Probing the Central Engine of Long Gamma-Ray Bursts and Hypernovae with Gravitational Waves

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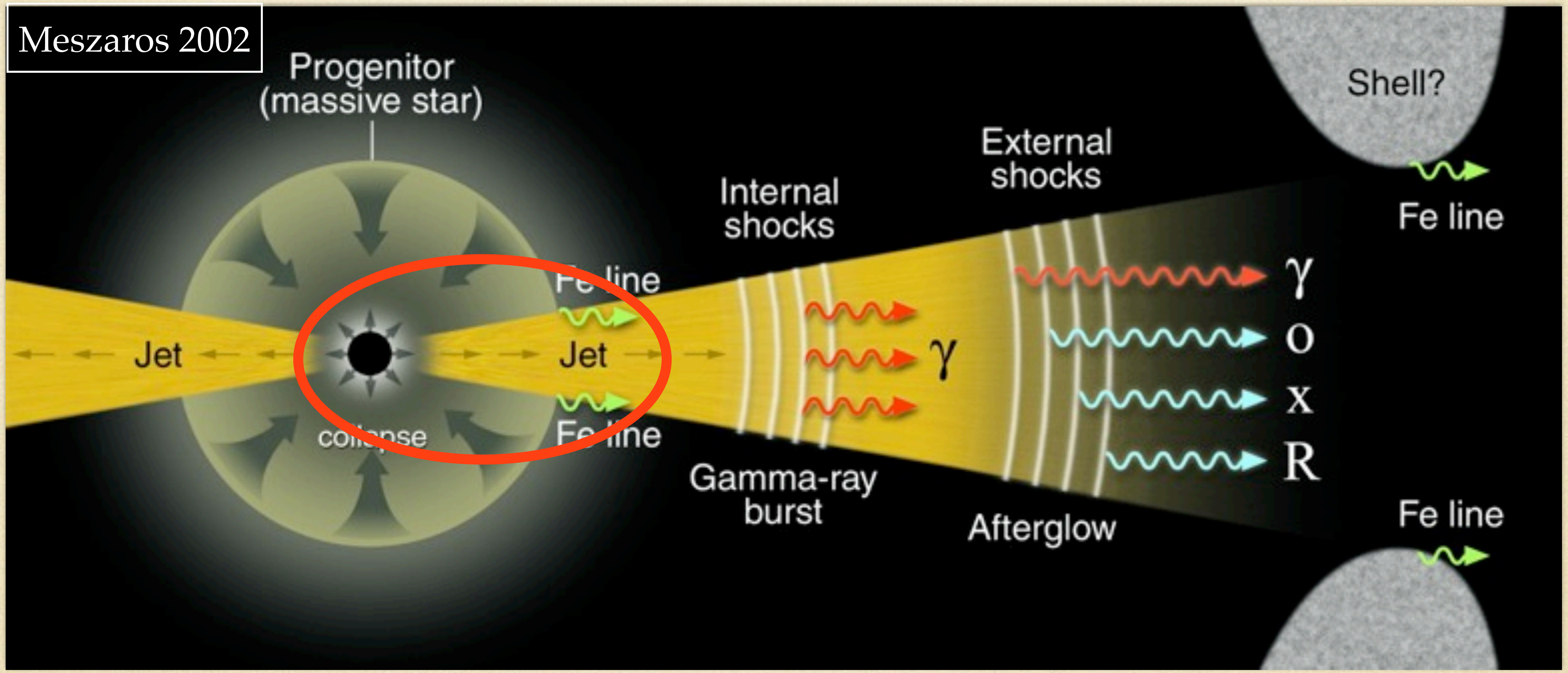
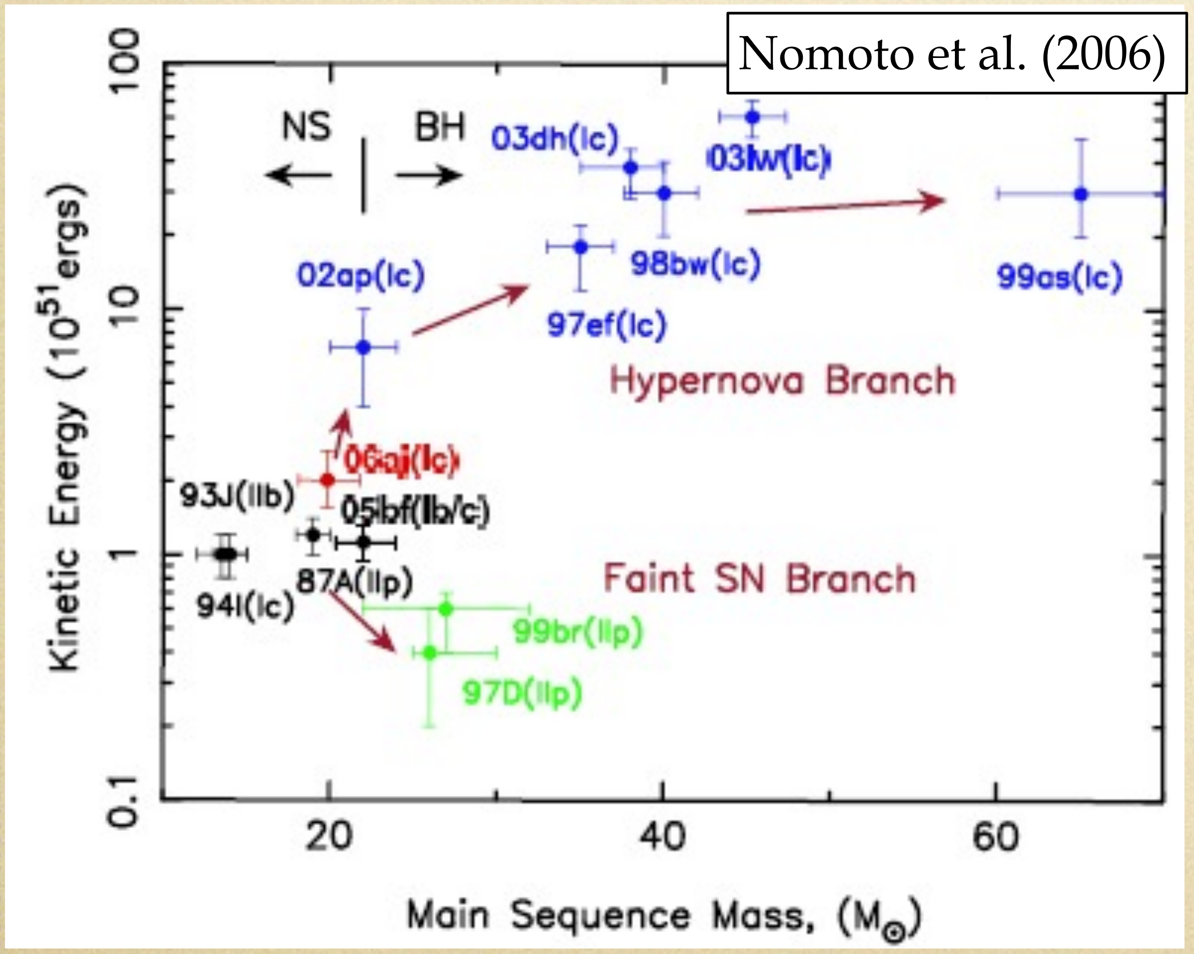


- The most luminous explosions in the Universe
- Small amount of matter accelerated to ultrarelativistic speeds and collimated in a jet
- In many of longer lasting events the total energy in γ rays ~ 10^{51} ergs.
- The required energy for a jet: **E~10^{52} ergs**

GRBs and SNe

GRB ⇔ SN association

GRB 980425 / SN 1998bw: (z=0.0085)
GRB 030329 / SN 2003dh: (z=0.1687)
GRB 031203 / SN 2003lw: (z=0.1055)
XRF 060218 / SN 2006aj: (z=0.0335)
GRB 081007 / SN 2008hw: (z=0.53)

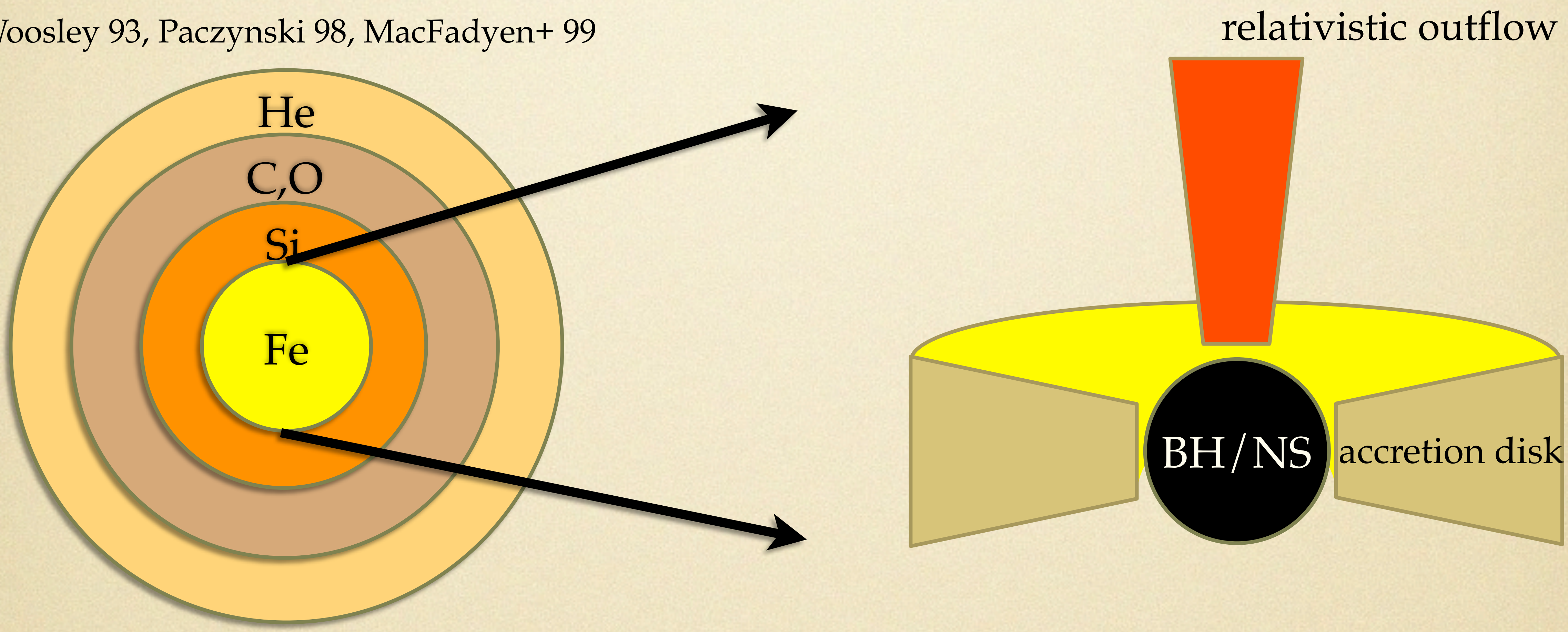


- Observations of GRB suggest that some GRBs are connected with some kind of SNe.
- SNe which associate with GRB are "Hypernovae" (HNe) with explosion energy, **E_{exp}~10^{52} ergs**.
- The central engine of GRBs is required to supply such an enormous explosion energy of GRBs/HNe.

Collapsar model

The most promising model of long GRBs

Woosley 93, Paczynski 98, MacFadyen+ 99

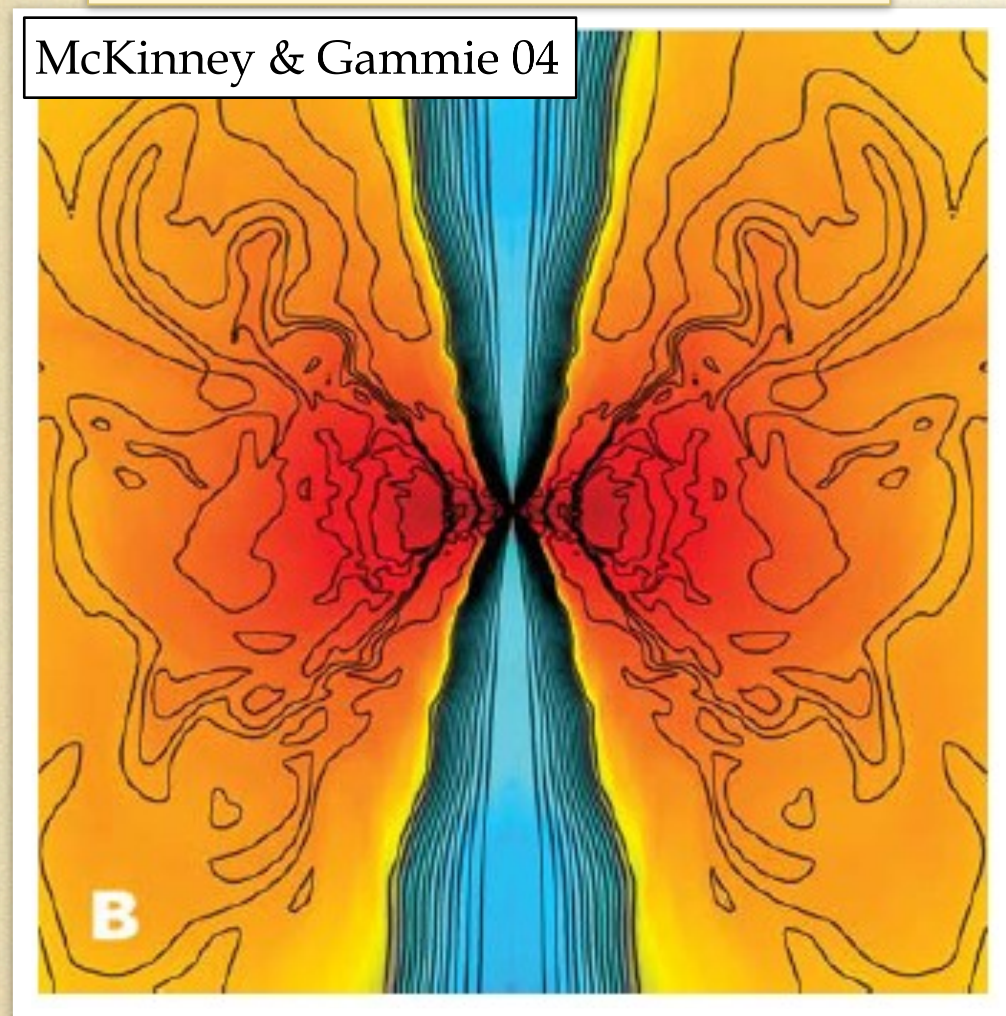


- Iron core of Massive star BH/NS + disk system
- Relativistic jet formation by some kind of “mechanism” ☞GRB
- Candidates of “mechanism”:
  magnetic force and **neutrino annihilation**

Magneto-driven jet

Blandford-Znajek process

McKinney & Gammie 04



rotation energy of a BH

☞Poynting flux ☞**jet production**

$$P_{\rm BZ} \sim 10^{51}\tilde{a}^2 \left(\frac{M_{\rm BH}}{3M_\odot}\right)^2 \left(\frac{B}{10^{15}{\rm G}}\right)^2 {\rm ergs\ s^{-1}}$$

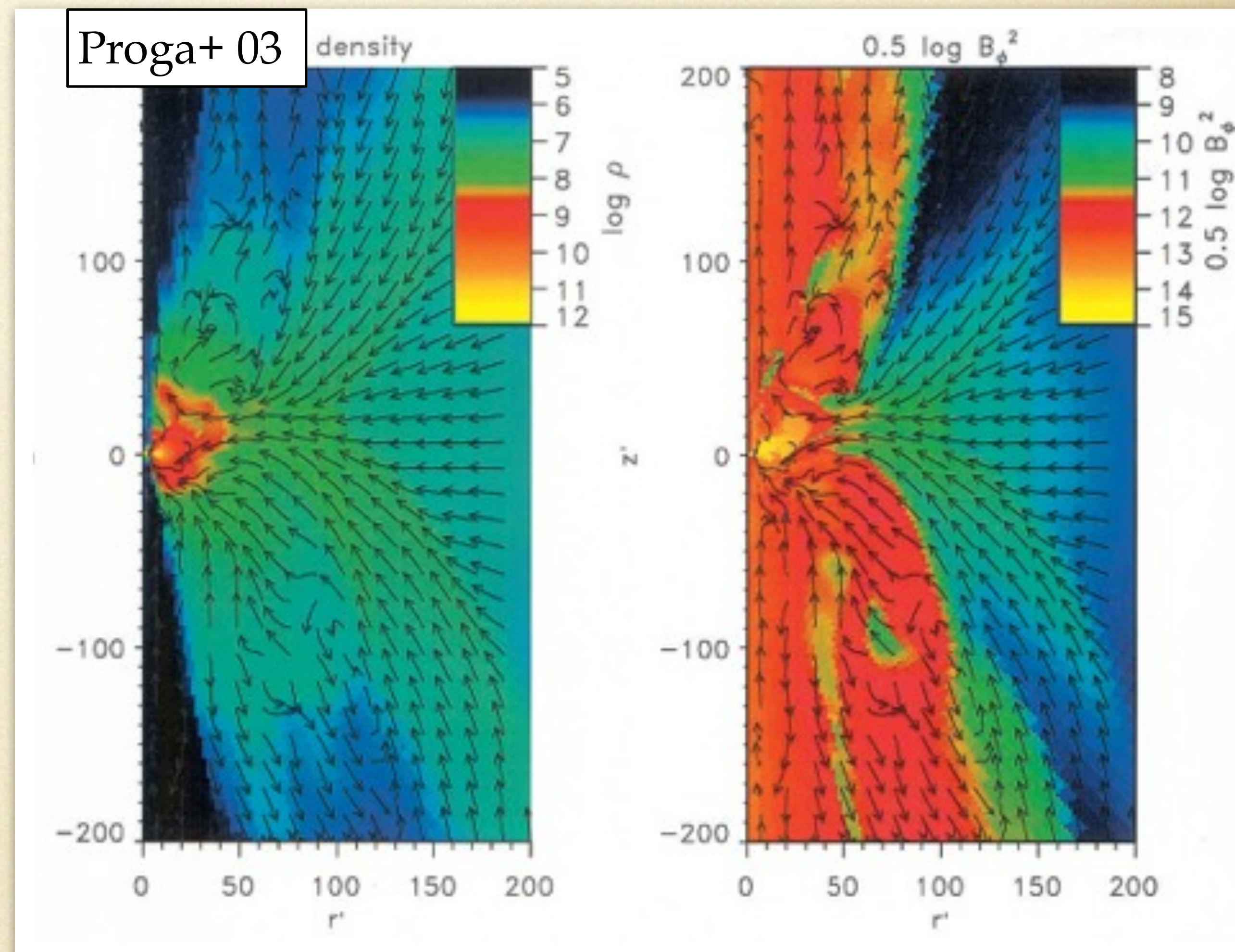
Lee+ 00

$$E_{\rm rot} = 5.4 \times 10^{54} f(\tilde{a}) \left(\frac{M}{3M_\odot}\right) {\rm ergs}$$

$$f(\tilde{a}) = 1 - \sqrt{\tfrac{1}{2}[1 + \sqrt{1 - \tilde{a}^2}]}$$

MHD process

Proga+ 03



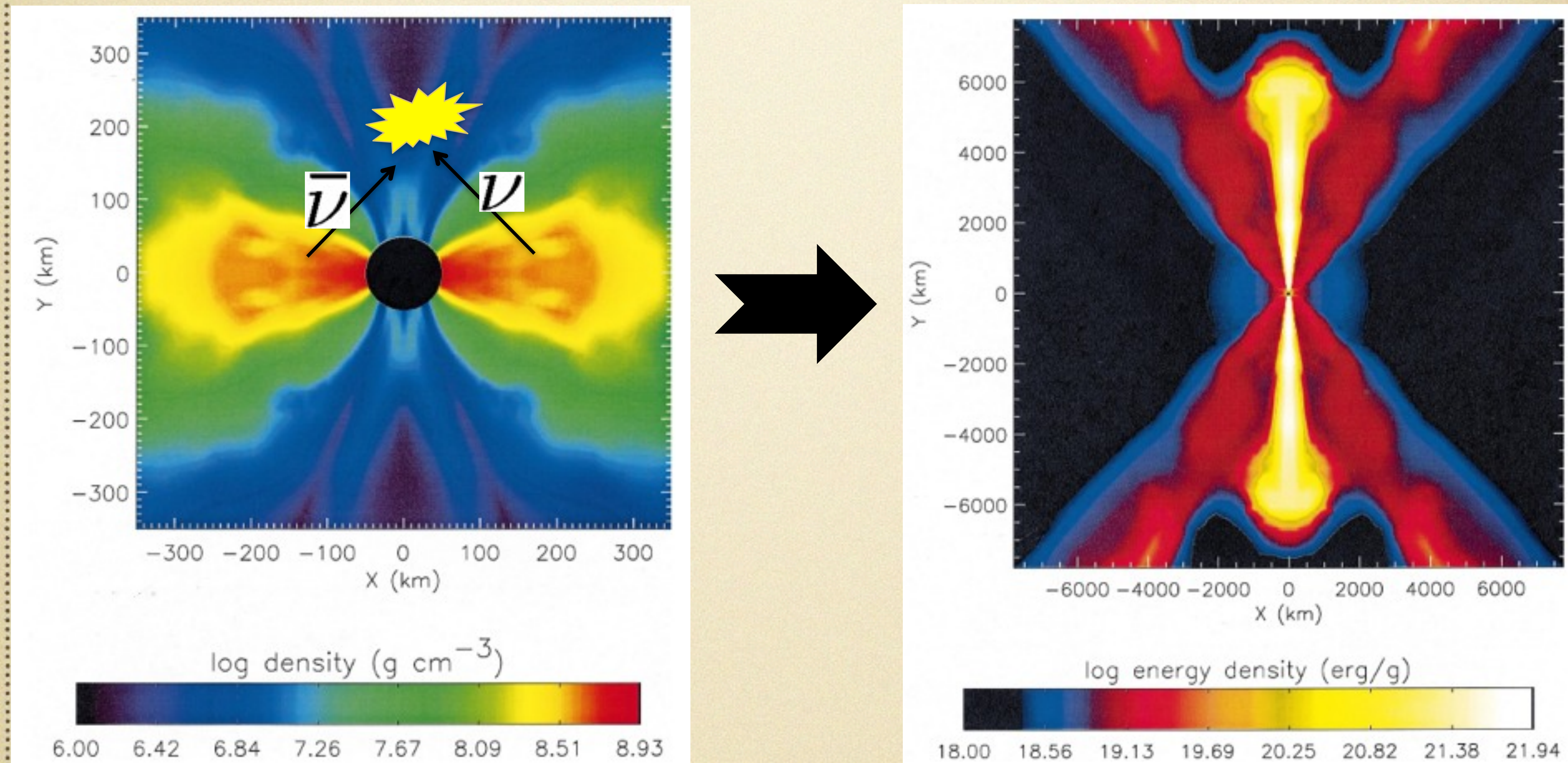
binding energy of an accretion disk

☞Poynting flux ☞**jet production**

$$P_{\rm MHD} \sim P_{\rm BZ}$$

Neutrino-driven jet

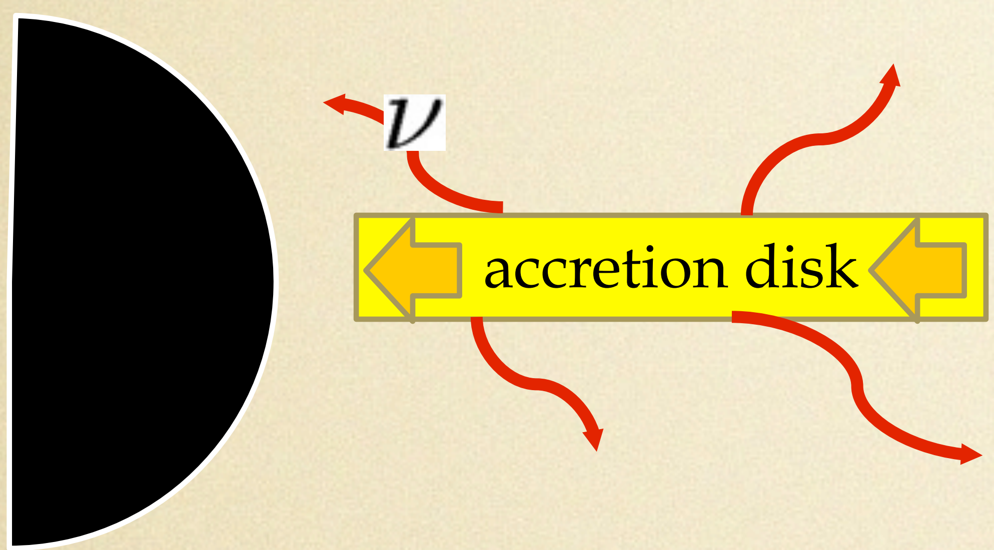
McFadyen & Woosley 99

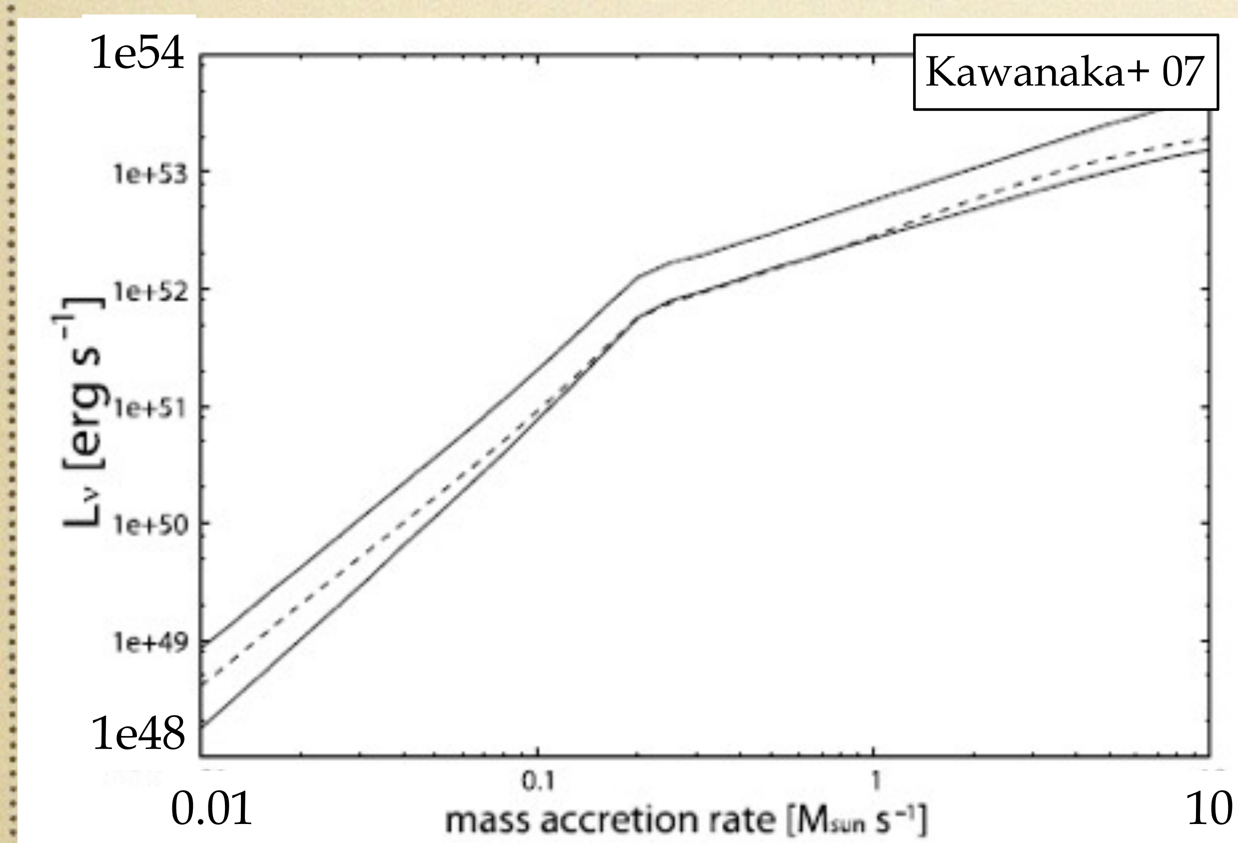


Neutrino pairs are generated in the hot disk
☞Impact each other ☞Energy deposition at rotational axis☞ **jet production**

NDAF

Neutrino Dominated Accretion Flow





- Model for hyper accretion disk
- The neutrino emission is the dominant source of cooling.

  (These neutrinos are suggested for the source of a jet)
- Depending on the accretion rate, the neutrino luminosity, L, becomes as large as 10^{53} erg/sec!

NDAF

Popham+ 99

TABLE 3

NEUTRINO ANNIHILATION EFFICIENCY

$\dot{M}$ ($M_\odot$ s^{-1})	α	a	M ($M_\odot$)	L_ν (10^{51} ergs s^{-1})	$L_{\nu\bar{\nu}}$ (10^{51} ergs s^{-1})	Efficiency (%)
0.01	0.1	0	3	0.015	3.9×10^{-8}	0.0003
0.01	0.03	0	3	0.089	2.9×10^{-7}	0.0003
0.01	0.01	0	3	0.650	9.0×10^{-6}	0.001
0.01	0.1	0.5	3	0.036	5.9×10^{-7}	0.002
0.01	0.01	0	10	0.049	6.4×10^{-9}	10^{-5}
0.05	0.1	0.5	3	1.65	1.8×10^{-3}	0.11
0.1	0.1	0	3	3.35	3.0×10^{-3}	0.09
0.1	0.03	0	3	6.96	1.7×10^{-3}	0.02
0.1	0.01	0	3	6.15	8.0×10^{-4}	0.01
0.1	0.1	0.5	3	8.03	0.039	0.5
0.1	0.1	0.95	3	46.4	2.0	4.2
0.1	0.1	0.95	6	26.2	0.79	3.0
1.0	0.1	0	3	86.3	0.56	0.6
1.0	0.1	0.5	3	142	3.5	2.5
10.0[a]	0.1	0	3	(781)	(200)	(26)
10.0[a]	0.1	0.5	3	(1280)	(820)	(64)

[a] The assumption that the neutrinos are optically thin breaks down for accretion rates of 10 $M_\odot$ s^{-1} and above. The neutrino annihilation luminosities and energies listed for these high-accretion simulations are upper limits.

The required energy for producing GRB jet is ~ 10^{51} erg/sec.
In order to achieve this, the total neutrino luminosity must be as large as ~ 10^{53} erg/sec!

(The efficiency of energy conversion is quite low.)

Summary of energy budget

Energy of GRB jet

$$E_{\mathrm{GRB-jet}} = 10^{52}\mathrm{ergs}$$

Energy available by models of central engine

BZ process $P_{\mathrm{BZ}} \sim 10^{51}\tilde{a}^2 \left(\frac{M_{\mathrm{BH}}}{3M_\odot}\right)^2 \left(\frac{B}{10^{15}\mathrm{G}}\right)^2 \mathrm{ergs\ s^{-1}}$

MHD process $P_{\mathrm{MHD}} \sim P_{\mathrm{BZ}}$

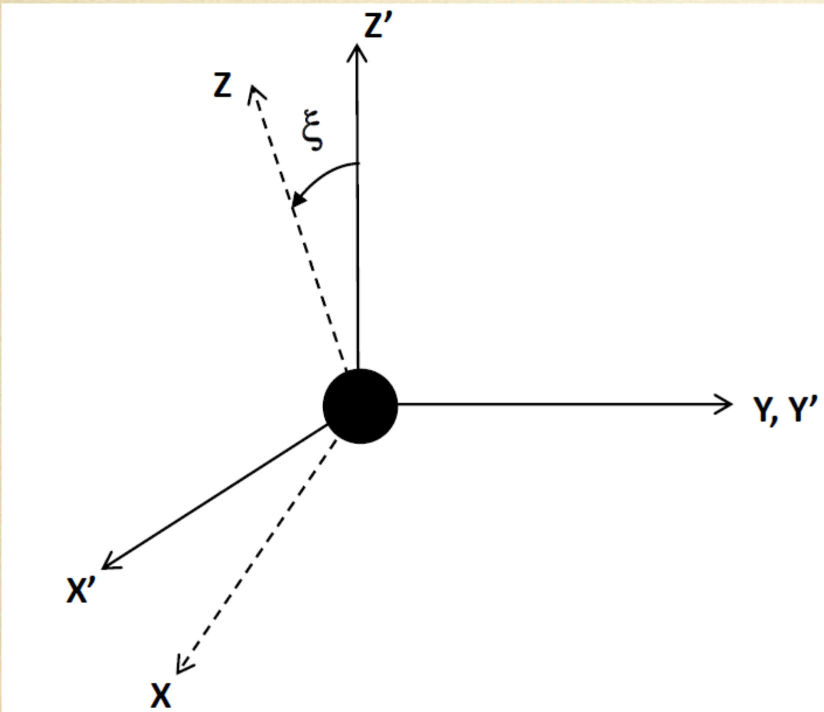
ν process $P_{\nu\bar{\nu}} \sim 10^{51}\mathrm{ergs\ s^{-1}}$

$$L_\nu \sim 10^{53}\mathrm{ergs\ s^{-1}}$$

Can we constrain this component using GW??

GW from anisotropic neutrino radiation

Epstein 78, Turner 78, Mueller & Janka 97



GW amplitude

$$h_+(t) = \frac{2G}{c^4 R}\int_{-\infty}^{t-R/c} dt' \int_{4\pi} d\Omega' \Psi(\Omega') \frac{dL_\nu}{d\Omega'}(\Omega', t')$$

neutrino luminosity per unit solid angle

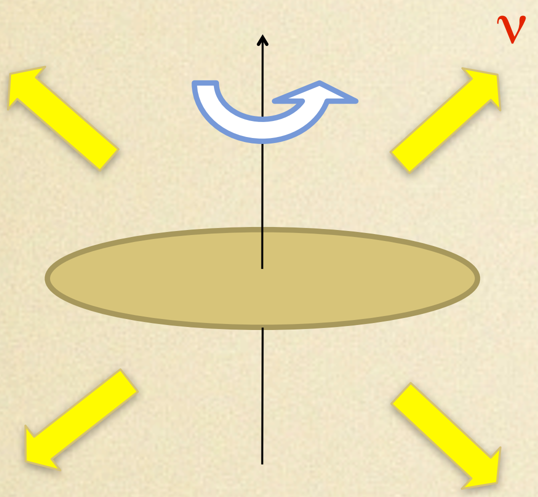
$$\Psi(\Omega') = (1+\cos\theta'\cos\xi + \sin\theta'\cos\phi'\sin\theta')\frac{(\sin\theta'\cos\phi'\cos\xi - \cos\theta'\sin\xi)^2 - \sin^2\theta'\sin^2\phi'}{(\sin\theta'\cos\phi'\cos\xi - \cos\theta'\sin\xi)^2 + \sin^2\theta'\sin^2\phi'}$$

Axisymmetric case

$$h_+(t) = \frac{2G}{c^4 R}\int_{-\infty}^{t-R/c} dt' \int_0^\pi \sin\theta' d\theta' \; \Phi(\theta') \frac{dL_\nu}{d\Omega'}(\theta', t'),$$

$$\Phi(\theta') = \begin{cases} -2\pi\left[1+\cos\theta'\,(2+\cos\xi)\right]\tan^2\left(\frac{\xi}{2}\right) & (\text{for} \quad \theta \geq \xi) \\ -2\pi\left[1+\cos\theta'\,(-2+\cos\xi)\right]\cot^2\left(\frac{\xi}{2}\right) & (\text{for} \quad \theta < \xi) \end{cases}$$

GW from thin disk

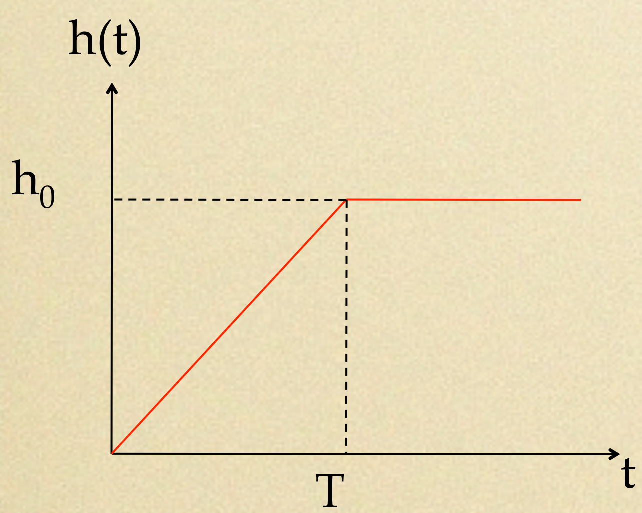


Neutrino emission

$$\frac{dL_\nu}{d\Omega'} = \frac{L_\nu}{2\pi}|\cos\theta|$$

GW amplitude (ξ=π/2)

$$\begin{aligned} h_+(t) &= \frac{2G}{c^4 R}\int_{-\infty}^{t-R/c} dt' \int_0^\pi d\theta' \Phi(\theta')\frac{dL_\nu}{d\Omega'}(\theta',t') \\ &= \frac{2G}{c^4 R}\int_{-\infty}^{t-R/c} dt' L_\nu(t') \times \int_0^\pi d\theta'(-1+2\cos\theta')\sin\theta'|\cos\theta'| \\ &= \frac{2G}{c^4 R}\left(\frac{1}{3}\right)\int_{-\infty}^{t-R/c} L_\nu(t')dt'. \end{aligned}$$



Final converged value

$$h_0 \sim 1.8 \times 10^{-21}\left(\frac{10\text{Mpc}}{R}\right)\left(\frac{E_\nu}{10^{54}\text{ergs}}\right)$$

R: distance
E_ν: total energy emitted by neutrino

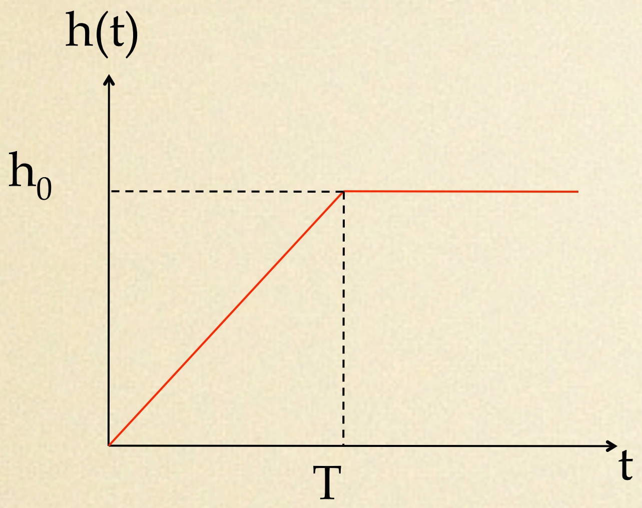
⇔E_{tot}=3x10^{53} ergs for ordinary SNe

cf.) GW from jet itself

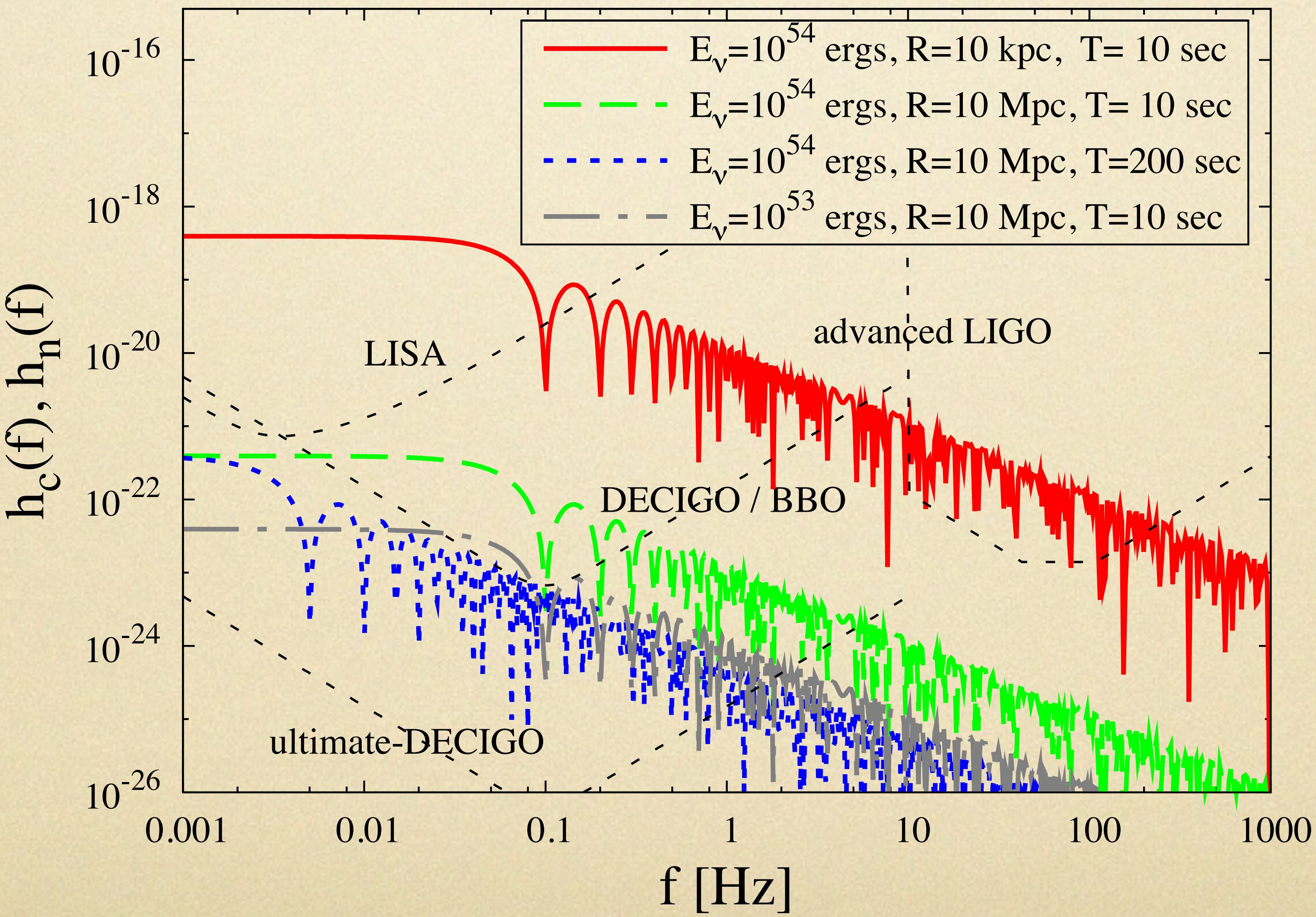
$$h_0 \sim 8.5 \times 10^{-24}\left(\frac{10\text{Mpc}}{R}\right)\left(\frac{E_{\text{jet}}}{10^{52}\text{ergs}}\right)$$

Sago+ 04
Hiramatsu+ 05

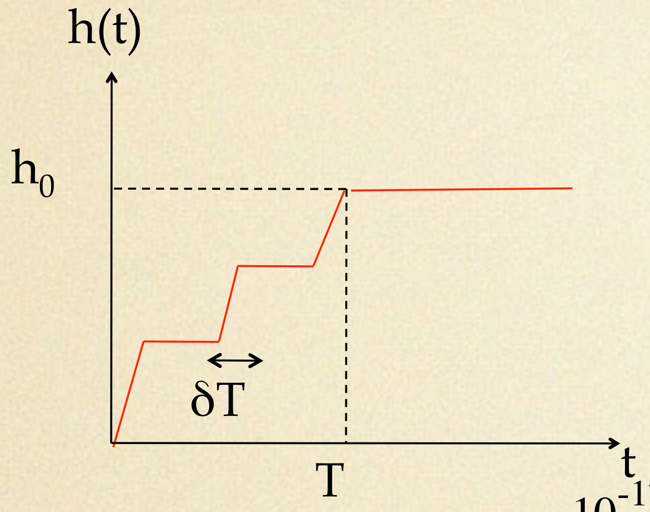
GW spctrum



$$h_c(f) \equiv f|\tilde{h}(f)| = \frac{h_0}{2\pi^2 T f}|\sin(\pi T f)|$$

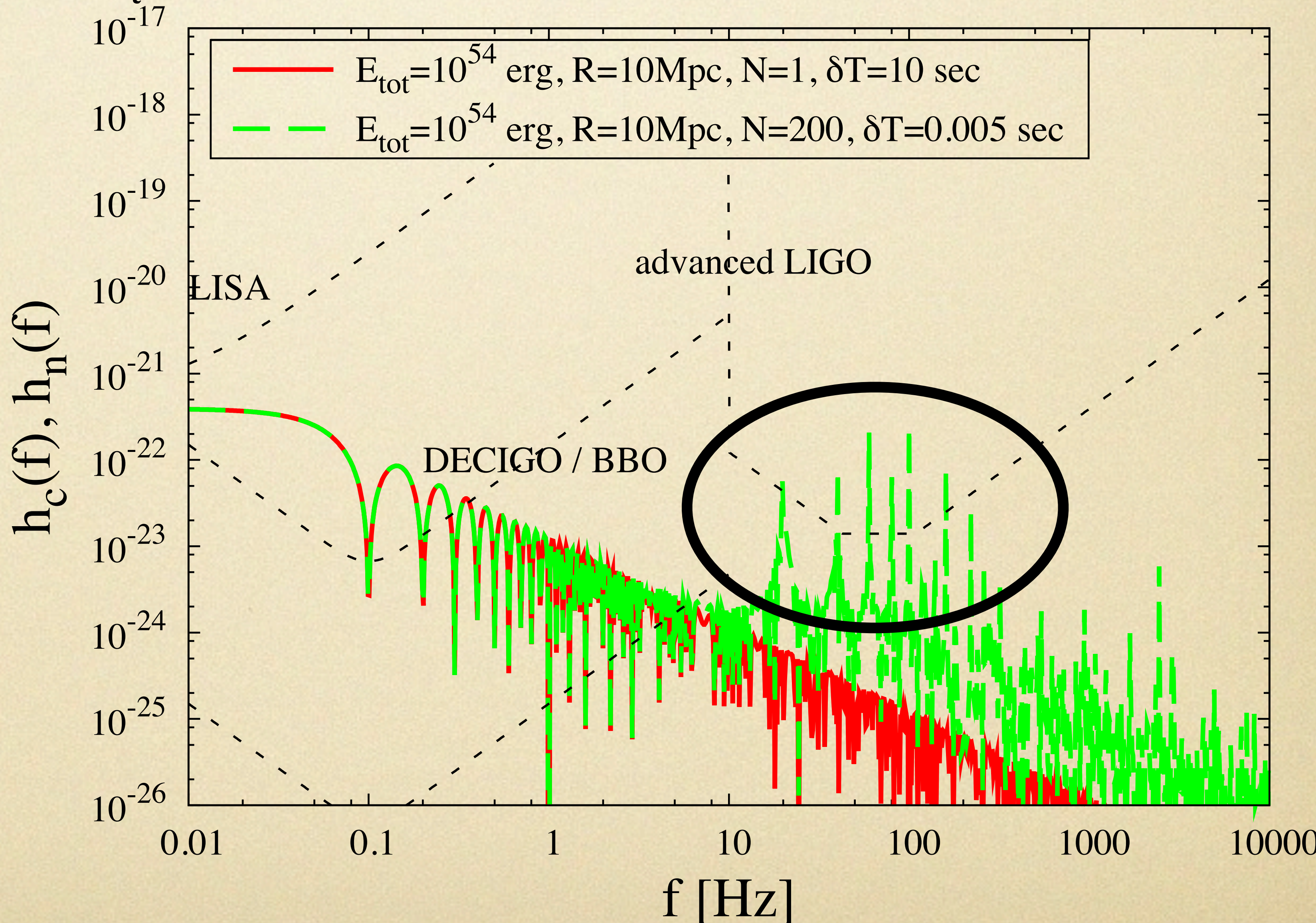


Effect of time variability

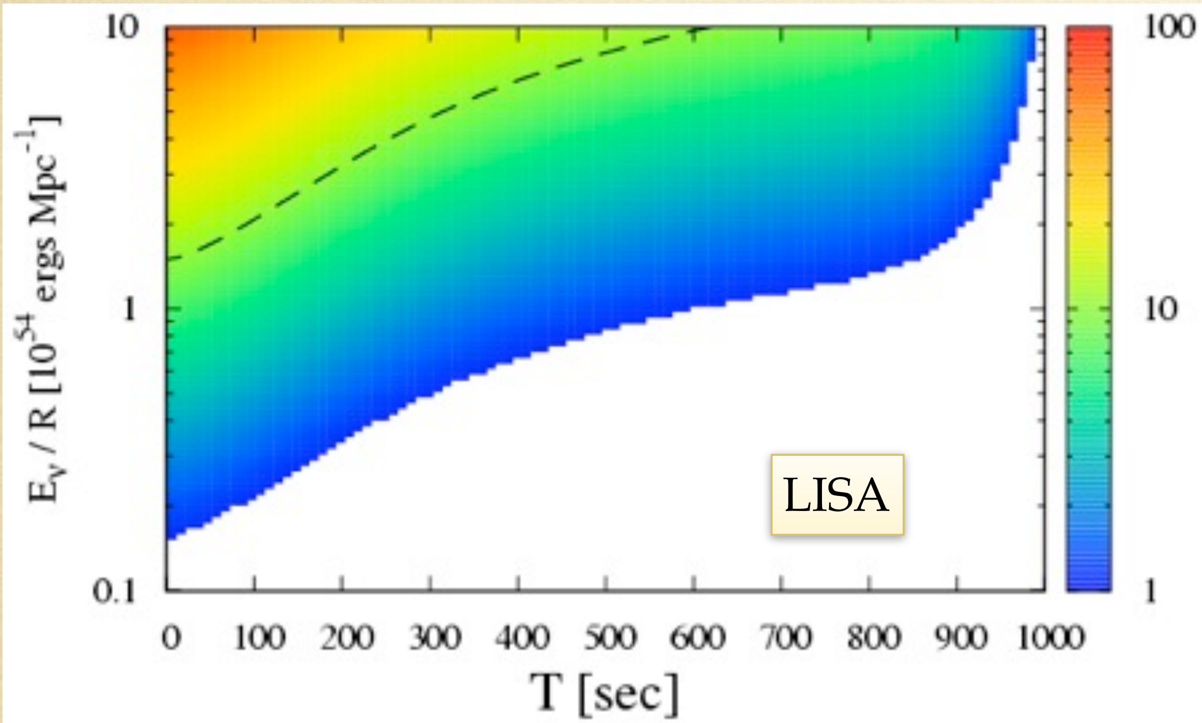


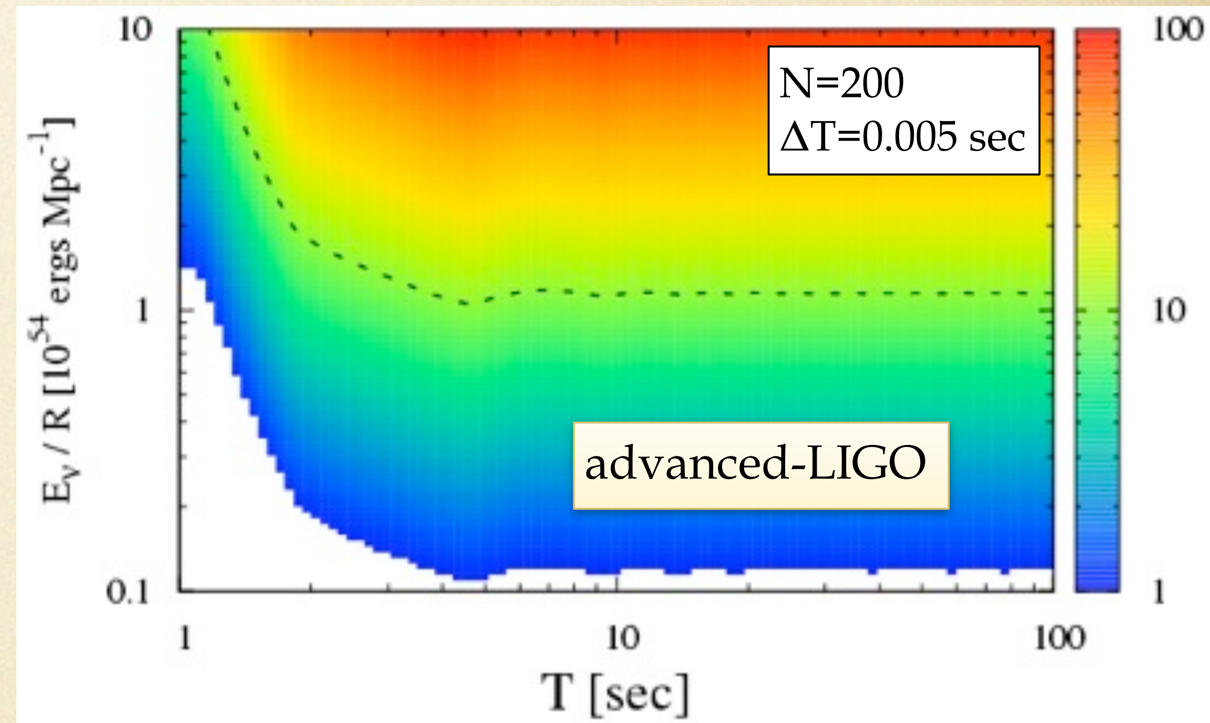
$$h_c(f) = \frac{\sqrt{\beta} h_\infty}{\pi^2 N \delta t f} \left| \frac{\sin(\pi \delta t f) \sin(\pi T f)}{\sin(\pi T f / N)} \right|$$

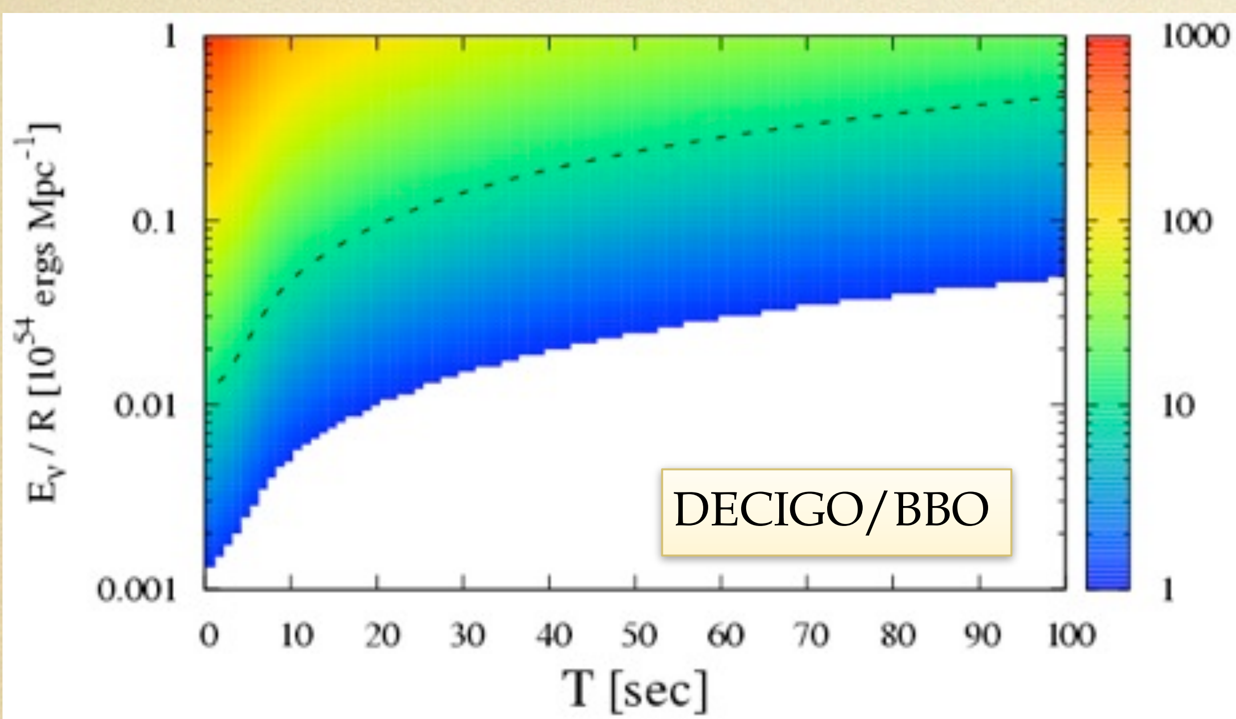
N: number of bursts



Signal-to-noise ratio







$$\mathrm{SNR} = \sqrt{\int_0^\infty d(\ln f)\frac{h_c(f)^2}{h_n(f)^2}}$$

SNR>10⇔

< 1 Mpc for ad.-LIGO (2015)

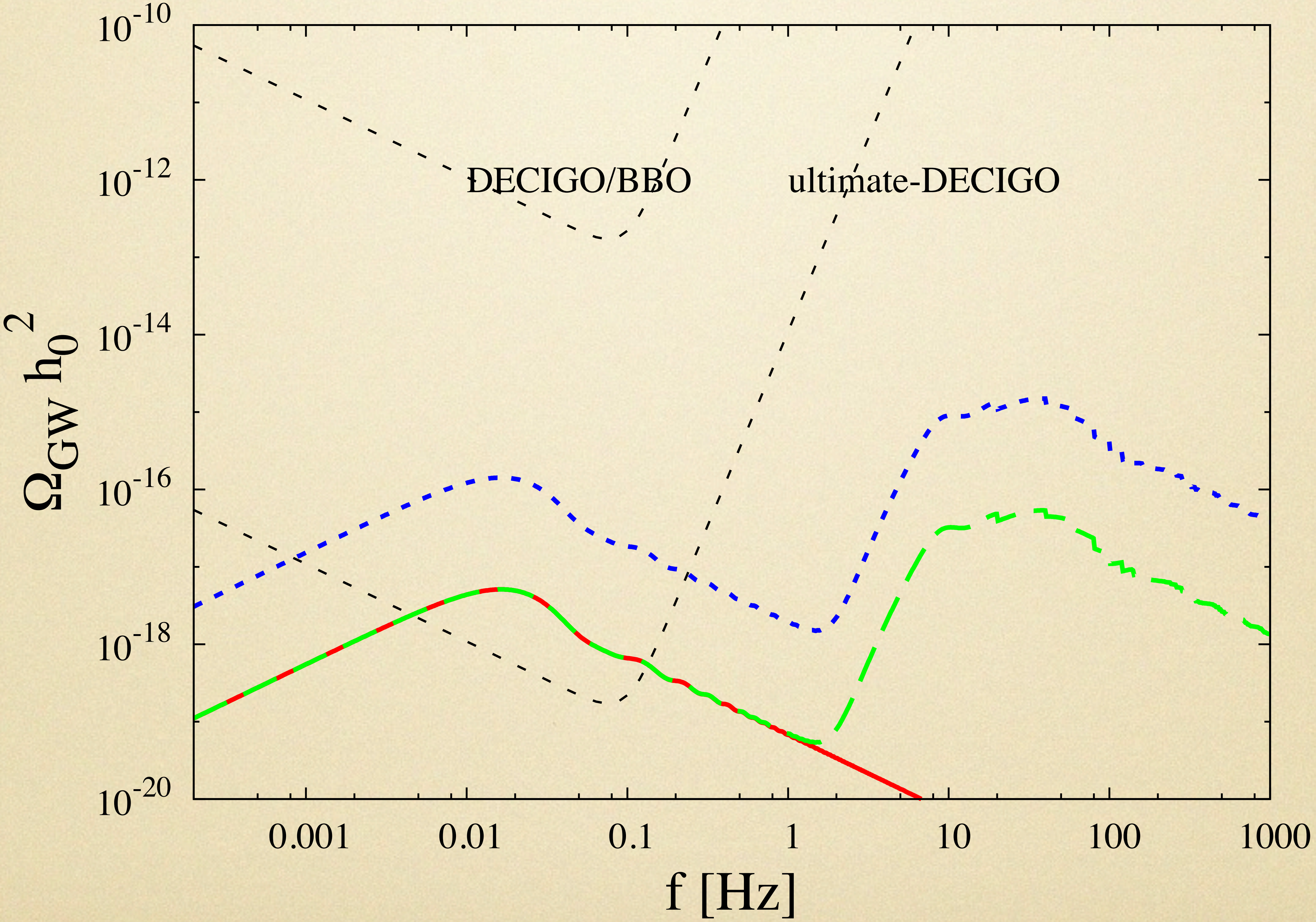
< 1 Mpc for LISA (2019)

< 100 Mpc for DECIGO/BBO (2024)

cf.) GRB rate⇔

~10 – ~1000 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Guetta+ 07)

Gravitational Wave Background



Summary

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MHD process $P_{\mathrm{MHD}} \sim P_{\mathrm{BZ}}$

ν process $P_{\nu\bar{\nu}} \sim 10^{51}\mathrm{ergs\ s^{-1}}$

$L_\nu \sim 10^{53}\mathrm{ergs\ s^{-1}}$ → GW