Primordial Black Holes:

The *r*-process from the little ones?

Gravitational radiation from the birth of the big ones?

IPMU *Conference on Primordial Black Holes*
Kashiwa, Japan, November 17, 2017

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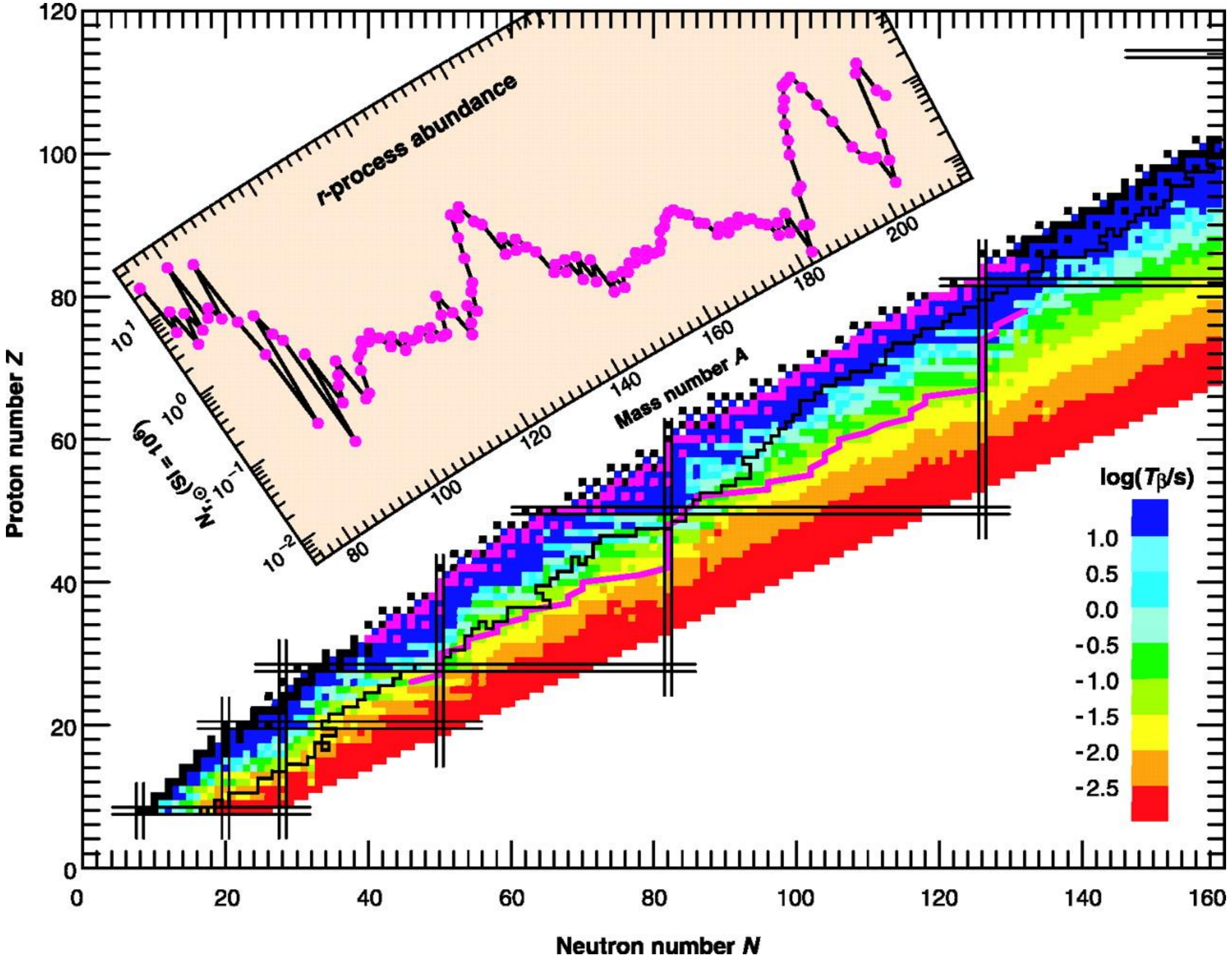
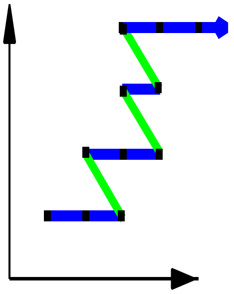


r-process abundance
$N_{r,\odot}$ (Si = 10^6)
10^1
10^0
10^{-1}
10^{-2}
Mass number A
80
100
120
140
160
180
200
log(T_β/s)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Proton number Z
0
20
40
60
80
100
120
Neutron number N
0
20
40
60
80
100
120
140
160

Nucleosynthesis – example *rapid neutron capture*

r-process

e. g. Uranium-238 Z=92, N=146 → need lots of neutrons



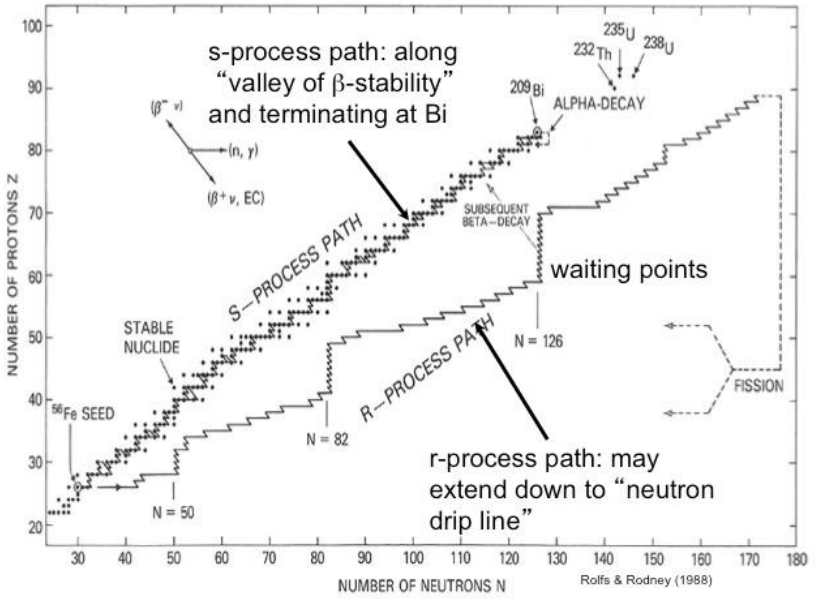
$$A(Z,N)+n \leftrightarrow A+1(Z,N+1)+\gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1)+e^-+\bar{\nu}_e$$

rapid neutron capture as compared with beta decay

in order to get the r-process nuclei, prefer a lot of neutrons

r- and *s*-process synthesis paths



s-process path: along "valley of β-stability" and terminating at Bi

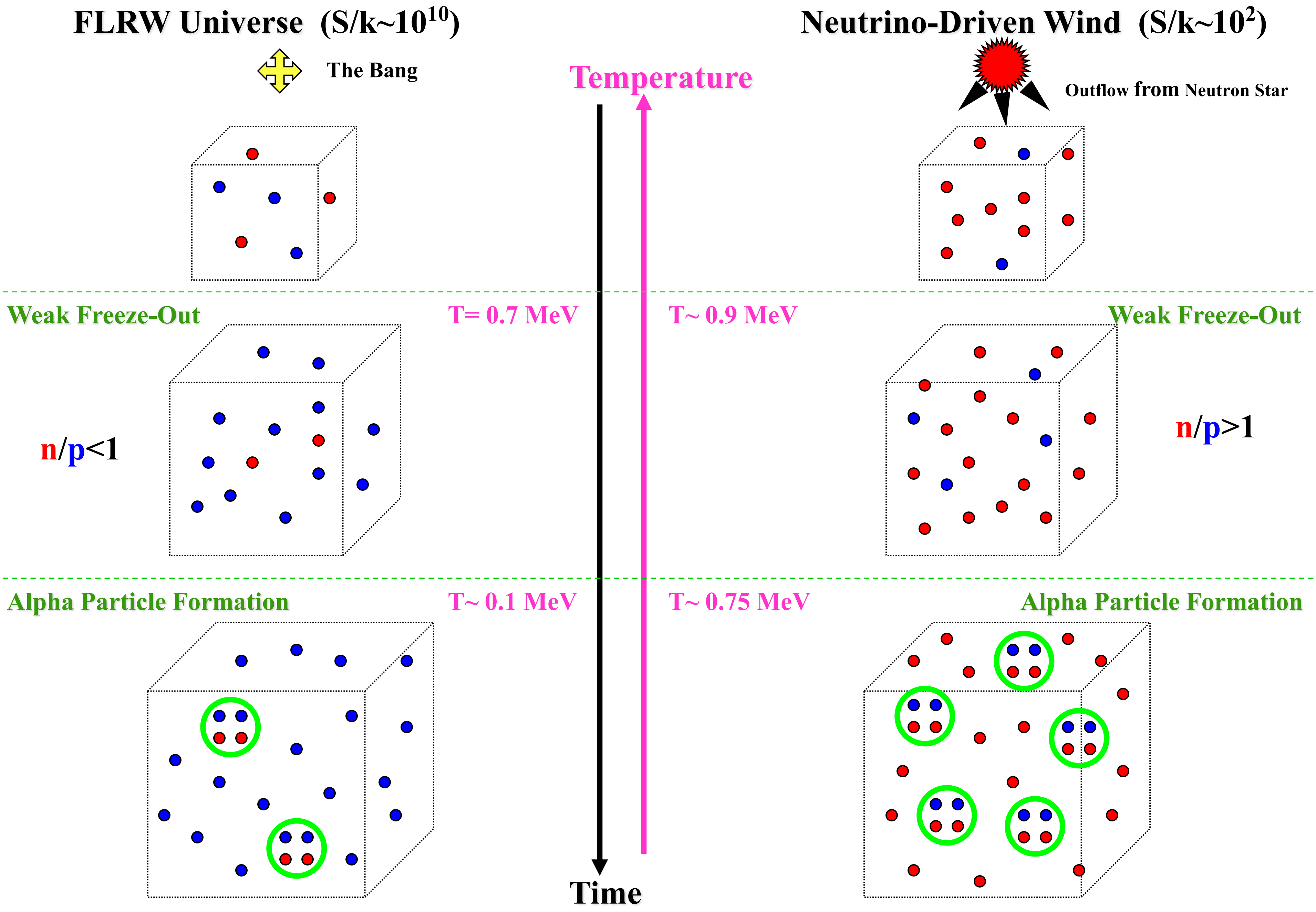
waiting points

r-process path: may extend down to "neutron drip line"

Rolfs & Rodney (1988)

Need neutron-to-seed ratio > 100 to make the $A = 195$ peak in the r-process.

Can do this by:
$*$ high entropy $s \rightarrow$ seed nucleus abundance $\propto s^{1-A}$ i.e., suppress the number of seeds
$*$ brute force low electron fraction, high neutron excess
$*$ Very short expansion time scale $\rightarrow$ no time to assemble seed nuclei because of the $\alpha + \alpha + n \rightarrow {}^9\mathrm{Be} + \gamma$ bottleneck



FLRW Universe (S/k~10^{10})

Neutrino-Driven Wind (S/k~10^{2})

The Bang

Temperature

Outflow from Neutron Star

Weak Freeze-Out

T= 0.7 MeV

T~ 0.9 MeV

Weak Freeze-Out

n/p<1

n/p>1

Alpha Particle Formation

T~ 0.1 MeV

T~ 0.75 MeV

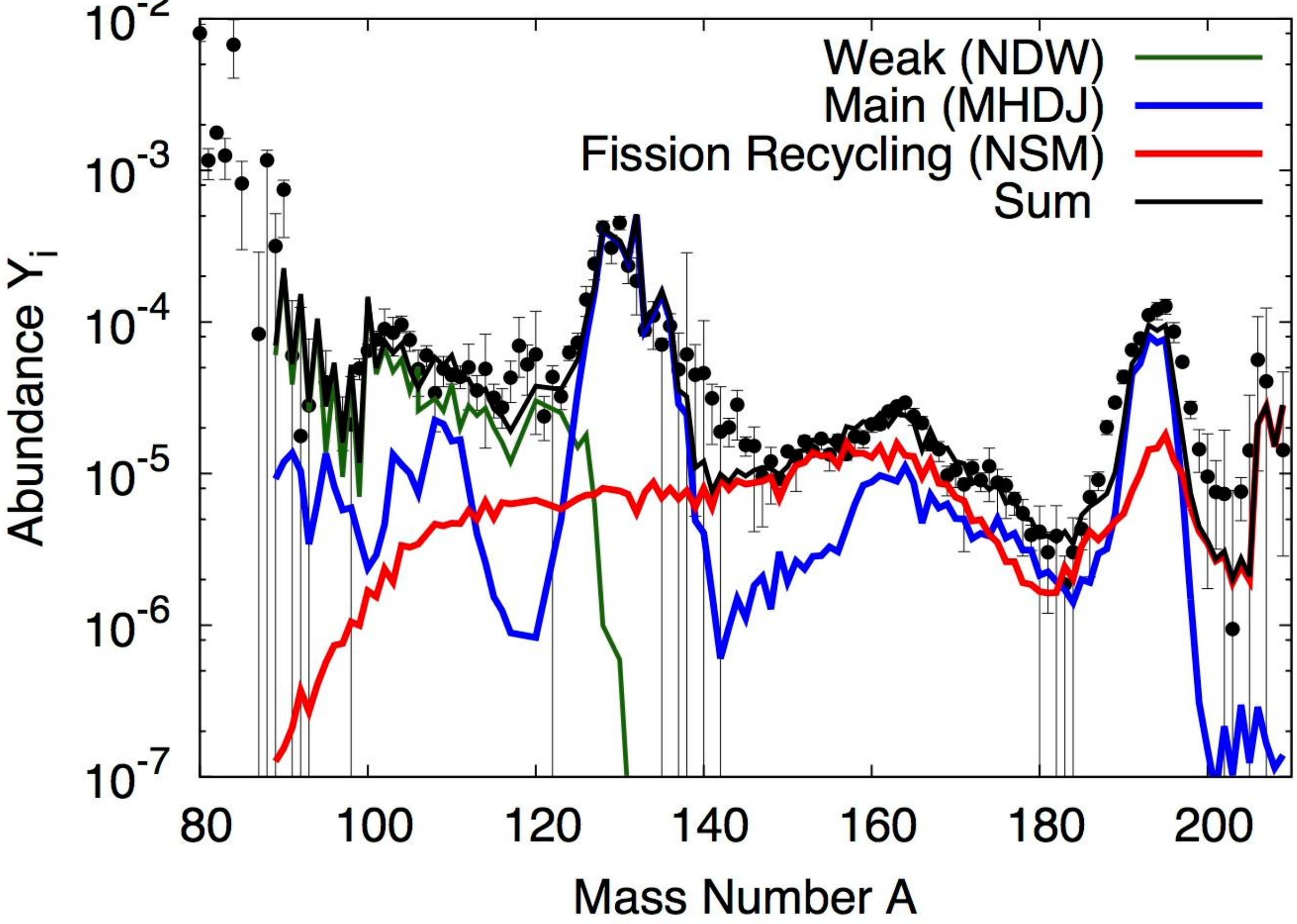
Alpha Particle Formation

Time

● PROTON

● NEUTRON

Taka Kajino

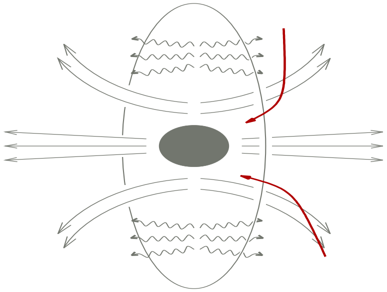


Weak (NDW)
Main (MHDJ)
Fission Recycling (NSM)
Sum
Abundance Y_i
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
80
100
120
140
160
180
200
Mass Number A

Compact Object Neutrino & Nuclear Physics

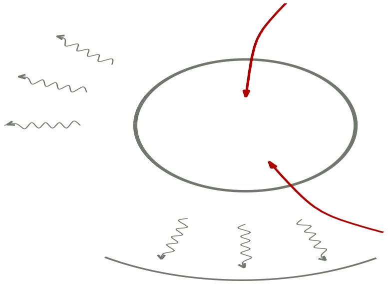
Event rate,
amount of ejecta right,
troubles with neutrinos

to understand these environments:
we need the nuclear-neutrino physics



compact object merger

Event rate?
Ejecta mass
per event?



standard core core collapse SN

Single Core Collapse to *Hot* Neutron Star

**Modest Initial Neutron Excess –
evolving toward . . . ??**

Merging *Cold* Neutron Stars

***Very* Neutron-rich initially
– heating and evolving toward
lower n-richness in ejecta ? ?**

r-Process arithmetic

r-Process mass fraction $= 10^{-7} \Rightarrow 10^4\,\mathrm{M}_\odot$ of r-process in the Galaxy

age of Galaxy is $\sim 10^{10}$ years

core collapse supernova rate: $10^{-2}\,\mathrm{yr}^{-1}\,\mathrm{MWEG}^{-1} \Rightarrow 10^8$ SN

$\Rightarrow$ need $10^{-4}\,\mathrm{M}_\odot$ of r-process per SN

NS-NS merger rate rate: $10^{-3} - 10^{-6}\,\mathrm{yr}^{-1}\,\mathrm{MWEG}^{-1} \Rightarrow 10^7 - 10^4$ mergers

$\Rightarrow$ need $10^{-3}\,\mathrm{M}_\odot$ to $1\,\mathrm{M}_\odot$ (!!) of r-process per merger

For NS-NS merger rate rate: $10^{-5}\,\mathrm{yr}^{-1}\,\mathrm{MWEG}^{-1} \Rightarrow 10^5$ mergers

$\Rightarrow$ need $0.1\,\mathrm{M}_\odot$ (!!) of r-process per merger

The Problem: Deep gravitational potential wells (nucleon gravitational binding energies $\sim 10\%$ of rest mass $\sim 100\,\mathrm{MeV}$); intense neutrino fluxes which can re-set n/p ratio:

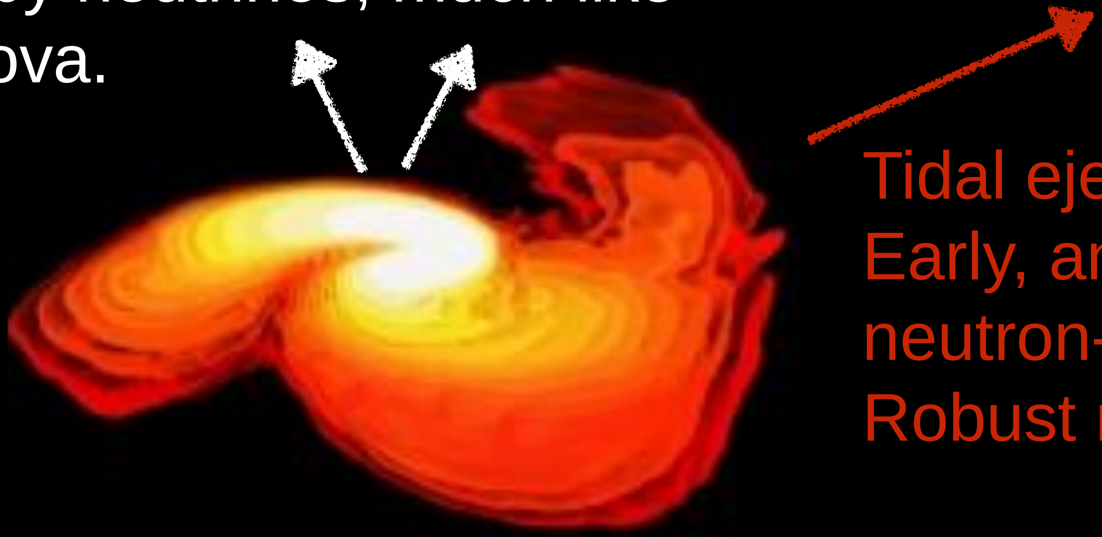
$$\left.\begin{array}{l}\nu_e + n \rightleftharpoons p + e^- \\ \bar{\nu}_e + p \rightleftharpoons n + e^+\end{array}\right\}$$

To preserve neutron excess must move baryons out of the potential well faster than the weak interaction can get a purchase on them!

B. Cote et al. “The Origin of the r-Process Elements in the Milky Way”
arXiv:1710.05875

GW170817 shows a kilonova signal – showing that
If this event is representative of all binary neutron star (BNS) mergers then the bulk
f the r-process materila in the Galaxy could have been made in these events

Merger Ejecta & Nucleosynthesis

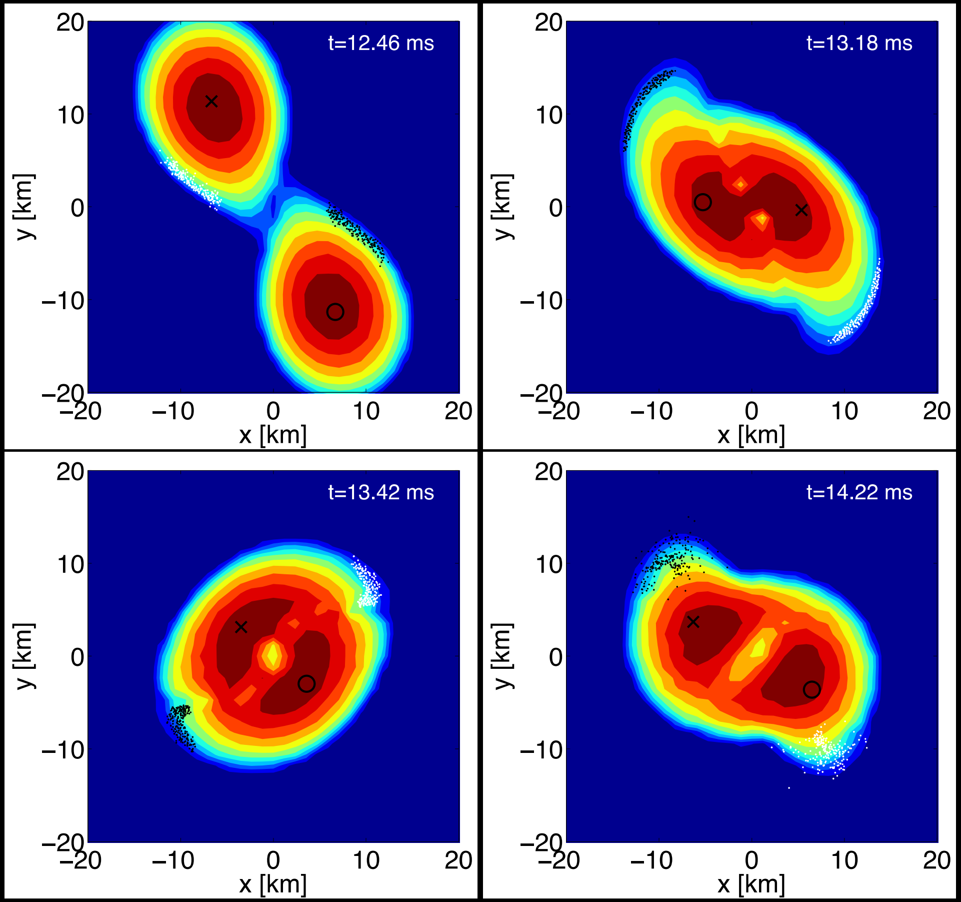


Shocked ejecta:
Processed by neutrinos, much like in a supernova.

Tidal ejecta:
Early, and very neutron-rich.
Robust r-process.

Amount and composition of the material ejected depends on the neutron star radius and neutrino interactions in dense matter.

Post Merger Dynamics: Transport Properties

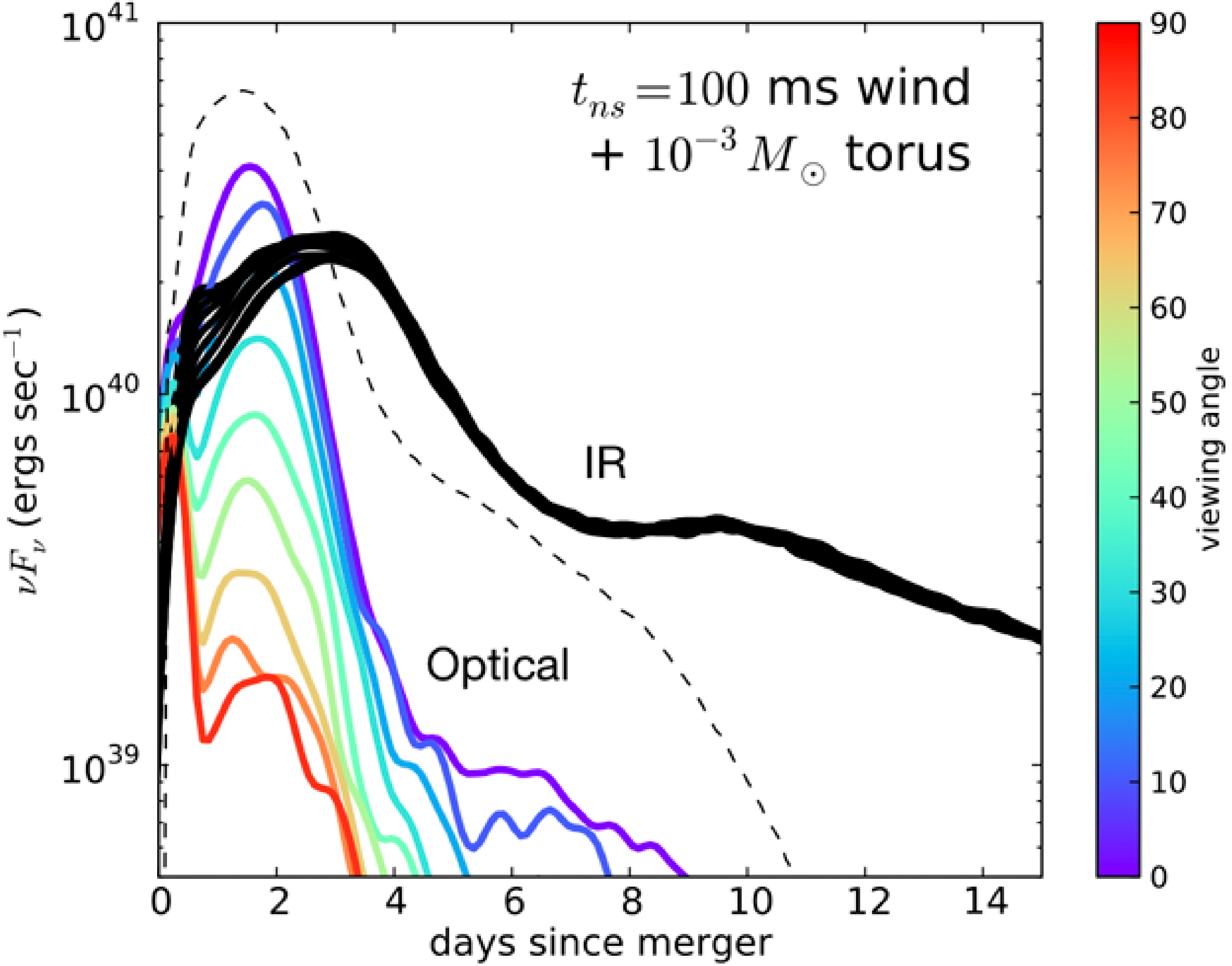


Bauswein & Stergioulas (2015)

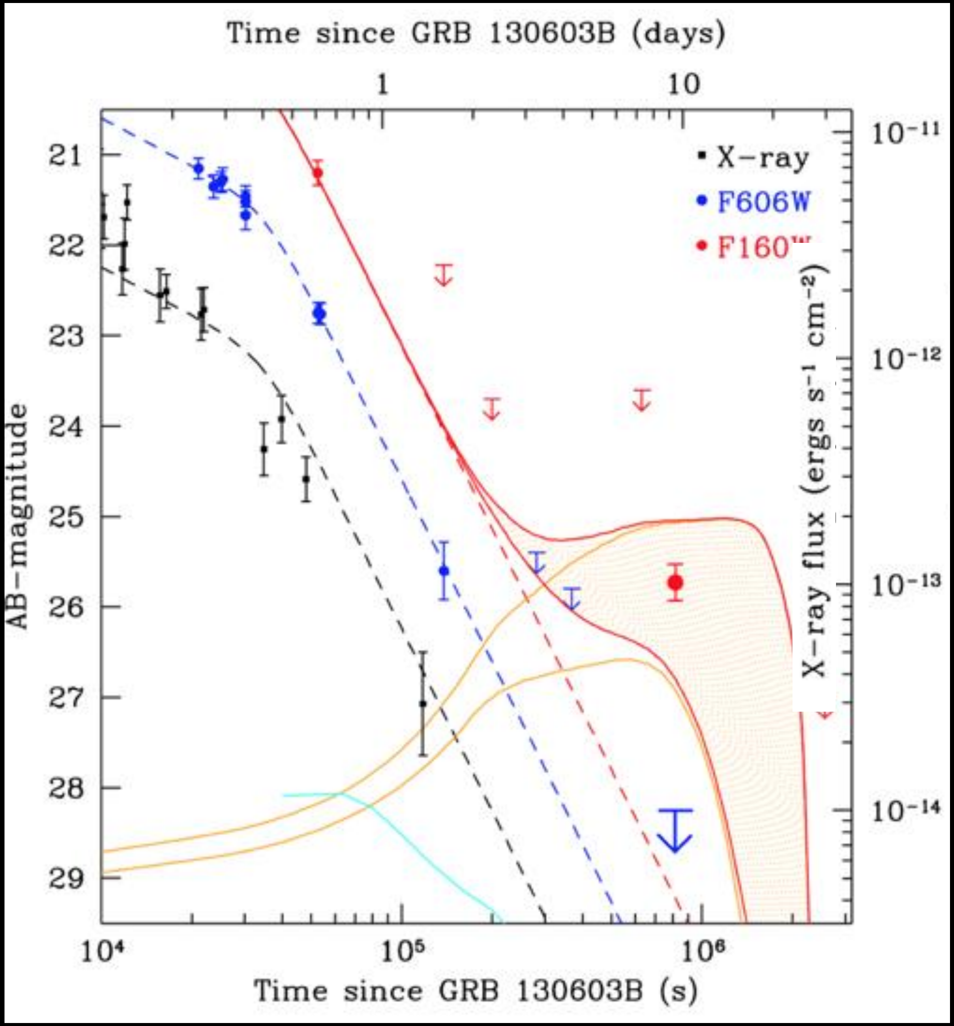
Typical temperature is ~ 30-60 MeV.

Neutrinos dominate cooling, heat transport and viscous damping.

Thermal conductivity and shear viscosity are determined by neutrino mean free paths in dense matter.


$t_{ns} = 100$ ms wind
$+ 10^{-3} M_\odot$ torus
IR
Optical
νF_ν (ergs sec^{-1})
10^{41}
10^{40}
10^{39}
0
2
4
6
8
10
12
14
days since merger
viewing angle
90
80
70
60
50
40
30
20
10
0

Ejecta and GRB afterglow: Kilonova



Detection of a Kilonova

Tanvir et al. 2013

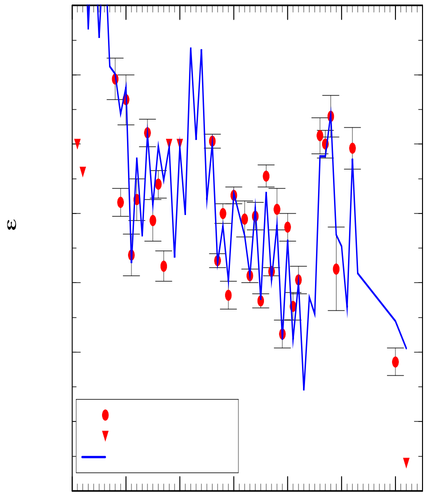
- Radioactive heavy elements synthesized and ejected can power an EM signal

Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011

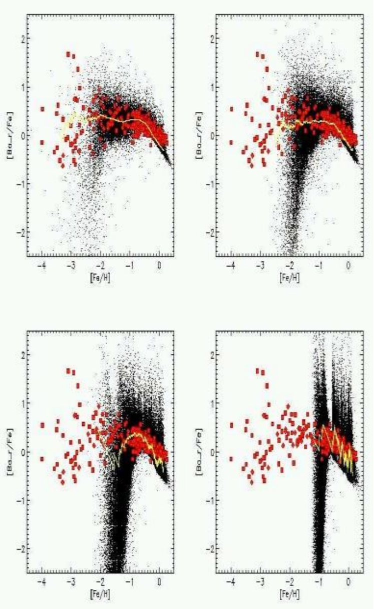
- Magnitude and color of the optical emission is sensitive to the composition of the ejecta.

Kasen 2013

supernovae vs. mergers



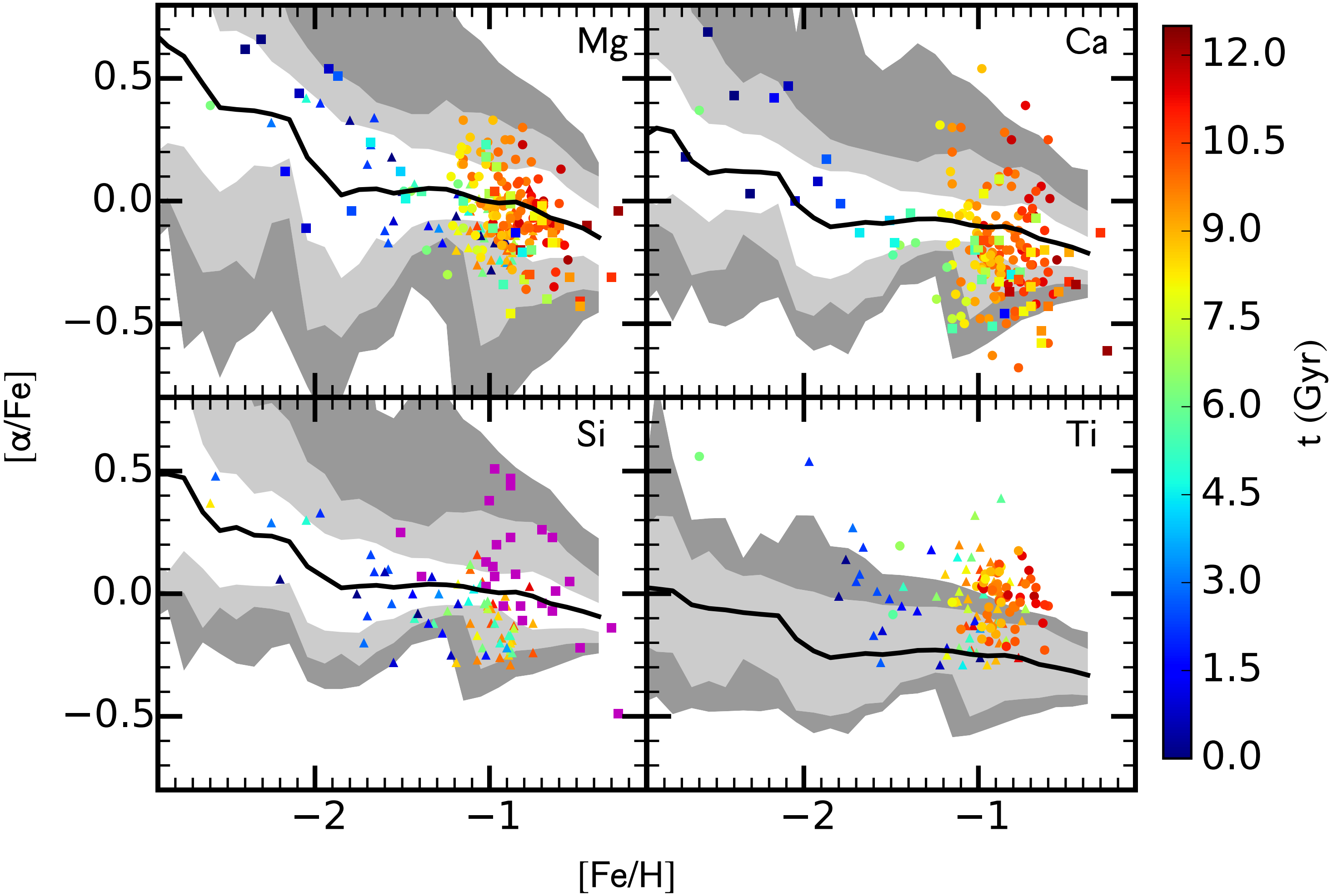
A number of old stars have a perfect “main” r-process



Not simple to reproduce r-process scatter in old stars with mergers

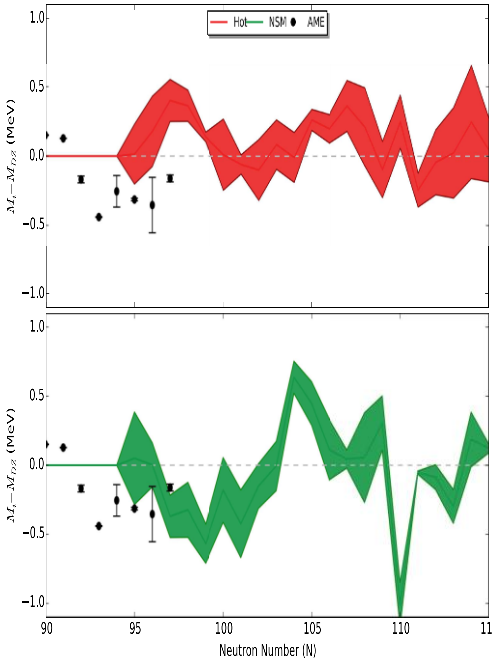
Core collapse supernovae have the right evolution time scale, but it is difficult to make enough neutrons. Compact object mergers have plenty of neutrons, but it is not obvious that they have the required evolution time scales. Figs from Cowan, Argast

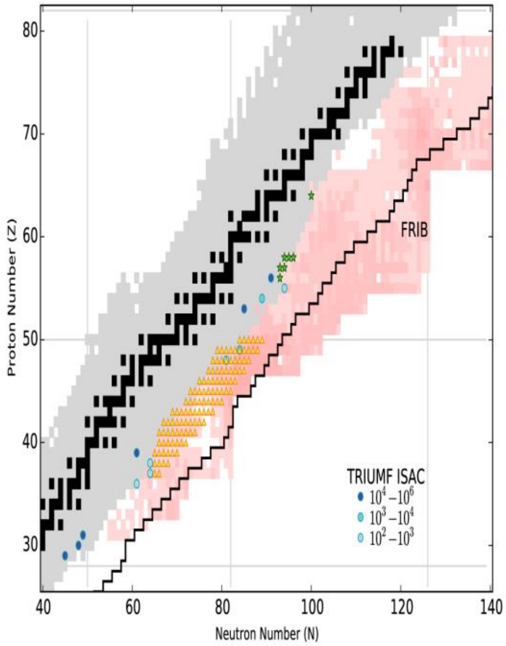
Chemical evolution of dwarf galaxies ---



- -- hangs on many of the nucleosynthesis observations – see Frebel’s work on Reticulum II
- -- insights into the effectiveness of baryonic feedback
- -- insights into the nature of dark matter and the origin of structure

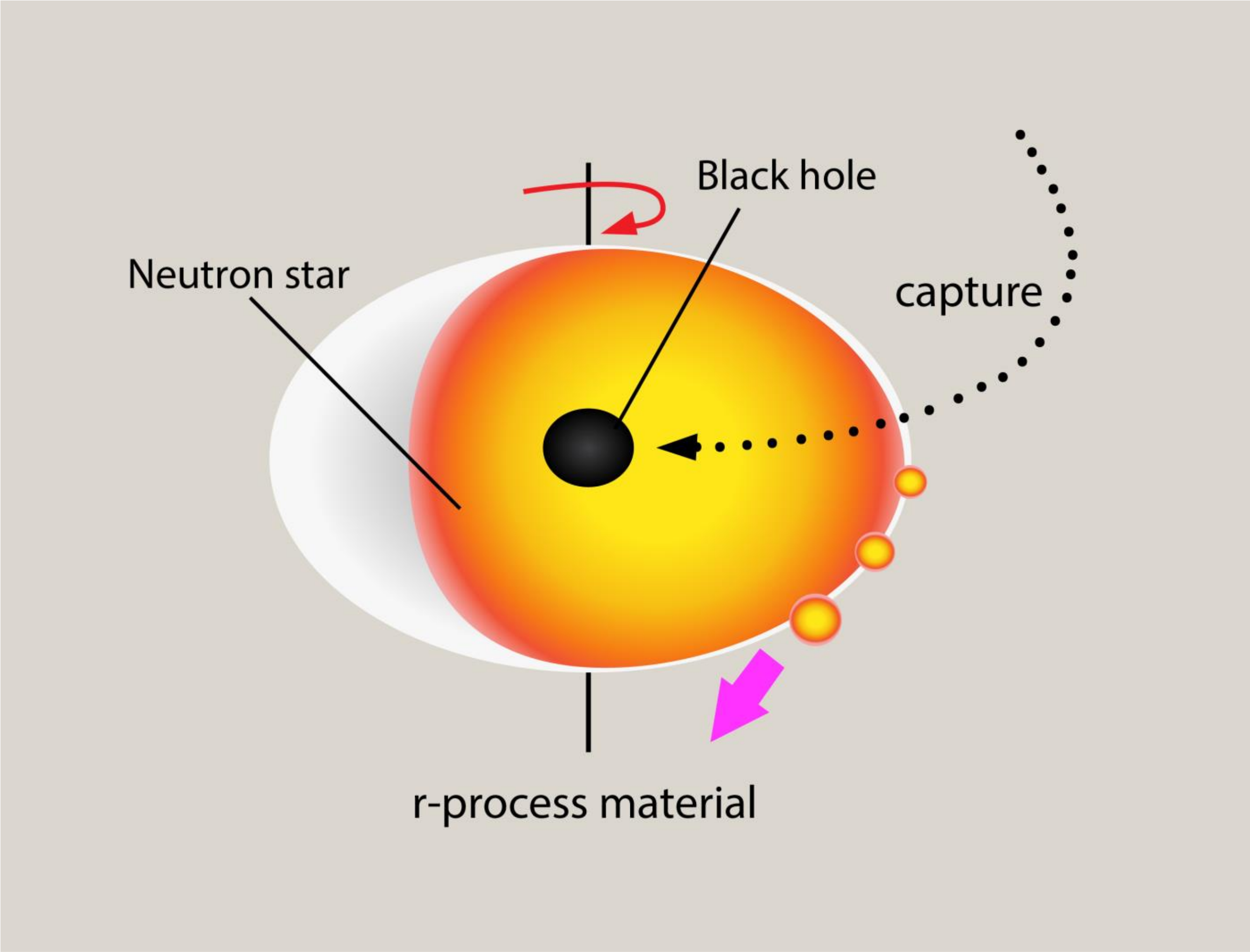
Neutrino physics, dense matter → improved predictions of r-process astrophysical conditions → FRIB predictions



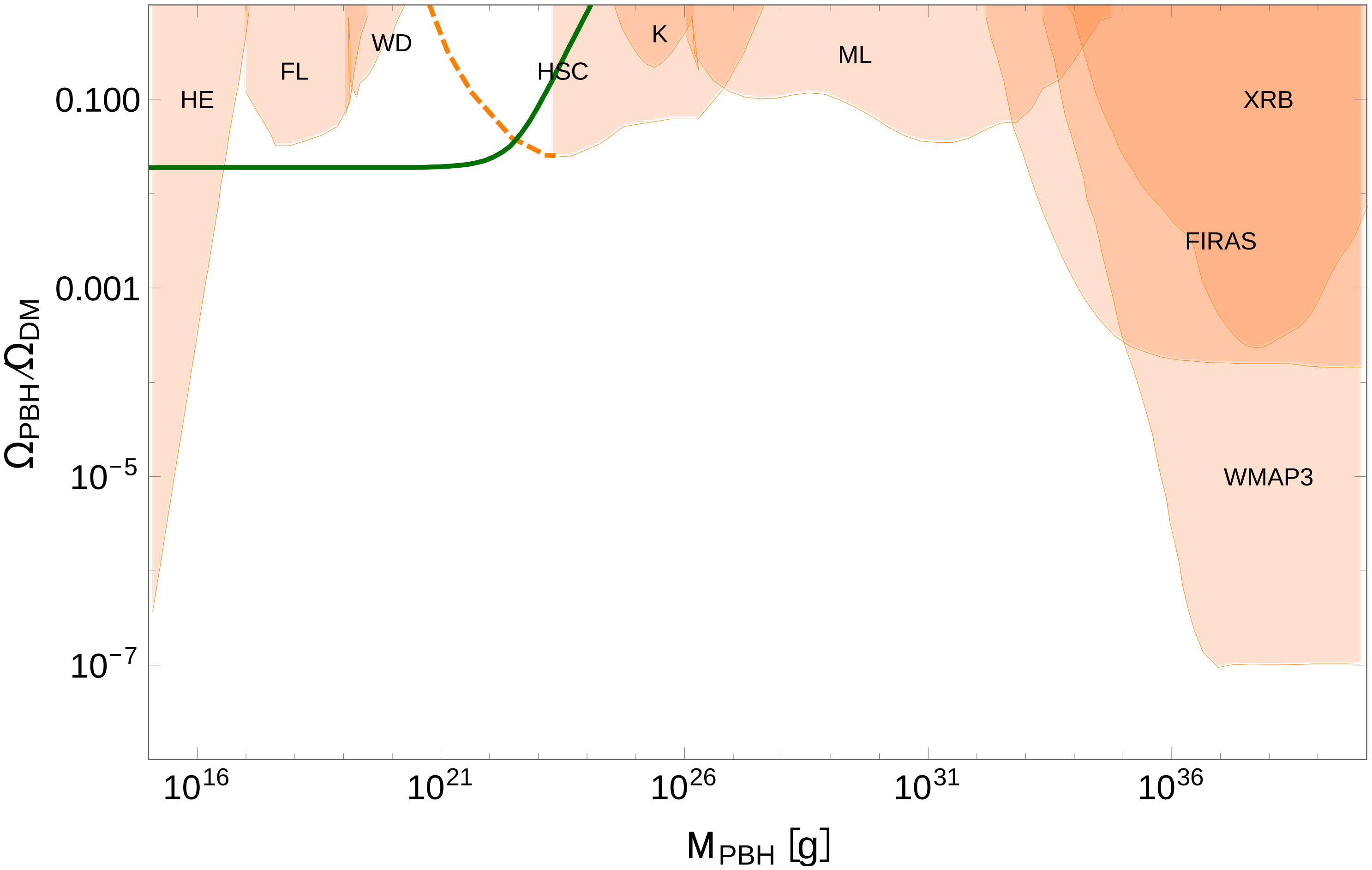


Predictions of the r-process required mass surface are different in supernova (top) and mergers (bottom) and within reach of radioactive beams (right).

Other ways . . . Disassembling neutron stars



“Primordial Black Holes and r-Process Nucleosynthesis, GMF, A. Kusenko, V. Takhistov, PRL, **119**, 061101 (2017)

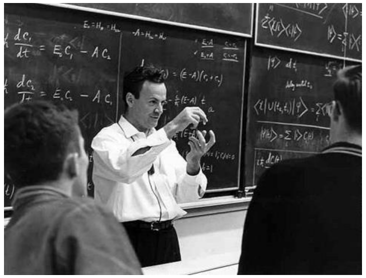

HE
FL
WD
HSC
K
ML
XRB
FIRAS
WMAP3
0.100
0.001
10^{-5}
10^{-7}
10^{16}
10^{21}
10^{26}
10^{31}
10^{36}
Ω_{PBH}/Ω_{DM}
M_{PBH} [g]

Supermassive Stars

$$\sim 10^6\,\mathrm{M}_\odot$$

Jung-Tsung Li, GMF, Chad T. Kishimoto arXiv:1708.05292 whenever the pressure support for the star is from particles moving near the speed of light the star is "**trembling on the verge of instability**"

MASS in $M_\odot$	**Main Seq. Entropy per baryon** s/k_B	**Collapse Entropy per baryon** s/k_B	**Iron core mass** in $M_\odot$	**Instability Mechanism**	**Fraction of rest mass radiated as neutrinos**	**Neutrino Trapping / Thermal equilibrium**
10 to ~ 100	**~ 10**	**~ 1**	**~ 1.4**	**Electron capture /** **Feynman-Chandrasekhar G.R. instab.**	**~ 10%** **Iron core mass**	**Yes**
~ 100 to ~ 10^4	**~ 100**	**~ 100**	**NONE**	$e^{\pm}$ **pair instability**	**~ 10%** **C/O burning core**	**Yes**
~ 10^4 to ~ 10^8	**~ 1000** **no main seq.**	**~ 1000**	**NONE**	**Feynman-Chandrasekhar G.R. Instability**	**~ 1%**	**No**

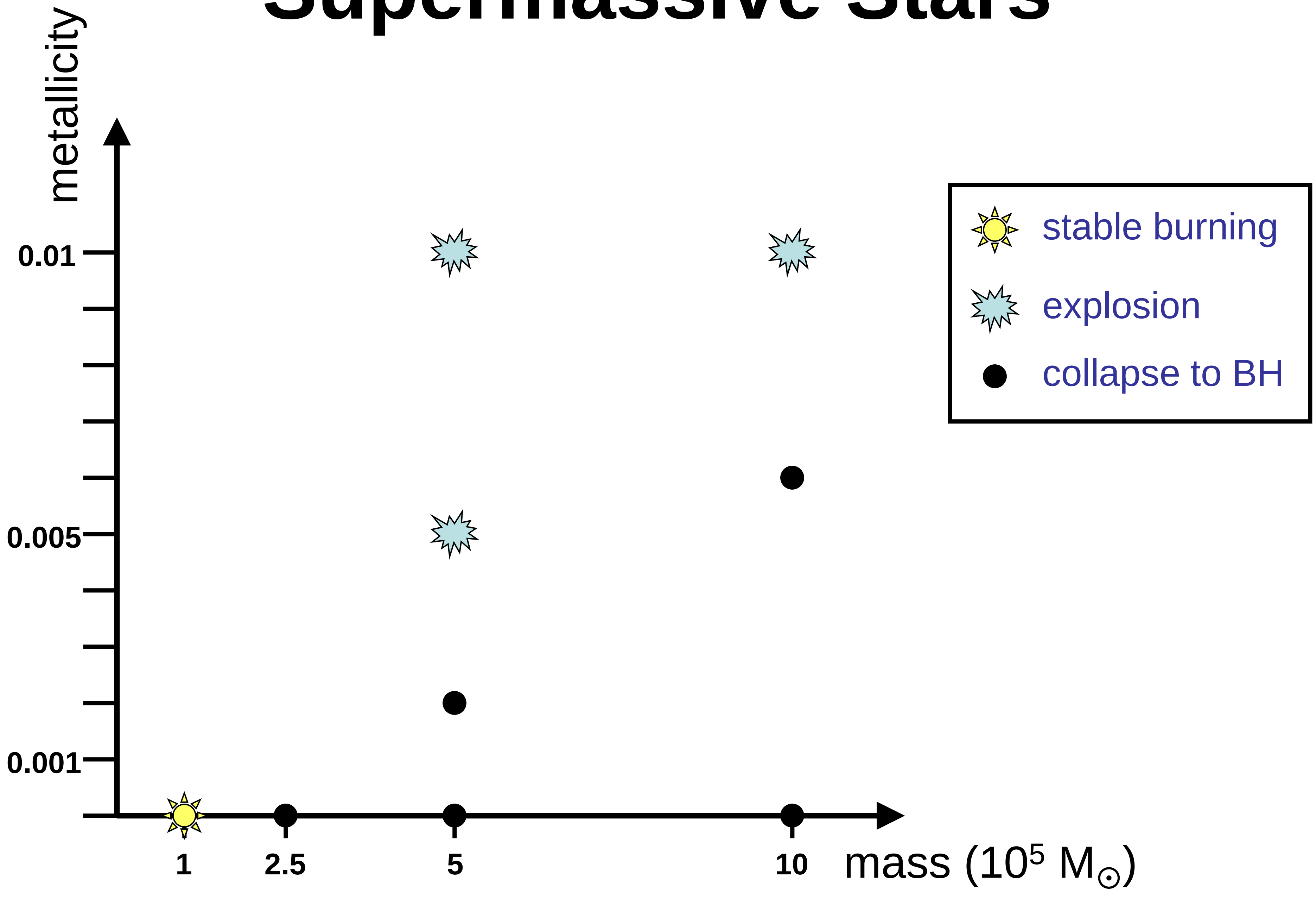


These stars go unstable as a result of the Feynman-Chandrasekhar General Relativistic instability and (for zero initial metals) collapse to a black hole.

This collapse is non-homologous on account of prodigious neutrino-pair production/loss.
Fuller, Woosley, Weaver Ap. J., 307, 675 (1986)

The star largely is transparent to neutrinos until a trapped surface forms.

Supermassive Stars



(after Fuller, Woosley, & Weaver 1986)

$*$ High entropy means that these objects are radiation/$e^{\pm}$-pair dominated

$*$ Neutrino pairs produced copiously via $e^- + e^+ \rightarrow \nu + \bar{\nu}$

$*$ Neutrino energy emission rate scales as **nine** power of temperature, $\sim T^9$, meaning that most of the neutrino radiation comes out just before black hole formation.

$*$ Stars with homologous core masses $M_{\rm HC} < 5 \times 10^4\,{\rm M}_\odot$ will have neutrino mean free paths smaller than the core size and therefor trap neutrinos via scattering – lower neutrino emission over a longer time scale.

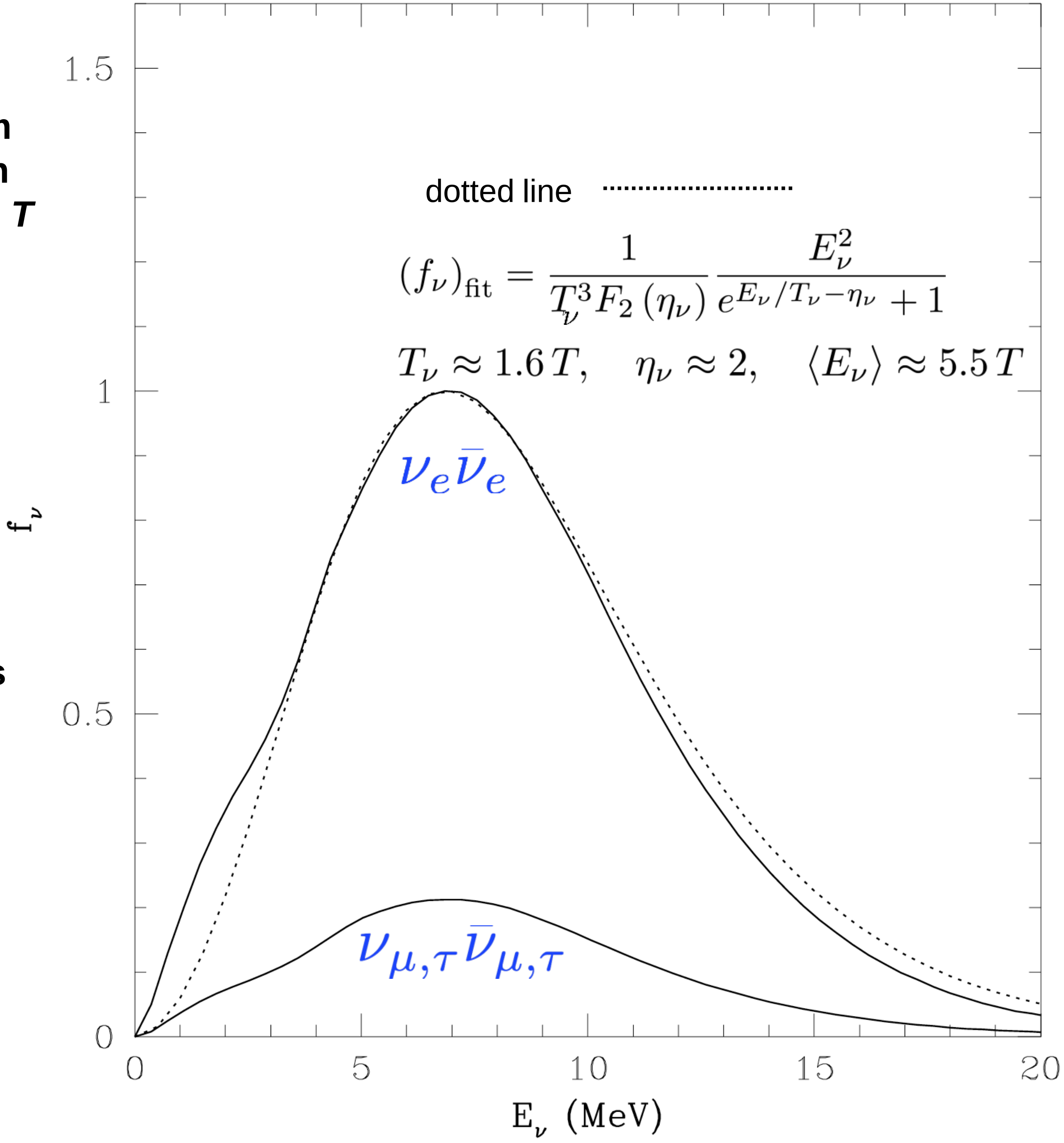
$*$ Stars with homologous core masses $M_{\rm HC} > 5 \times 10^5\,{\rm M}_\odot$ will not get hot enough to radiate a significant fraction of the star's rest mass before they become black holes.

Neutrino/antineutrino energy spectra resulting from electron/positron annihilation in a plasma with temperature *T*

Ratio of fluxes:

$$\frac{\varphi_{\nu_e\bar{\nu}_e}}{\varphi_{\nu_\mu\bar{\nu}_\mu}} \approx \frac{5}{1}$$

Why? **electron flavor neutrinos have both neutral and charged current production channels; mu and tau flavor neutrinos produced only in the neutral current channel**

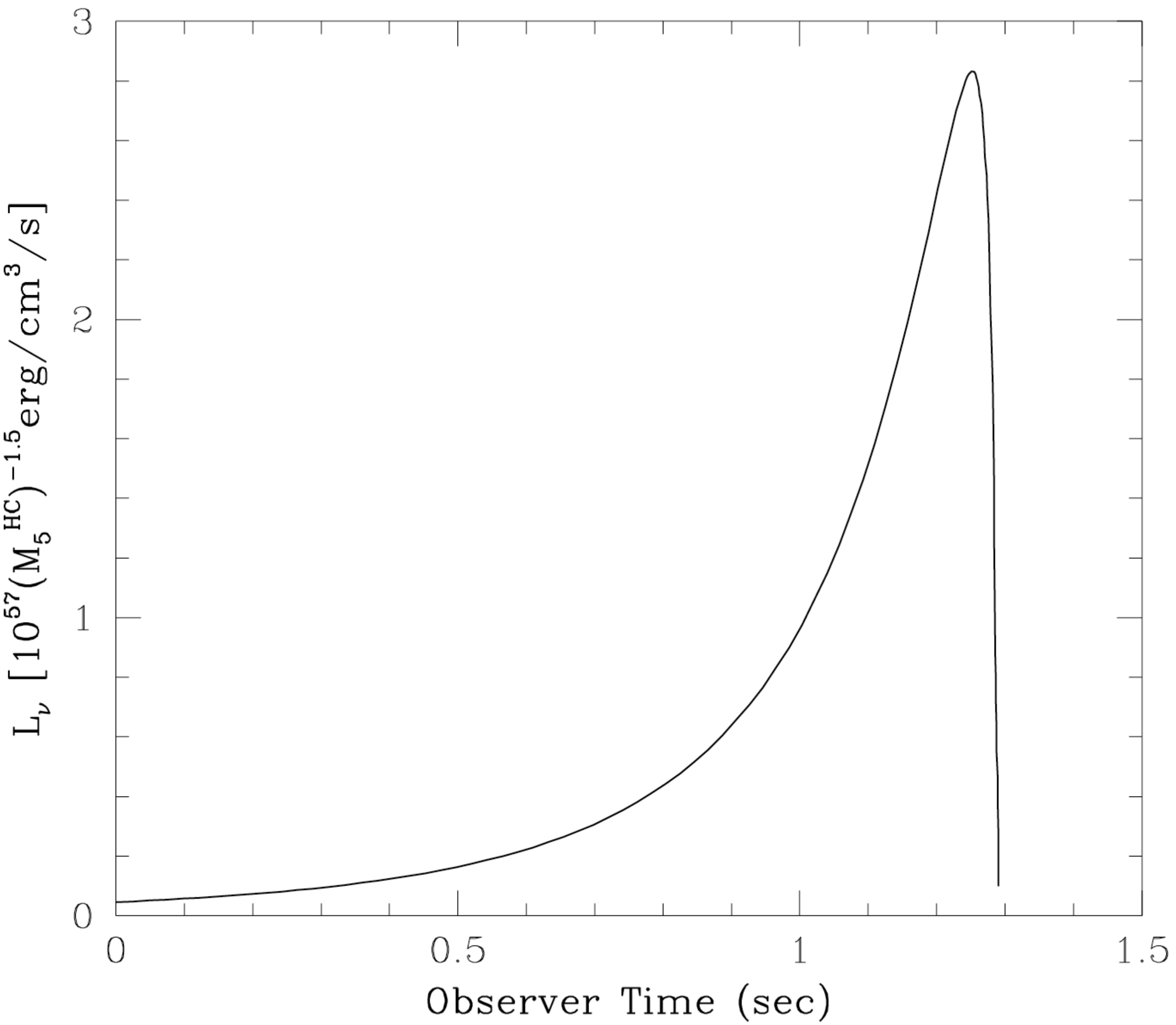


dotted line ....

$$(f_\nu)_{\rm fit} = \frac{1}{T_\nu^3 F_2(\eta_\nu)} \frac{E_\nu^2}{e^{E_\nu/T_\nu - \eta_\nu} + 1}$$

$$T_\nu \approx 1.6\,T, \quad \eta_\nu \approx 2, \quad \langle E_\nu \rangle \approx 5.5\,T$$

X. Shi & G. M. Fuller, Astrophys. J. 503, 307 (1998).



$$M_5^{\mathrm{HC}} \equiv \frac{M_{\text{homol. core}}}{10^5\,\mathrm{M}_\odot}$$

X. Shi & G. M. Fuller, Astrophys. J. 503, 307 (1998).

Linear memory!

- The non-oscillatory piece in the waveform.
- The source consists of several freely moving objects -- gravitationally unbound to each other.
- A few examples of linear memory
  1. Hyperbolic binary stars (bremsstrahlung) [Turner 1977; Kovacs & Thorne 1978]
  2. Matter or neutrinos ejected from supernova [Epstein 1978; Muller & Jenka 1997]
  3. Gamma ray bursts [Sago et al. 2014]

Matter ejected to infinity

Linearized field Eq: $\Box h^{TT}_{\mu\nu} = -16\pi T^{TT}_{\mu\nu}$

$$\Delta h_{ij}{}^{TT} = \Delta \sum_a \left. \frac{4M_a}{r(1-v_a^2)^{1/2}} \frac{v_a^i v_a^j}{1-\mathbf{N}\cdot\mathbf{v}_a} \right]$$

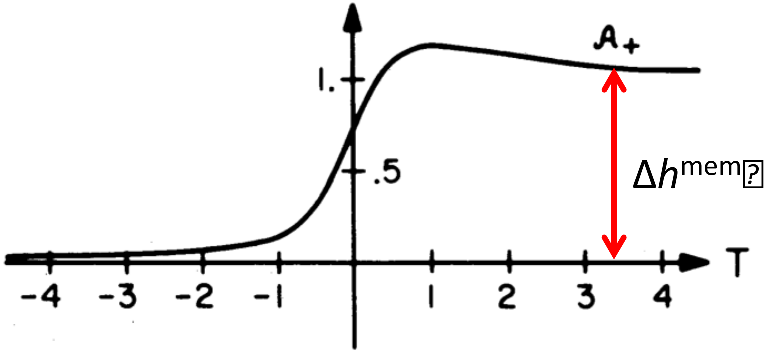
The gravitational-wave with “*memory*” !

- Non-oscillating part in the waveform
- Produce **permanent** changes in the separation of free-fall test masses.
- Initial strain $h^{TT}_{ij}=0$ before the signal arrives; and non-zero strain $h^{TT}_{ij}\neq 0$ after the signal has passed:

$$\Delta h^{\rm mem} = h(t\to\infty) - h(t\to-\infty)$$

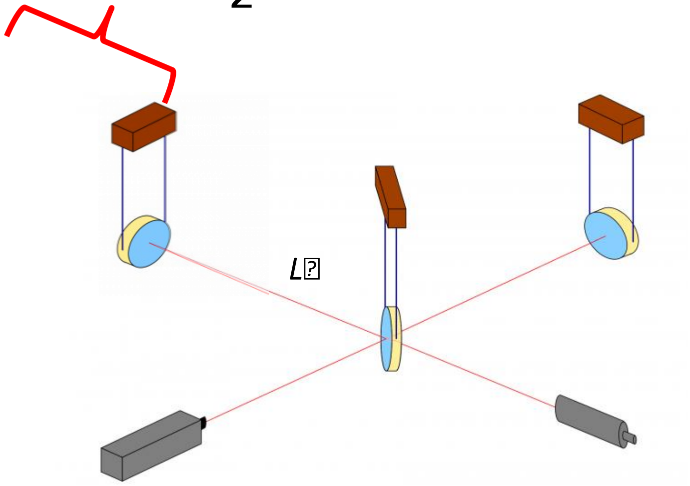
- Leave a DC (constant) offset on the strain after the burst has passed by.

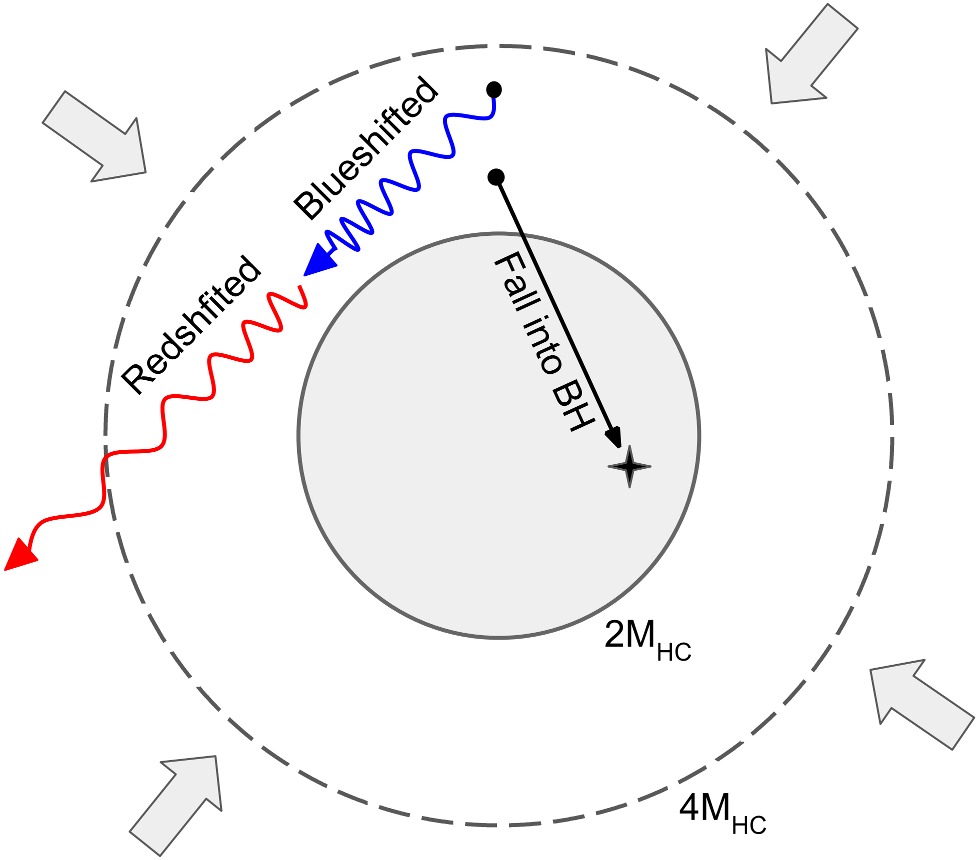
(Two stars in a hyperbolic orbit)

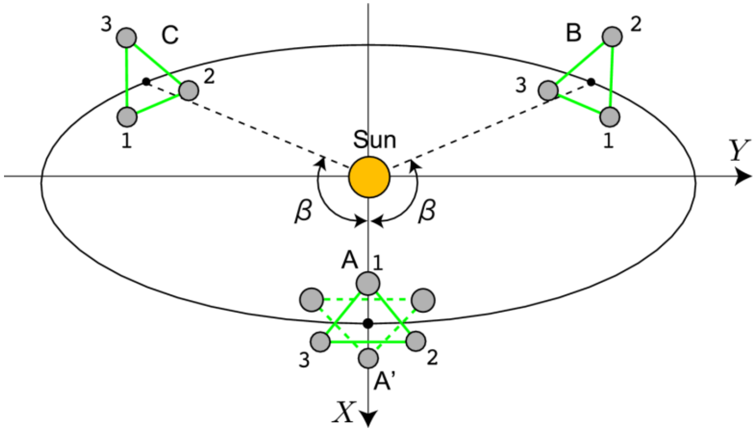


Kovacs & Thorne, *ApJ, 224., 62* (1978)

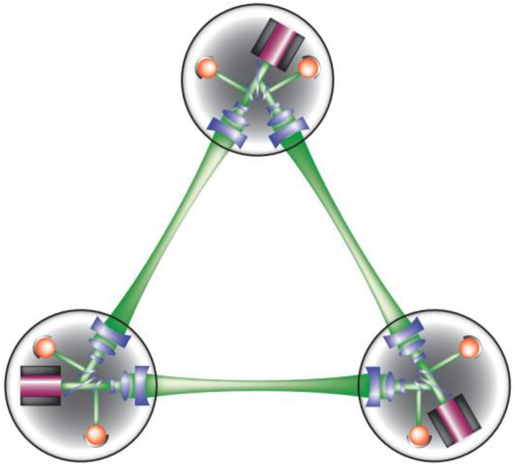
$$\delta x^{\rm mem} = \frac{L}{2}\Delta h_+^{\rm mem}$$



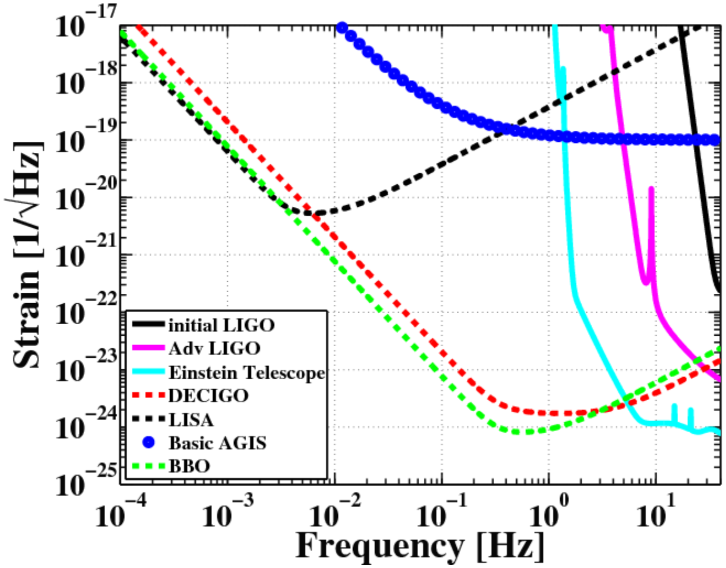

Blueshifted
Redshfited
Fall into BH
$2M_{HC}$
$4M_{HC}$

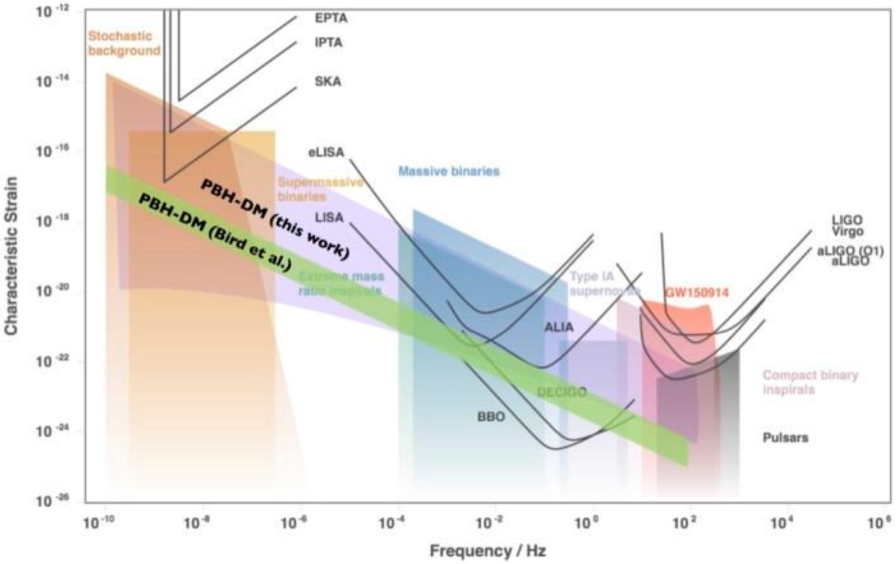


Cosmological test of gravity with polarizations of stochastic gravitational waves around 0.1-1 Hz - Nishizawa, Atsushi *et al.*
Phys.Rev. D81 (2010) 104043 arXiv:0911.0525 [gr-qc]



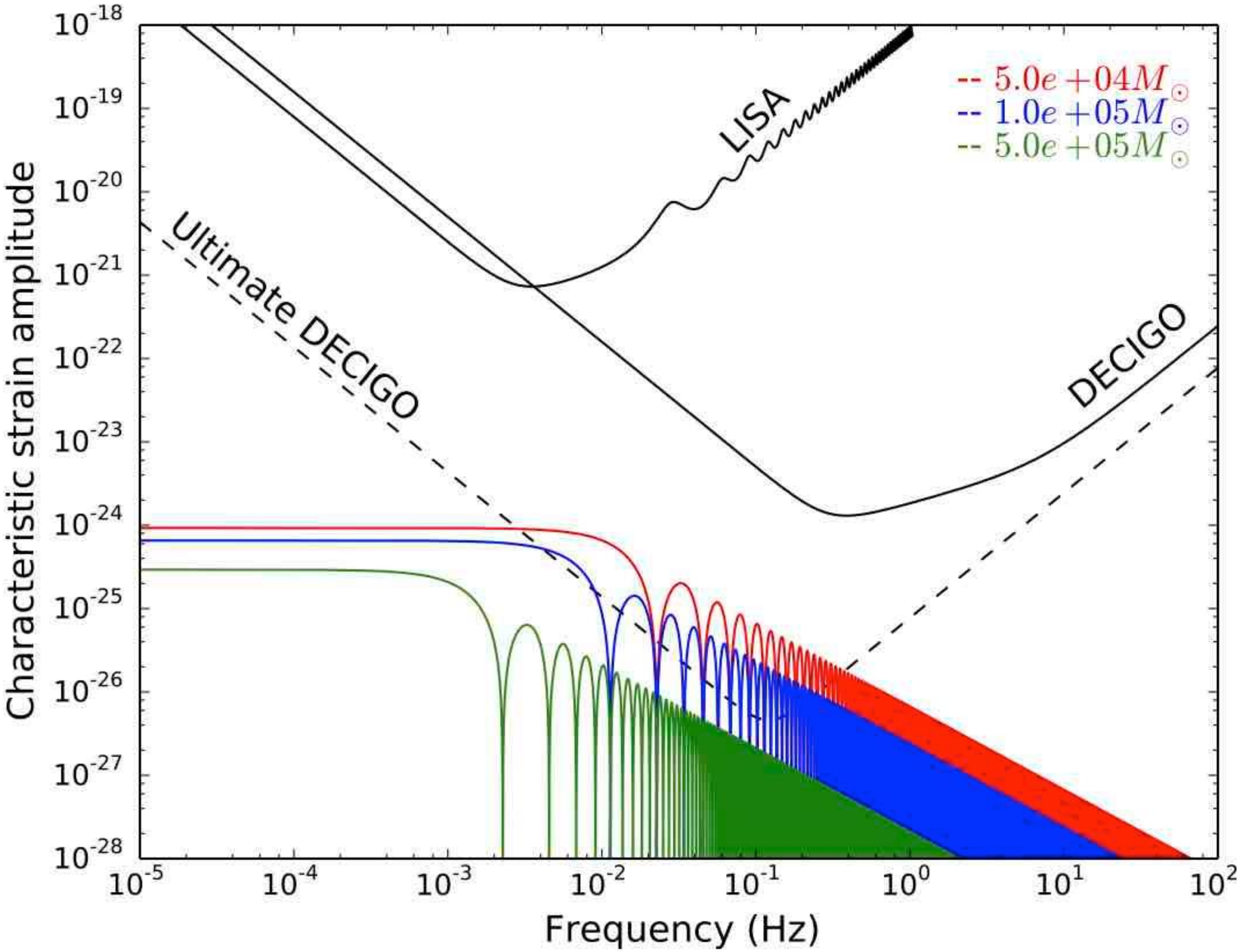
DECIGO constellation concept~¥cite{Sato:DECIGO2009}

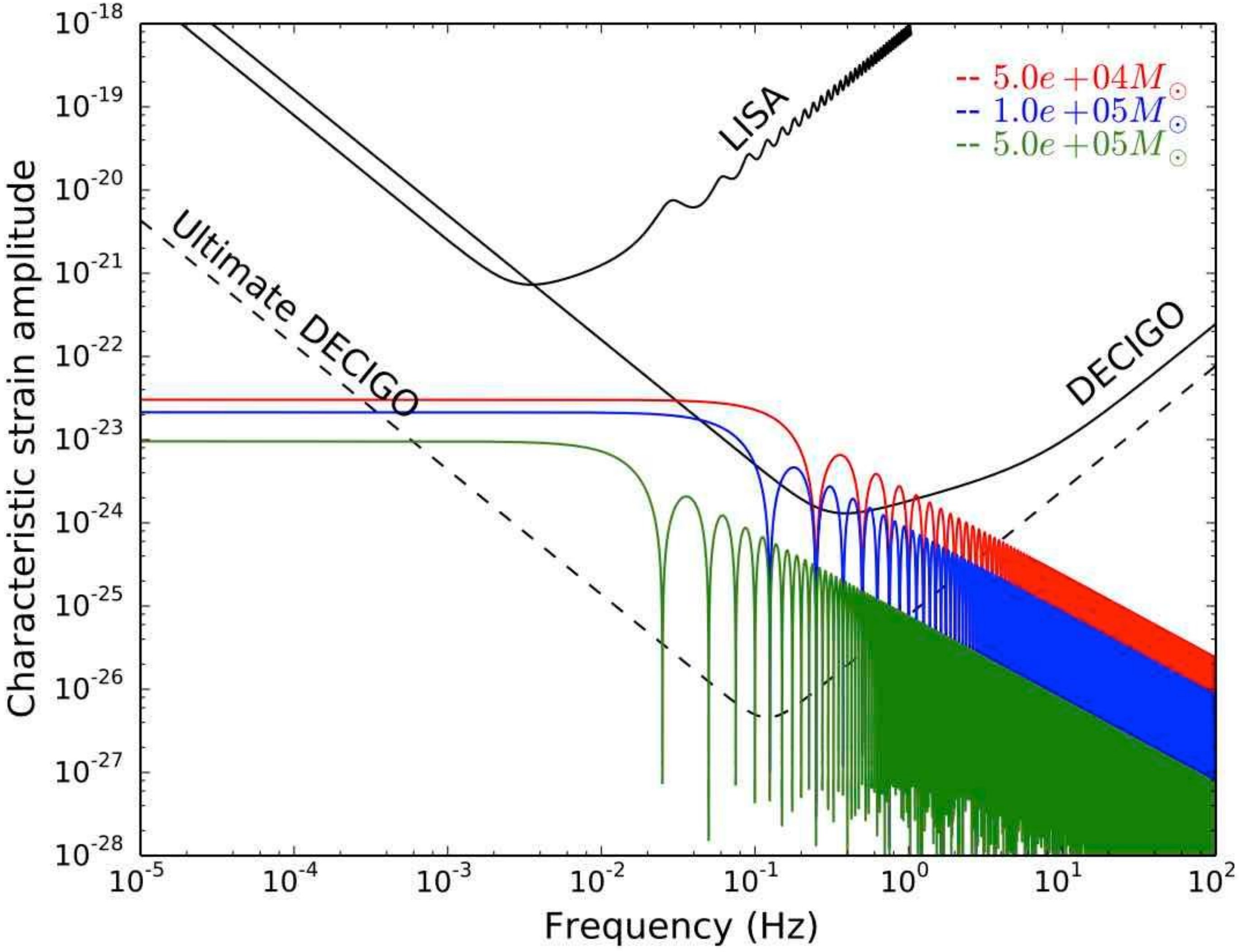




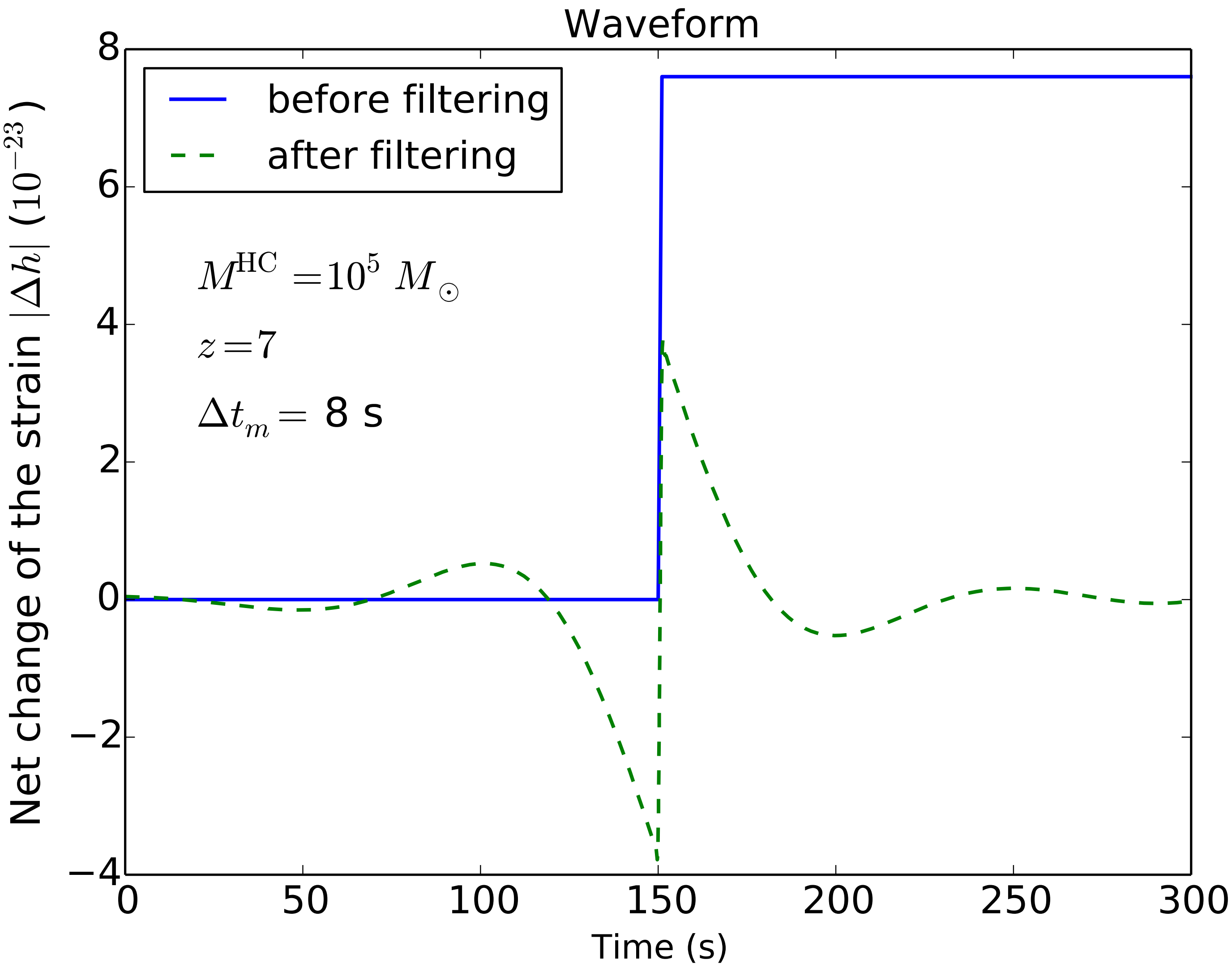
Left:
Adhikari, Rana X Rev.Mod.Phys. 86 (2014) 121 arXiv:1305.5188 [gr-qc] LIGO-P1200121

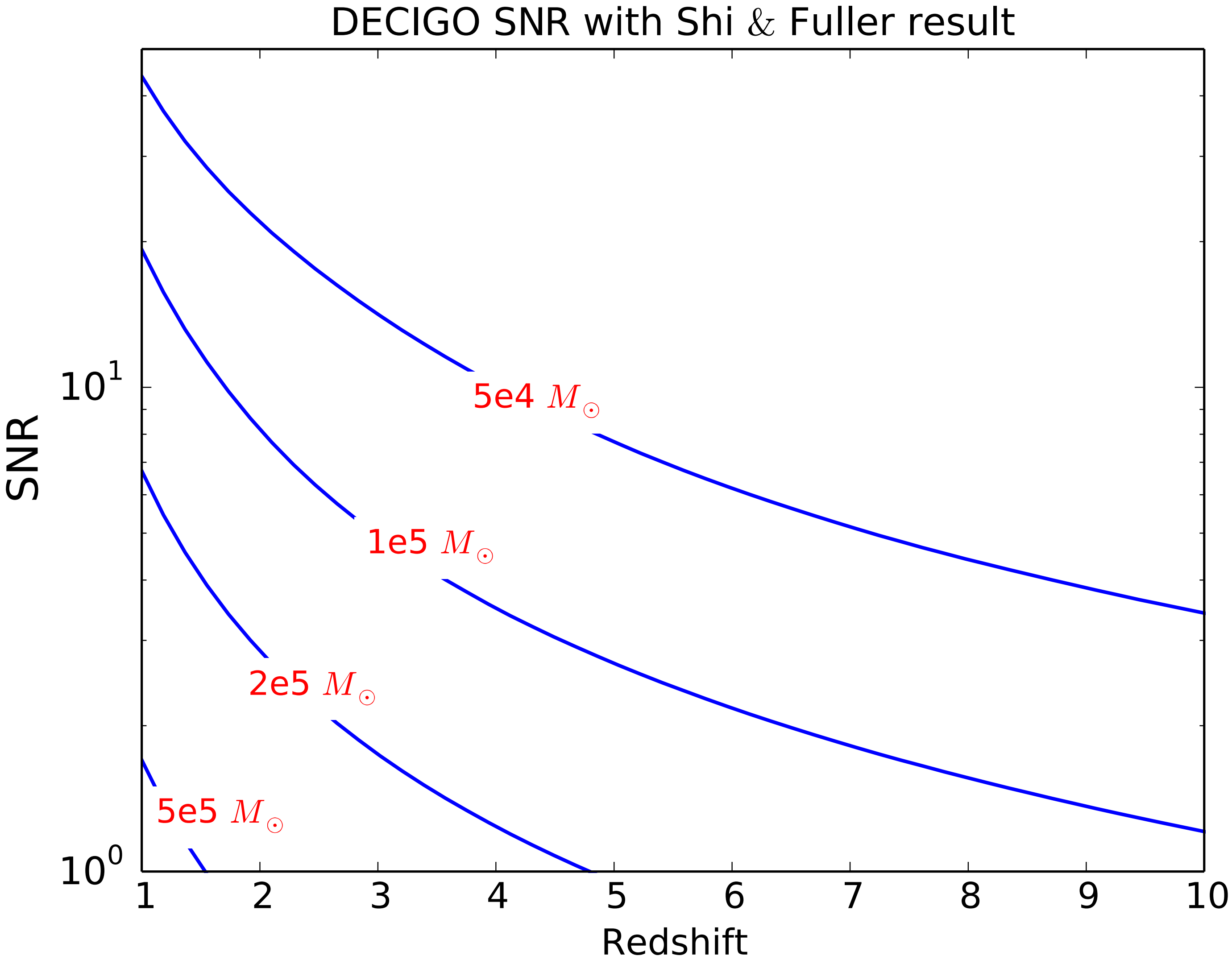
Right:
https://arxiver.wordpress.com/2016/10/27/detecting-the-gravitational-wave-background-from-primordial-black-hole-dark-matter-cea/#jp-carousel-203276

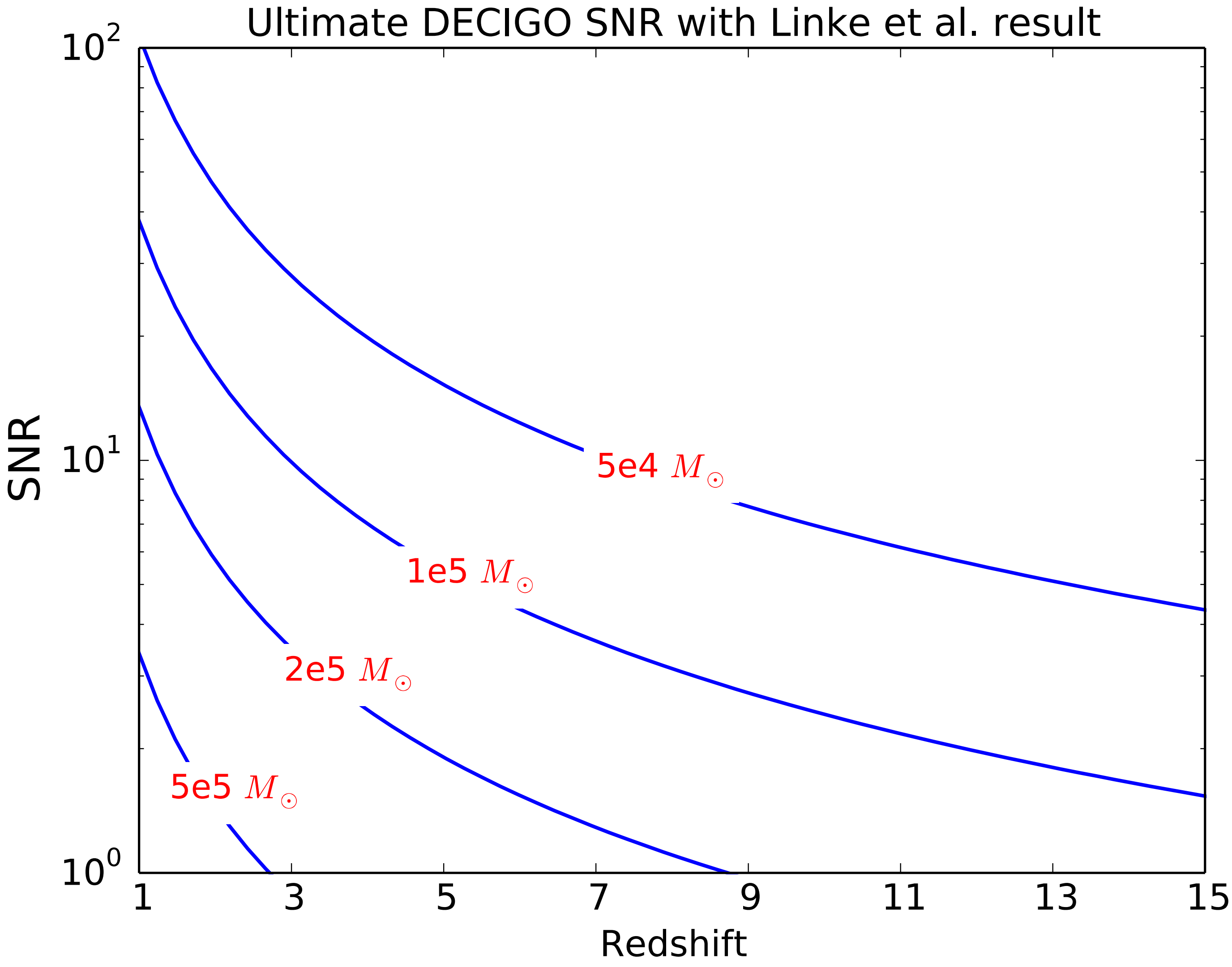

Characteristic strain amplitude
Frequency (Hz)
LISA
Ultimate DECIGO
DECIGO
$5.0e+04M_\odot$
$1.0e+05M_\odot$
$5.0e+05M_\odot$
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

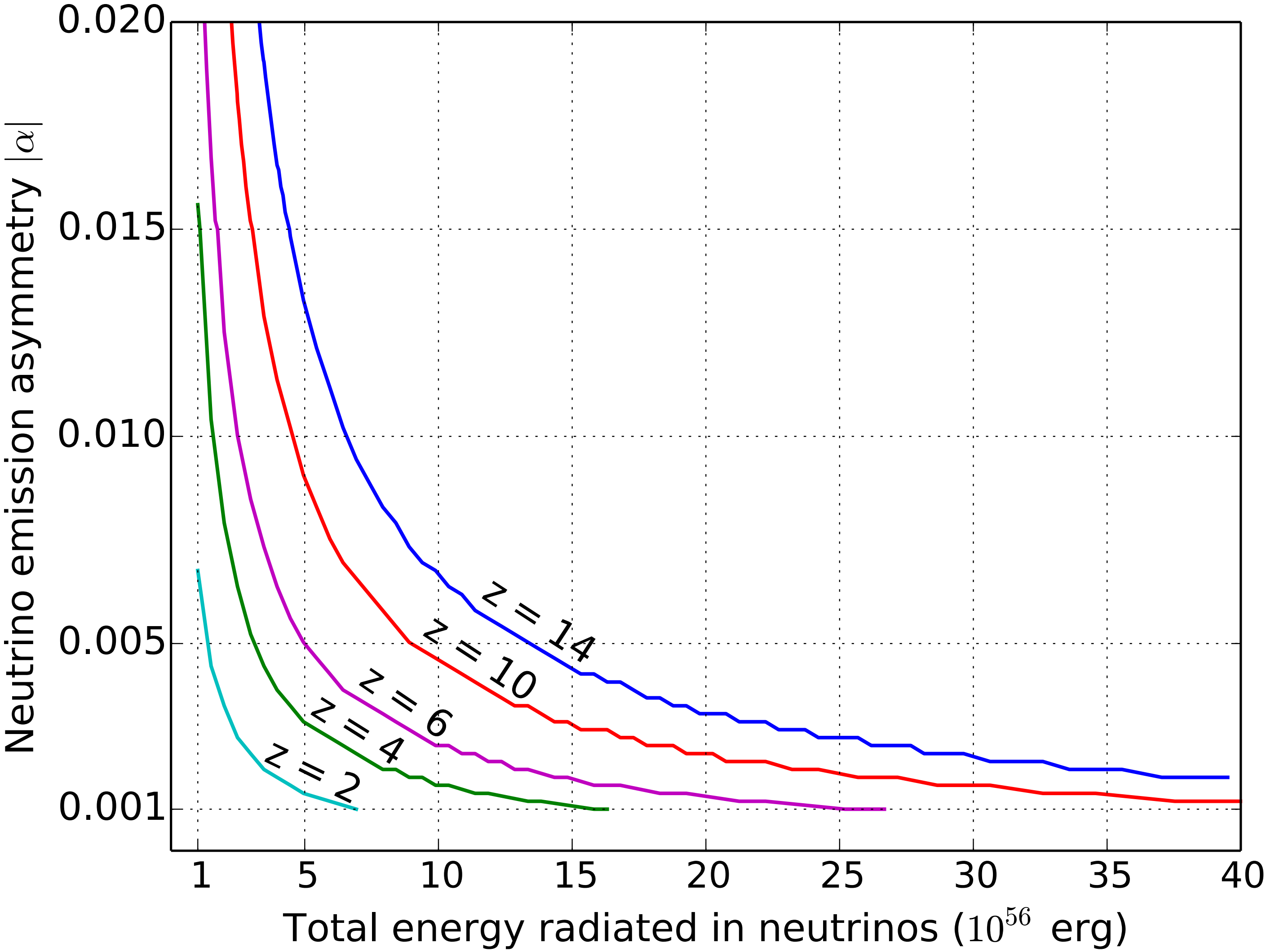


$5.0e+04M_\odot$
$1.0e+05M_\odot$
$5.0e+05M_\odot$
LISA
Ultimate DECIGO
DECIGO
Characteristic strain amplitude
Frequency (Hz)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}


Waveform
before filtering
after filtering
$M^{\rm HC}=10^5\ M_\odot$
$z=7$
$\Delta t_m=$ 8 s
Net change of the strain $|\Delta h|$ (10^{-23})
Time (s)
8
6
4
2
0
−2
−4
0
50
100
150
200
250
300


DECIGO SNR with Shi $\&$ Fuller result
SNR
10^1
10^0
Redshift
1
2
3
4
5
6
7
8
9
10
5e4 $M_\odot$
1e5 $M_\odot$
2e5 $M_\odot$
5e5 $M_\odot$


Ultimate DECIGO SNR with Linke et al. result
10^2
10^1
10^0
SNR
1
3
5
7
9
11
13
15
Redshift
5e4 $M_\odot$
1e5 $M_\odot$
2e5 $M_\odot$
5e5 $M_\odot$


Neutrino emission asymmetry $|\alpha|$
0.020
0.015
0.010
0.005
0.001
1
5
10
15
20
25
30
35
40
Total energy radiated in neutrinos (10^{56} erg)
z = 14
z = 10
z = 6
z = 4
z = 2