Gravitational wave astrophysics

What astronomers can do *for* and *with* Virgo

Gijs Nelemans
Radboud University Nijmegen

Radboud Universiteit Nijmegen

FOM

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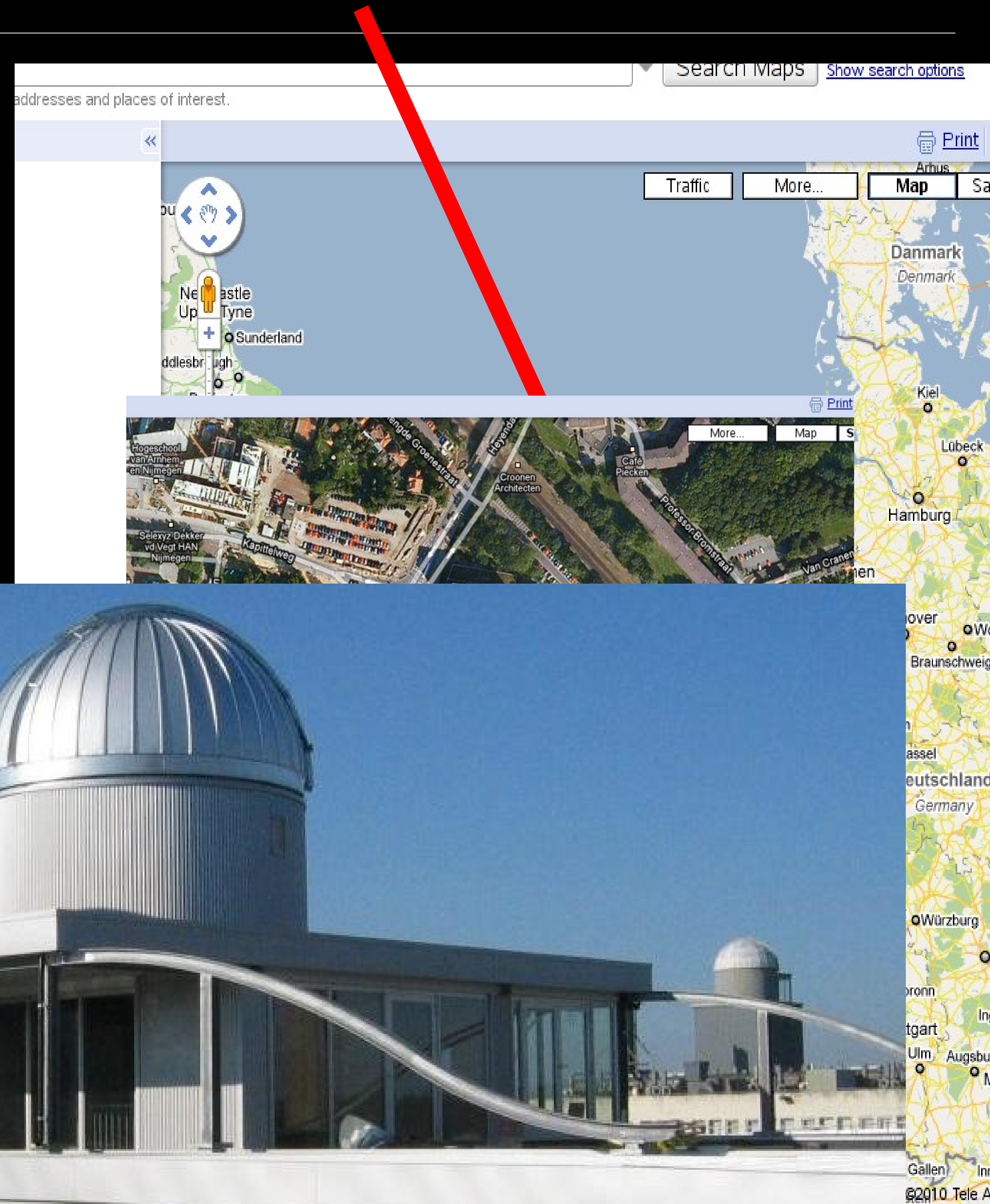
Outline

- Our group at Radboud University
- Introduction: motivation and GW astrophysics
- Evolution of (massive) stars and binaries
  - How do NS and BH form
  - Rates of GW events, now and with aVirgo
- Dedicated optical observations to complement GW data
  - BlackGEM array
- Joint EM/GW data analysis
  - Aid first detections; lower trigger thresholds; complementary data
  - Examples
- The Dutch role in Virgo and the role of Virgo in NL
- Conclusions

Radboud University Nijmegen

- Young department
- Compact binaries, astroparticle physics (LOFAR)
- Part of Dutch Astronomy research school NOVA

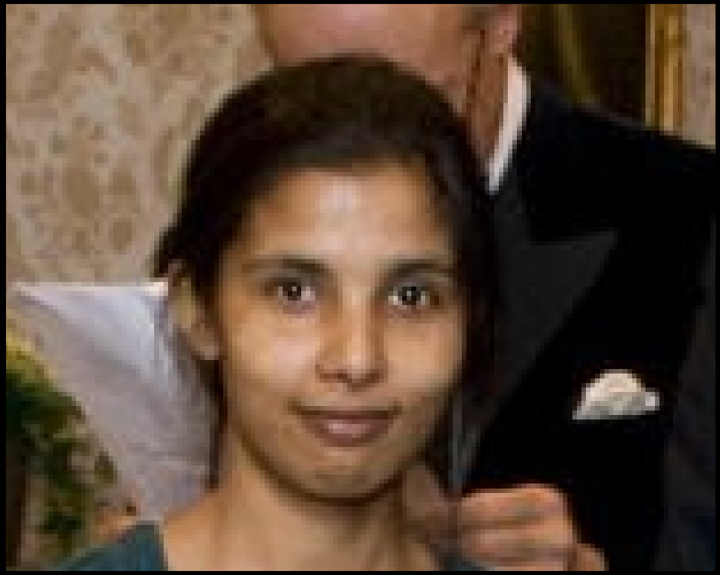


GW group @ Radboud University

- Link compact binaries → eLISA sources
- Program to study EM/GW complementarity for Virgo and eLISA
- Develop EM observational strategies
- Data analysis
- Optical telescopes, transients (PTF)

Paul Groot (head dept, optical obs)

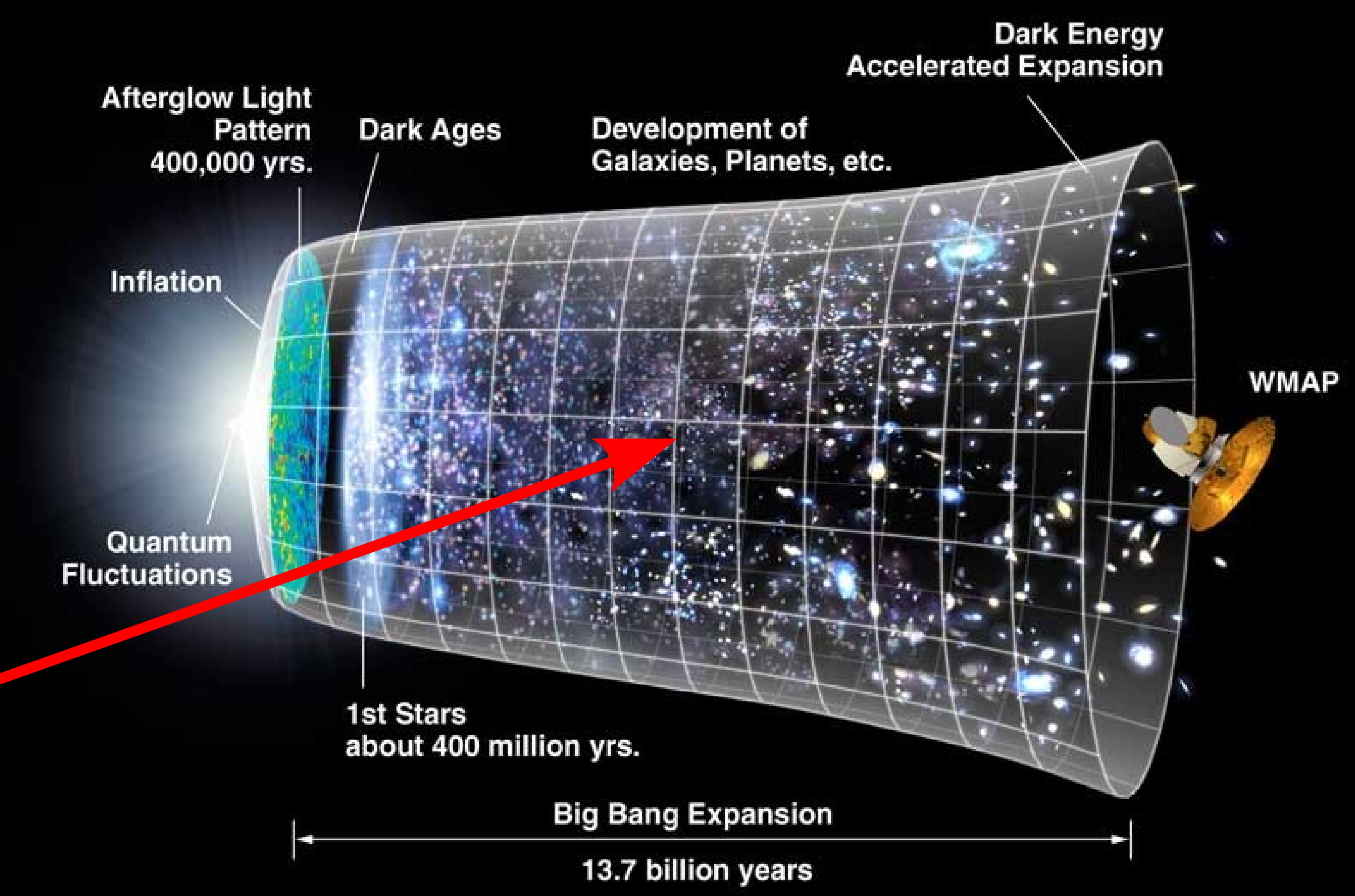
Marc van der Sluys (post-doc, data an.)



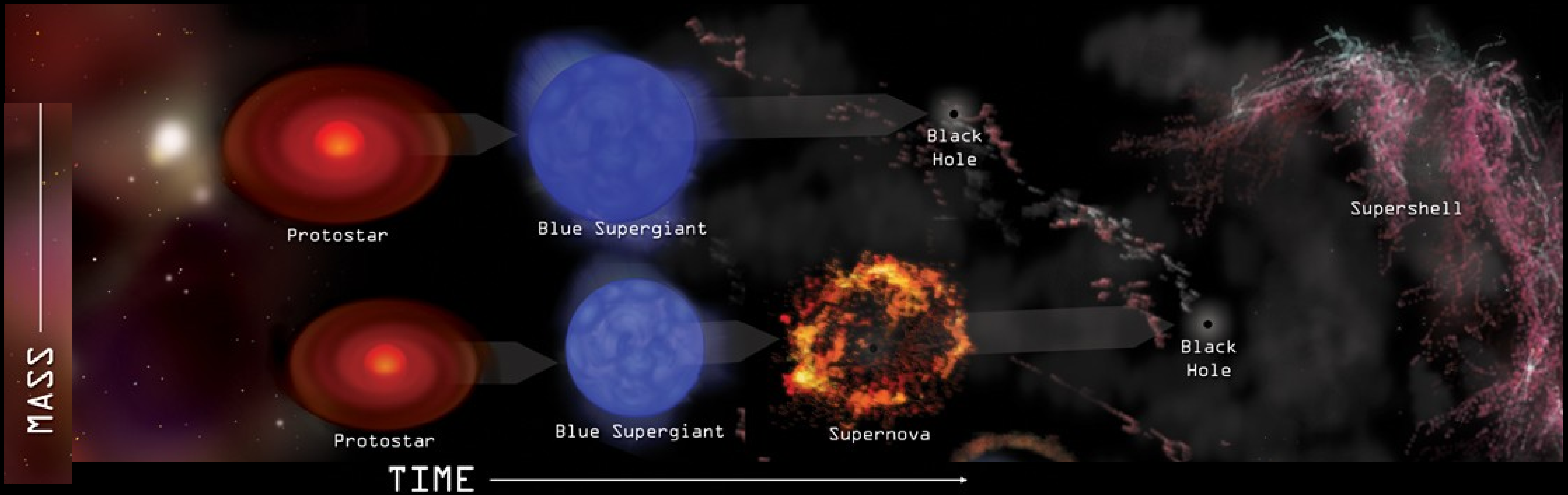
Sweta Shah (PhD, data an.

1 Introduction

- The Universe
- Gravity and astrophysics
- Four (or more?) reasons for GW studies
  - Test GR
  - Early Universe (inflation)
  - Cosmology
  - “Astrophysics”
- Compact binaries (NS, BH)
- Supermassive BH mergers
- Galactic binaries



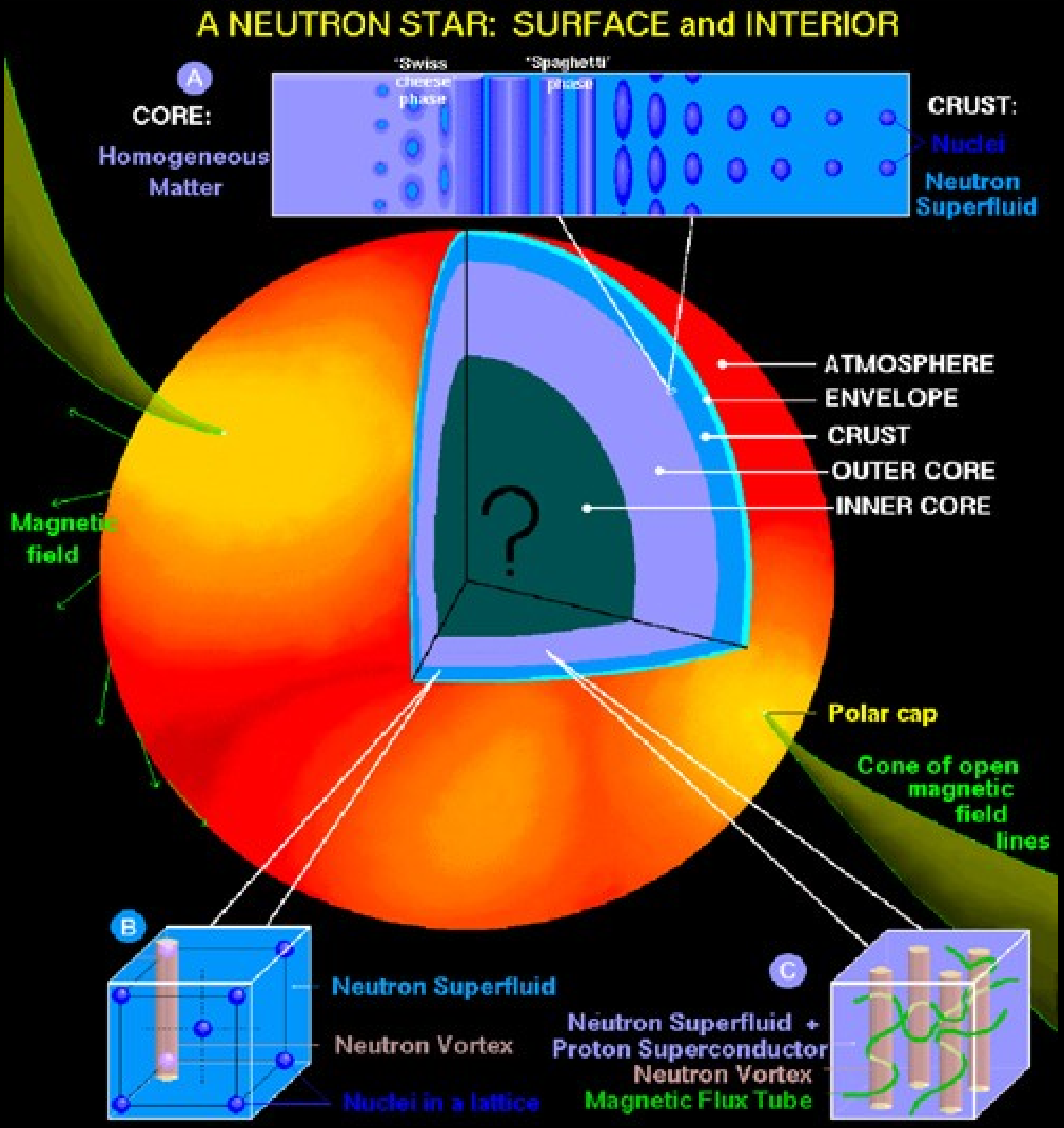
Massive stars: formation of NS and BHs



- Which stars form Neutron stars?
- How are Black Holes formed?
- How do supernova explosions work?

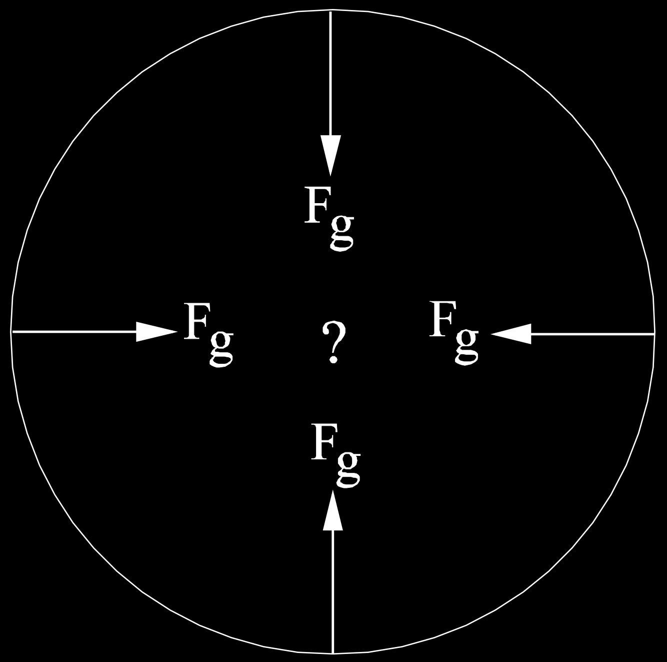
Matter at super-high densities

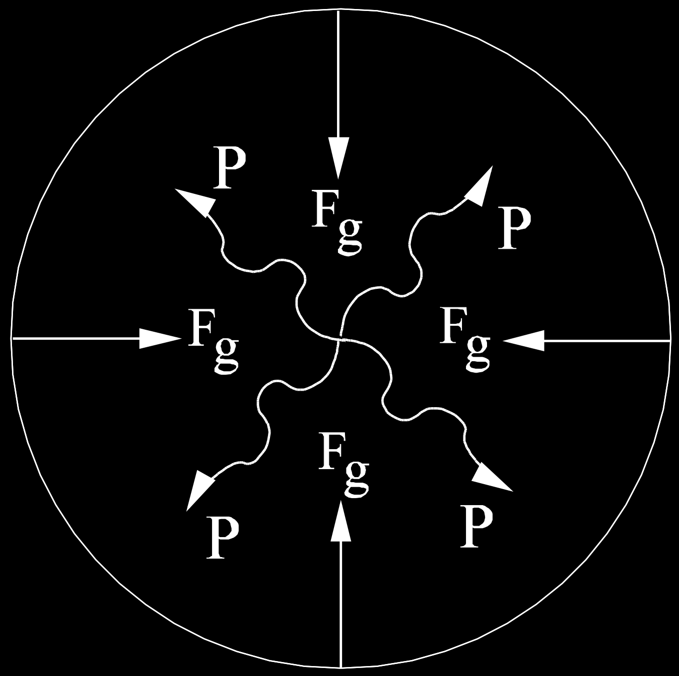
- Neutron star: laboratory for super-high densities
- Superfluid, supercondicting
- Equation of state [P = P(ρ, T)] unknown



2 Evolution of (massive) stars and binaries

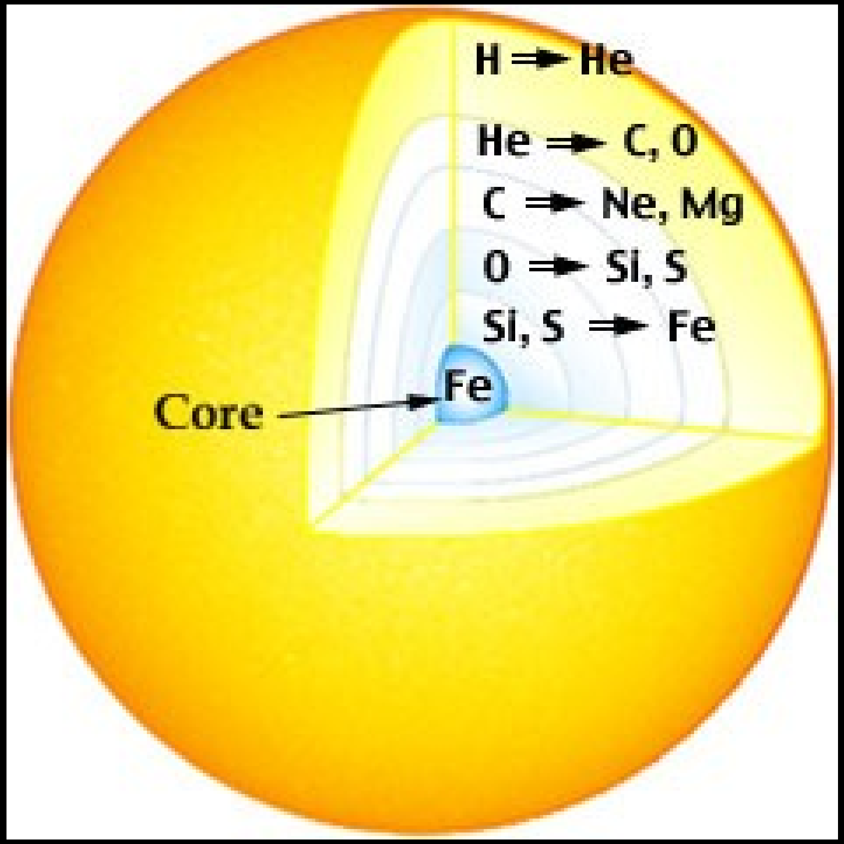
- Basics of stellar structure
- Gas (ionised), radiation
- Balance between gravity and...
- (gas) Pressure
- Caused by high temperature due to nuclear fusion....

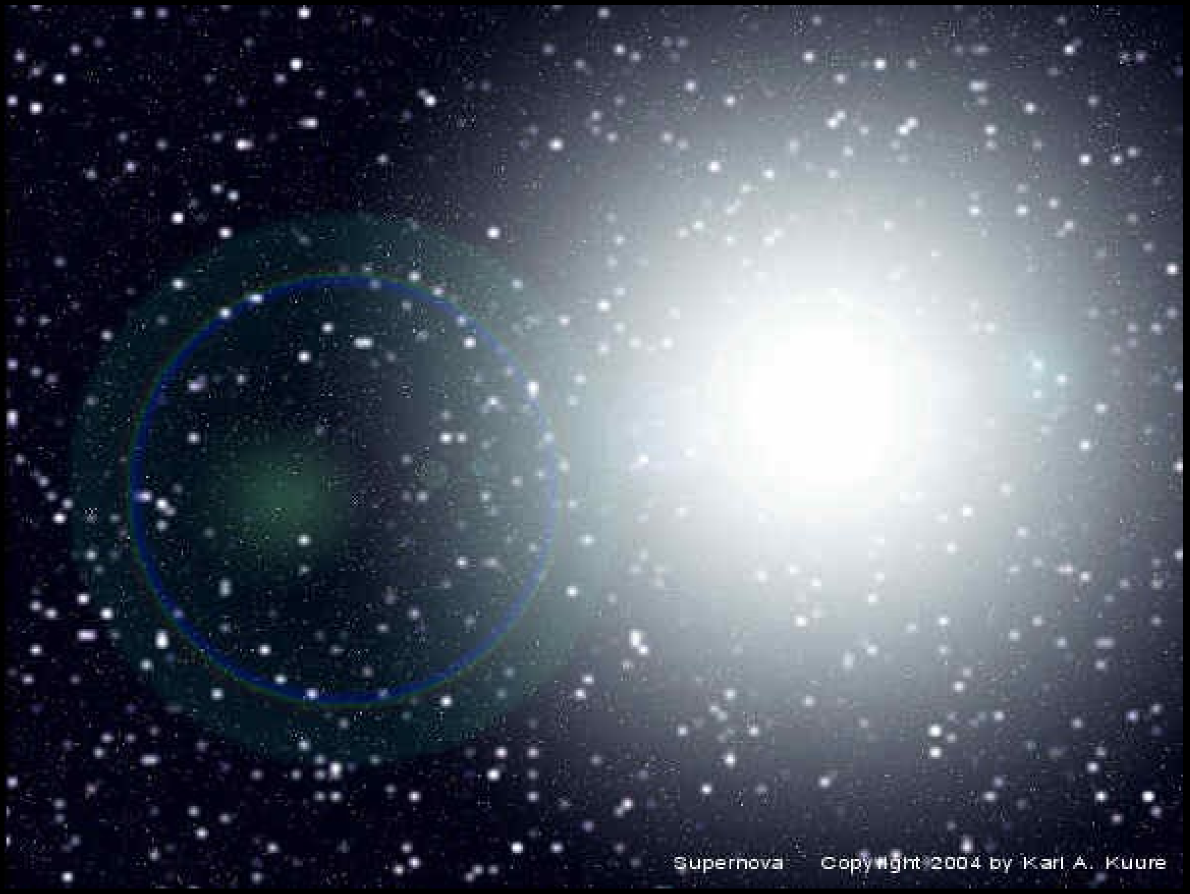




Evolution of a massive star

- First H fused in He, later to C,O,Ne, Mg, Si,S,Fe
- At Fe no more energy to be gained

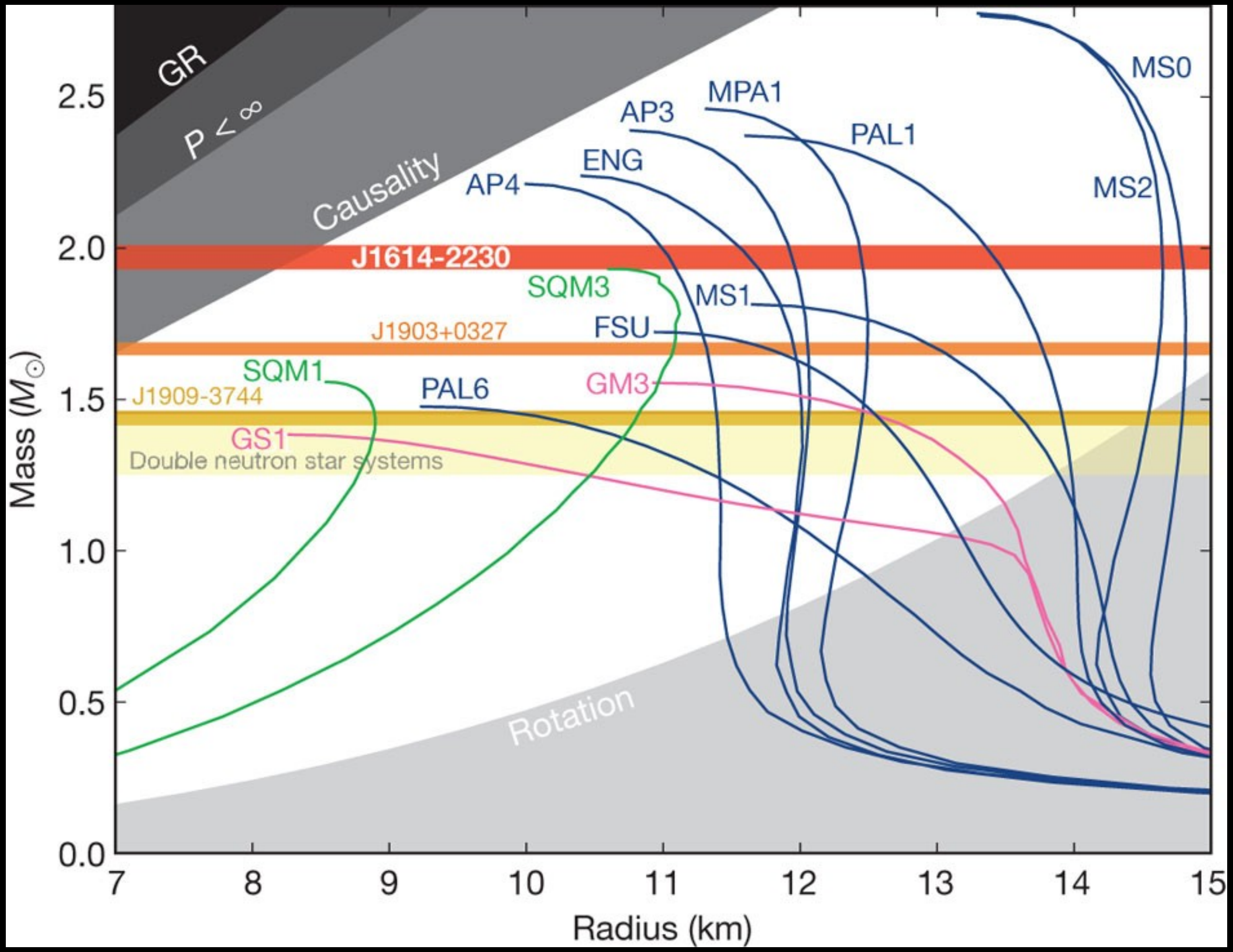




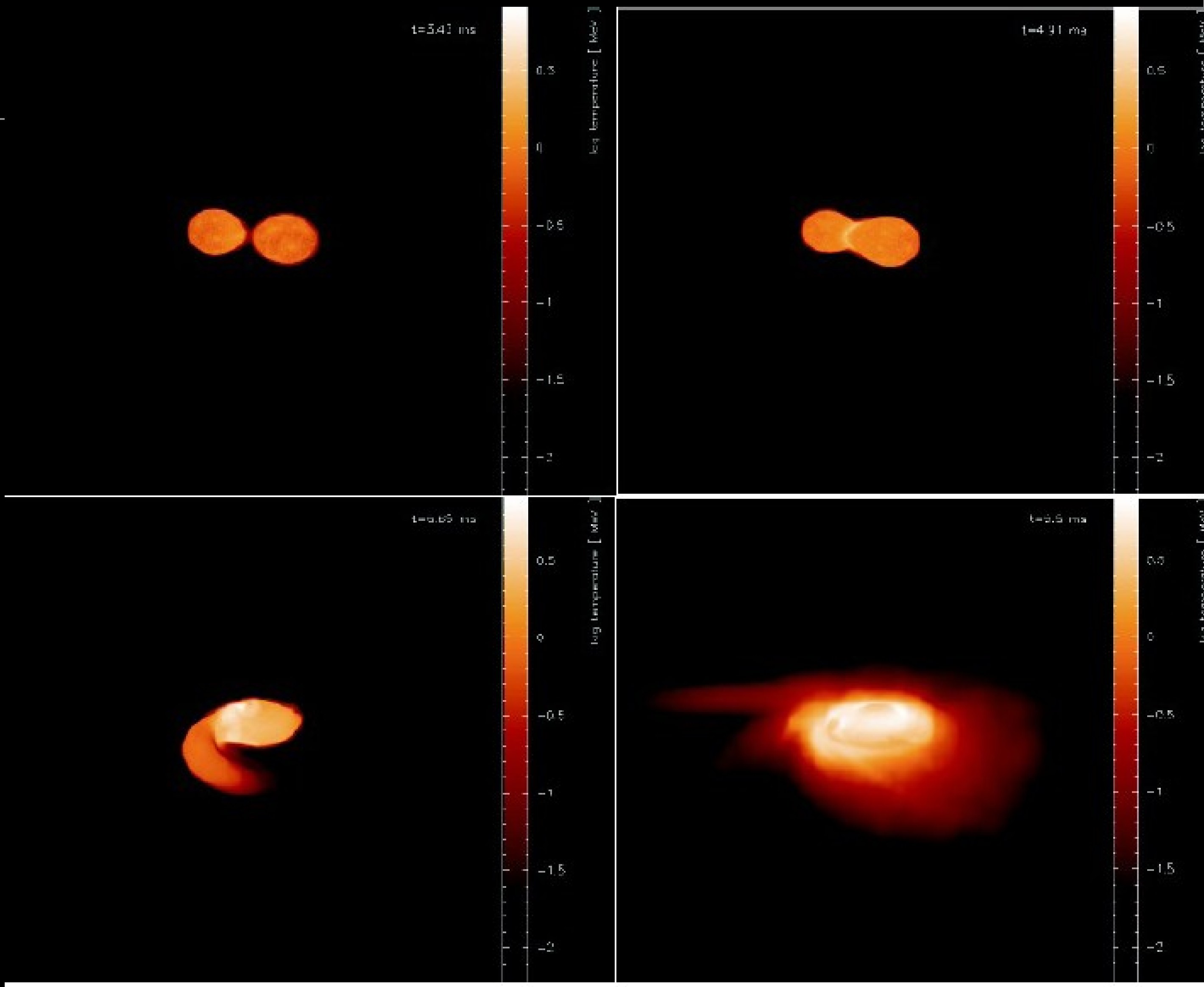
- Pressure drops → collapse
- Formation Neutron star? Kick?
- Reverse shock → Supernova?
- Fall back → BH formation?

Neutron stars

- Which stars form NS?
- What causes a SN?
- NS EoS!



Lattimer & Prakash, Demorest et al. 2011

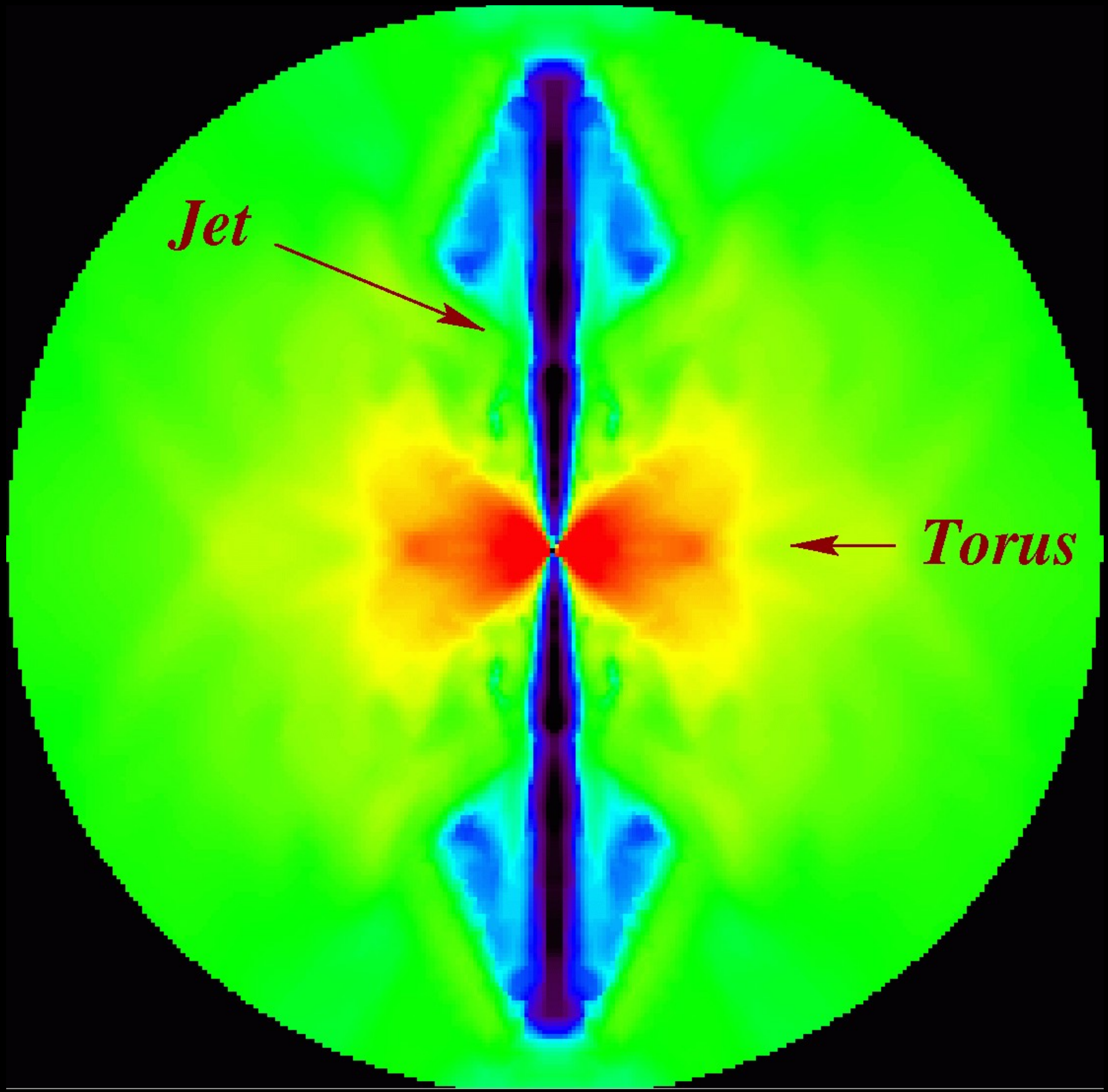


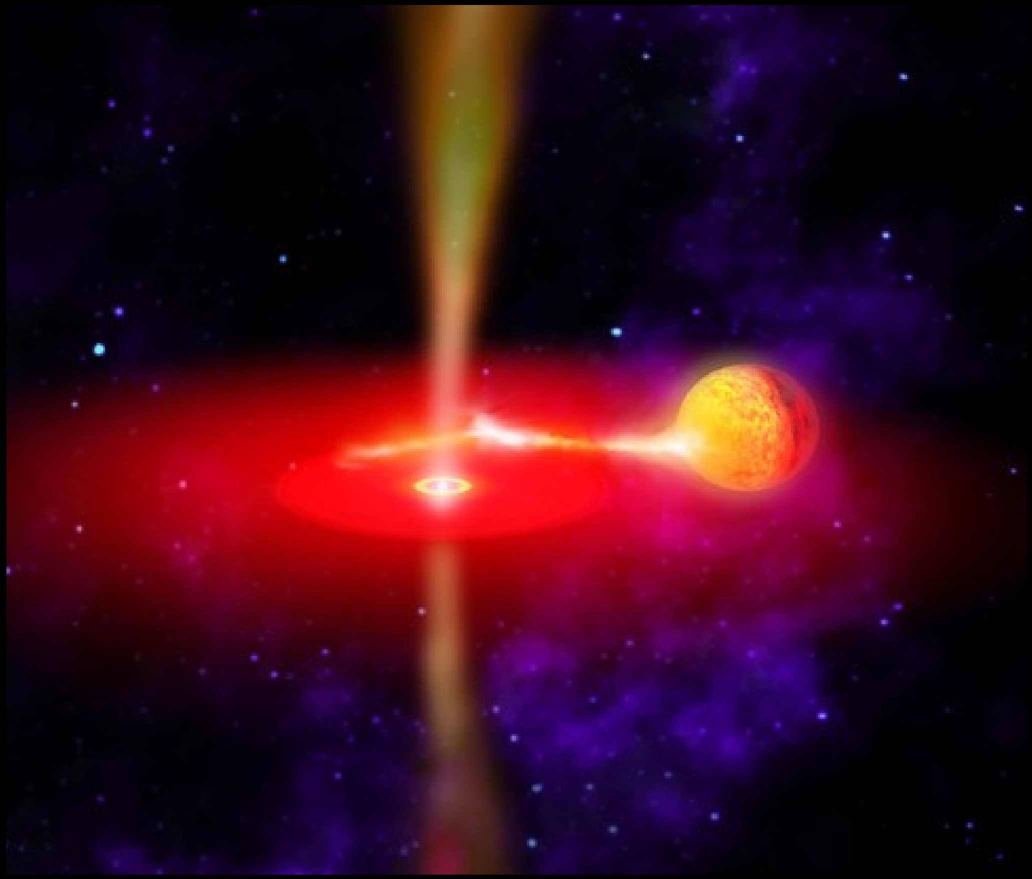
Price & Rosswog 2006

- Neutron star mass measurement
- Mergers!

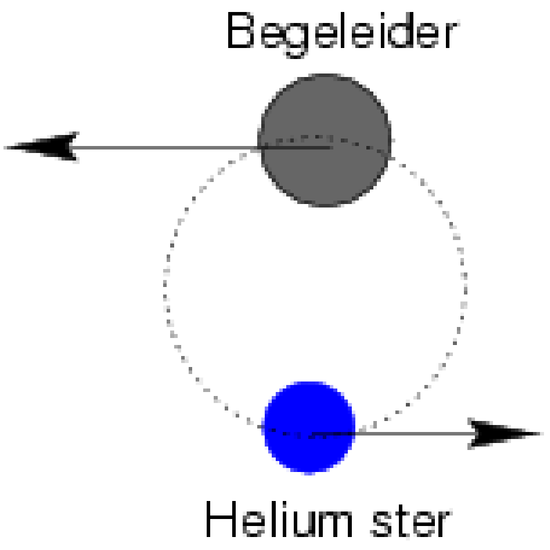
Black Holes

- Direct formation or fall back?
- Result of NS+NS merger
- Influence metallicity?
- First stars?





Inprint of BH formation (SN) on X-ray binary



Nelemans et al. 1999

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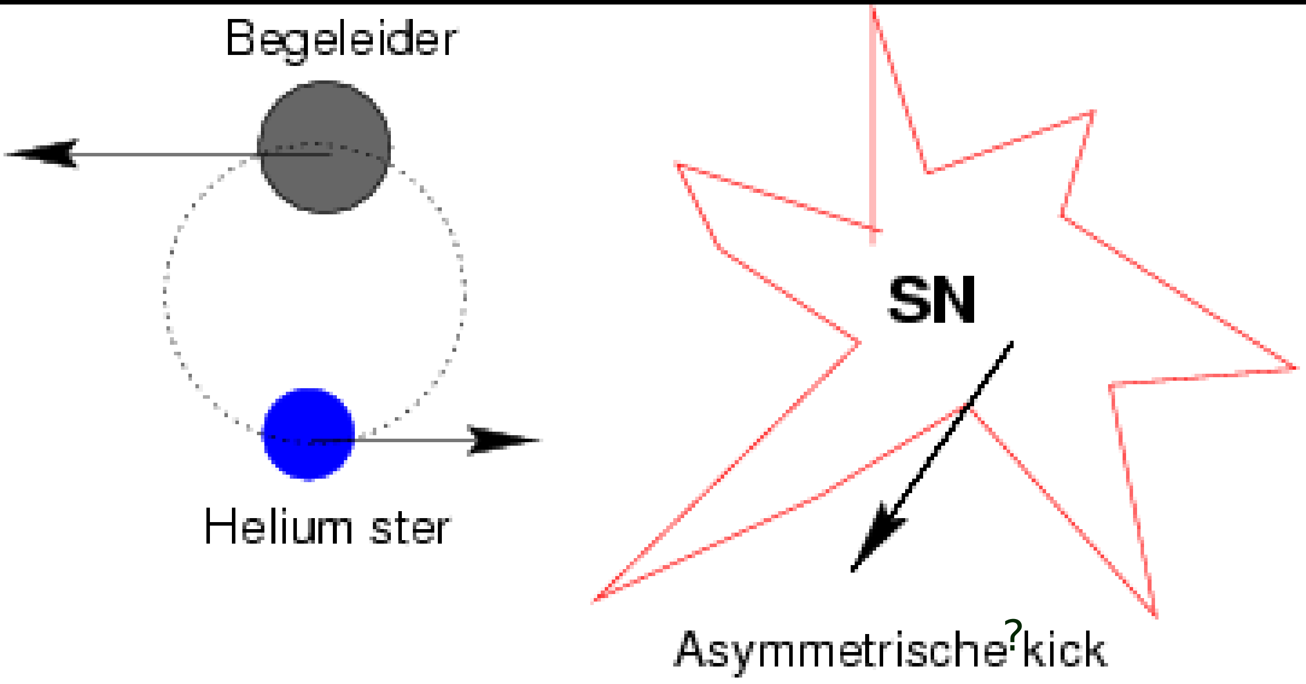

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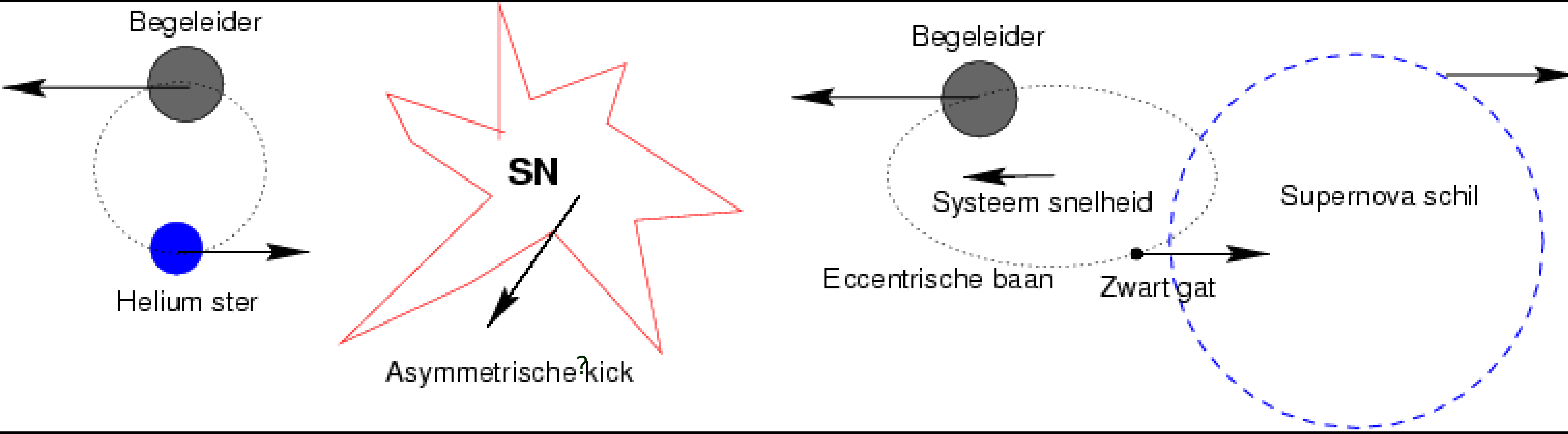
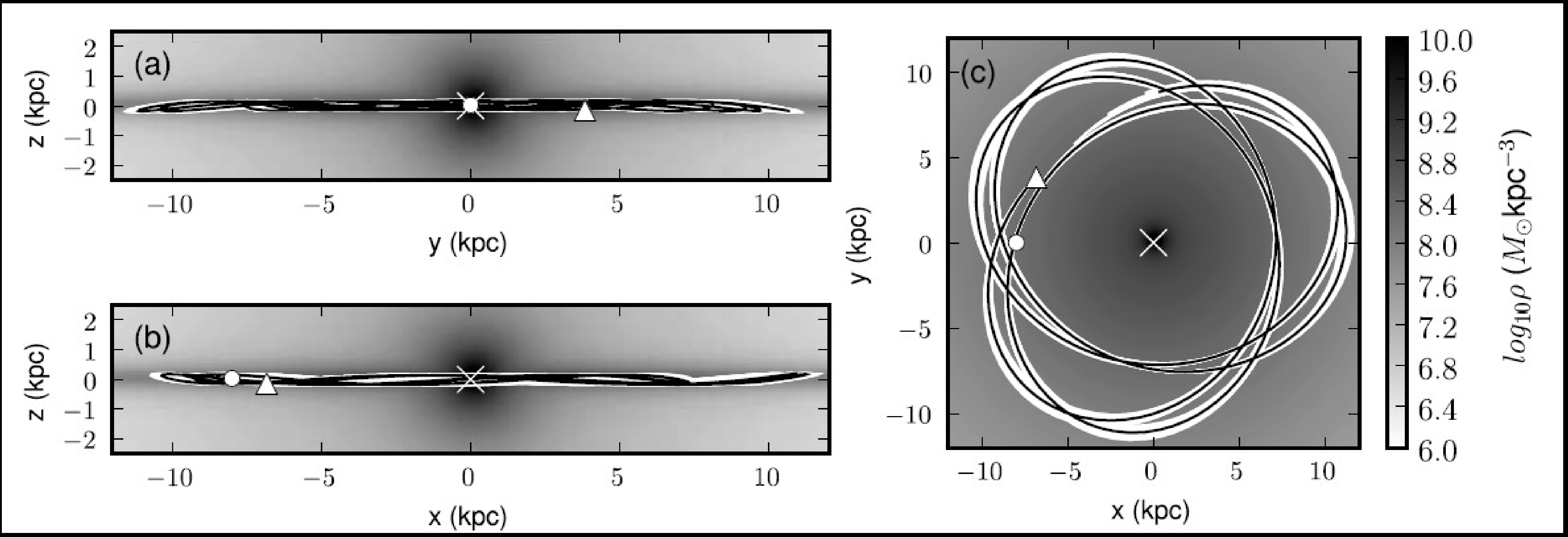
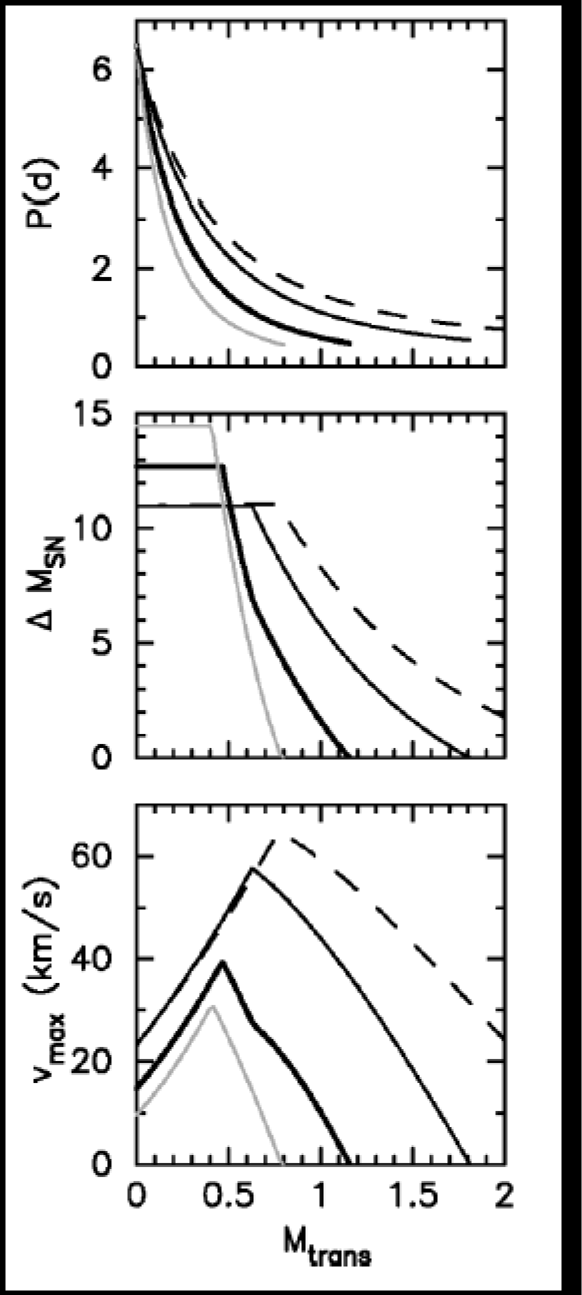


Nelemans et al. 1999

V404 Cyg

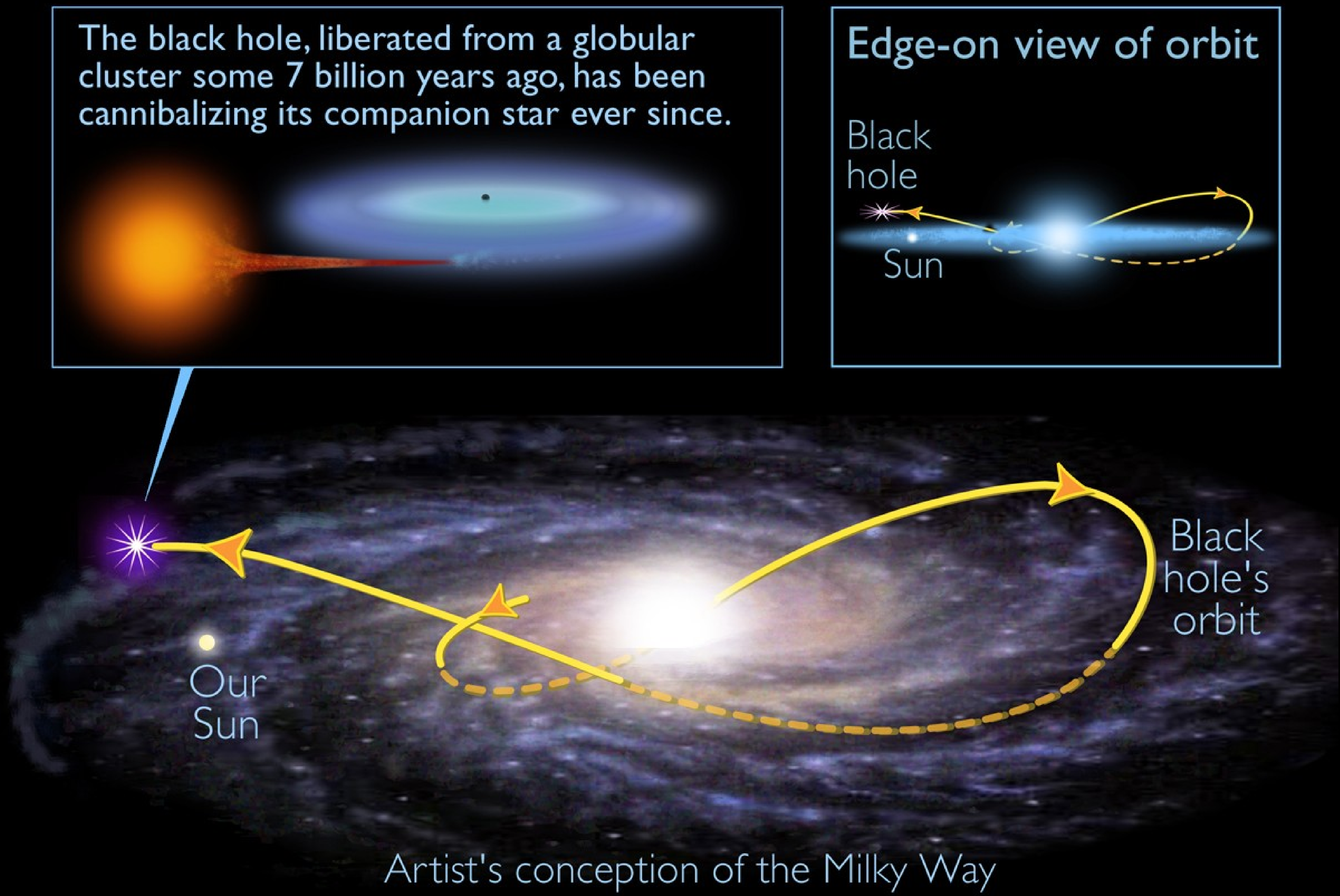




- Distance and proper motion from radio VLBI
- Reconstruct orbits, determine system velocity
- Constrain BH formation and kick

Miller-Jones et al. 2009a,b

Black hole's wild ride through the Milky Way

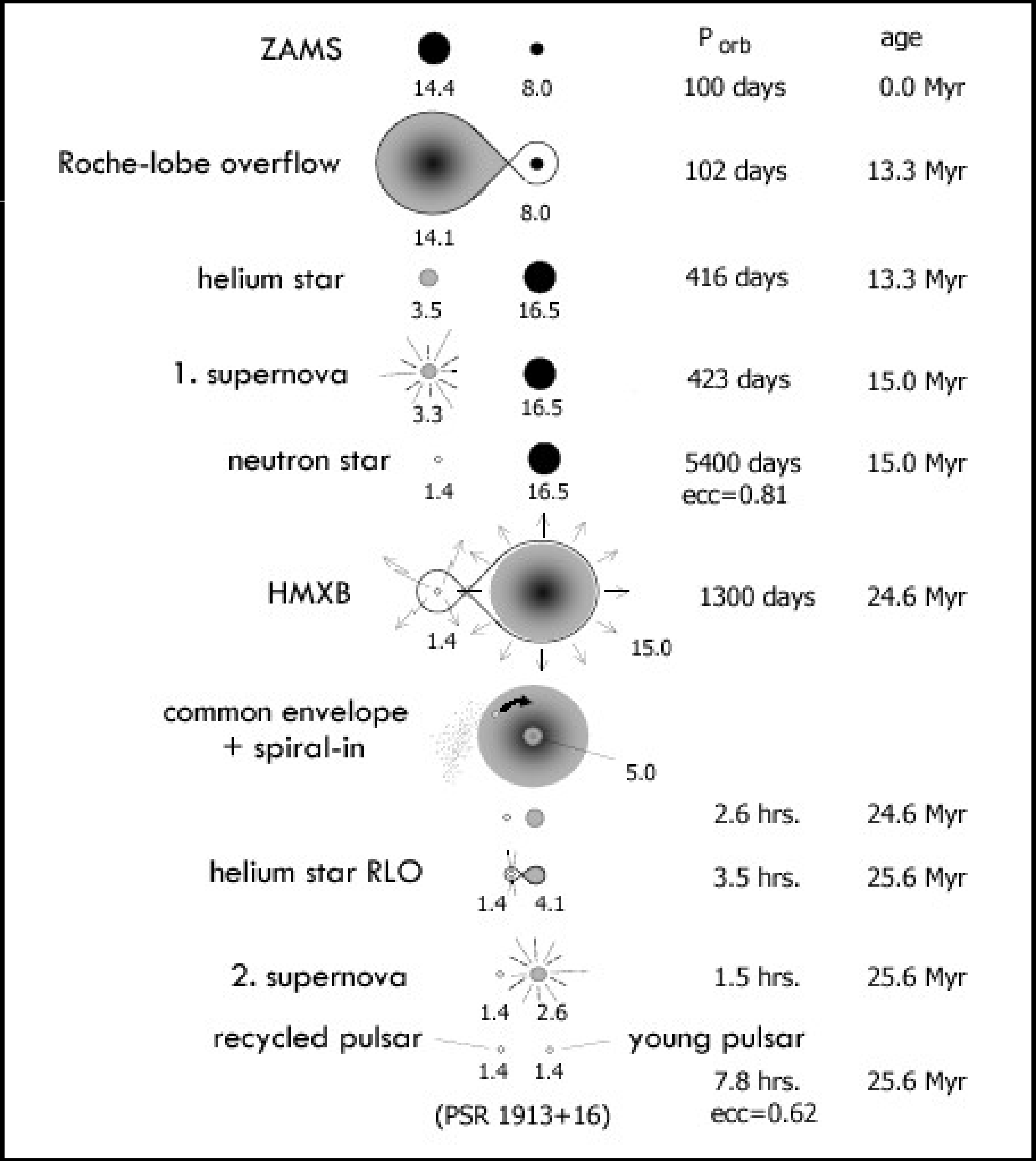


Mirabel et al.

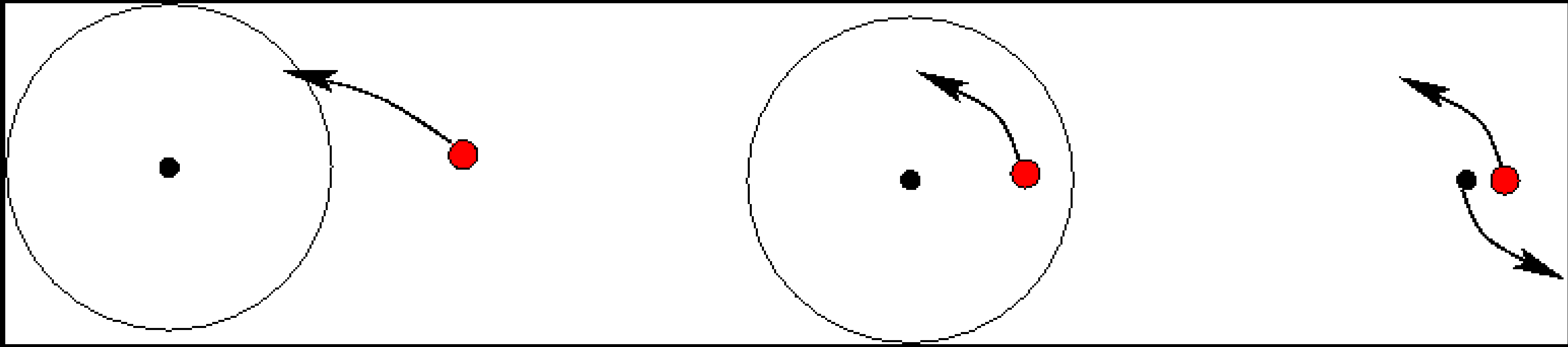
Evolution of binaries

- Not only stars, also interaction
- Common envelope!
- Outcome?
- Physics?

Nelemans et al. 2000,
Nelemans & Tout 2005



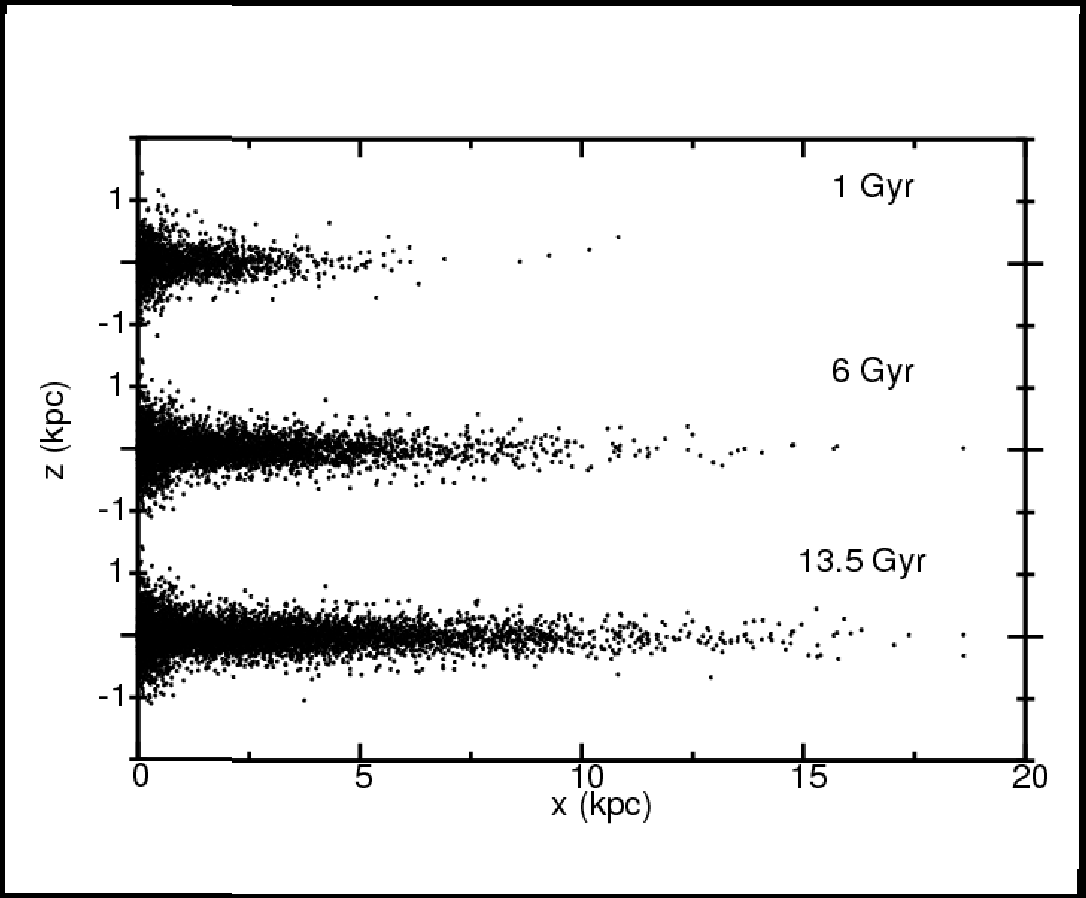
Tauris & van den Heuvel



Rates I: population synthesis

- Recipes for stellar and binary evolution (rapid)
  - Single stars: M,R,L,X,Mc,stellar wind(t) + remnant (supernova)
  - (tides),Mass transfer (stability, common envelope...)

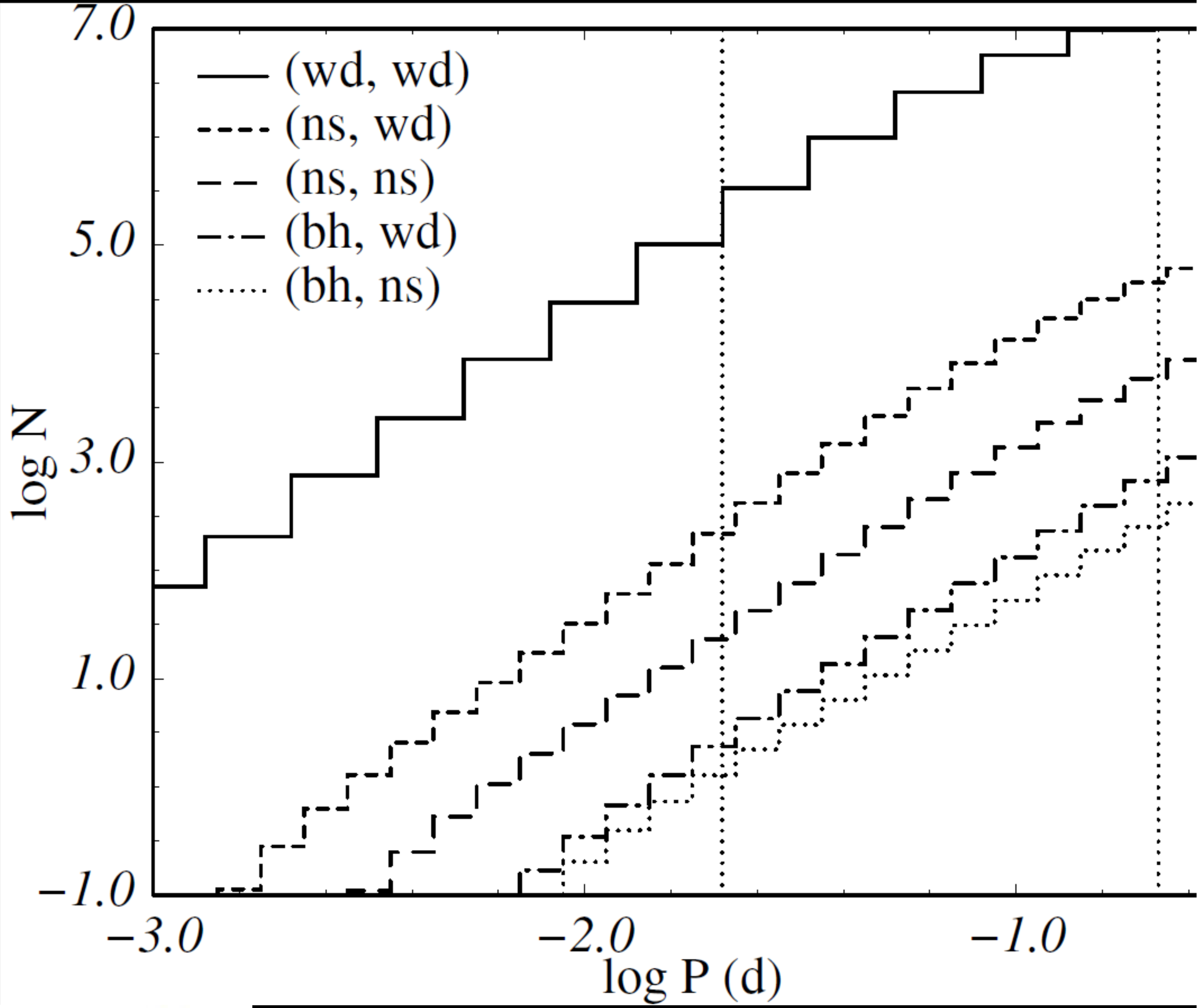
Portegies Zwart & Verbunt, 1996
Nelemans et al. 2001
Toonen et al., submitted



- Model for initial distributions
  - M1 (IMF)
  - m/M
  - P or a
- “Normalisation”
  (e.g. model for the star formation history)

Resulting numbers and merger rates

Type	ν	ν_{merg}	#
(wd, wd)	2.5×10^{-2}	1.1×10^{-2}	1.1×10^{8}
[wd, wd)	3.3×10^{-3}	–	4.2×10^{7}
(ns, wd)	2.4×10^{-4}	1.4×10^{-4}	2.2×10^{6}
(ns, ns)	5.7×10^{-5}	2.4×10^{-5}	7.5×10^{5}
(bh, wd)	8.2×10^{-5}	1.9×10^{-6}	1.4×10^{6}
(bh, ns)	2.6×10^{-5}	2.9×10^{-6}	4.7×10^{5}
(bh, bh)	1.6×10^{-4}	–	2.8×10^{6}



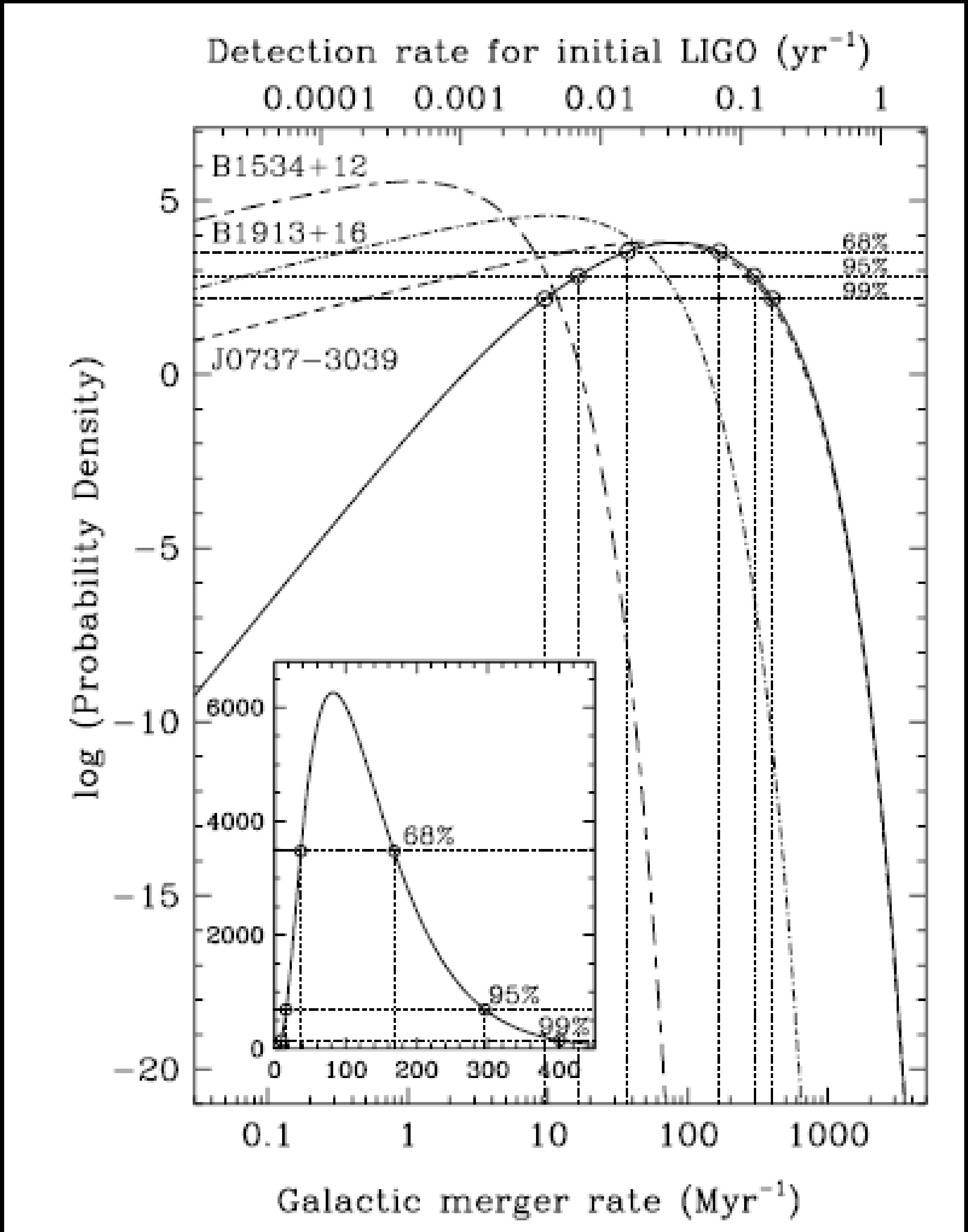
- Calculate birth/merger rates for typical galaxy
- Convert to LIGO/Virgo detection rates

Nelemans et al. 2001

Source	$N_{\text{low}}\, yr^{-1}$	$N_{\text{real}}\, yr^{-1}$	$N_{\text{high}}\, yr^{-1}$
NS+NS	0.4	40	400
NS+BH	0.2	10	300
BH+BH	0.4	20	1000

Abadie et al. 2010

Rates II: (individual) observed systems



- Double NS in the Galaxy
- Also information from progenitor binaries (X-ray binaries)
- Examples M100 X-1, IC 10 X-1

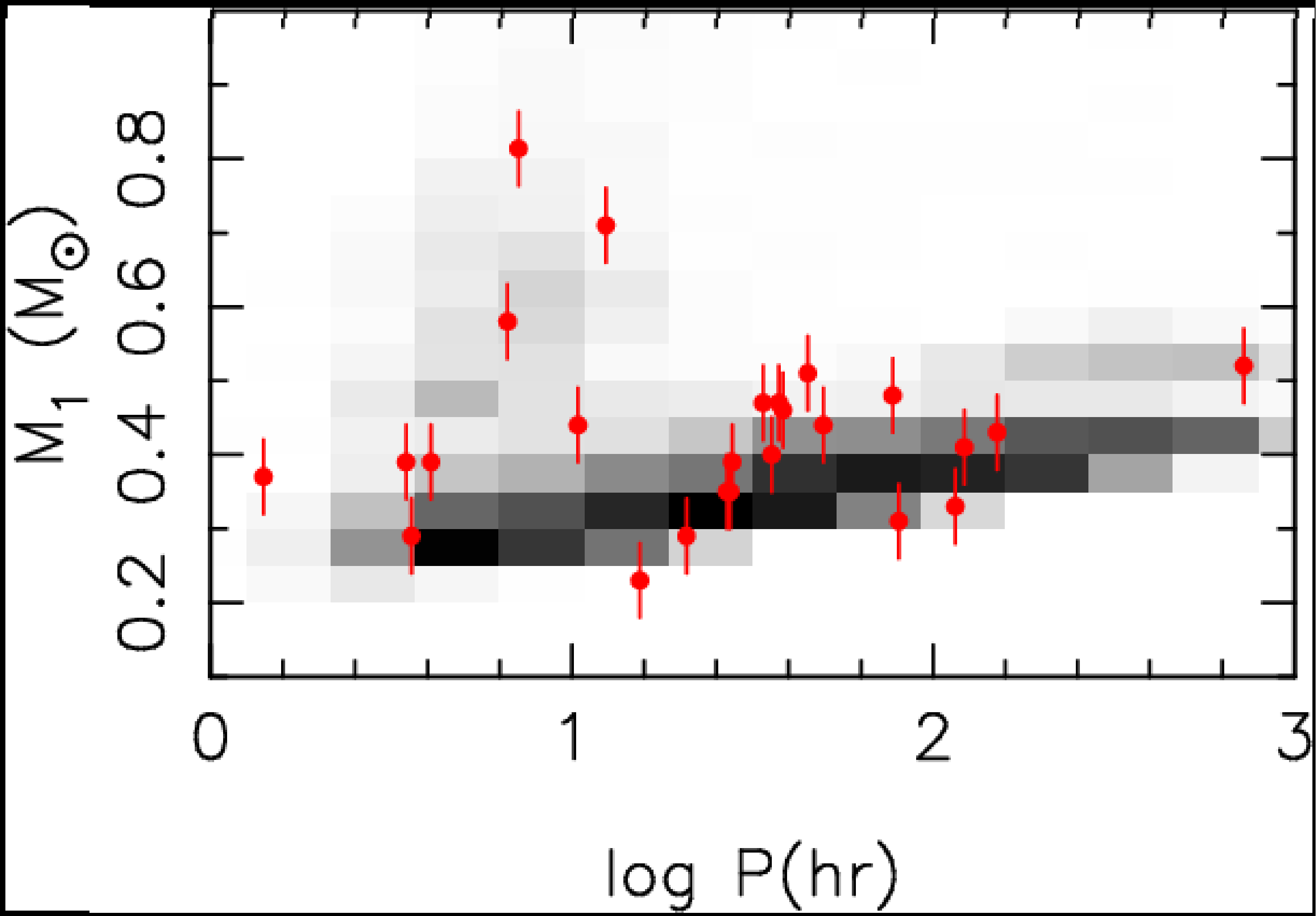
Kim et al.

One step further: compare with observations

- Double white dwarfs
- Total number: 100 million
- Birth rate: 1/50 years
- Merger rate: 1/125 years

- Including selection effects
- Reasonable agreement with observations (plot not up to date)

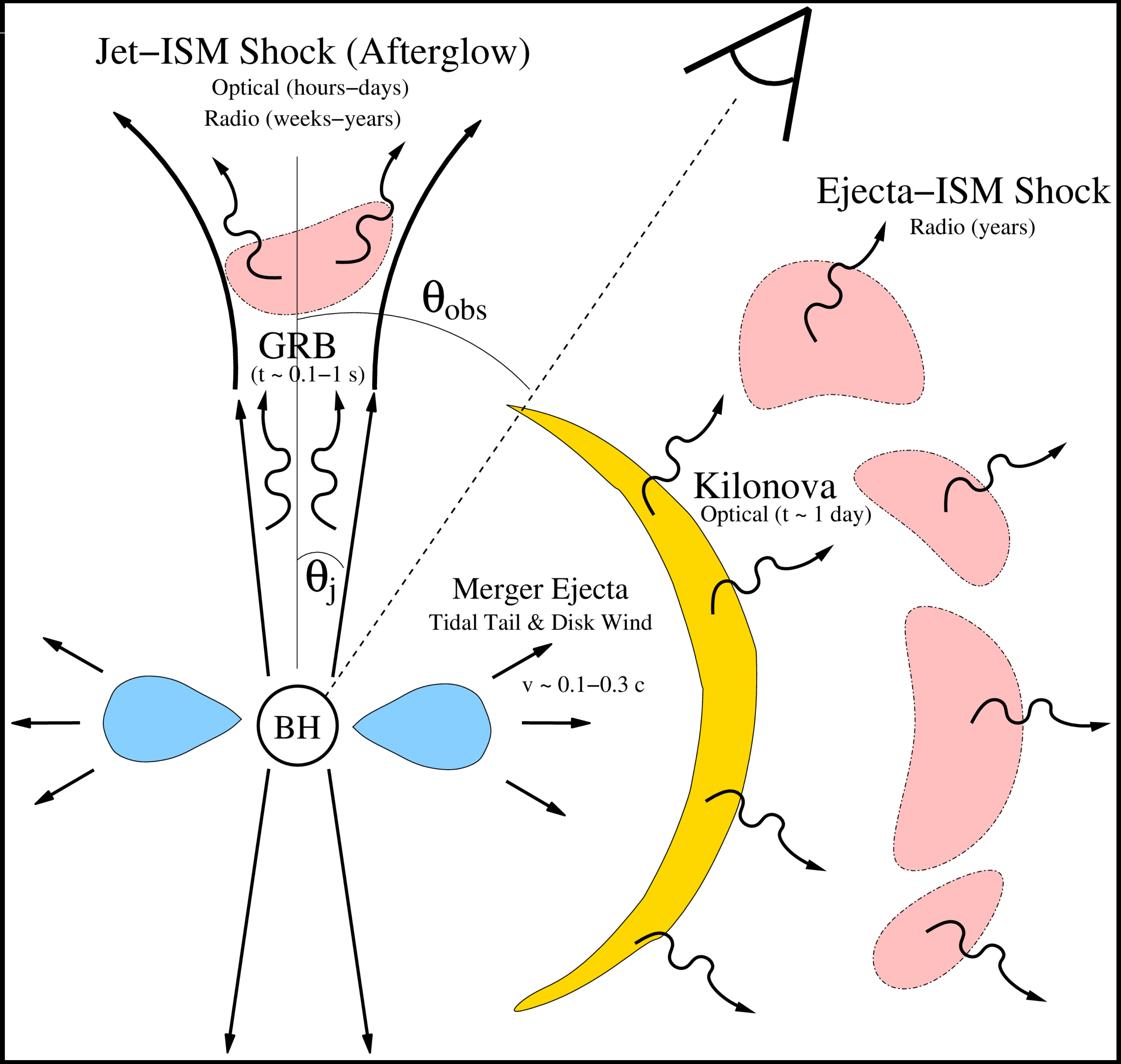
- *Next step: do the same for double NS*



Nelemans et al. 2001a,b, 2005

3 Dedicated complementary optical observations

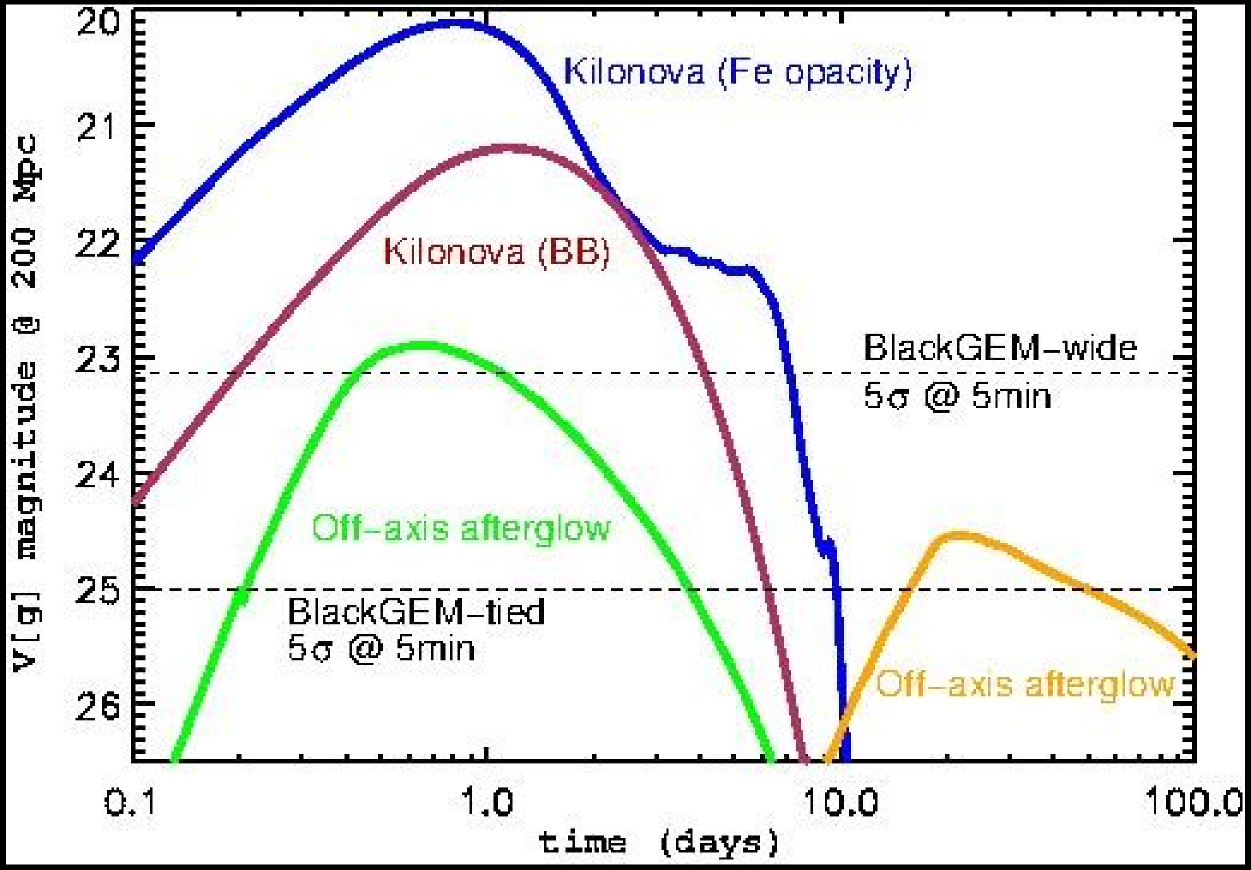
- Many GW sources have EM counterpart
- Gamma-ray burst? (beaming)
- Interaction with environment (radio, late)
- Radioactive material (kilonova)
- Advantage optical
  - Well known
  - Sensitive
  - Lots of additional information (redshift, environment etc.)



Metzger & Berger 2010, Narkar & Piran 2011

BlackGEM array

- Dedicated array of (15x0.5m) optical telescopes
- Chile (excellent site, complement PTF in north)
- Design studies at RU, contacts with ESO
- ERC proposal

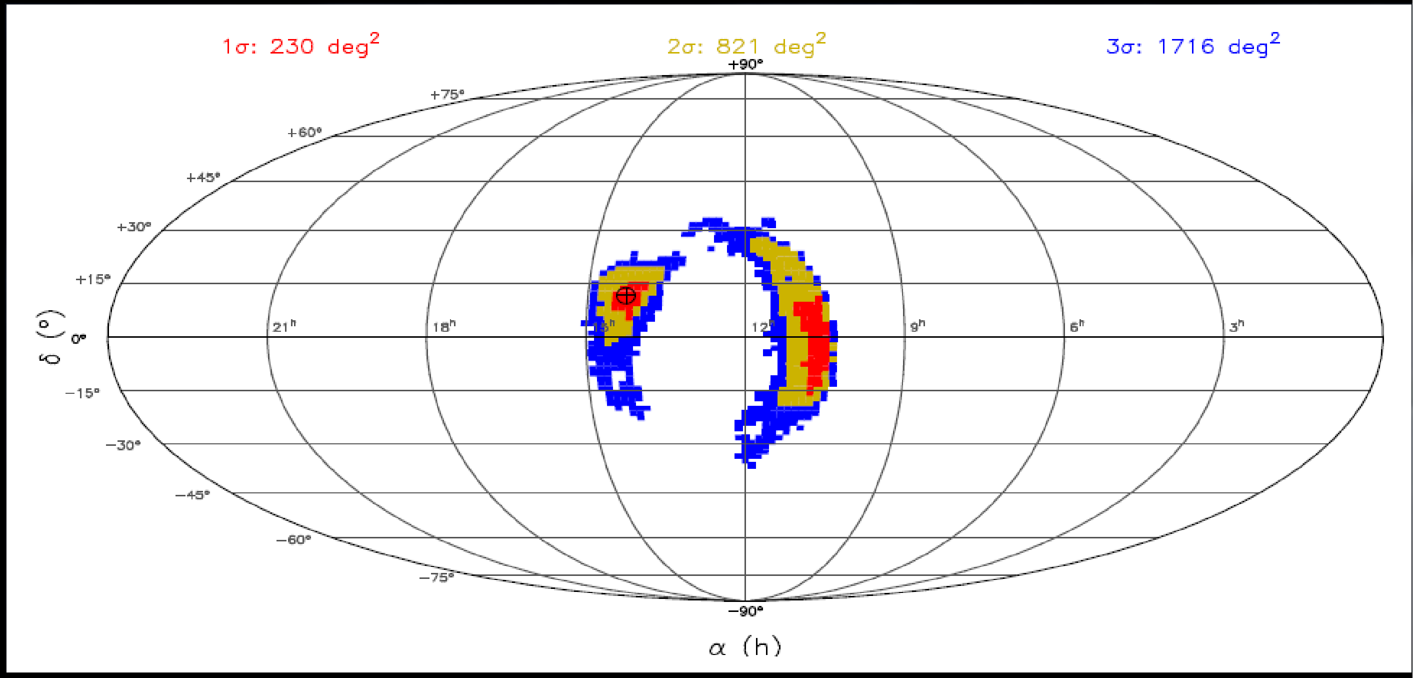


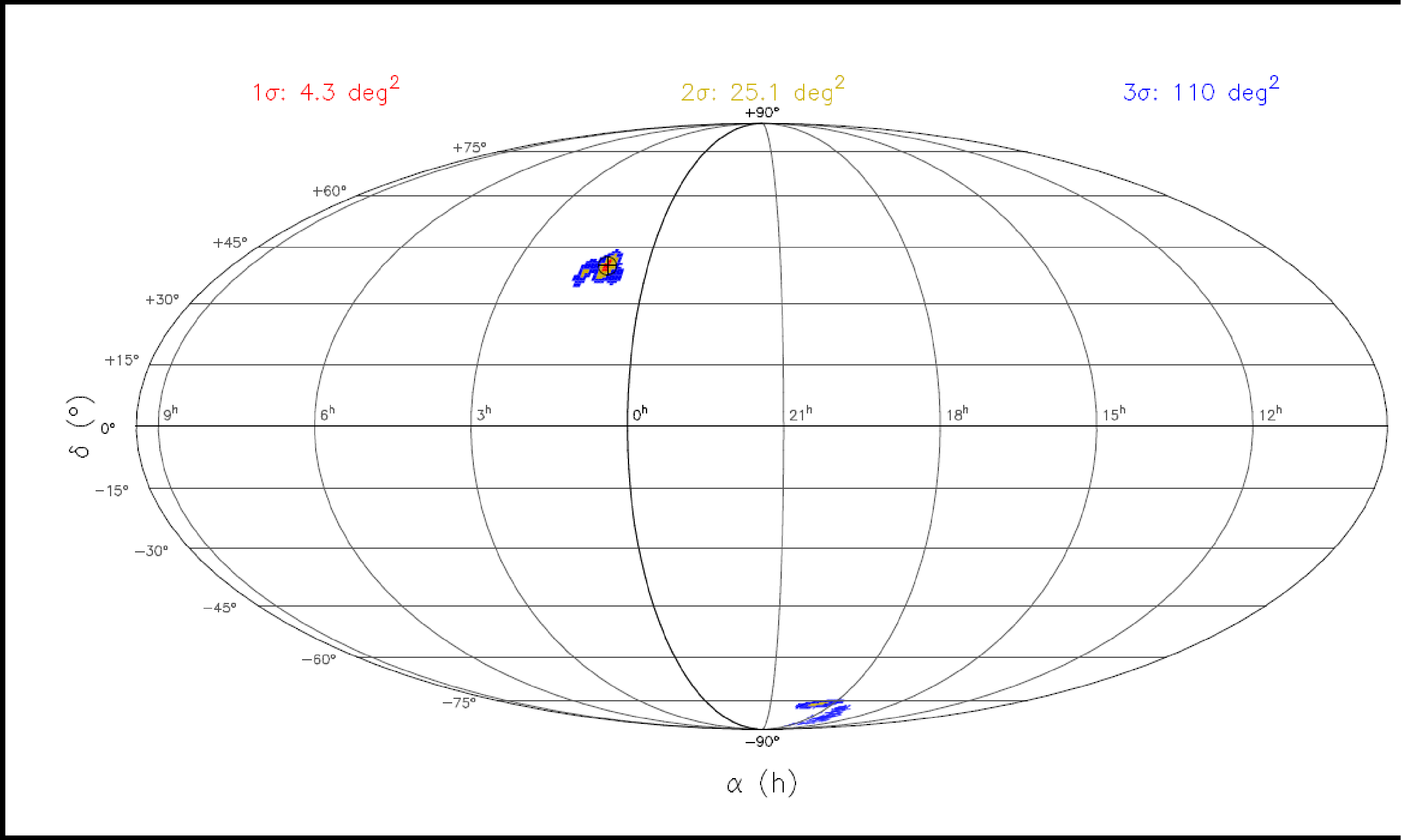
BlackGEM and Virgo

- Develop optimal observing strategies
  - Error box estimates (telescope design)
  - Possible optical signatures and their implication (NS or BH?)
  - Observing mode and speed
- Triggering
  - Collaboration with Urbino

4 Combining EM/GW data analysis

- Detect GW sources also with EM instruments
- Three uses
  - Aid first detections (confidence)
  - Lower trigger thresholds (more sources)
  - Complementary data

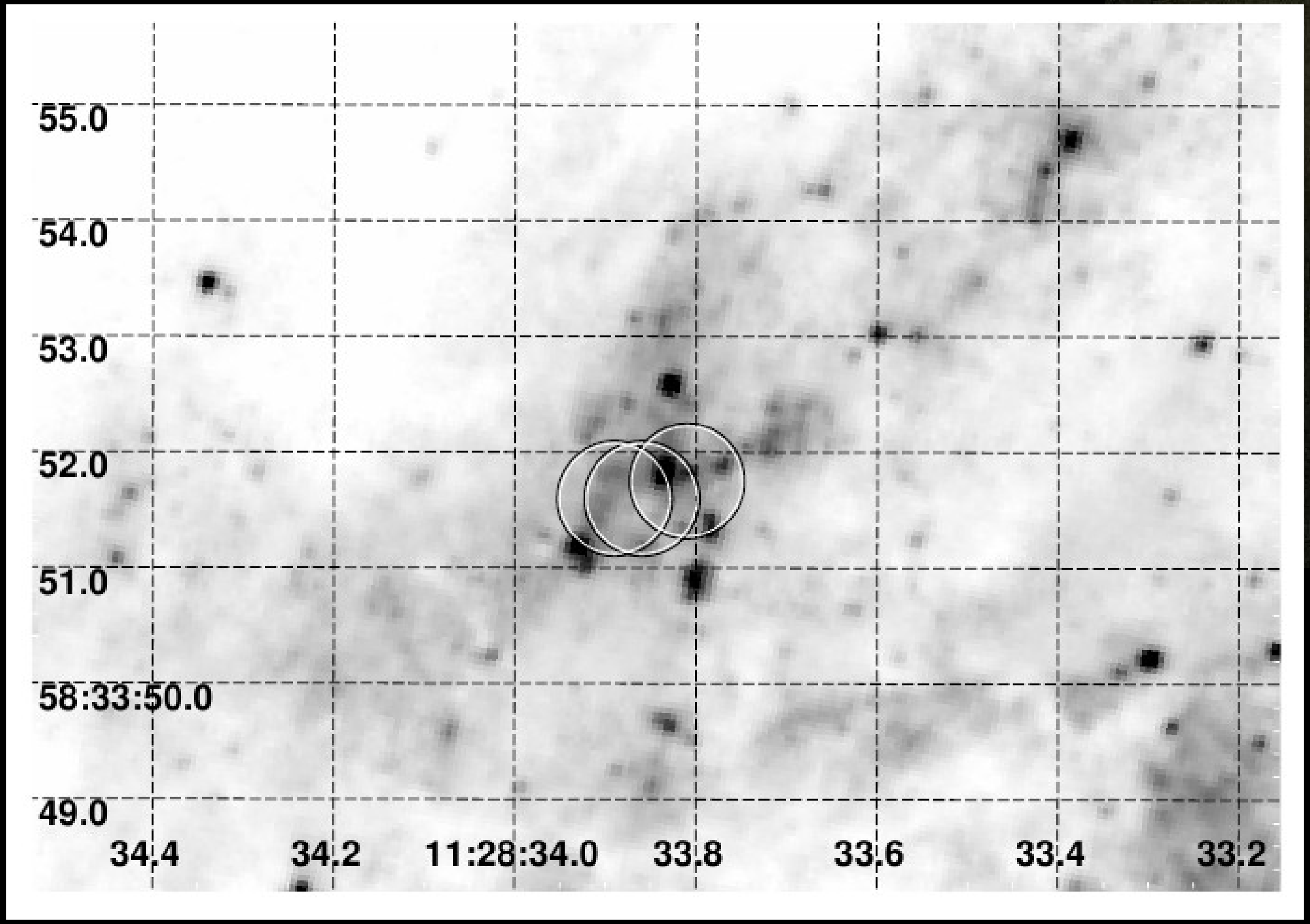




Van der Sluys et al. 2008; 2012

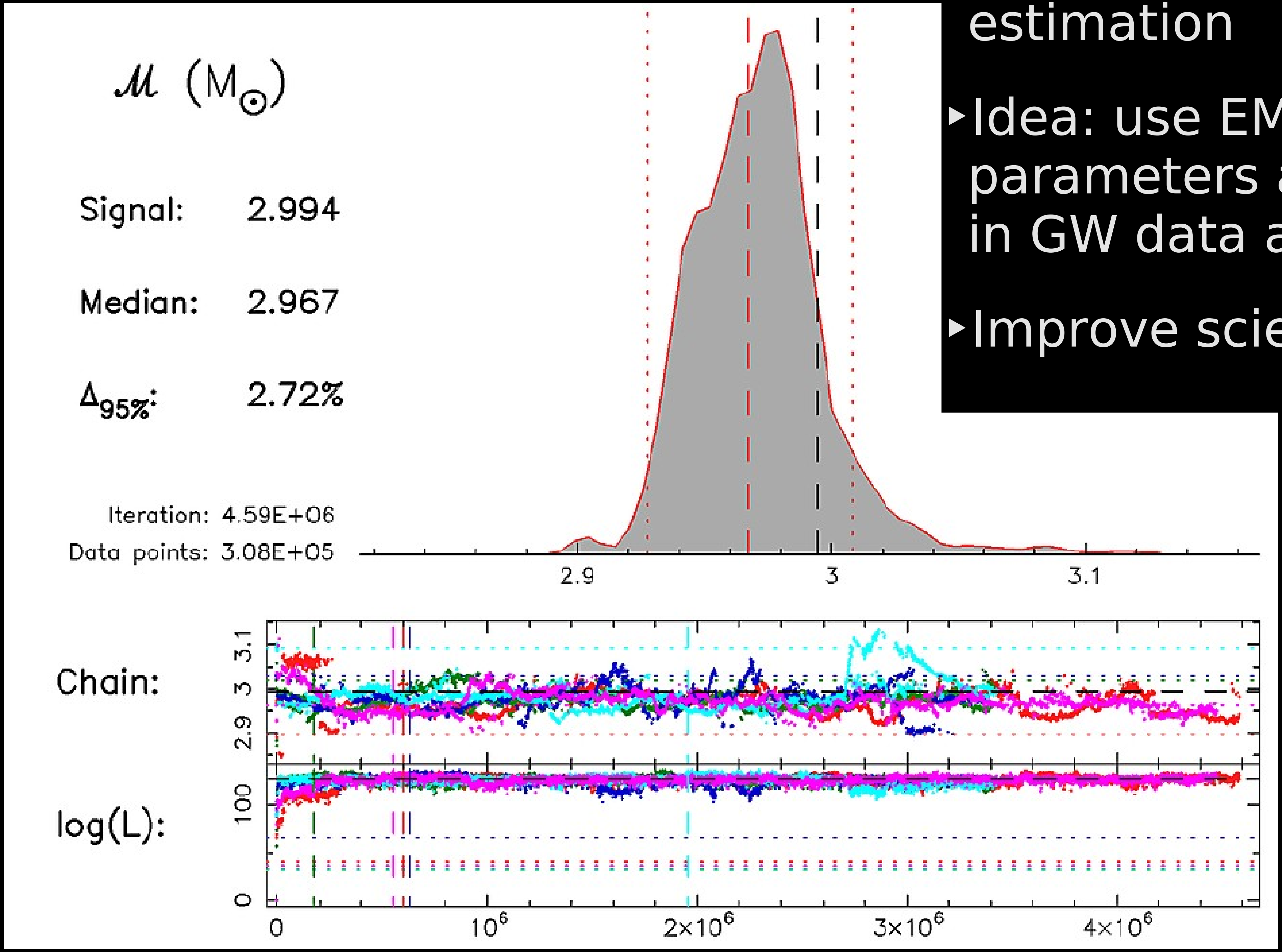
Complementary data I: host and environment

- Example: site of supernova SN2010O in Arp 299, Ibc supernova (GW progenitor?) close to youngish star cluster
- Detailed study of environment possible



Voss et al. 2011

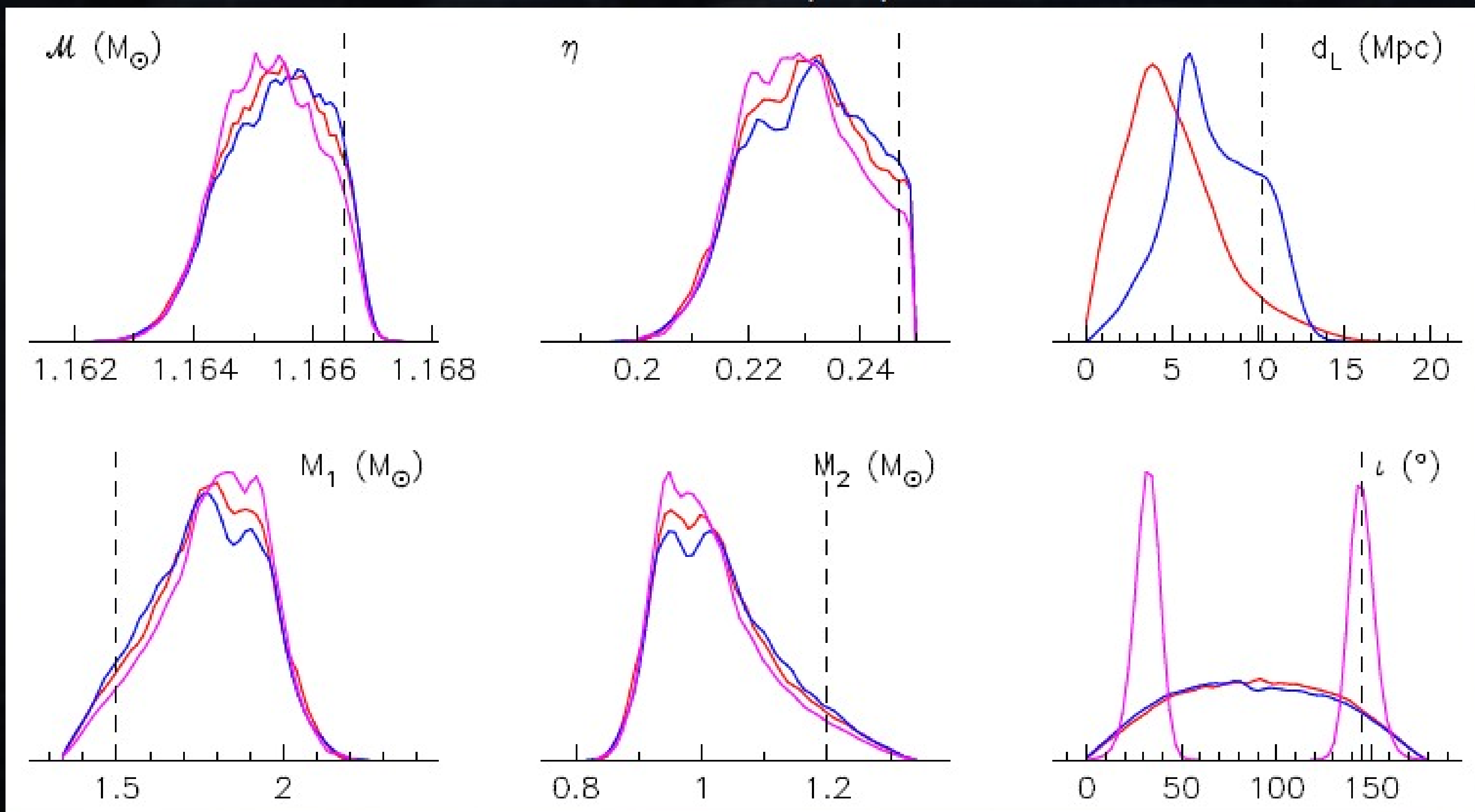
Complementary data II: joint analysis



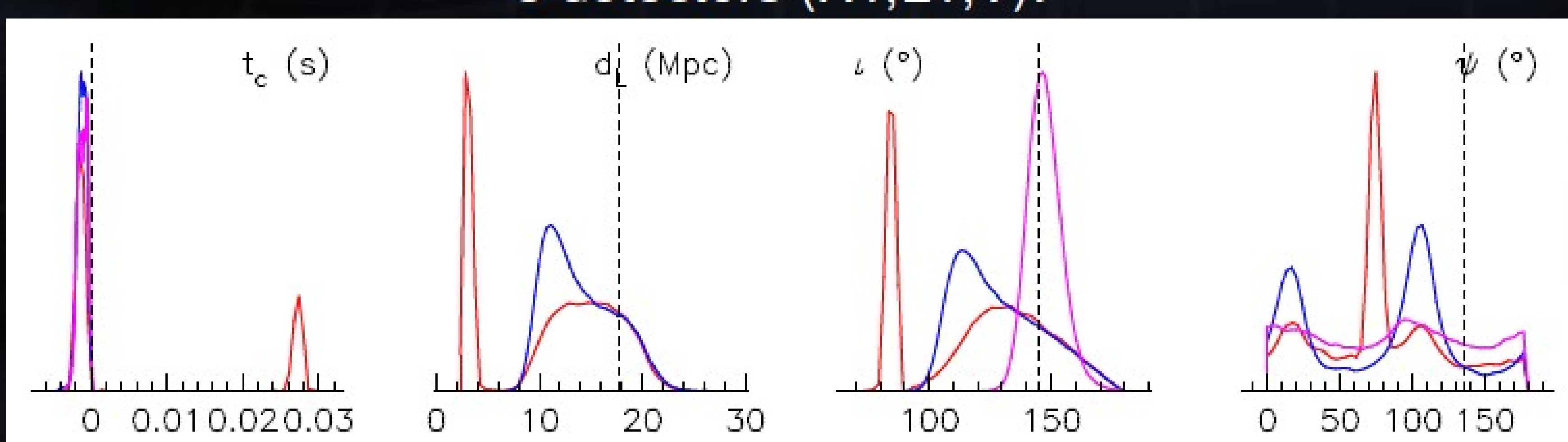
- Markov Chain Monte Carlo methods to do parameter estimation
- Idea: use EM data to constrain parameters and use as priors in GW data analysis
- Improve science!

Joint analysis: example I

1 detector (H1):



3 detectors (H1,L1,V):



NS-NS, non-spinning:
$1.2 + 1.5\,M_\odot$
$d_L \approx 10.2 - 17.8$ Mpc
(Σ SNR=15.0)

No astrophysical information

Sky position known

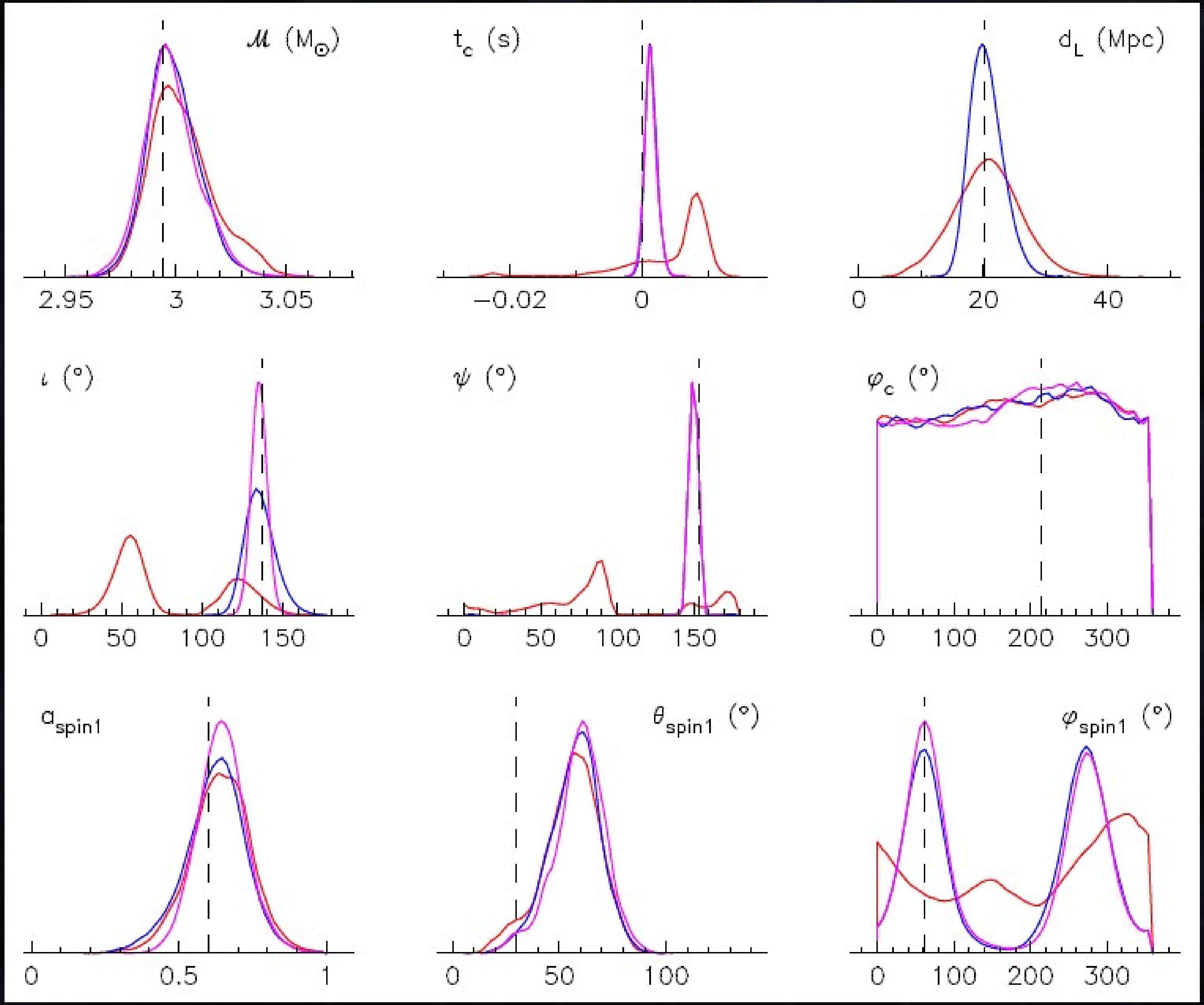
Sky position and distance known

van der Sluys et al., in preparation

See also: **Nissanke et al., 2010**

Joint analysis: example II

2 detectors (H1,L1):



BH-NS, spinning BH:
$10 + 1.4\,M_\odot$, $a_{\rm spin} = 0.6$
$d_L \approx 20.2$ Mpc (Σ SNR=15.0)

No astrophysical information

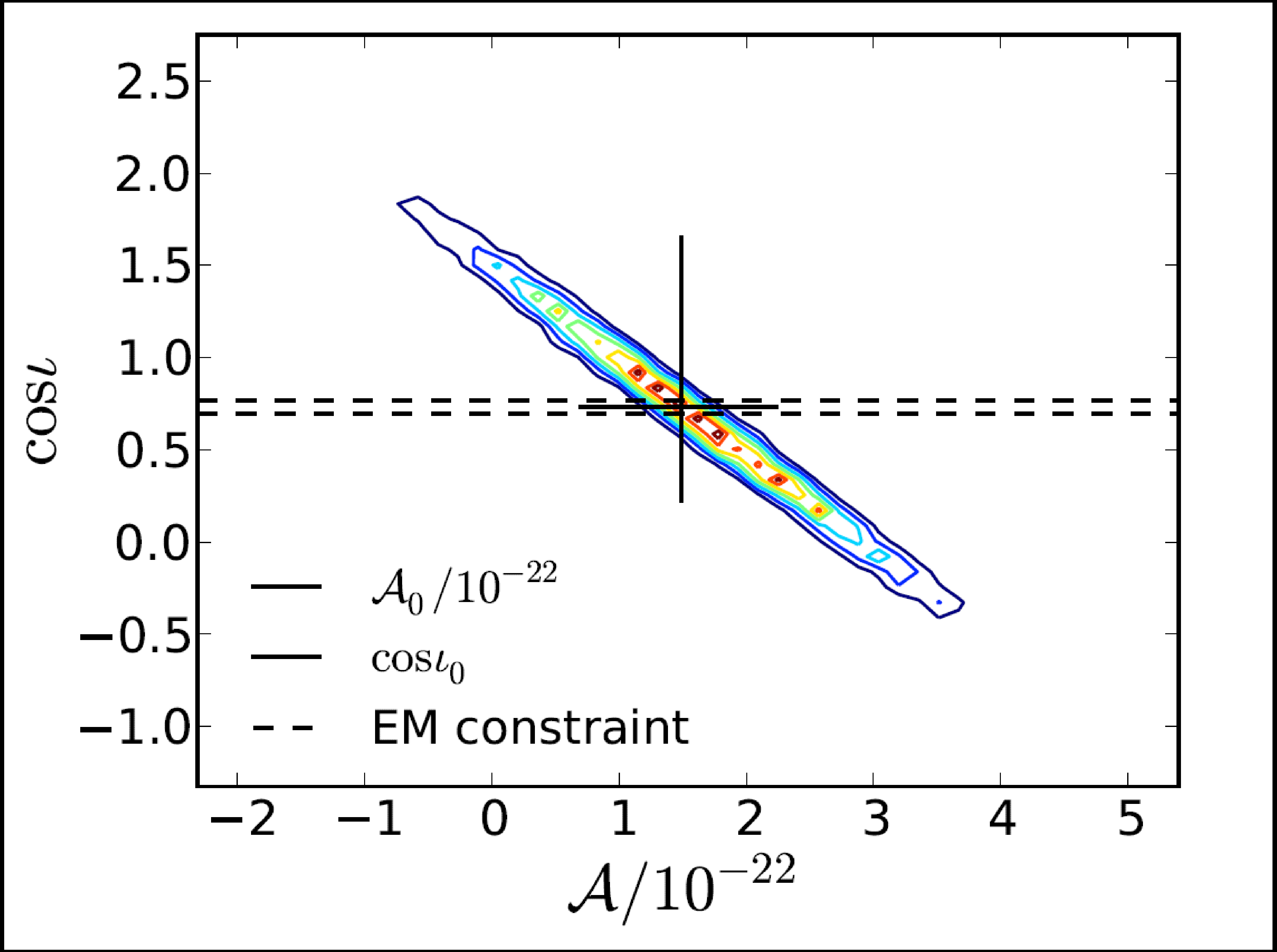
Sky position known

Sky position and distance known

van der Sluys et al., in preparation

Joint analysis: example III

- Example from low-frequency source (eLISA verification binary)



Shah et al. In prep

NL in Virgo, Virgo in NL

- Nikhef and VU groups: hardware, data analysis
- Radboud University: data analysis, optical obs, astrophysics
- Dutch situation: Physics and Astronomy
  - Separate communities
  - Separate organisation
  - Separate funding (FOM, NWO-EW, NOVA)
- Astroparticle physics: Cosmic rays, Gravitational waves (Neutrino's)
- Gravitational wave research currently mostly funded via Physics (FOM)
- Virgo membership astronomy dept would politically be good
- Astronomy members (politically) good for Virgo!?

Conclusions

- Many reasons to do GW science, also astrophysics
- Virgo sources
  - Tracers massive star evolution, formation NS, BH
  - Constrain binary evolution, merger outcomes
- Study of binary populations useful now and together with GW data
- Dedicated optical telescope (array) big advantage
- Combining GW and EM data useful in many respects
  - Intricate connection, not just sending out triggers, but collaborate!
- Initial efforts to study joint data analysis
  - Promising, but again collaboration needed
- Astronomy department joining might be good for Virgo