Extracting broadband spectra from long duration GRBs

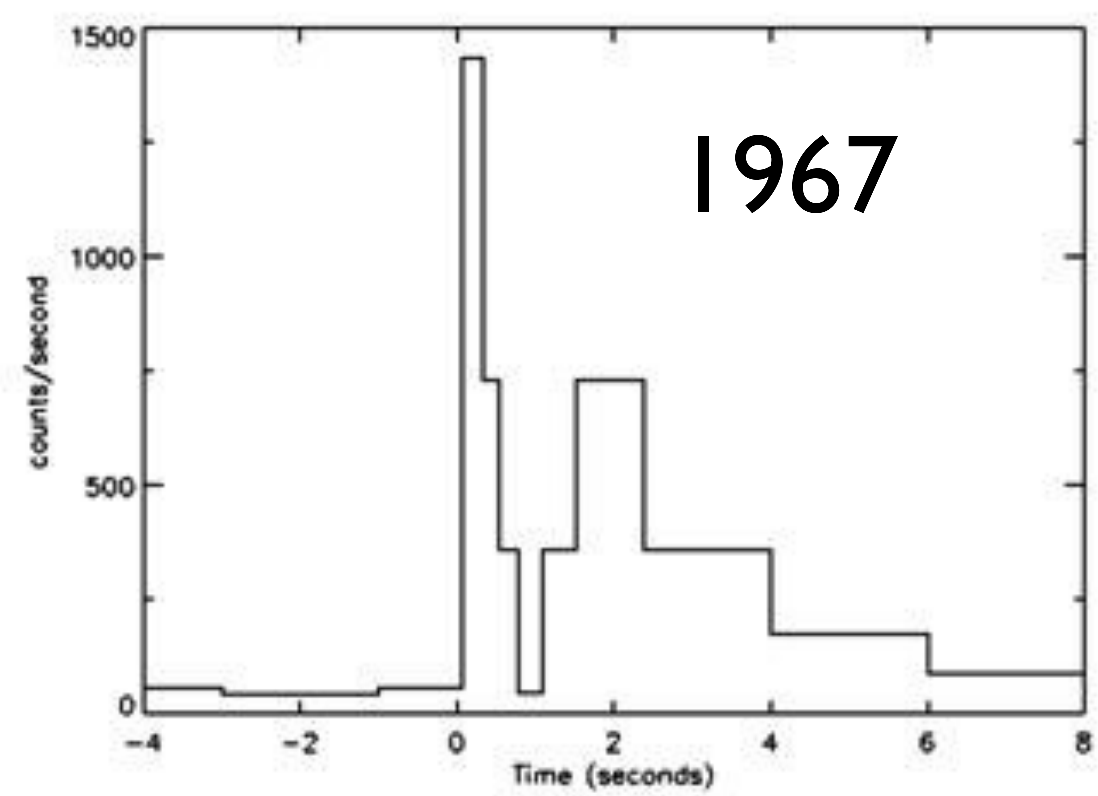
Maurice H.P.M. van Putten

6th Japan-Korea Workshop on Kagra
June 20-21 NAOJ
2014

GRBs: *the most relativistic events in the Universe*

Prompt GRB emission

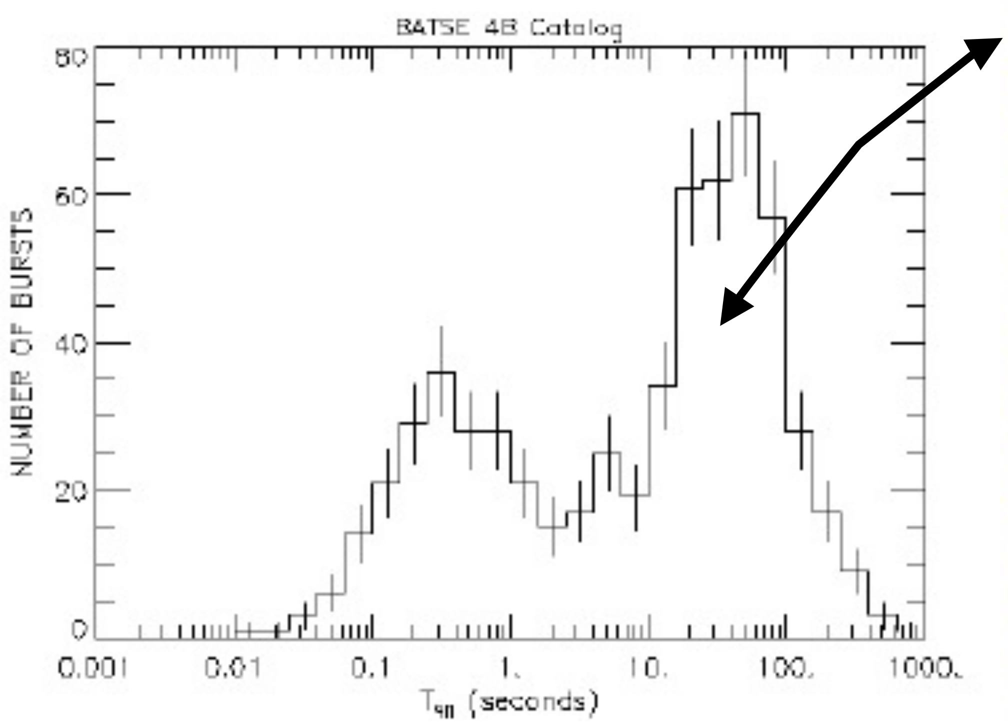
- Non-thermal HE emission from *ultra-relativistic* shocks
- Energetic baryon-poor inner engines

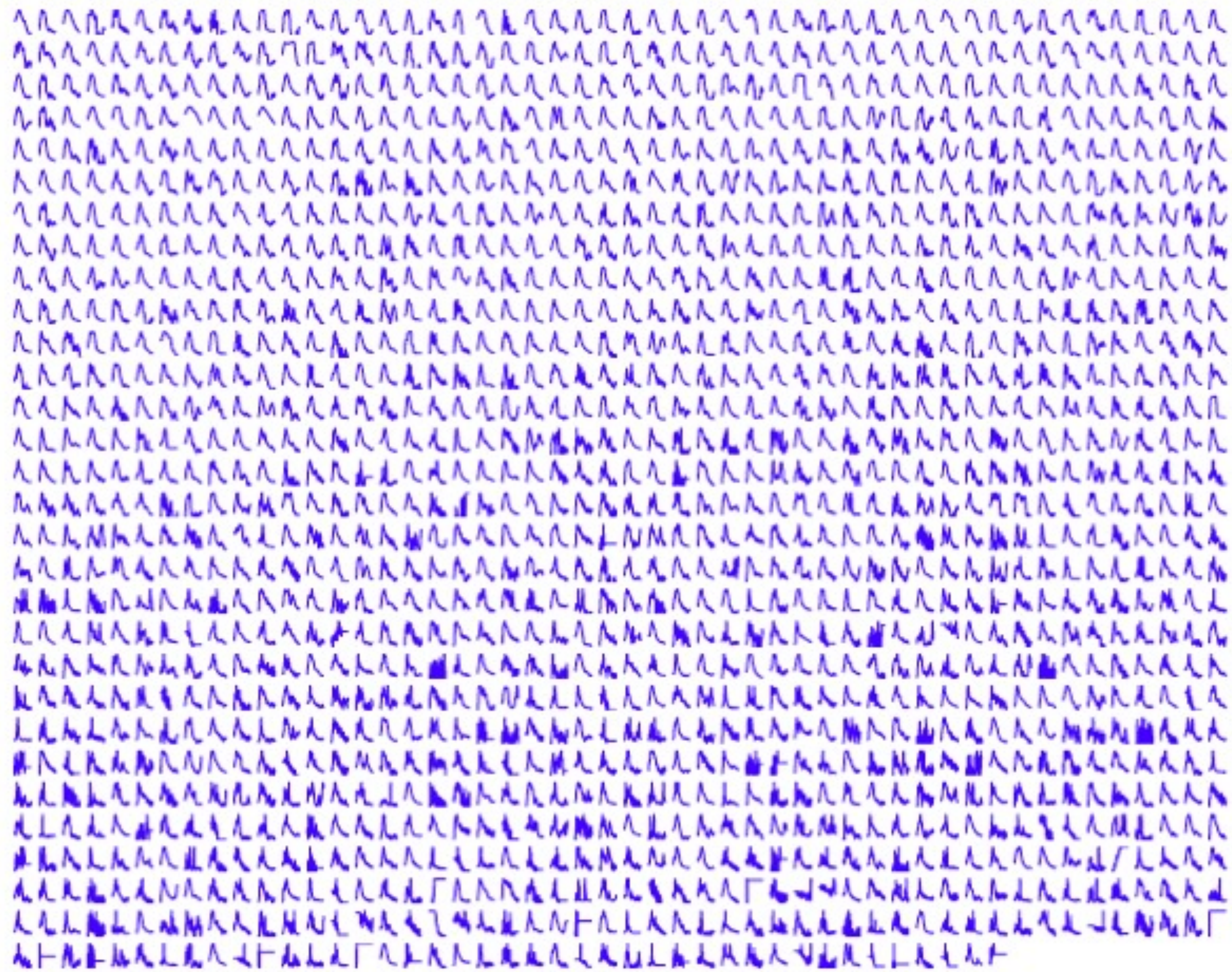


GRBs: *the most relativistic events in the Universe*

BATSE classification in short and long events

- short due to mergers, long from core-collapse SNe





1491 long GRBs

GRBs: *the most relativistic events in the Universe*

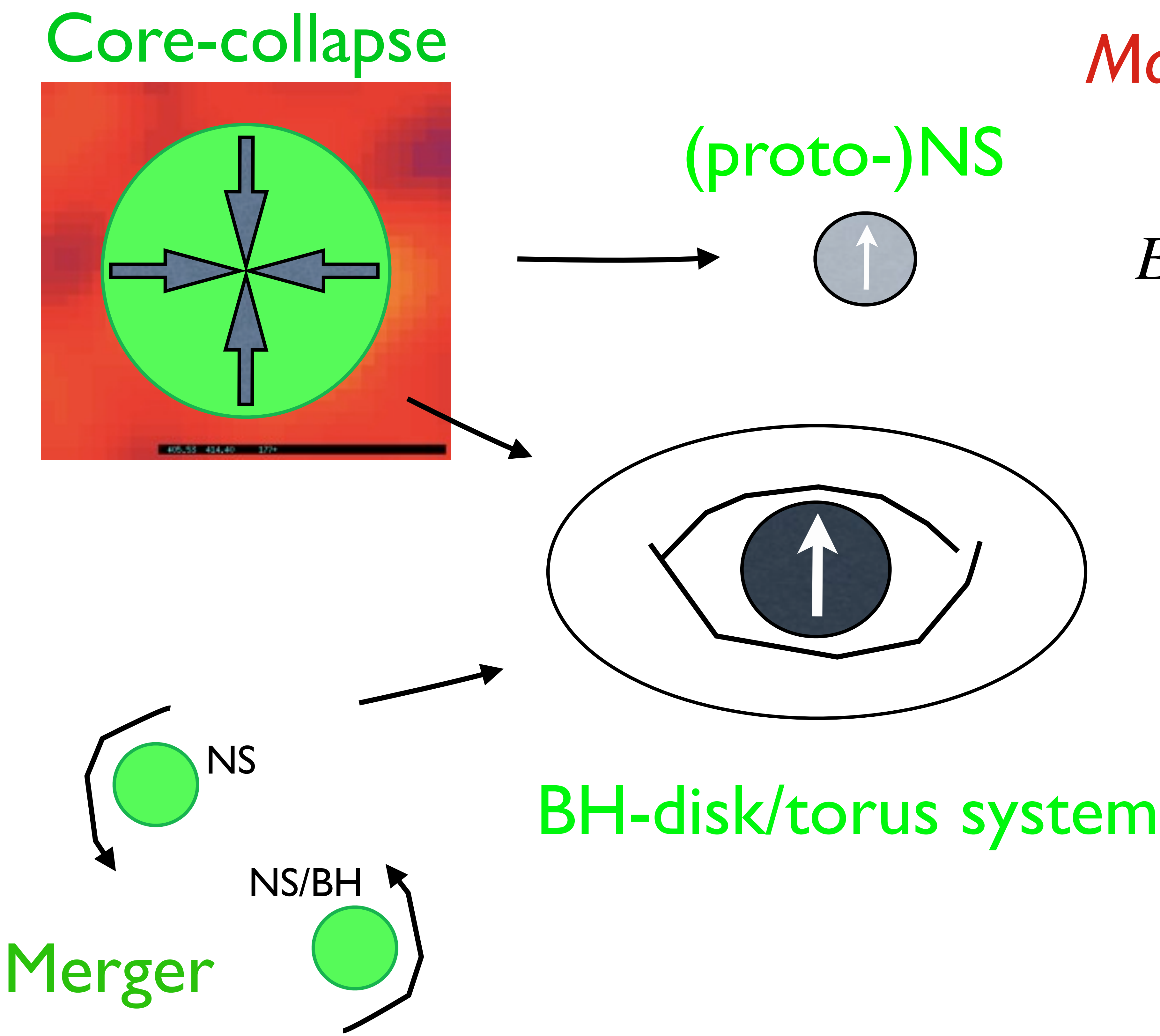
Swift discovery of new events that challenges BATSE's

- short GRBs with Extended Emission (SGRBEE)
- long GRBs with no association to a supernova (LGRBN)

SGRBEE	060614 [d,e,f,g]	108.7	0.125	faint SFR [20,21]	0.21±0.09 [20]	55 [20]
	050724 [d,e,f,g]	69	0.258	elliptical, weak spiral [22]	0.0099 [23]	-
	071227A [e,f]	1.8	0.384	edge-on spiral [24]	0.008 [25]	-
	061210 [d,e,f,g]	85.3	0.41	bulge dominated [26]	0.046 [26]	-
	061006 [d,e,f,g]	129.9	0.438	exponential disk profile [27]	0.18	955
	070714B [d,e,f,g]	64	0.92	moderately SF galaxy [28]	0.16 [28,29]	-
	050911 [d,e]	16.2	1.165	EDCC493 cluster [30]	0.0019 [30]	-
LGRBN	060505	4	0.089	spiral, ionized H, no SN [31]	0.0012 [21] - 0.0039	120
	060614 [d,e,f,g]	108.7	0.125	faint SFR, no SN [20]	0.21±0.09 [21]	-
	061021	46	0.3462	no SN [32]	0.68	630

van Putten, Lee, Della Valle, Amati & Levinson, under review

Astronomical origin of GRBs



Maximal rotational energy

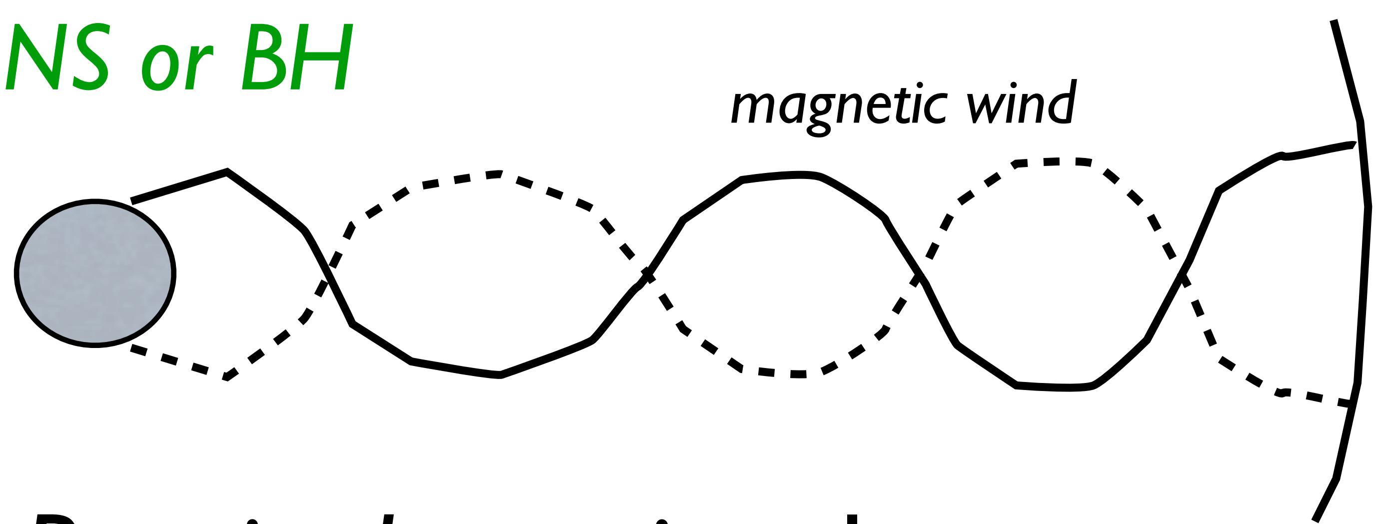
$$E_c \cong 3\times10^{52}\,\mathrm{erg}$$

$$E_{rot}^{max} \cong 6\times10^{54}\,\mathrm{erg}$$

van Putten, 2009, MNRAS, 396, L81

Explosion energies in GRB-supernovae

spindown model of Bisnovatyi-Kogan (1970)



$$\beta_{ej} \simeq \begin{cases} 4\%(typical) \\ 10\%(relativistic) \end{cases}$$

Required rotational energy

$$\frac{E_{rot}}{E_c} \geq \frac{E_{k,SN}}{\eta E_c}$$

Efficiency (baryon-loading)

$$\frac{1}{2}\beta_{ej} < \eta < 1$$

$$\left.\frac{E_{k,SN}}{\eta E_c}\right|_{\eta=0.25} \cong \begin{cases} 10 \text{ GRB 031203/SN 2003lw} \\ 5.3 \text{ GRB 030329/SN 2003dh} \end{cases}$$

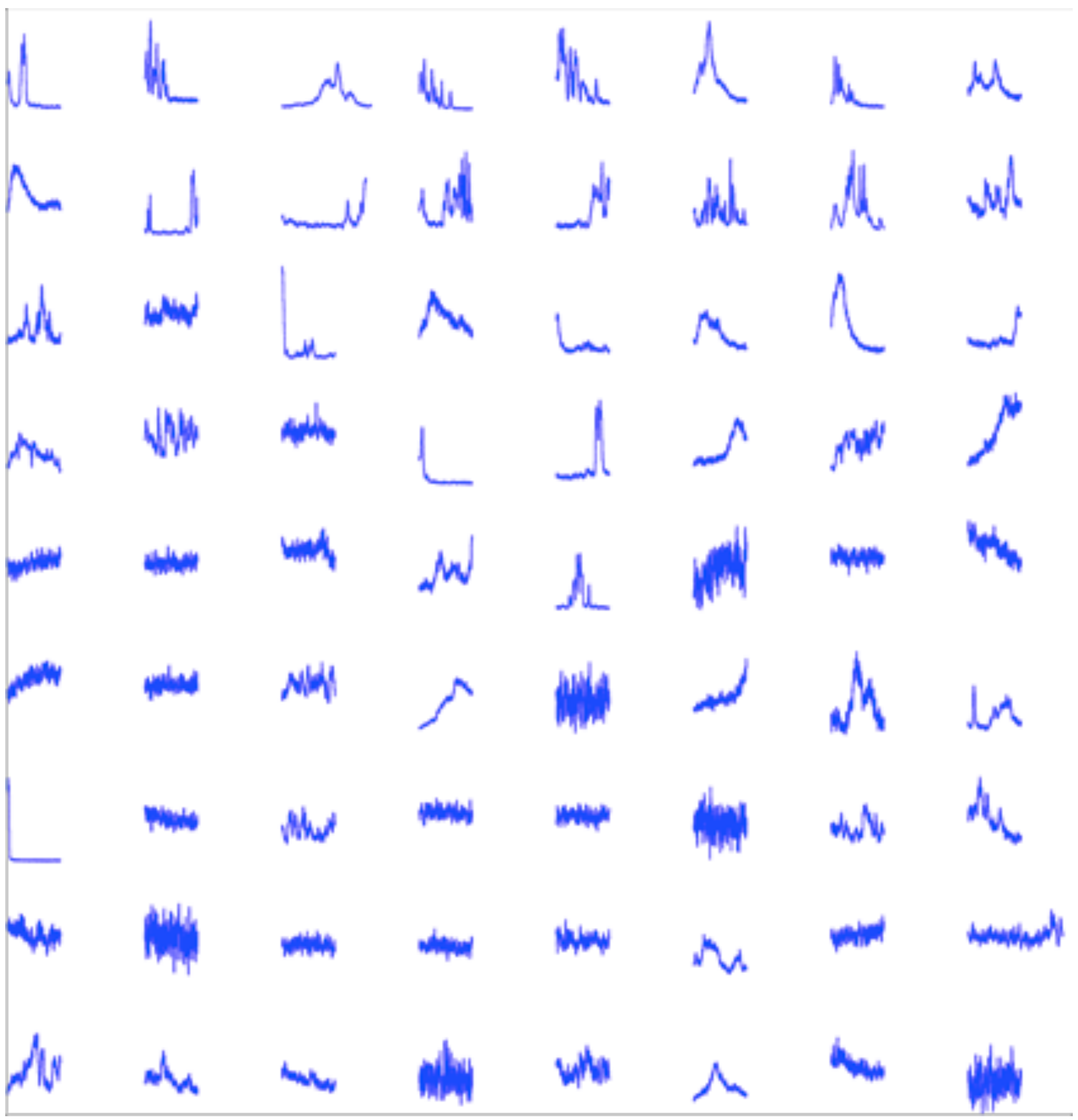
GRB 031203,030329 harbor BHS not (P)NS

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

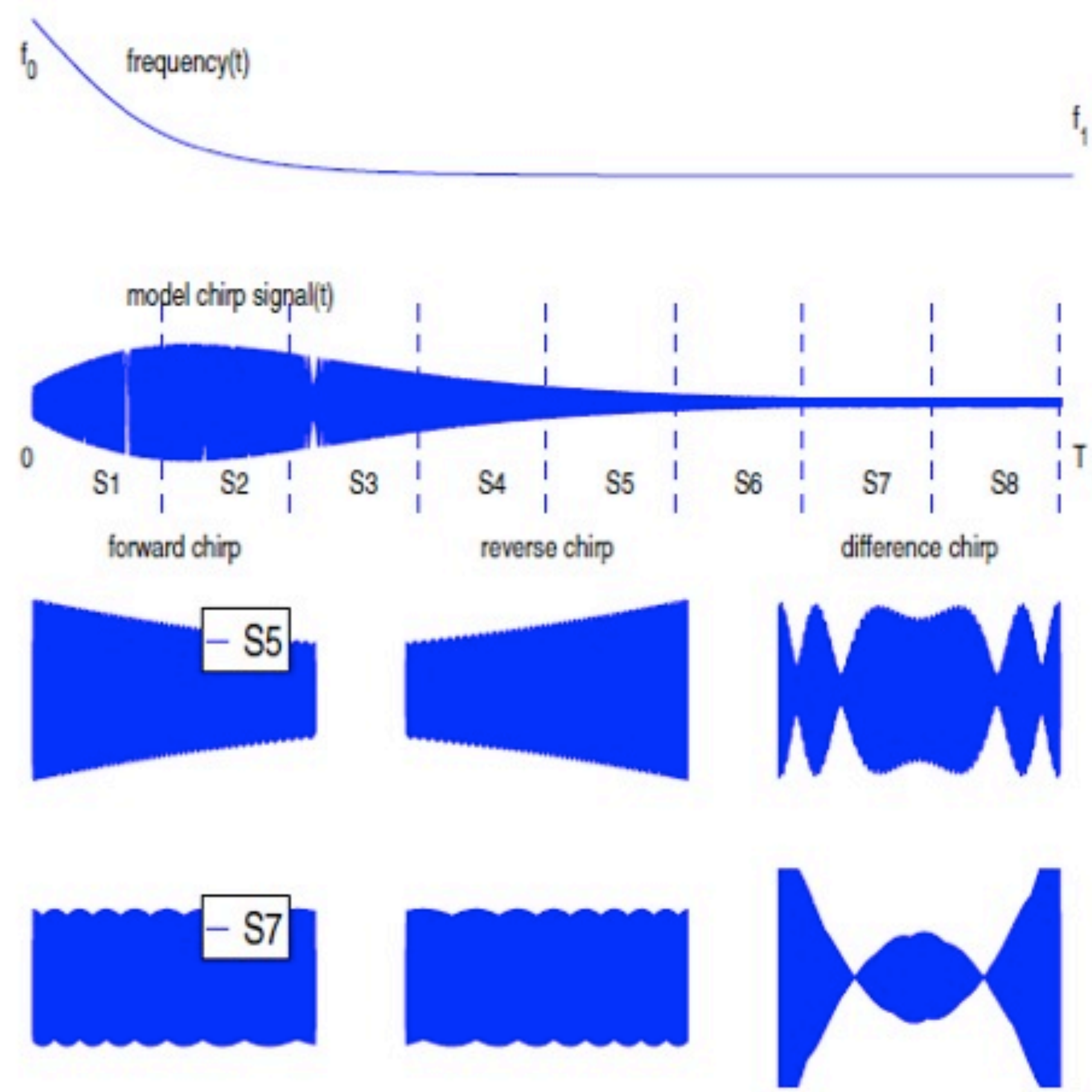
Broadband Fourier-chirp spectrum of long GRBs

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

72 light curves of BeppoSAX (2 kHz)



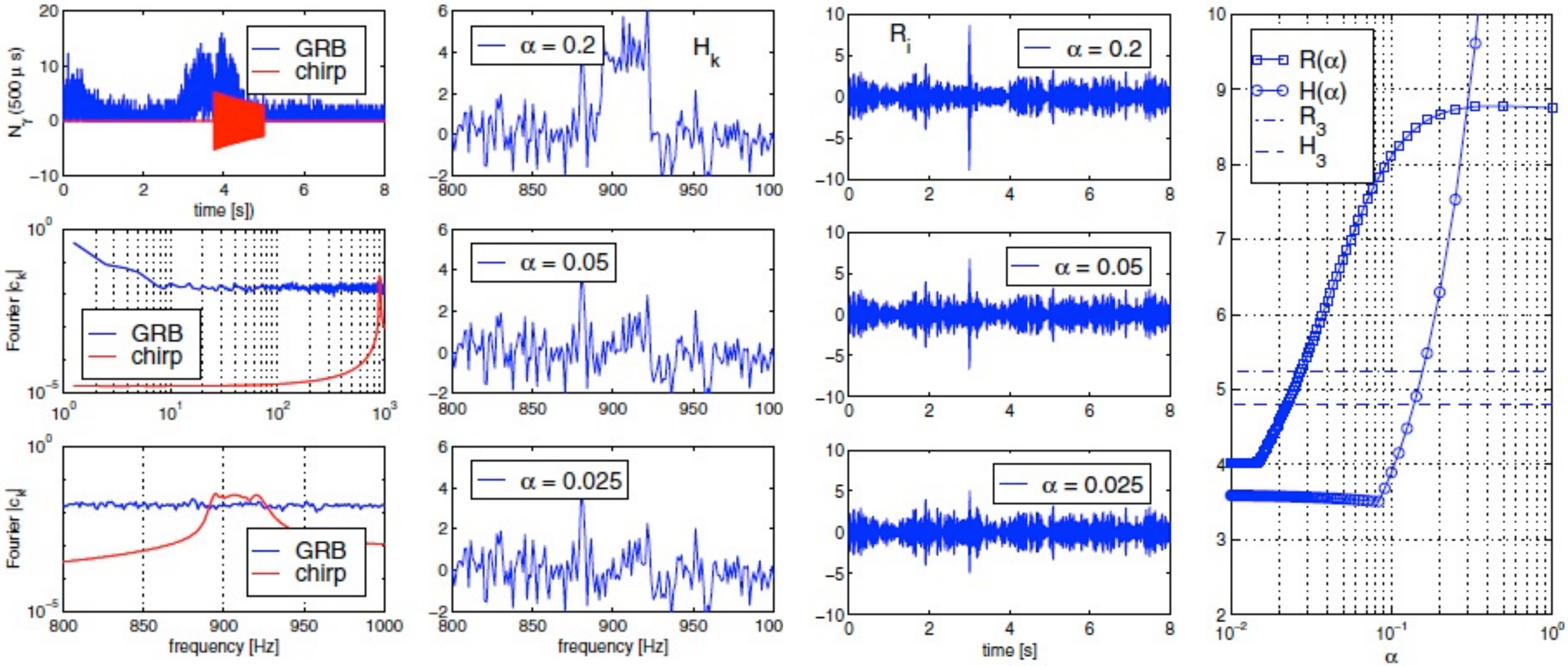
Side stepping Fourier, search for up- and down chirps by matched filtering



Broadband Fourier-chirp spectrum of long GRBs

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

Matched filtering test results



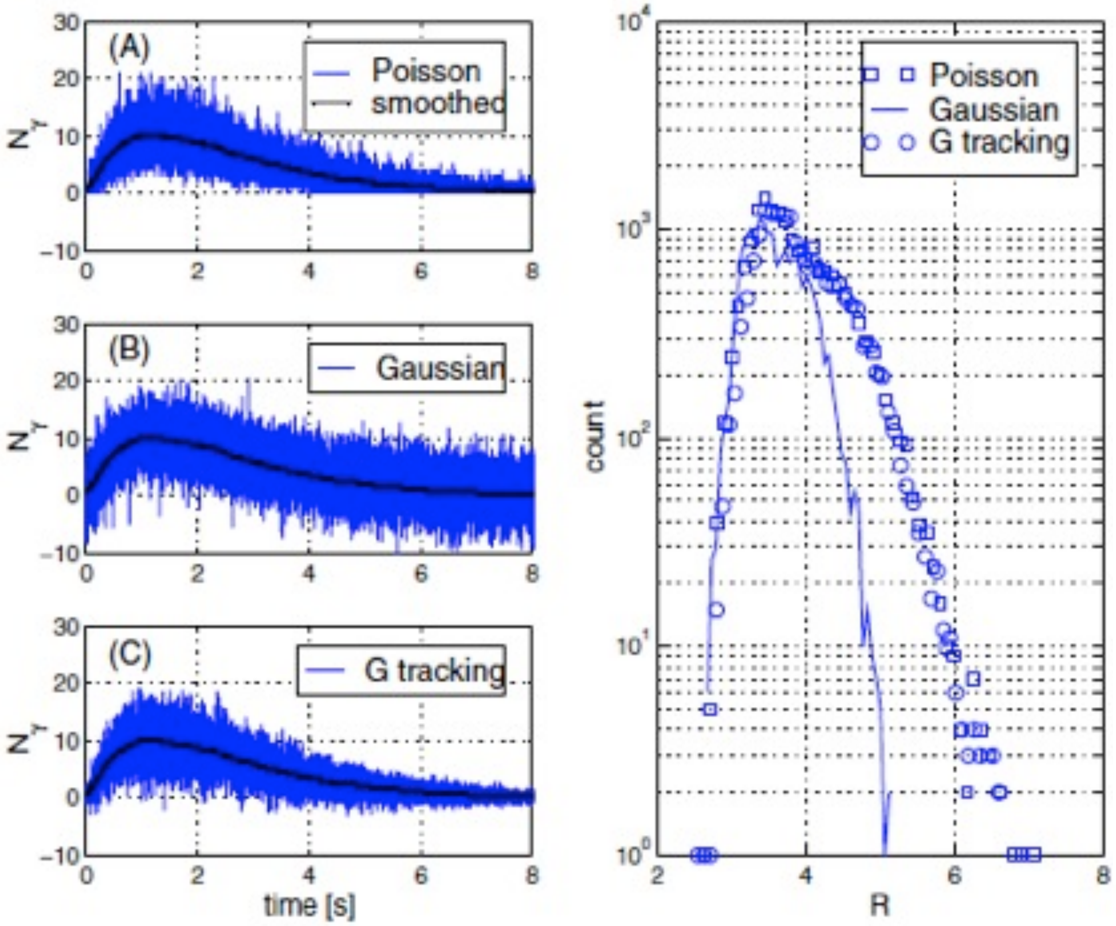
Matched filtering approximately one order of magnitude more sensitive than Fourier in SNR

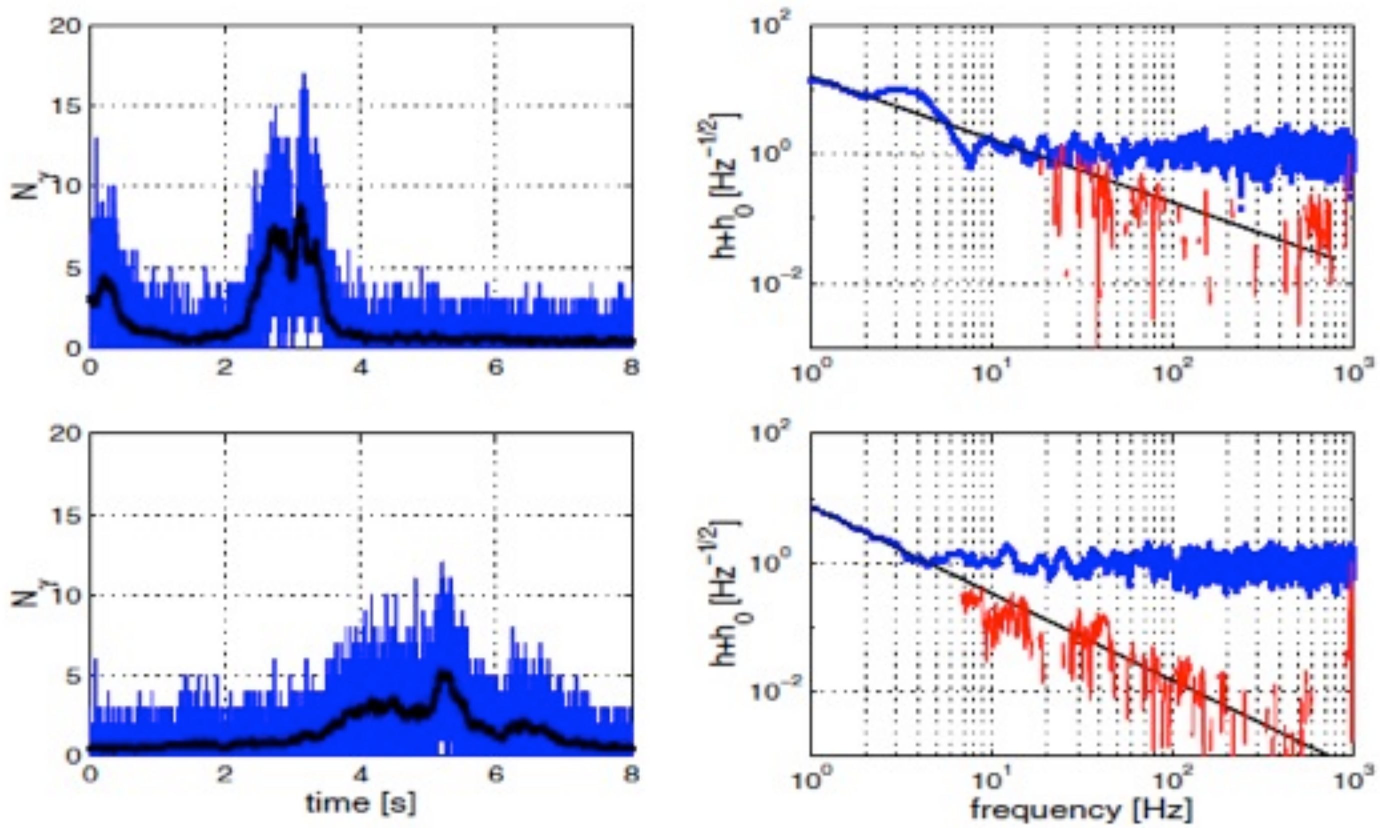
Broadband Fourier-chirp spectrum of long GRBs

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

"MF on data *minus* MF on control"

$$h(f) = \frac{R(f) - R_0(f)}{R_0(f)\sqrt{B(f)}}, \quad h_k = \frac{|c_k| - s_0}{\sigma_0\sqrt{B_0}}.$$





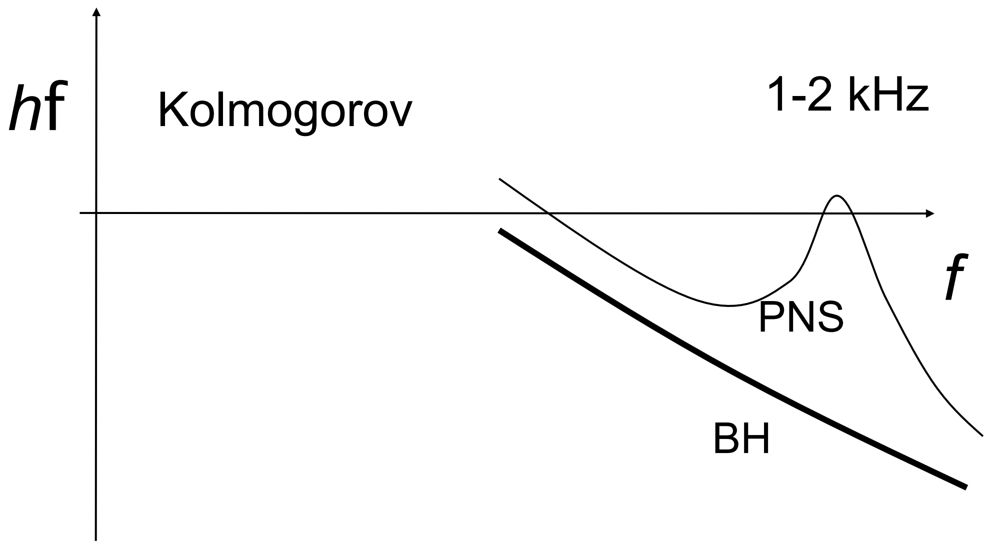
Control: synthetic light curves with computer generated Poisson noise tracking 2 Hz filtered lc

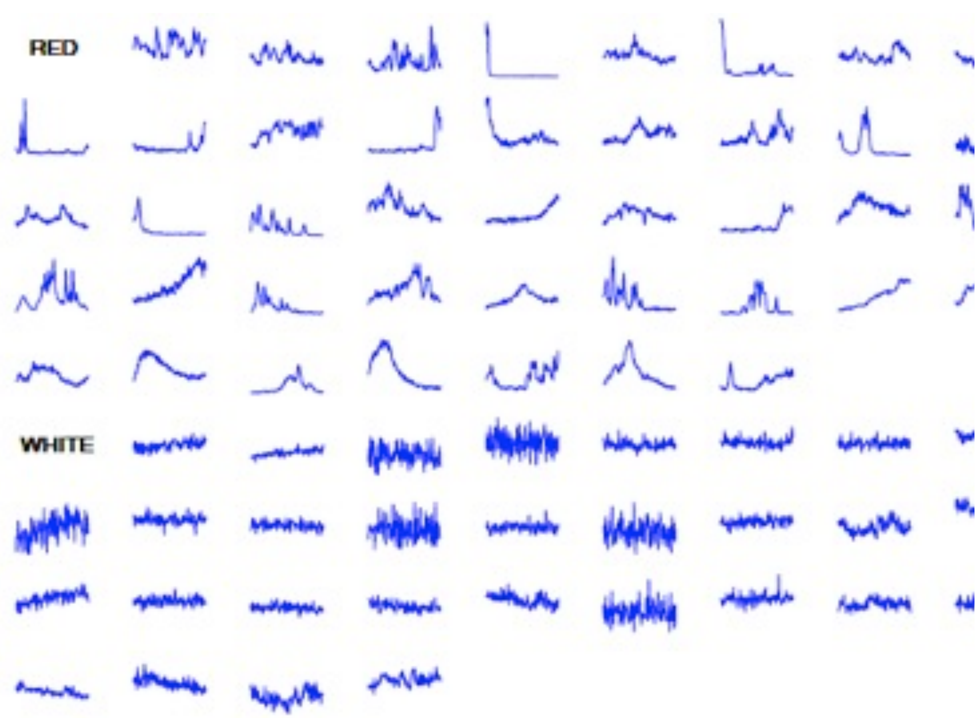
Kolmogorov spectrum to 1 kHz

(MF over 8.64 million chirp templates)

Broadband Fourier-chirp spectrum of long GRBs

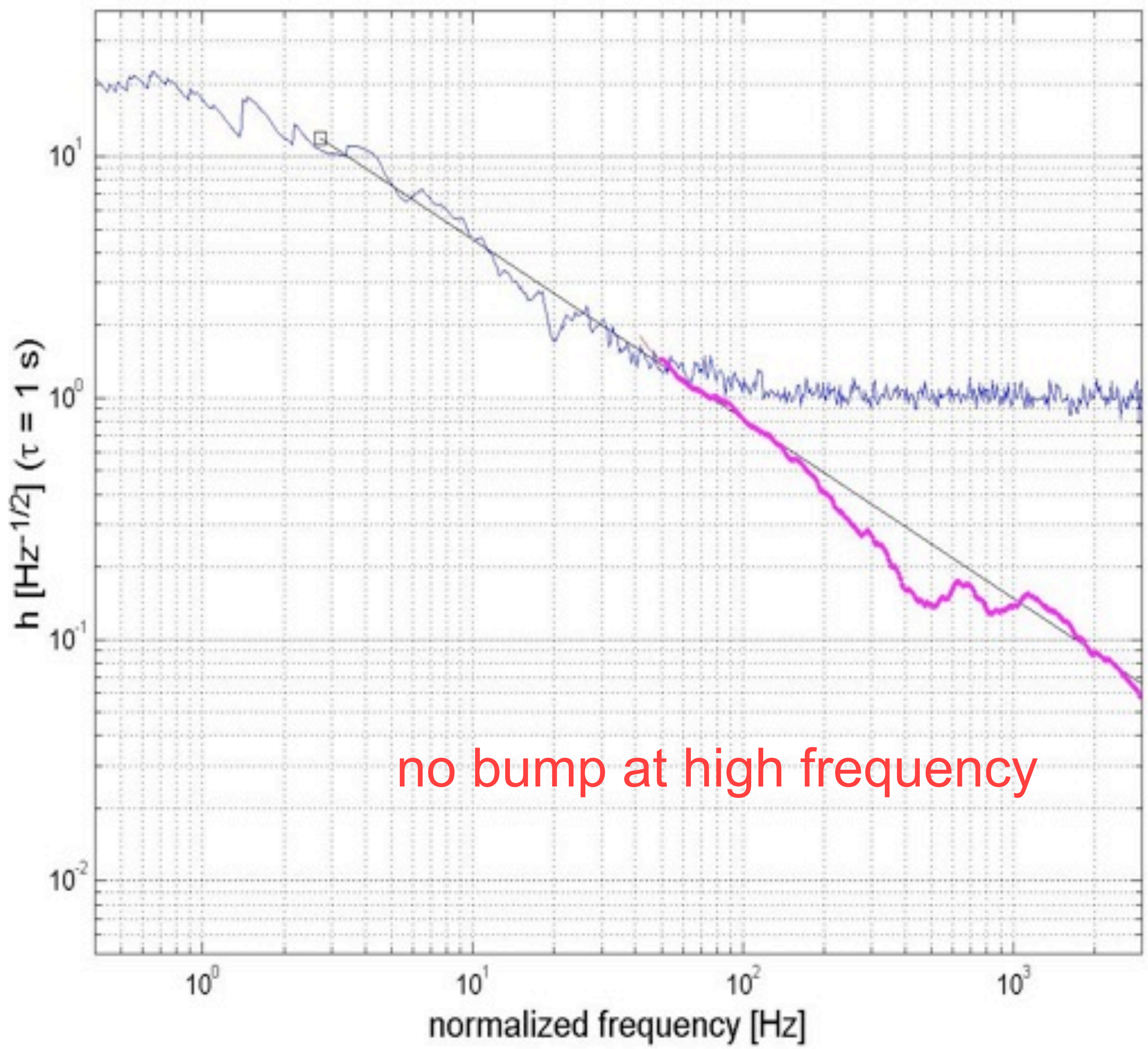
Van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146





Red: 1.26 photons/bin
White: 0.59 photons/bin

Extension of Kolmogorov spectrum in comoving frame to few kHz



no bump at high frequency

Rotating black holes of Roy P. Kerr

Energy in angular momentum

Stored in frame dragging in the surrounding spacetime
(*detected* by GP-B and LAGEOS II)

Loosing angular momentum, spacetime relaxes towards a Schwarzschild black hole

Rotating black holes: energies

$$\Omega_H = \frac{1}{2M}\tan(\lambda/2) \qquad (\sin\lambda = J/M^2)$$

van Putten, 1999, Science, 284, 115

Maximal spin frequency: 10 kHz for a 10 solar mass black hole

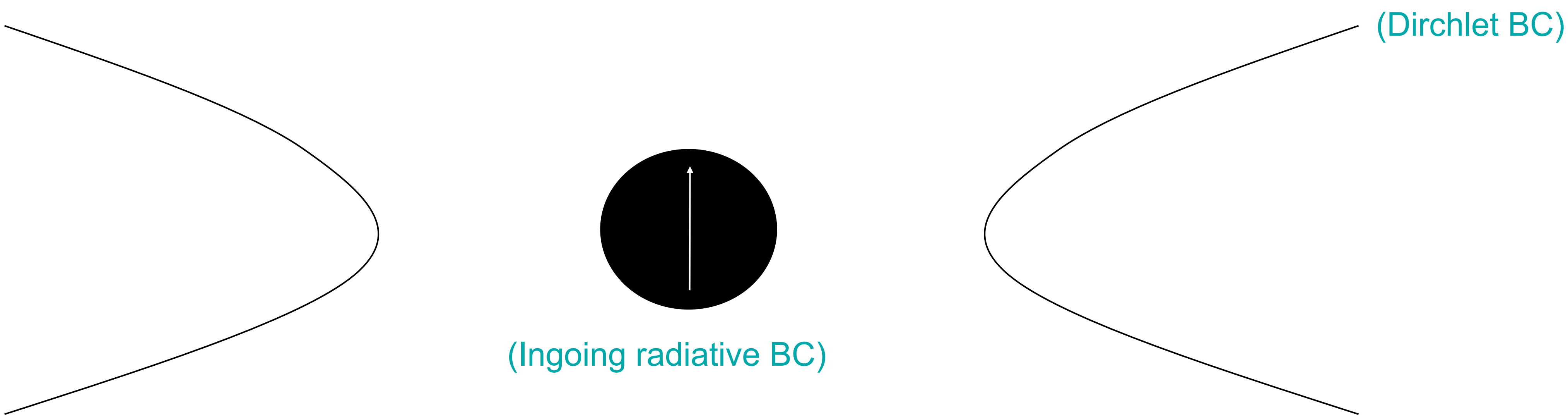
Rotational energy $$\left(\frac{E_{rot}}{M}\right)_{BH} = 2\sin^2(\lambda/4)$$

$$\max\left(\frac{E_{rot}}{M}\right)_{BH} = 0.2929 \sim 30\max\left(\frac{E_{rot}}{M}\right)_{NS}$$

Like a spinning top $$\left(\frac{E_{rot}}{\Omega_H J}\right)_{BH} / \left(\frac{E_{rot}}{\omega J}\right)_{Newton(toy)} = 1-1.16$$

Rotating black holes: non-thermal radiation

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



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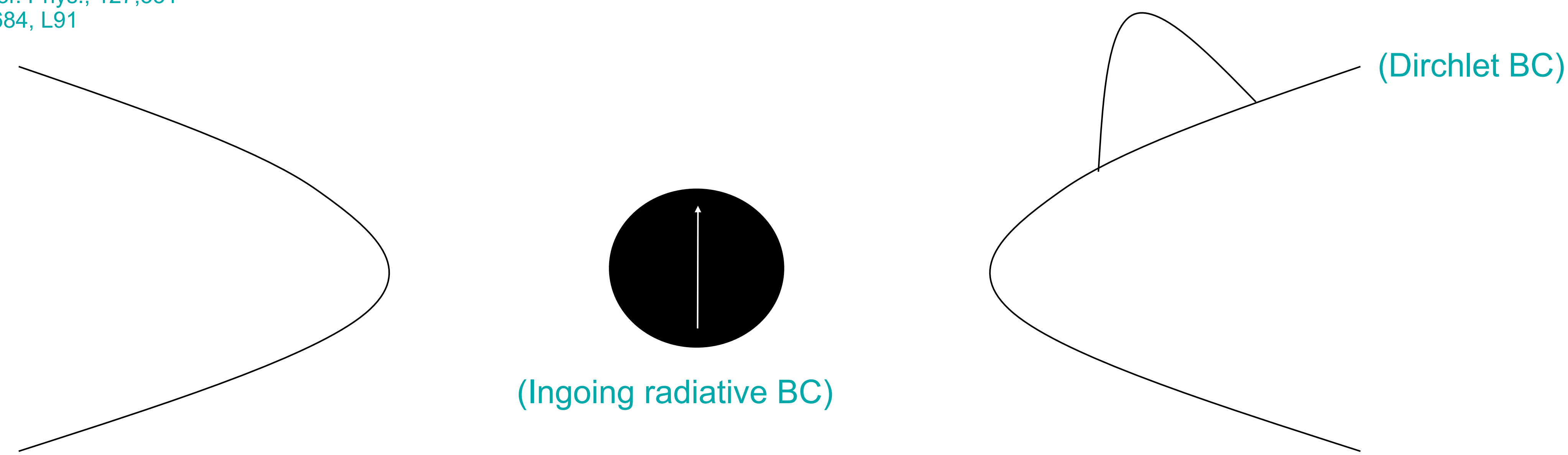

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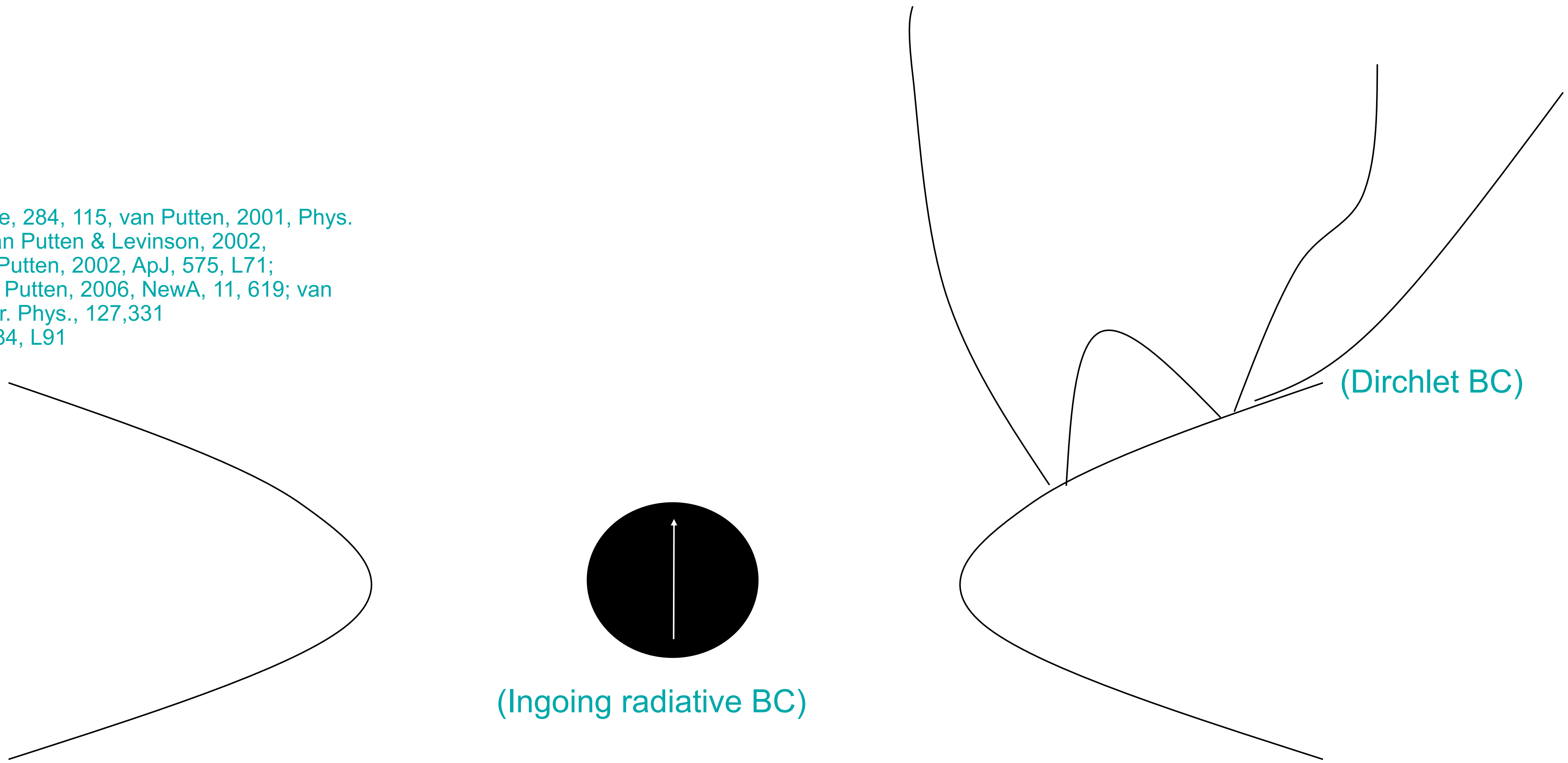

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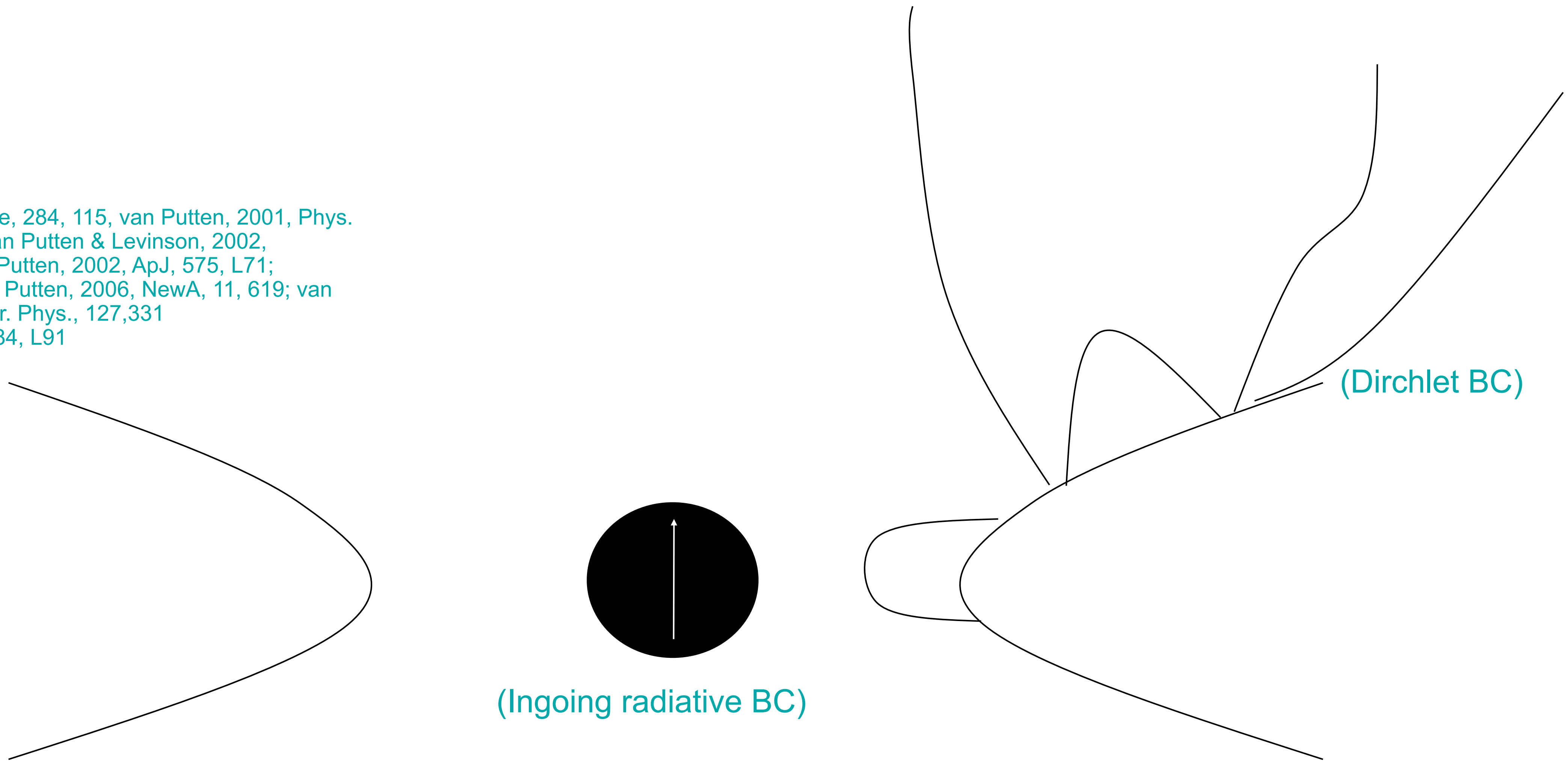

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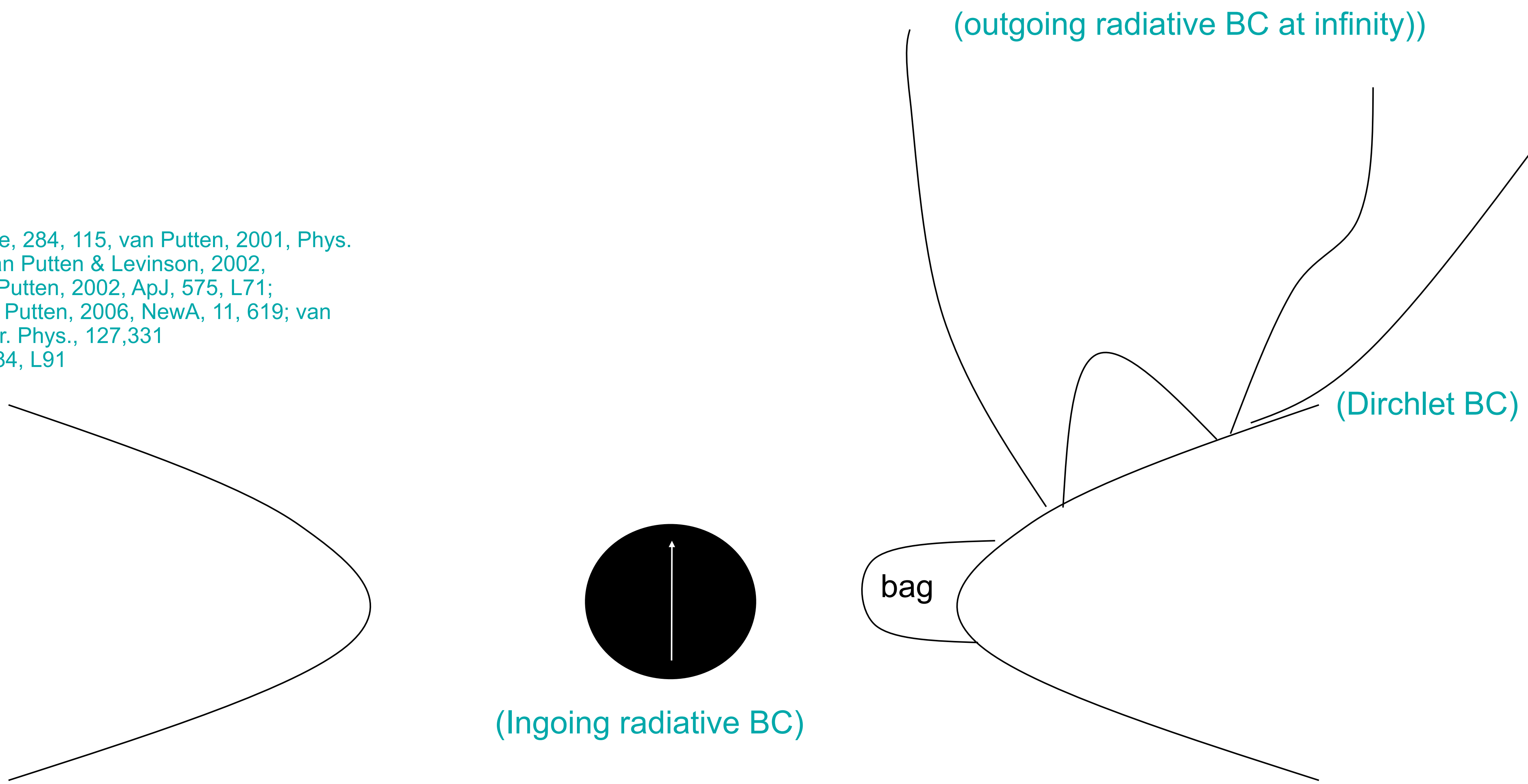

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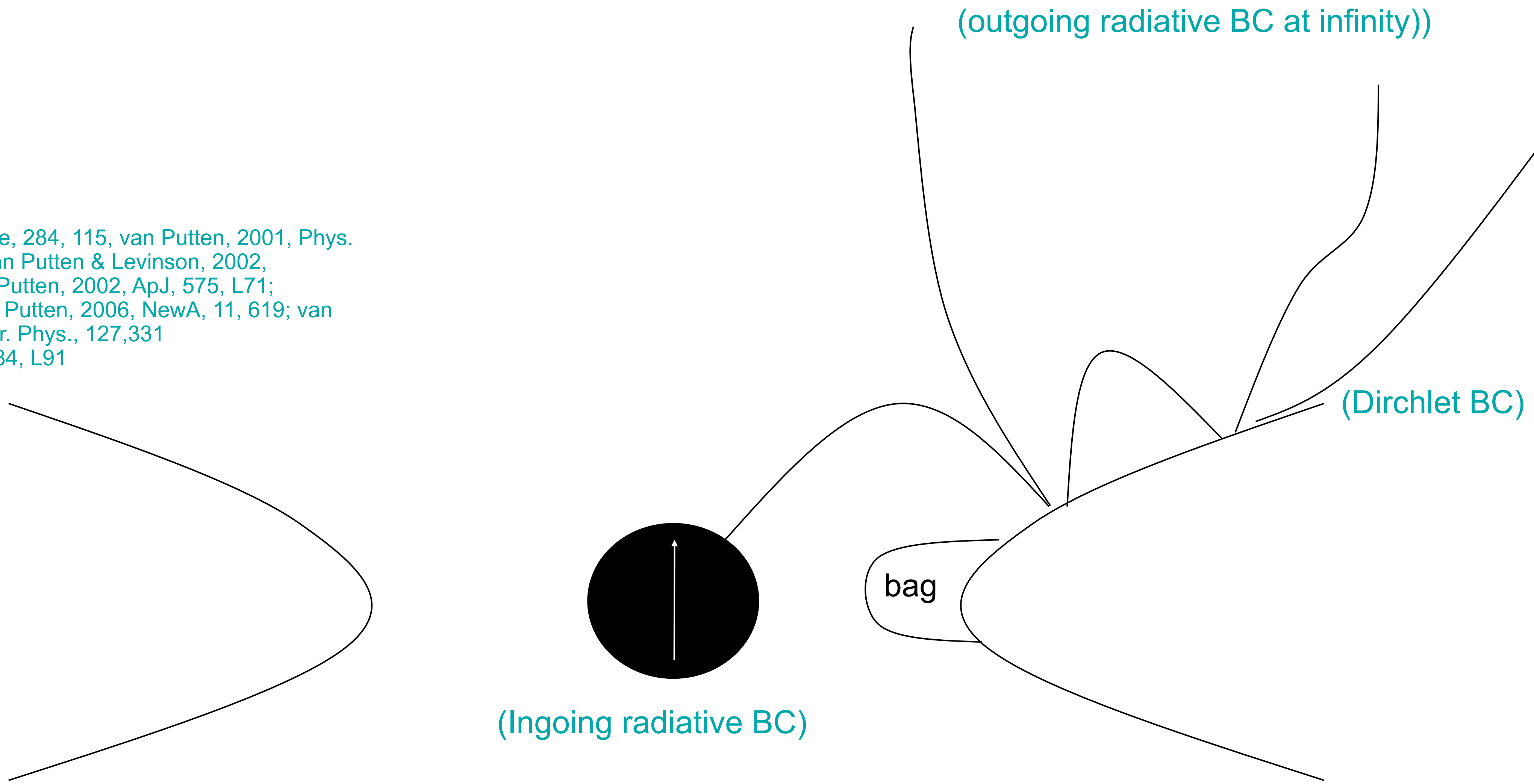

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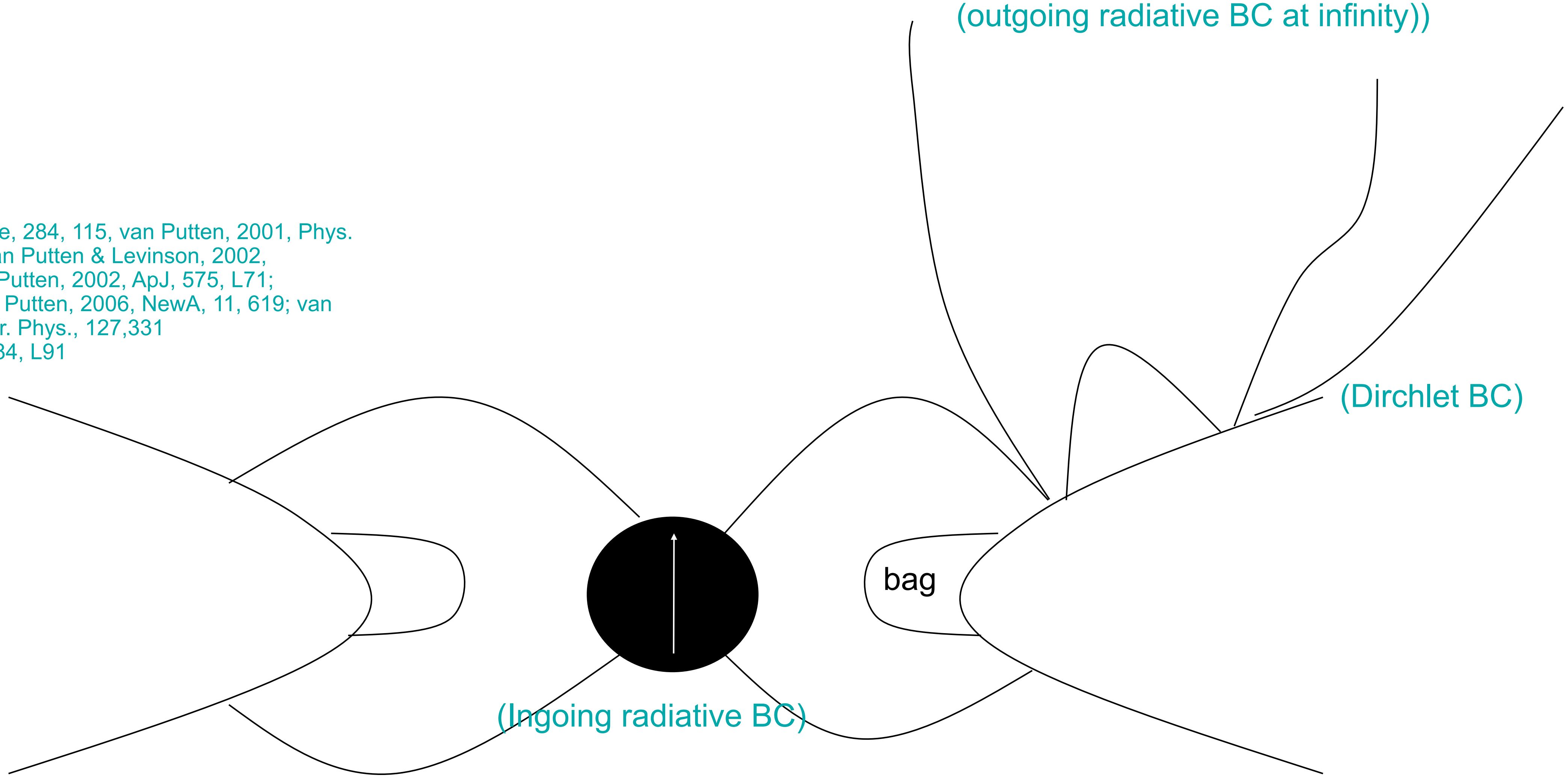

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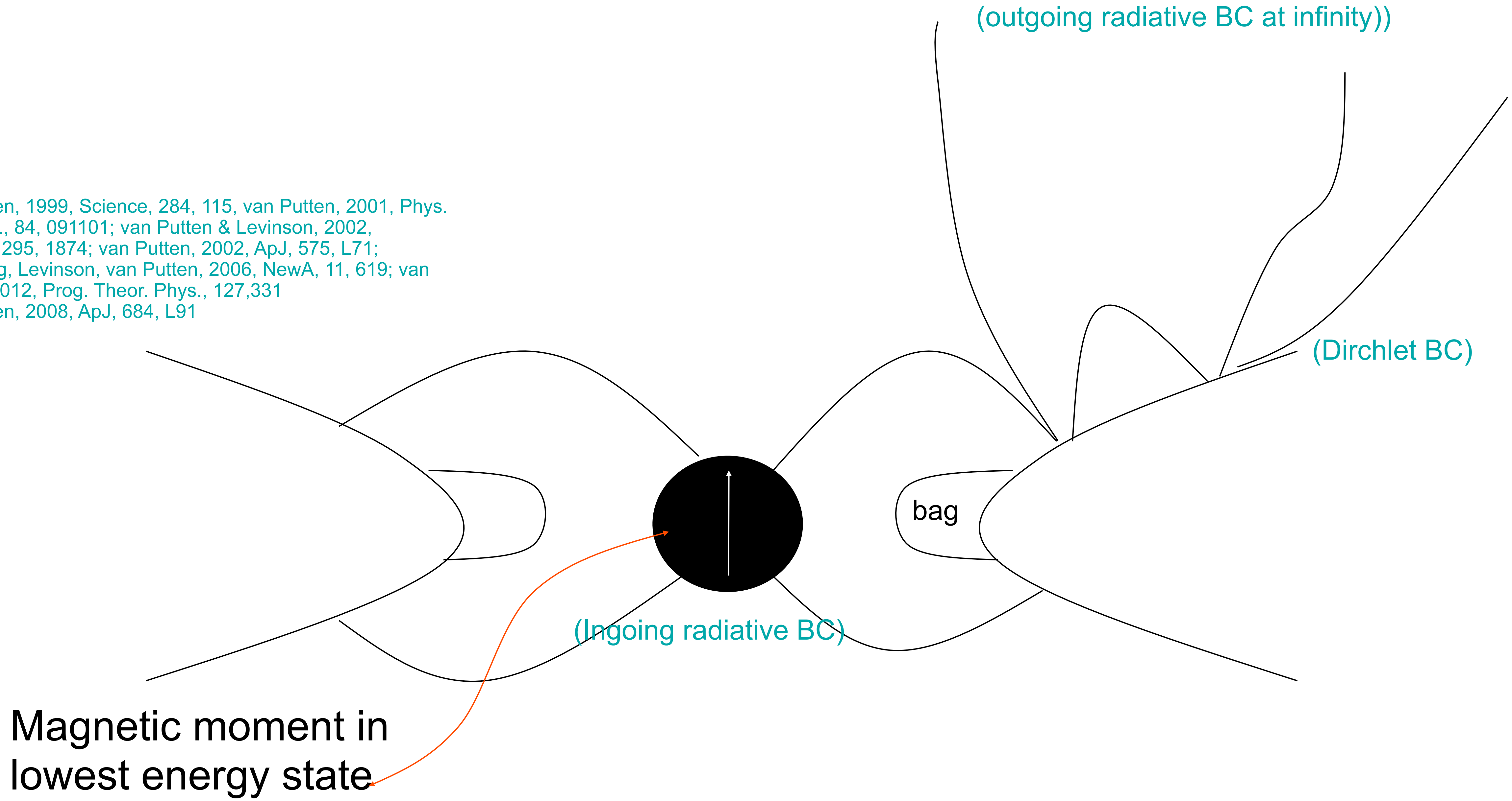

Black hole in its lowest energy state supports open flux tubes from H to infinity

Sunday, June 22, 14

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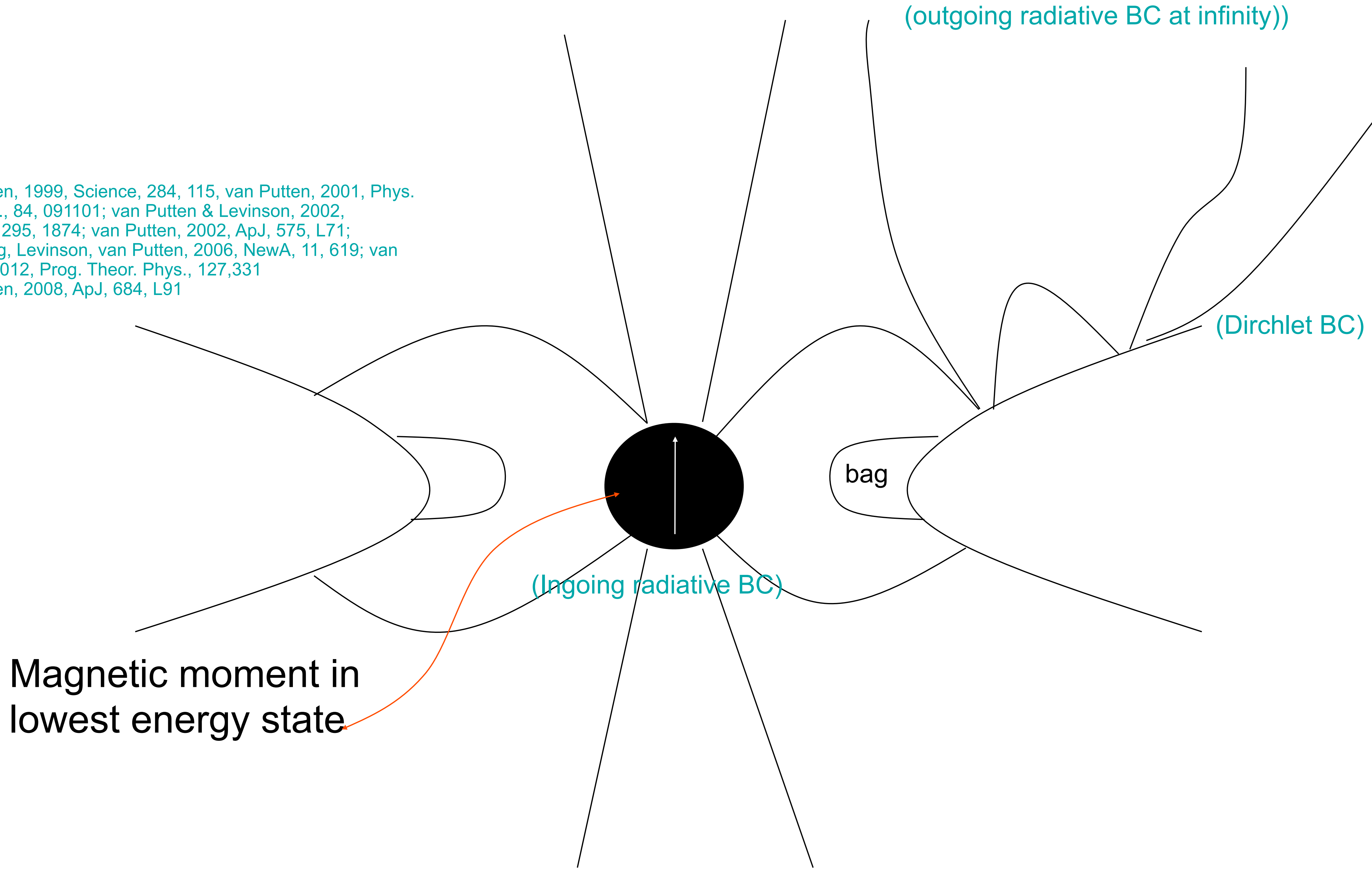

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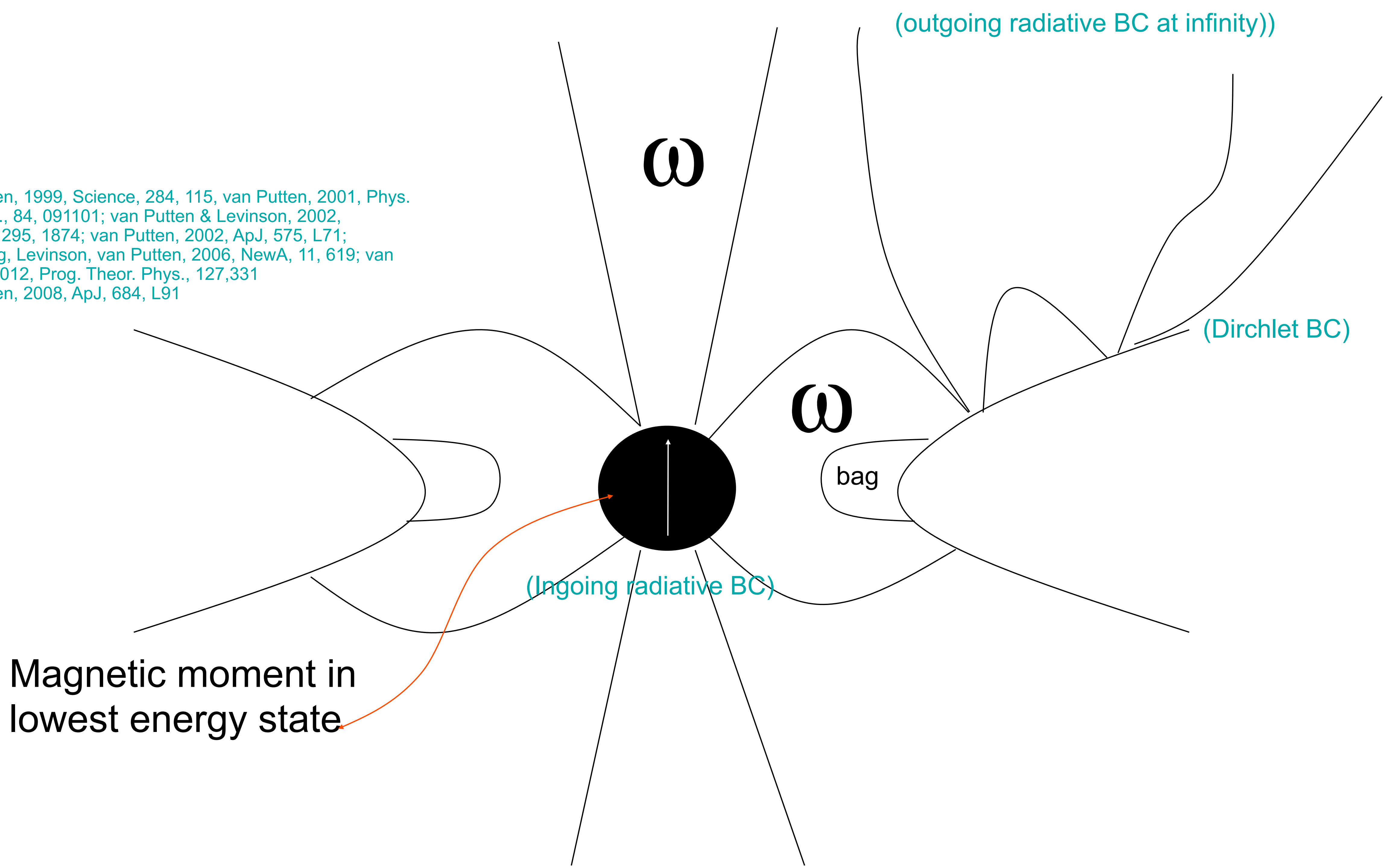

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Rotating black holes: non-thermal radiation

$$E = \omega J_p$$

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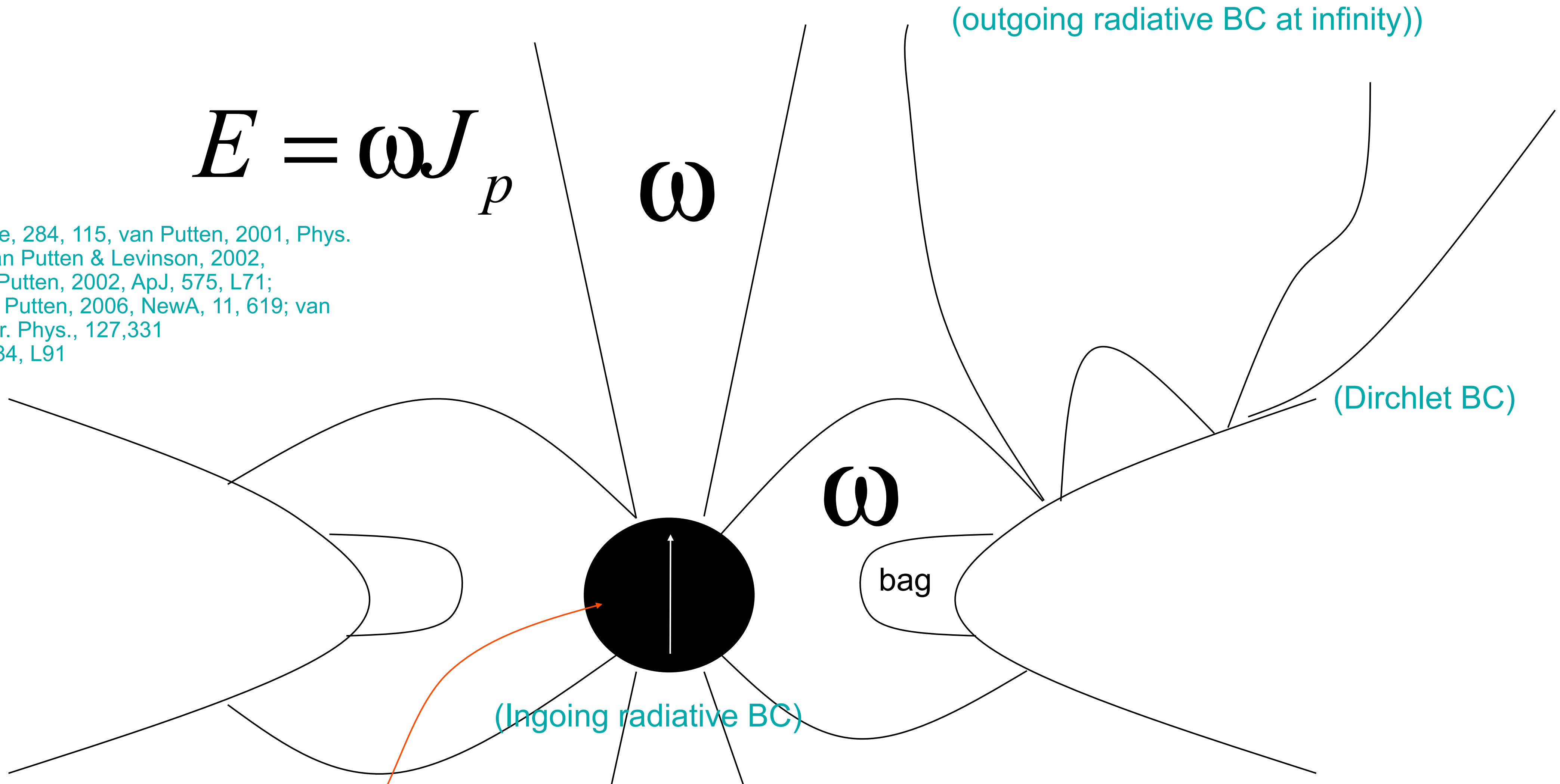

Magnetic moment in lowest energy state

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

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

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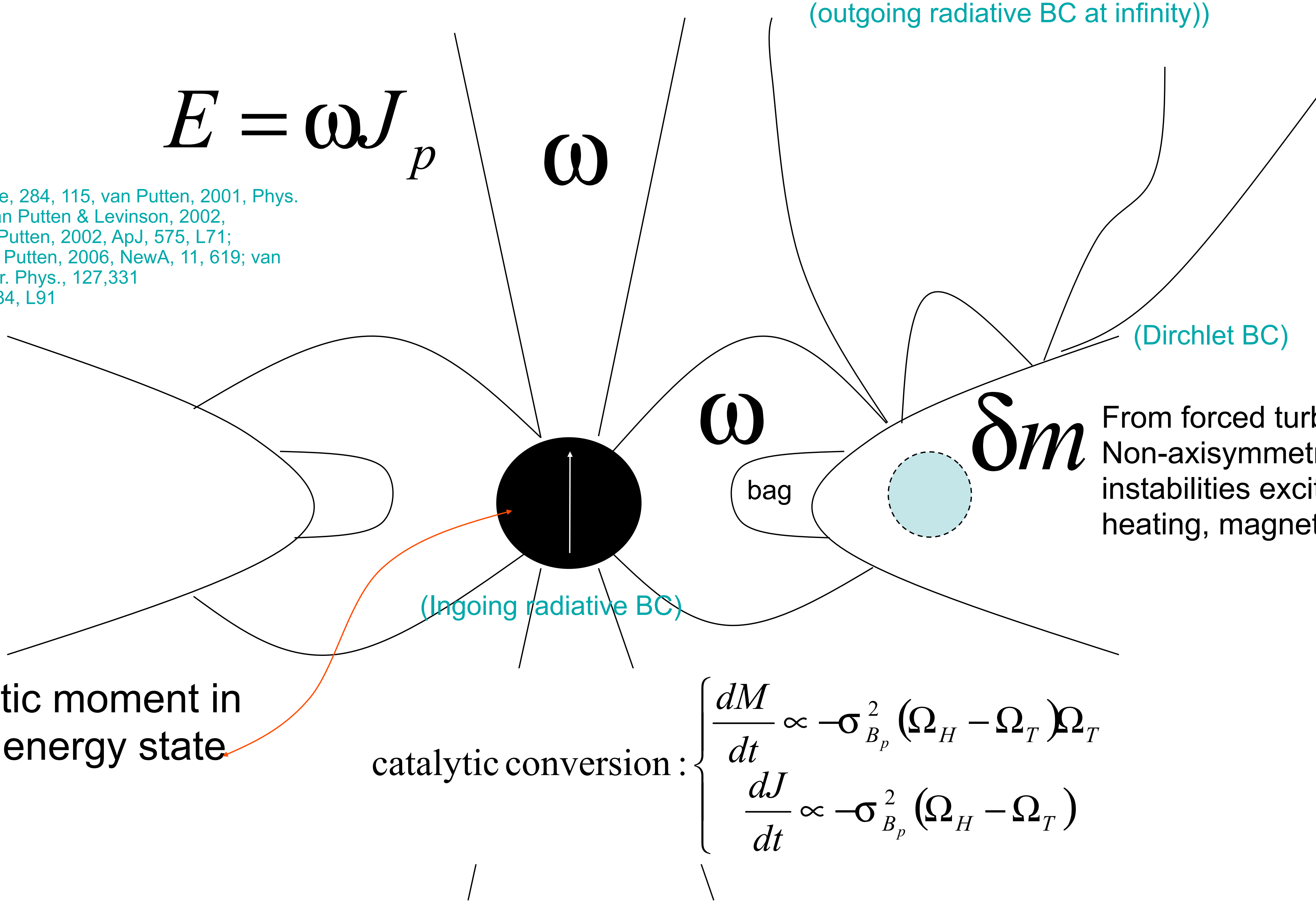

From forced turbulence, Non-axisymmetric instabilities excited by heating, magnetic pressure

Magnetic moment in lowest energy state

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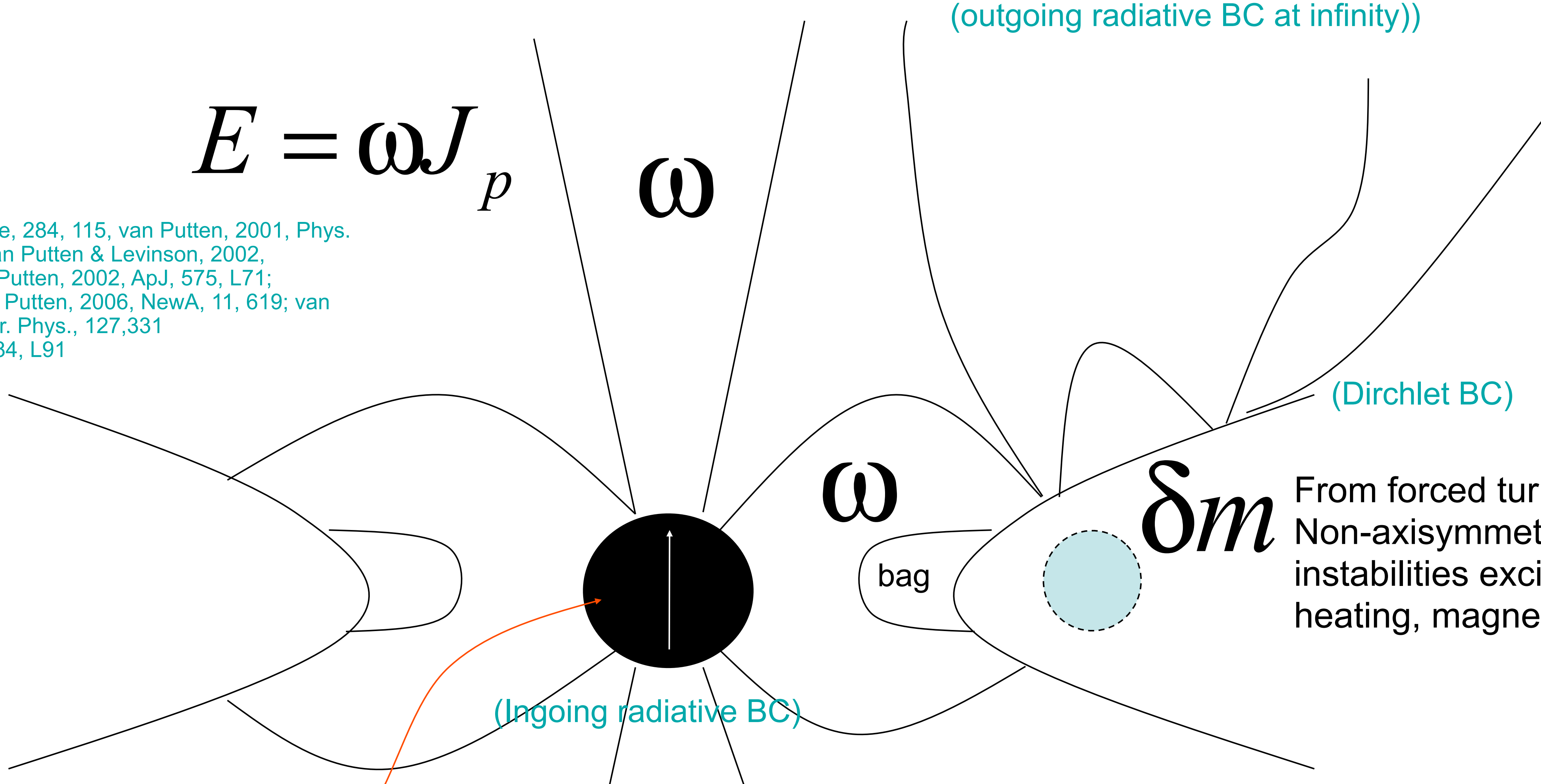

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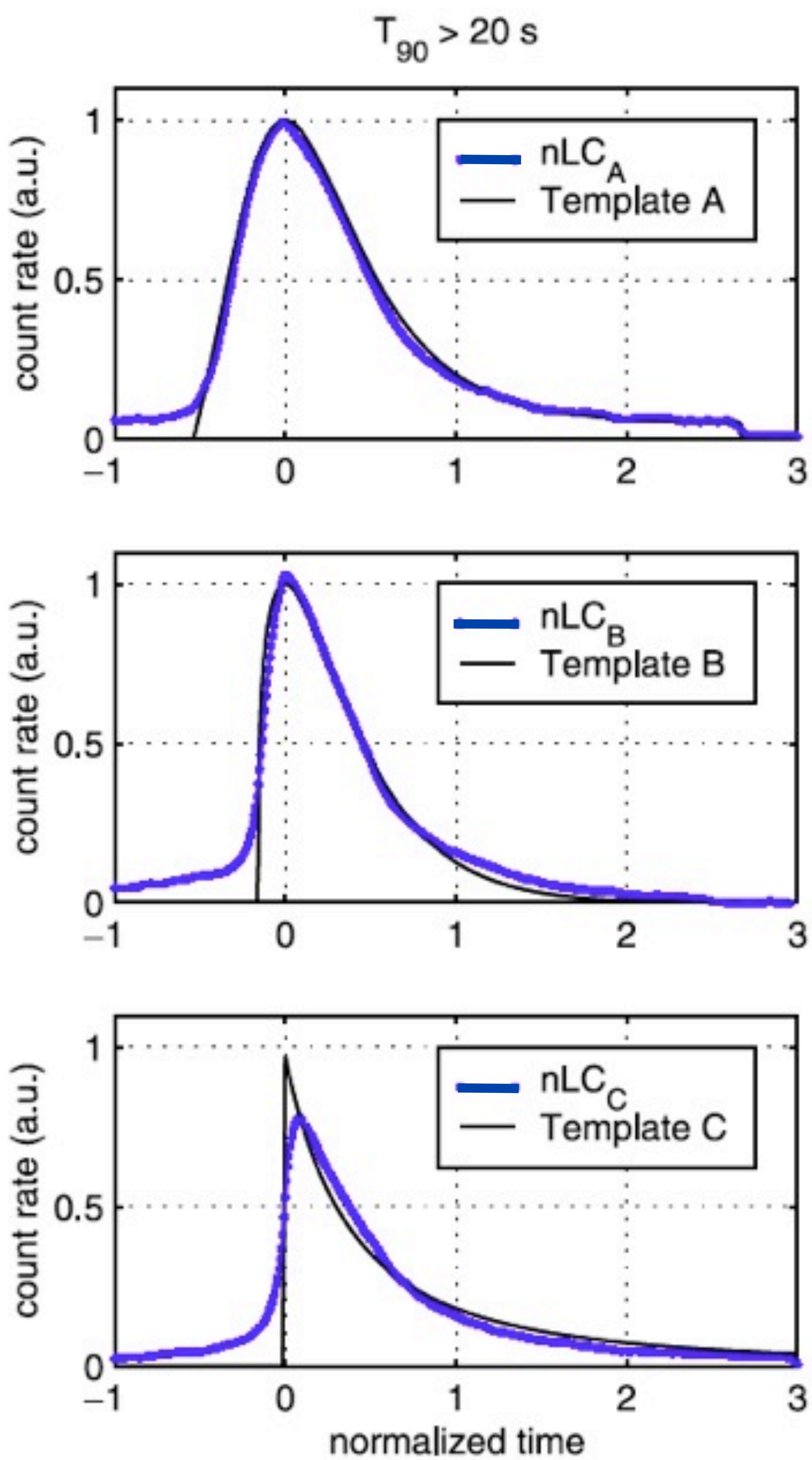
radiation

$$L_{GW} = 2\times 10^{51} \left(\frac{M}{4R}\right)^5 \left(\frac{M_D}{0.01 M_H}\right)^2 \left(\frac{\delta m}{0.1 M_D}\right)^2 \text{ erg s}^{-1}$$

Evidence for BH loosing angular momentum in LGRBs

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



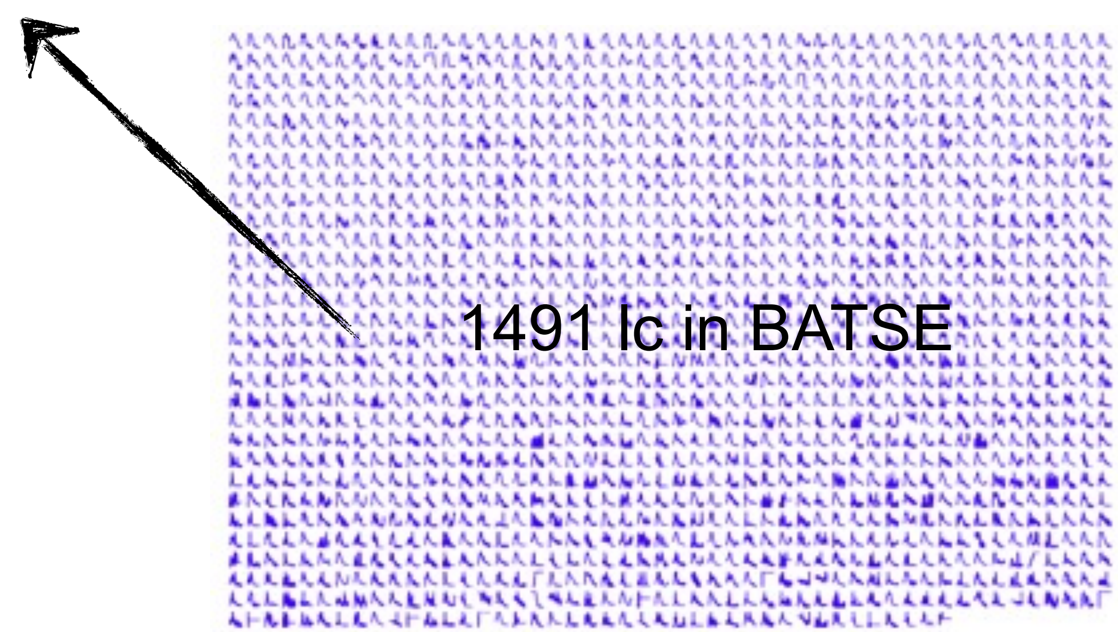
A: BH loosing angular momentum to matter at the ISCO

B: BH loosing angular momentum to matter further out

C: NS loosing angular momentum in magnetic winds

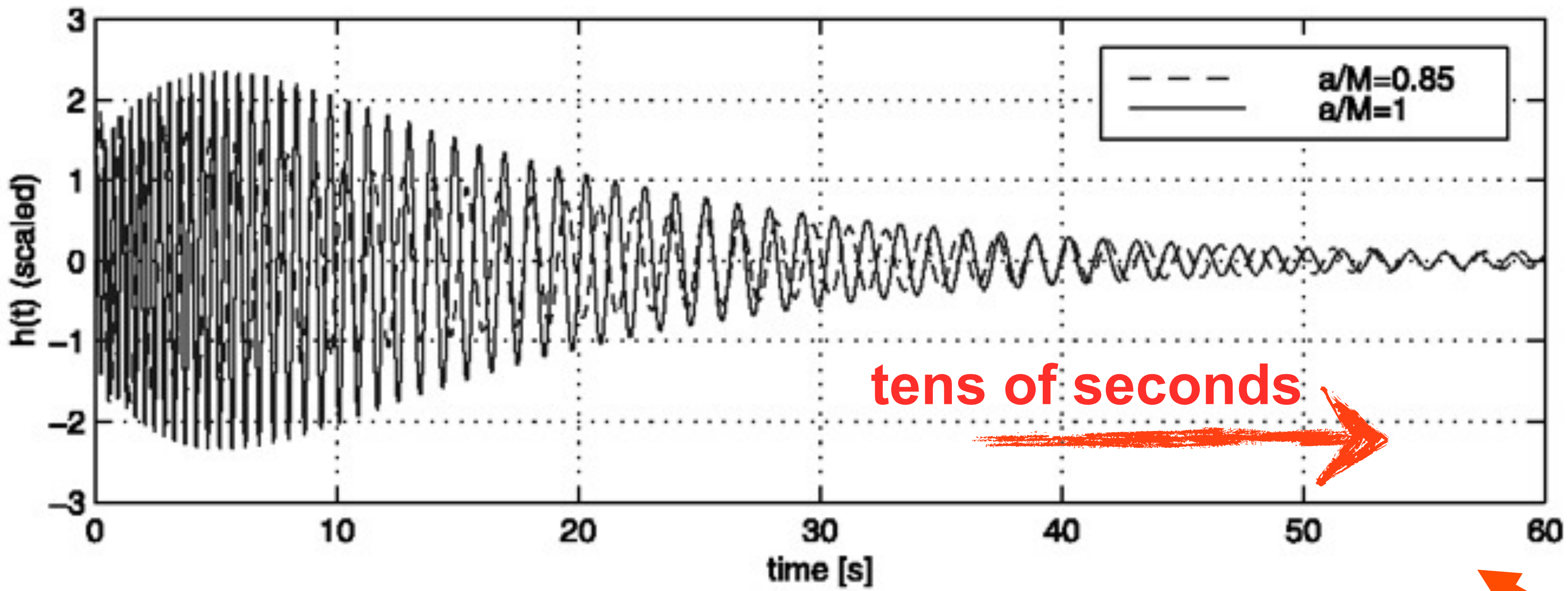
Most favored: Model A

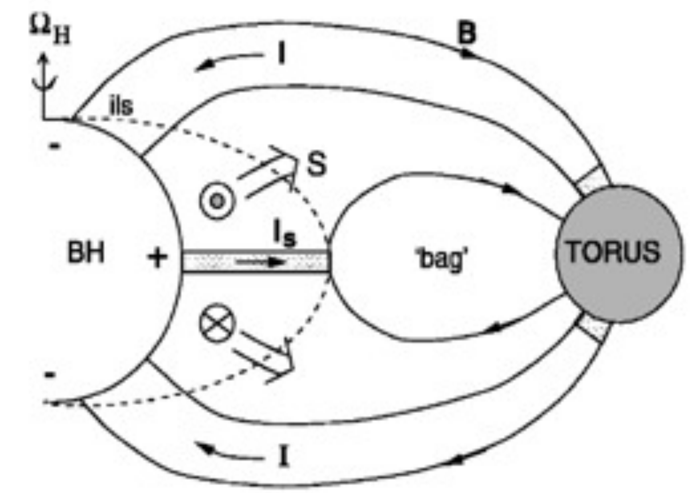
Least favored: Model C



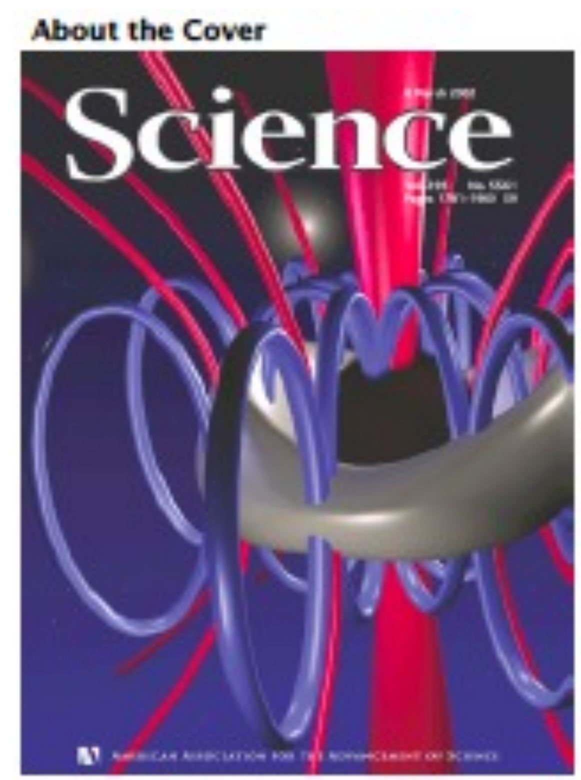
Long duration chirps in GWs from GRBs

Heating by dissipation in MHD turbulence,
balanced by *cooling* in gravitational radiation,
MeV neutrinos and outflow in magnetic winds





van Putten, 1999, Science, 284, 115



van Putten & Levinson, 2002, Science, 295, 1874

Late-time asymptotic frequency in the source frame

$$f_{GW} = 600 - 700 \text{ Hz} \left(\frac{M}{10 M_{Solar}} \right)^{-1}$$

(fixed by the ISCO in the Kerr metric)

van Putten, 2001, Phys. Rev. Lett., 84, 091101, van Putten, 2002, ApJ, 575, L71, van Putten, 2008, ApJ, 684, L91

Formation of non-axisymmetric mass distributions

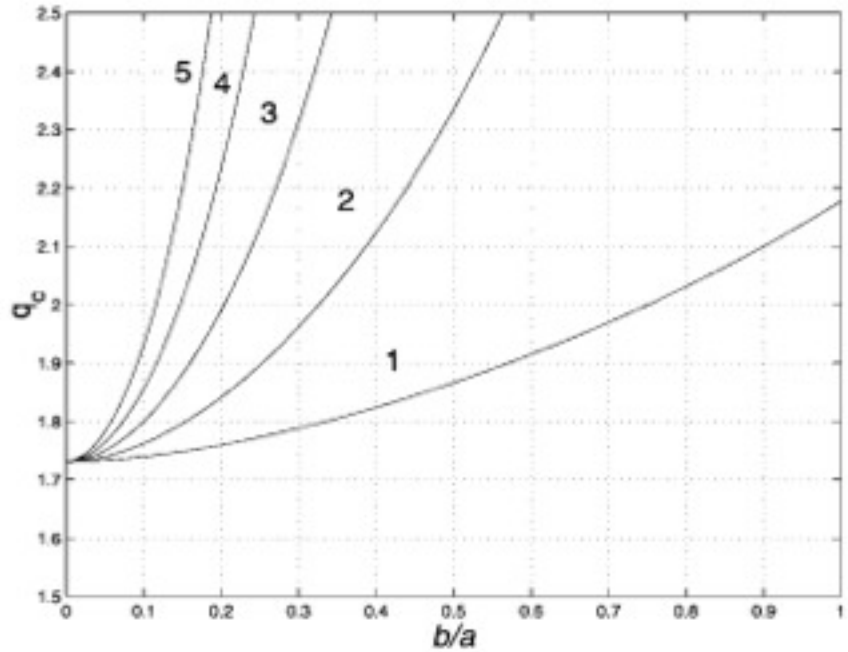
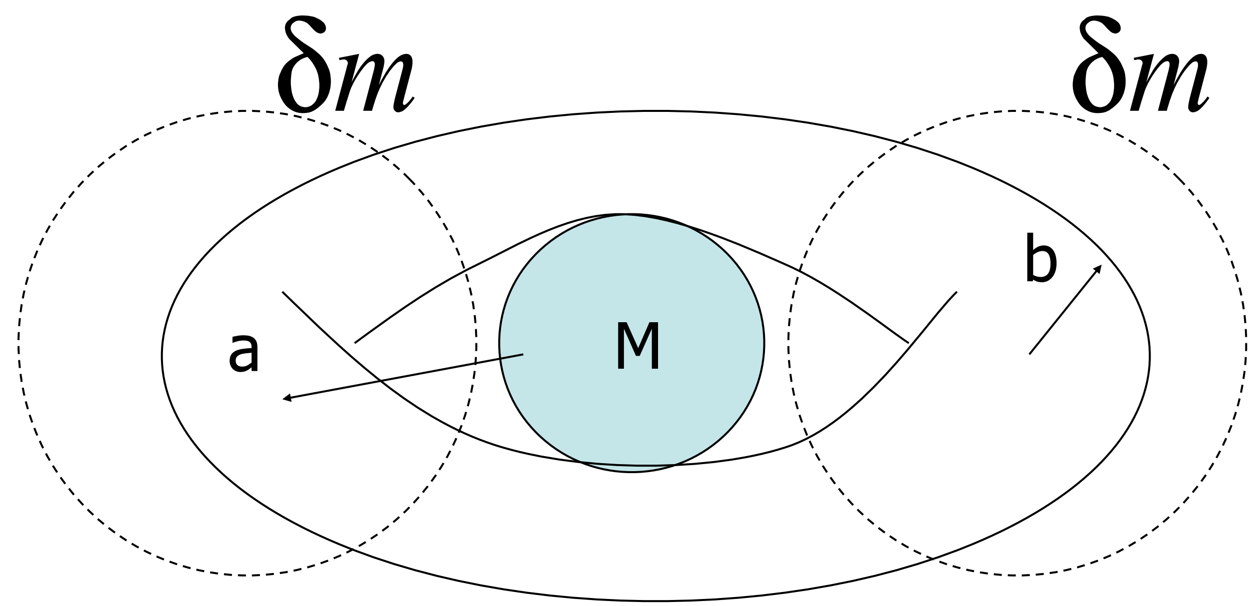


FIG. 2.—Diagram showing the neutral stability curves for buckling modes in a torus of incompressible fluid, as an extension of the Papaloizou-Pringle instability to large ratios of minor-to-major radius b/a. Curves of critical rotation index q_c are labeled with azimuthal quantum numbers $m = 1, 2, \ldots$, where instability sets in above and stability sets in below. Of particular interest is the range $q \lesssim 2$, where the $m = 0$ mode is Rayleigh-stable. For $q = 2$, the torus is unstable for $b/a < 0.7385$ ($m = 1$), 0.3225 ($m = 2$) and, asymptotically, for $b/a \simeq 0.56/m$ ($m \geq 3$).

Chandrasekhar-Friedman-Schutz instability. It may be noted that



m=2

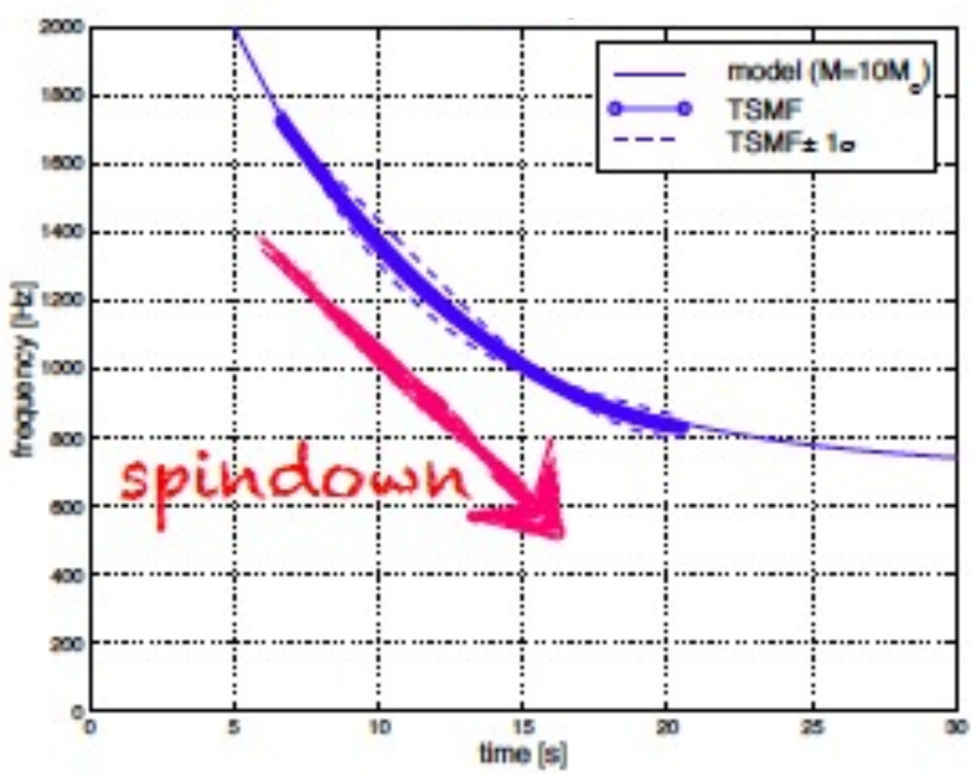
Wide tori are m = 1,2,... unstable

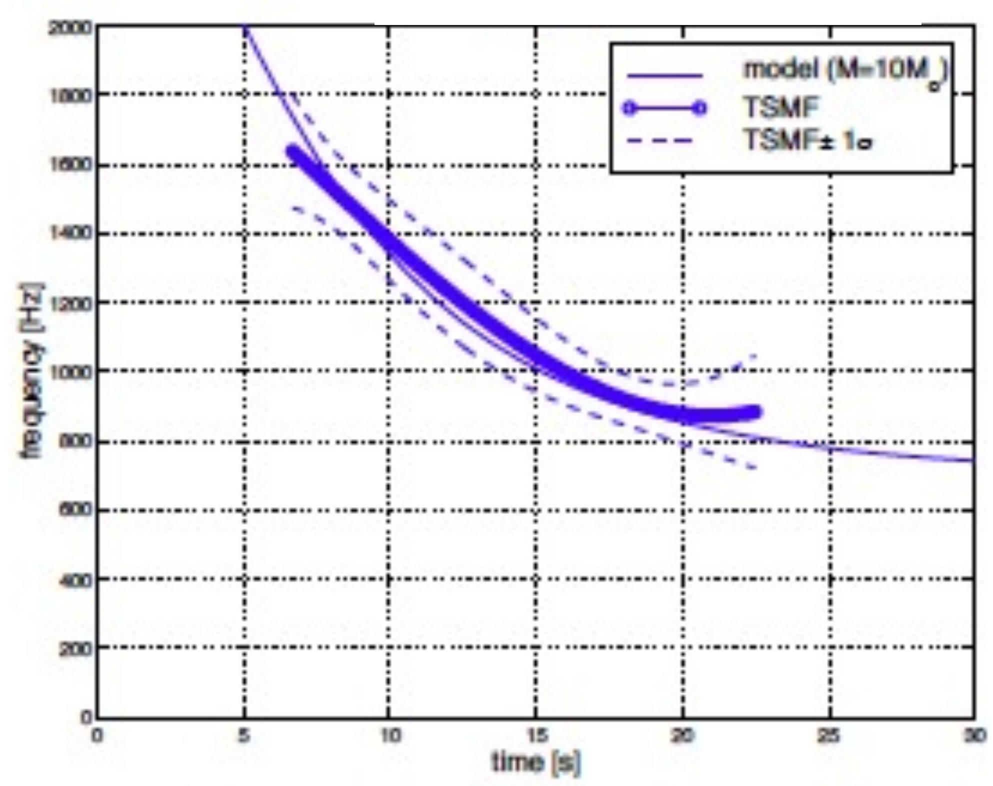
Lowest order modes are unstable first:

Most of GW-emission from lowest order modes ~ LIGO-Virgo/KAGRA bandwidth

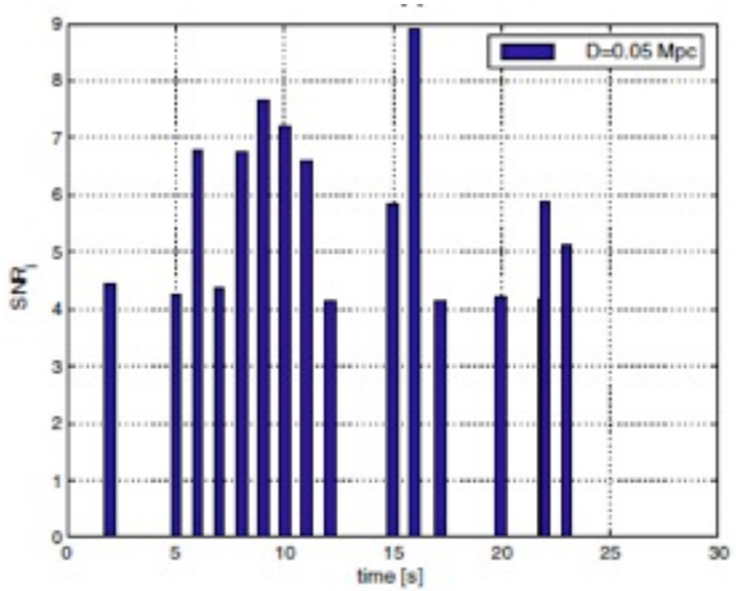
Bromberg, Levinson, van Putten, 2006, 11, 619; Van Putten, 2002, ApJ, 575, L71

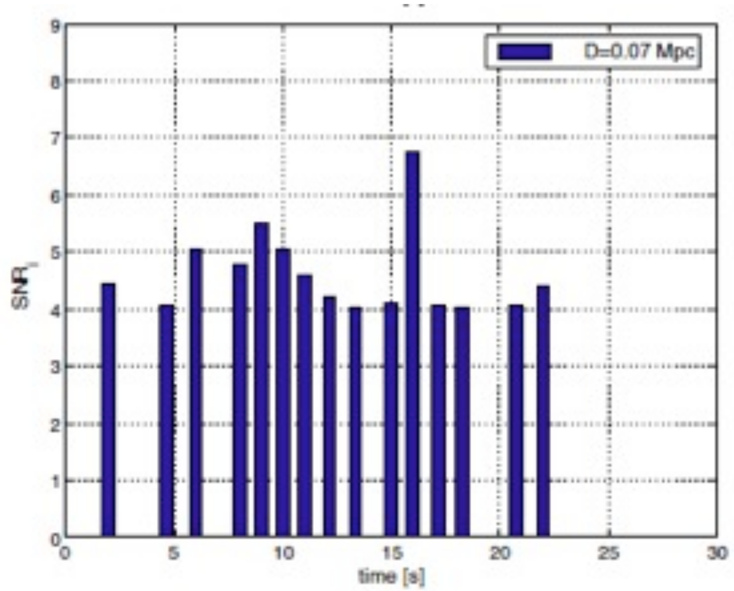
Broadband gravitational wave chirps from GRBs/CC-SNe





Extrapolating these TAMA 300 results to Advanced detectors at 2e-24@1000 Hz:





D ~ 35 Mpc

(for a full chirp detection)

Time-Sliced Matched Filtering (tau=1 s)

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

PROPOSED SEARCH triggered by nearby hyper-energetic core-collapse supernovae:

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

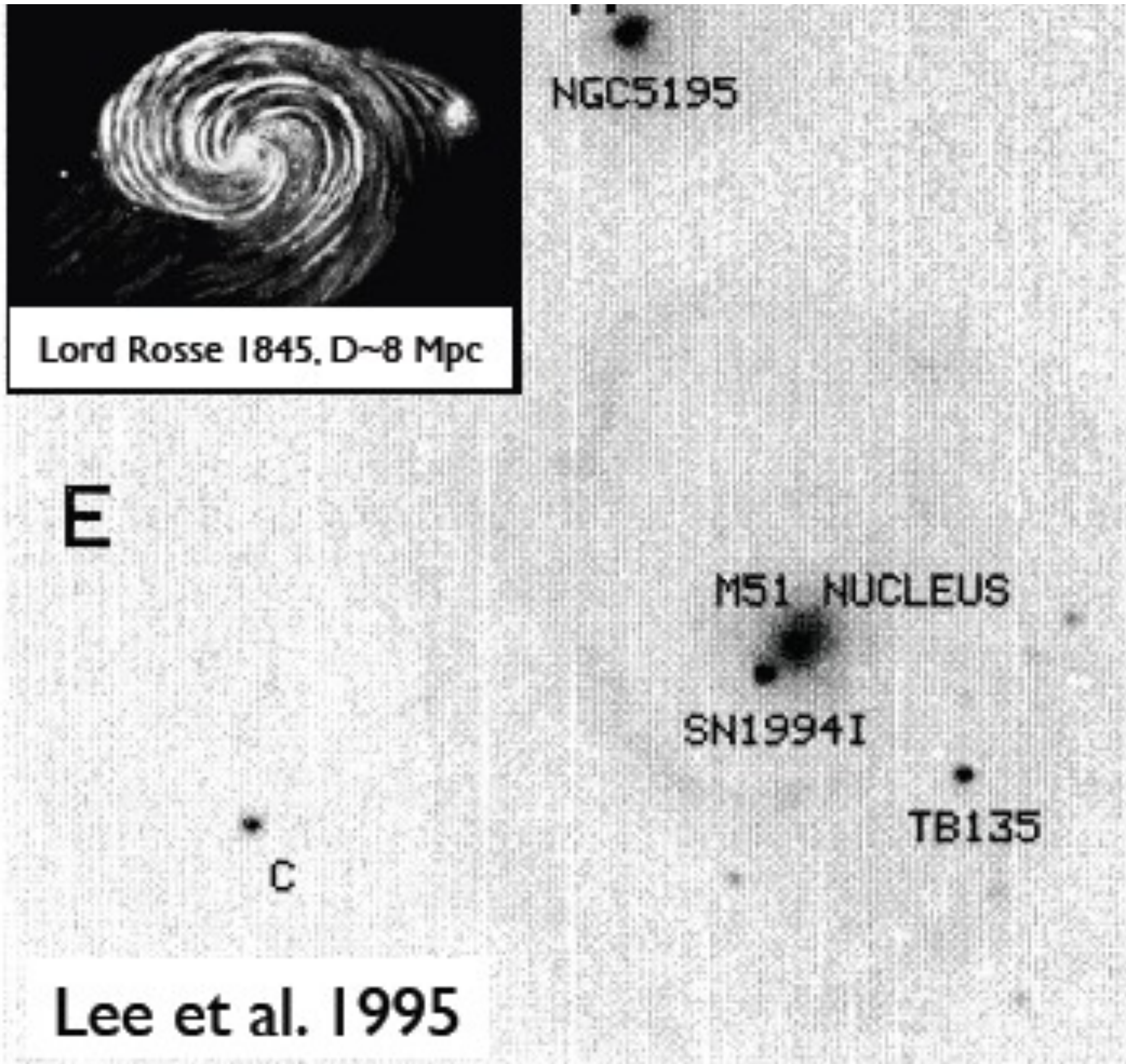
Extract broadband Fourier-chirp spectra from GW detector output,

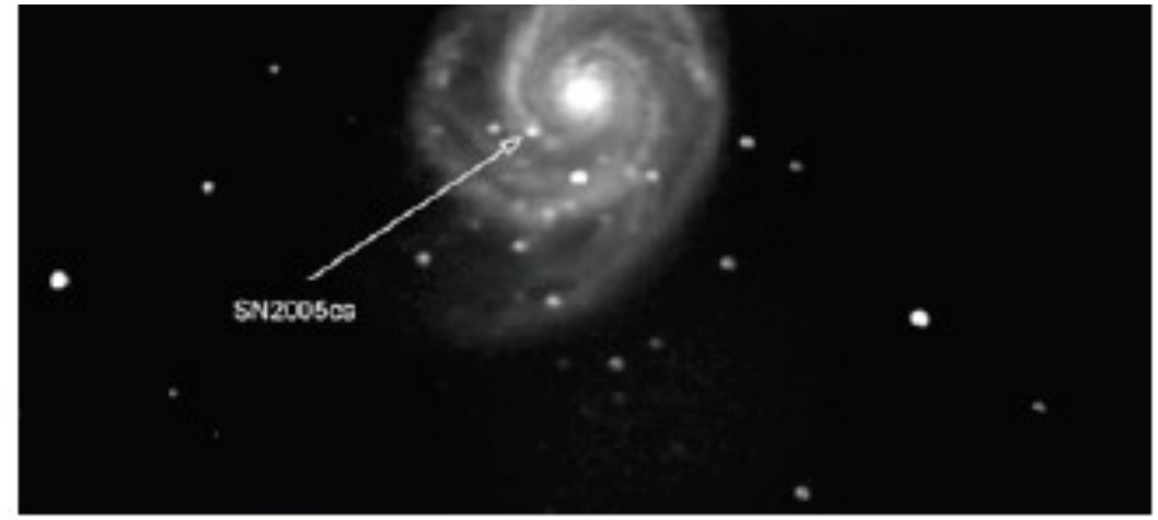
using Time Sliced Matched Filtering with (colored) Gaussian as a control

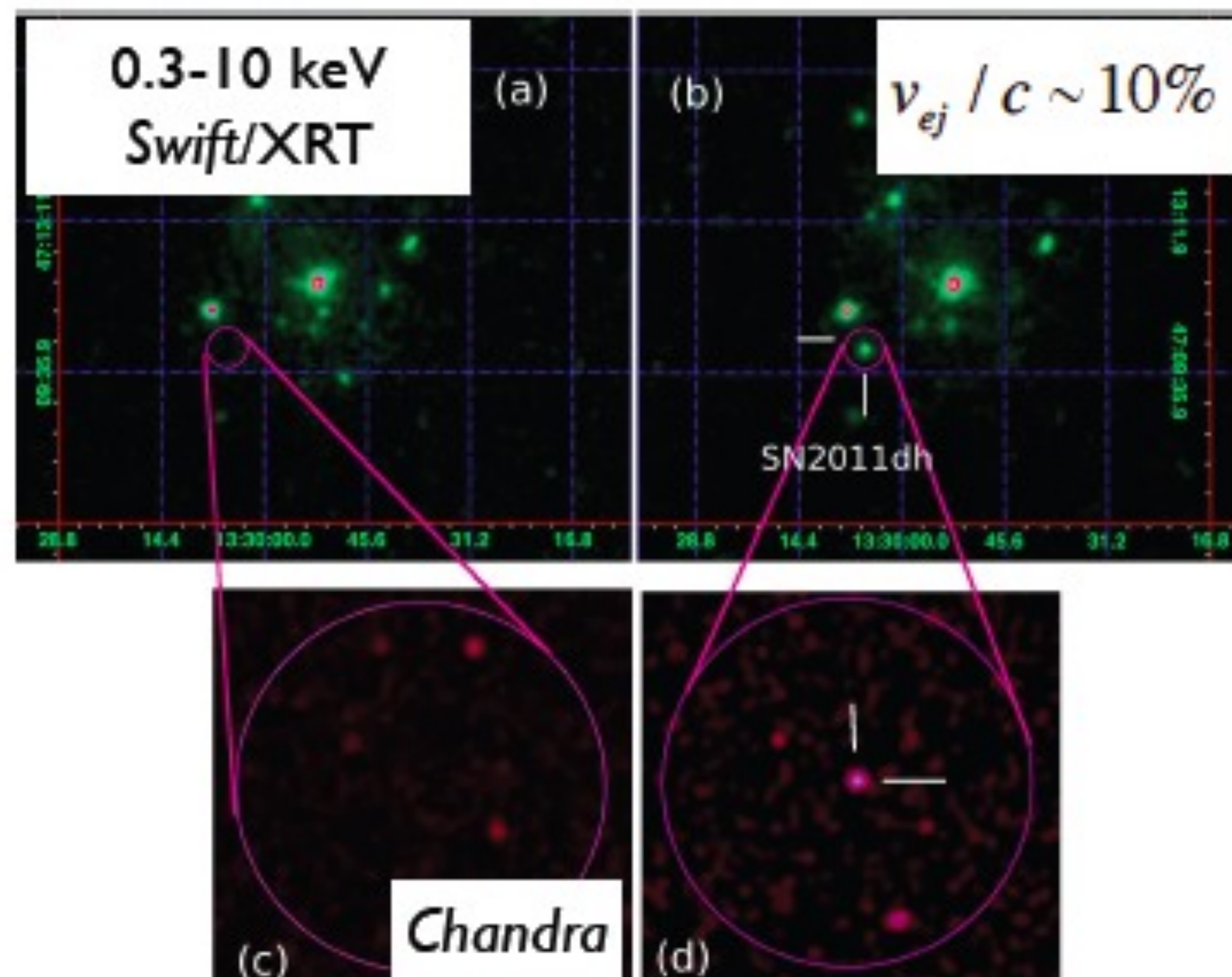
from a scan over about 10 million chirp templates

by embarrassingly parallel computing on conventional many-core clusters

Bright outlook on nearby CC-SNe as TOOs for GWs







Soderberg et al., 2011, arXiv:1107.1876

SN1994i: Type Ic, M~12-30 solar
SN2005cs: Type II, M~18.1 solar
SN2011dh: Type II-P, M~13 solar

once every ~8.5 years