Novel Tests of General Relativity

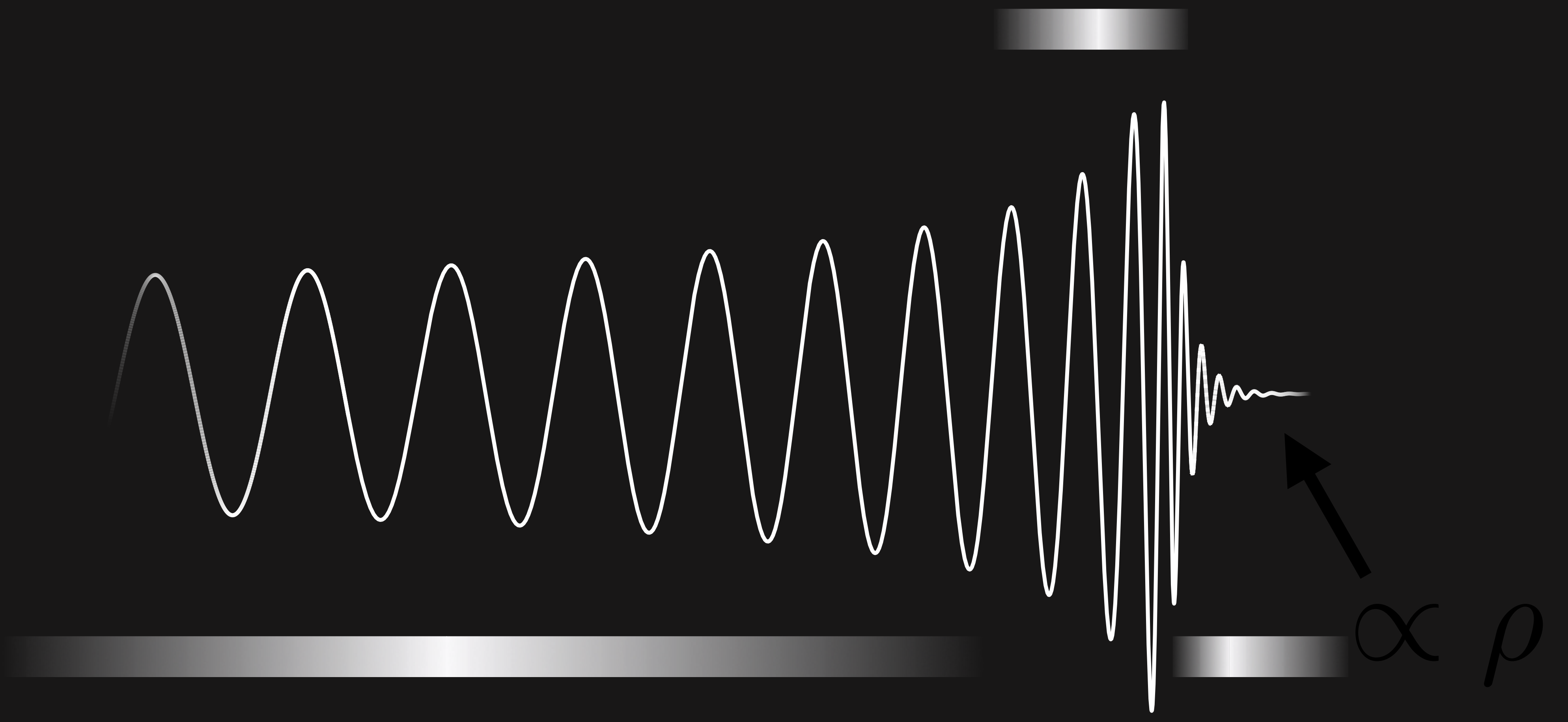
Mentors:

Ben Farr
McCormick Fellow, University of Chicago
Asst. Professor, University of Oregon

Will Farr
Professor, University of Birmingham

Jeandrew Brink
Professor, Stellenbosch University

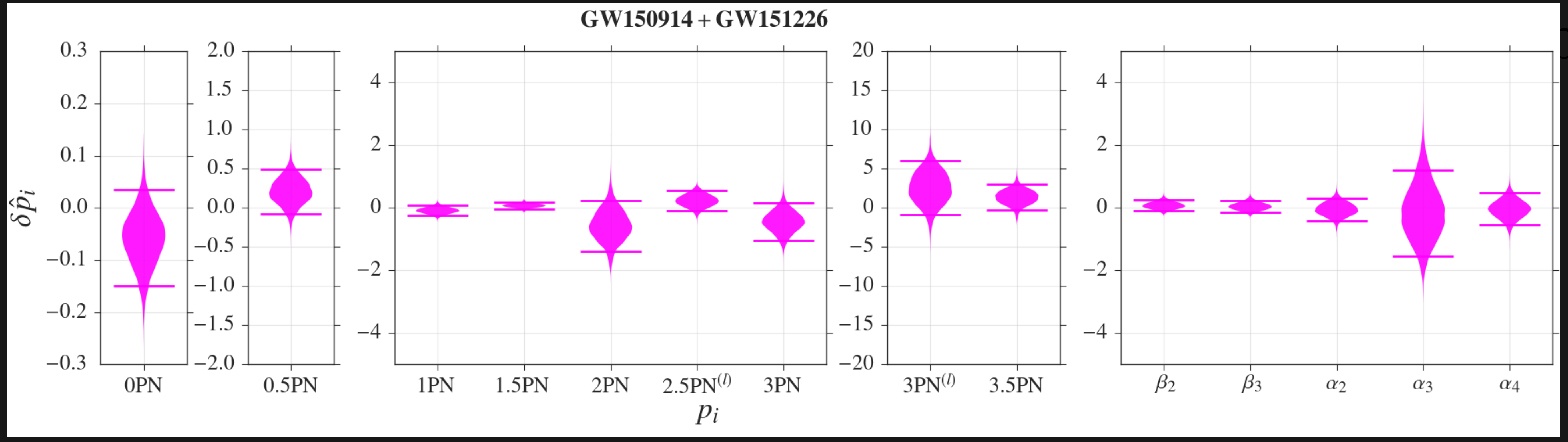
merger
fits to numerical simulations

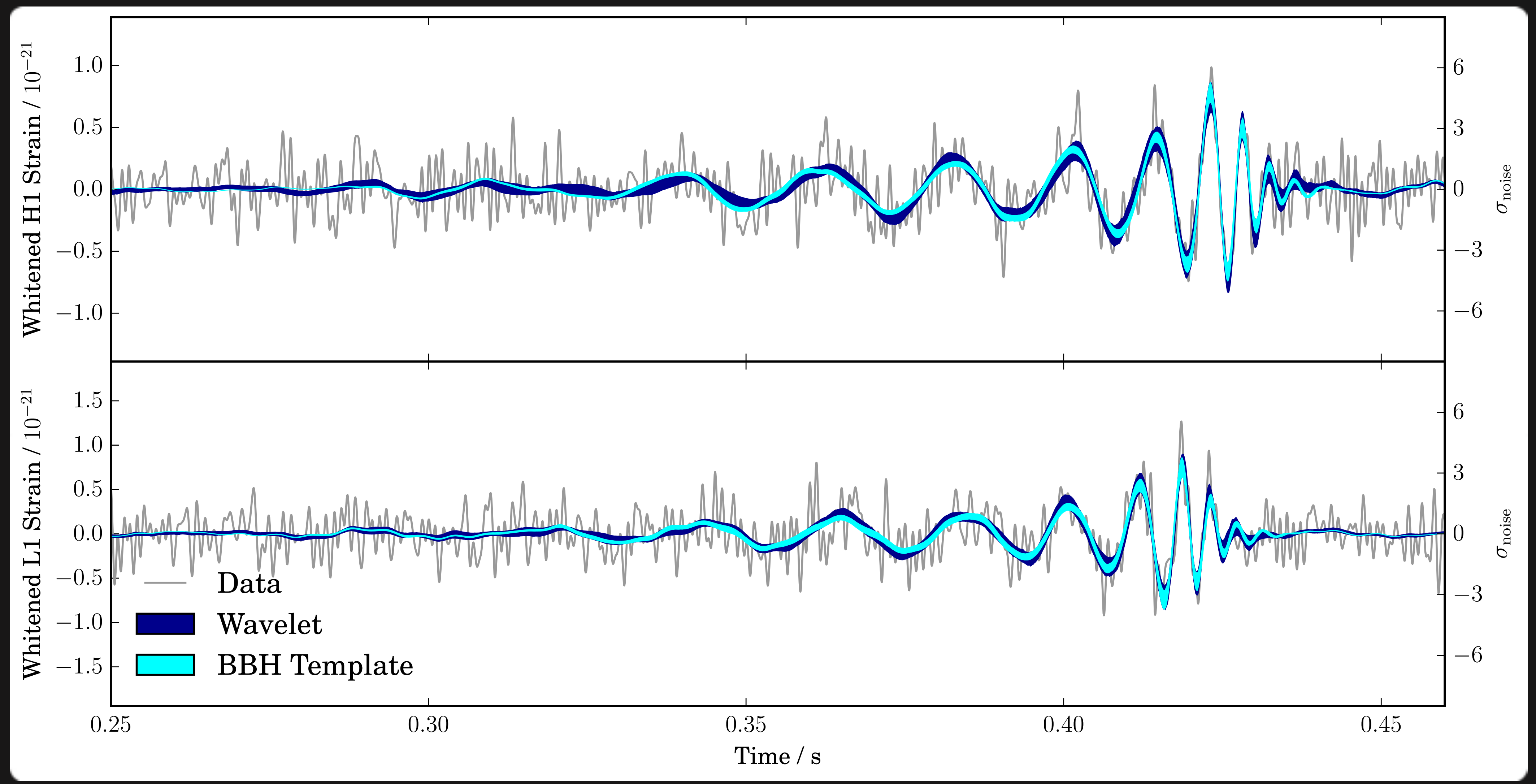


inspiral
post-Newtonian approximation

ringdown
quasi-normal modes

inspiral-merger
corrections





Abbott et al. (2016)
PRL 116, 221101

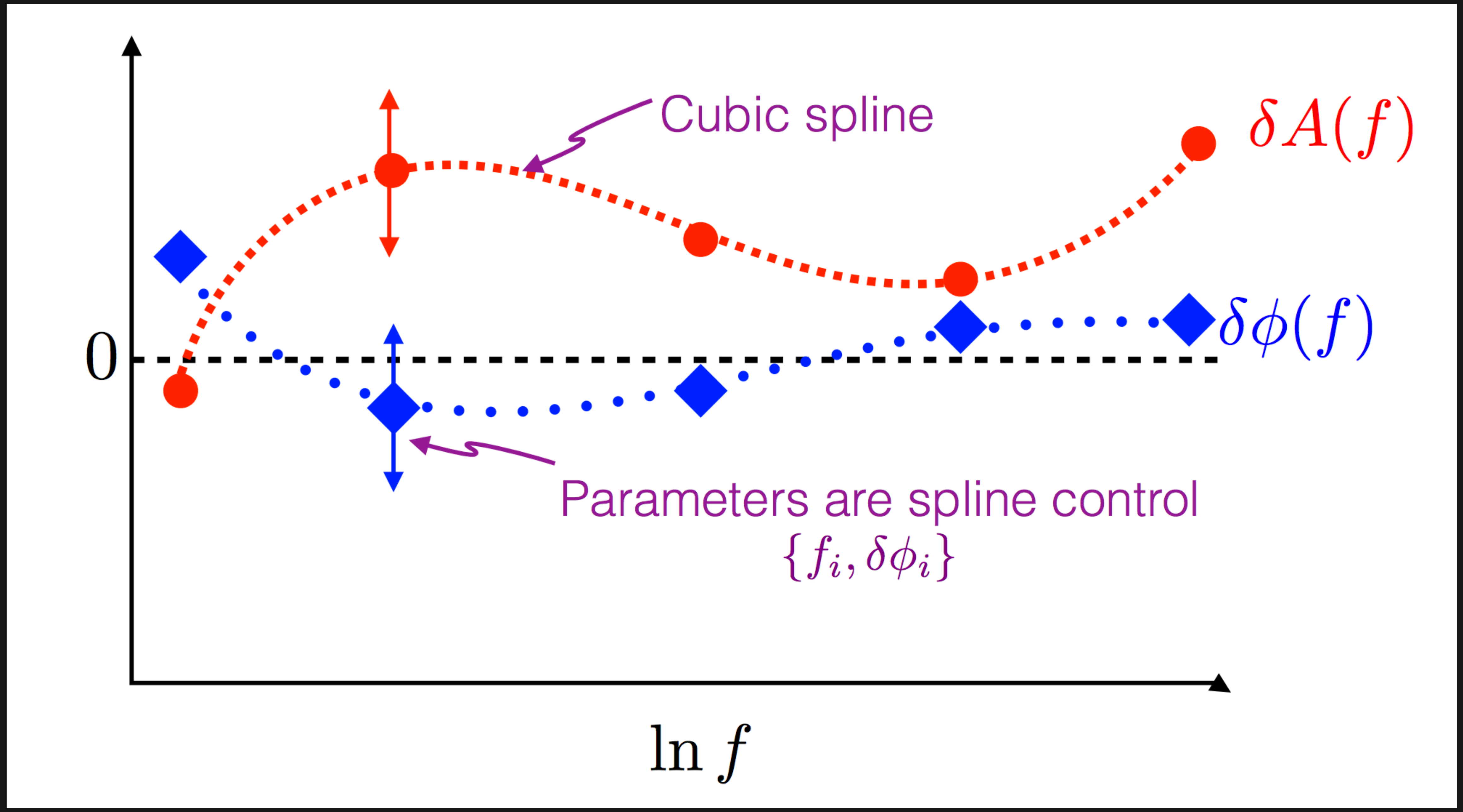
inspiral
corrections to post-Newtonian

merger-ringdown
corrections

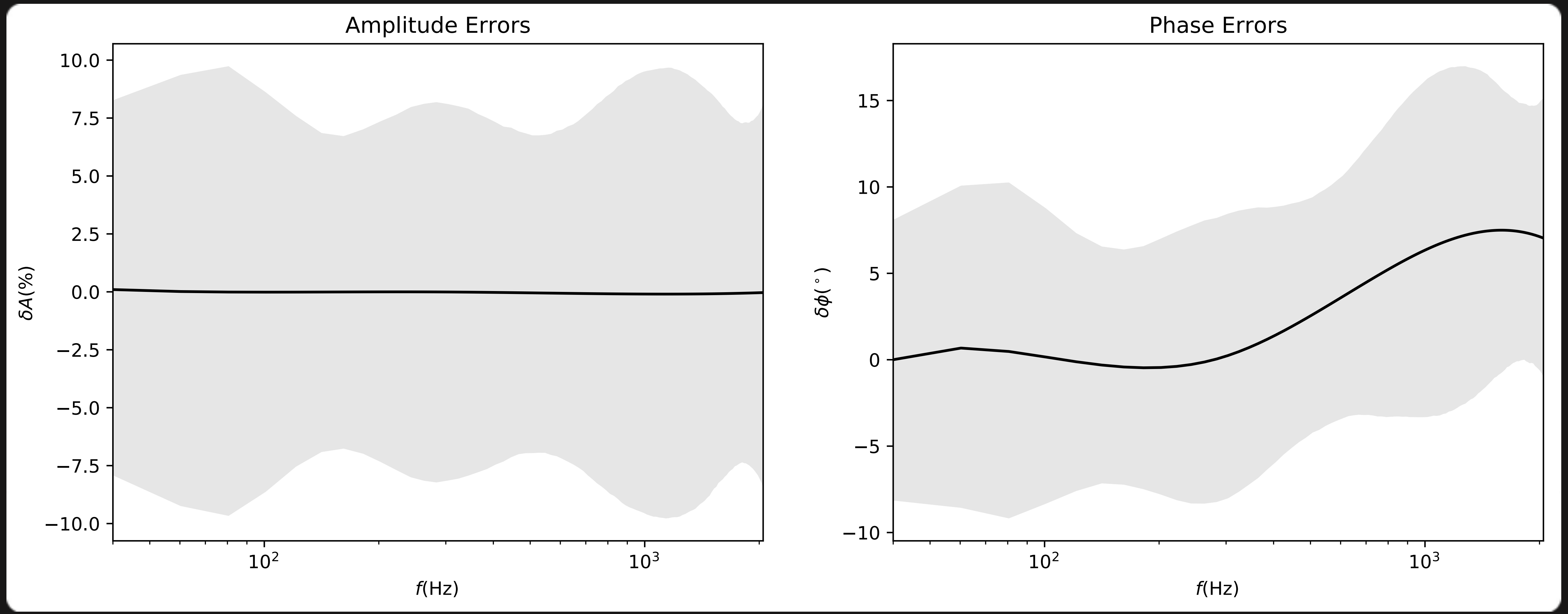
Abbott et al. (2016)
PRL 116, 241102

Novel Tests of General Relativity

$$h_{\mathrm{obs}}(f) = (1 + \delta A(f))h(f)e^{i\delta\phi(f)}$$



courtesy: T. Littenberg

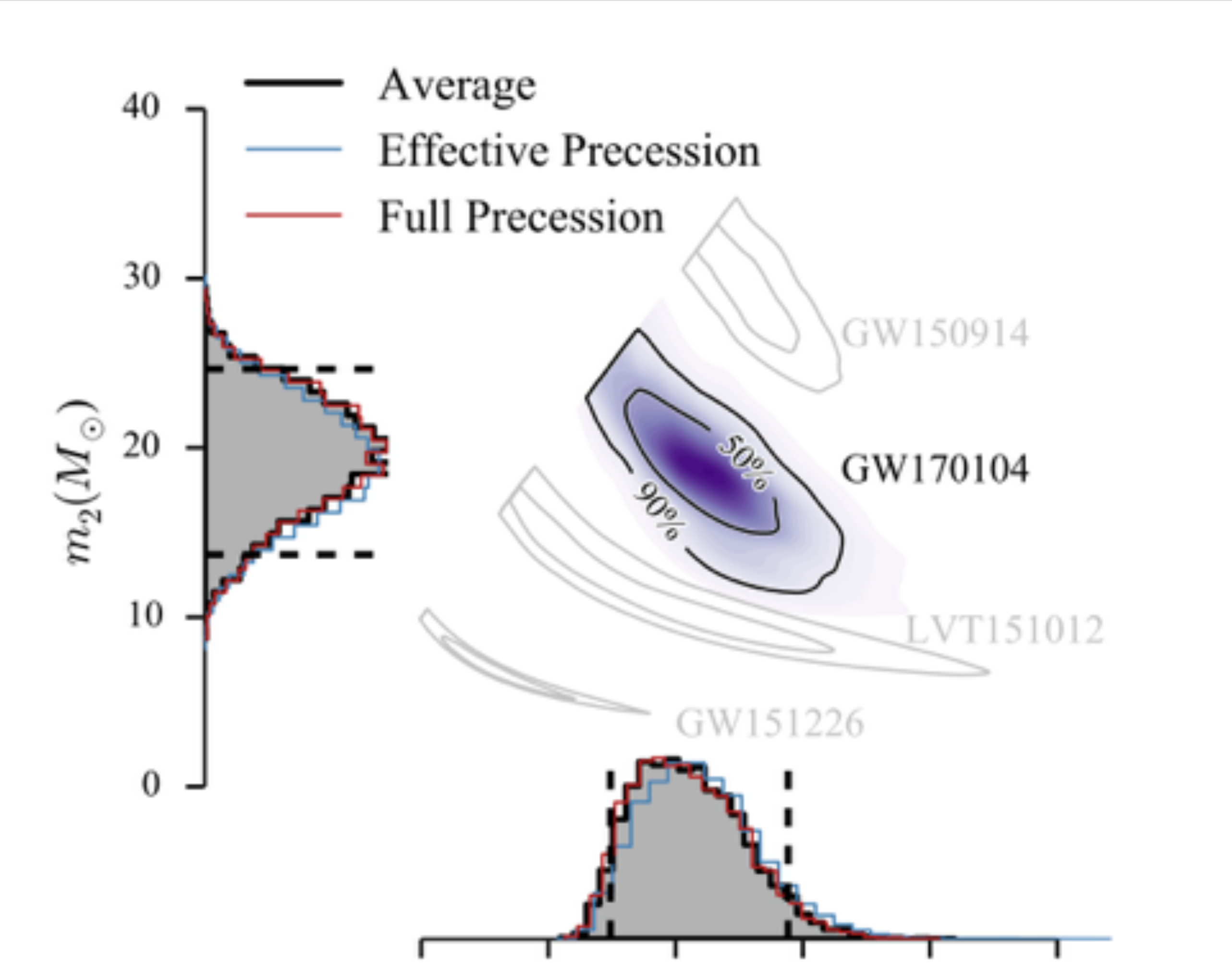


1. Implement splines to model coherent deviations from GR.
2. Test on mock non-GR waveforms.
3. Constrain possible deviations in LIGO's BBHs.

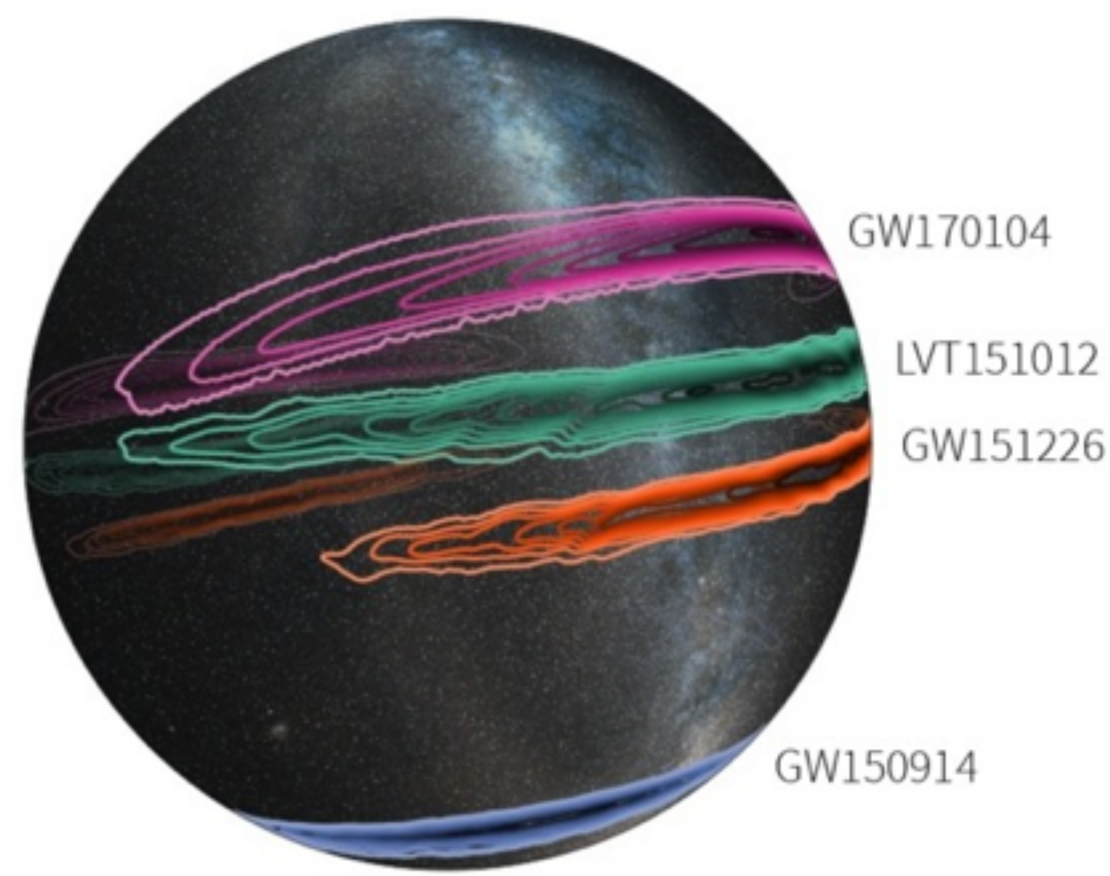
Project 2: Characterizing EM-bright gravitational wave sources in non-stationary interferometer noise

Mentors: Jonathan Gair, *Reader - University of Edinburgh*
Joey Shapiro Key, *Asst. Professor - University of Washington Bothell*
Ben Farr, *Asst. Professor - University of Oregon*
Jess McIver, *Postdoc - Caltech*

Parameter estimation for detected gravitational wave sources includes estimation of masses, spins, and other physical parameters, as well as sky location.

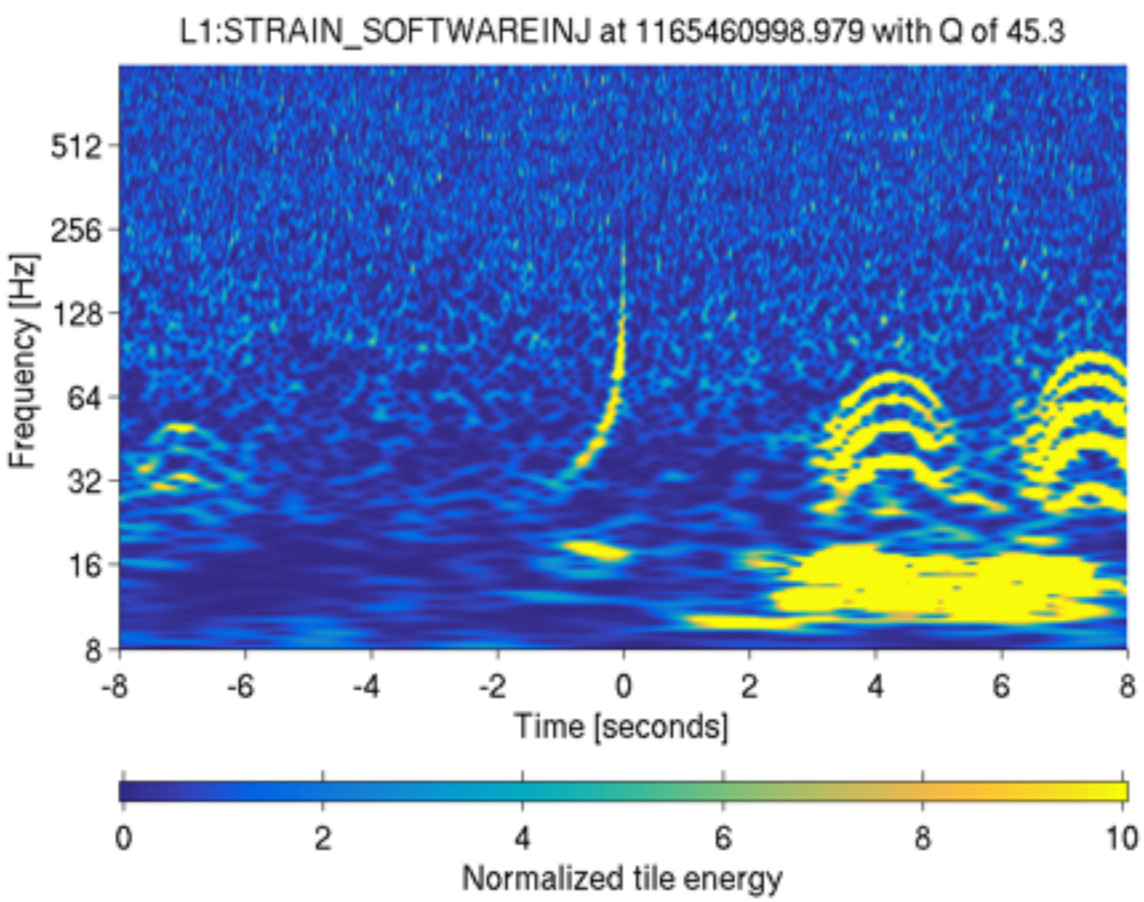


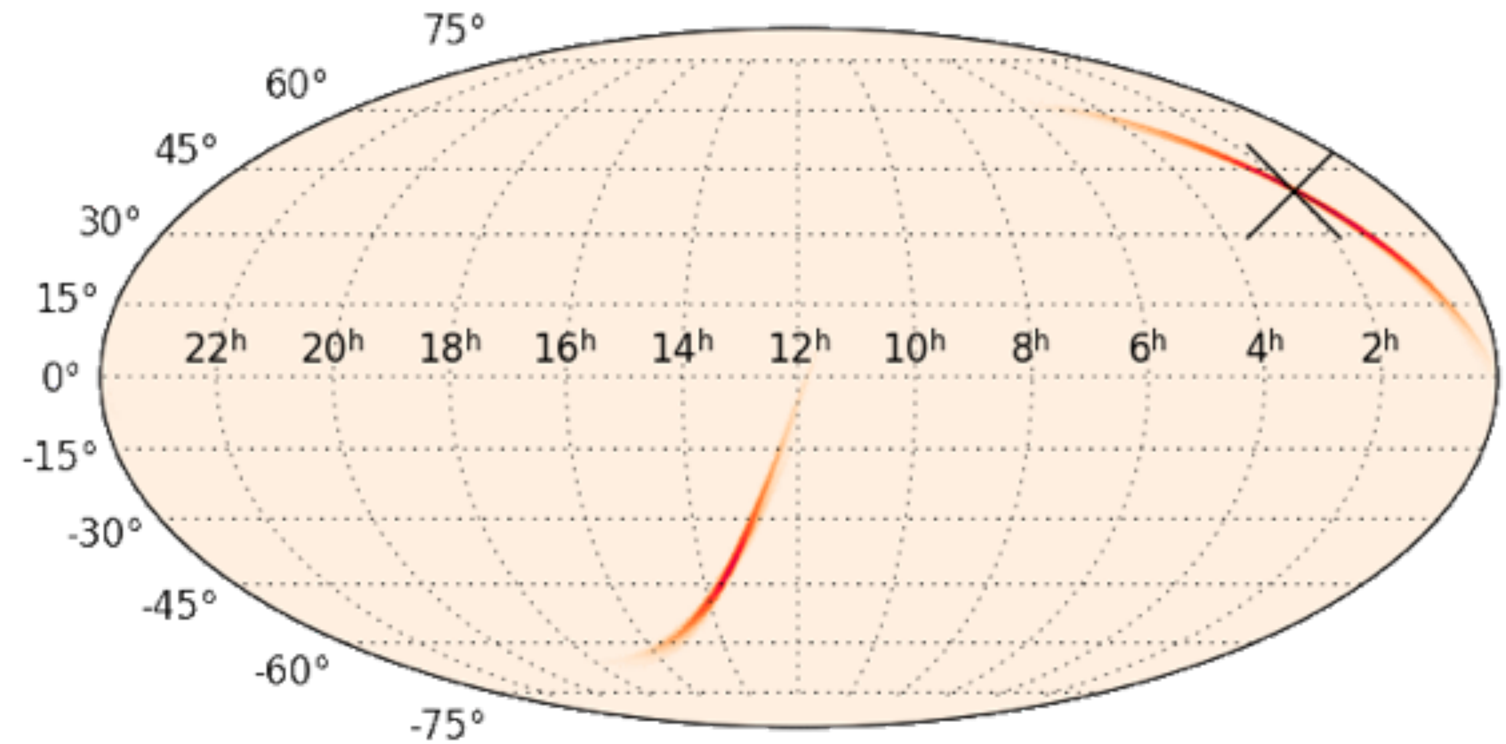
PRL 118, 221101 (2017)



LIGO/Caltech/MIT/Leo Singer
(Milky Way image: Axel Mellinger)

Project 2 goals





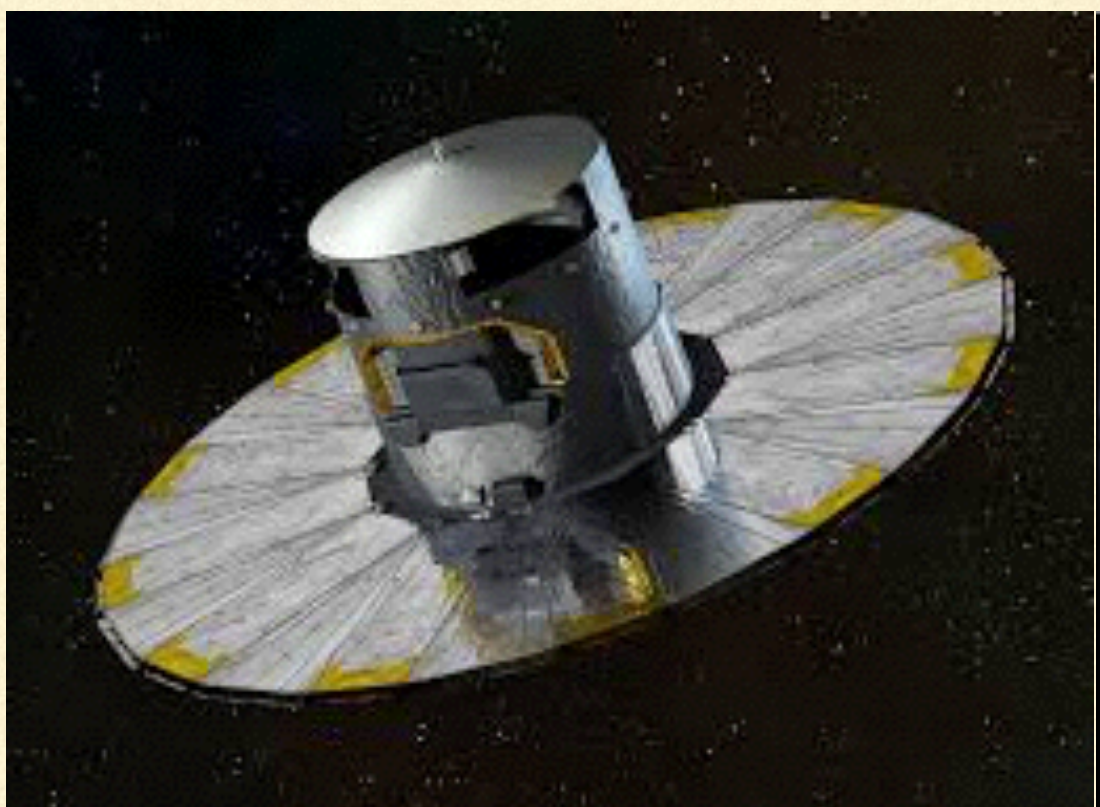
This summer we plan to:

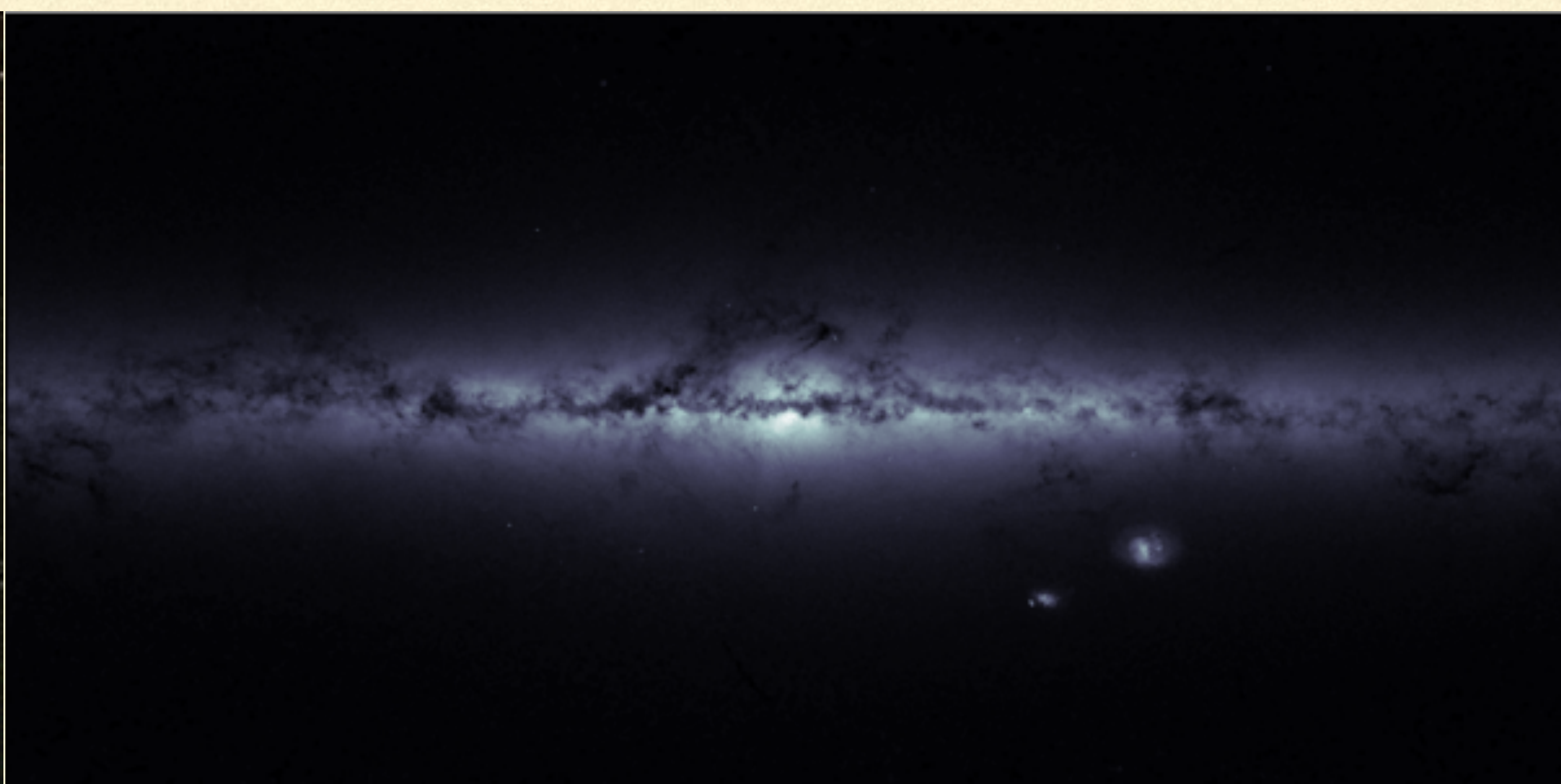
1. Target real, common data defects in the LIGO detectors
2. Inject EM-bright (containing at least one neutron star) simulated gravitational wave signals into affected data
3. Characterize the impact of data defects on the recovery of signals and estimation of sky location, masses, and spins
4. Explore techniques for mitigation

Any mitigation techniques we identify may be incorporated into parameter estimation pipelines and the GW trigger alert approval process for low-latency alerts!

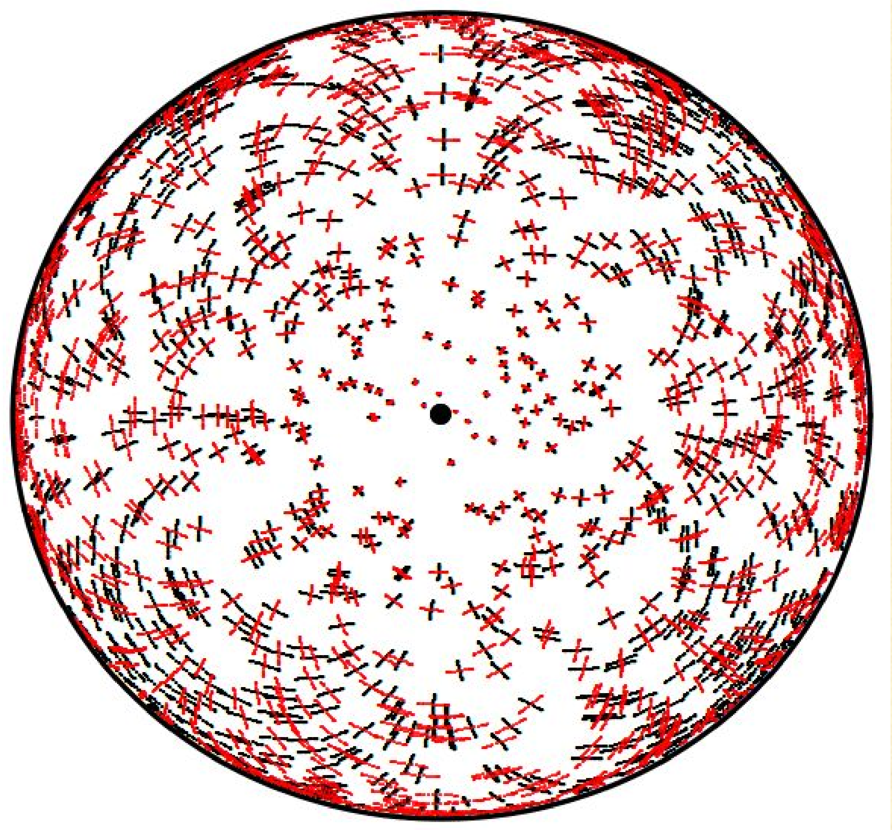
PROJECT 3: **ASTROPHYSICS WITH ASTROMETRIC DETECTION OF GRAVITATIONAL WAVES**

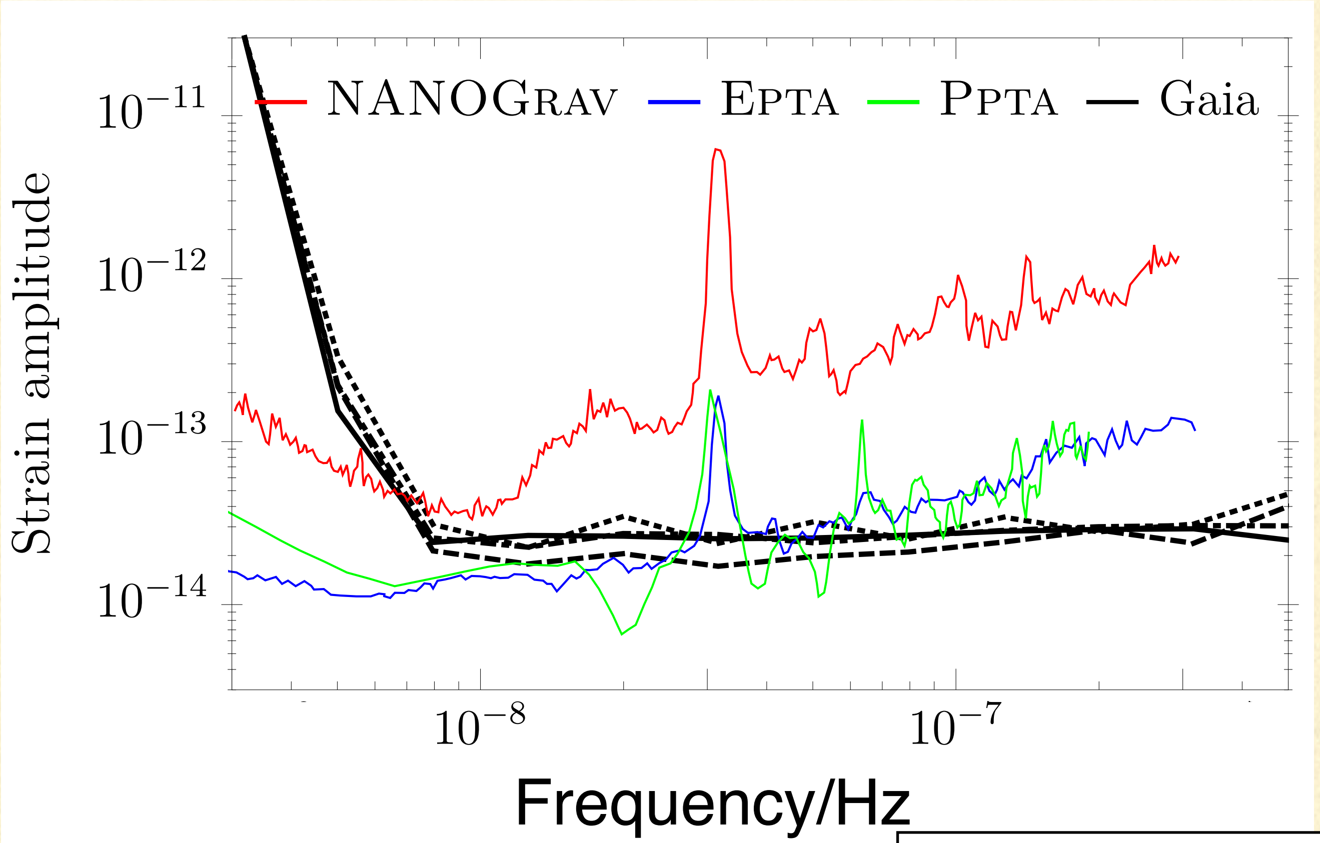
Jonathan Gair, Enrico Ramirez-Ruiz





- Astrometric satellites like GAIA measure precise positions of stars on the sky.
- Gravitational waves perturb the apparent locations. Use these perturbations to detect GWs! Similar principle to pulsar timing.
- Many open questions, including
  - what astrophysics and fundamental physics will these observations allow?
  - how do you map the gravitational wave background using astrometric measurements?
  - what are the prospects for third-generation astrometric missions?





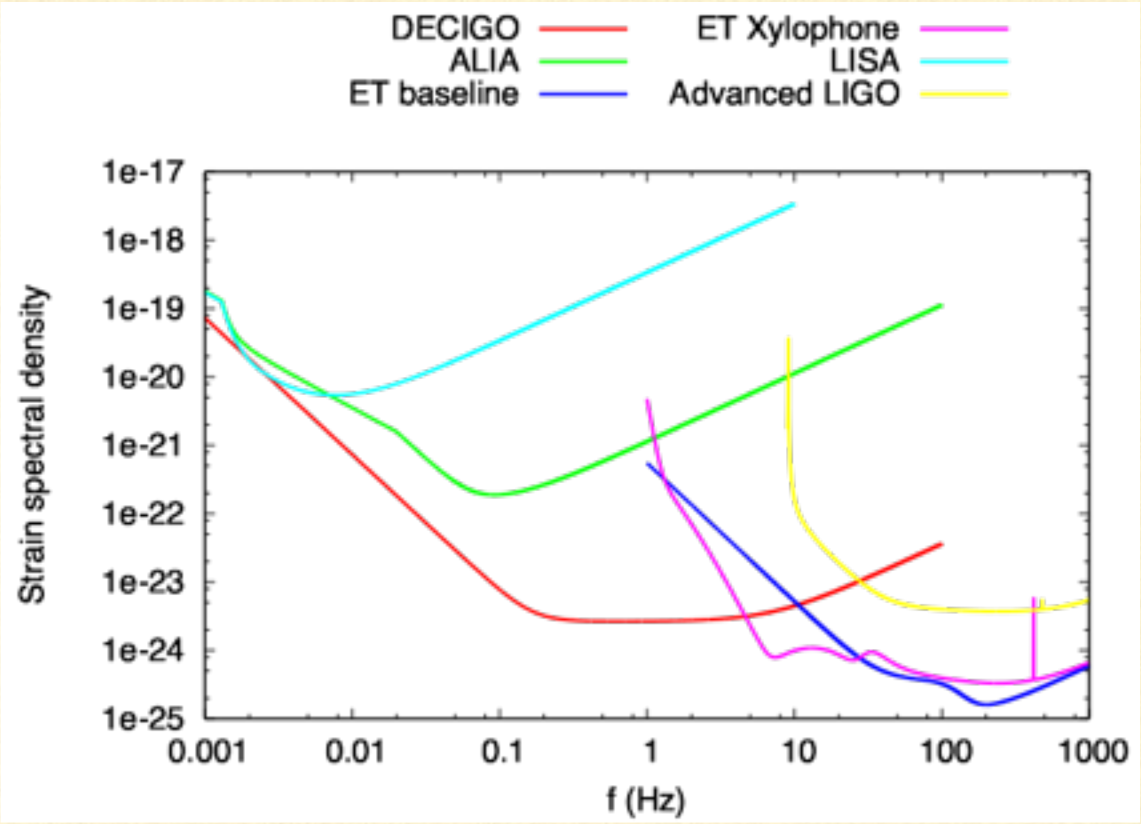
Moore et al. (2017)

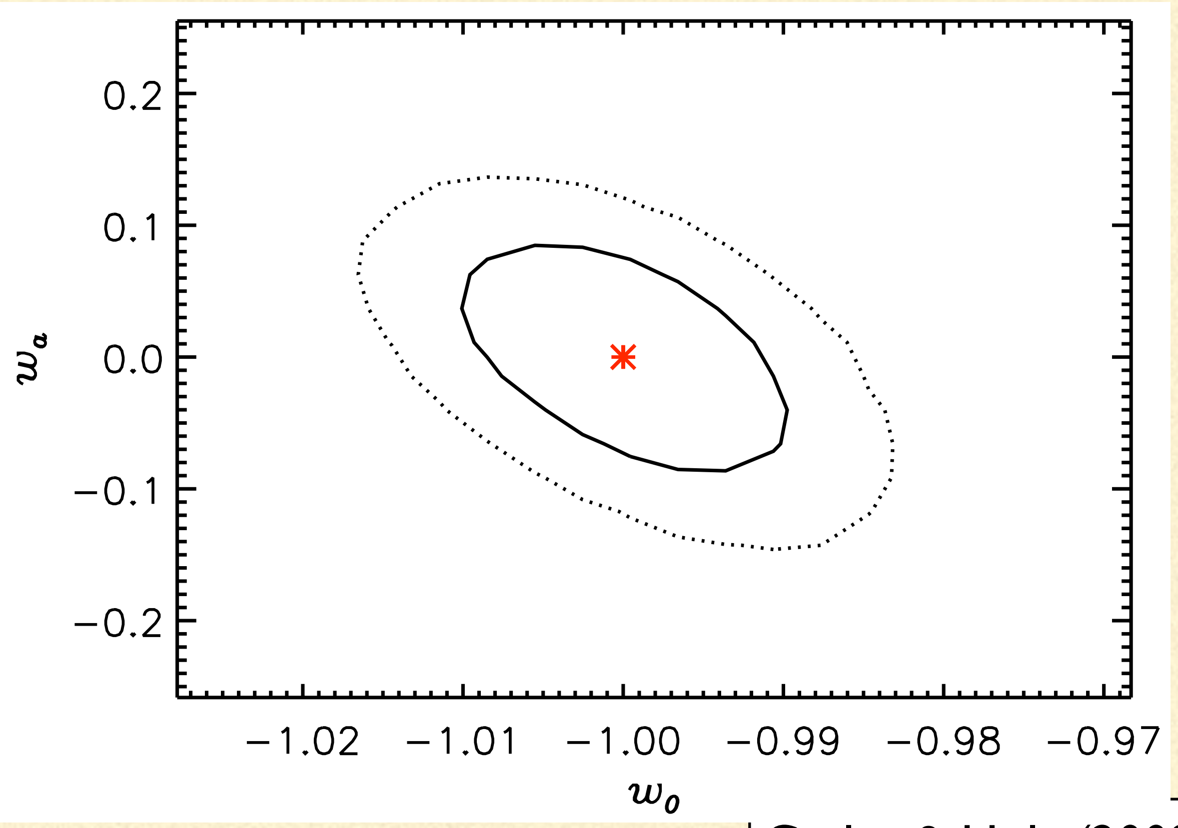
Jonathan Gair: Reader (associate professor) in the School of Mathematics at the University of Edinburgh. Research focus is on gravitational wave data analysis (for LIGO, LISA and PTAs), source modelling and science exploitation.

Enrico Ramirez-Ruiz: Professor at UC Santa Cruz and (currently) a Niels Bohr Professor in Copenhagen. Research is on the astrophysics of the violent Universe, including gamma-ray bursts, accretion phenomena and electromagnetic counterparts to gravitational wave sources.

PROJECT 4: **MAPPING THE WEAK LENSING POTENTIAL USING DECIHERTZ GRAVITATIONAL WAVE SOURCES**

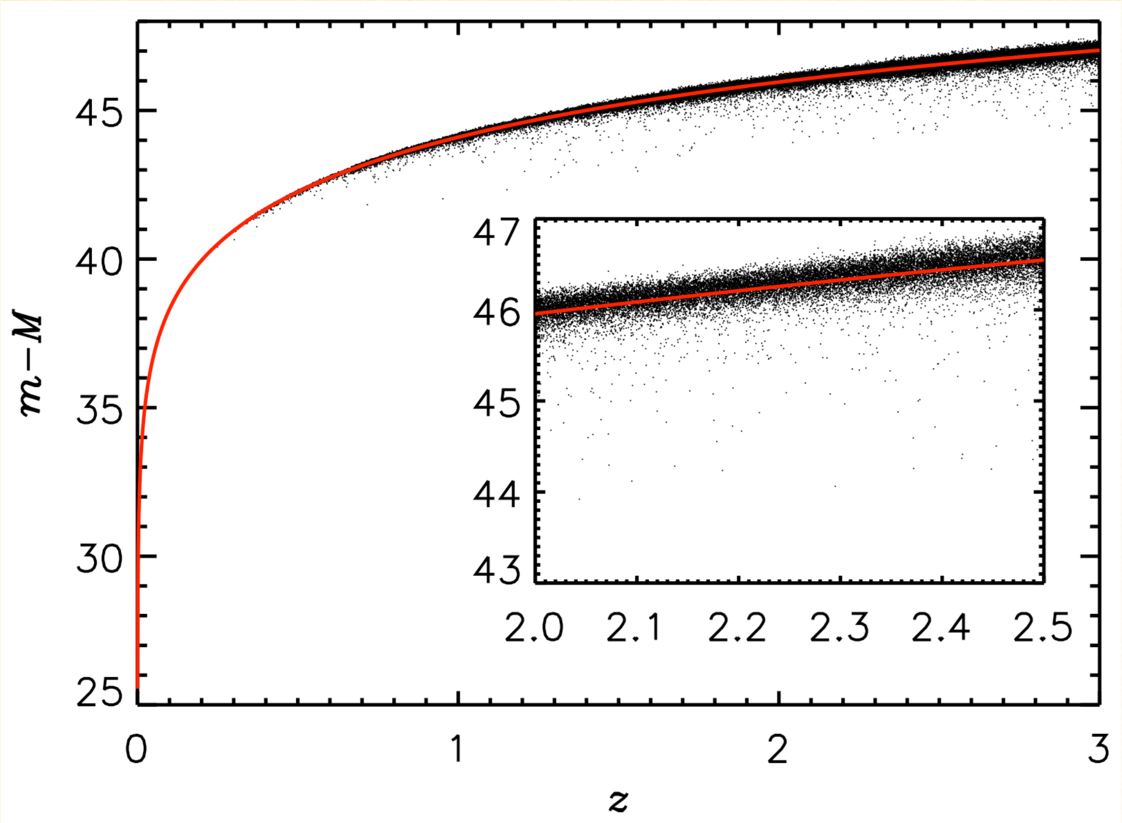
Jonathan Gair, Daniel Holz, Joey Key

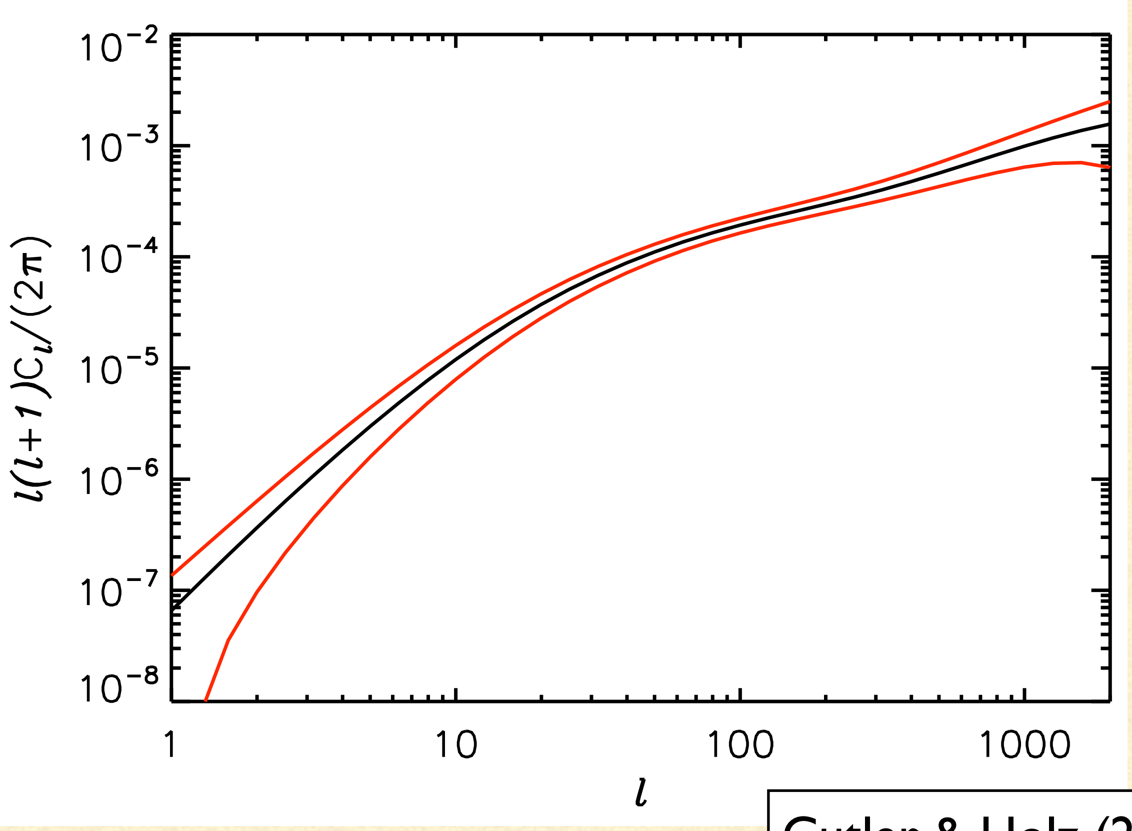




Cutler & Holz (2009)

- Gravitational wave sources can be used for cosmology by providing precise luminosity distance measurements.
- Two complications:
  - can't measure redshift using GWs alone;
  - GW sources suffer from weak lensing which introduces distance errors.
- But: next generation detectors will see enough sources with sufficient precision to both determine cosmological parameters and map the weak lensing potential.

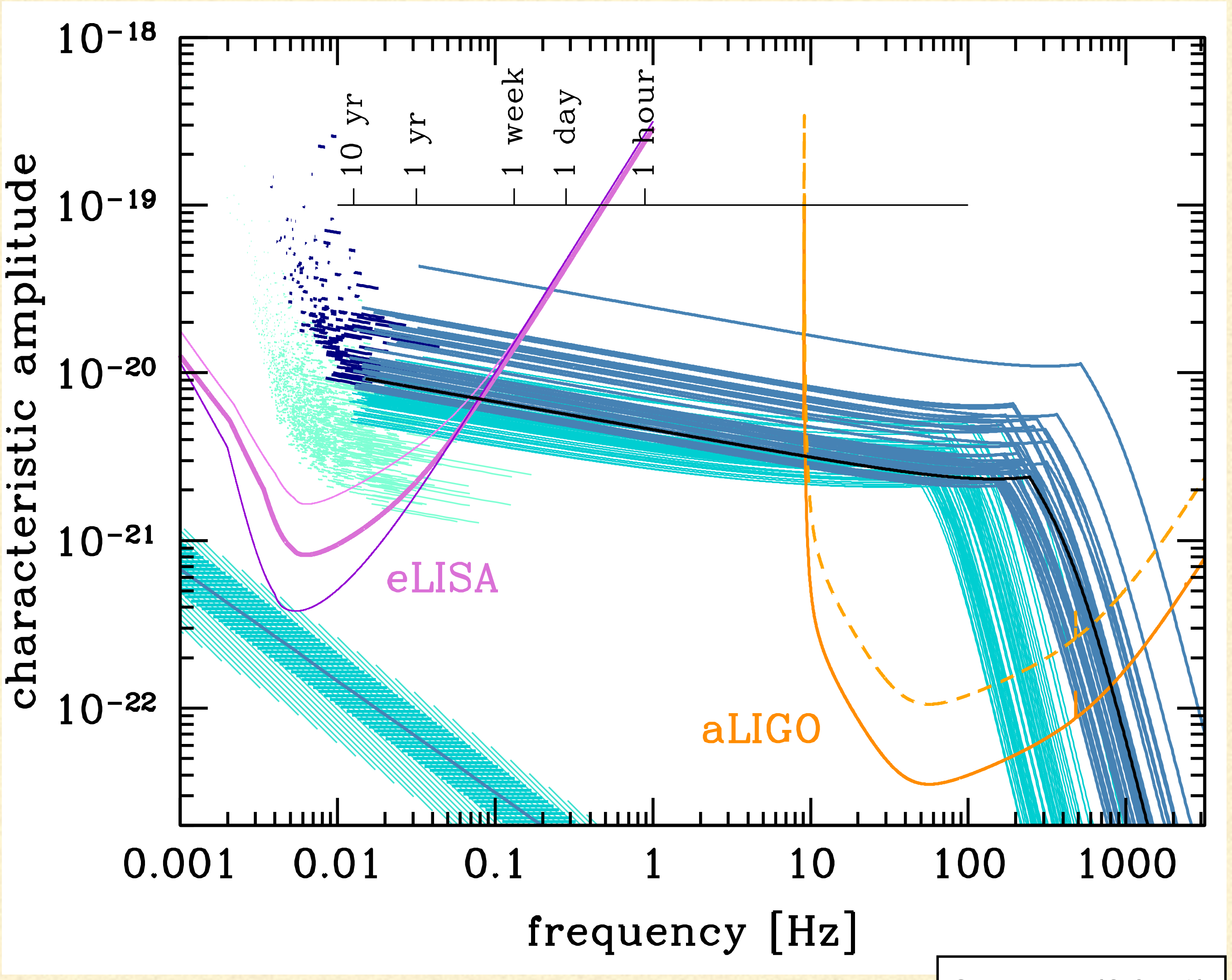




Cutler & Holz (2009)

What's new?

- Previous studies focussed on neutron star binaries.
- LIGO observations of GW150914, LVT151012, GW151226 and GW170104 show that there is a large astrophysical population of black hole binaries.
- Black hole binaries can be seen further away and characterised more precisely.
- This project will explore what we will be able to do using observations of the BBH population.



Sesana (2016)

Jonathan Gair: Reader (associate professor) in the School of Mathematics at the University of Edinburgh. Research focus is on gravitational wave data analysis (for LIGO, LISA and PTAs), source modelling and science exploitation.

Daniel Holz: Associate Professor at the University of Chicago. Research focus on using gravitational wave observations for physics, astronomy and cosmology.

Joey Key: Assistant Professor at the University of Washington Bothell. Research interests in parameter estimation for gravitational wave sources detected by LIGO, LISA and PTAs. Also very involved in Education and Public Outreach.

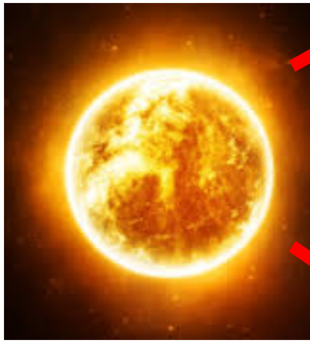
Resolving failed supernovae fractions with the Hyper-Kamiokande neutrino detector

Erin O'Sullivan (weeks 1-5.5)

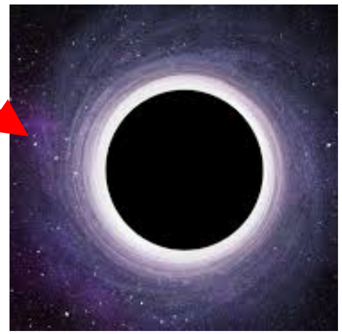
Irene Tamborra (weeks 1,2,4)

Meng-Ru Wu (weeks 1-3,6)

Star collapses



Successful explosion



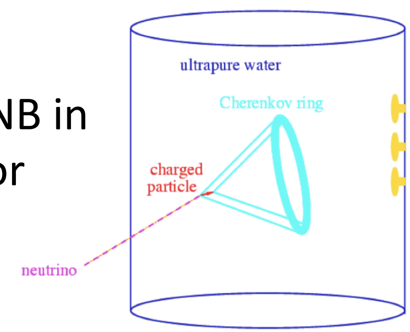
Unsuccessful explosion
(forms black hole)

Imprints on the diffuse supernova background (DSNB) – unsuccessful = higher average neutrino E

The QUESTION:

How well can we determine the fraction of unsuccessful explosions from the measured DSNB in Hyper-K and how does this compare with BH-BH merger rates we can measure in LIGO?

We measure the DSNB in our neutrino detector



Improvements on past efforts through…

- More complete modeling of the experimental response
- Improved SN-BH redshift evolution model
- More realistic time evolution of the neutrino signal

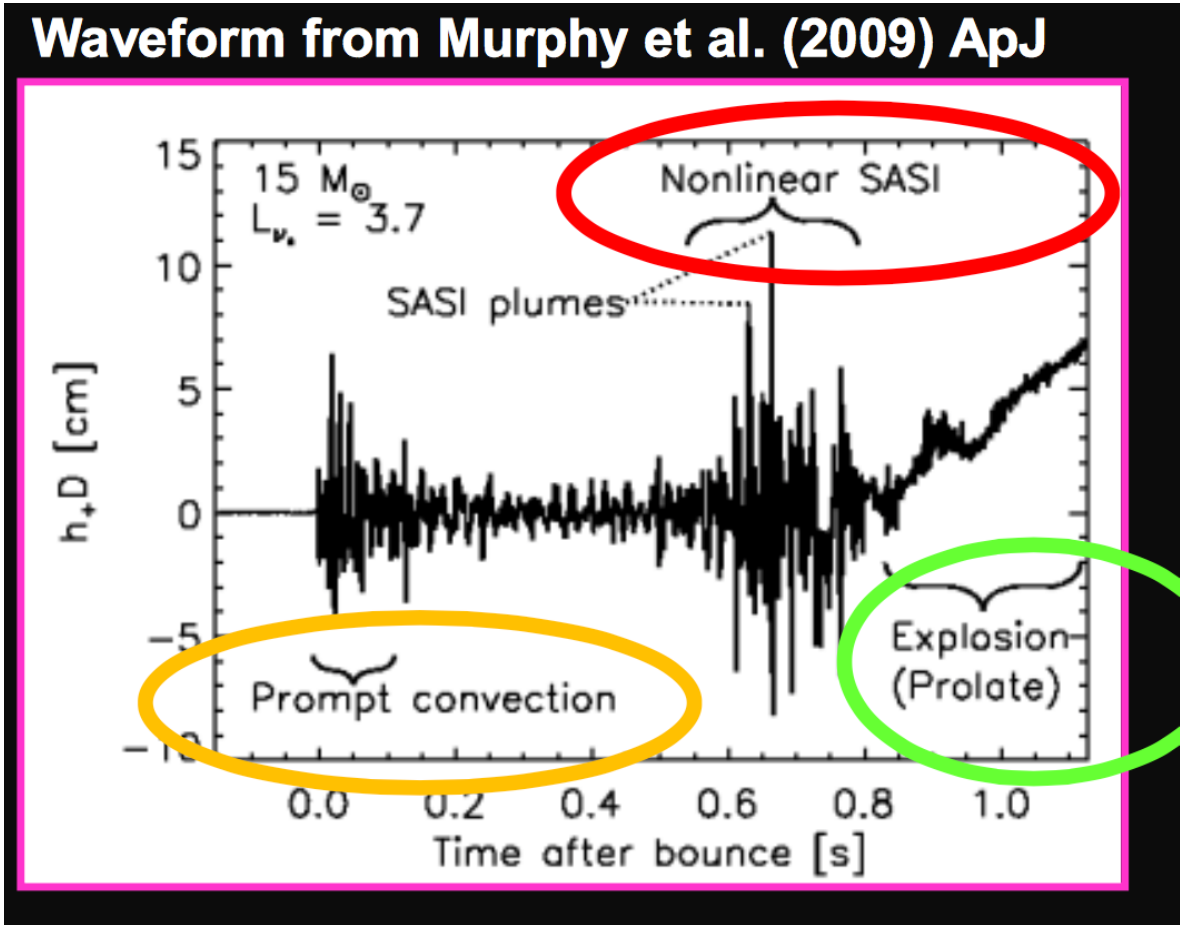
Gravitational Wave Probes of Supernovae

Duncan Brown, Chris Fryer, Philipp Moesta, Nicole Lloyd-Ronning

Second to compact object mergers, core-collapse supernovae are one of the primary sources for aLIGO GW emission.

In principle, GWs can probe the rotation and convection in the supernova engine.

However, what we can learn and when we can learn it (when we'll get a detection of sufficient signal) has not been discussed in a systematic way.

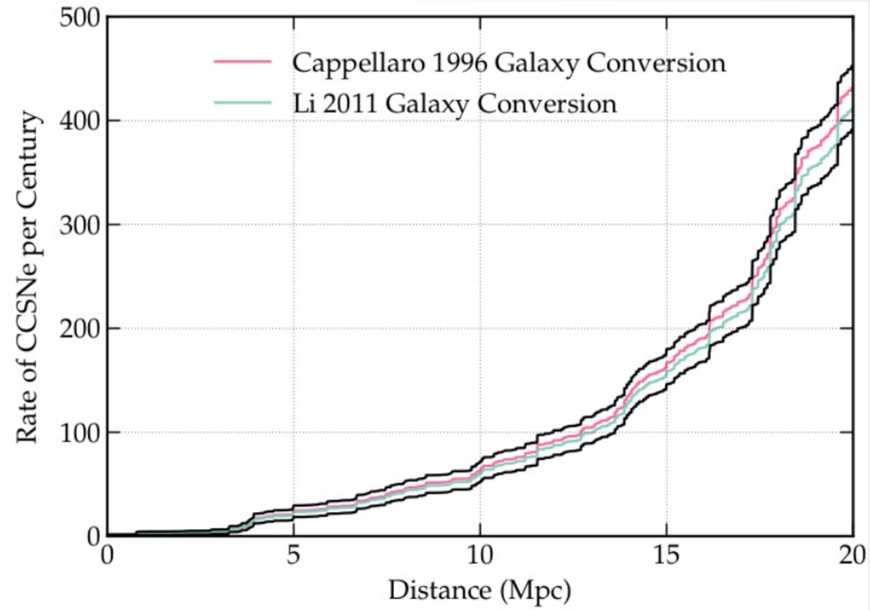


The goal of this project is to do a systematic study of all aspects of this calculation.

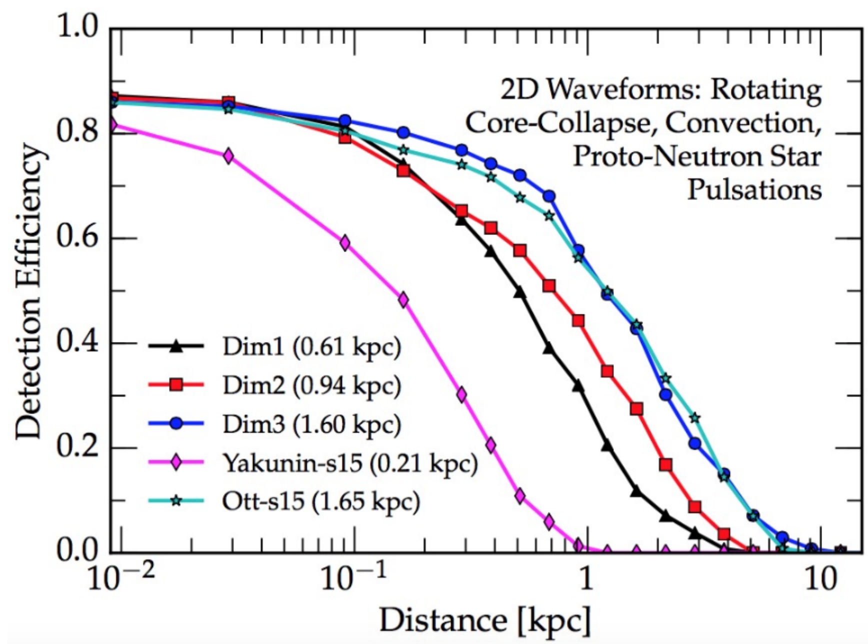
Project Outline

Tasks:

- Statistical Study of rate of local group supernova from historical records – understanding the biases and uncertainties.
- Tie properties of the explosion (rotation, asymmetries, convection growth time, MHD engines, etc.) to signal properties.
- Determine what type of signal is needed to extract these properties to get an observational distance.
- Combine distance with rate to see how long we have to wait (and whether we'll need the next generation telescope.

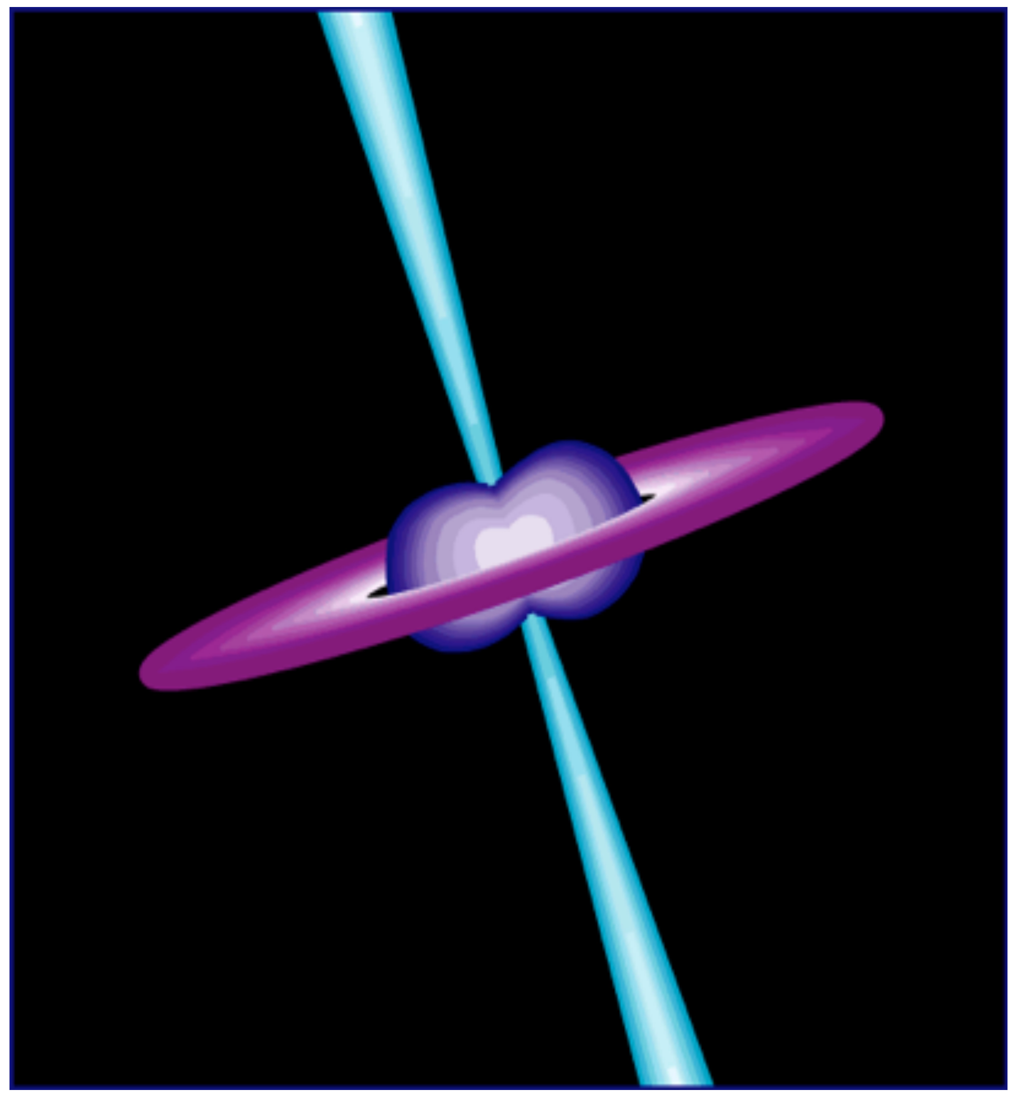


Gill et al 2017 (in preparation),



Szczepańczyk (2016)

Non-Thermal Optical Transients from Neutron Star Mergers

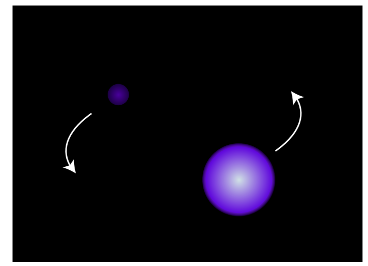


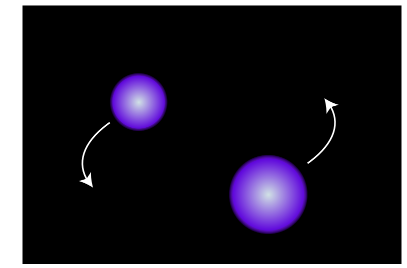
KSP, July 2017

Nicole Lloyd-Ronning, **Chris Fryer** (LANL), Stephan Rosswog (Stockholm), Enrico Ramirez-Ruiz (UCSC)

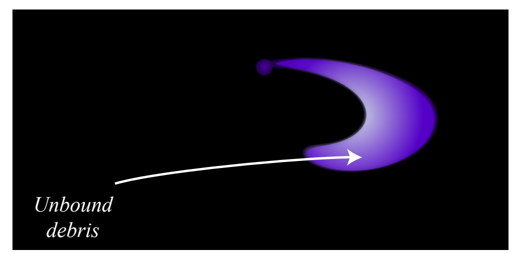
•Events in the Life of a Coalescing Compact Binary:

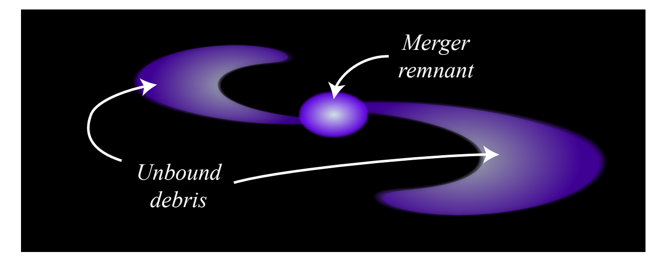
- *secular evolution*



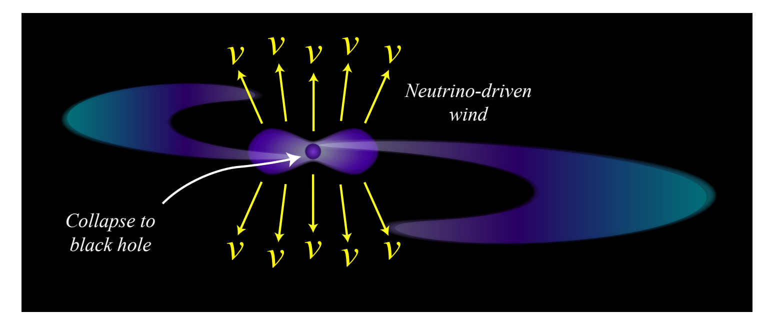


- *dynamical stability of close binaries*

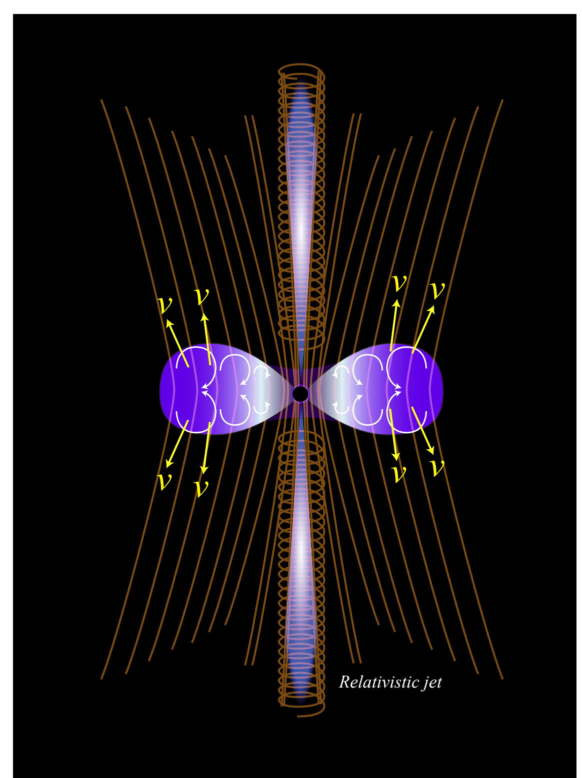




- *hypermassive neutron stars and delayed collapse*

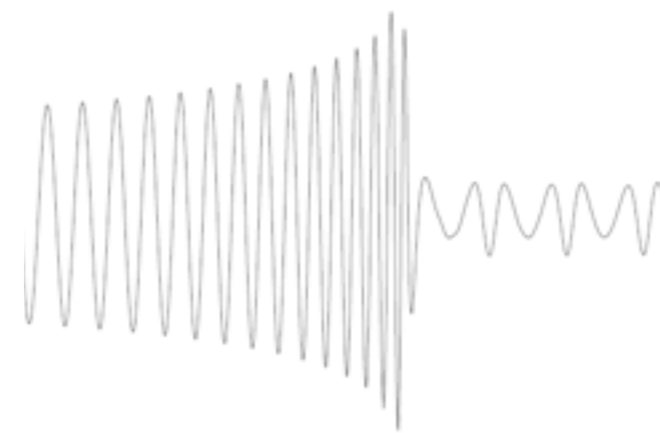


- *accretion disk evolution*

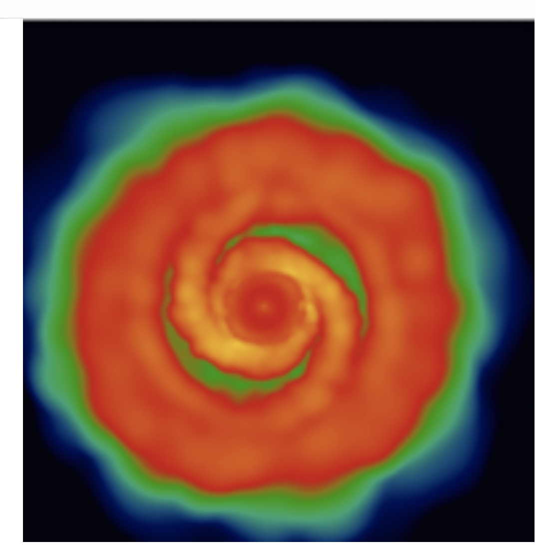


$$E \sim \Gamma M c^2 (\Gamma \sim 10^3)$$

Observational Tests: *Compact Source*



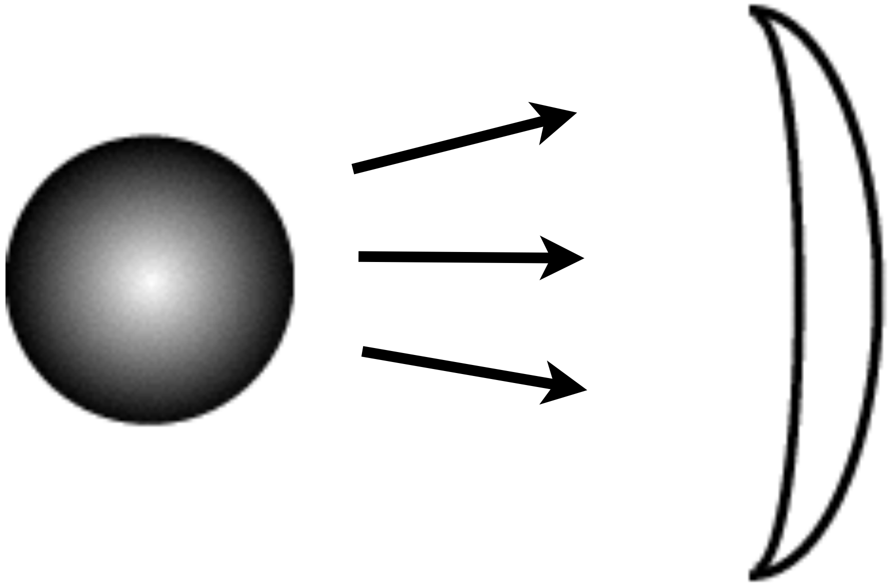
- gravitational waves



- thermal neutrinos

Observational Tests: *Outflow*

•most observations tell us less about the primary power source than about secondary reprocessing of this power.



Observational Tests: *Outflow*

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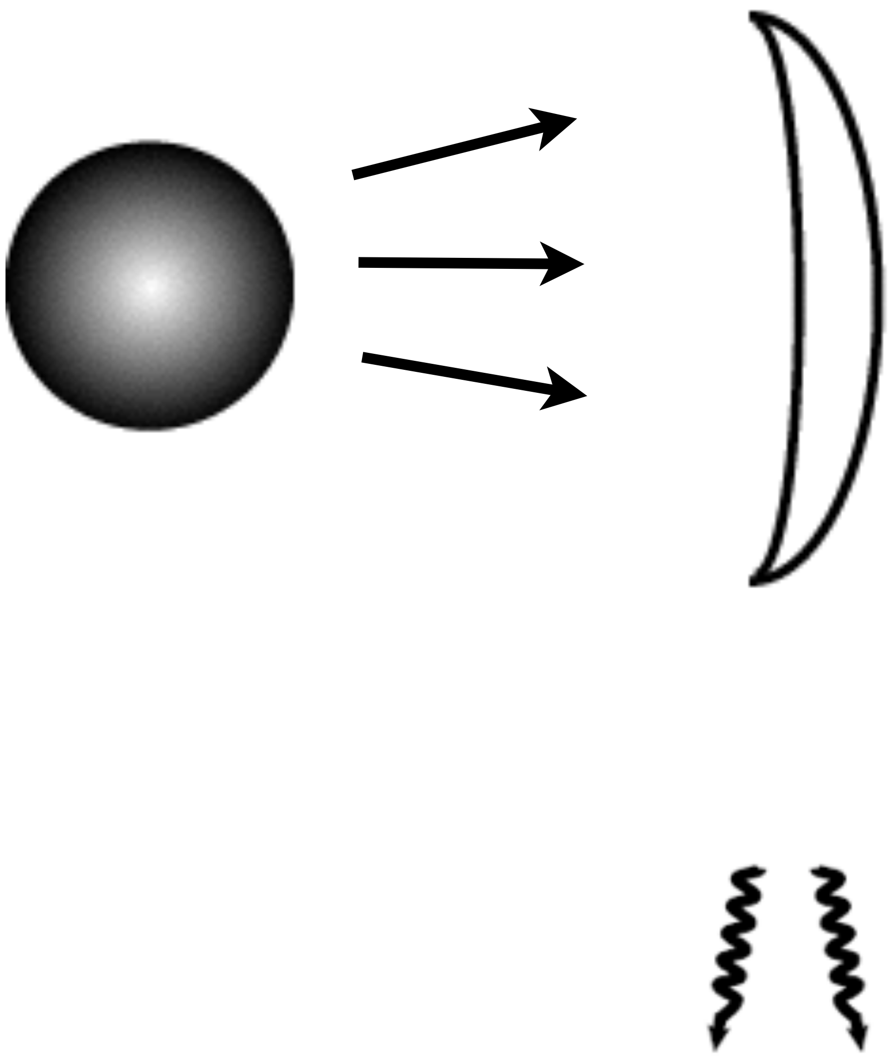
dissipation within outflow



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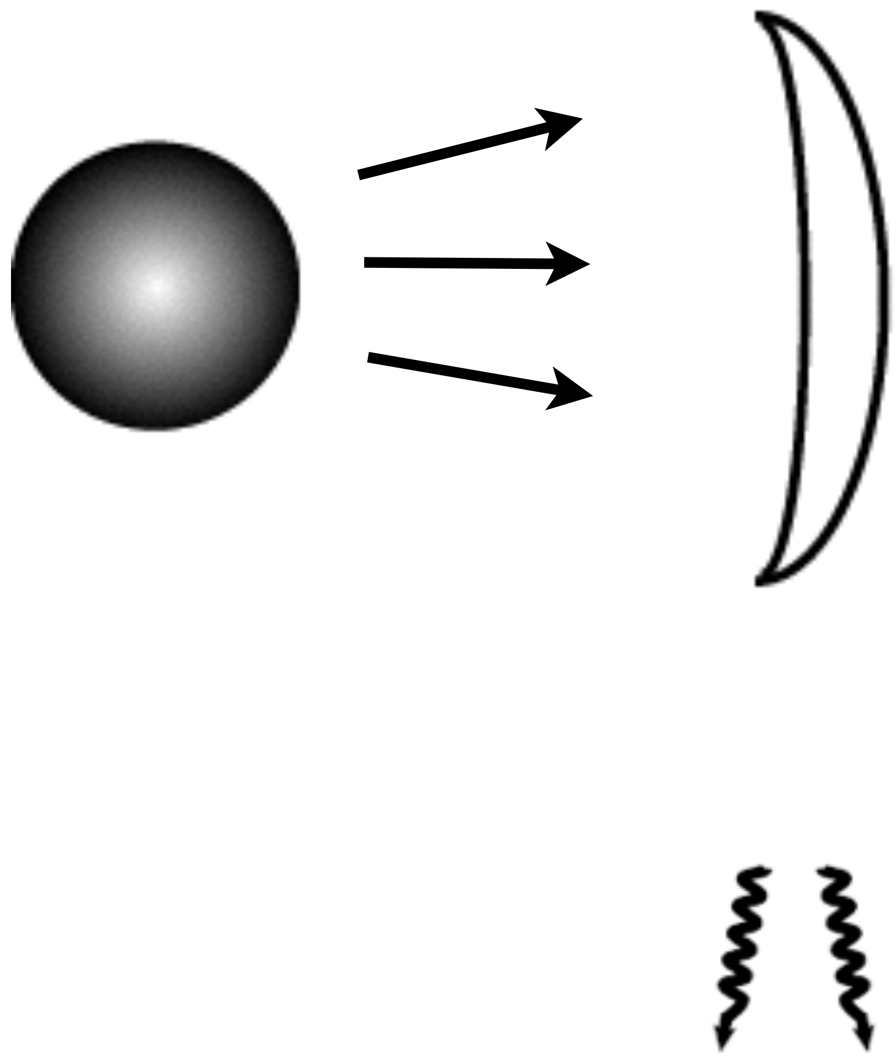

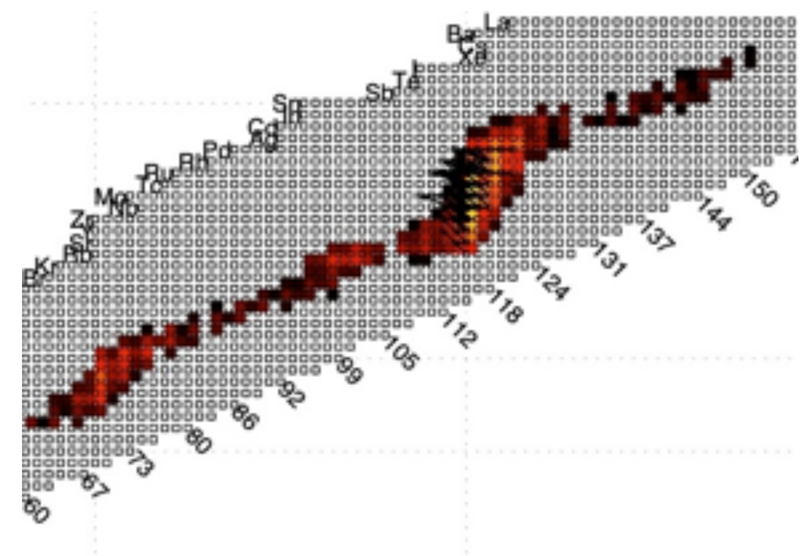

- composition: nuclear heating

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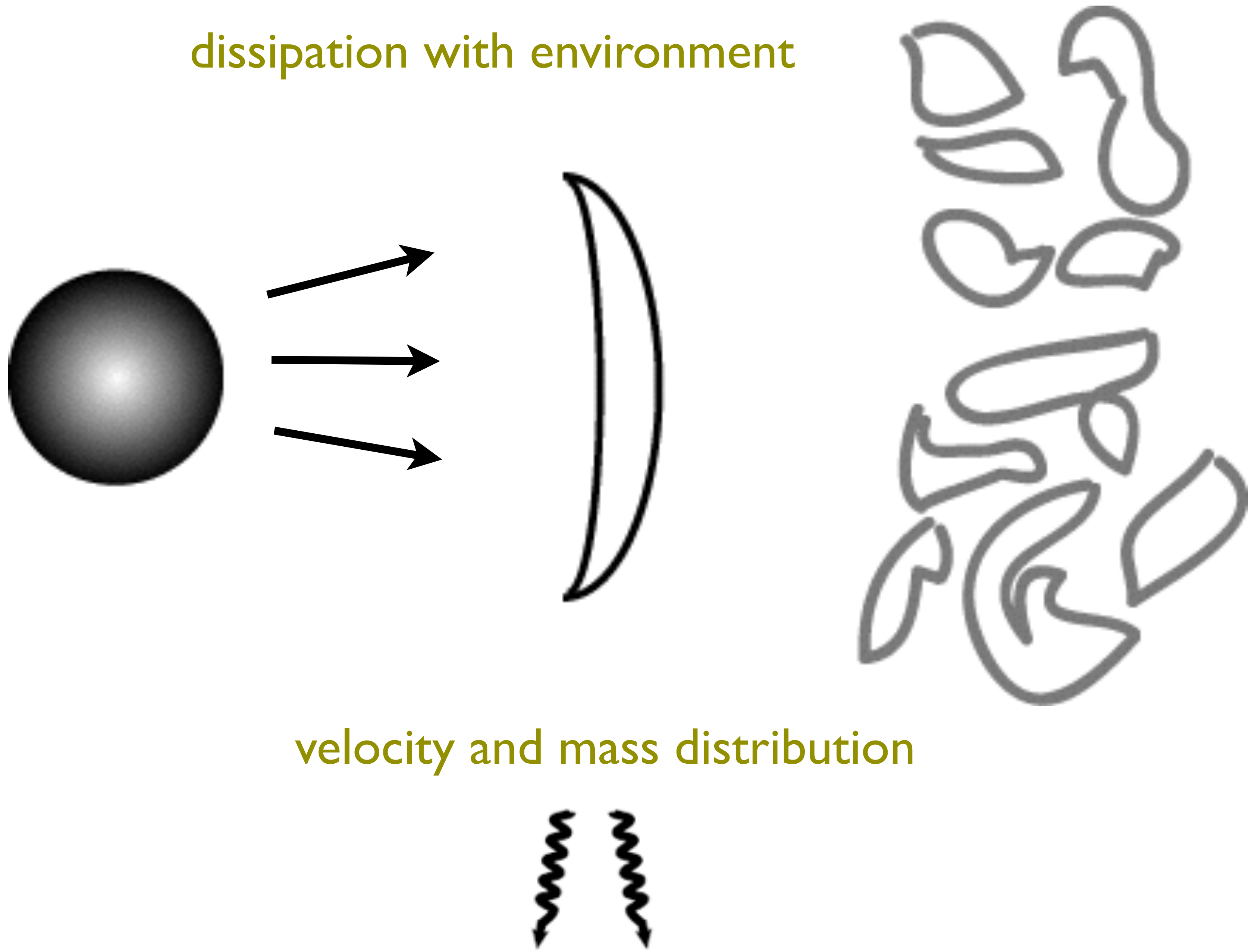

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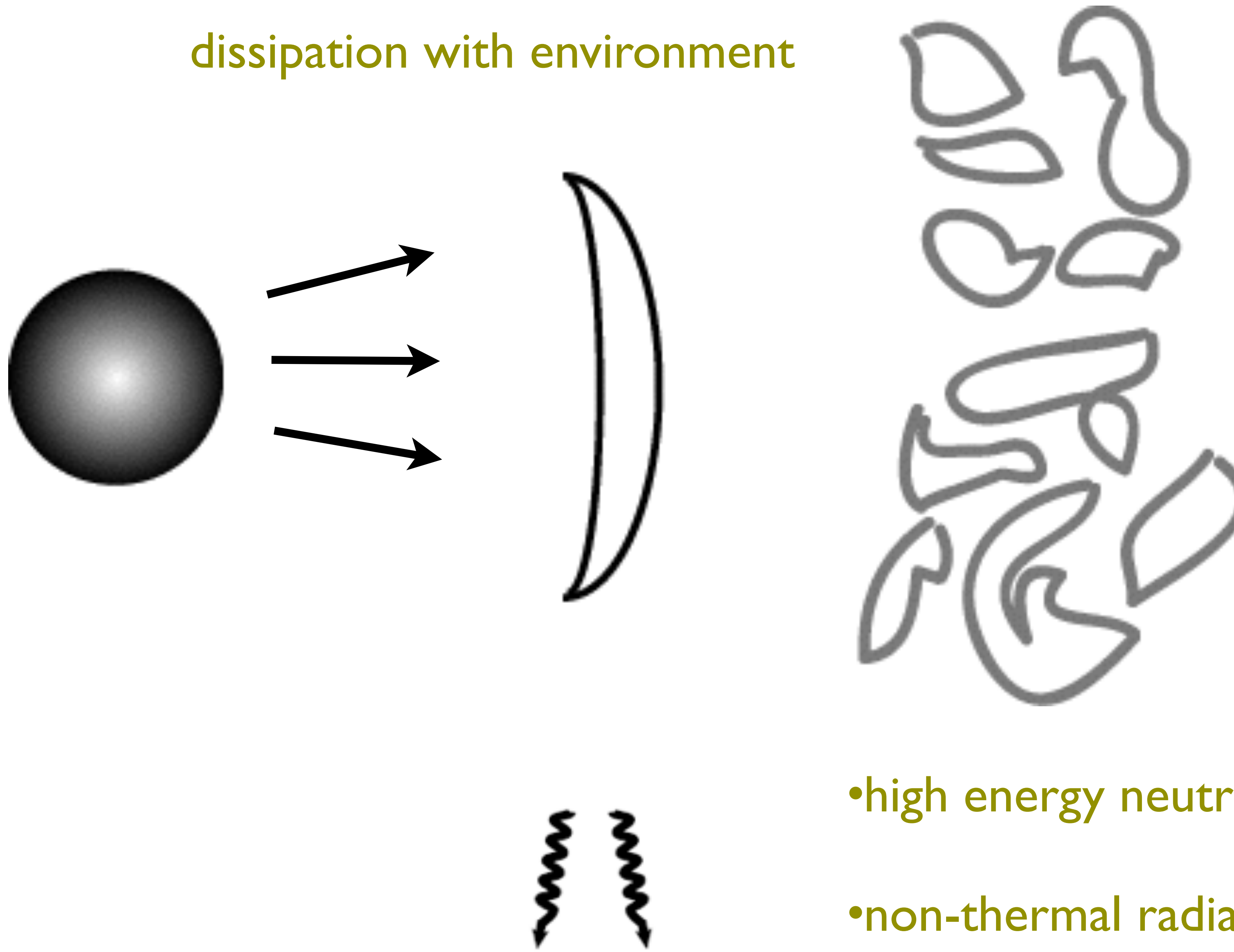


•high energy neutrinos

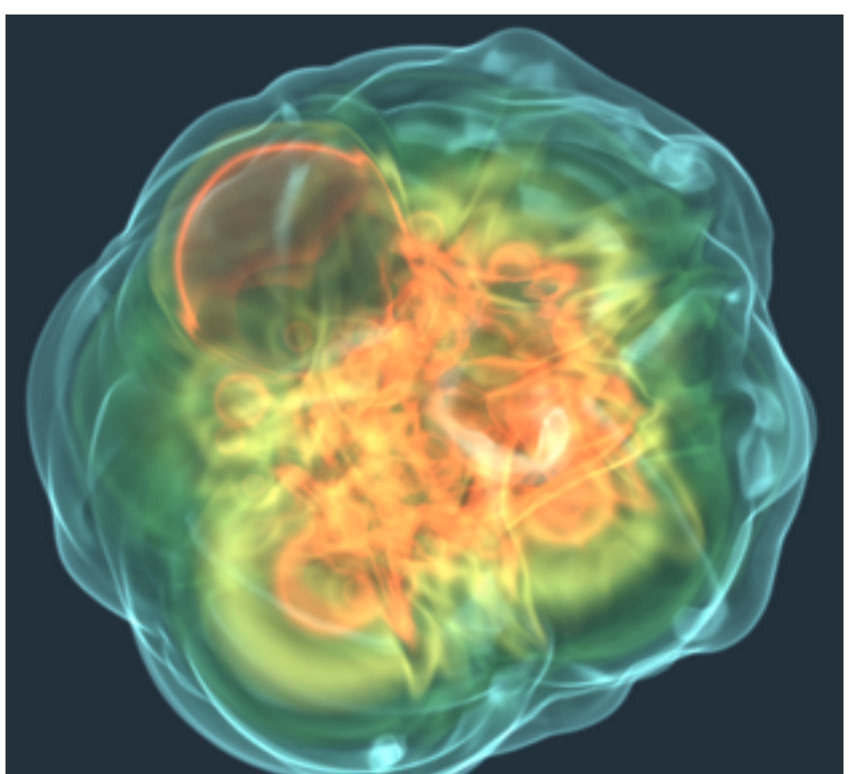
•non-thermal radiation

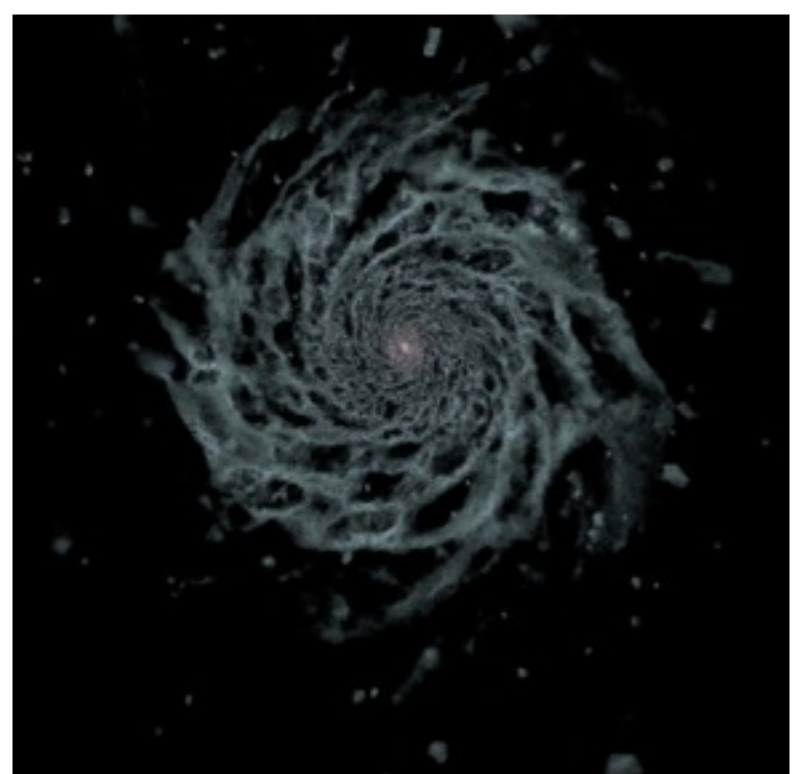
•cosmic rays

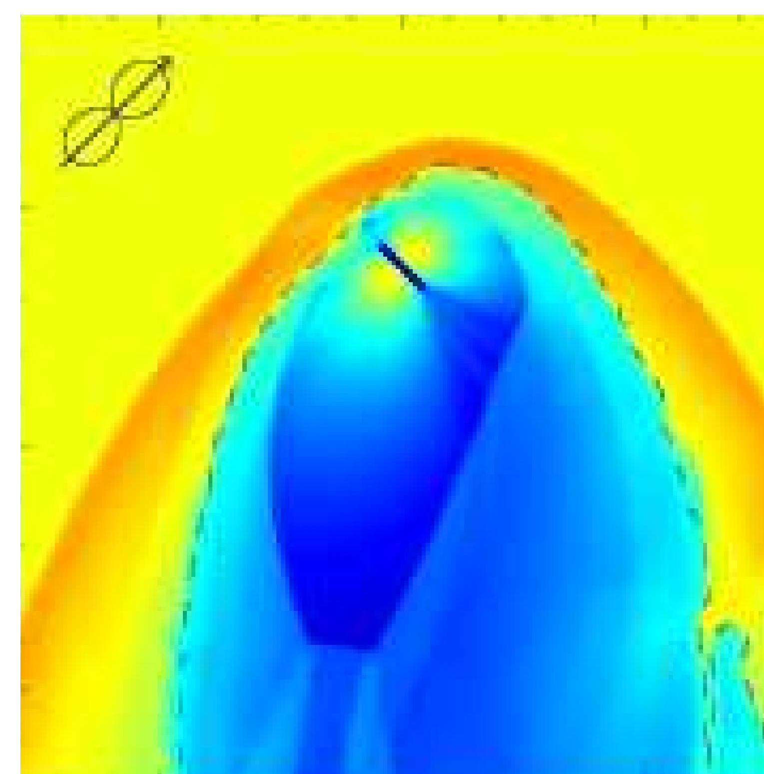
Non-Thermal Optical Transients

- trans-relativistic, mildy collimated outflows
- mildy relativistic ejecta
- relativistic jets

detailed models of the external medium +
detailed relativistic hydrodynamical models







Neutrinos and gravitational waves from core-collapse supernovae

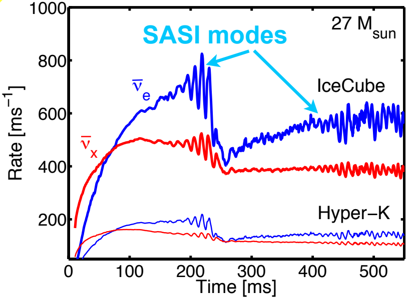
Philipp Moesta, Evan O'Connor, Erin O'Sullivan, Irene Tamborra, Meng-Ru Wu

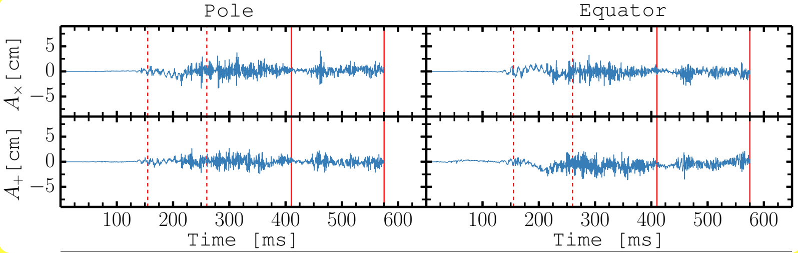
Kavli Summer Program in Astrophysics
Copenhagen, July 10-Aug. 18, 2017

What do we want to do?

Use neutrino and GW data from multi-D hydrodynamical simulations of core-collapse supernovae to learn about progenitor properties.

Learning about the neutron-star radius

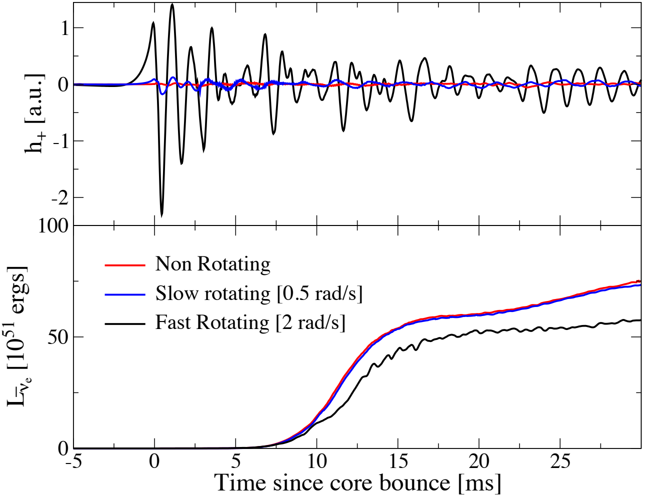




Neutrinos and GWs carry imprints of hydro instabilities and core bounce time.
By looking at SASI frequency, we can learn about the **neutron-star radius.**

Tamborra et al., PRL (2013), Tamborra et al., PRD (2014). Andresen et al., MNRAS (2017).

Learning about the core rotation



Neutrinos and GWs carry imprints of core rotation.
Neutrino luminosity and GWs exhibit oscillations in the fast rotating case.

Ott et al., PRD (2012).

Outlook

★ Gravitational waves and neutrinos are messengers of the supernova core properties

★ By combining the GW and nu signals, we will learn about

- Neutron star radius
- Supernova bounce time
- Core rotation

Methods

★ Extract gravitational wave and neutrino signals from multi-D hydro simulations.

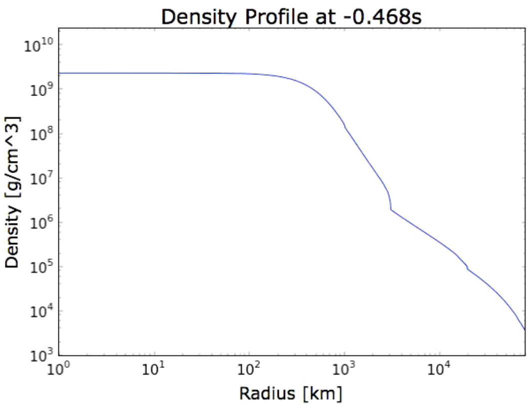
★ Simulate expected signals in Hyper-Kamiokande and Advanced-LIGO.

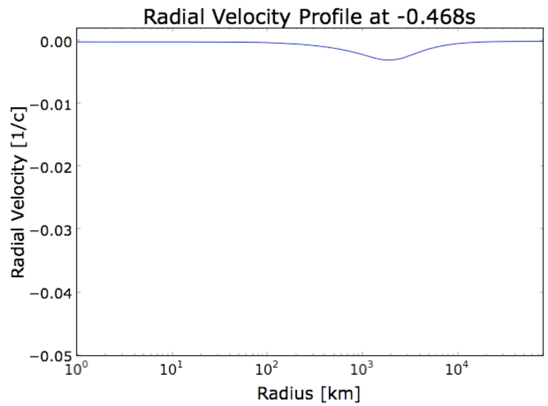
★ Look for correlations between neutrinos and gravitational waves.

★ Forecast determinability of progenitor properties.

#9: Predicting Black Hole Remnant masses from Failed Supernovae

Black holes form in failed core-collapse supernovae, or 'un-novae' – there is no bright optical display





In a failed supernovae…

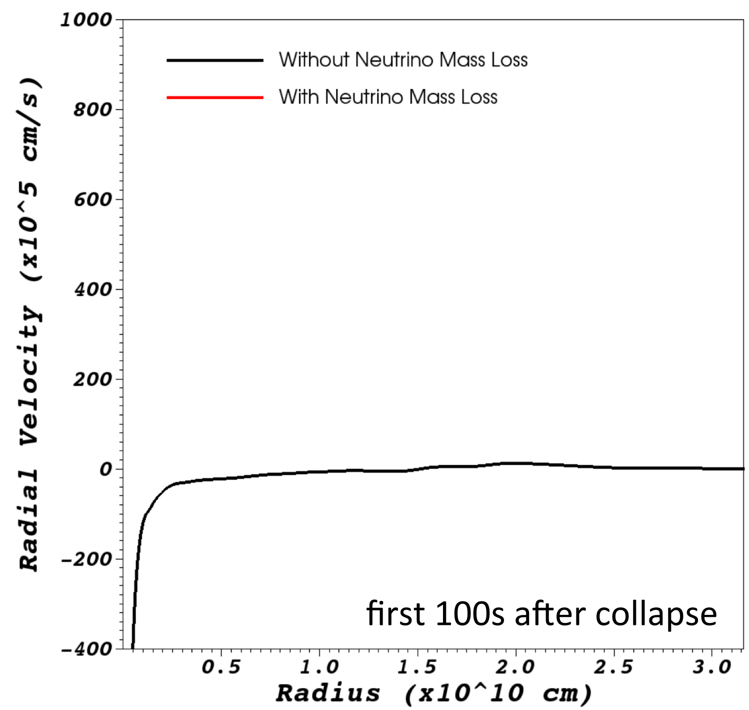
- typical lifetimes of neutron star are ~1 – few seconds
- but depends on equation of state
- hot neutron star radiates neutrinos

Black hole mass is bound by two limits:

- Maximum neutron star mass ~2-3Msun
- Presupernova mass of the star set by mass loss & binary interactions

Recent work by Lovegrove & Woosley (2013), building on work from Nadezhin (1980) reveal a mechanism to eject the outer layers (hydrogen shell) following a failed supernova

Crucial to predicting the final black hole remnant mass and connect to GW observations



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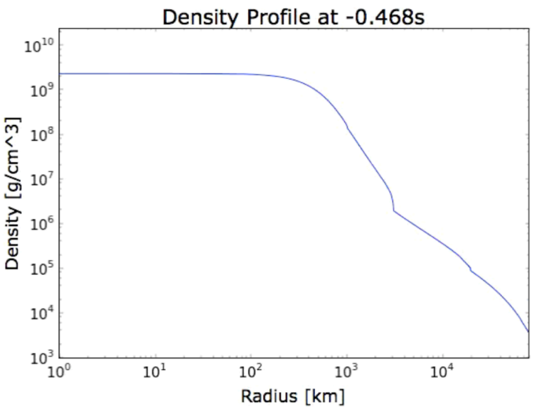

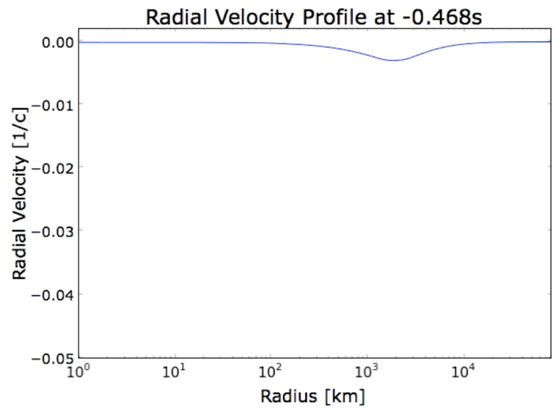

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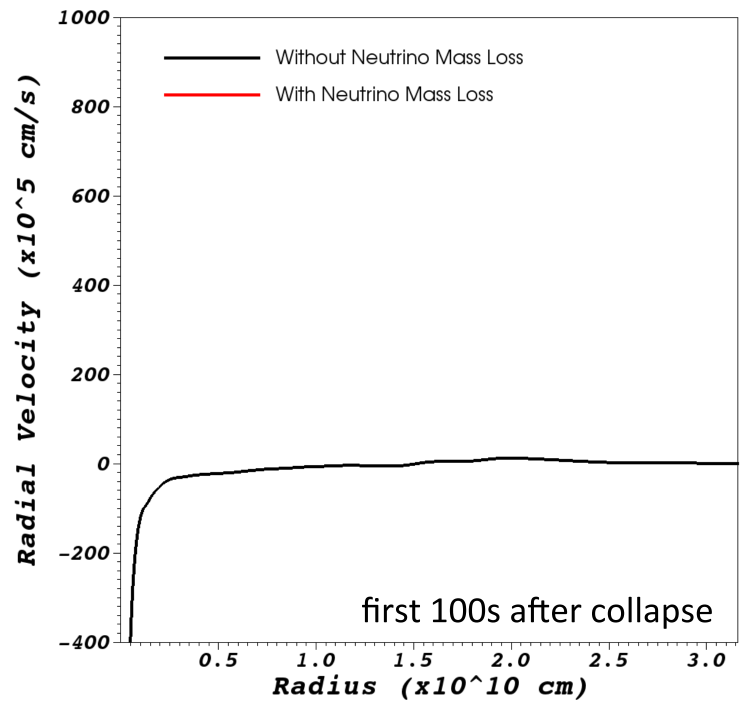
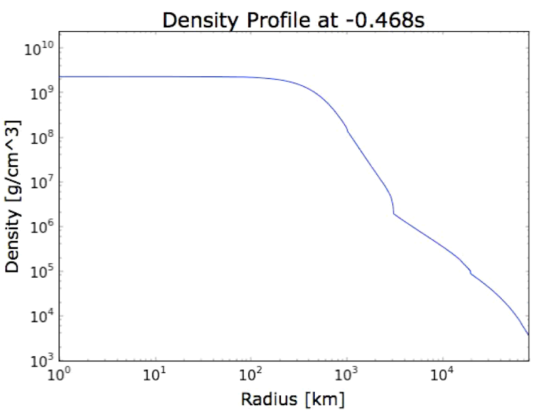
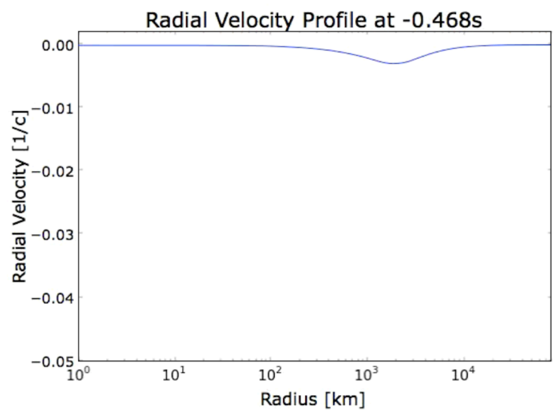


#9: Predicting Black Hole Remnant masses from Failed Supernovae

Black holes form in failed core-collapse supernovae, or 'un-novae' – there is no bright optical display





In a failed supernovae…

- typical lifetimes of neutron star are ~1 – few seconds
- but depends on equation of state
- hot neutron star radiates neutrinos

Black hole mass is bound by two limits:

- Maximum neutron star mass ~2-3Msun
- Presupernova mass of the star set by mass loss & binary interactions

Recent work by Lovegrove & Woosley (2013), building on work from Nadezhin (1980) reveal a mechanism to eject the outer layers (hydrogen shell) following a failed supernova

Crucial to predicting the final black hole remnant mass and connect to GW observations

Methods:
Will use GR1D, FLASH, and SNEC:
- realistic neutrino loss
- dynamic shock development
- eventual envelope ejection

Explore full range of progenitors and equations of state to make definitive predictions on which stars can eject their hydrogen envelopes in an un-novae

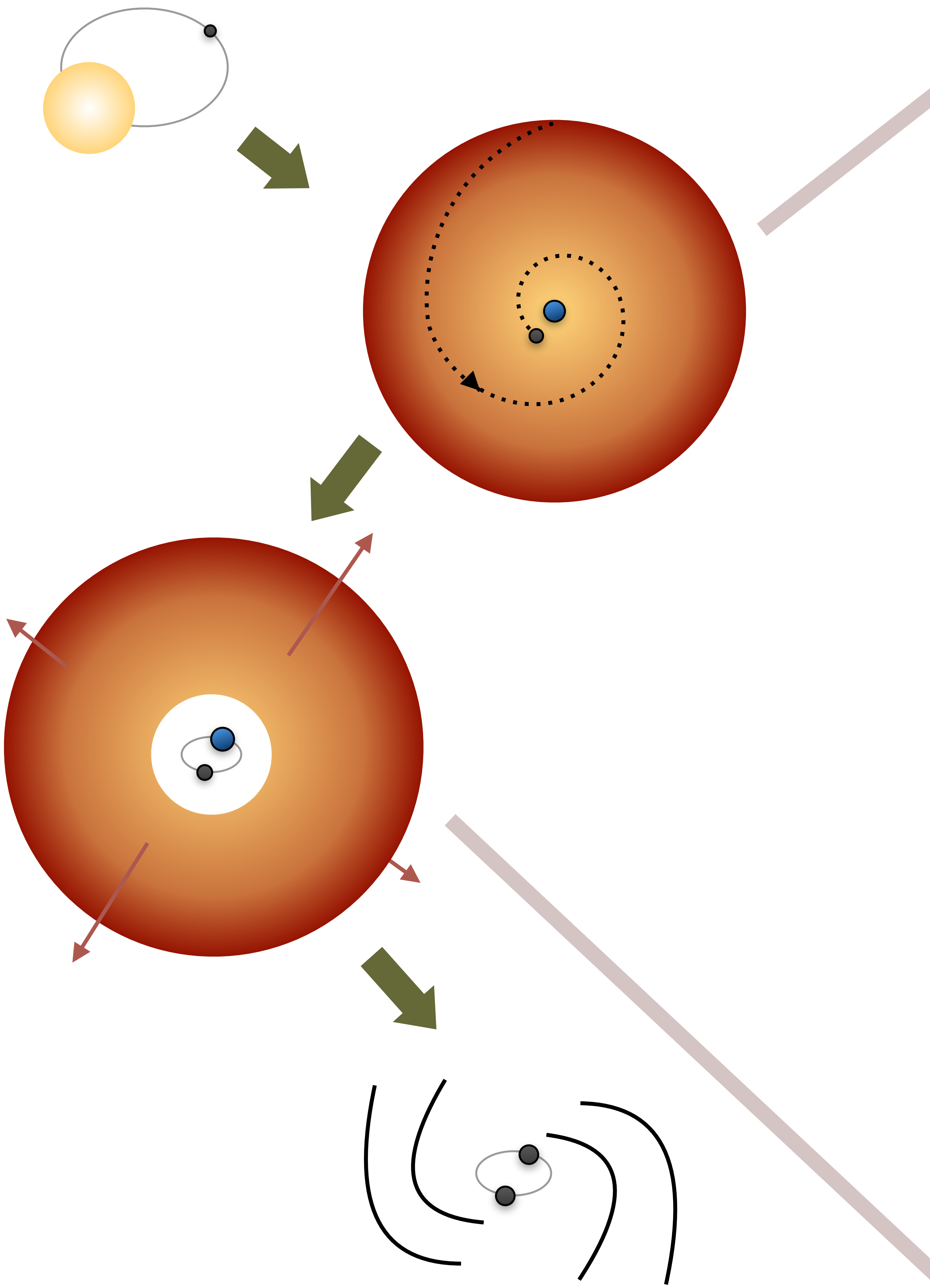
Project #10 - Short GRBs as EM counterparts of GW: formation channel studies

Carl Haster, Daniel Holz, Alex Nielsen, Silvia Piranomonte

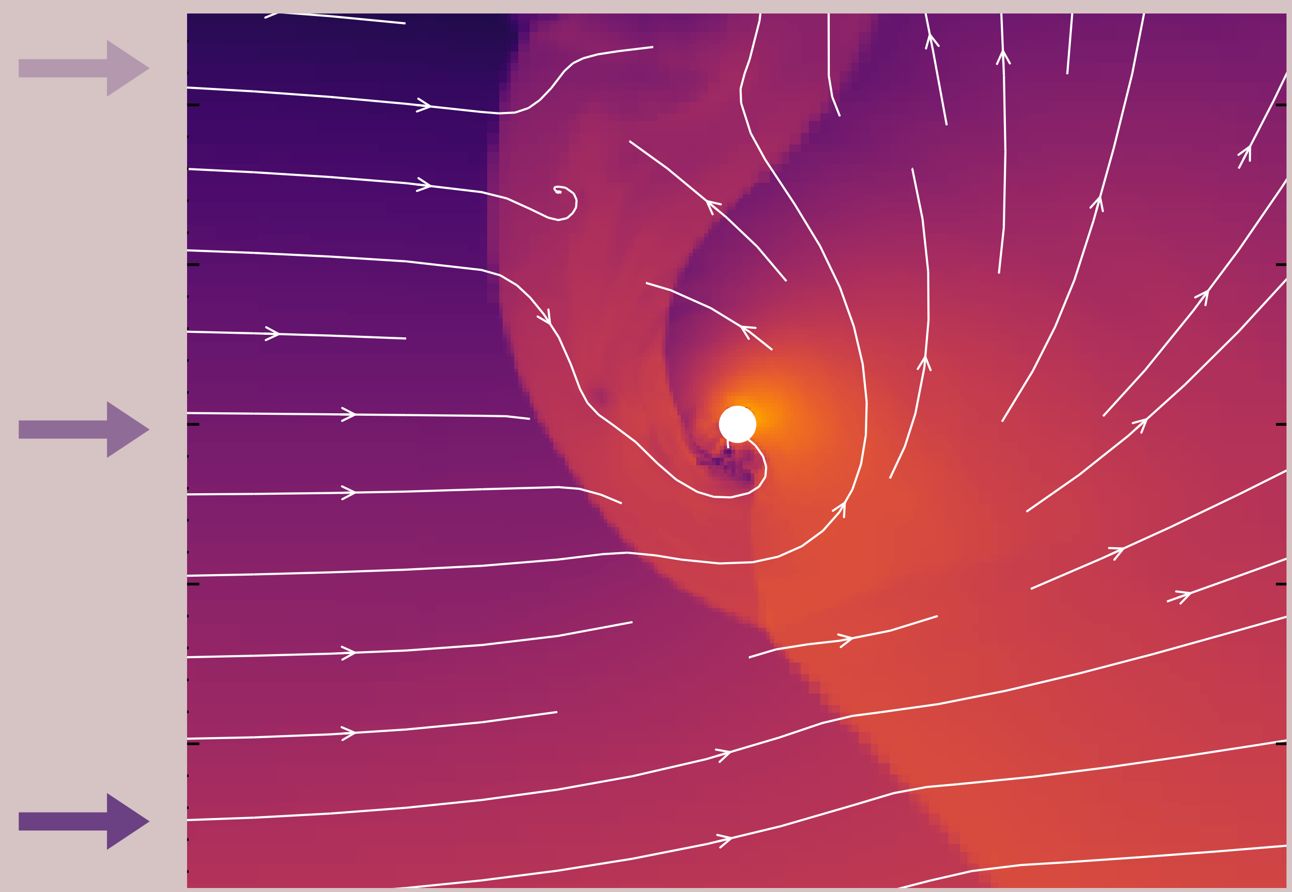
- GRBs most luminous EM sources; BBHs most luminous GW sources. Are they connected?!
- Short GRBs are thought to result from BNS and/or NSBH progenitor
  - what is currently known about SGRBs and Kilonovae environments?
- What can joint observations constrain about formation environments of SGRBs?
  - Smoking gun observables?
- Limits on formation from current rate estimates
  - Both observational rates and from population synthesis

Local simulations of common envelope: the bridge to binary population modeling

Morgan MacLeod, Tassos Fragos, Ilya Mandell, Enrico Ramirez-Ruiz



Goal: build a grid of FLASH simulations of local conditions around objects in CE



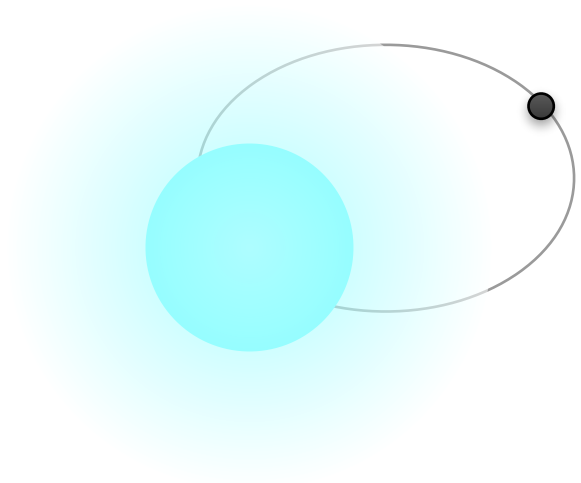
Measure: Drag forces and accretion rates as a function of flow conditions

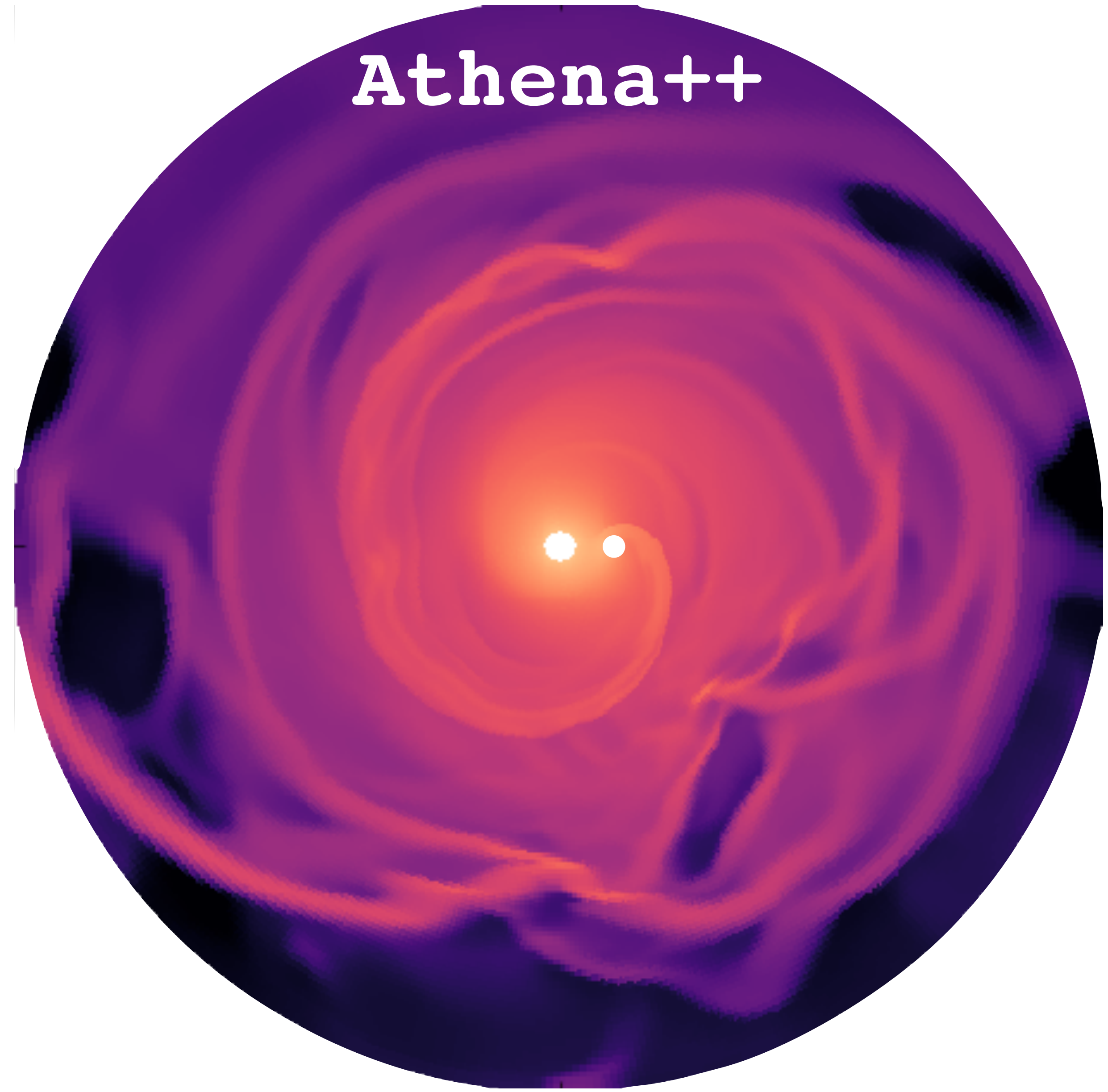
Application: Modeling the transformation of general binary populations through the CE phase of their evolution

Modeling wind capture in HMXBs:

Toward understanding electromagnetic emission from precursors to the LIGO sources

Morgan MacLeod, Tassos Fragos





NGC 300 X-1, IC 10 X-1:
two x-ray binaries which appear to be precursors of LIGO-like sources

- 20-30 solar mass BH + WR star
- Wind from WR star is captured by the BH -> x-ray emission

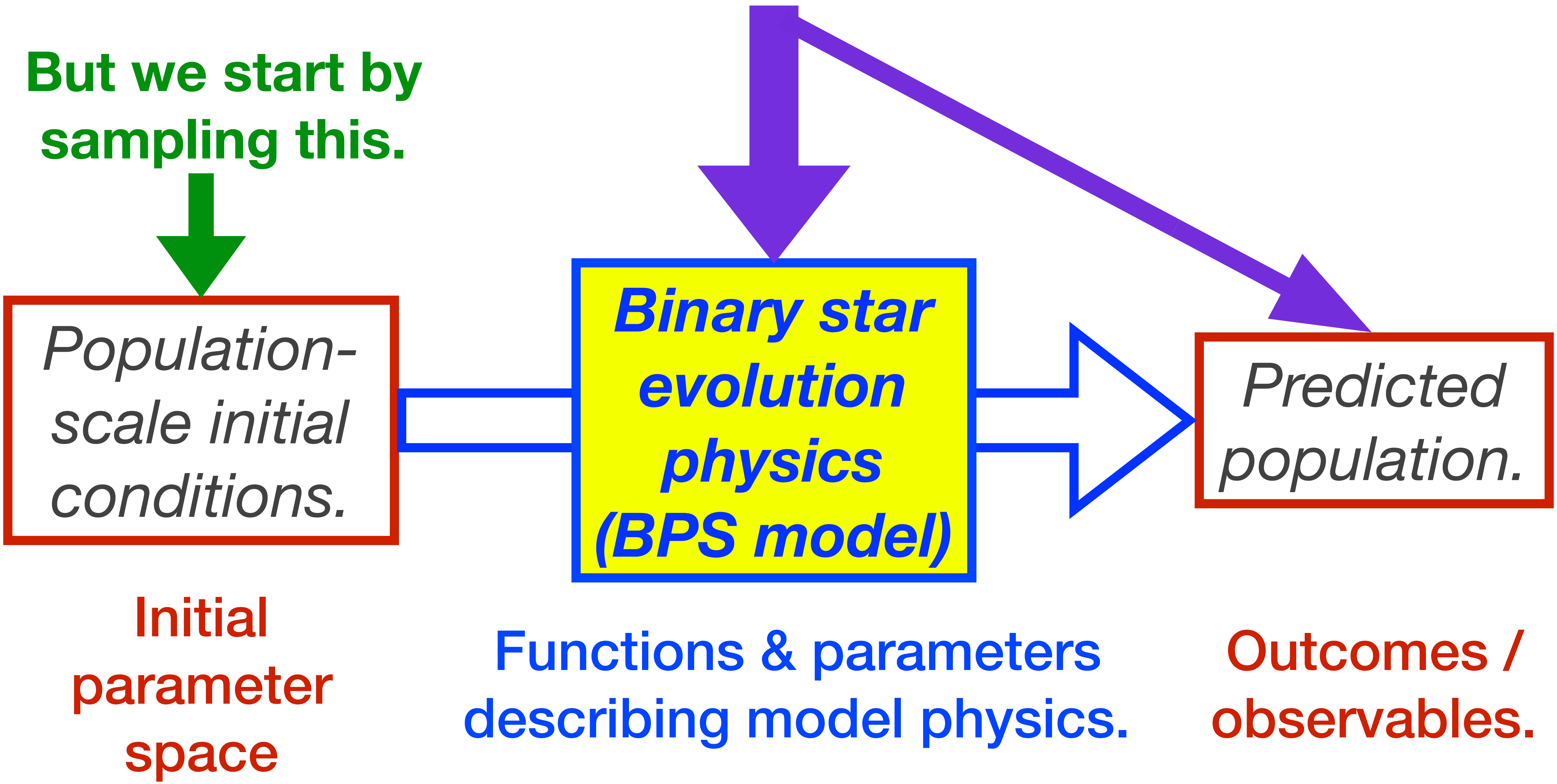
(e.g. Bulik 2011)

Goal: model the wind flows in observed HMXB systems toward understanding their evolution and the associated x-ray emission
Measure: rates of mass accretion and angular momentum evolution (torques)

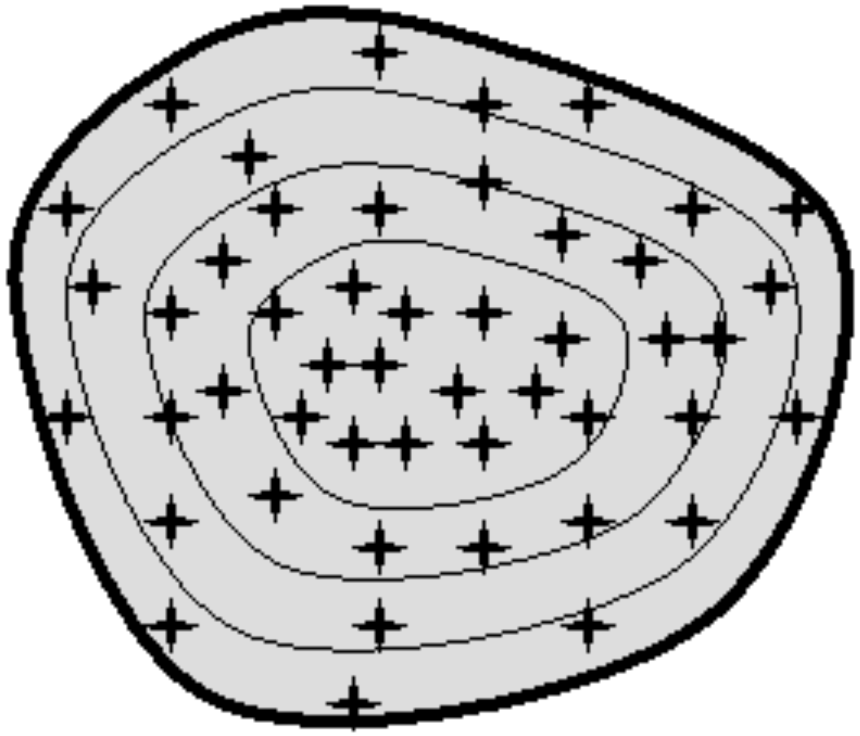
Efficiently sampling the initial parameter space for BPS

Ilya Mandel, Stephen Justham, Tassos Fragos

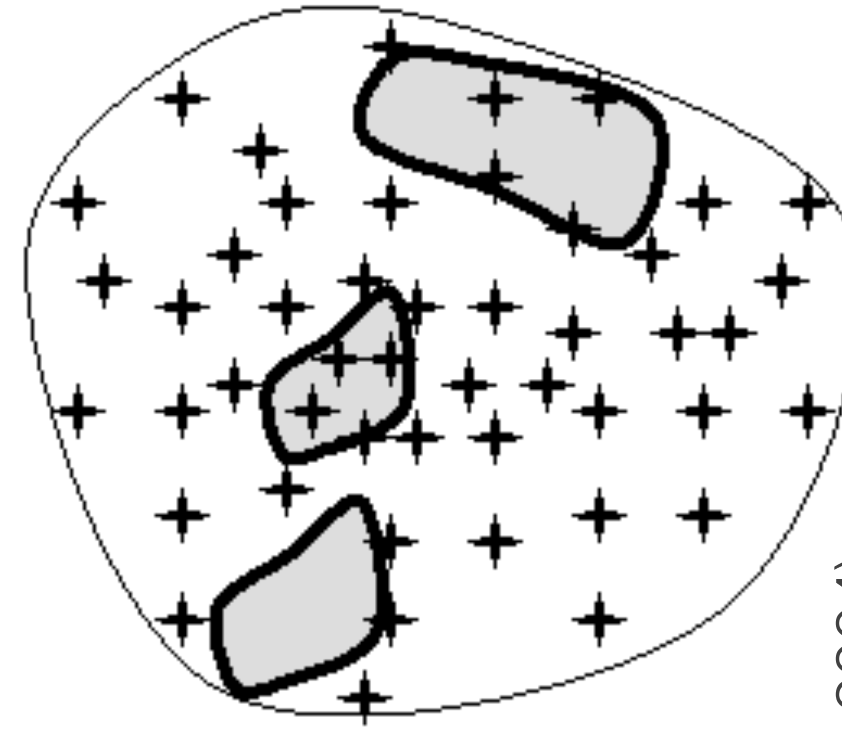
We normally care about constraining the physics of reality (or making population predictions for given assumptions).



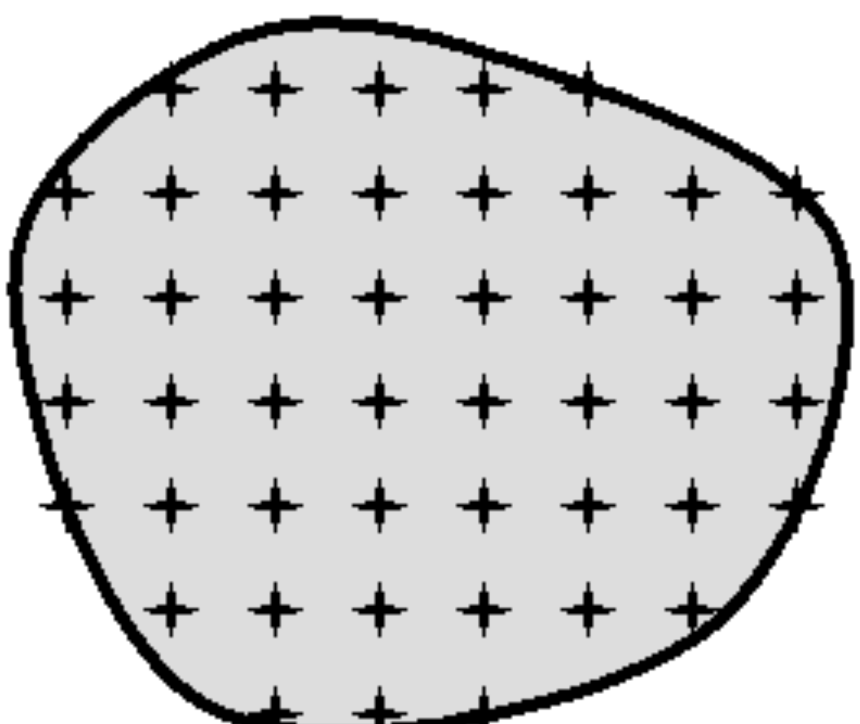
Two standard ways of sampling initial conditions



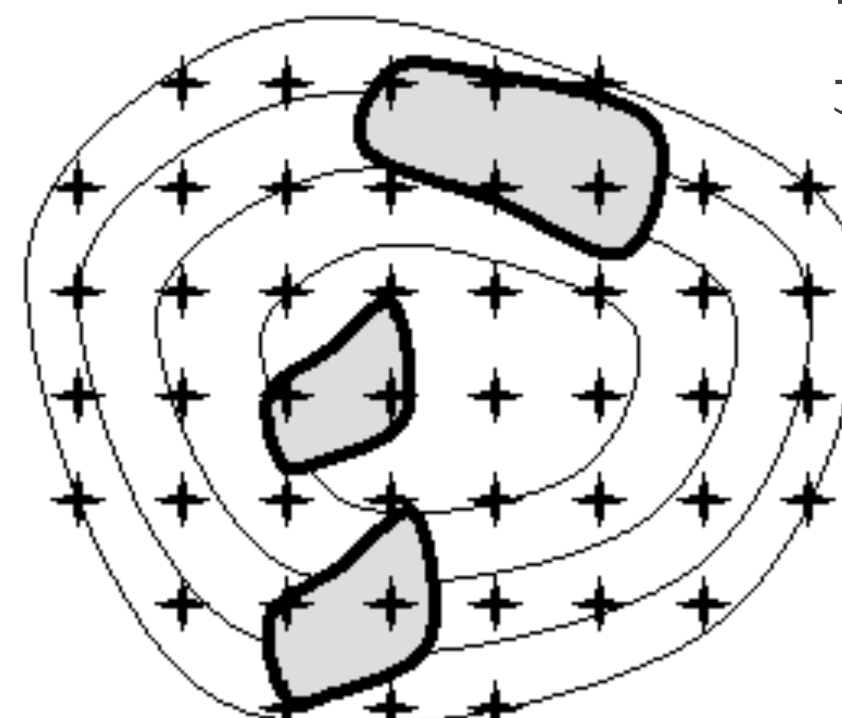
Typically: apply formation probability in initial sampling.



INITIAL CONDITIONS → EVOLUTION → OUTCOMES



Or: ignore formation probability when exploring outcomes; later weight outcomes by formation probabilities.



(Justham, PhD, 2004)

Neither obviously optimal or especially sophisticated…

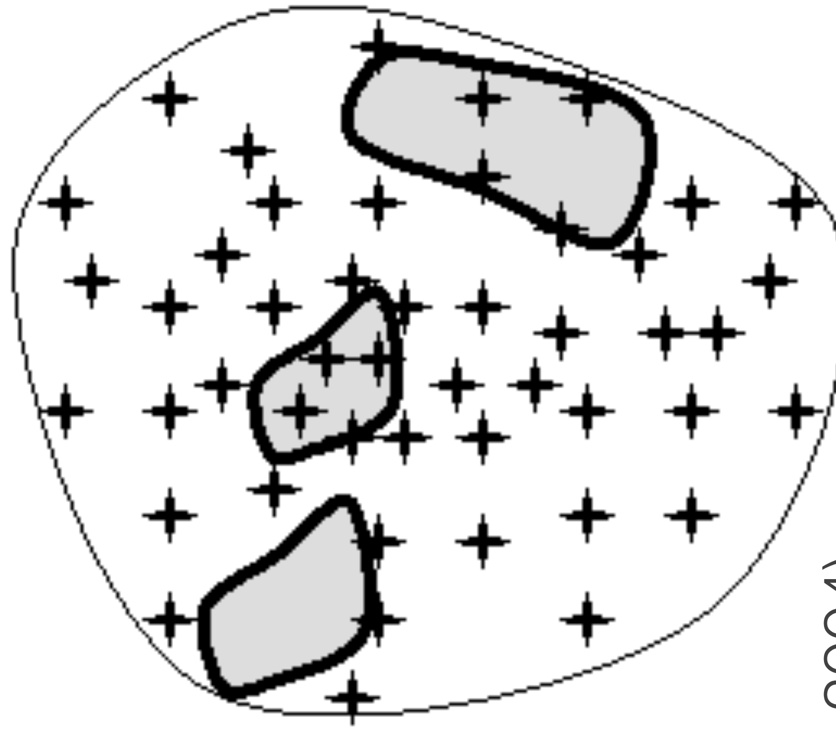
Project aims

Quantify how choices of sampling method influence:

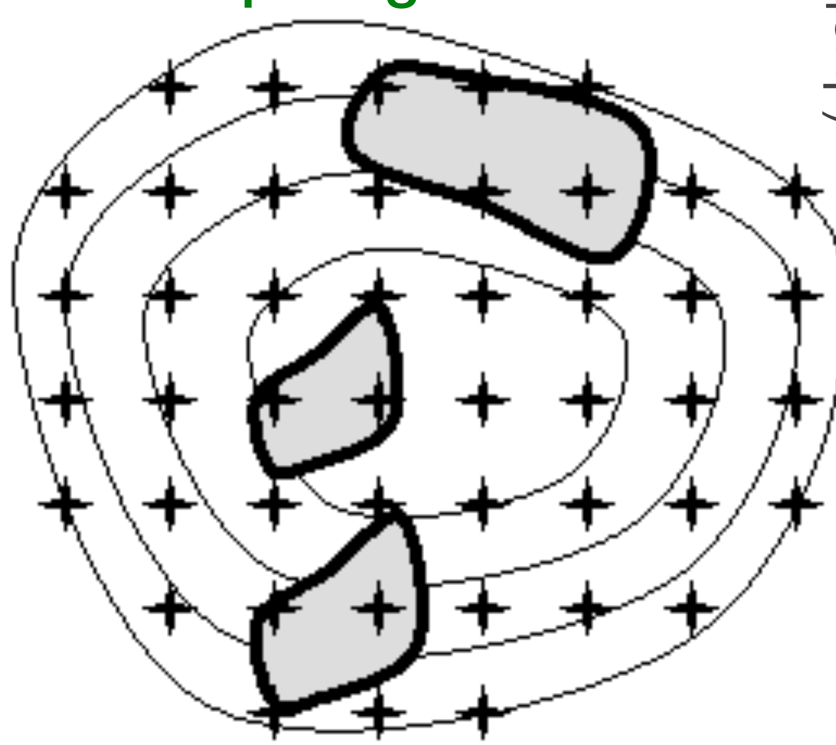
— computational efficiency
— sampling noise in predictions
& limits on statistical uncertainty
— ability to constrain model space.

Investigate more modern sampling methods.

Might be pursued in a range of ways, from experimentally comparing methods to more theoretical study.



Sampling noise in predictions often overlooked when comparing models.

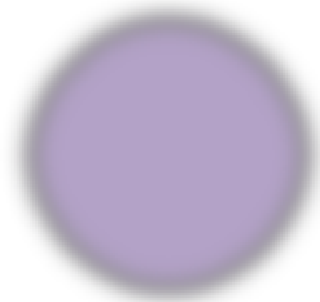


(Justham, PhD, 2004)

Evolution and fate of massive stars: LBVs & binary mergers.

Philipp Podsiadlowski & Stephen Justham

The LIGO detections have increased the focus on potential progenitors of merging ≈30 $M_\odot$ BHs.

$96.2\ M_\odot$  **ZAMS**  $60.2\ M_\odot$

Initial masses from one Belczynski et al. (2016) route to GW150914 via isolated binary evolution.

But our understanding of even the *isolated* evolution of stars with such high masses is currently confused…

Standard idea: LBVs are stars $\gtrsim 40 M_\odot$, losing mass in outbursts.

(Significant LBV mass loss might even suppress their participation in the CE channel to BH-BH mergers.)

But: the *observed* LBV population appears inconsistent with that.

(Debated, but see, e.g., Smith & Tombleson 2015; Smith 2016.)

Suggested in those papers that:

The observed LBVs may be dominated by mergers (or runaway mass gainers).

If true, a significant puzzle to solve.

("LBV" is a term with unhelpfully diverse meanings. Here we don't mean such extreme events as the Great Eruption of Eta Carinae, but we're also interested in those. **A third potential project if you are also interested.**)

At least two potential related projects:

If the observed LBVs are dominated by mergers (or runaway mass gainers), how could we explain that?

Are mergers somehow more susceptible to outbursts than single stars of the same mass?

Perhaps mergers/gainers spend significantly more time in the LBV-unstable region?

Some LBV-mass stars are expected to later produce pair-instability SNe. What is the merger contribution to PISNe?

Several interesting possibilities, including less restrictive Z-dependence than single-star PISNe.

See Justham, Podsiadlowski & Vink (2014) for more.

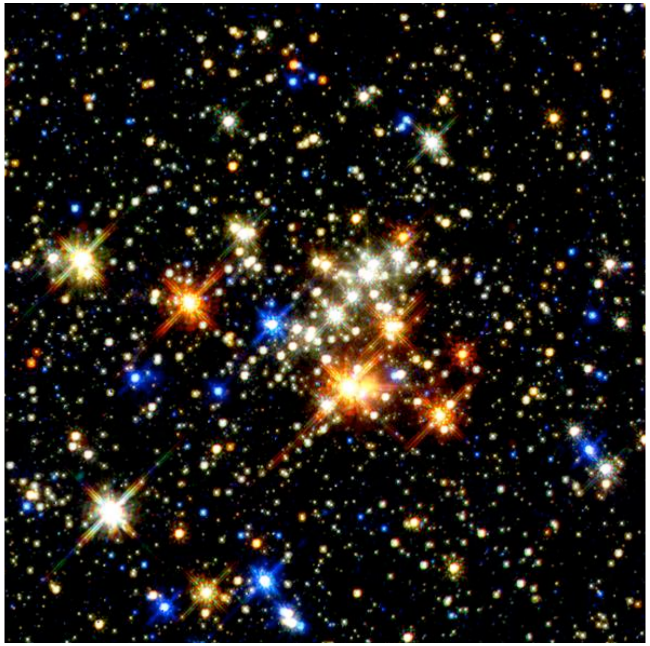
(Especially the HR diagrams for post-merger LBVs.)

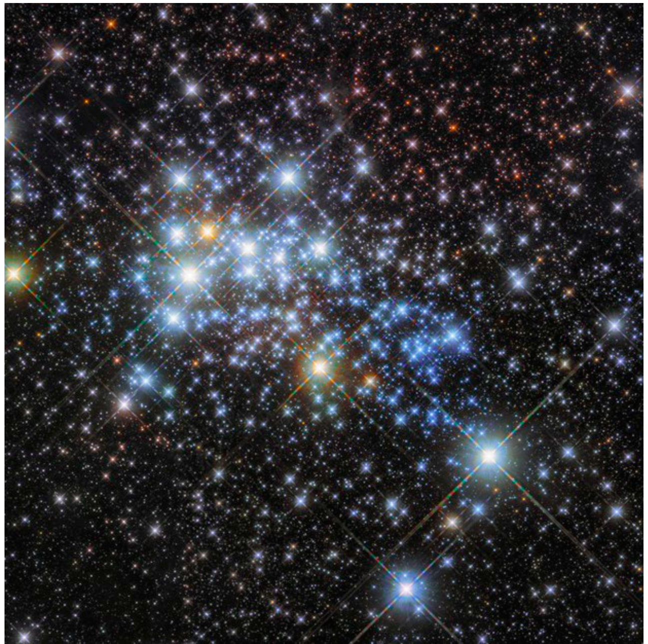
(Especially section 6.3.)

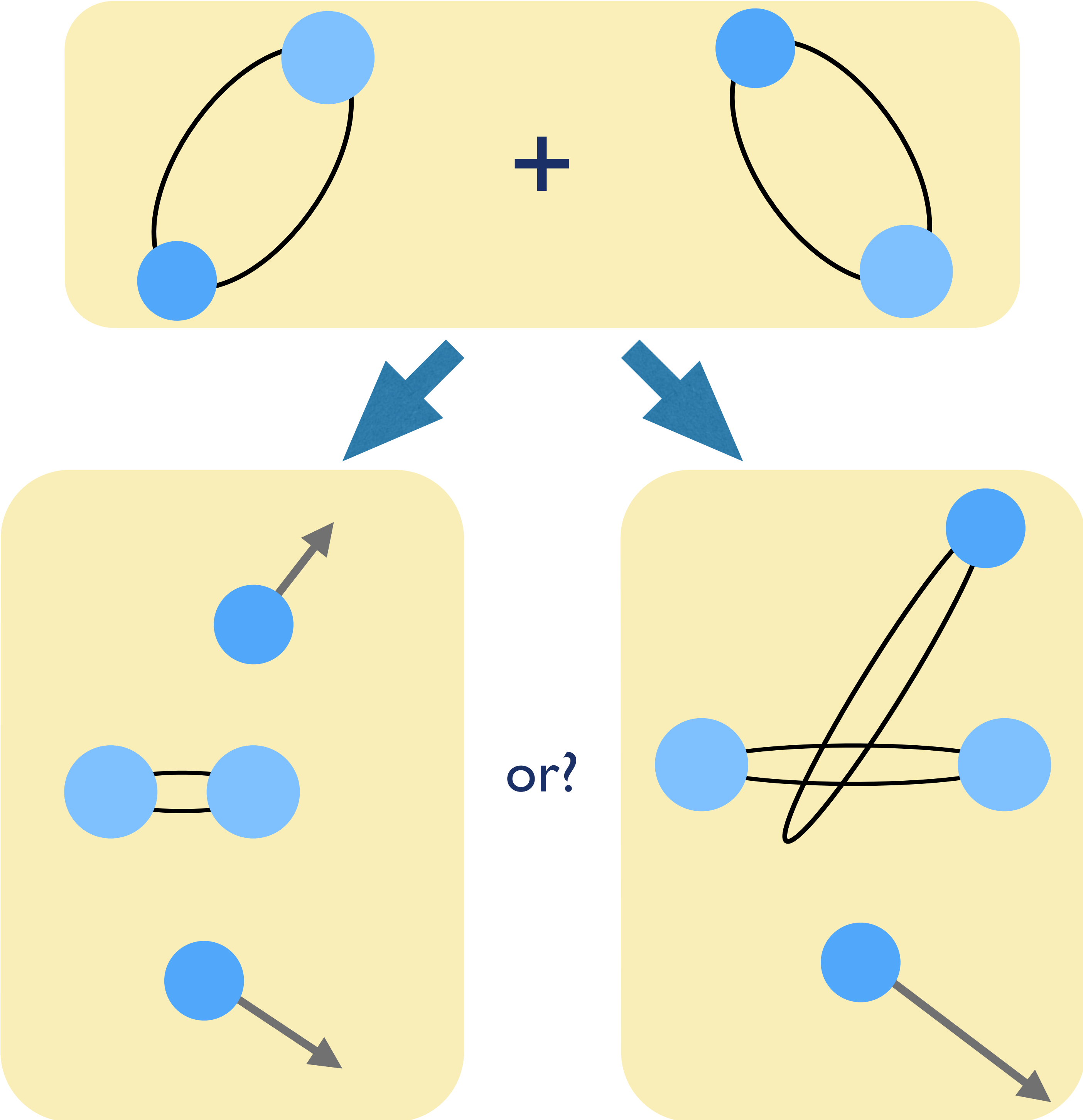
The effects of birth environments on massive binaries

Ross Church & Melvyn B. Davies (Lund)
Ilya Mandel (Birmingham)
Cole Miller (Maryland)
Carl Rodriguez (MIT)

The idea







Quantify *rates* & *importance* for BHB formation

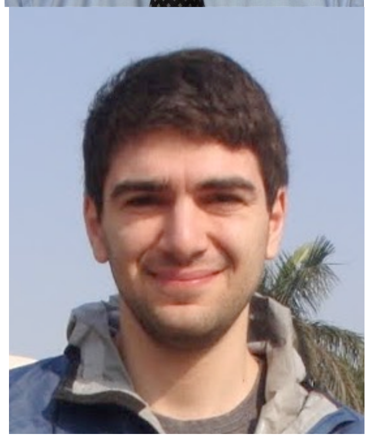
The team

Ross Church
(Lund)

Cole Miller
(Maryland)

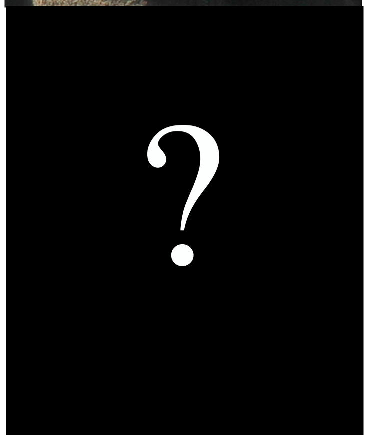
Melvyn B. Davies
(Lund)

Carl Rodriguez
(MIT)



Ilya Mandel
(Birmingham)

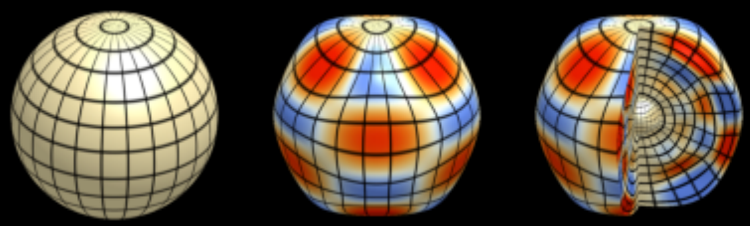
You!



Binary-Binary interactions with General Relativistic effects included in the N-body equation-of-motion

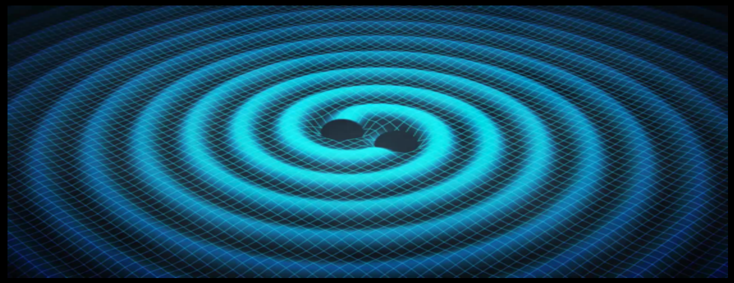
Carl-Johan Haster, Carl Rodriguez, Enrico Ramirez-Ruiz, Johan Samsing

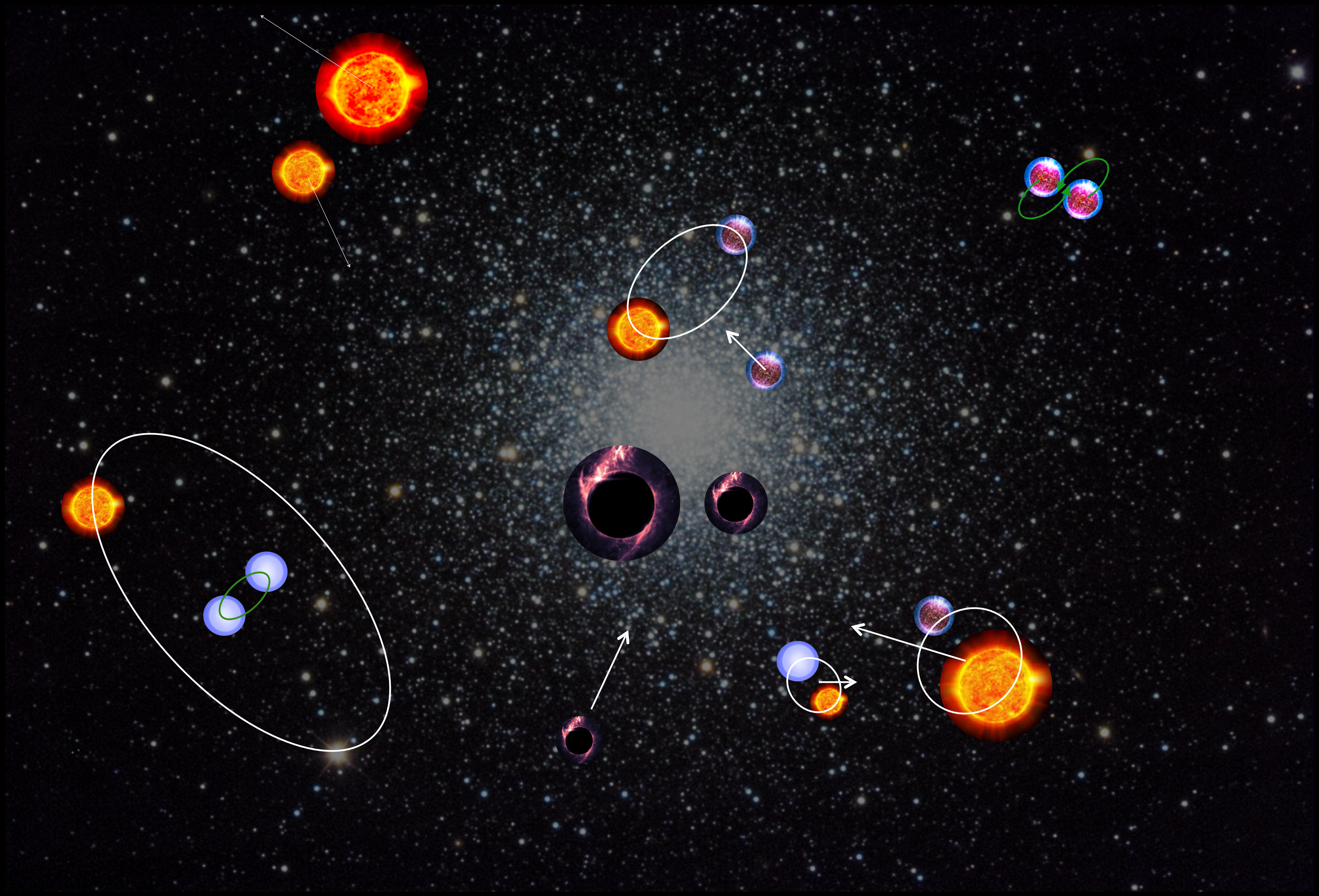
Tidal Oscillations



Dynamics

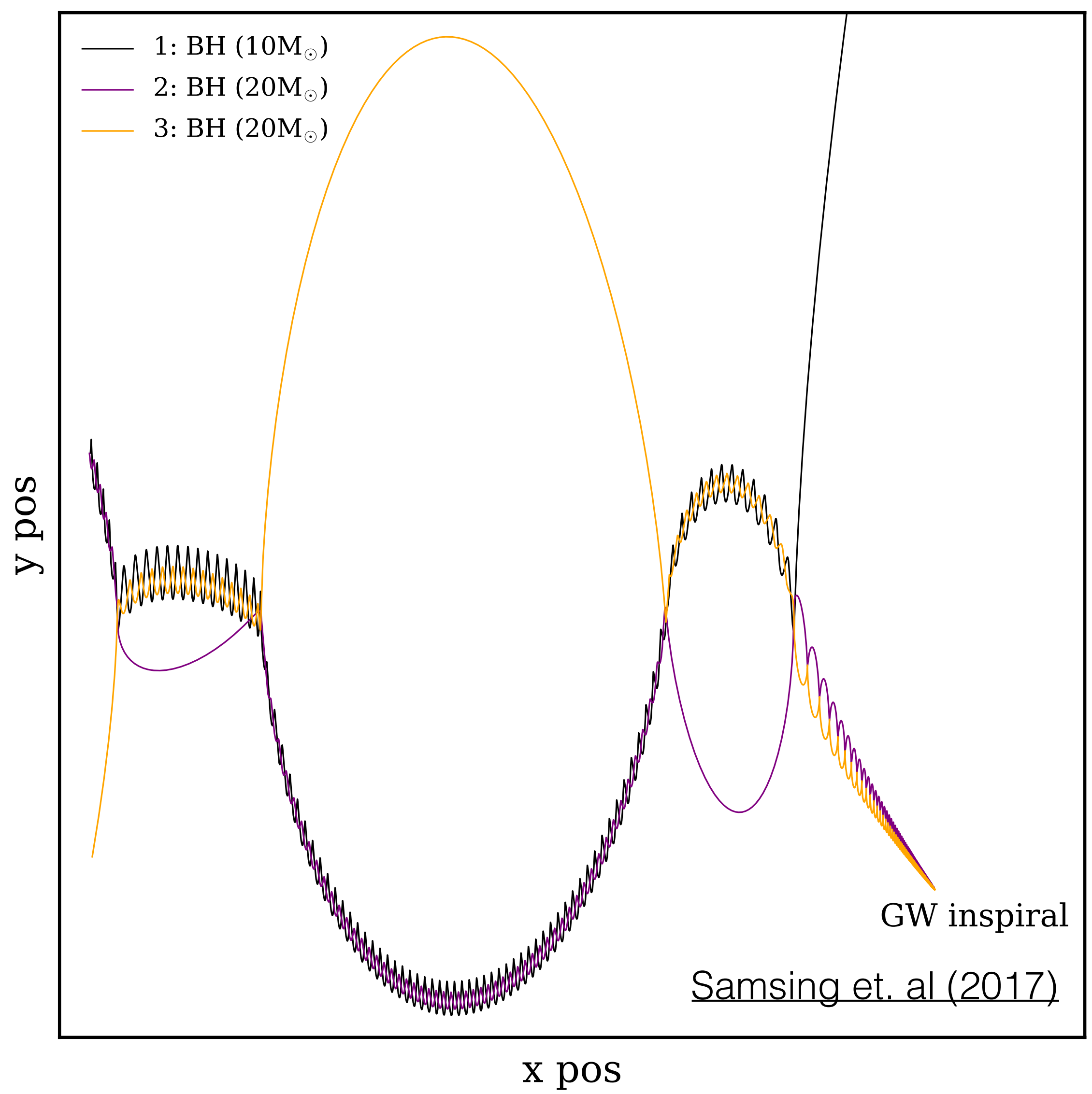
Gravitational Waves



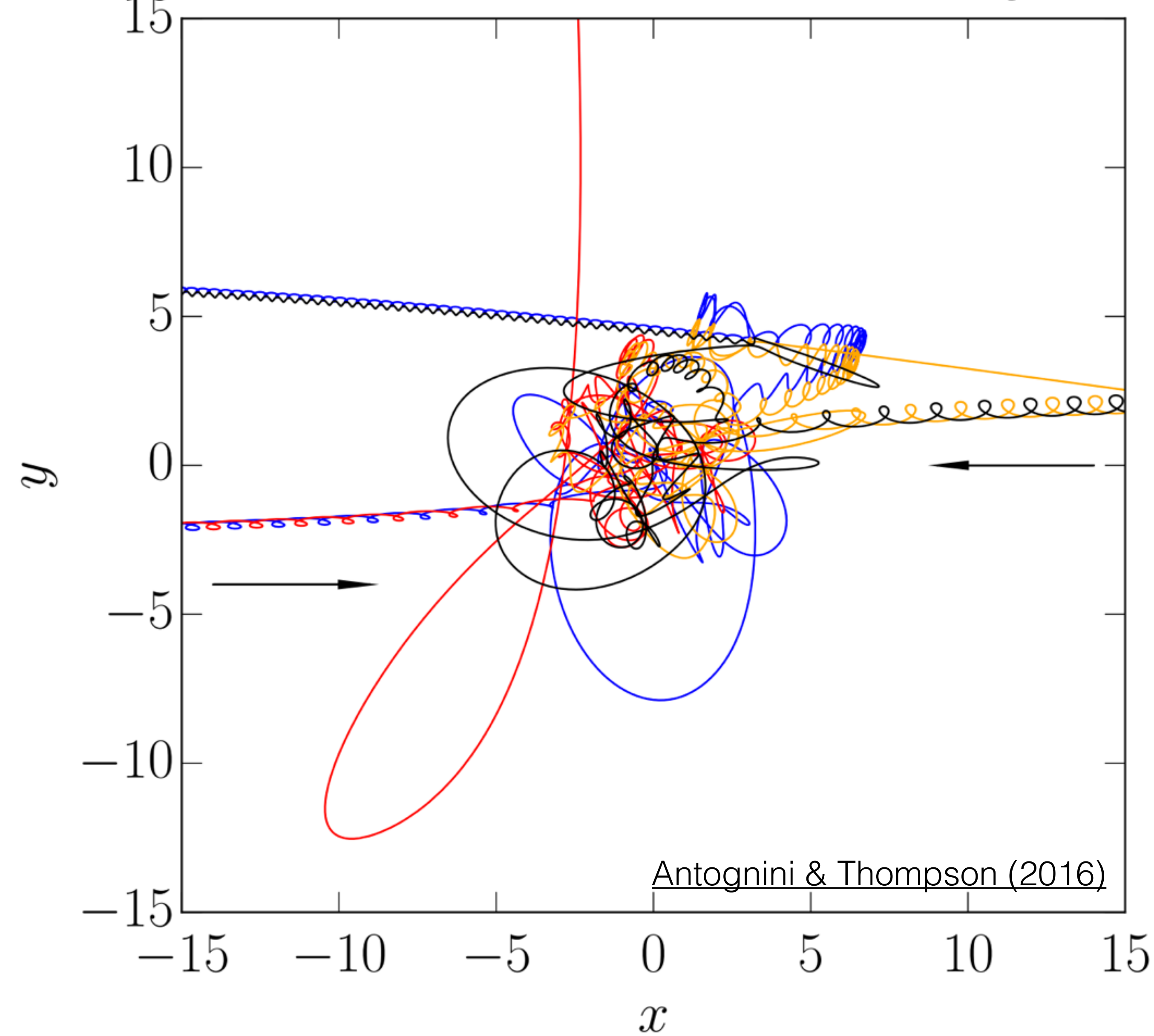


Formation of High Eccentricity GW Mergers

Binary-Single Scattering



Binary-Binary Scattering

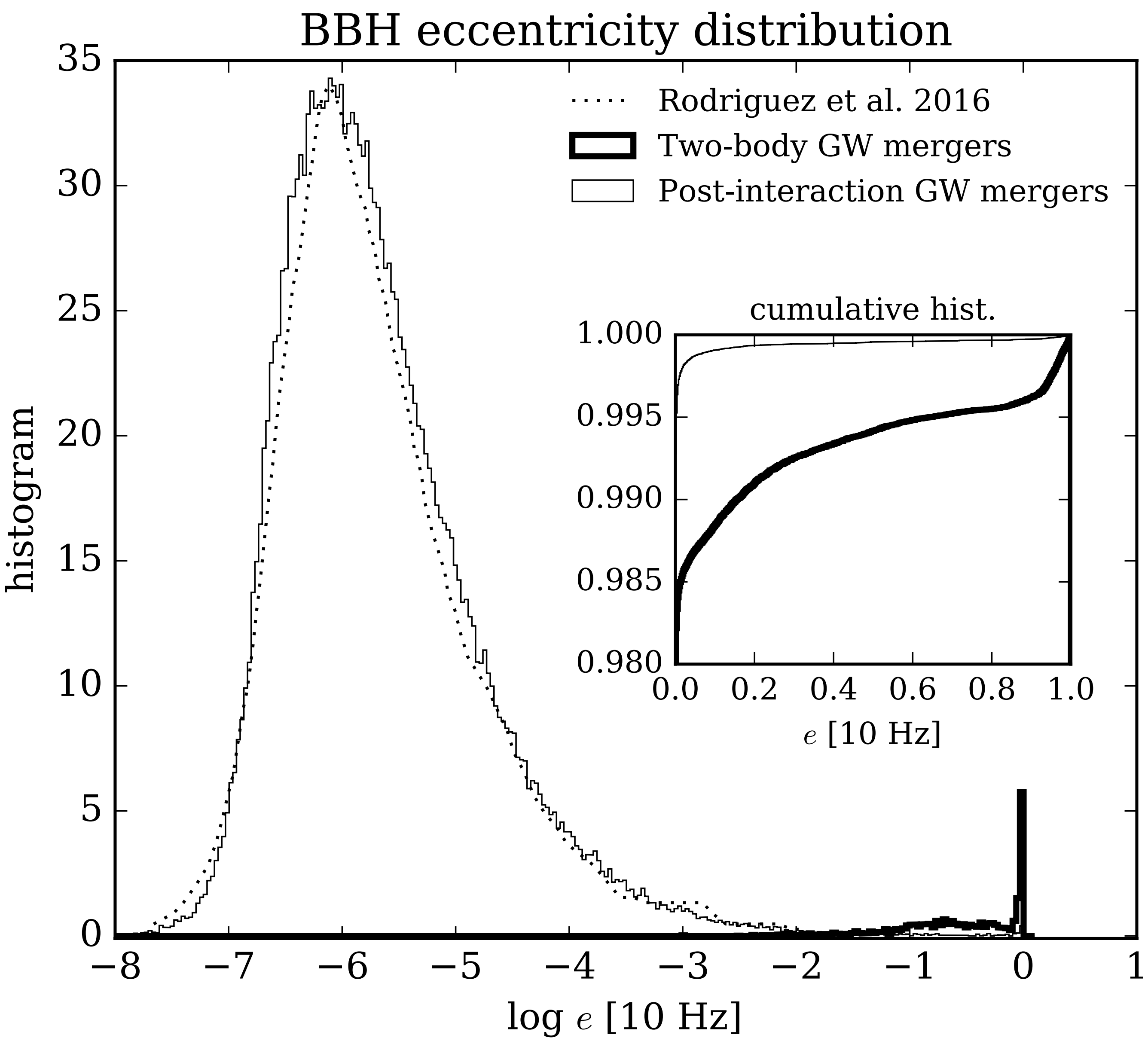


(General Relativistic)

(Newtonian Gravity)

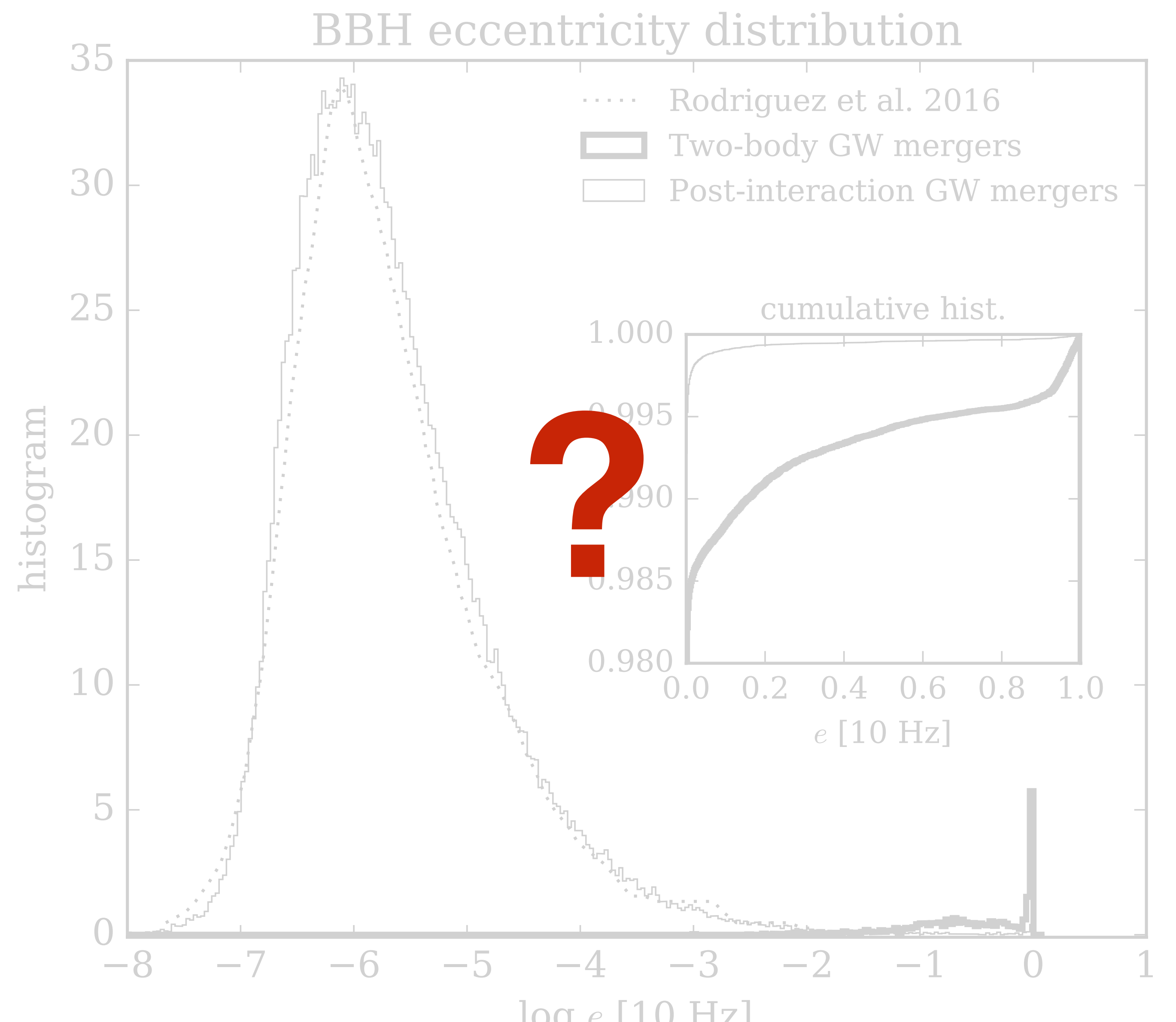
Formation of High Eccentricity GW Mergers

Binary-Single Scattering



(General Relativistic)

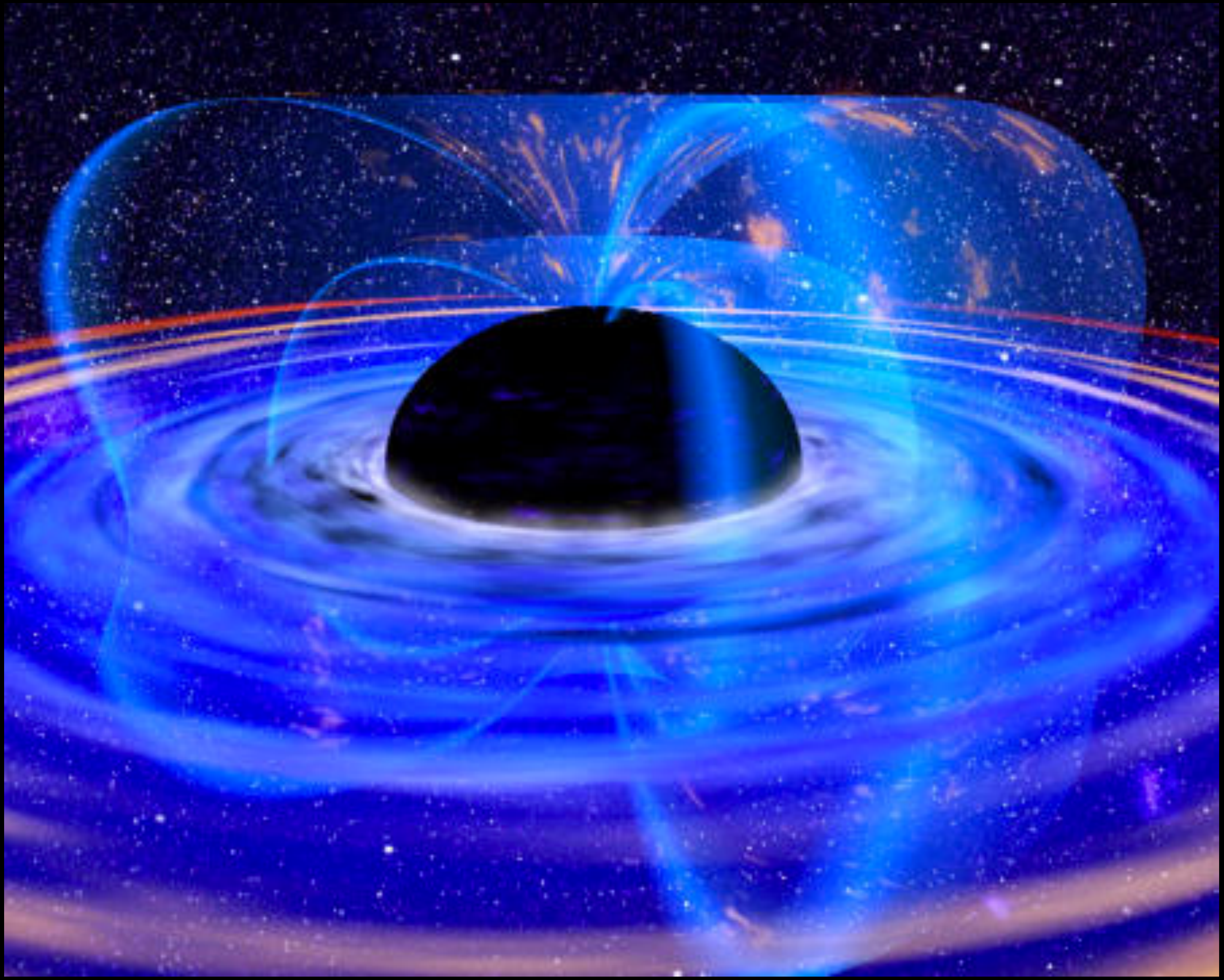
Binary-Binary Scattering



(General Relativistic)

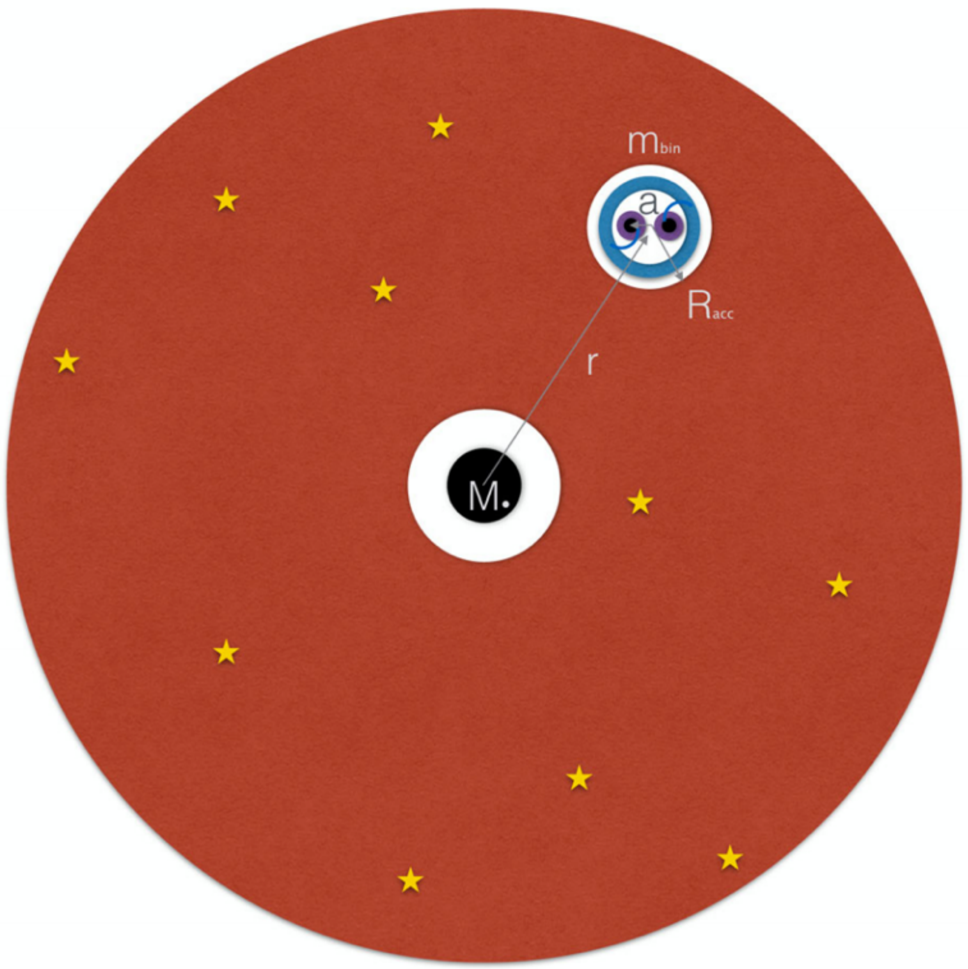
Few-body interaction near super-massive black-holes

Cole Miller, Enrico Ramirez-Ruiz, Johan Samsing



Black Holes in AGN discs

Disc



(Stone et. al 2016)

- Interactions in SMBH tidal field
- Gas drag and toques
- Co-planar
- Retro-grade or pro-grade

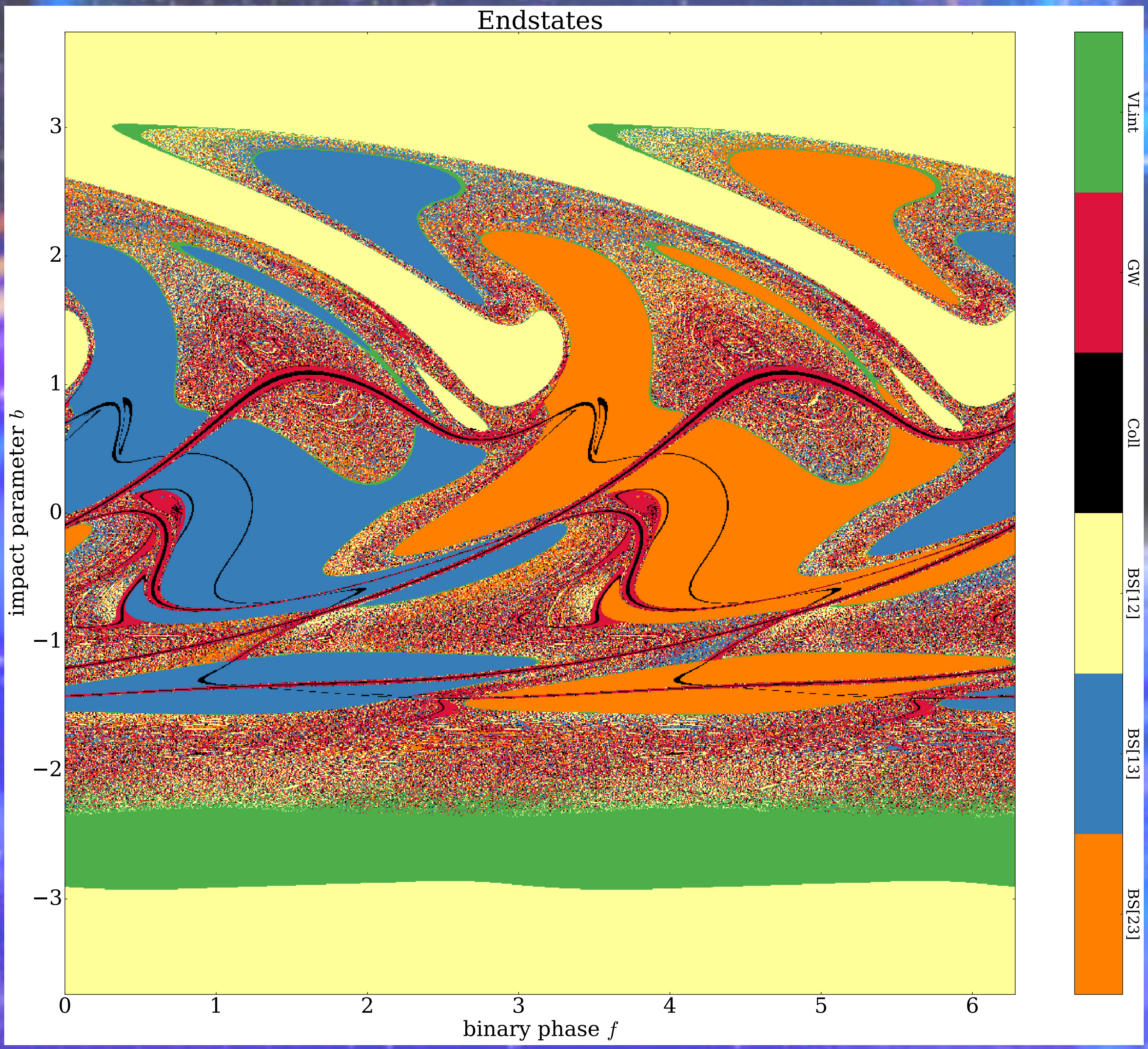
V.S.

Cluster

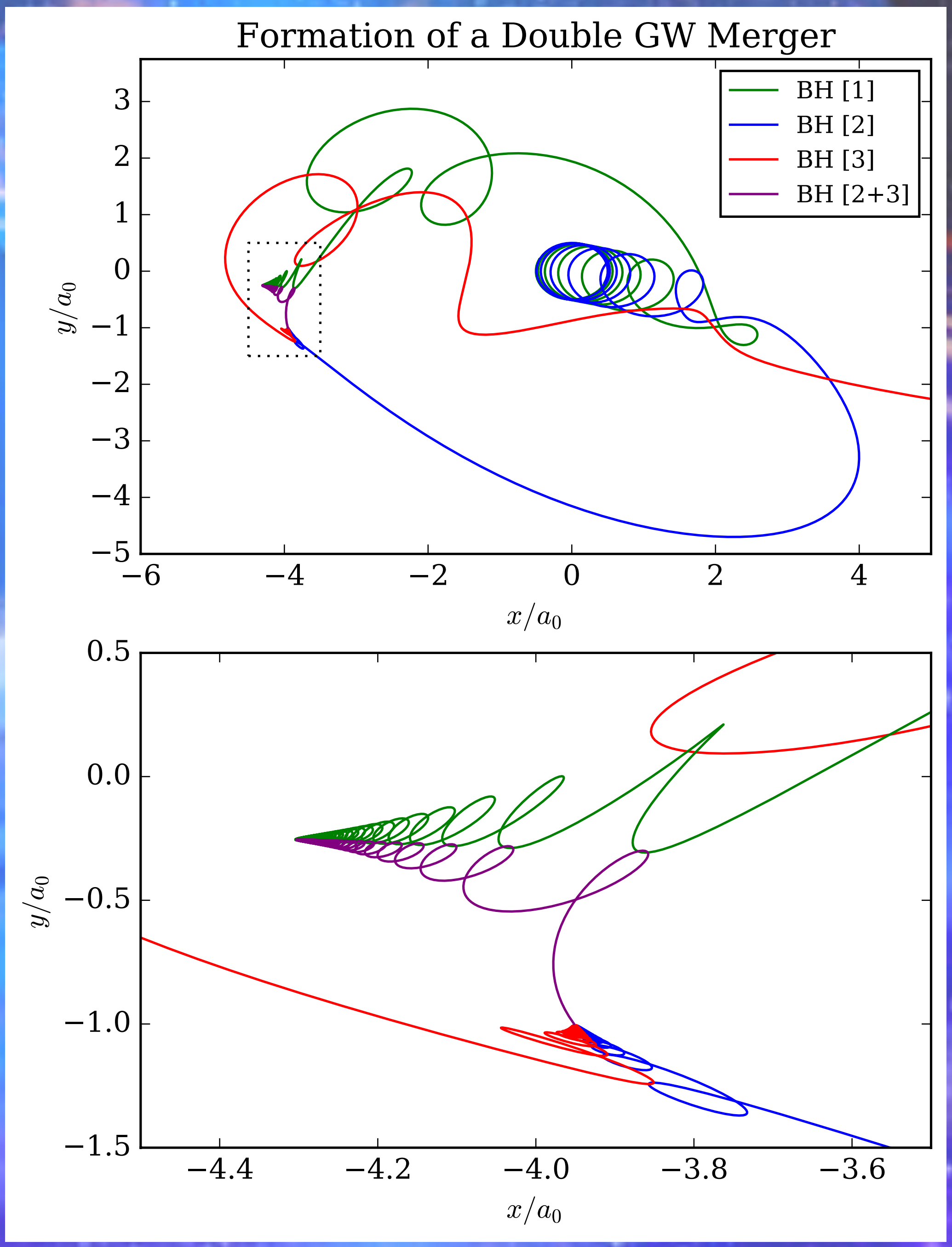
- Isolated interactions
- No external forces
- Isotropic
- Isotropic

These differences can lead to unique observables!

Examples

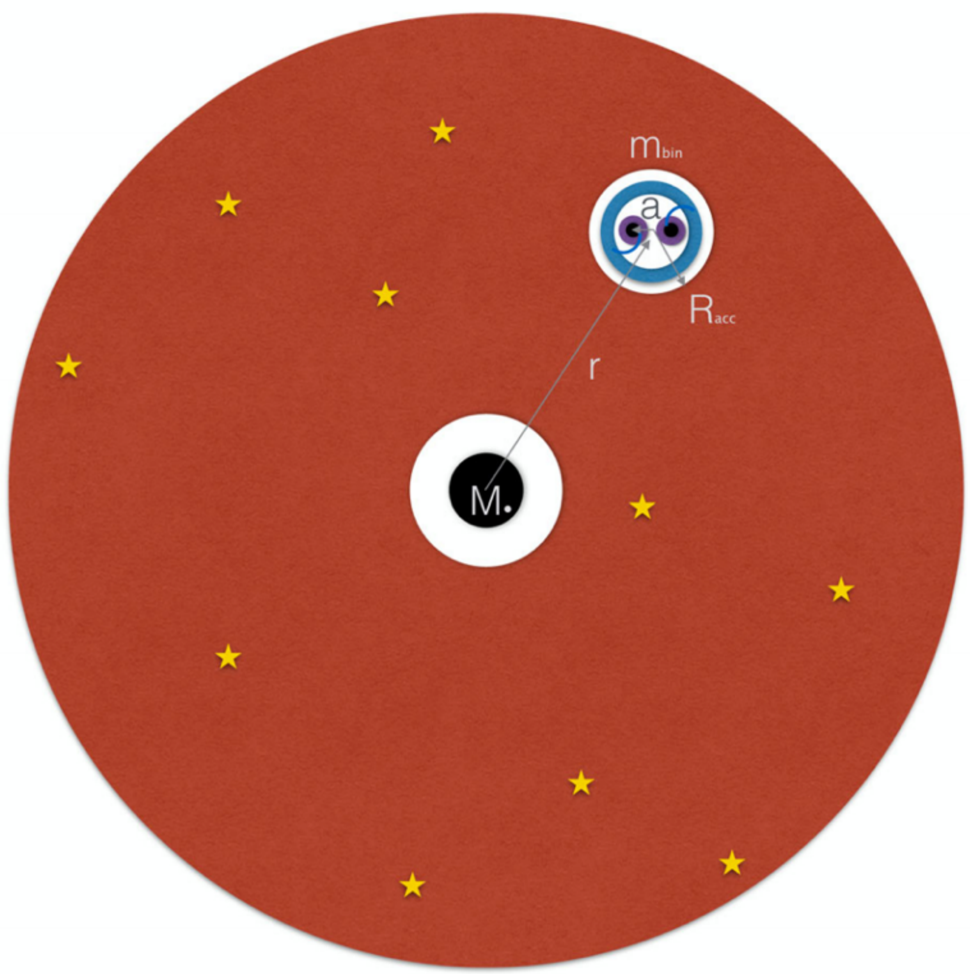


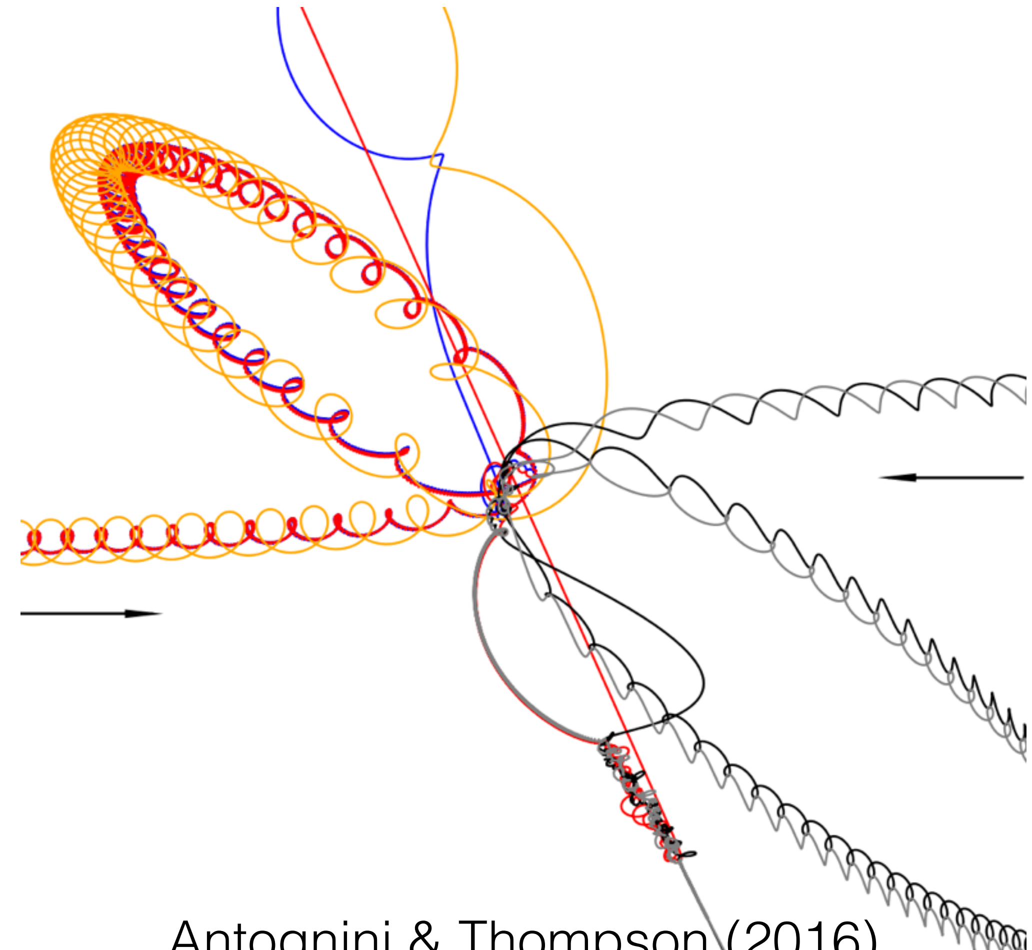
Endstates
impact parameter b
binary phase f
VLint
GW
Coll
BS[12]
BS[13]
BS[23]



Formation of a Double GW Merger
BH [1]
BH [2]
BH [3]
BH [2+3]
y/a_0
x/a_0

Project Outline





Antognini & Thompson (2016)

- Include gas, SMBH, and GR
- few-body scatterings
- BH merger/eccentricity dist.
- Effects from gas, SMBH, GR?
- Compare with competing channels

Project No. 18. Low angular momentum leading to BH assembly in LIGO progenitors

Agnieszka Janiuk (1), Enrico Ramirez (2)

(1) Center for Theoretical Physics
Polish Academy of Sciences
Warsaw

(2) Dept. of Astronomy and Astrophysics
University of California
Santa Cruz

Kavli Summer Program, Copenhagen, 11.07.2017

- LIGO BHs are probably produced by direct collapse, when the entire star at the end of its life collapses to form the BH.
- This is appealing because you can form large BHs without invoking very rare, significantly more massive stars.
- This collapse should lead to a quasi-spherical accretion in order for feedback to not be too damaging.
- The binding energy of the star is much lower than that of the resulting BH by a factor of $(v_{esc}/c)^2 \sim 1/10^6)$, which implies that a small amount of feedback could help unbind the star and prevent the formation of a massive BH.
- This outs severe constraints on the angular momentum content of the star as well as on the resultant spin of the BH.

HARM code: High Accuracy Relativistic Magnetohydrodynamics (Gammie et al. 2003). The code provides solver for continuity and energy-momentum conservation equations in GR:

$$\nabla_\mu(\rho u^\mu) = 0 \qquad \nabla_\mu T^{\mu\nu} = 0$$

Energy tensor contains electromagnetic and gas parts:

$$T^{\mu\nu} = T^{\mu\nu}_{\rm gas} + T^{\mu\nu}_{EM}$$

$$T^{\mu\nu}_{gas} = \rho h u^\mu u^\nu + p g^{\mu\nu} = (\rho + u + p) u^\mu u^\nu + p g^{\mu\nu}$$

$$T^{\mu\nu}_{EM} = b^2 u^\mu u^\nu + \frac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu; \quad b^\mu = u_\nu {}^{*}\!F^{\mu\nu}$$

The magnetic fields can be small. EOS of ideal gas

$$p = K\rho^\gamma = (\gamma - 1)u$$

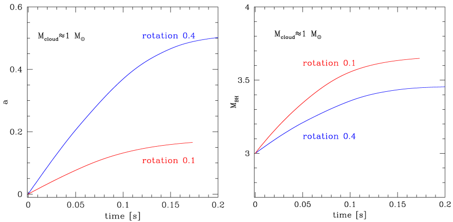
Change of mass and spin of the black hole

Black hole accretes both mass and angular momentum. Adopting Kerr-Schild coordinates t, r, θ, ϕ, this accretion rate is given by the stress-energy tensor integrated on the horizon

$$\dot{J} \equiv \int d\theta d\phi \sqrt{-g}\, T^r{}_\phi$$

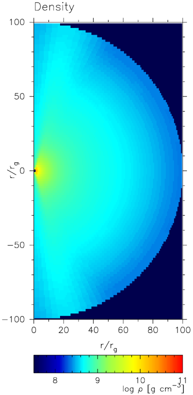
$$\dot{M} = \dot{E} \equiv \int d\theta d\phi \sqrt{-g}\, T^r{}_t$$

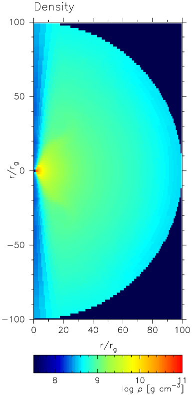
(cf. Gammie, McKinney & Shapiro 2004).



Preliminary computation with HARM-2D. Bondi cloud plus small rotation

Collapsing cloud

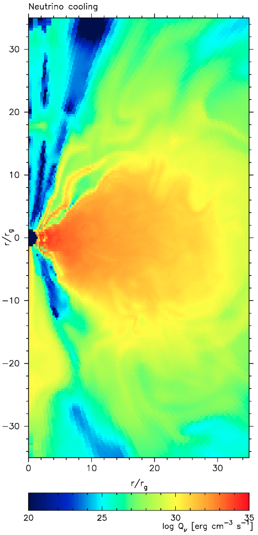




- Bondi solution, supplied with a small angular momentum.
- Example parameters: black hole mass $M = 3M_{\odot}$ initial spin $a = 0$, cloud mass $M_c = 1M_{\odot}$, non-magnetized, adiabatic $\gamma = 4/3$.
- Density profiles at t=10,000 M (1 day computation, single CPU, resolution of 128x128)

- Hyperaccretion: rates of 0.01-10 $M_{\odot}/s$
- EOS is not ideal, plasma composed of partially-degenerate n, p, e^{+}, e^{-} (Fermi gas)
- Chemical and pressure balance required by nuclear reactions
- Charge neutrality condition
- Neutrino absorption & scattering

Popham et al. 1999; Di Matteo et al. 2002; Kohri et al. 2002, 2005; Chen & Beloborodov 2007; Janiuk et al. 2004; Lee & Ramirez-Ruiz 2006; Janiuk, Yuan, Perna & Di Matteo 2007; Janiuk et al. 2013, Janiuk 2017



- Compute the slowly-rotating quasi spherical collapse with changing black hole spin and mass
- Supply the initial conditions with a more realistic density profile, as results from the stellar evolutionary model
- Discuss the effects of varying the angular momentum content in the collapsing progenitor, derived using stellar evolution models.
- Possible follow up: detailed description of microphysics in the GRB engine, torus and outflows, coupled with GR-MHD evolution (Fermi gas EOS, with $P(\rho, T)$ from tabulated models; magnetic fields and transport of angular momentum also possible to add)
- It will then be possible to obtain more advanced model of the event and physical parameters of the black hole (spin, mass).

Summary Project #19:

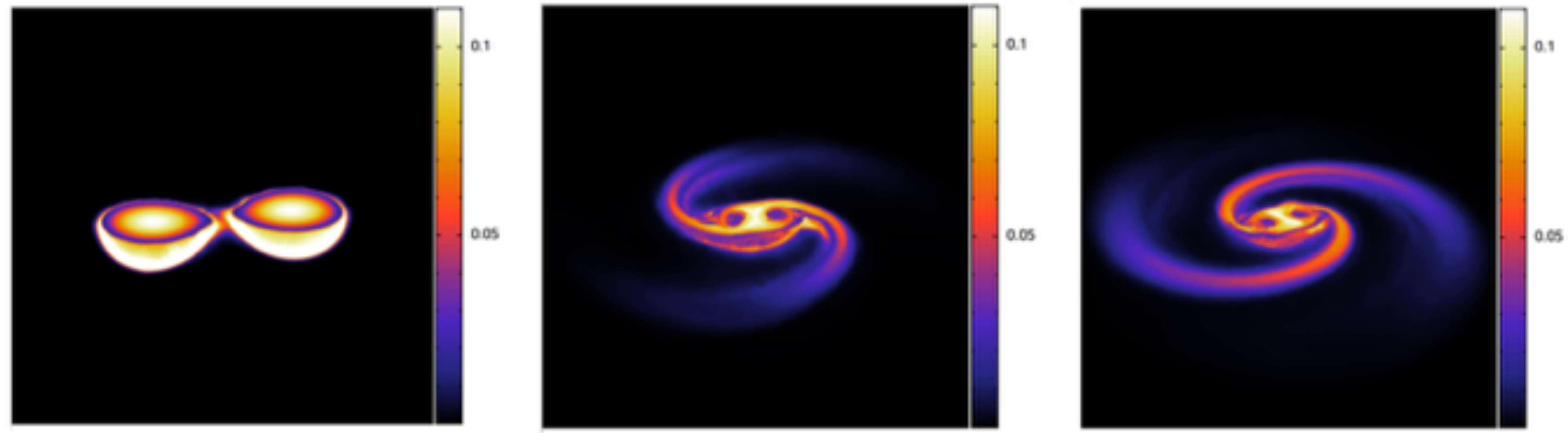
The luminosity function of macronovae

Ryan Foley (Santa Cruz; lead)
Enrico Ramirez-Ruiz (Santa Cruz)
Stephan Rosswog (Stockholm)

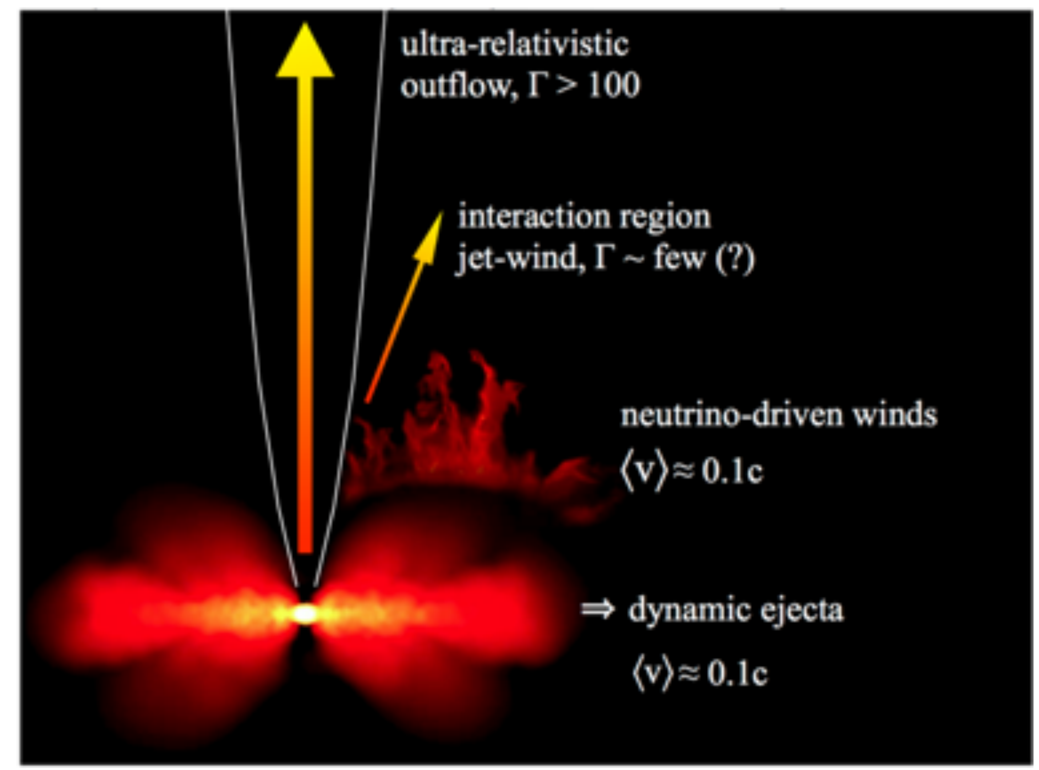
major aim: understand EM-transients accompanying major GW-sources

specific goal: infer/constrain the luminosity function of macronovae

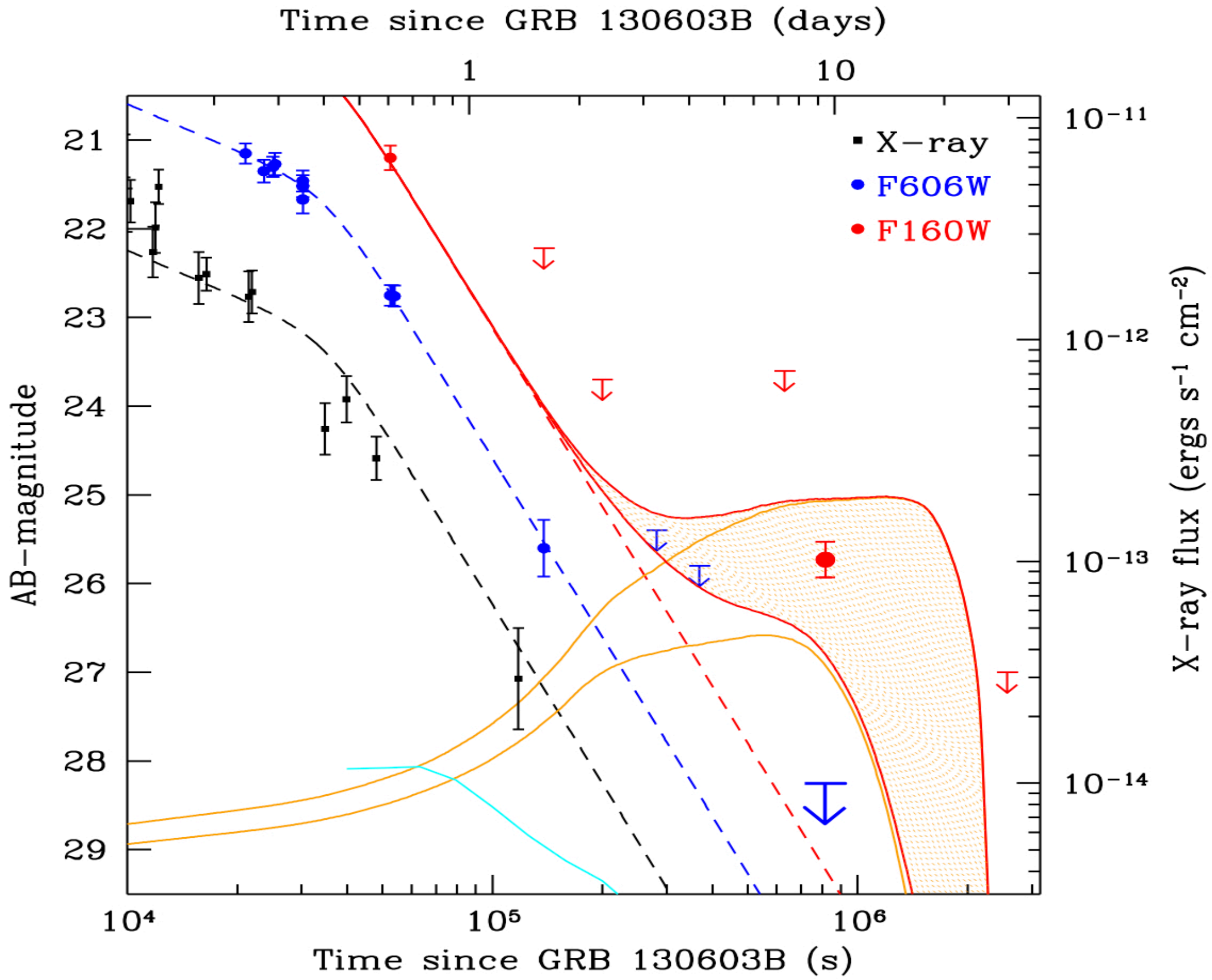
strategy: interpret data of "macronova candidates" as being due to macronovae; derive limits on their luminosity function nsns and nsbh mergers eject matter via various channels

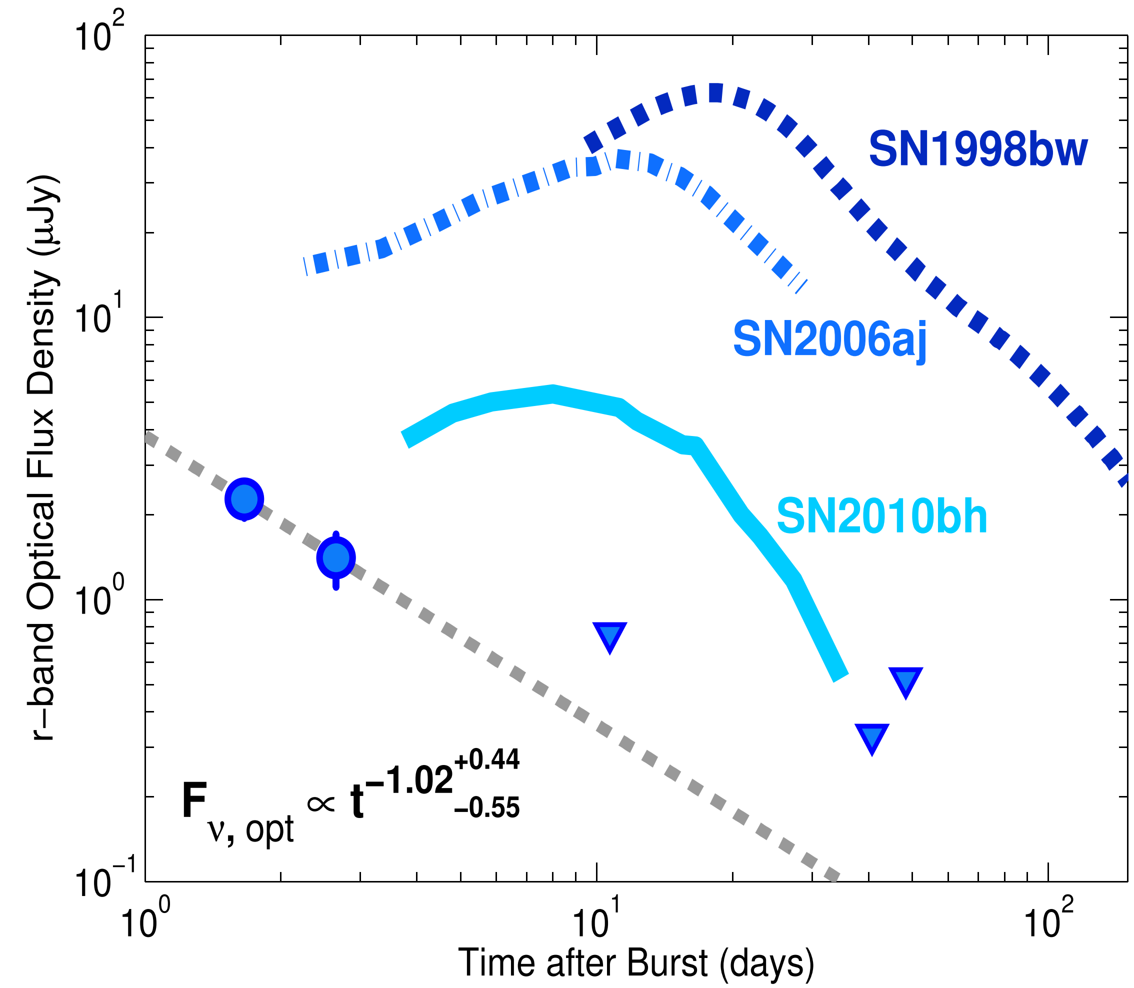


being extremely neutron-rich, this matter undergoes rapid neutron capture nucleosynthesis



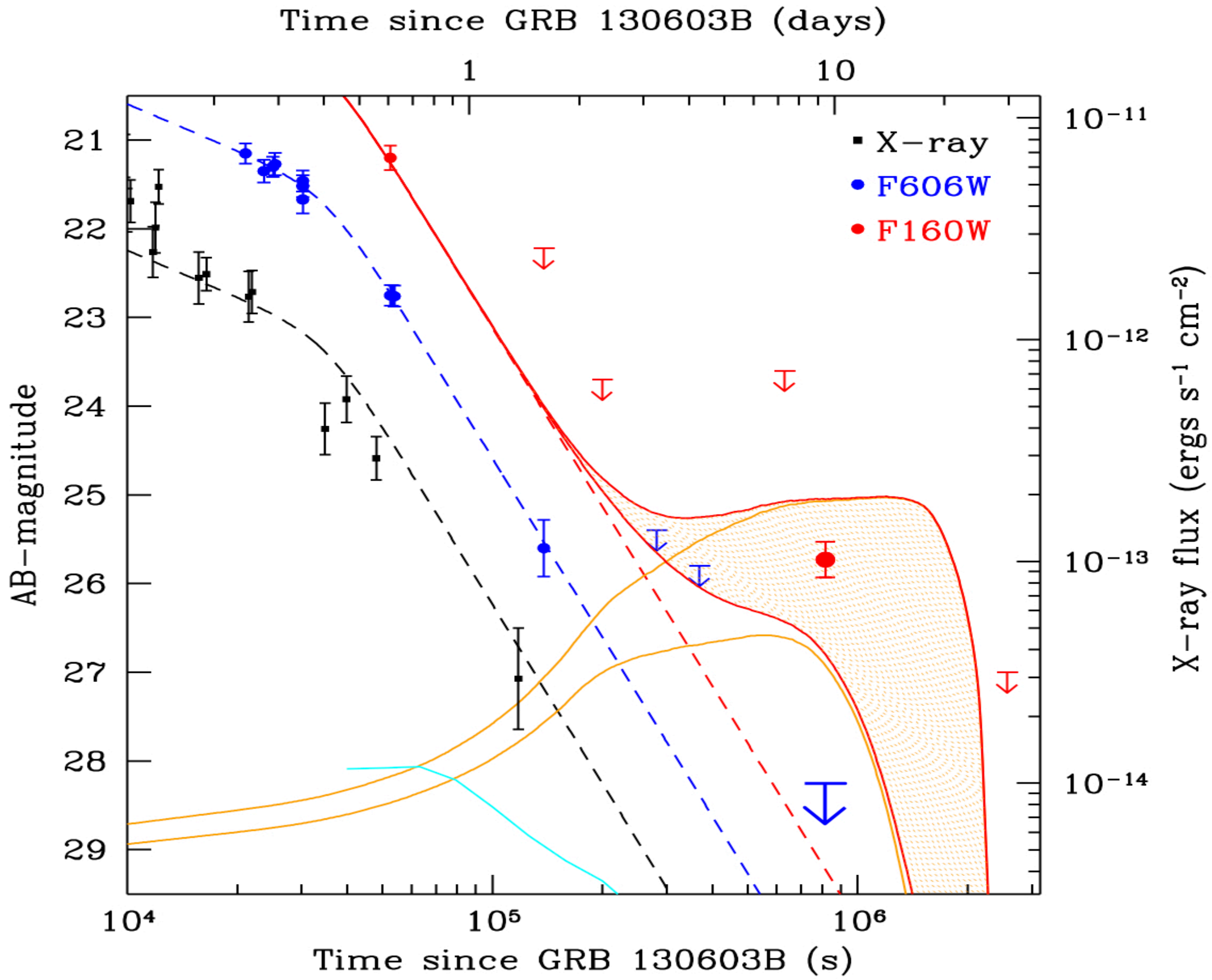
the radioactivity in the expanding ejecta will cause an electromagnetic transient (“macronova”)

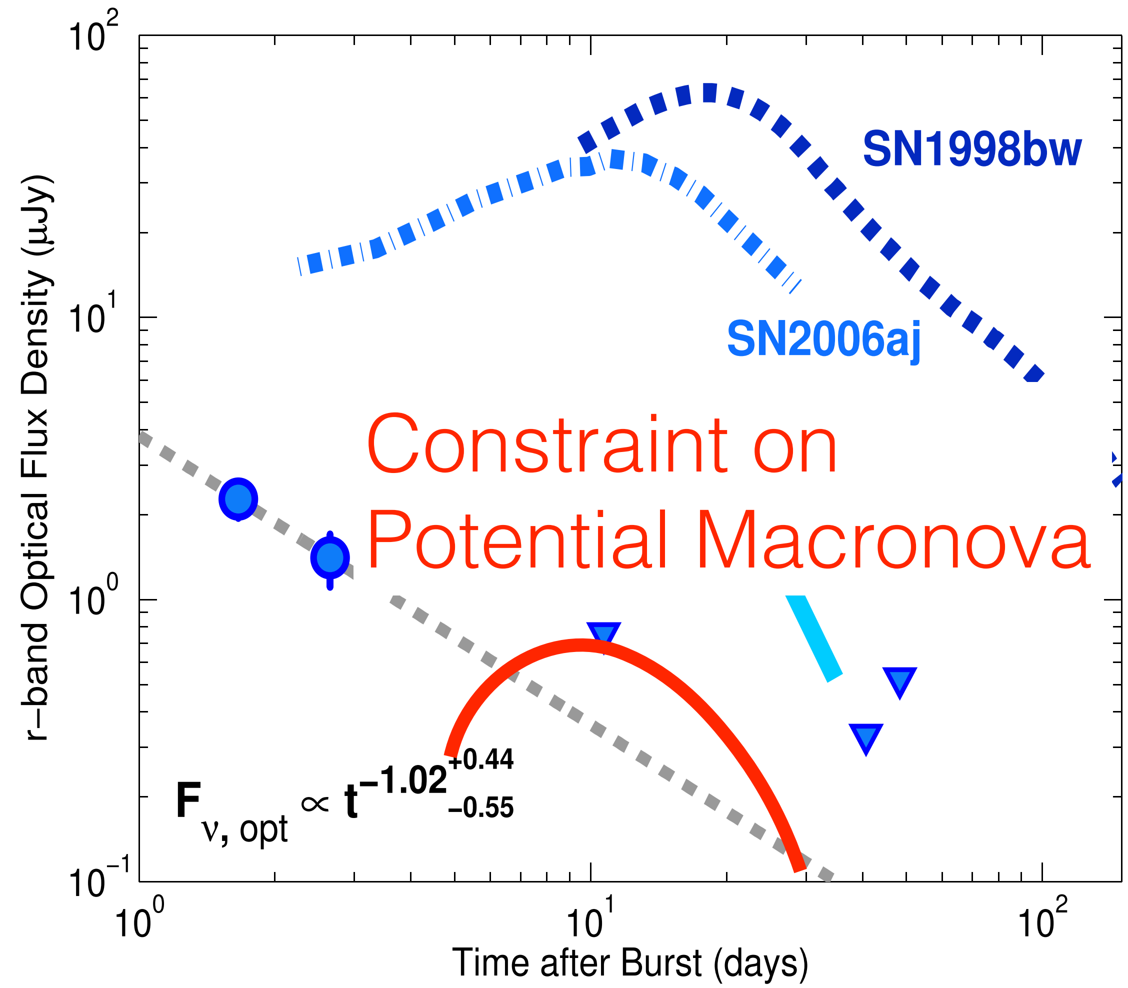




Some short GRBs have excess late-time emission, while others don't to deep limits. These data constrain the luminosity function of isotropic emission associated with BNS mergers and physical demographics of macronovae.

We will fit existing short GRB data with a combined model of afterglow and macronova emission to determine what we might see for off-axis, LIGO-discovered BNS mergers.





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We will fit existing short GRB data with a combined model of afterglow and macronova emission to determine what we might see for off-axis, LIGO-discovered BNS mergers.

Testing Compact Binary Formation Models with SN Observations

Chris Belczynski, Ben Farr, Chris Fryer, Dan Holz

A number of uncertainties in binary models make it difficult to predict firm rates on the formation of NS/NS, NS/BH, and BH/BH binaries. But a number of constraints exist that can be used to constrain binary population synthesis models:

1. Compact binary observations: e.g. X-ray binaries and binary pulsar systems.
2. Supernovae: Many supernova progenitors are produced by binaries.

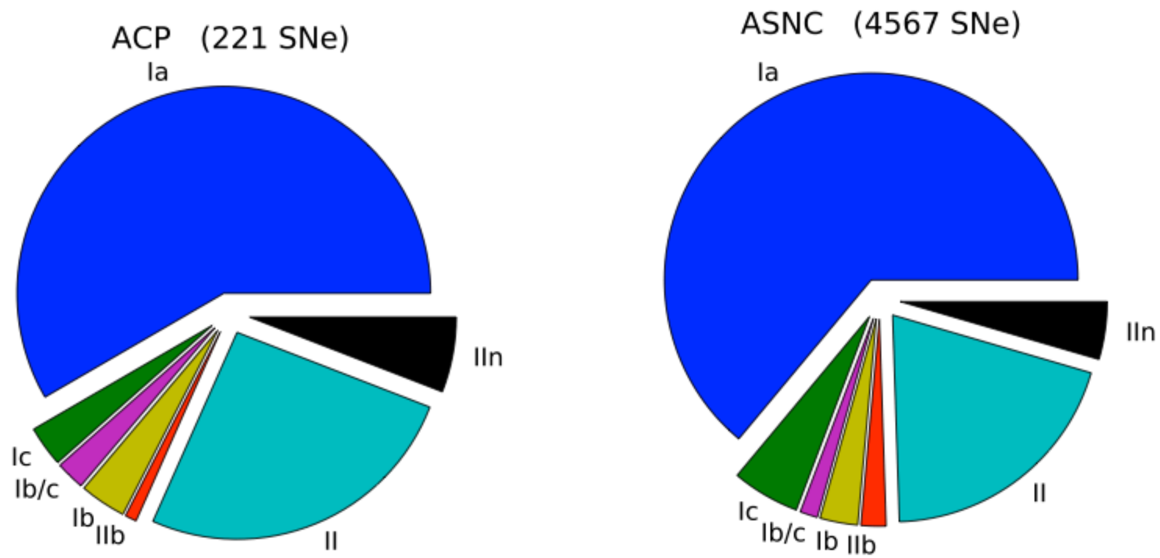


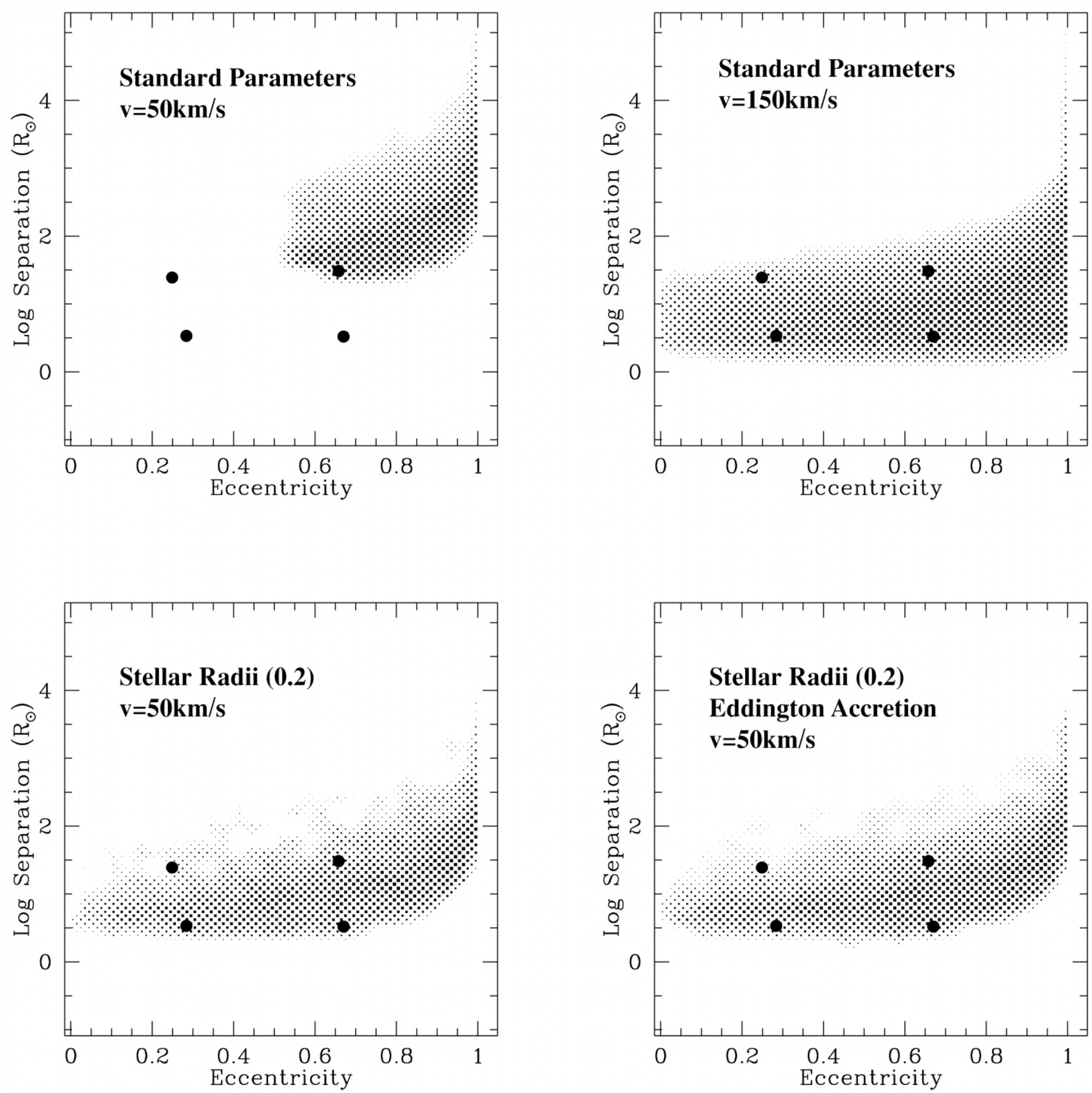
Fig. 3 Left panel: Type distribution of the 221 SNe classified through the ACP (May 2011 - October 2013): 60.4% type-Ia; 24.6% type-II; 5.5% type-IIn; 3.6% type-Ib; 2.7% type-Ib/c; 3.2% type-Ic. Right panel: distribution of 4567 SNe collected in the ASNC (excluded the SNe with an uncertain classification), which lists all SNe with IAU designation announced via CBET.

The goal of this project is to study these constraints on binary population models and compare these constraints to the current and potential GW observations.

Compact Binary Constraints

Although predictions of the rates of compact binaries have been notoriously inaccurate (the LIGO team used these observations to predict that aLIGO should have already observed 100 NS/NS binary mergers), observed eccentricities and separations can be used to constrain models.

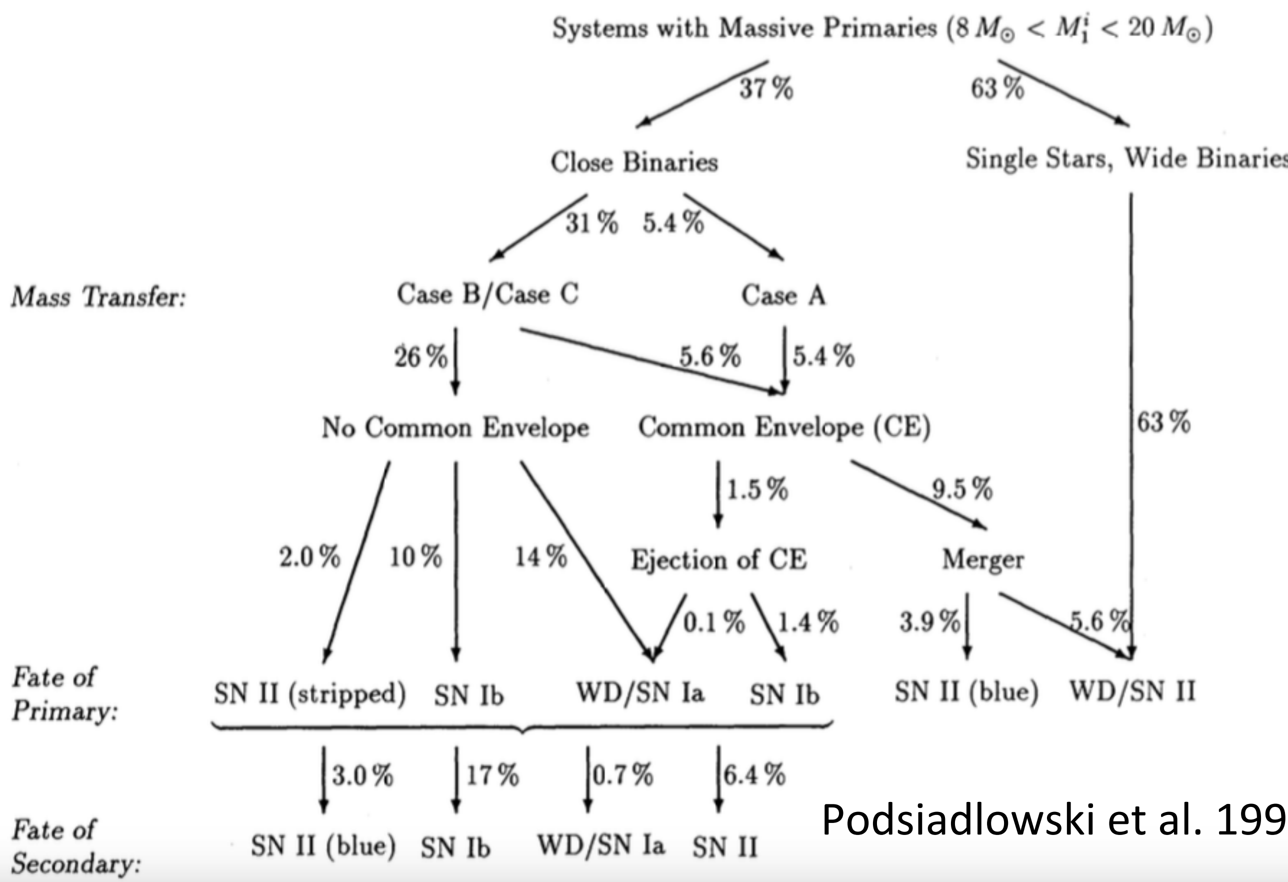
Similarly, observed spins for both pulsars and BH X-ray binaries place constraints on the stellar progenitors.



Supernovae and Binaries

Binaries may play an important role in making Ib, Ic, Iin, and IIb supernovae. In this project, we will both study the importance of binaries in producing these supernovae and the constraints supernova types place on binary population synthesis.

Other transients also may require binary progenitors: GRBs, Superluminous Supernovae, … We will study the role binaries play on these transients as well.



Podsiadlowski et al. 1991