Memory-triggered supernova neutrino detection

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Arizona State University

Fermilab

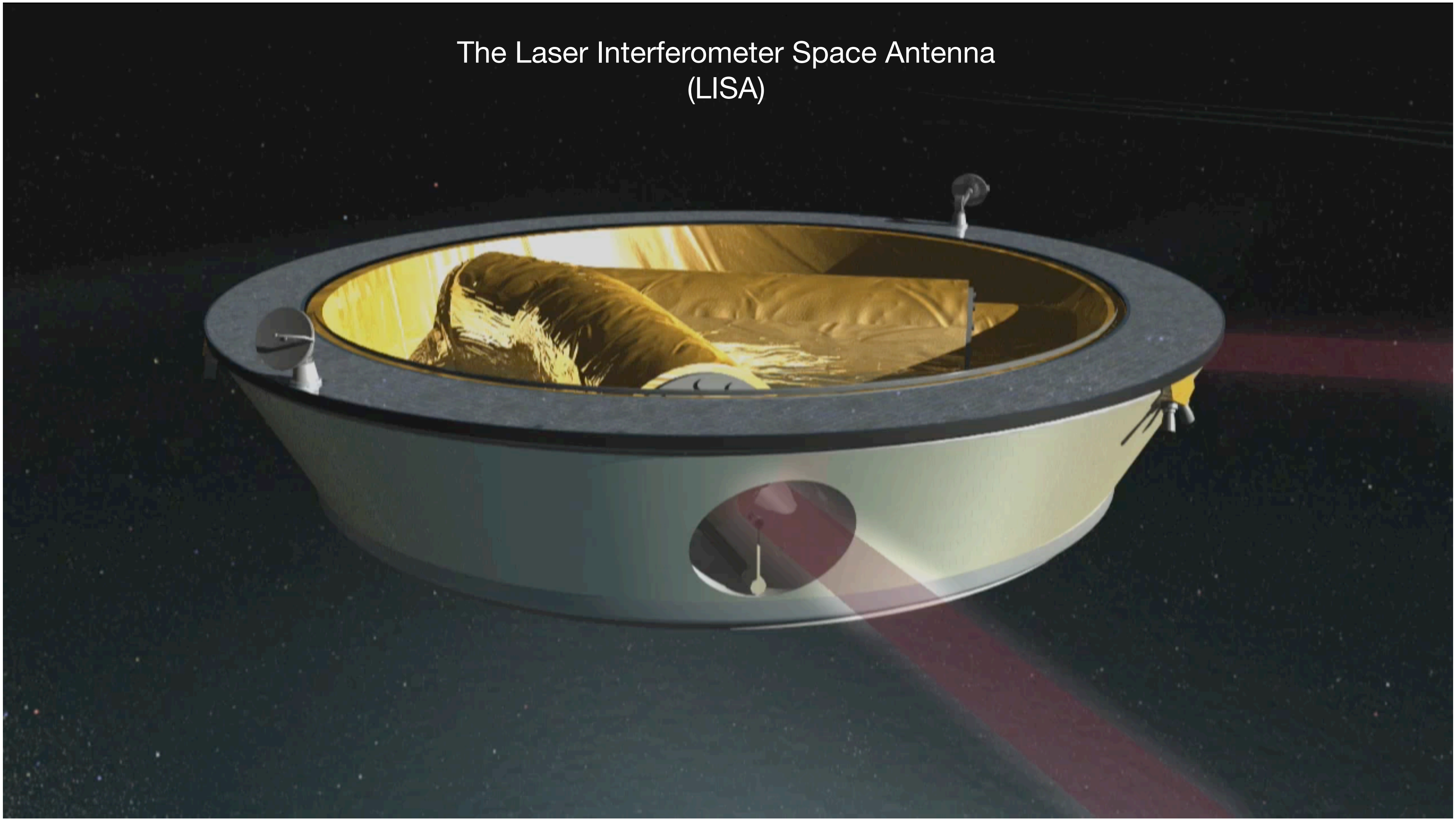
NSF

Based on

The neutrino gravitational memory from a core collapse supernova: phenomenology and physics potential
MM, C. Cardona, C. Lunardini
JCAP 07 (2021) 055 (arXiv: 2105.05862).

Memory-triggered supernova neutrino detection
MM, Z. Lin, C. Lunardini
Submitted to PRL **(arXiv: 2110.14657)**

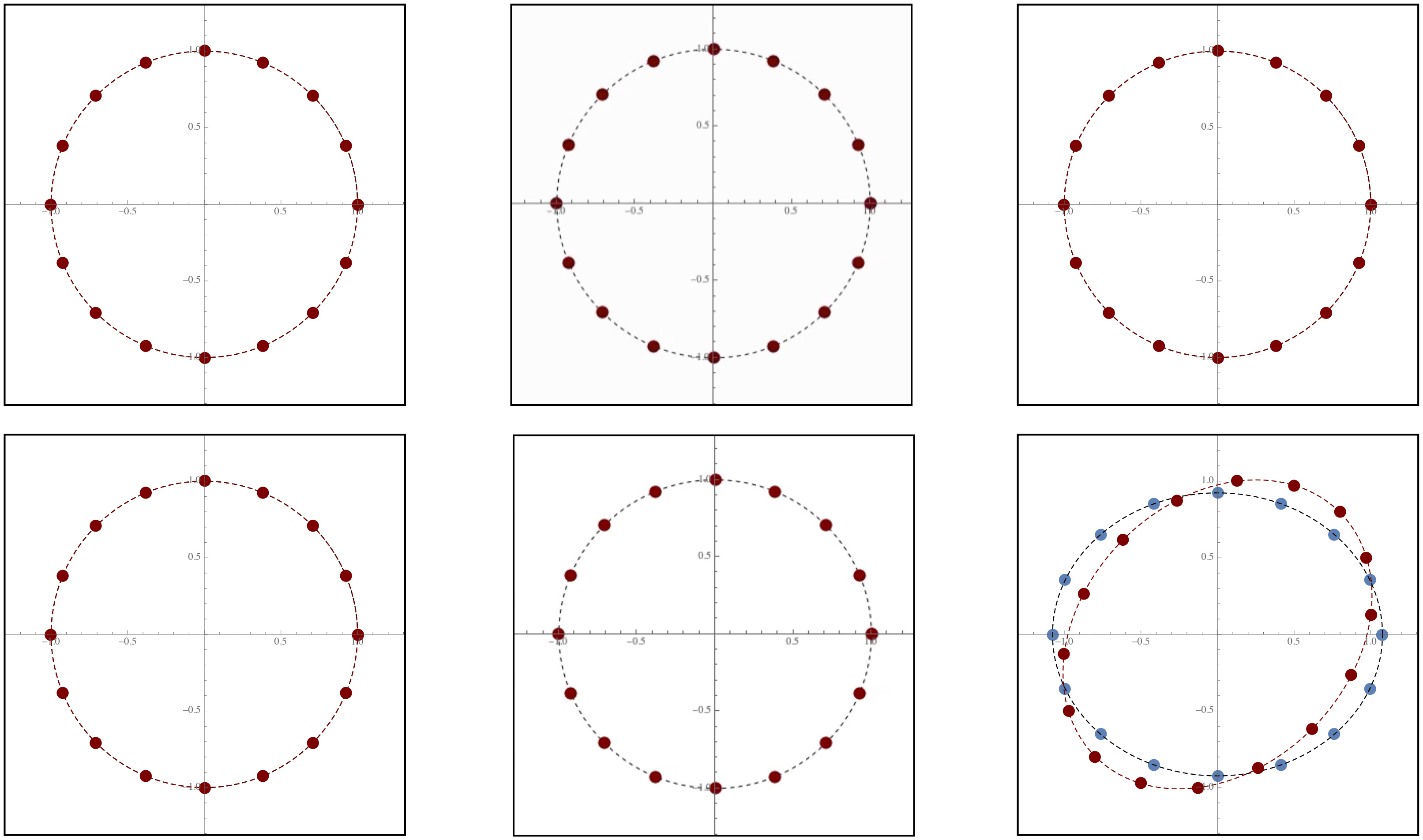
What is Gravitational Wave (GW) memory?



Animation Credits: Chris Meaney and NASA

What is Gravitational Wave (GW) memory?

Before Passage of GW | **GW passing through a detector say LISA** | **After the GW has passed**



Without memory

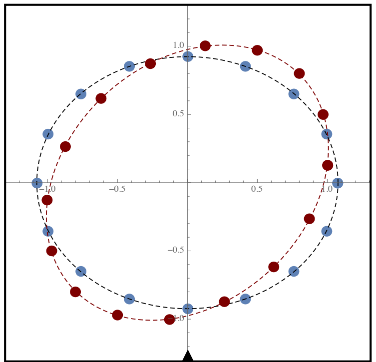
With memory

● : '+' Polarization
● : 'x' Polarization

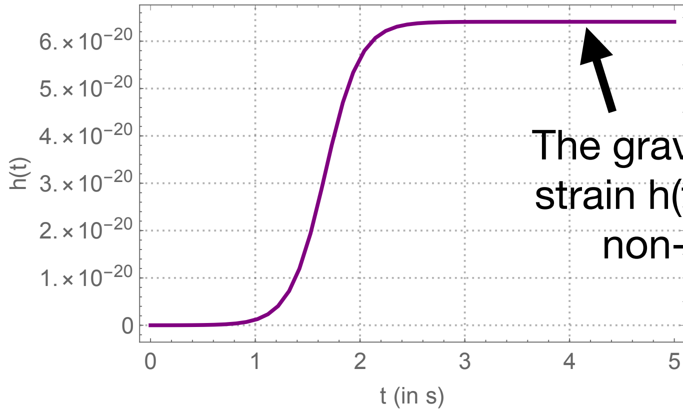
GW is propagating perpendicular to the screen

Animation Credits: Joel Frederico

What is Gravitational Wave (GW) memory?



Permanent distortion of the local space-time metric



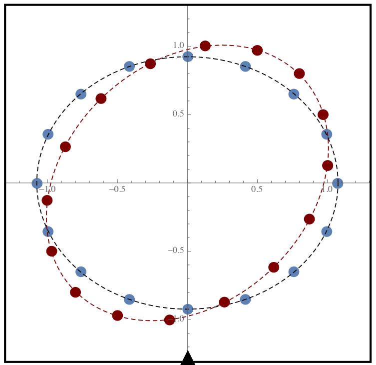
The gravitational wave strain h(t) remains at a non-zero value

Causes:

Gravitationally unbound systems:
Anisotropic emission of energy (mass/radiation)

M. Favata, The gravitational-wave memory effect, Class. Quant. Grav. 27 (2010) 084036

What is Gravitational Wave (GW) memory?



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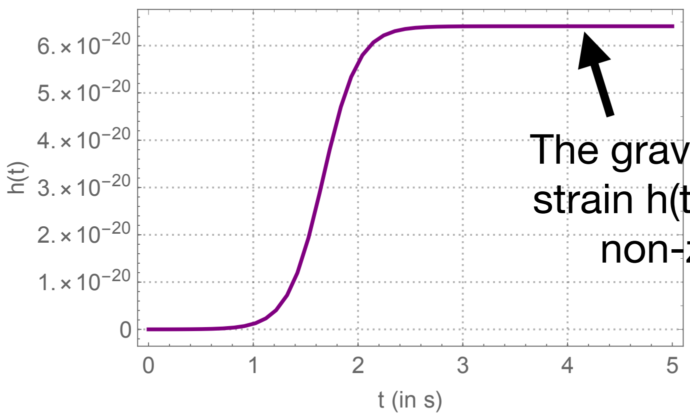


The gravitational wave strain h(t) remains at a non-zero value

Causes:

Gravitationally unbound systems: Anisotropic emission of energy (mass/radiation)

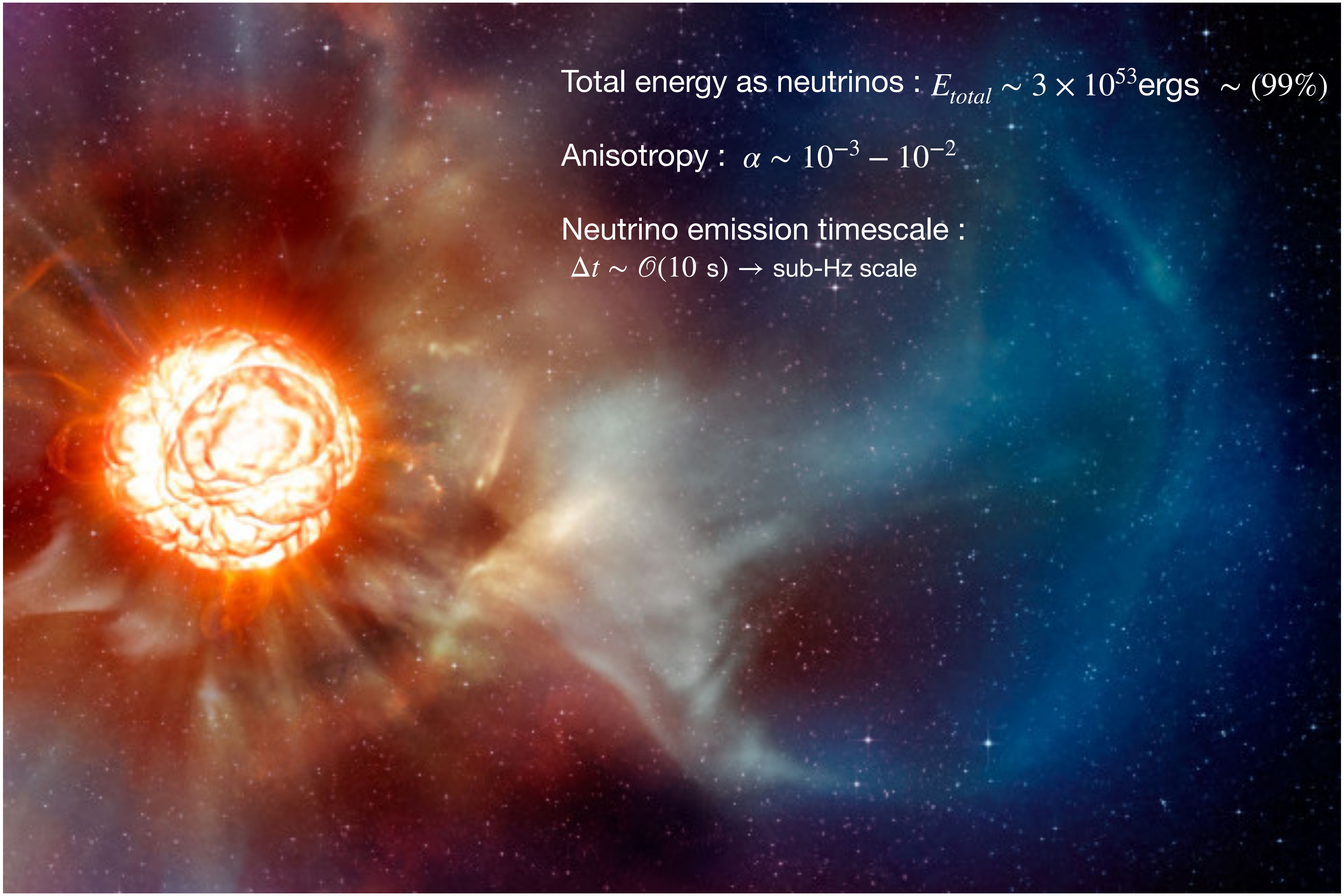
<u>The GW memory has never been observed!</u>

Need:

a) A very powerful emitter
b) Anisotropy
c) Detectors in the frequency regimes of interest

M. Favata, The gravitational-wave memory effect, Class. Quant. Grav. 27 (2010) 084036

An Ideal Candidate: Core-collapse Supernova (CCSN)



Total energy as neutrinos : $E_{total} \sim 3 \times 10^{53}$ergs $\sim (99\%)$

Anisotropy : $\alpha \sim 10^{-3} - 10^{-2}$

Neutrino emission timescale :
$\Delta t \sim \mathcal{O}(10\ \mathrm{s}) \rightarrow$ sub-Hz scale

Credits: European Southern Observatory, L. Calçada

Phenomenological Model: Formalism

Begin with Einstein's field equation:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\,8\pi G T_{\mu\nu}$$

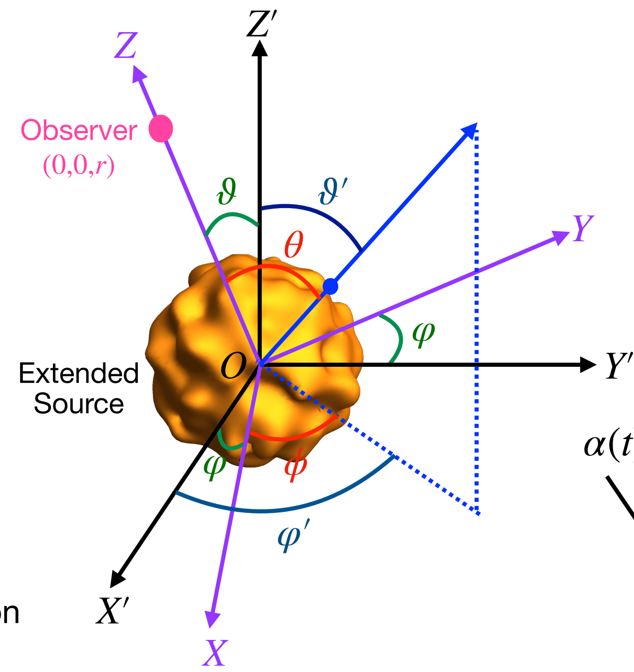
Invoke weak field approximation (since we are very far away from the source $r \to \infty$)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Small perturbation

Black Box….

(Calculations in progress)



$$\alpha(t) = \frac{1}{L_\nu(t)} \int_{4\pi} d\Omega' \; \Psi(\vartheta', \varphi') \, \frac{dL_\nu(\Omega', t)}{d\Omega'}$$

Angular dependence put together in anisotropy parameter

$$h_{TT}^{xx} = h(t) = \frac{2G}{rc^4} \int_{-\infty}^{t-r/c} dt' \;\; L_\nu(t') \;\; \alpha(t')$$

Change of separation for two free-falling masses

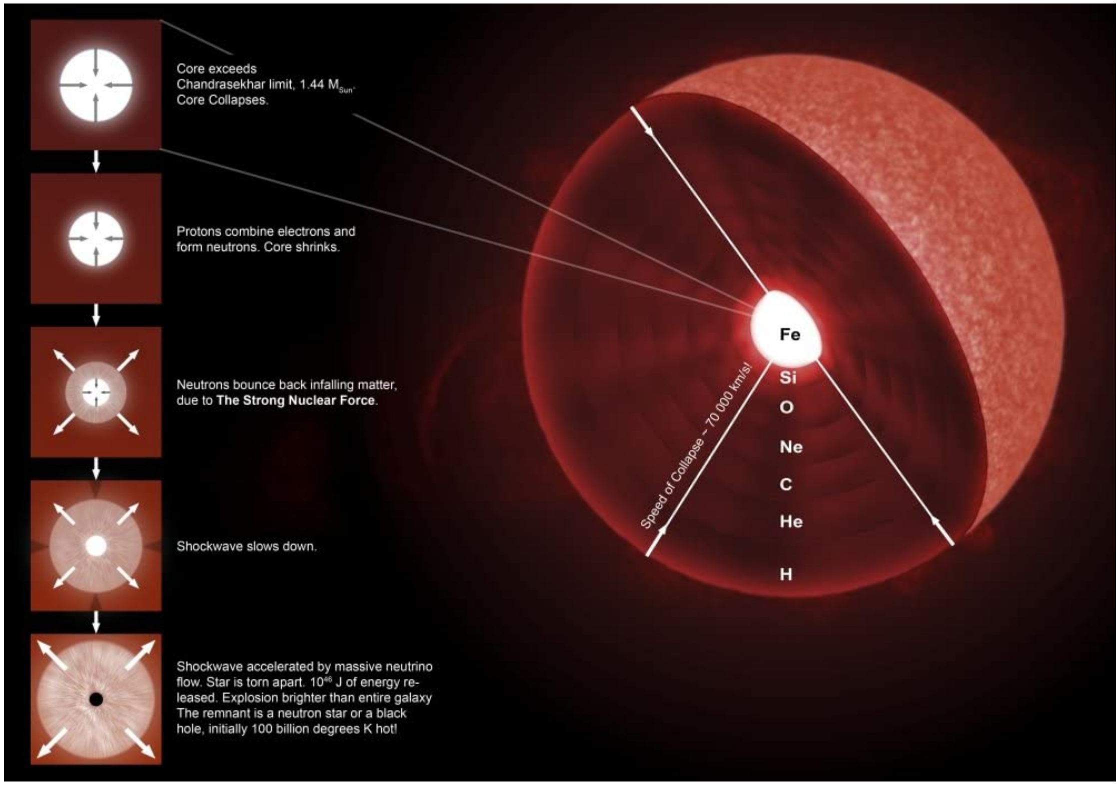
$$\delta l_j = \frac{1}{2} h_{jk}^{TT} l^k$$

Epstein, Astrophys. J. 223 (1978) 565
E. Mueller and H.T. Janka, AAP 317 (1997) 140

Supernova (SN) neutrinos - Review

Also see: Prof. Alex Friedland's talk

CCSN: death of a massive (>10 M_{sun}) star



Red or Blue supergiants: advanced stages of nuclear burning

↓

Fe core: Fusion turns off: loss of pressure

↓

Core collapses

↓

Collapsed core: very dense (nuclear densities): Incompressible

↓

Infalling matter bounces off: Shockwave produced

↓

Shockwave stalls

→ Shockwave re-energized → Star explodes: Supernova
Neutron star forming collapse (NSFC)

→ Shockwave dies down → Failed Supernova
Black hole forming collapse (BHFC)

Credits: https://images-na.ssl-images-amazon.com/images/I/61yf26rpIXL._AC_SL1000_.jpg

Supernova (SN) neutrinos - Review

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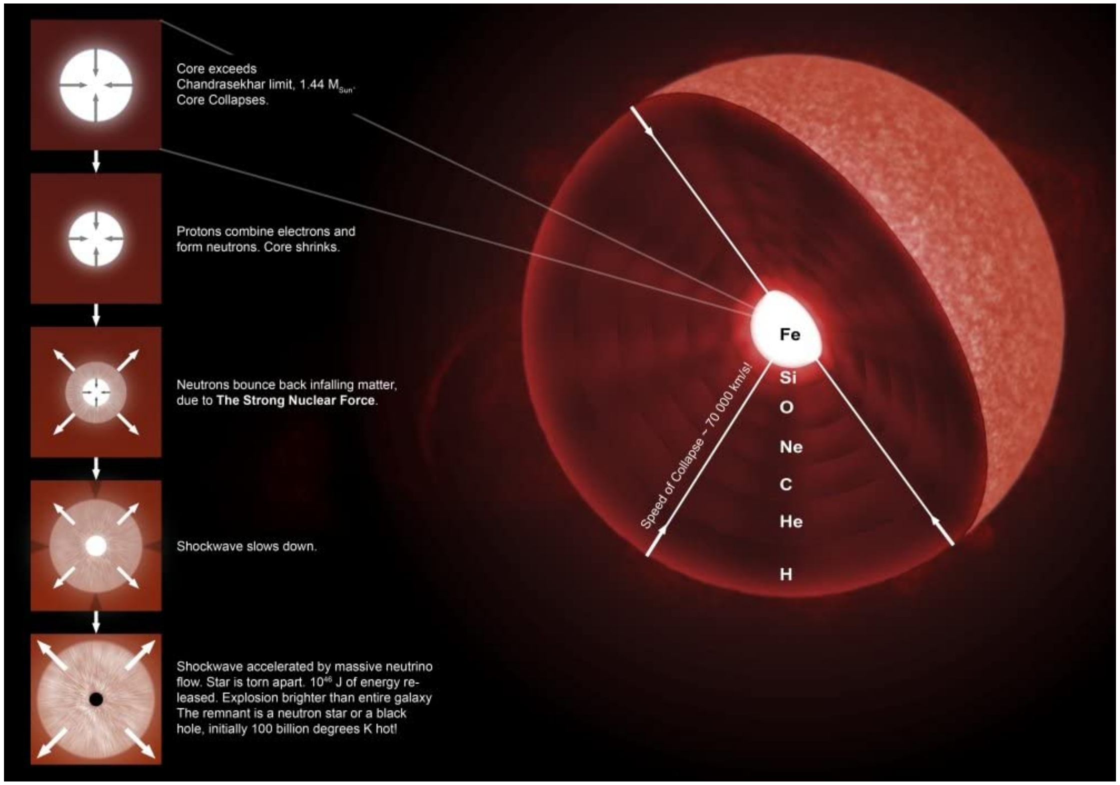

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↓

Infalling matter bounces off: Shockwave produced

↓

Star explodes: Supernova

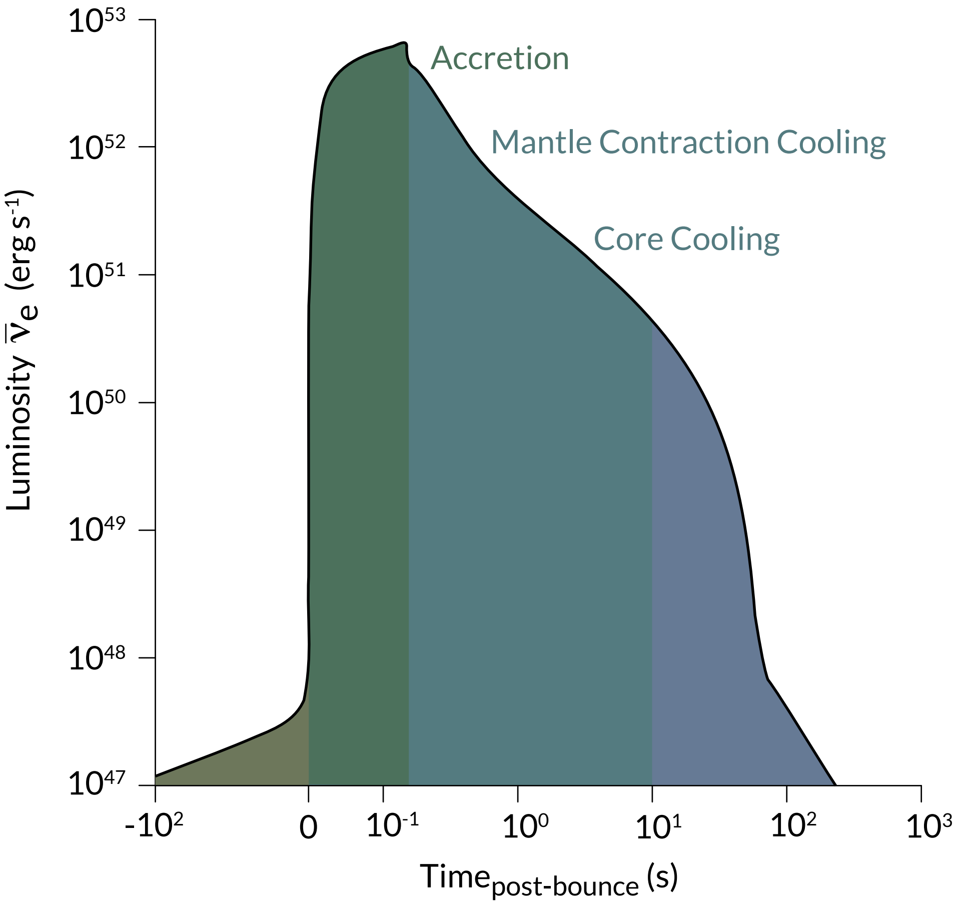
Neutrinos emitted right after the collapse: collapsed core cools

Shockwave stalled: accelerated by neutrinos

Giunti and Kim. Fundamentals of Neutrino Physics and Astrophysics (2007)

Janka, Langanke, Marek and Martinez-Pinedo, et.al. Phys. Rept., 442:38–74, (2007)

SN neutrino emission phases

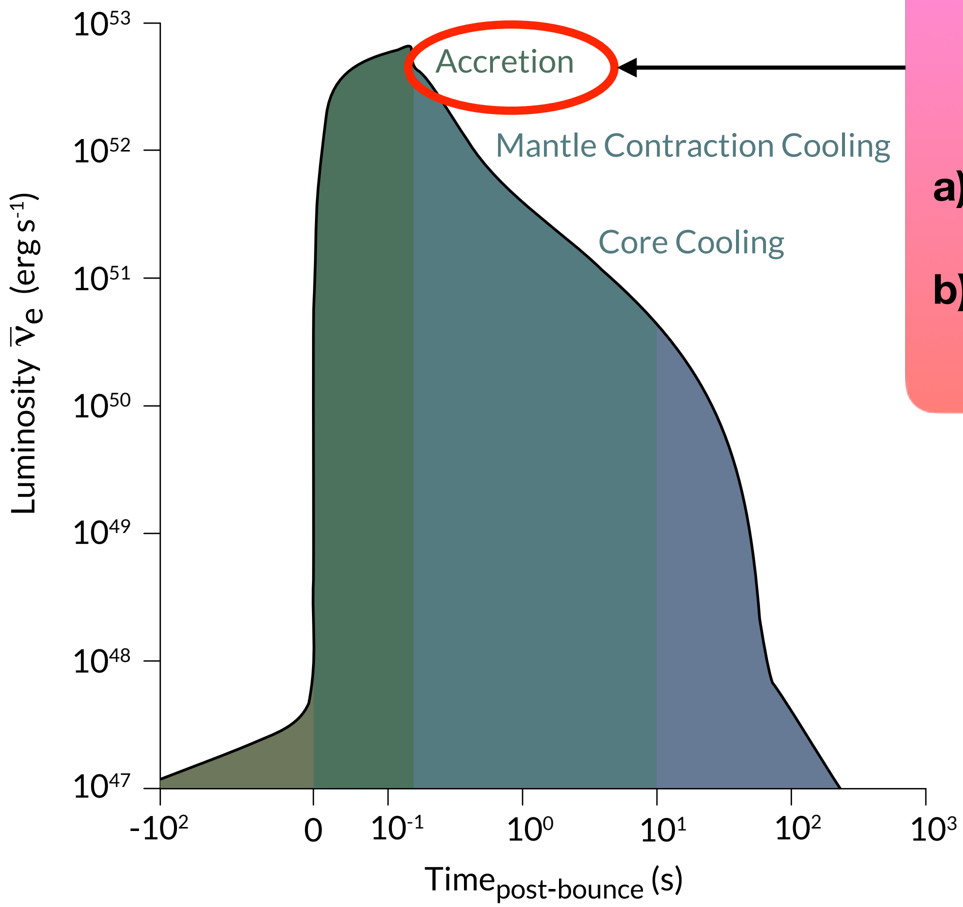


Following
Li, Roberts & Beacom,
2020

Neutrino burst: $\sim \mathcal{O}(10 \text{ s})$
Accretion phase: t ~ 0.003 - 0.5 s
Cooling phase: t ~ 0.5 - 10 s

Graphics by: Frank Timmes

Anisotropy Parameter



Following
Li, Roberts & Beacom,
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Anisotropy develops during accretion phase, due to:

a) Convection

b) SASI (Standing Accretion Shock Instability)

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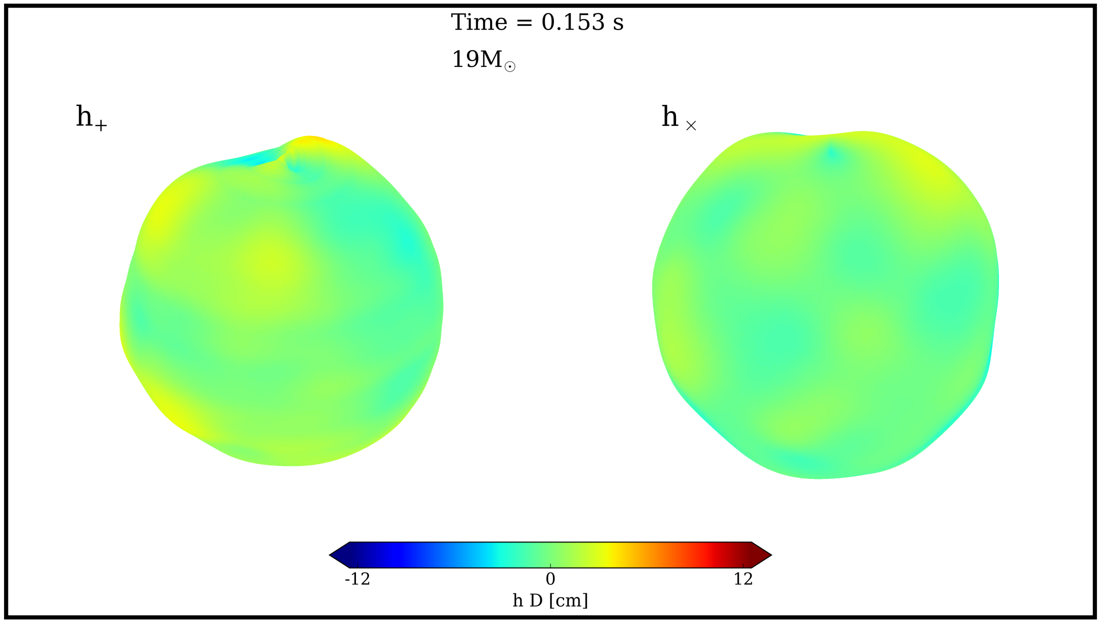
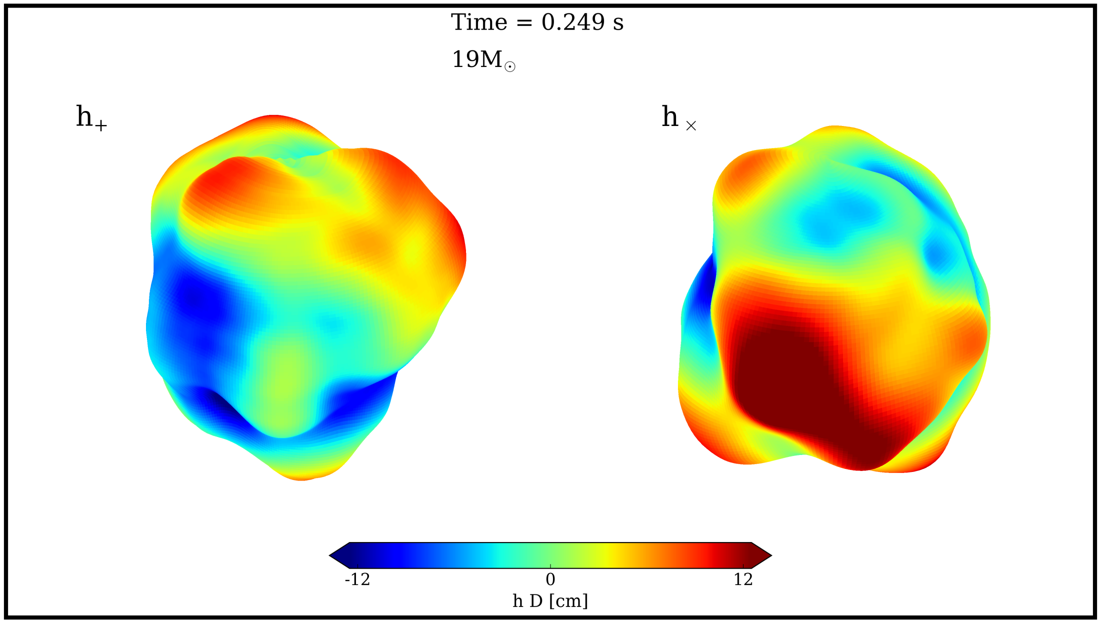
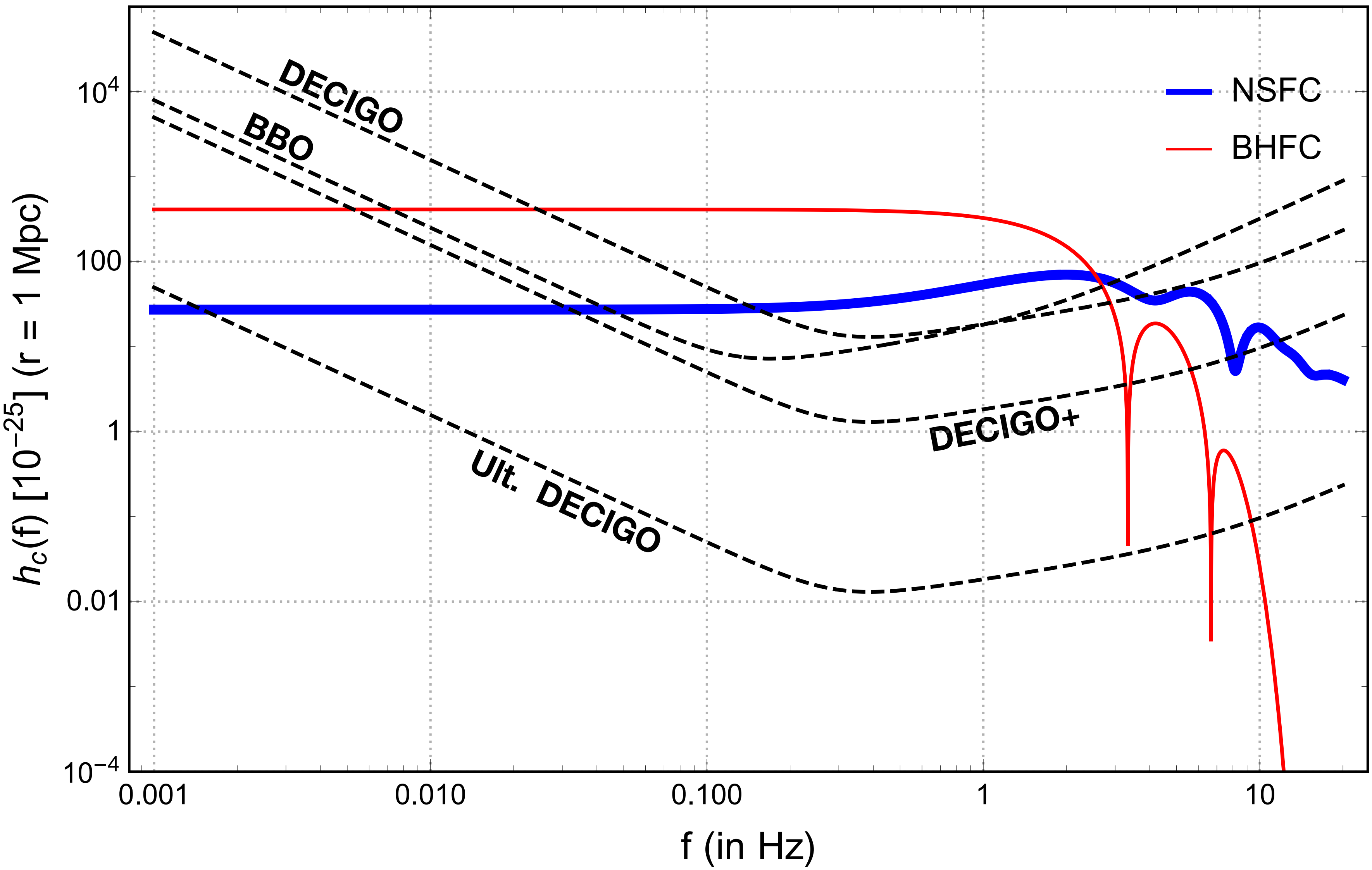




Vartanyan and Burrows, Astrophys. J. 901 (2020) 108.

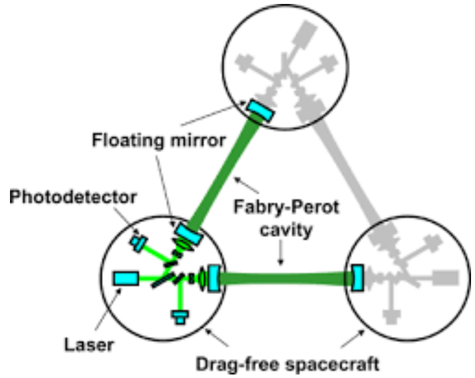
Characteristic strain (r = 1 Mpc)

Will be detectable up to $\mathcal{O}(1)$ Mpc – $\mathcal{O}(10)$ Mpc

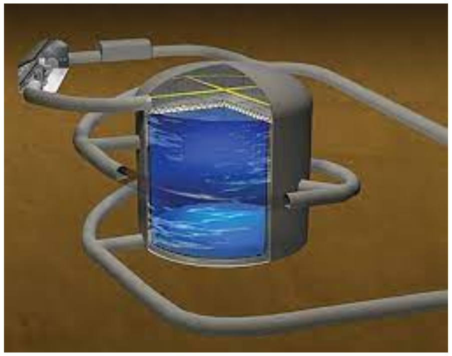


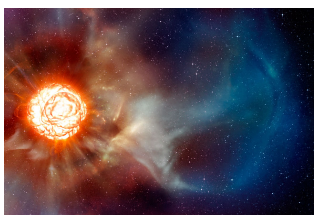
The idea

DECIGO

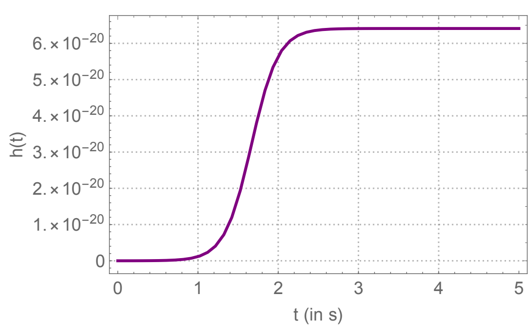


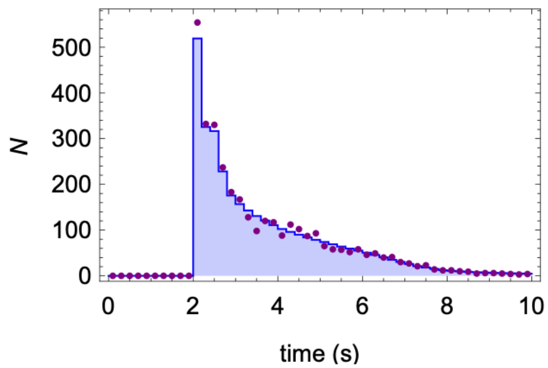
HyperK





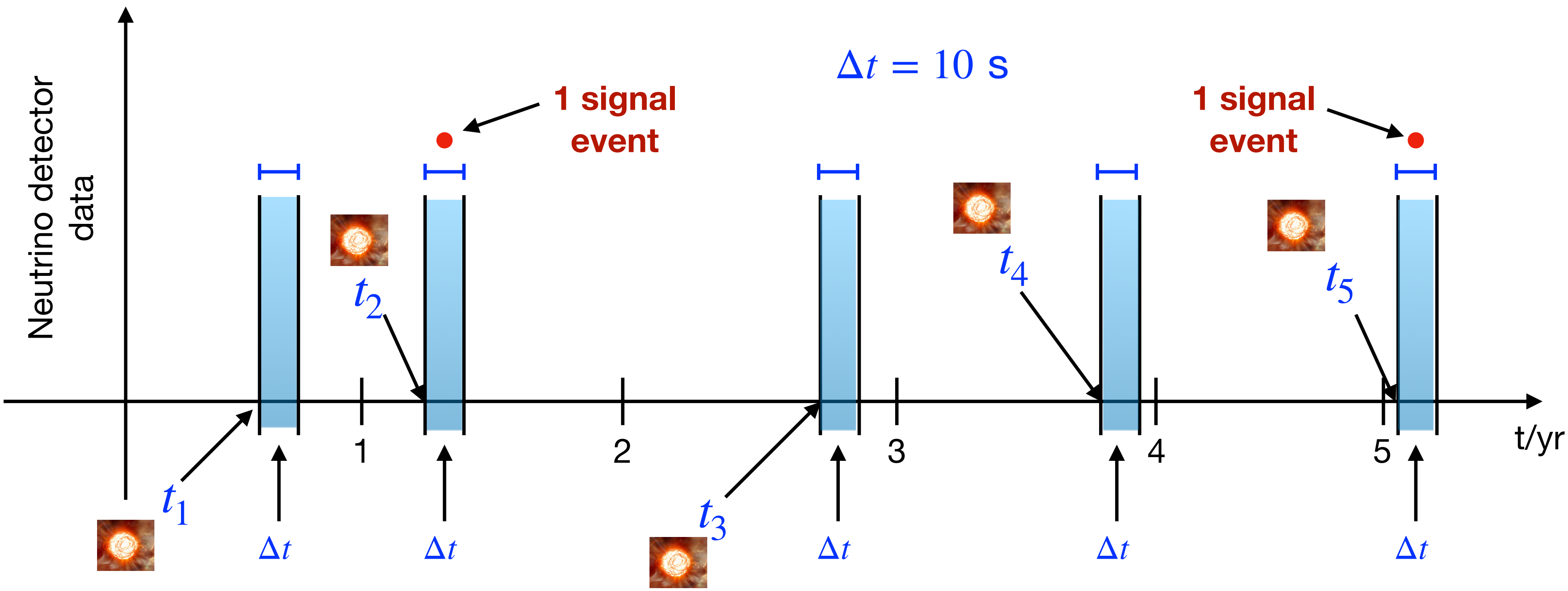
→ **Neutrino GW Memory in the GW detector** → **Neutrinos in the neutrino detector**





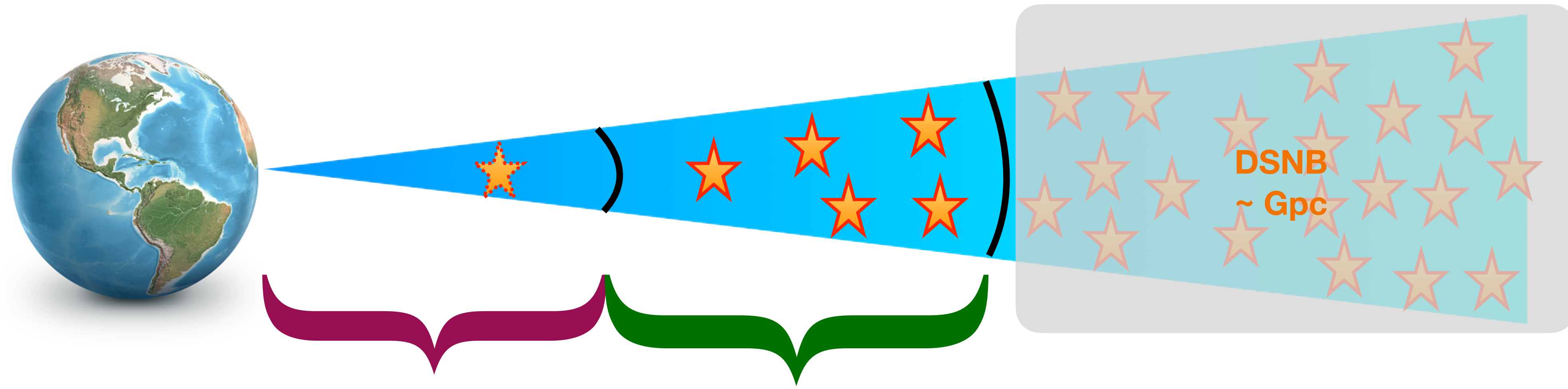
The idea

→ **Neutrino GW Memory in the GW detector** → **Neutrinos in the neutrino detector**



Motivation for memory-triggered search

Neutrino events	**High statistics**	**Low statistics**



	~ kpc	**~ Mpc**
CCSN rate	**~ 0.01/yr**	**~ 1/yr**

Fig. Motivation: John Beacom, TAUP, Munich, Germany, Sept 2011

Motivation for memory-triggered search

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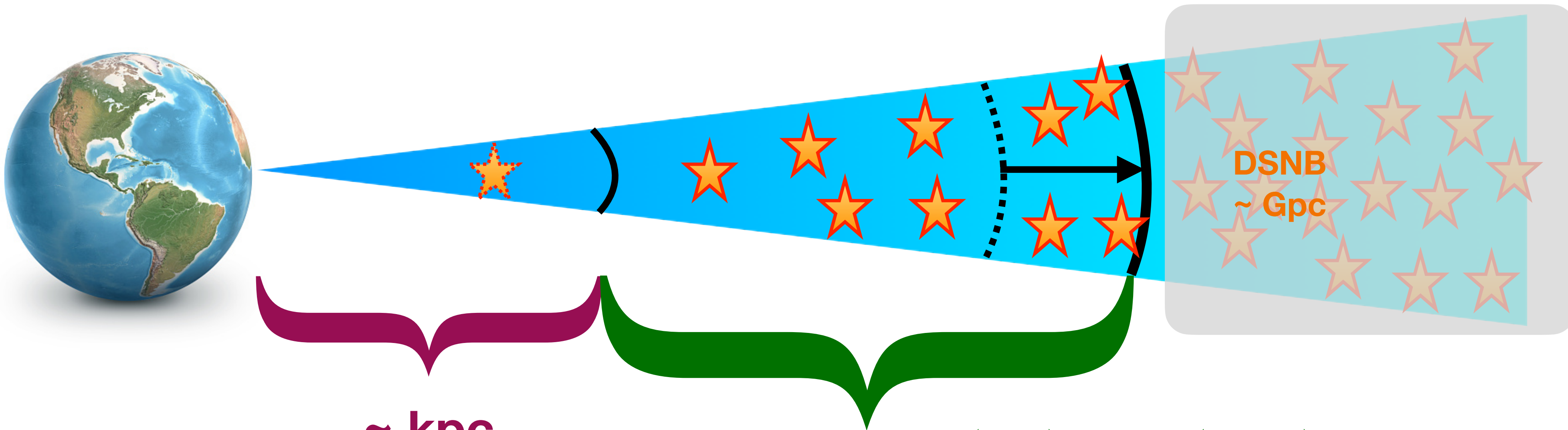

~ kpc

$\sim \mathcal{O}(10) - \mathcal{O}(100)$ **Mpc**

CCSN rate — **~ 0.01/yr** — **~ 1/yr**

$\sim \mathcal{O}(10) - \mathcal{O}(100)$ **neutrinos/Mt/decade**

Fig. Motivation: John Beacom, TAUP, Munich, Germany, Sept 2011

Motivations for triggered-searches

WHY?

Deliver a local sample of neutrino events from CCSNe:
Population averaged energy, luminosity

Comparison with DSNB (diffuse supernova neutrino background) or Galactic CCSNe

Understanding SN populations including NSFC and BHFC

and much more….

Motivations for triggered-searches

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Deliver a local sample of neutrino events from CCSNe:
Population averaged energy, luminosity

Comparison with DSNB (diffuse supernova neutrino background) or Galactic CCSNe

Understanding SN populations including NSFC and BHFC

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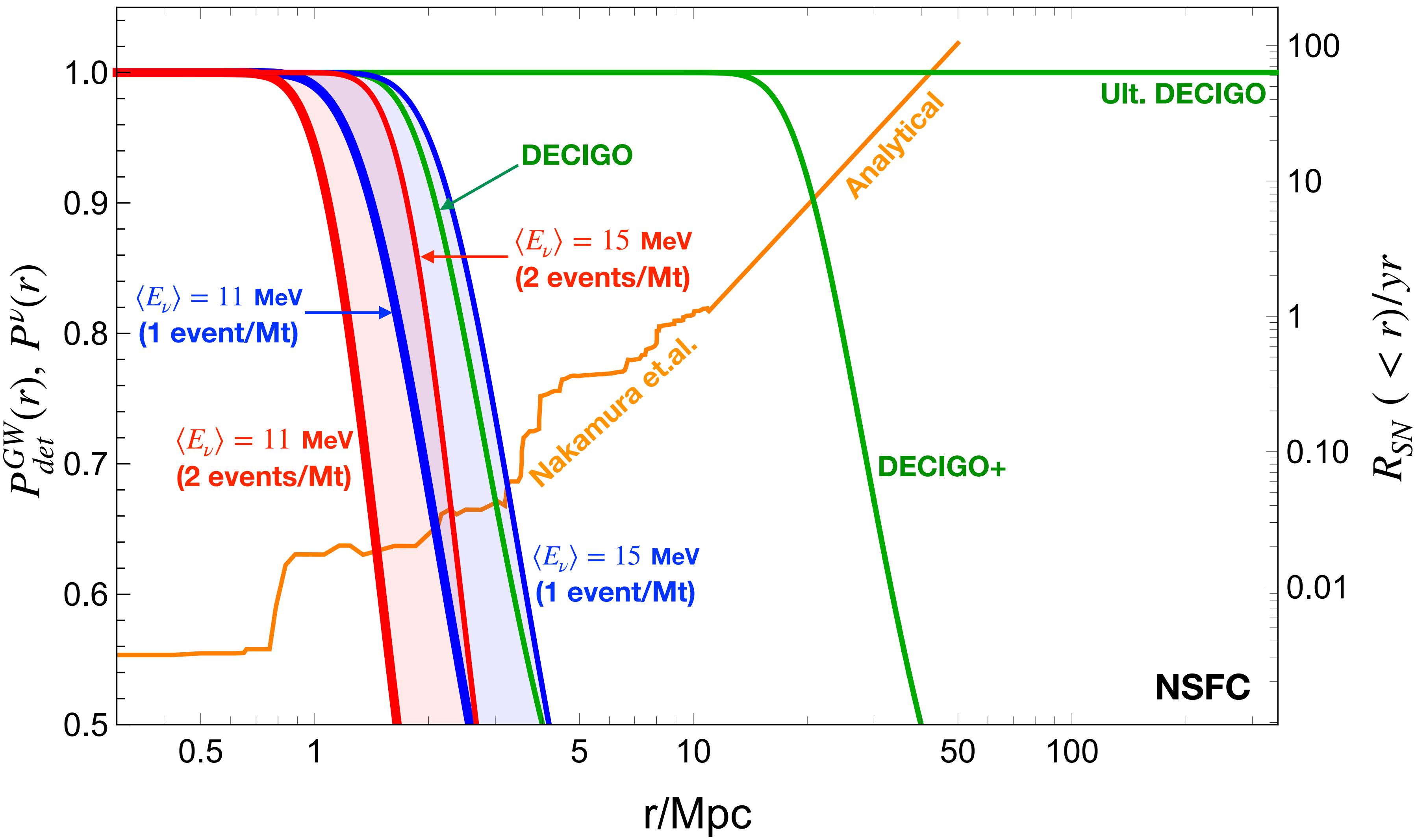
CHALLENGES:

CCSNe in immediate neighborhood are extremely rare

Limited distance ~ 1-3 Mpc to have significant statistics

Detection probabilities and CCSN rates



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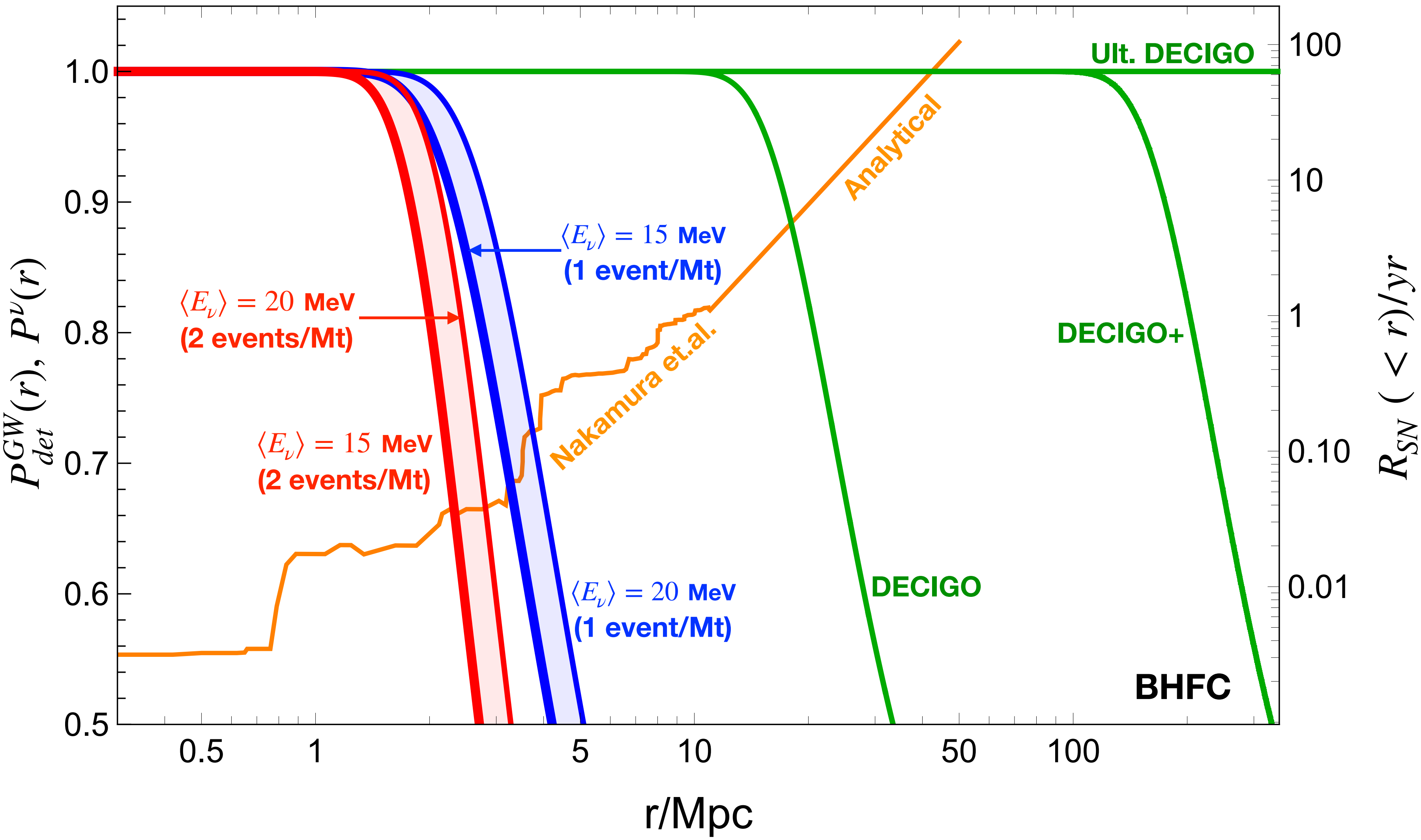


Recipe in brief

$$N_\nu^{trig}(D) = \Delta T \sum_{j, r_j < D} R_j N(r_j) P_{det}^{GW}(r_j)$$

Detector running time → ΔT

CCSN rate in the galaxy *j* → R_j

Predicted number of neutrino events in detector from a CCSN in the galaxy *j* → $N(r_j)$

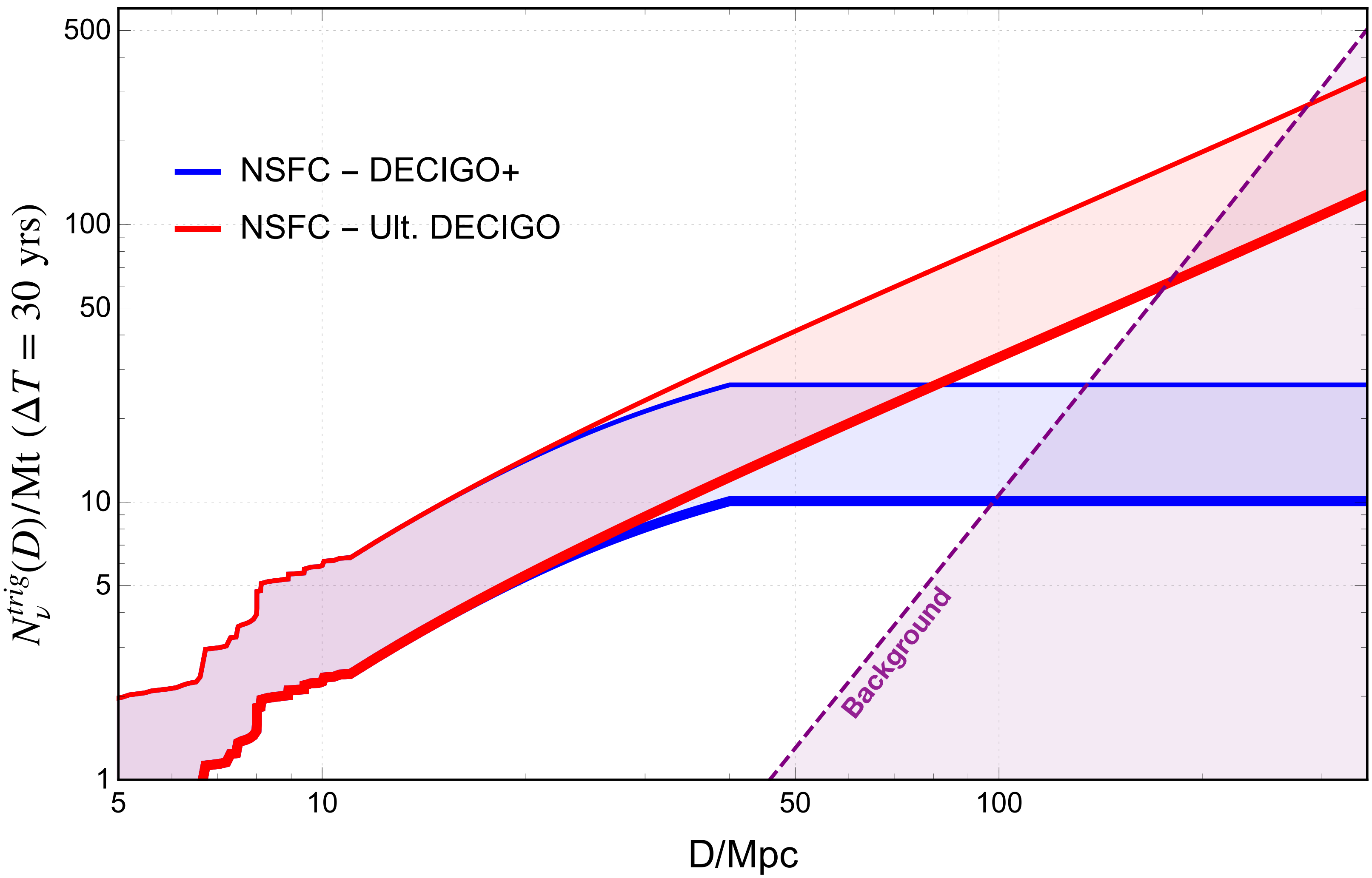
Total number of memory-triggered neutrino events from all CCSNe within a distance D → $N_\nu^{trig}(D)$

Index of the galaxy, *j=1,2,….* → j

Distance to the galaxy *j* → r_j

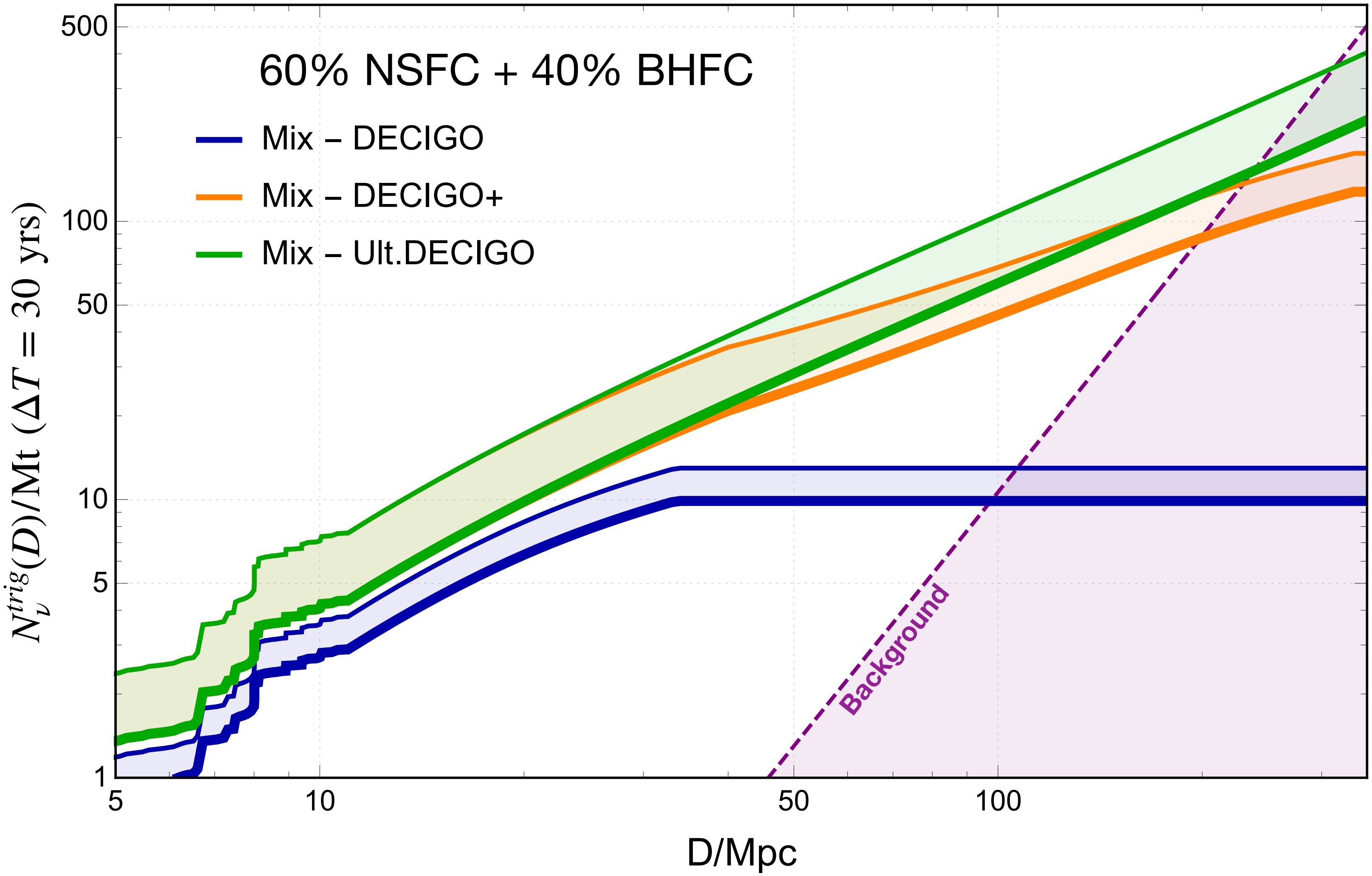
Probability of detecting the memory from a CCSN in the galaxy *j* → $P_{det}^{GW}(r_j)$

Results: Events and background - NSFC



Untriggered backgrounds would be orders of magnitude higher!

Results: Events and background - Mix



Untriggered backgrounds would be orders of magnitude higher!

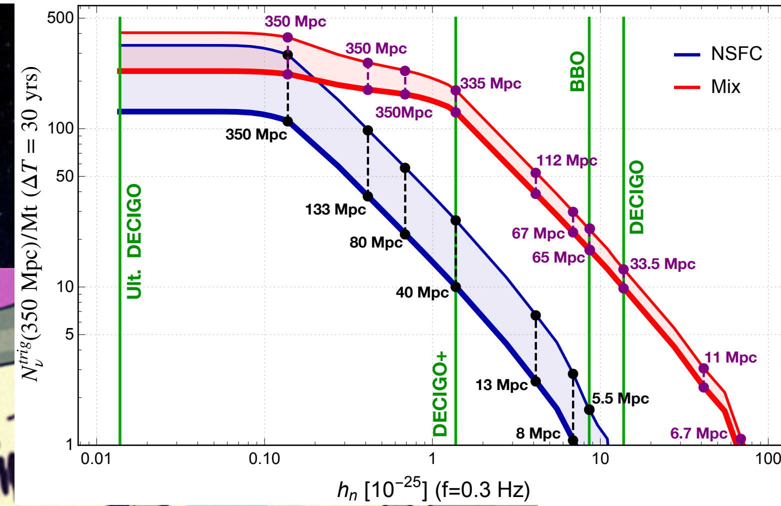
Takeaways

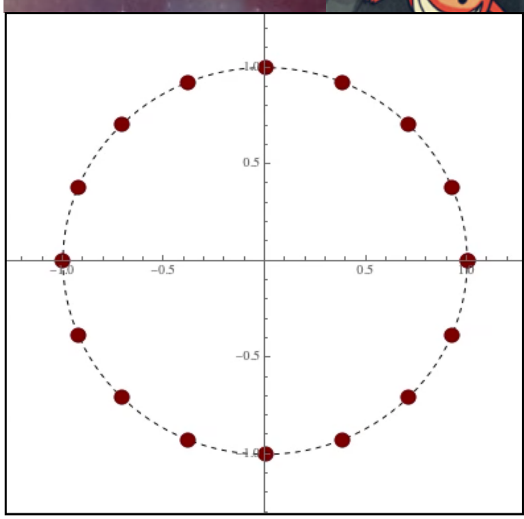
A new multi messenger approach to CCSNe: neutrino GW memory enables time-triggered search of supernova neutrinos.

- Could be realized in a few decades: upcoming deci-Hz GW interferometers and megaton scale neutrino detectors.

- Will help in performing various statistical studies on the clean sample of neutrinos collected, giving further insights and information about SN neutrinos, NSFC, BHFC, etc. in the local Universe.

- For example, DECIGO+ will allow robust time triggers for supernovae at distances D ~ 40 – 300 Mpc, resulting in a nearly background-free sample of ~ 3 – 70 neutrino events per Mt per decade of operation.





Thank You!

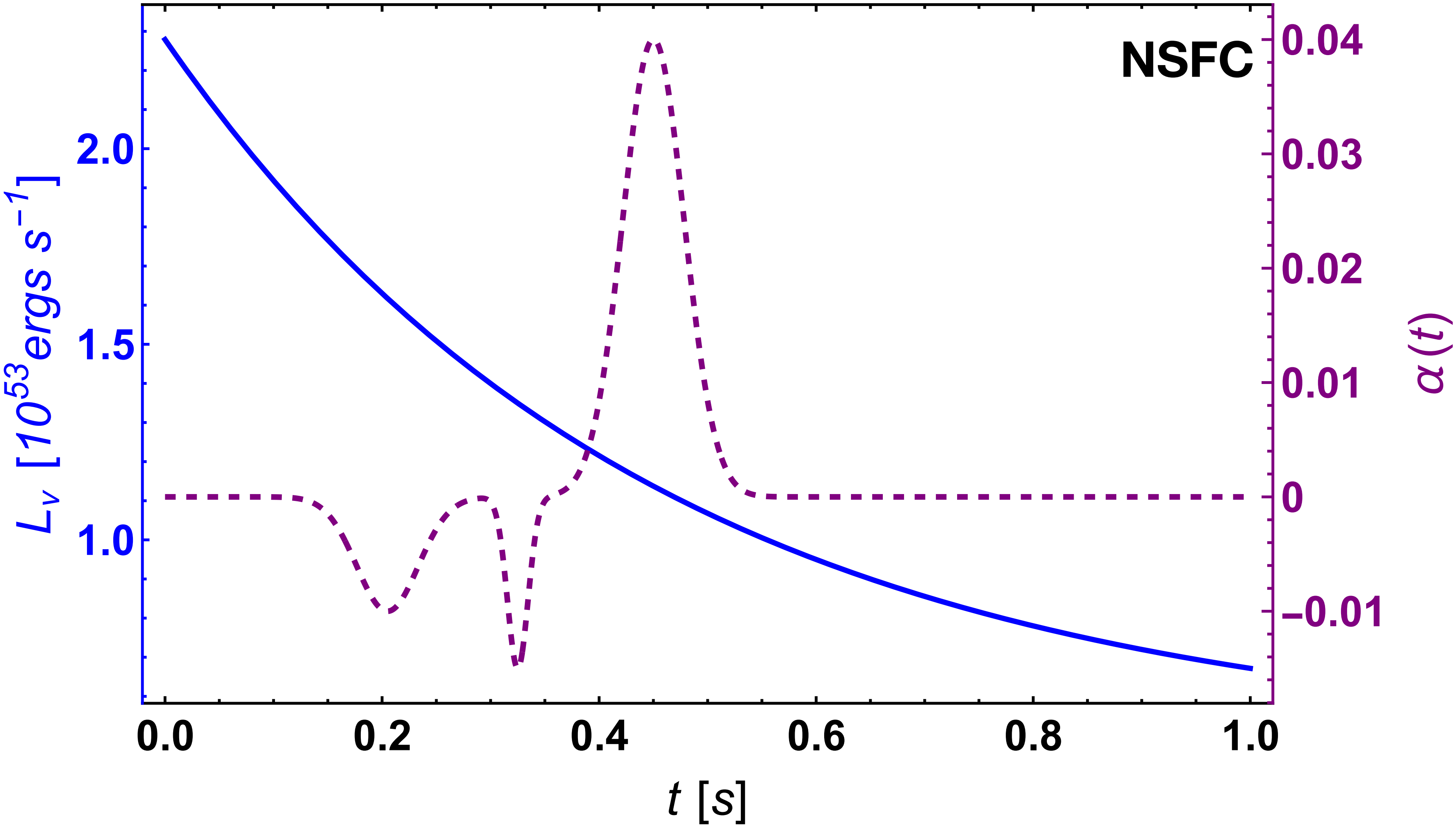
Team Neutrino reporting from a core-collapse supernova!

Backup

Neutrino flux parameters

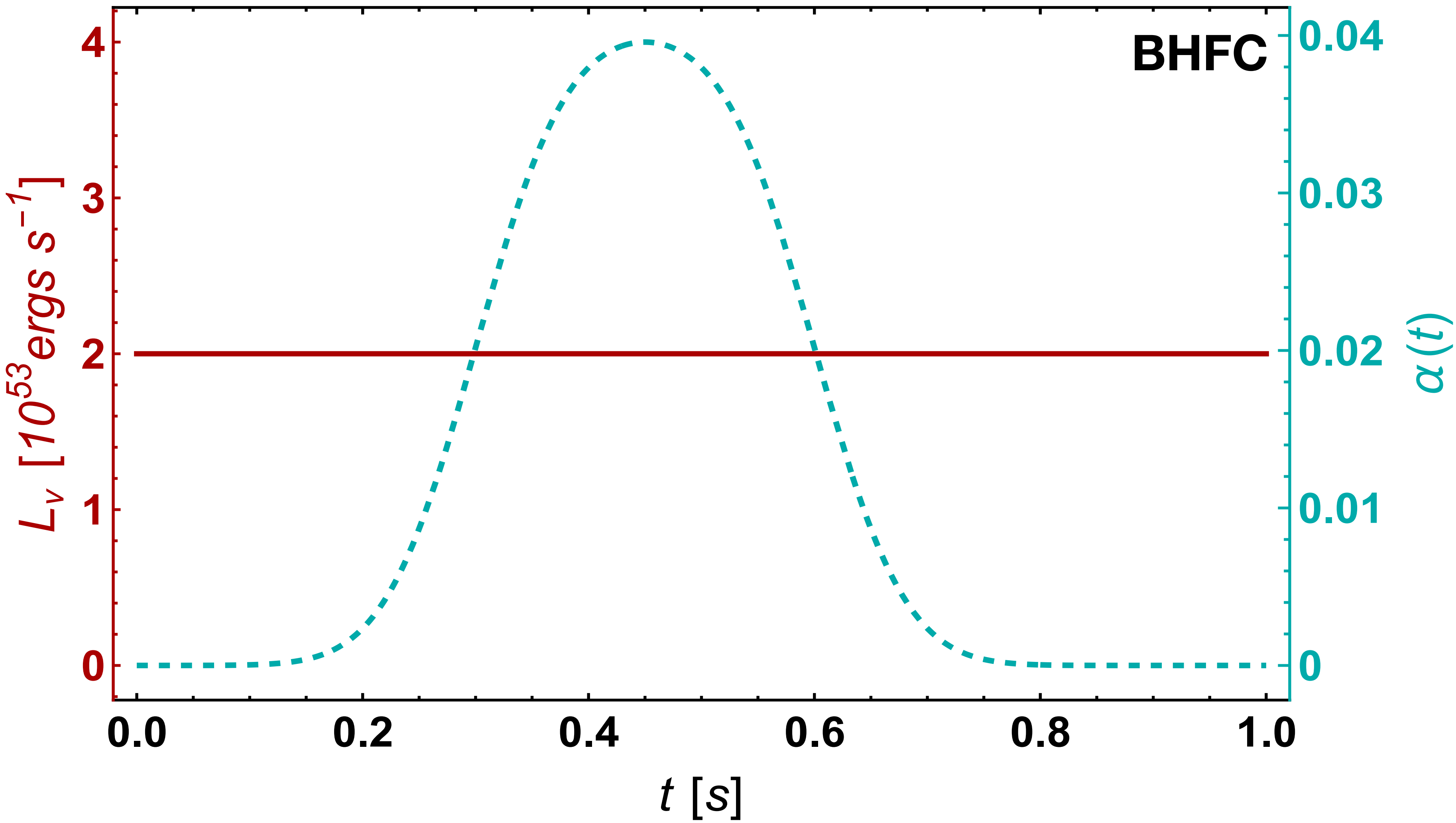
Model	Energy ($\times 10^{53}$ ergs)		β	$\langle E_\nu \rangle$ (In MeV)	
	Ac. Ph.	$\bar{\nu}_e$		Lower	Upper
NSFC	1.2	0.5	3	11	15
BHFC	2	0.45	2	15	20

Models: NSFC

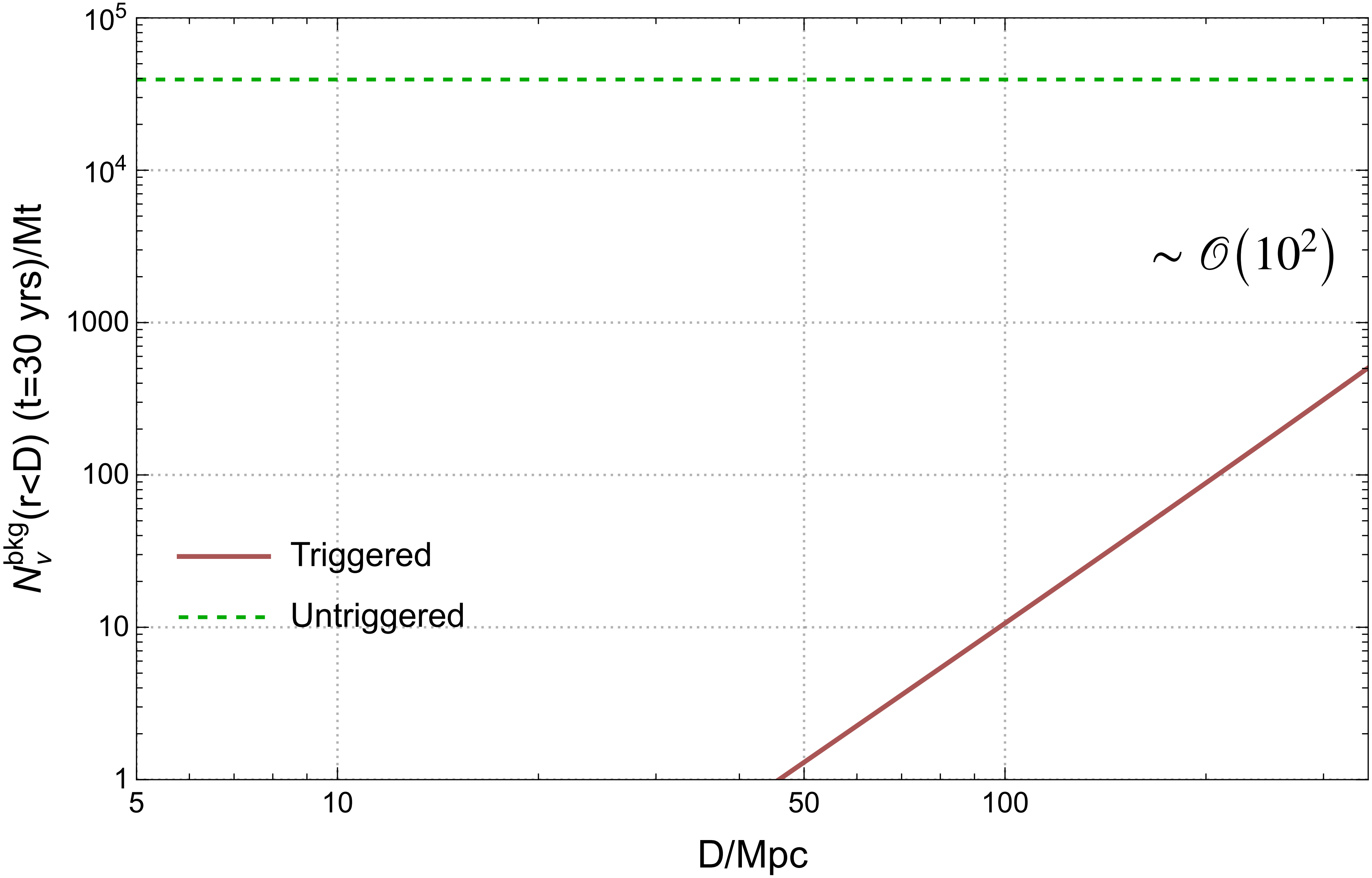


NSFC
2.0
1.5
1.0
L_ν [10^{53}ergs s^{-1}]
0.04
0.03
0.02
0.01
0
−0.01
$\alpha(t)$
0.0
0.2
0.4
0.6
0.8
1.0
t [s]

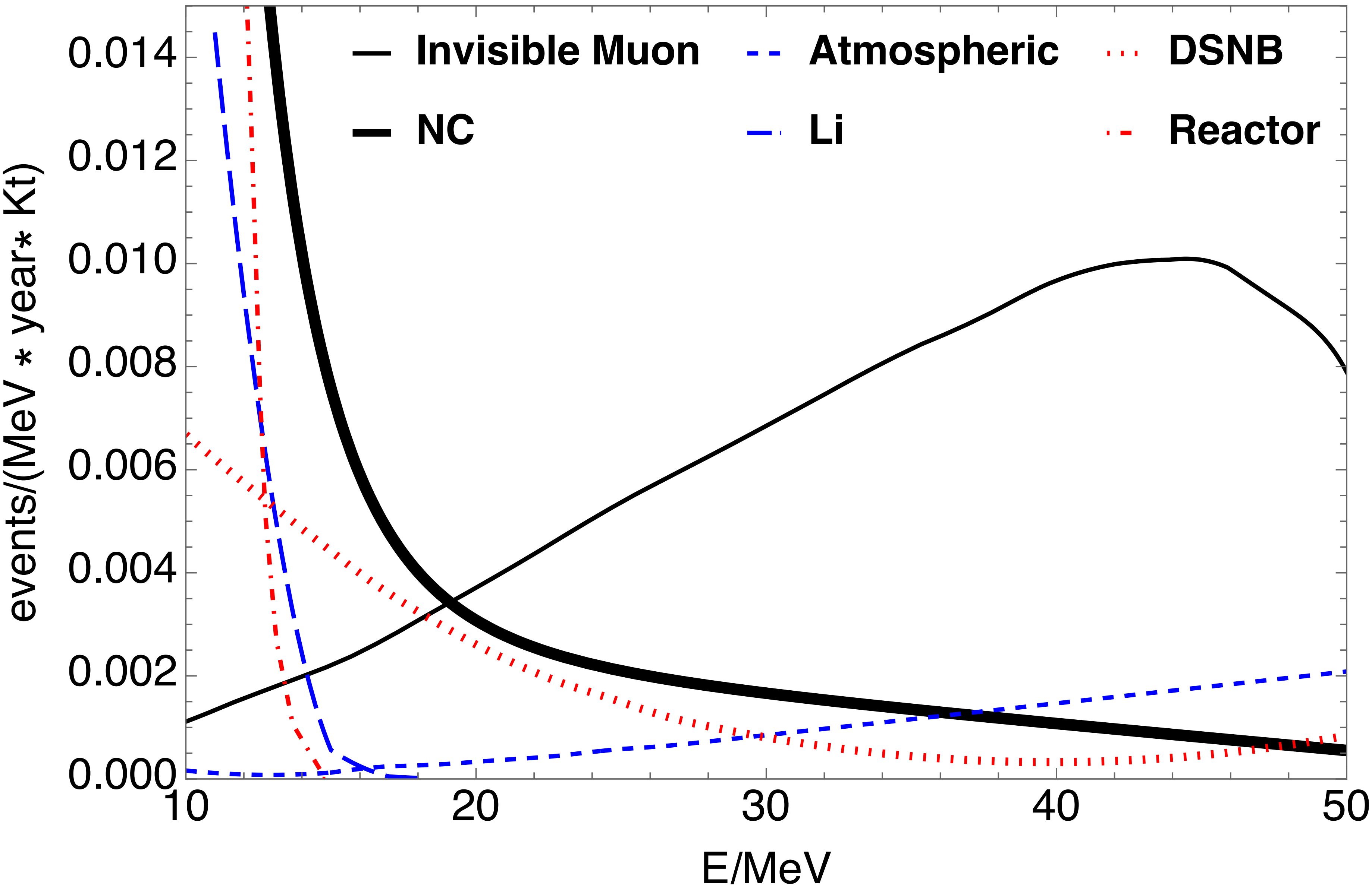
Models: BHFC


BHFC
4
3
2
1
0
0.04
0.03
0.02
0.01
0
0.0
0.2
0.4
0.6
0.8
1.0
L_ν [10^{53}ergs s^{-1}]
$\alpha(t)$
t [s]

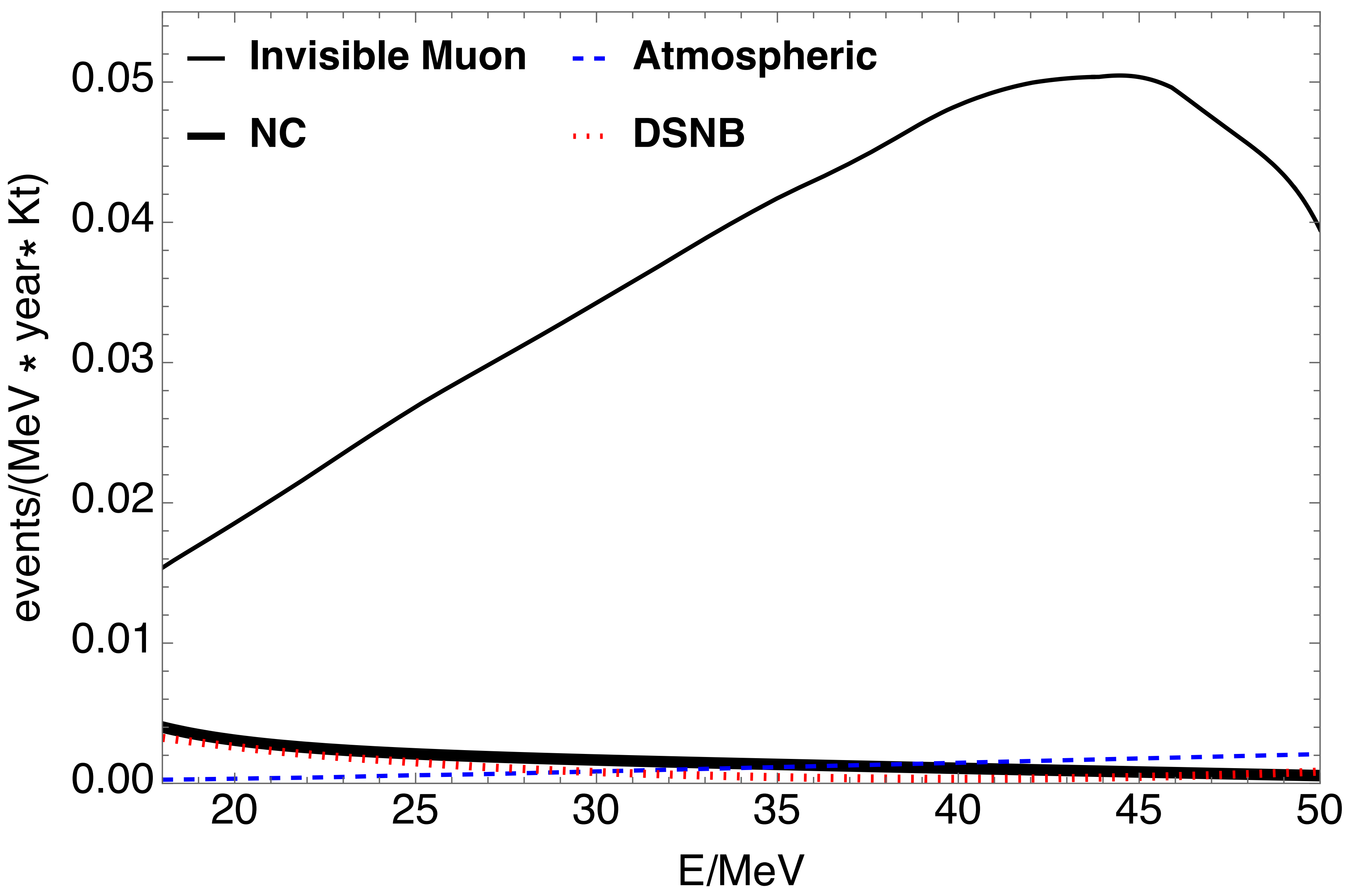
Comparison of backgrounds



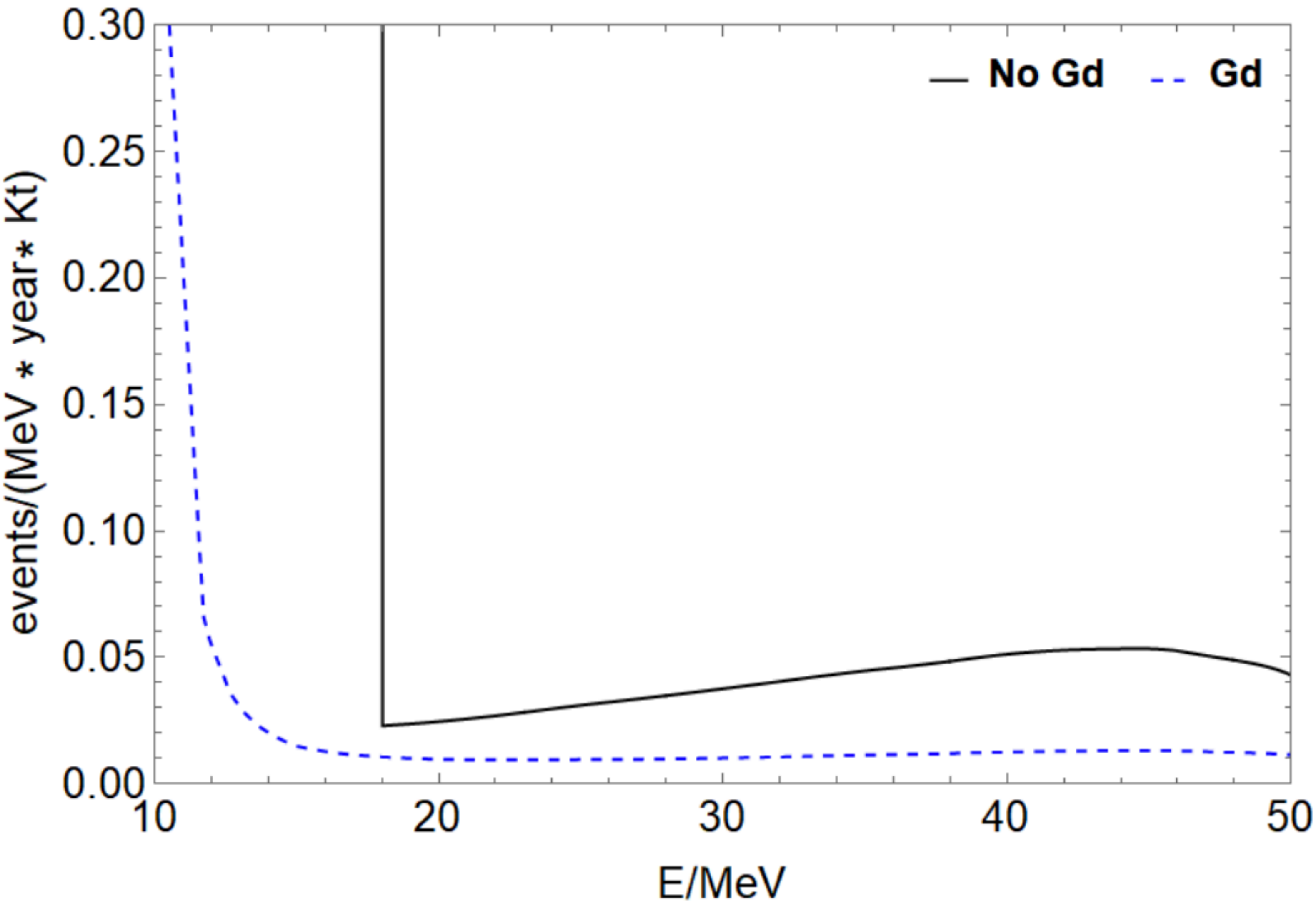
Individual backgrounds in HyperK (with Gd)



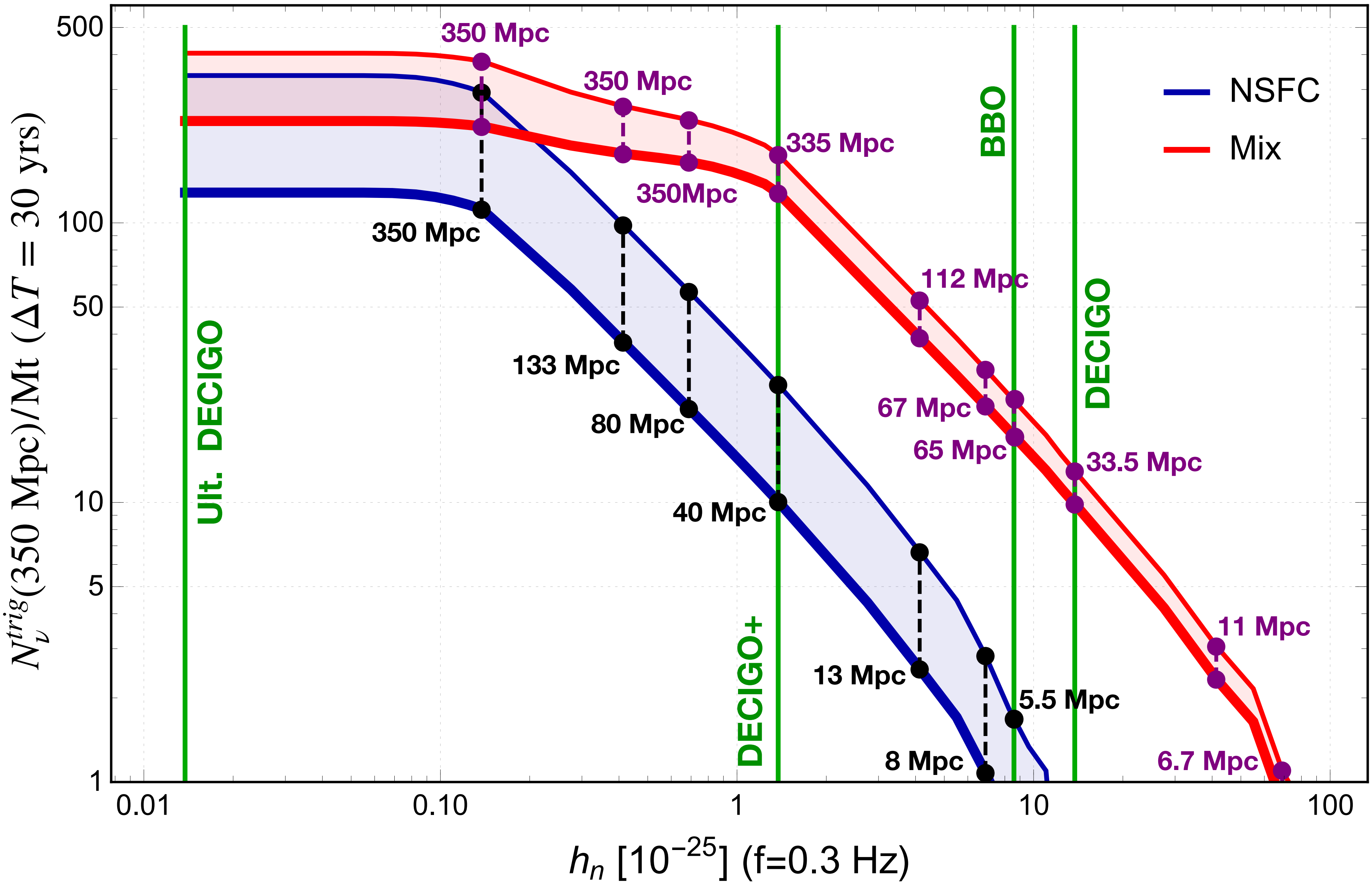
Individual backgrounds in HyperK (without Gd)



Total Background in HyperK



Overview: For GW experimental groups



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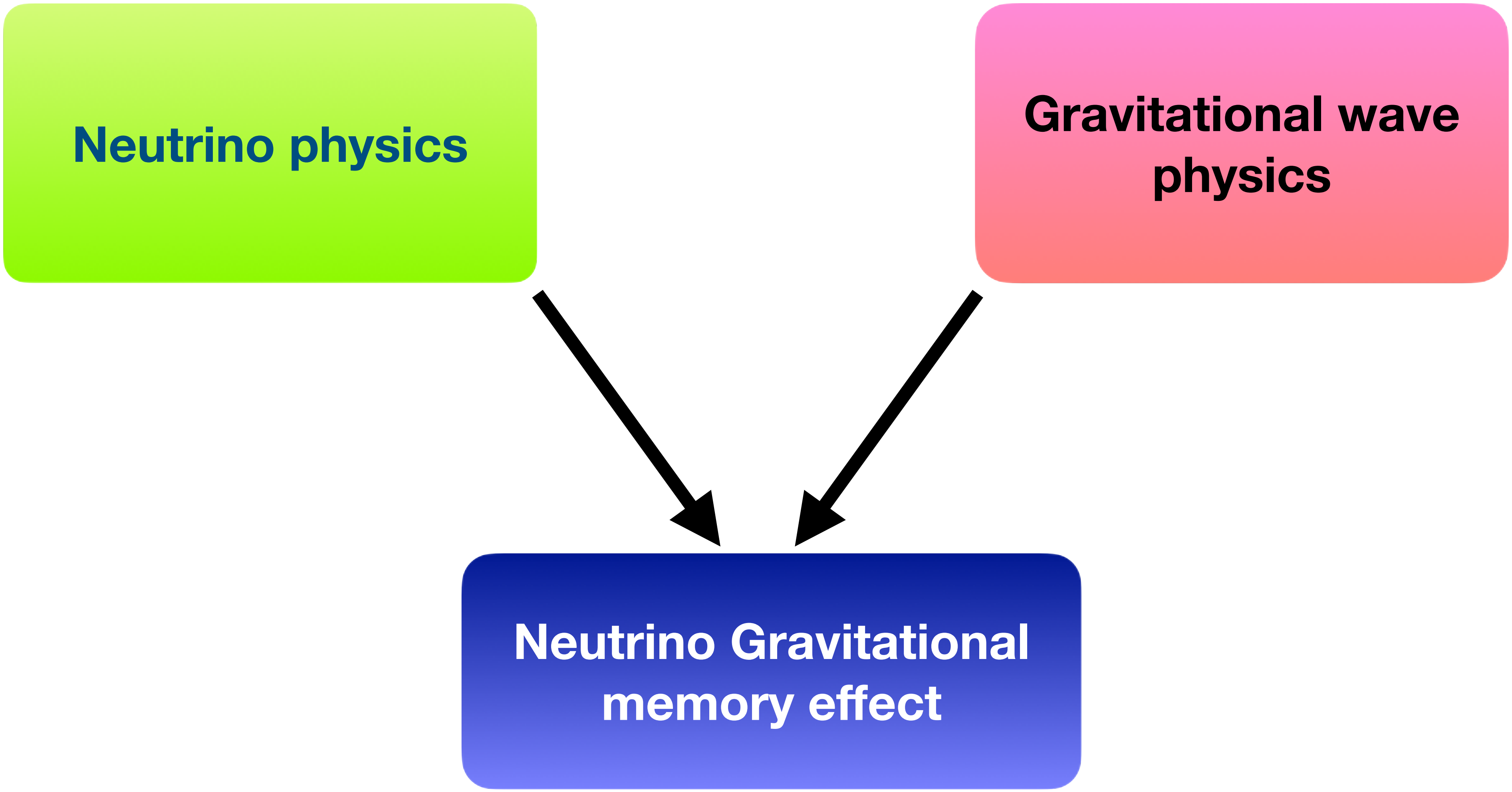

Phenomenological Model: Ingredients

Luminosity $L_\nu(t)$:

$$L_\nu(t) = \lambda + \beta \exp\left(-\chi t\right)$$

Anisotropy parameter $\alpha(t)$:

$$\alpha(t) = \kappa + \sum_{j=1}^{N} \xi_j \exp\left(-\frac{(t-\gamma_j)^2}{2\sigma_j^2}\right)$$

$$h_{TT}^{xx} = h(t) = \frac{2G}{rc^4}\int_{-\infty}^{t-r/c} dt' \; L_\nu(t') \; \alpha(t')$$

$$h(t) = \sum_{j=1}^{N}\left\{\left[h_{1j}\left(erf(\rho_j\;\tau_{1j}) + erf\left(\rho_j(t-\tau_{1j})\right)\right)\right] + \left[h_{2j}\left(erf(\rho_j\;\tau_{2j}) + erf\left(\rho_j(t-\tau_{2j})\right)\right)\right]\right\} + \left[h_3\left(\frac{\beta}{\chi}\left(1-\exp(-t\chi)\right) + \lambda t\right)\right]$$

Effective parameters from $L_\nu(t)$ and $\alpha(t)$: $h_{1j}, \rho_j, \tau_{1j}, h_{2j}, \tau_{2j}, h_3$

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Effective parameters from $L_\nu(t)$ and $\alpha(t)$: $h_{1j}, \rho_j, \tau_{1j}, h_{2j}, \tau_{2j}, h_3$

In frequency space,

$$\tilde{h}(f) = \sum_{j=1}^{N}\left[\left(h_{1j}\frac{i}{\pi f}\exp\Big(\frac{-\pi^2 f^2}{\rho_j^2}\Big)\exp\Big(i2\pi f\tau_{1j}\Big)\right) + \left(h_{2j}\frac{i}{\pi f}\exp\Big(\frac{-\pi^2 f^2}{\rho_j^2}\Big)\exp\Big(i2\pi f\tau_{2j}\Big)\right)\right] + \left(\sqrt{2\pi}\;h_3\frac{\beta}{\chi}\Big(\frac{1}{i2\pi f} - \frac{1}{-\chi + i2\pi f}\Big)\right)$$

Characteristic strain $h_c(f)$:

Dimensionless quantity.

$$h_c(f) = 2f\,|\tilde{h}(f)|$$

Helps in computing the signal to noise ratio (SNR) and compare the signal to the sensitivity curve of the detector.

Recipe in brief

$$N_\nu^{trig}(D) = \Delta T \sum_{j, r_j < D} R_j N(r_j) P_{det}^{GW}(r_j)$$

Rate of CCSN (how many such events):

Use calculated rate of CCSNe below 11 Mpc (local volume)

Analytical rate beyond 11 Mpc using cosmic SFR, Salpeter IMF….

Neutrino detectors:

Water Cherenkov detectors

Main channel: IBD

Quasi thermal emission spectra - mean energy

Flux at earth - depends on distance and emission spectra

Calculate number of events in detector from a CCSN - depends on distance

GW detectors:

Calculate SNR - depends on distance to source

Calculate probability of detection given a fixed false alarm probability - depends on SNR

References

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