Gravitational wave memory-triggered supernova neutrino detection

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Based on

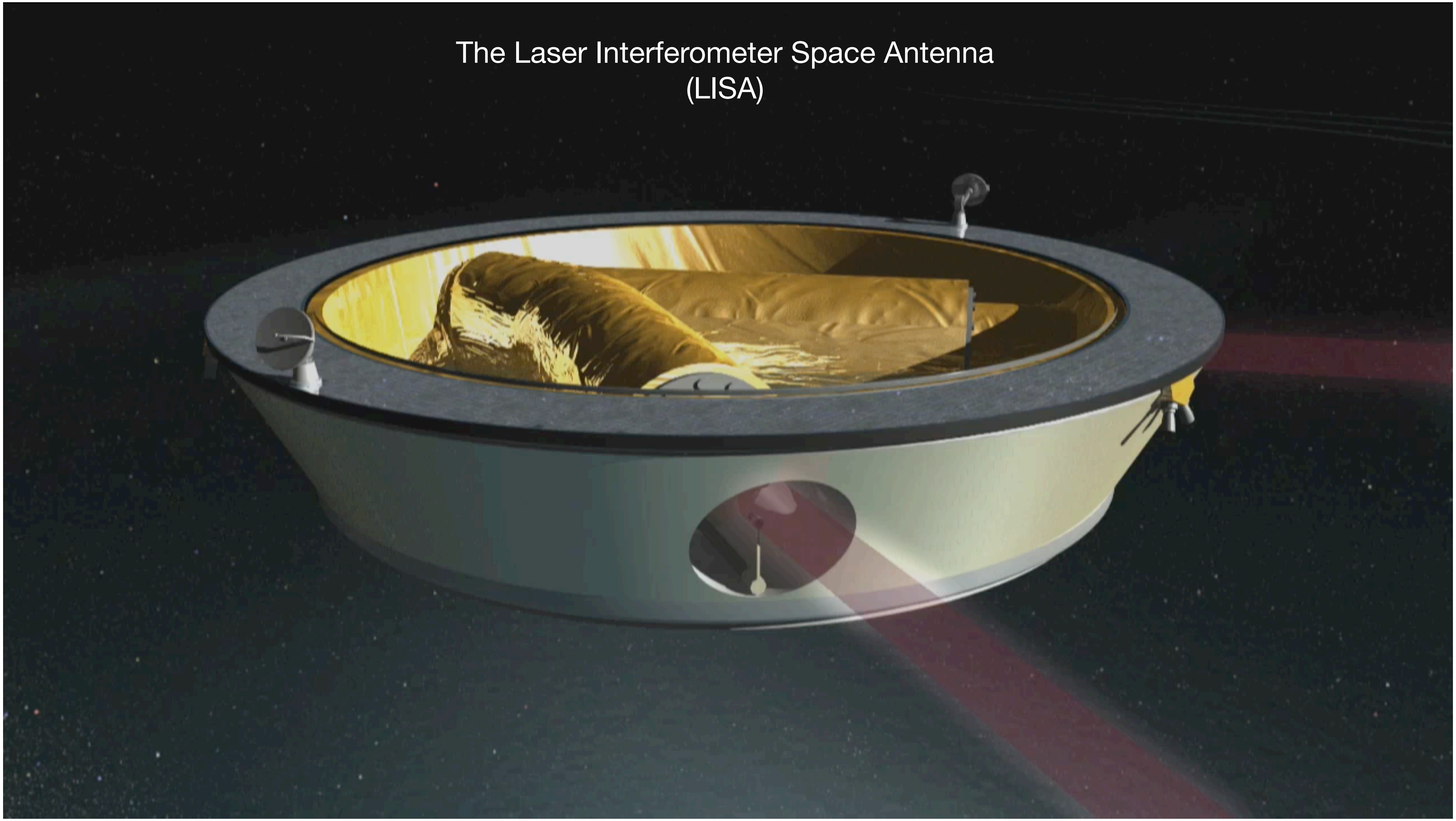
The neutrino gravitational memory from a core collapse supernova: phenomenology and physics potential

MM, C. Cardona, C. Lunardini
JCAP 07 (2021) 055 (arXiv: 2105.05862).

Memory-triggered supernova neutrino detection

MM, Z. Lin, C. Lunardini
Phys.Rev.D 106 (2022) 4, 043020 (arXiv: 2110.14657).

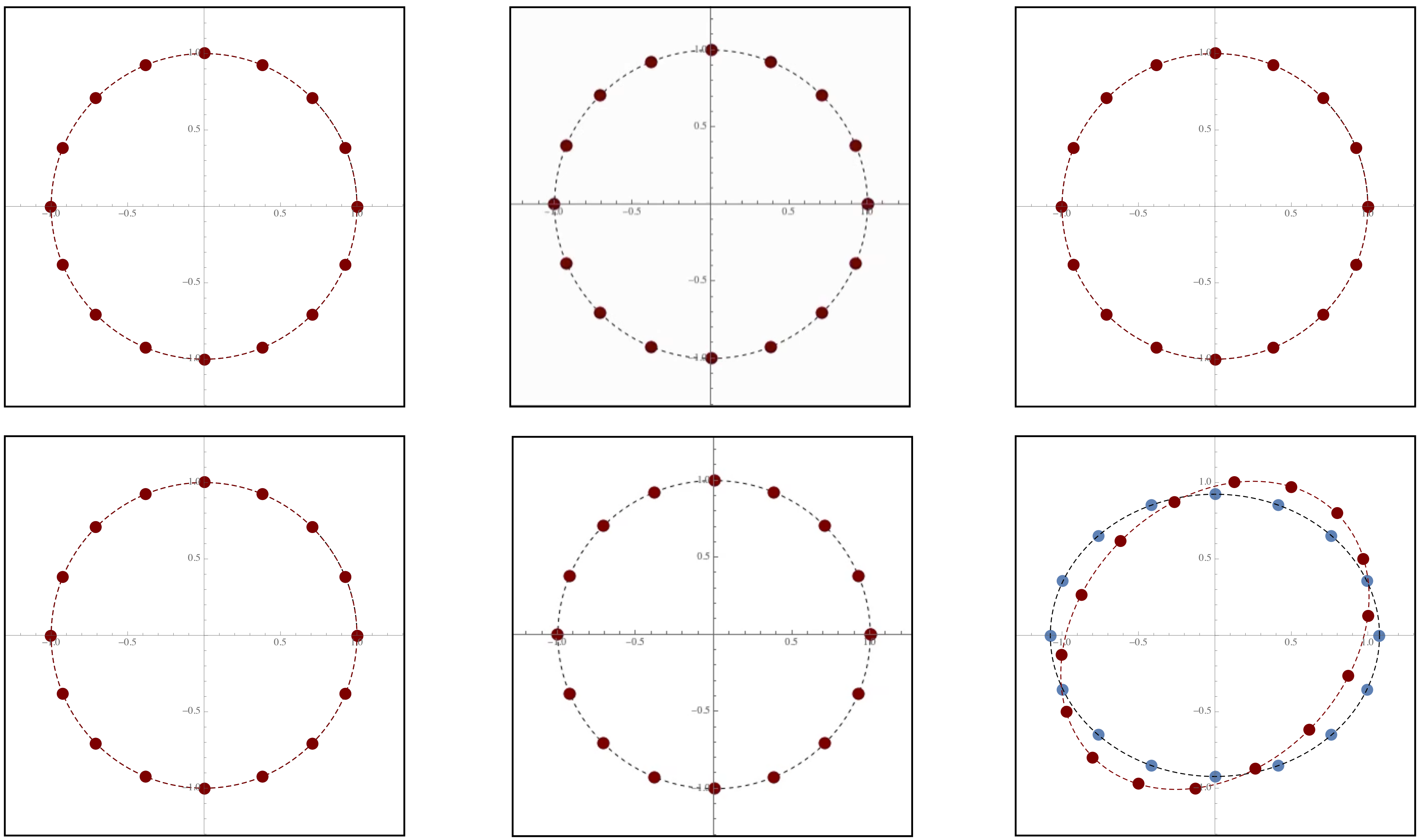
What is Gravitational wave memory?



Animation Credits: Chris Meaney and NASA

What is Gravitational wave memory?

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



Without memory

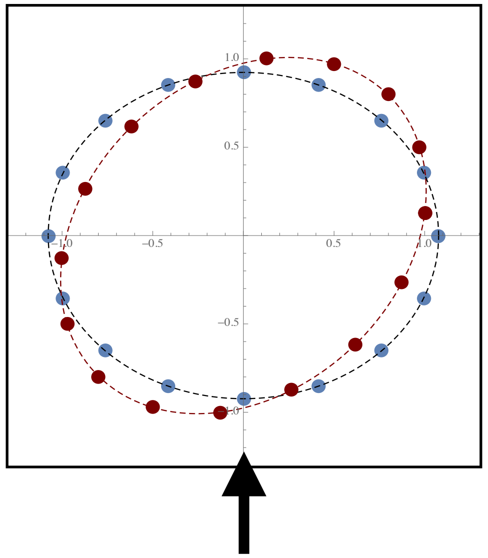
With memory

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

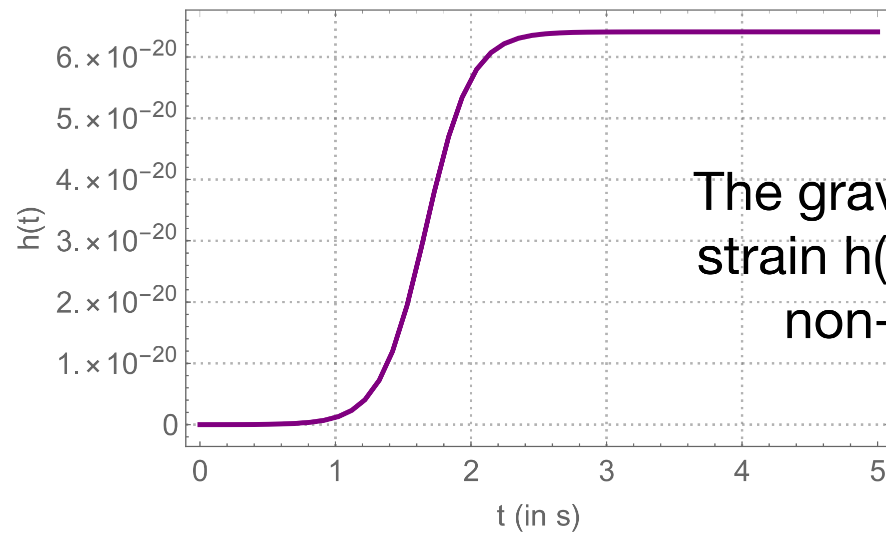
GW is propagating perpendicular to the screen

Animation Credits: Joel Frederico

What is Gravitational wave memory?



Permanent distortion of the local space-time metric



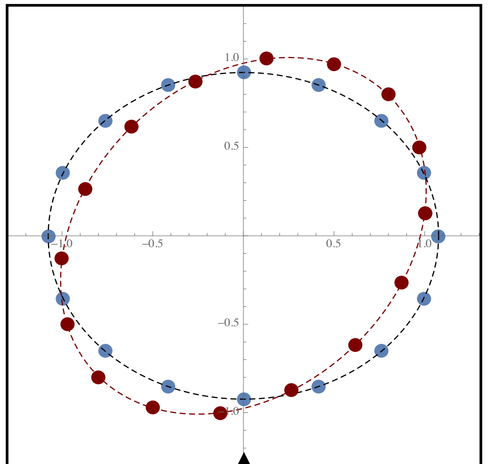
The gravitational wave strain h(t) remains at a non-zero value

Causes:

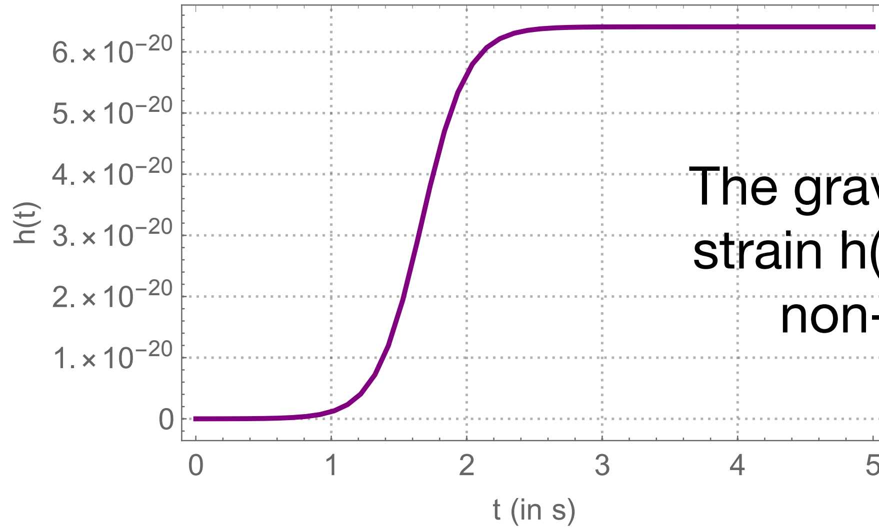
Gravitationally unbound systems:
Anisotropic emission of energy (mass/radiation)

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

What is Gravitational wave 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)

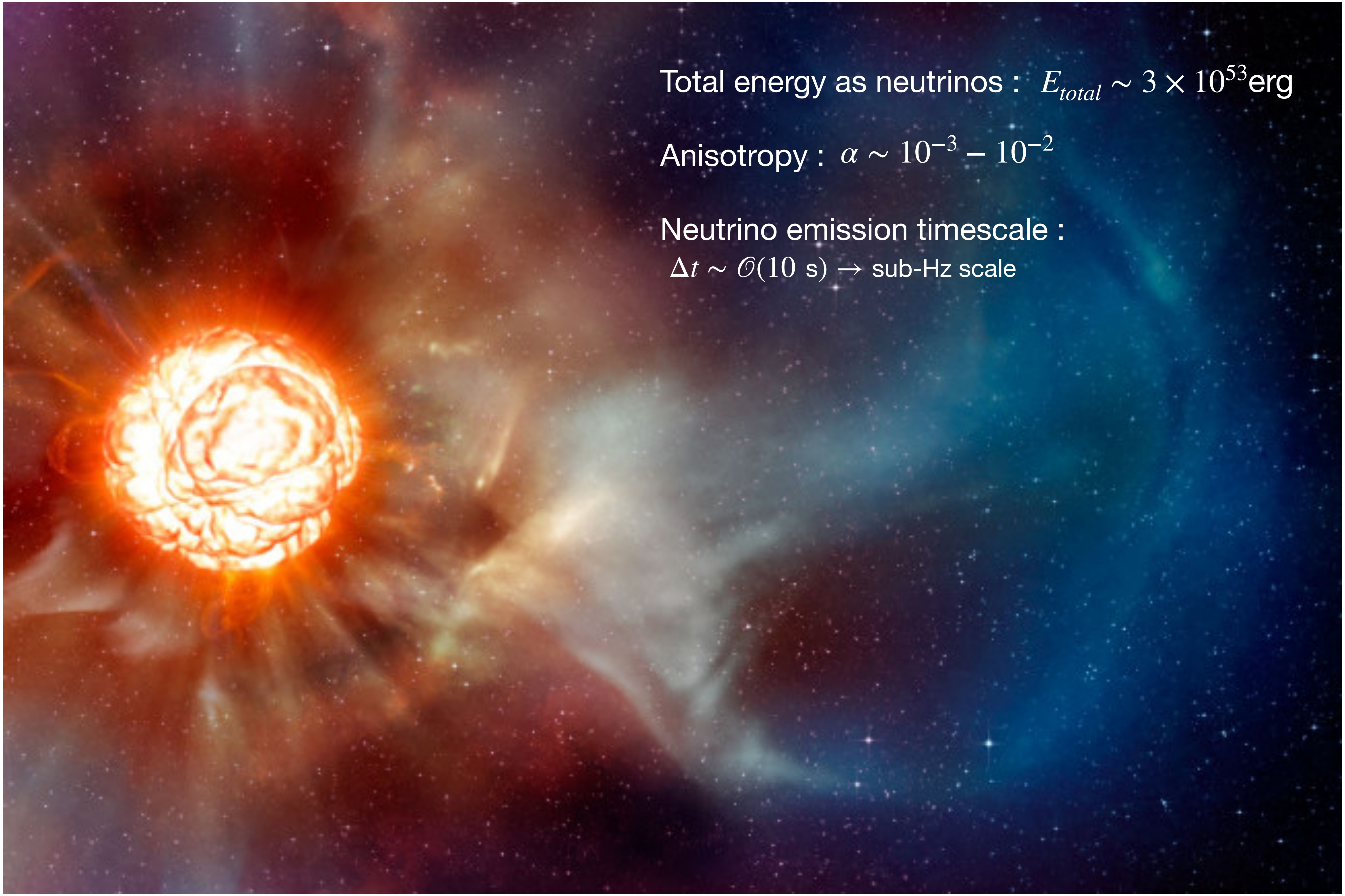
<u>The GW memory has never been observed!</u>

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: CCSN



Credits: European Southern Observatory, L. Calçada

Motivations - ν GW memory from CCSN

The SN ν GW memory has never been observed!

Large number of next-generation sub-Hz interferometers :

Space-based interferometers:

DECIGO (DECi-hertz Gravitational-wave Observatory)
BBO (Big Bang Observer)
ALIA (Advanced Laser Interferometer Antenna)
LISA (Laser Interferometer Space Antenna)
AMIGO (Astrodynamical Middle-frequency Interferometric Gravitational wave Observatory)

Atom-interferometers:

MAGIS (Mid-band Atomic Gravitational Wave Interferometric Sensor)
AEDGE (Atomic Experiment for Dark matter and Gravity Exploration in space)
AION (Atom Interferometer Observatory and Network)
ELGAR (European Laboratory for Gravitation and Atom-interferometric Research)
ZAIGA (Zhaoshan long-baseline Atom Interferometer Gravitation Antenna)

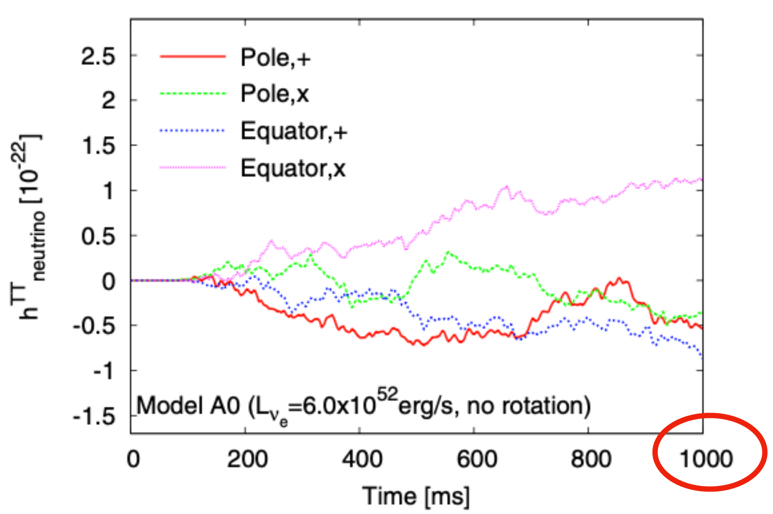
Motivations - ν GW memory from CCSN

The SN ν GW memory has never been observed!

Large number of next-generation sub-Hz interferometers

Numerical simulations are computationally very intense, costly and hence limited to ~ 1 s :

Fig. Credits: Kei Kotake et al 2011 ApJ 736 124



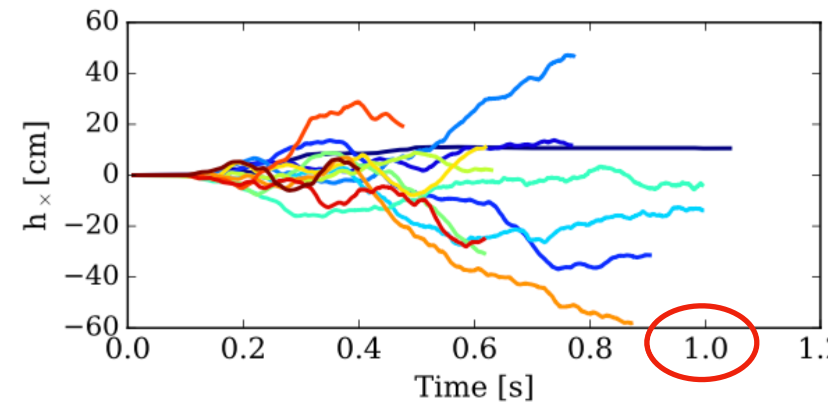


Fig. Credits: Vartanyan and Burrows, Astrophys. J. 901 (2020) 108.

Motivations - ν GW memory from CCSN

The SN ν GW memory has never been observed!

Large number of next-generation sub-Hz interferometers

Numerical simulations are computationally very intense, costly and hence limited to ~ 1 s :

Phenomenological models help in supplementing the numerical simulations.

Extend to longer times of neutrino emission, thus giving a plausible picture of the memory contribution from the neutrinos for the entire duration of emission.

Provides a description which can then be adapted to different scenarios - Large/small progenitors, case with/without rotation.

References

Theory :

Zel'dovich and Polnarev, Sov. Astron. 18 (1974) 17.
Braginskii. And Thorne, Nature 327 (1987) 123.
Epstein, Astrophys. J. 223 (1978) 565.
M. Favata, The gravitational-wave memory effect, Class. Quant. Grav. 27 (2010) 084036

Phenomenology of neutrino memory :

Sago, Ioka, Nakamura and Yamazaki, Phys. Rev. D 70 (2004) 104012.
Suwa and Murase, Physical Review D 80 (2009).
Li, Fuller and Kishimoto, Phys. Rev. D 98 (2018) 023002.

Numerical Simulations :

Burrows and Hayes, Phys. Rev. Lett. 76 (1996) 352.
Mueller and Janka, AAP 317 (1997) 140.
Kotake, Ohnishi and Yamada, The Astrophysical Journal 655 (2007) 406.
Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951.
Muller, Janka and Wongwathanarat, Astron. Astrophysik. J. 537 (2012) A63.
Yakunin et al., Phys. Rev. D 92 (2015) 084040.
Vartanyan and Burrows, Astrophys. J. 901 (2020) 108.
Vartanyan, Burrows, Wang, Coleman and White, Phys. Rev. D 107, 103015 (2023)

Picture Credits: Stephane Andre

Phenomenological Model: Formalism

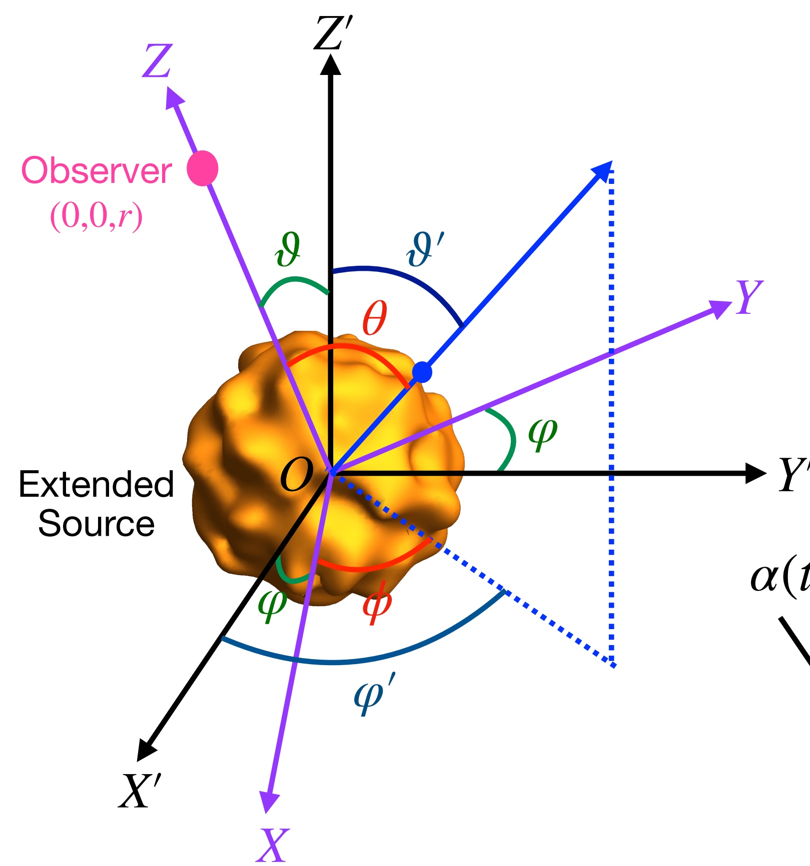
Begin with Einstein's field equation:

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

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

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

Small perturbation



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

Angular dependence put together in anisotropy parameter

Black Box….

(Calculations in progress)

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

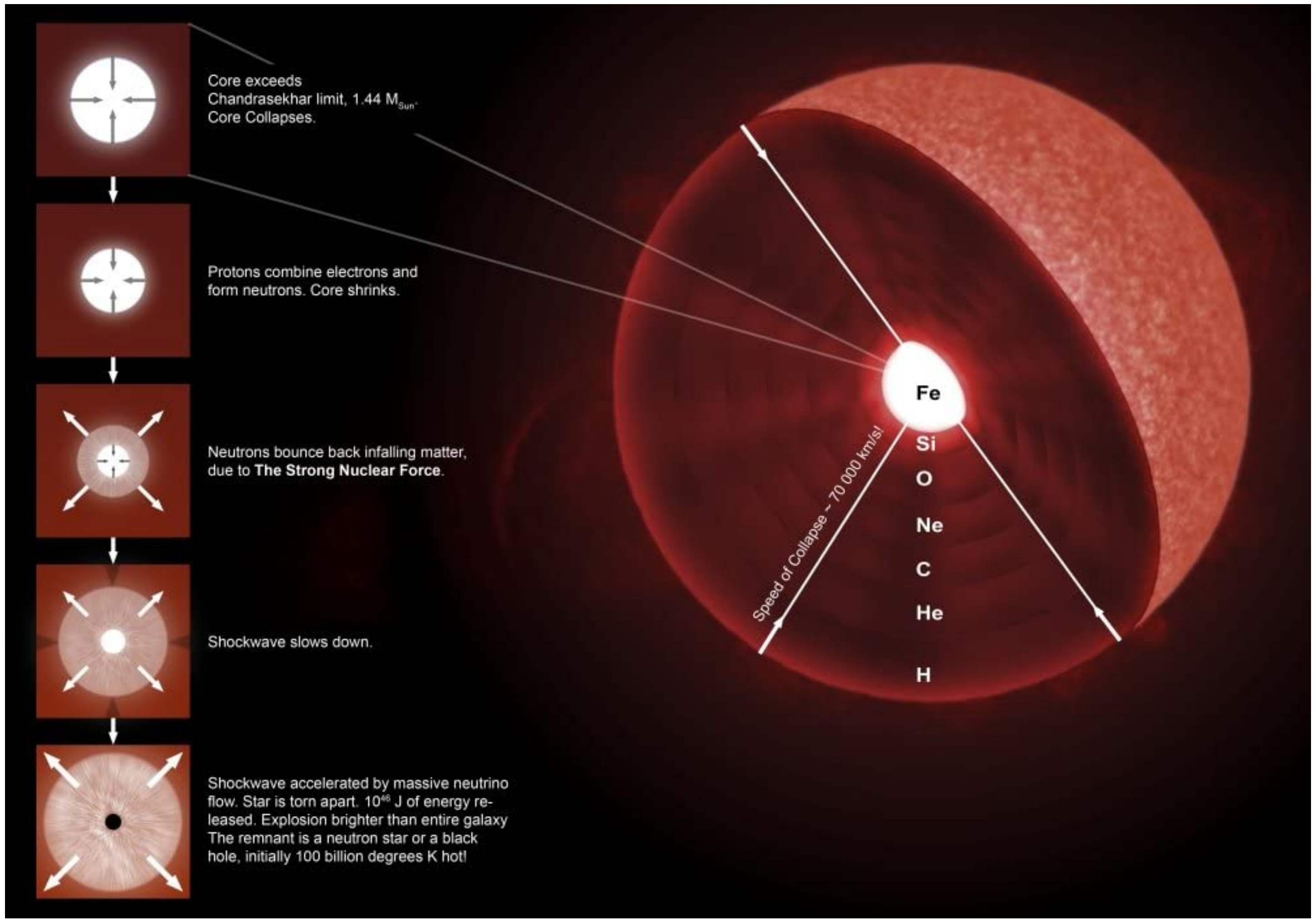
Change of separation for two free-falling masses

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

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

Core-collpase supernovae (CCSNe)

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

↓

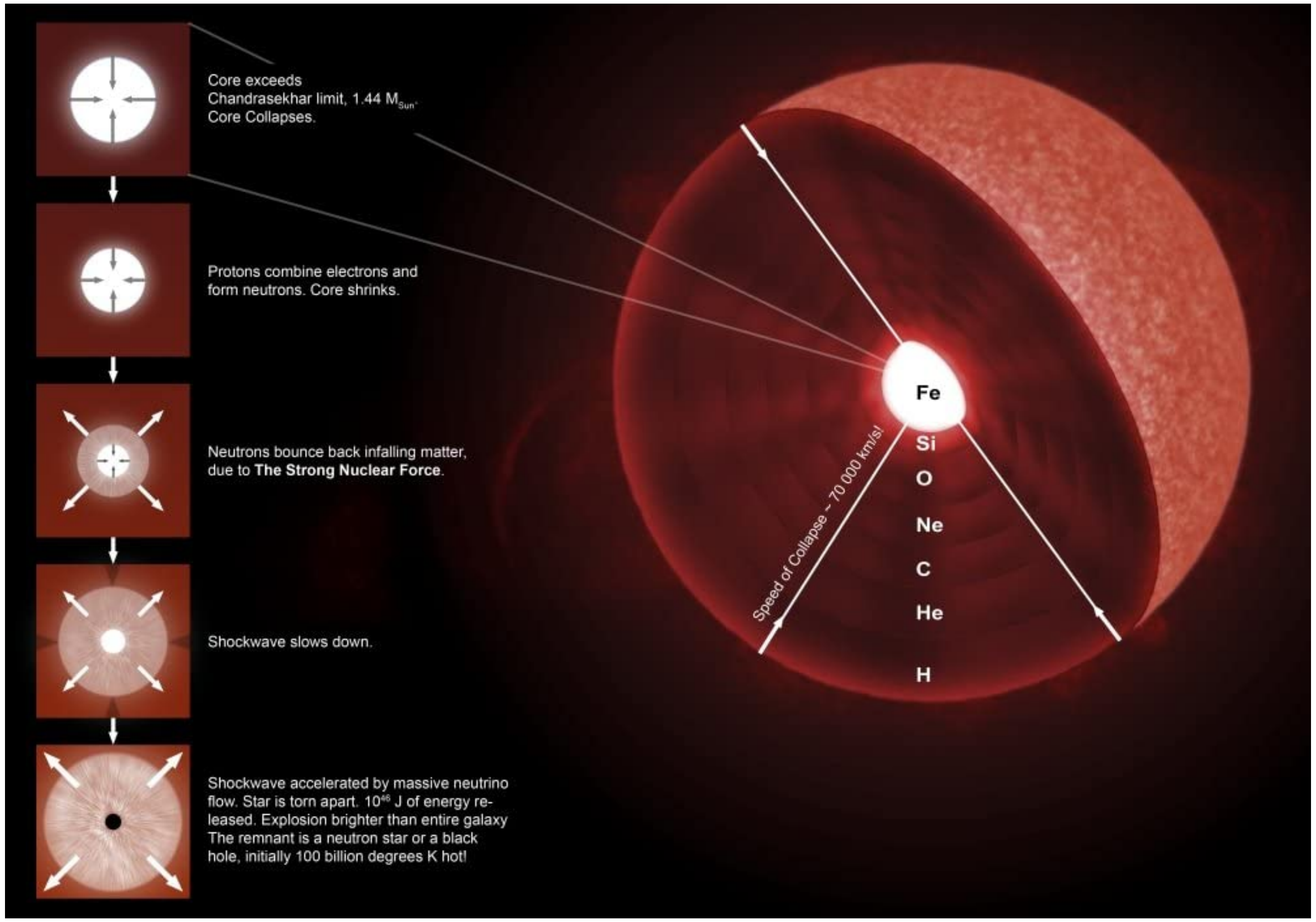
Shockwave stalls

- → 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

Core-collpase supernovae (CCSNe)

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

↓

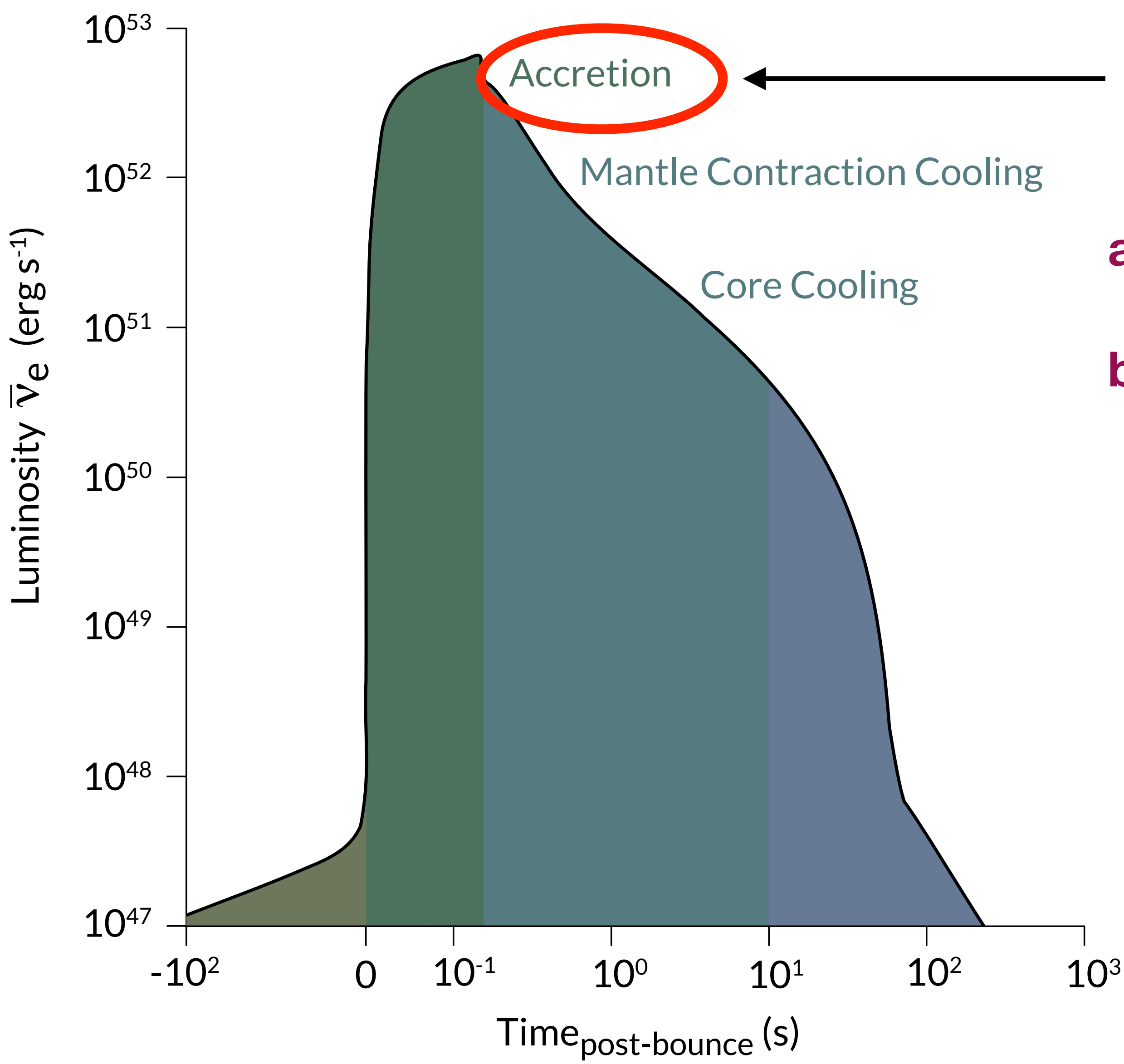
Star explodes: Supernova

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)

The anisotropy parameter α

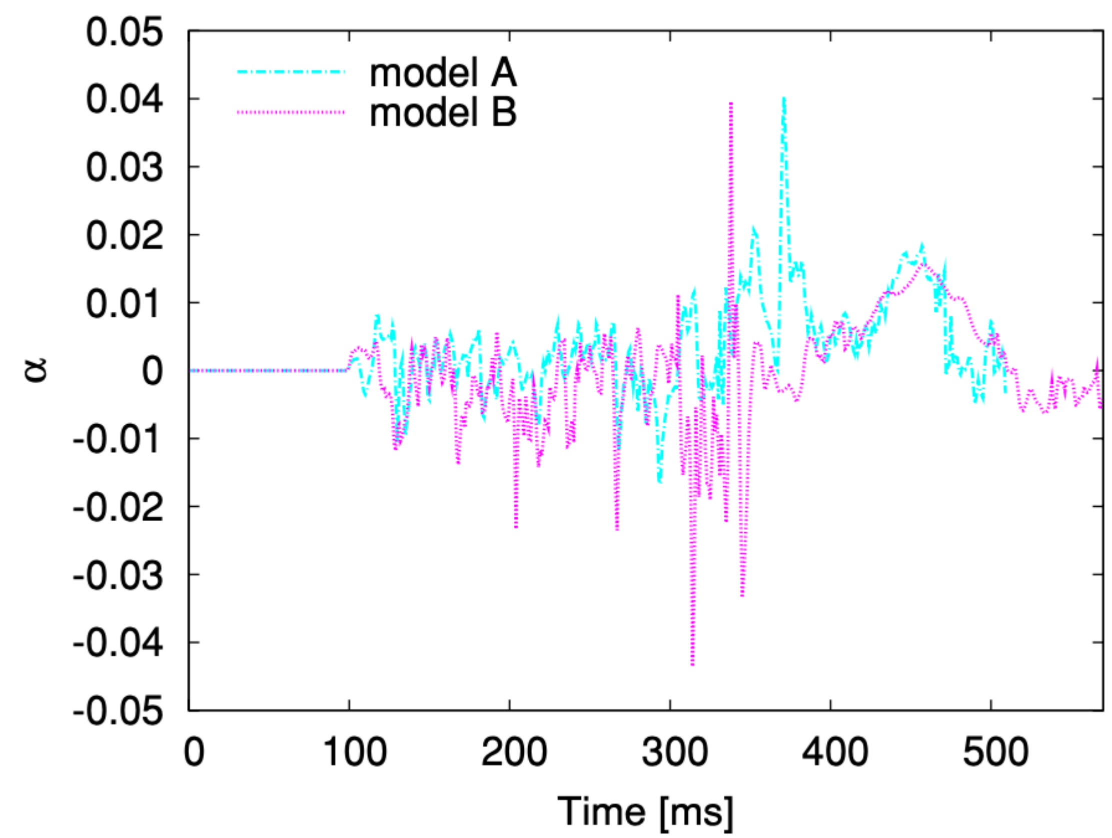


Following
Li, Roberts & Beacom,
2020

Anisotropy develops during accretion phase, due to:

a) Convection

b) SASI (Standing Accretion Shock Instability)



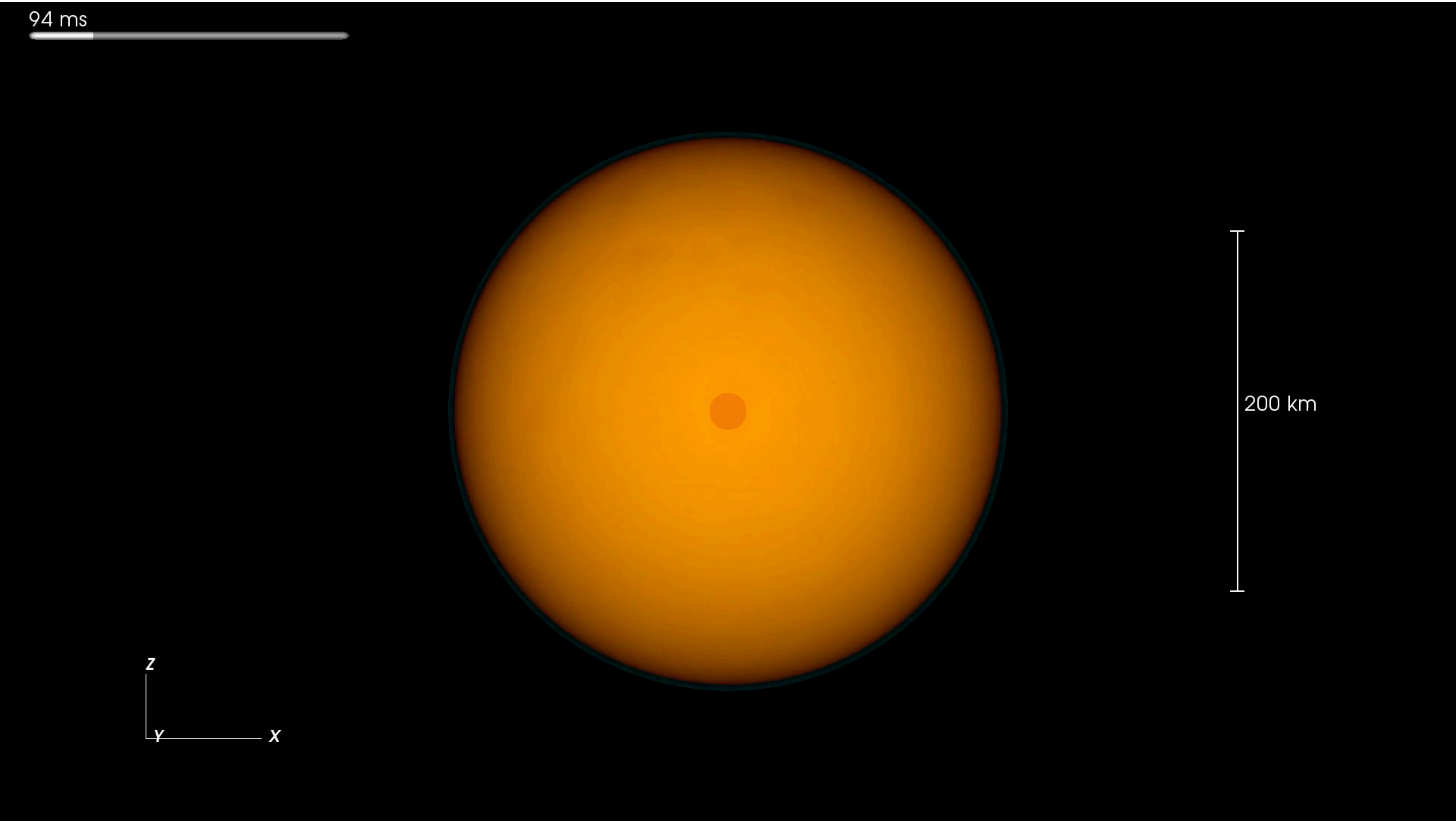
$\mathcal{O}\left(10^{-2}\right)$ for 2-D simulations

$\mathcal{O}\left(10^{-3}\right)$ for 3-D simulations

Fig. Credits: Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951

Graphics by: Frank Timmes

Development of anisotropy in the progenitor



Hanke et al., 2013, ApJ, 770, 66
Visualization by Elena Erastova and Markus Rampp, MPCDF

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 $\alpha(t)$: $h_{1j}, \rho_j, \tau_{1j}, h_{2j}, \tau_{2j}, h_3$

In frequency space,

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

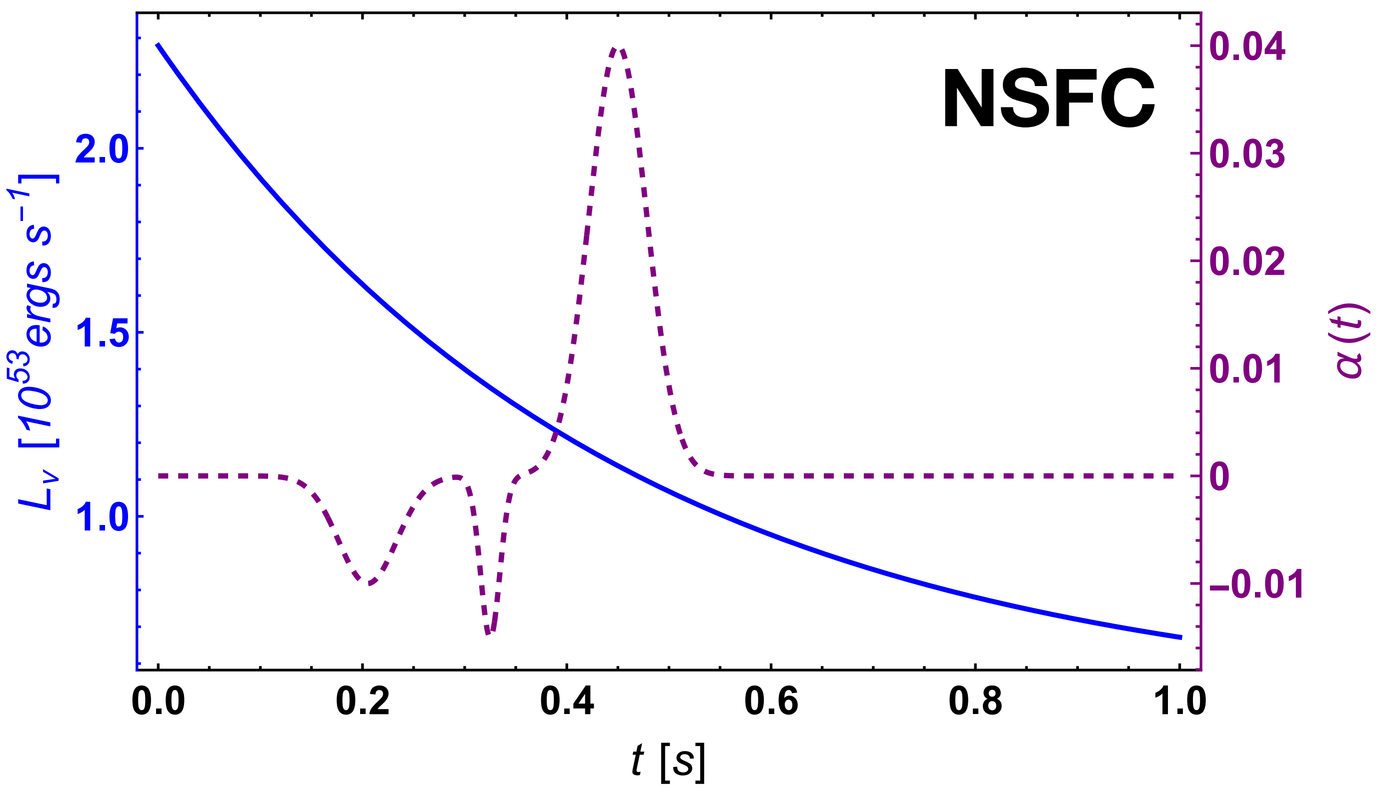
Characteristic strain $h_c(f)$:

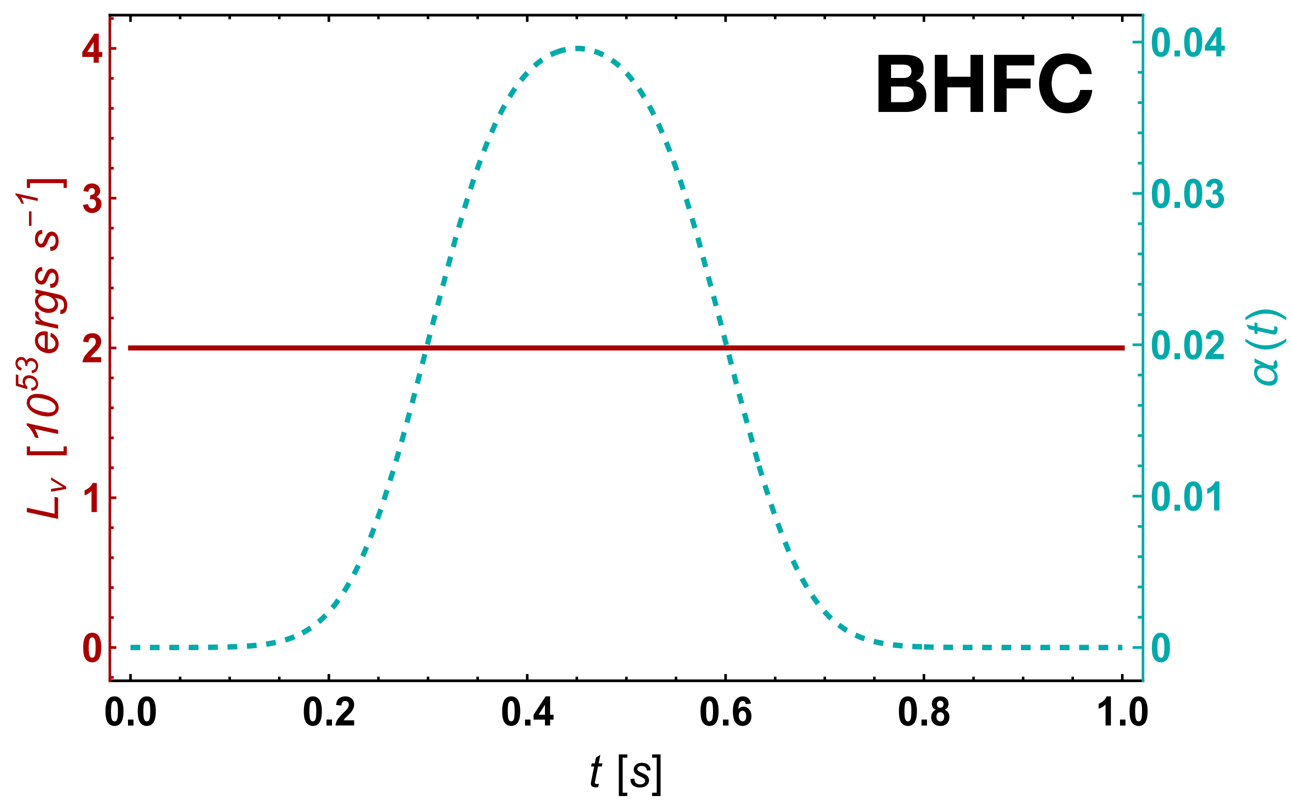
Dimensionless quantity.

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

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

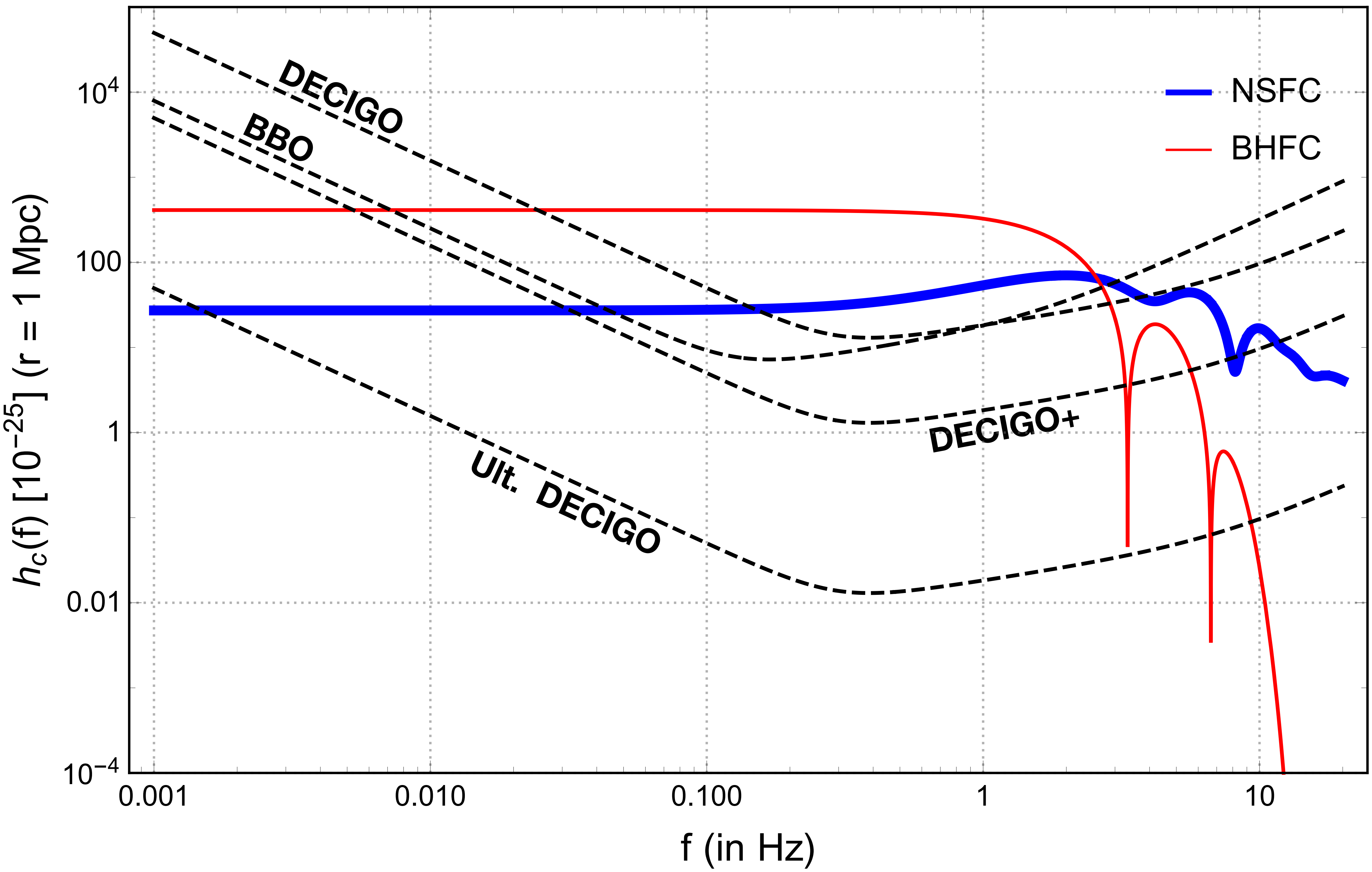
Models


NSFC
L_ν [10^{53}ergs s^{-1}]
2.0
1.5
1.0
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]


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

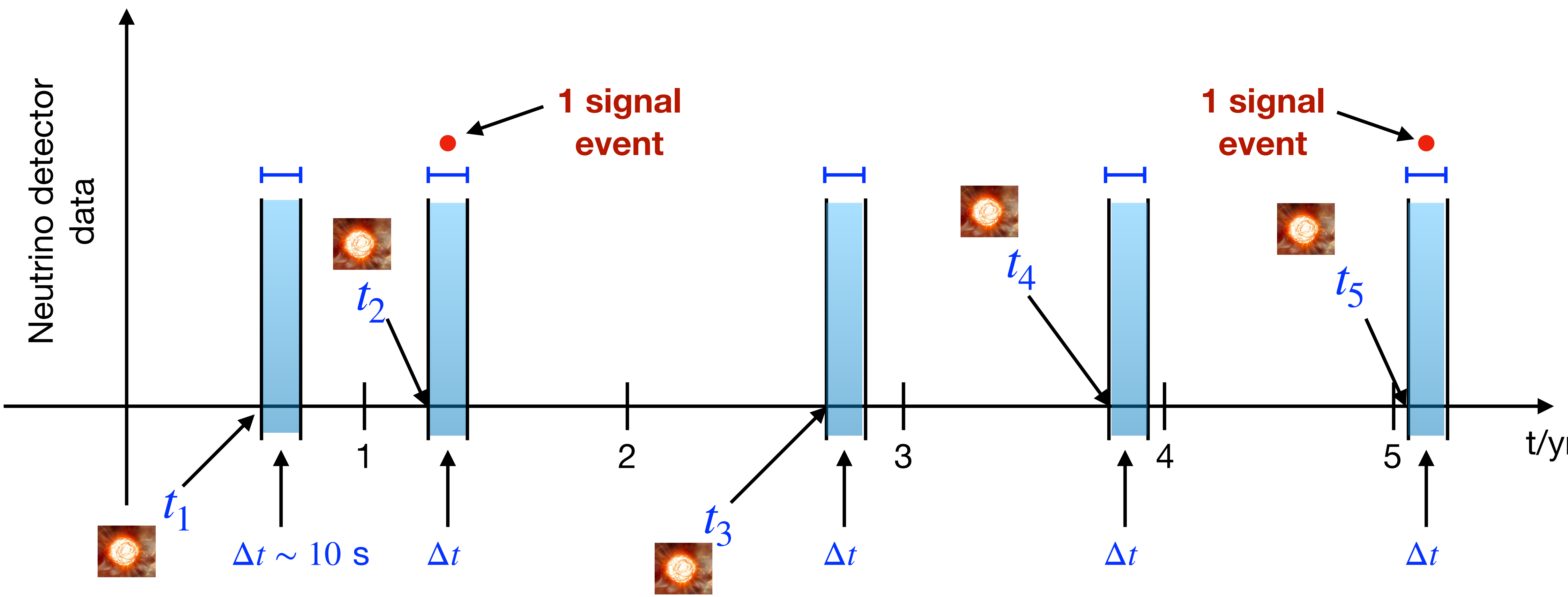
Characteristic strain (r = 1 Mpc)

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



Memory triggered SN neutrino detection

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



Motivations for memory-triggered searches

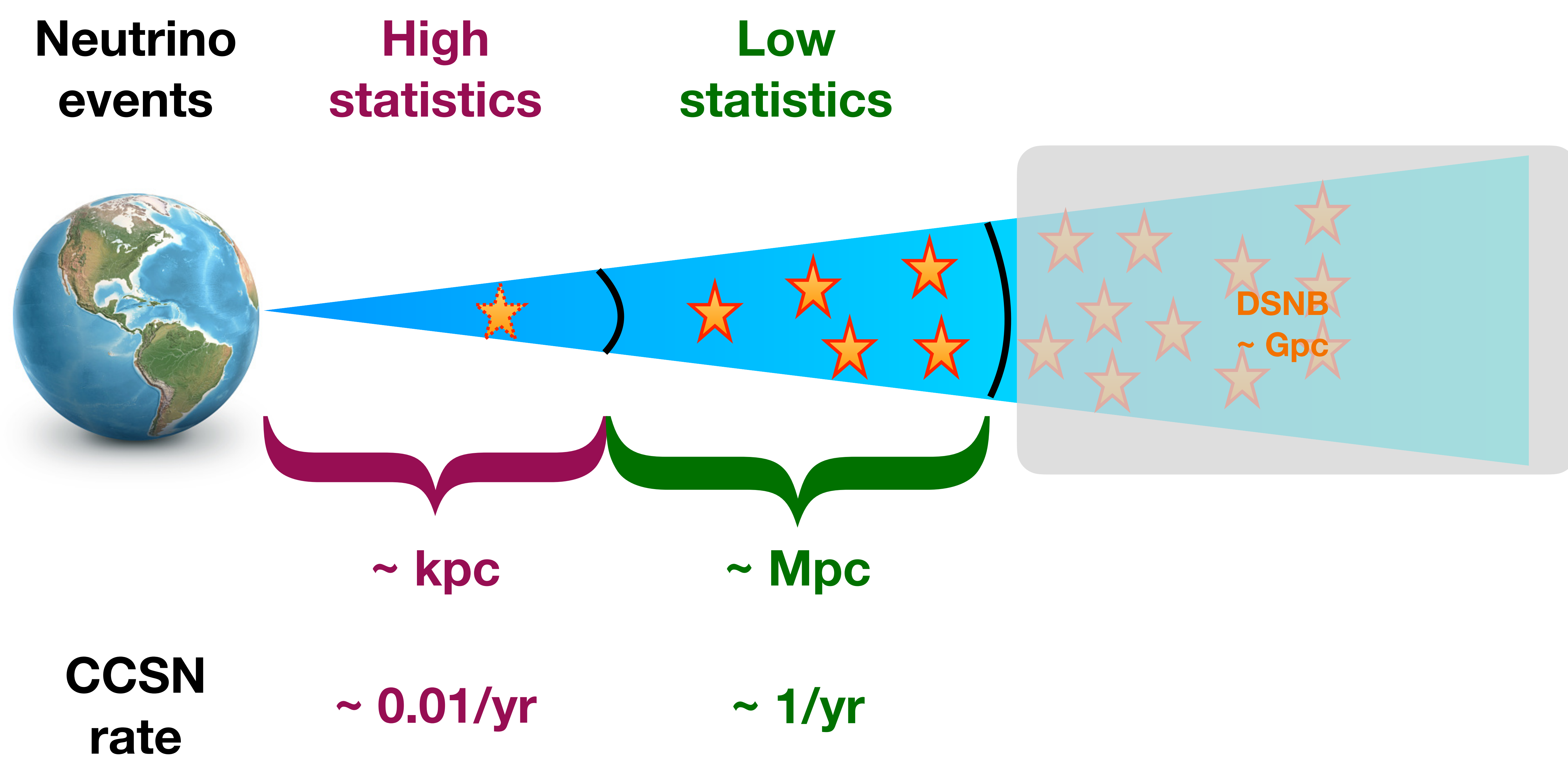
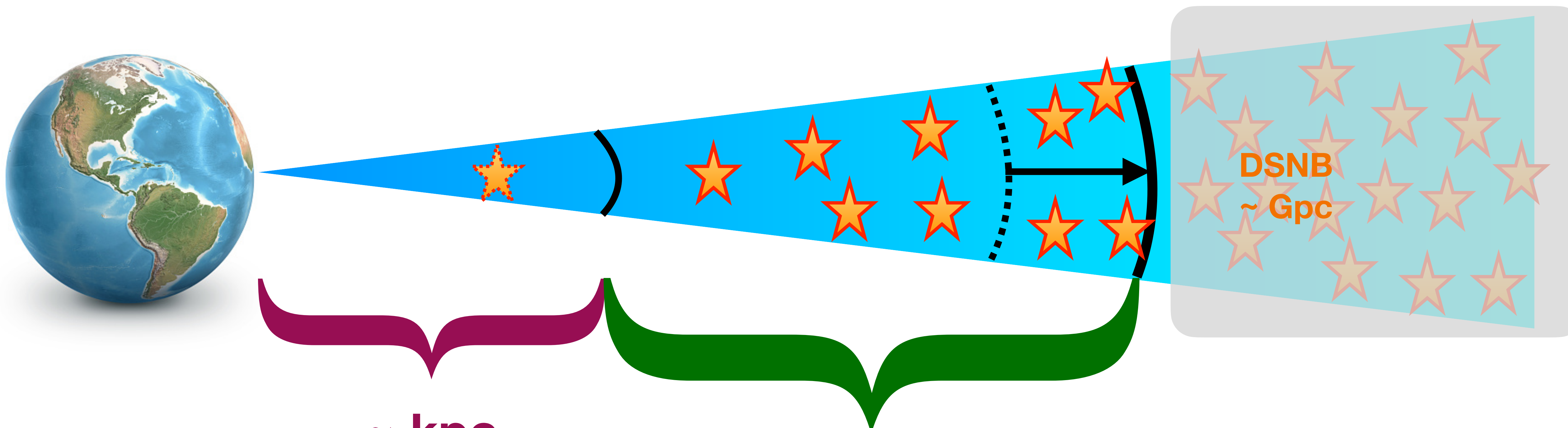


Fig. Motivation: John Beacom, TAUP, Munich, Germany, Sept 2011

Motivations for memory-triggered searches

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



	~ 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 memory-triggered searches

WHY?

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

Comparison with DSNB or Galactic CCSNe

Understanding SN populations including NSFC and BHFC

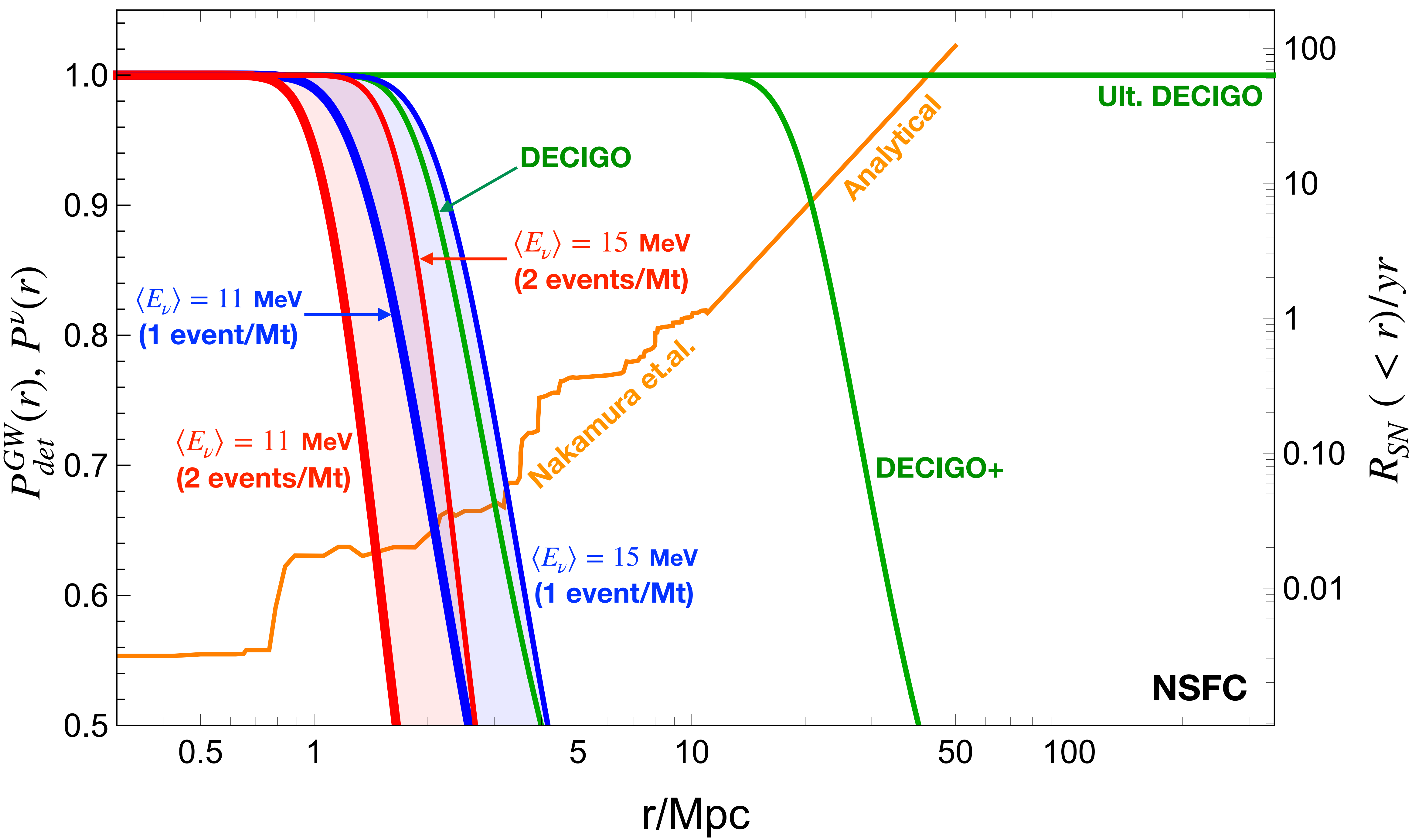
and much more….

CHALLENGES:

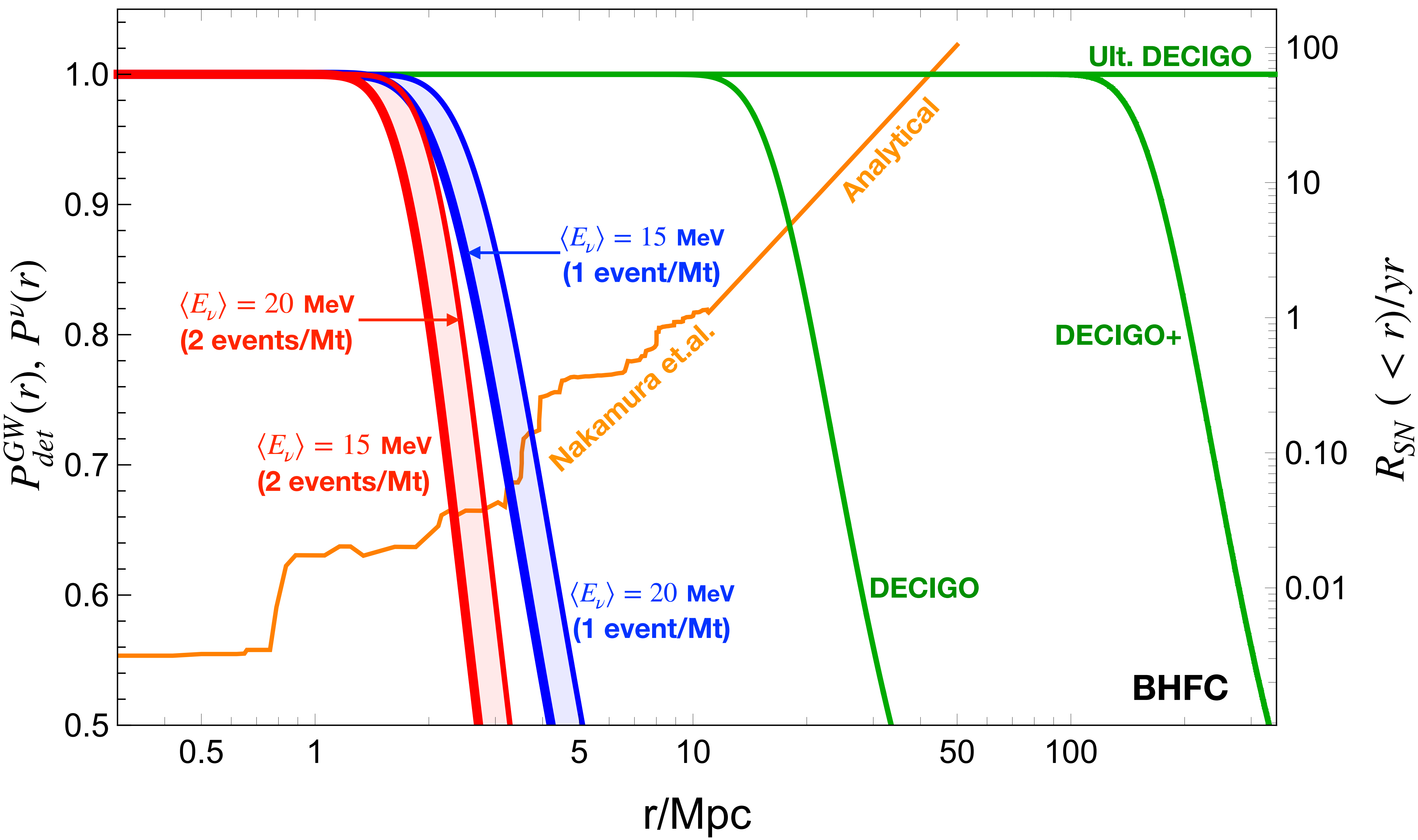
CCSNe in immediate neighborhood are extremely rare

Limited distance ~ 1-3 Mpc to have significant statistics

Detection probabilities and CCSN rates



Detection probabilities and CCSN rates



Recipe in brief

Detector running time

CCSN rate in the galaxy *j*

Predicted number of neutrino events in detector from a CCSN in the galaxy *j*

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

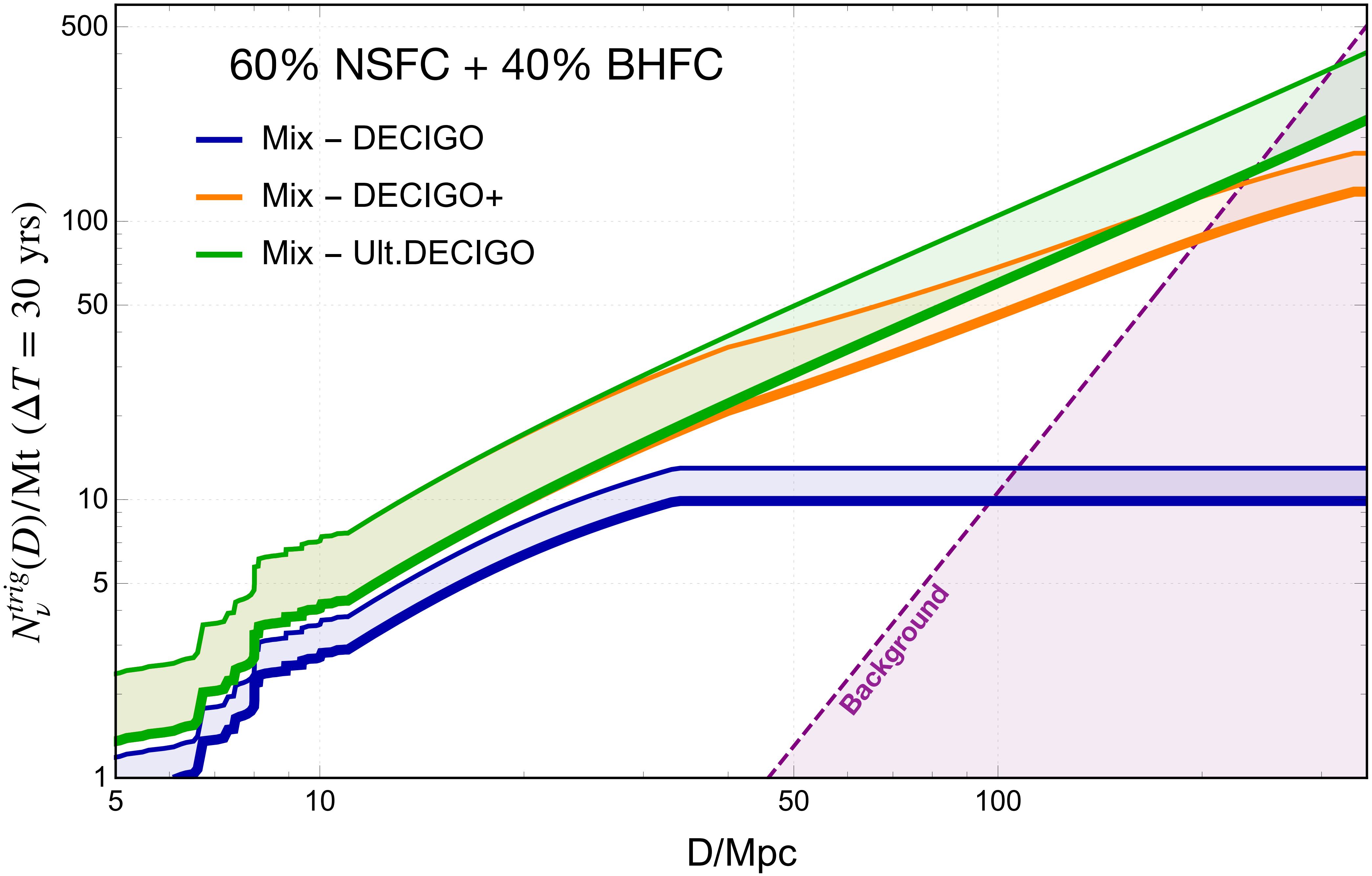
Total number of memory-triggered neutrino events from all CCSN within a distance D

Index of the galaxy, *j=1,2,….*

Distance to the galaxy *j*

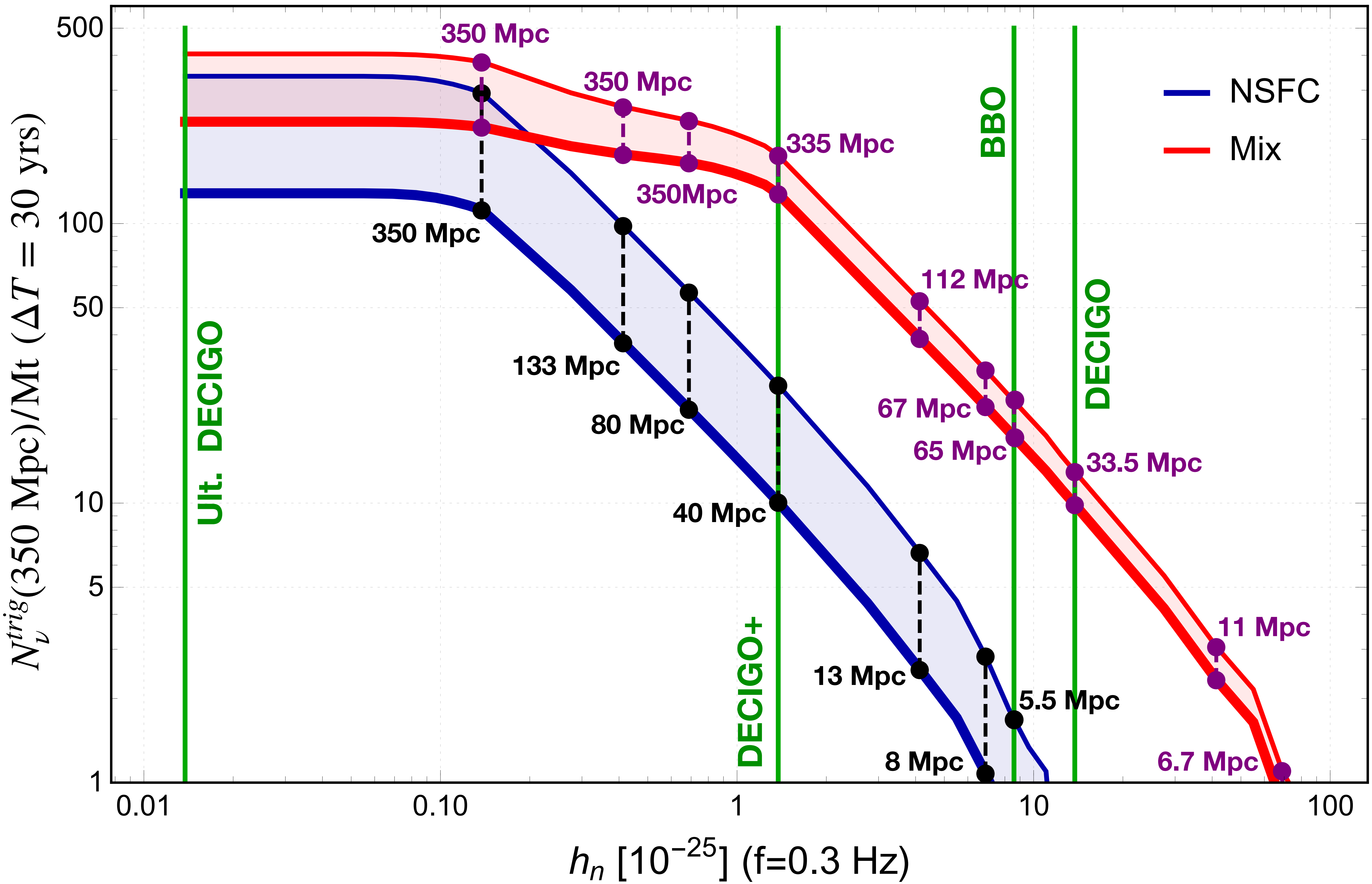
Probability of detecting the memory from a CCSN in the galaxy *j*

Results: Events and background



Untriggered backgrounds would be orders of magnitude higher!

Overview: for GW experimental groups



Takeaways

The SN neutrino memory is detectable at DeciHz interferometers

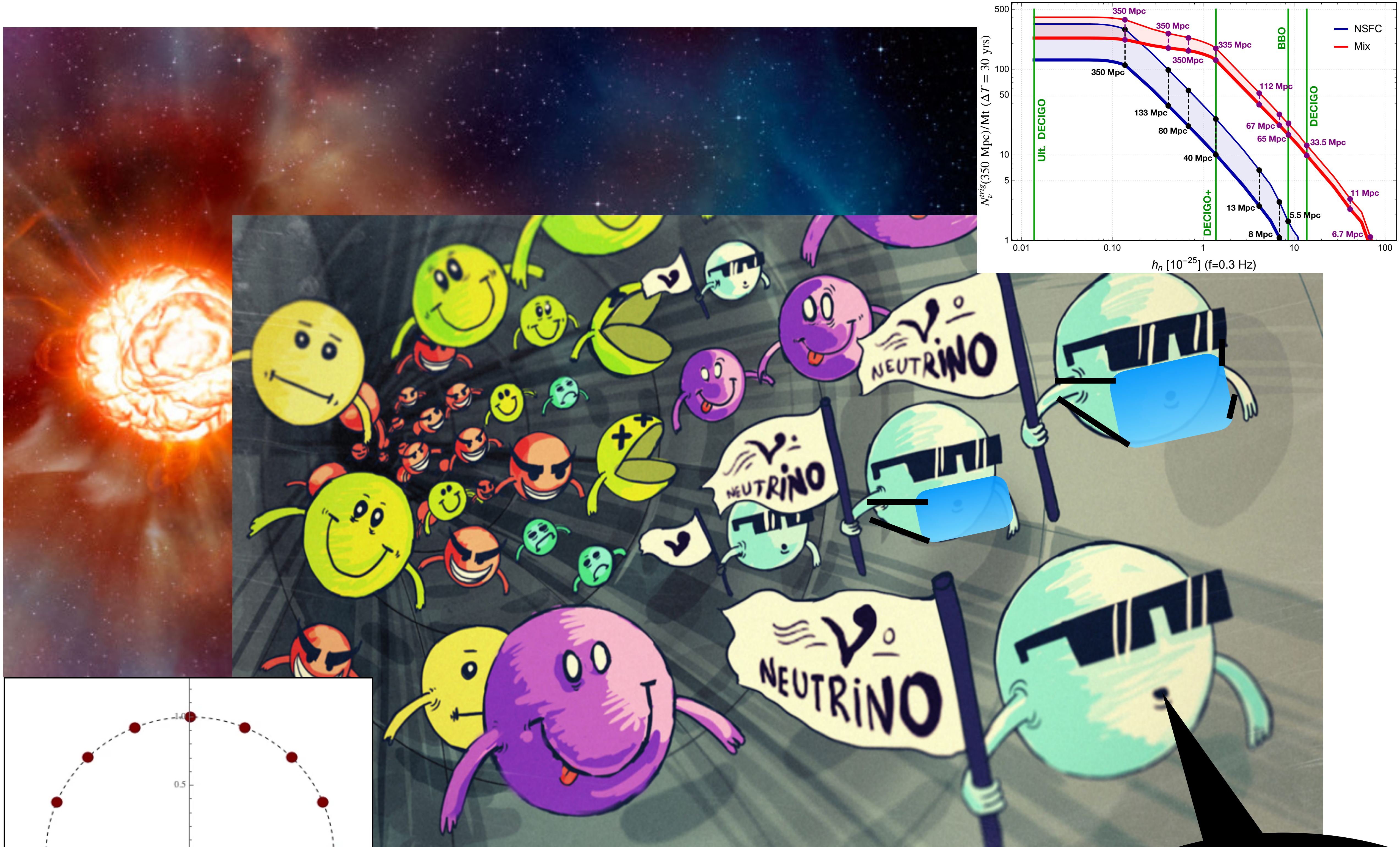
- This work provides a **new phenomenological model** which is: a) **consistent with numerical simulations**, b) **completely analytical** which is useful for phenomenological studies, detector response studies, data fits, etc.

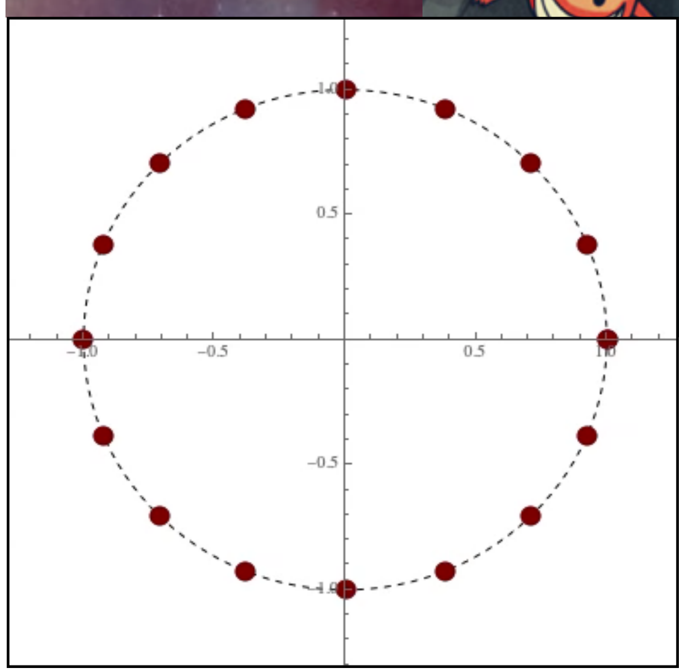
- Helps in providing a plausible picture by **complementing the numerical simulations which are computationally intensive**.

New multi-messenger approach to CCSNe: neutrino GW memory enables time-triggered searches 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.





Thank You!

Team Neutrino reporting from a core-collapse supernova!

Backup

Phenomenological Model: Formalism

Begin with Einstein's field equation:

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

↓

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

↓

Wave equation for the perturbation :

$$\Box^2 h_{\mu\nu} = -16\pi G S_{\mu\nu}$$

← Effective stress-energy tensor

$$S_{\mu\nu} = T_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T^{\lambda}_{\lambda}$$

↑ Stress-energy tensor

↓

Solution of the wave equation :
(Retarded Green's function)

$$h_{\mu\nu} = 4G\int d^3\vec{x}'\left(\frac{S_{\mu\nu}(\vec{x}', t - |\vec{x} - \vec{x}'|)}{|\vec{x} - \vec{x}'|}\right)$$

Epstein, Astrophys. J. 223 (1978) 565
S. Weinberg, Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity (1972)
C.W.Misner, K.Thorne and J. Wheeler, Gravitation, W.H. Freeman, San Francisco (1973)

Phenomenological Model: Formalism

$$\vec{n} = \frac{\vec{x}}{r}$$

Rate of energy loss

Ansatz for the source :

$$S^{ij}(t,x) = \frac{(n^i n^j)_{TT}}{r^2} \int_{-\infty}^{\infty} \sigma(t')\ f(\Omega', t')\ \delta(t - t' - r) dt'$$

Angular distribution of emission

Distance to source

TT: Transverse-traceless

Primed coordinate: Coordinate system for source

Epstein, Astrophys. J. 223 (1978) 565

Phenomenological Model: Formalism

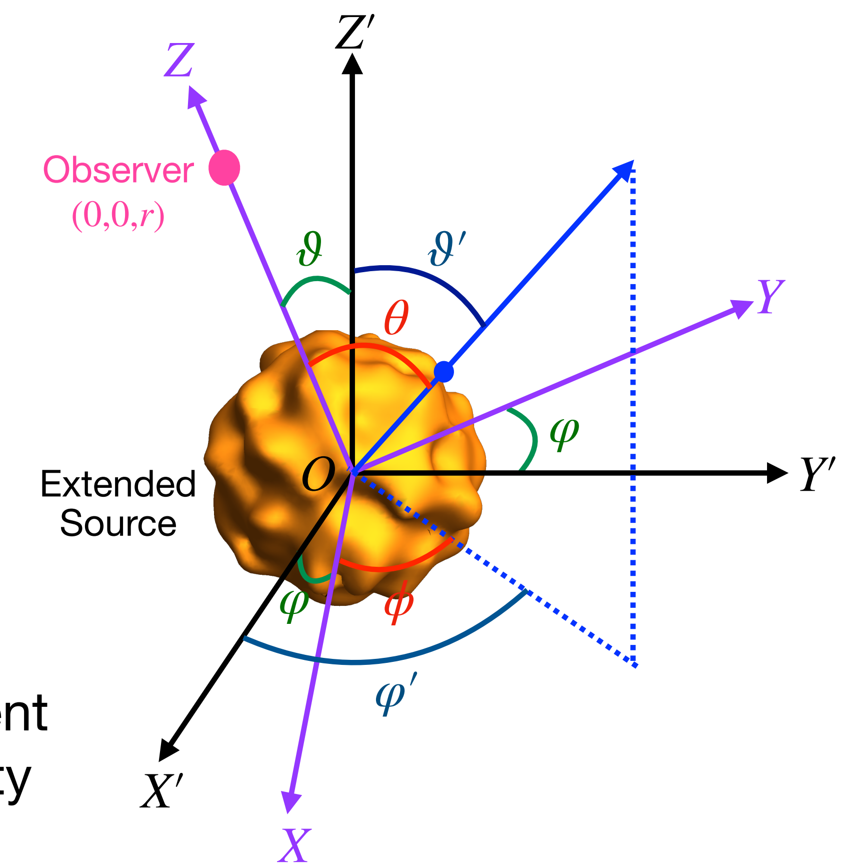
Ansatz for the source :

$$S^{ij}(t,x) = \frac{(n^i n^j)_{TT}}{r^2}\int_{-\infty}^{\infty} \sigma(t')f(\Omega',t')\delta(t-t'-r)dt'$$

$$h_{TT}^{ij}(t,x) = \frac{4G}{rc^4}\int_{-\infty}^{t-r/c} dt' \int_{4\pi} \frac{(n^i n^j)_{TT}}{1-\cos\theta}\frac{dL_\nu(\Omega',t')}{d\Omega'}d\Omega'$$

Direction dependent neutrino luminosity

$$f(\Omega',t')\sigma(t') = \frac{dL_\nu(\Omega',t')}{d\Omega'}$$



Phenomenological Model: Formalism

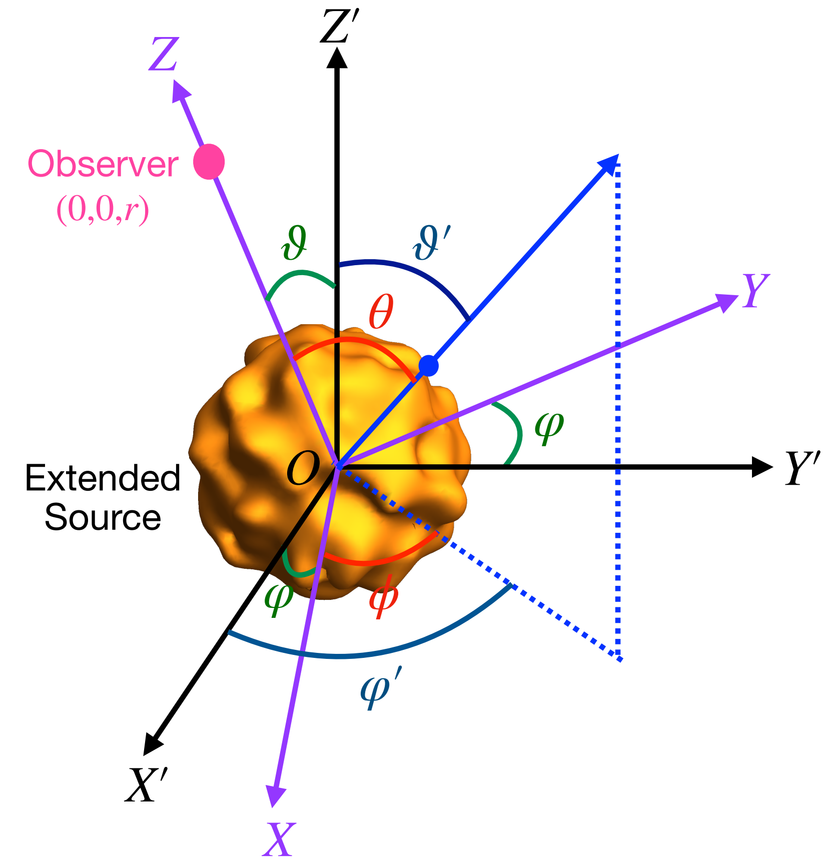
Ansatz for the source : $S^{ij}(t,x) = \dfrac{(n^i n^j)_{TT}}{r^2} \displaystyle\int_{-\infty}^{\infty} \sigma(t')f(\Omega',t')\delta(t-t'-r)dt'$

$\downarrow$

$$h_{TT}^{ij}(t,x) = \frac{4G}{rc^4}\int_{-\infty}^{t-r/c} dt' \int_{4\pi} \frac{(n^i n^j)_{TT}}{1-\cos\theta}\frac{dL_\nu(\Omega',t')}{d\Omega'}d\Omega'$$

$\downarrow$

\+ polarization : $h_{TT}^{xx} = \dfrac{2G}{rc^4}\displaystyle\int_{-\infty}^{t-r/c} dt' \int_{4\pi} (1+\cos\theta)\cos 2\phi \frac{dL_\nu(\Omega',t')}{d\Omega'}d\Omega'$



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

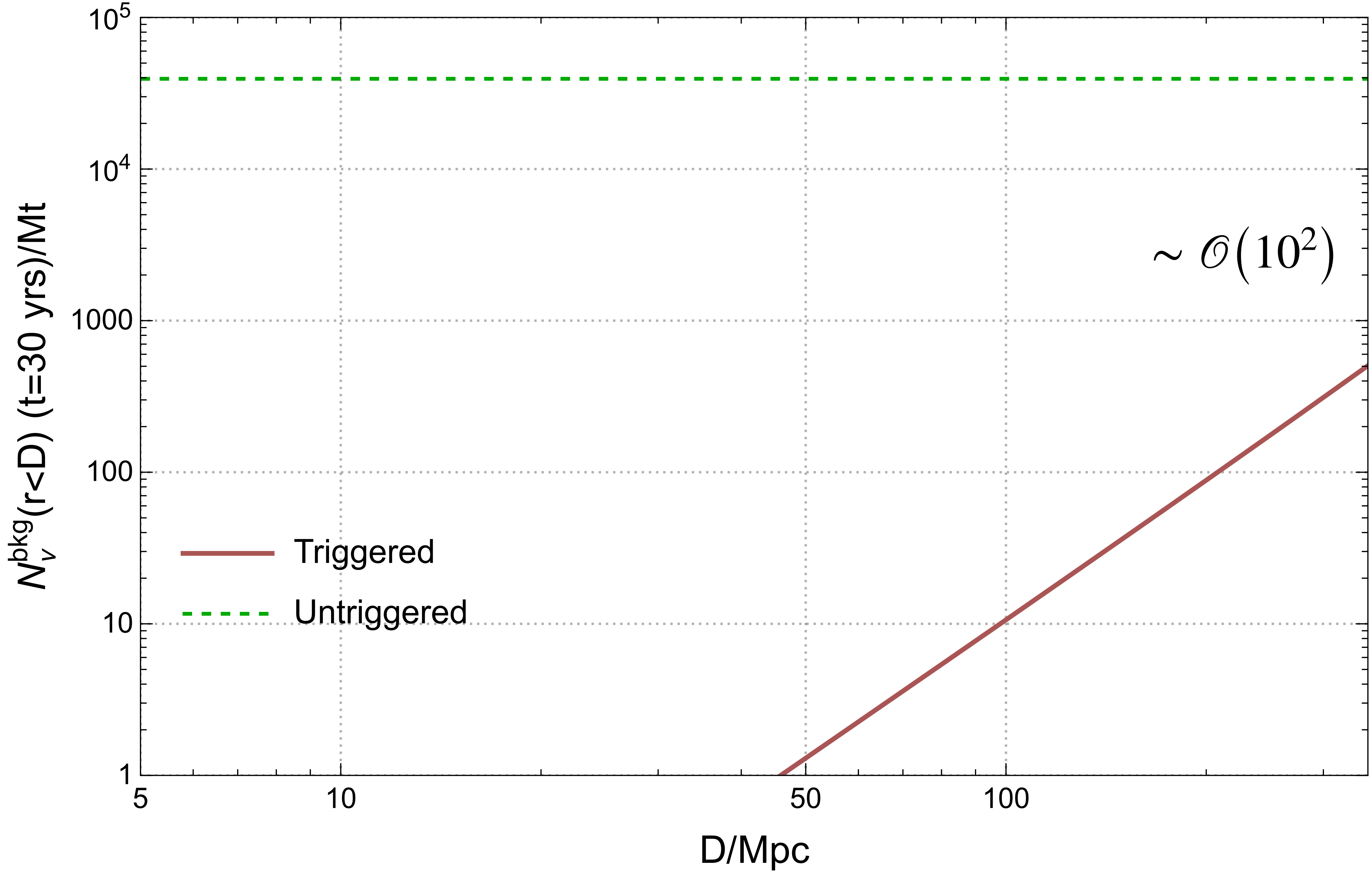
Angular dependence put together in anisotropy parameter

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

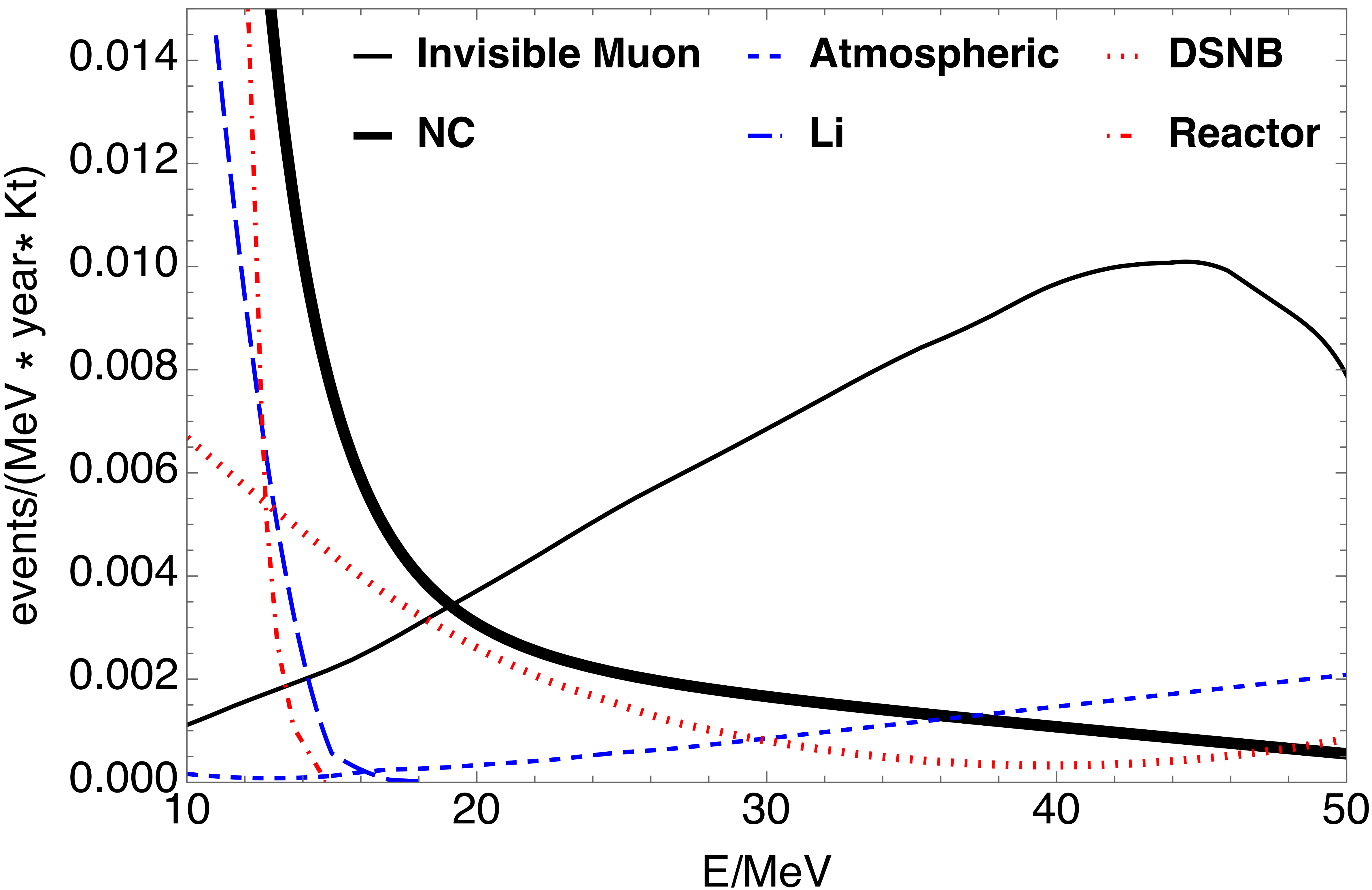
Change of separation for two free-falling masses

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

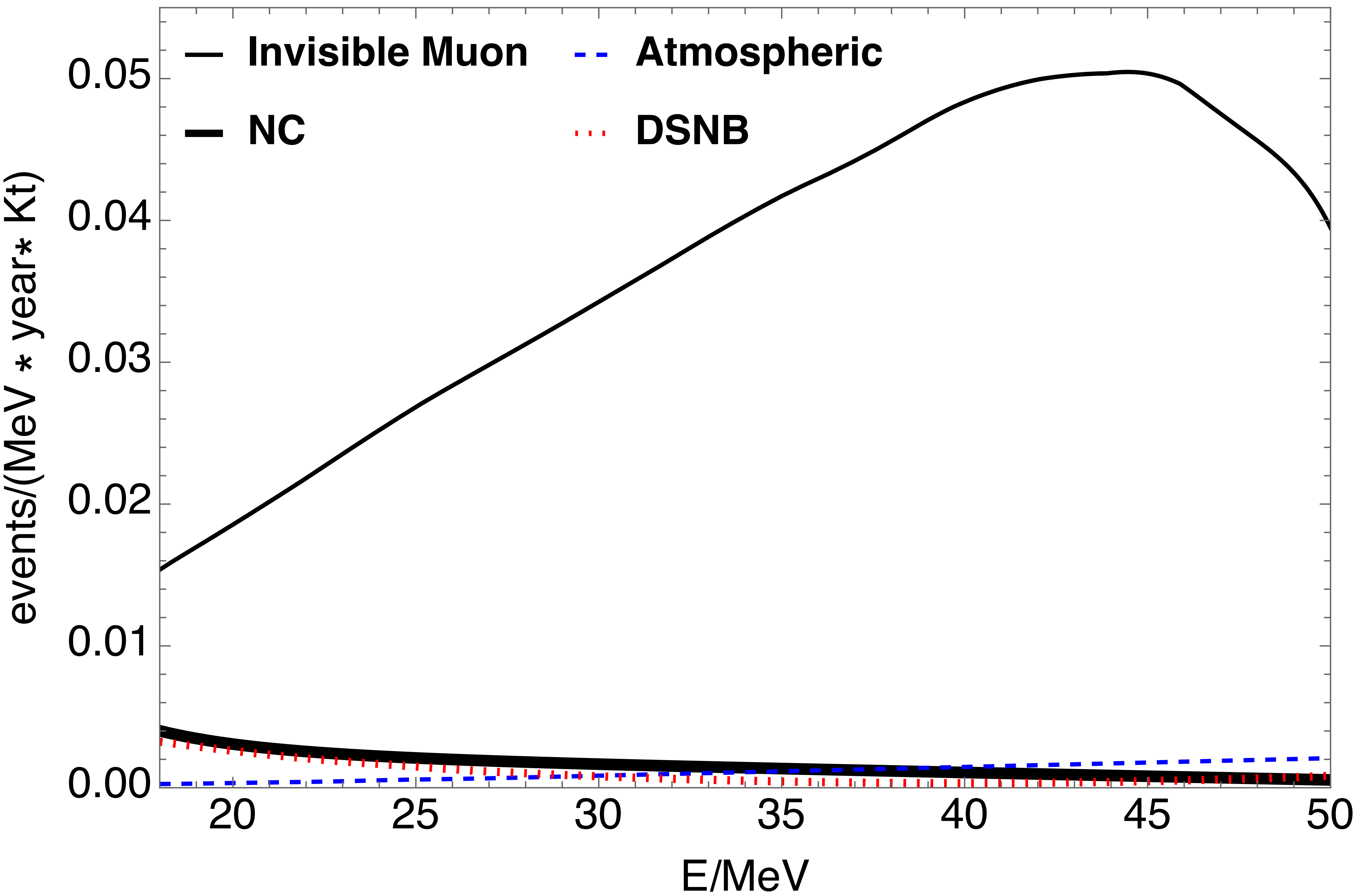
Comparison of backgrounds



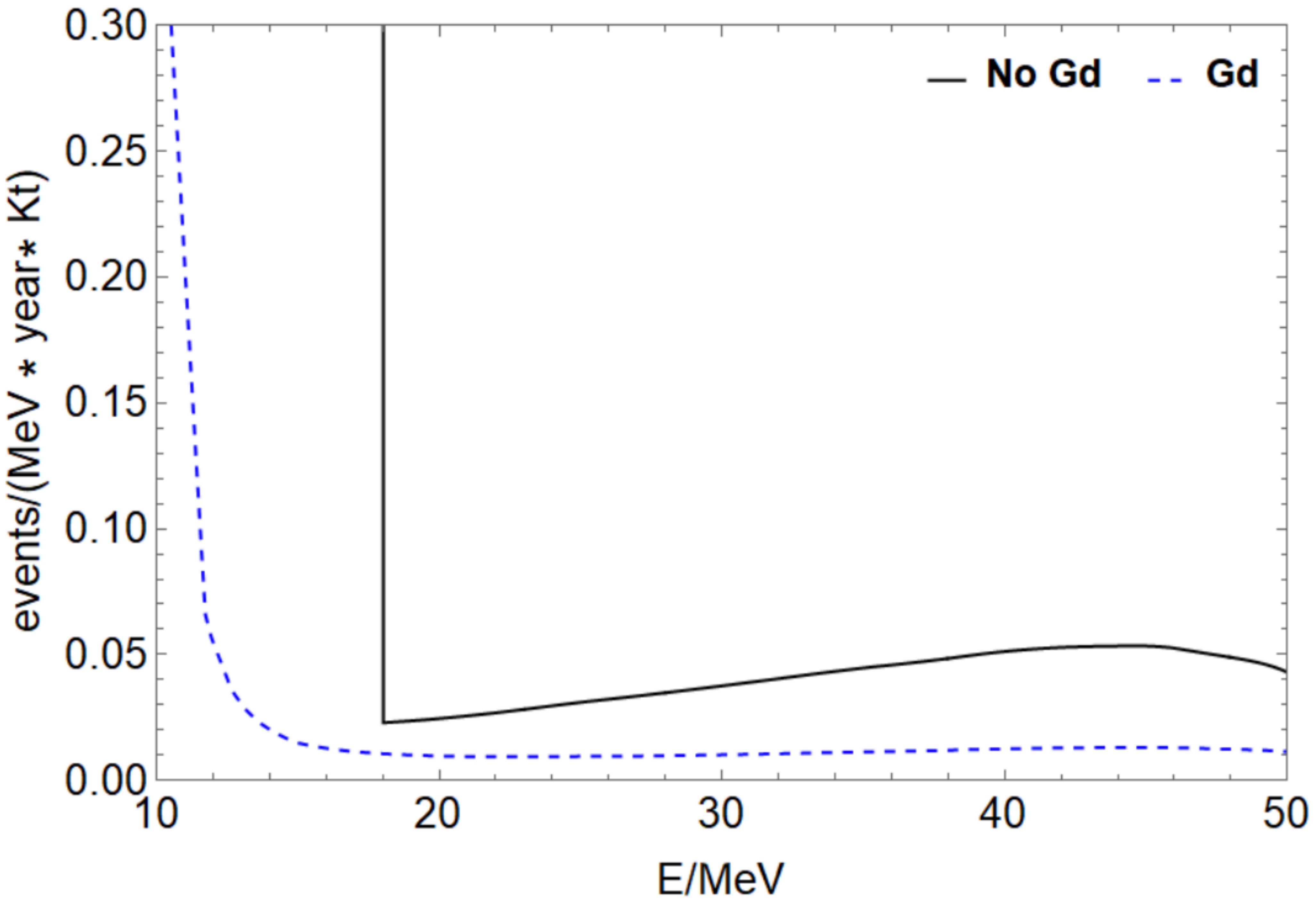
Individual backgrounds in HyperK (with Gd)



Individual backgrounds in HyperK (without Gd)



Total background in HyperK



Details about the SASI movie

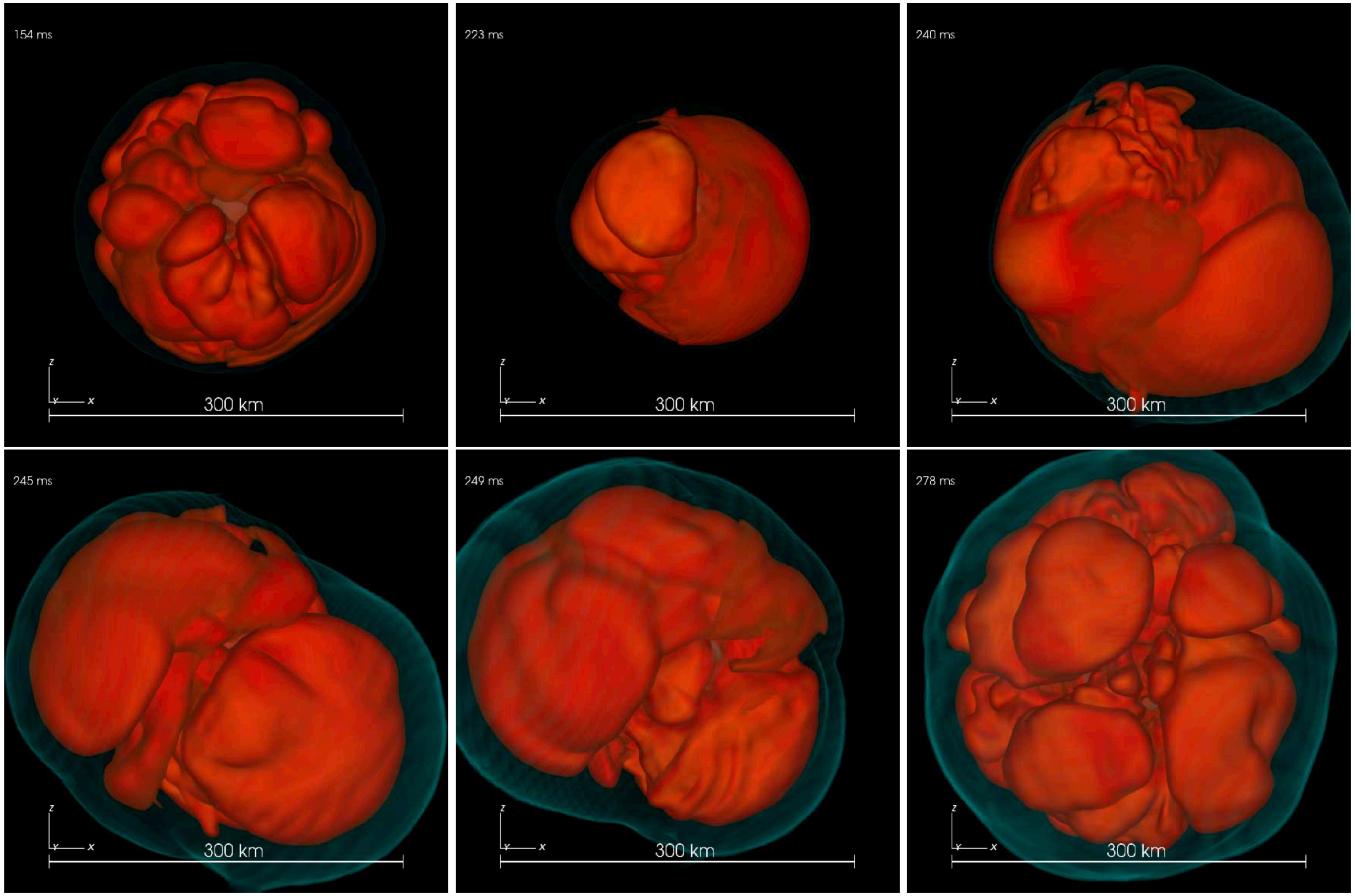
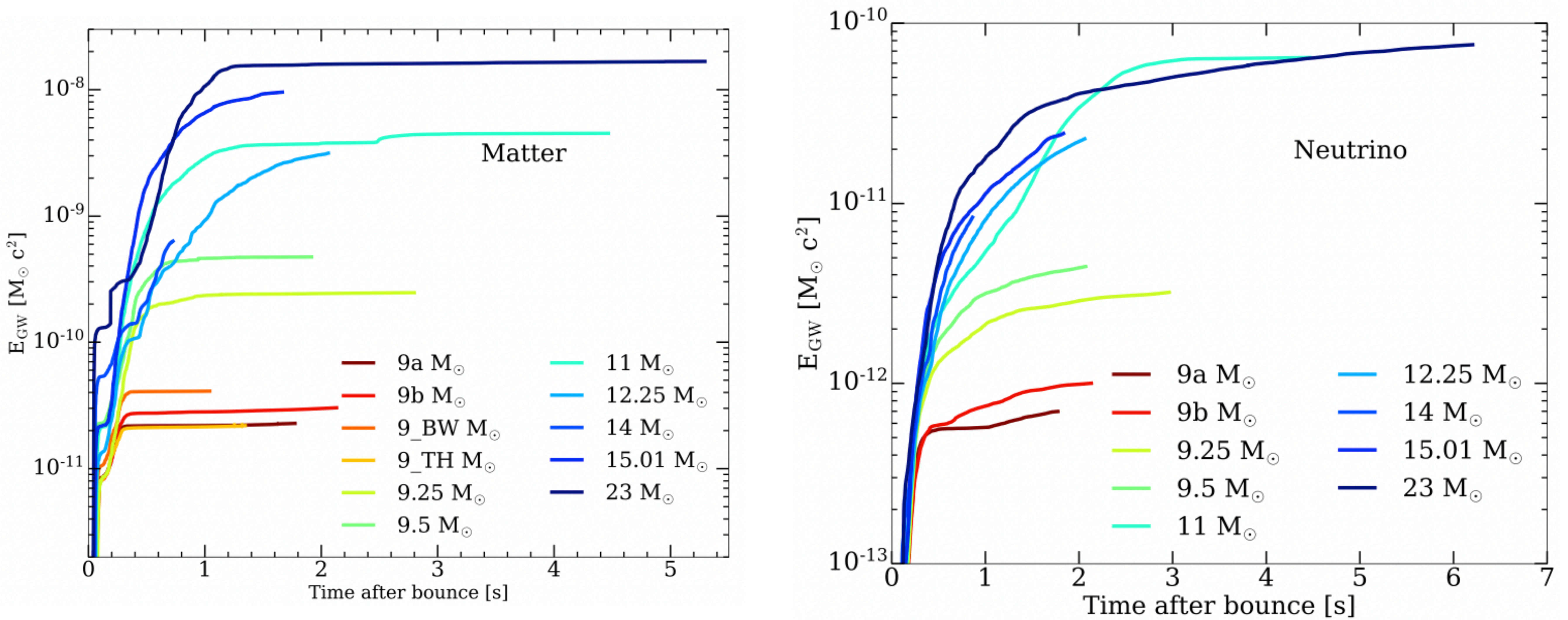


Figure 1. Snapshots of phases with convective and SASI activity in the evolution of the 27 $M_\odot$ model at 154 ms, 223 ms, 240 ms (*upper panels, from left to right*), 245 ms, 249 ms, and 278 ms (*lower panels, from left to right*). The volume rendering visualizes surfaces of constant entropy: The outer, bluish, semi-transparent surface is the supernova shock, the red surfaces are entropy structures in the postshock region. The upper left panel displays mushroom-like plumes of expanding, high-entropy matter that are typical of neutrino-driven buoyancy. The upper middle and right plots and the lower left and middle panels show distinctly different entropy structures of dipolar (and quadrupolar) asymmetry, which engulf the still visible buoyant plumes with their higher-order spherical harmonics mode pattern. The entropy asymmetries of $\ell = 1, 2$ character are caused by global shock sloshing motions, which create hemispheric high-entropy shells in phases of shock expansion. At 223 ms and 240 ms the shock has pushed towards the lower right corner of the panels whereas at 245 ms and 249 ms it is in a phase of violent expansion motion towards the upper left corner of the plots. All stages exhibit a strong deformation of the shock. At 278 ms the vivid SASI phase is over, the shock is more spherical again, and the postshock entropy structures correspond to neutrino-driven plumes.

Hanke et al., 2013, ApJ, 770, 66

Comparison between energy radiated in GW waves due to matter and neutrino anisotropy



Vartanyan, Burrows, Wang, Coleman and White, Phys. Rev. D 107, 103015 (2023)

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:

Main channel: IBD

Quasi thermal emission spectra - mean energy

Flux at earth - depends on distance and emission spectra

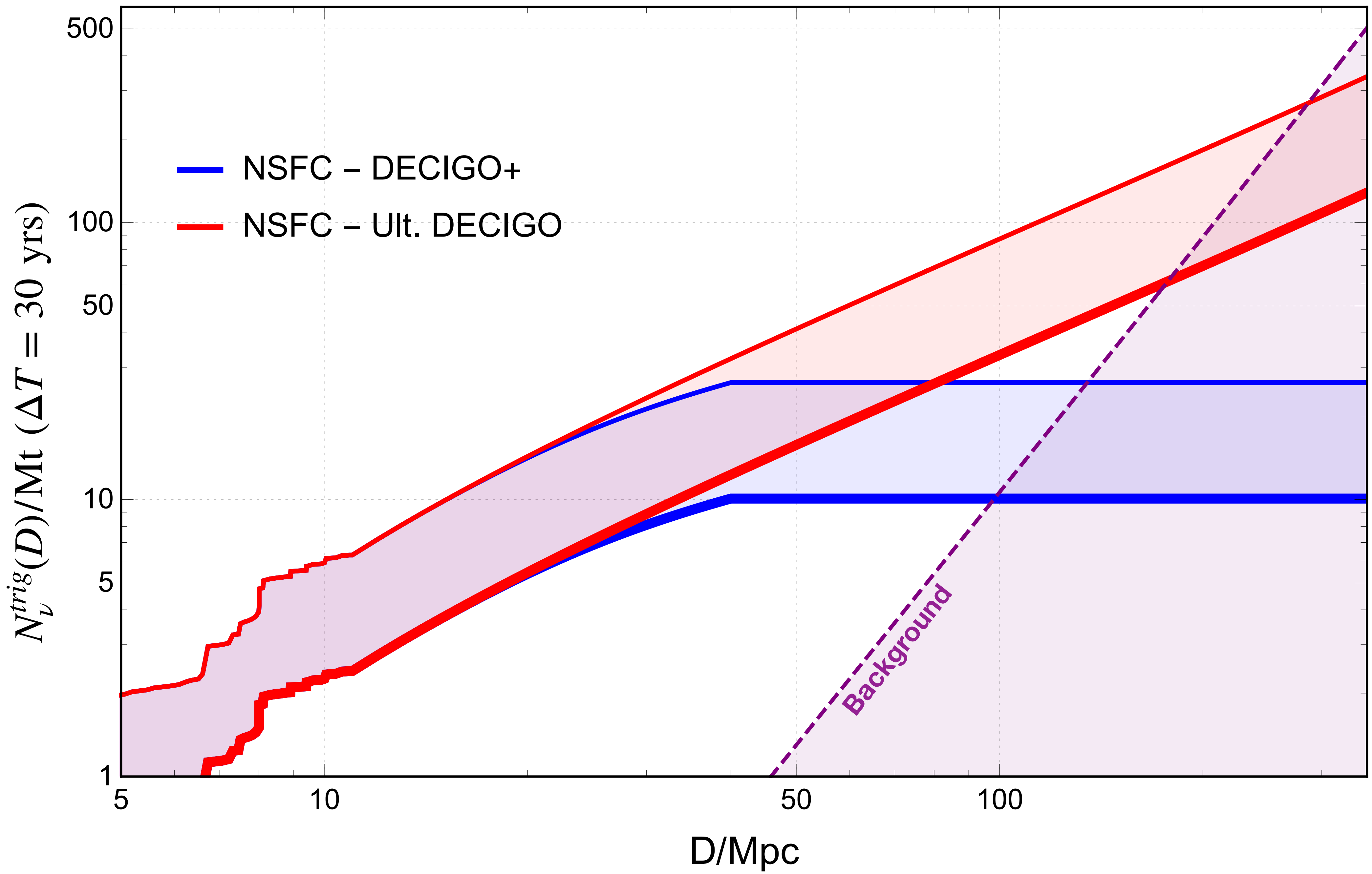
Calculate number of events in detector from a CCSN - depends on distance

GW detectors:

Calculate SNR - depends on distance to source

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

Results: Events and background - NSFC



Untriggered backgrounds would be orders of magnitude higher!