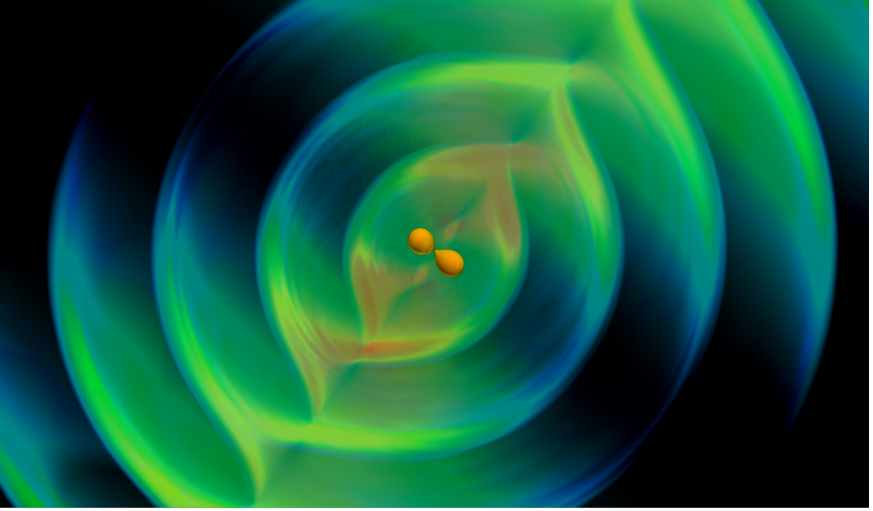
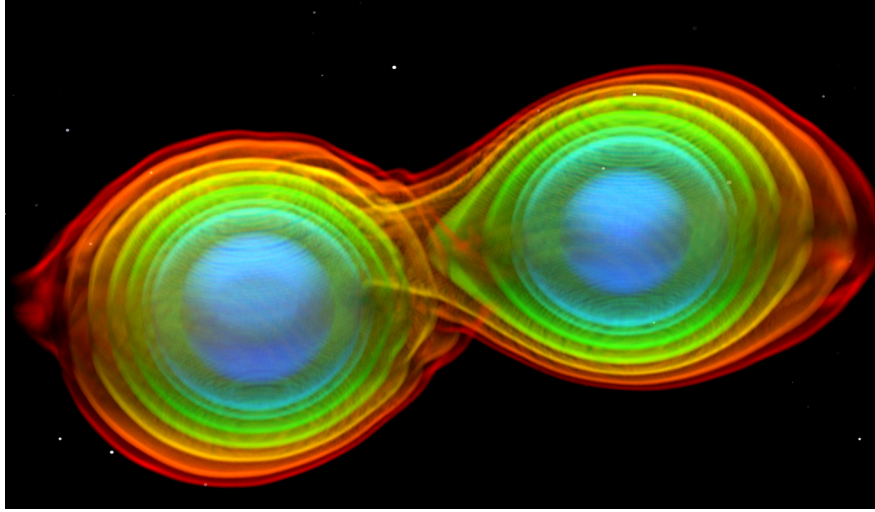
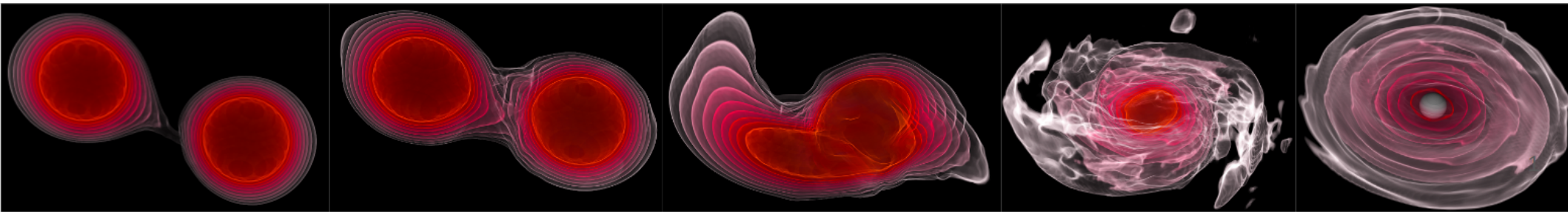




# Guest Lecture: Numerical Relativity

Lecture 4: Gravitational Waves MSc Course



# Why do we need numerical relativity?

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T_{\mu\nu}$$

only a limited number of analytical solutions e.g.:

- **1916 Schwarzschild metric**
- **1963 Kerr metric**
- **1939 TOV equation**
- 1995 Rotating Disk of Dust
- ...

*We are far away from having any kind of solution of two orbiting compact object!*

# Structure of the Lecture

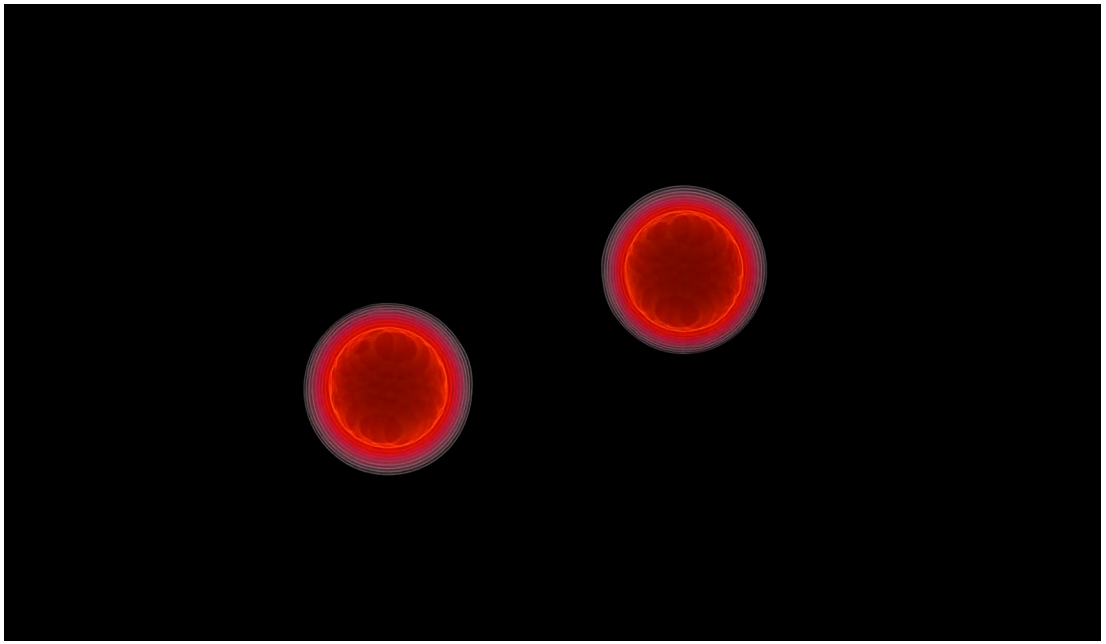
1.) 3+1-decomposition

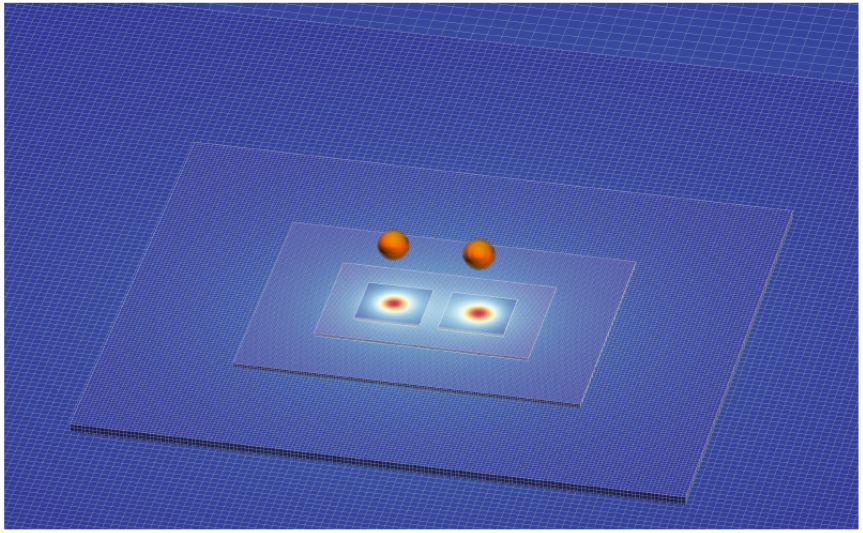
2.) requirements for successful simulations

3.) simple computational methods

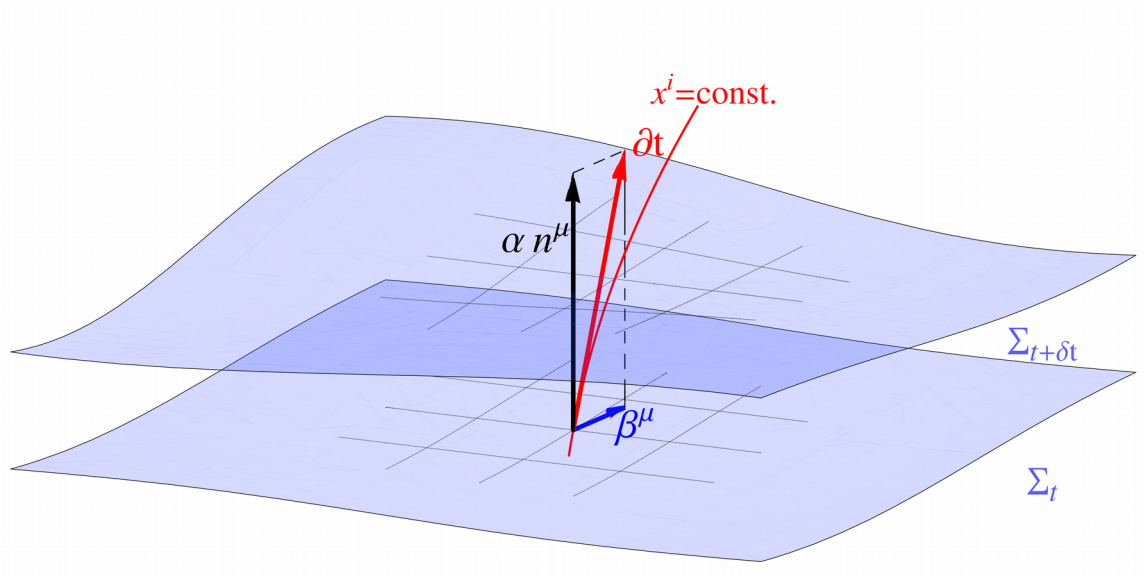
4.) applications

- binary black hole simulations
- binary neutron star simulations

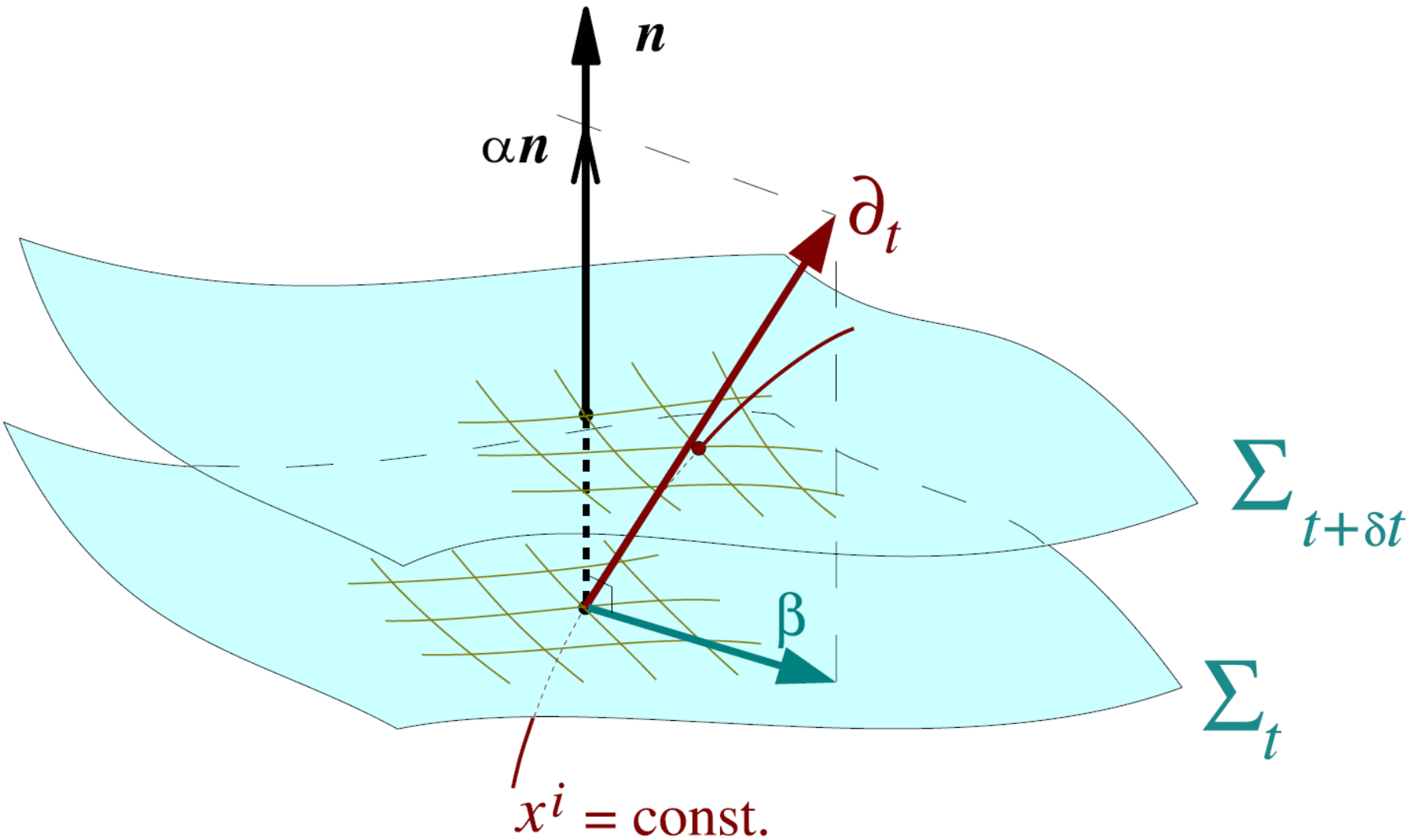




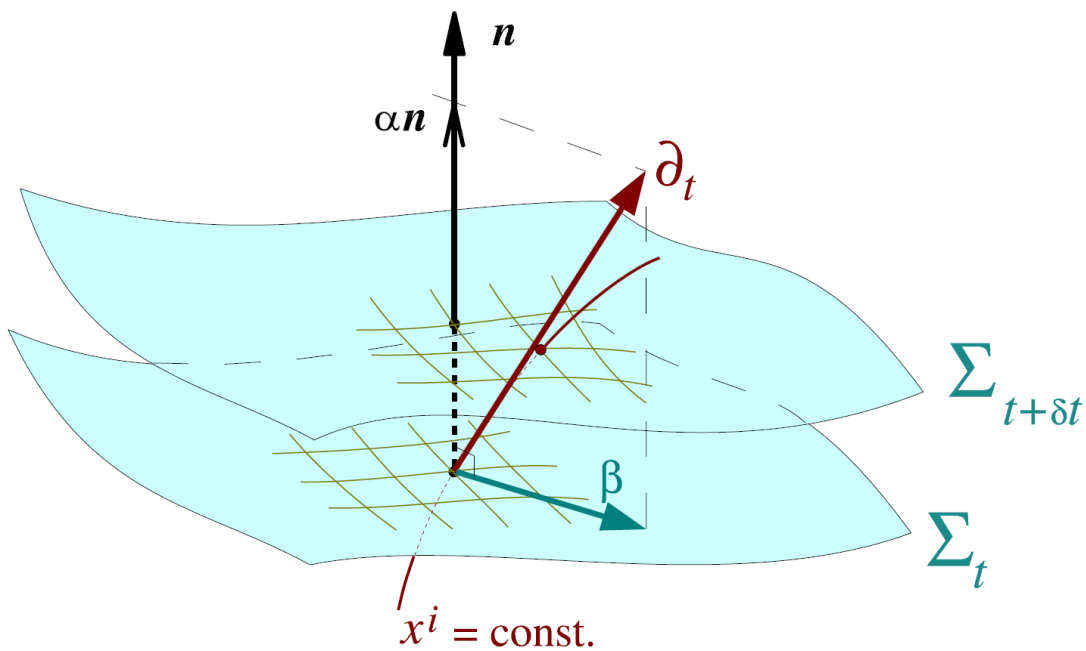
# 3+1- decomposition



# Foliation of four-dimensional spacetime



# Foliation of four-dimensional spacetime




normal vector:

$$n_\mu = -\alpha \nabla_\mu t$$

induced metric:

$$\gamma_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$$

shift and lapse:

$$n^\mu = \left(\frac{1}{\alpha}, -\frac{\beta^i}{\alpha}\right)$$

$$\mathrm{d}s^2 = (-\alpha^2 + \beta_i\beta^i)\mathrm{d}t^2 + 2\beta_i \mathrm{d}t\mathrm{d}x^i + \gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

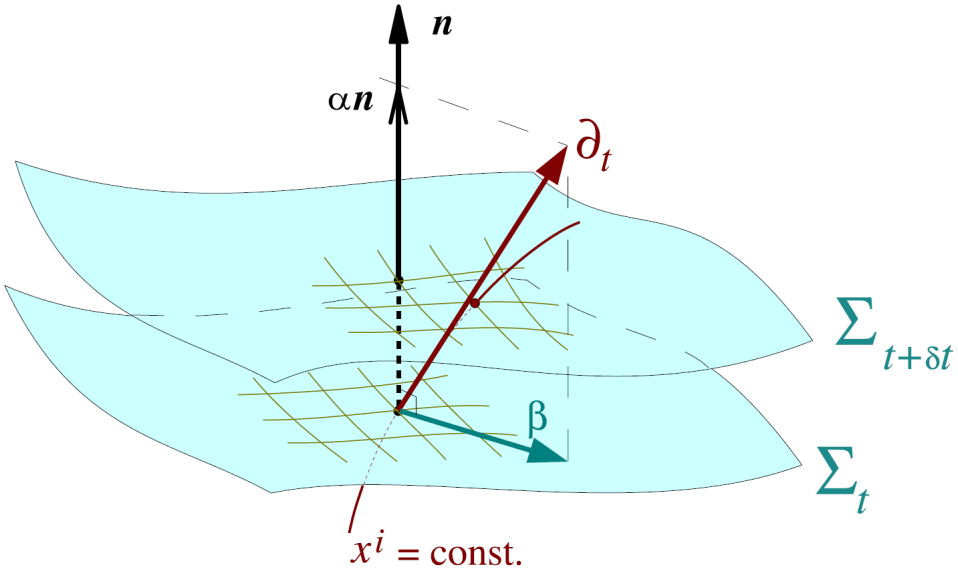
extrinsic curvature:

$$K_{\mu\nu} = -P^\sigma_\mu \nabla_\sigma n_\nu$$

projection operator

$$P^\mu_\nu = \delta^\mu_\nu + n^\mu n_\nu$$

# Foliation of four-dimensional spacetime

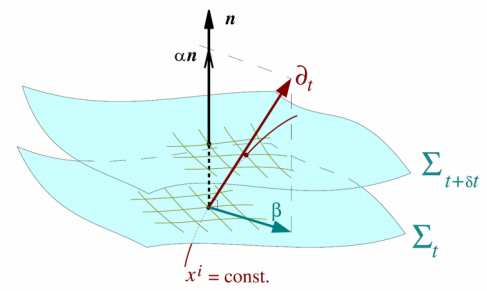



$$\gamma_{ij} = \begin{pmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{pmatrix}$$

$$K_{ij} = \begin{pmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{pmatrix}$$

$$\partial_t \gamma_{ij} = -2\alpha K_{ij} + D_i \beta_j + D_j \beta_i$$

# Splitting the Field Equations



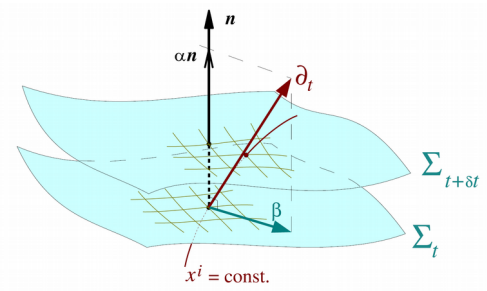

We have split the 4D spacetime, but need to do the same for the field equation:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T_{\mu\nu}$$

idea: use projections of 4D quantities to compute 3D variables e.g.:

$$\begin{aligned} P^{\delta}_{\alpha} P^{\kappa}_{\beta} P^{\lambda}_{\mu} P^{\sigma}_{\nu} {}^{(4)}R_{\delta\kappa\lambda\sigma} &= {}^{(3)}R_{\alpha\beta\mu\nu} + K_{\alpha\mu} K_{\beta\nu} - K_{\alpha\nu} K_{\beta\mu} \\ P^{\delta}_{\alpha} P^{\kappa}_{\beta} P^{\lambda}_{\mu} n^{\sigma} {}^{(4)}R_{\delta\kappa\lambda\sigma} &= D_{\beta} K_{\alpha\mu} - D_{\alpha} K_{\beta\mu}, \end{aligned}$$

# Splitting the Field Equations




Constraint Equations:

$$ {}^{(3)}R + K^2 - K_{\alpha\beta}K^{\alpha\beta} = 16\pi E $$

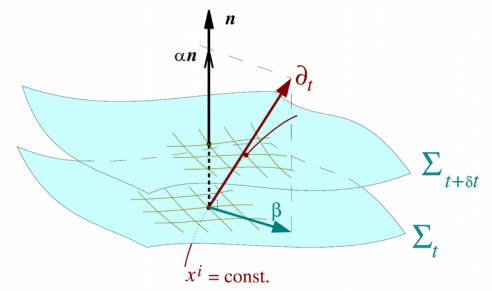
Hamiltonian Constraint

$$ D_j K^{ij} - D^i K = 8\pi S^i $$

Momentum Constraint

***Question: Which other constraint equations do you know in classical physics?***

# Splitting the Field Equations




Evolution Equations:

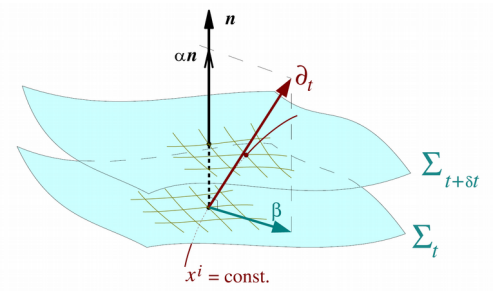
$$\partial_t \gamma_{ij} = -2\alpha K_{ij} + D_i \beta_j + D_j \beta_i$$

$$\partial_t K_{ij} = -D_i D_j \alpha + \beta^k \partial_k K_{ij} + K_{ik} \partial_j \beta^k + K_{kj} \partial_i \beta^k +$$
$$\alpha \left( {}^{(3)}R_{ij} + K K_{ij} - 2 K_{ik} K^k{}_j \right) + 4\pi\alpha \left( \gamma_{ij} (S - E) - 2 S_{ij} \right)$$

**ADM-Equations**
Richard Arnowitt, Stanley Deser, Charles Misner
1959

***Question: Can we now evolve everything?***

# Splitting the Field Equations




Evolution Equations:


$$\beta_j + D_j\beta_i$$

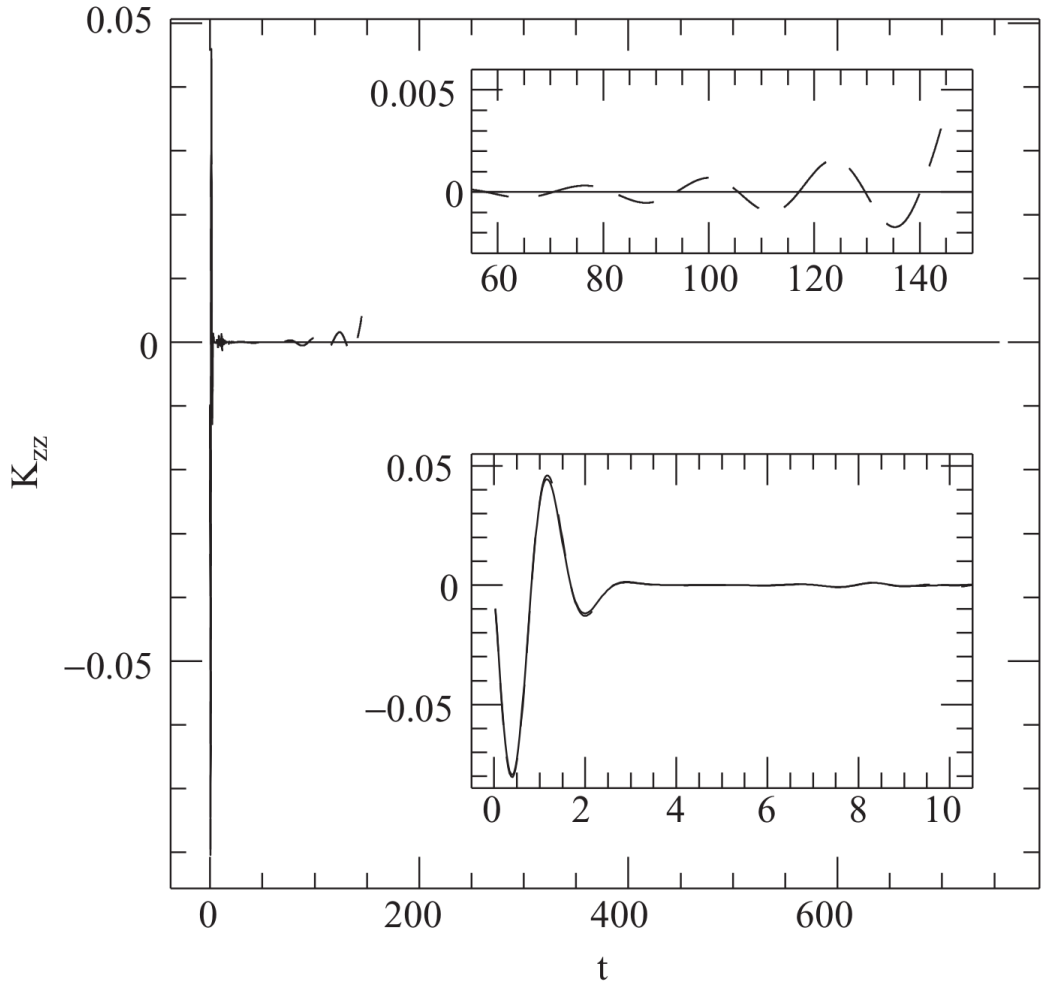
$$j + K_{ik}\partial_j\beta^k + K_{kj}\partial_i\beta^k +$$

$$\alpha\left(\left(3\right. \quad + \quad - 2K_{ik}K^{\ }_{j}\right) + 4\pi\alpha\left(\gamma_{ij}(S-E) - 2S_{ij}\right)$$

**ADM-Equations**
Richard Arnowitt, Stanley Deser, Charles Misner
1959

***Question: Can we now evolve everything?***

# ADM Evolution Equations




Reformulation is necessary to obtain well posed problem (strongly hyperbolic)

# An example: CTT + Z4c scheme

conformal transerve- traceless transformation for initial computation:

$$\bar{\gamma}_{ij} = \psi^{-4}\gamma_{ij} \qquad \bar{A}_{ij} = \psi^2 A_{ij}$$

Constraint Equations:

$$\begin{aligned} \bar{D}^i\bar{D}_i\psi - \frac{1}{12}\psi^5 K^2 + \frac{1}{8}\psi^{-7}\bar{A}_{ij}\bar{A}^{ij} - \frac{1}{8}\psi\ {}^{(3)}\bar{R} &= -2\pi\psi^5 E, \\ \bar{D}_j\bar{A}^{ij} - \frac{2}{3}\psi^6\bar{\gamma}^{ij}\bar{D}_j K &= 8\pi\psi^{10}S^i. \end{aligned}$$

there are other alternatives to recast the equations

# An example: CTT + Z4c scheme

transformation for evolution equations:

$$R_{\alpha\beta} + \nabla_\alpha Z_\beta + \nabla_\beta Z_\alpha = 8\pi \left( T_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} T \right) + \kappa_1 \left( t_\alpha Z_\beta + t_\beta Z_\alpha - (1+\kappa_2) g_{\alpha\beta} \right) t_\gamma Z^\gamma$$

add constraints to evolution system

transformation:

$$\begin{aligned} \tilde{\gamma}_{ij} &= \chi \gamma_{ij} \\ \tilde{A}_{ij} &= \chi (K_{ij} - \frac{1}{3} \gamma_{ij} K) \\ \hat{K} &= \gamma^{ij} K_{ij} - 2\Theta, \quad \Theta = -n_\alpha Z^\alpha \end{aligned}$$

# An example: CTT + Z4c scheme

***Question: How do the coordinates evolve?***

transformation for evolution equations:

$$\partial_t \chi = \frac{2}{3}\chi\left(\alpha(\hat{K}+2\Theta) - D_i\beta^i\right) \tag{2.39}$$

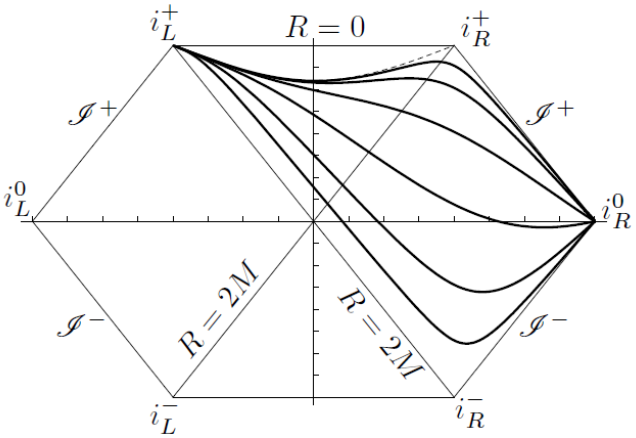
$$\partial_t \tilde{\gamma}_{ij} = -2\alpha\tilde{A}_{ij} + \beta^k\partial_k\tilde{\gamma}_{ij} + 2\tilde{\gamma}_{k(i}\partial_{j)}\beta^k - \frac{2}{3}\tilde{\gamma}_{ij}\partial_k\beta^k, \tag{2.40}$$

$$\begin{aligned}\partial_t \hat{K} &= -D^iD_i\alpha + \alpha\left(\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}(\hat{K}+2\Theta)^2\right)\\ &\quad +4\pi\alpha(S+E) + \beta^k\partial_k\hat{K} + \alpha\kappa_1(1-\kappa_2)\Theta\end{aligned} \tag{2.41}$$

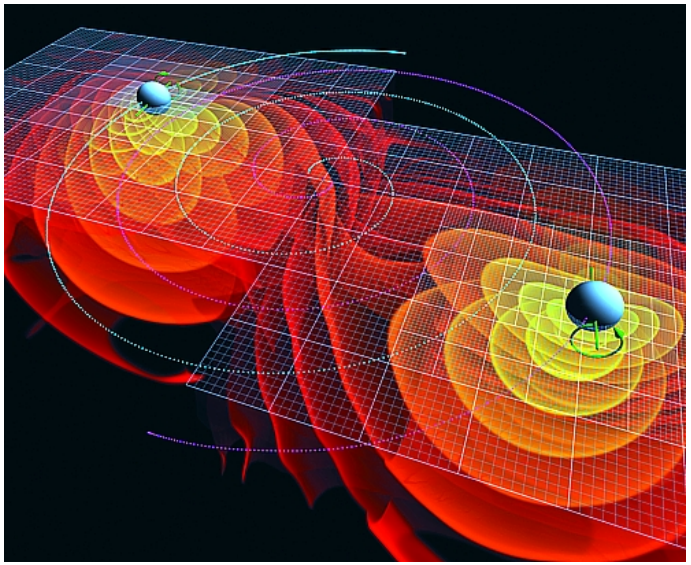
$$\begin{aligned}\partial_t \tilde{A}_{ij} &= \chi\left(-D_iD_j\alpha + \alpha\left({}^{(3)}R_{ij} - 8\pi S_{ij}\right)\right)^{TF} + \alpha\left((\hat{K}+2\Theta)\tilde{A}_{ij} - 2\tilde{A}^k{}_j\tilde{A}_{kj}\right)\\ &\quad +\beta^k\partial_k\tilde{A}_{ij} + 2\tilde{A}_{k(i}\partial_{j)}\beta^k - \frac{2}{3}\tilde{A}_{ij}\partial_k\beta^k\end{aligned} \tag{2.42}$$

$$\begin{aligned}\partial_t \tilde{\Gamma}^i &= -2\tilde{A}^{ik}\partial_k\alpha + 2\alpha\left(\tilde{\Gamma}^i_{kl}\tilde{A}^{kl} - \frac{3}{2}\tilde{A}^{ik}\partial_k\ln(\chi) - \frac{1}{3}\tilde{\gamma}^{ik}\partial_k(\hat{K}+2\Theta) - 8\pi\tilde{\gamma}^{ik}S_k\right)\\ &\quad +\tilde{\gamma}^{kl}\partial_k\partial_l\beta^i + \frac{1}{3}\tilde{\gamma}^{ik}\partial_l\partial_k\beta^l - 2\alpha\kappa_1(\tilde{\Gamma}^i - \bar{\Gamma}^i)\\ &\quad +\beta^k\partial_k\tilde{\Gamma}^i - \bar{\Gamma}^k\partial_k\beta^i + \frac{2}{3}\bar{\Gamma}^i\partial_k\beta^k,\end{aligned} \tag{2.43}$$

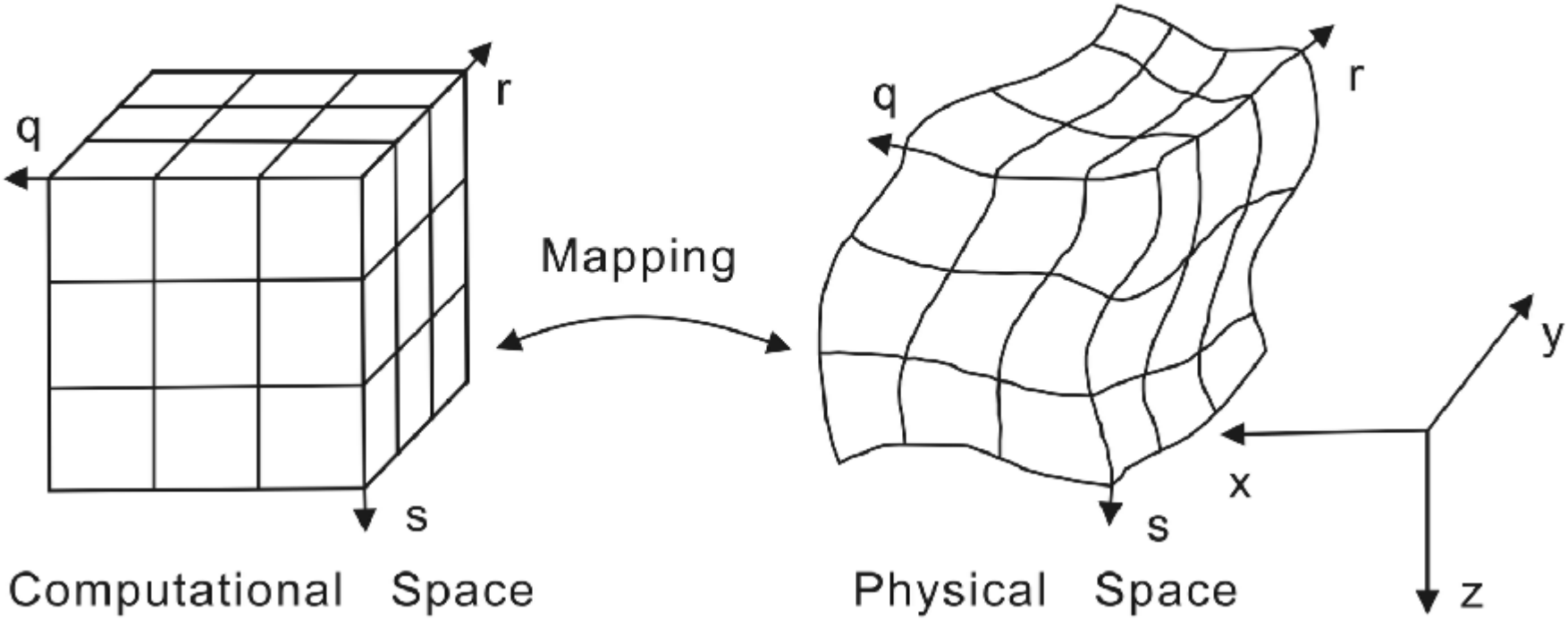
$$\begin{aligned}\partial_t \Theta &= \frac{\alpha}{2}\left({}^{(3)}R - \tilde{A}_{ij}\tilde{A}^{ij} + \frac{2}{3}(\hat{K}+2\Theta)^2\right)\\ &\quad -\alpha\left(8\pi E + \kappa_1(2+\kappa_2)\Theta\right) + \beta^i\partial_i\Theta,\end{aligned} \tag{2.44}$$



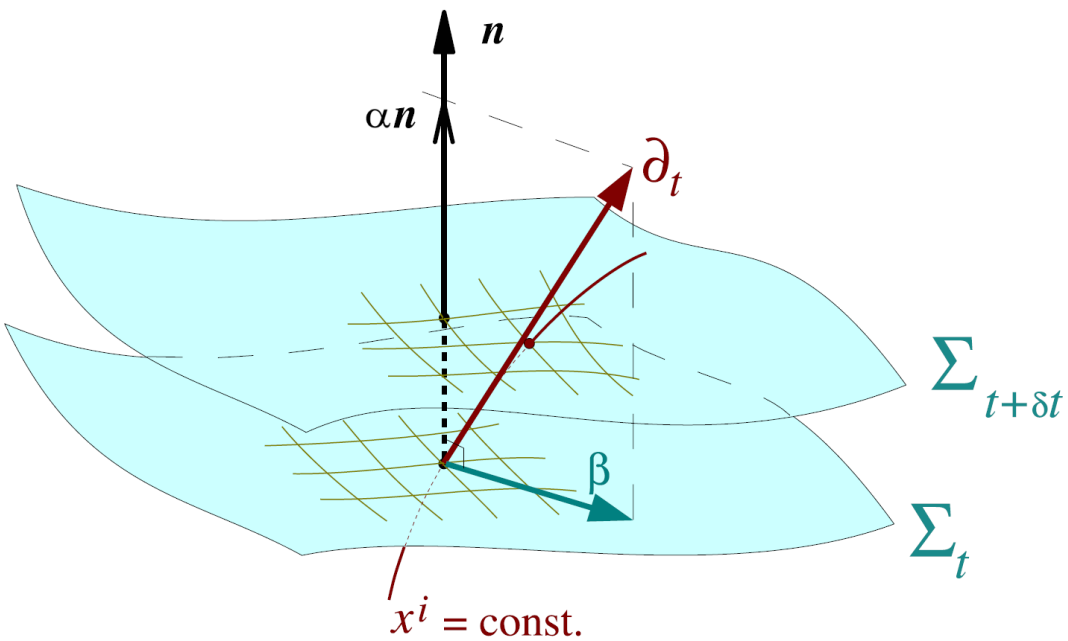

# Requirements for a successful simulation



# Gauge/Coordinate choice

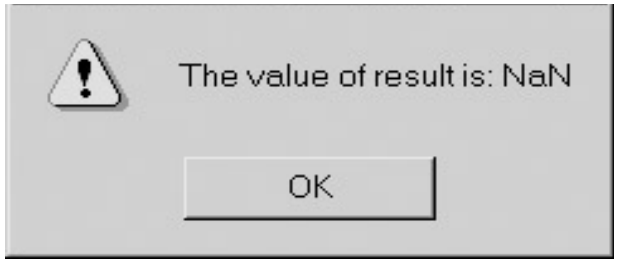


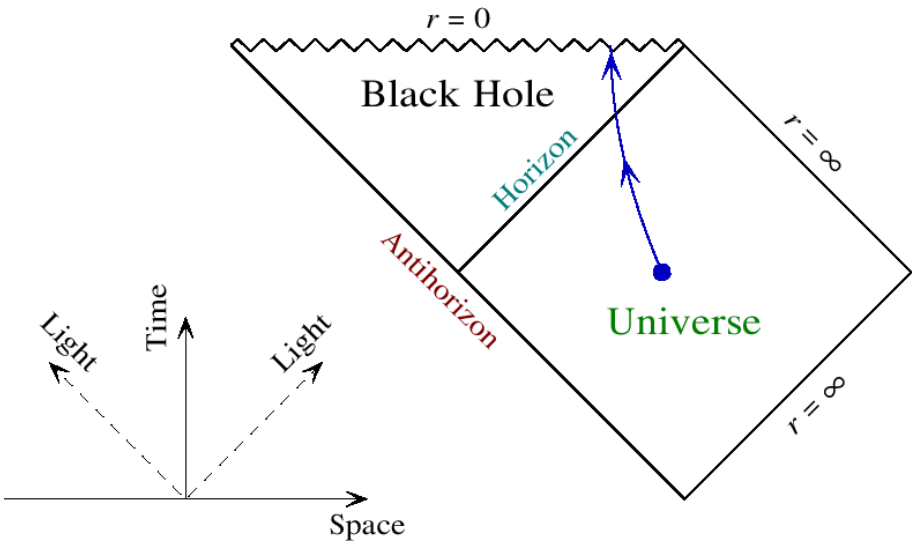
# Gauge/Coordinate choice – geodesic slicing –



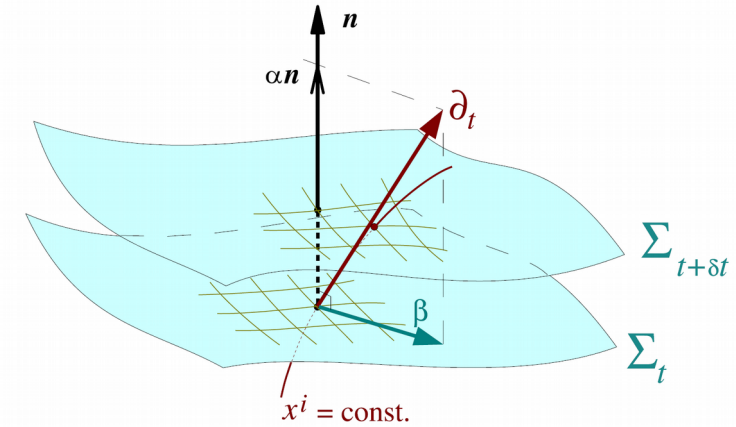

$$\alpha = 1 \ , \ \beta^i = 0$$

***Question: What will happen when you evolve a Schwarzschild BH?***



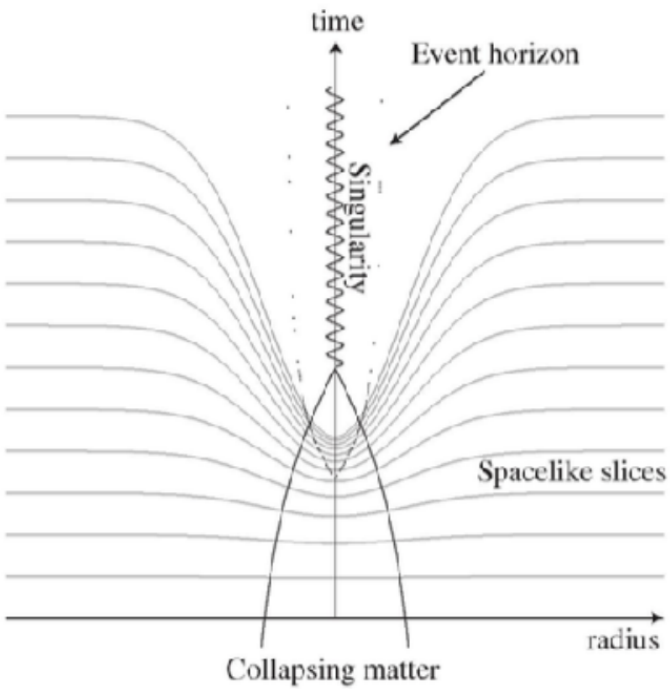
# Gauge/Coordinate choice – How to evolve BHs –

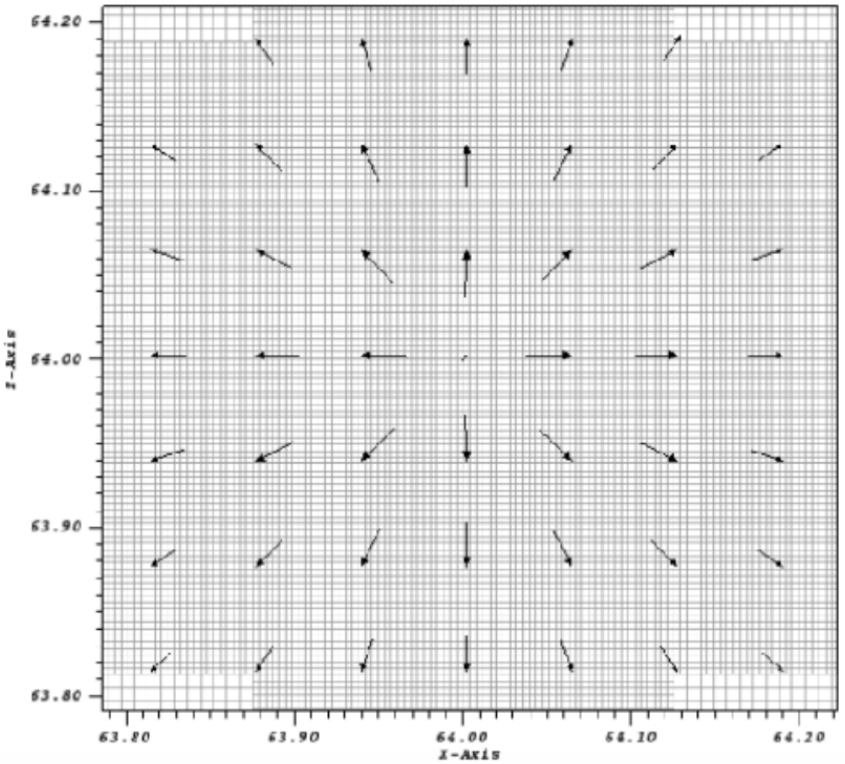



**moving puncture gauge**, e.g.:

$$\partial_t \alpha = -2\alpha K$$

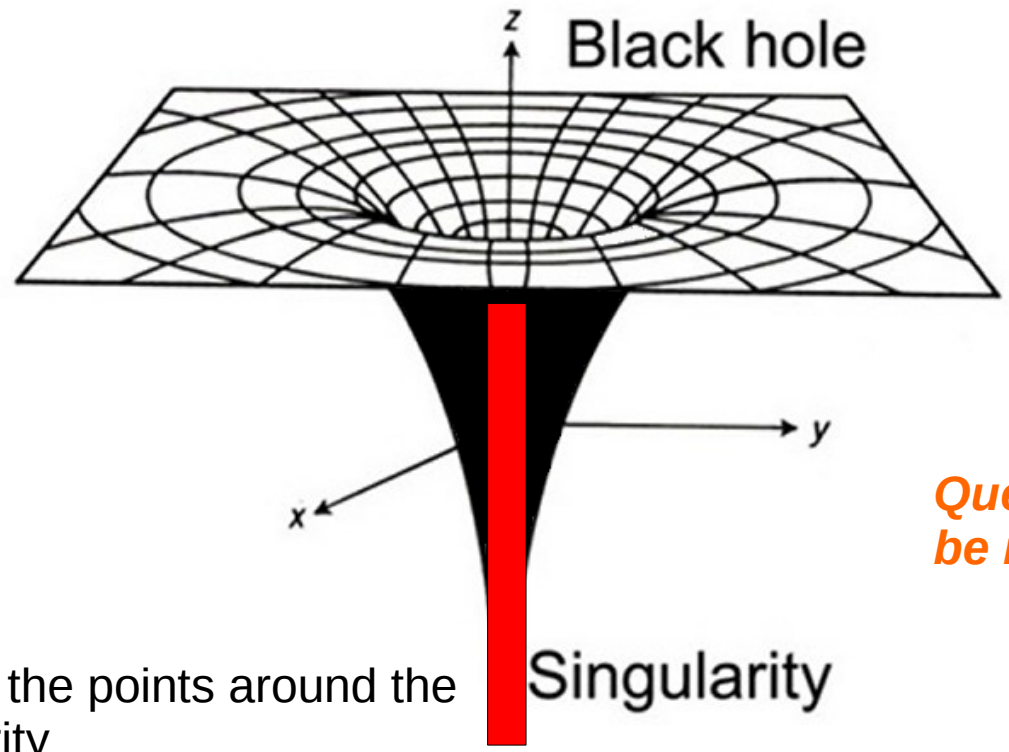
$$\partial_t \beta^i = B^i \ , \quad \partial_t B^i = \frac{3}{4}\partial_t \tilde{\Gamma}^i - \eta B^i$$



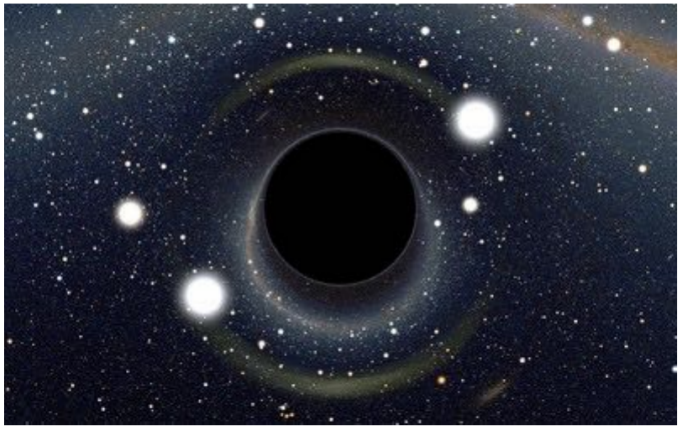



# Gauge/Coordinate choice
# – How to evolve BHs –

**excision**



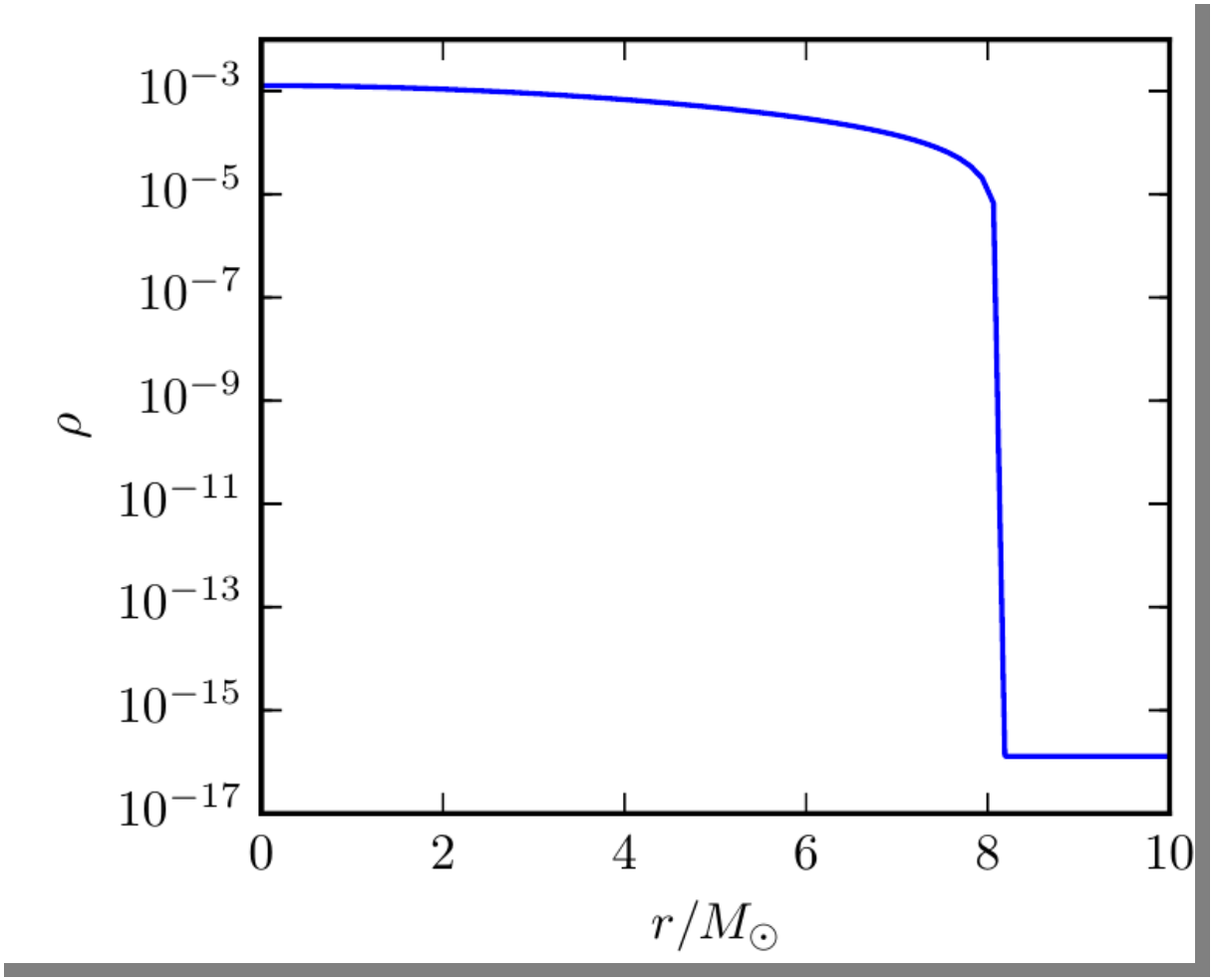

remove the points around the singularity

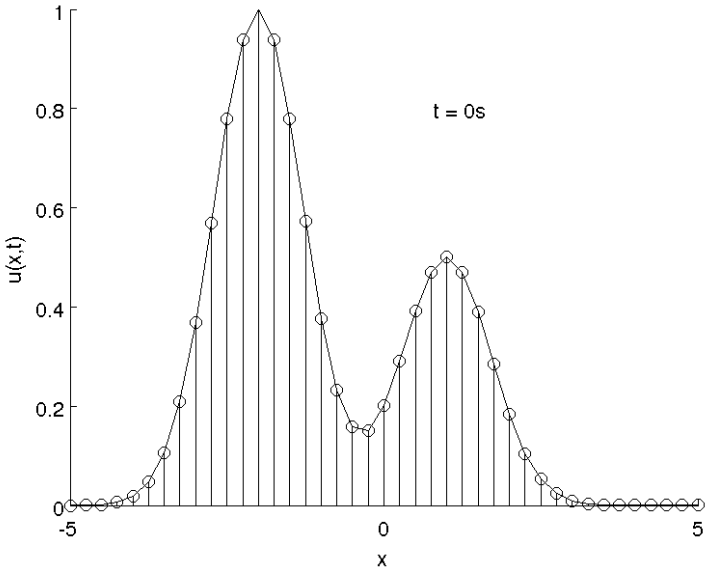


***Question: Should the excision boundary be inside or outside of the horizon?***

# Artificial Atmosphere

Computation of pure
Vacuum is not possible





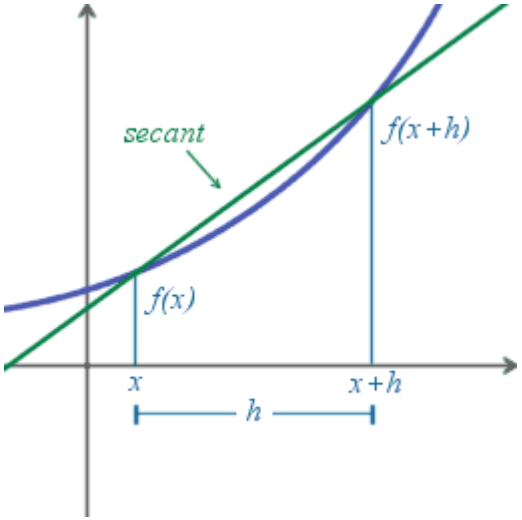

# Computational methods

# Approximation of derivatives

*Question: How to compute derivatives numerically?*

# Approximation of derivatives

- Finite differences
- Finite elements
- Finite volume
- Spectral method
- Discontinous Galerkin
- ...



# Finite differencing

Taylor expansion around central point

$$f(x) = f(x_j) + (x - x_j) f'(x_j) + \frac{(x - x_j)^2}{2} f''(x_j) + \mathcal{O}\left((x - x_j)^3\right)$$

use neighboring gridpoints $x_{j-1}, x_{j+1}$

$$f'(x_j) = \frac{f(x_{j+1}) - f(x_{j-1})}{x_{j+1} - x_{j-1}} + \mathcal{O}\left((x_{j+1} - x_{j-1})^2\right)$$

# Spectral methods

approximate function by series expansion

$$f(x) = \sum_n a_n \Phi_n$$

$$a_n = \int_A^B f(x)\Phi_n(x)\omega(x)\mathrm{d}x$$

# Spectral methods

approximate function by series expansion

$$f(x) = \sum_n a_n \Phi_n$$

$$a_n = \int_A^B f(x)\Phi_n(x)\omega(x)\mathrm{d}x$$

assuming a finite number of points

$$f_{N,j} = \sum_{n=0}^{N-1} a_n \Phi_{n,j}, \quad \text{with} \quad a_n = \sum_{j=0}^{N-1} f_{N,j}\Phi_{n,j}\omega_j$$

# Spectral methods

approximate function by series expansion

$$f(x) = \sum_n a_n \Phi_n$$

$$a_n = \int_A^B f(x)\Phi_n(x)\omega(x)\mathrm{d}x$$

assuming a finite number of points

$$f_{N,j} = \sum_{n=0}^{N-1} a_n \Phi_{n,j}, \quad \text{with} \quad a_n = \sum_{j=0}^{N-1} f_{N,j}\Phi_{n,j}\omega_j$$

approximation of derivatives

$$\partial_x f_{N,j} = \sum_{n=0}^{N-1} a_n \partial_x \Phi_{n,j} = \sum_{n=0}^{N-1} b_n \Phi_{n,j}$$

# Spectral methods

$$\Phi(t, x^i) = \sum_N c_N \ \phi_N$$

$$\phi_N = \{x^0, x^1, x^2, x^3, x^4, ...\}$$

$c_0 = 1$

$c_1 = 0$

$c_2 = -1/2$

$c_3 = 0$

$c_4 = 1/24$

$c_5 = 0$

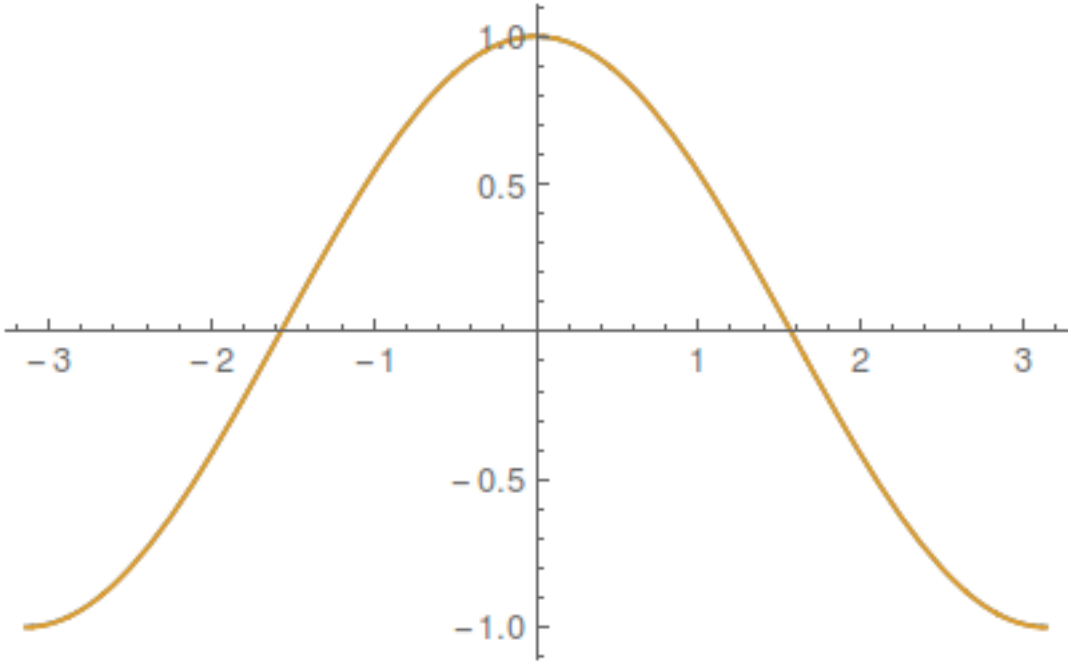
$c_6 = -1/720$

$c_7 = 0$

$c_8 = 1/40320$

$c_9 = 0$

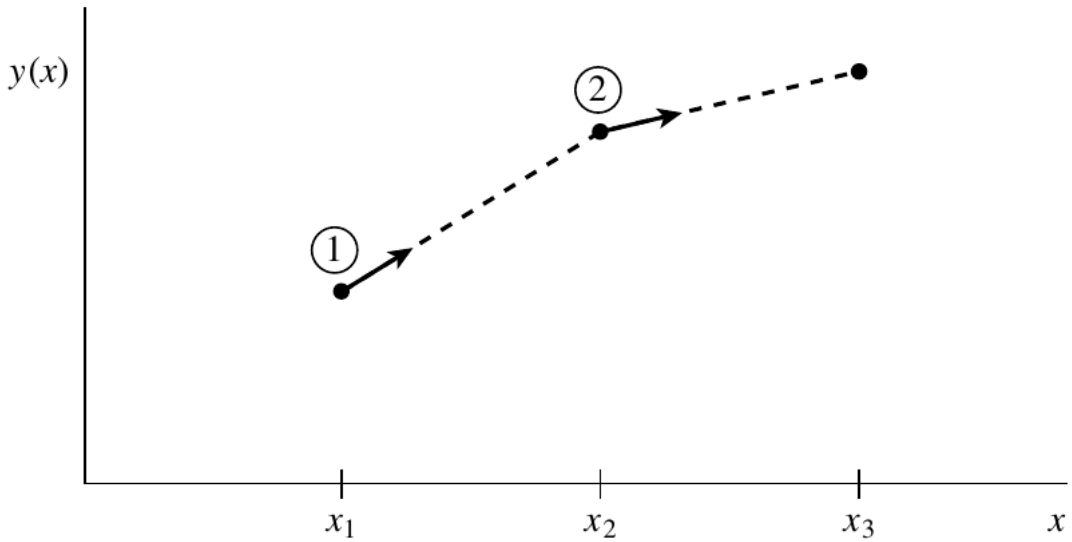
$c_{10} = -1/3268800$



# Explicit time integration

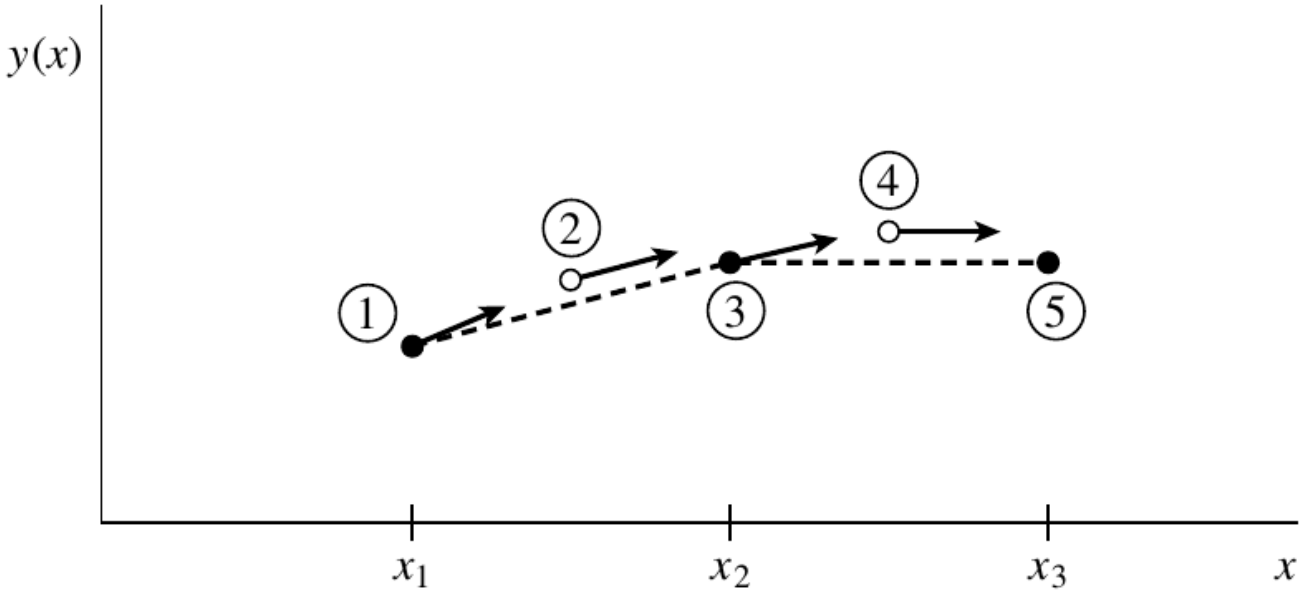
Euler method:

$$y_{n+1} = y_n + hf(x_n, y_n)$$




***Question: How to do better?***

# Explicit time integration



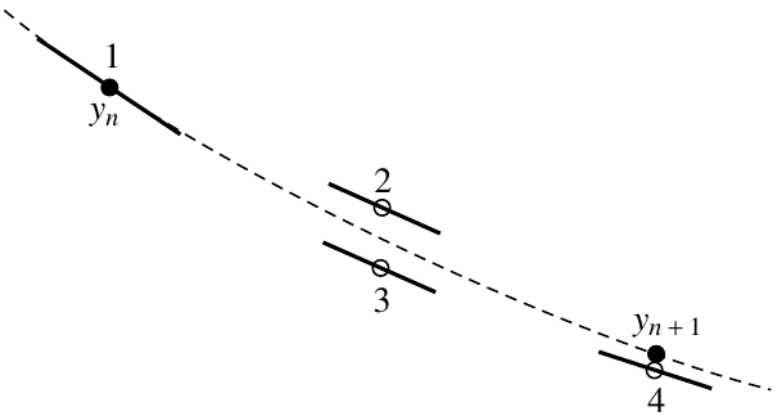

$$k_1 = hf(x_n, y_n)$$

$$k_2 = hf\left(x_n + \tfrac{1}{2}h, y_n + \tfrac{1}{2}k_1\right)$$

$$y_{n+1} = y_n + k_2 + O(h^3)$$

Convergence order improved by additional, intermediate step

# $4^{th}$ order explicit Runge-Kutta

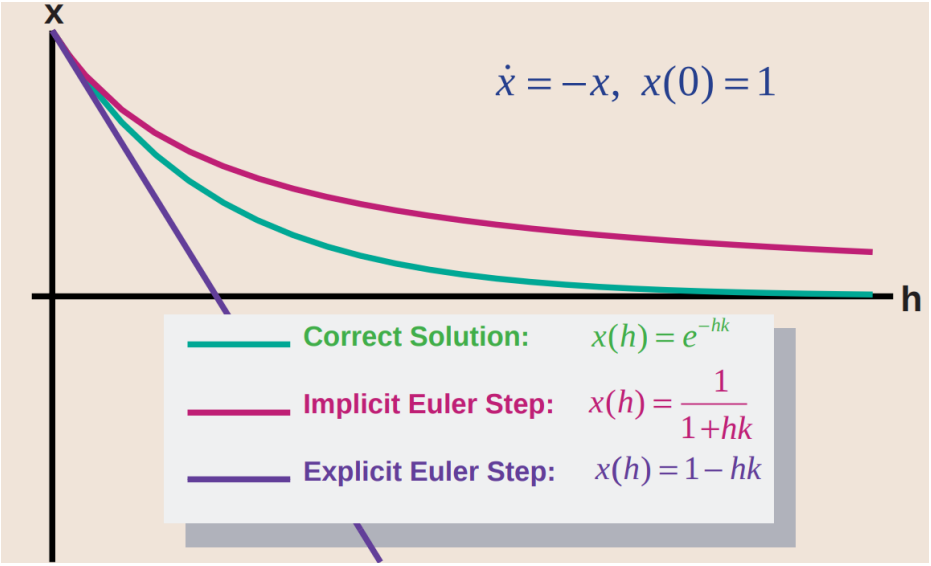



$$
\begin{aligned}
k_1 &= hf(x_n, y_n) \\
k_2 &= hf(x_n + \frac{h}{2}, y_n + \frac{k_1}{2}) \\
k_3 &= hf(x_n + \frac{h}{2}, y_n + \frac{k_2}{2}) \\
k_4 &= hf(x_n + h, y_n + k_3) \\
y_{n+1} &= y_n + \frac{k_1}{6} + \frac{k_2}{3} + \frac{k_3}{3} + \frac{k_4}{6} + O(h^5)
\end{aligned}
$$

*Why not going to higher order?*

# Time integration (more advanced)

- Implicit methods
  - necessary for stiff ODEs




***How can you obtain the formula for implicit time integration?***

- Partially-implicit
- adaptive time stepping

# Method of lines

- principle idea: replace the spatial derivatives algebraic approximations
- only the initial value variable, typically time in a physical problem remains
- one obtains a system of ODEs that approximate the original PDE
- apply any integration algorithm for initial value ODEs to compute an approximate numerical solution to the PDE

# Method of lines

Example: *heat equation*

$$\frac{\partial u}{\partial t} - \beta^2 \Delta u \quad = \quad f$$

$$\frac{\partial u_j}{\partial t} - \frac{\beta^2}{h^2}(u_{j-1} - 2u_j + u_{j+1}) = f_j(t)$$

**Homework: wave equation**

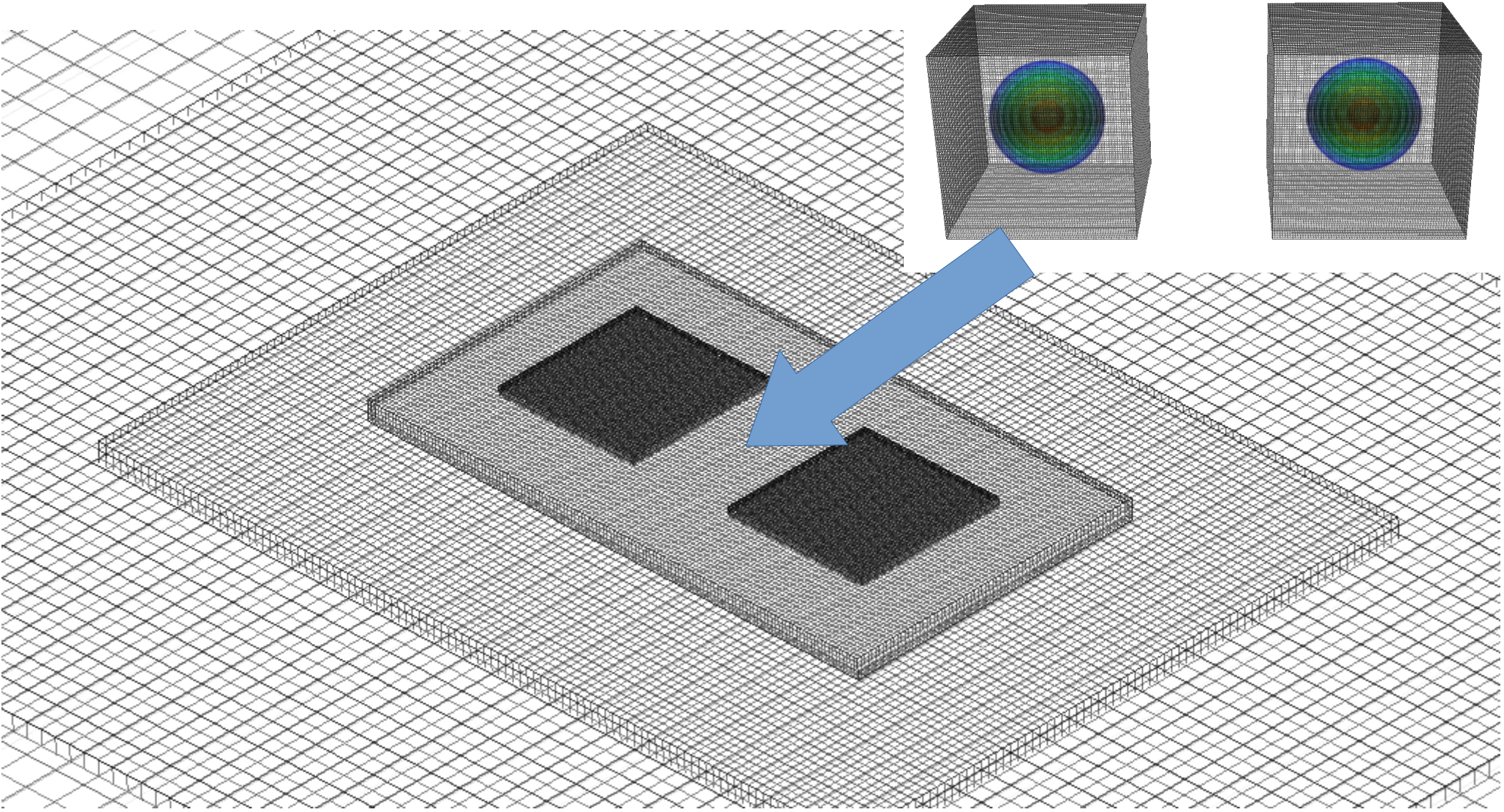
# Some of the add ons for NR simulations

- Adaptive mesh refinement techniques
- Berger-Oliger/Collela time stepping
- high-order shock capturing schemes
- ...

# Mesh refinement

***Question: Can all level go with the same time step?***

- Box-in-box mesh refinement



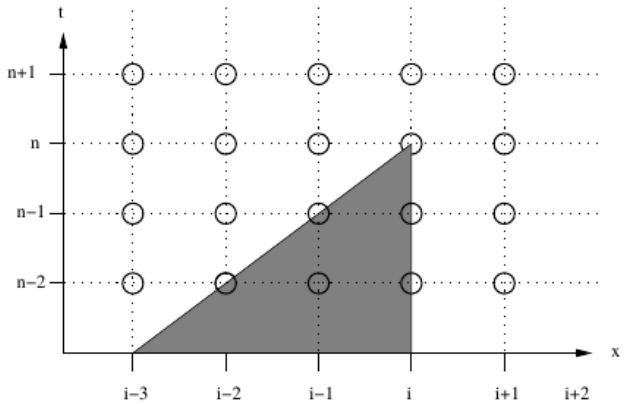
# Mesh refinement

trade-off between efficiency, accuracy, and stability

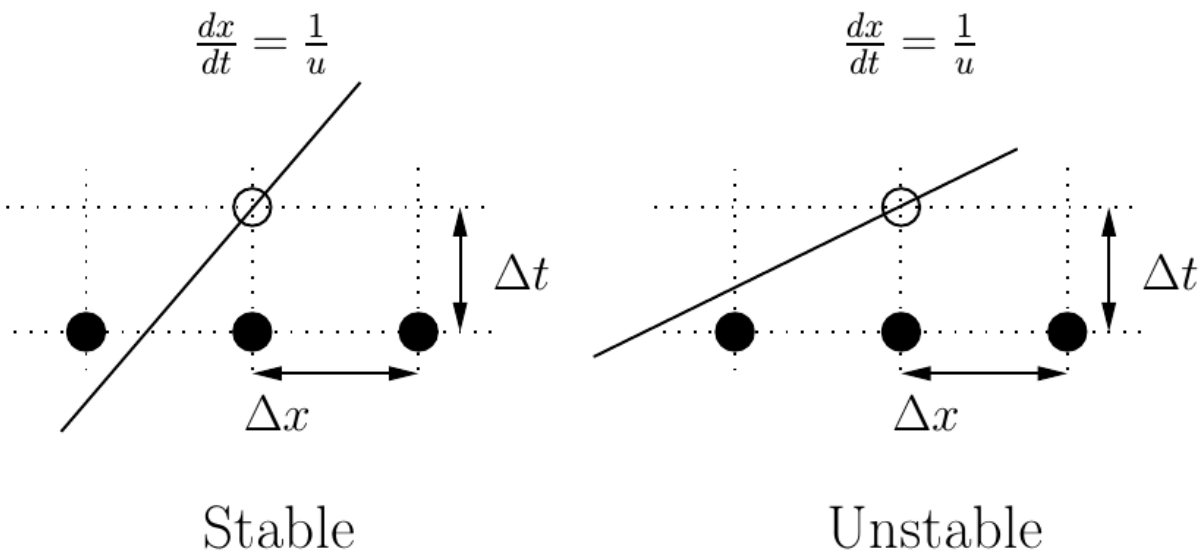
- *Efficiency:* “Faster” evolution with larger time step
- *Accuracy:* Smaller time step decreases time integration error
- *Stability:* Courant-Friedrichs-Lewy condition needs to be fulfilled

# Mesh refinement

*Stability:*



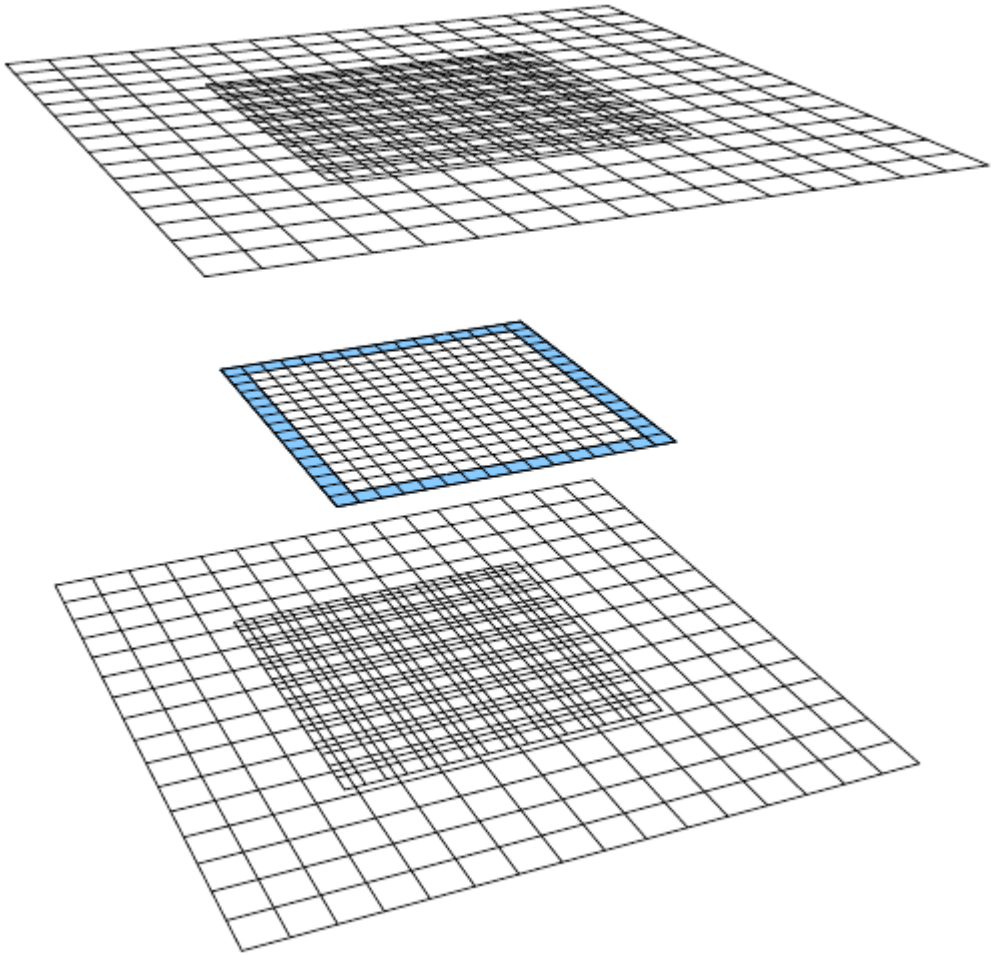

(a) Numerical domain of dependence




e.g. 1D advection equation

$$CFL \equiv \frac{|u|\Delta t}{\Delta x} \leq 1$$

# Berger – Oliger time stepping



2 (3) important steps:

- prolongation

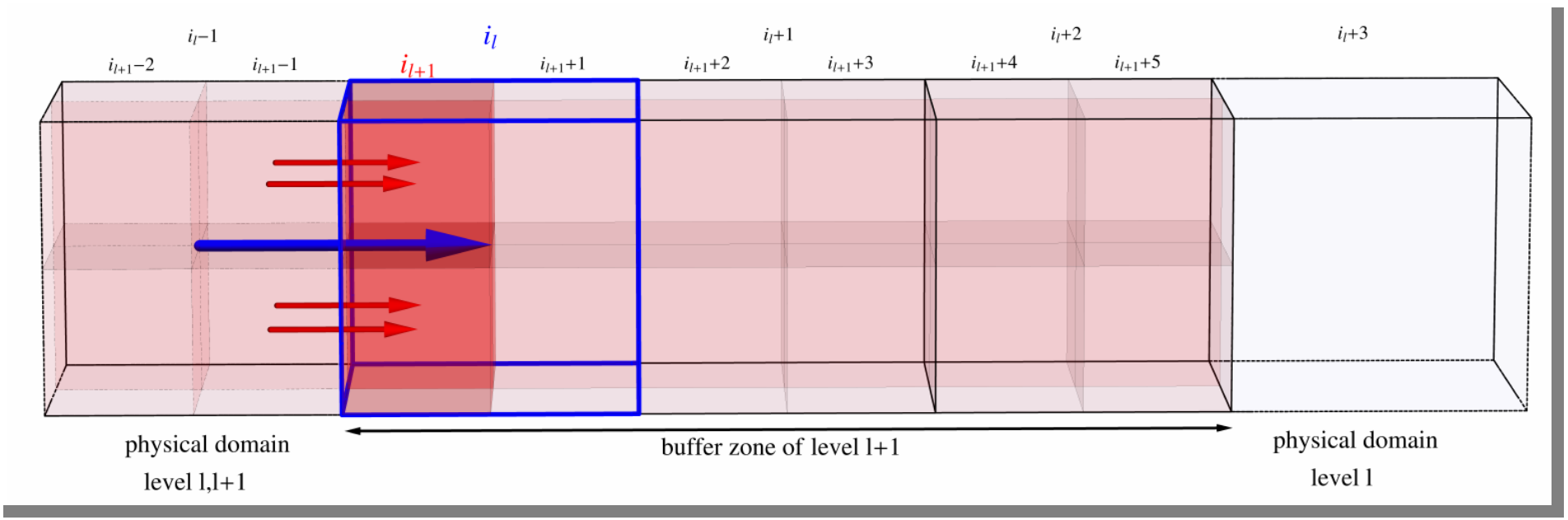
- restriction

- correction (if matter is present)

# Berger – Colella

## Correction step:

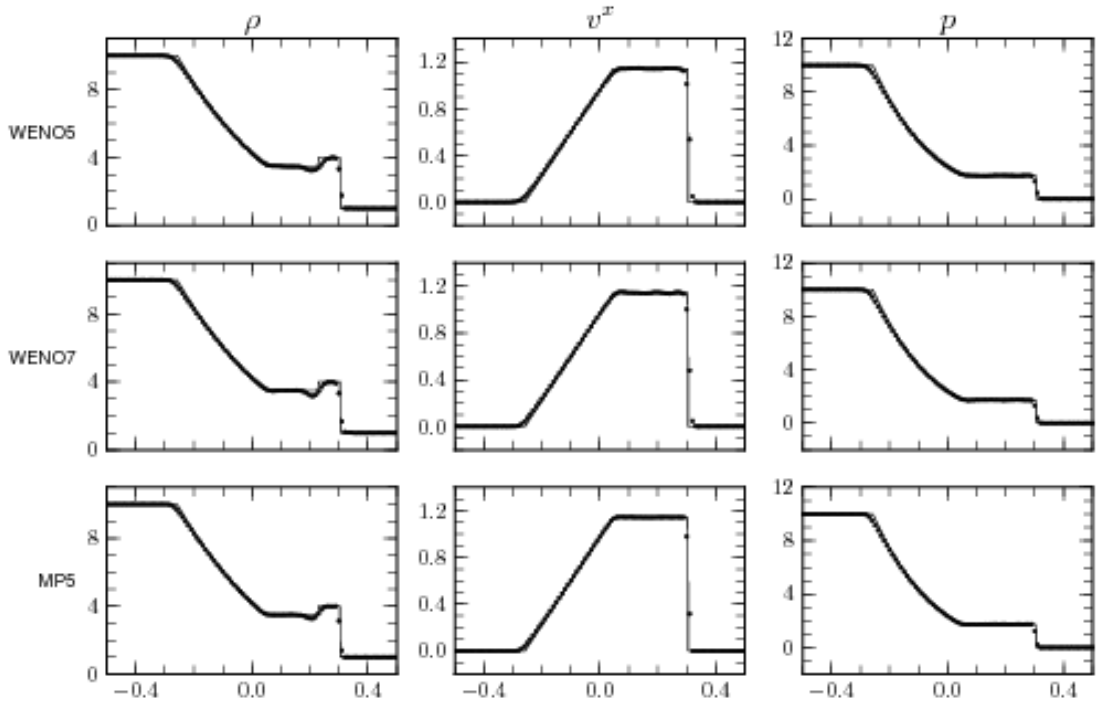
- Correcting for flux differences within different refinement levels



# High resolution shock capturing

## Problem:

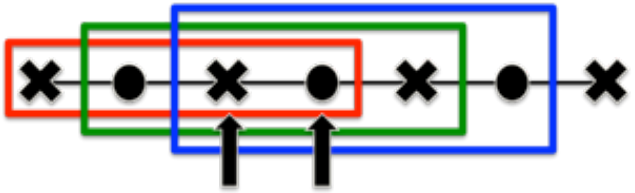
- What happens when function is not-smooth



# High resolution shock capturing
# – example: WENO schemes –

$$\begin{cases} u_t + \nabla \cdot f(u) = 0 \\ u(x,0) = u_0(x) \end{cases}$$

How to compute the flux?



$f_j \qquad f_{j+1/2}$

$$\frac{2}{3} f_{j-1/2} + \frac{1}{3} f_{j+1/2} = \frac{1}{6} f_{j-1} + \frac{5}{6} f_j \longrightarrow c_1 = \frac{2}{10} \quad \omega_1$$

$$\frac{1}{3} f_{j-1/2} + \frac{2}{3} f_{j+1/2} = \frac{5}{6} f_j + \frac{1}{6} f_{j+1} \longrightarrow c_2 = \frac{5}{10} \quad \omega_2$$

$$\frac{2}{3} f_{j+1/2} + \frac{1}{3} f_{j+3/2} = \frac{1}{6} f_j + \frac{5}{6} f_{j+1} \longrightarrow c_3 = \frac{3}{10} \quad \omega_3$$

$$\frac{3}{10} f_{j-1/2} + \frac{6}{10} f_{j+1/2} + \frac{1}{10} f_{j+3/2} = \frac{1}{30} f_{j-1} + \frac{19}{30} f_j + \frac{10}{30} f_{j+1}$$

$$\Downarrow$$

$$\left(\frac{2}{3}\omega_1 + \frac{1}{3}\omega_2\right) f_{j-1/2} + \left(\frac{1}{3}\omega_1 + \frac{2}{3}(\omega_2 + \omega_3)\right) f_{j+1/2} + \frac{1}{3}\omega_3 f_{j+3/2} = \frac{\omega_1}{6} f_{j-1} + \frac{5(\omega_1 + \omega_2)}{6} f_j + \frac{\omega_2 + 5\omega_3}{6} f_{j+1}$$

# HPC Computing

| Rank | Site | System | Cores | Rmax (TFlop/s) | Rpeak (TFlop/s) | Power (kW) |
|---|---|---|---|---|---|---|
| 1 | National Supercomputing Center in Wuxi<br>China | **Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway<br>NRCPC | 10,649,600 | 93,014.6 | 125,435.9 | 15,371 |
| 2 | National Super Computer Center in Guangzhou<br>China | **Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P<br>NUDT | 3,120,000 | 33,862.7 | 54,902.4 | 17,808 |
| 3 | Swiss National Supercomputing Centre (CSCS)<br>Switzerland | **Piz Daint** - Cray XC50, Xeon E5-2690v3 12C 2.6GHz, Aries interconnect , NVIDIA Tesla P100<br>Cray Inc. | 361,760 | 19,590.0 | 25,326.3 | 2,272 |
| 4 | Japan Agency for Marine-Earth Science and Technology<br>Japan | **Gyoukou** - ZettaScaler-2.2 HPC system, Xeon D-1571 16C 1.3GHz, Infiniband EDR, PEZY-SC2 700Mhz<br>ExaScaler | 19,860,000 | 19,135.8 | 28,192.0 | 1,350 |
| 5 | DOE/SC/Oak Ridge National Laboratory<br>United States | **Titan** - Cray XK7, Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x<br>Cray Inc. | 560,640 | 17,590.0 | 27,112.5 | 8,209 |
| 6 | DOE/NNSA/LLNL<br>United States | **Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom<br>IBM | 1,572,864 | 17,173.2 | 20,132.7 | 7,890 |
| 7 | DOE/NNSA/LANL/SNL<br>United States | **Trinity** - Cray XC40, Intel Xeon Phi 7250 68C 1.4GHz, Aries interconnect<br>Cray Inc. | 979,968 | 14,137.3 | 43,902.6 | 3,844 |
| 8 | DOE/SC/LBNL/NERSC<br>United States | **Cori** - Cray XC40, Intel Xeon Phi 7250 68C 1.4GHz, Aries interconnect<br>Cray Inc. | 622,336 | 14,014.7 | 27,880.7 | 3,939 |
| 9 | Joint Center for Advanced High Performance Computing<br>Japan | **Oakforest-PACS** - PRIMERGY CX1640 M1, Intel Xeon Phi 7250 68C 1.4GHz, Intel Omni-Path<br>Fujitsu | 556,104 | 13,554.6 | 24,913.5 | 2,719 |
| 10 | RIKEN Advanced Institute for Computational Science (AICS)<br>Japan | K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect<br>Fujitsu | 705,024 | 10,510.0 | 11,280.4 | 12,660 |
| 11 | DOE/SC/Argonne National Laboratory<br>United States | **Mira** - BlueGene/Q, Power BQC 16C 1.60GHz, Custom<br>IBM | 786,432 | 8,586.6 | 10,066.3 | 3,945 |
| 12 | Texas Advanced Computing | **Stampede2** - PowerEdge | 368,928 | 8,317.7 | 18,215.8 | |

Cartesius Cluster – SurfSARA

***Fun Question: Which rank has Netherland's fastest HPC cluster?***

Top 500 List

# HPC Computing

Parallelization strategies:

- MPI [Message Passing Interface]
- OpenMP [Open Multi-Processing]
- pthread [POSIX Thread]

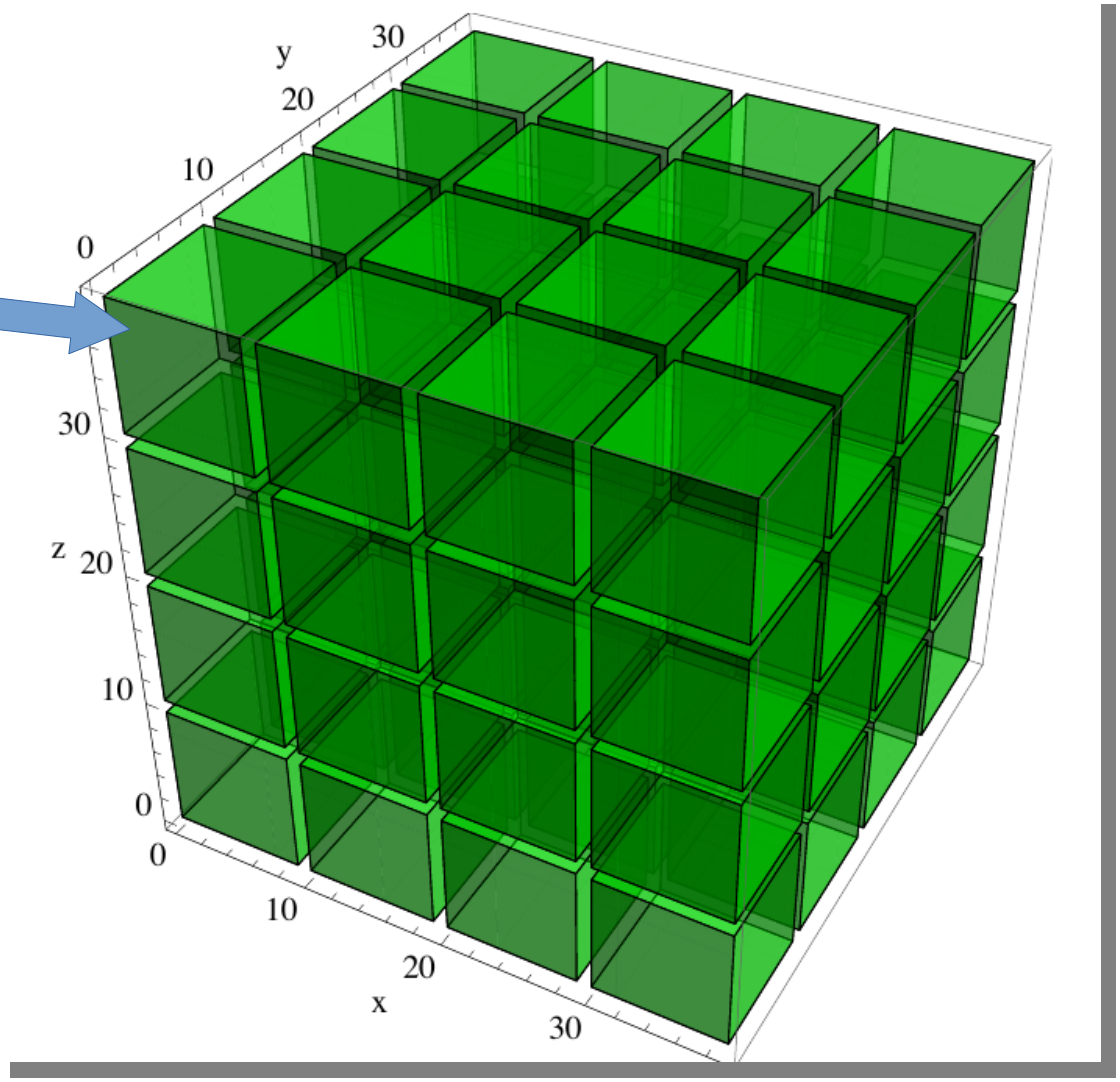
  …

- CUDA [Compute Unified Device Architecture]
- OpenCL [Open Computing Language]

# HPC Computing

- Hybrid MPI/OpenMP scaling

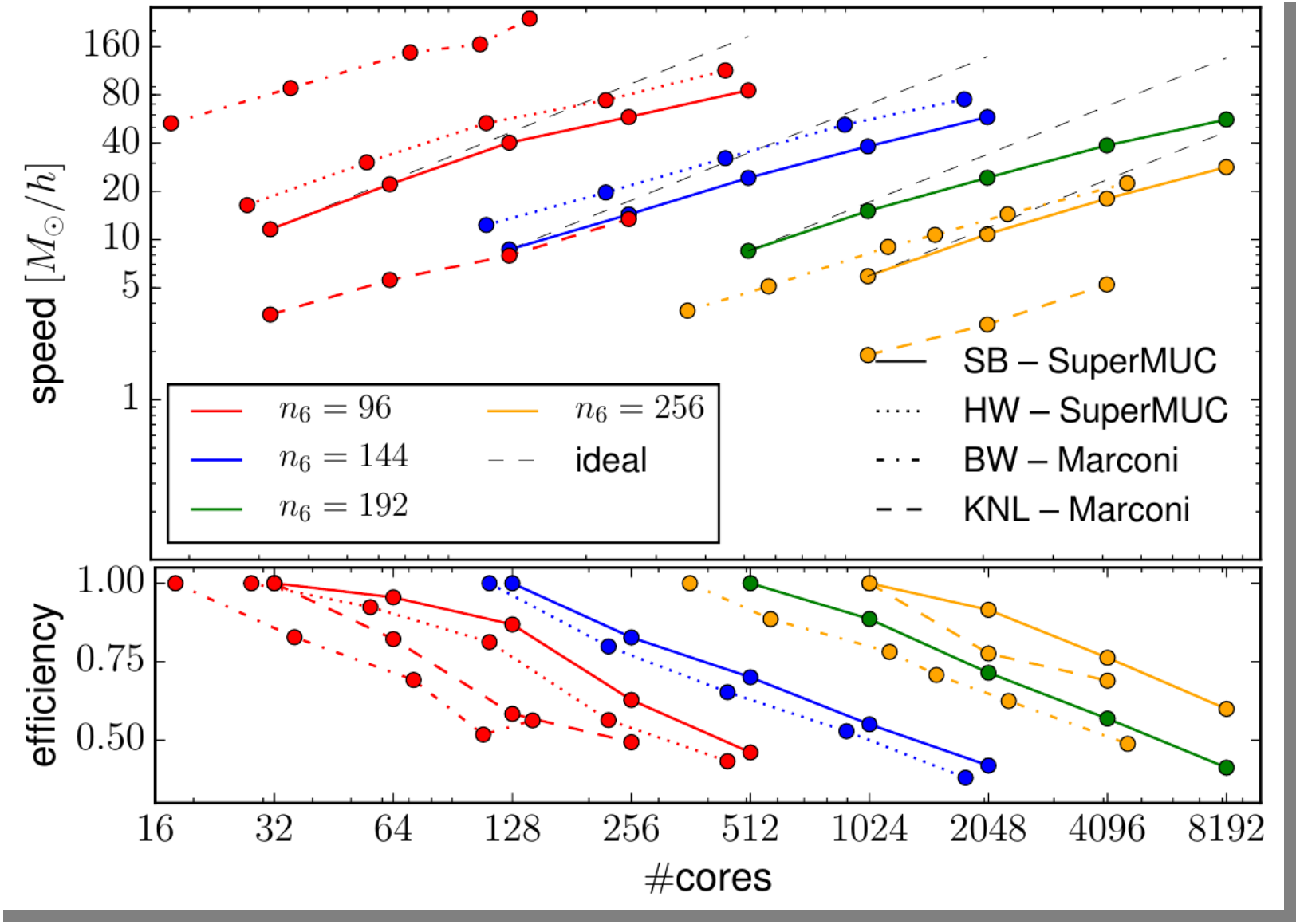
one box/ MPI – process
each box has multiple
OpenMP threads



# HPC Computing

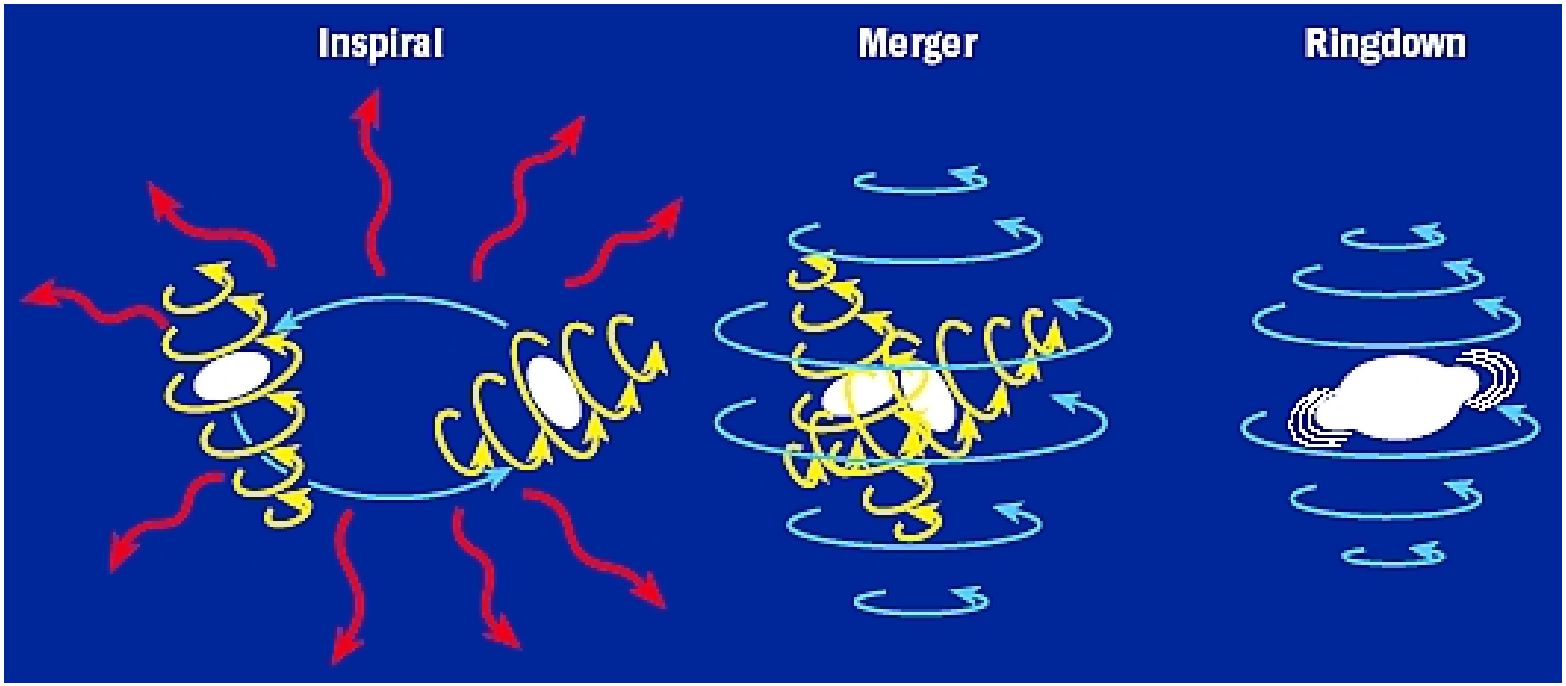
## Performance

$$\text{efficiency} = \frac{\text{speed}_2/\text{speed}_1}{\#\text{cores}_2/\#\text{cores}_1}$$



# Applications
# – BBH simulations –

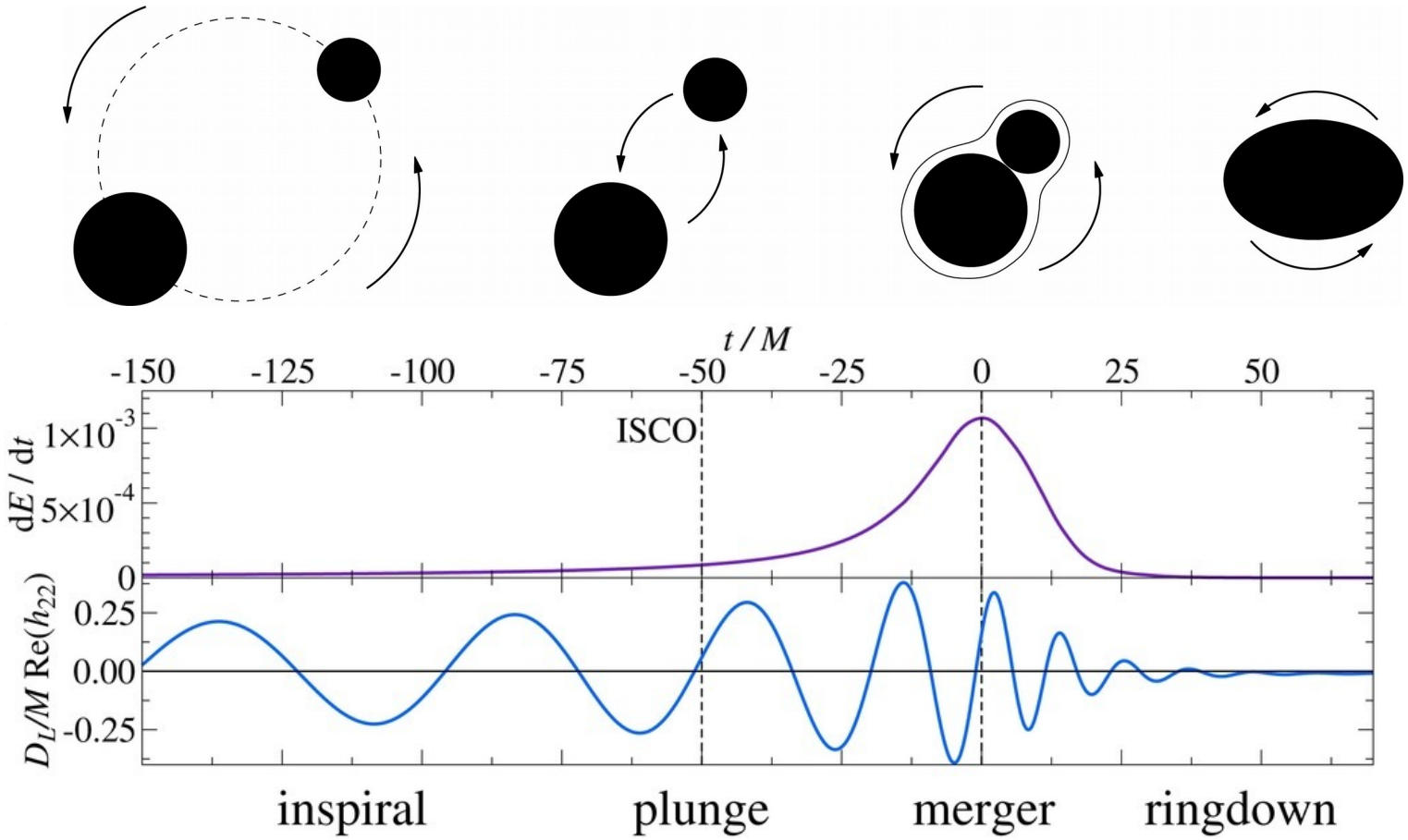
Numerical relativity simulation needed to understand the time around merger



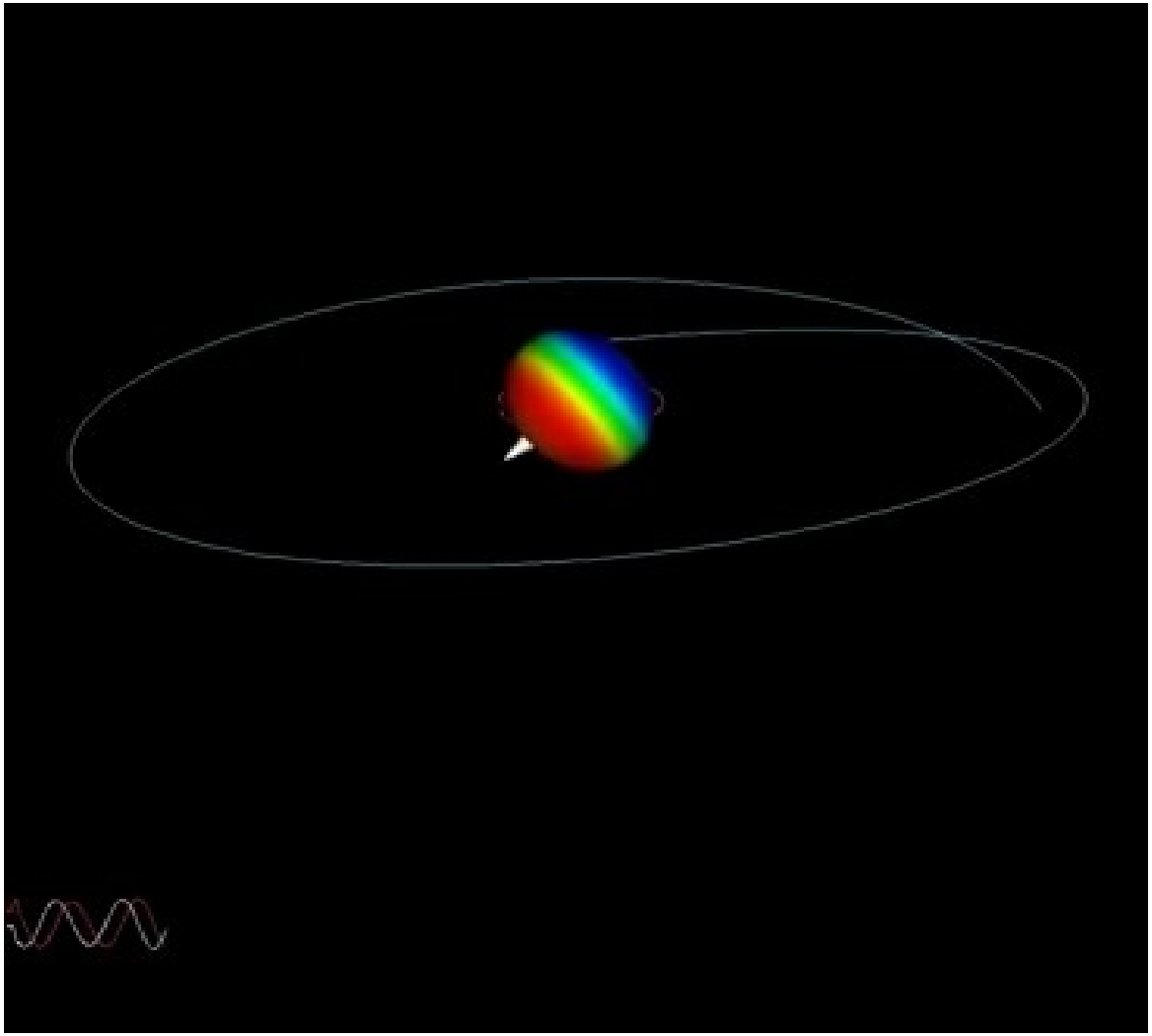

Post-Newtonian Approximation

Numerical Relativity

Perturbation Theory

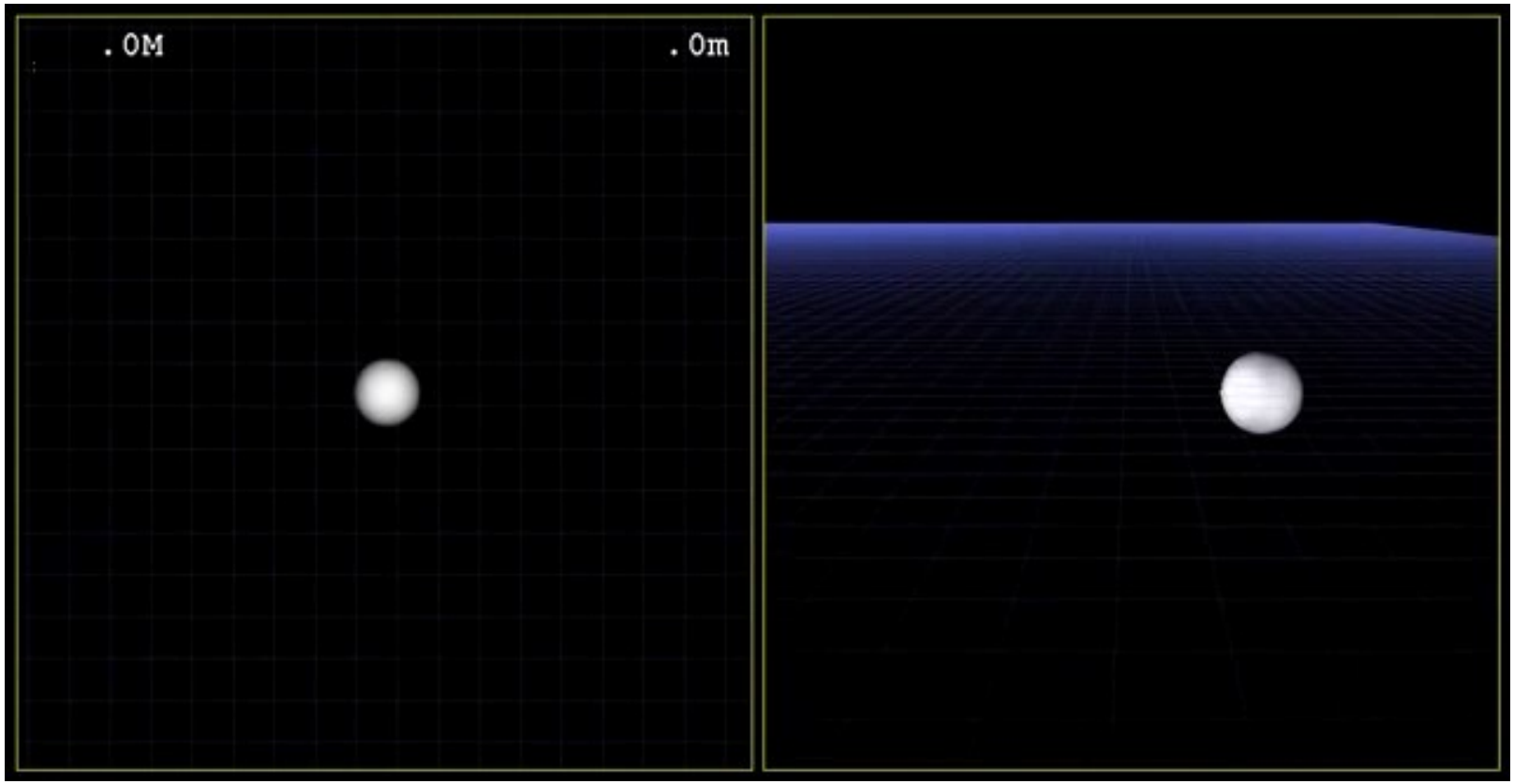

t / M
-150
-125
-100
-75
-50
-25
0
25
50
ISCO
dE / dt
1×10^-3
5×10^-4
0
D_L/M Re(h_22)
0.25
0.00
-0.25
inspiral
plunge
merger
ringdown

# Example: highly precessing BBH



https://www.youtube.com/watch?v=grA5KfDlsAY

# Example: large mass ratio BBH

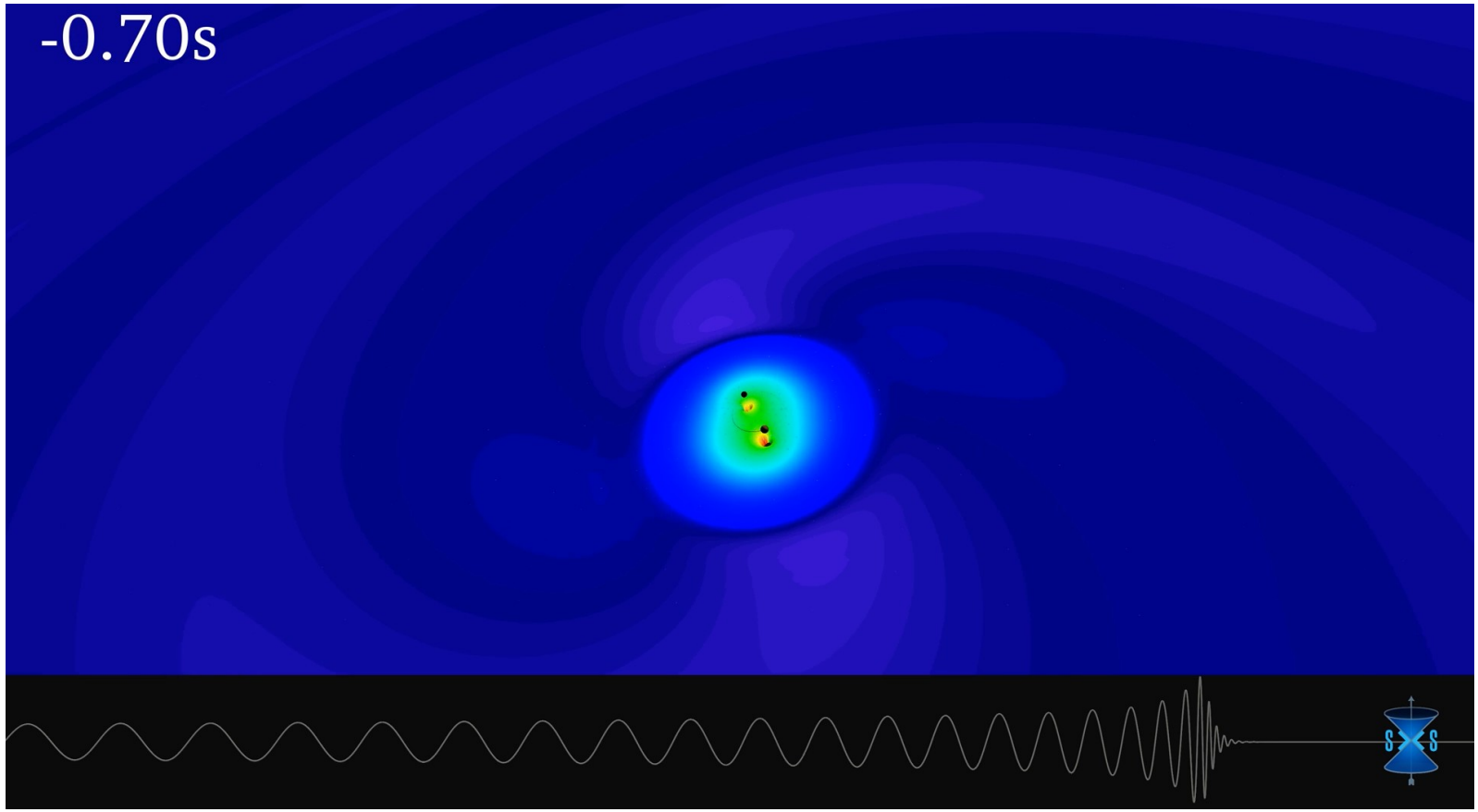



**https://www.youtube.com/watch?v=Dxfx3NIanHk**

# The first BBH detection

https://www.youtube.com/watch?v=-vYJdh8wALg

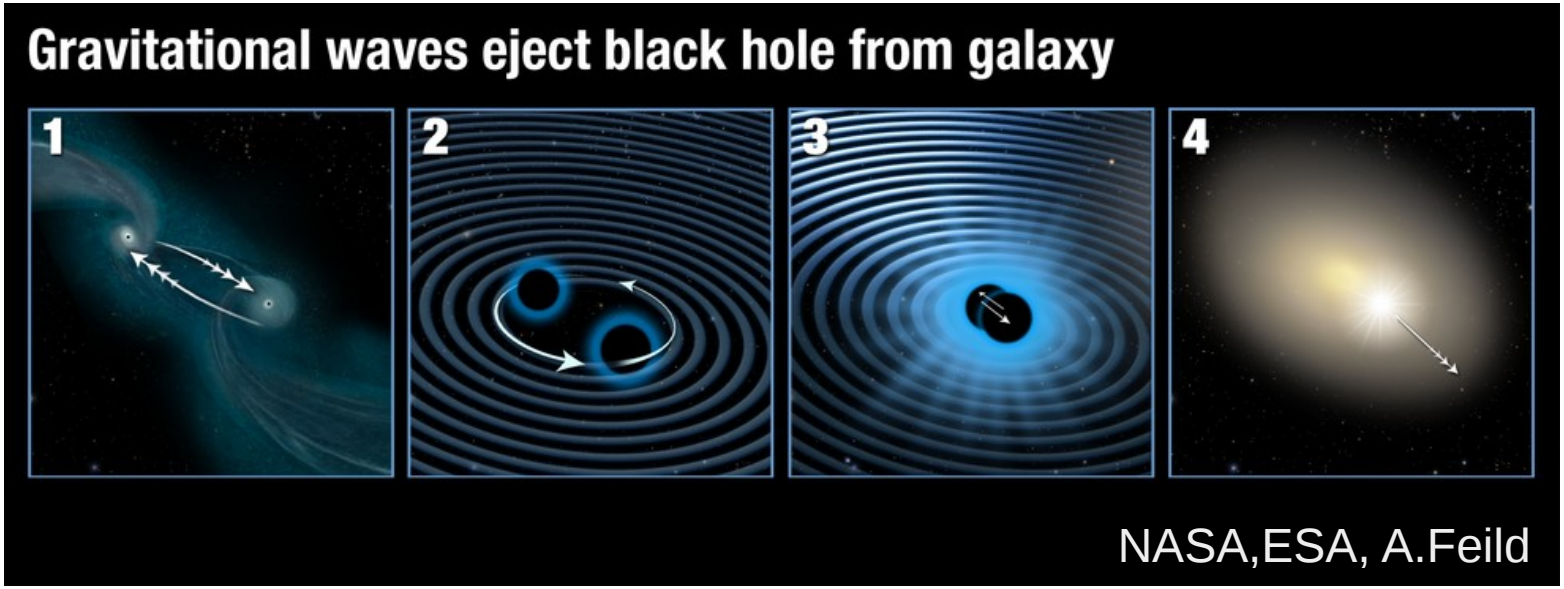
# The first BBH detection




https://www.youtube.com/watch?v=c-2XIuNFgD0&t=11s

# What NR told us about BBHs

- Merger part is less violent than expected




- remnants can obtain a large kick due to GW emission

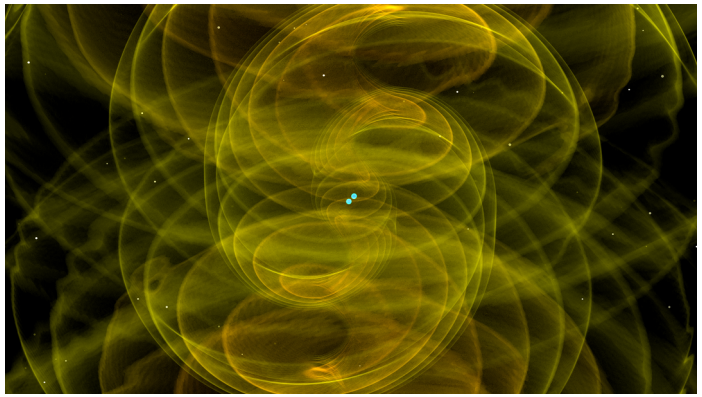
# Applications
# – BNS simulations –

# Multimessenger Picture

## Gravitational Waves

-inspiral signal: chirp

-postmerger signal

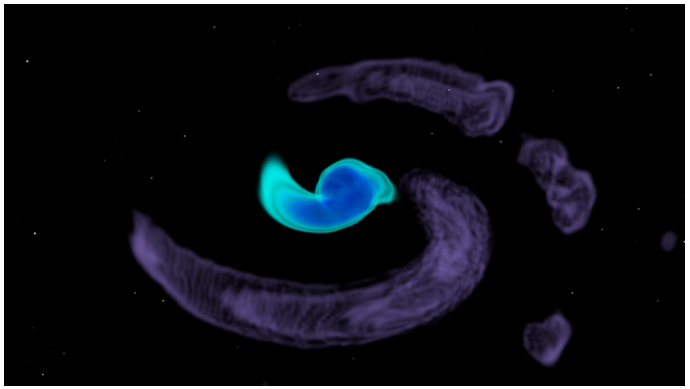


## Electromagnetic Waves

-short GRB

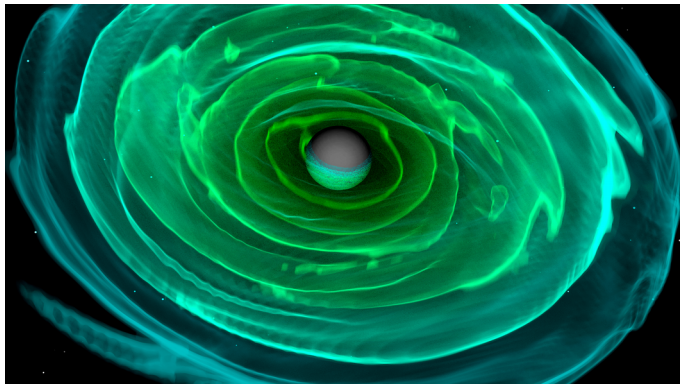
-kilo/macronovae

-radio flares

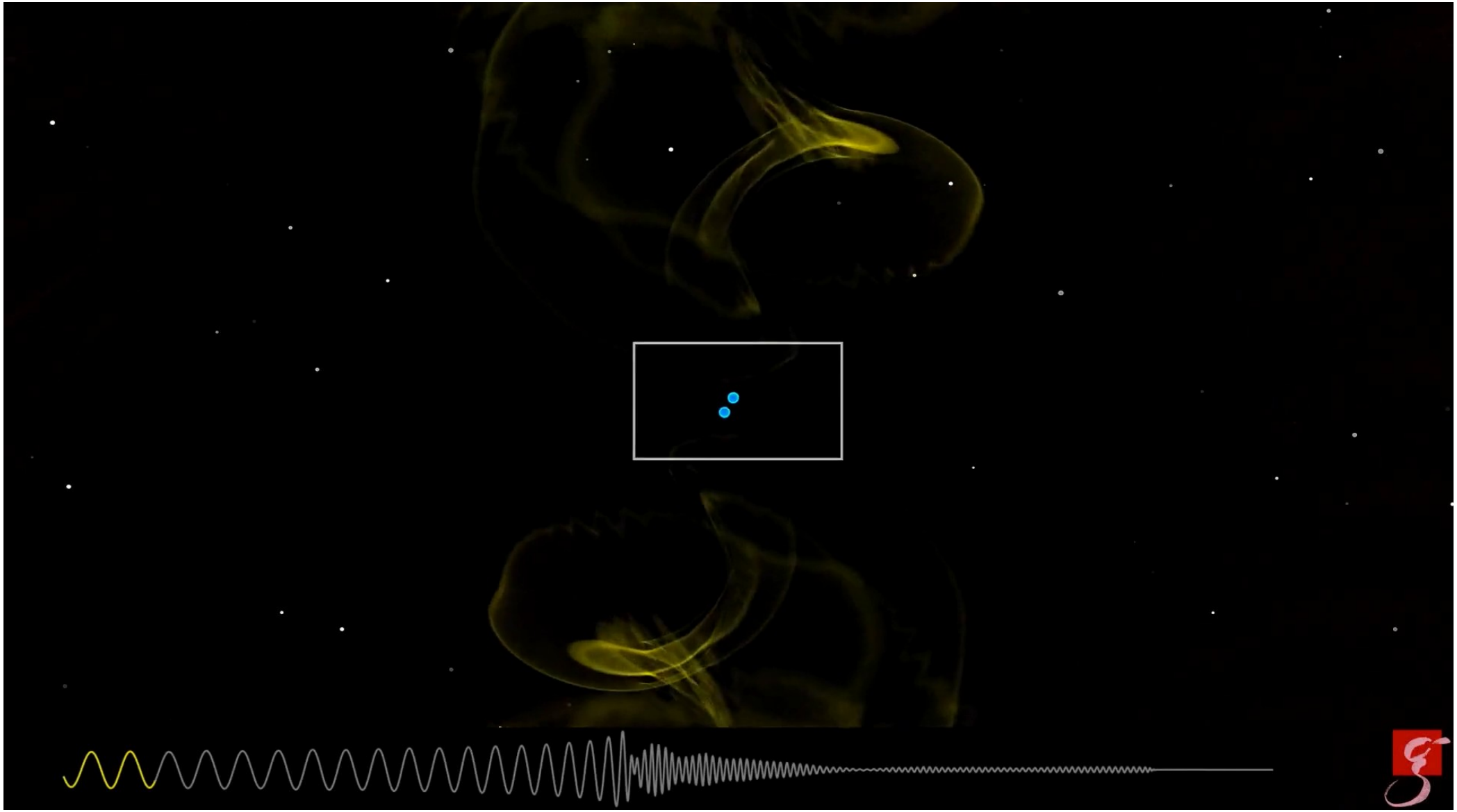


## Neutrinos

-high neutrino luminosity

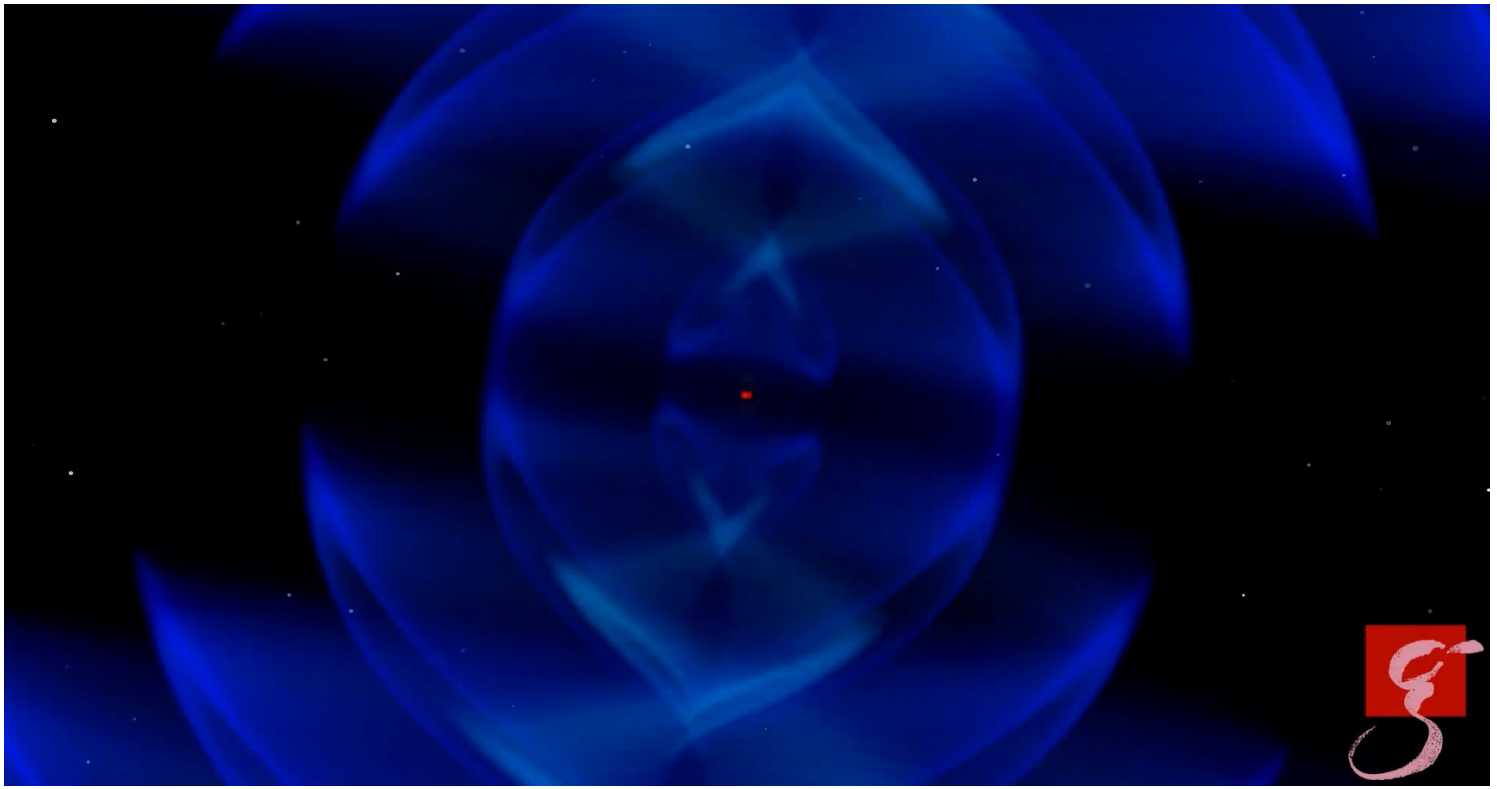


# The BNS merger



https://www.youtube.com/watch?v=V6cm-0bwJ98

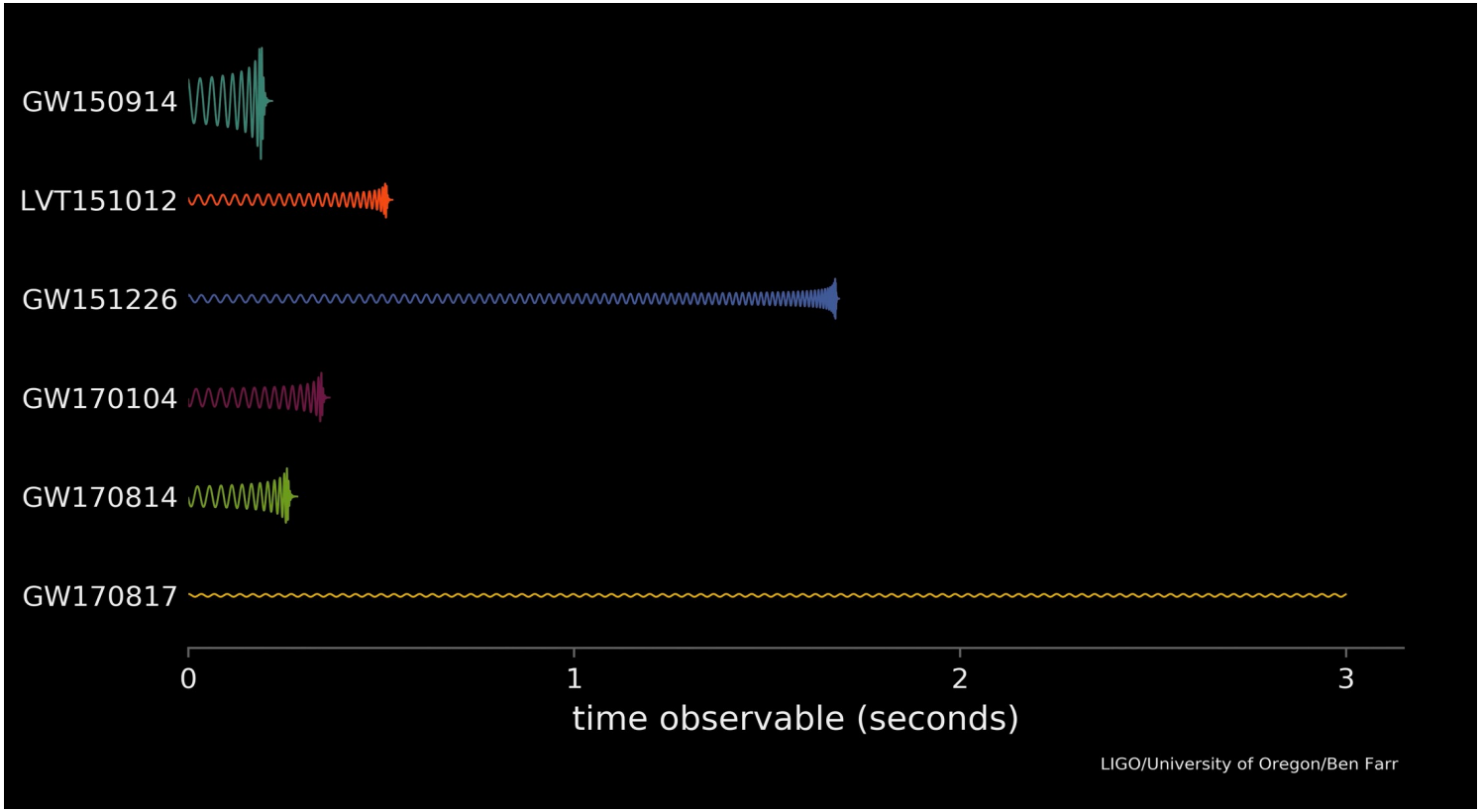
# Gravitational Waves



https://www.youtube.com/watch?v=B7DnRkQub-U

# Gravitational Waves

LIGO detected several hundred of orbits for GW170817



# Waveform variety

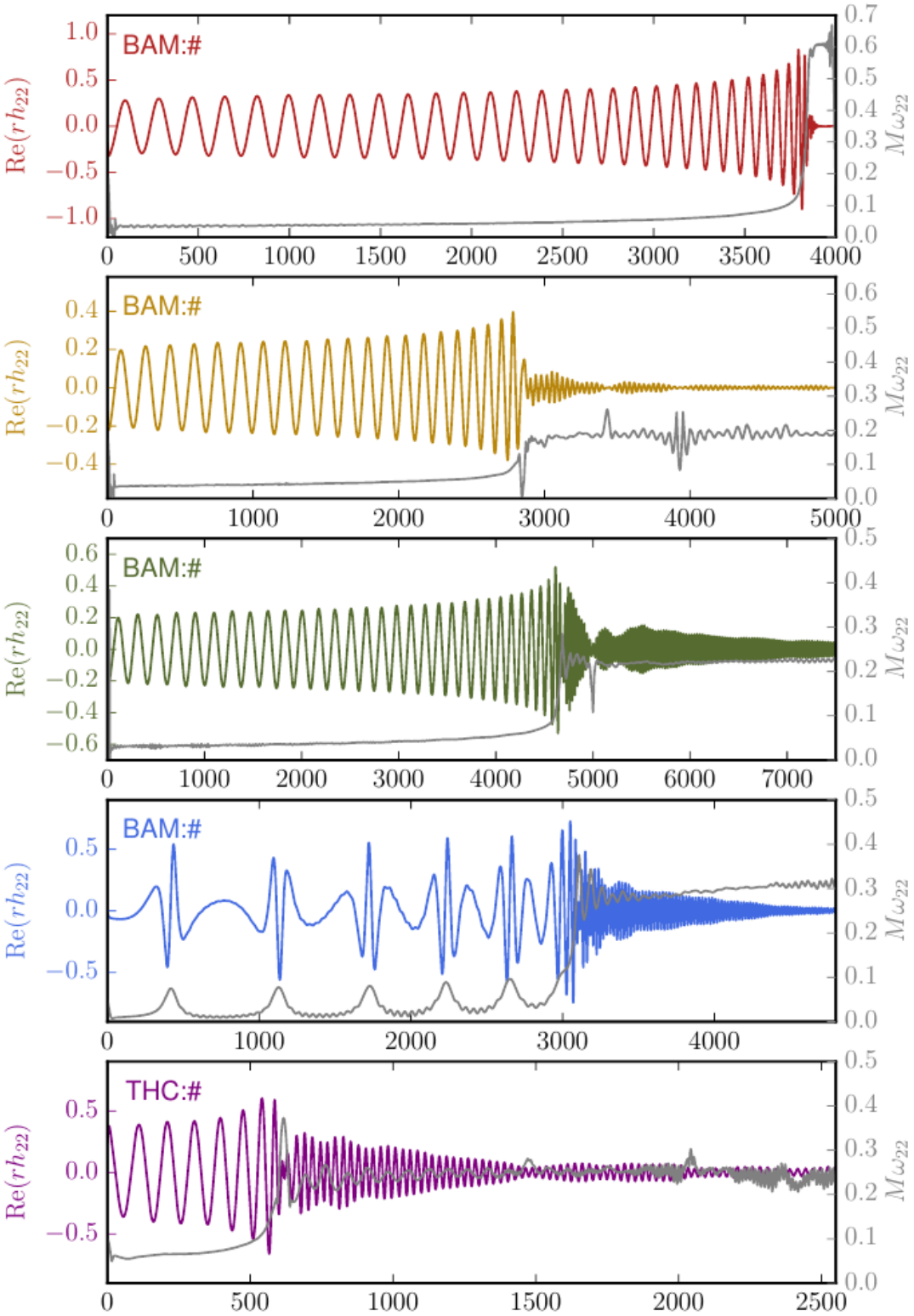
High masses

High mass ratio

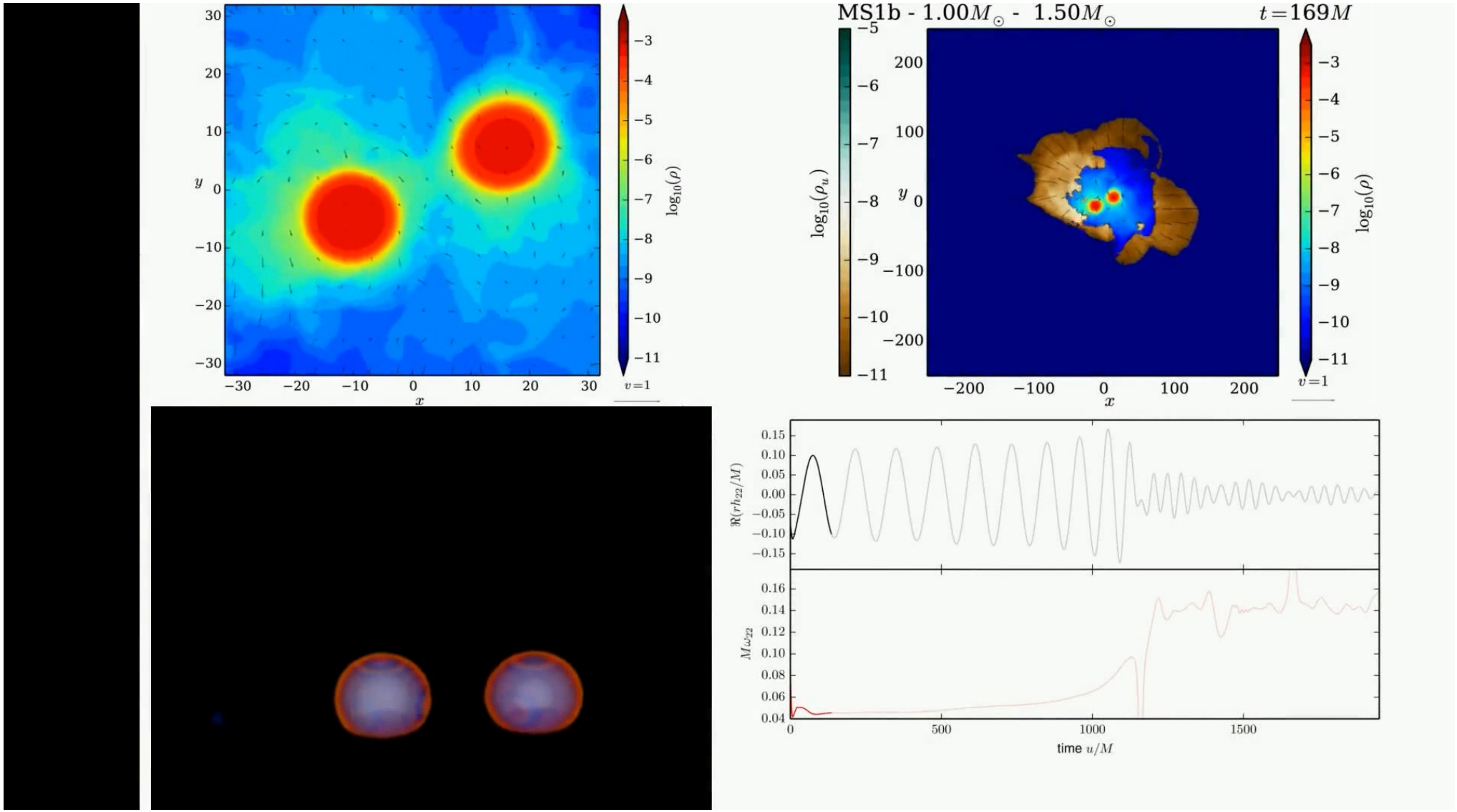
Precessing

Highly eccentric

Realistic microphysics



# An example: a high mass ratio BNS

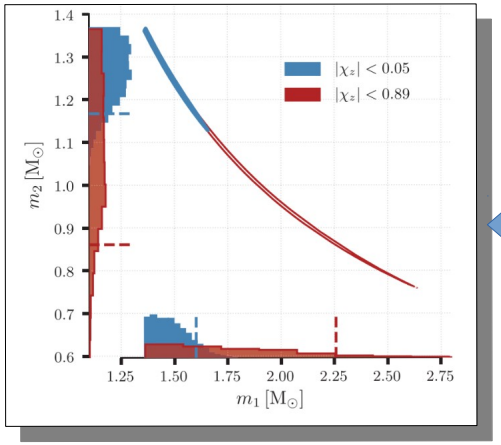


# Gravitational Waves

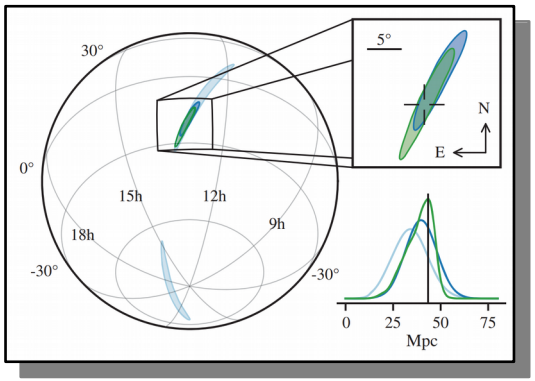
- Chirp signal during the inspiral

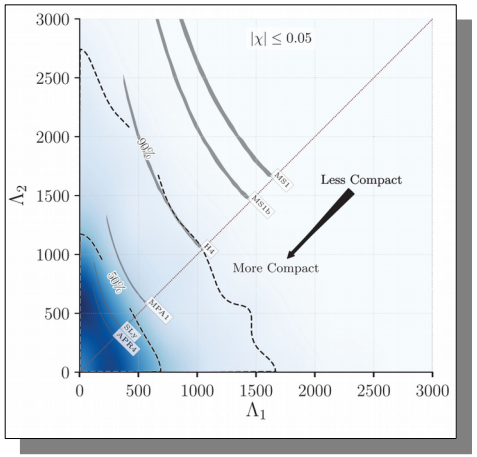
**28 sq-deg**

Determine the mass

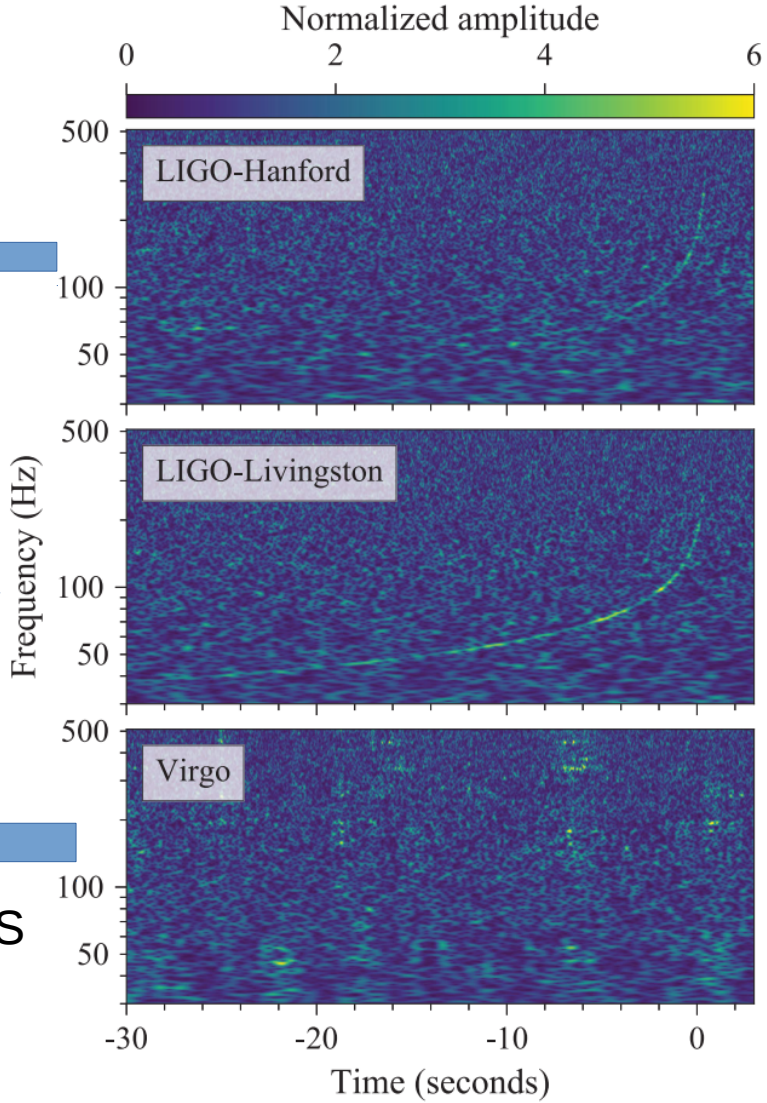



Sky localization



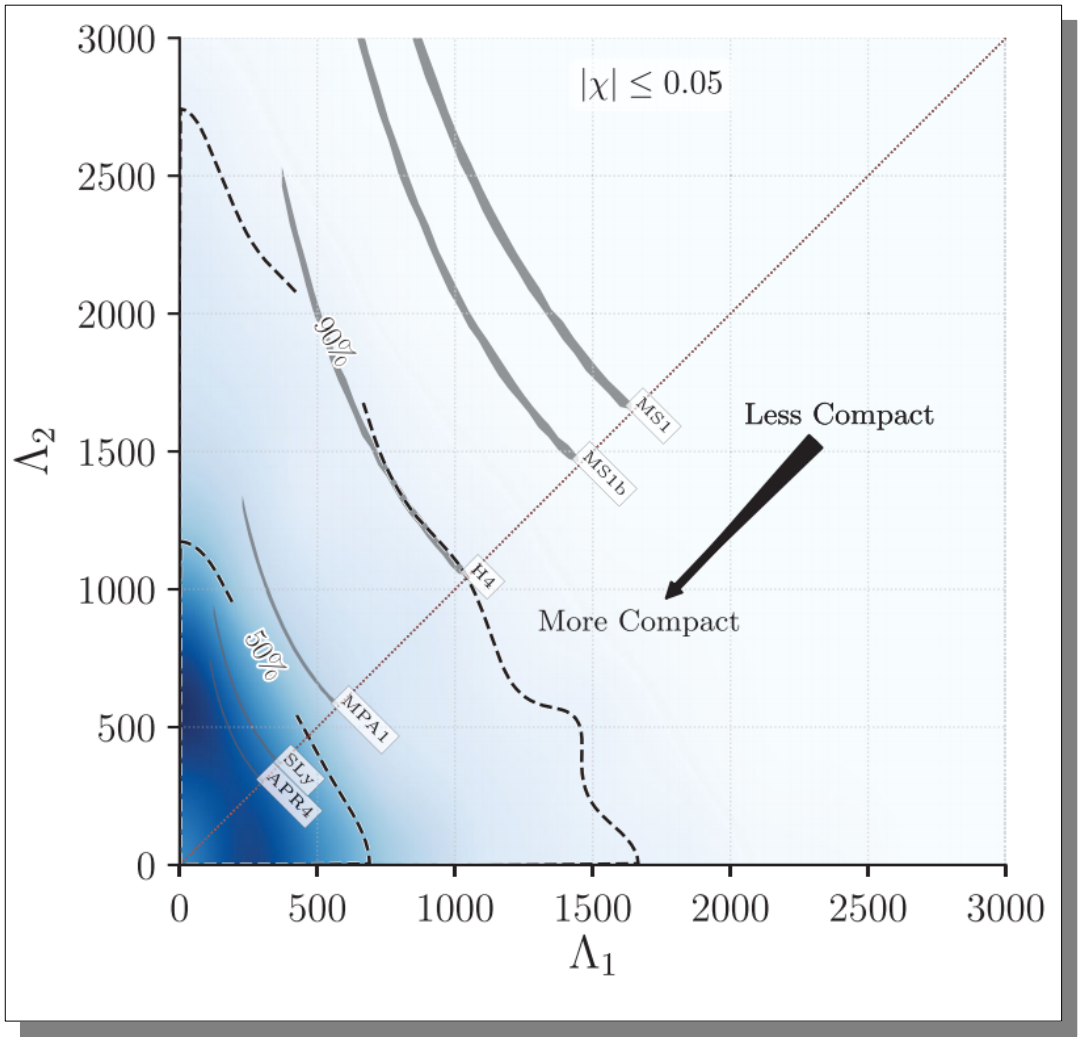

Determine the EOS




Phys.Rev.Lett. 119 (2017) no.16, 161101

# Gravitational Waves: Parameter Estimation

- Determine the Equation of State

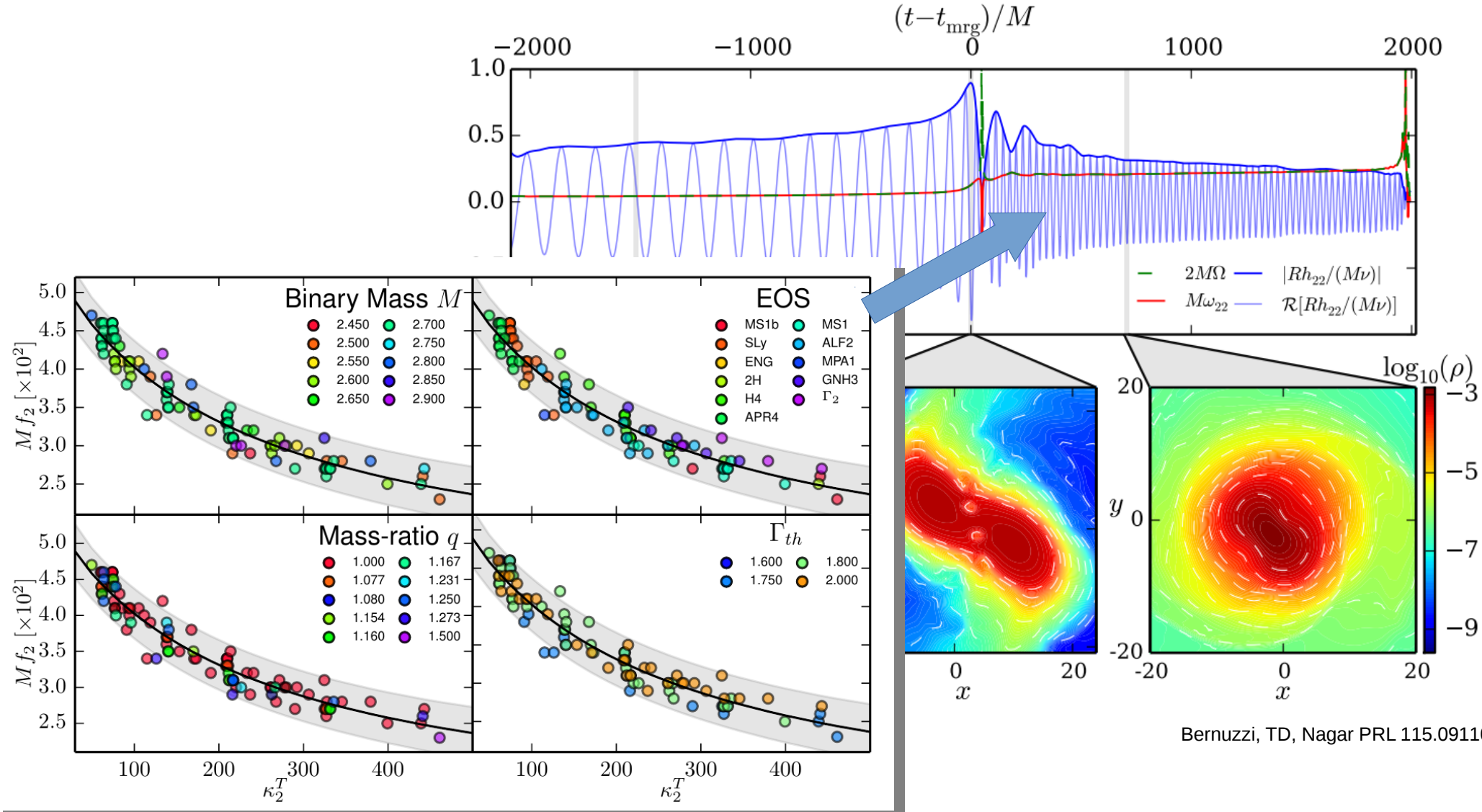



GW observations
favor Nss with smaller radii

Phys.Rev.Lett. 119 (2017) no.16, 161101

# Gravitational Waves: Postmerger

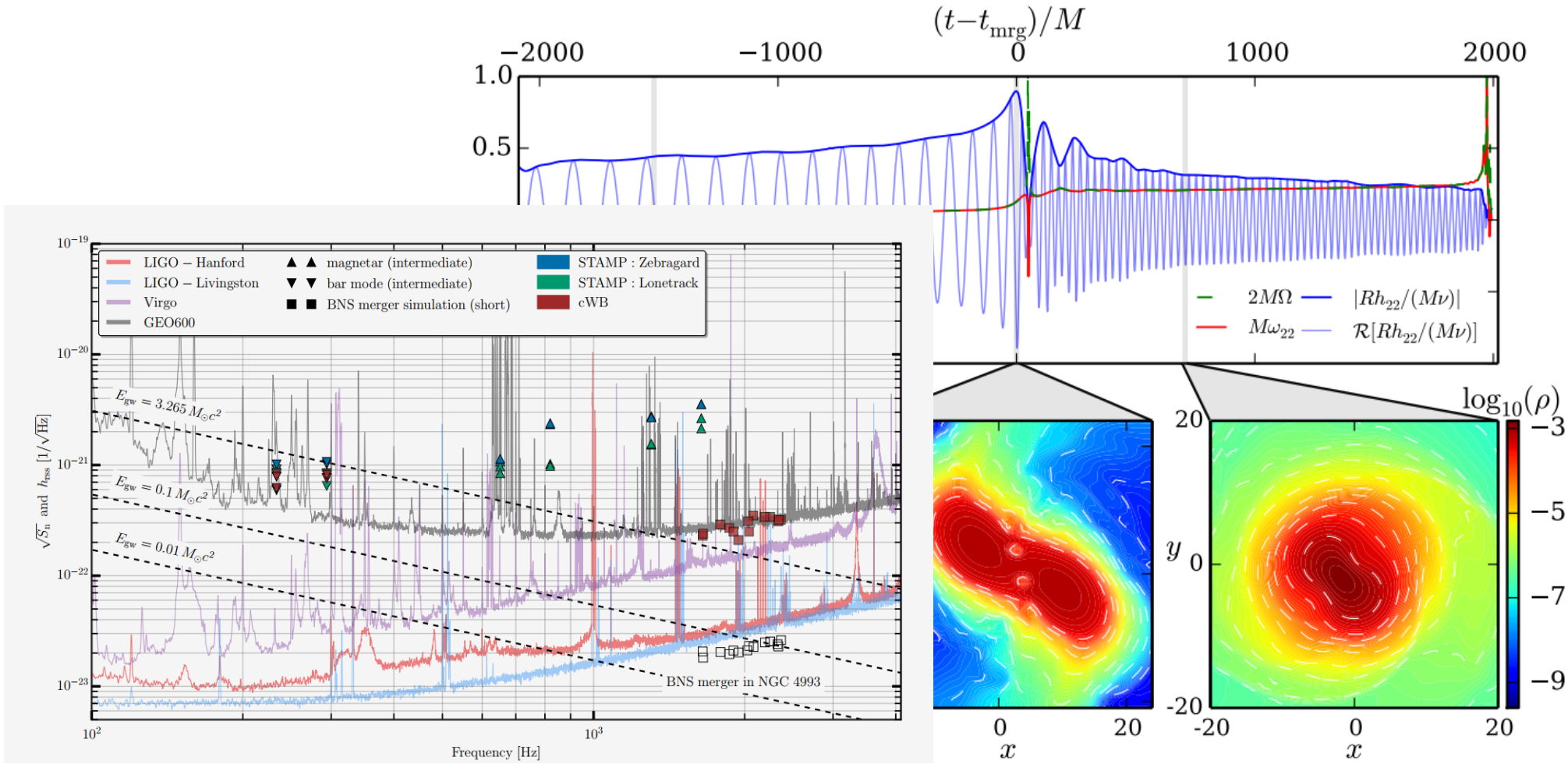
- postmerger signal at higher frequencies with low chances of detection




Bernuzzi, TD, Nagar PRL 115.091101

# Gravitational Waves: Postmerger

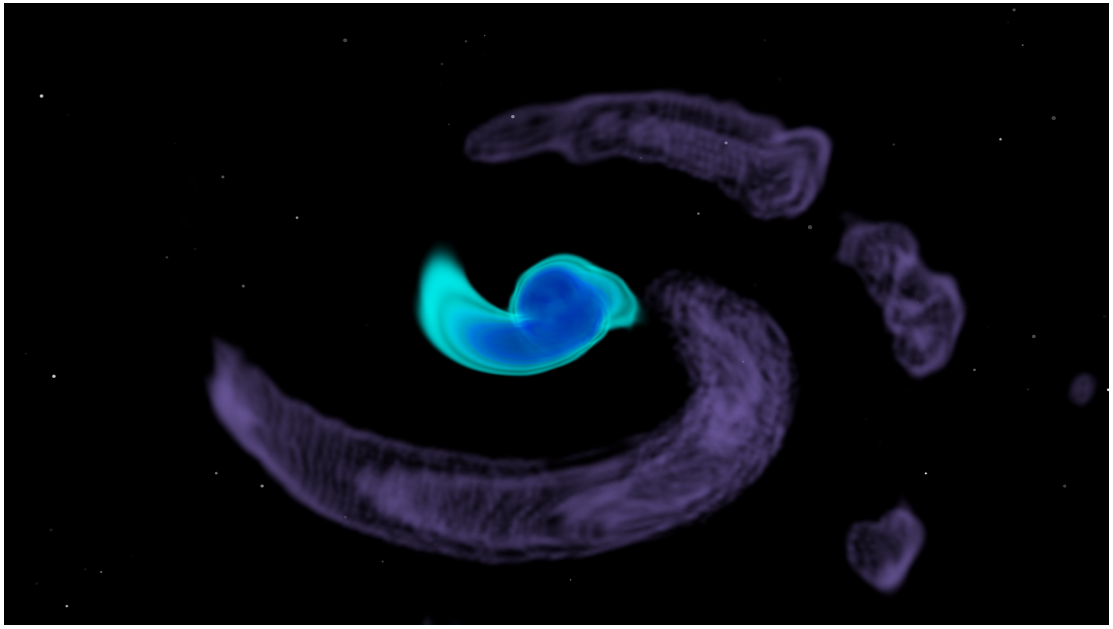
- postmerger signal at higher frequencies with low chances of detection




arXiv:1710.09320

no postmerger signal for GW170817 detected

# Neutrinos



# Neutrinos

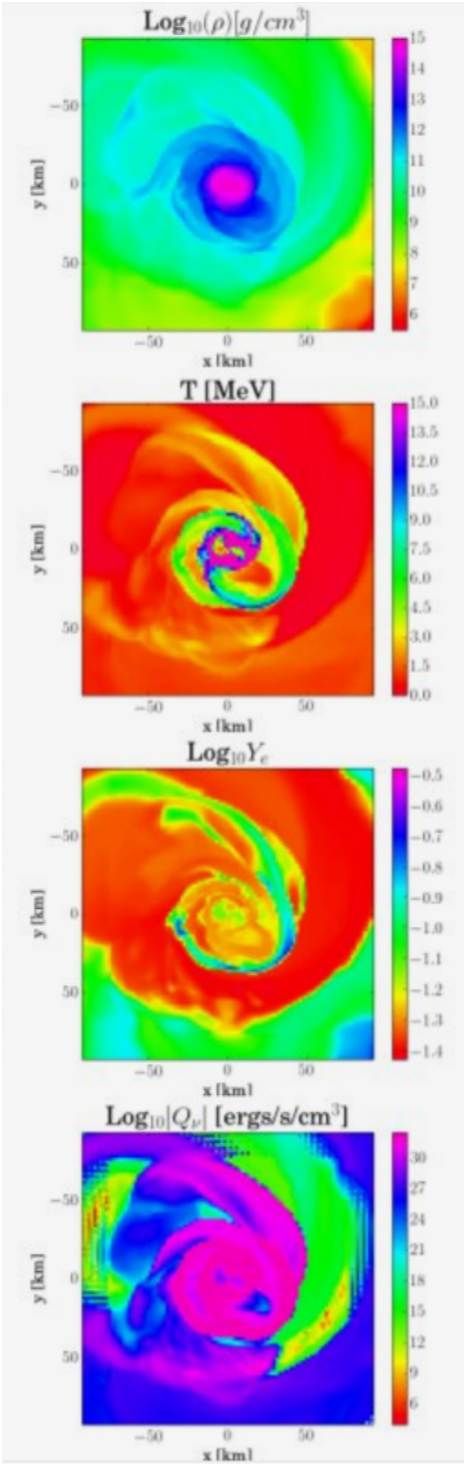
- heating during the NS merger
  virial temperature

$$T_{\rm vir} \sim 25 \text{ MeV } (M/2.5 \text{ M}_\odot) \ (100 \text{ km}/R)$$

Electron- positron production

$$n + e^+ \rightarrow p + \bar{\nu}_e$$

- Also production of heavy leptons etc.




Lehner et al., arXiv:1603.00501

# Neutrinos

- Detection of neutrinos very unlikely

@10kpc

| EoS | $q$ | $t$ [ms] | $\langle E_{\bar{\nu}_e} \rangle$ [MeV] | $\langle E_{\nu_e} \rangle$ [MeV] | $L_{\bar{\nu}_e}$ [$10^{53}$ erg/s] | $R_\nu$ [#/ms] |
|---|---|---|---|---|---|---|
| NL3 | 1.0 | 3.4 | 18.5 (22.4) | 15.2 (18.3) | 0.7 | 18 |
| NL3 | 0.85 | 3.0 | 15.6 (18.7) | 12.6 (15.1) | 0.8 | 18 |
| DD2 | 1.0 | 3.3 | 18.3 (22.1) | 14.6 (17.4) | 1.1 | 28 |
| DD2 | 0.85 | 2.8 | 18.1 (21.7) | 15.1 (18.0) | 1.0 | 25 |
| DD2 | 0.76 | 2.4 | 19.7 (23.9) | 14.8 (17.9) | 1.3 | 36 |
| SFHo | 1.0 | 3.5 | 24.6 (29.7) | 23.5 (28.3) | 3.5 | 121 |
| SFHo | 0.85 | 3.9 | 17.8 (21.3) | 15.3 (17.9) | 2.0 | 50 |

emission for 10ms up to 2s
< 5000 neutrinos

Lehner et al, arXiv:1603.00501

**GW170817 @ 40Mpc**

< 0.0003 neutrinos

THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed


CrossMark

**Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory**

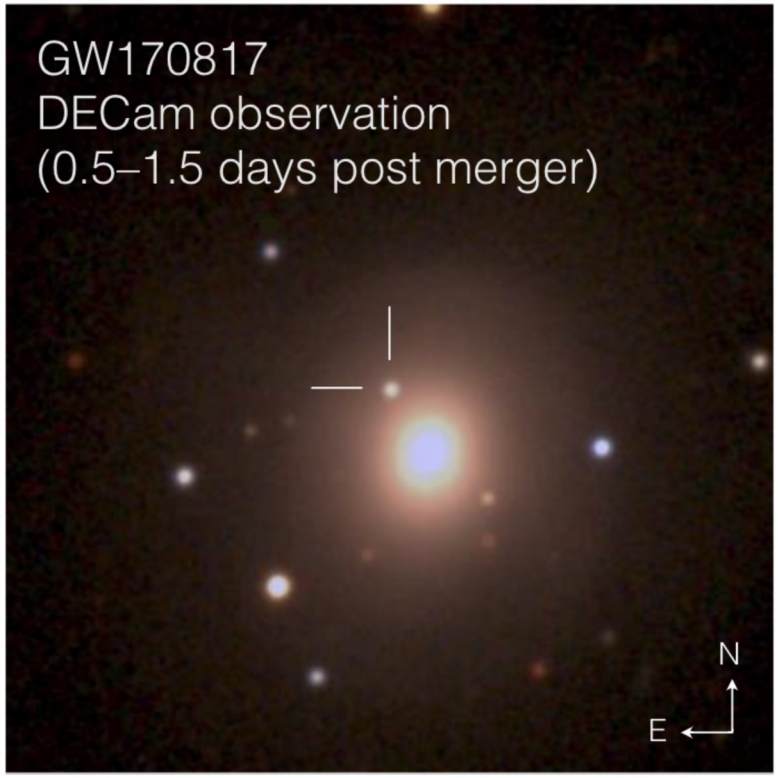
ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

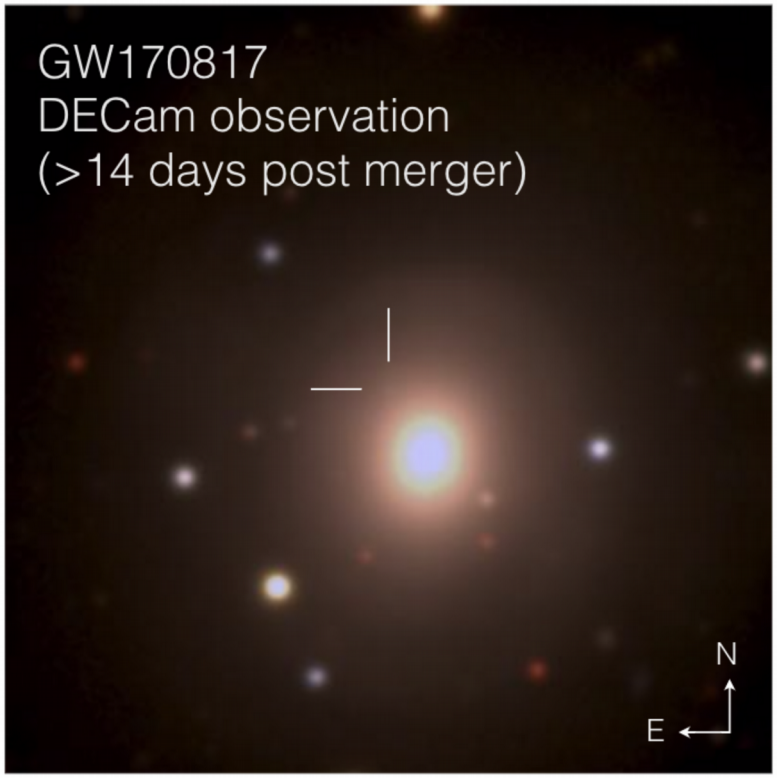
*Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29*

**Abstract**

The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation

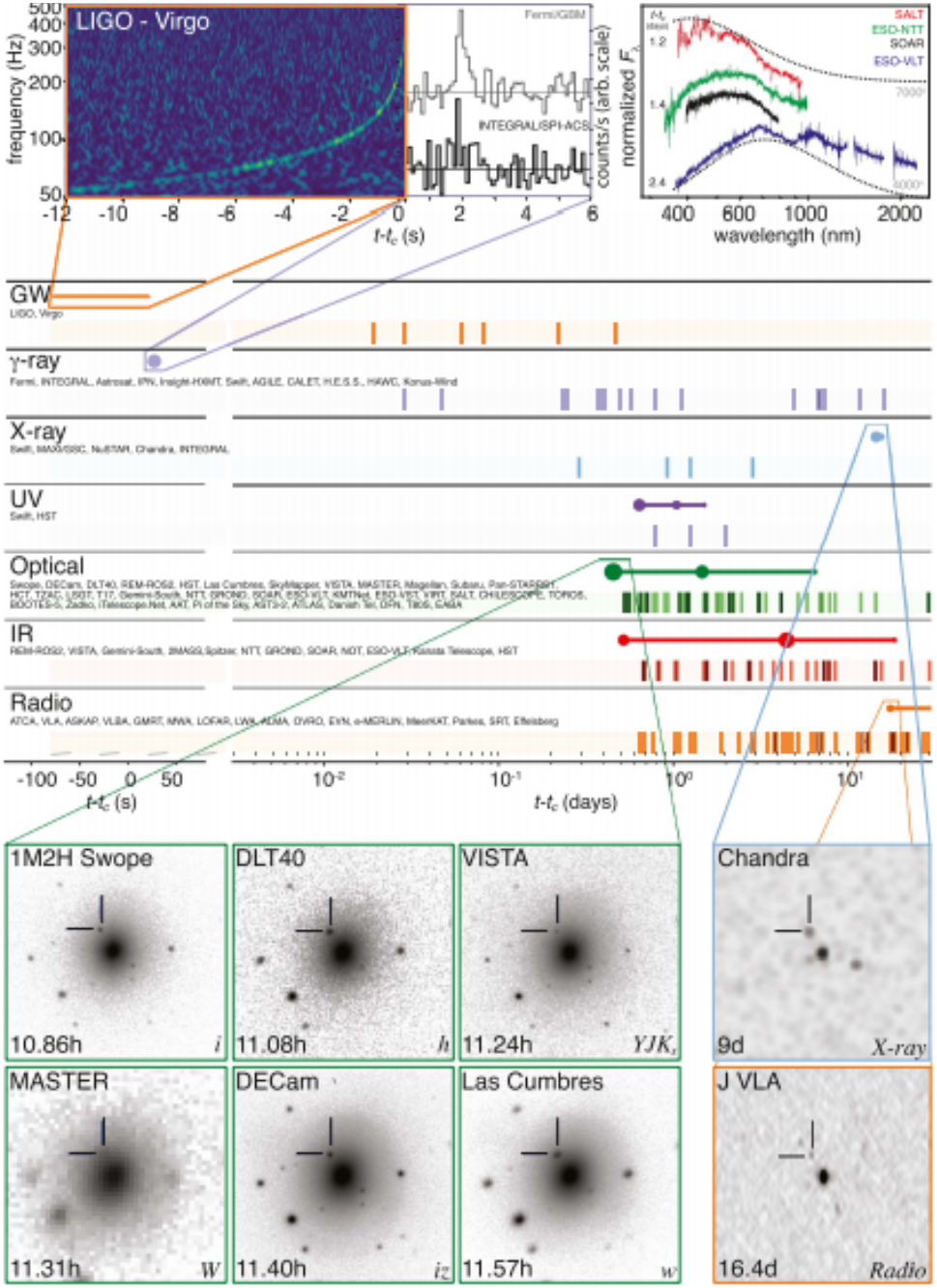
# EM signals


GW170817
DECam observation
(0.5–1.5 days post merger)
N
E


GW170817
DECam observation
(>14 days post merger)
N
E

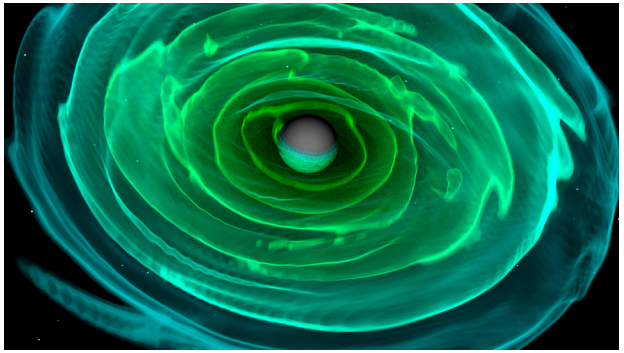
# EM Signals

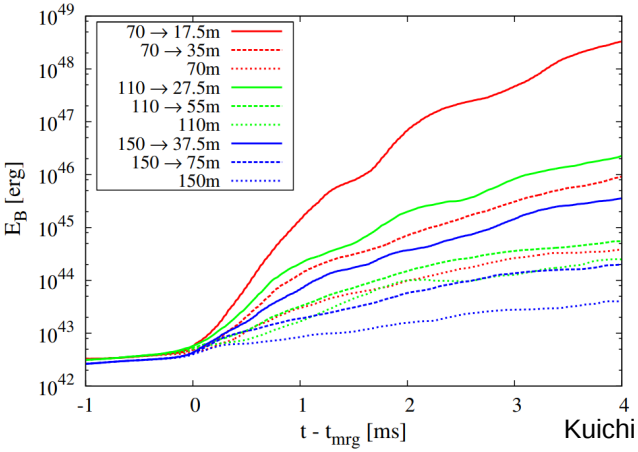
## Timeline



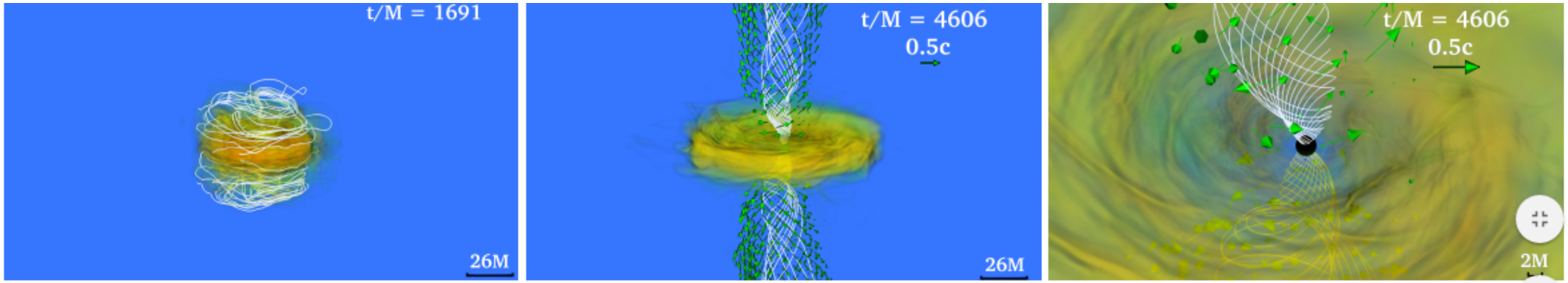
# EM Signals – sGRBs

- BH + disk system
  - Neutrino & anti-neutrino annihilation
  - Magnetic field amplification and jet formation





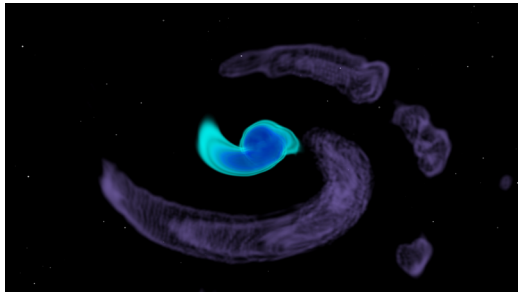

Kuichi et al., PRD92, 124034

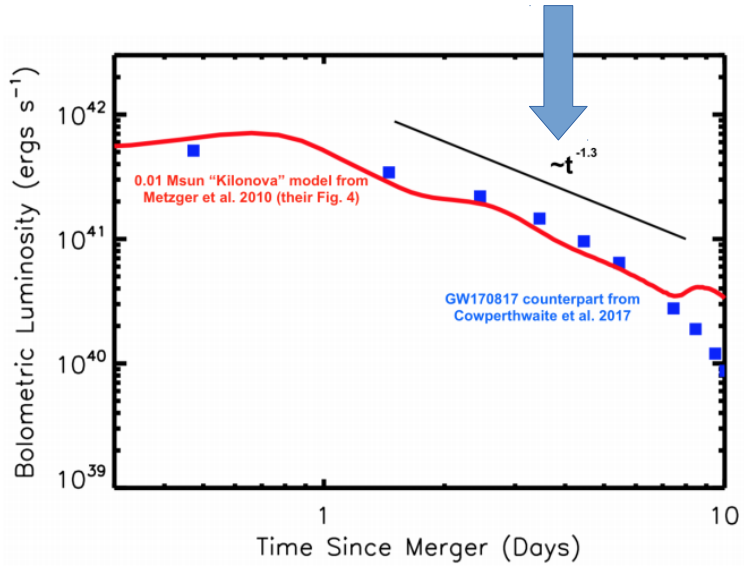


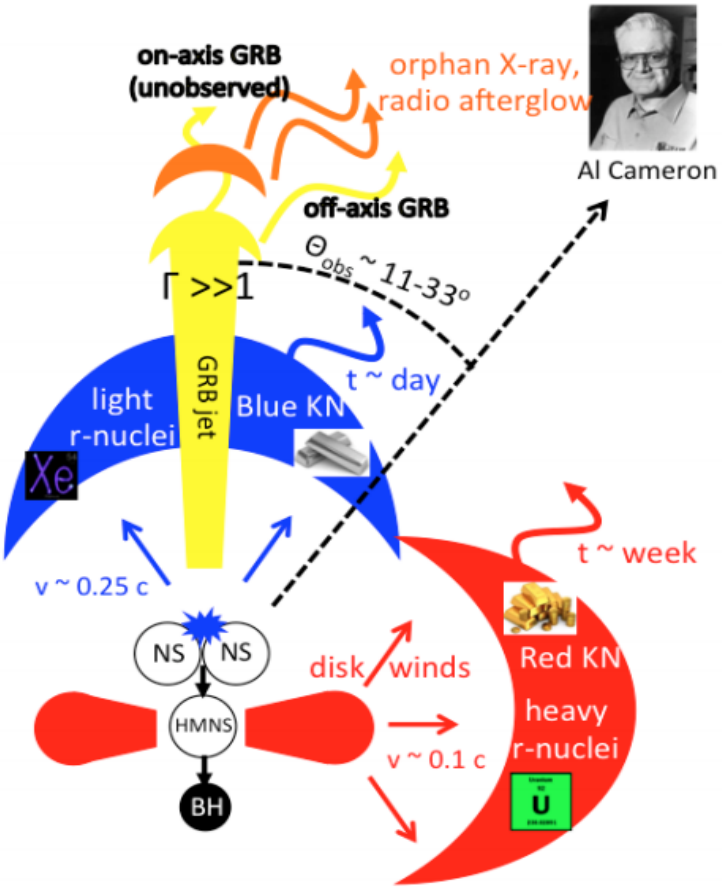

Ruiz et al., APJ. 824 (2016), L6

# EM Signals – Kilonova

- pseudo-black body radiation from r-process elements
- formation of heavy elements



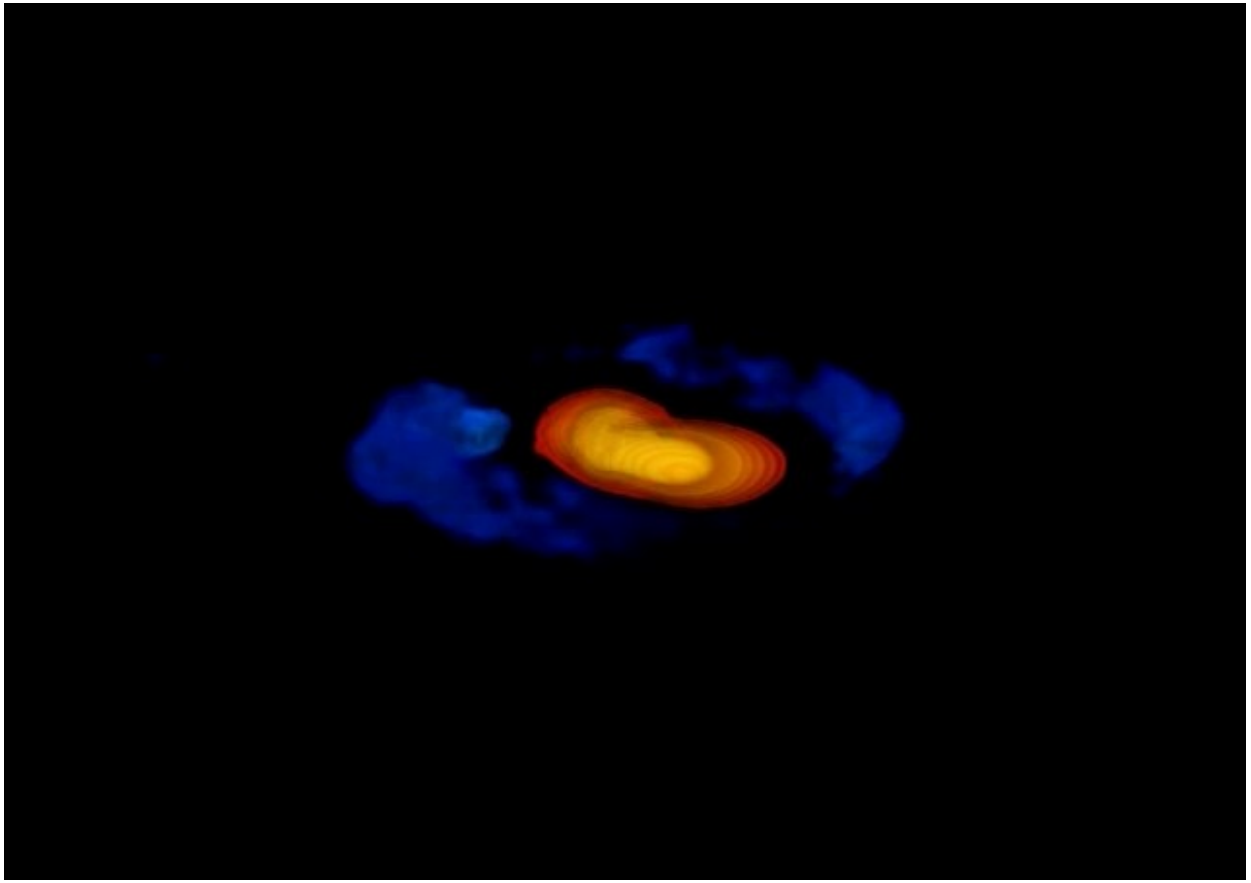



Metzger, arxiv:1710.05931

# Incorporating NR results

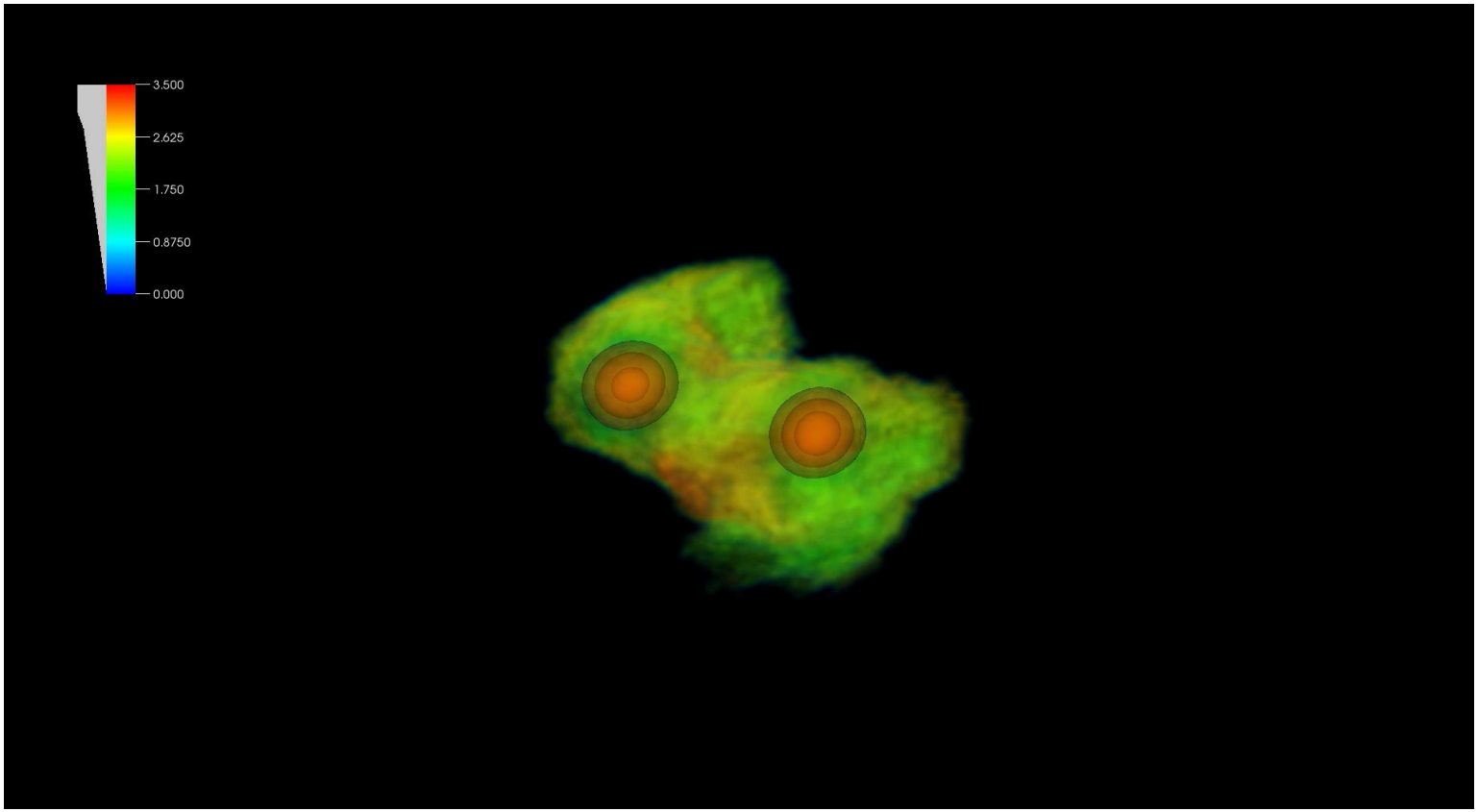
- Predicting the ejecta mass



https://www.youtube.com/watch?v=qPL6ZHBLFiI

# Incorporating NR results

- Predicting the ejecta mass

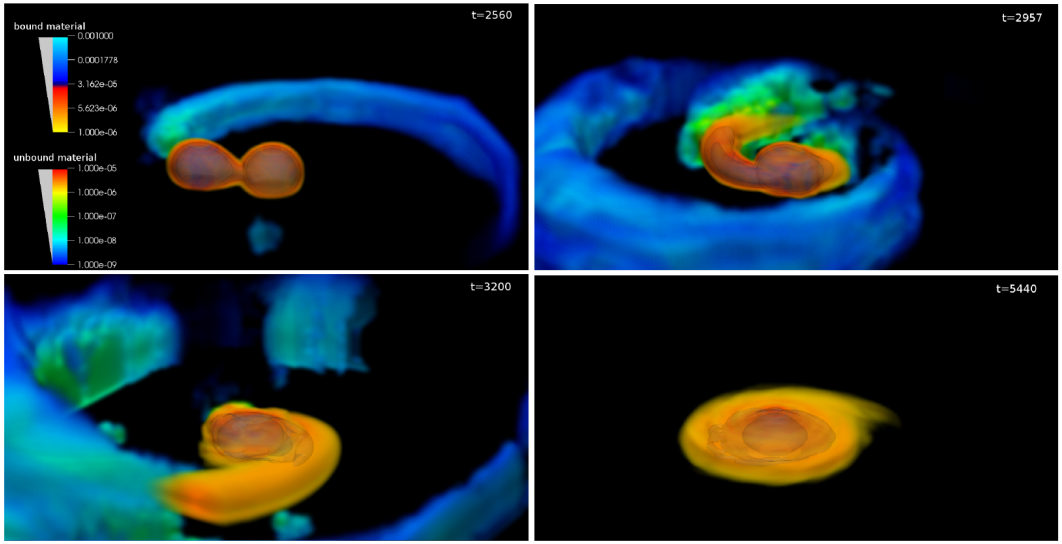


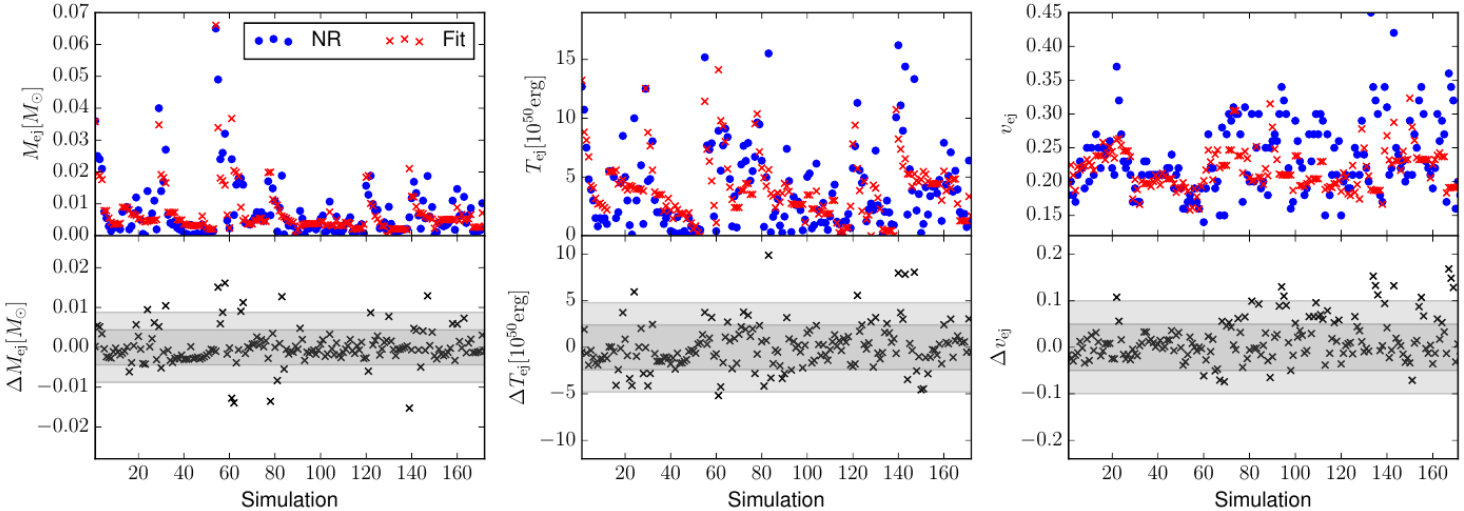

https://www.youtube.com/watch?v=qPL6ZHBLFiI

# Incorporating NR results

TD, Ujevic CQG. 34 (2017), 105014
Coughlin, TD et al, APJ. 849 (2017) no.1, 12

- Predictions about ejecta mass and compositions
  - dynamical ejecta:
    - tidal tail
    - shock heating
  - disk winds
    - neutrino driven winds
    - magnetic winds
    - secular

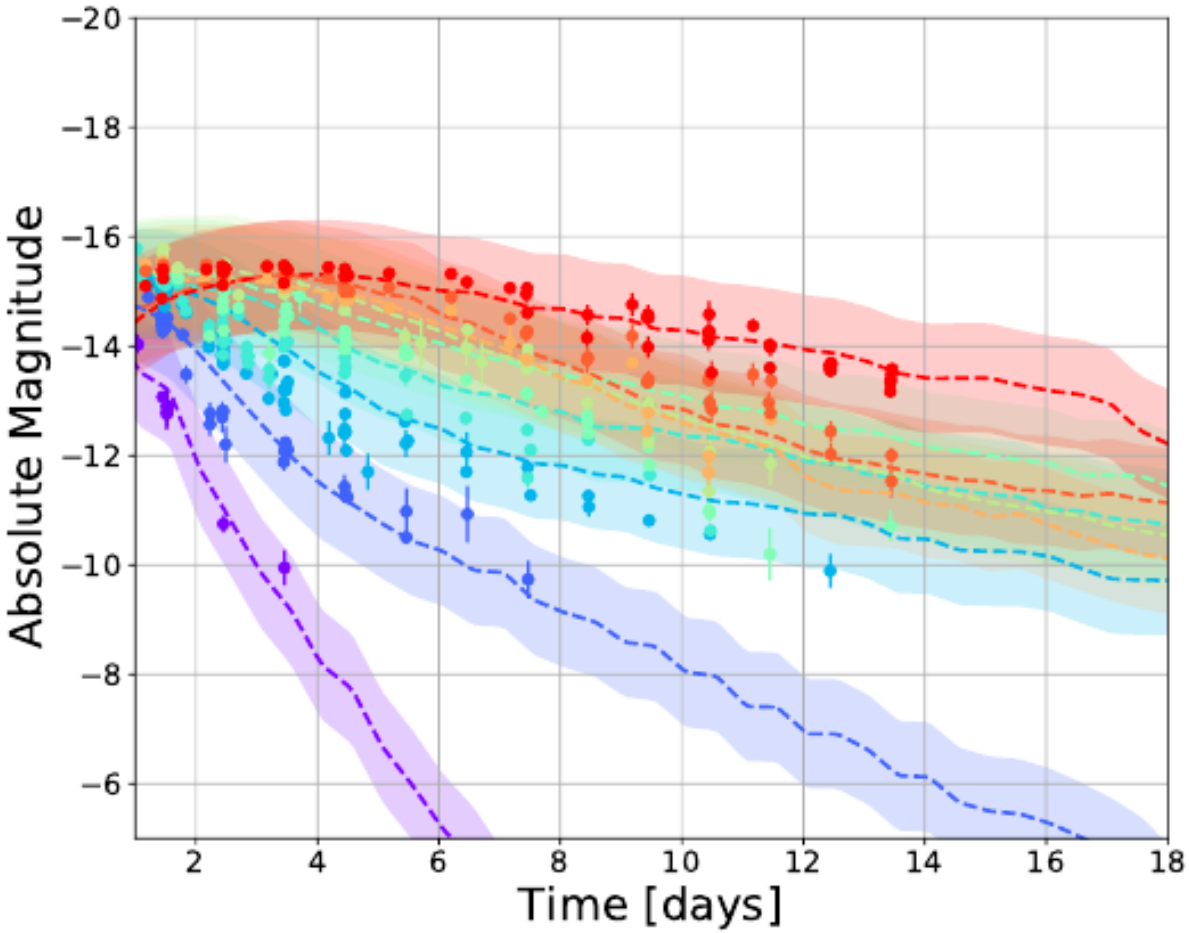


# EM Signals – Kilonova

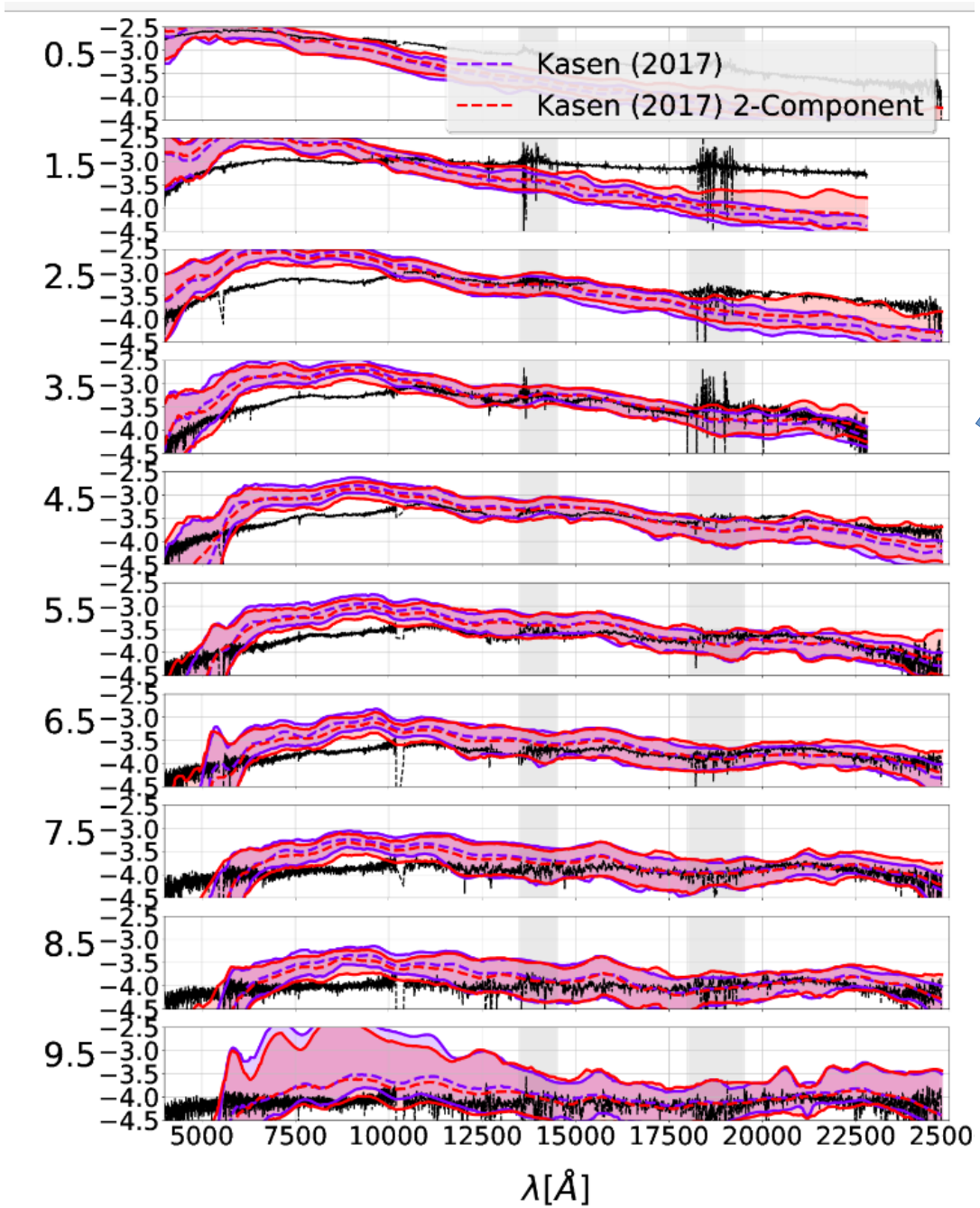
Coughlin, TD, et al., 2018 in prep.

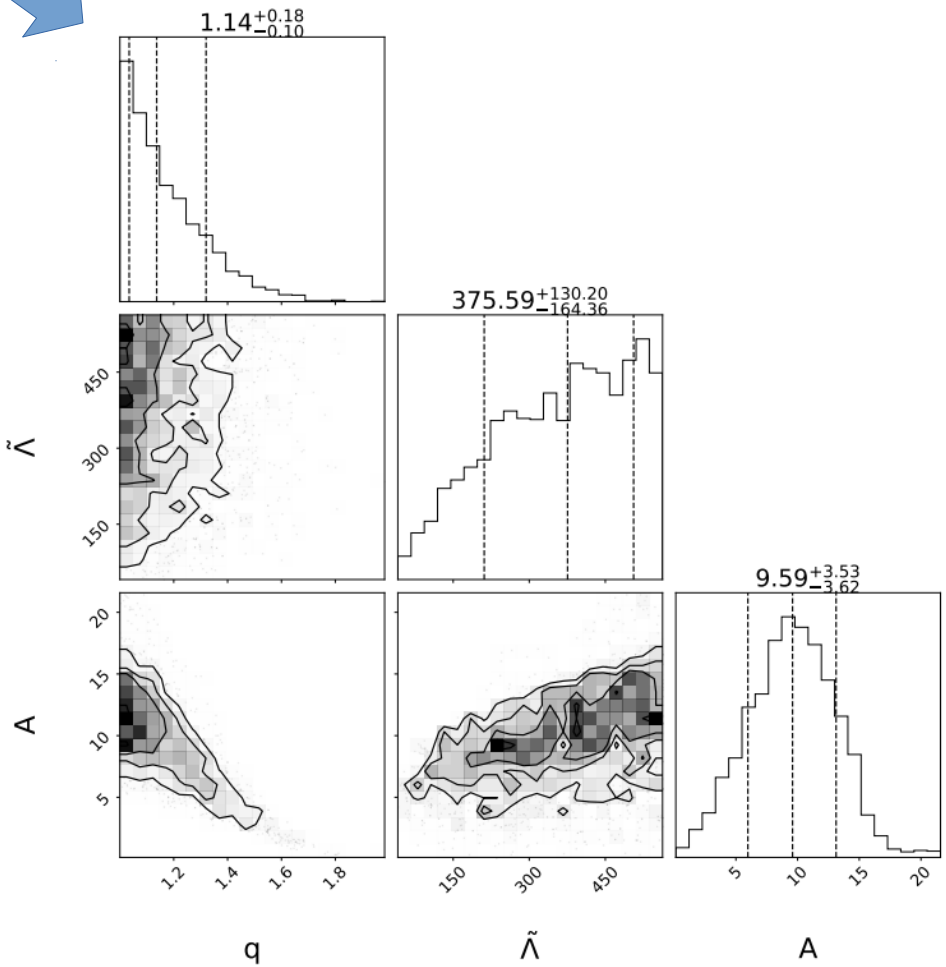
- two component model based on atomic structure and radiative transfer simulations



# EM Signals Kilonova

Coughlin, TD, et al., 2018 in prep.



# Things to remember:

1.) Fundamental idea behind the 3+1 – decomposition and why it is needed

2.) Additional things one should worry about when doing numerical simulations
(BH treatment, Gauge choice, …)

3.) Basics of finite differencing and spectral methods

4.) Method of lines

5.) Principle idea of: mesh refinement, Berger-Oliger time stepping, HPC Computing

6.) Applications of BBH simulations (computation of the waveforms close to merger, …)

7.) Applications of BNS simulations (predicting GWs close to merger and in the postmerger, measurement of the ejected material, estimation of neutrino luminosity,...)