Astrophysical signatures

of the

QCD phase transition

The Astrophysical Journal, 335:301–305, 1988 December 1

SUPERNOVA EXPLOSIONS AND THE SOFT EQUATION OF STATE

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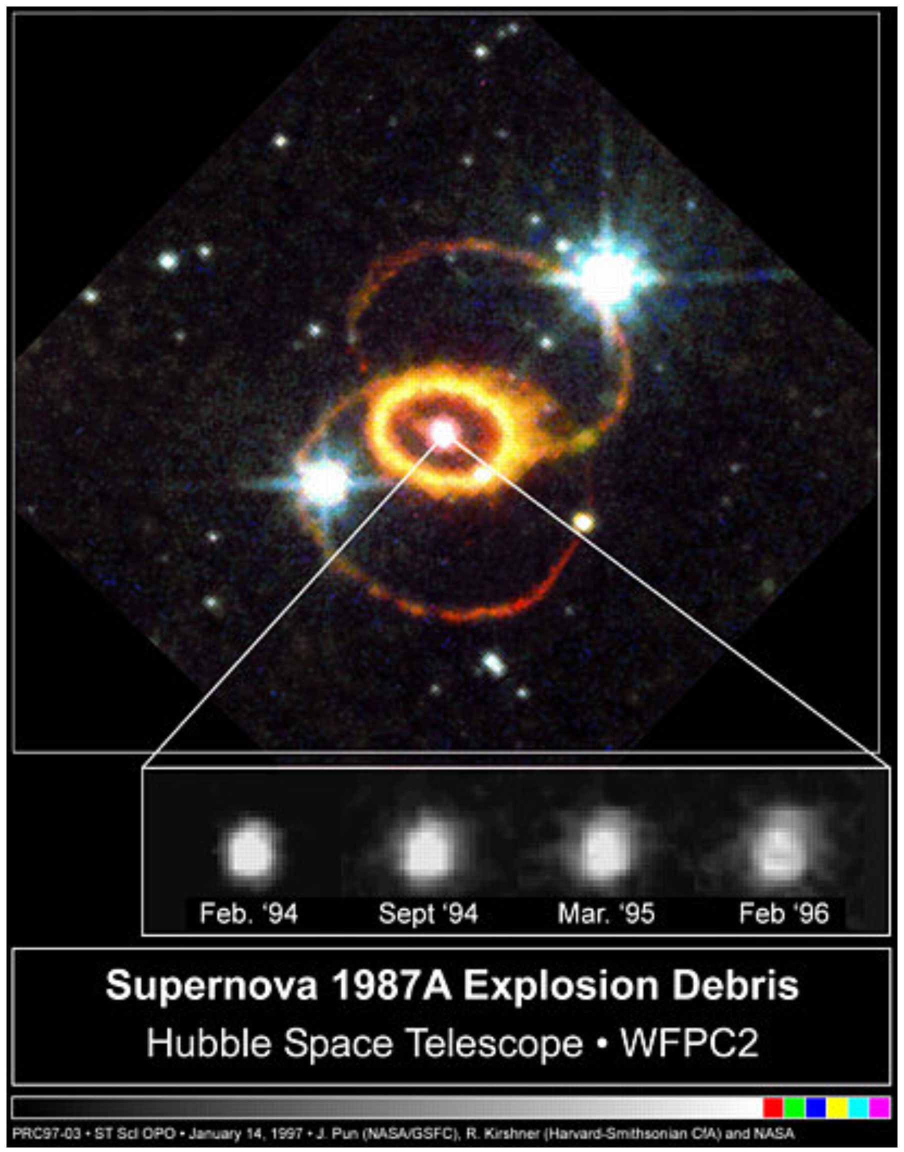
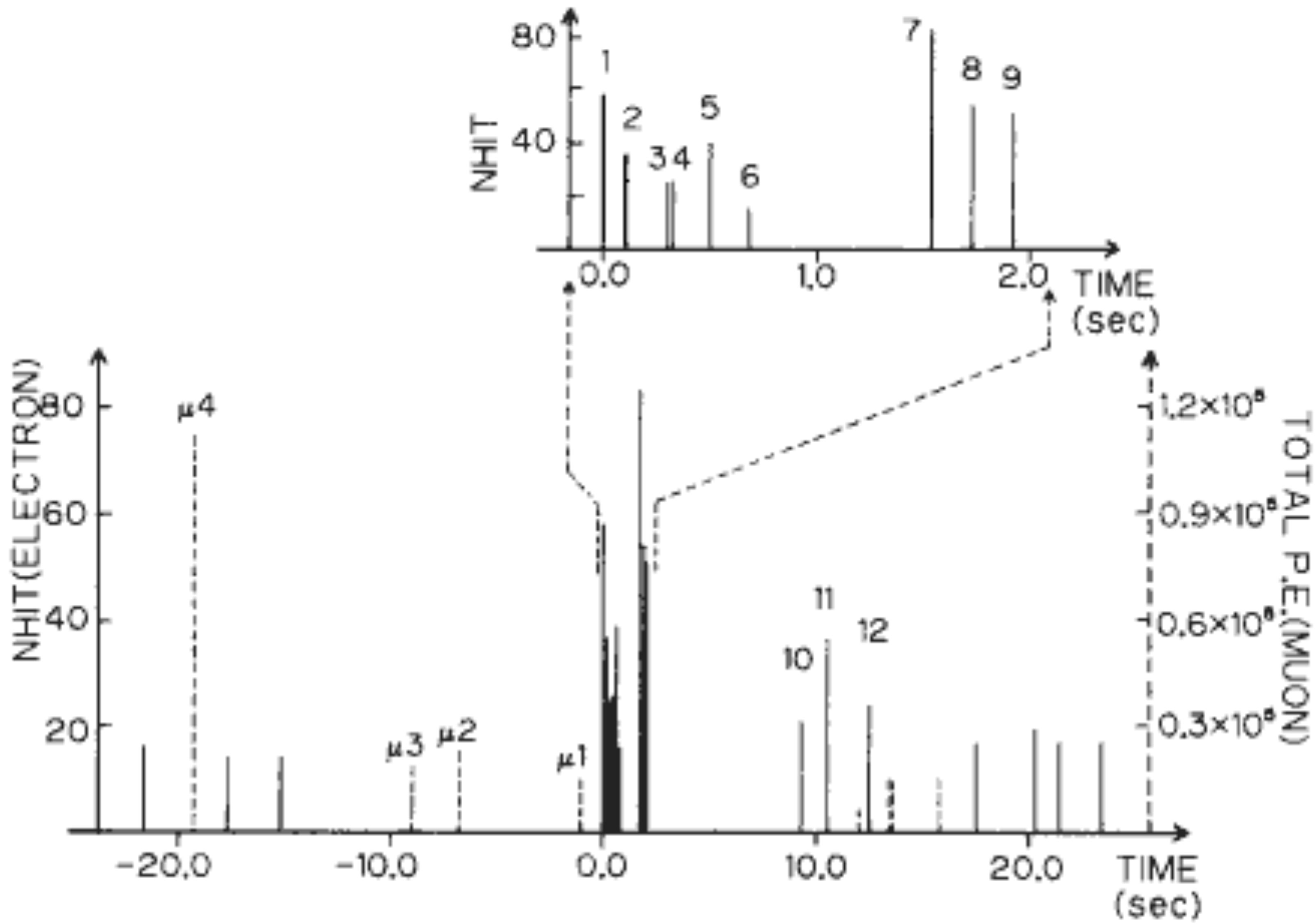
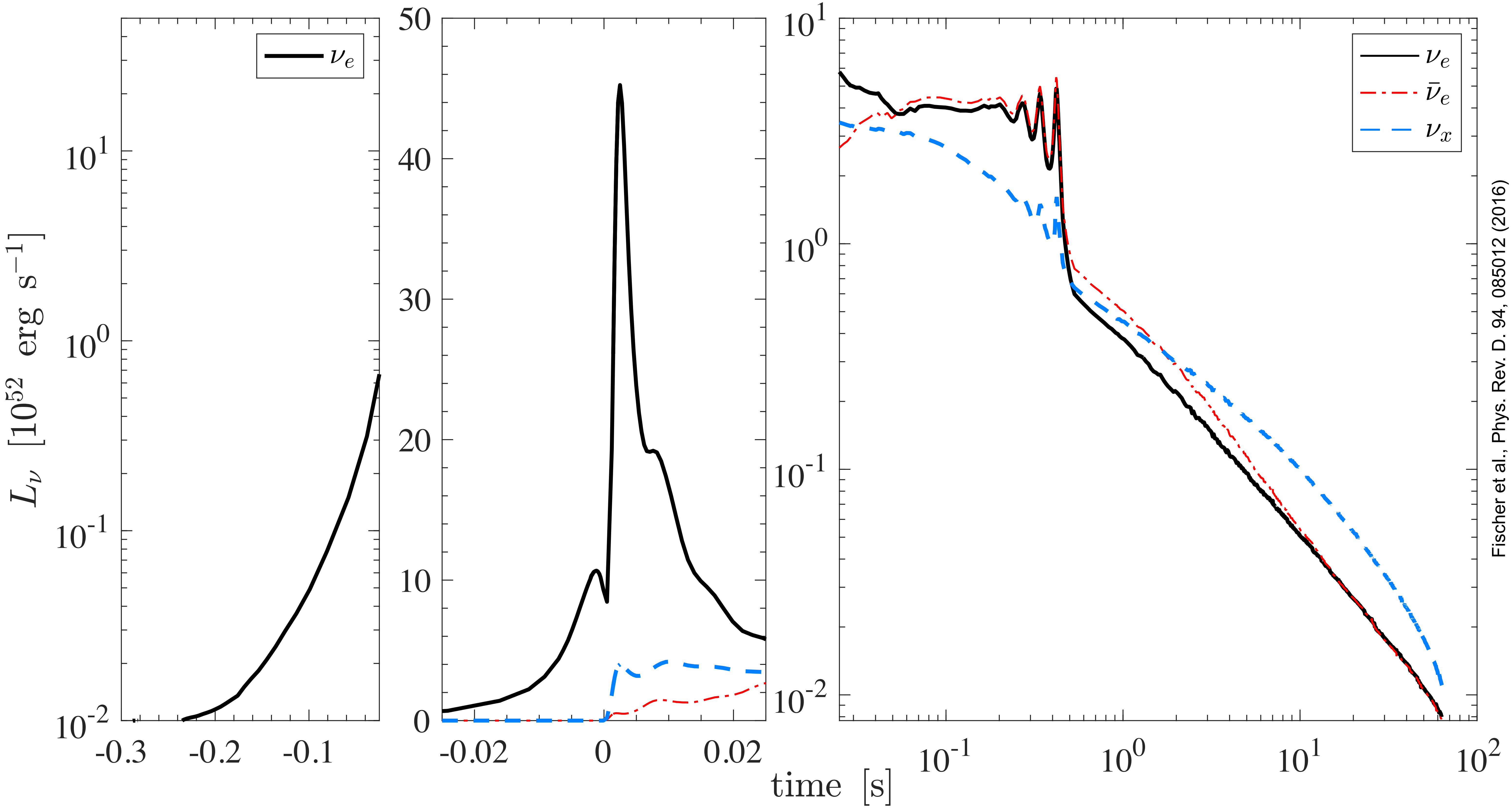




Hirata et al., Phys. Rev. Lett. 58, p.1490 (1987)

Core-collapse supernova neutrino signals from simulations



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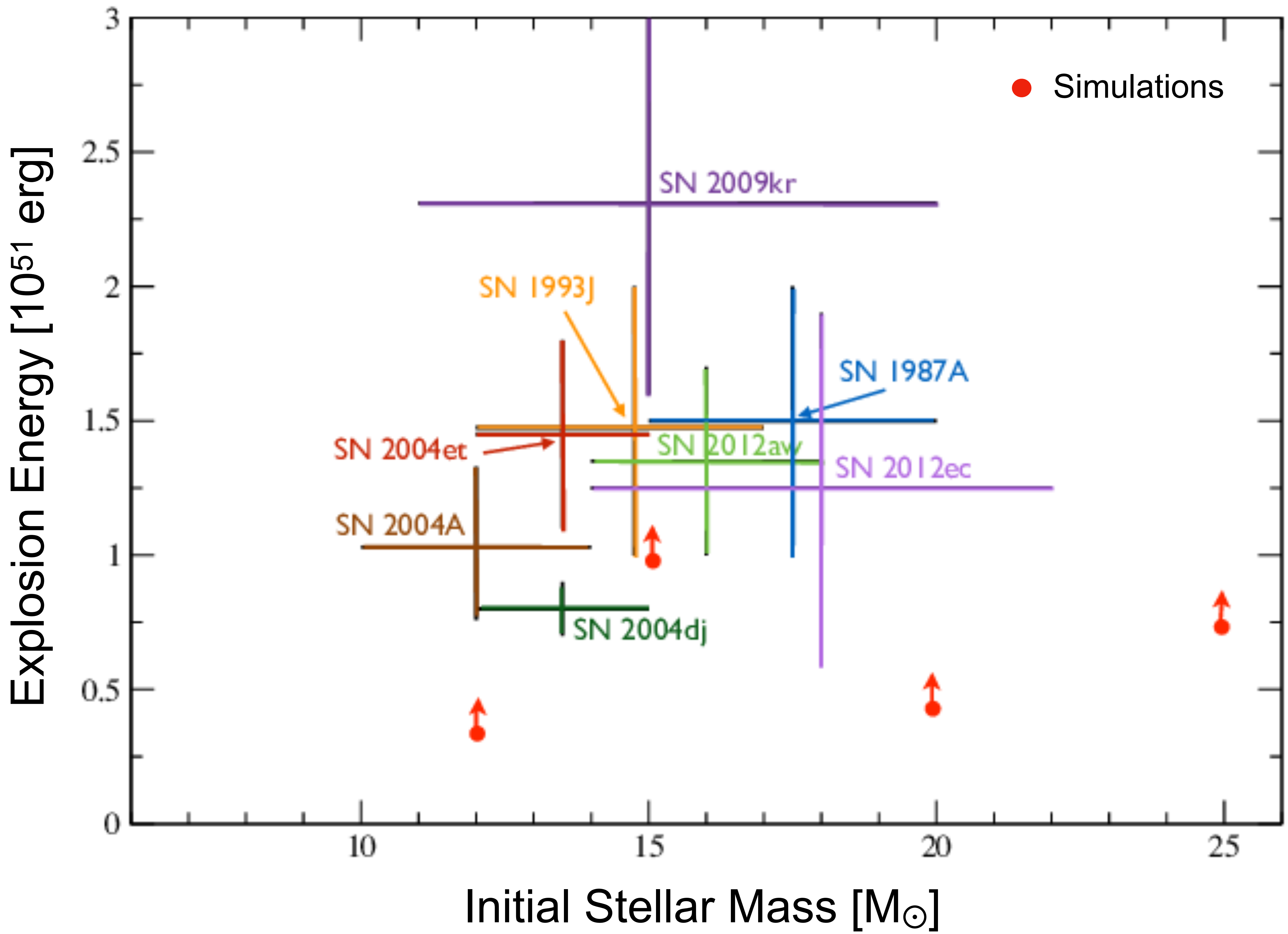
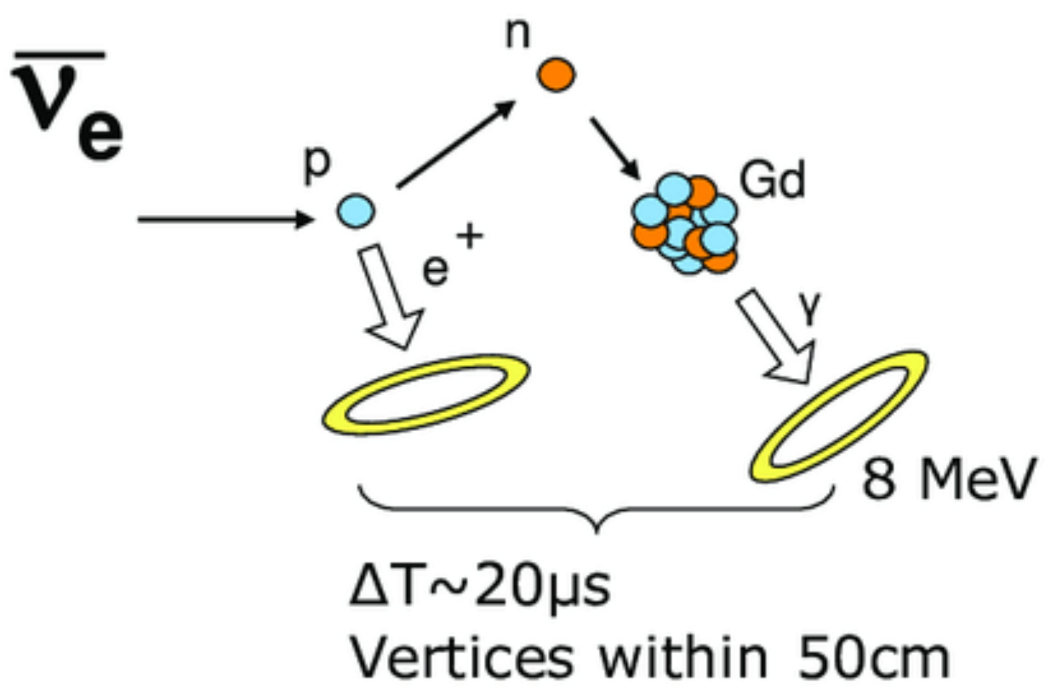
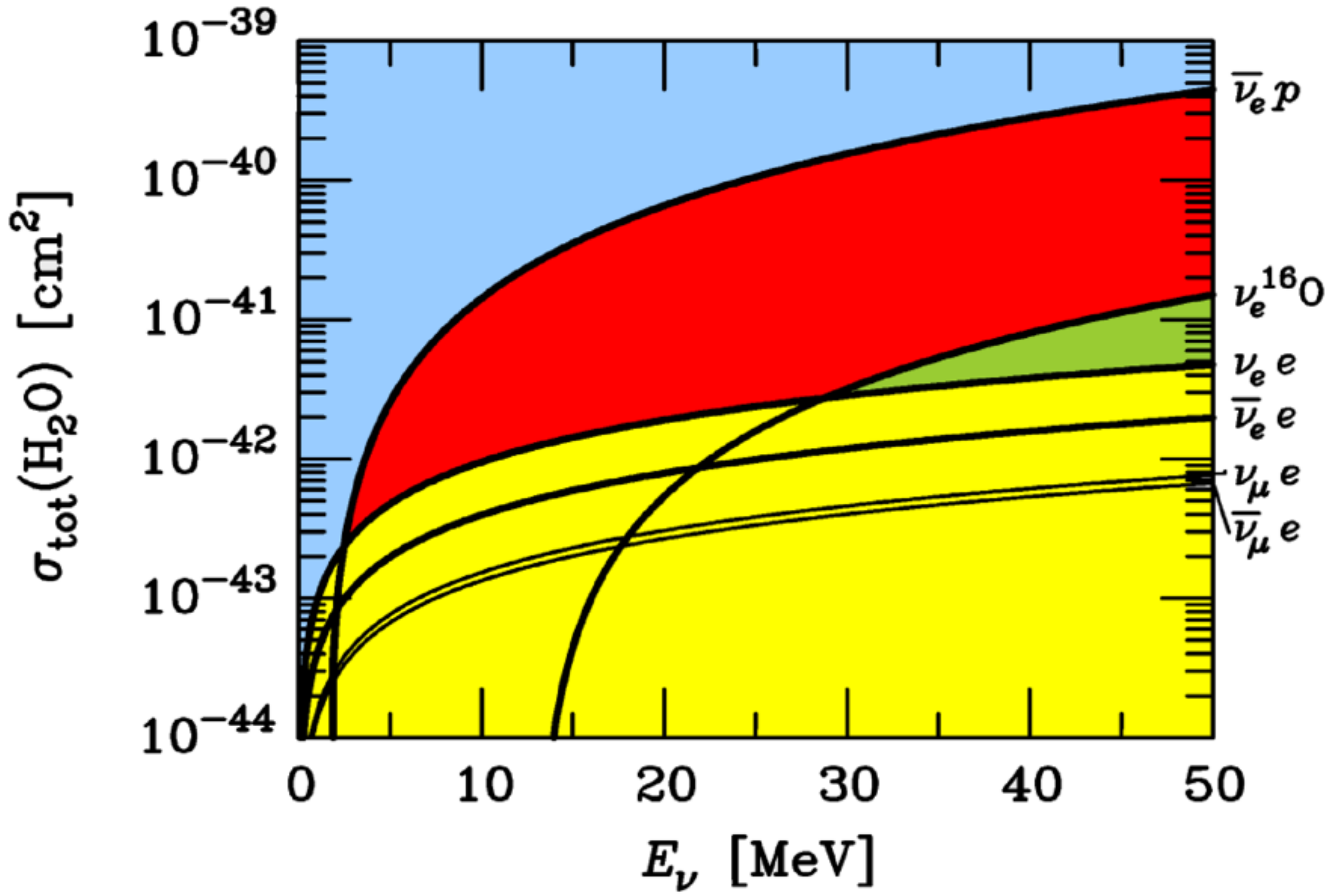
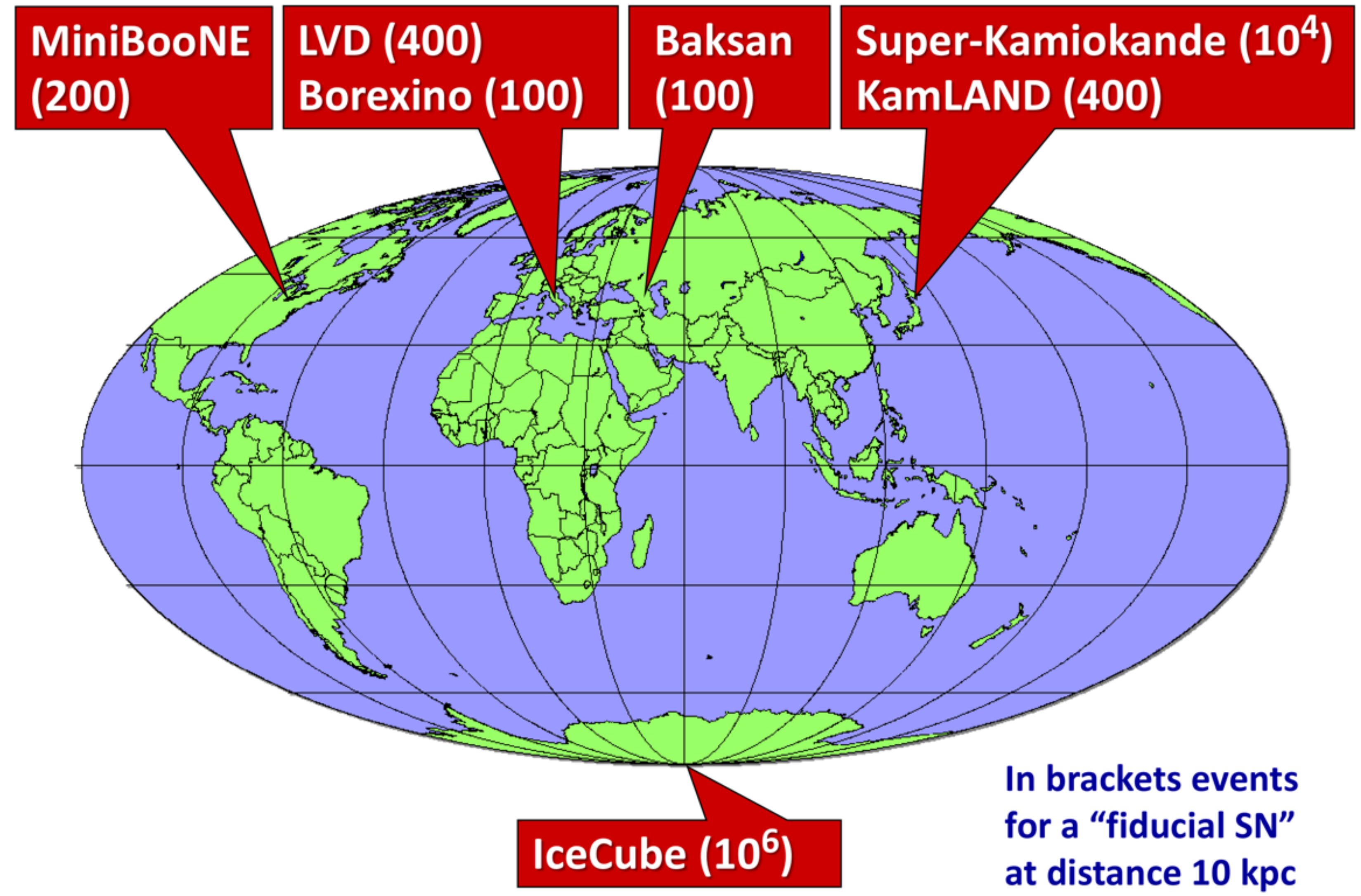

Simulations
SN 2009kr
SN 1993J
SN 1987A
SN 2004et
SN 2012aw
SN 2012ec
SN 2004A
SN 2004dj
Explosion Energy [10^{51} erg]
Initial Stellar Mass [$M_\odot$]
0
0.5
1
1.5
2
2.5
3
10
15
20
25

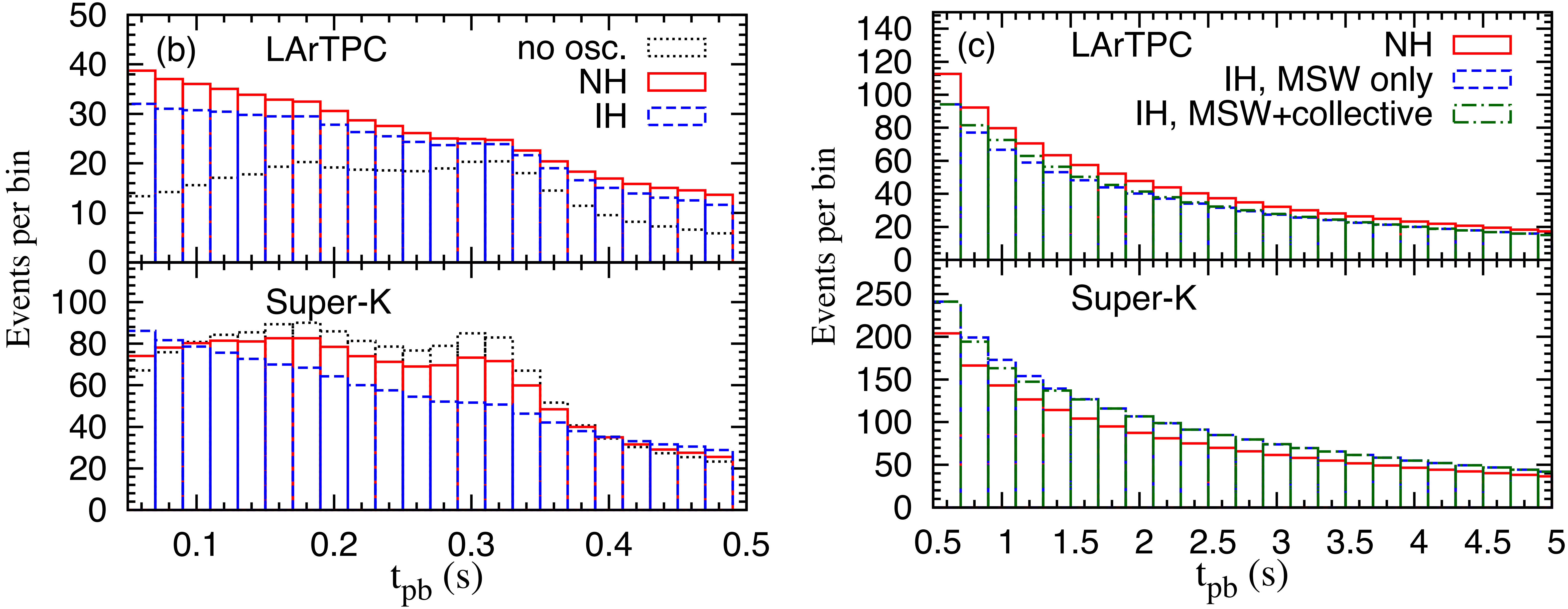






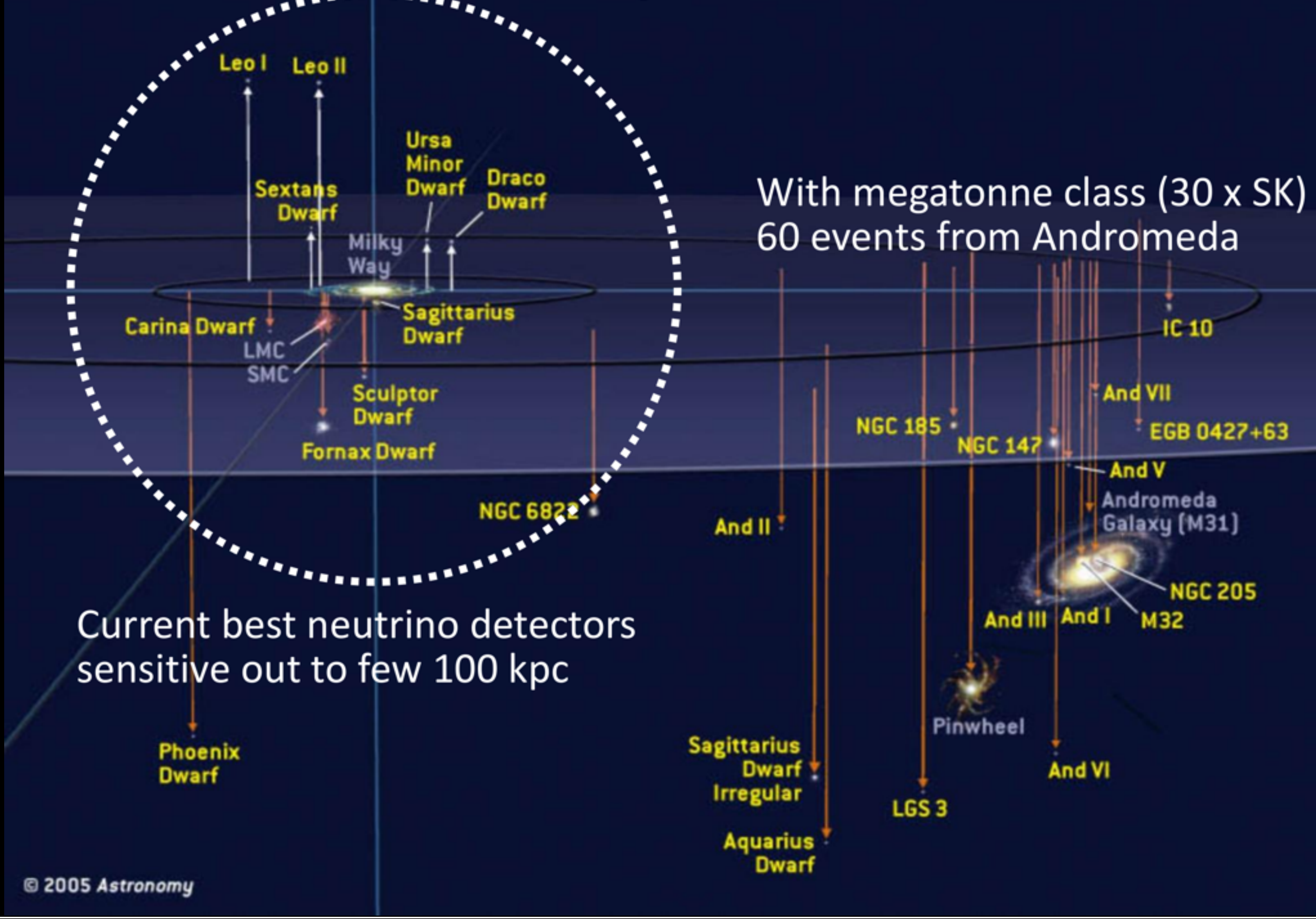
In brackets events for a "fiducial SN" at distance 10 kpc

Expected event rate for the next galactic core-collapse supernova

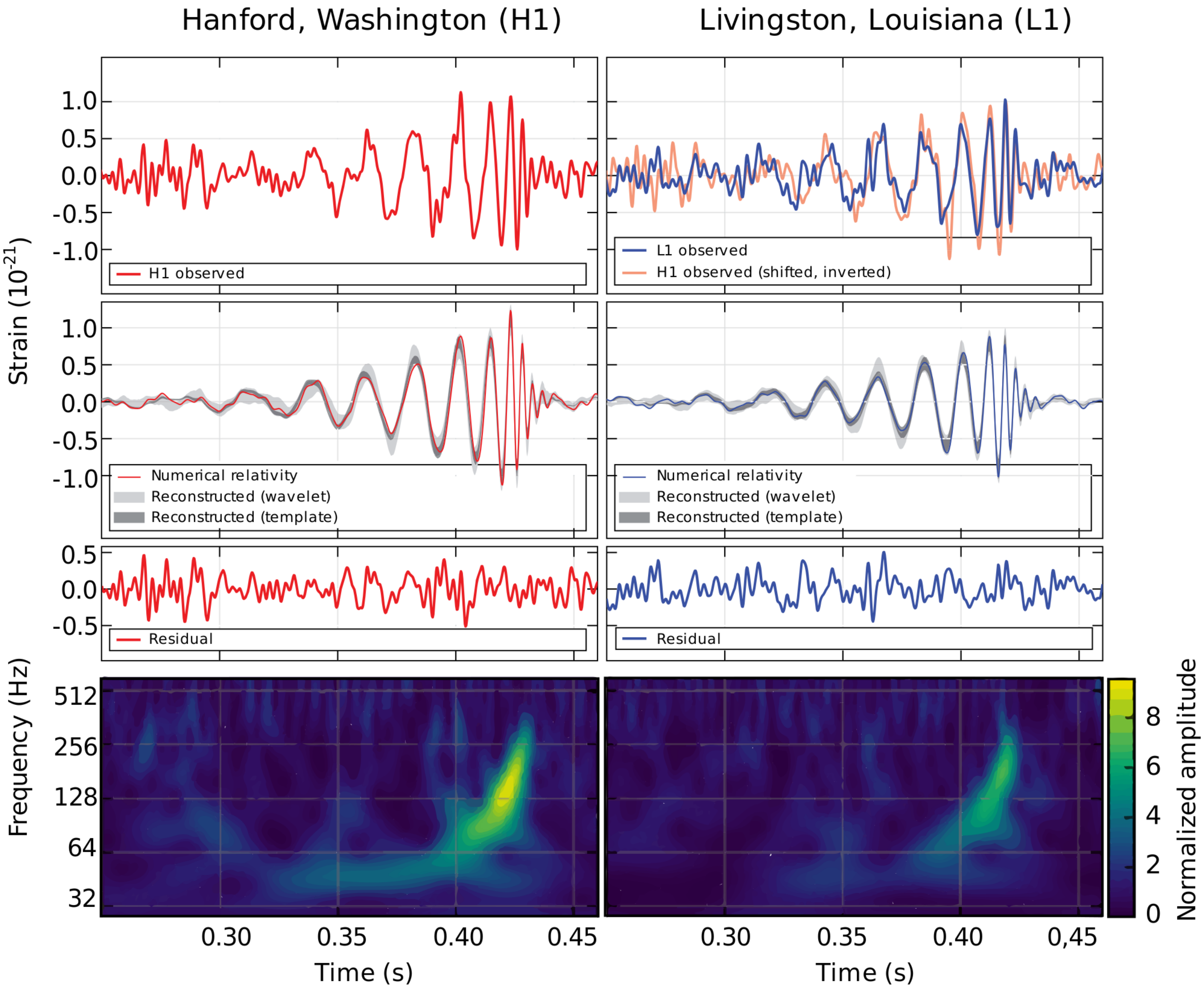


Wu et al., Phys. Rev. D. 89, 061303 (2015)

Local Group of Galaxies

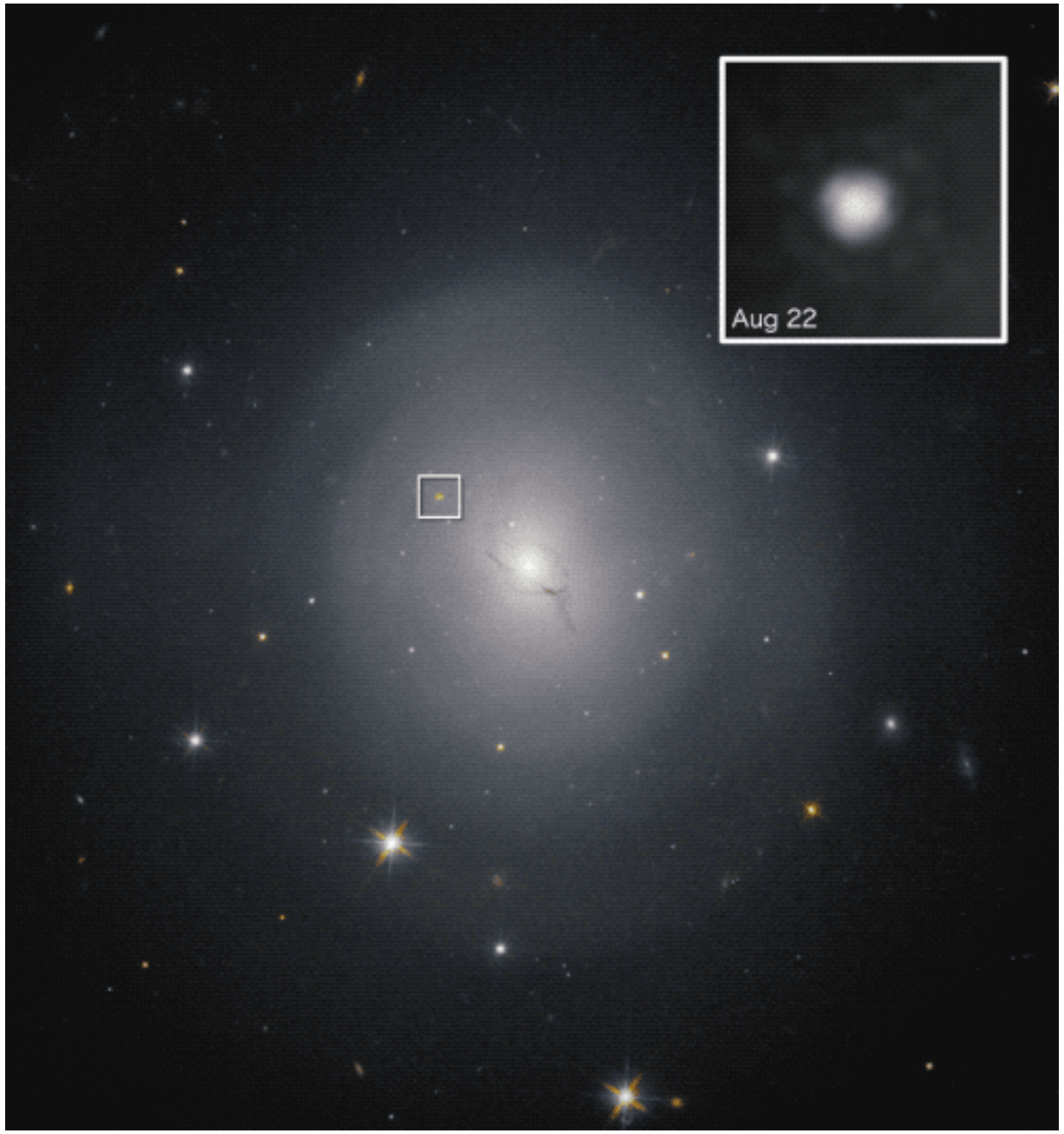


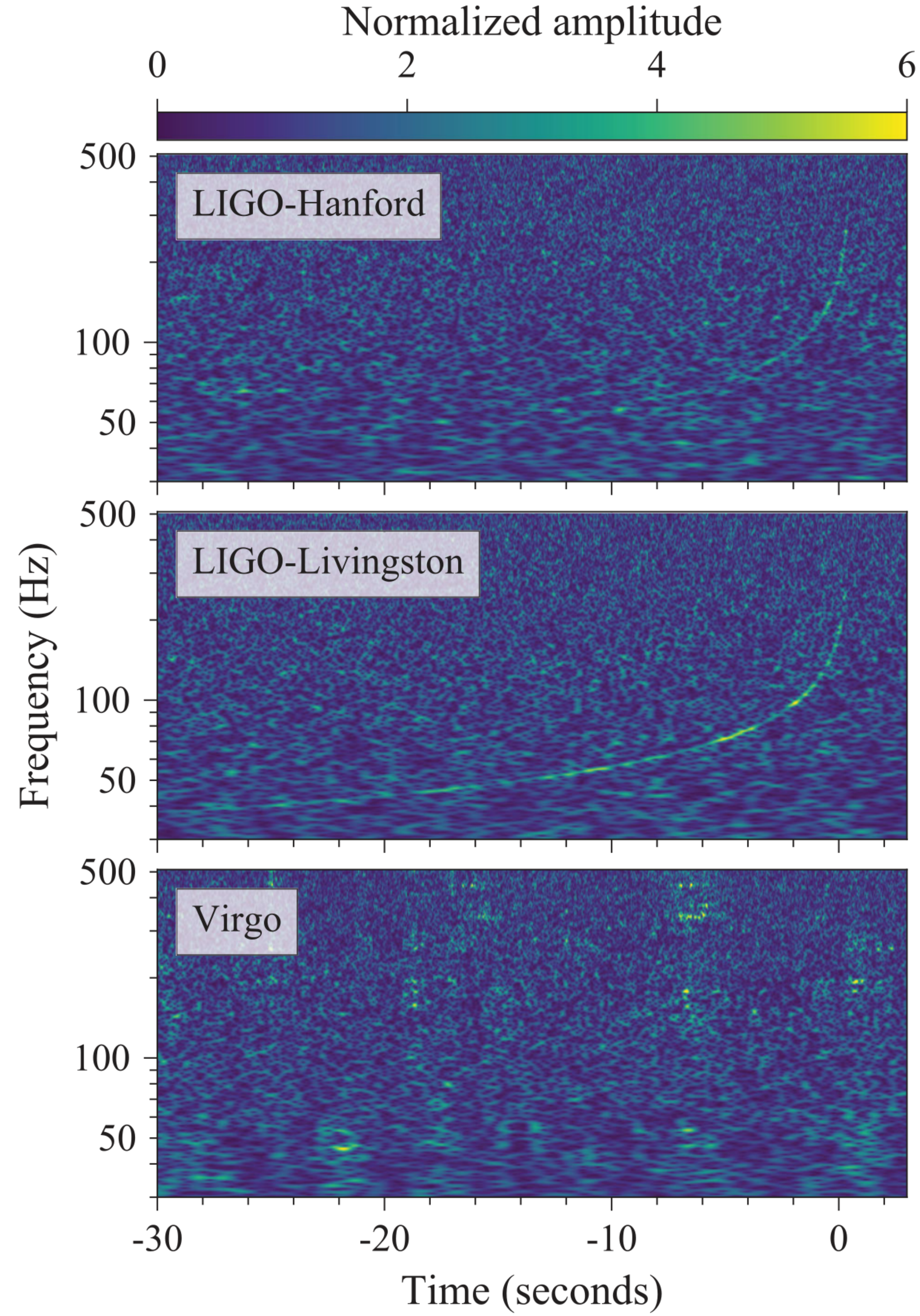
GW150914



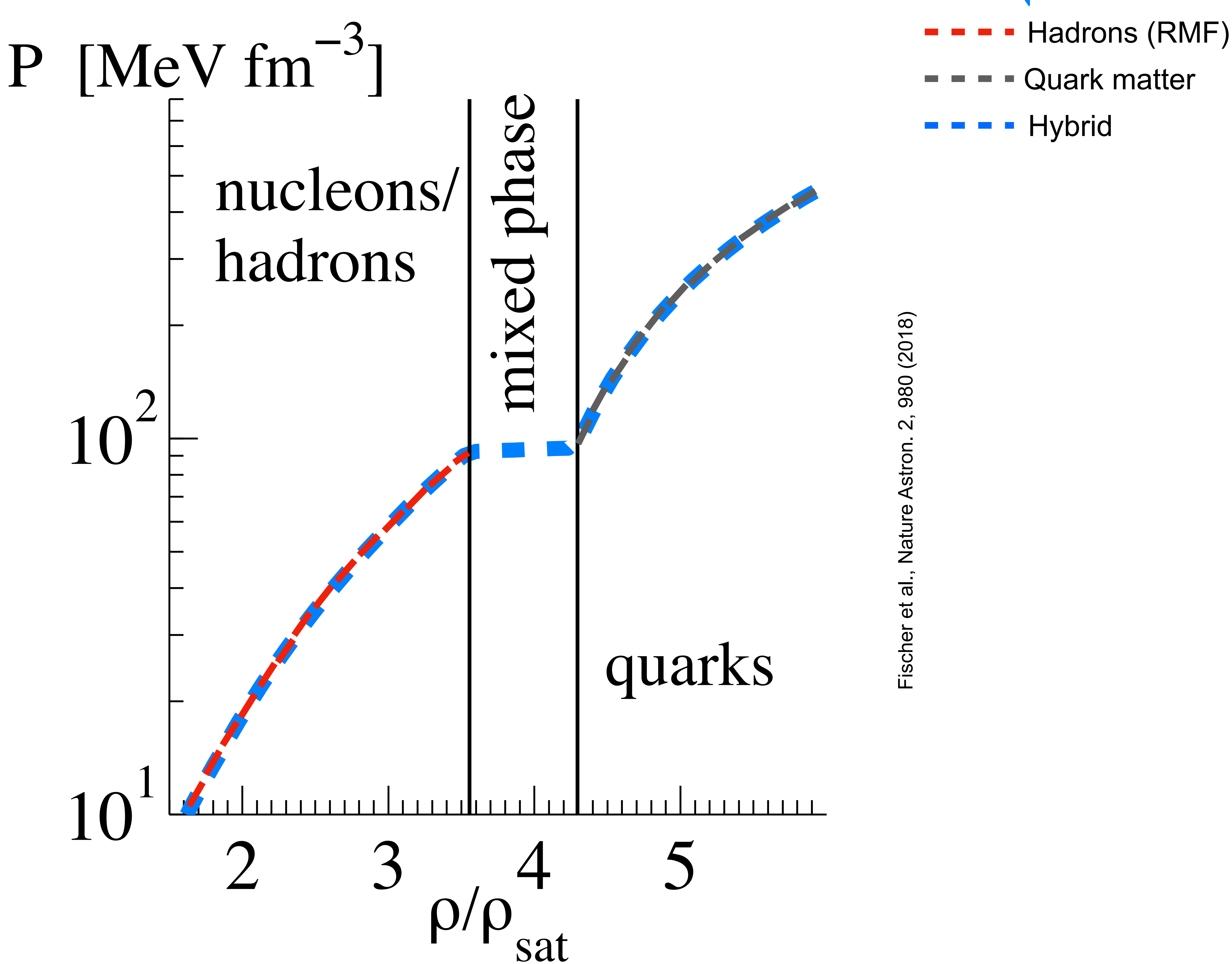
LIGO/VIRGO collaboration, PhDs. Rev. Lett. 116, 061102 (2016)

GW170817

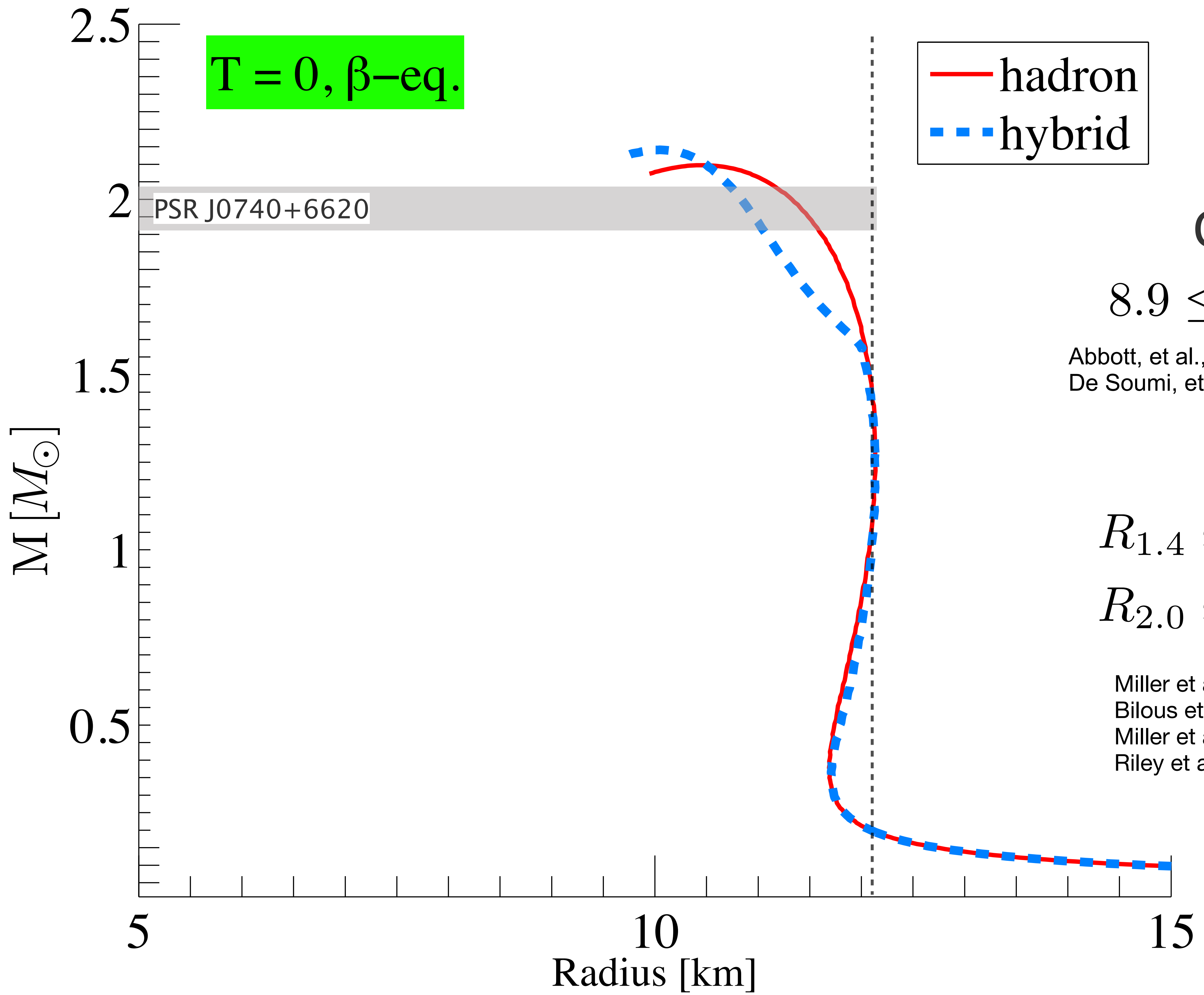




LIGO/VIRGO collaboration, PhDs. Rev. Lett. 119, 161101 (2017)



Fischer et al., Nature Astron. 2, 980 (2018)



GW170817

$$8.9 \leq R_{1.4} \leq 13.2 \text{ km}$$

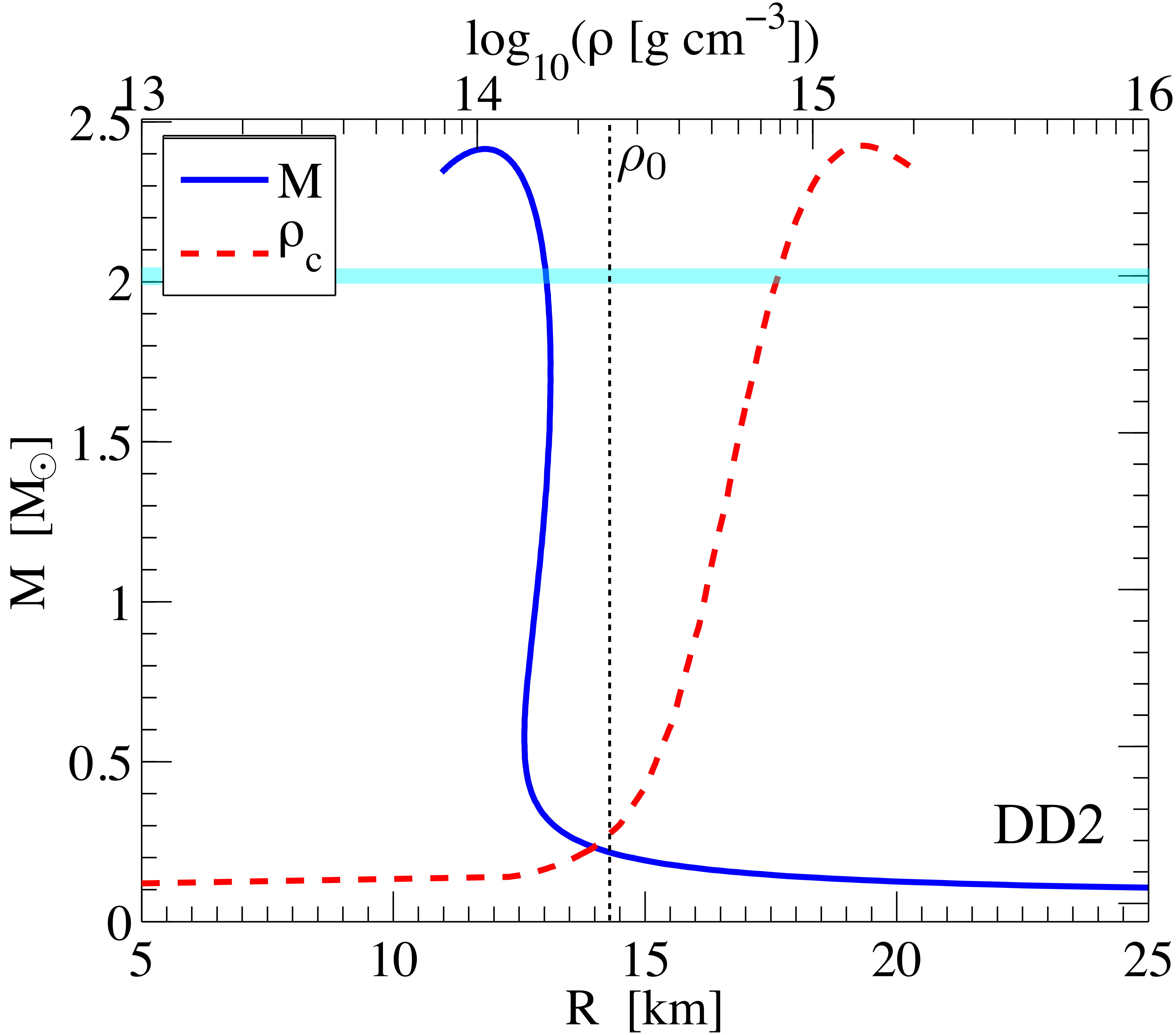
Abbott, et al., Phys. Rev. Lett., 121, 161101 (2018)
De Soumi, et al., Phys. Rev. Lett., 121, 091102 (2018)

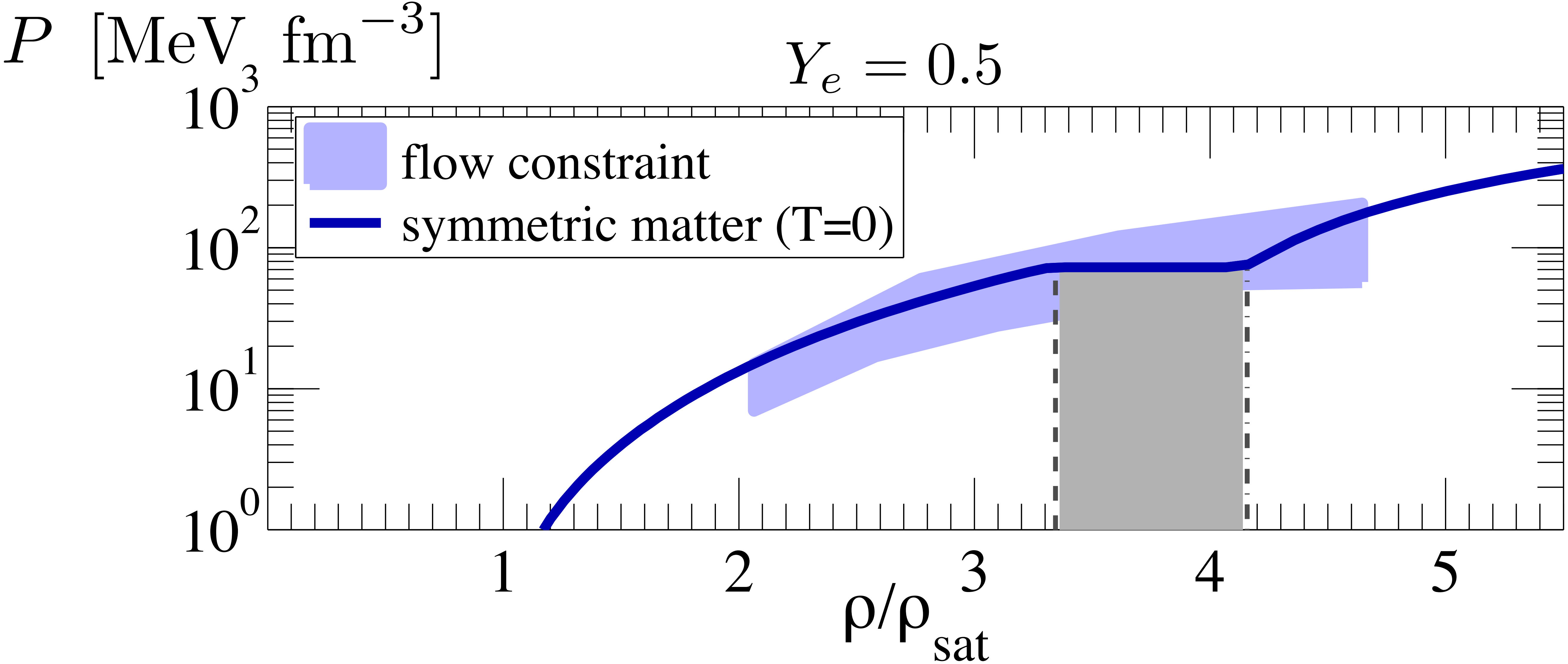
NICER

$$R_{1.4} \simeq 12.2 - 14.5 \text{ km}$$

$$R_{2.0} \simeq 11.5 - 13.5 \text{ km}$$

Miller et al., Astrophs. J. Lett., 887, L24 (2019)
Bilous et al., Astrophs. J. Lett., 887, L23 (2019)
Miller et al., Astrophs. J. Lett., 918, L28 (2021)
Riley et al., Astrophs. J. Lett., 918, L27 (2021)

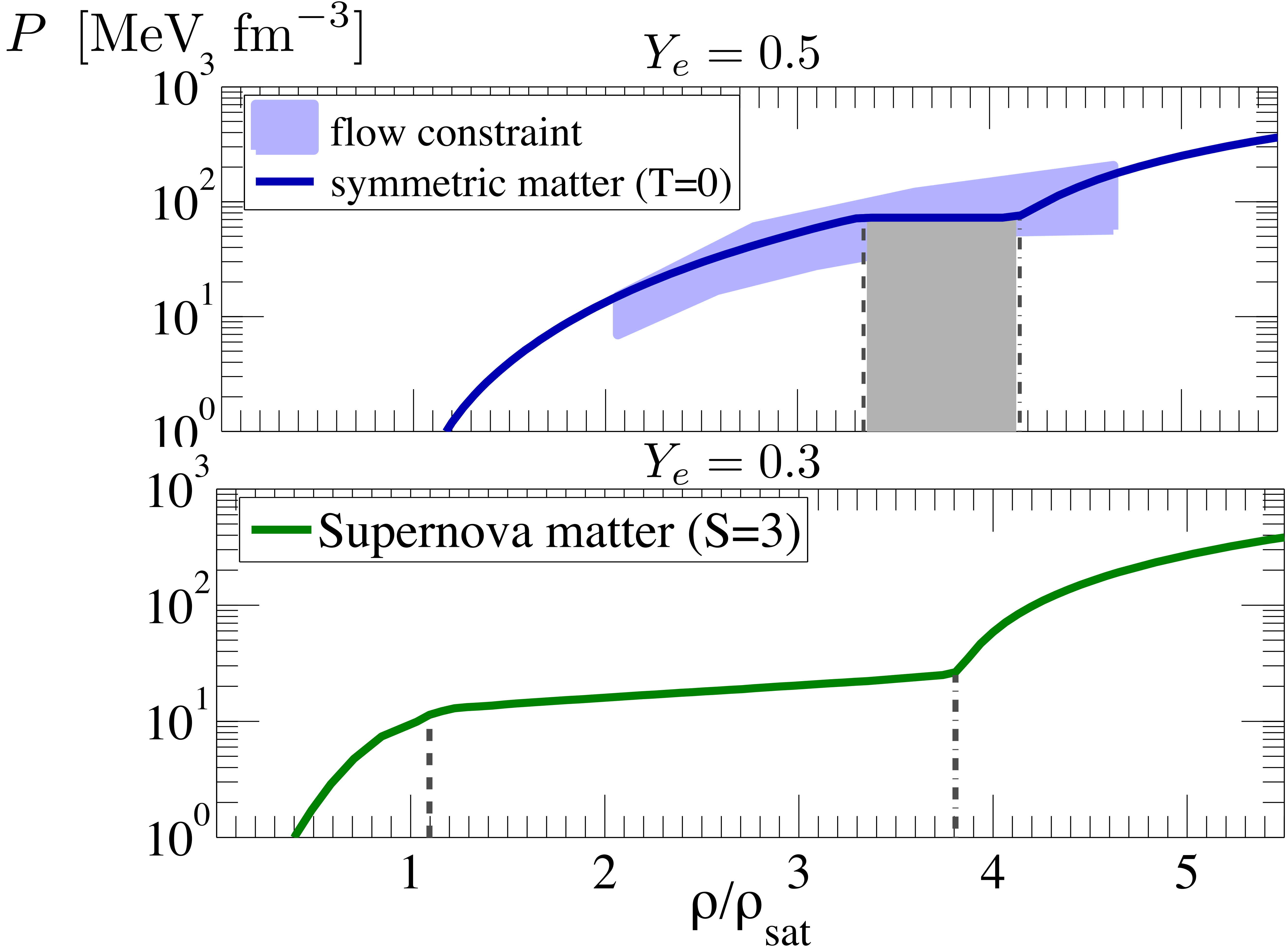

log10(ρ [g cm−3])
13
14
15
16
2.5
2
1.5
1
0.5
0
M [M⊙]
M
ρc
ρ0
DD2
5
10
15
20
25
R [km]



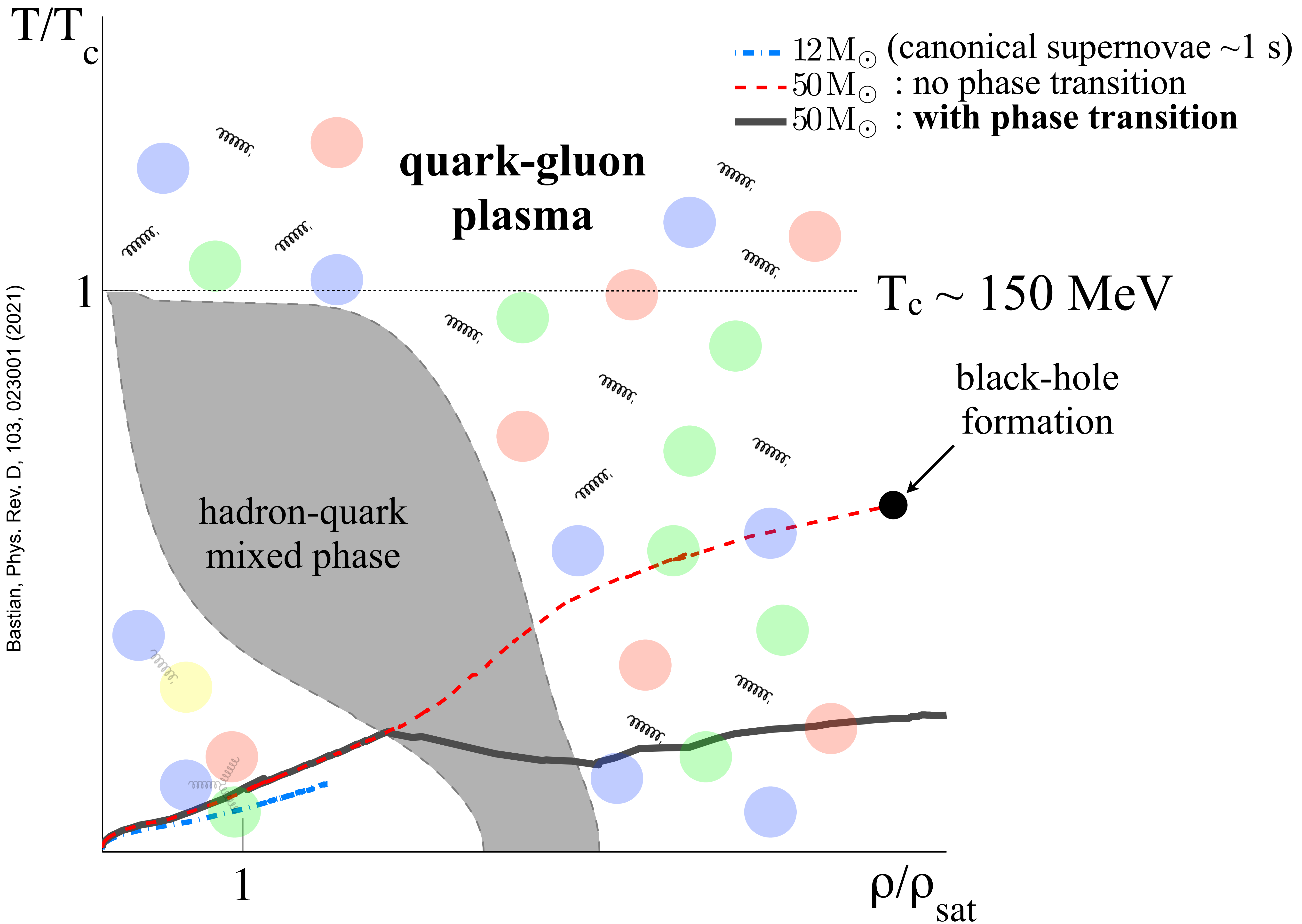
$$\frac{\partial \rho\,\mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\,\rho\,\mathbf{u}) + \nabla P = \ldots$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot ([\varepsilon + P]\,\mathbf{u}) = \ldots$$

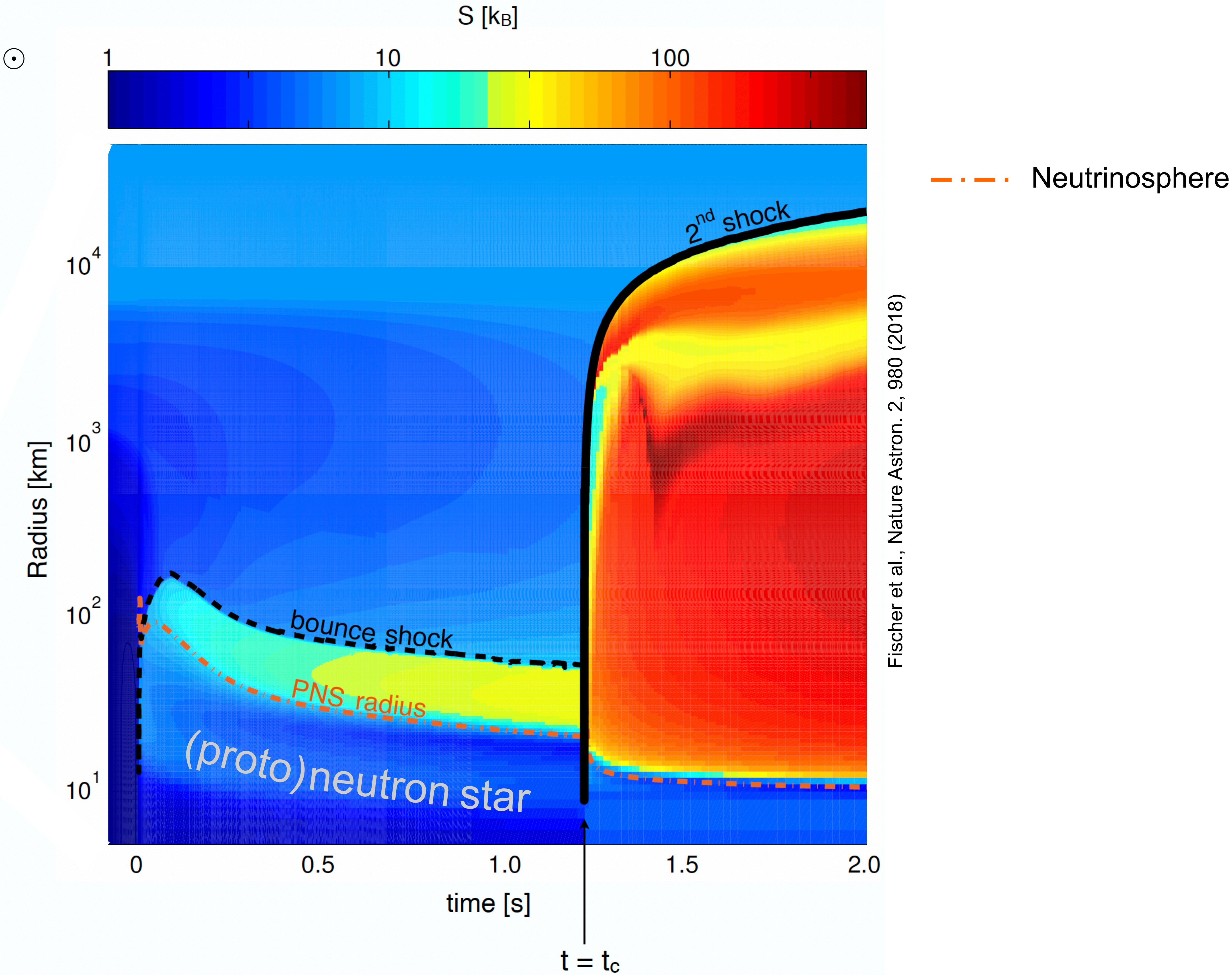
Danielewicz et al., Science 298, 1592 (2002)



Fischer et al., Nature Astron. 2, 980 (2018)


T/T_c
12 M⊙ (canonical supernovae ~1 s)
50 M⊙ : no phase transition
50 M⊙ : with phase transition
quark-gluon plasma
1
T_c ~ 150 MeV
black-hole formation
hadron-quark mixed phase
1
ρ/ρ_sat
Bastian, Phys. Rev. D, 103, 023001 (2021)

$M_{ZAMS} = 50\ M_\odot$



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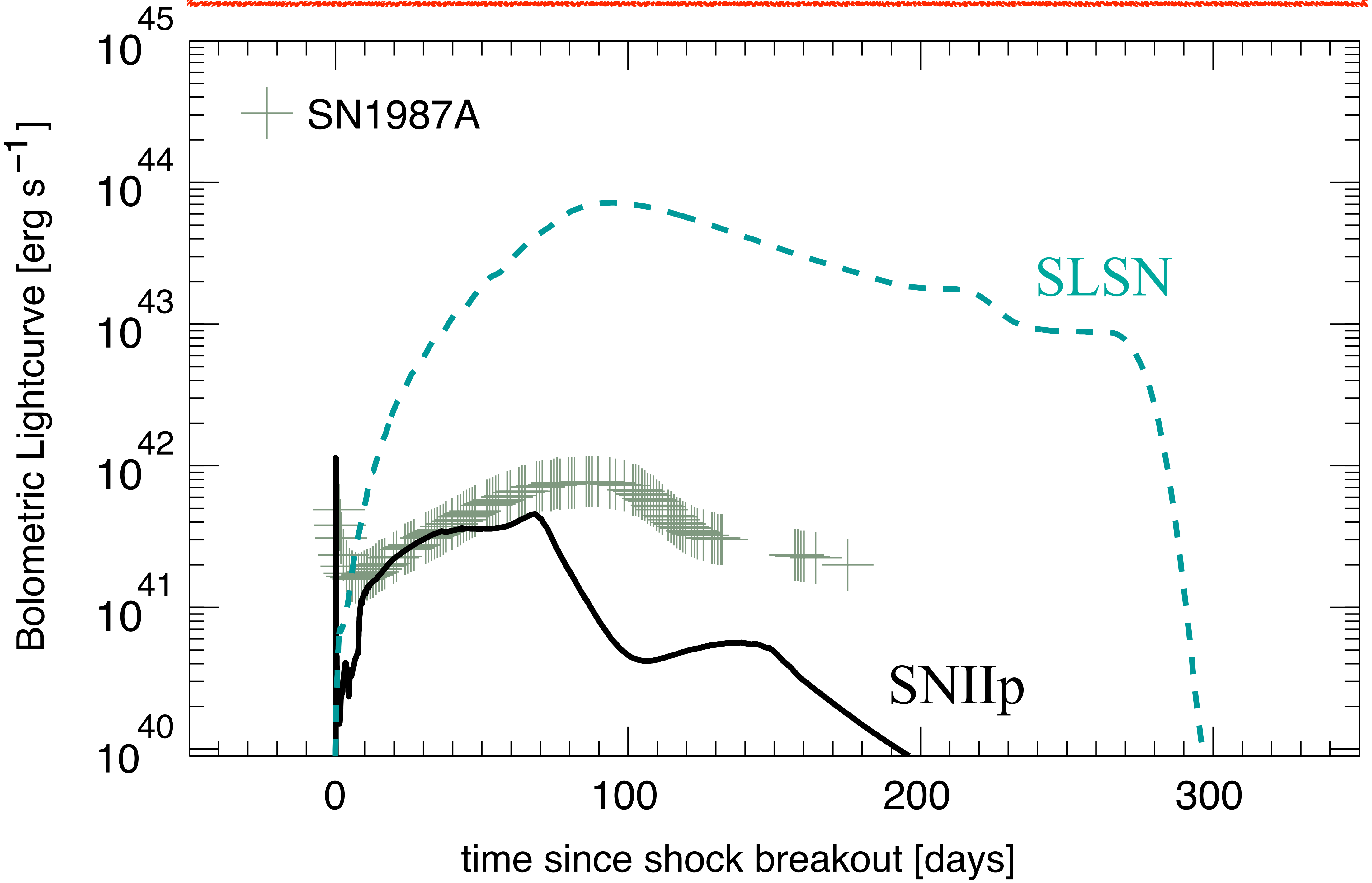
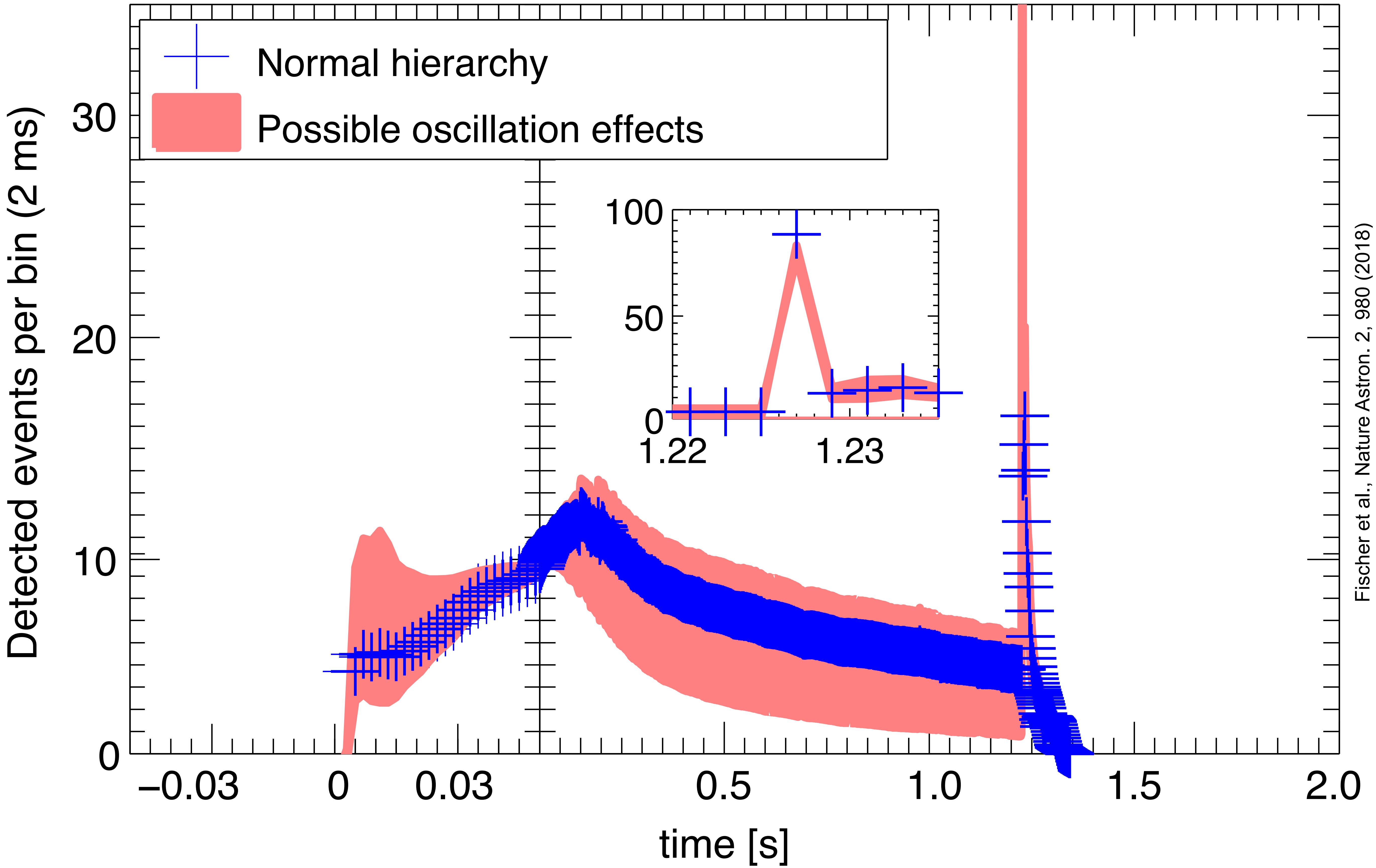
$$E_{\rm expl} = 3 \times 10^{51}\ {\rm erg}$$
$$M_{\rm NS} \simeq 2\ M_\odot$$
$$M_{\rm Ni} \simeq 0.024\ M_\odot$$



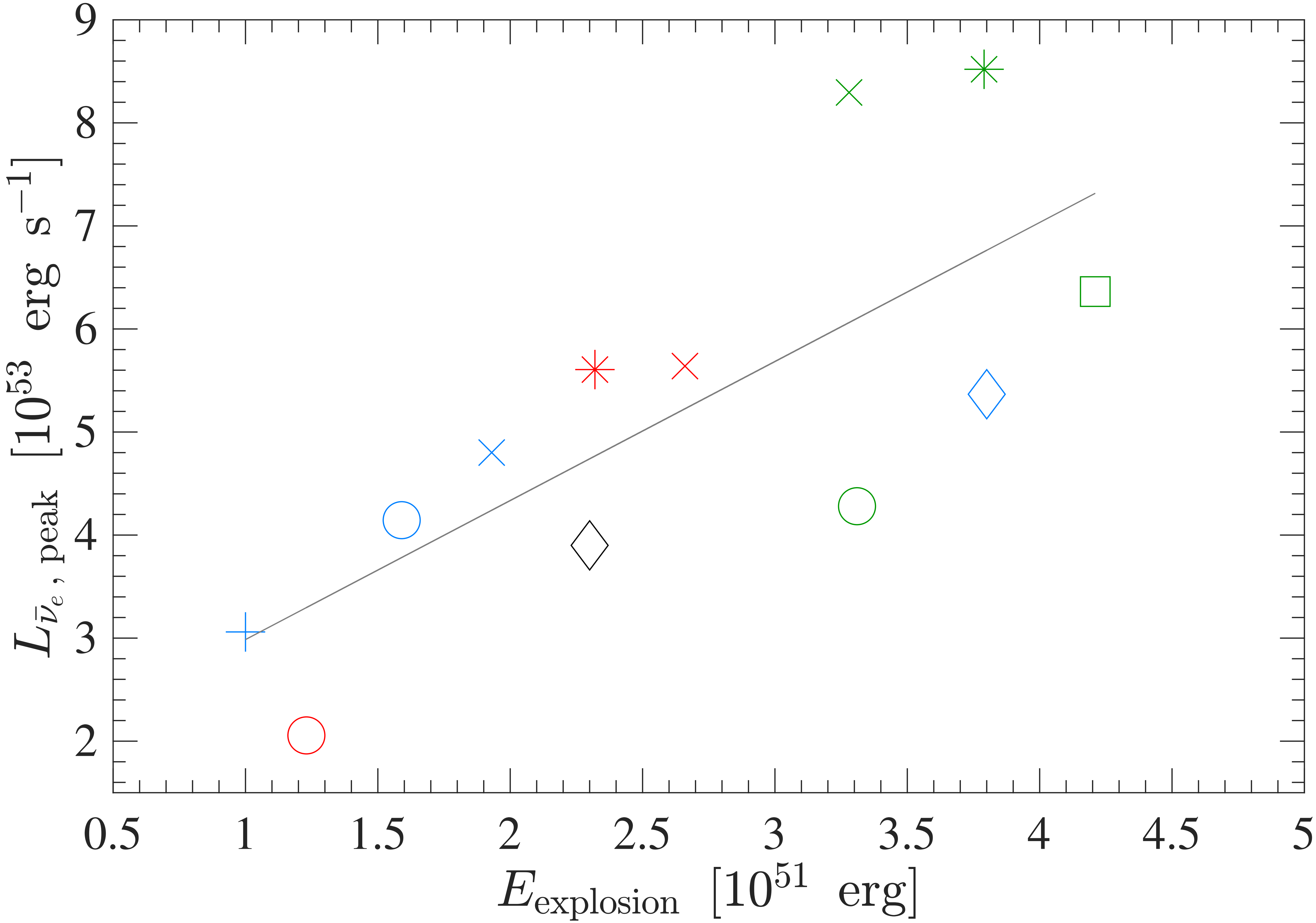
Fischer et al., Nature Astron. 2, 980 (2018)



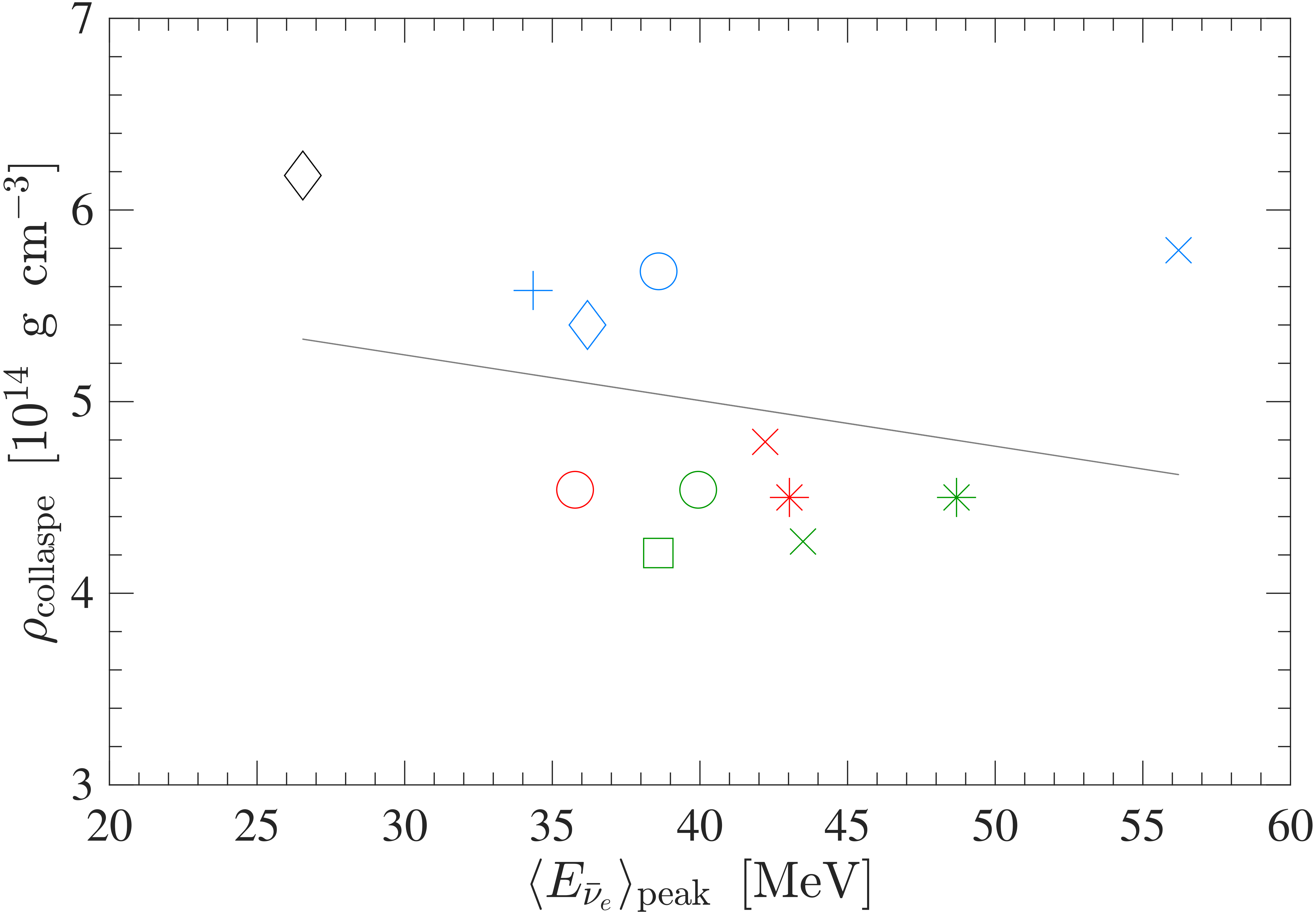
Normal hierarchy
Possible oscillation effects
Detected events per bin (2 ms)
time [s]
0
10
20
30
−0.03
0
0.03
0.5
1.0
1.5
2.0
100
50
0
1.22
1.23
Fischer et al., Nature Astron. 2, 980 (2018)

Khosravi Largani et al., ApJ 964, 143 (2024)

Progenitor	EOS RDF	$t_{\rm burst}$ (s)	$L_{\bar{\nu}_e,{\rm peak}}$ (10^{53} erg s^{-1})	$\langle E_{\bar{\nu}_e}\rangle_{\rm peak}$ (MeV)	$E_{\rm expl}$ (10^{51} erg)
s25a28	1.9	0.345	6.36	38.59	4.21
s30a28	1.2	1.056	4.80	56.21	1.93
s30a28	1.8	0.833	5.64	42.21	2.66
s30a28	1.9	0.580	8.30	43.49	3.28
s40a28	1.2	0.895	4.15	38.60	1.59
s40a28	1.8	0.717	2.06	35.77	1.23
s40a28	1.9	0.491	4.28	39.94	3.31
s40.0	1.8	0.694	5.61	43.03	2.32
s40.0	1.9	0.443	8.52	48.69	3.79
u50	1.1	1.227	3.90	26.55	2.3
u50	1.2	0.819	5.37	36.19	3.8
s75.0	1.2	1.803	3.06	34.35	1.0

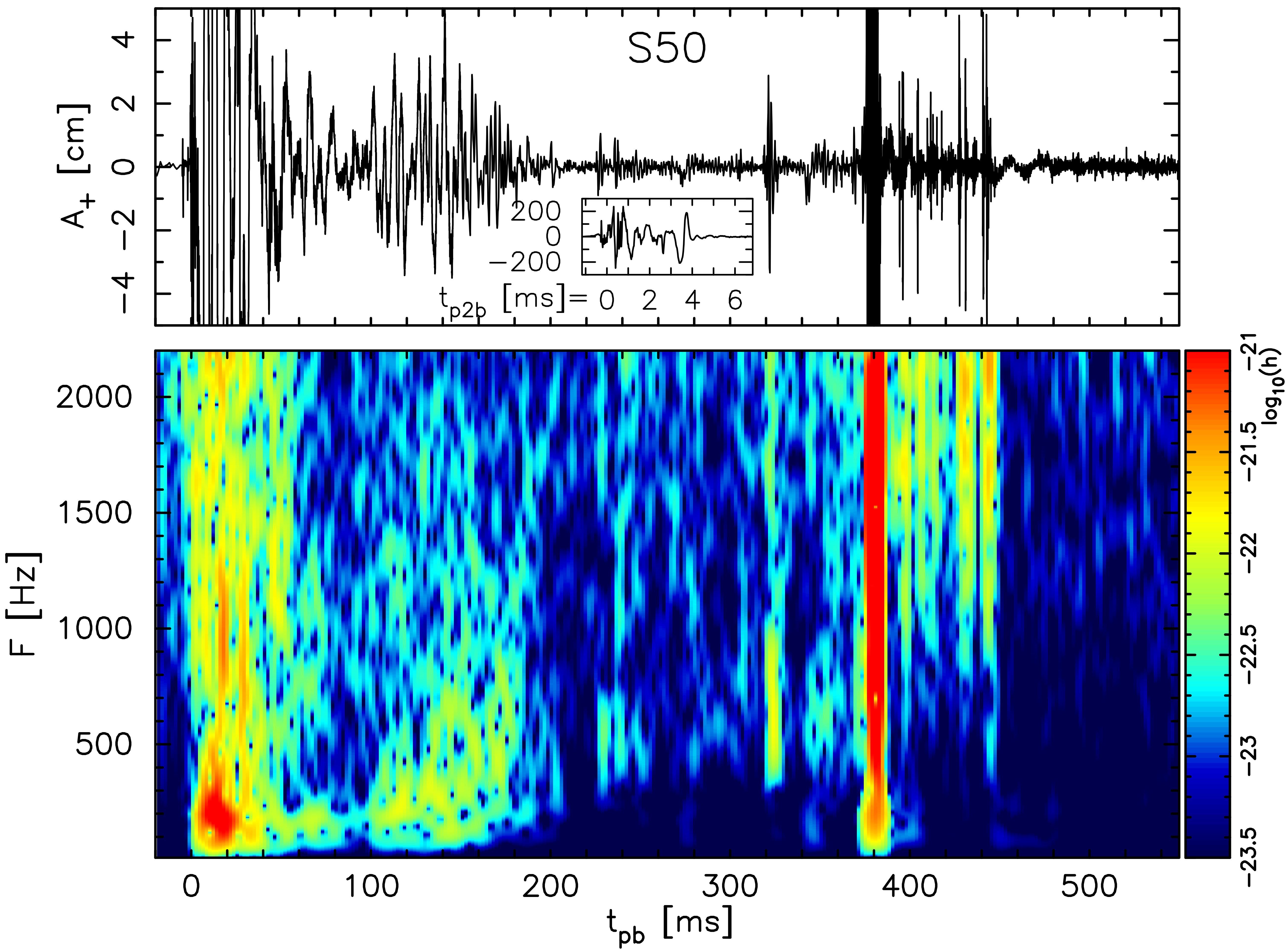


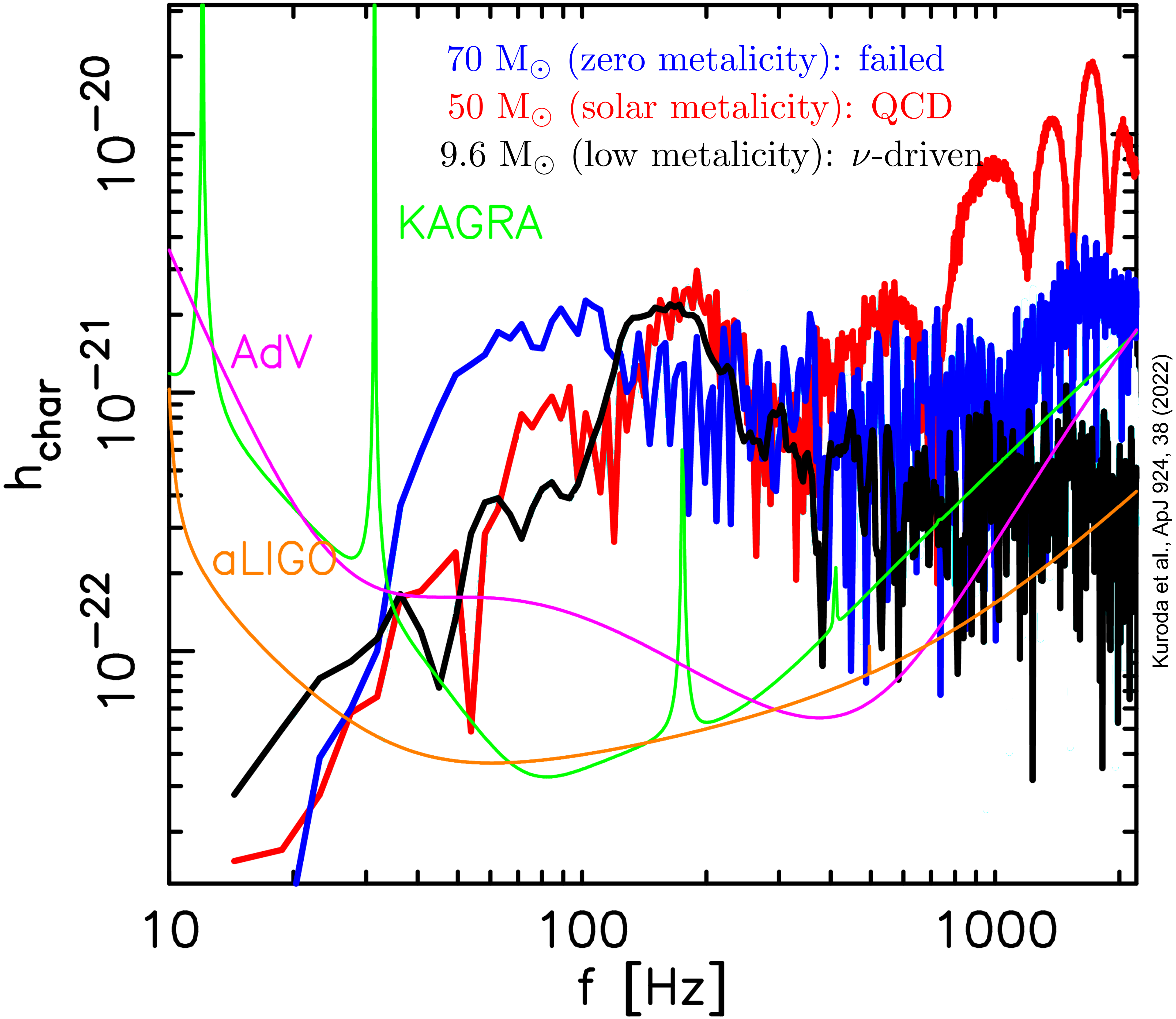
9
8
7
6
5
4
3
2
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
$L_{\bar{\nu}_e\,,\,\mathrm{peak}}$ $[10^{53}$ erg s$^{-1}]$
$E_{\mathrm{explosion}}$ $[10^{51}$ erg$]$

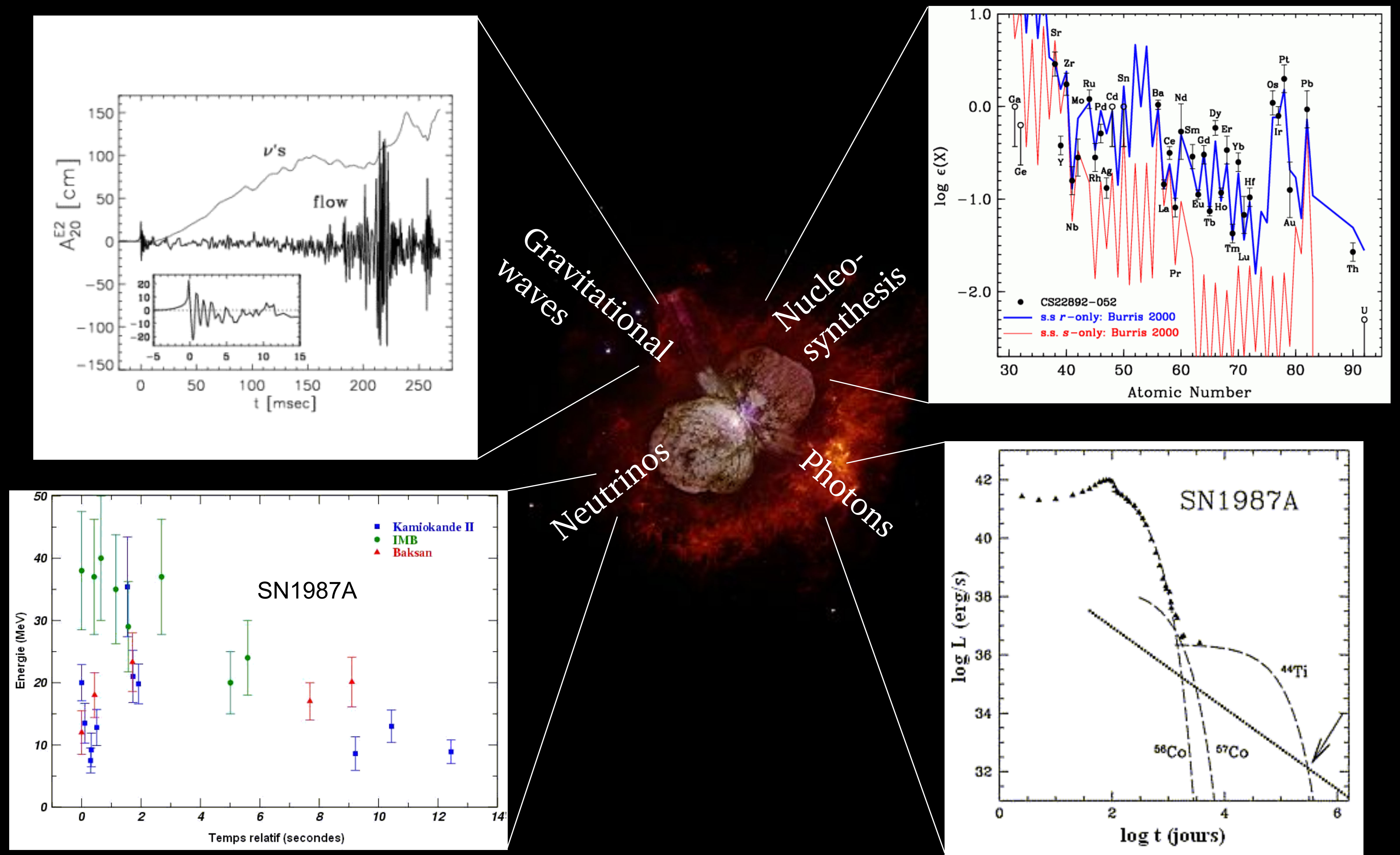


$\rho_{\rm collaspe}$ $[10^{14}$ g cm$^{-3}]$
7
6
5
4
3
20
25
30
35
40
45
50
55
60
$\langle E_{\bar{\nu}_e} \rangle_{\rm peak}$ [MeV]

Kuroda et al., ApJ 924, 38 (2022)
Zha et al., PRL 125, 051102 (2020)




70 $M_\odot$ (zero metalicity): failed
50 $M_\odot$ (solar metalicity): QCD
9.6 $M_\odot$ (low metalicity): ν-driven
KAGRA
AdV
aLIGO
h_{char}
10^{-20}
10^{-21}
10^{-22}
10
100
1000
f [Hz]
Kuroda et al., ApJ 924, 38 (2022)


Gravitational waves
Nucleo-synthesis
Neutrinos
Photons
ν's
flow
A^{E2}_{20} [cm]
t [msec]
log ε(X)
Atomic Number
CS22892-052
s.s r-only: Burris 2000
s.s. s-only: Burris 2000
Kamiokande II
IMB
Baksan
SN1987A
Energie (MeV)
Temps relatif (secondes)
SN1987A
log L (erg/s)
log t (jours)
^{44}Ti
^{56}Co
^{57}Co