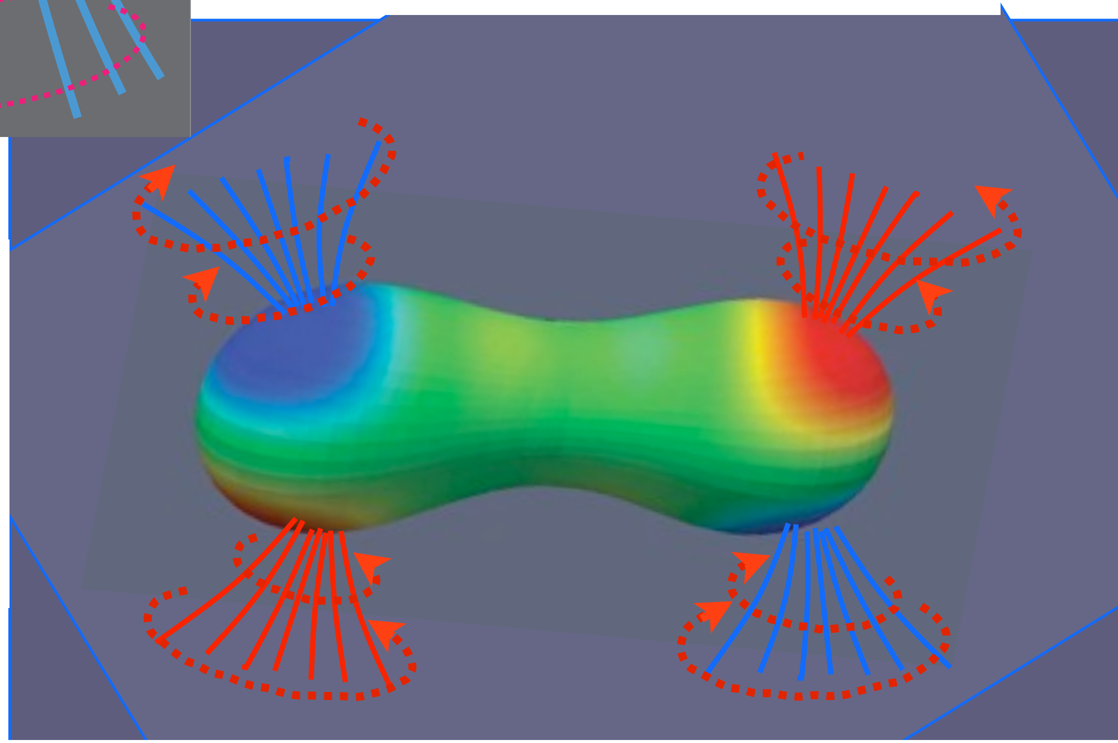
Fast-spinning hole, a=0.95

Head-On Collision of Spinning Black Holes

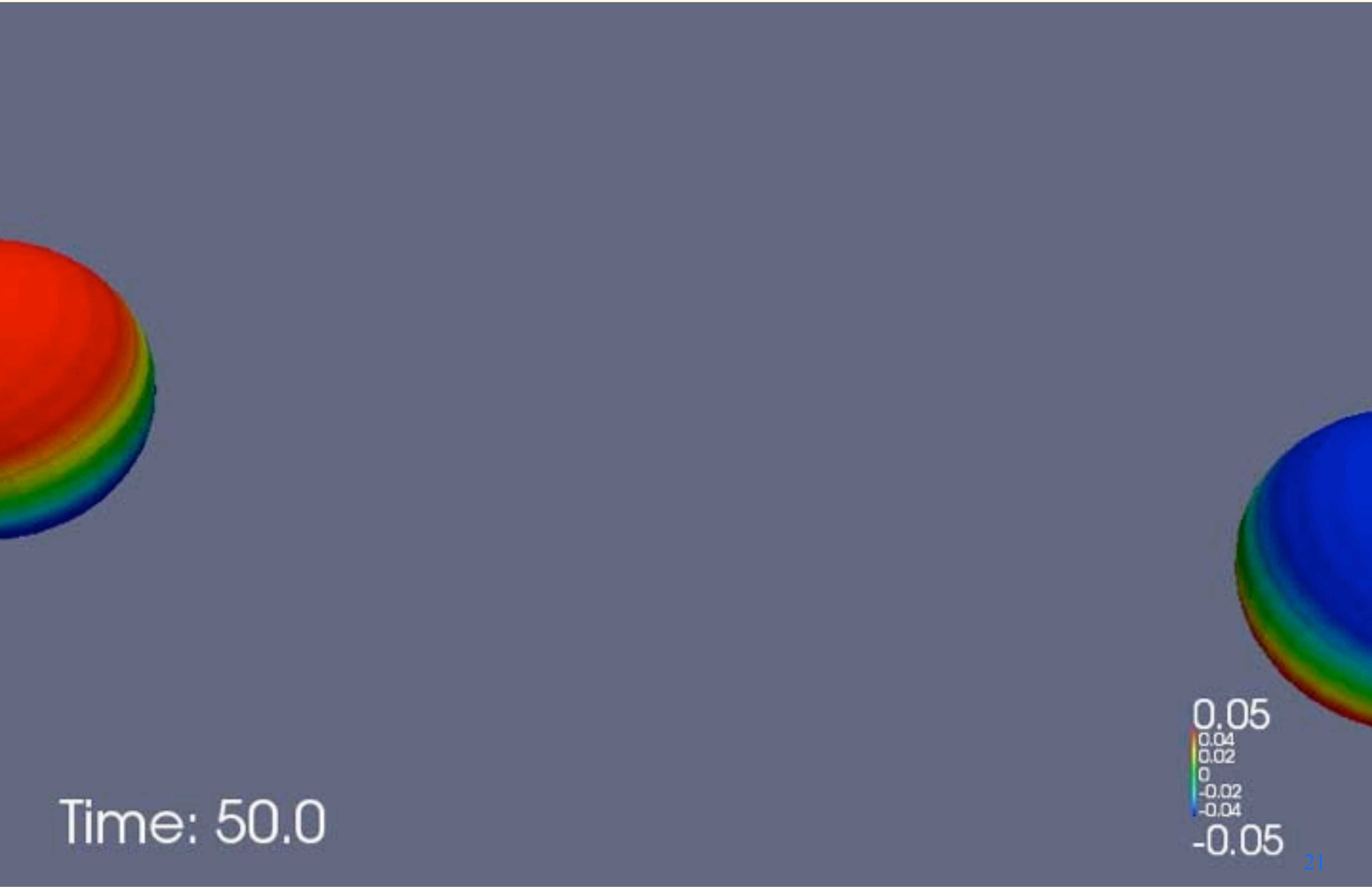




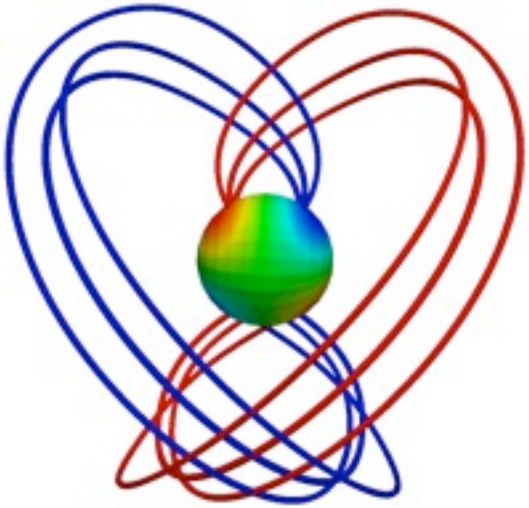
Vortexes robustly retain their individuality

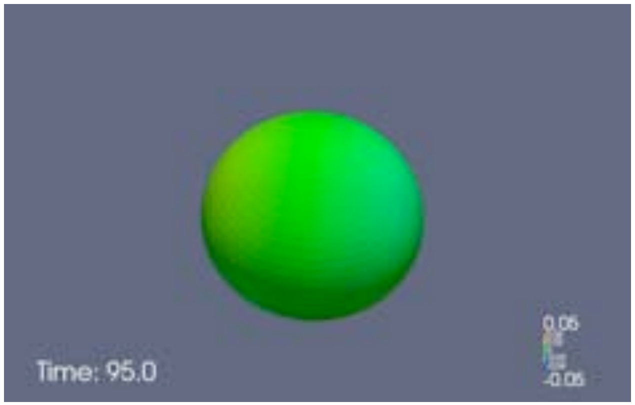


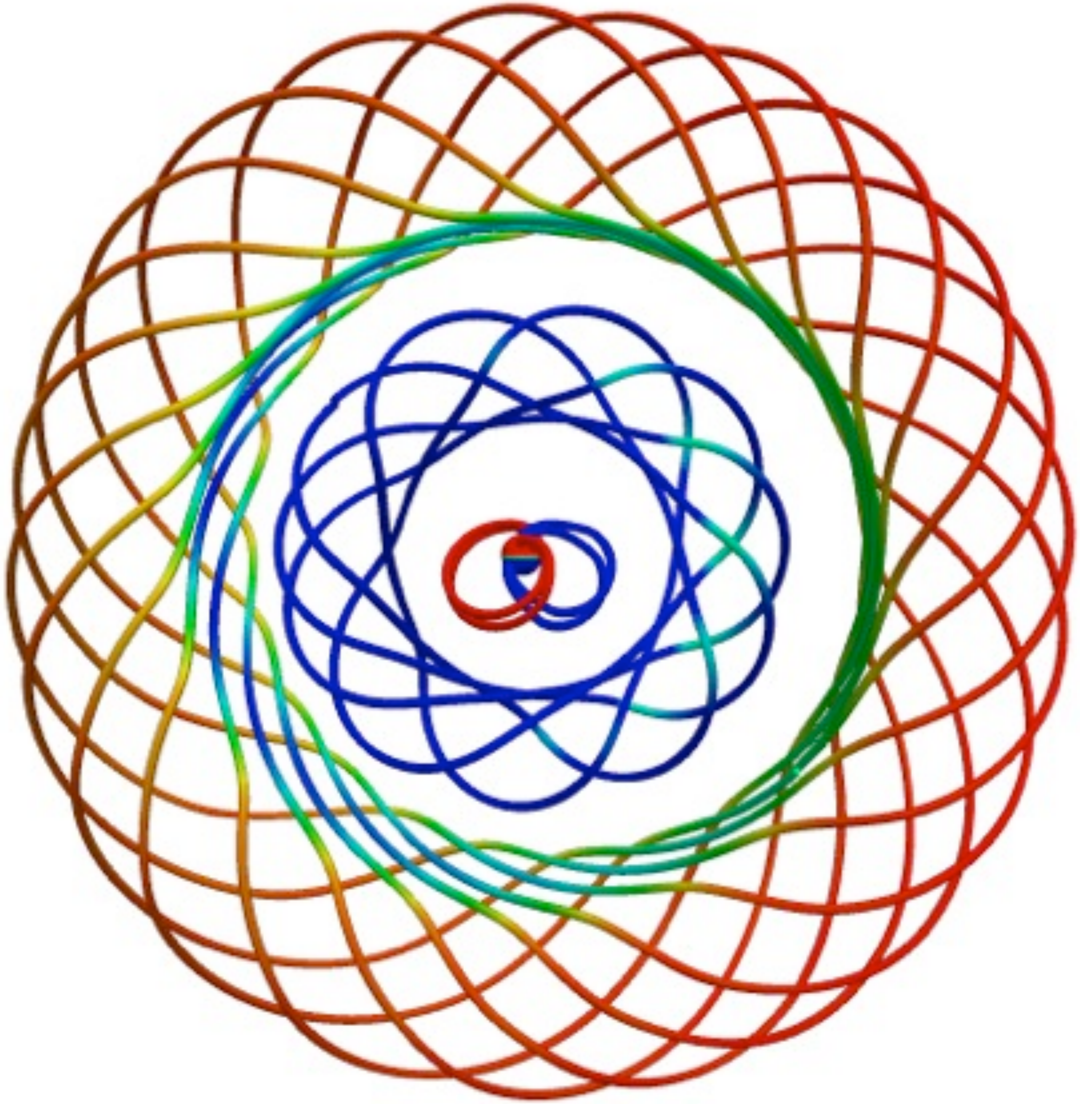
Head-On Collision of Spinning Black Holes



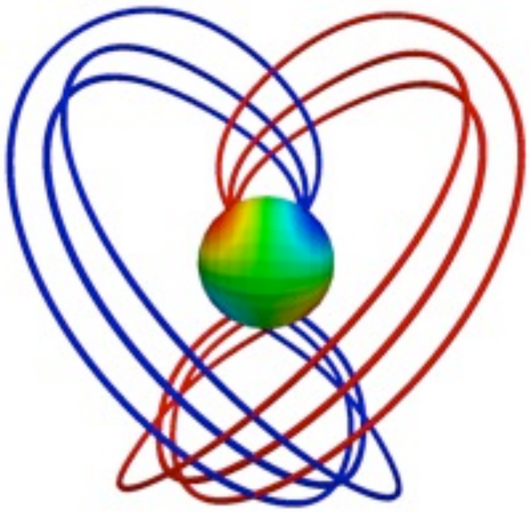
Sloshing Ejects Vortexes

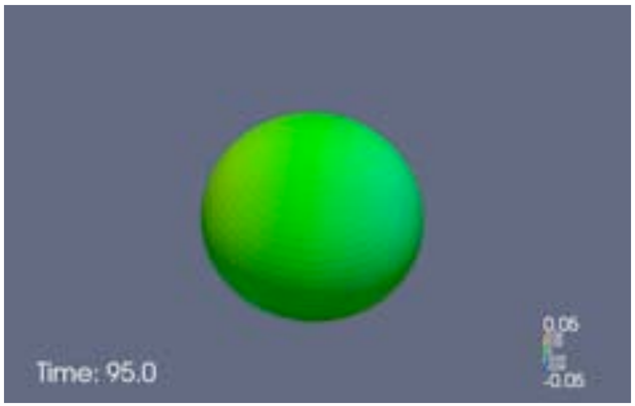


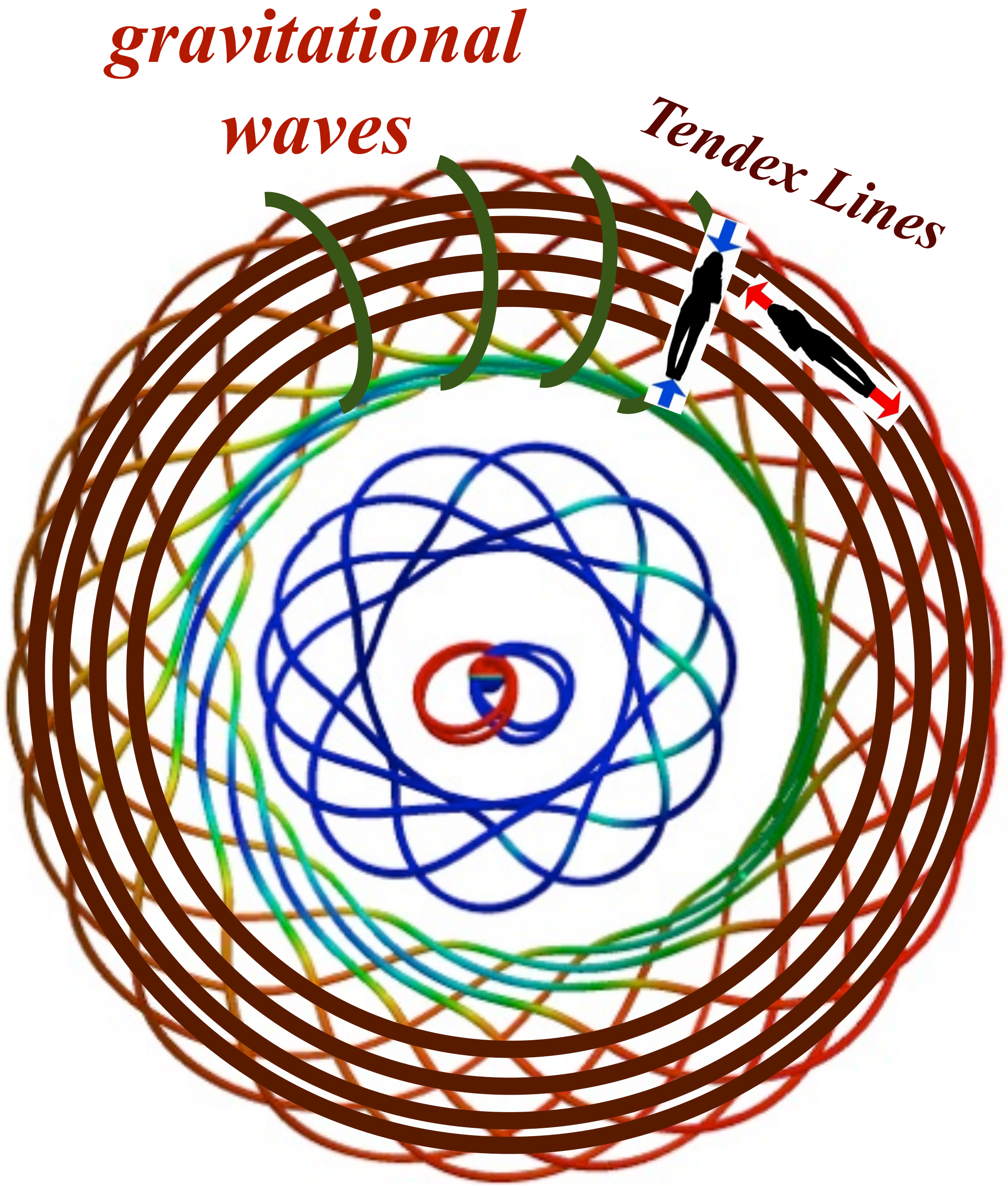




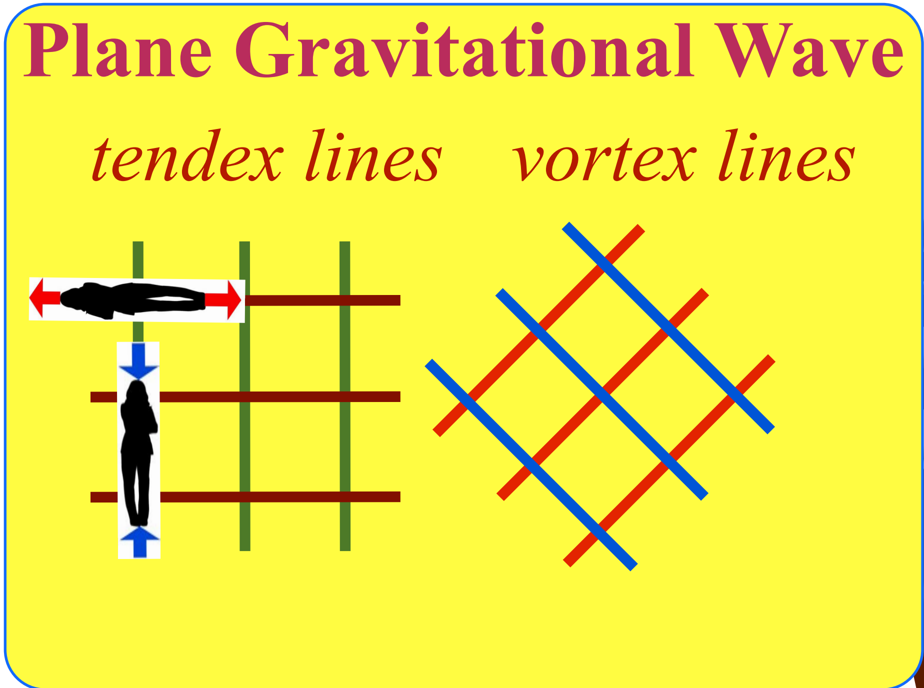
Sloshing Ejects Vortexes

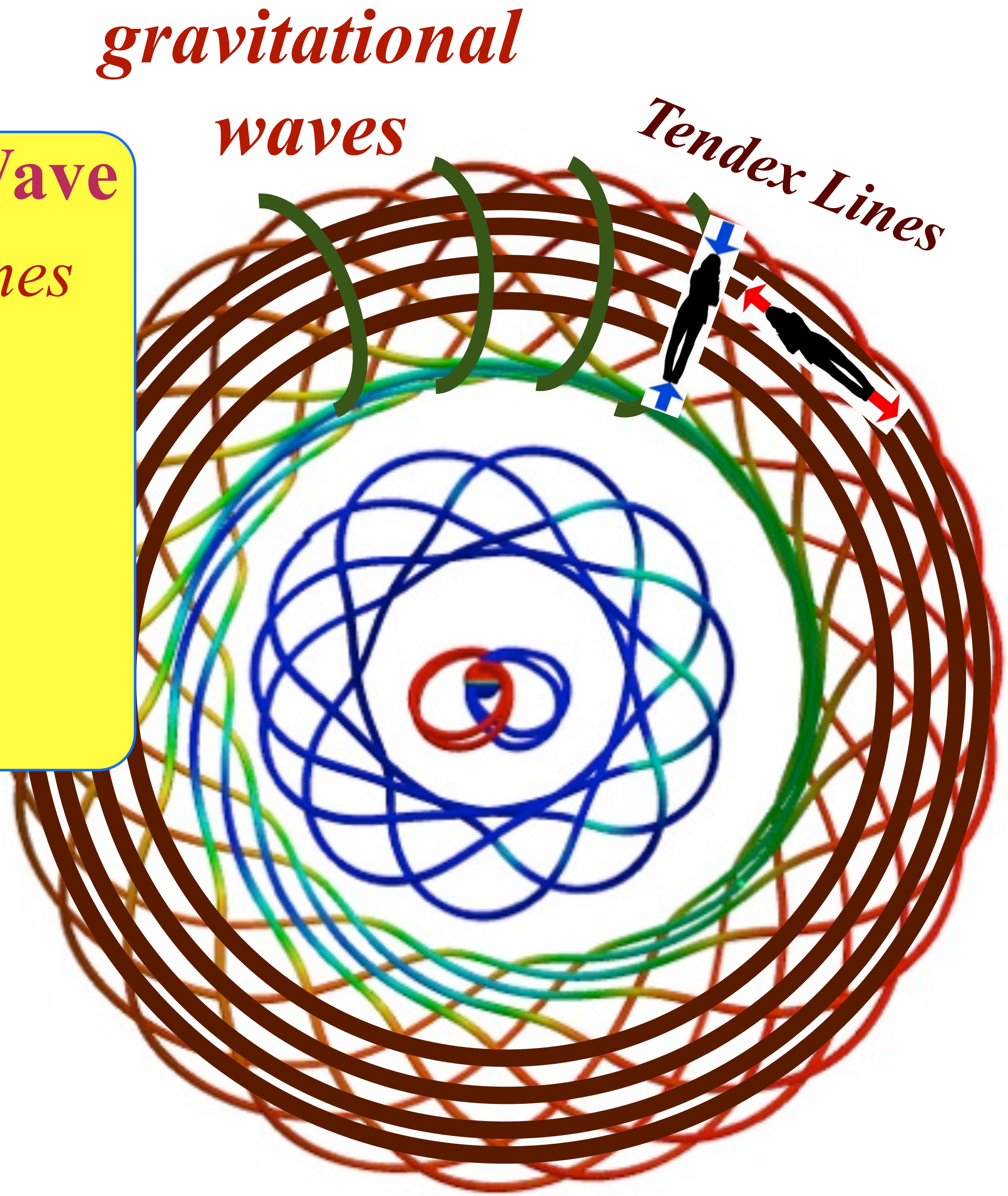




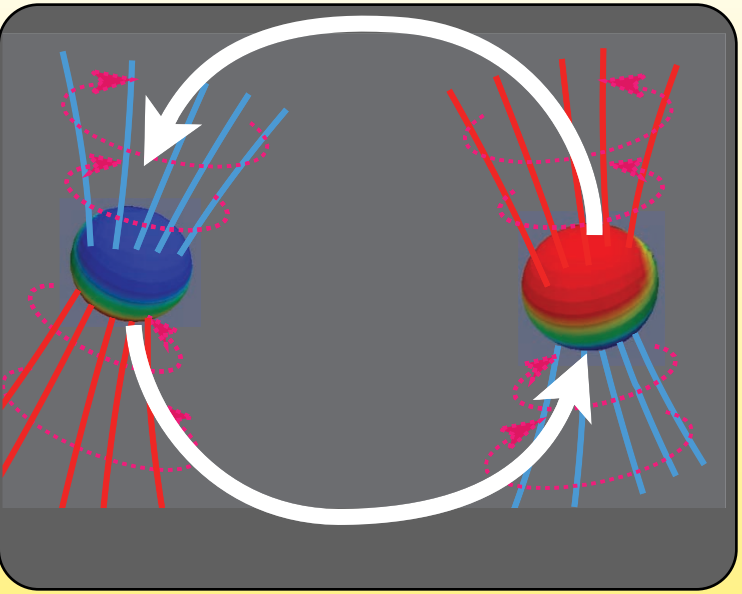


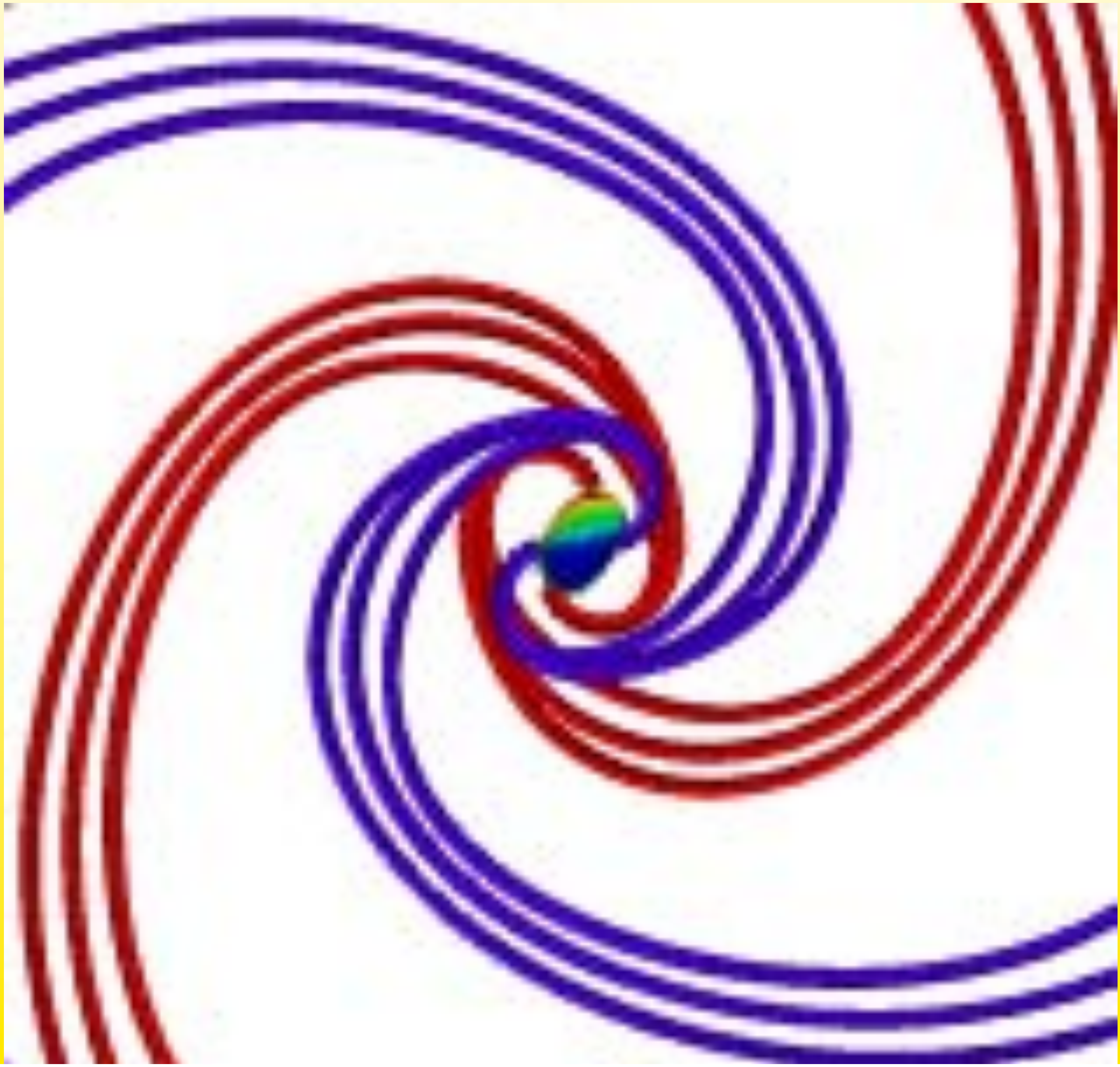
Sloshing Ejects Vortexes





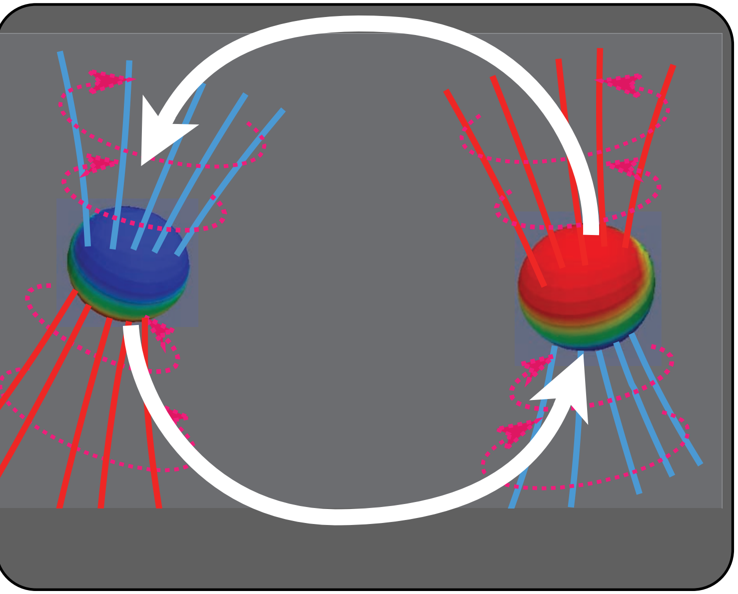
Orbiting Collision



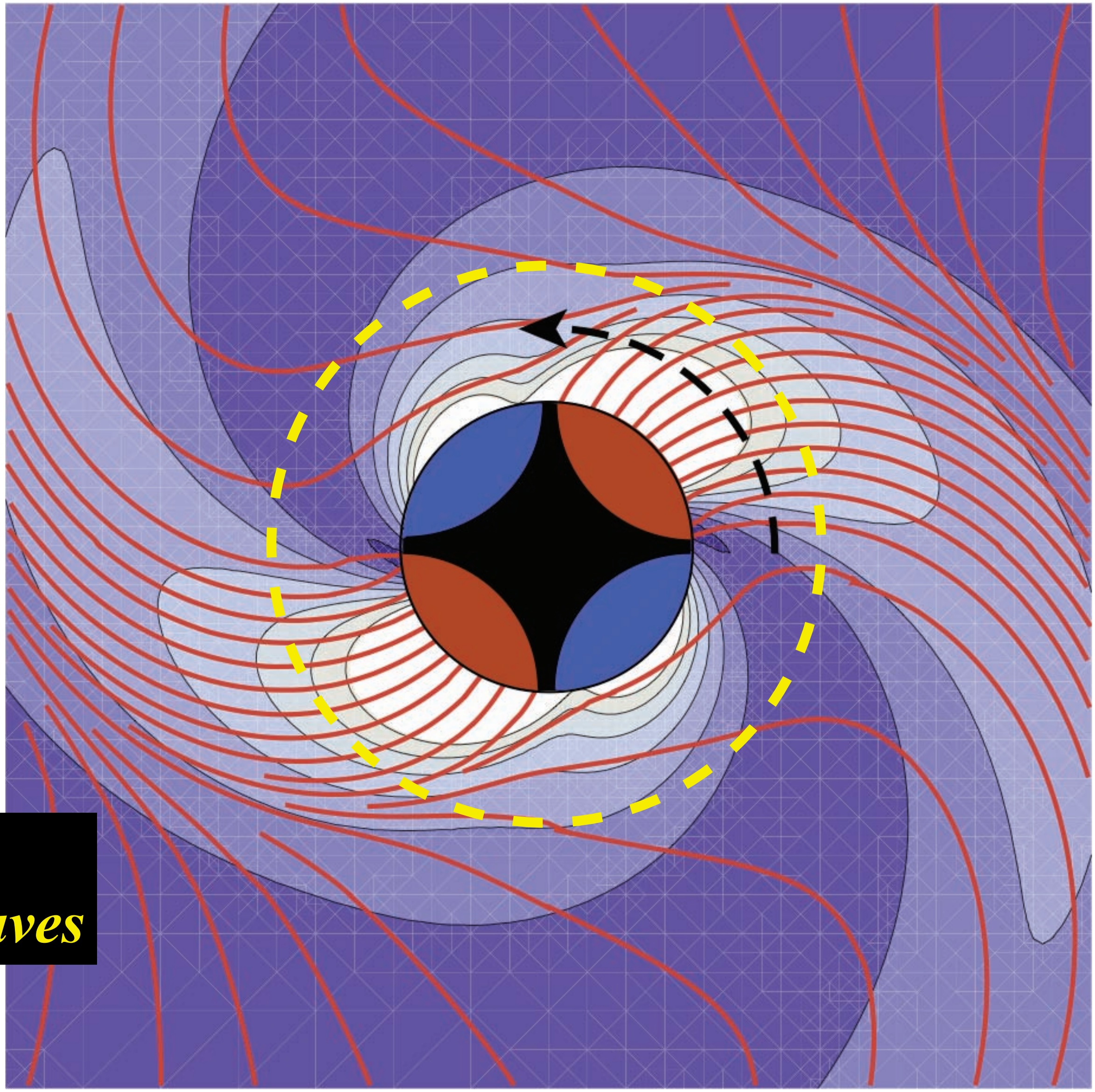


gravitational waves

Vortexes Attached to Black Hole

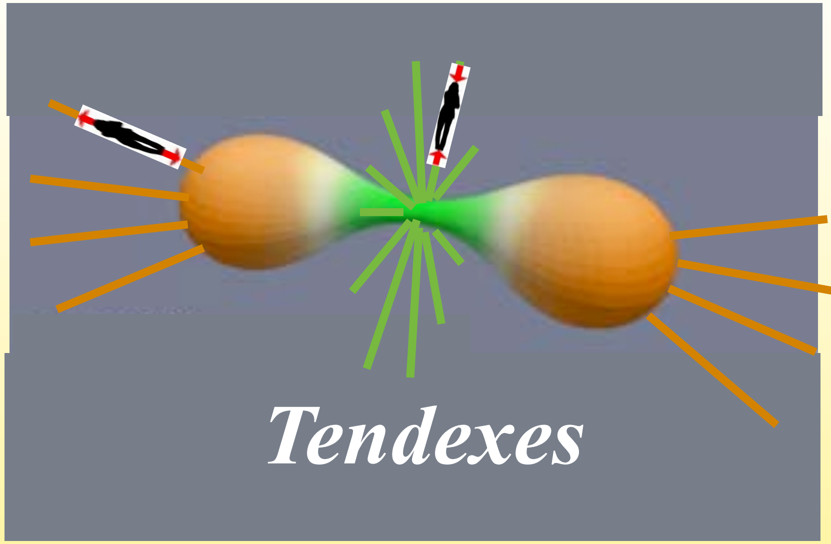


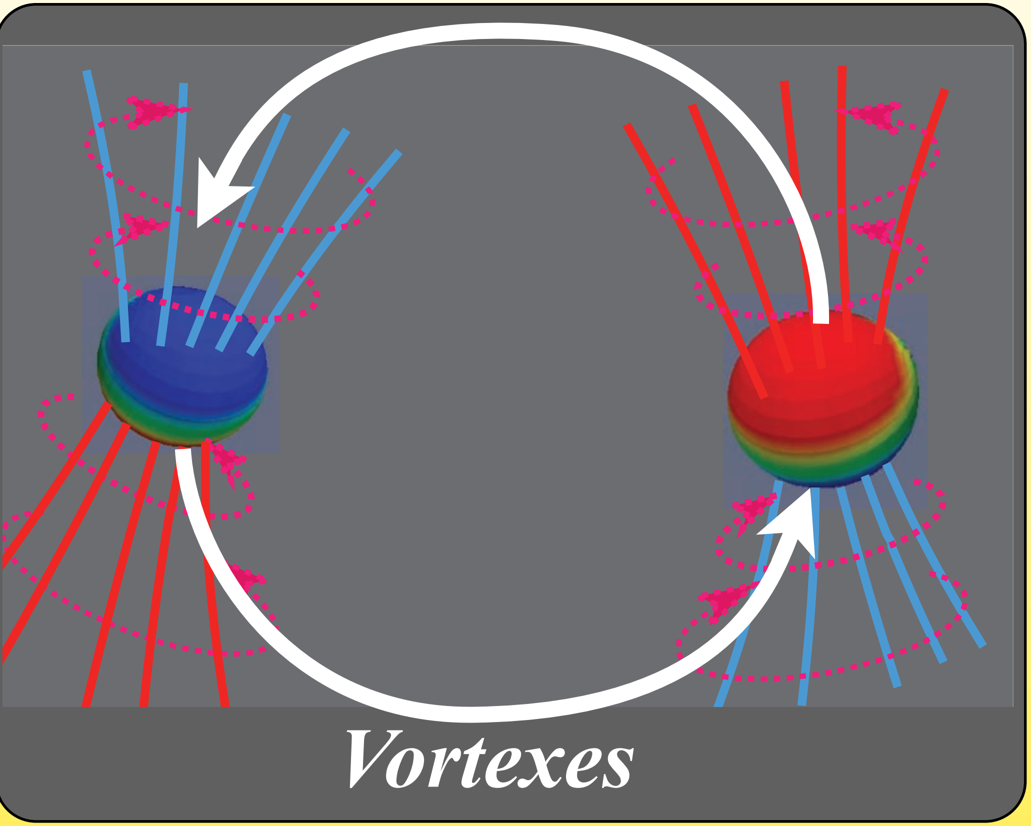
- Vortexes Travel around hole

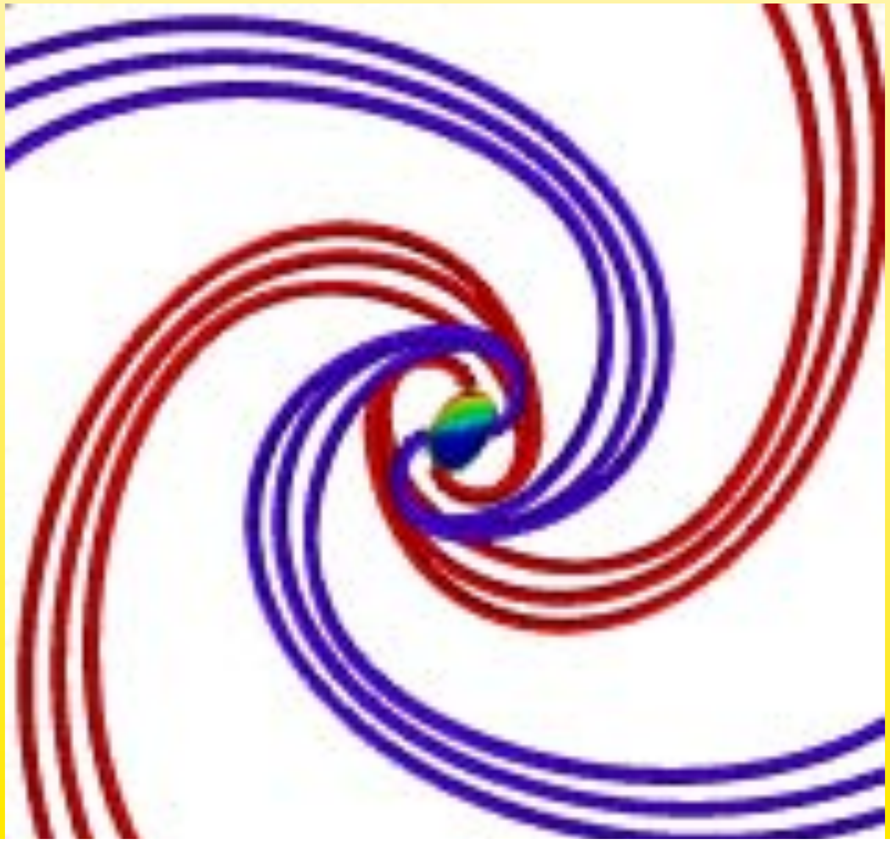


Near-zone vortexes generate gravitational waves

Orbiting Collision

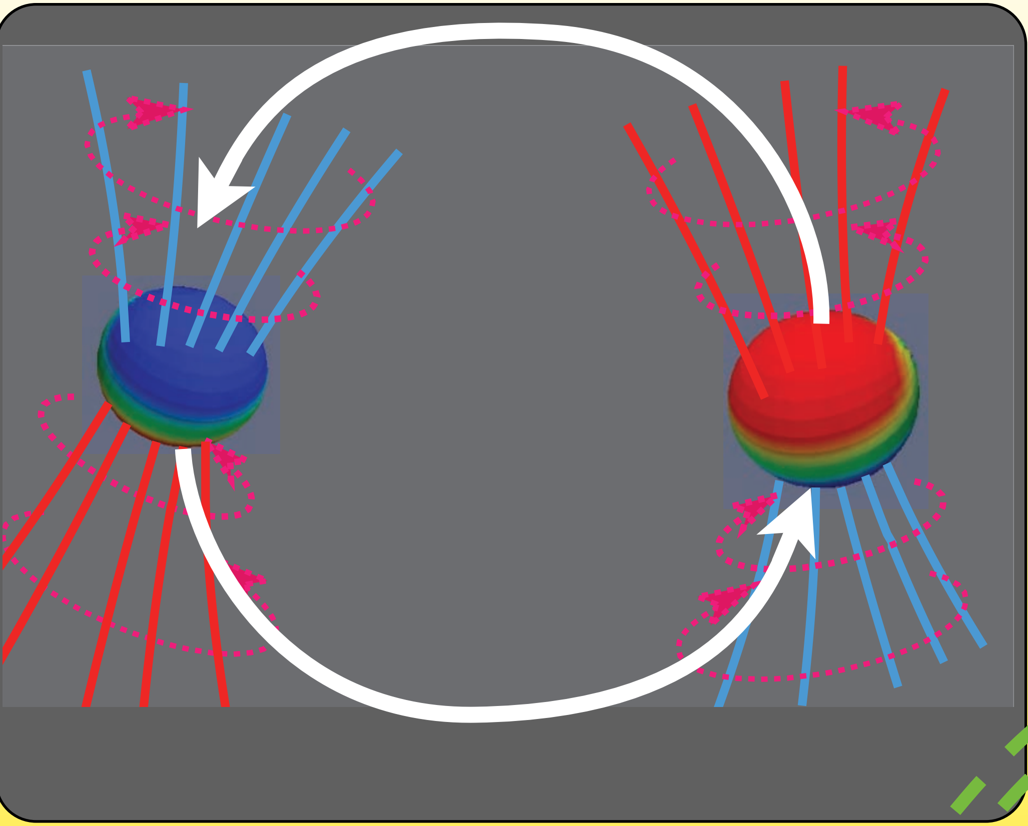


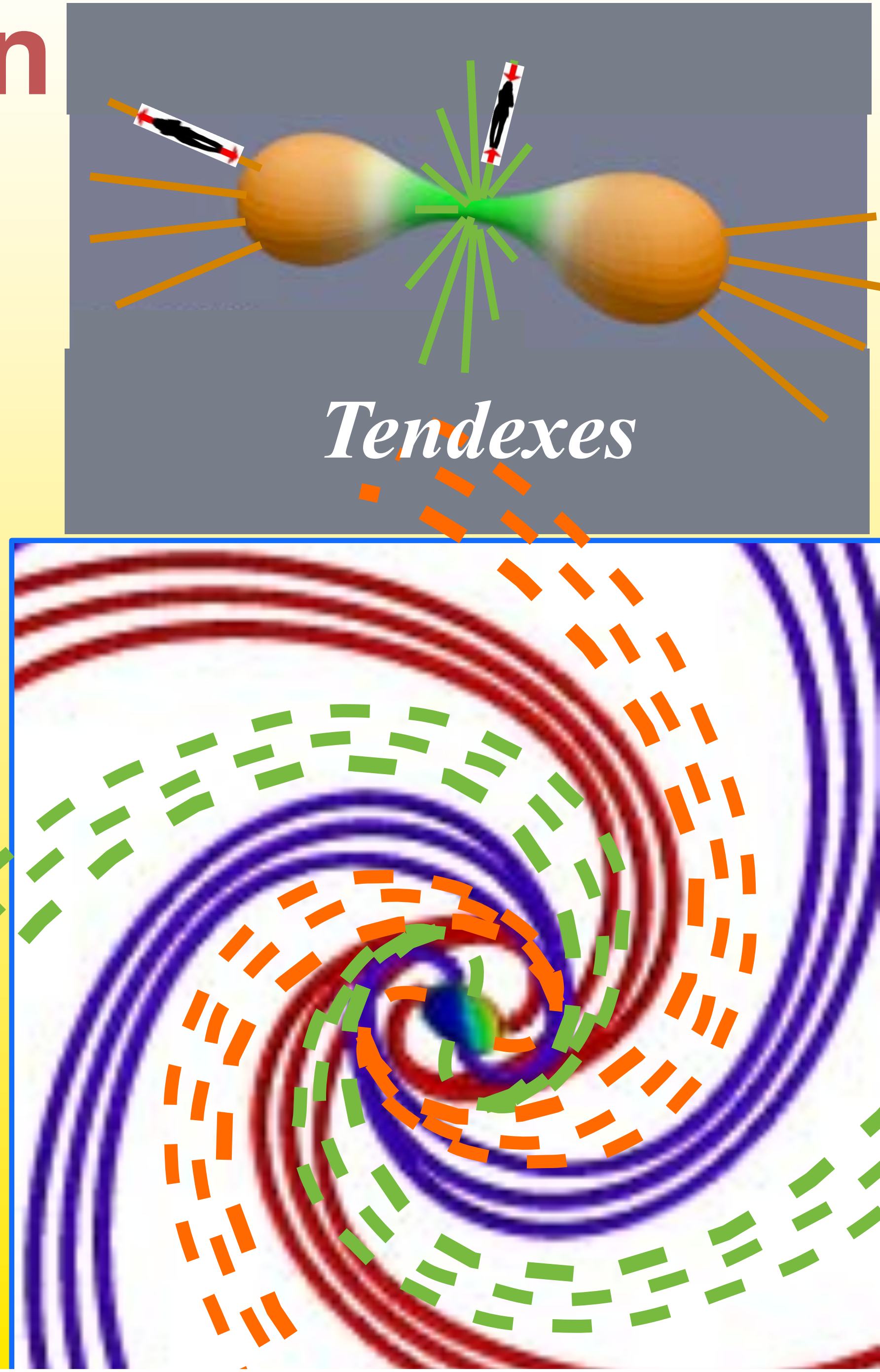




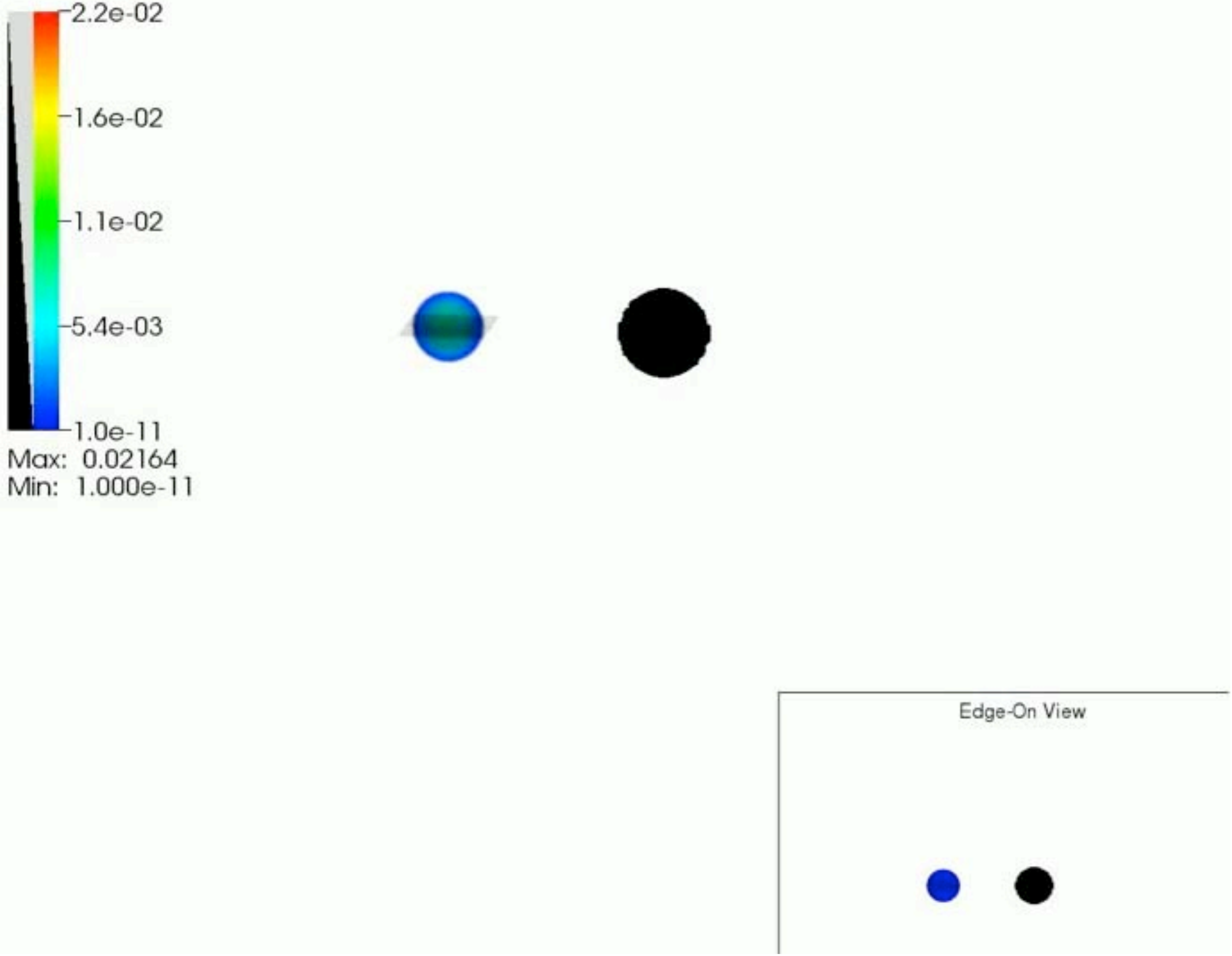
gravitational waves

Orbiting Collision





Beating of 2 types of waves can produce huge radiation-reaction kicks: ~4000 km/sec

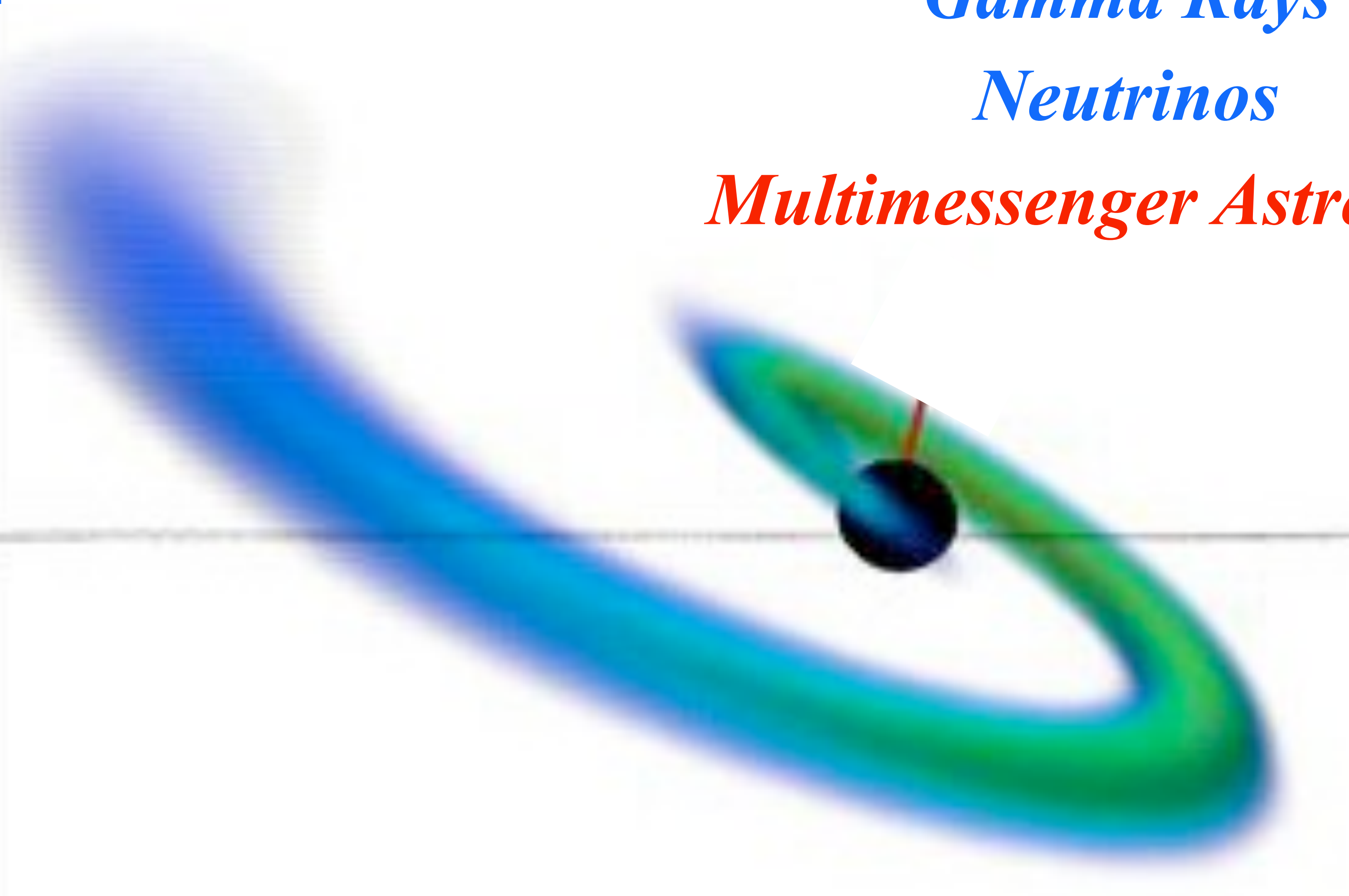

2.2e-02
1.6e-02
1.1e-02
5.4e-03
1.0e-11
Max: 0.02164
Min: 1.000e-11
Edge-On View

Gravitational Waves

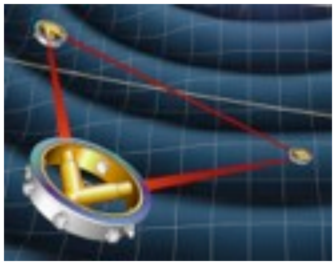
Gamma Rays

Neutrinos

Multimessenger Astronomy



Gravitational Wave Observations

Ground-based Interferometers 	Wave Frequencies 10 Hz to 10,000 Hz	Black holes: 2 to one thousand solar masses
Space-based Interferometers 	Wave Frequencies 0.0001 Hz to 0.1 Hz Wave Periods 10 sec to 3 hours	Black holes: 10 thousand to 10 million solar masses
Pulsar Timing 	Wave Periods A month to 30 years	Black holes: 100 million to 10 billion solar masses

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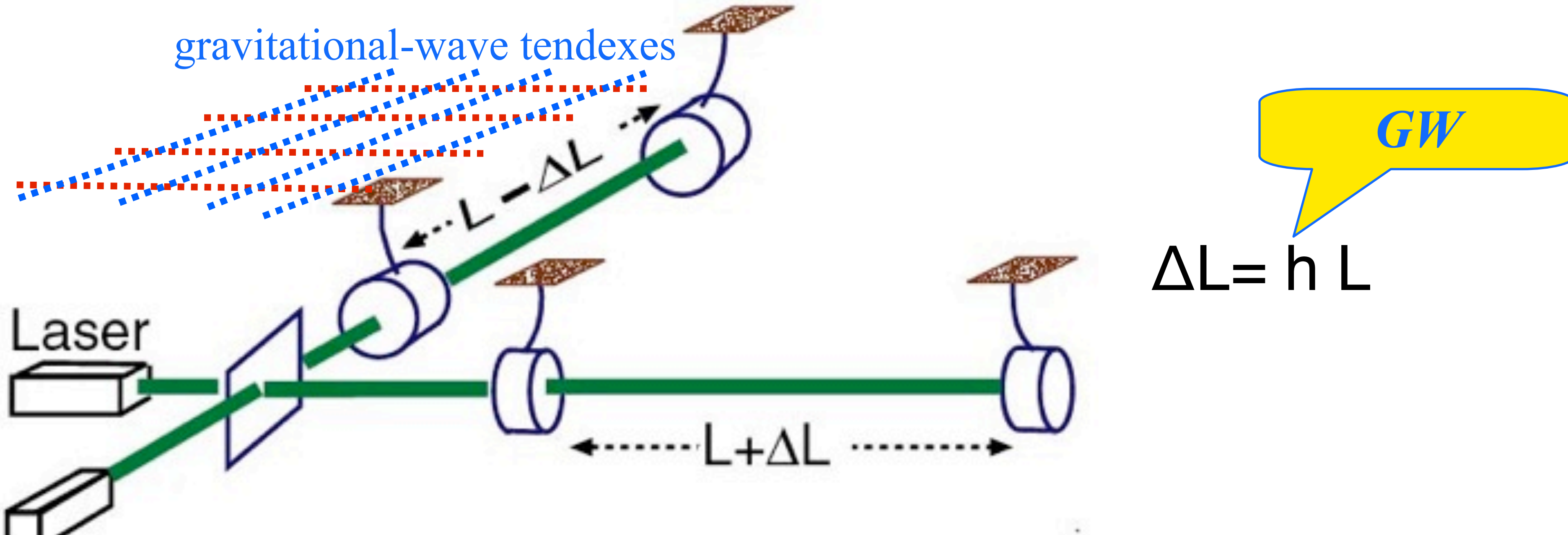
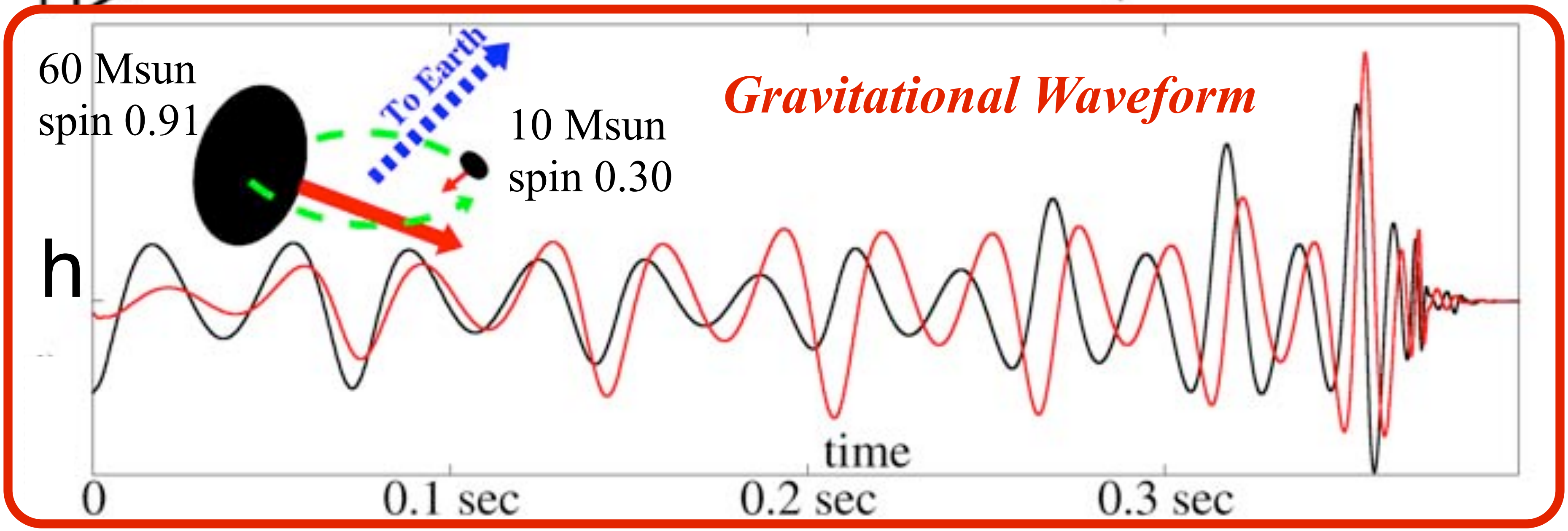
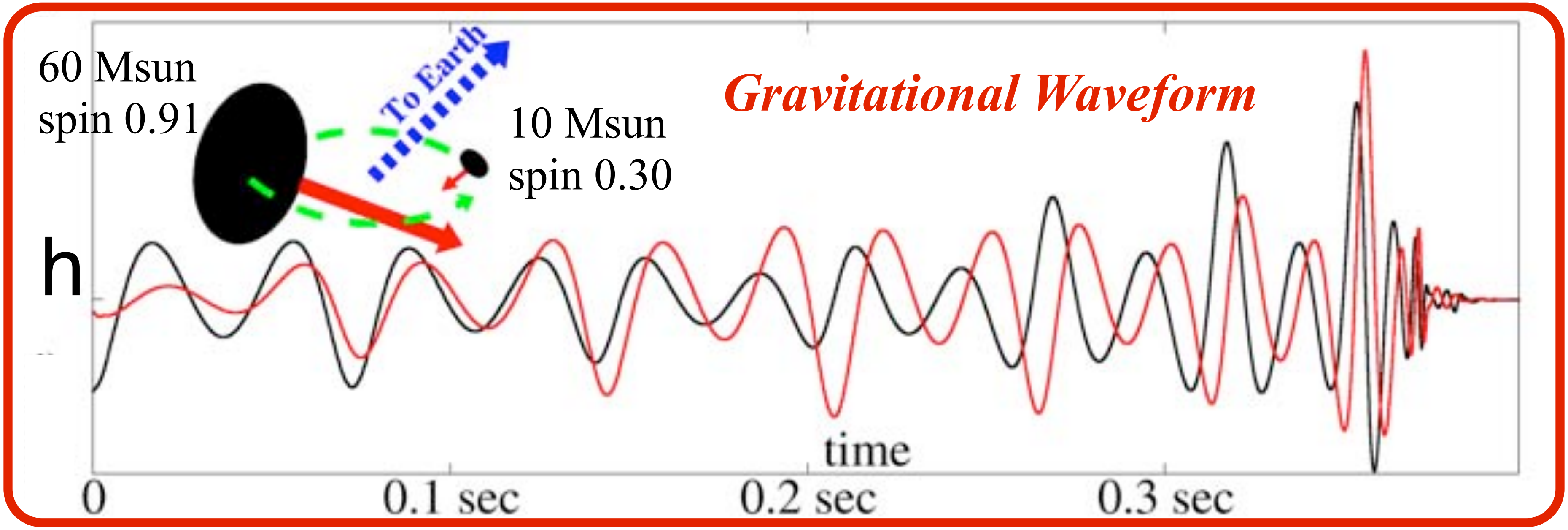
Laser Interferometer Gravitational-Wave Detector - "GW Interferometer"

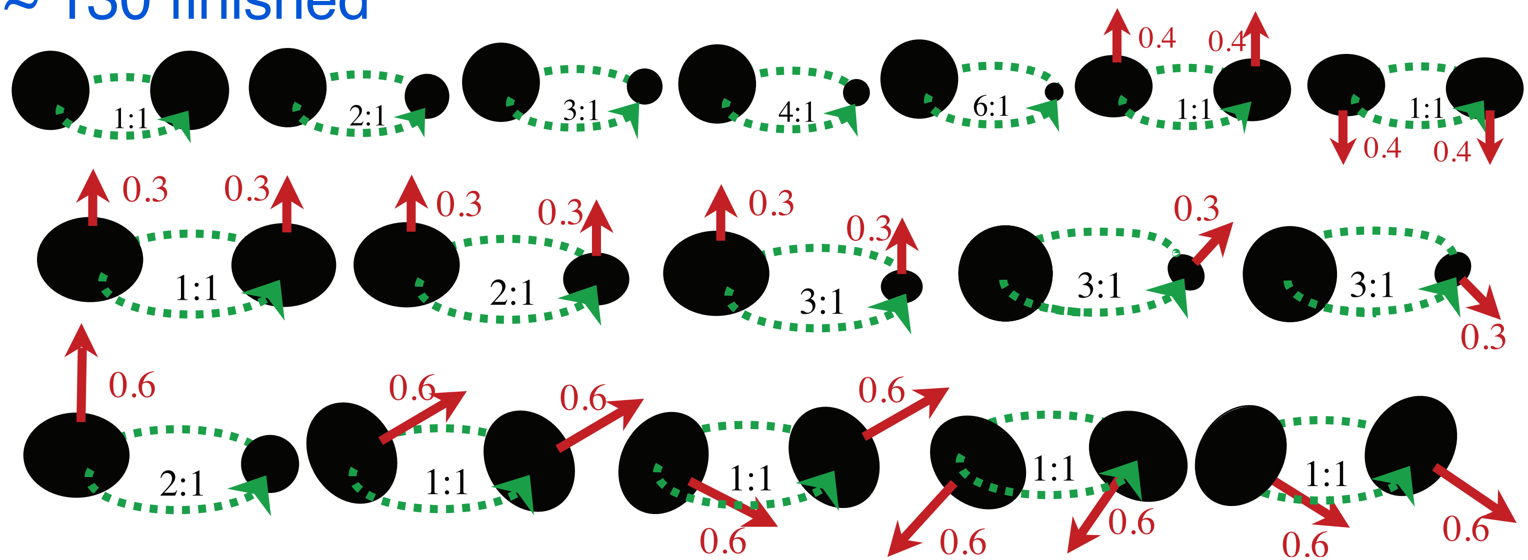




Dictionary of Gravitational Waveforms



- Now carrying out ~1000 simulations to underpin the dictionary; ~ 130 finished



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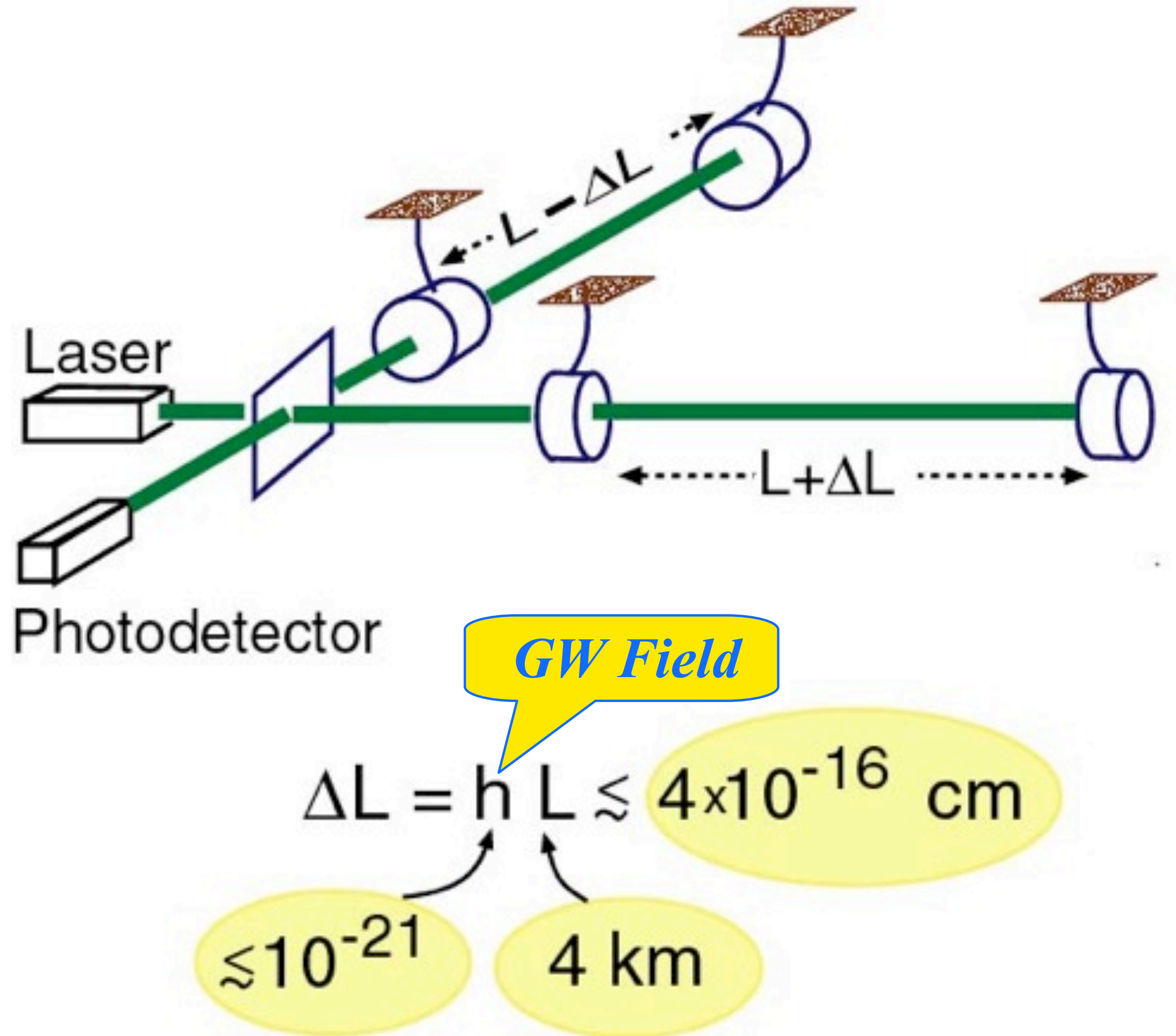
Gravitational Wave Interferometer



Network of Ground Based GW Interferometers

High-frequency band: 10 to 10,000 Hz

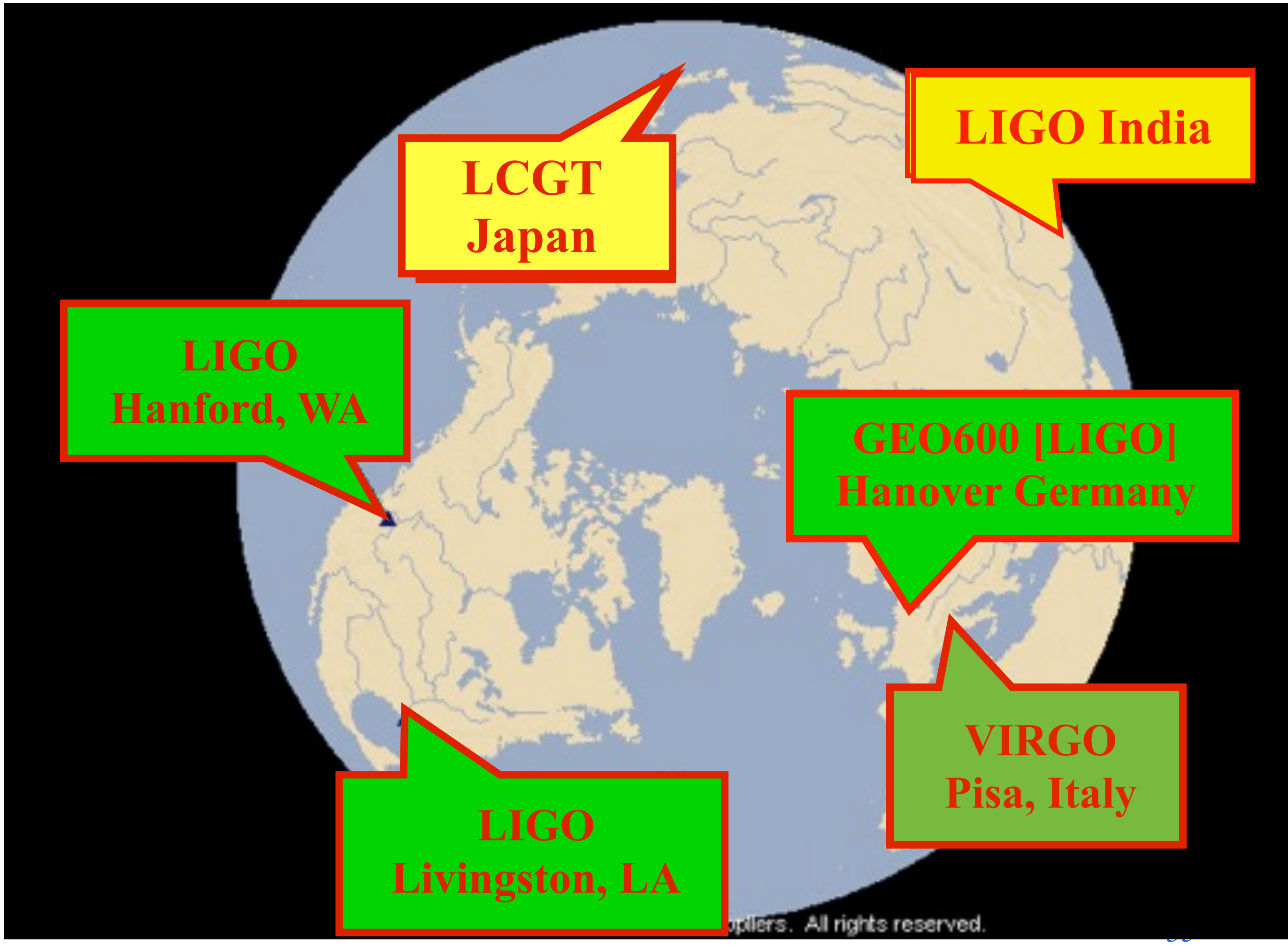
BHs: 2 to 1,000 Solar Masses

Network Required for:

Detection Confidence

Waveform Extraction

Direction by Triangulation



LIGO: Laser Interferometer Gravitational Wave Observatory

Collaboration of ~850 scientists at ~75 institutions in 13 nations [D. Reitze, Director; G. Gonzalez, Spokesperson]

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

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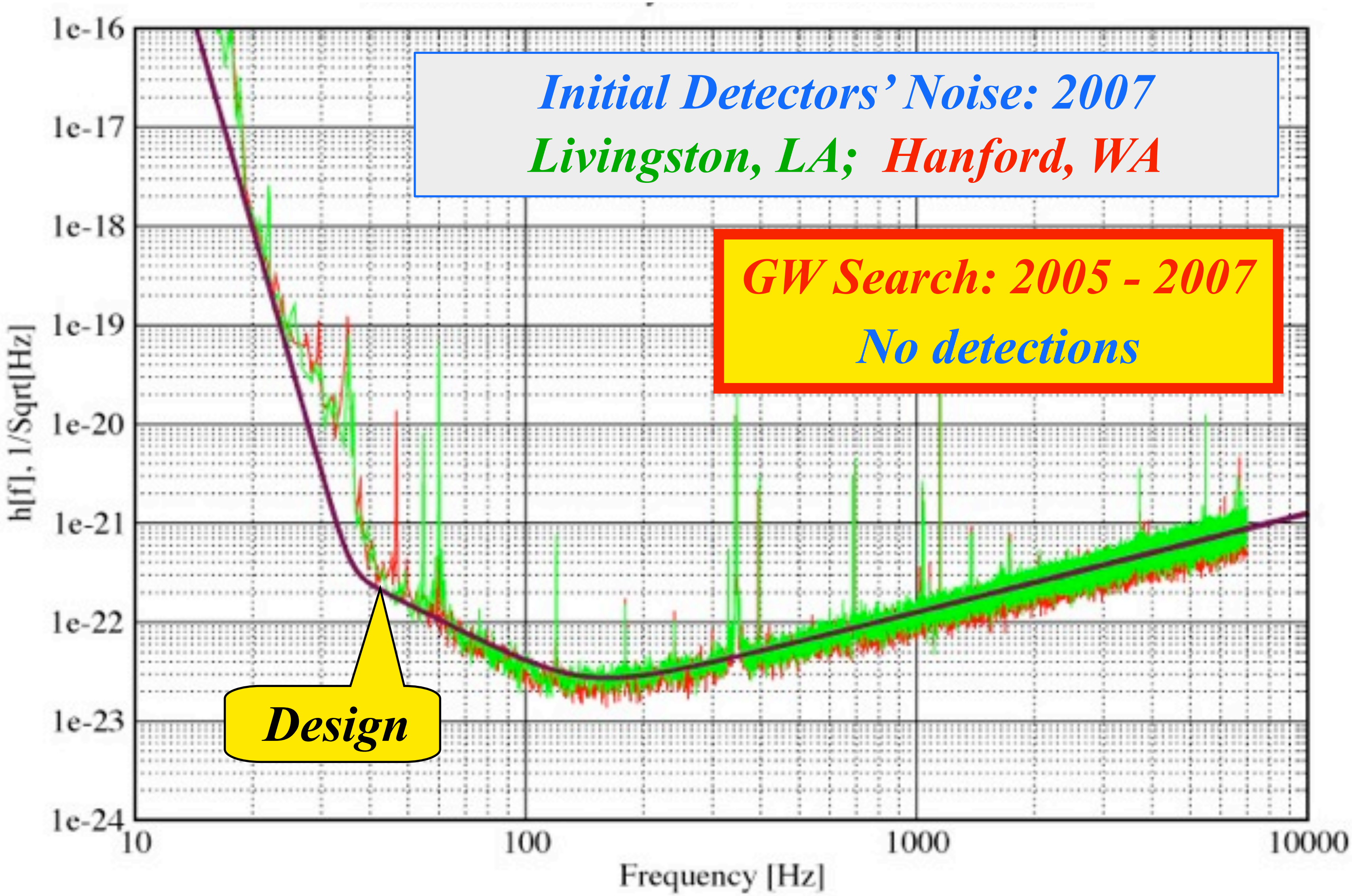
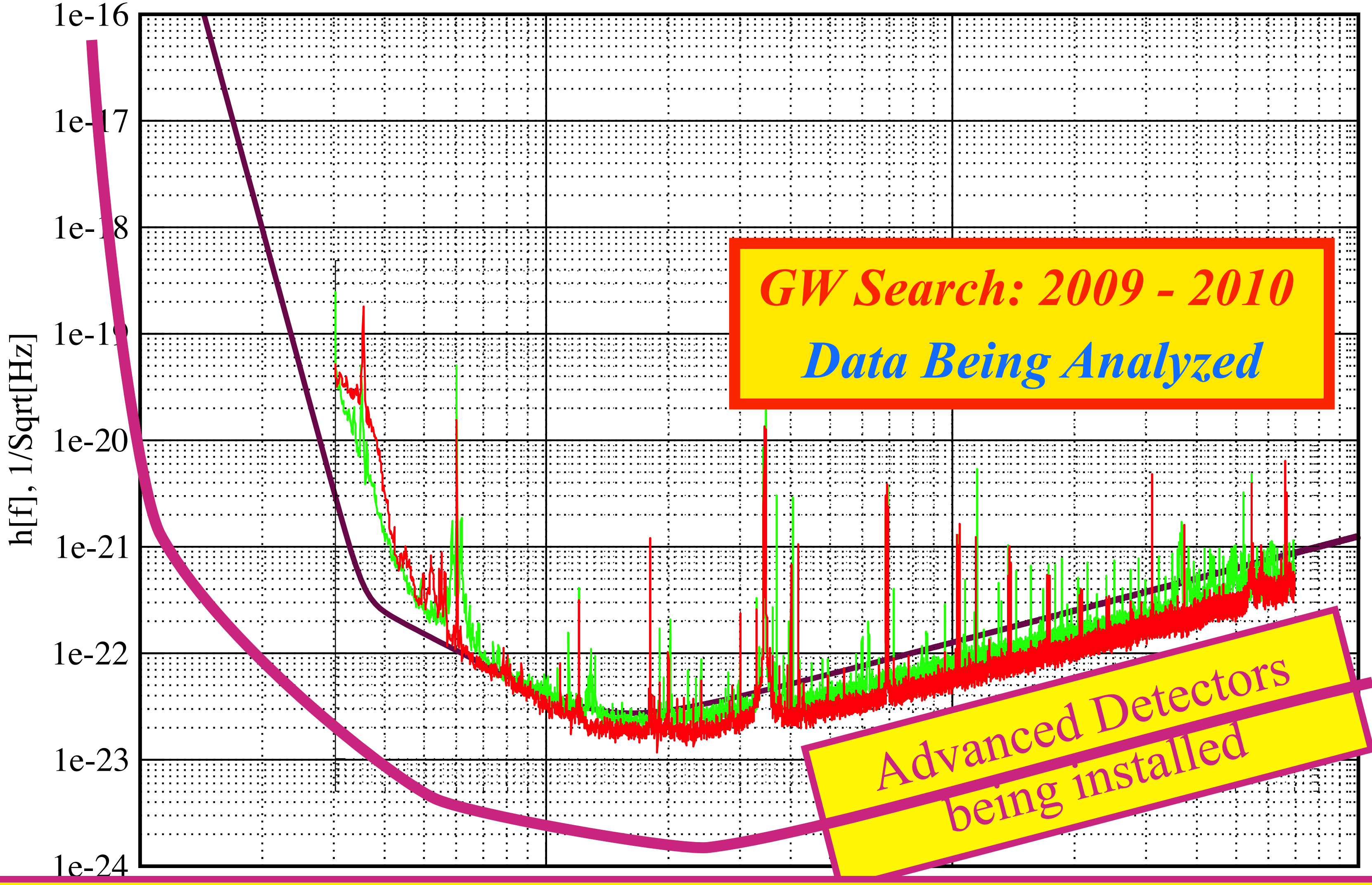
Sequence of Interferometers in LIGO

- 1989 Proposal for LIGO: 2-step strategy:
  - » ***Initial interferometers*** *- plausible but not likely to see GWs*
  - » ***Advanced interferometers*** *- likely to see GWs from a variety of sources*
- Initial interferometers, 2005-10:
  - » *BH/BH out to 300 million light years*
  - » *none seen yet - interesting limits*
- Advanced interferometers: installation began 2010. Searches near design sensitivity 2017 - …
  - » *BH/BH out to 4 billion light years: ~3/yr - 1/day*
  - » *Many other sources*

Initial LIGO Noise

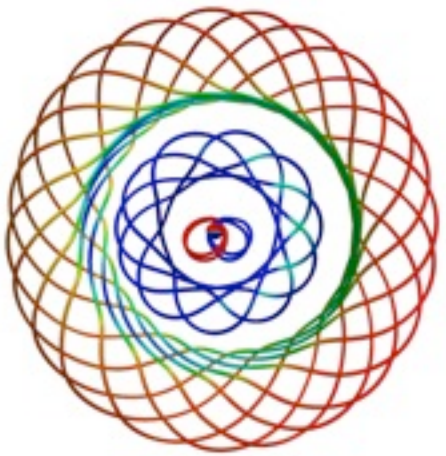


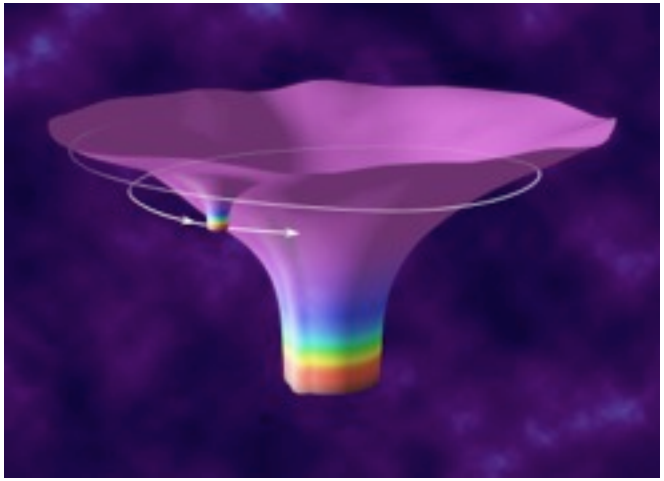
Initial LIGO Noise

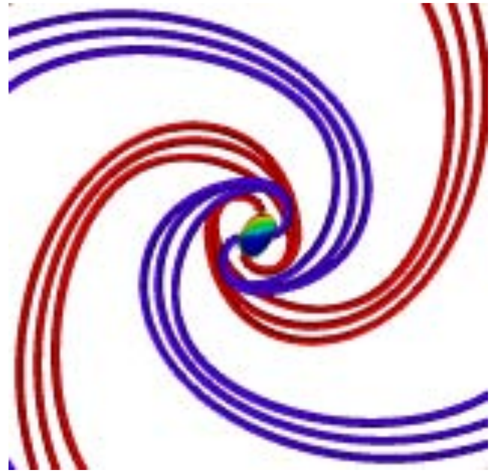


Expect: BH/BH mergers - 3/d to 1/2yr; neutron star binaries 6/d-1/2yr; pulsars; LMXBs; central engines of supernovae & gamma ray bursts;...

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