A broadband detection algorithm for LIGO-Virgo and KAGRA searches of long gravitational wave bursts in energetic core-collapse supernovae

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MG14 July 2015

Outline

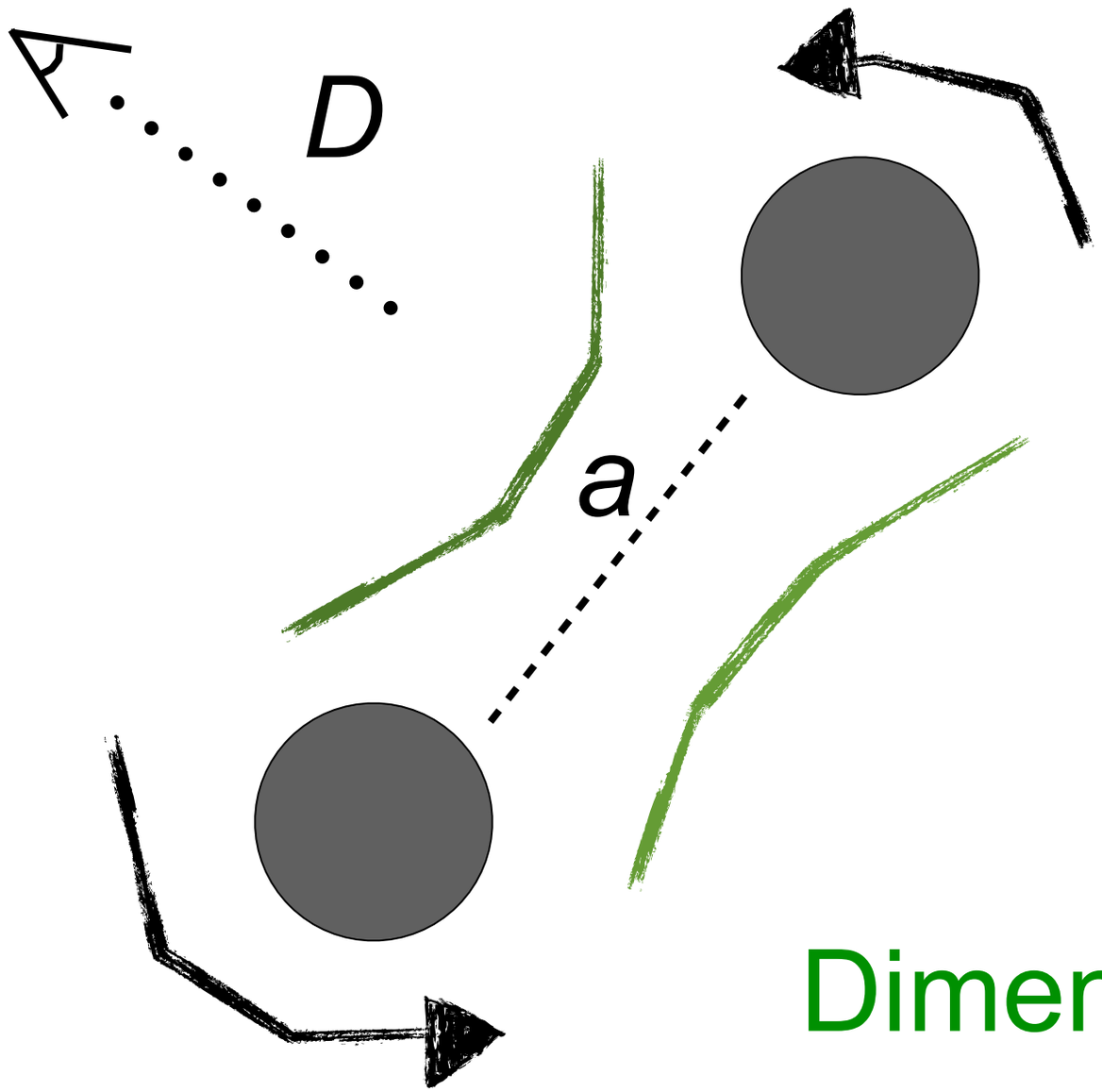
Gravitational waves

Lessons from Swift, BeppoSAX, BATSE:

- GRB-SNe from spin down of near-extremal black holes

Search algorithm for broadband long-duration GWBs from nearby CC-SNe

Dynamical curvature



Rotating tidal field

$$\omega = 2\Omega_{\text{orbit}}$$

$$\Omega_{\text{orbit}} \cong \sqrt{\frac{M}{a^3}}$$

Dimensionless strain

$$h = h_0 + h_1(t) = \frac{M}{D} + h_1(t)$$

Gravitational waves

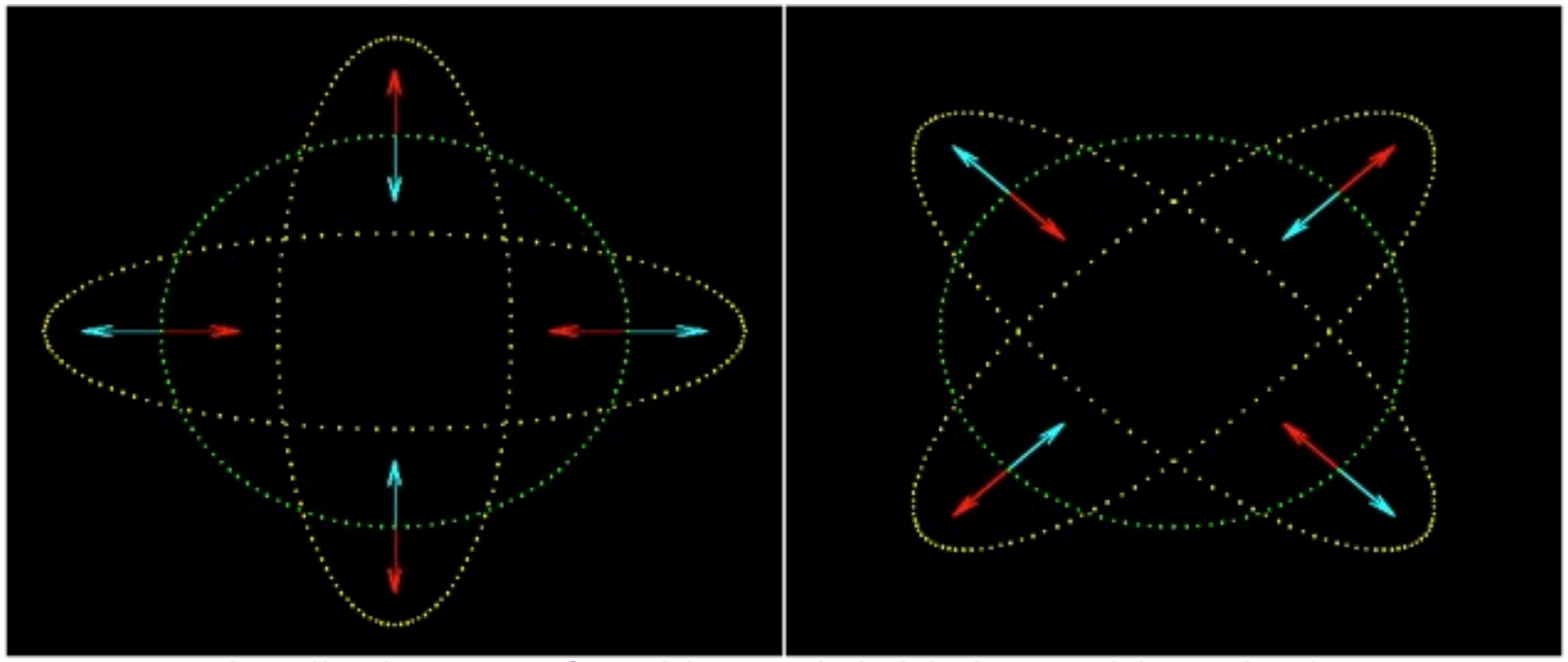
GR: a coupled elliptic-hyperbolic system of equations

(in SO(3,1) four-covariant form, van Putten & Eardley 1996)

Newton's law embodied by elliptic part

GW waves embodied by hyperbolic part

G_{ab}(GW) = rotating tidal fields



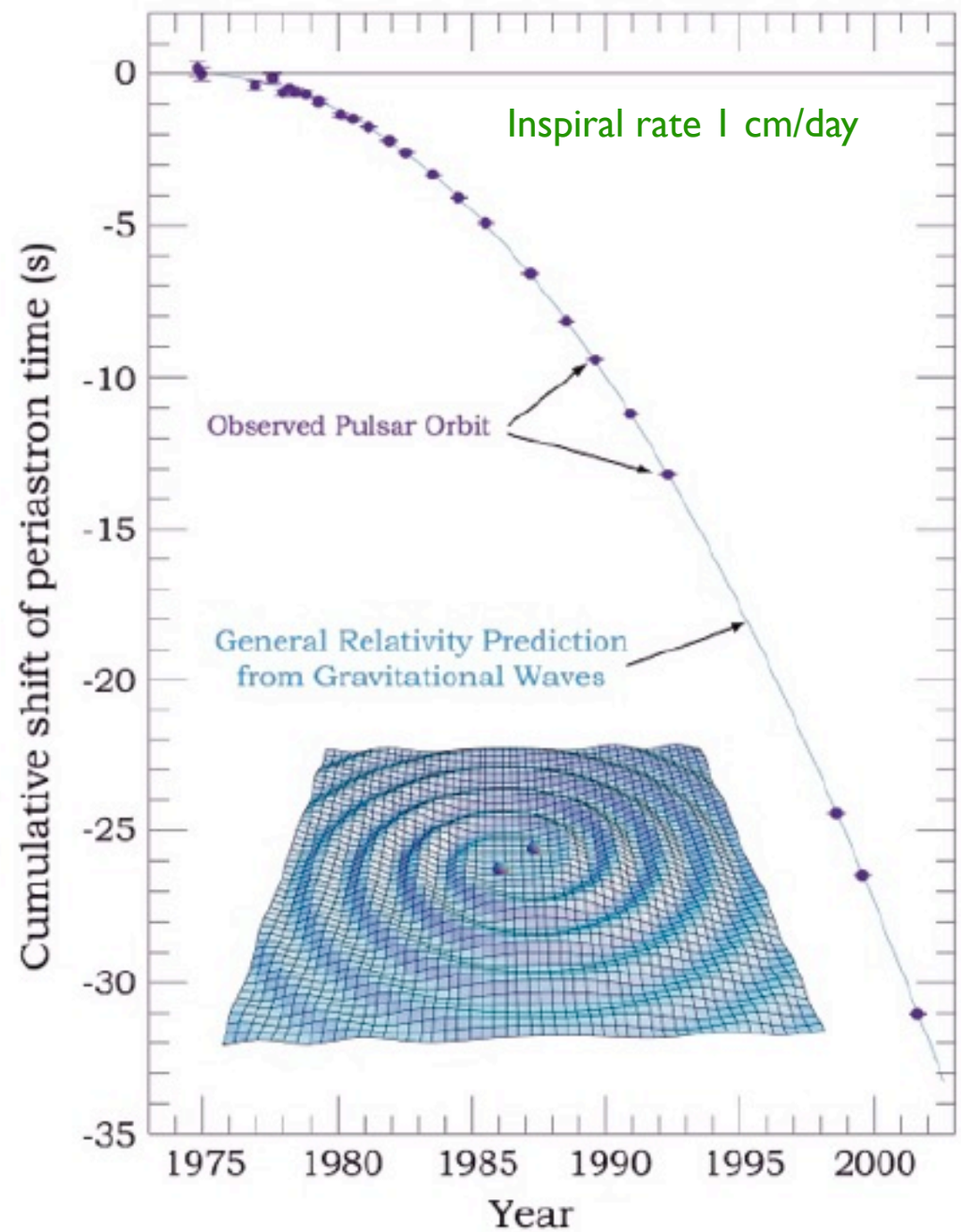
http://carina.astro.cf.ac.uk/groups/relativity/research/part4.html

Gentle sources...

PSR 1913+16

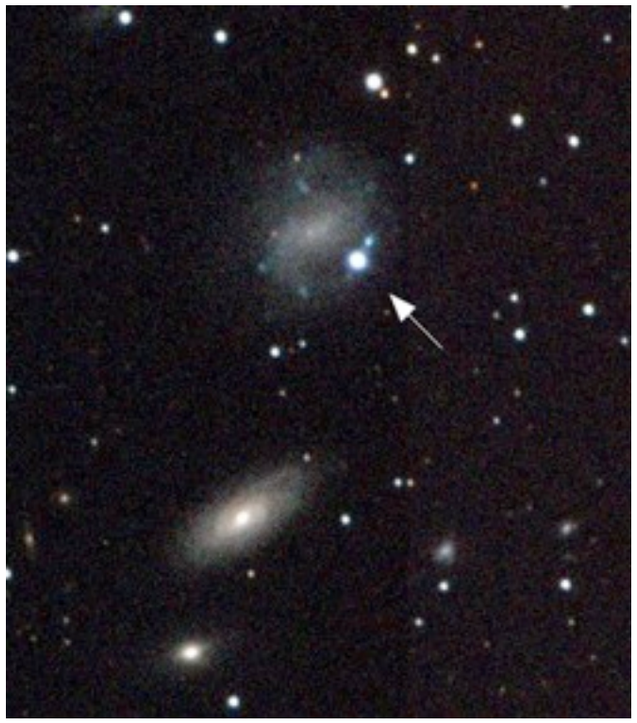
P = 7.75 hr
e = 0.617
F(e) = 11.8
L_{GW} = 0.2% L_{Solar}

Hulse-Taylor 1974
Nobel Prize 1993



Extreme transient events: CC-SNe and LGRBs

GRB 980425/SN1998bw



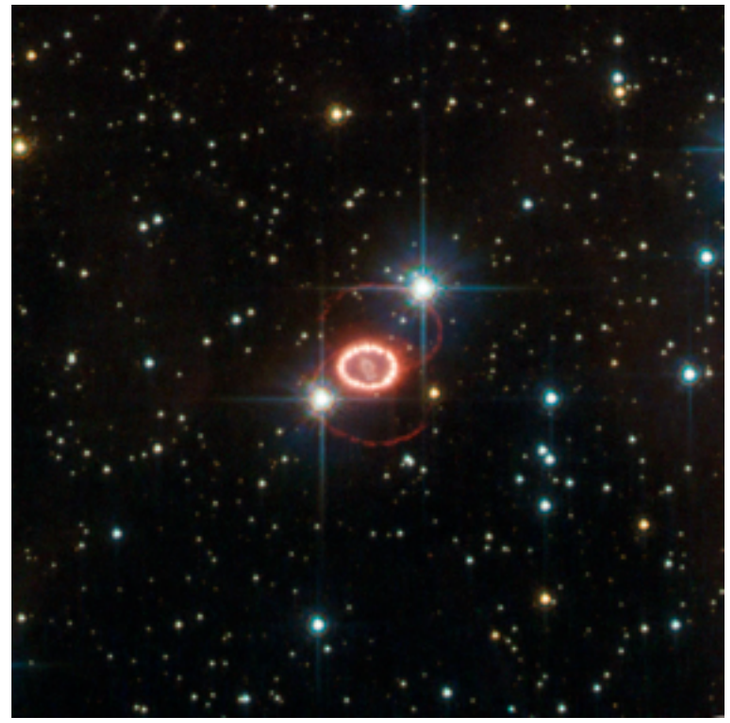
Radio-loud, aspherical

$$E_k \cong 2\times10^{51}\ \mathrm{erg}\left(M_{ej}/2M_\odot\right)$$

$$v_{ej} \cong 0.2\,c$$

Hoeflich et al. 1999
Wieringa et al. 1999

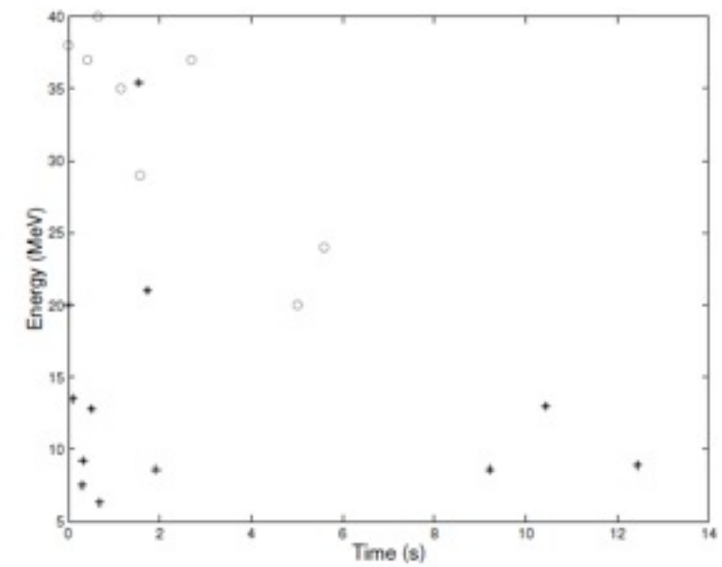
SN1987A Type II



Radio-loud, aspherical,
relativistic radio jets,
BH remnant?

$$E_k \cong 1\times10^{51}\ \mathrm{erg}$$

Turtle et al. 1987
Nisenson & Papaliolios 1999



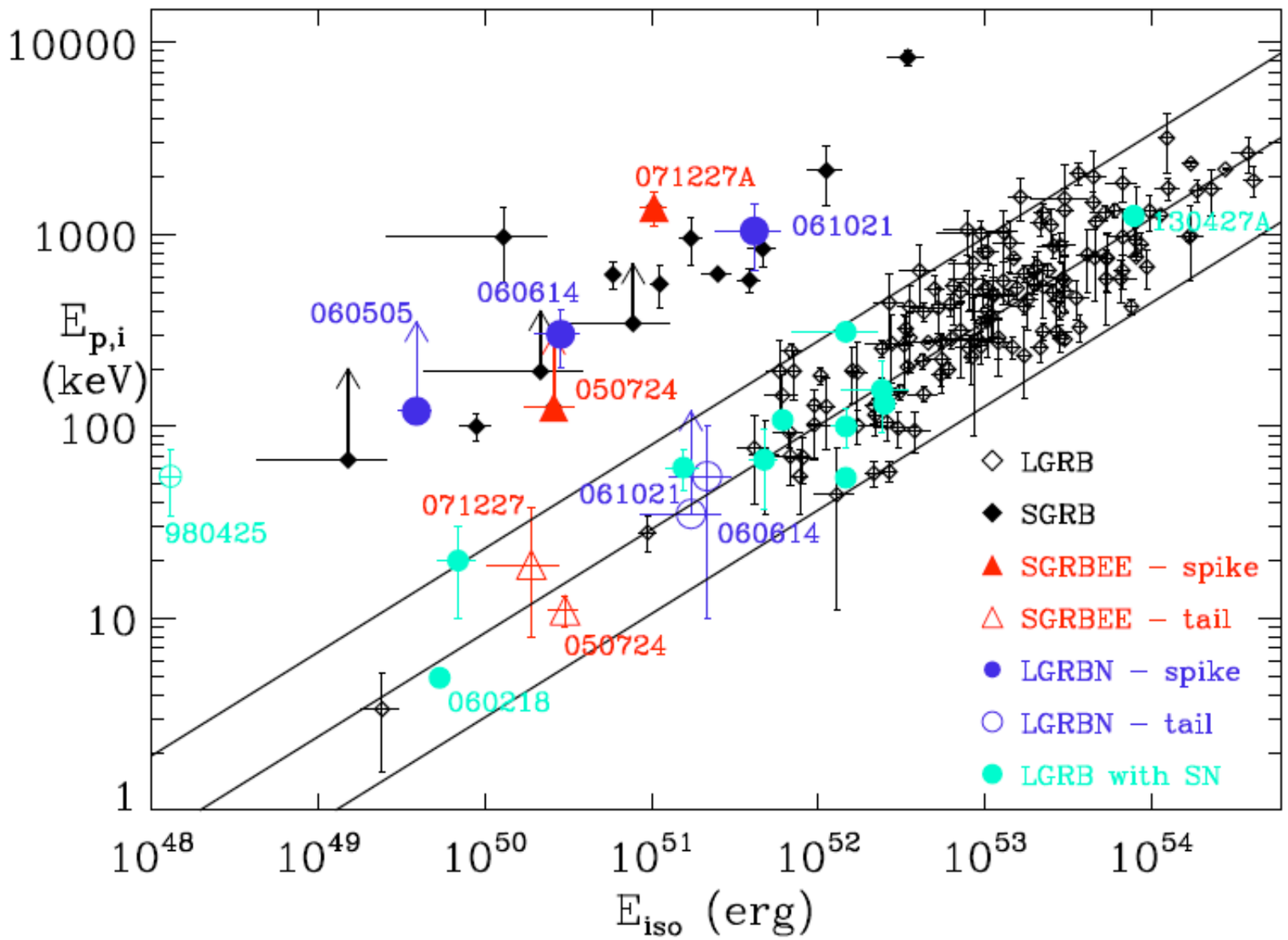
$$E_\nu \cong 10^{53}\ \mathrm{erg}$$

Probably powered by magnetic winds from an angular momentum-rich inner engine

Bisnovatyi-Kogan, G. S. 1970, Astron. Zh., 47, 813
van Putten, Della Valle, Levinson, 2011, A&A, 535, L6

Swift phenomenology

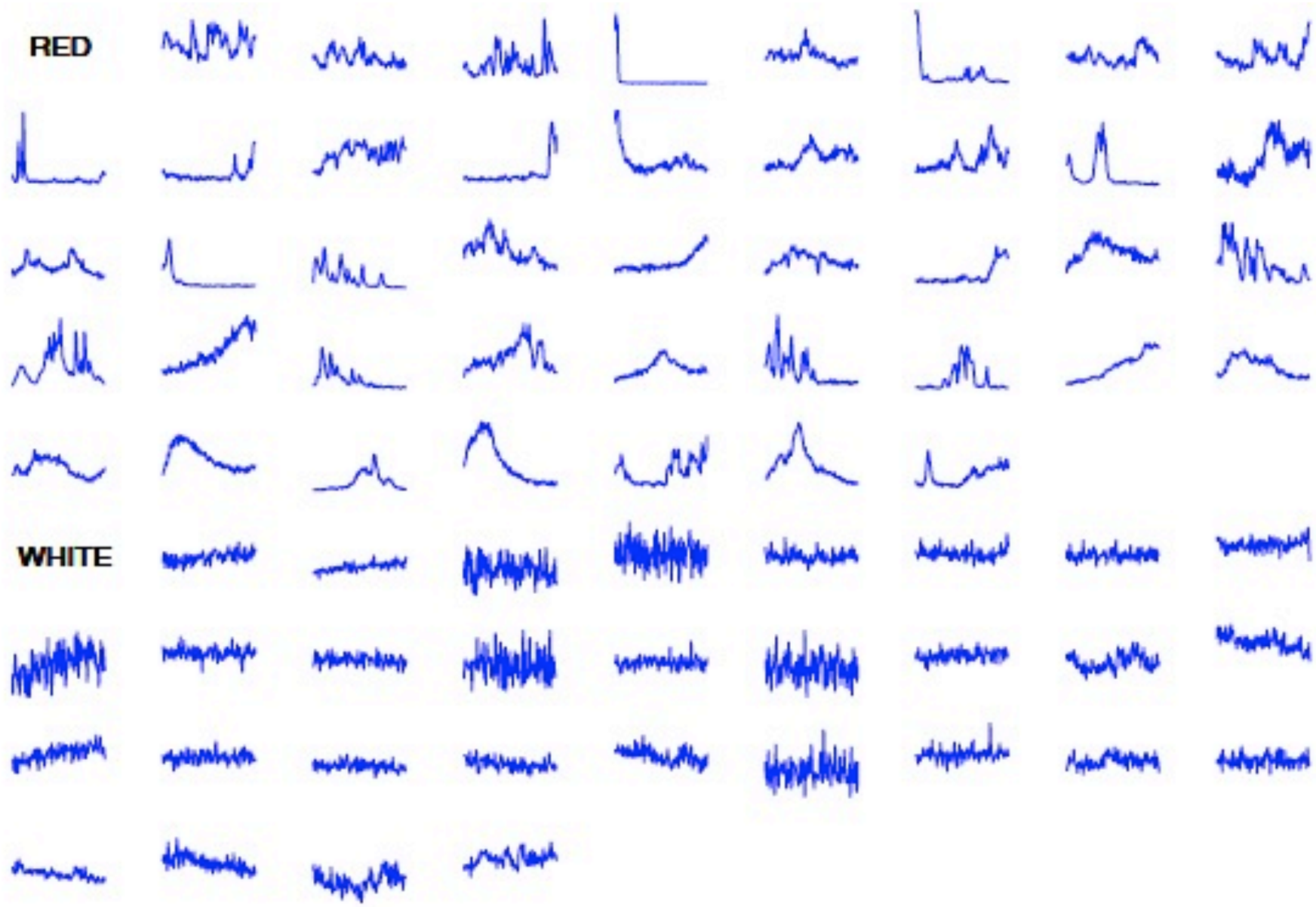
LGRBs, SGRBs, SGRBEEs, LGRBNs: soft EE satisfy same Amati relation



Van Putten, Lee, Della Valle, Amati & Levinson, 2014, MNRAS, 444, L58

BHs as a common inner engine

BeppoSAX sample of LGRBs at 2 kHz

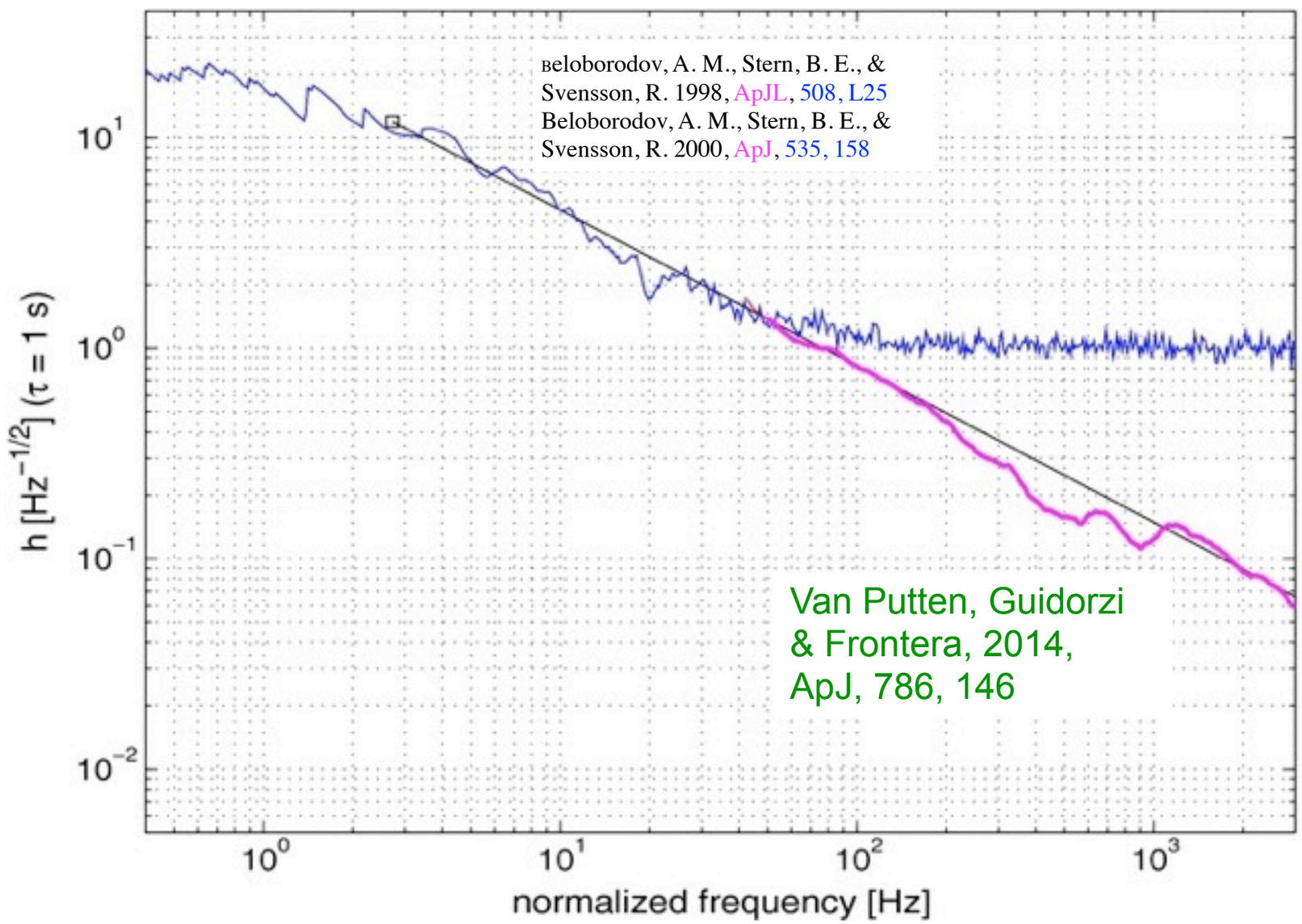


***Red*:** 1.26 photons/0.5 ms bin: non-trivial autocorrelation fn
***White*:** 0.59 photons/0.5 ms bin: trivial autocorrelation fn

van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146

BeppoSAX phenomenology

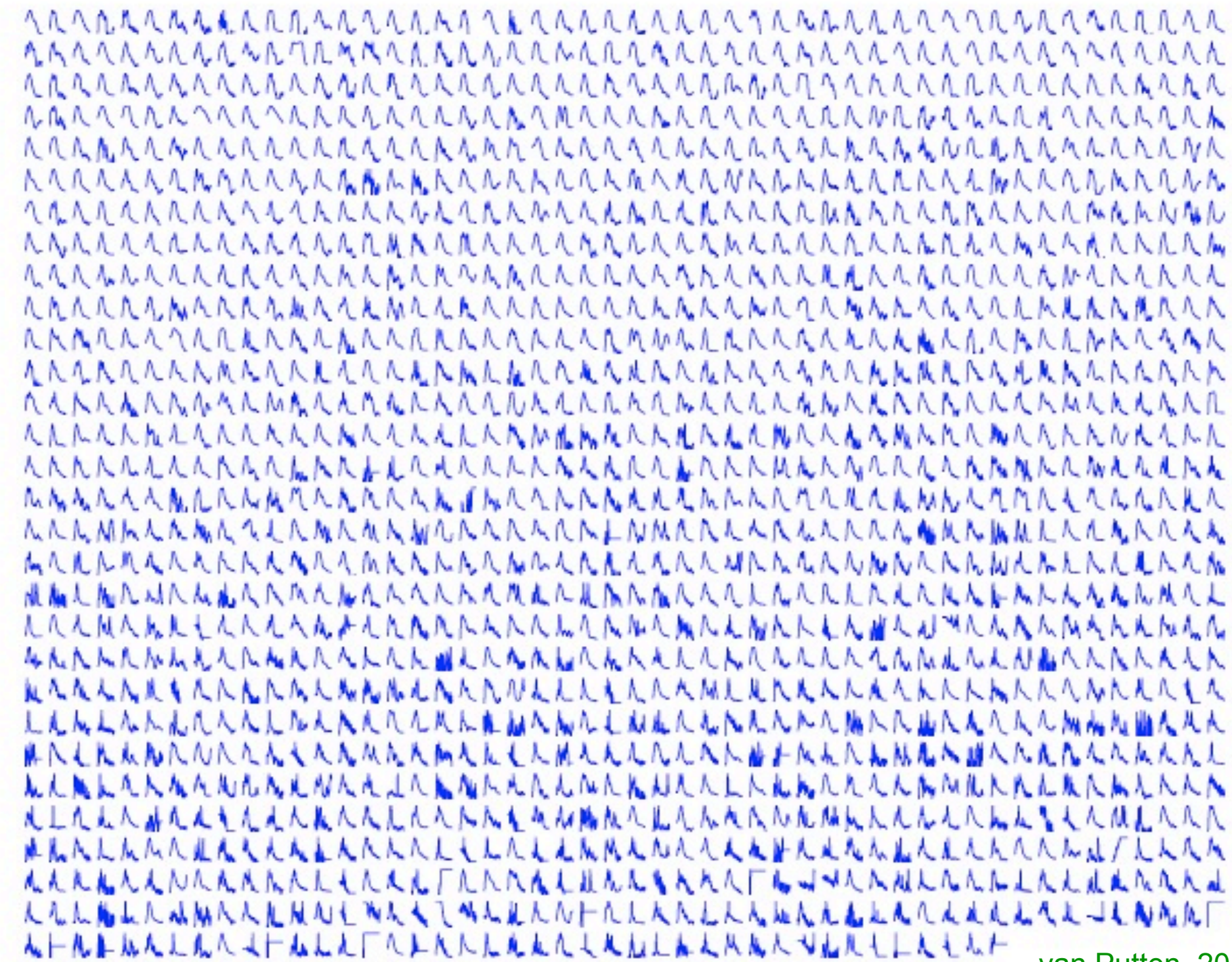
Matched filtering analysis of 2 kHz light curves (1.26 photons/0.5ms bin)



Smooth extension of Kolmogorov spectrum

no evidence for proto-PSR

BATSE Catalog of LGRBs

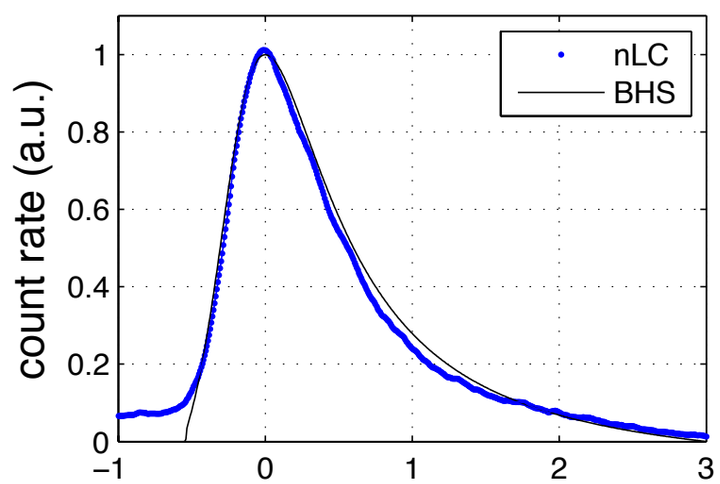


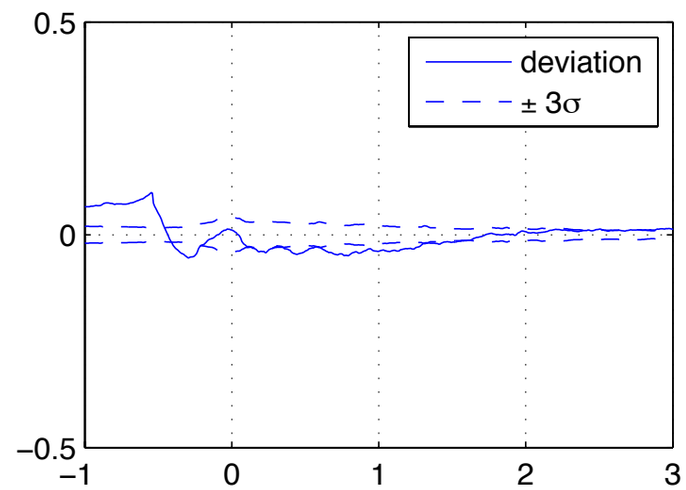
van Putten, 2012, PTP, 127, 331

Spin-down in BATSE light curves of LGRBS

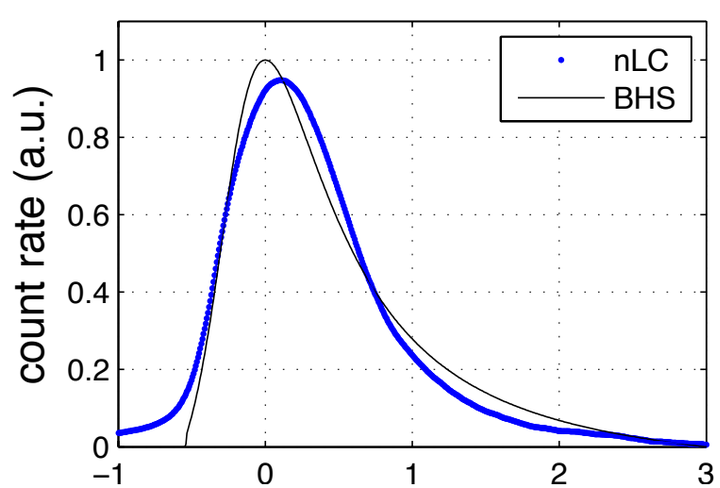
Matched filtering analysis against model of BH spin down against torus at ISCO

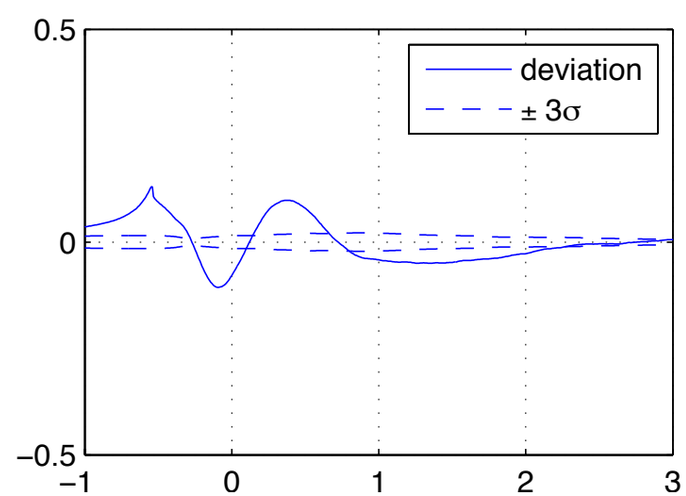
$T_{90} > 20$ s



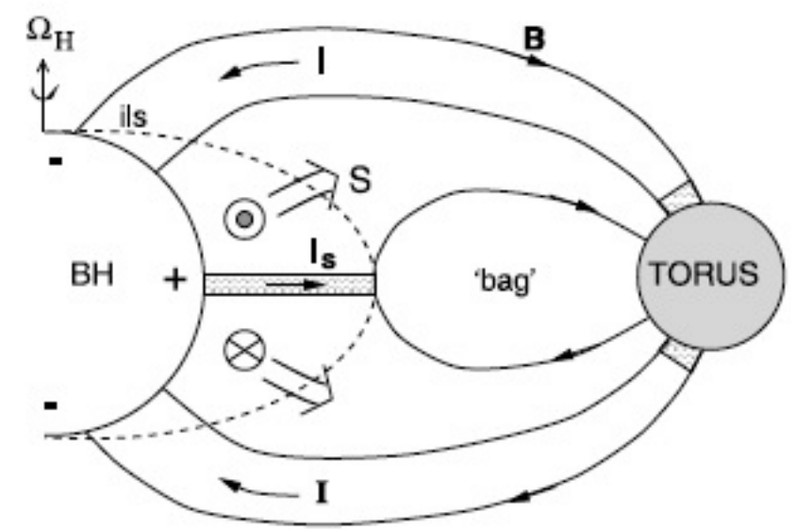


$2\ s < T_{90} < 20\ s$





BH-torus connection



van Putten, 1999, Science, 284, 115
van Putten & Levinson, 2002, Science, 295, 1874

van Putten & Gupta, 2009, MNRAS, 394, 2238
van Putten, 2012, Prog. Theor. Phys., 127, 331

LGRBs from near-extremal BHs

Enhanced luminosity from intermittency

Intermittent black hole-torus magnetosphere

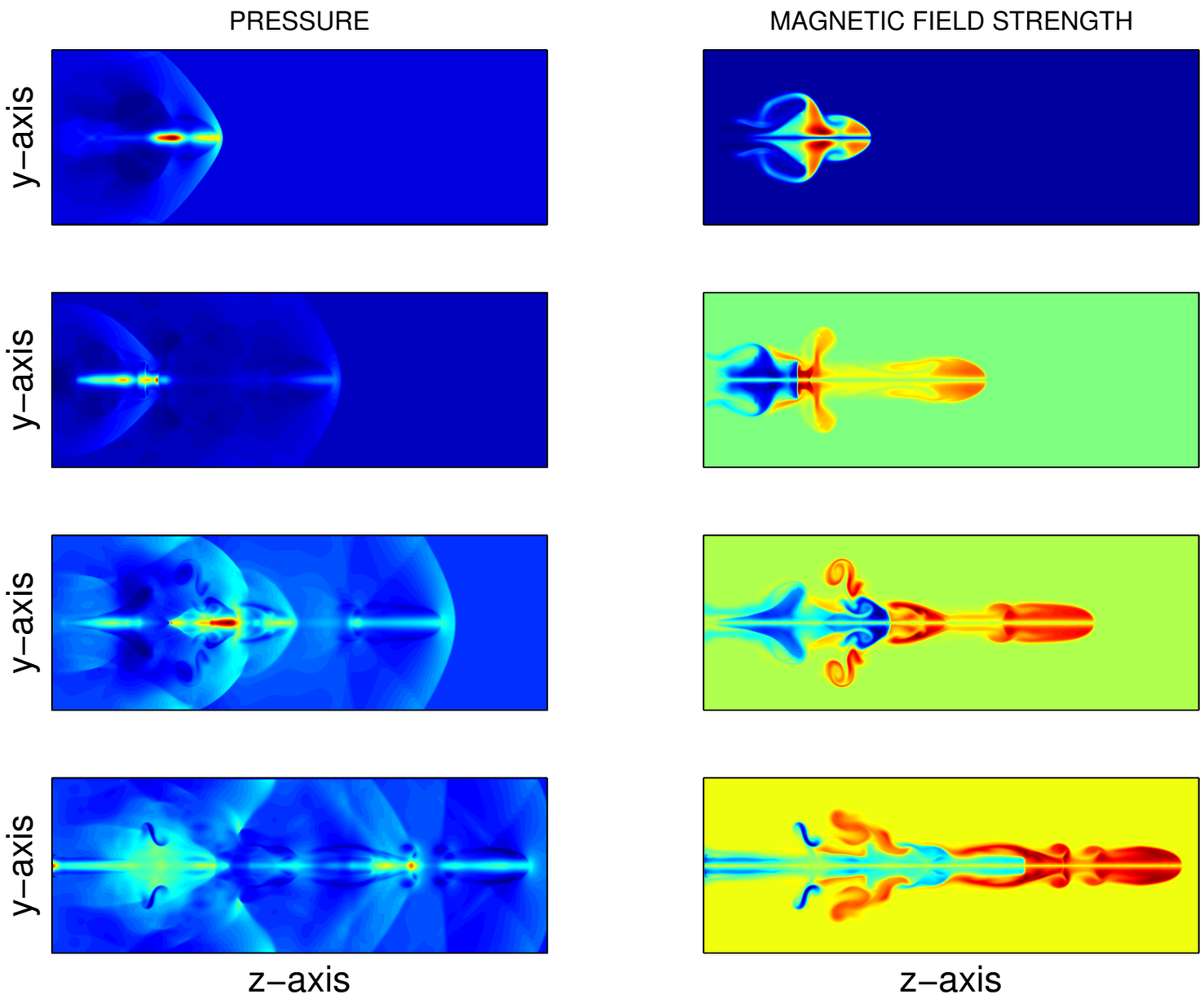
Intermittent luminosity >> continuous luminosity:

$$\left\langle L_w^i \right\rangle = \frac{4}{3} L_w^c \left(\frac{T}{\tau} \right)$$

e.g. with random reversals of the orientation of magnetic fields in the inner engine

van Putten, 2015, MNRAS, 447, L11

Intermittent inner engines



van Putten, 2015, MNRAS, 447, L11

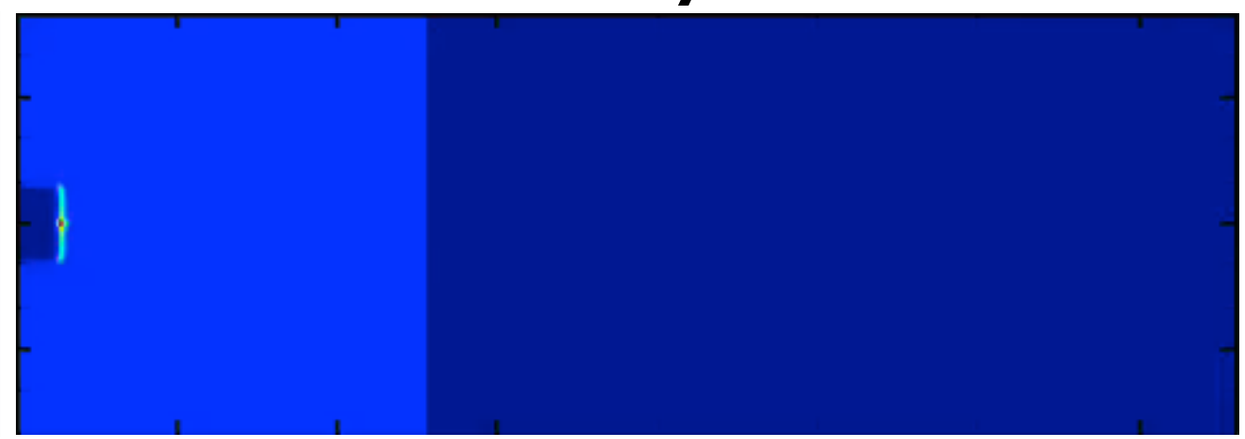
LGRB from intermittent outflows

Magnetically striped long-lived relativistic MHD ejecta

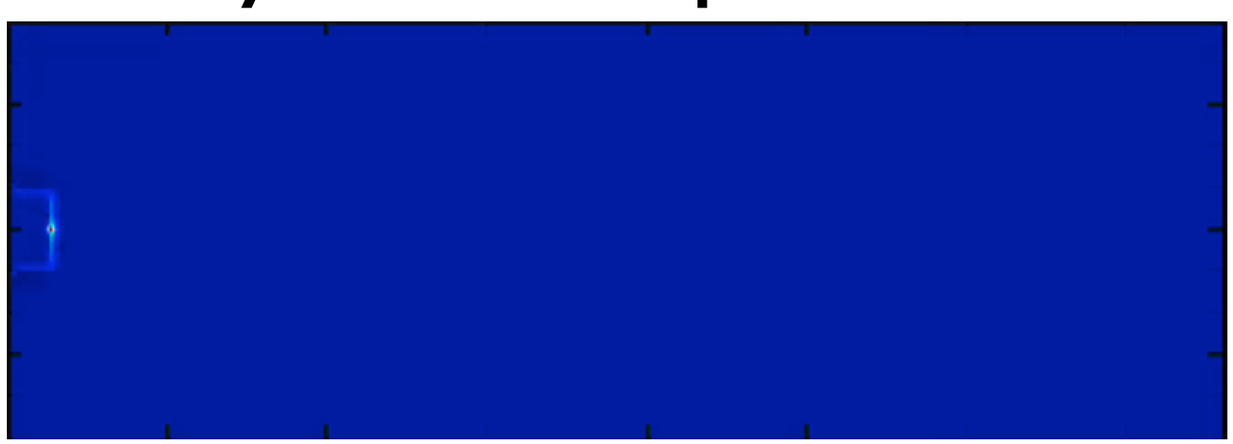
"Double shot" experiment:

velocity

density



hydrostatic pressure

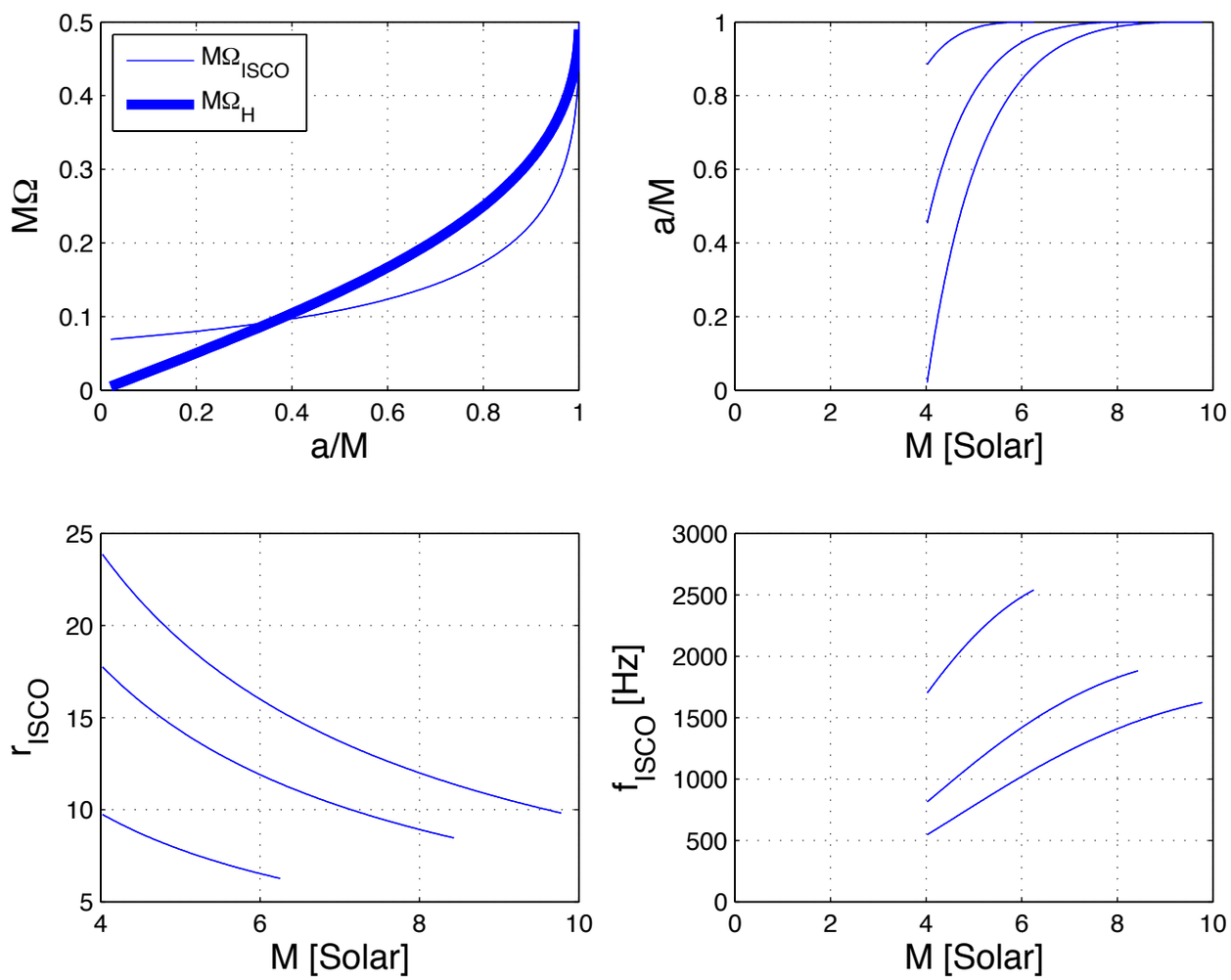


azimuthal magnetic field

van Putten, 2015, MNRAS, 447, L11

Formation of rapidly rotating BHs

Bardeen accretion: $\begin{cases} \dot{M} = e\dot{m} \\ \dot{J} = j\dot{m} \end{cases}$



van Putten, 2015, ApJ, in press

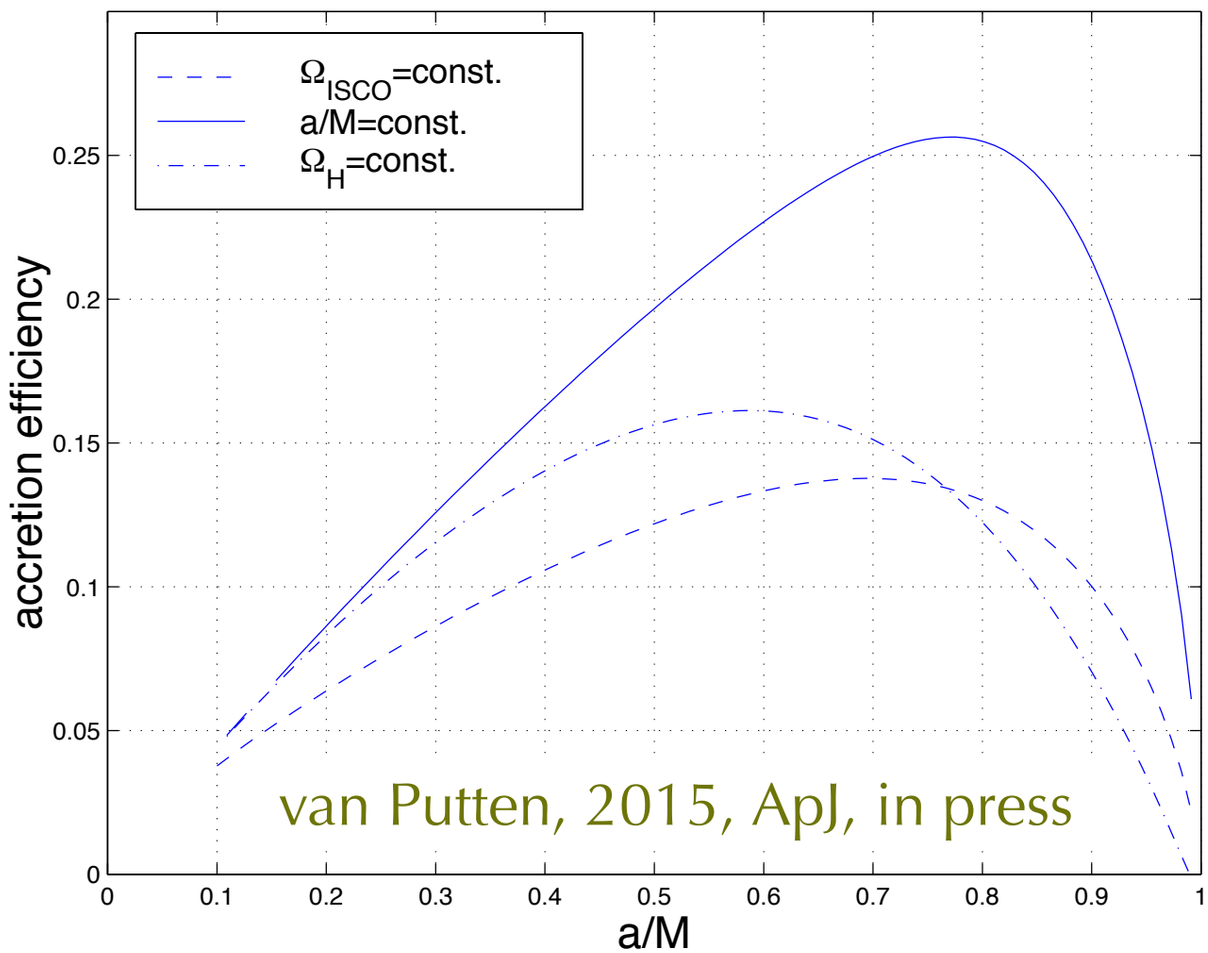
Surge in mass and angular momentum

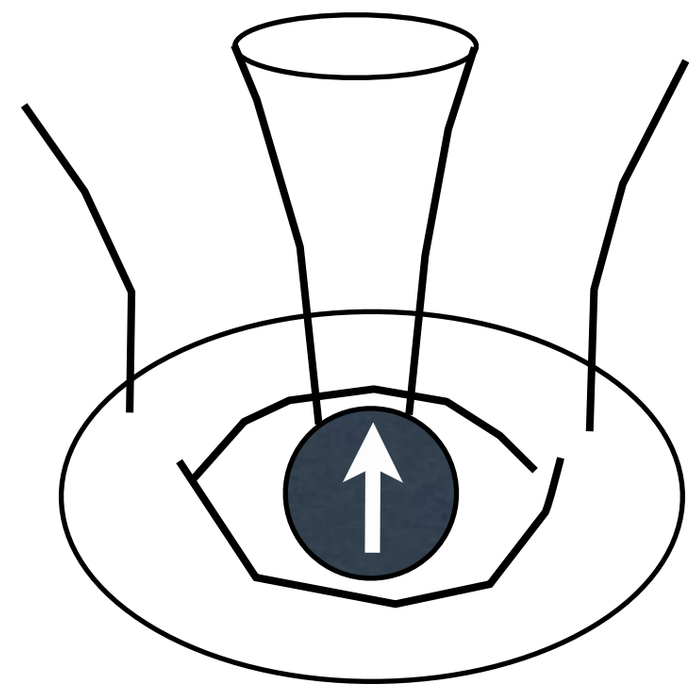
End point will be near-extremal close to the Thorne limit

Modified Bardeen accretion

Hyper-accretion with outflows

$$\begin{cases} \dot{M} = e\dot{m} - L_j \\ \dot{J} = j\dot{m} - 2\dfrac{L_j}{\Omega_H} \end{cases}$$





Surge continues unless efficiency is anomalously high
End point is still a rapidly rotating black hole

Canonical outcome of hyper-accretion

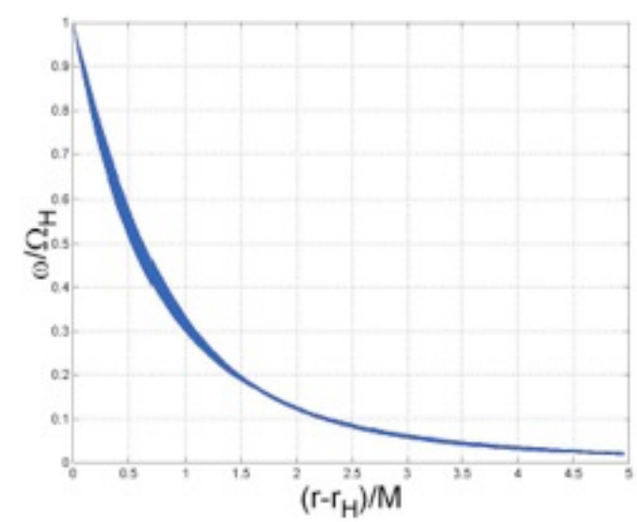
Near-extremal black holes as initial conditions to LGRBs

Non-relativistic frame dragging

Gravity Probe B: Everitt et al., 2011, PRL. 106, 221101
LAGEOS II: Ciufolini, I., & Pavils, E.C., 2004, Nature, 431, 958

Relativistic frame dragging

$$E_r \cong 6\times10^{54}\left(\frac{M}{10M_\odot}\right)\ \mathrm{erg}$$



van Putten, 2015, MG13, 1799

Calorimetric ratios from BH spin down

$$R_* \equiv \frac{E_*}{E_{rot}} \cong \frac{E_*}{(1-2)M_\odot} :$$

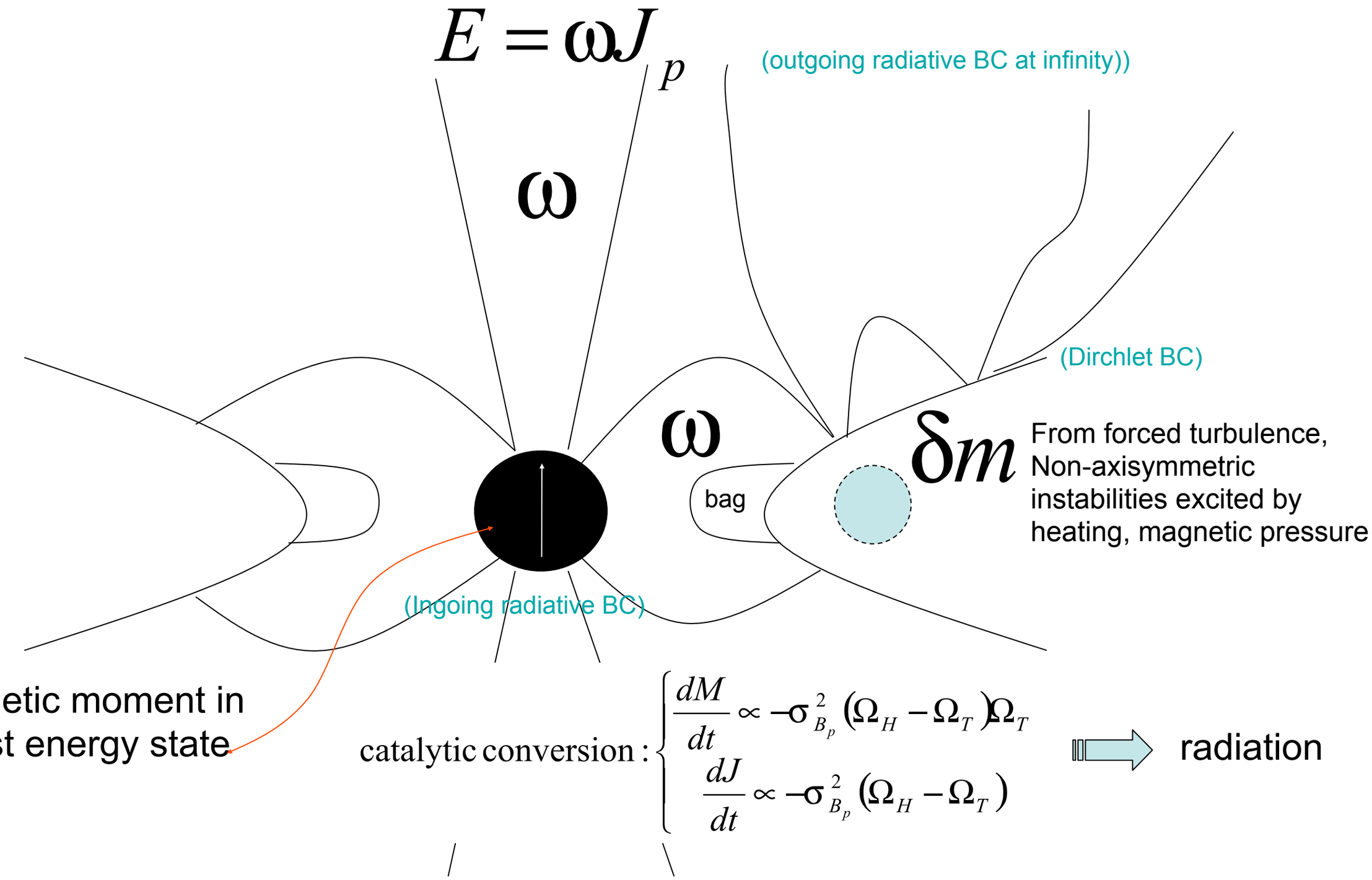
$$R_j + R_k + R_D + R_S \cong 1$$

Jets	kinetic energy accompanying supernova	dissipation inner disk or torus	entropy creation event horizon

(more detailed balance would include finite efficiencies for *j*,*k*)

van Putten, 2015, ApJ, in press

Near-extremal black holes as initial conditions to LGRBs



Magnetic moment in lowest energy state

$$\text{catalytic conversion}: \begin{cases} \dfrac{dM}{dt} \propto -\sigma_{B_p}^2 (\Omega_H - \Omega_T)\Omega_T \\ \dfrac{dJ}{dt} \propto -\sigma_{B_p}^2 (\Omega_H - \Omega_T) \end{cases}$$

⇨ radiation

Black hole in its lowest energy state supports open flux tubes from H to infinity

van Putten, 1999, Science, 284, 115, van Putten, 2001, Phys. Rev. Lett., 84, 091101; van Putten & Levinson, 2002, Science, 295, 1874; van Putten, 2002, ApJ, 575, L71; Bromberg, Levinson, van Putten, 2006, NewA, 11, 619; van Putten, 2012, Prog. Theor. Phys., 127,331
van Putten, 2008, ApJ, 684, L91

Effective calorimetric ratios

Table 1. Sample of GRB-SNe. References refer to SNe except for GRB 070125. E_* is expressed in units of 10^{51} erg.

GRB	Supernova	z	E_γ	E_{SN}	η	E_r/E_c	Ref.
980425	Sn1998bw	0.008	< 0.001	50	1	1.7	1
031203	SN2003lw	0.1055	< 0.17	60	0.25	10	2
060218	SN2006aj	0.033	< 0.04	2	0.25	0.25	3
100316D	SN2006aj	0.0591	0.037-0.06	10	0.25	1.3	4
030329	SN2003dh	0.1685	0.07-0.46	40	0.25	5.3	5

Jet-to-rotational energy:

$$R_j \equiv \frac{E_j}{E_{rot}} \cong 0.2\% \left(\frac{\varepsilon}{0.16} \right)^{-1}$$

Kinetic energy-to-rotational energy:

$$R_k \equiv \frac{E_{SN}}{E_{rot}} \cong 0.5\%$$

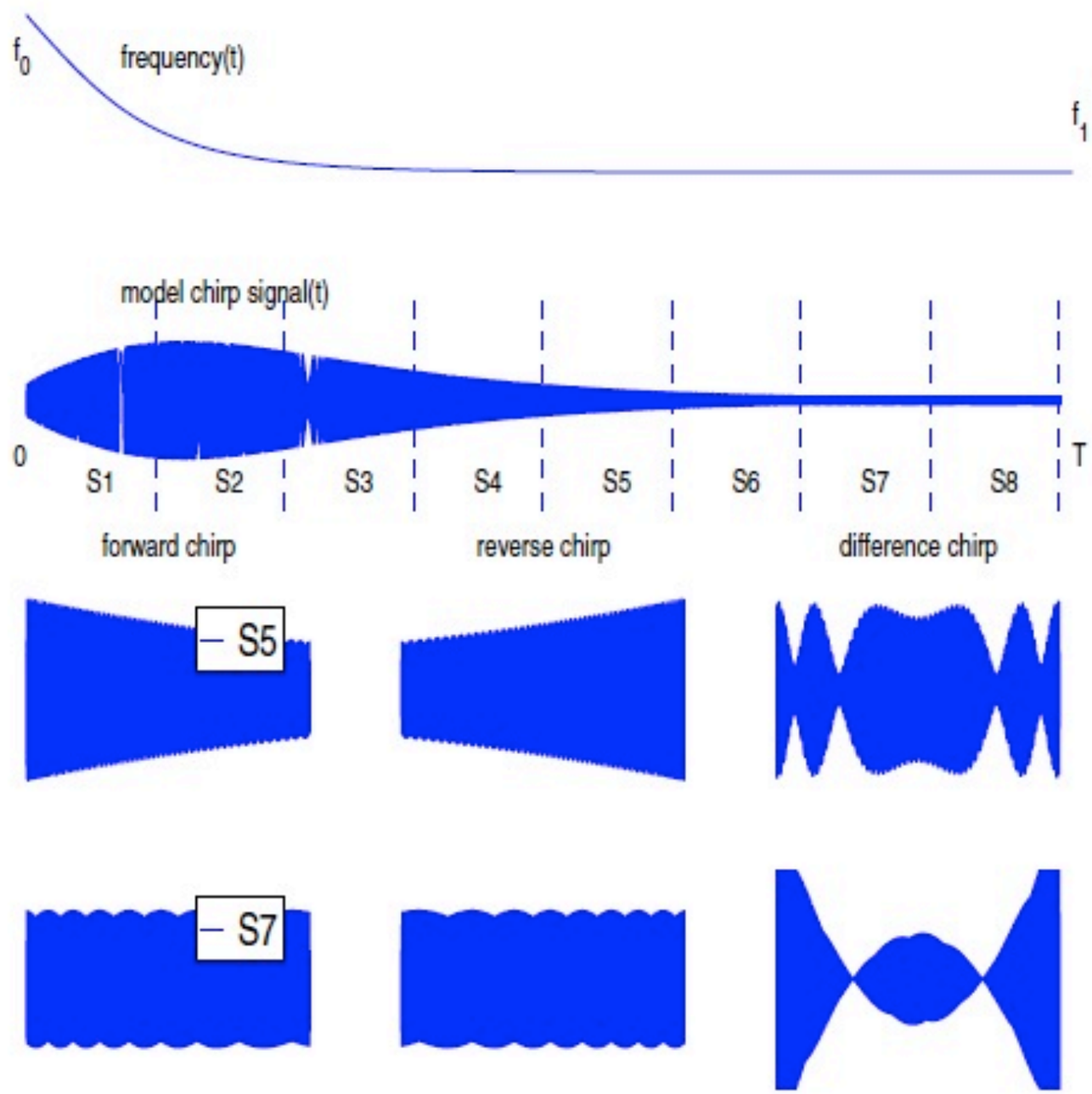
Spin down against HD matter:

$$R_D = O(1), \qquad R_{jD} = \frac{R_j}{R_D} << 1$$

van Putten, 2015, ApJ, in press

Probing inner engines by matched filtering

Side step Fourier by TSMF using a bank of chirp templates

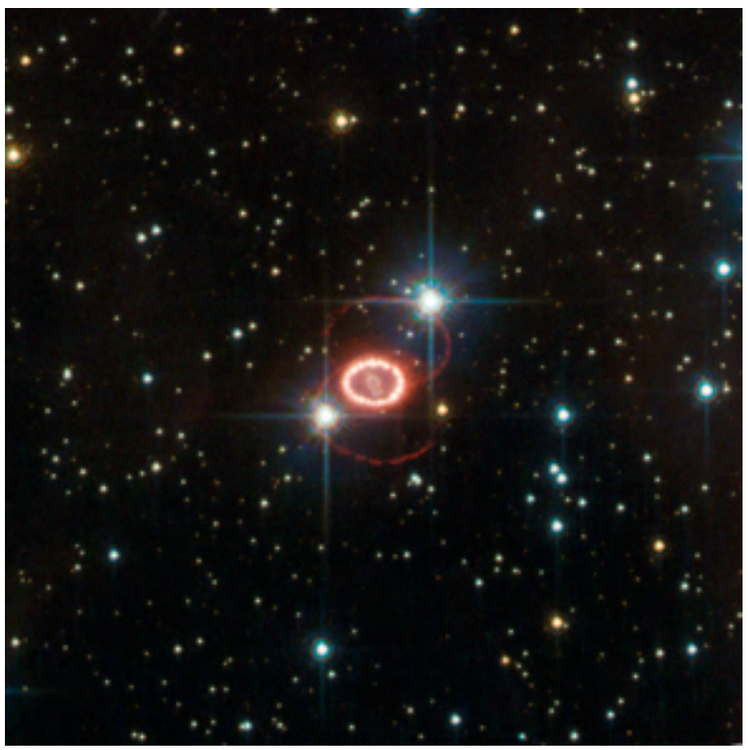


van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146

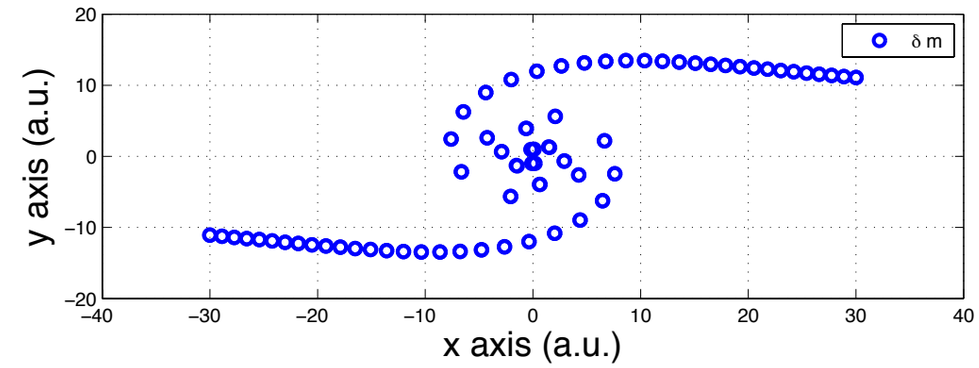
Did SN1987A produce a GWB?

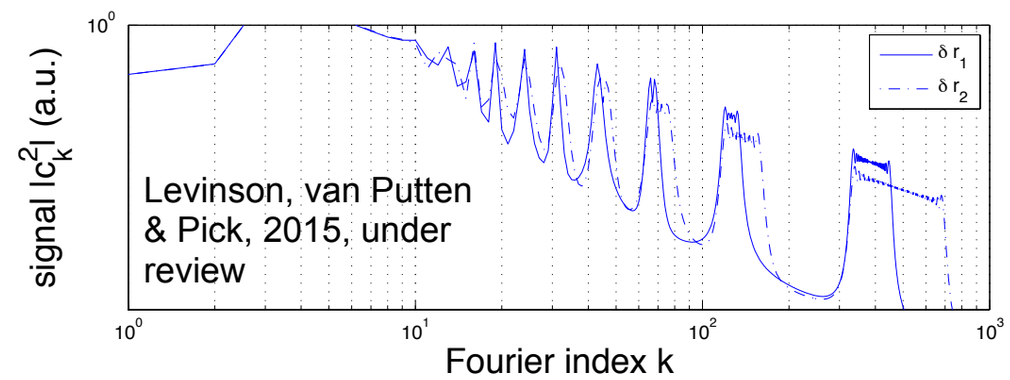
All ingredients are there !

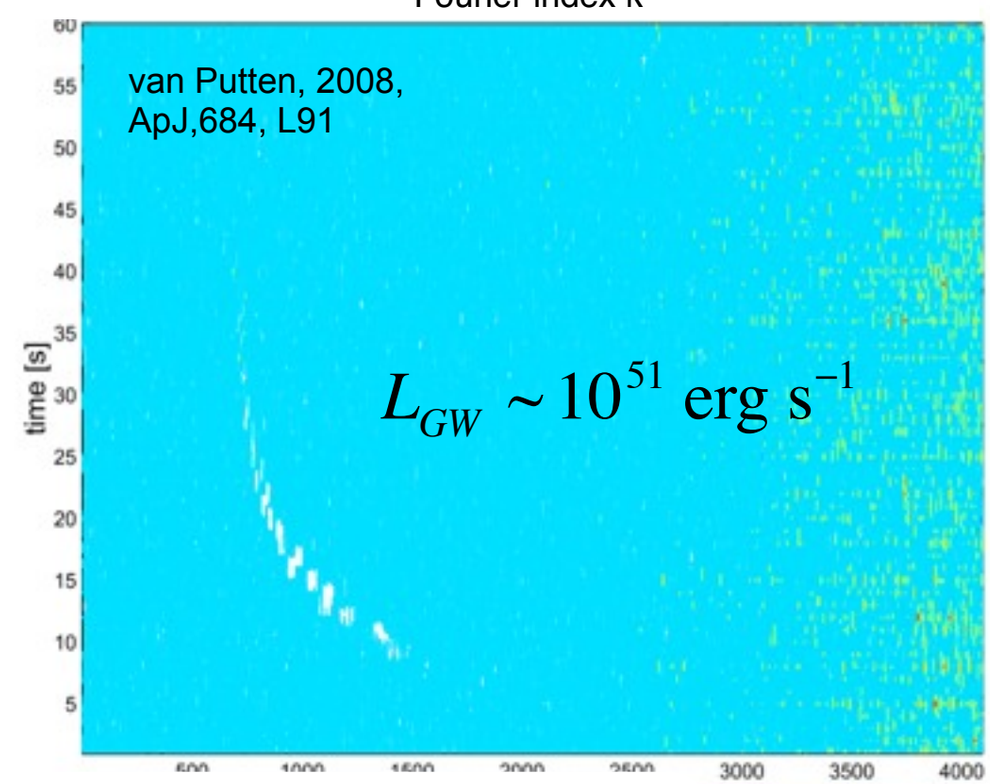
Aspherical explosion and massive MeV burst with no PSR remnant: angular momentum-rich high density matter around newly formed BH



?







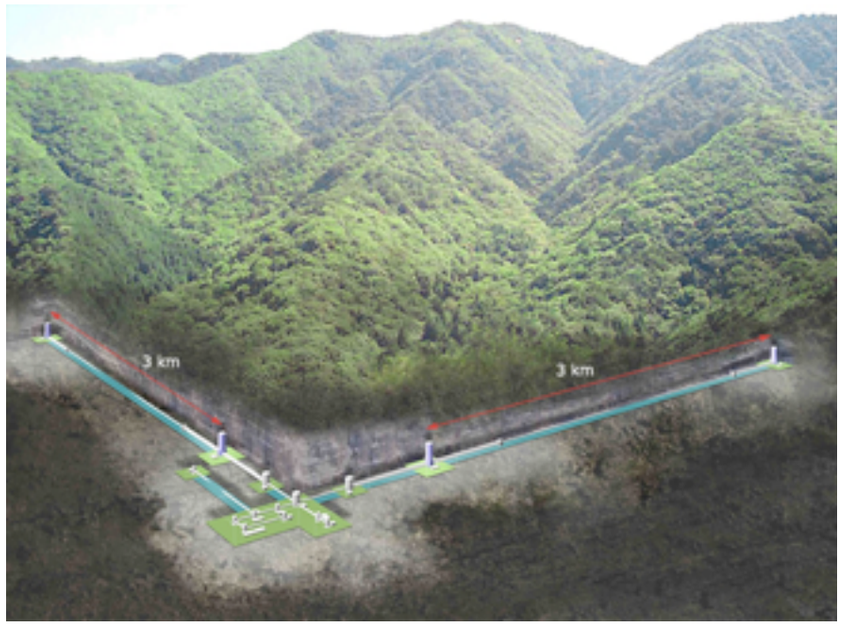
$$L_{GW} \sim 10^{51}\ \mathrm{erg\ s^{-1}}$$

$$L_{GW} = 2 \times 10^{51} \left(\frac{\xi}{0.1}\right)^2 \left(\frac{\sigma}{0.01}\right)^2 \left(\frac{4M}{a}\right)^5 \ \mathrm{erg\ s^{-1}}$$

$$h = 3.4 \times 10^{-23}\, M_1 \frac{\xi}{0.1} \frac{\sigma}{0.01} \left(\frac{D}{20\,\mathrm{Mpc}}\right)^{-1} \left(\frac{f}{600\,\mathrm{Hz}}\right)^{\frac{2}{3}}$$

Gravitational-wave Detectors in US, EU and Japan

http://www.ligo.caltech.edu, http://www.ego-gw.it



Probing CC-SNe by TSMF

$$h_{eff} \sim \left(\frac{M}{D}\right)\left(\frac{E_{GW}}{M}\right)^{\frac{1}{2}} \sim 10^{-21}$$

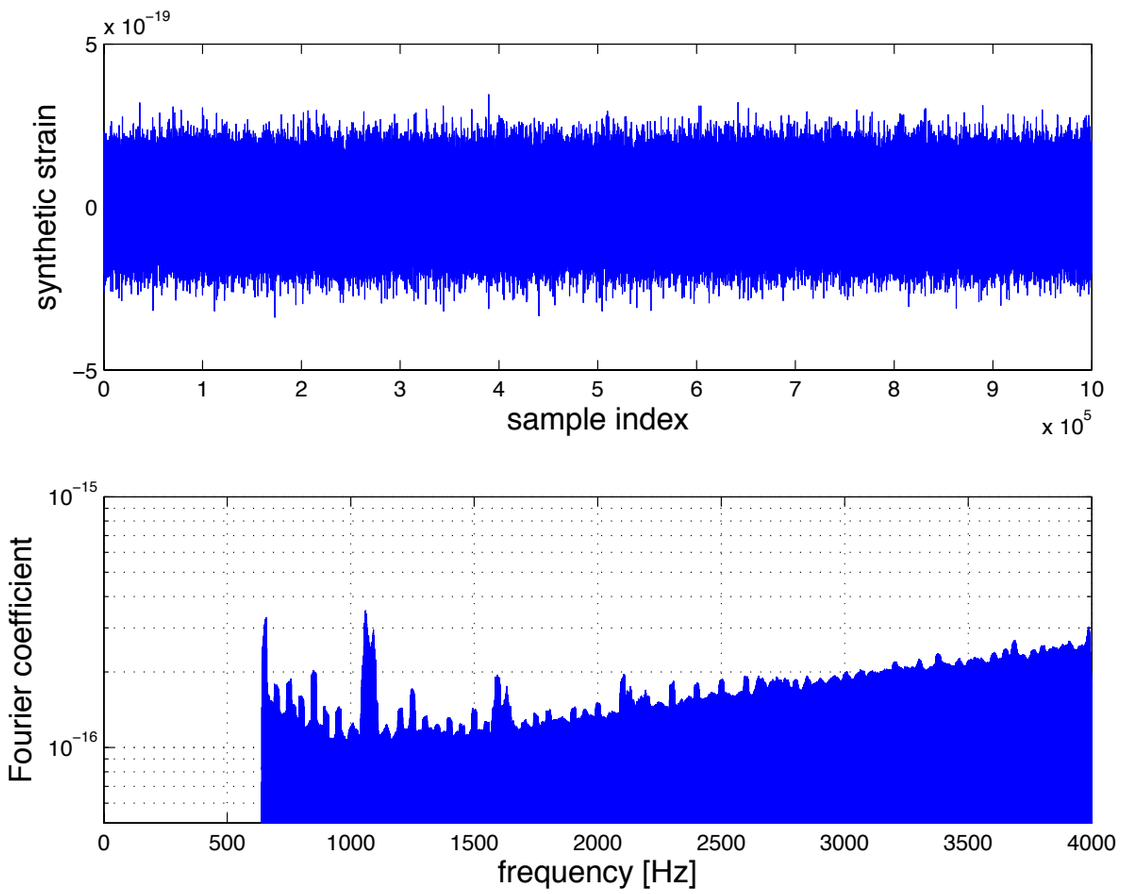
$$h_{eff}^{(r)} = h_{eff}\left(\frac{\tau}{T}\right)^{\frac{1}{2}} \sim 10^{-22}$$

Chirp detection by TSMF (tau=1 s)

van Putten, Tagoshi, Tatsumi, Masa-Katsu & Della Valla, 2011, PRD, 83, 044046

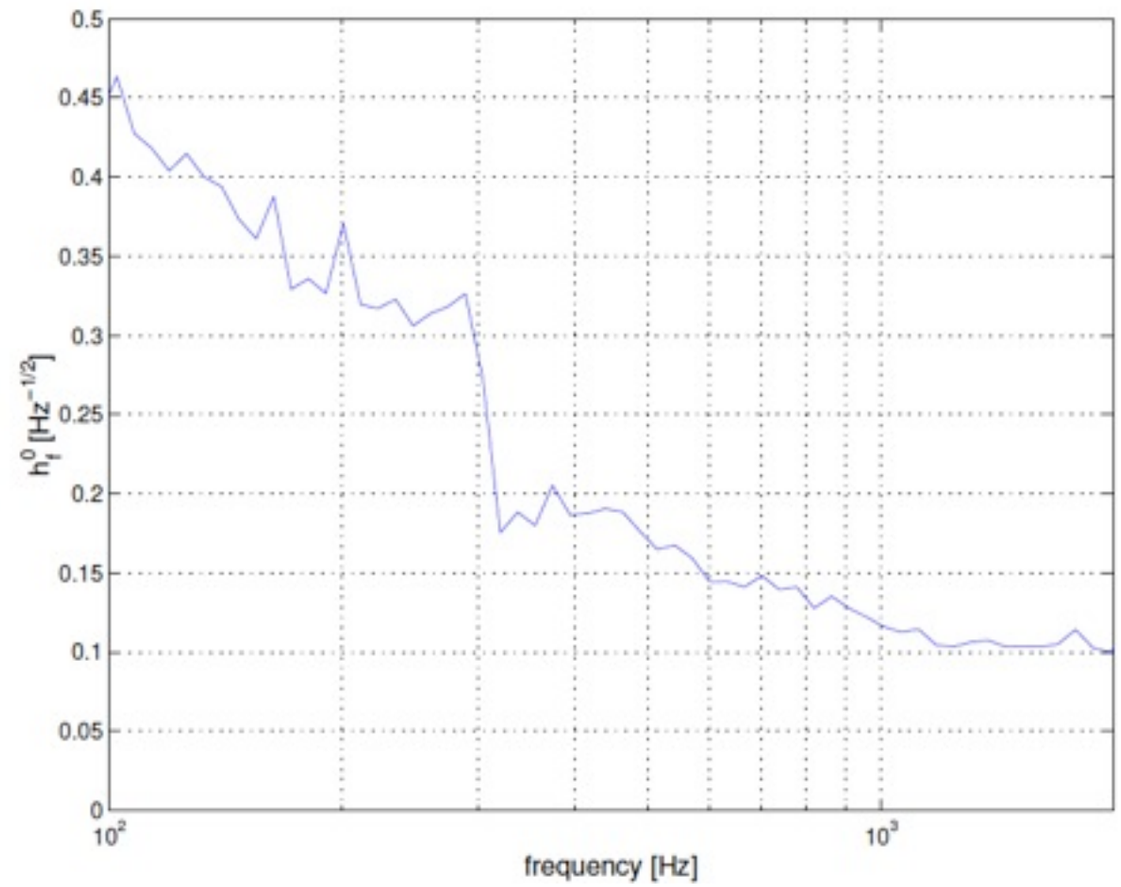
Expected sensitivity distance ~ 100 Mpc for Adv LIGO-Virgo (at high laser power)

Fourier versus TSMF



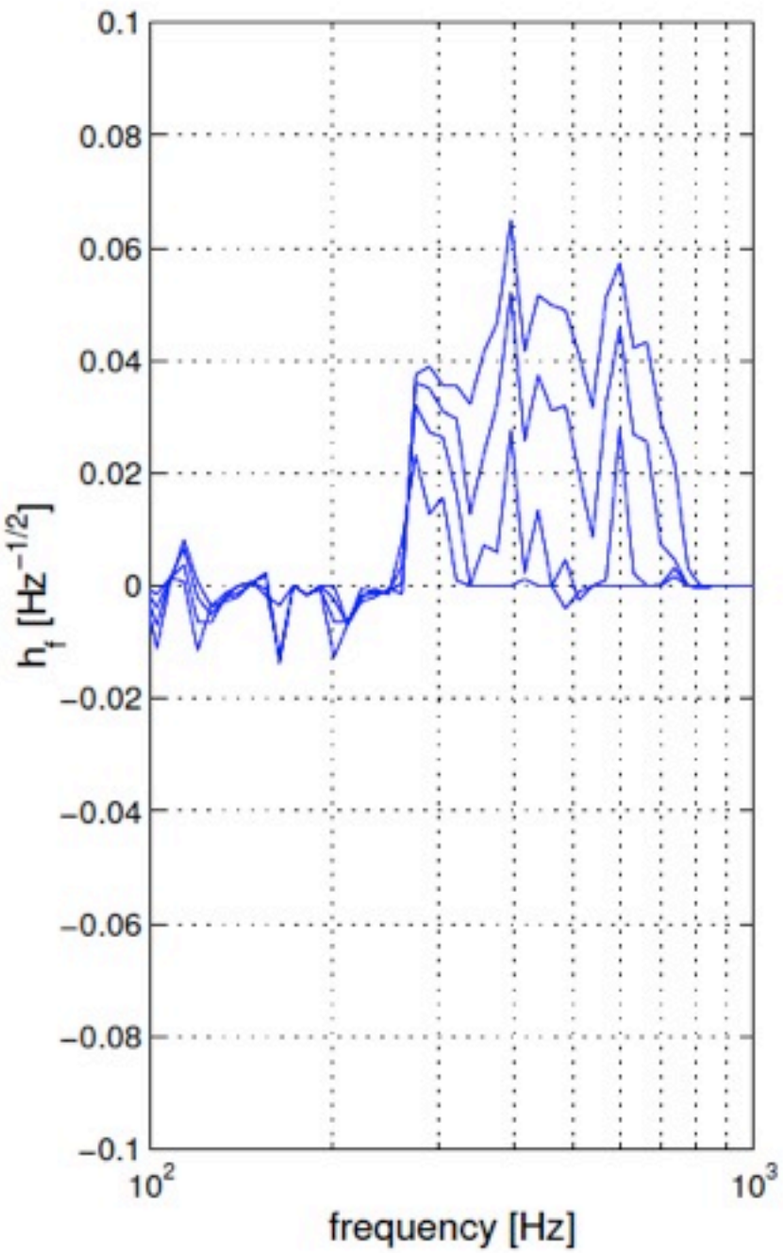
Fourier spectrum

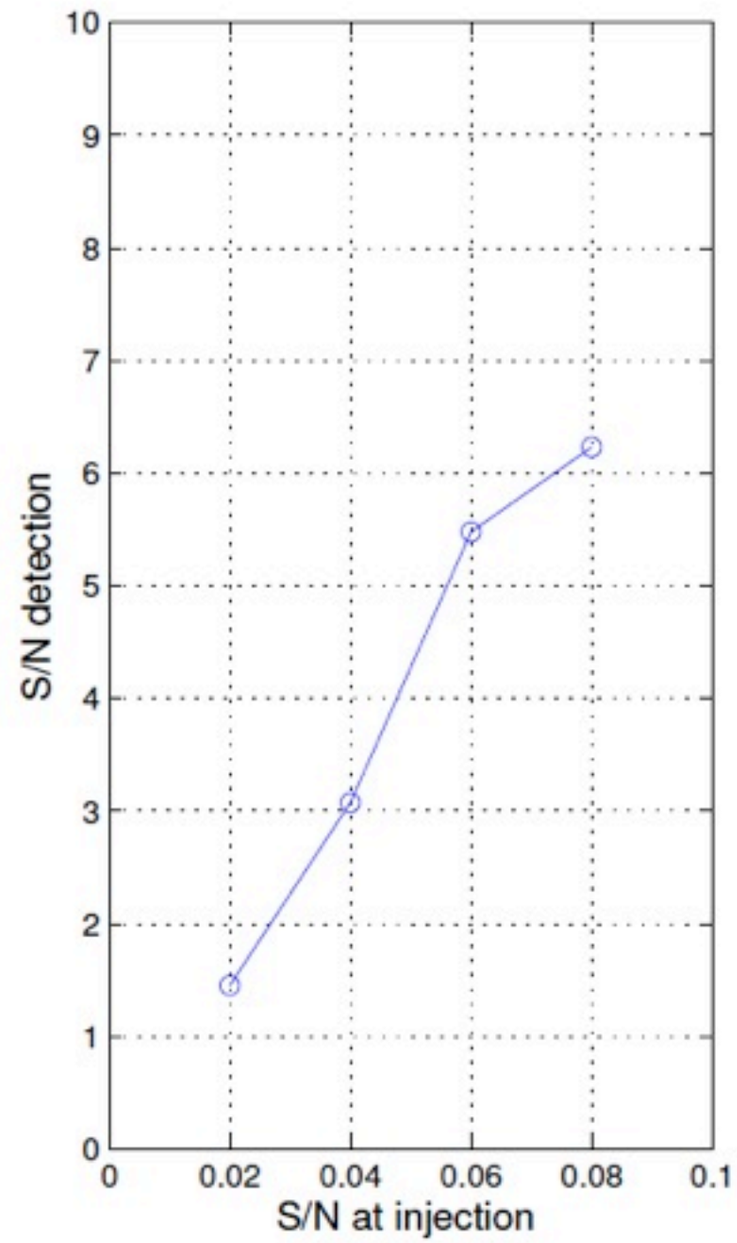
Spectrum extracted by TSMF
using 8.64 million chirp templates



van Putten, 2015, ApJ, in press

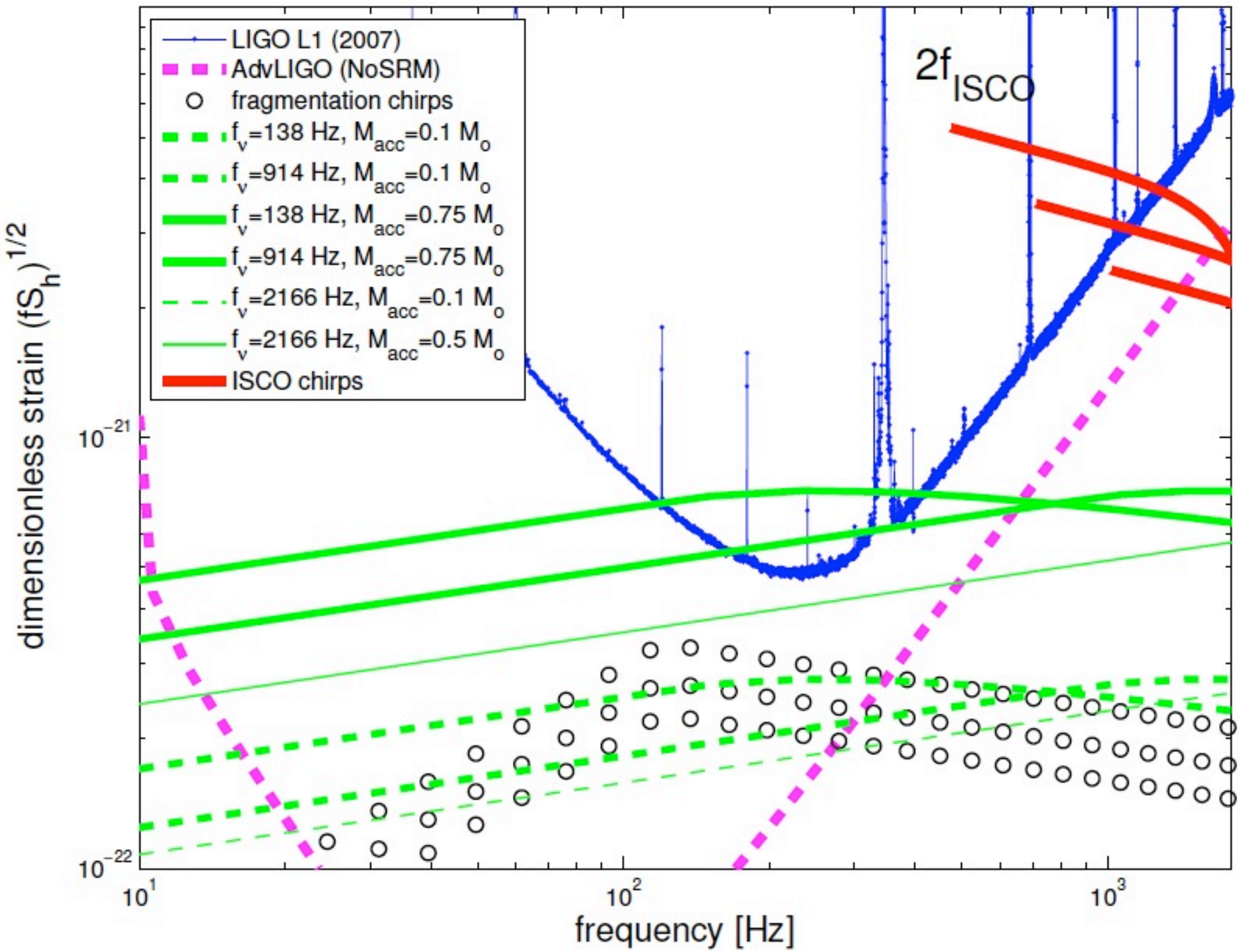
Maximal sensitivity source detection by TSMF





van Putten, 2015, ApJ, in press

Broadband GW emission from CC-SNe



van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle

(under review)

Conclusions and outlook

Swift, BeppoSAX, BATSE:

LGRBs from spin down of near-extremal black holes

GWBs expected from energetic CC-SNe forming near-extremal BHs

- High density matter in aspherical SN1987A
- SNIc association with normal long GRBs
- SNIc event rate of ~100/yr within 100 Mpc

GWBs from SNIc are competitive with mergers if just 1% is successful

We propose

(a) Search for the most nearby CC-SNe by dedicated optical surveys
e.g., one every decade in M51, M82 (J.-E. Heo et al., NewA, to appear)

(b) Probe nearby CC-SNe with TSMF using ~10 million chirp templates

Sensitivity range ~100 Mpc for Advanced LIGO-Virgo, KAGRA

Supplementary slide

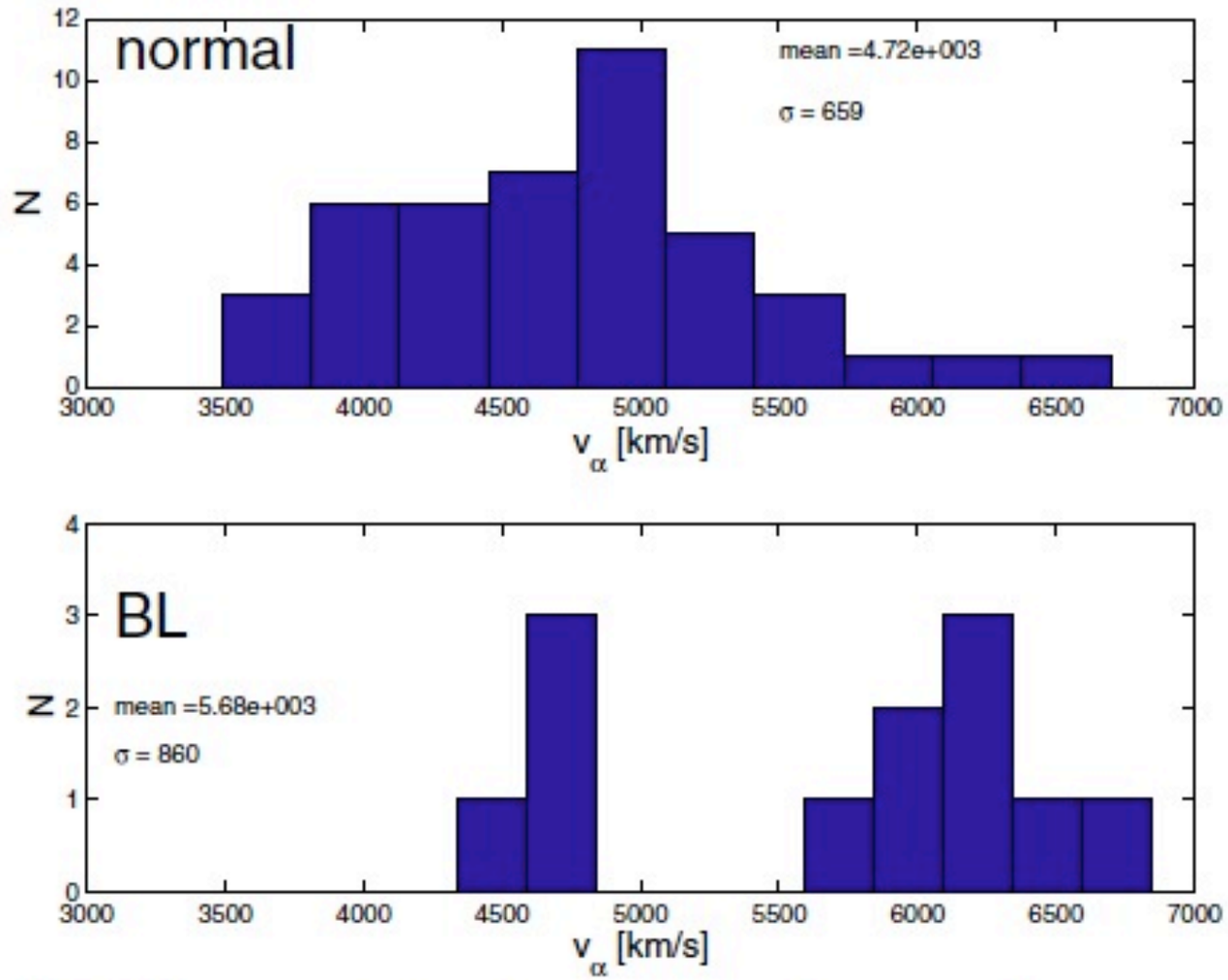


Fig. 1. Histograms of the ejection velocities in core-collapse events compiled by Maurer et al. (2010), in 44 normal and 12 broad-line (BL) events. The mean velocity 5680 km s^{-1} of the latter is 3.9 standard deviations away from the mean velocity 4720 km s^{-1} of the first, which is indicative of a separate group of relatively hyper-energetic events.

van Putten, Della Valle & Levinson, 2011, A&A, 535, L6