DETECTING NEUTRINOS FROM MATTER-RICH BINARY MERGERS

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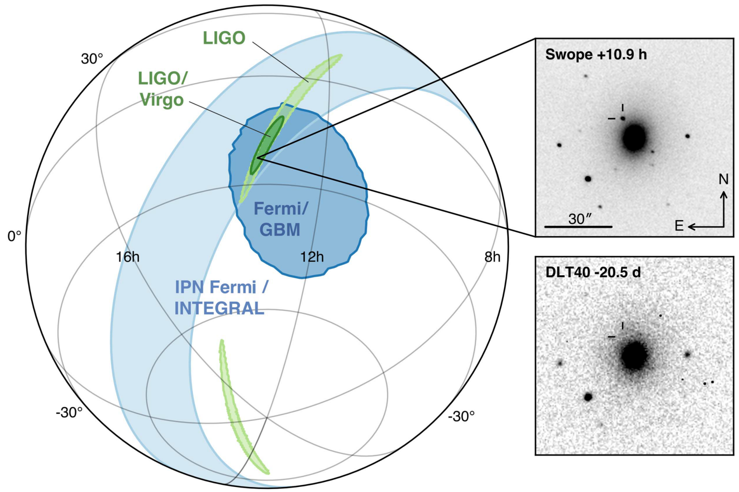
Zidu Lin and CL, arXiv:1907.00034, accepted in PRD

INTRODUCTION

The multi-messenger era



- GW170817 : the first binary neutron star merger observation
  - GW *and electromagnetic* counterpart
  - Insights into origin of heavy elements, short gamma ray bursts, properties of gravity, etc.

Abbott et al. (LIGO-Virgo) ApJ Lett., 848:L12, 2017
Abbott et al., ApJ 848 (2017) no.2, L12
Abbott et al. (LIGO-Virgo, Fermi-GBM, Integral), ApJ. 848 (2017) no.2, L13

- Neutrinos still missing in binary mergers observations
- A future neutrino detection will be *important* to:
  - Learn about the post-merger phase
  - Test r-process nucleosynthesis
  - Understand the genesis of gamma ray bursts from mergers

Thermal neutrinos from mergers: detectable?

- Supernova-like emission: E~ 10-20 MeV, $E_{tot} \sim 10^{51} - 10^{52}$ ergs
- BUT : mergers are at least 10^2 times less frequent than supernovae!

- The diffuse merger neutrino flux is detectable *in principle*
  - Up to O(1) events/year in Mt-scale detectors
  - *Overwhelmed by background* (diffuse supernova flux, atmospheric, etc.)

O. L. Caballero, G. C. McLaughlin, R. Surman, and R. Surman, PRD80, 123004 (2009).
T. S. H. Schilbach, O. L. Caballero, and G. C. McLaughlin (2018), arXiv: 1808.03627.

- Idea: use *time-coincidence* with GW for background reduction

K. Kyutoku and K. Kashiyama, PRD97, 103001 (2018)
Zidu Lin and CL, arXiv:1907.00034

Next generation detectors: synergies

- HyperKamiokande neutrino detector
  - 0.3 – 1 Mt water Cherenkov, *start construction April 2020*
  - Main channel: $\bar{\nu}_e + p \to n + e^+$
  - Option of Gadolinium addition for background reduction

- Next GW projects: Voyager, Cosmic Explorer, Einstein Telescope
  - Improved distance reach, up to redshift z ~ 2
  - > 10 times enhanced observed merger rate (compared to Adv. LIGO)

K. Abe et al. (Hyper-Kamiokande) (2018), arXiv:1805.04163.

Gadolinium addition: J. F. Beacom and M. R. Vagins, PRL 93, 171101 (2004)

Advanced LIGO: J. Abadie et al. (LIGO Scientific, VIRGO), Class. Quant. Grav. 27, 173001 (2010).

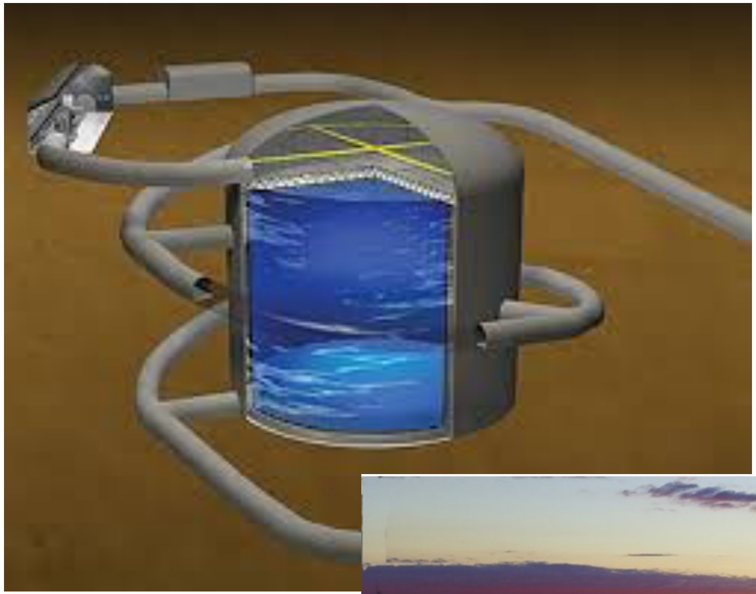
Voyager: B. P. Abbott et al., https://dcc.ligo.org/ LIGO-T1600119/public (2016), the lsc-virgo white paper on instrument science (-2017 edition). Technical Report T1600119, LIGO and Virgo Scientific
Collaborations.

Einstein Telescope: M. Punturo et al., Class. Quant. Grav. 27, 194002 (2010).

Cosmic explorer: B. P. Abbott et al. (LIGO Scientific), Class. Quant. Grav.
34, 044001 (2017).

redshift reach : C. Mills, V. Tiwari, and S. Fairhurst, Phys. Rev. D97,
104064 (2018).

http://www.hyperk.org



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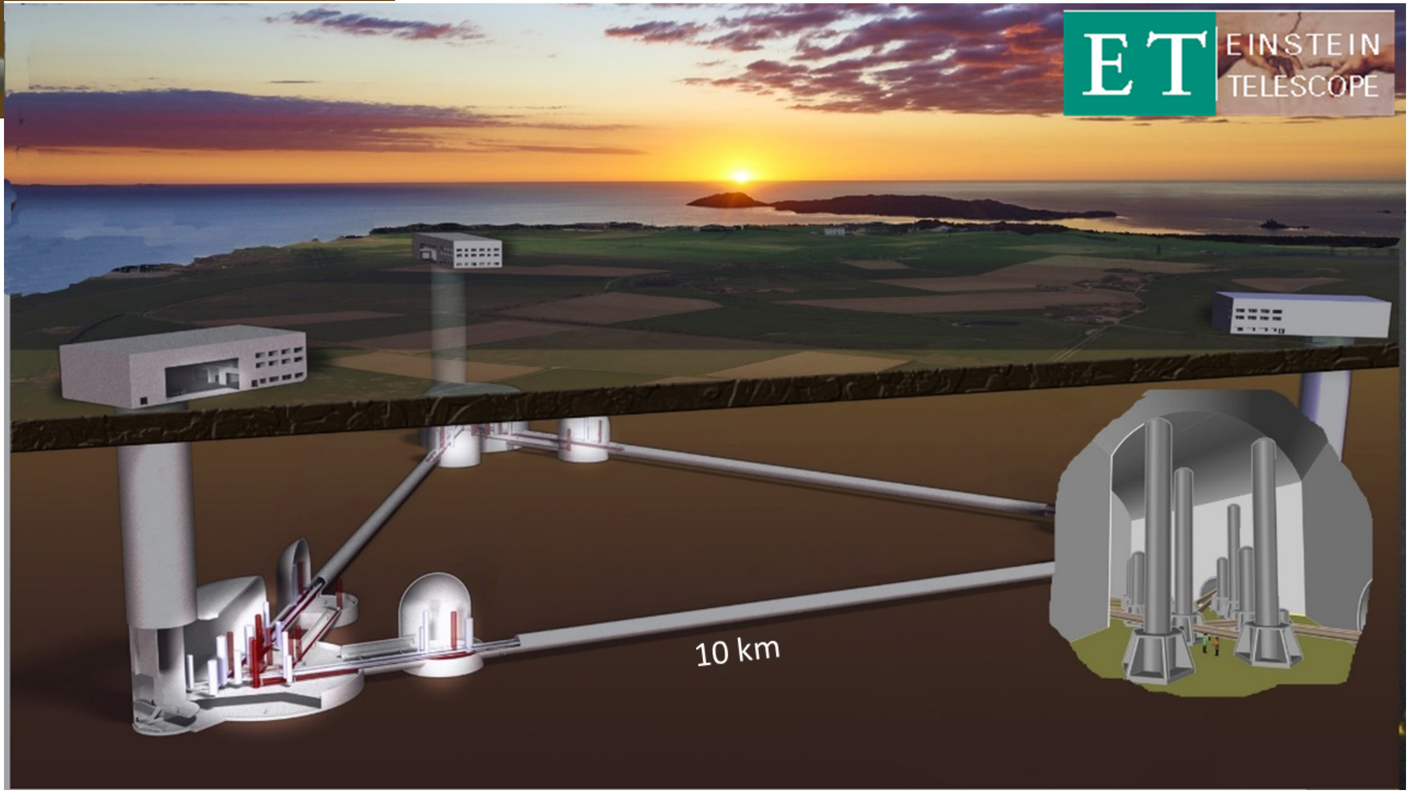
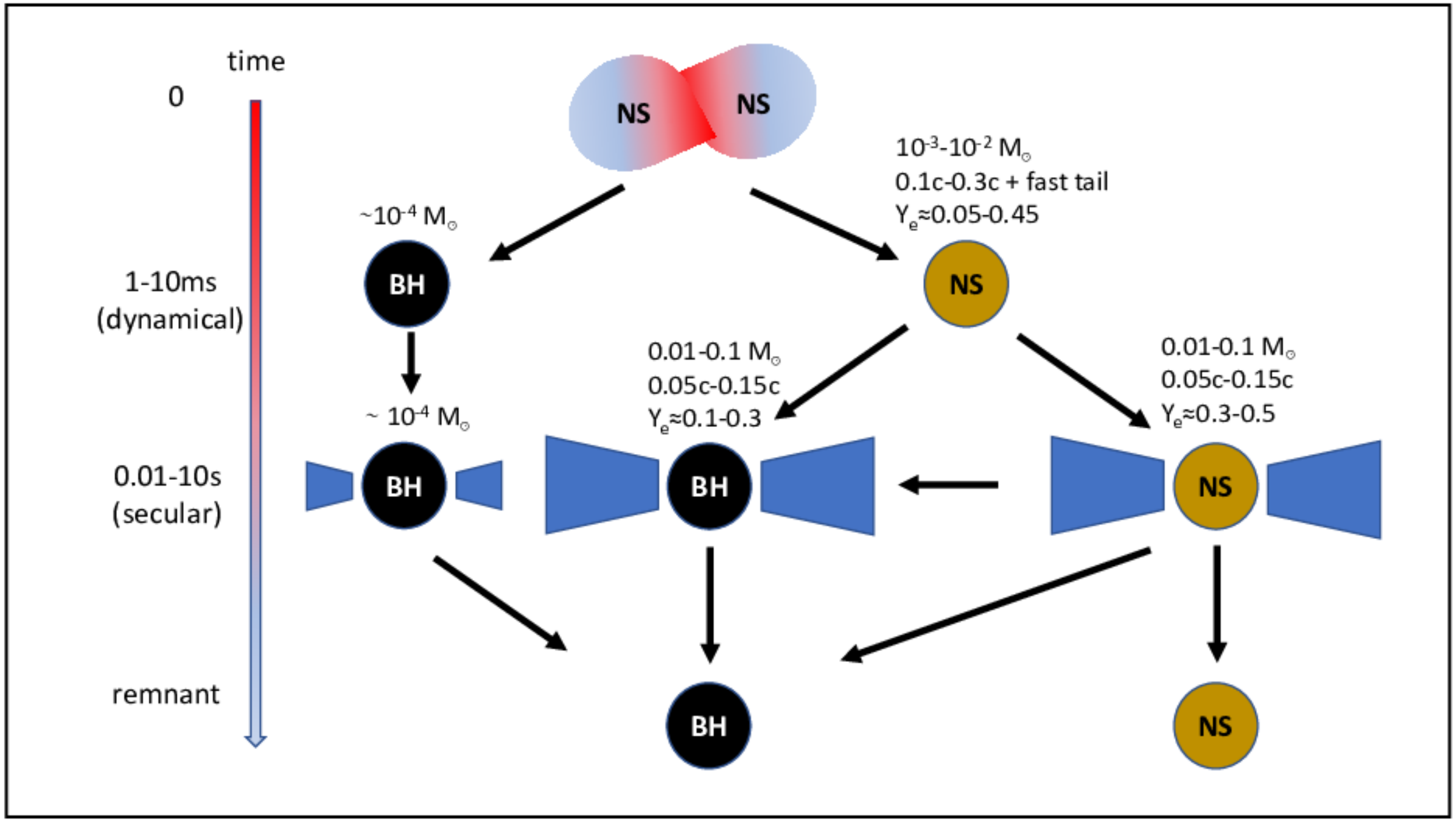


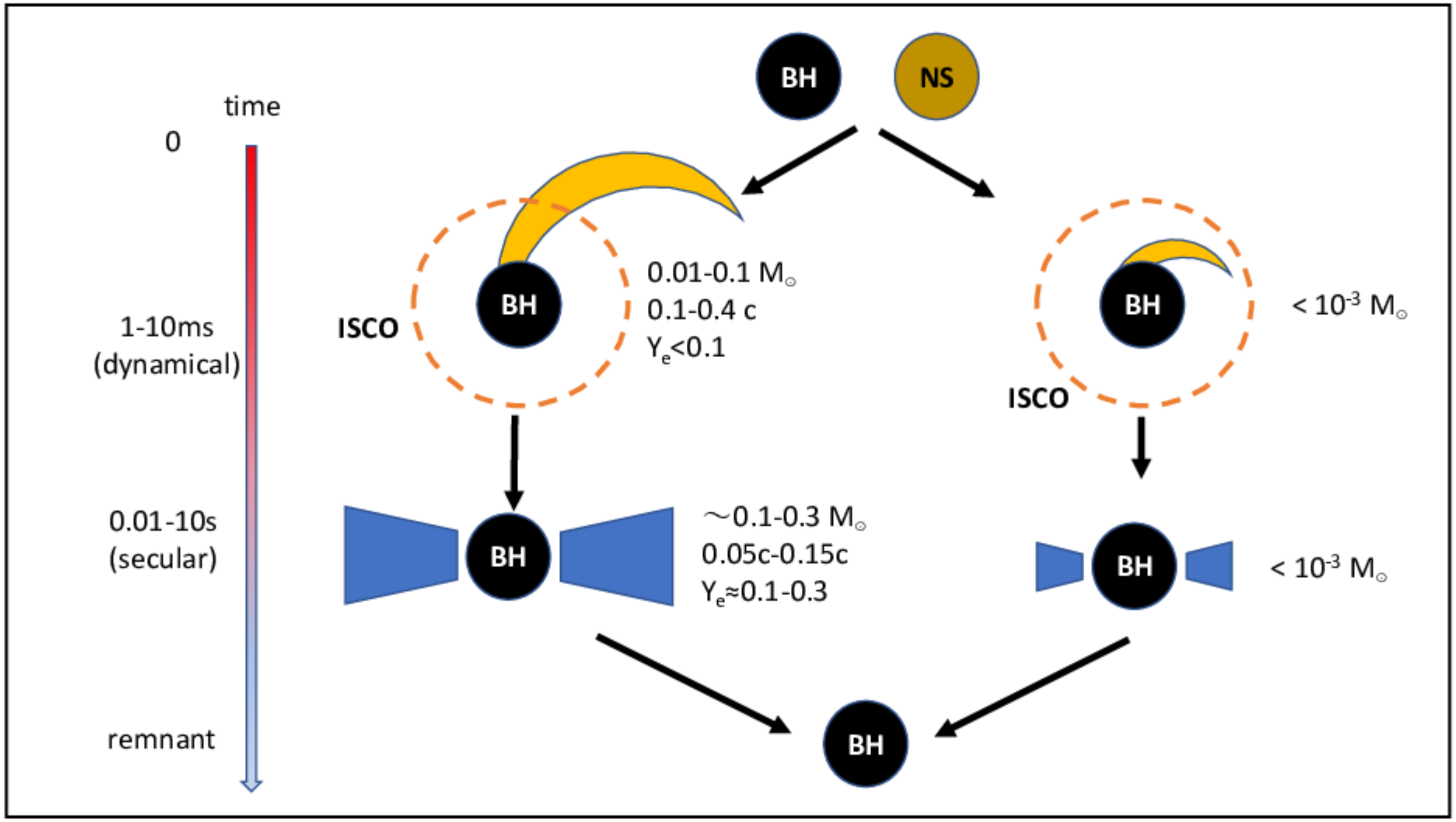
GENERALITIES: NEUTRINOS AND MERGERS

Binary neutron star (BNS) mergers



Nakar et al., arXiv:1912.05659

Neutron star-black hole (NSBH) mergers



Nakar et al., arXiv:1912.05659

Thermal neutrino emission

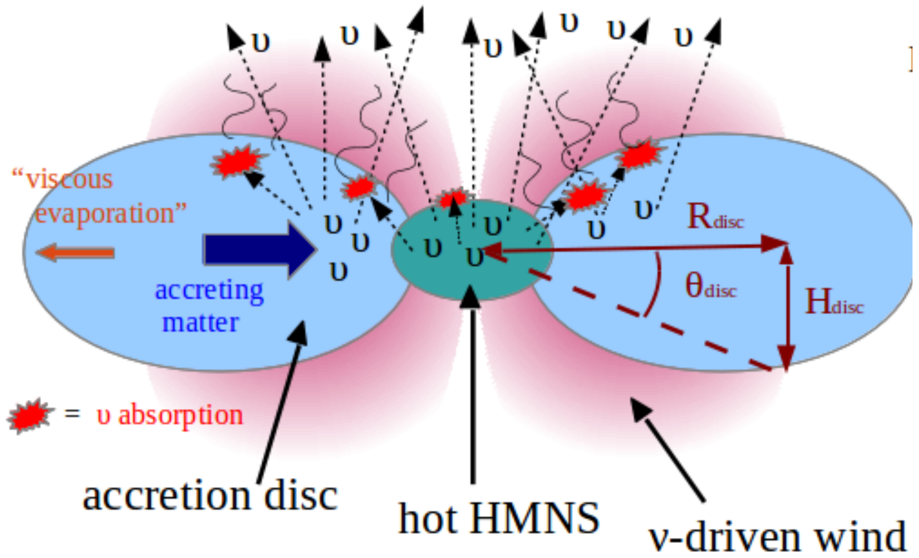


Image from Perego et al., MNRAS 443 (2014) no.4

- BNS and NSBH: neutrinos emitted from neutrinosphere in the accretion disc
- For BNS : emission from hot hypermassive neutron star

- From numerical simulations:

$T_{99}(s)$	$\mathcal{E}_{\bar{\nu}_e}(10^{51}erg)$	$\langle E_{\bar{\nu}_e}\rangle(MeV)$	type	CR	CRM ($M_\odot$)	DM ($M_\odot$)	Model	Ref
0.58	4.4	18	BNS	HMNS	3	0.03	Hinf	J.Lippuner(2017)
0.40	2.0	16.5	BNS	BH	3	0.03	B090	
0.30	1.8	15.4	NSBH	BH	8.1	0.1	BF15	
0.10	1.0	17.8	BNS	BH	3	0.03	M3A8m03a5	O.Just(2015)
0.27	11.2	16	NSBH	BH	6	0.3	M6A8m3a5	
0.99	14	10	BNS	HMNS	2.7	0.2	DD2-1351350-On-H	S.Fujibayashi(2017)
0.58	40	20	BNS	HMNS	3		M	Y.Sekiguchi(2011)
0.08	19.8	24	NSBH	BH	6.6	0.49	A5	H.T.Janka (1999)
0.16	23.2	28	NSBH	BH	11.6	0.47	B10	

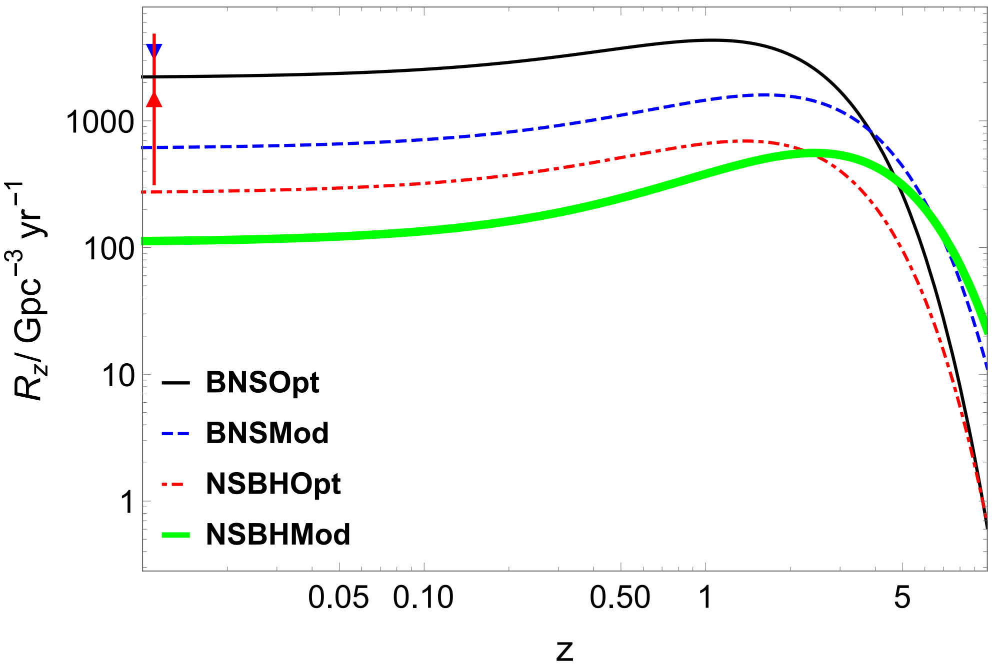
- T99 : duration of neutrino burst
- CR = central remnant
- D = disc

H. T. Janka, T. Eberl, M. Ruffert, and C. L. Fryer, ApJ 527, L39 (1999).
Y. Sekiguchi, K. Kiuchi, K. Kyutoku, and M. Shibata, PRL 107, 051102 (2011).
O. Just et al., MNRAS 448, 541 (2015).
S. Fujibayashi, Y. Sekiguchi, K. Kiuchi, and M. Shibata, ApJ 846, 114 (2017).
J. Lippuner et al., MNRAS 472, 904 (2017).

Cosmological rates

- Large uncertainty from evolution models

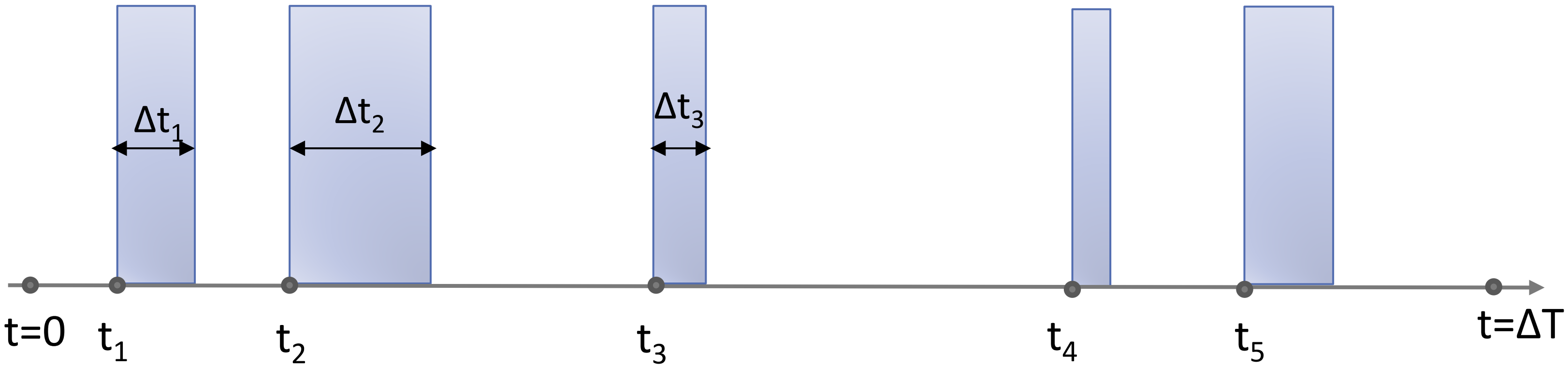
M. Mapelli and N. Giacobbo, MNRAS 479, 4391 (2018).
J. J. Eldridge, E. R. Stanway, and P. N. Tang, MNRAS 482, 870 (2019).



Abbott et al., ApJ 832, L21 (2016).
Abbott et al., PRL 119, 161101 (2017).

DETECTABILITY

Idea: time coincidence



- From GW: i=1,2,3,…,N mergers. Merger type, time t_i, redshift z_i
- From theory: estimated neutrino burst duration, Δt_i
  - Conservative: $\Delta t_i = \Delta t = 1$ s . Captures entire neutrino emission.
- *to reduce background* : keep only neutrino data in $[t_i, t_i+\Delta t\,]$; impose $z < z_{max}$;

K. Kyutoku and K. Kashiyama, PRD97, 103001 (2018)
Zidu Lin and CL, arXiv:1907.00034

Event rates

- (Observed) merger rate and number of background events:

$$\frac{dV}{dz} = \frac{4\pi D_c^2 c}{H(z)} \qquad D_c = \int_0^z \frac{c}{H_0\sqrt{\Omega_m(1+\tilde{z})^3+\Omega_\Lambda}} d\tilde{z}$$

$$N_{z_{max}} = \int_0^{z_{max}} \frac{R(z)dV}{(1+z)dz} dz$$

$$\boxed{N_b \simeq (N_{z_{max}} \Delta T)(n_b \Delta t)}$$

- Number of signal events (inverse beta decay in water):
  - Diffuse flux approximation

$$F_{\bar{\nu}_e}(E) = \frac{\mathcal{E}_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e} \rangle} \frac{2}{3T^3\zeta(3)} \frac{E^2}{e^{E/T}+1},$$

$$\Phi_{\bar{\nu}_e}(E) = f_{osc} \frac{c}{H_0} \int_0^{z_{max}} R(z) F_{\bar{\nu}_e}(E') \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}},$$

$$E' = E(1+z)$$

$$f_{osc} = 1$$

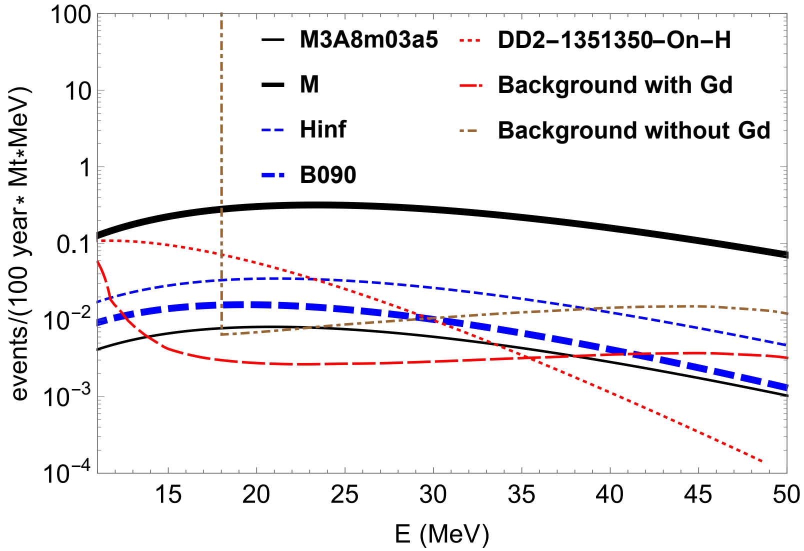
(phenomenological factor to account for oscillations)

$$\boxed{N_s \simeq N_t \Delta T \int_{E_{th}}^{E_{max}} \eta(E) \Phi_{\bar{\nu}_e}(E) \sigma(E) dE}$$

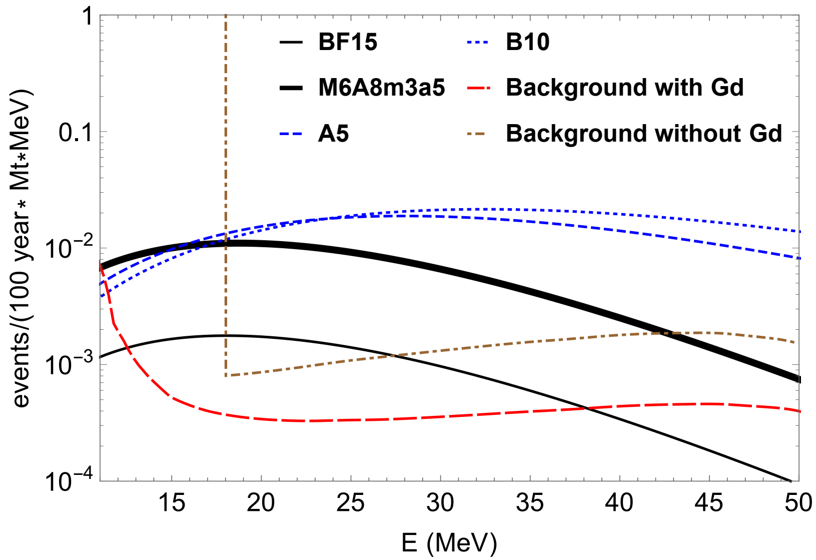
$$(\bar{\nu}_e + p \rightarrow n + e^+)$$

Results: event rates at Mt-scale detector

BNS mergers, z_{max}=0.05



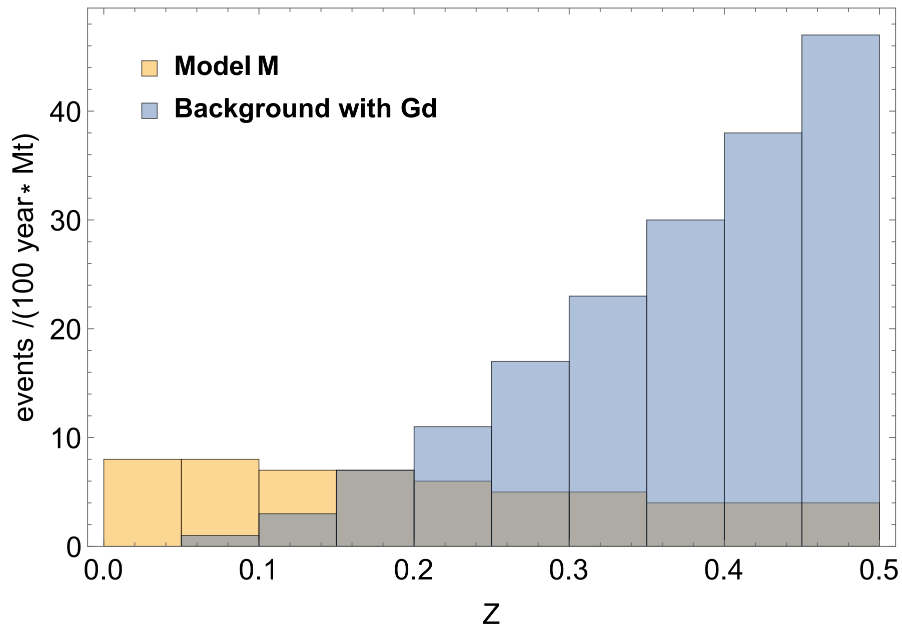
NSBH mergers, z_{max}=0.05



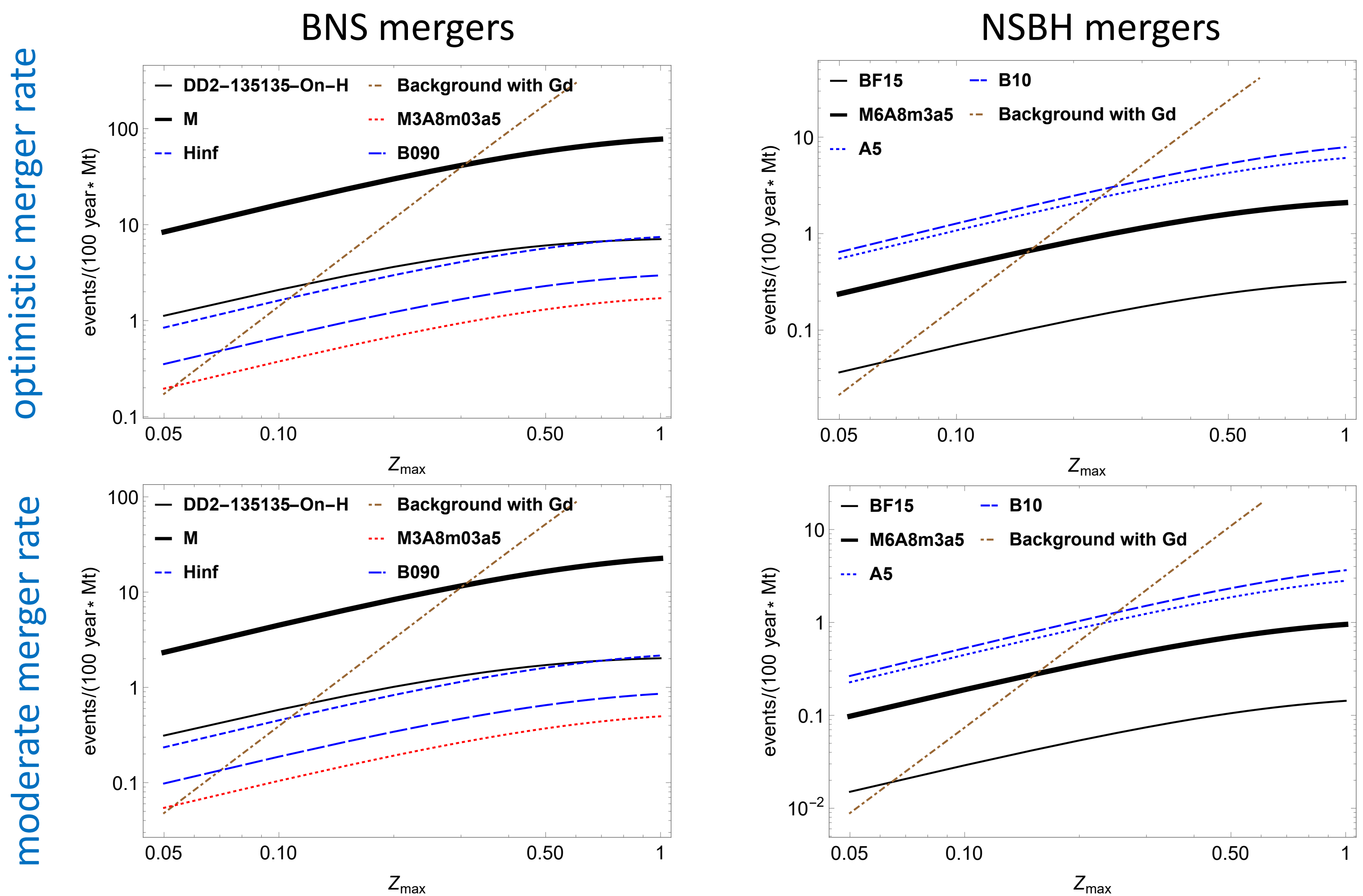
- z_{max}=0.05 ; optimistic merger rates used
- Signal/background $\gtrsim$ 1 in suitable energy window

redshift dependence

BNS mergers, event rates in redshift bins



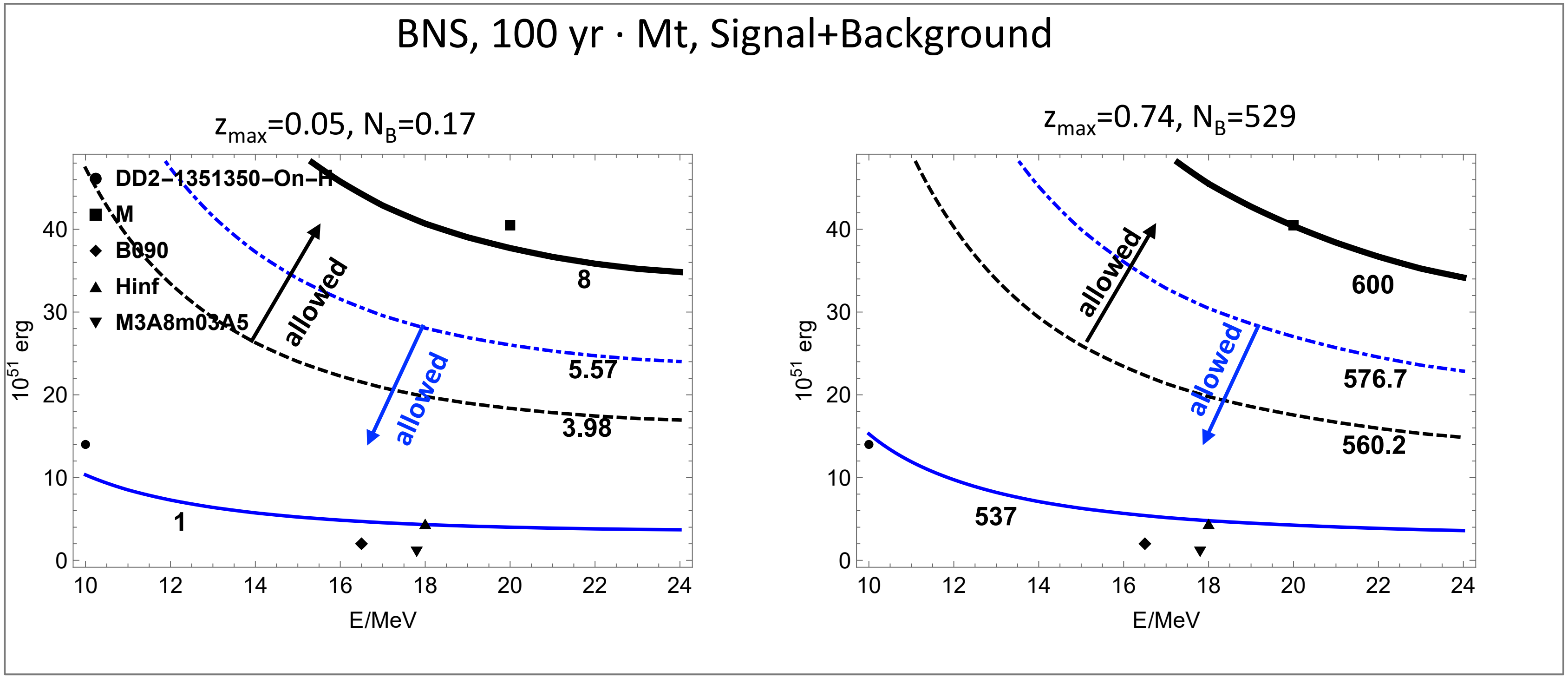
- for most optimistic parameters:
  - Up to ~ 100 signal events from mergers at z<0.5 .
  - Signal/background $\gtrsim$ 1 for z_{max} < 0.15



- Number of events for $0<z<z_{max}$. 3 σ significance achieved for z_{max} up to ~0.7

Constraining the parameter space

- Exclusion of extreme parameters possible

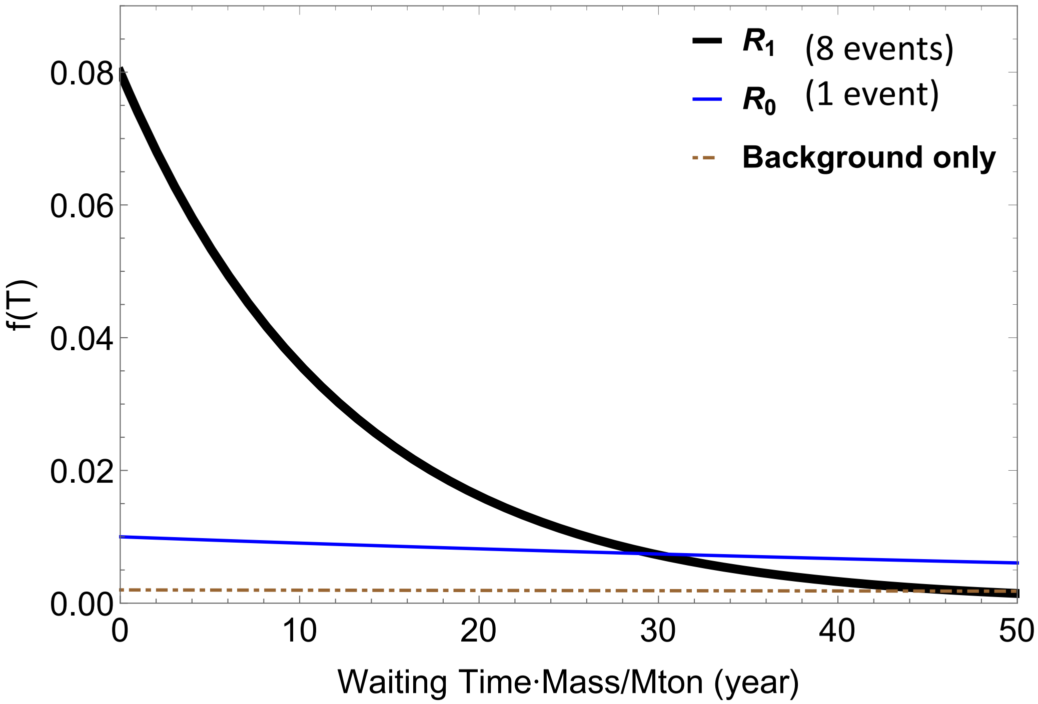


Solid: central value; non-solid: 90% CL contours. Merger rate assumed known.

Constraints from time to first detection

- Even zero or one event observed can give constraints!
  - Probability that first detection occurs in interval [T, T + dT]

$$f(T) = \frac{dF(T)}{dT} = Re^{-RT}$$



CONCLUSIONS

A truly multi-messenger scenario

- Detecting eutrinos from binary mergers *is realistic*
  - *Only* with synergy between next generation neutrino detectors and GW detectors (time coincidence)
- O(0.1 – 100) events expected for 100 yr · Mt exposure
  - Decades might pass before first detection
  - Single detections might be statistically significant (if low z)
- Even low statistics (or non-detection) can constrain the parameter space
  - Implications on post-merger physics (type of remnant, r-process, etc.)

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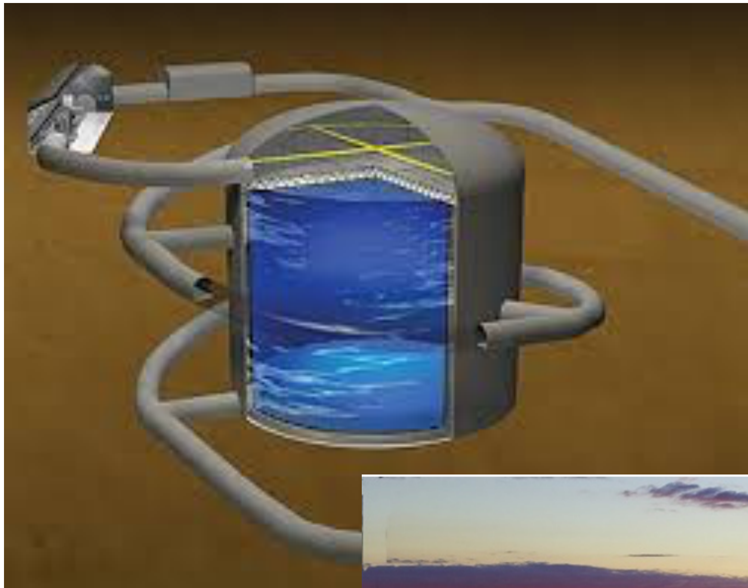

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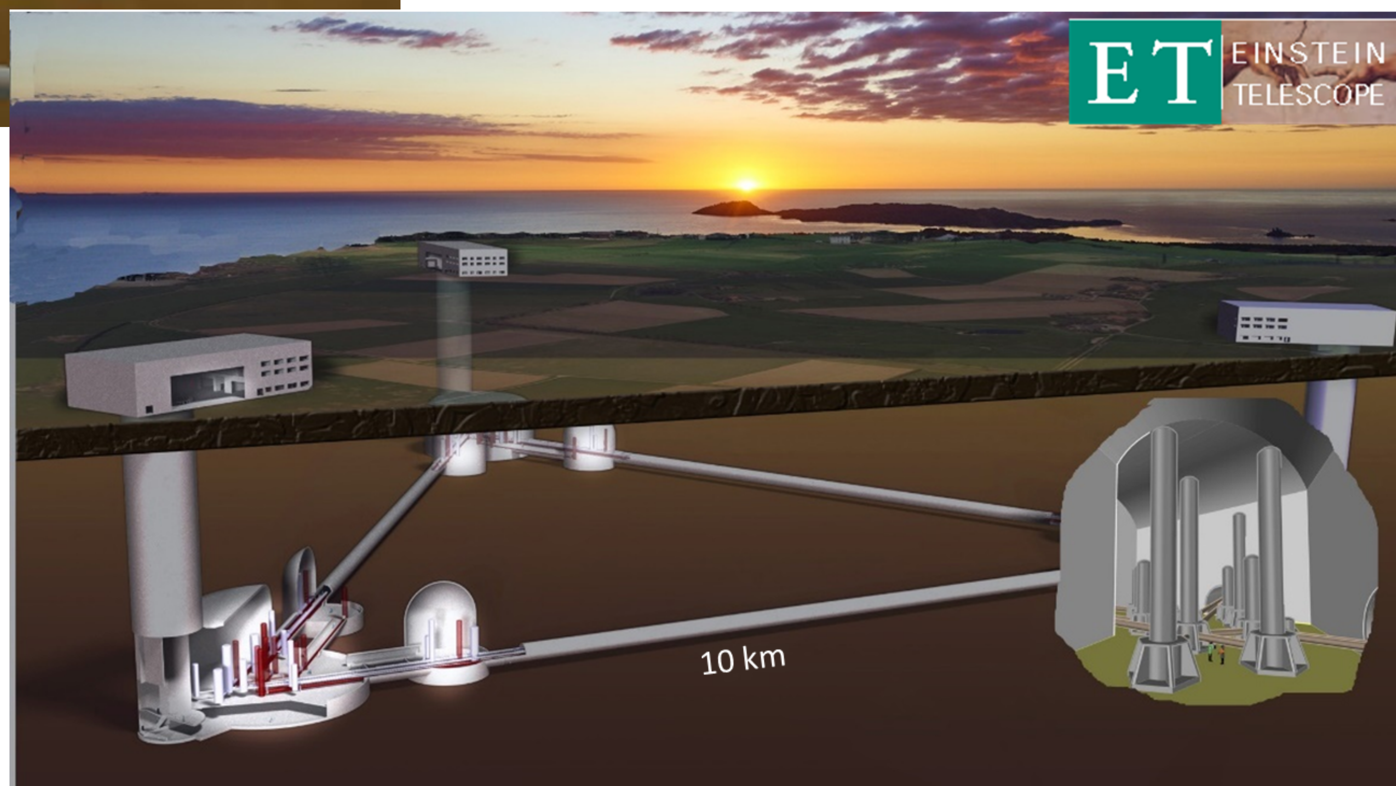


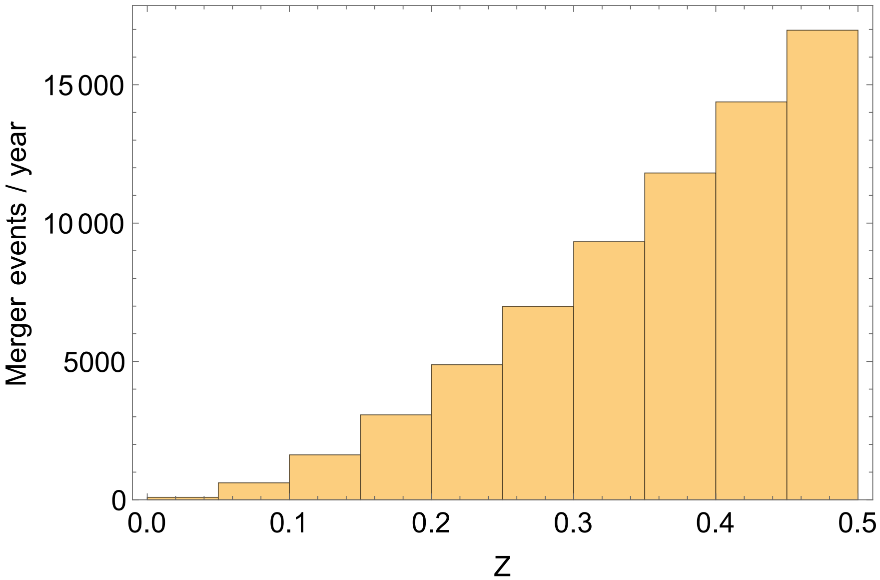
BACKUP

Merger rate

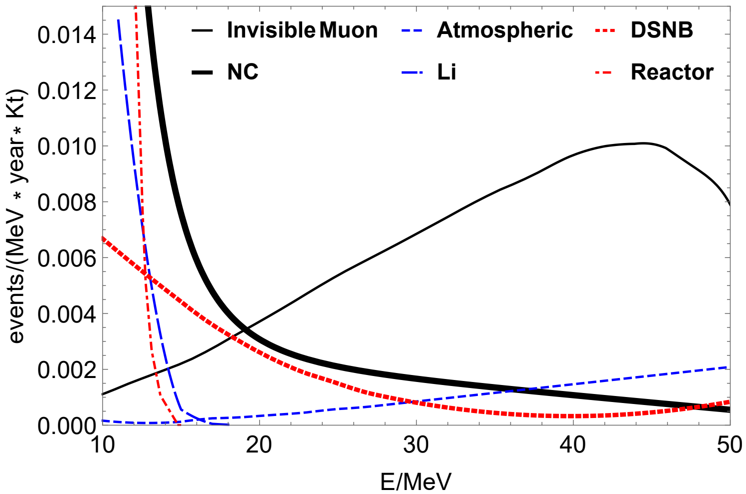
$$\frac{dV}{dz} = \frac{4\pi D_c^2 c}{H(z)} ,$$

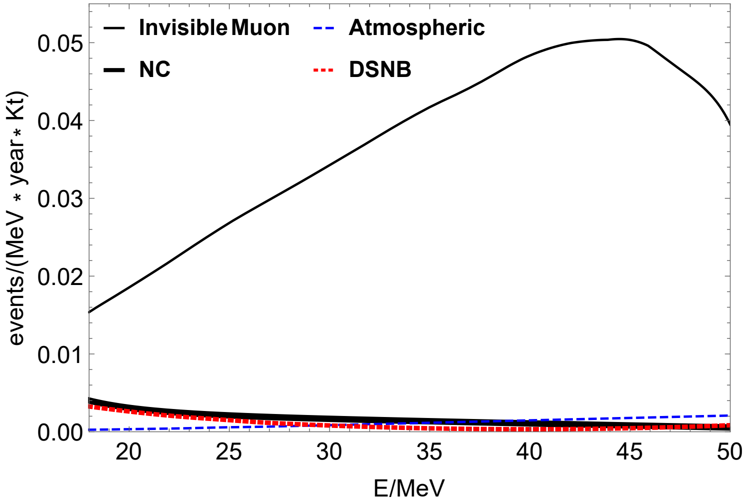
$$D_c = \int_0^z \frac{c}{H_0\sqrt{\Omega_m(1+\tilde{z})^3+\Omega_\Lambda}} d\tilde{z}$$

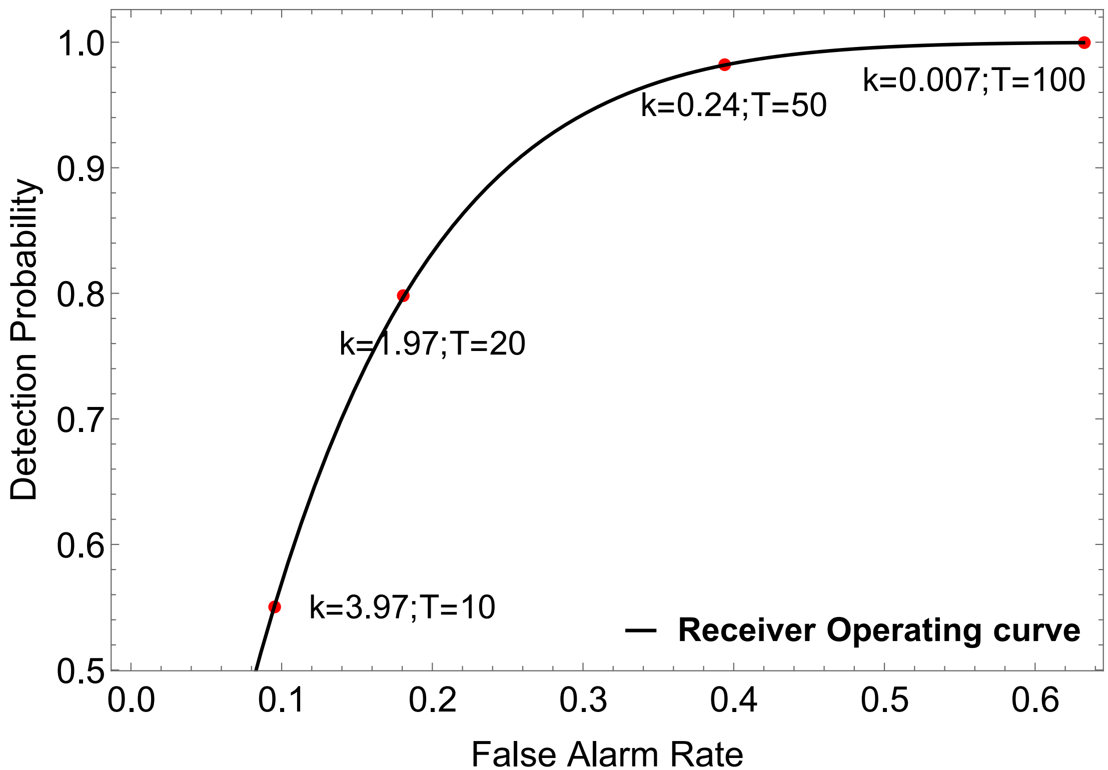
$$N(z_{max}) = \int_0^{z_{max}} \frac{R(z)dV}{(1+z)dz} dz$$



Background composition







Detection Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
False Alarm Rate
k=0.007;T=100
k=0.24;T=50
k=1.97;T=20
k=3.97;T=10
Receiver Operating curve

H. T. Janka, T. Eberl, M. Ruffert, and C. L. Fryer, Astrophys. J. 527, L39 (1999).

Y. Sekiguchi, K. Kiuchi, K. Kyutoku, and M. Shibata, Phys. Rev. Lett. 107, 051102 (2011).

O. Just et al., Mon. Not. Roy. Astron. Soc. 448, 541 (2015).

S. Fujibayashi, Y. Sekiguchi, K. Kiuchi, and M. Shibata, Astrophys. J. 846, 114 (2017).

J. Lippuner et al., Mon. Not. Roy. Astron. Soc. 472, 904 (2017).