# Astrophysical Problems in the Gravitational Wave Era

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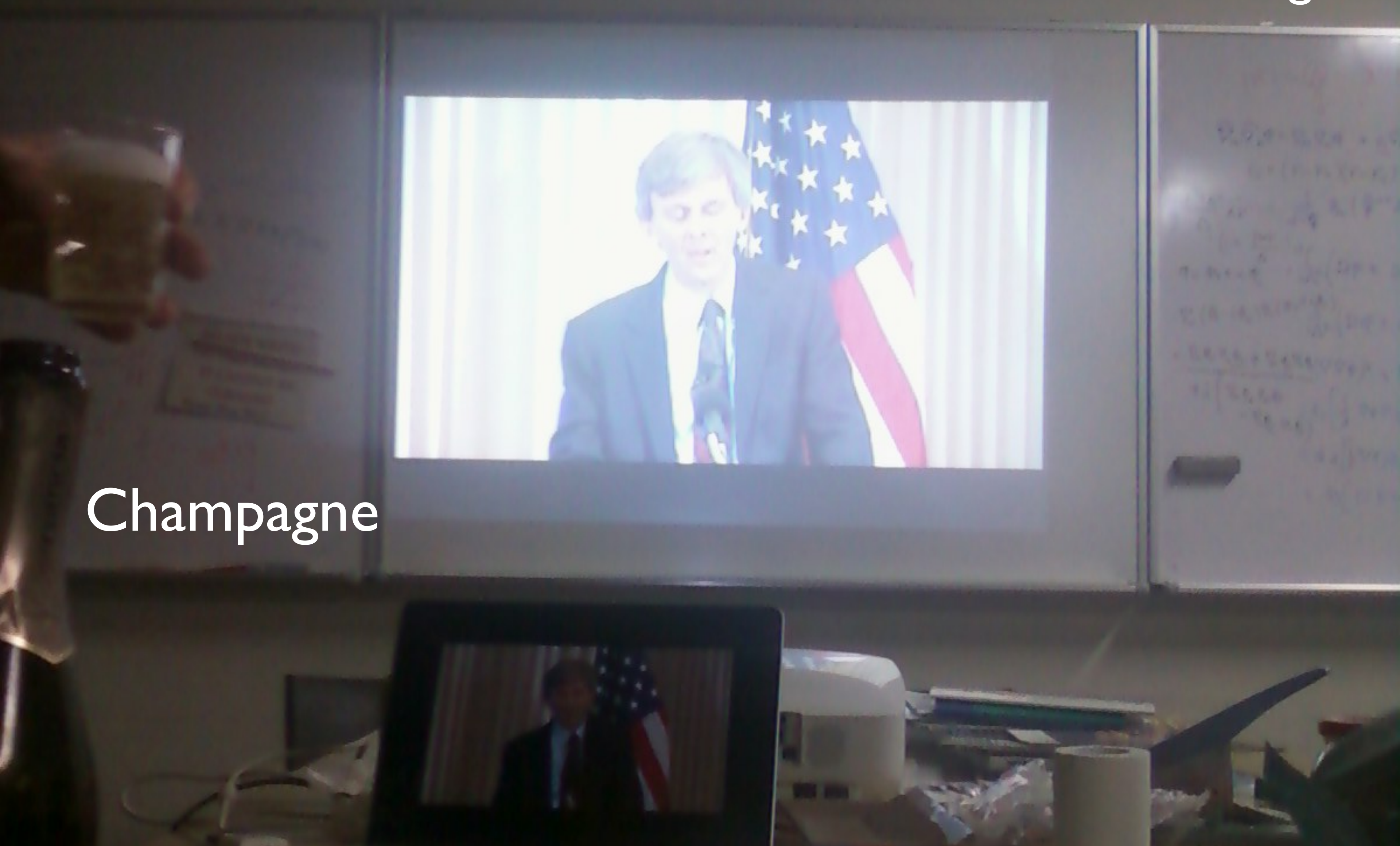
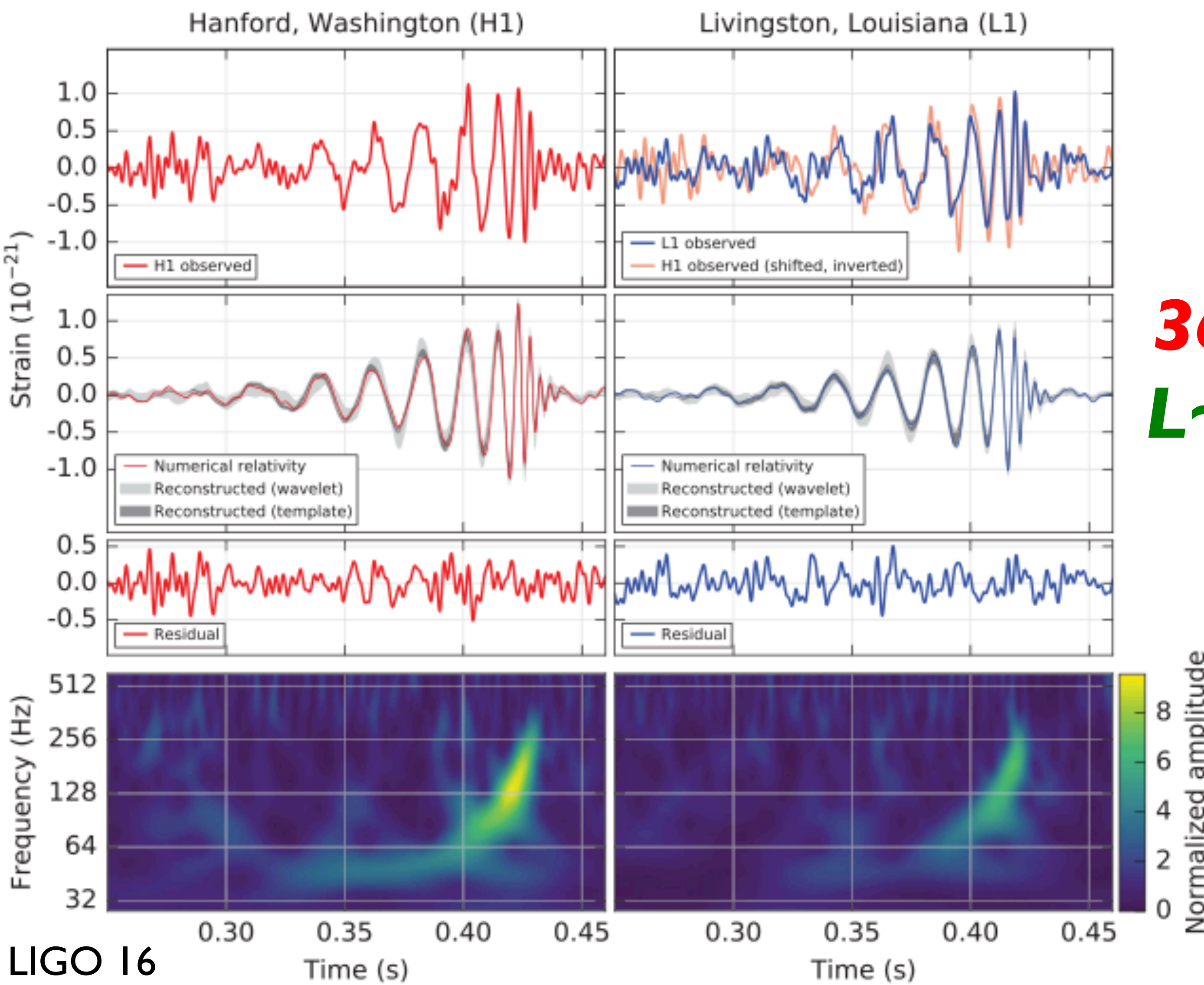
# We Did It!



# GW150914




***1st direct detection***

***BH-BH***

***$36M_\odot+29M_\odot$***

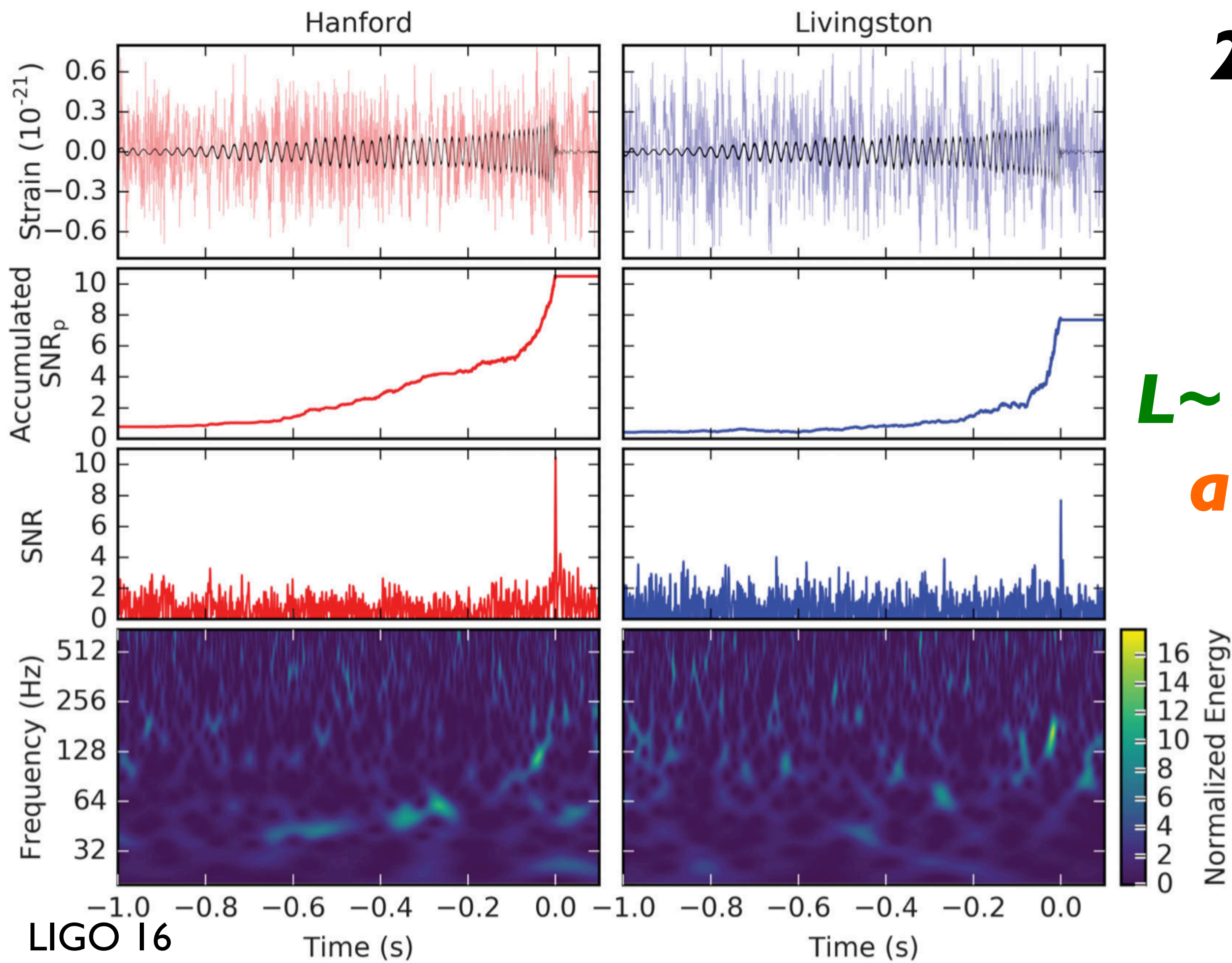
***$L\sim 200M_\odot c^2/s$***

***$\sim 10^{-3}\ c^5/G$***

30-350Hz bandpass
First at L1
6.9+0.5-0.4ms
later at H1

LIGO 16

# GW151226




LIGO 16

**2nd event**

**BH-BH**

**$14.2M_\odot$**

**$+7.5M_\odot$**

**$L\sim170M_\odot c^2/s$**

**$a_{1or2} > 0.2$**

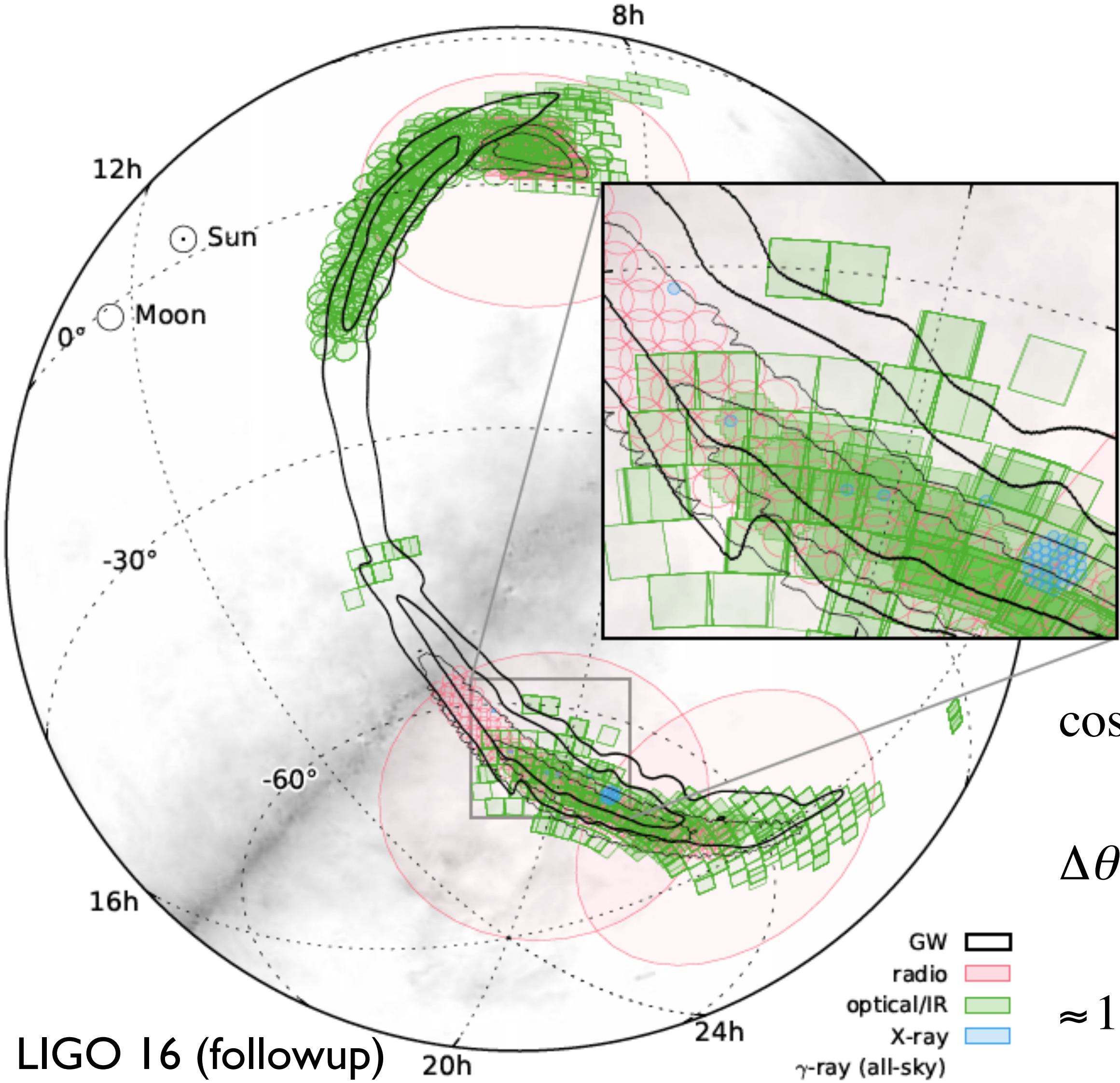
LVT151012

$R_{GW}\sim$9-240 events $Gpc^{-3}$ $yr^{-1}$

# Big Discoveries

- First direct detection of GWs
- First discovery of binary BHs
- Brightest sources (>GRB)
- Quasi-normal mode (still not clear)
- Low metallicity (Old) star
- Testing GR, e.g., $|v_{graviton} - c| < 10^{-19}$

# Bad Localization




LIGO 16 (followup)

**~600 deg²!!**

Bigger than Moon

We need KAGRA, IndIGO

$$\cos\theta = \frac{c\delta t}{D}$$

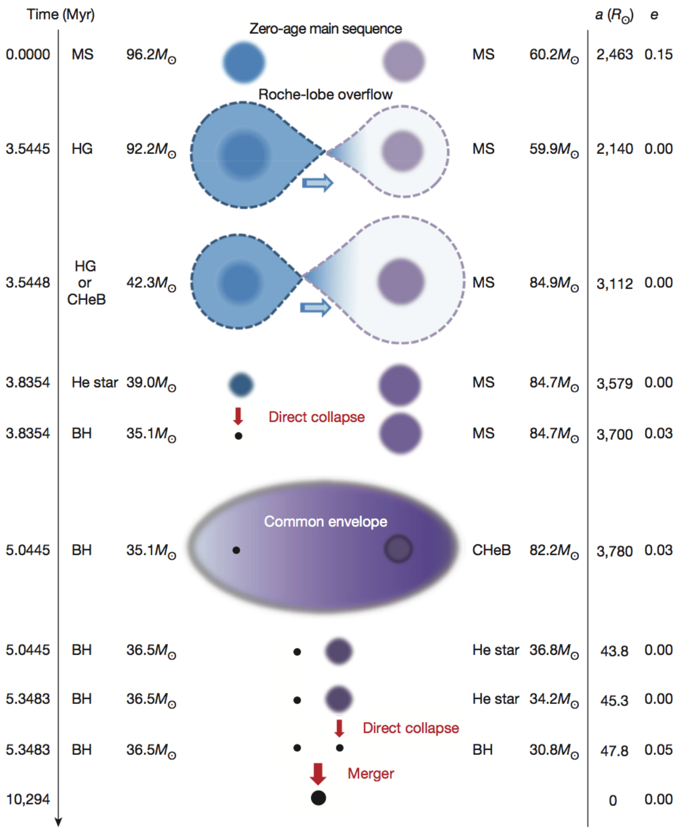
$$\Delta\theta \approx \frac{\Delta(c\delta t)}{D} \approx \frac{cf^{-1}}{D\cdot SNR}$$

$$\approx 17\,\mathrm{deg}\left(\frac{f}{100\,Hz}\right)^{-1}\left(\frac{D}{10^3\,km}\right)^{-1}\left(\frac{SNR}{10}\right)^{-1}$$

# What is the Origin?

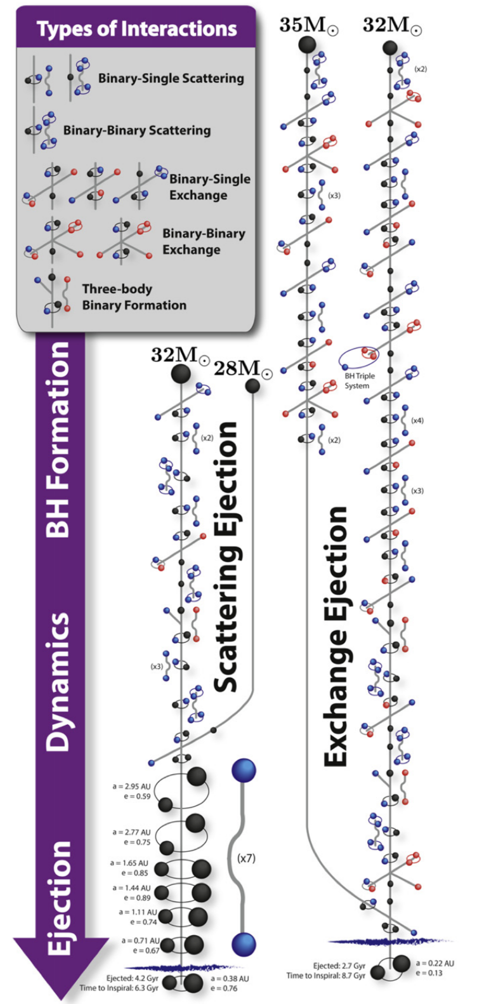
# What is the Origin?

## Binary evolution




Postnov & Yungelson 14
Belczynski+ 16
van den Heuvel+ 17
Mandel & de Mink 16
Kinugawa+ 16

## Stellar cluster




Rodriguez+ 16
O'Leary+ 16

Antonini & Rasio 16
Bartos+ 16
Stone+ 16

## Near galactic nuclei

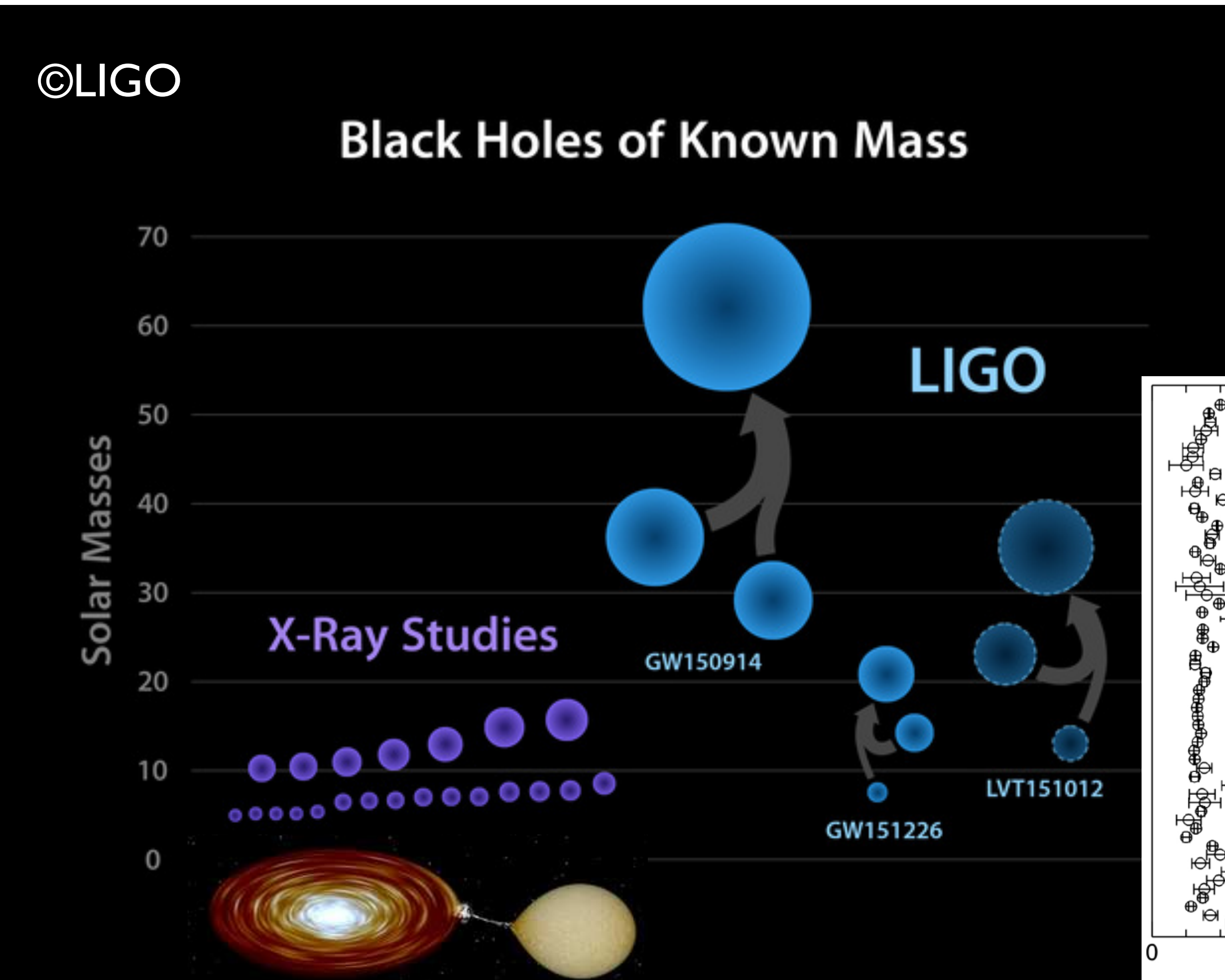
## Primordial black hole

Sasaki+ 16
Bird+ 16
Binnilov+ 16
Carr+ 16
Kawasaki+ 16

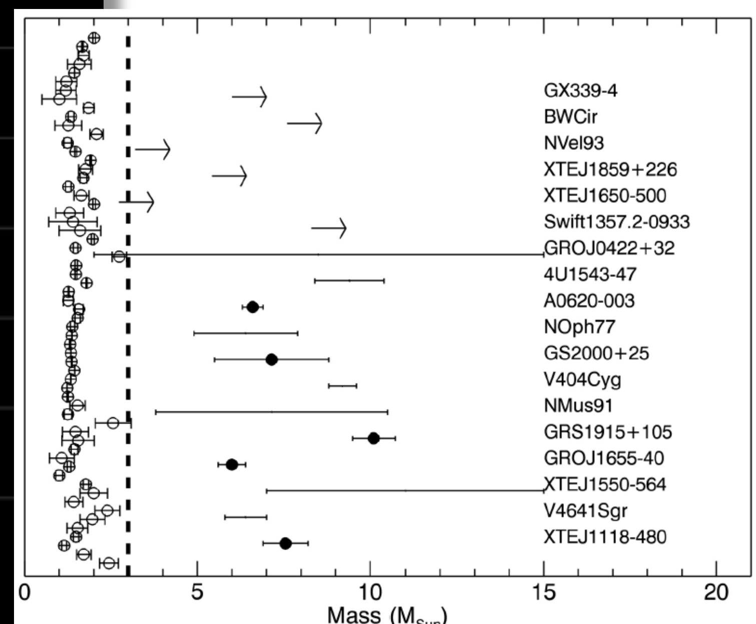
# Clues

- Mass
- Rate
- Separation
- Spin
- Eccentricity

# Mass

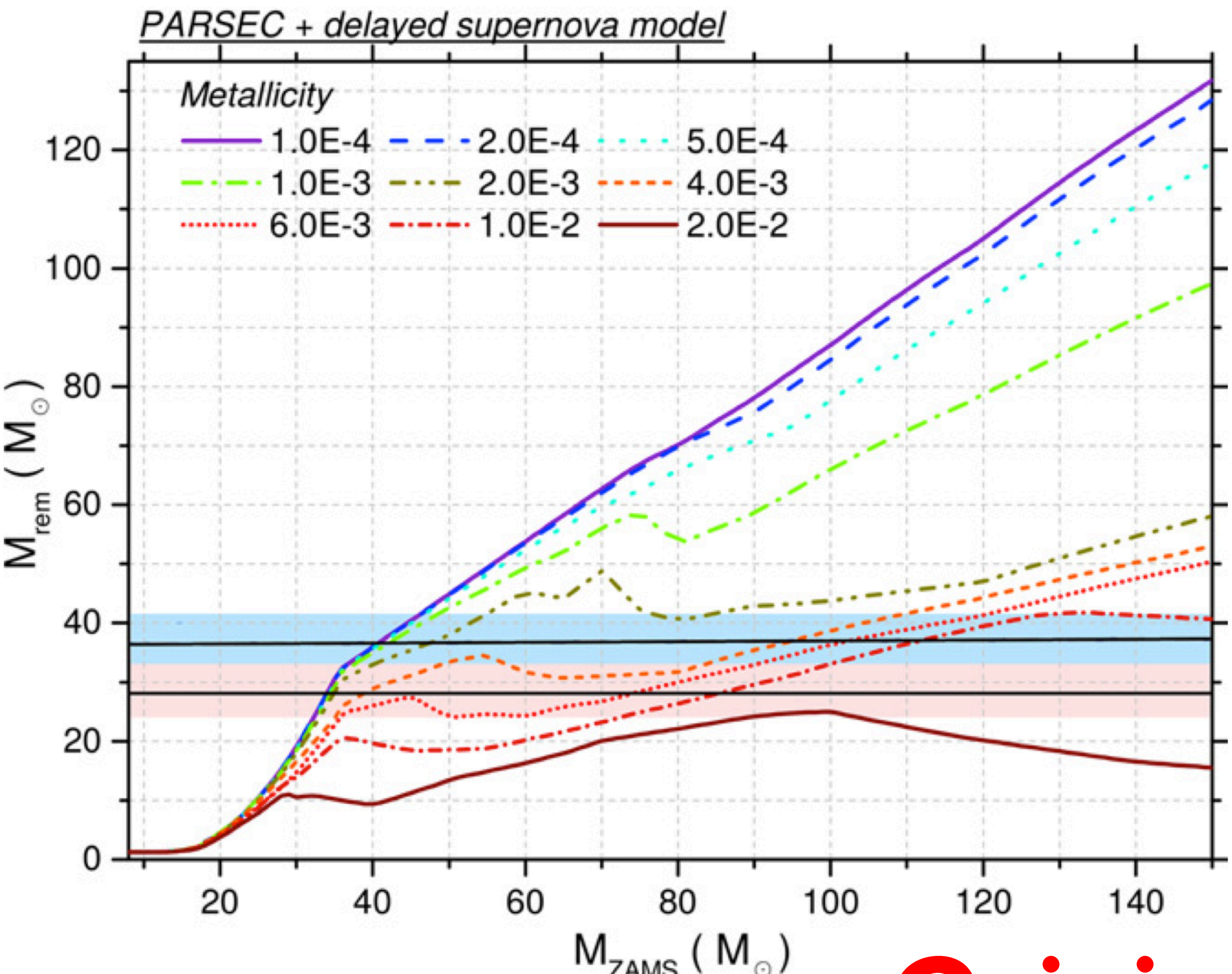



$M_{GW150914} > M_{Milky\ Way}$ X-ray binaries




Corral-Santana+ 16

# Low Metallicity




LIGO(astro) 16

Heavy elements like C should be little in the star

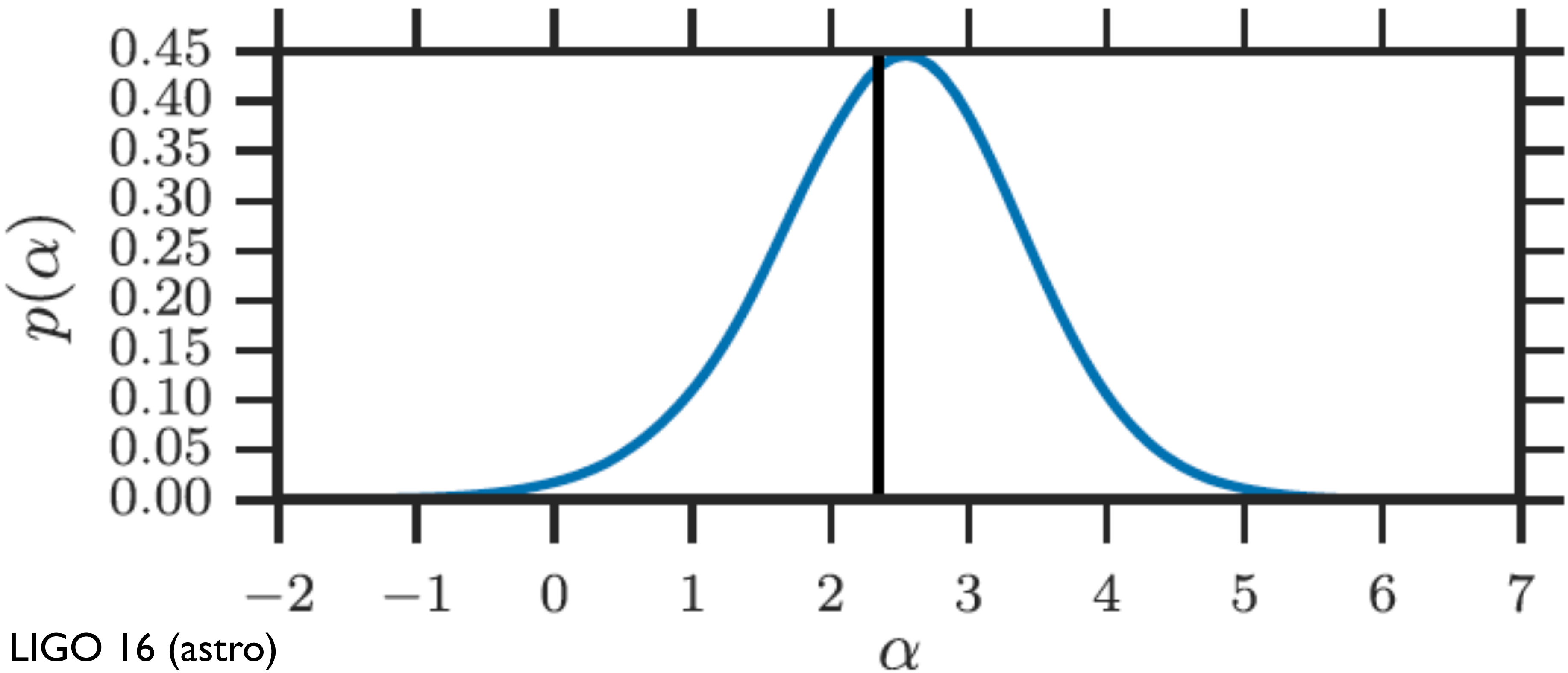
Otherwise stellar wind
⇒ mass loss
⇒ too small M

**Origin: Old stars**

# Mass Function

~ Salpeter mass function

$$p(m_1) \propto m_1^{-\alpha},\ \alpha \sim 2.5^{+1.5}_{-1.6}$$

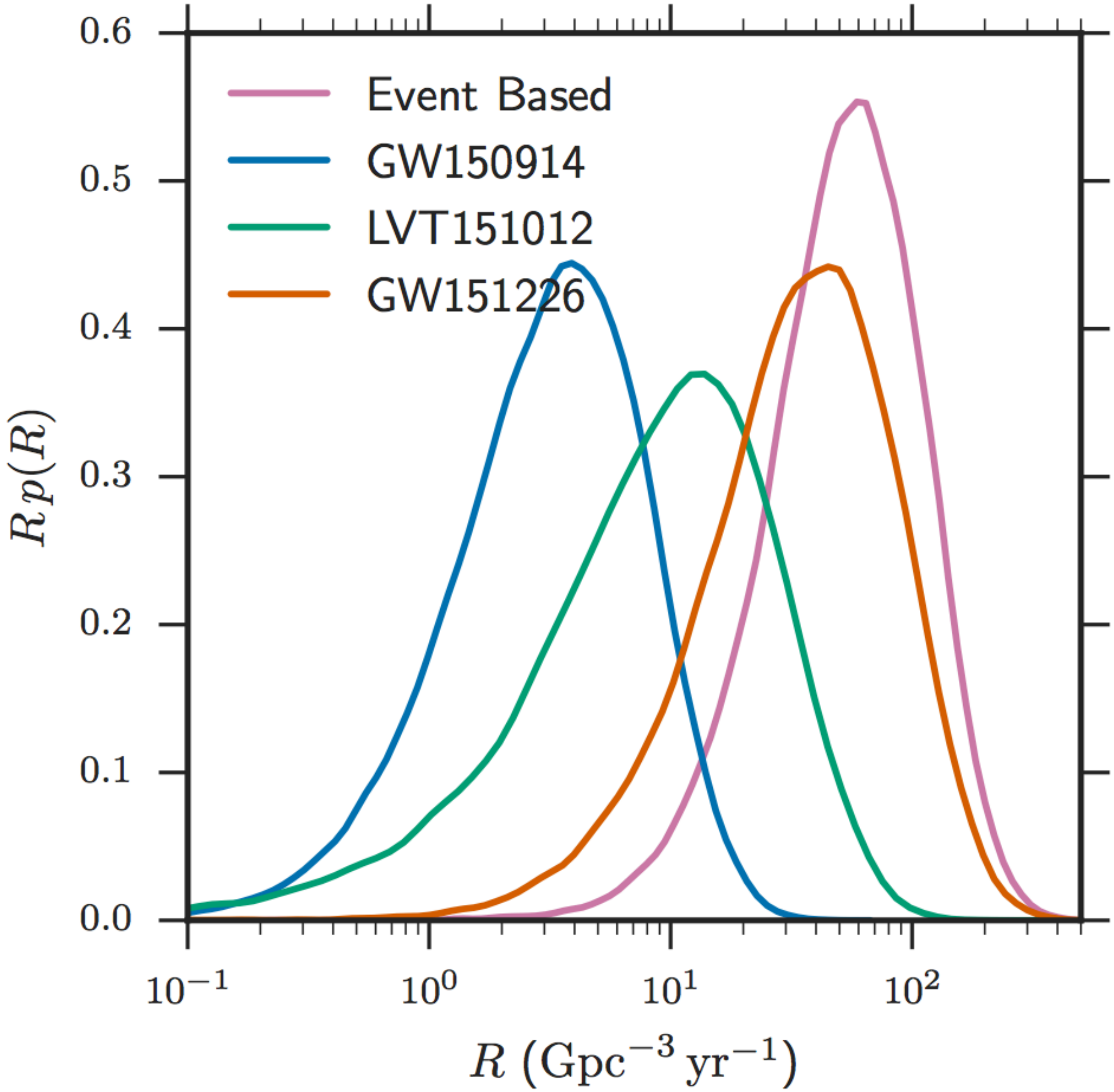



LIGO 16 (astro)

# Clues

- Mass ⇒ Low metal (Old star)
- Rate
- Separation
- Spin
- Eccentricity

# High Event Rate




**9-240 $Gpc^{-3}$ $yr^{-1}$**

**~0.1% $R_{supernova}$**

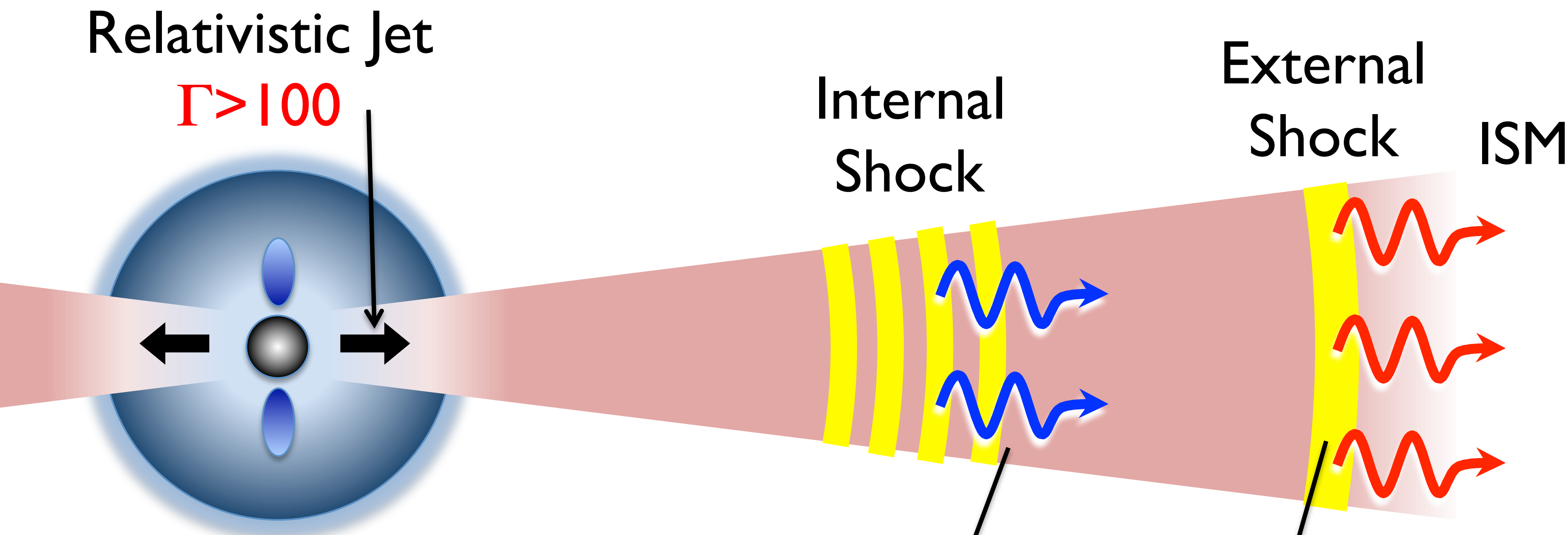
**~$R_{superluminous\ SN}$**

**~$R_{GRB\ (beaming\ corr.)}$**

**~$R_{NS\text{-}NS}$**

**~3/hr/Universe**

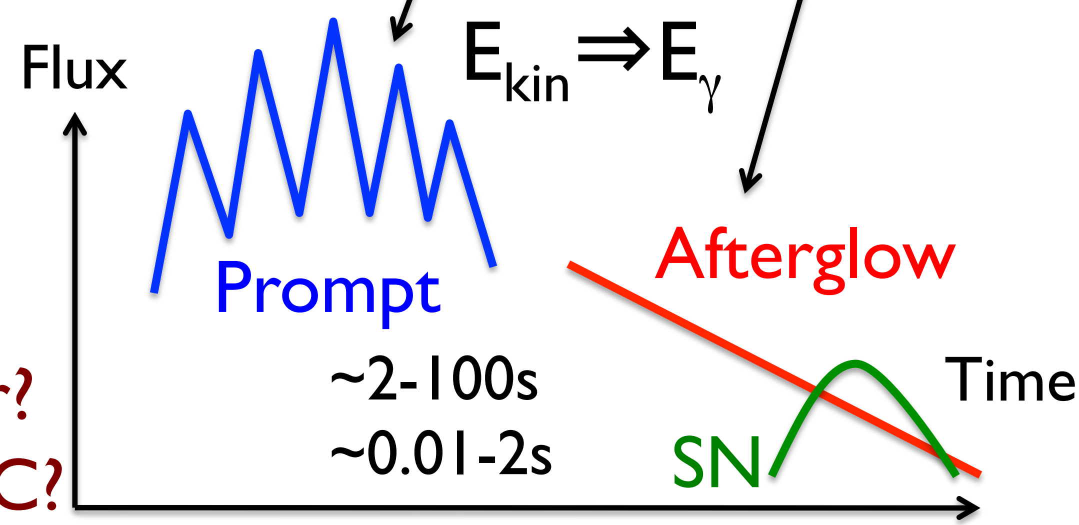
# Gamma-Ray Bursts



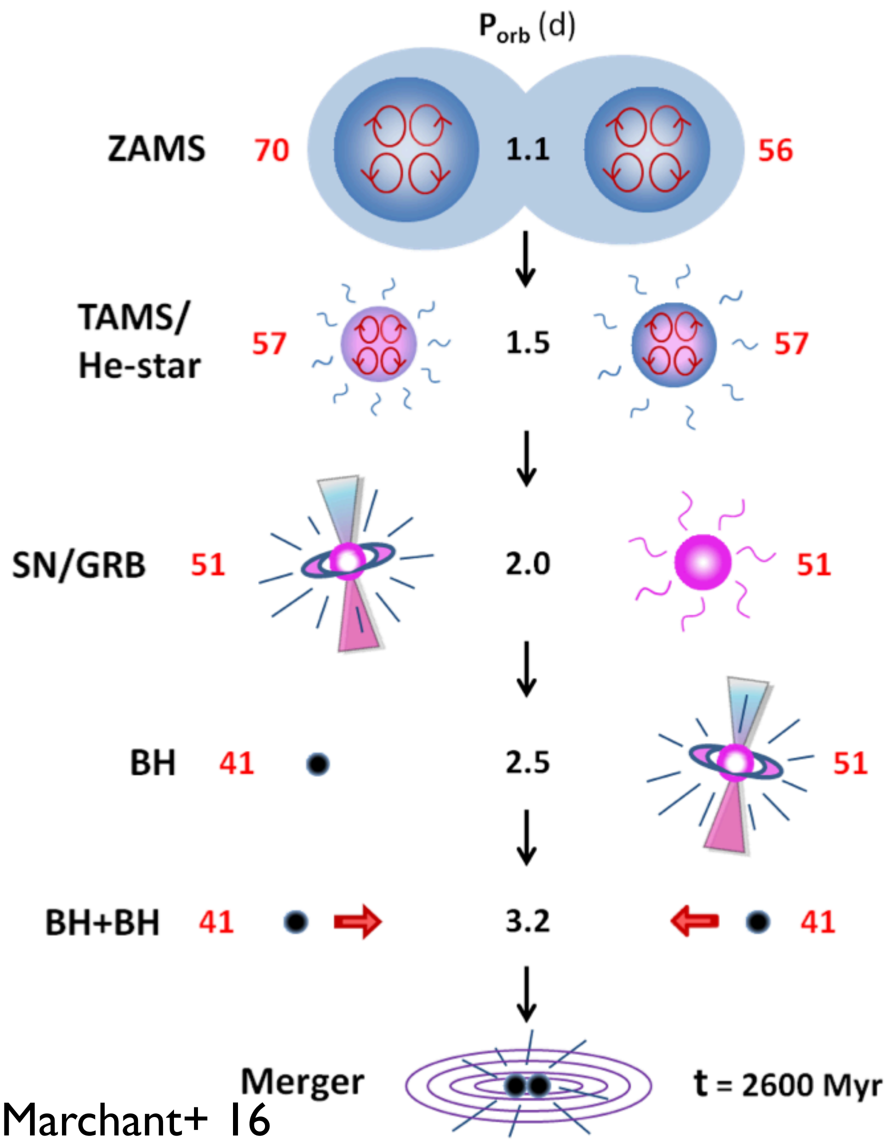

~2-3/day@Cosmological

Long: Massive Stellar
Collapse to BH/NS

Short: NS-NS/BH merger?
Magnetar? WD/NS AIC?

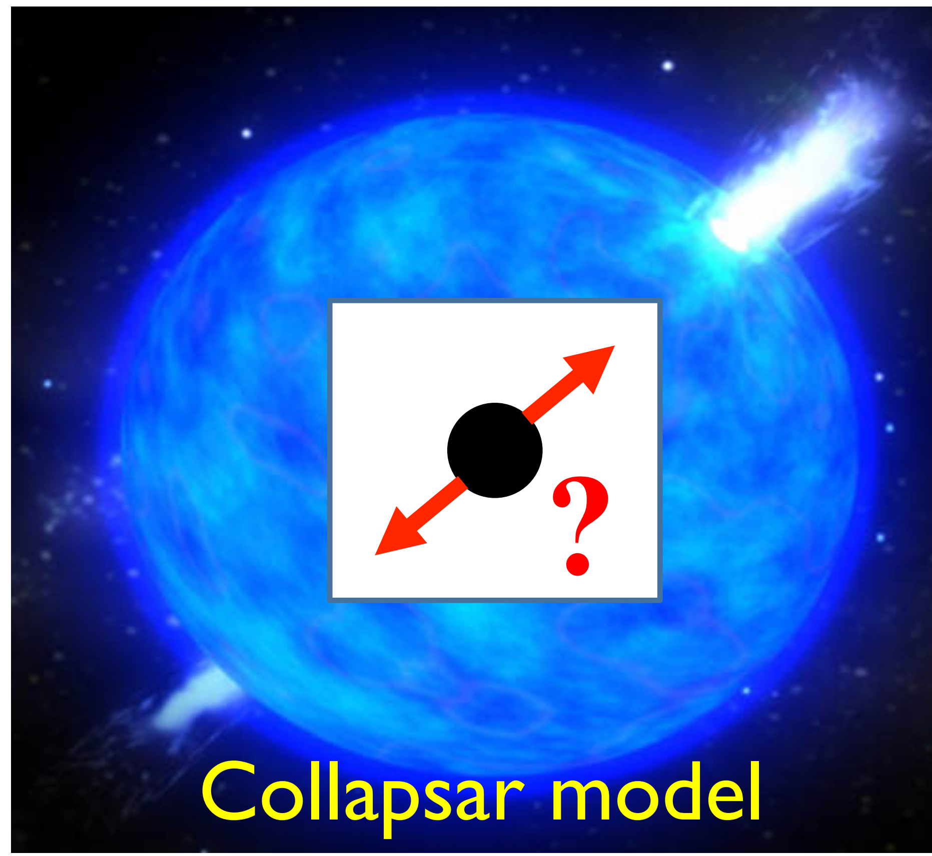


# Gamma-Ray Bursts?



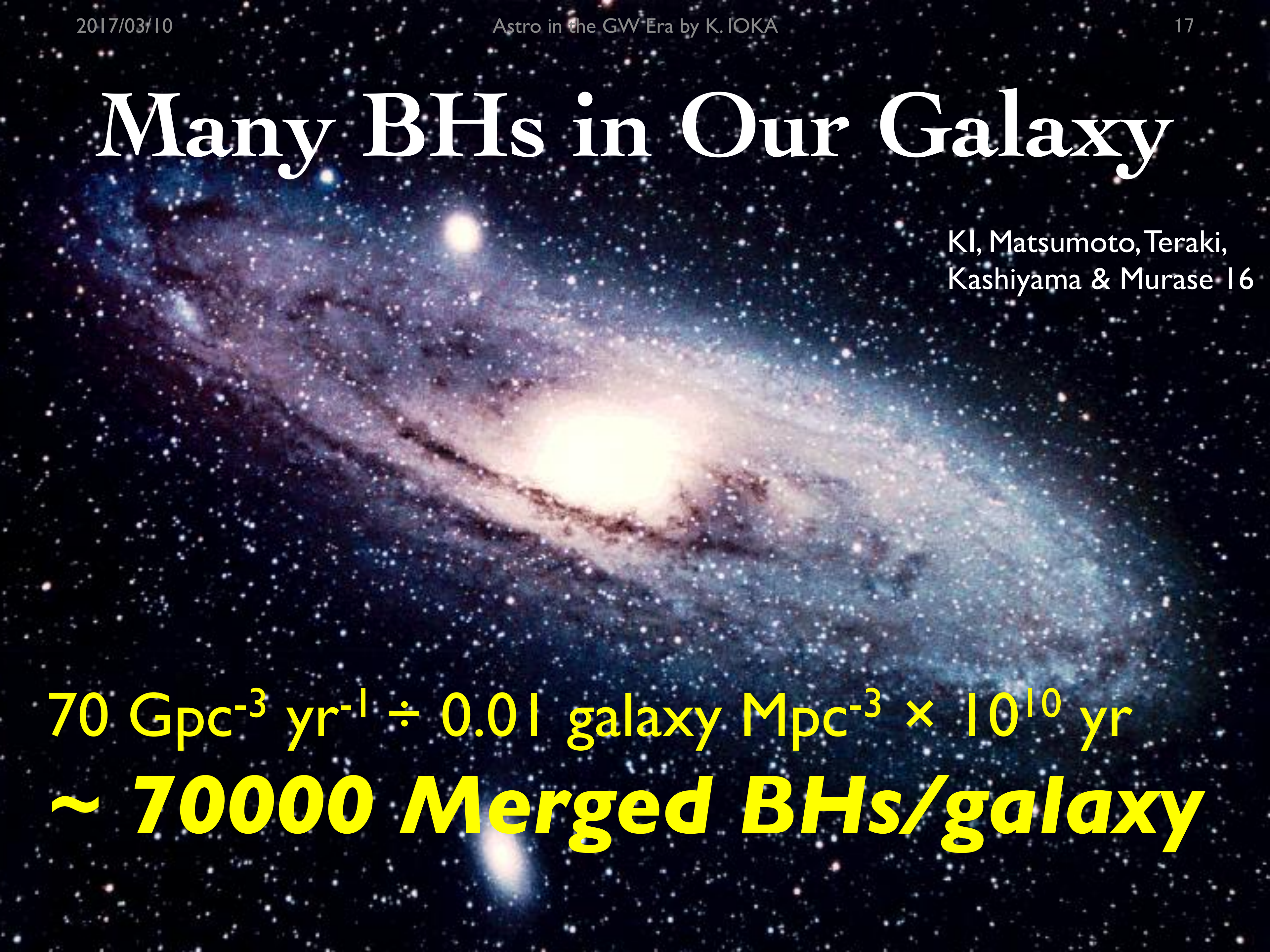

Marchant+ 16

## ~ BH formation




**GW rate ~ GRB rate**

# Many BHs in Our Galaxy

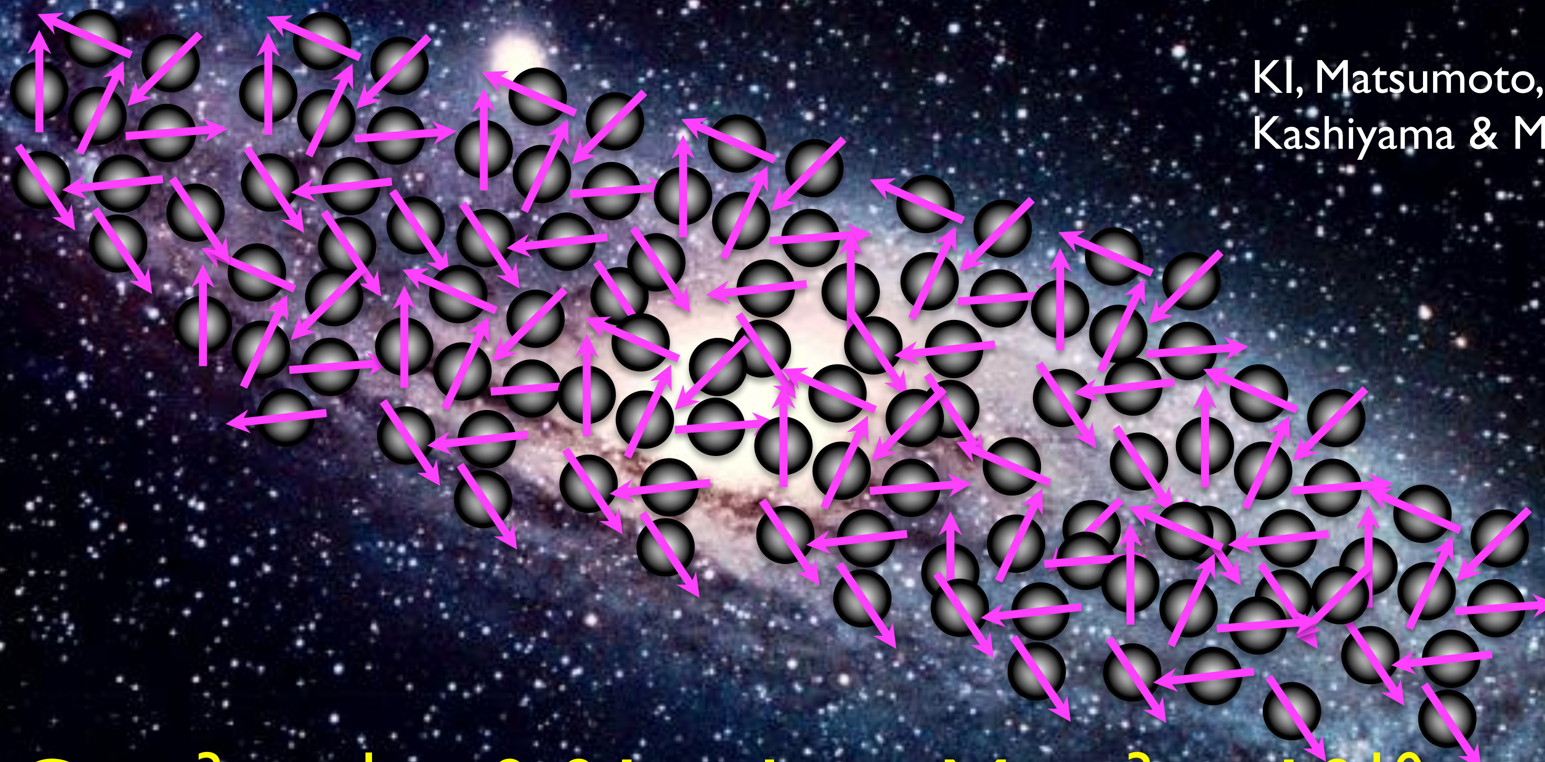


KI, Matsumoto, Teraki, Kashiyama & Murase 16

70 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ ÷ 0.01 galaxy $\mathrm{Mpc}^{-3}$ × $10^{10}$ yr

***~ 70000 Merged BHs/galaxy***

# Many BHs in Our Galaxy



KI, Matsumoto, Teraki, Kashiyama & Murase 16

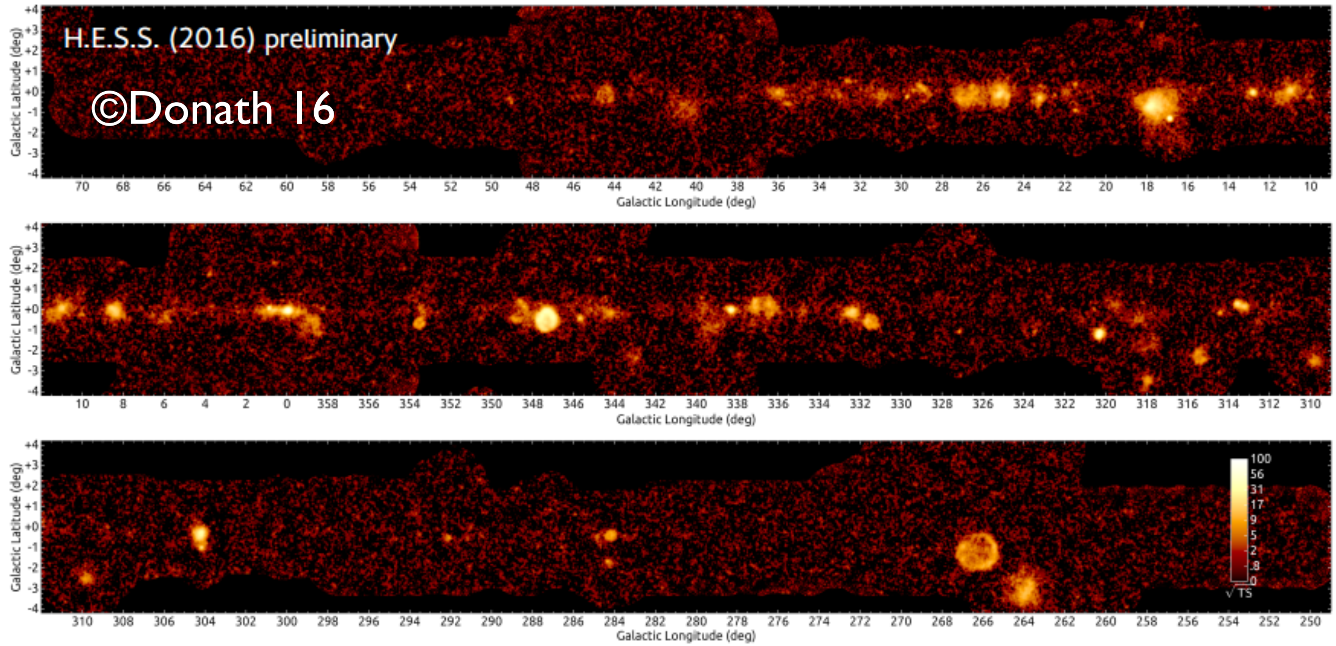
$70\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} \div 0.01$ galaxy $\mathrm{Mpc}^{-3} \times 10^{10}$ yr

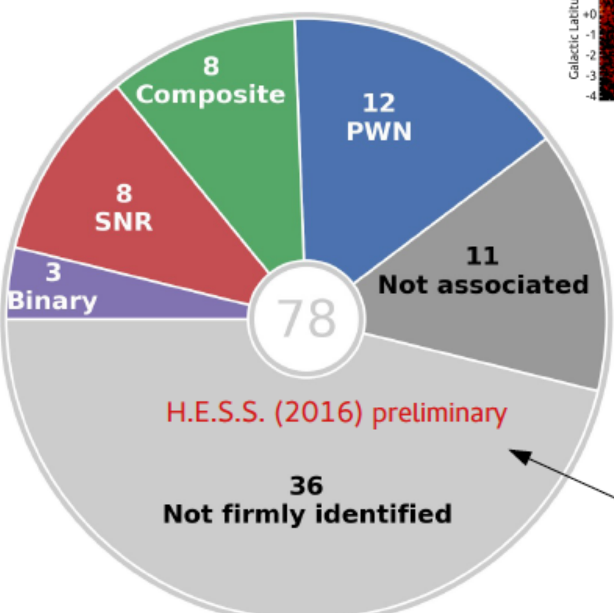
***~ 70000 Merged BHs/galaxy***

***$E_{spin}$~$10^8$ Supernovae***

# High Energy Sources?

TeV-PeV γ-ray & cosmic-ray sources in our Galaxy




Sources with multiple associations

***Most are unidentified***

Some are dark accelerators

⇔ ***Accreting BHs?***

KI, Matsumoto, Teraki, Kashiyama & Murase 16

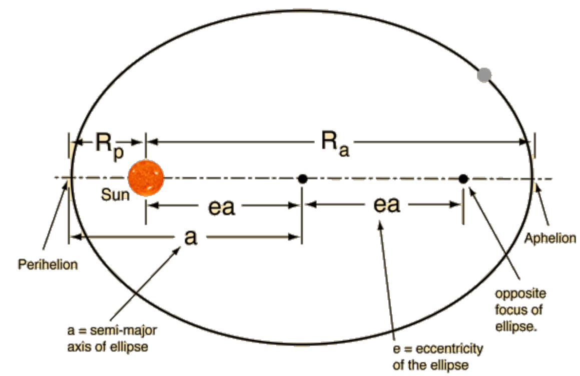
# Clues

- Mass ⇒ Low metal (Old star)
- Rate ⇒ GRB? Galactic BHs?
- Separation
- Spin
- Eccentricity

# Very Close Binary

## GW coalescence time

$$t_{GW} \cong \frac{5}{256}\frac{a}{c}\frac{c^2 a}{Gm_1}\frac{c^2 a}{Gm_2}\frac{c^2 a}{GM}\left(1-e^2\right)^{7/2}$$

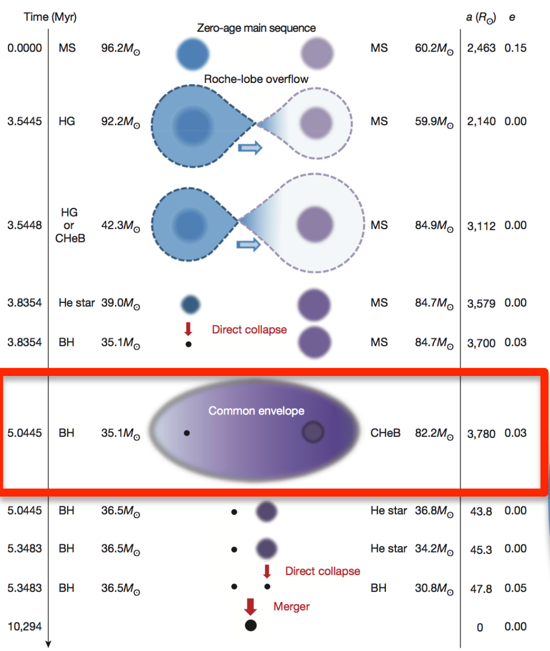



$R_a = a(1+e)$ $R_p = a(1-e)$

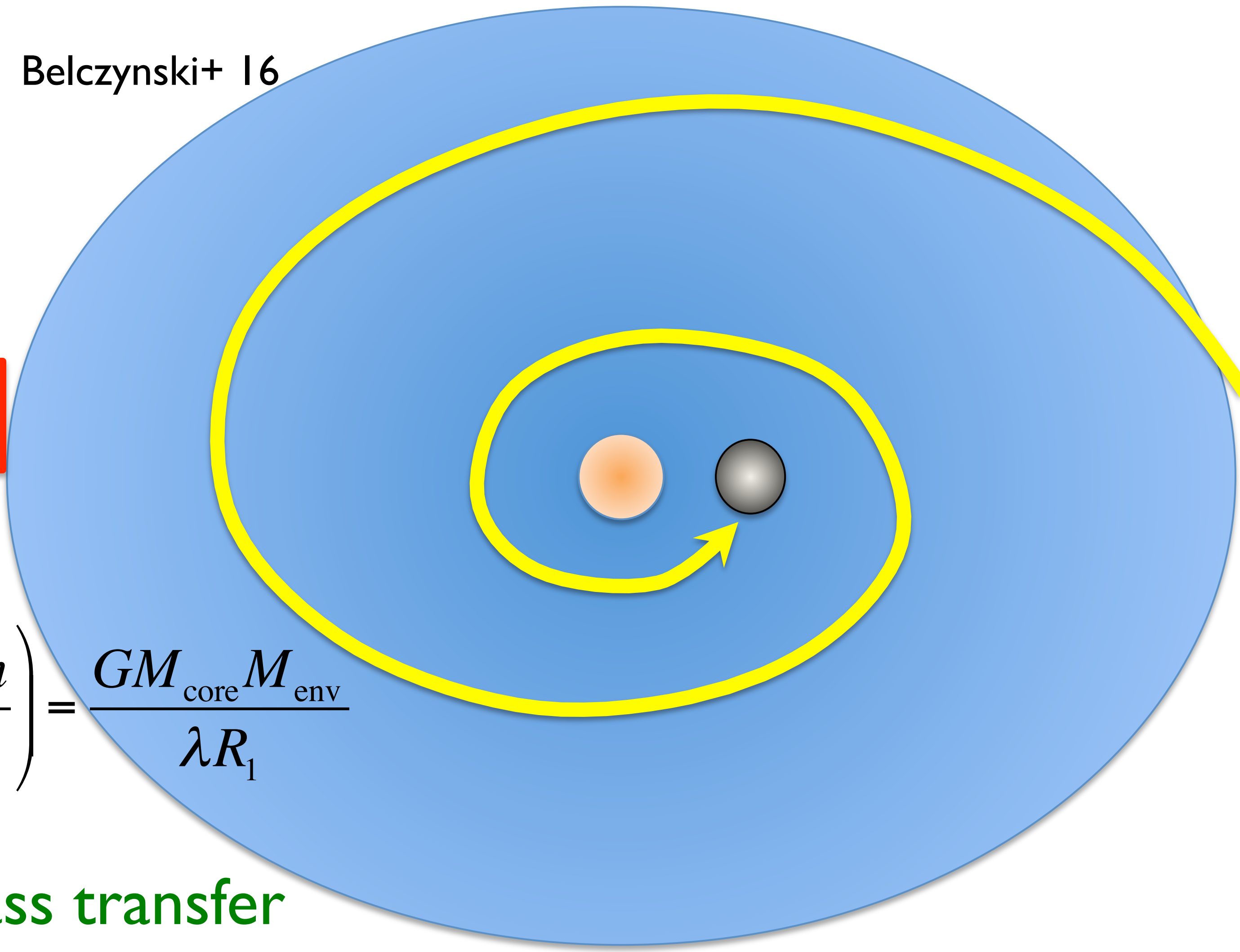
$$\approx 10^{10}\,\mathrm{yr}\left(\frac{a}{3\times 10^{12}\,\mathrm{cm}}\right)^4\left(\frac{m_1}{30M_\odot}\right)^{-3}\left(\frac{2/q}{1+q}\right)\left(1-e^2\right)^{7/2}$$

closer than Mercury for $t_{GW}<t_H$!

# Common Envelope Phase




Belczynski+ 16



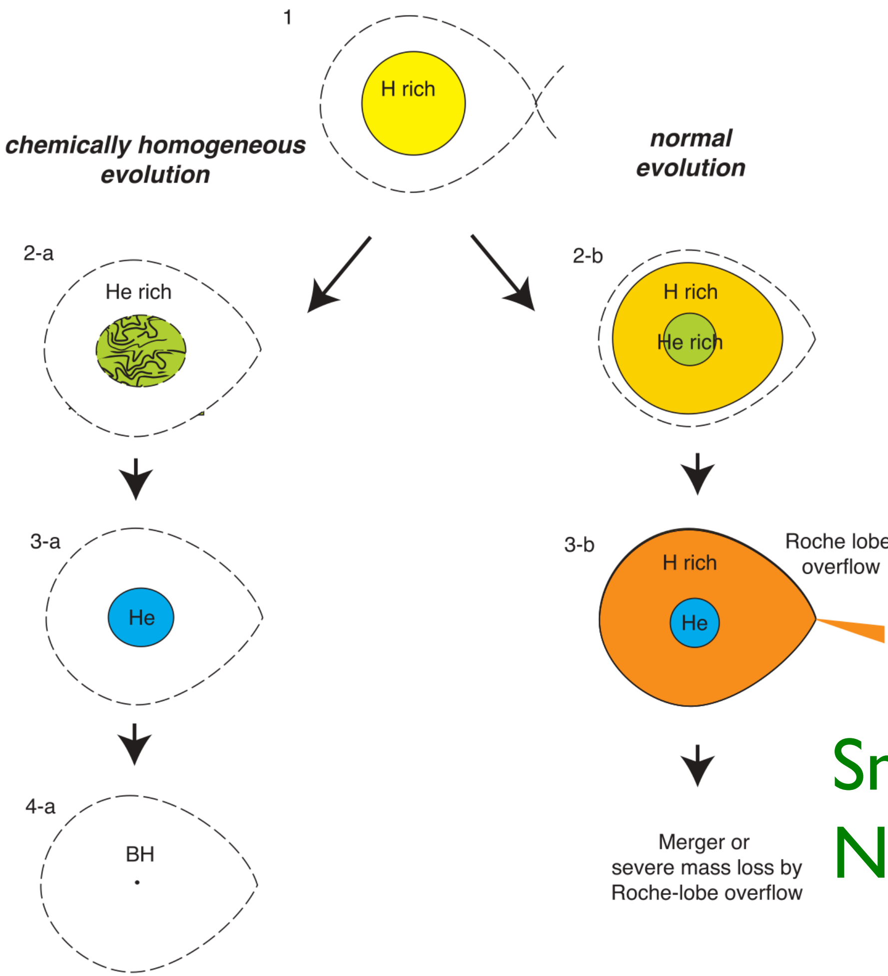
$$\alpha\left(\frac{GM_{\rm core}m}{2a_f}-\frac{GM_{\rm tot}m}{2a_i}\right)=\frac{GM_{\rm core}M_{\rm env}}{\lambda R_1}$$

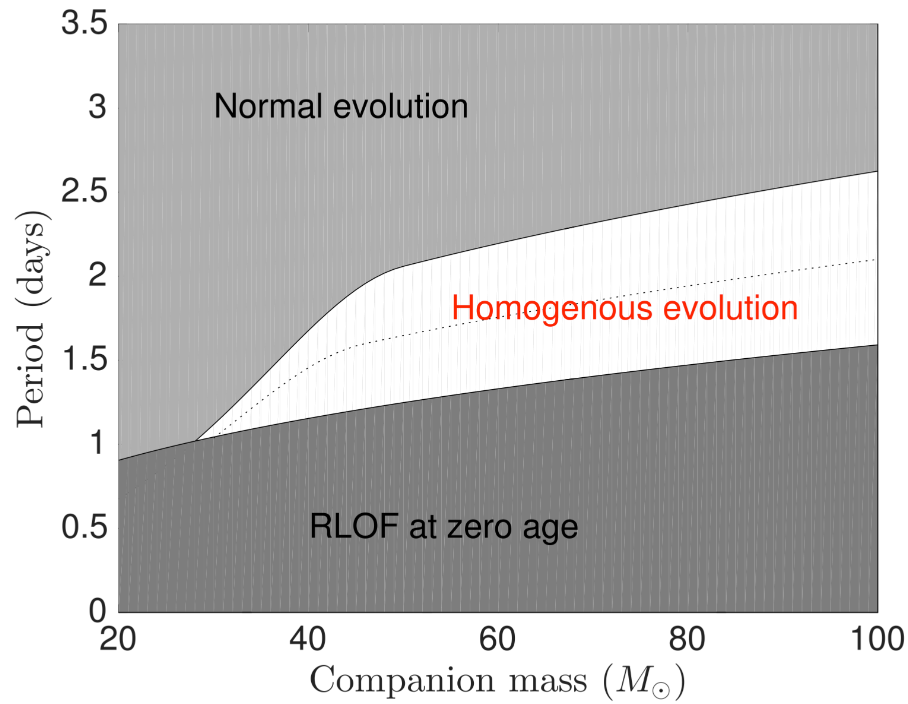
Caveat: Stable mass transfer (w/o CE) for radiative envelopes?

van den Heuvel+ 17, Inayoshi+ 17

# Chemically Homogeneous Evolution

## Fast rotation ⇒ Meridional circulation ⇒ CHE




Small $a_0$ ⇒ Tidally lock ⇒ Spin up

No envelope ⇒ Good for GRB

Yoon+ 12, Mandel & De Mink 16, Marchant+ 16

# Why Pop III binaries become 30Msun BH-BH

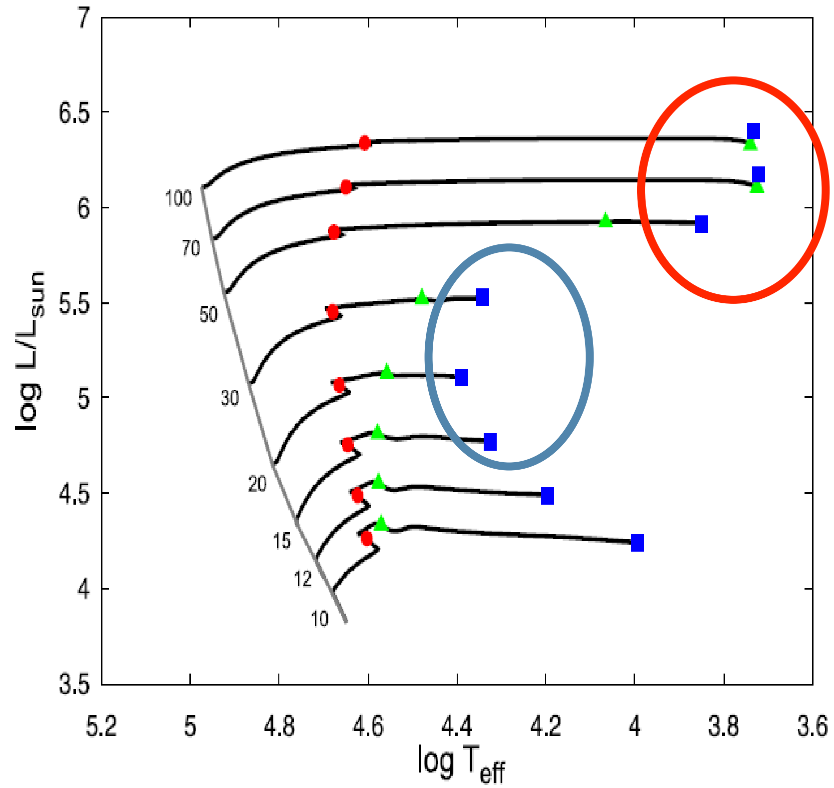



**Figure 1.** The Hertzsprung-Russell (HR) diagram for the Pop III stars of mass 10 $M_\odot \leqslant M \leqslant 100\ M_\odot$ using the data taken from Marigo et al. (2001). The number attached to each solid curve is the mass of each star in unit of $M_\odot$. The dashed line shows the ZAMS (Zero Age Main Sequence) stars. Red circles, green triangles and blue squares correspond to the beginning of He-burning, the end of the He-burning and the beginning of the C-burning, respectively.

- M>50Msun red giant
  →Mass transfer is unstable
  →common envelope
  →1/3~1/2 of initial mass
  (~25-30Msun)

- M<50Msun blue giant
  →Mass transfer is stable
  →mass loss is not so effective
  →2/3~1 of initial mass
(25-30Msun)

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# Population III BHs

THE ASTROPHYSICAL JOURNAL, **277**:445–469, 1984 February 15


## COSMOLOGICAL CONSEQUENCES OF POPULATION III STARS

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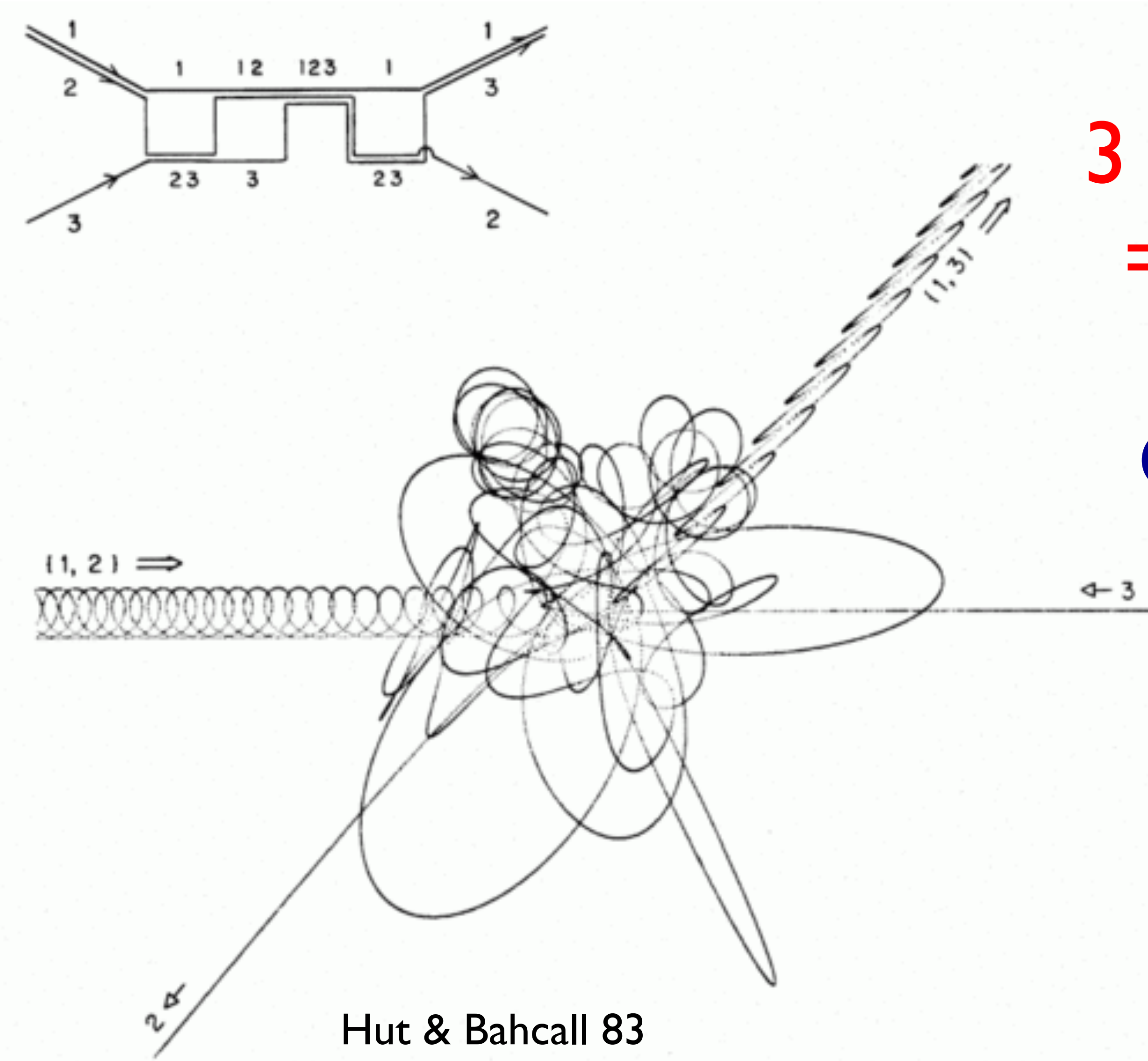
*Received 1982 October 6; accepted 1983 August 2*

## ABSTRACT

We examine the possible cosmological consequences of Population III stars. Their dark remnants could provide the "missing mass." Their light could have produced either the entire 3 K background or observable distortions in its spectrum. Their heat or explosions could have reionized the universe and perhaps produced galaxies. Their helium yield could suffice to provide an alternative explanation for the observed "primordial" abundance, and their heavy-element yield could have produced a burst of pregalactic enrichment. We discuss which sort of stars could best fulfill these roles and conclude that the most plausible candidates would be "Very Massive Objects" in the mass range $10^2$–$10^5$ $M_{\odot}$. Even if Population III stars played none of these roles, consideration of the associated effects places strong constraints on their mass spectrum and formation epoch.

*Subject headings:* cosmology — stars: interiors — stars: massive — stars: stellar statistics — stars: weak-line

# Stellar Cluster




Hut & Bahcall 83

3 body interaction
⇒ Tight binaries

Globular cluster?
Galactic center?

# Near Galactic Nuclei?

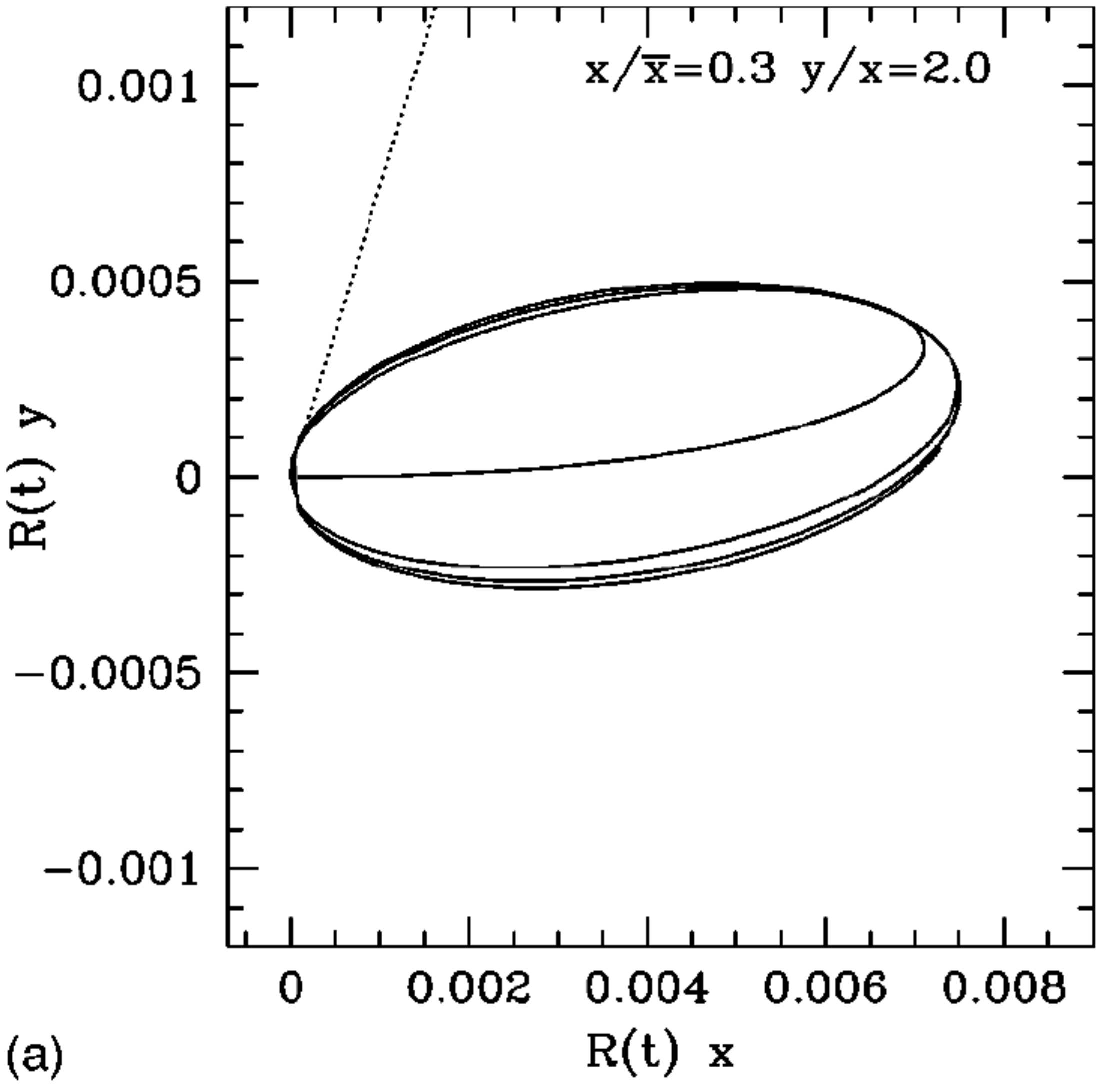

Near galactic center

High stellar density
- 3-body
- Repeated

High gas density
- Gas drag
- EM counterpart?

Antonini & Rasio 16
Bartos+ 16
Stone+ 16

# Primordial Black Hole




Early universe
⇒ Small $a_0$

3-body ⇒ $J_{orbit}$
Very eccentric

Nakamura, Sasaki, Tanaka & Thorne 97
KI+ 98a,b
Sasaki, Suyama, Tanaka & Yokoyama 16
Carr+ 16, Kawasaki+ 16

# My 1st Paper

PHYSICAL REVIEW D, VOLUME 58, 063003

## Black hole binary formation in the expanding universe: Three body problem approximation

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[2]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
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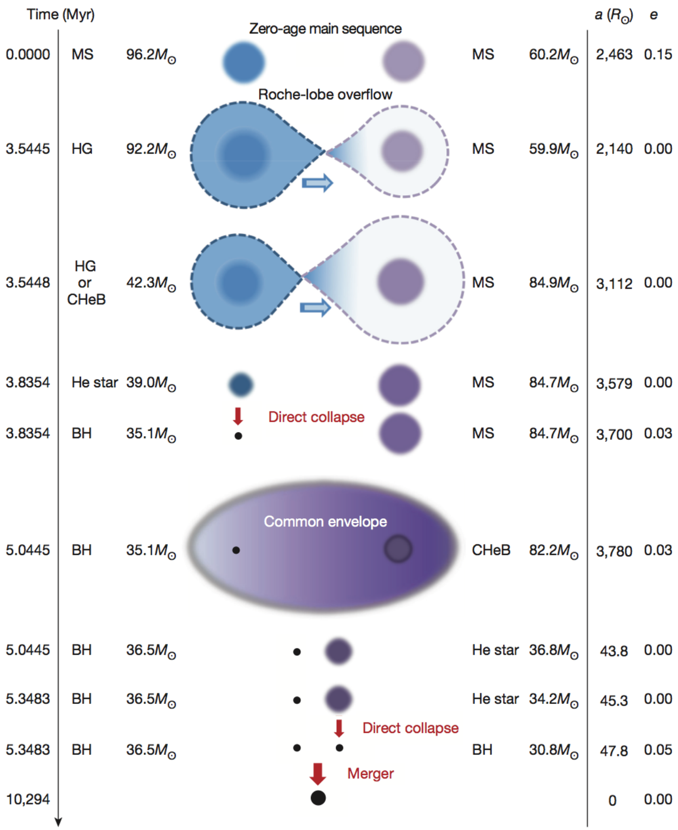
(Received 9 February 1998; published 27 August 1998)

We study black hole MACHO binary formation through three-body interactions in the early universe at $t \sim 10^{-5}$ s. The probability distribution functions of the eccentricity and the semimajor axis of binaries as well as of the coalescence time are obtained assuming that the black holes are randomly formed in space. We confirm that the previous order-of-magnitude estimate for the binary parameters is valid within $\sim 50\%$ error. We find that the coalescence rate of the black hole MACHO binaries is $\sim 5 \times 10^{-2} \times 2^{\pm 1}$ events/yr/galaxy, taking into consideration several possible factors which may affect this estimate. This suggests that the event rate of coalescing binary black holes will be at least several events per year within 15 Mpc. The first LIGO-VIRGO interferometers in 2001 will be able to verify whether or not the MACHOs are black holes.

In those days, I had an intensive lecture by B. Carr at YITP

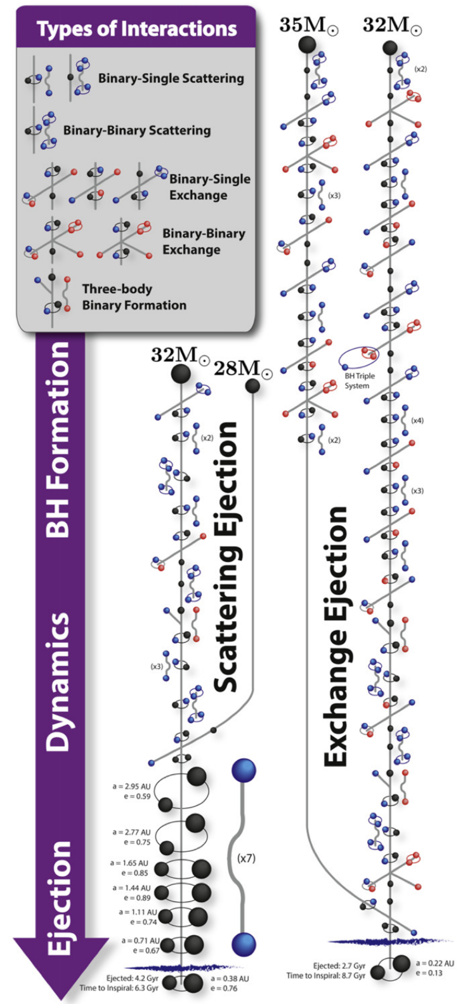
# What is the Origin?

## Binary evolution




Postnov & Yungelson 14
Belczynski+ 16
van den Heuvel+ 17
Mandel & de Mink 16
Kinugawa+ 16

## Stellar cluster




Rodriguez+ 16
O'Leary+ 16

Antonini & Rasio 16
Bartos+ 16
Stone+ 16

## Near galactic nuclei

## Primordial black hole

Sasaki+ 16
Bird+ 16
Binnilov+ 16
Carr+ 16
Kawasaki+ 16

# BH-Wolf Rayet Binaries

**We know sources similar to GW150914**

IC10: Dwarf irregular (low metal), $t_{synch}$<0.02Myr, $a_{WR}$~0.7

Builk+ 10, Esposite+ 15, but see Laycock+ 15

**Table 6.** Properties of observed WR–BH binaries and candidates (denoted by stars), and of their host galaxies.

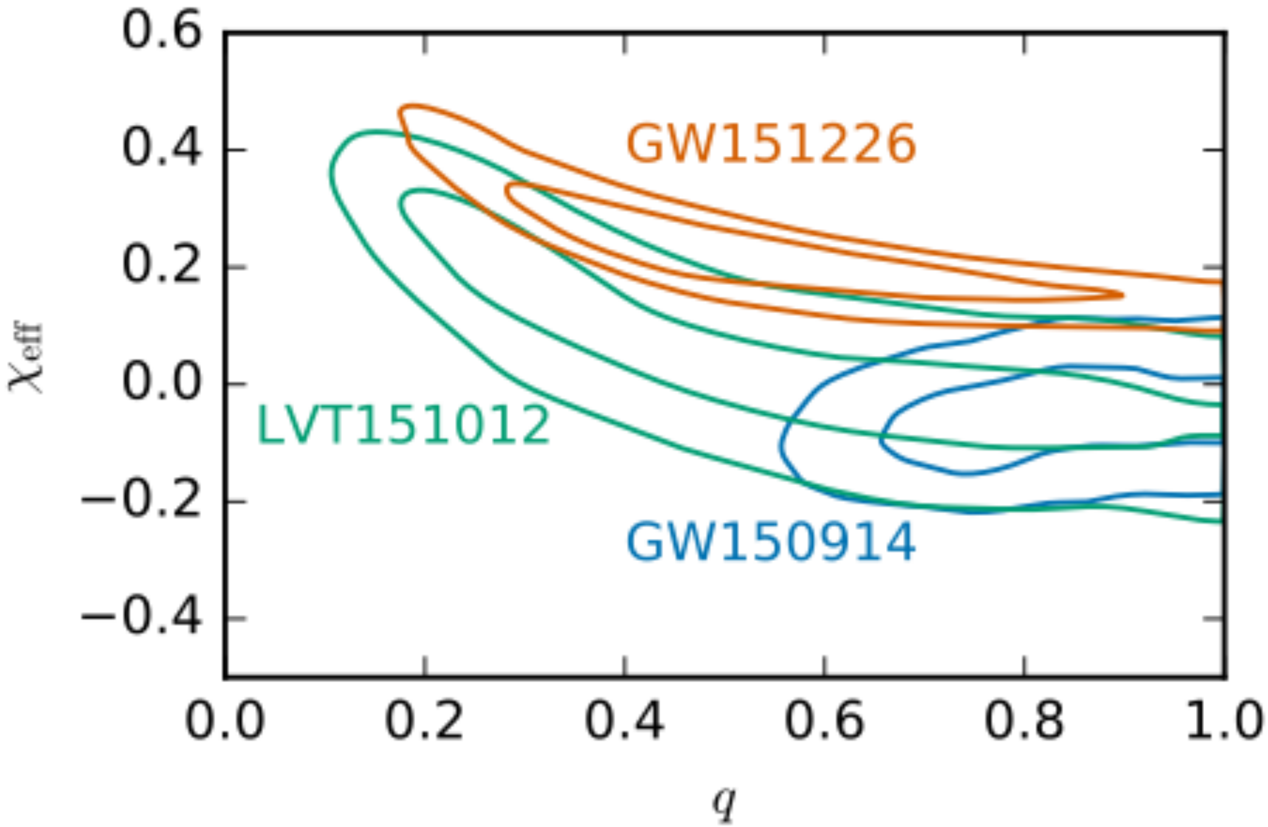
| Host galaxy | Source | Period (h) | BH mass[a] ($M_\odot$) | WR mass[a] ($M_\odot$) | SFR[b] ($M_\odot$ $yr^{-1}$) | $Z$[b] ($Z_\odot$) | $t_{GW}$[c] (Gyr) |
|---|---|---|---|---|---|---|---|
| IC 10 | X-1 | 34.9 | 33 | 35 | 0.07 | 0.22 | 1.4 |
| NGC 300 | X-1 | 32.8 | 20 | 26 | 0.14 | 0.19 | 1.7 |
| NGC 4490 | CXOU J123030.3+413853* | 6.4 | – | – | 4.5 | 0.23 | 0.038 |
| NGC 253 | CXOU J004732.0−251722.1* | 14.5 | – | – | 4.0 | 0.24 | 0.33 |
| Circinus | CG X-1* | 7.2 | – | – | 1.5 | 0.10 | 0.052 |
| M101 | ULX-1 | 196.8 | 20 | 19 | 3.1 | 0.17 | 200 |
| Milky Way | Cyg X-3 | 4.8 | 3 | 7 | 0.25 | 0.31 | 0.051 |

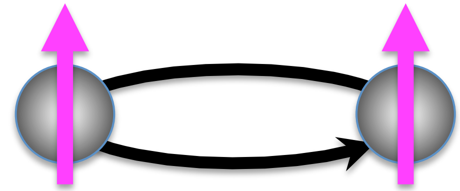
[a]For the BH and WR masses, we list only the fiducial values that we use to derive the merger rates $R$ in equation (2). Most of these masses are very uncertain, as discussed in Prestwich et al. (2007), Silverman & Filippenko (2008), Carpano et al. (2007a,b), Crowther et al. (2010), Esposito et al. (2013c), Maccarone et al. (2014), Liu et al. (2013), and Shrader et al. (2010).

# Clues

- Mass ⇒ Low metal (Old star)
- Rate ⇒ GRB? Galactic BHs?
- Separation ⇒ Field binary?
- Spin
- Eccentricity

# Low Spin



$$\chi_{\rm eff} \equiv \frac{m_1}{M}\chi_1 + \frac{m_2}{M}\chi_2$$

GW150914: $-0.06^{+0.14}_{-0.14}$

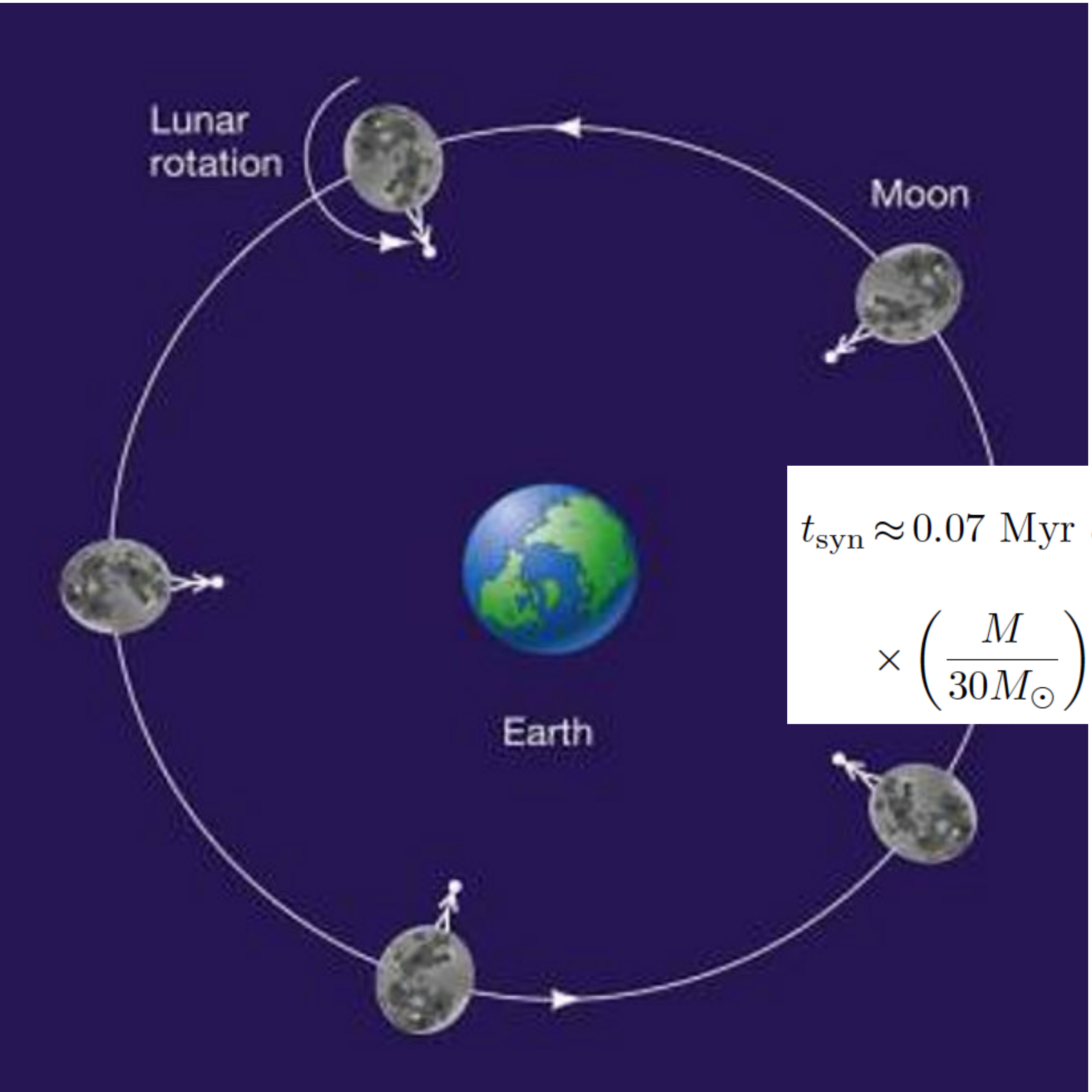
GW151226: $0.21^{+0.20}_{-0.10}$

LVT151012: $0.0^{+0.3}_{-0.2}$

The Sun (P~26 days) ⇒ χ~0.2

Typical O star (R~$10^{12}$cm, v~100km/s) ⇒ χ~30

# Tidal Locking




Close binary
⇒ Tidal torque
synchronizes
the orbit and spin

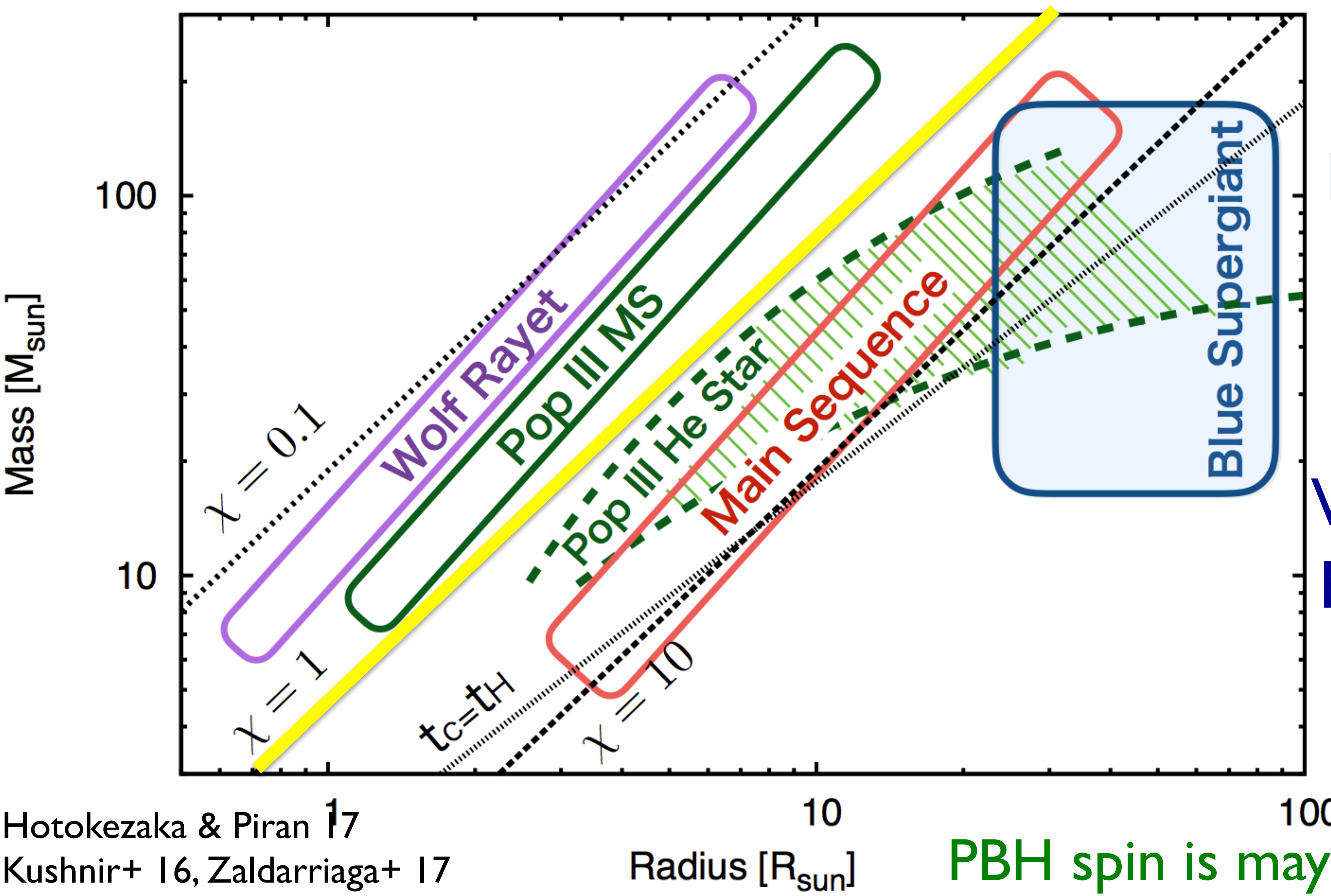
$$t_{\rm syn} \approx 0.07\ {\rm Myr}\ q^{-2} \left(\frac{1+q}{2}\right)^{-5/6} \left(\frac{\epsilon}{0.075}\right) \left(\frac{R}{14R_\odot}\right)^{-7} \times \left(\frac{M}{30M_\odot}\right)^{-1/2} \left(\frac{a}{44R_\odot}\right)^{17/2} \left(\frac{E_2}{10^{-6}}\right)^{-1}, \quad (6)$$

− may be shorter than the stellar lifetime

− sensitive to a & R

Kushnir+ 16

# Spin Constraint




MS △
wind?
CE?

WR* &
PopIII*

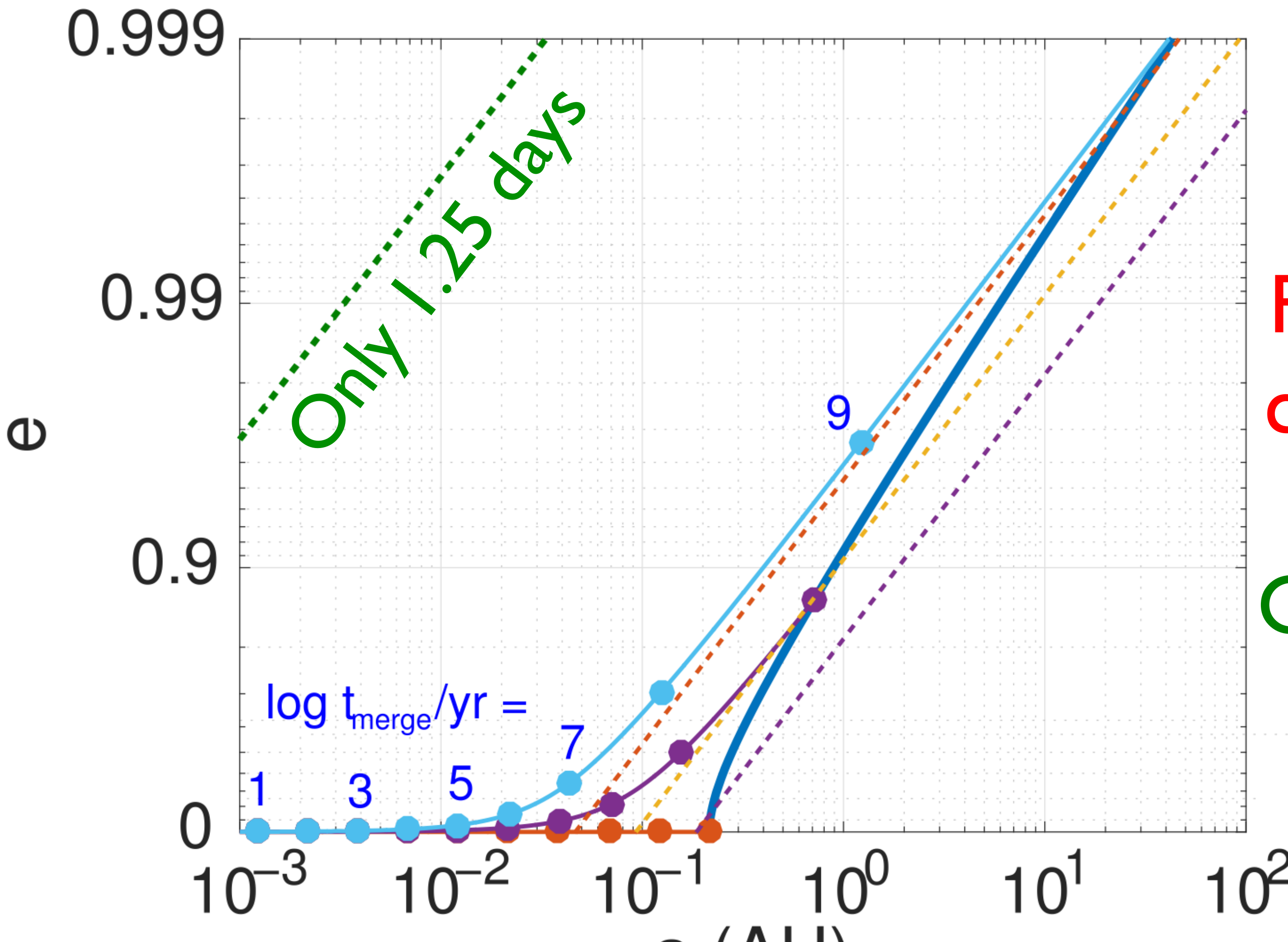
Hotokezaka & Piran 17
Kushnir+ 16, Zaldarriaga+ 17

PBH spin is maybe low

# Clues

- Mass ⇒ Low metal (Old star)
- Rate ⇒ GRB? Galactic BHs?
- Separation ⇒ Field binary?
- Spin ⇒ WR*? Pop III*?
- Eccentricity

# Circularization



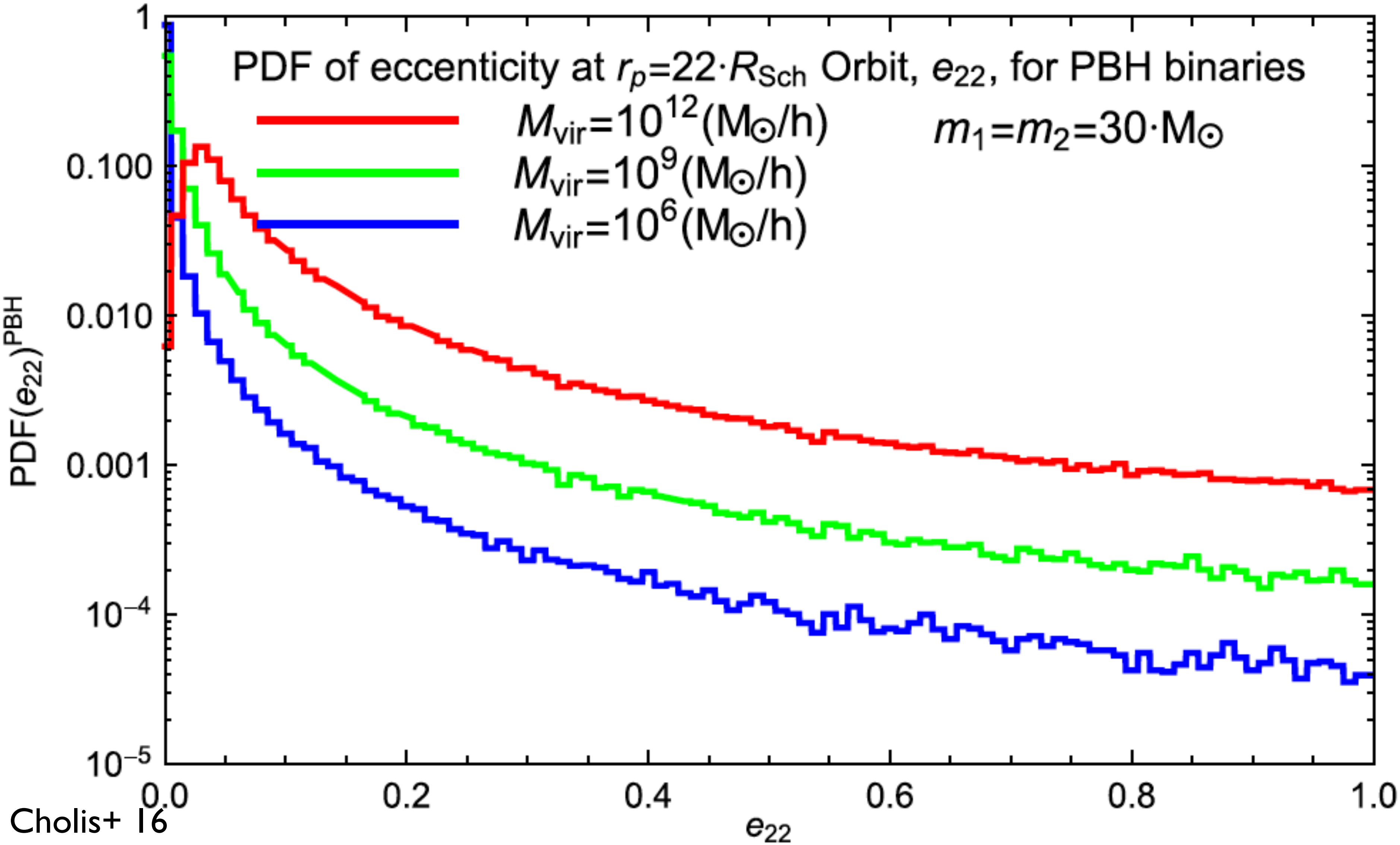

Quickly $e \rightarrow 0$

Field binary cannot have $e \neq 0$

Only cluster and PBH

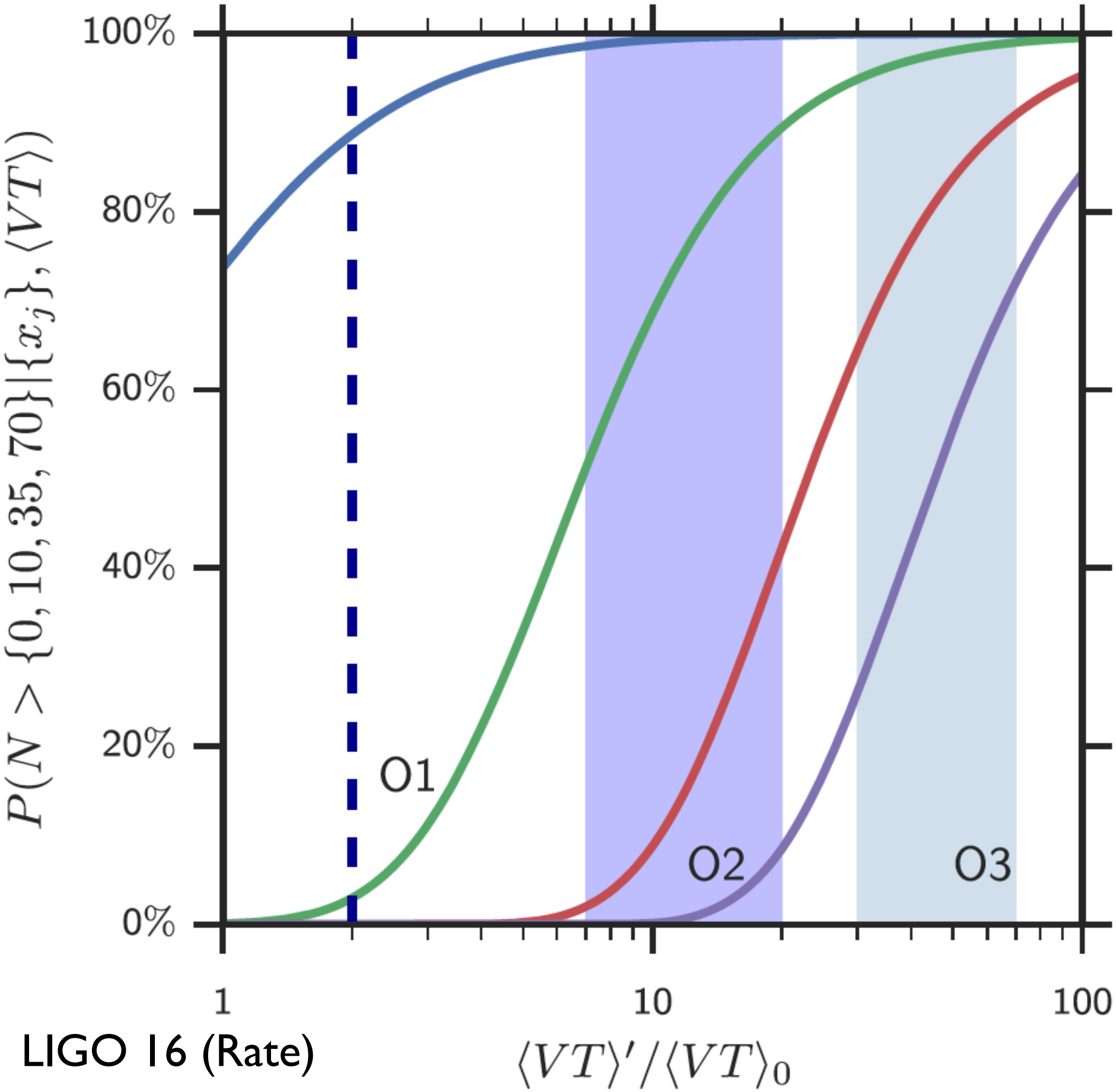
LIGO16 (astro)

# PBH Binary is Eccentric




Cholis+ 16

# Future Event Rate




LIGO 16 (Rate)

O2: 2nd observing run
O3: 3rd observing run

New events will come

Caveat:
As of Mar. 6, 2017
L1: 90Mpc, H1: 58Mpc
for NS-NS
~ Similar to O1

# New GW Events or Noise?

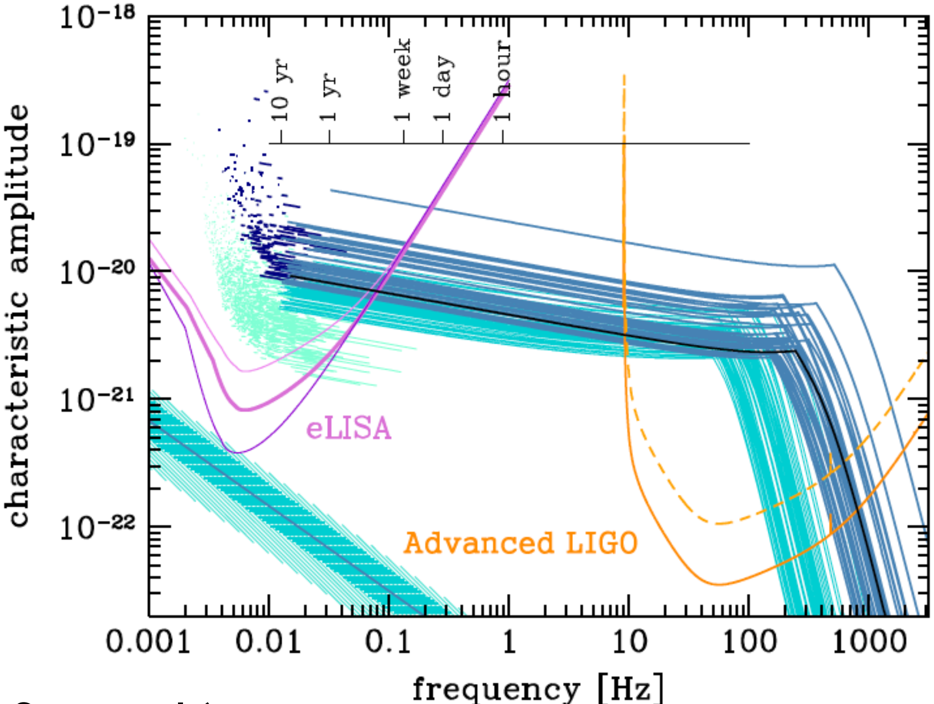
## NEWS

### UPDATE ON LIGO'S SECOND OBSERVING RUN

28 January 2017 -- The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of January 23 approximately 12 days of Hanford-Livingston coincident science data have been collected, with a scheduled break between December 22, 2016 and January 4, 2017. Average reach of the LIGO network for binary merger events have been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

So far, 2 event candidates, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for observational followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

# Space GW Observatories




Sesana+16

Low frequency band

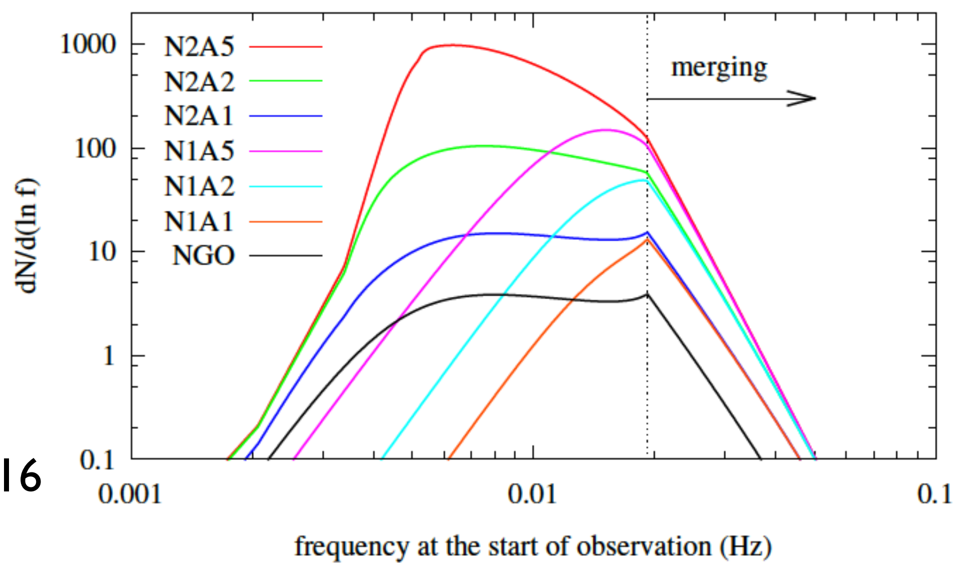
***LISA ~0.01Hz***

***DECIGO ~0.1Hz***

→ Ground ~100Hz

Guaranteed sources

Good localization




Kyutoku & Seto 16

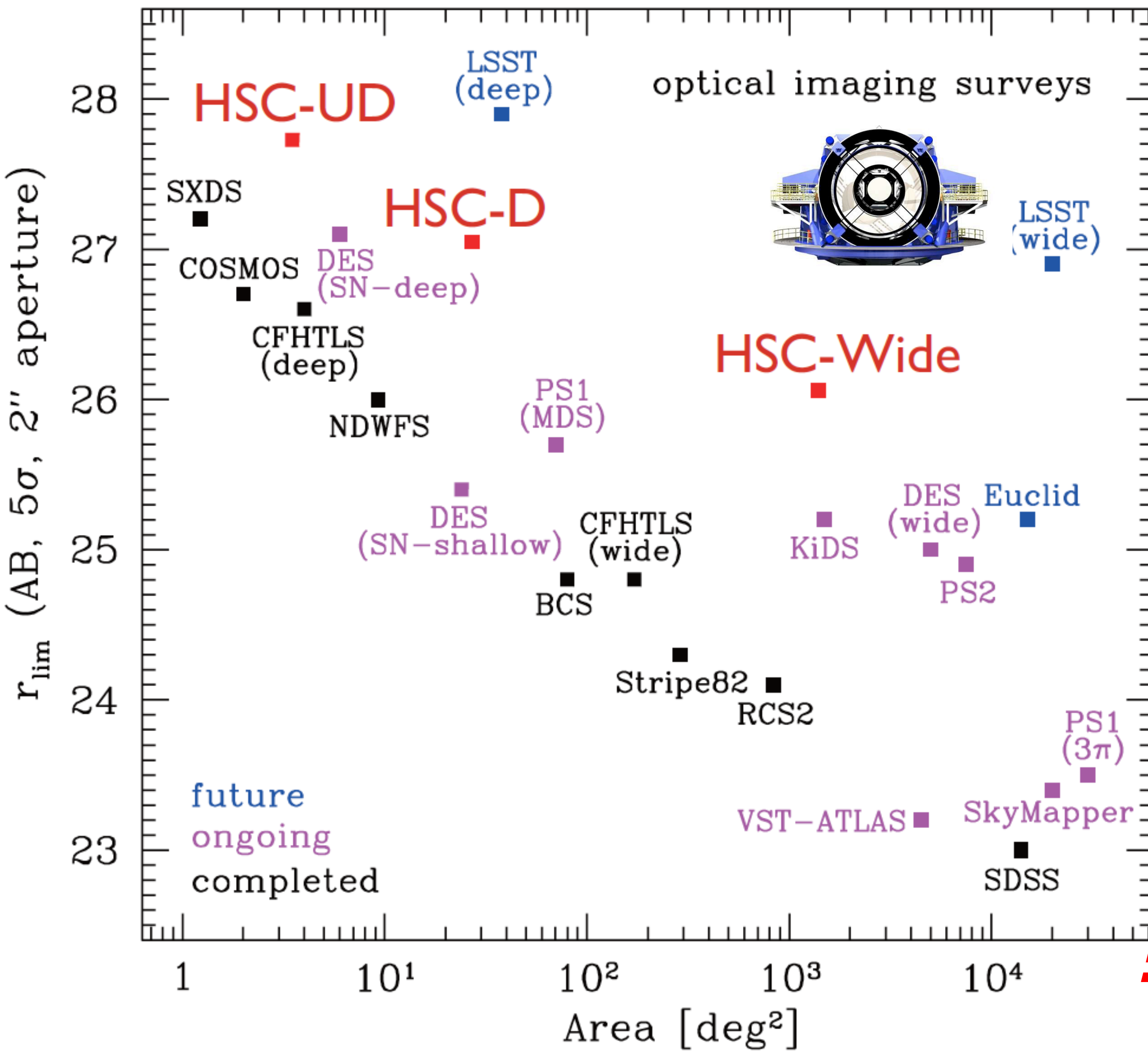
Seto 16

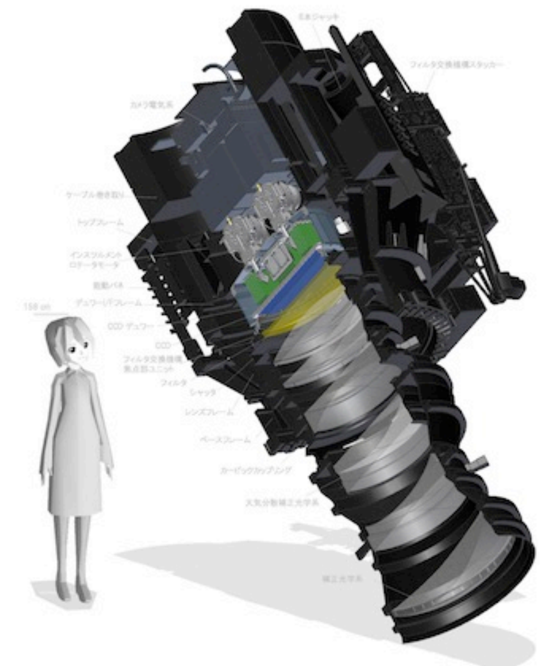
# Clues

- Mass ⇒ Low metal (Old star)
- Rate ⇒ GRB? Galactic BHs?
- Separation ⇒ Field binary?
- Spin ⇒ WR*? Pop III*?
- Eccentricity ⇒ PBH?

**+ *EM counterparts***

# Deep-Wide-Fast Survey

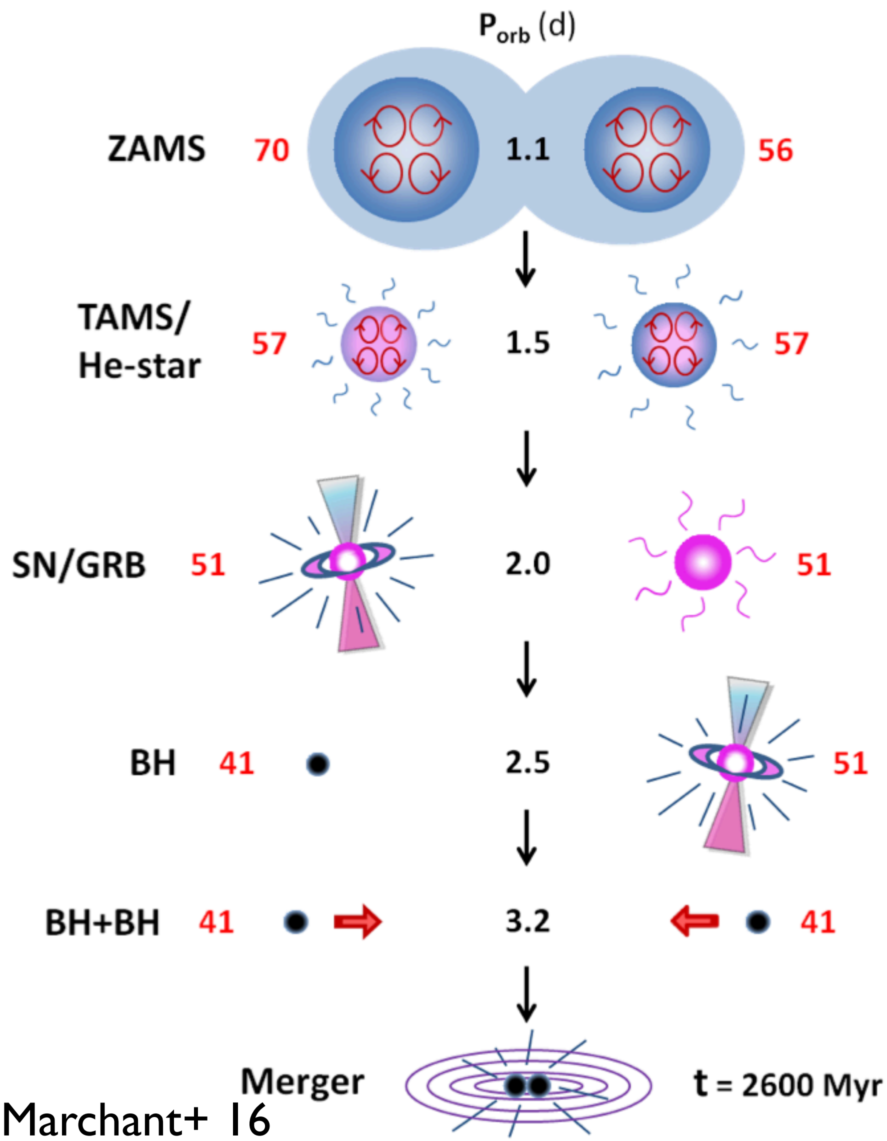


**Dark-energy-driven optical-IR survey**

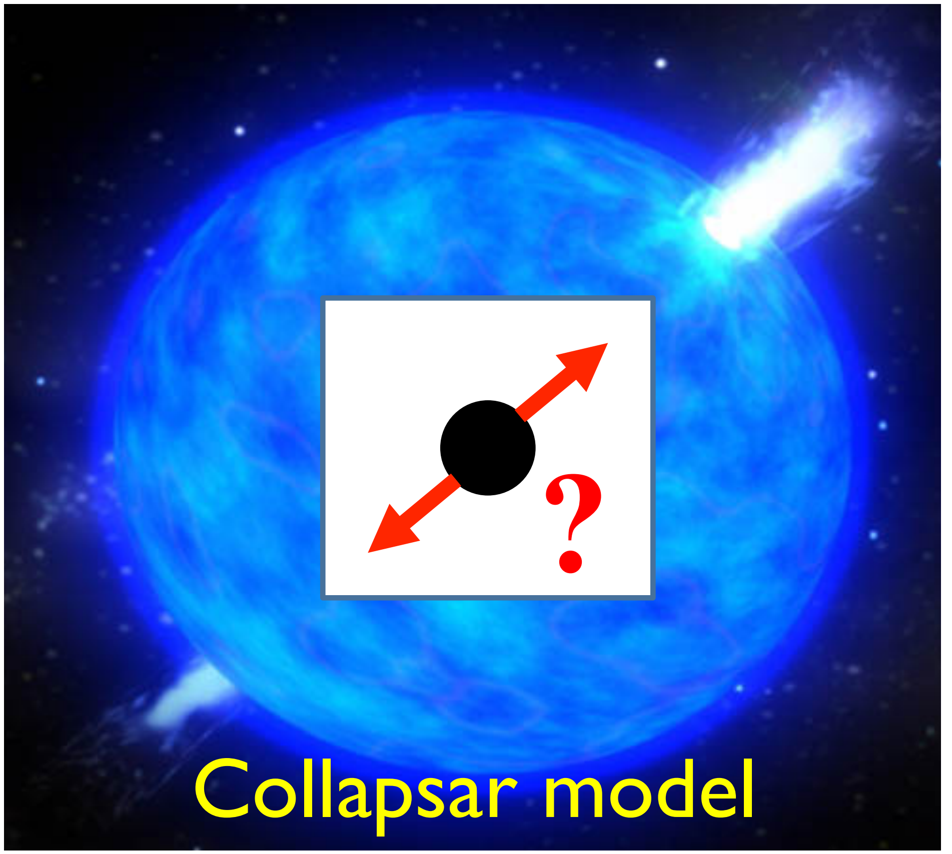
**⇒ *BH transients***

# Gamma-Ray Bursts?



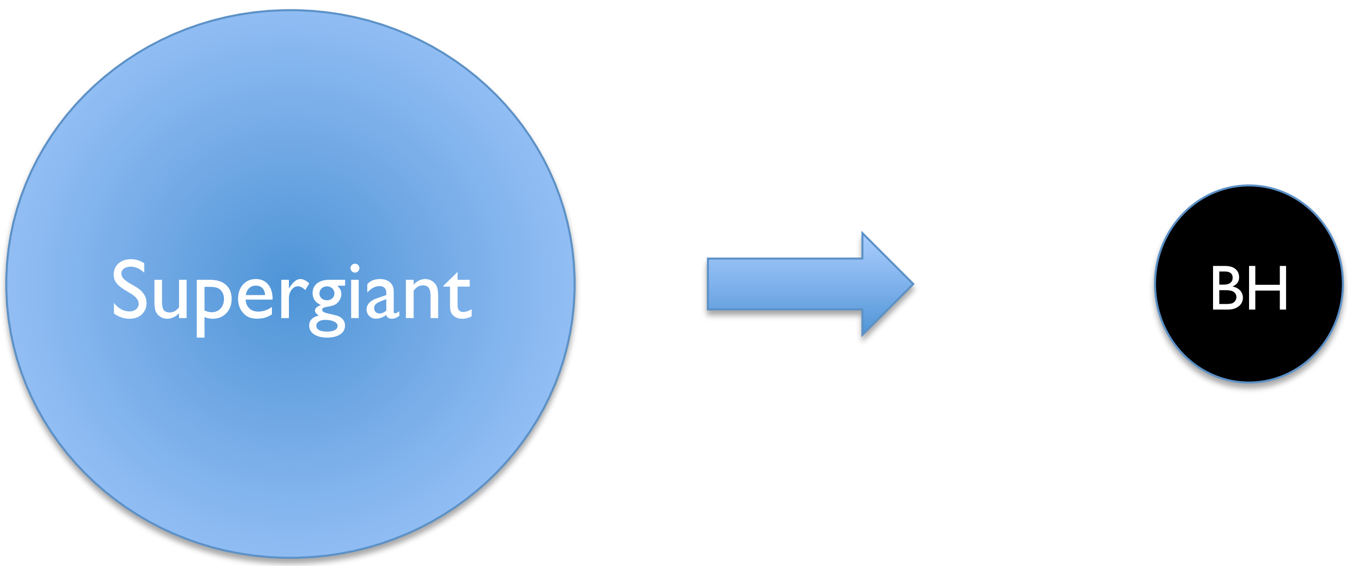

Marchant+ 16

**~ BH formation**




**GW rate ~ GRB rate**

# Survey about Nothing




Kochanek+ 08

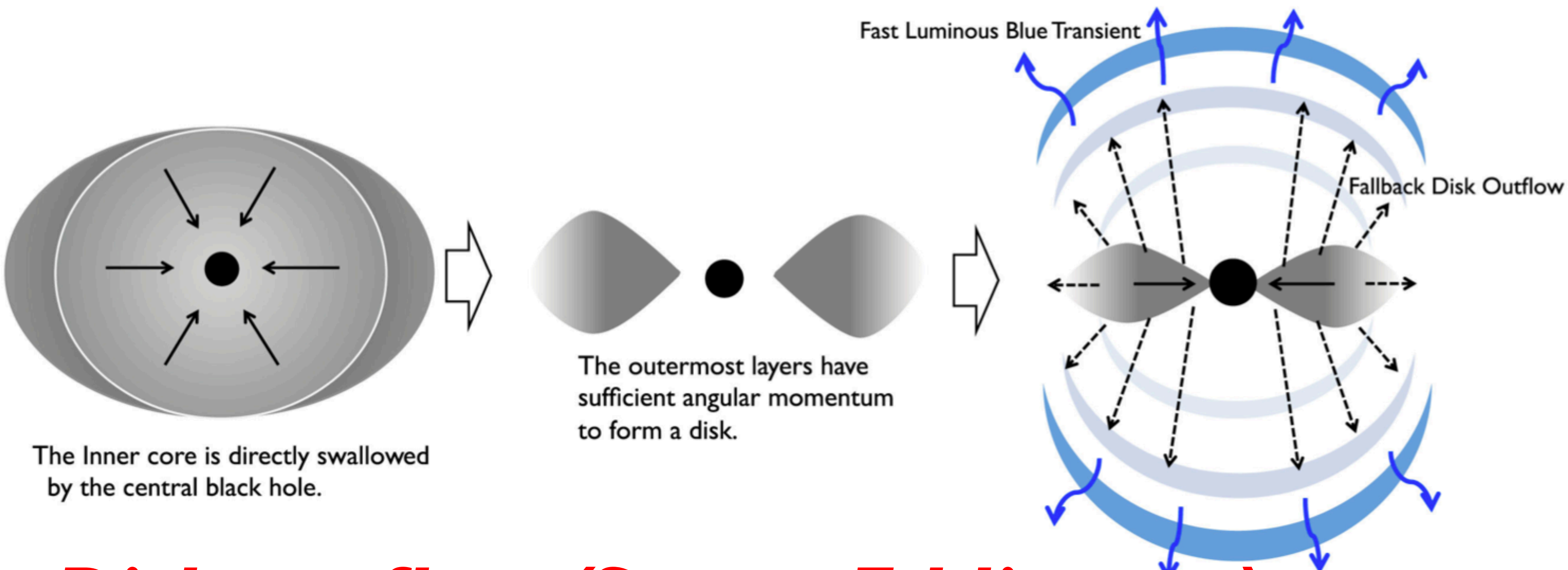
***Disappearance of massive stars***

$t_{age} \sim 10^6$ yr

Watch ~$10^6$ supergiants ⇒ 1 events/yr

The accompanying star is modulated with $P_{orbit}$

# New-born BH




**Disk outflow (Super-Eddington)**

UV-Optical transients

t~a few days

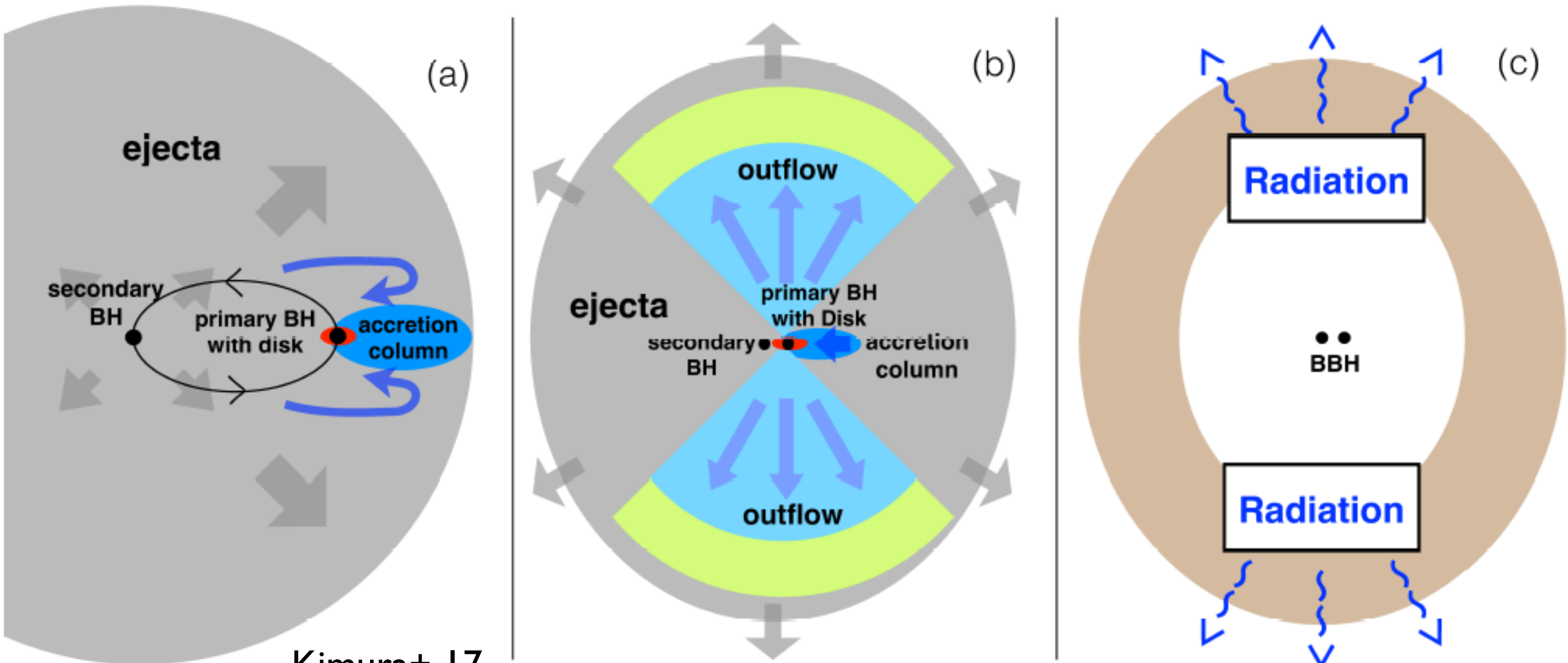
L~1e42-44 erg/s~supernova

Pan-STARRS may have already detected

Kashiyama & Quataert 15

# Companion-Induced Transient

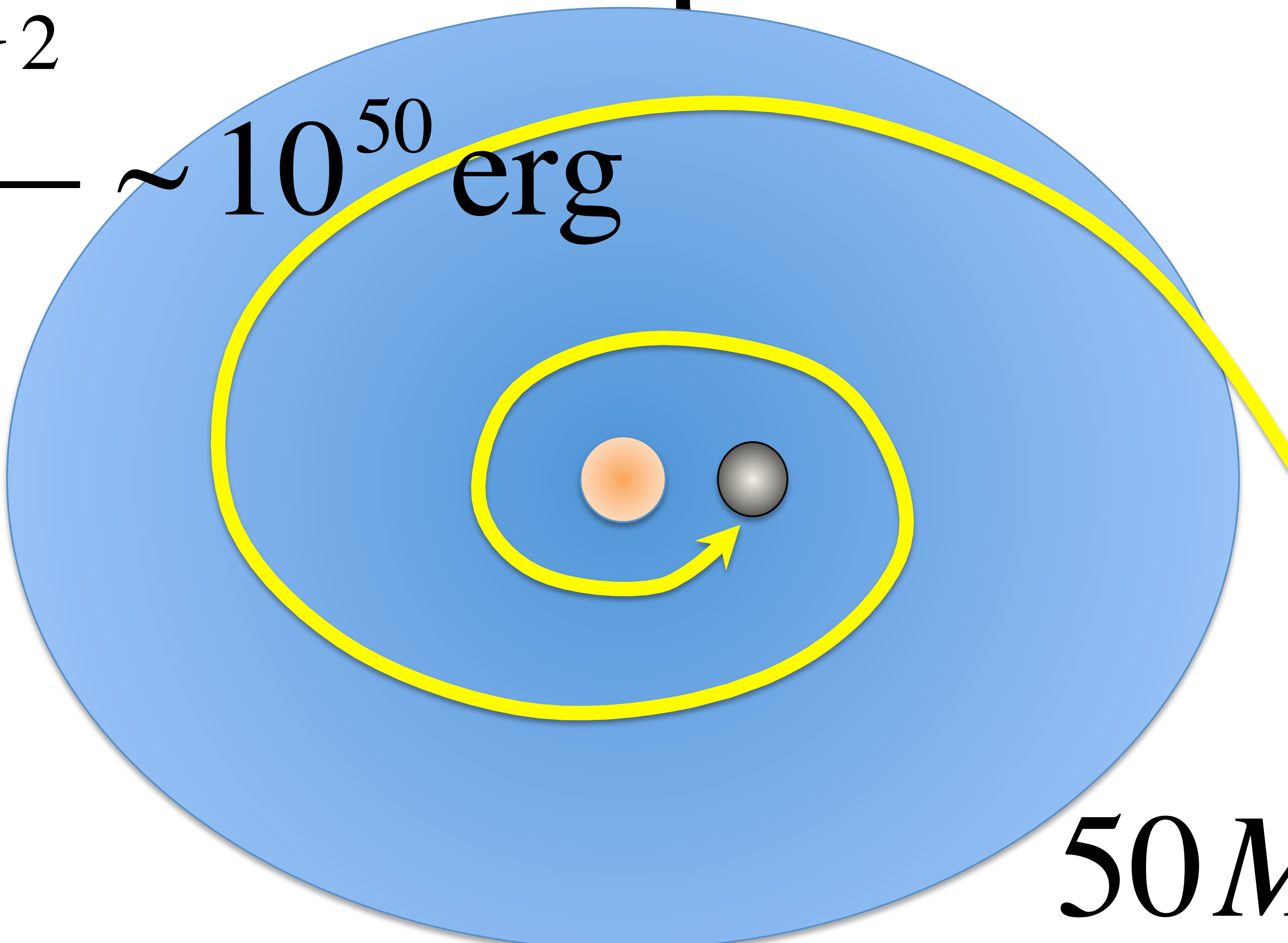
BH formation ⇒ Ejecta ⇒ Accretion ⇒ Outflow ⇒ Supernova-like emission




Kimura+ 17

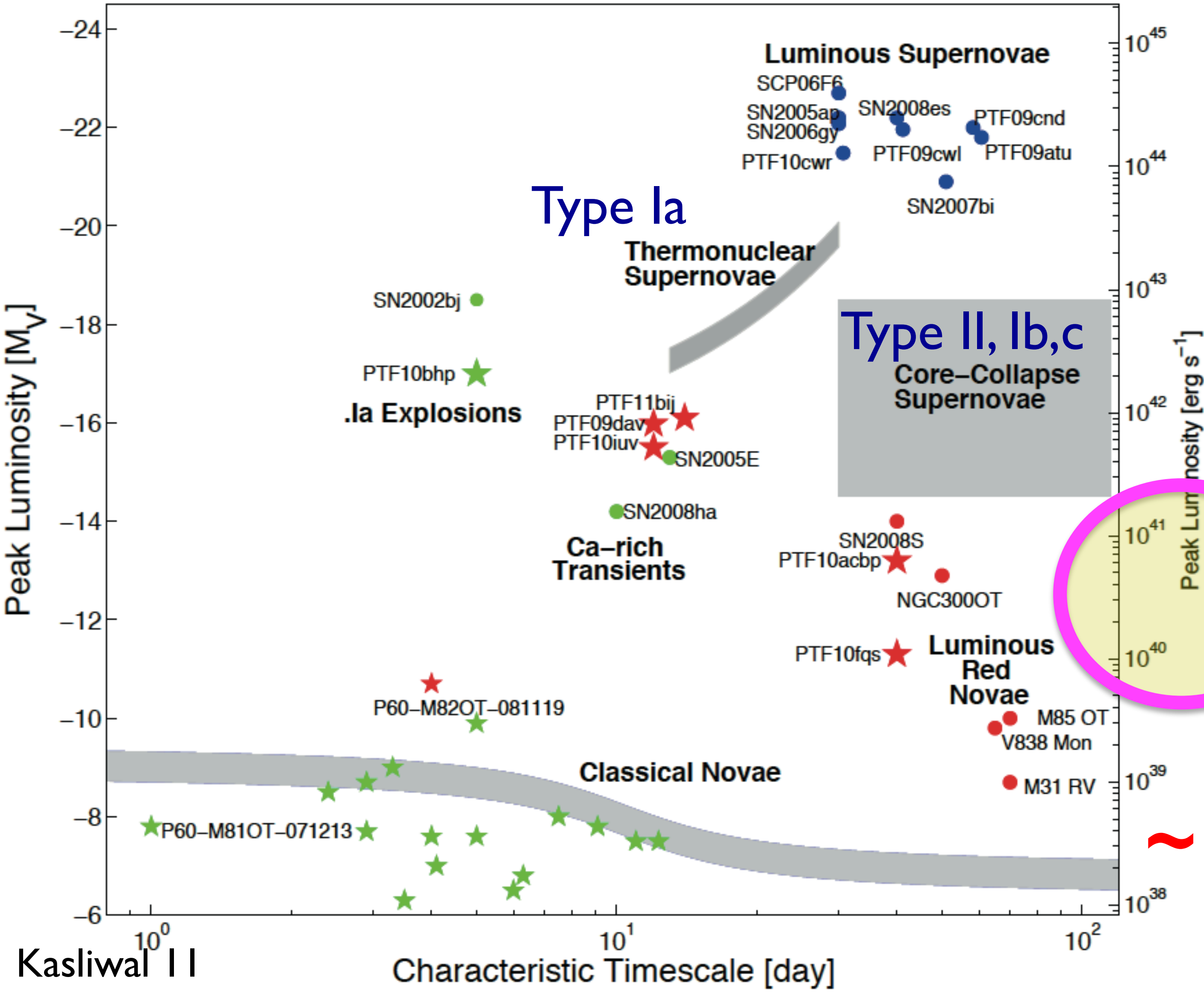
# Common Envelope Phase ~ Weak Supernova?

$$\frac{GM^2}{r} \sim 10^{50}\,\mathrm{erg}$$



$50\,M_\odot$

# Odd Luminous Red Nova?



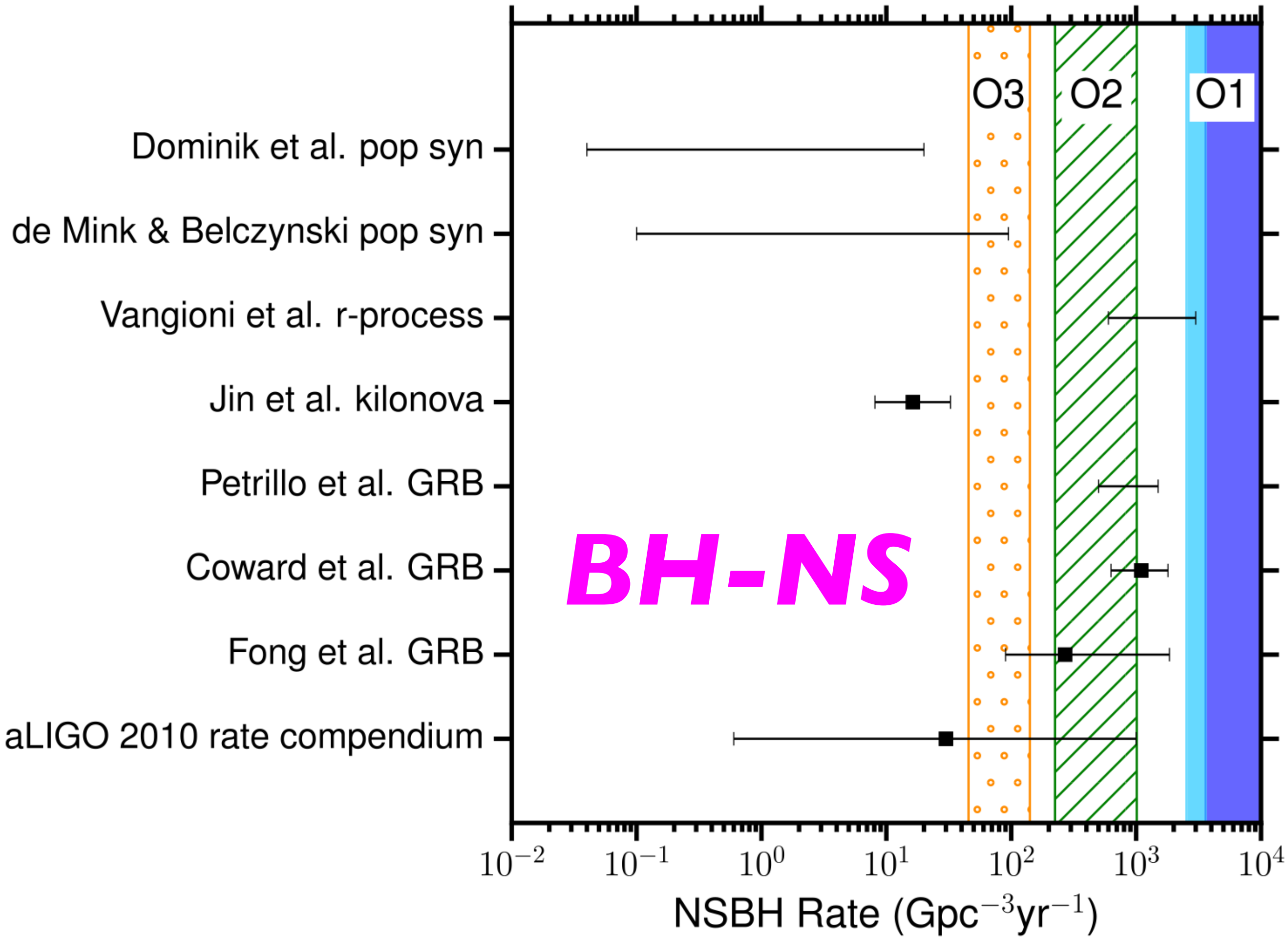

Kasliwal 11

***Luminous Red Nova ~ CE?***

Also emission from initial collision

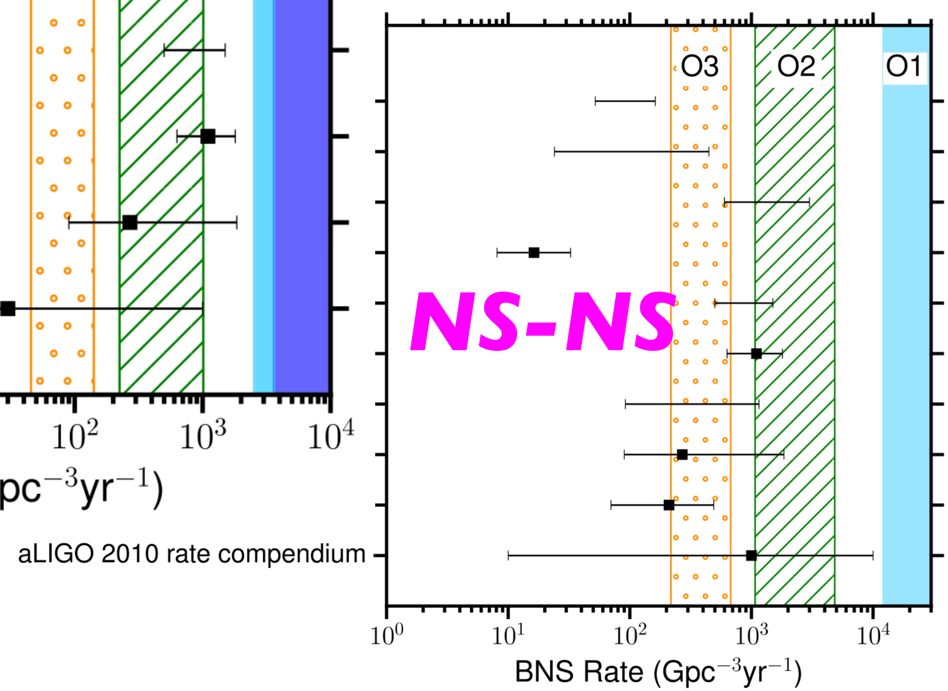
***BH-BH ~ Super CE?***

# BH-NS & NS-NS



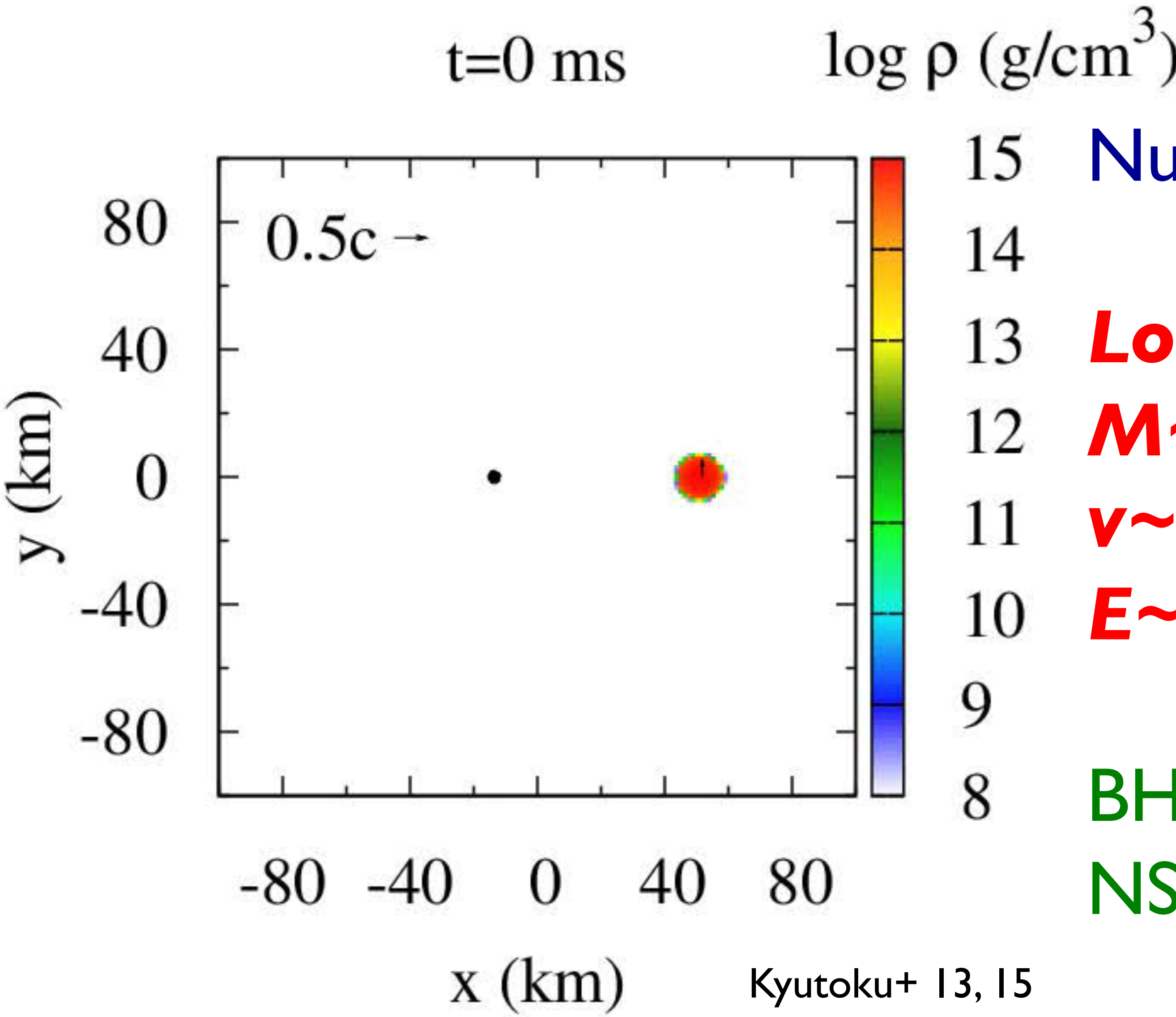

Next: BH-NS?

Small $M_{charp}$




LIGO 1607.07456

# BH-NS




Numerical relativity

***Low $Y_e$ ejecta***
***$M \sim 0.01$-$0.1 M_\odot$***
***$v \sim 0.1$-$0.3c$***
***$E \sim 10^{49}$-$10^{51}$ erg***

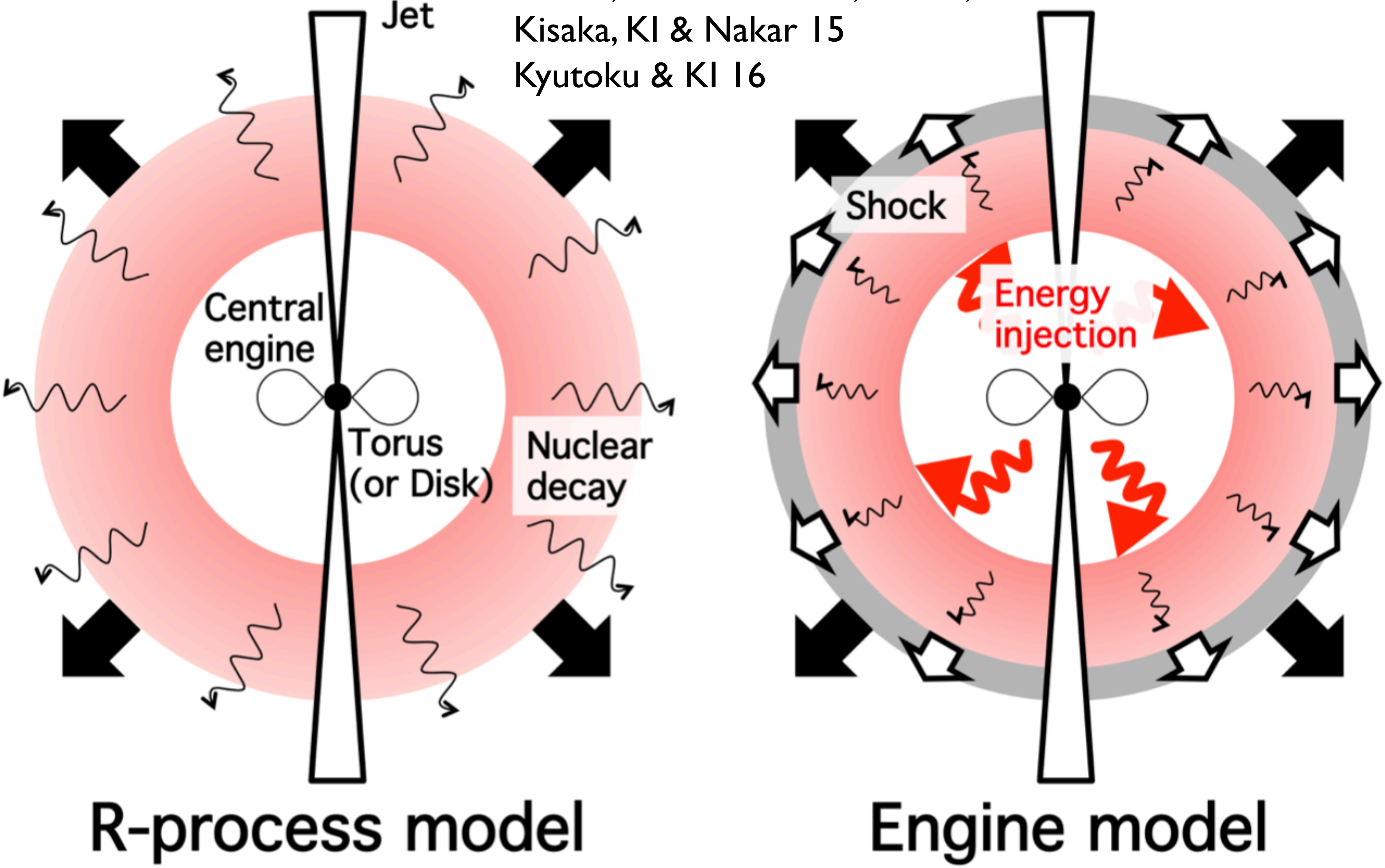
BH-NS: Anisotropic
NS-NS: Spherical

Kyutoku+ 13, 15

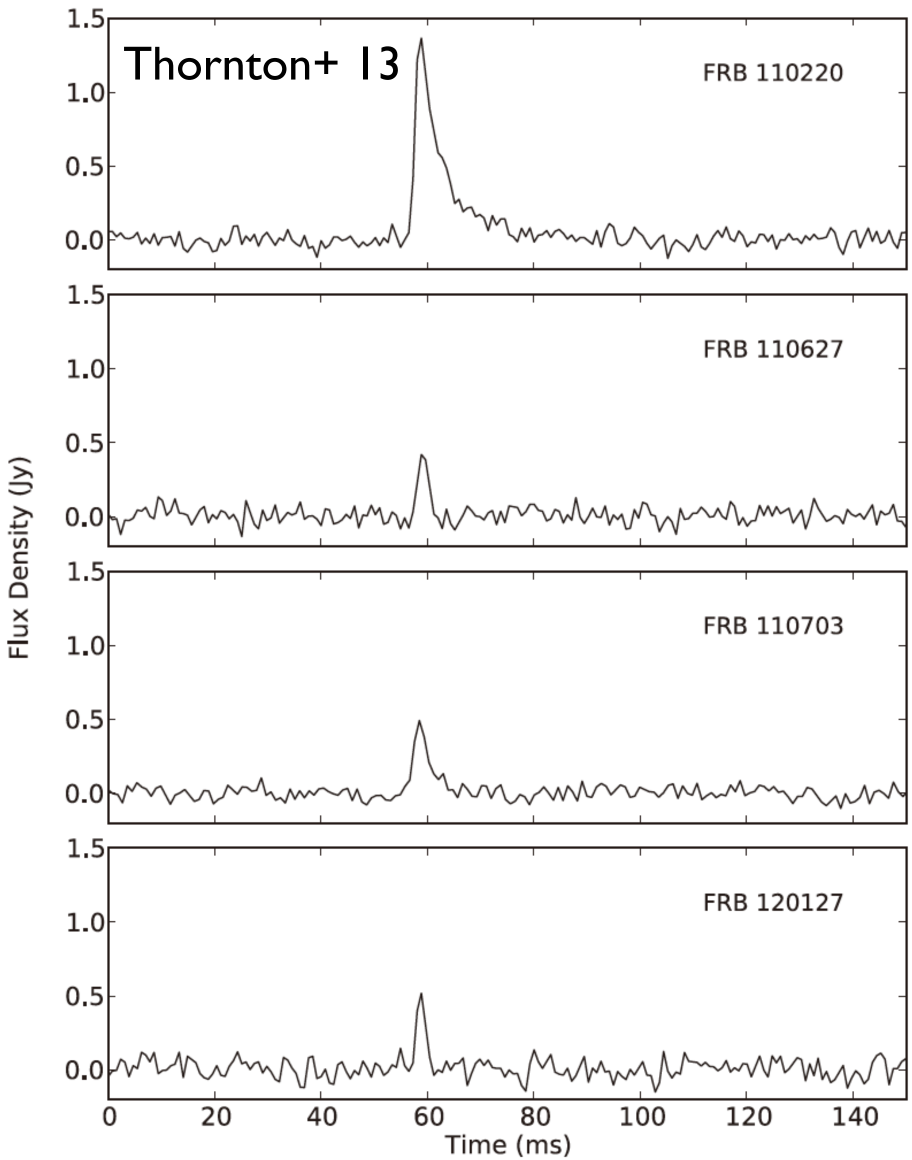
# r-Process Elements?

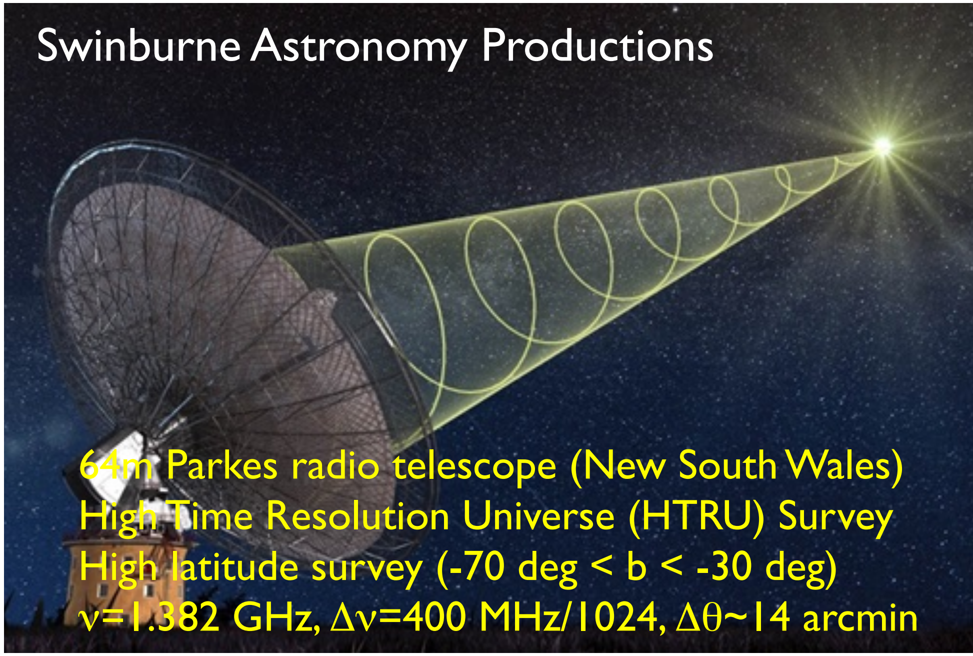
# Macronovae/Kilonova?

Kisaka, KI & Takami 14; Kisaka, KI & Nakamura 15
Kisaka, KI & Nakar 15
Kyutoku & KI 16



# Fast Radio Bursts




**F=0.6-8.0 Jy ms !!!**

**Most luminous radio transients if cosmological**

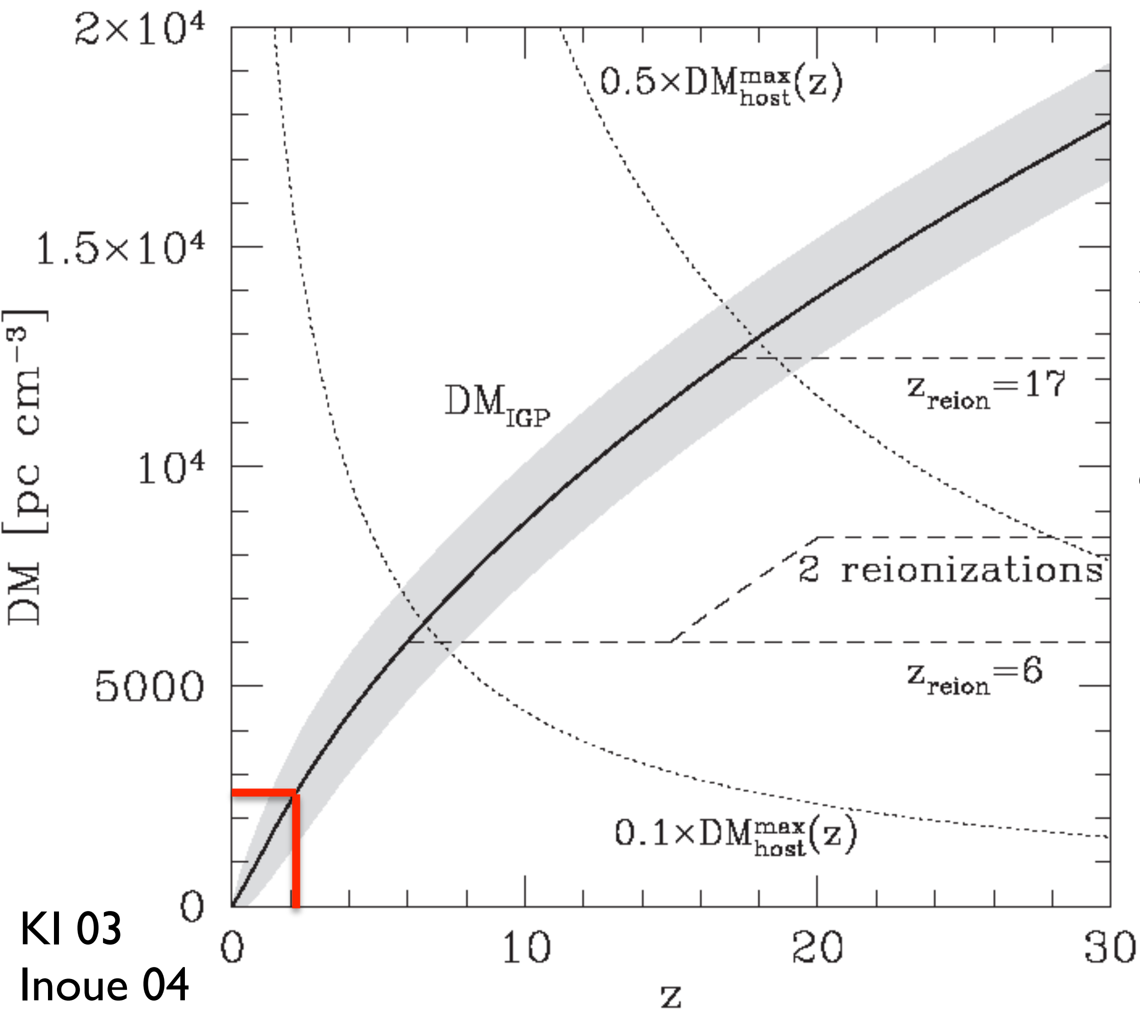
# Possible Origins

- ***Perytons*** Burke-Spolaor+ 11; Kulkarni+ 14
- ***Galactic***
  - Nearby flaring star Loeb, Shvartzvald & Maoz 13
  - RRAT (Rotating Radio Transient; intermittent pulsar)
- ***Extragalactic***
  - Magnetar giant flare Popov & Postnov 07; Thornton+ 13; Lyubarsky 14; Penn & Conner 15
  - ***NS-NS merger*** ***Hansen & Lyutikov 01; Totani 13***
  - WD-WD merger Kashiyama+ 13
  - Collapse of hypermassive NS Falcke & Rezzolla 13; Zhang 13
  - Supernova into a nearby star Colgate+ 71,75; Egorov & Postnov 09
  - Supergiant pulse Cordes & Wasserman 15
  - Pulsar-orbiting bodies Mottez & Zarka 14

# FRB Cosmology

Dispersion measure ~ 2595.90 pc/cc (FRB160102)

©Bailes 16




KI 03
Inoue 04

**⇒ z>2**

$$\mathrm{DM_{IGP}} = \frac{3cH_0\Omega_b}{8\pi G m_p}\int_0^z \frac{(1+z)\,dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

DM ⇒ Distance

⇔ Dark energy

Missing baryon

Reionization

# Astrophysical Problems

- Mass ⇒ Low metal (Old star)
- Rate ⇒ GRB? Galactic BHs?
- Separation ⇒ Field binary?
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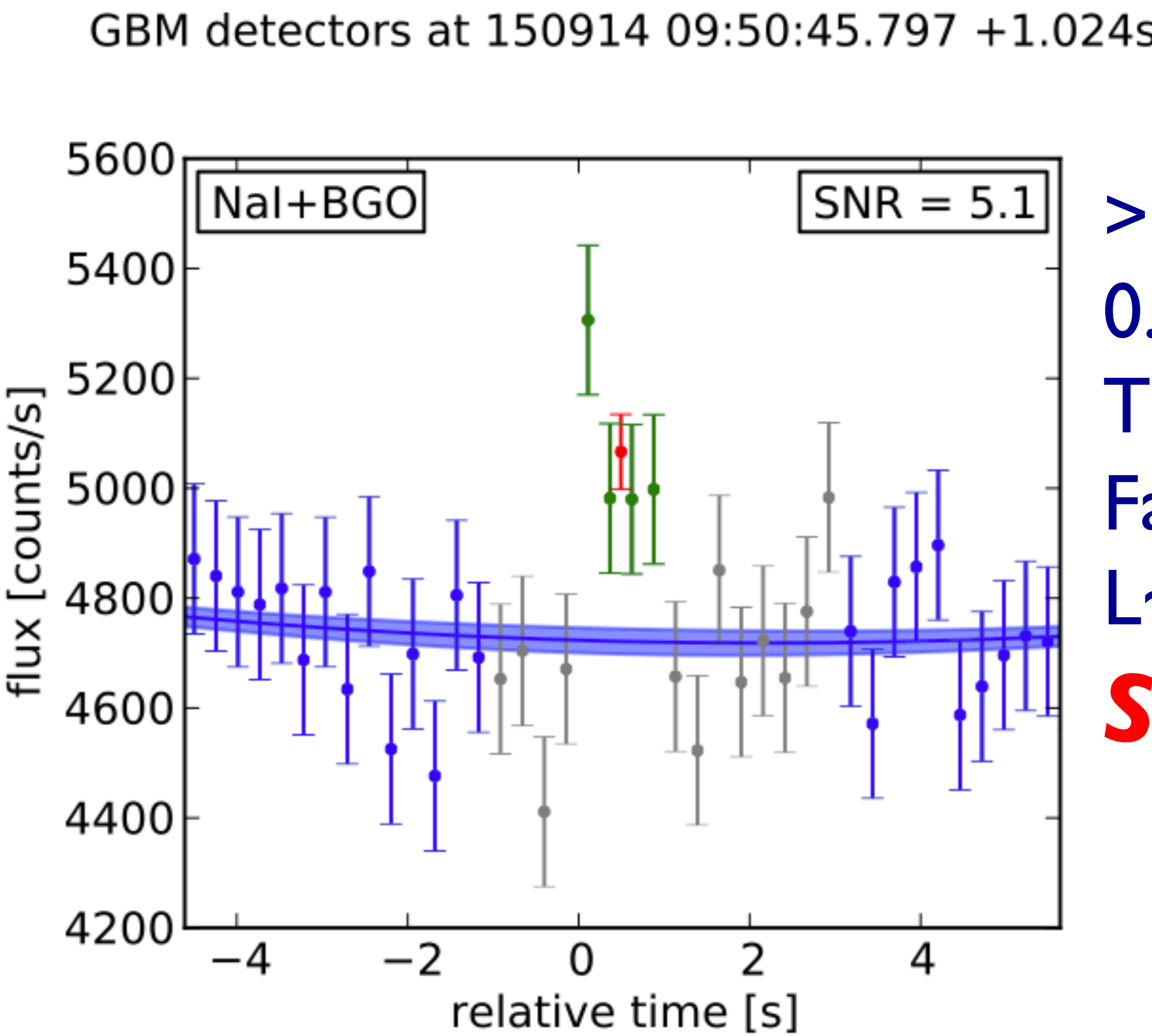
+ ***EM counterparts***

***Thank You***

# Thank You

# Fermi γ-ray Burst Monitor




>50keV

0.4s after GW

T~1sec

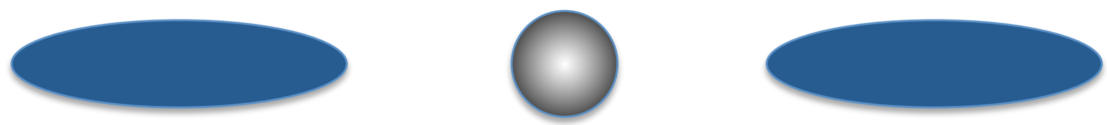
False alarm~0.0022

$L \sim 1.8^{+1.5}_{-1.0}$e49erg/s

***Short GRB!?***

Fermi+ 16

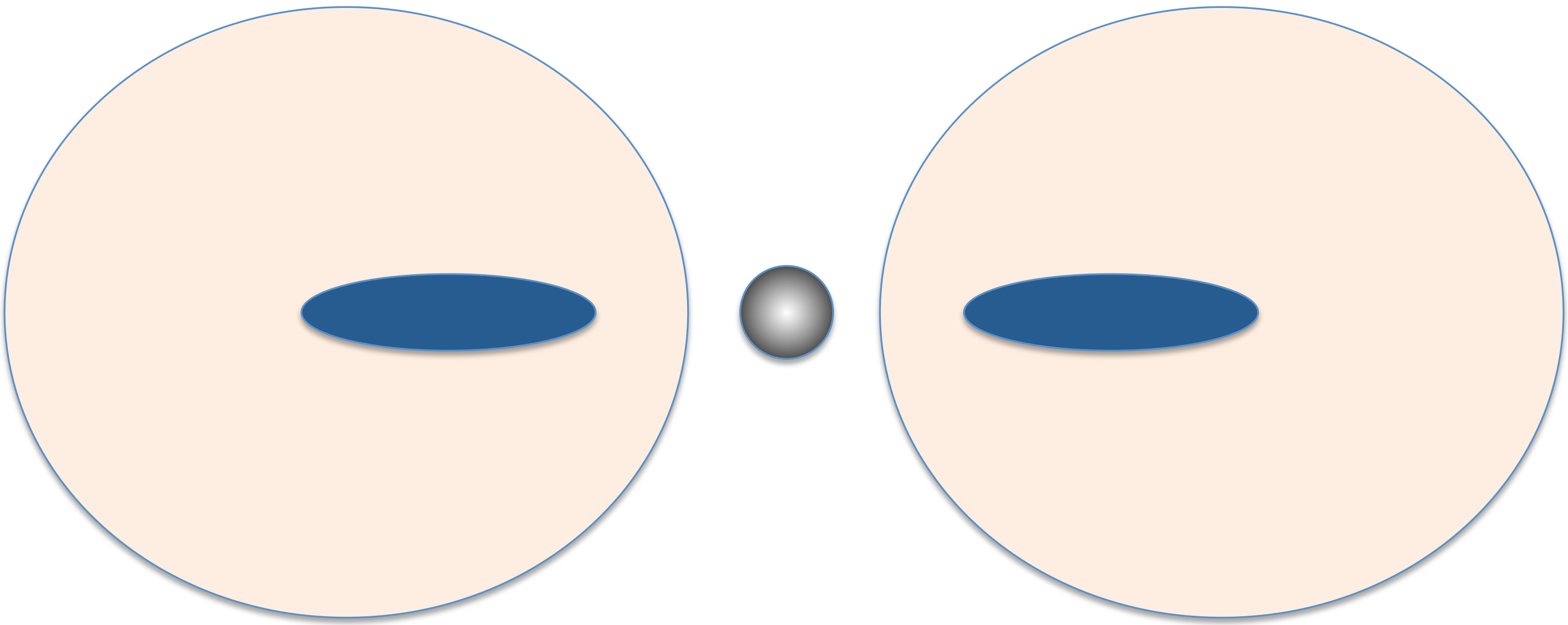
# Dead Disk



Cold neutral disk
No MRI, No accretion
Accretion only at merger

Perna+ 15

# Dead Disk Evaporation



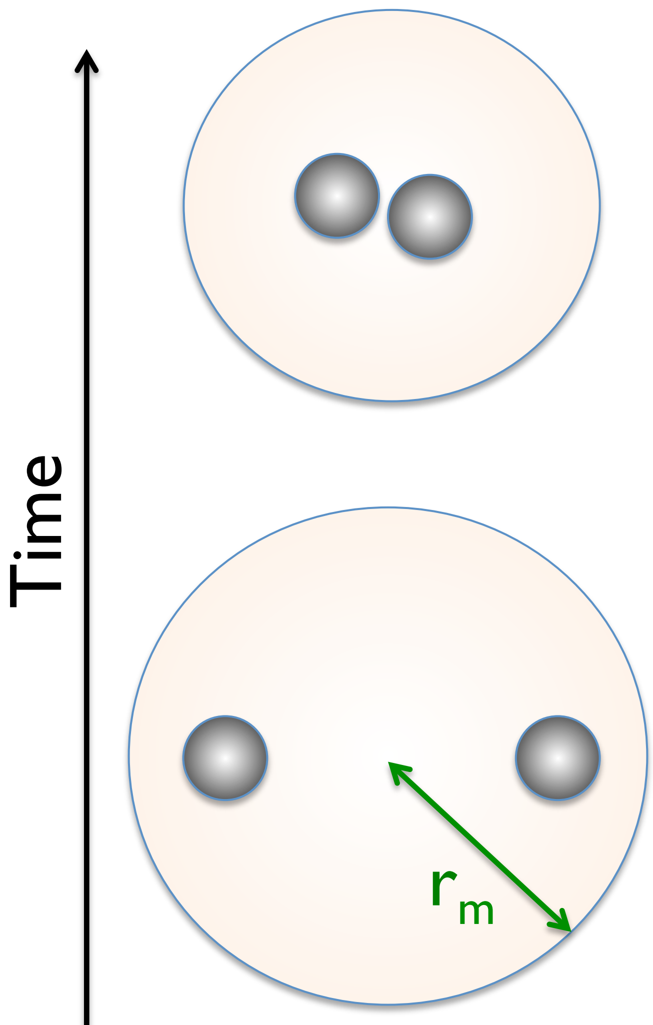
**_ISM accretion ⇒ Hot disk ⇒ Evaporation_**

$$\dot{M}_{\rm eva} \sim 2\pi r^2 n_i v_i m_p \sim 1\times 10^{15}\,{\rm g\,s^{-1}} \left(\frac{r}{10^{12}\,{\rm cm}}\right)^{-5/2} \left(\frac{M}{60M_\odot}\right)^{4} \left(\frac{n}{1\,{\rm cm^{-3}}}\right)^{5/2} \left(\frac{V}{40\,{\rm km\,s^{-1}}}\right)^{-9/2}$$

$t_{\rm eva} \sim 10^6$ yr for $M_{\rm dead\ disk} \sim 10^{-5} M_\odot$

KI+ 16

# No-Go?




Going back time
by say $t_b$~1000 sec

$$r_m \sim 10^{10}\,\mathrm{cm}\left(\frac{t_b}{10^3\,\mathrm{sec}}\right)^{2/3}$$

$$\frac{E_{\mathrm{binding}}}{M_m c^2} = \frac{GMM_m/r_m}{M_m c^2}$$

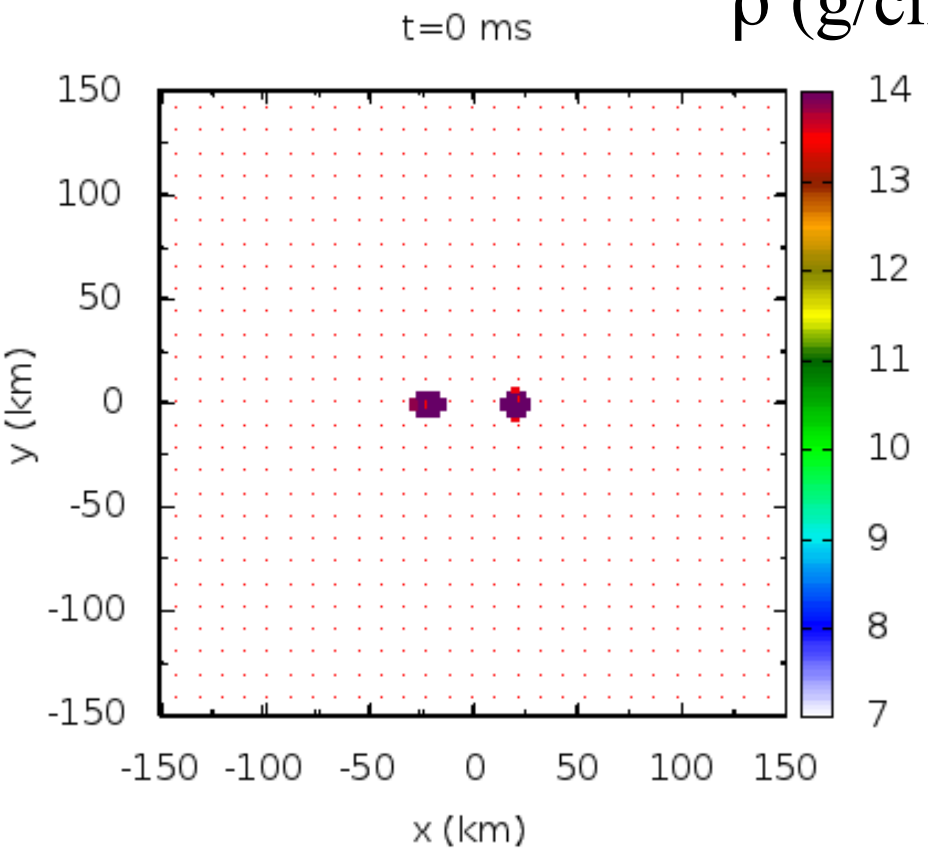
$$\sim 10^{-3}\left(\frac{t_b}{10^3\,\mathrm{sec}}\right)^{-2/3}$$

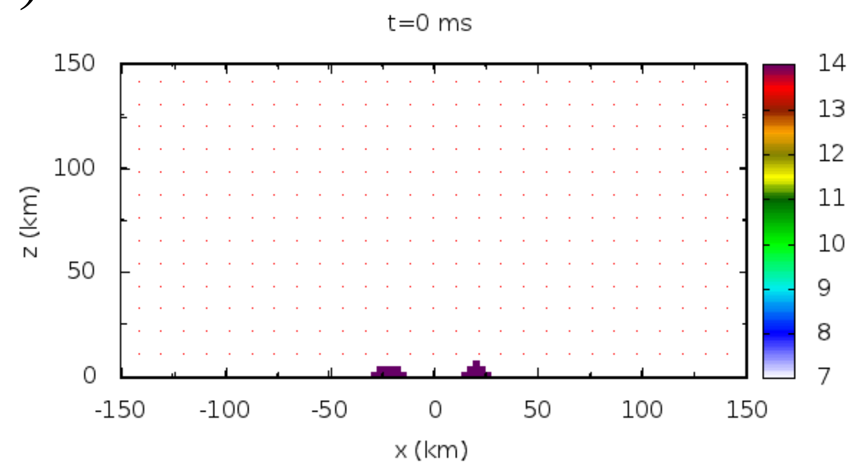
Accretion occurred ⇒ Super Edd. outflow ⇒ Unbound

# Merger of 1.3-1.4 $M_{sun}$ NS:

## EOS=APR4: stiff but relatively soft

$\rho$ (g/cm$^3$)




**Relatively wider view**

**Orbital plane** **$X$-$Z$ plane**

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