LIGO + multi-messenger astrophysics:

how can we get the most out of observations?

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Lake Louise Winter Institute | February 21, 2017

End of the road.

Multimessenger astrophysics with gravitational waves

Gravitational waves:

black hole / neutron star

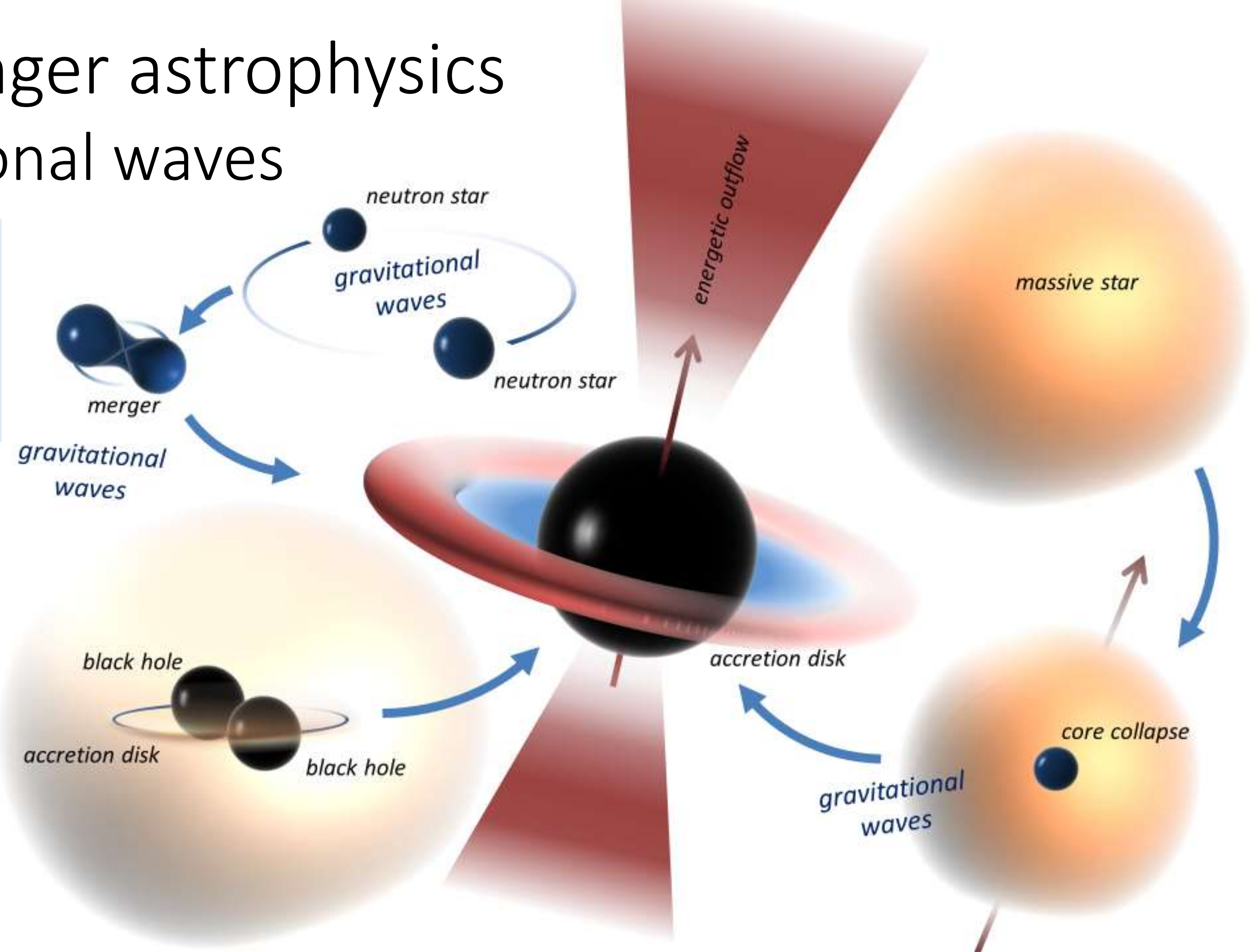
formation / evolution

Powerful transients:

1. compact binary merger
2. core collapse supernova

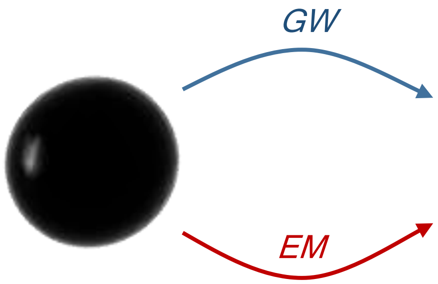
Goals:

1. Detect more
2. Learn more

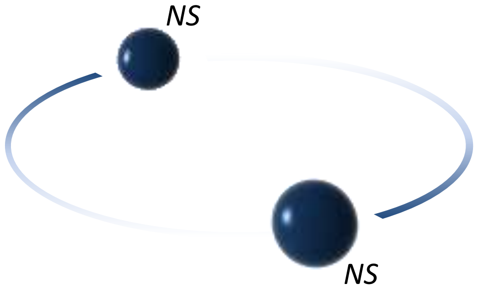


science targets

PHYSICS

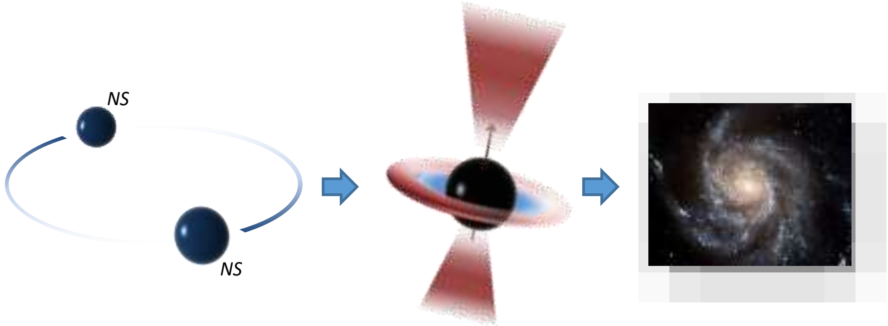


speed of gravity



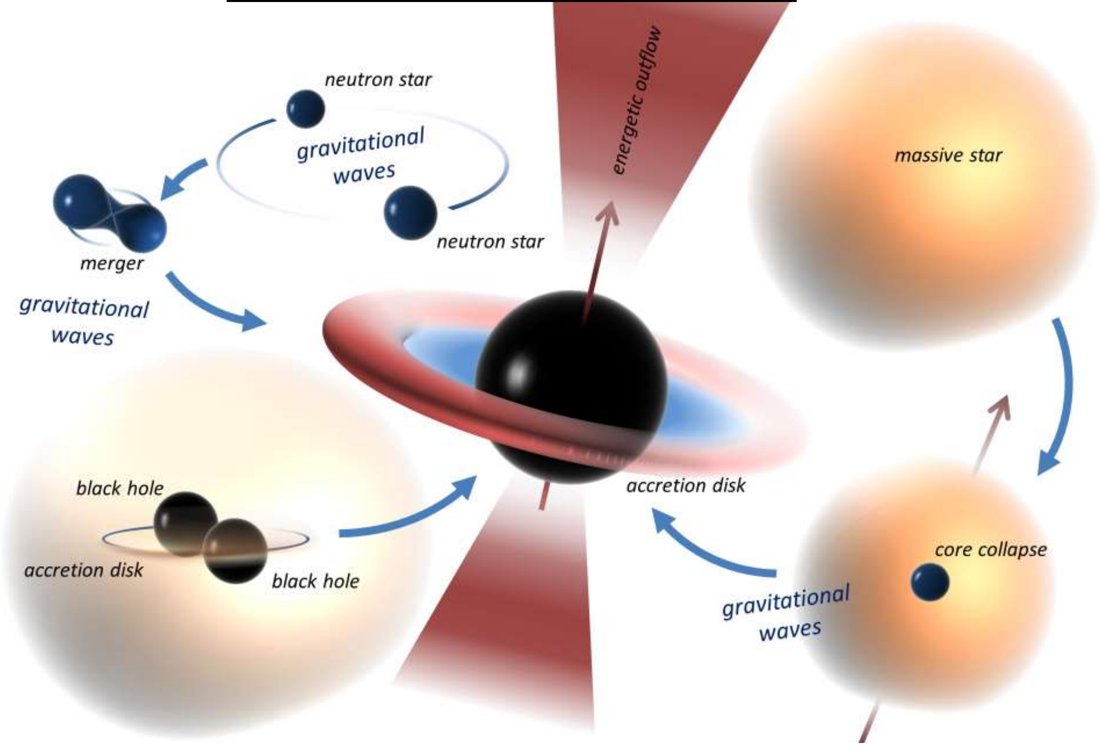
Equation of state of supranuclear matter

COSMOLOGY



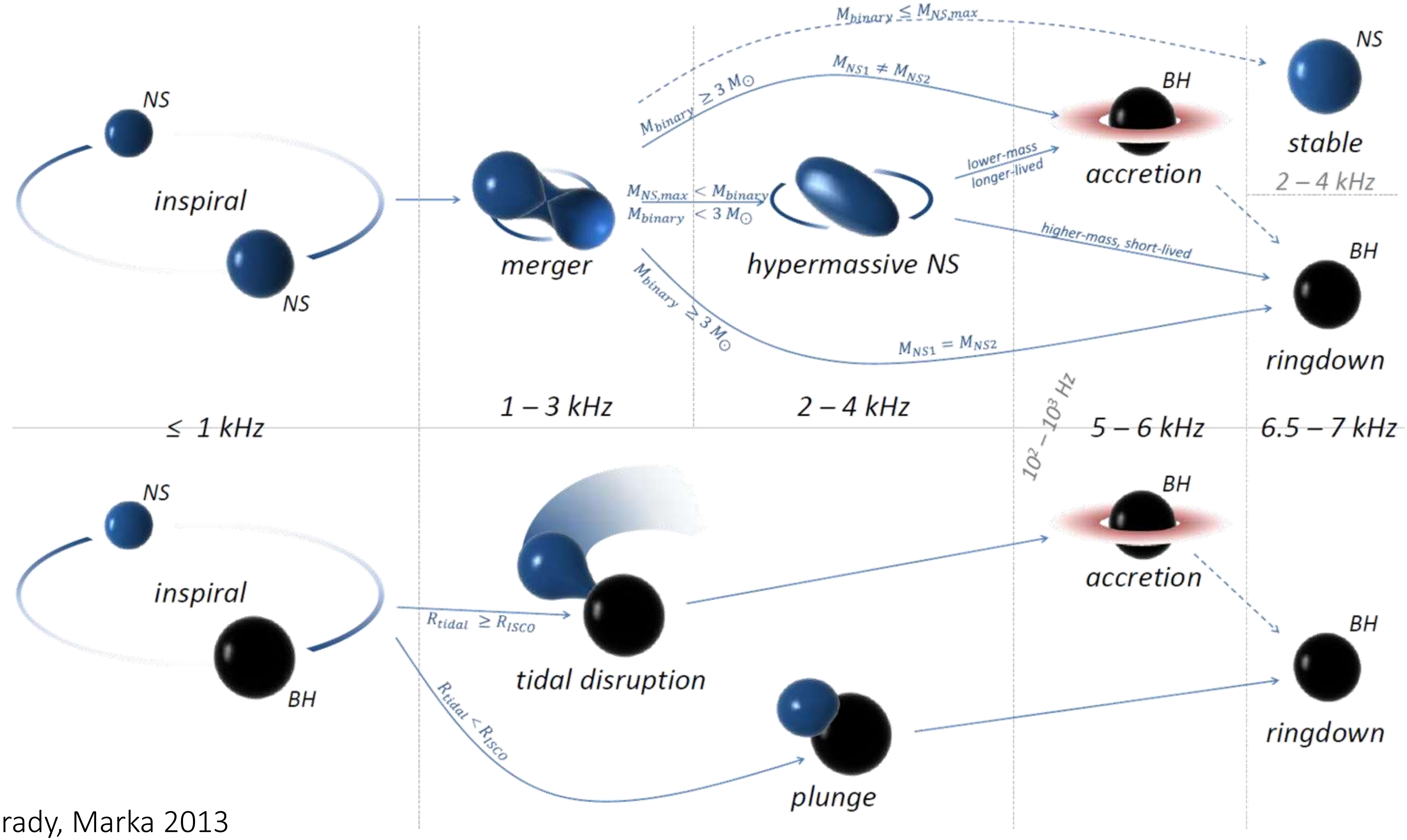
Alternative distance ladder

ASTROPHYSICS



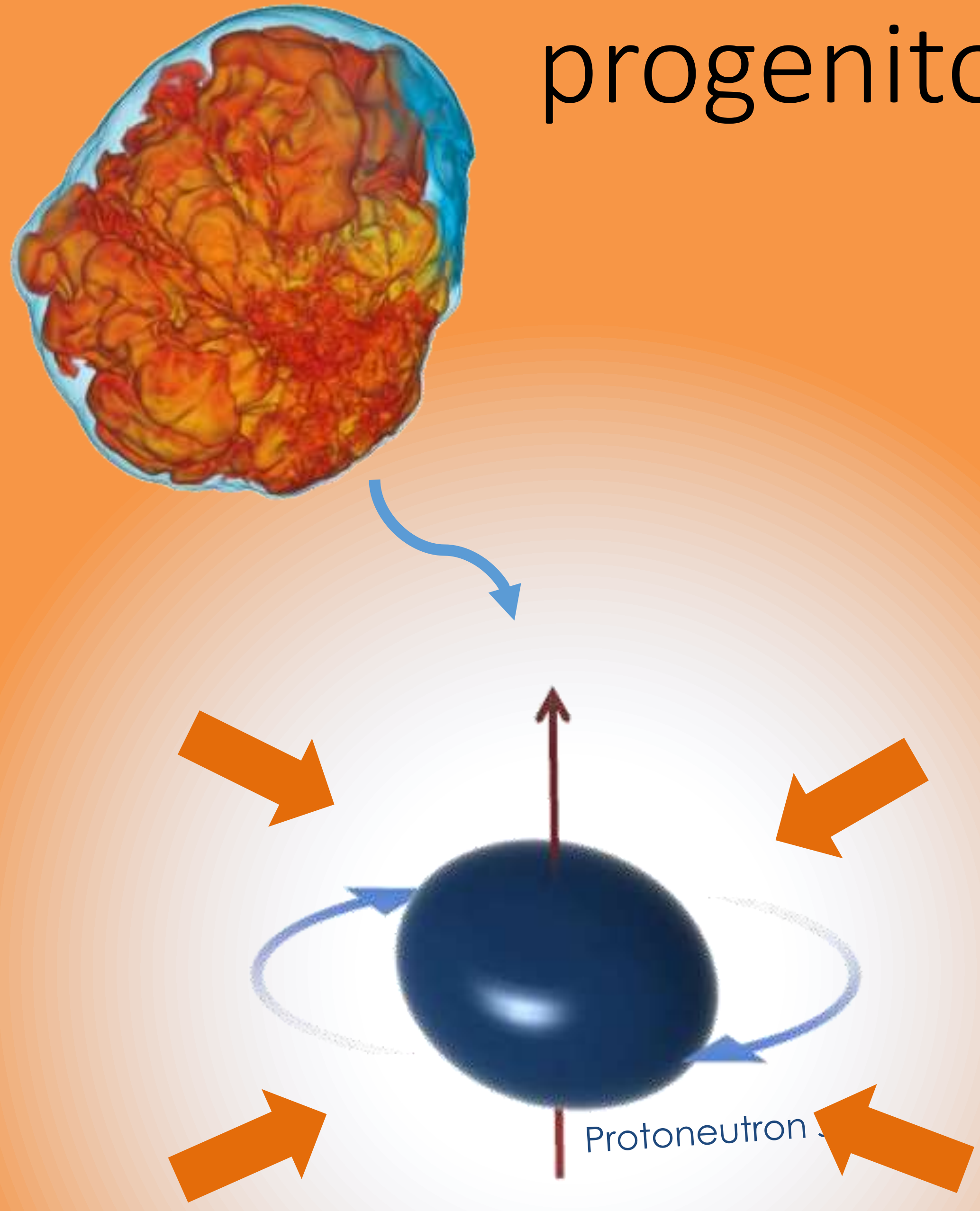
- *Black hole accretion*
- *Binary formation channels*
- *High-energy particle acceleration*
- *Origin of heavy nuclei*
- *…*

progenitor: neutron star mergers



Bartos, Brady, Marka 2013

progenitor: core-collapse supernova
(rapidly rotating core)



Bartos, Brady, Marka 2013

GWs from rapidly rotating cores?

Relevant distance scale:

Low-luminosity GRB / CCSN with jets: 10^2-10^3 Gpc^{-3} yr^{-1}
(Guetta & della Valle 2006; Soderberg+ Nature 2010)

(Beaming factor ~ 10)

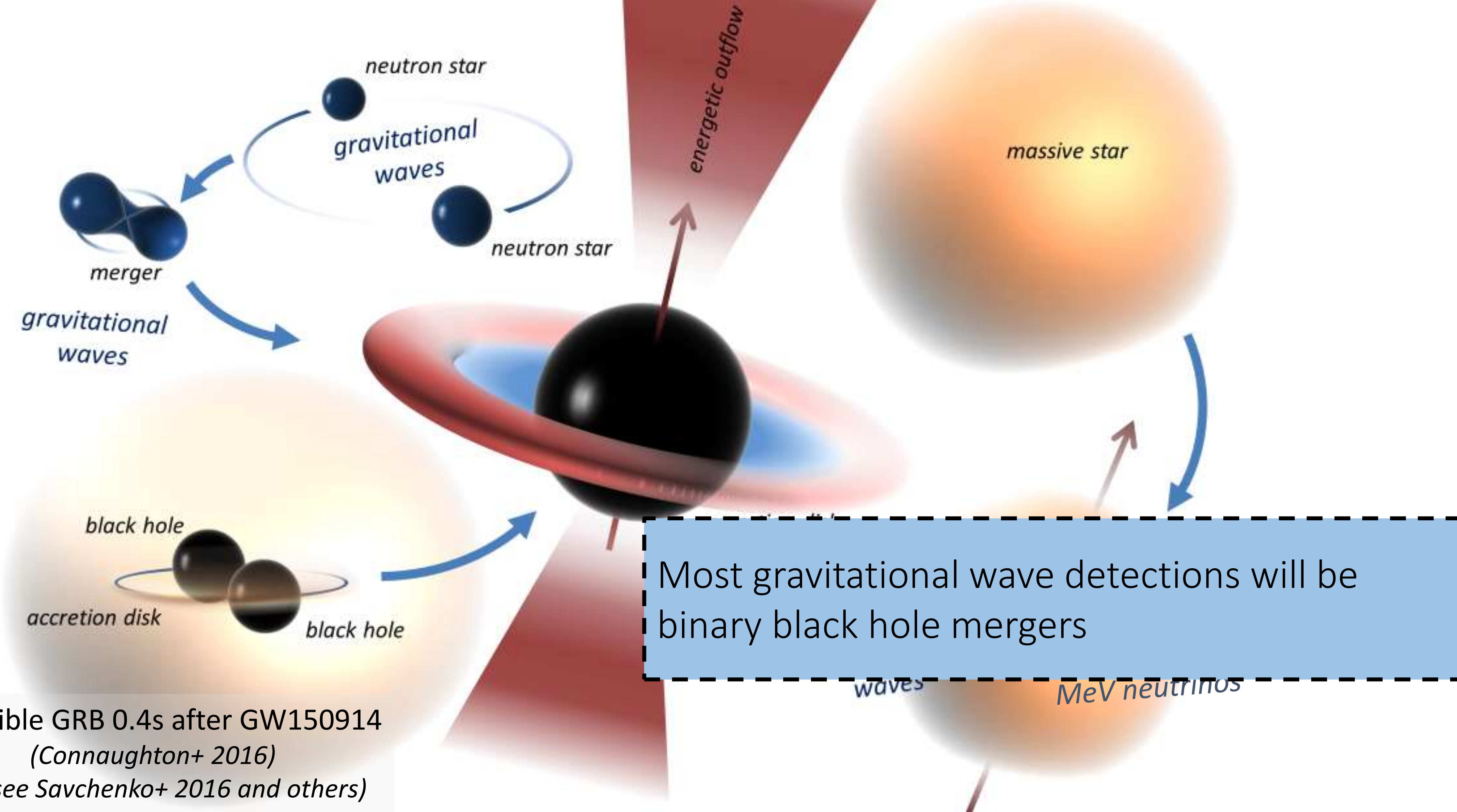
→ 50-100 Mpc

Differential rotation (e.g. Corvino+ 2010)

- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

Fallback accretion? *(Piro, Thrane, 2012)*

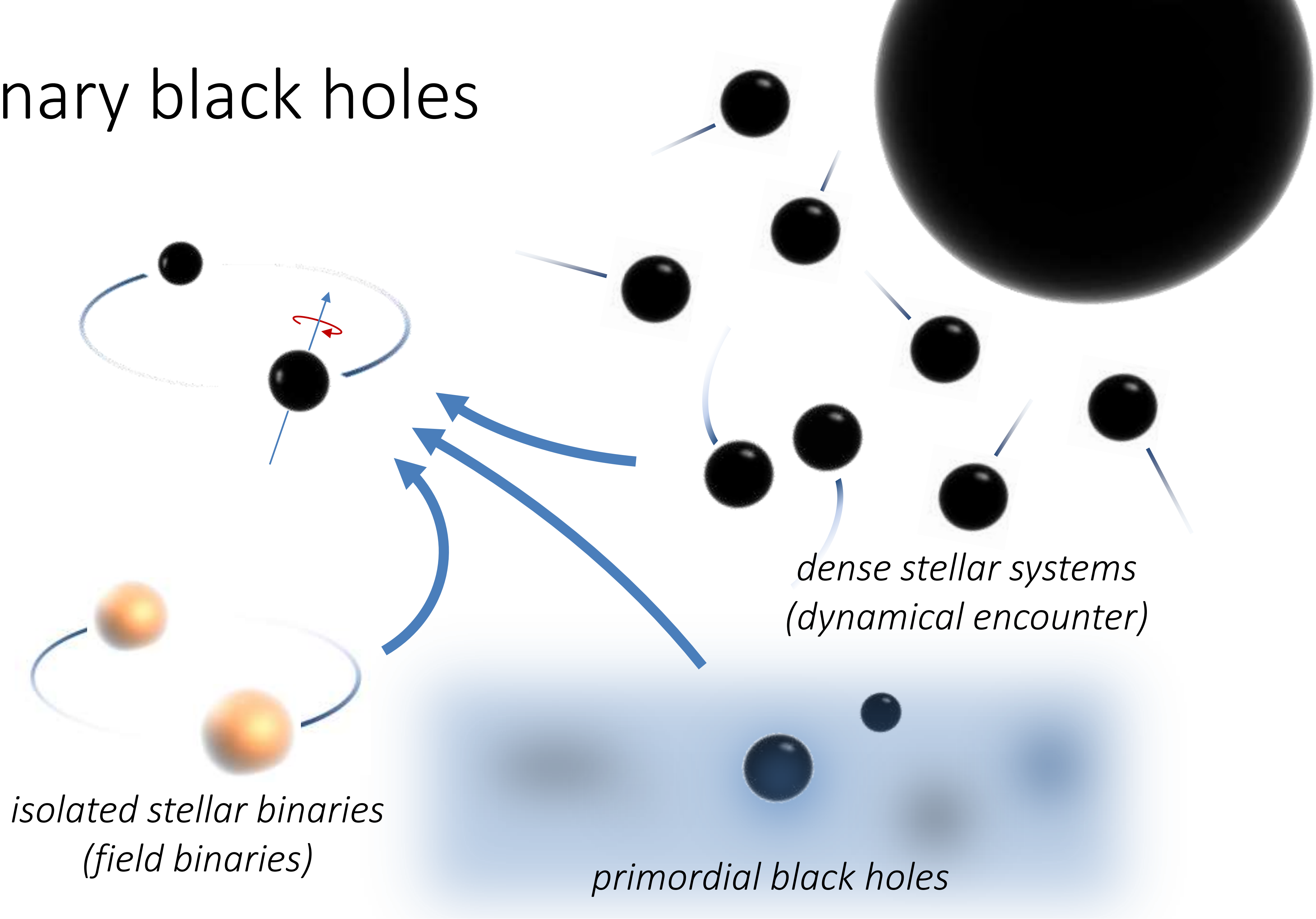
black hole mergers as multimessenger sources?



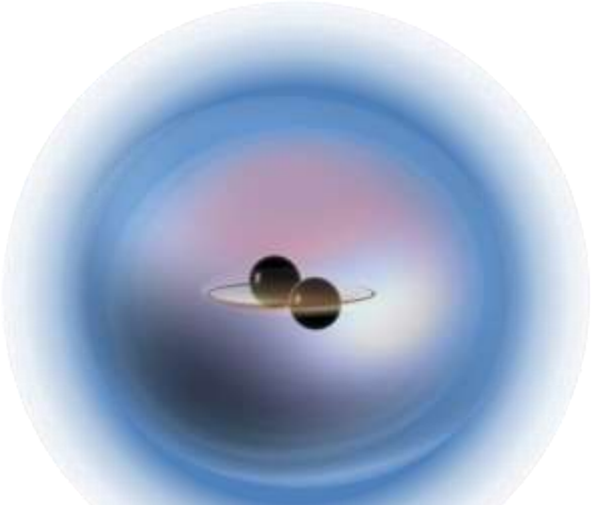
Most gravitational wave detections will be binary black hole mergers

Fermi-LAT possible GRB 0.4s after GW150914
(Connaughton+ 2016)
(but see Savchenko+ 2016 and others)

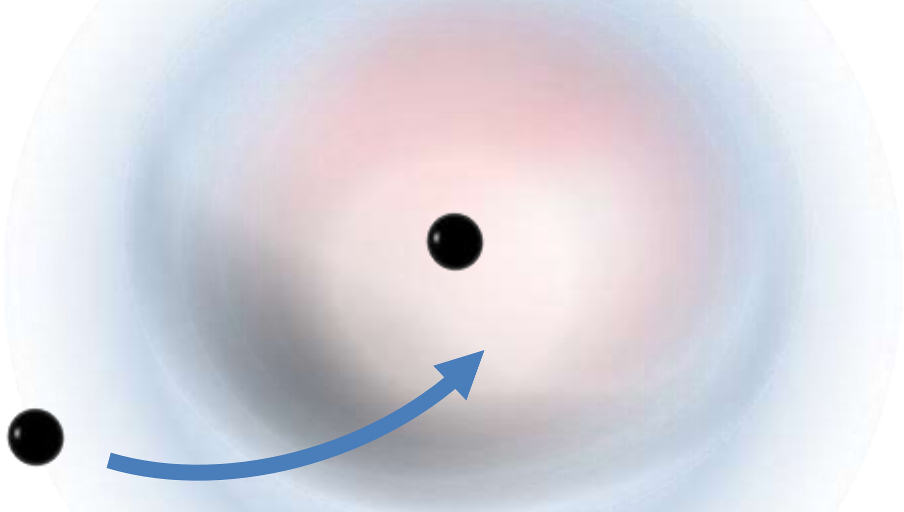
binary black holes



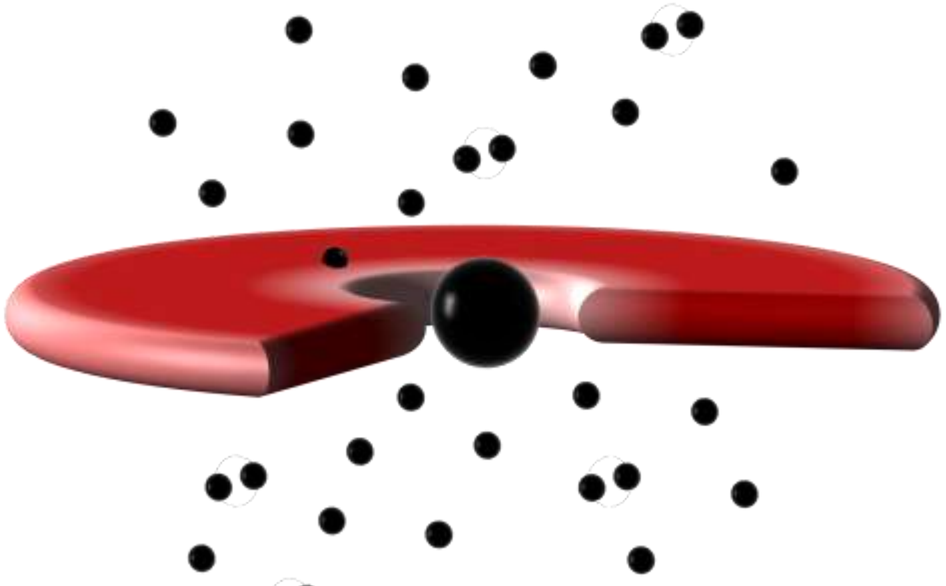
possible source of dense environment



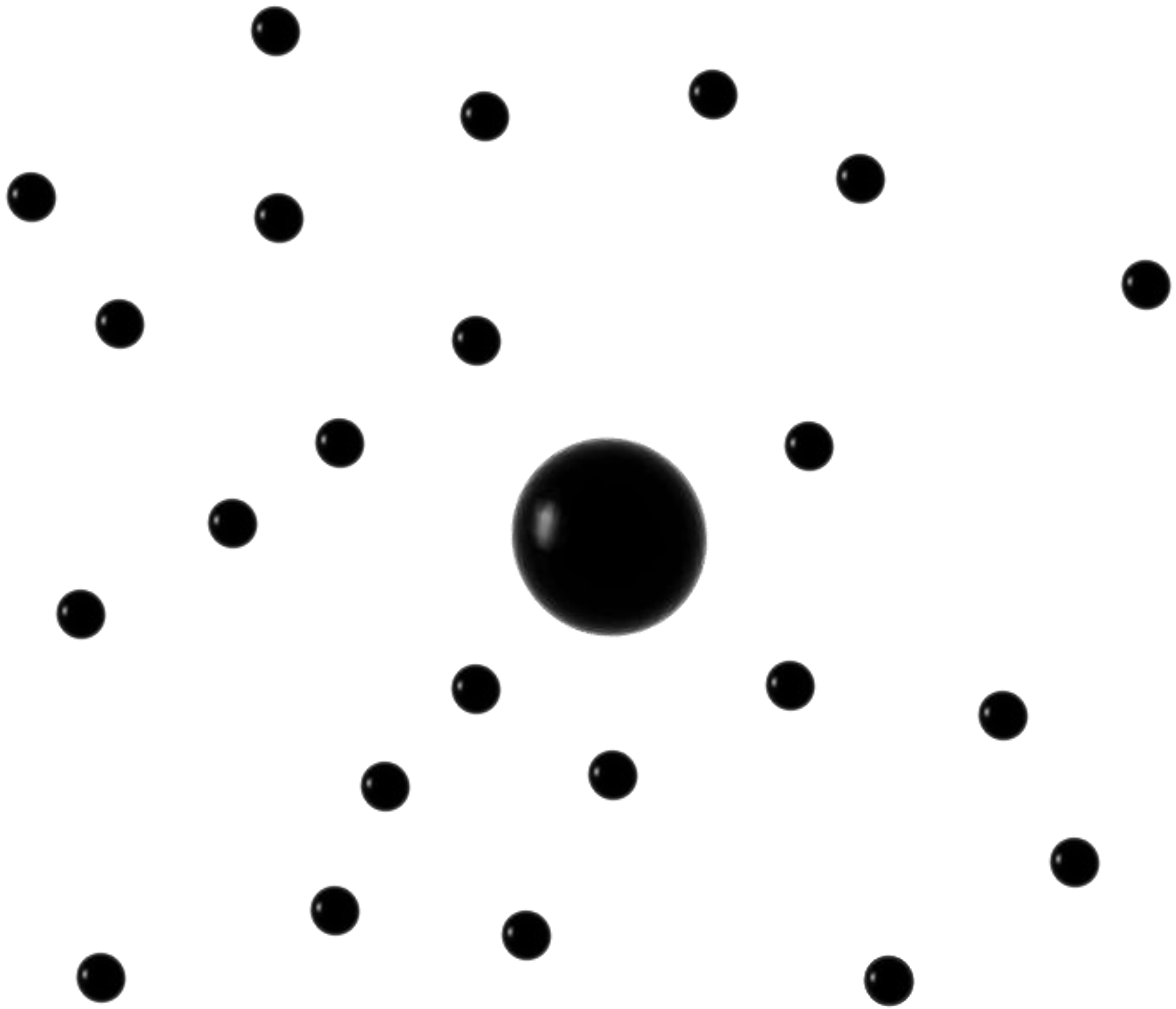
Stellar core collapse: collapsing core clumps
(Loeb 2016)



Gas remains from stellar progenitor
(Perna+ 2016)

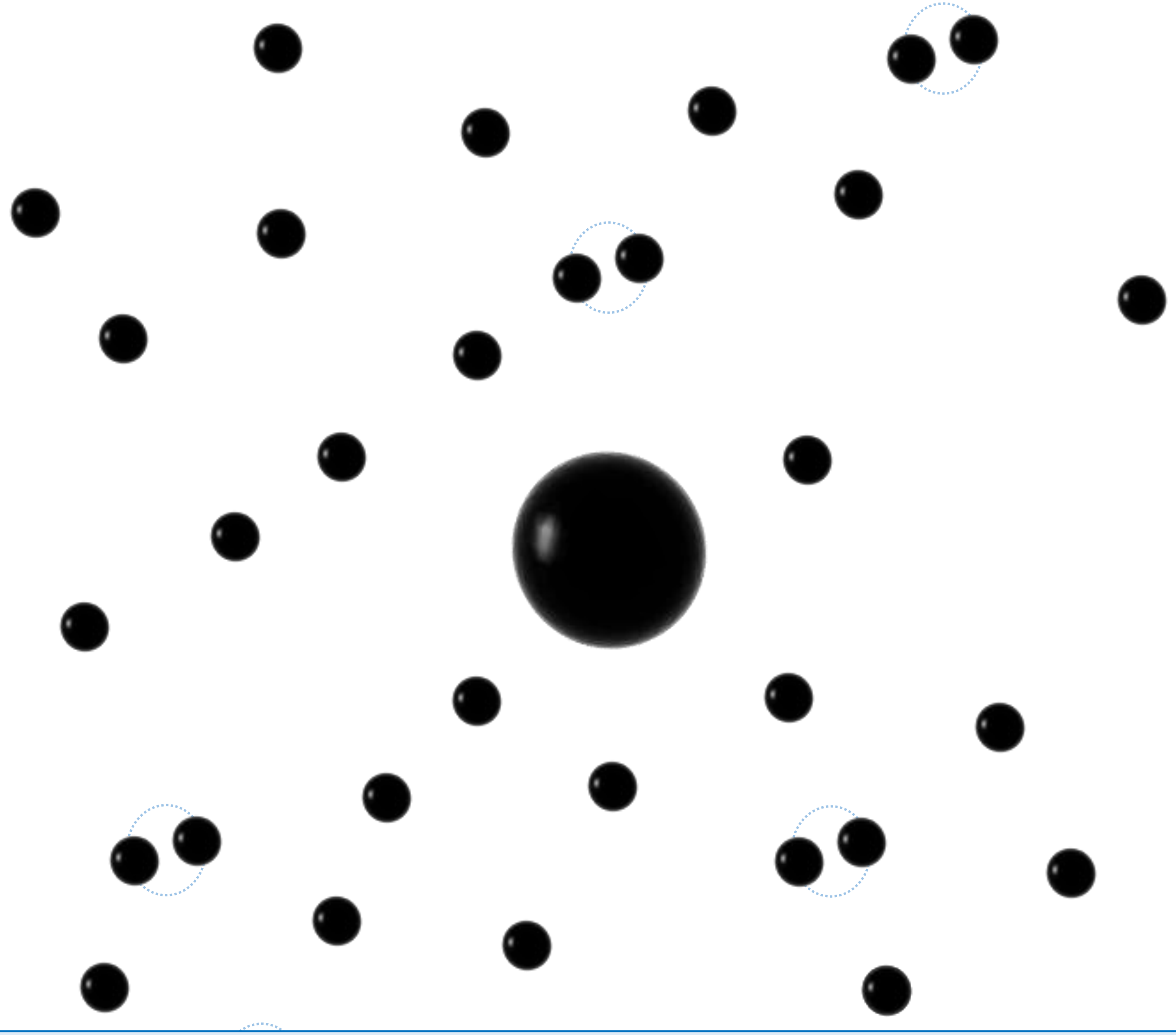


Black holes form/reside/move into dense environment
(Bartos+ 2016, Stone+ 2016)



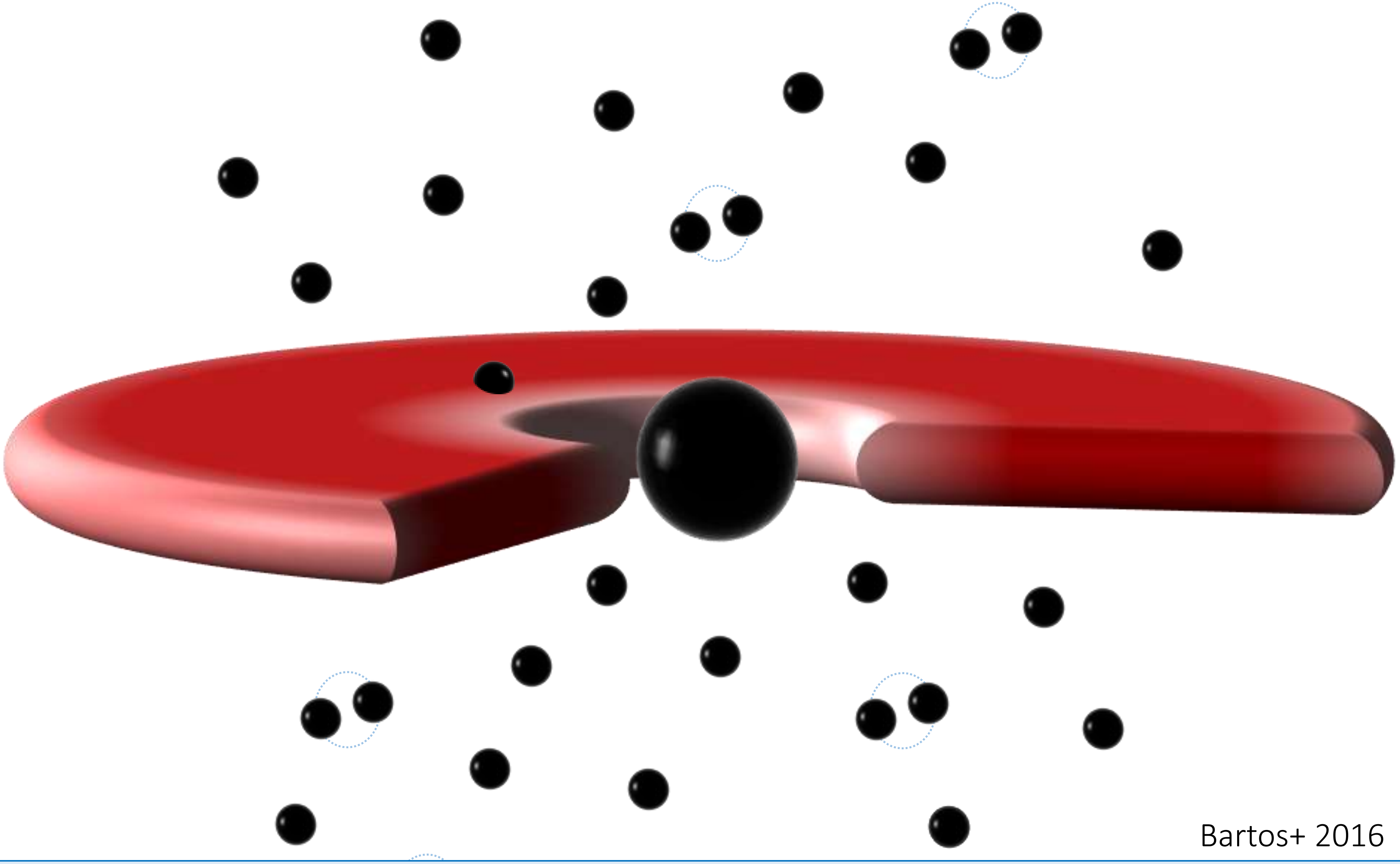
Bartos+ 2016

Galactic centers may harbor thousands of stellar mass black holes within the inner parsec (Morris 1993, O’Leary+ 2009).

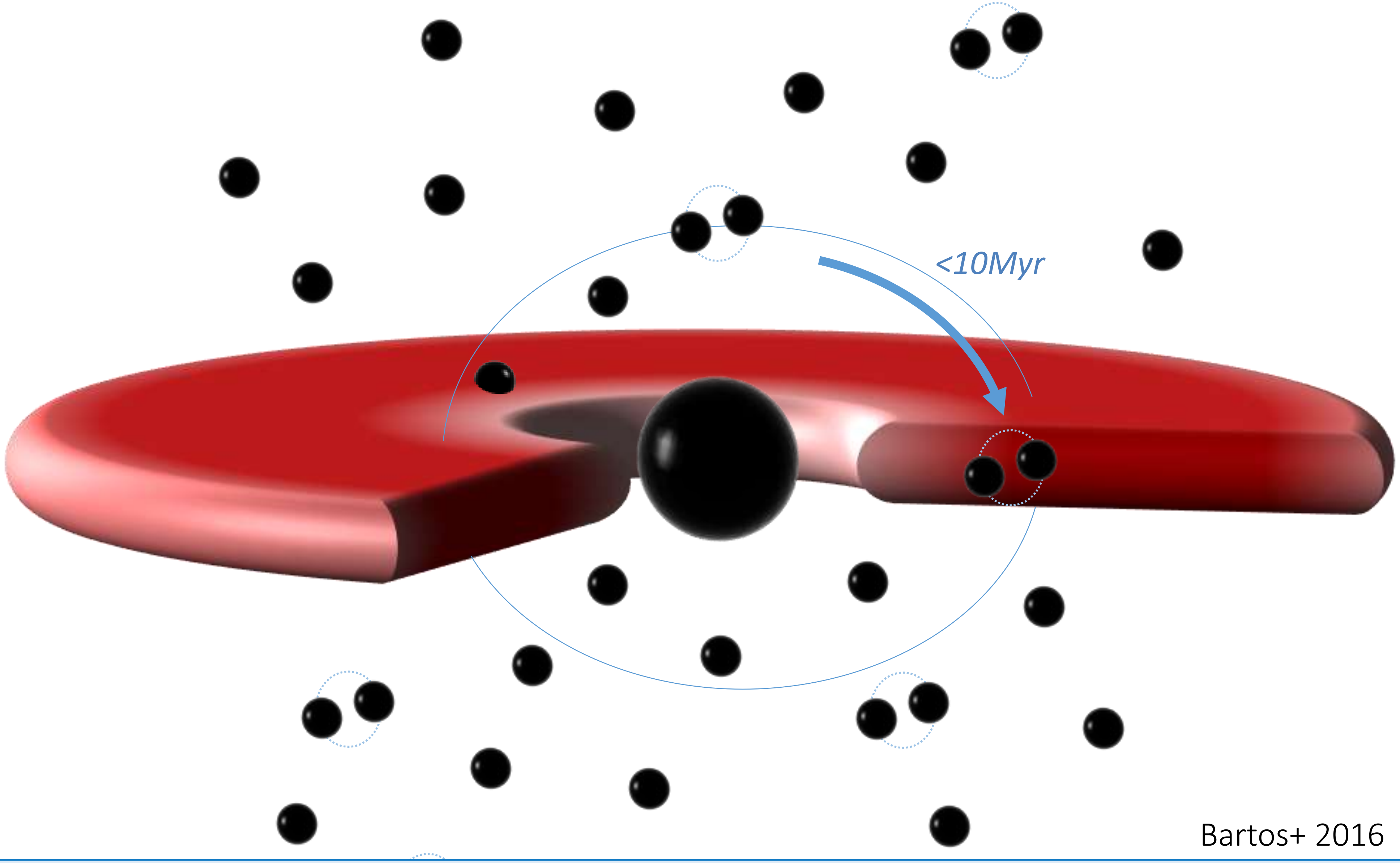


Bartos+ 2016

A fraction of black holes may be in binaries (30%; Pfuhl 2014).

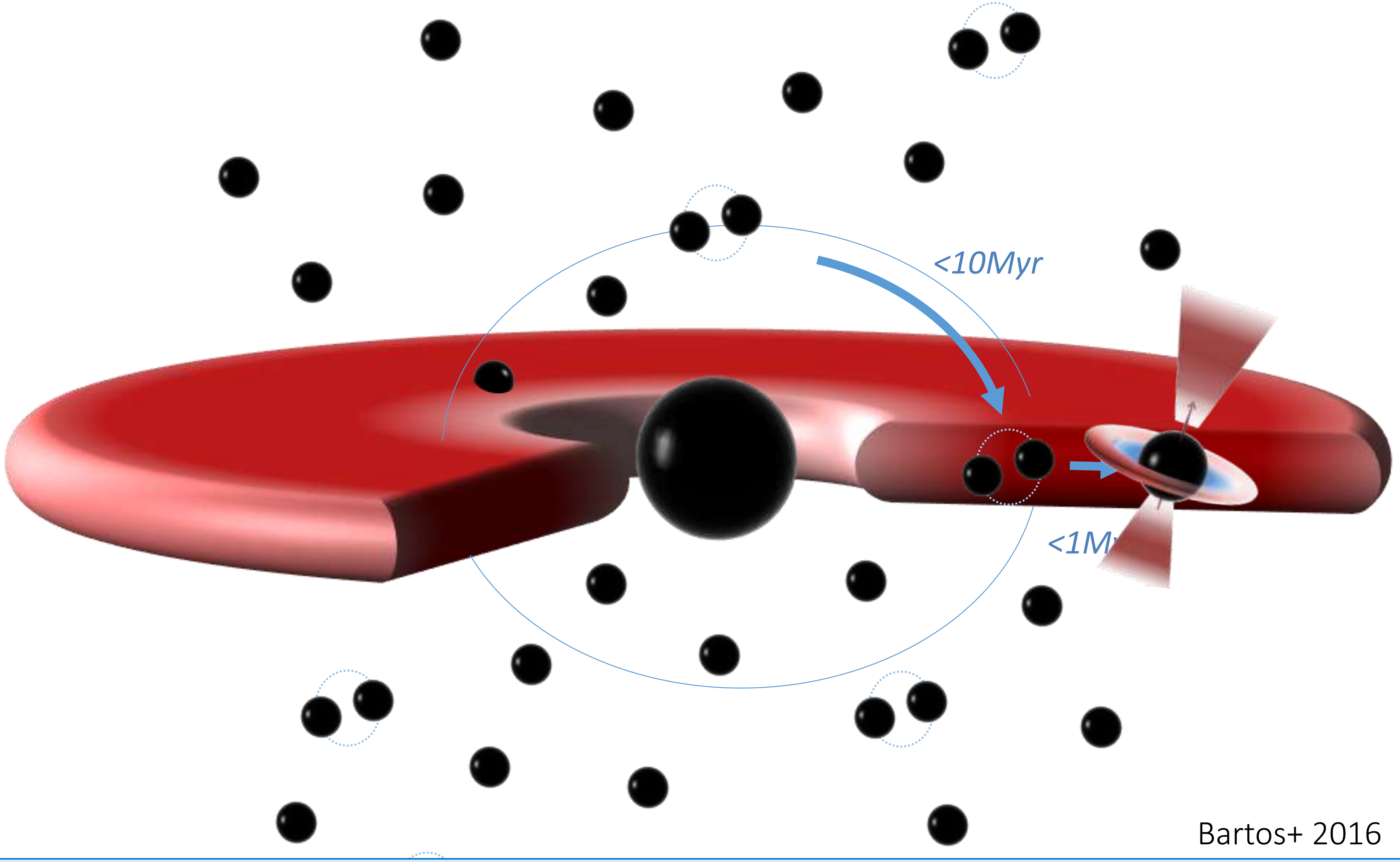

Bartos+ 2016

Some galactic centers accrete large amounts of gas (active galactic nuclei).

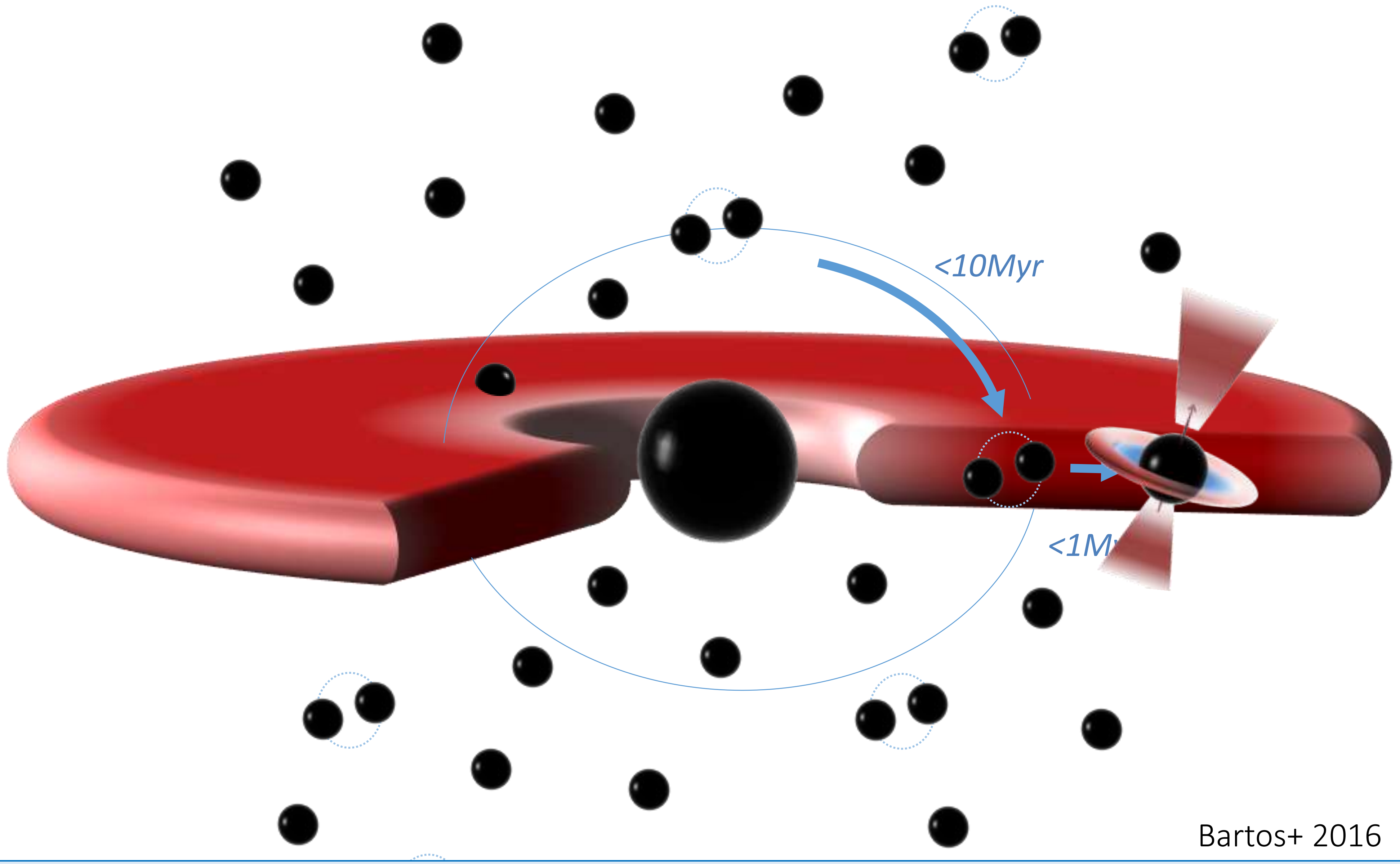


Bartos+ 2016

Binaries migrate into the disk…



…and then rapidly inspiral via dynamical friction.



Bartos+ 2016

…and then rapidly inspiral via dynamical friction.

The road ahead.

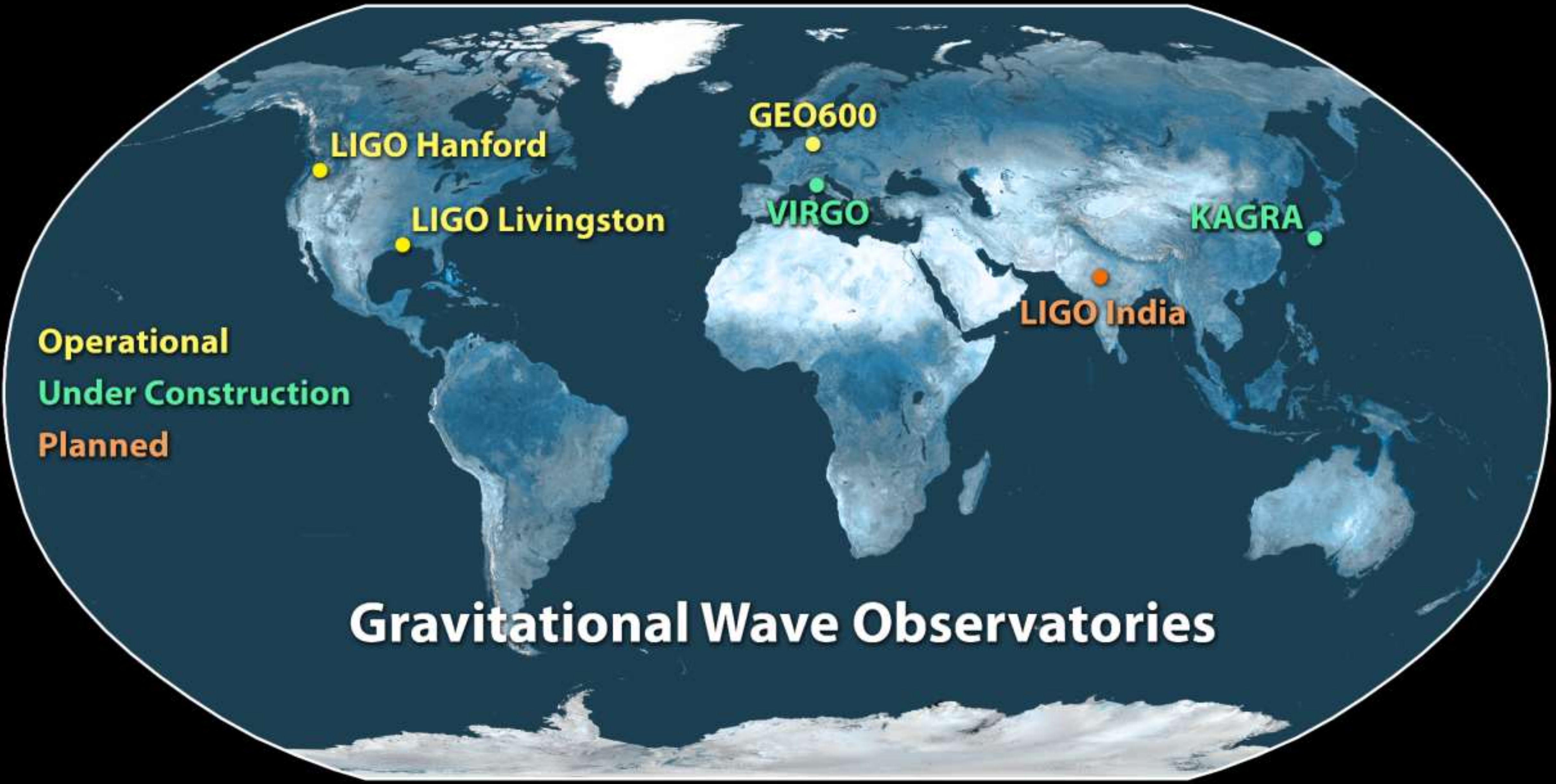
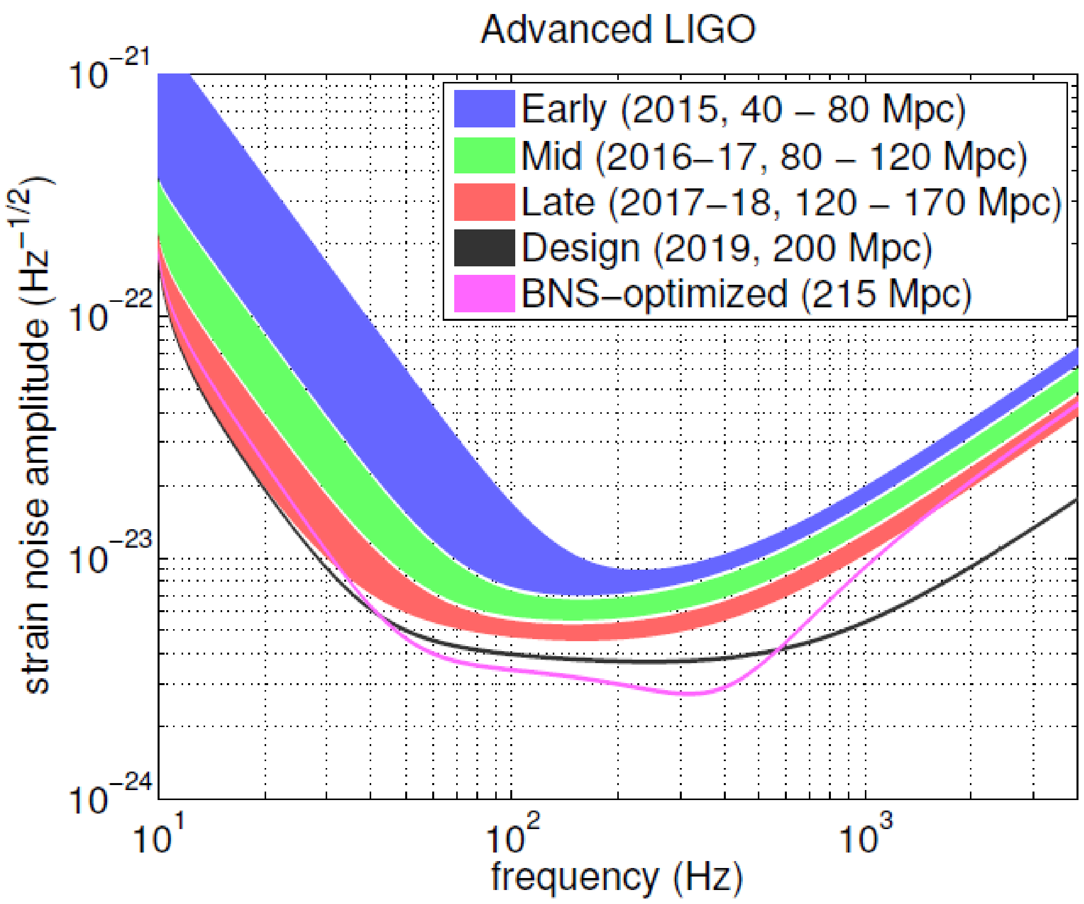


Image credit: LIGO

sensitivity timeline



Aasi+ Living Reviews in Relativity, vol. 19, no. 1 (2016)

Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections
2015	3 months	40 – 80	–	0.0004 – 3
2016–17	6 months	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	200	130	0.4 – 400

- *Annually improving detectors*
- *Especially at low frequencies*
- *Increasing observation time*
- *More detectors → better localization*

O1 → 2.9 binary black hole mergers

O2 → ~ same sensitivity

× 2 longer observation

$2 \times 2.9 \sim 6$ more events

O4 → × 3 greater range

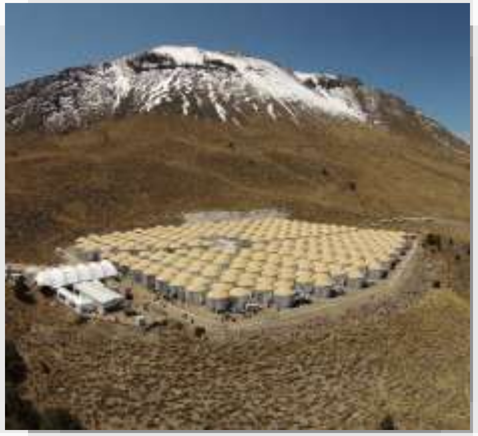
× 4 longer observation / year

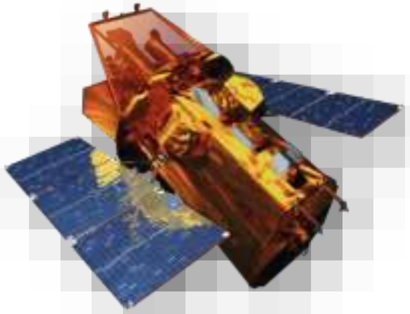
$\times (3)^3 \times 4 \times 2 \rightarrow \sim 1$ event/day

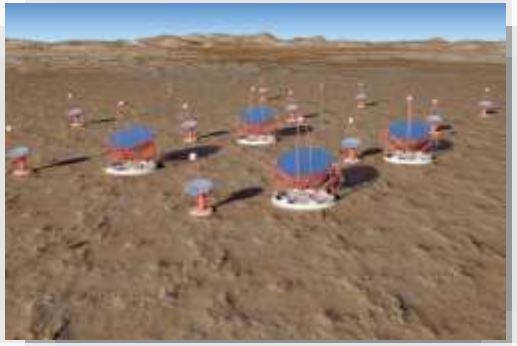
(more detectors will help detect even more)

Abbott+ PRL 116, 061102 (2016)

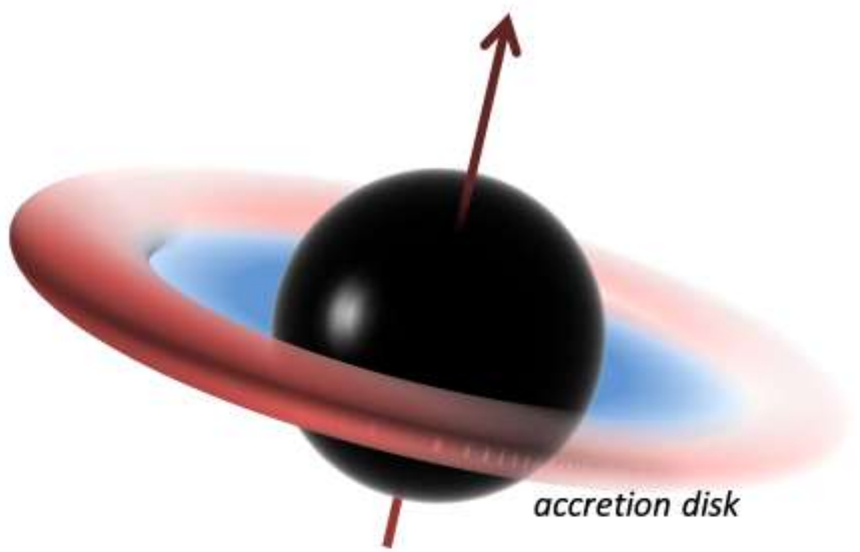
friends 80+





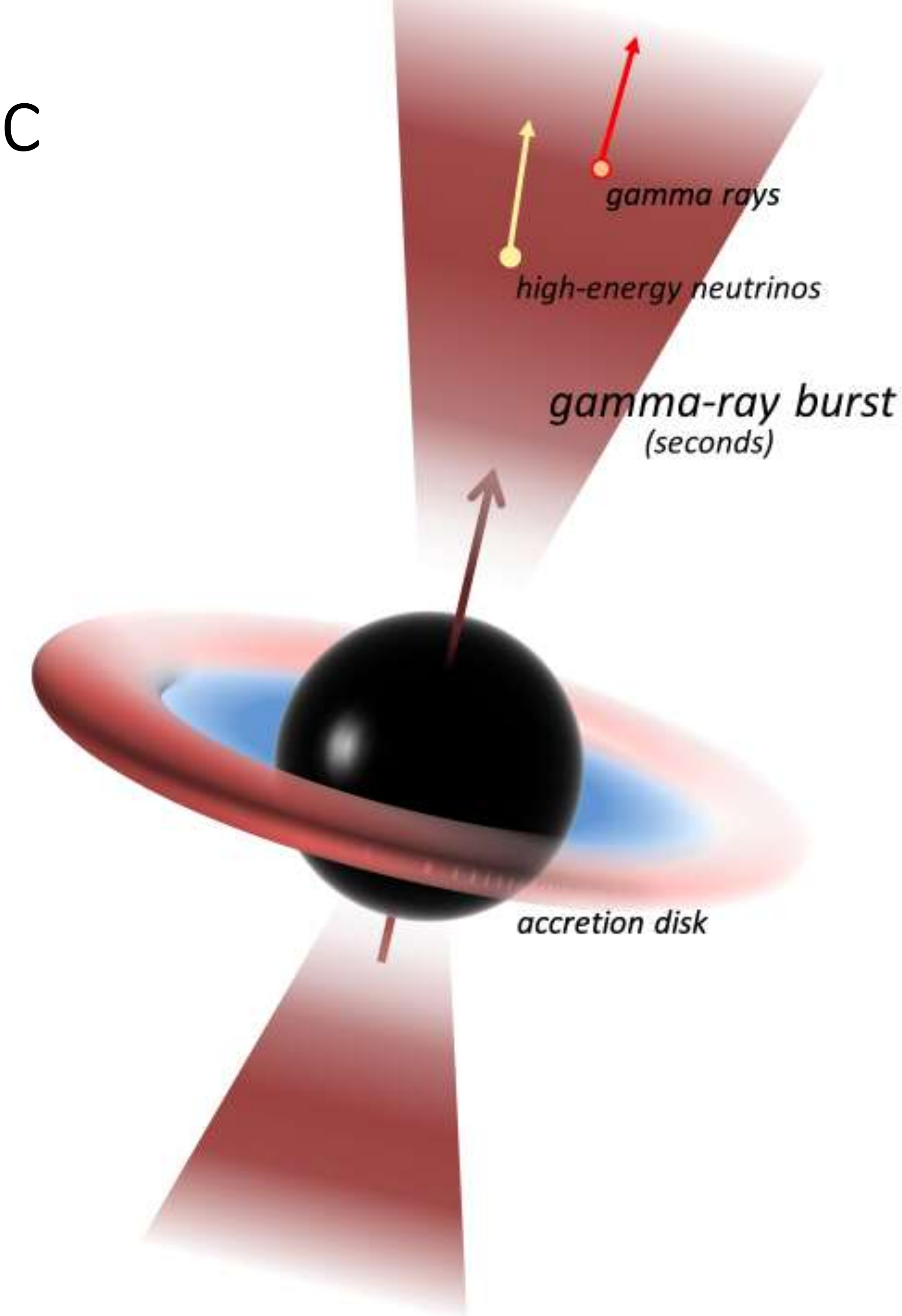


electromagnetic signature

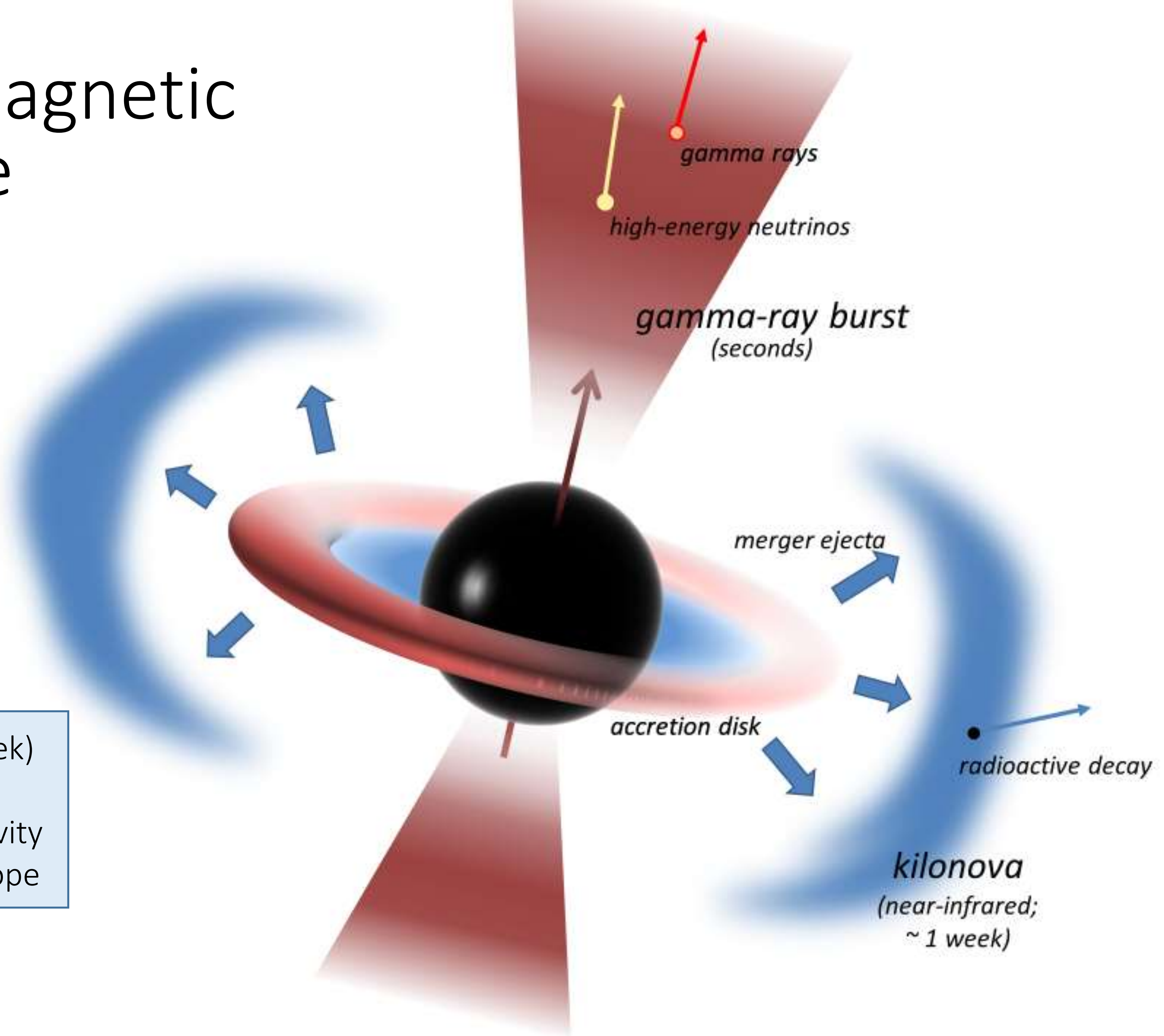


electromagnetic signature

- Beamed
- Good gamma-ray FoV (Fermi GBM: 64%; LAT: 20%; Swift BAT: 16%; XRT: 0%)
- Gamma-ray long term?
- Follow-up difficult (limited localization)



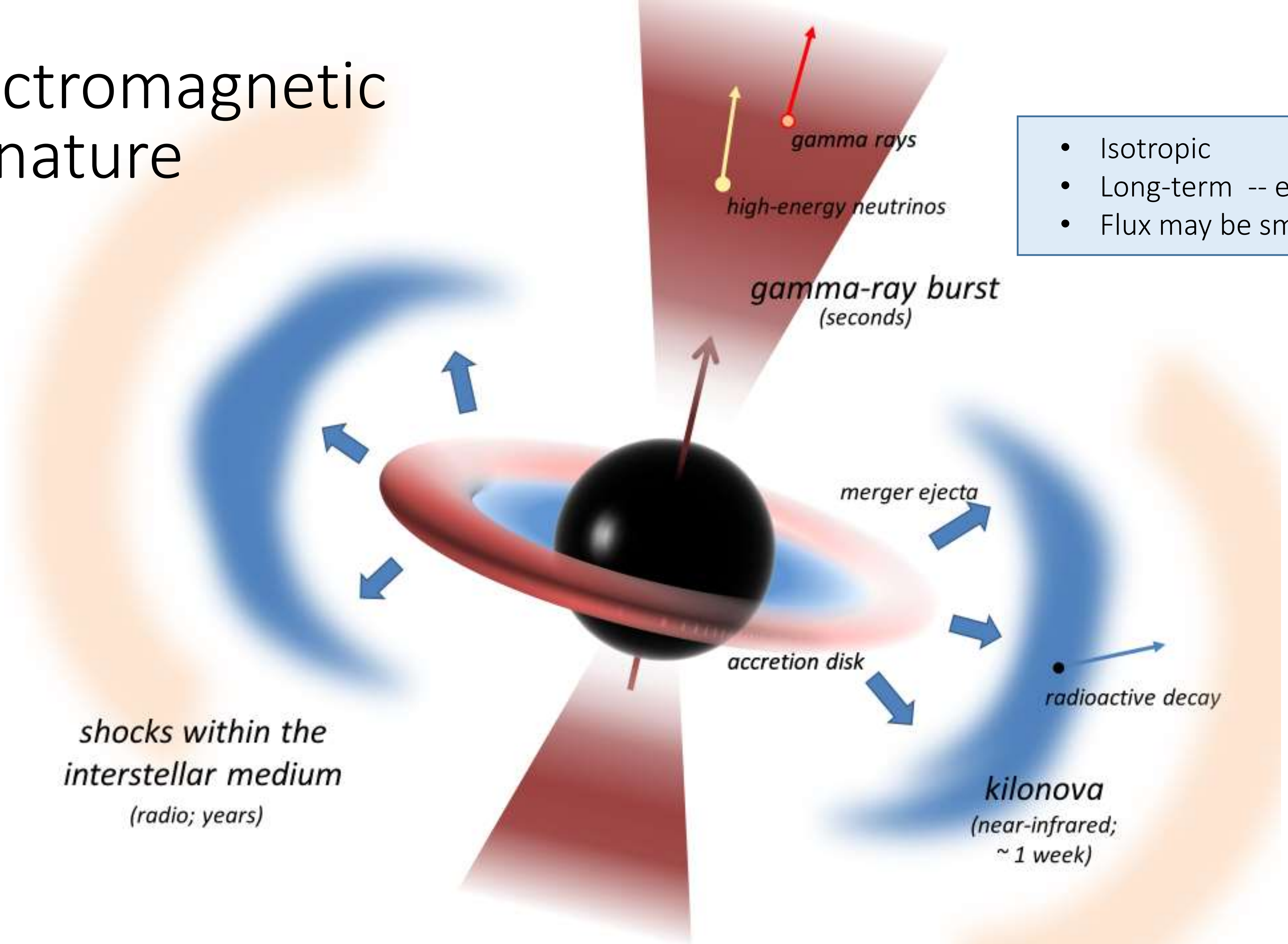
electromagnetic signature



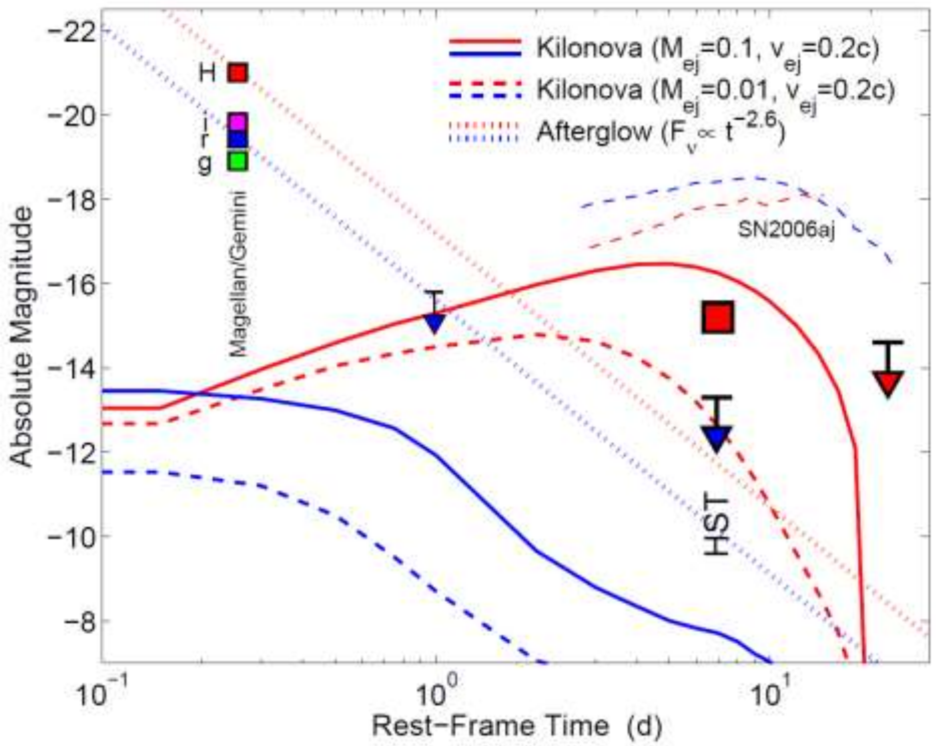
- Good time frame (~week)
- Isotropic
- Limited IR FoV / sensitivity
- → not for every telescope

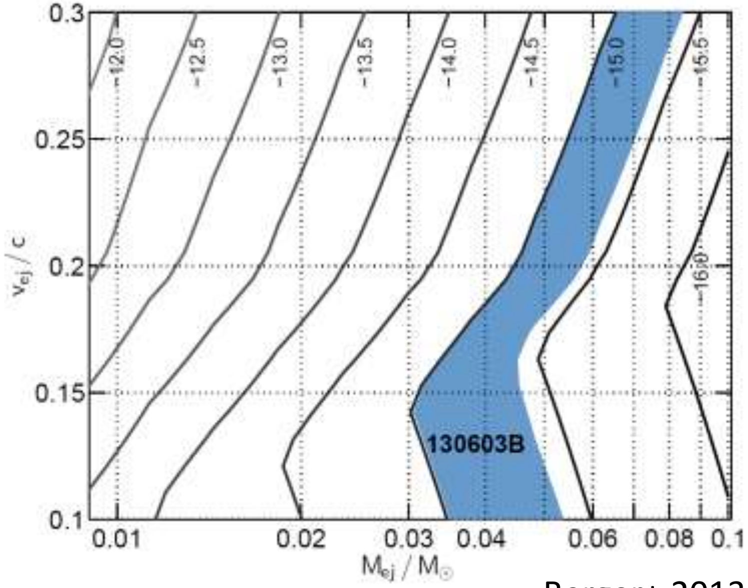
electromagnetic signature

- Isotropic
- Long-term -- easy follow-up
- Flux may be small?



kilonovae

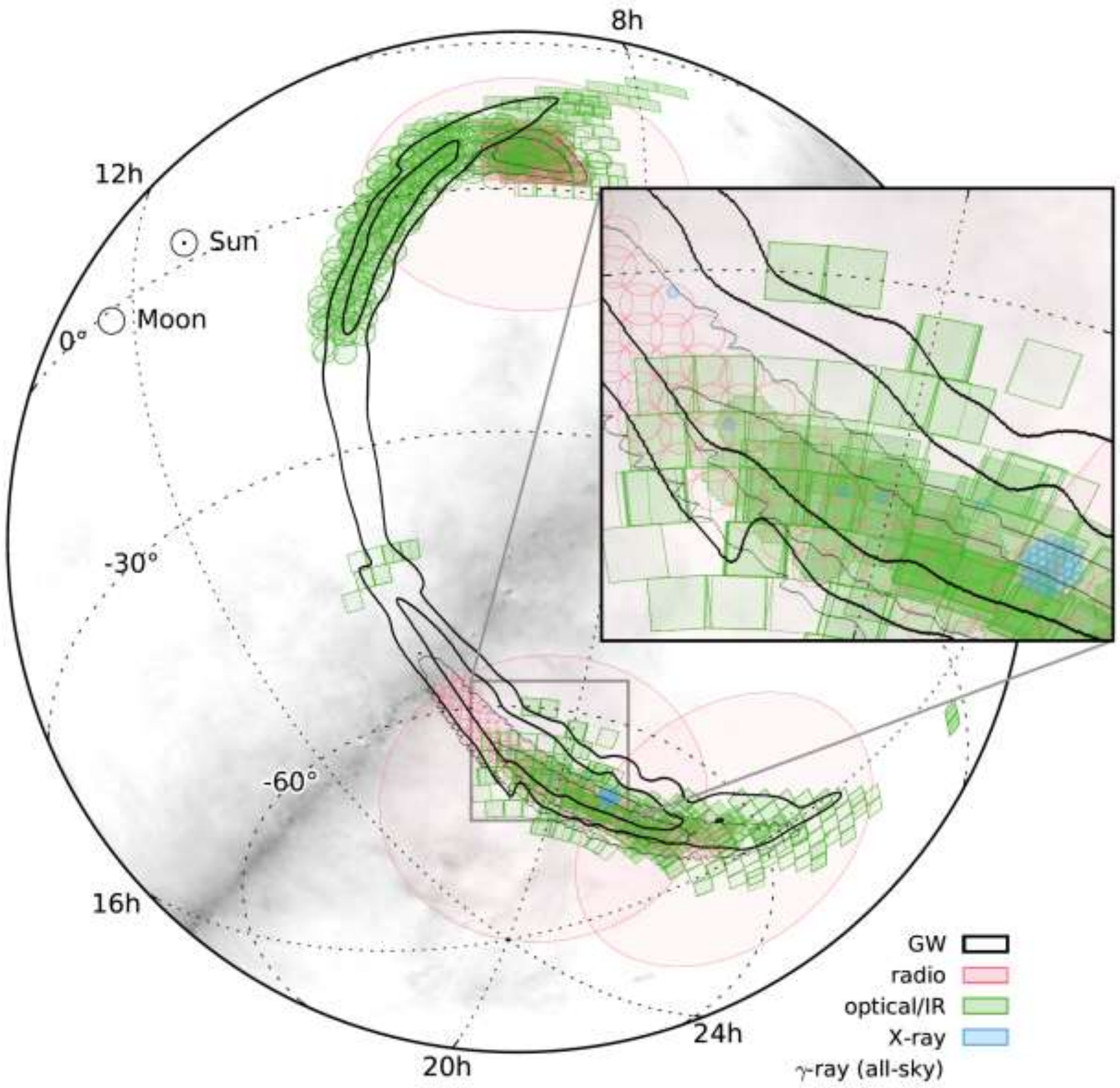




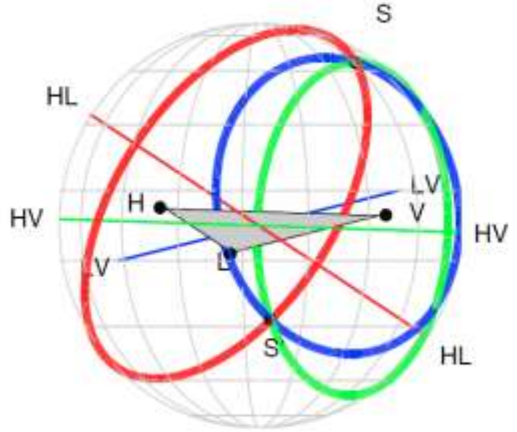
Berger+ 2013

- ✓ Kilonova found coincident with GRB 130603B (Tanvir+ Nature 2013)
- ✓ Estimates on ejected mass/velicty from compact binary merger
- ✓ Consistent with expected emission properties

localization



Abbott et al. 2016 (1602.08492)

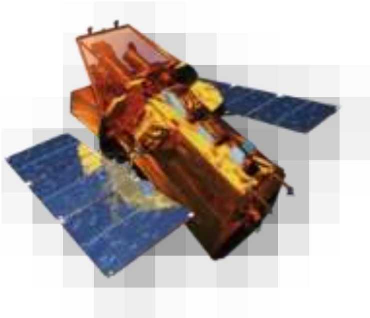


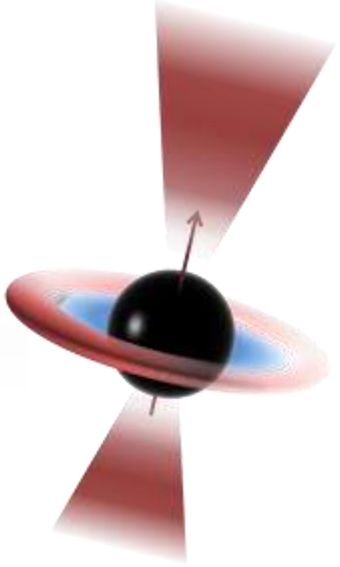
Chatterji+ PRD 2006

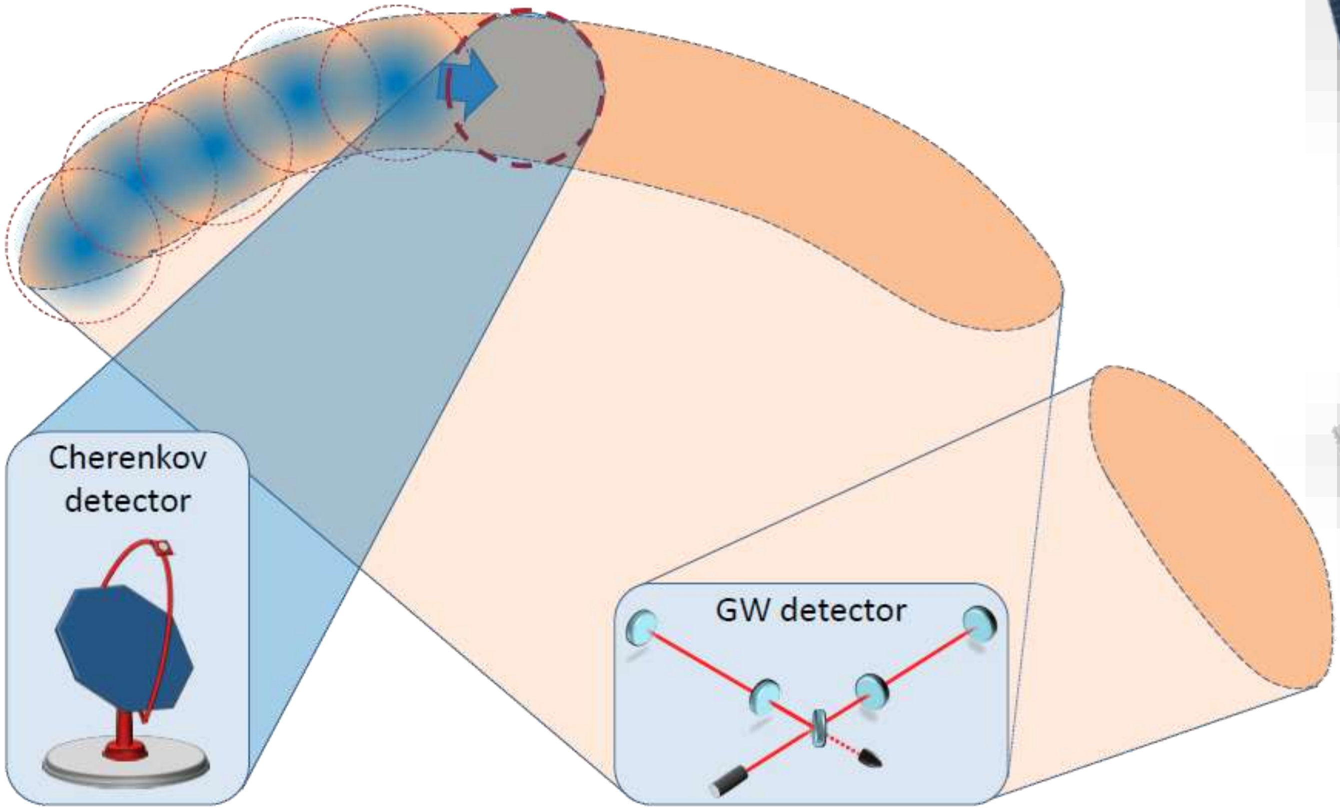
- 100-1000 deg^2
- Improves with more detectors
- Difficult to cover for many optical observatories
- Significant transient foreground (SNe)
- 1/month FAR LIGO triggers

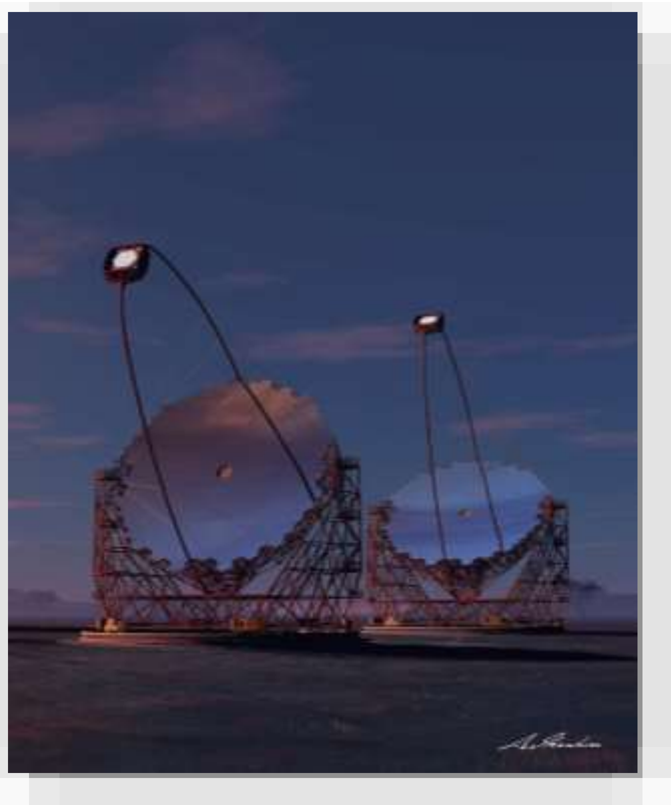
high-energy emission --- early targeting

- Gamma-ray bursts – all-sky observation
- GeV photons --- large FoV telescopes with quick response (CTA from 2018+)
- Beaming is not good.





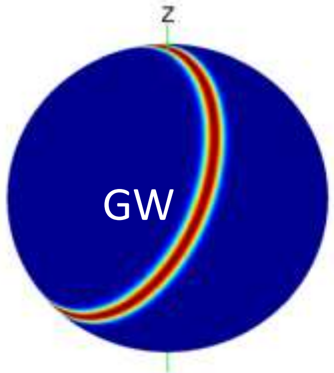




Bartos+ MNRAS 2014

neutrino early warning & targeting

- Neutrinos --- all-sky observation
- High-energy neutrinos --- sub-degree directional resolution
- MeV neutrinos --- warning on nearby supernova

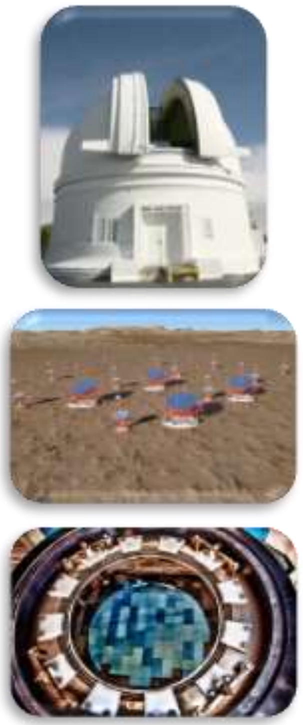


gravitational waves

+

neutrinos

→

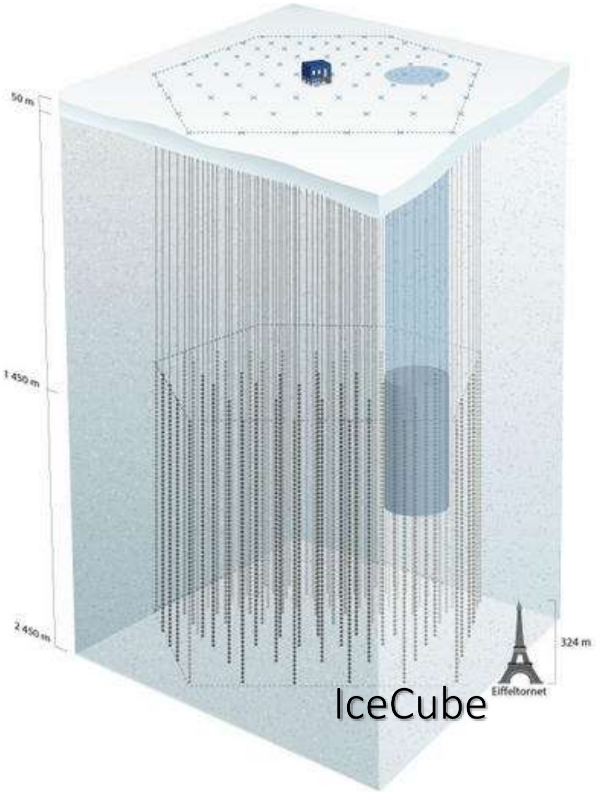


electromagnetic follow-up

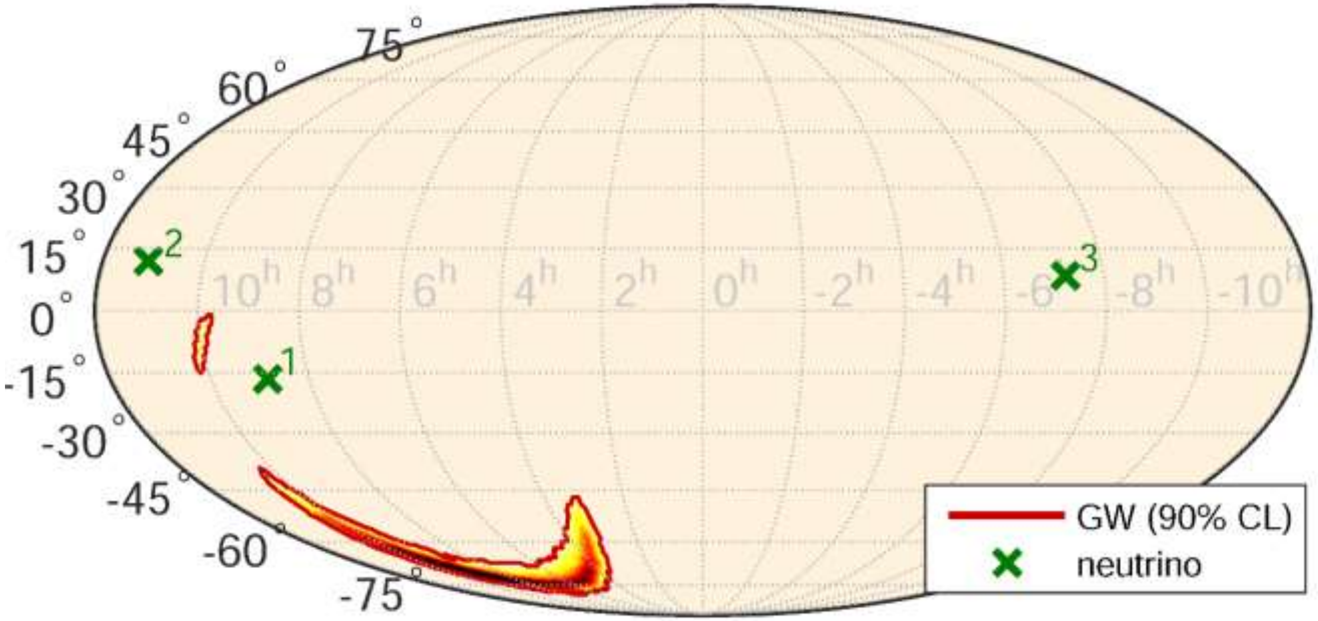
neutrino counterpart for gravitational waves

Super-Kamiokande

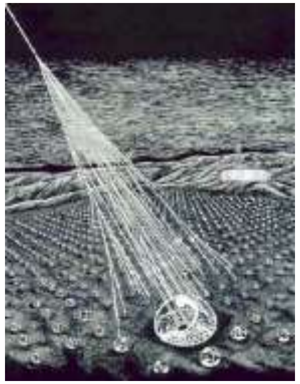
Abe+ ApJL 2016



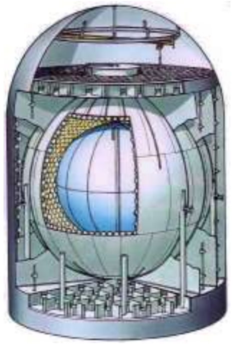
IceCube



Pierre Auger

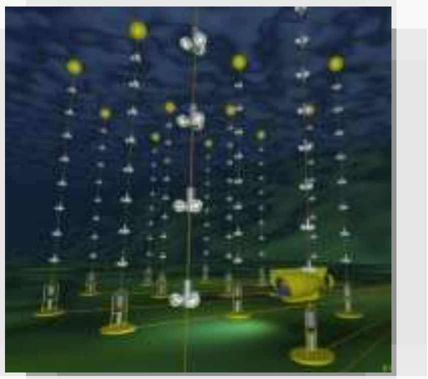


KamLAND



KamLAND 2016 (1606.07155)

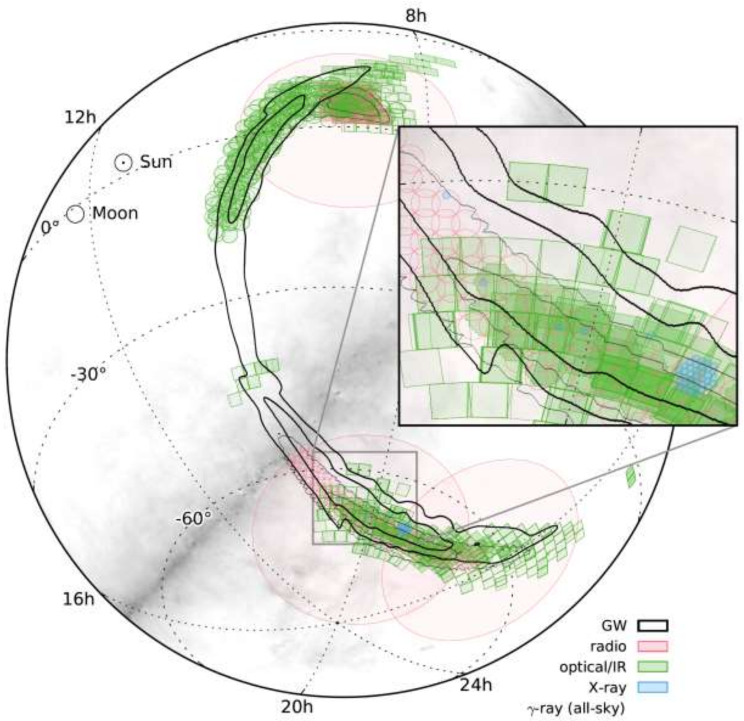
ANTARES



#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

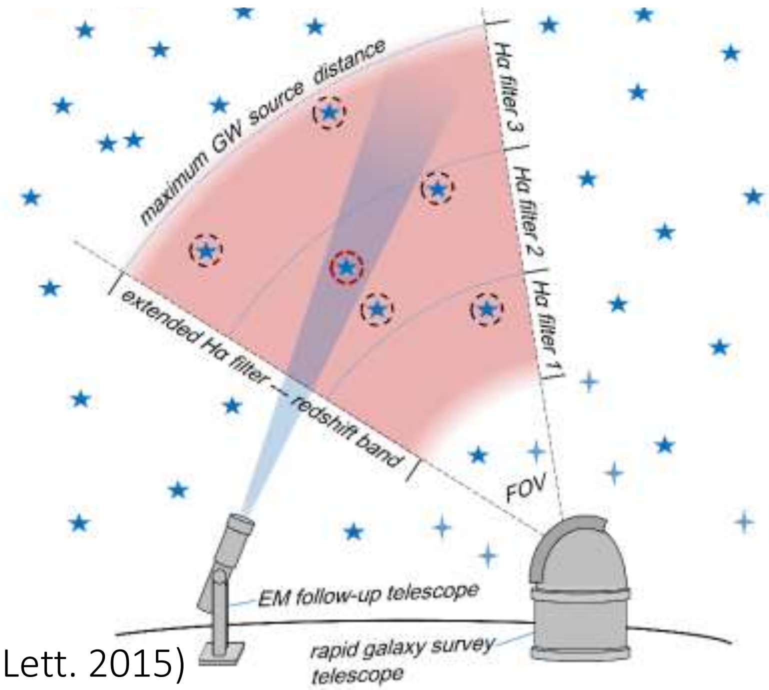
ANTARES+IceCube+LIGO+Virgo PRD 2016 (1602.05411)

galaxy catalogs *(on the fly?)*



- Benefits
  - Target for small FoV telescopes (e.g. Swift-XRT)
  - Decrease false positive rate (abundant transients)
- Current catalogs are not complete
  - GWGC, GLADE, CLU (~40% complete @ 200Mpc)
- Not clear what the good prior is for galaxies (Berger 2014)
- Option: ToO cataloging (Bartos+ 2015)
  - ✓1 week
  - ✓200-500 Mpc
  - ✓100 deg^2
  - ✓Meter class telescopes work.

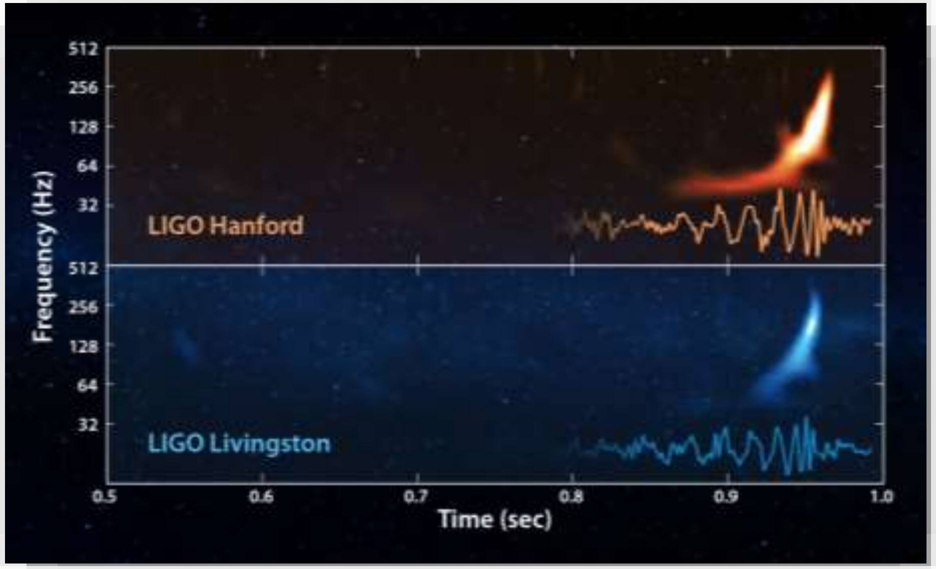
Using galaxies is "essentially" multimessenger by itself.



(Bartos+ ApJ Lett. 2015)

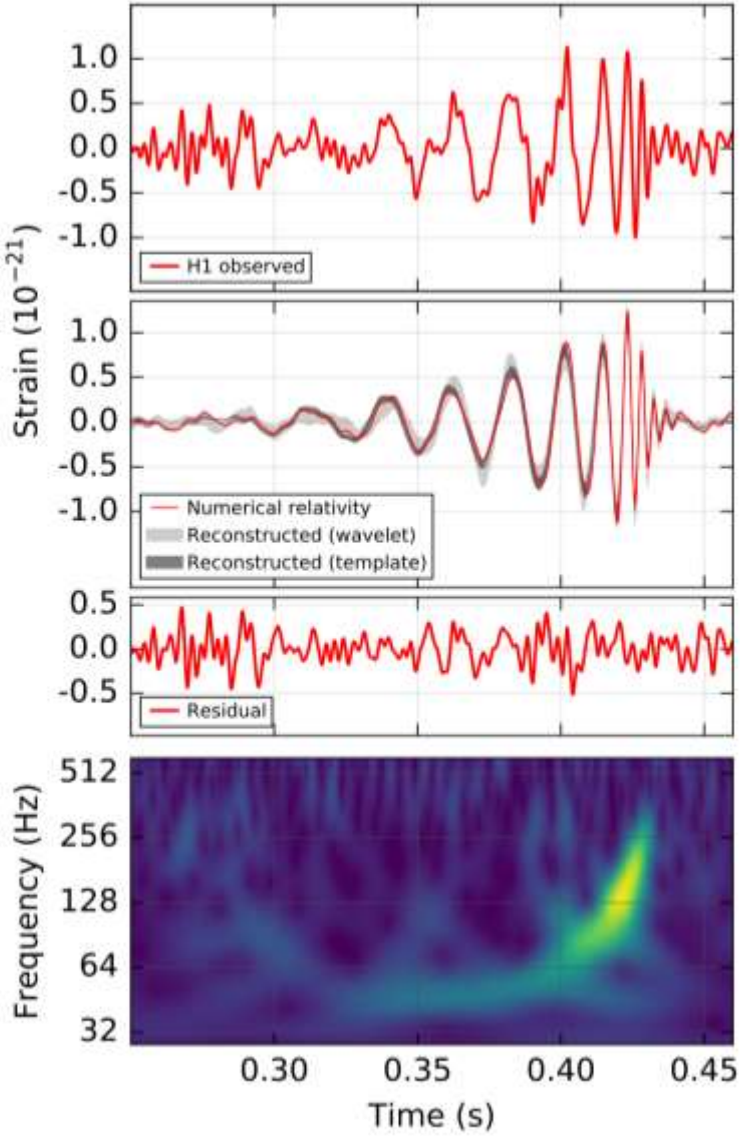
SEARCH FOR GRAVITATIONAL WAVE TRANSIENTS

- Cast a wide net: **Generic** searches
  - minimal assumptions
  - first to find GW150914
  - good at higher significance
- **Template** based searches
  - detailed model assumptions
  - farther horizon distance
- **Multimessenger** searches
  - both generic and templated
  - more source information
  - increased sensitivity
  - farther horizon distance

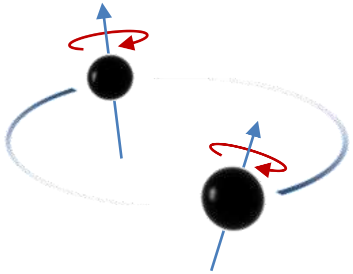


LIGO+Virgo PRL 116, 061102 (2016)

Other way to increase detection rate: improve GW searches



- Matched filter technique using numerical+analytical waveforms. O(10^5) templates.



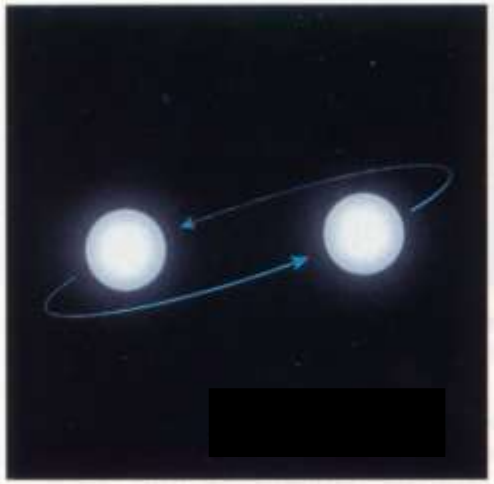
15 (+2) parameters

masses (2)
distance (1)
direction (2)
orientation (2)
spin (6)
time (1)
phase (1)
+ eccentricity (2)

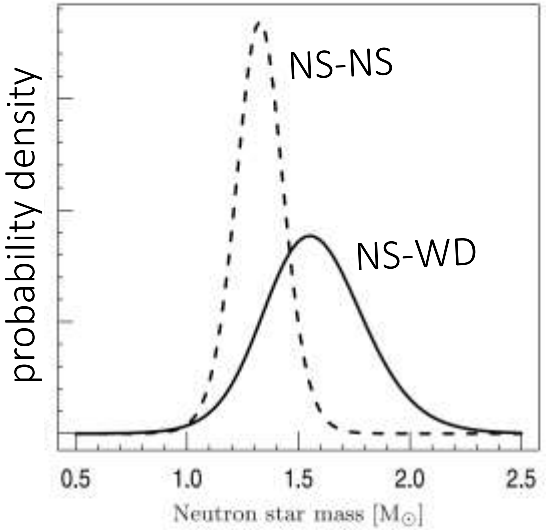
- Mature search algorithms. Development:
    - eccentricity
    - perpendicular spin
    - neutron Star tidal deformation
    - detector characterization

Disruption: astrophysical information

neutron star mass distribution



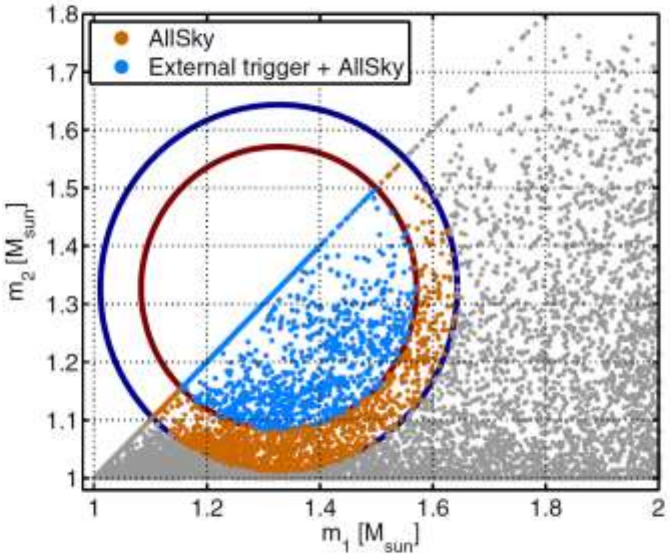
- possible mass range: $\approx 1M_\odot - 3M_\odot$
- NS-NS observed in very narrow mass range: $M_{NS} = 1.33 \pm 0.11$



Improvement for optimal size or weighted template bank

- All-sky: **15%**
- *Multimessenger:* ***60%***

Bartos & Marka PRL 2015



Takeaway

Multimessenger-gravitational wave astrophysics:

- ✓ More information is more science.

Gravitational-wave detectors:

- ✓ Rapidly expanding horizon (soon 1 detection/day)
- ✓ Substantial multimessenger effort underway

Road ahead:

- ✓ Initially binary black holes → multimessenger?
- ✓ New, large-scale observatories (LSST, CTA, JWST, SKA, …)
- ✓ Localization / host galaxy catalogs
- ✓ Astrophysical information → GW searches