Jet flares as beacons for gravitational waves

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with

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The sky in black holes

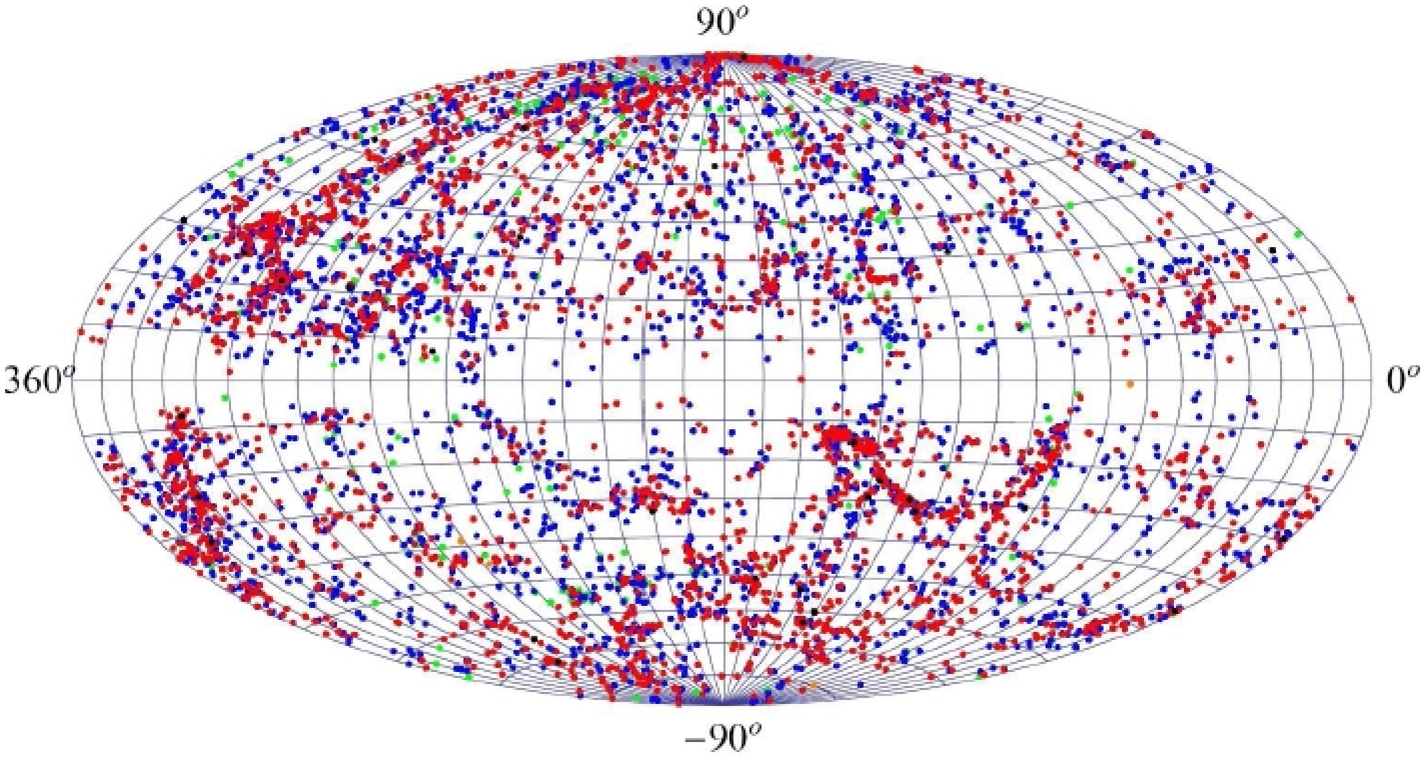


Figure 1. Aitoff projection in galactic coordinates of 5,895 NED SMBH candidate sources. The complete sample is complete in a sensitivity sense, in order to derive densities one needs a volume correction. The color code is Orange, Green, Blue, Red, Black corresponding to masses above $10^5 M_\odot$, $10^6 M_\odot$, $10^7 M_\odot$, $10^8 M_\odot$, $10^9 M_\odot$, respectively. With the exception of the less numerous first range (Orange), representing compact star clusters, the rest are SMBHs.

L. Á. Gergely, P. L. Biermann, L. I. Caramete: *Class. Quantum Grav.* 27 194009 (2010)

SMBH mass function

The mass distribution $\Phi_{BH}(m)$ of the galactic central SMBHs in the mass range $10^6 \div 3\times10^9$ solar masses ($M_\odot$) well described by a broken powerlaw

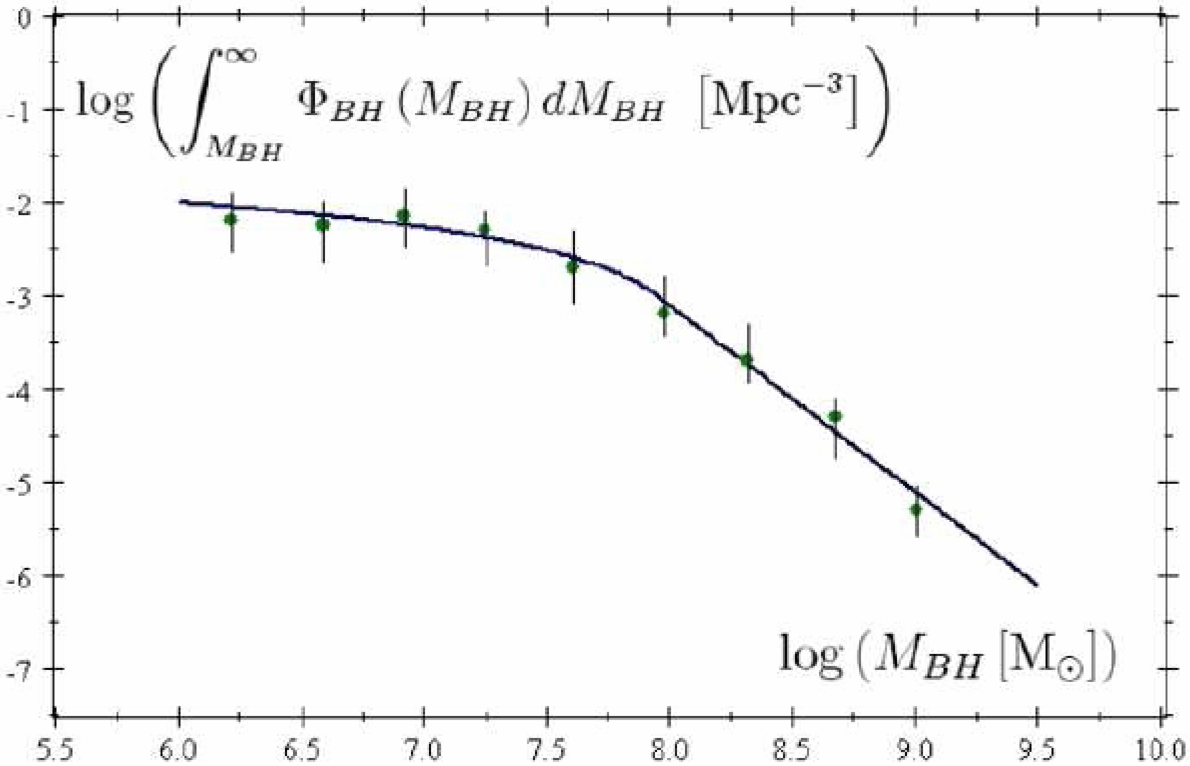
[1] W. H. Press, P. Schechter, *Astrophys. J.* **187**, 425 (1974)
[2] A. S. Wilson, E. J. M. Colbert, *Astrophys. J.* **438**, 62 (1995)
[3] T. R. Lauer et al., *Astrophys. J.* **662**, 808L (2007)

Confirmed by observational surveys

[4] L. Ferrarese et al., *Astrophys. J. Suppl.* **164**, 334 (2006)
[5] L. I. Caramete, P. L. Biermann, *Astron. Astroph.* **521**, A55 (2010)

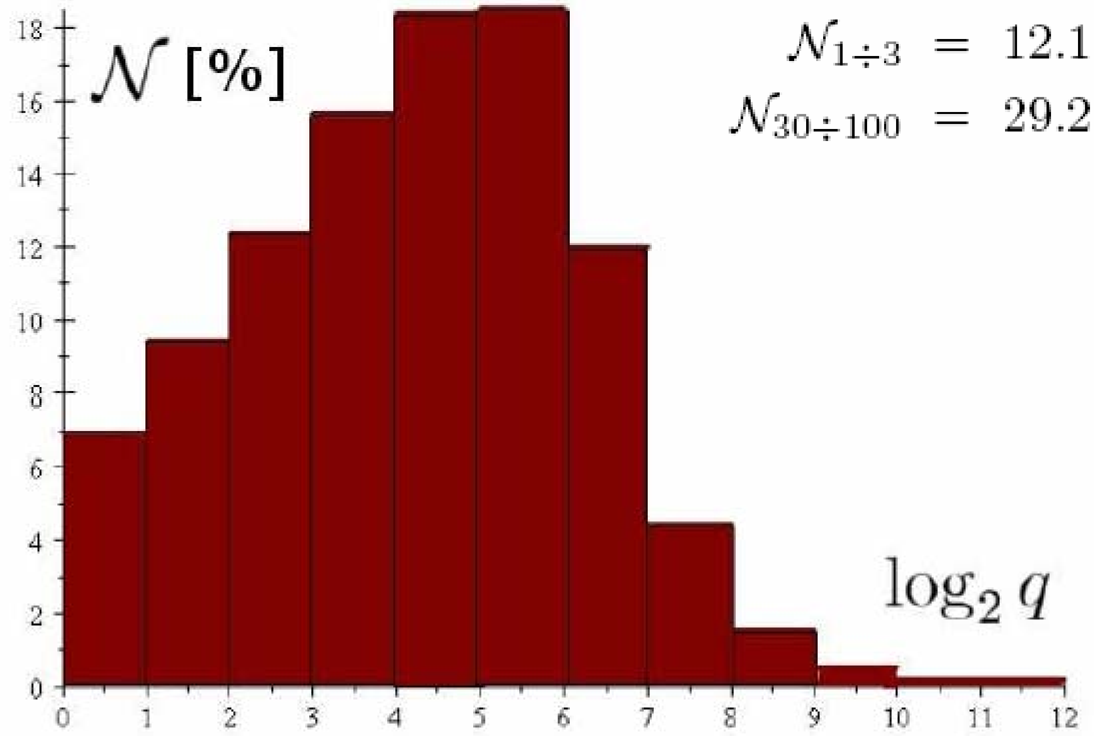
Break at about $10^8 M_\odot$,
$\Phi_{BH}(m)\sim m^{-1}$ below and
$\Phi_{BH}(m)\sim m^{-3}$ above.
The fit with [5] gives

$$m_* = 10^{7.95}\mathrm{M}_\odot \approx 8.9\times10^7\mathrm{M}_\odot.$$



L. Á. Gergely, P. L. Biermann:
[arXiv:1208.5251 [gr-qc]]

Typical mass ratio of SMBH binaries II.



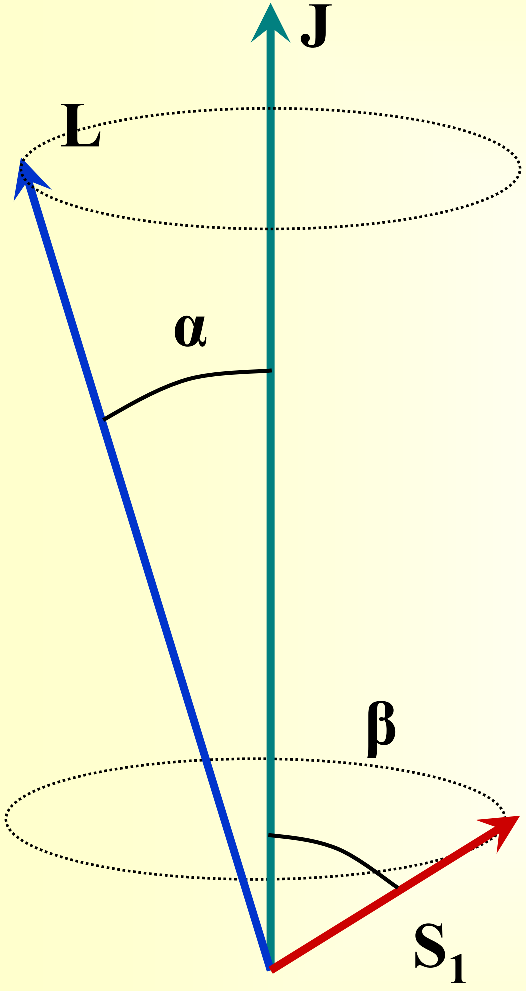
$$\mathcal{N}_{1\div3} = 12.1\ \% \,, \quad \mathcal{N}_{3\div30} = 48.9\ \% \,,$$
$$\mathcal{N}_{30\div100} = 29.2\ \%, \quad \mathcal{N}_{100\div3000} = 9.8\ \% \,.$$

FIG. 2: (Color online) The number of SMBH encounters with mass ratios q as function of $\log_2 q$.

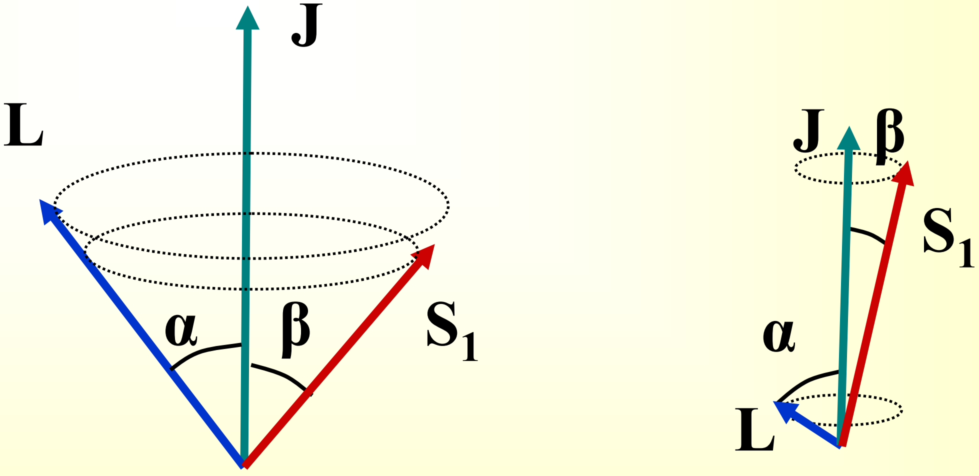
L. Á. Gergely, P. L. Biermann: [arXiv:1208.5251 [gr-qc]]

The dominant spin flips

- due to GW emission the spin aligns to the original **J** direction



L. Á. Gergely, P. L. Biermann,
Astrophys. J. **697**, 1621 (2009)



Key elements: (i) typically the BHs are not equal mass, $m_2 << m_1$, neglect $S_2 \sim m_2^2$

(ii) the direction of **J** is conserved, (iii) the magnitude of $\mathbf{S_1}$ is conserved → spin-flip

How large is the spin-flip ?

In the majority of cases it happens during the inspiral!

L. Á. Gergely,
P. L. Biermann,
L. I. Caramete:
Class. Quantum Grav. 27 194009 (2010)

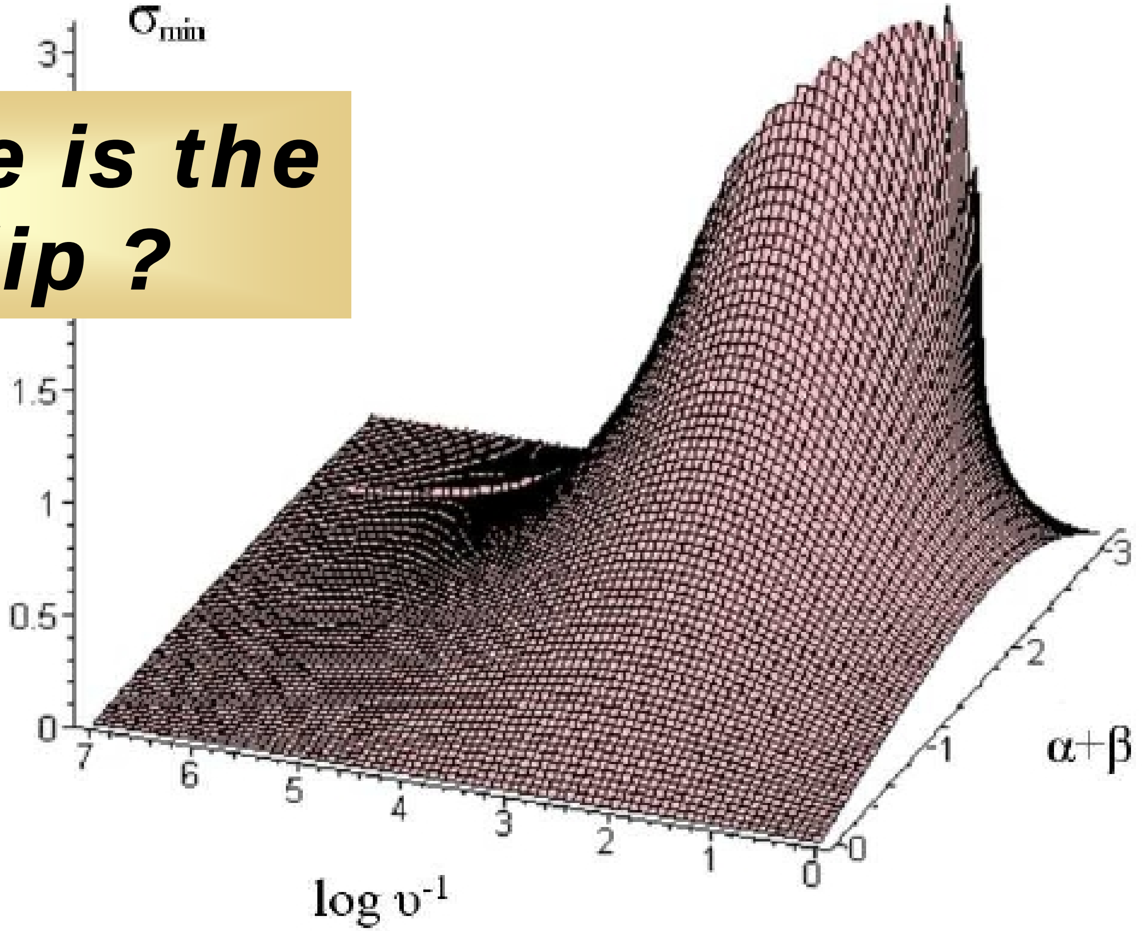
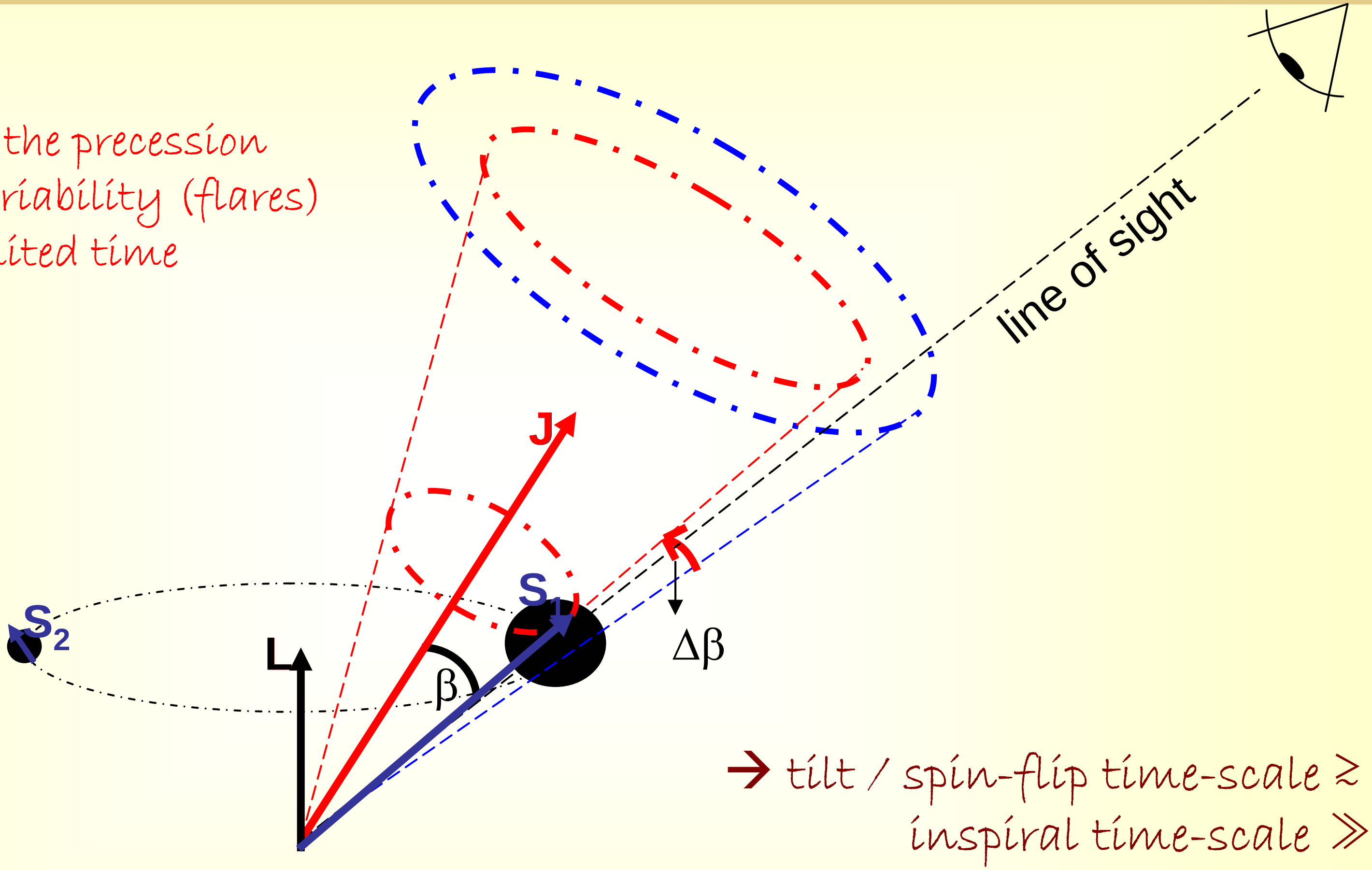


Figure 2. The spin-flip angle $\sigma_{\min}$ as function of the relative orientation of the spin and orbital angular momentum $\alpha + \beta$ (a constant during inspiral), and mass ratio ν. For a given mass ratio the spin-flip angle has a maximum shifted from $\pi/2$ towards the anti-aligned configurations. The mass ratios $\nu = 1$; $1/3$; $1/30$ and $1/1000$ are located on the $\log \nu^{-1}$ axis at 0; 1.09; 3.40 and 6.91, respectively, confirming the prediction, that a significant spin-flip will happen in the mass ratio range $\nu \in (1/30, 1/3)$. For mass ratios smaller than $1/100$ the spin does not flip at all, as the infalling SMBH acts as a test particle.

Jet variability due to precession

The narrowing of the precession cone will cause variability (flares) in the jet for a limited time



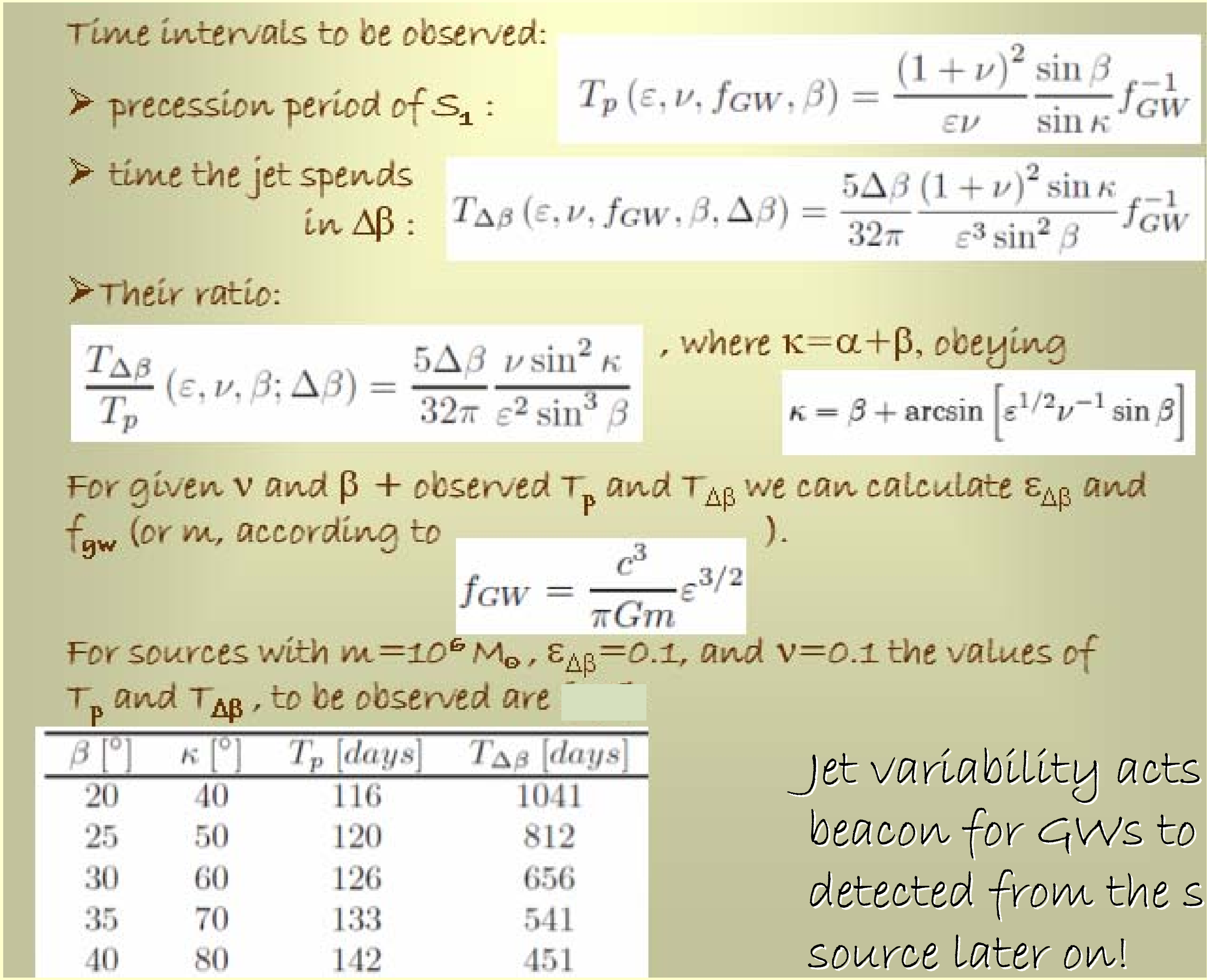
Jet measurements:
source location +
two time intervals
→ help in
reconstructing
the parameters of
the binary

→ tilt / spin-flip time-scale ≳
inspiral time-scale ≫
precession time-scale ≫
orbital time-scale

→ E.M. counterparts to the strongest GW emission likely !!!

M. Tápai, L. Á. Gergely, Z. Keresztes, P. J. Wiita, Gopal-Krishna, P. L. Biermann: *Proceedings of the 6th Workshop of Young Researchers in Astronomy and Astrophysics on The Multi-wavelength Universe - from Starbirth to Star Death*, Budapest, Hungary (2012)

Jet variability due to precession II.



Time intervals to be observed:

- precession period of S_1 :

$$T_p(\varepsilon,\nu,f_{GW},\beta) = \frac{(1+\nu)^2}{\varepsilon\nu}\frac{\sin\beta}{\sin\kappa}f_{GW}^{-1}$$

- time the jet spends in $\Delta\beta$:

$$T_{\Delta\beta}(\varepsilon,\nu,f_{GW},\beta,\Delta\beta) = \frac{5\Delta\beta}{32\pi}\frac{(1+\nu)^2\sin\kappa}{\varepsilon^3\sin^2\beta}f_{GW}^{-1}$$

- Their ratio:

$$\frac{T_{\Delta\beta}}{T_p}(\varepsilon,\nu,\beta;\Delta\beta) = \frac{5\Delta\beta}{32\pi}\frac{\nu\sin^2\kappa}{\varepsilon^2\sin^3\beta}$$

, where $\kappa=\alpha+\beta$, obeying

$$\kappa = \beta + \arcsin\left[\varepsilon^{1/2}\nu^{-1}\sin\beta\right]$$

For given ν and β + observed T_p and $T_{\Delta\beta}$ we can calculate $\varepsilon_{\Delta\beta}$ and f_{gw} (or m, according to

$$f_{GW} = \frac{c^3}{\pi G m}\varepsilon^{3/2}$$

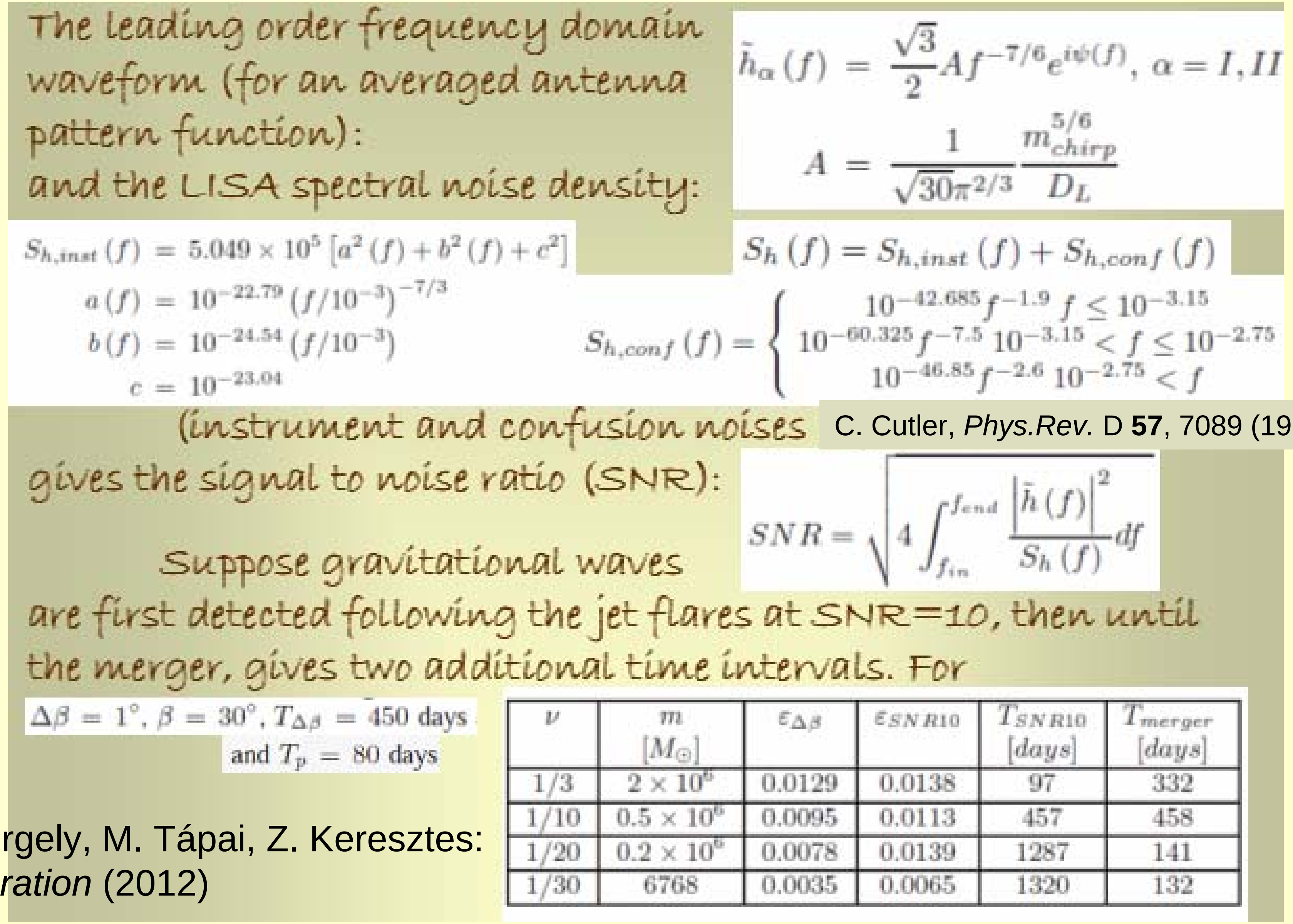
).

For sources with $m=10^6 M_\odot$, $\varepsilon_{\Delta\beta}=0.1$, and $\nu=0.1$ the values of T_p and $T_{\Delta\beta}$, to be observed are

β [°]	κ [°]	T_p [days]	$T_{\Delta\beta}$ [days]
20	40	116	1041
25	50	120	812
30	60	126	656
35	70	133	541
40	80	142	451

Jet variability acts as a beacon for GWs to be detected from the same source later on!

Complementary GW measurements



The leading order frequency domain waveform (for an averaged antenna pattern function):

$$\tilde{h}_{\alpha}(f) = \frac{\sqrt{3}}{2} A f^{-7/6} e^{i\psi(f)},\ \alpha = I, II$$

$$A = \frac{1}{\sqrt{30}\pi^{2/3}} \frac{m_{chirp}^{5/6}}{D_L}$$

and the LISA spectral noise density:

$$S_{h,inst}(f) = 5.049 \times 10^{5} \left[a^{2}(f) + b^{2}(f) + c^{2}\right]$$

$$a(f) = 10^{-22.79} (f/10^{-3})^{-7/3}$$

$$b(f) = 10^{-24.54} (f/10^{-3})$$

$$c = 10^{-23.04}$$

$$S_h(f) = S_{h,inst}(f) + S_{h,conf}(f)$$

$$S_{h,conf}(f) = \begin{cases} 10^{-42.685} f^{-1.9} & f \leq 10^{-3.15} \\ 10^{-60.325} f^{-7.5} & 10^{-3.15} < f \leq 10^{-2.75} \\ 10^{-46.85} f^{-2.6} & 10^{-2.75} < f \end{cases}$$

(instrument and confusion noises

C. Cutler, *Phys.Rev.* D **57**, 7089 (1998

gives the signal to noise ratio (SNR):

$$SNR = \sqrt{4 \int_{f_{in}}^{f_{end}} \frac{\left|\tilde{h}(f)\right|^{2}}{S_h(f)} df}$$

Suppose gravitational waves are first detected following the jet flares at SNR=10, then until the merger, gives two additional time intervals. For

$\Delta\beta = 1°$, $\beta = 30°$, $T_{\Delta\beta} = 450$ days

and $T_p = 80$ days

ν	m $[M_{\odot}]$	$\varepsilon_{\Delta\beta}$	ε_{SNR10}	T_{SNR10} $[days]$	T_{merger} $[days]$
1/3	2×10^{6}	0.0129	0.0138	97	332
1/10	0.5×10^{6}	0.0095	0.0113	457	458
1/20	0.2×10^{6}	0.0078	0.0139	1287	141
1/30	6768	0.0035	0.0065	1320	132

L. Á. Gergely, M. Tápai, Z. Keresztes:
in preparation (2012)

Combined GW & jet measurements

Jet measurements give sky location and redshift +

- precession period T_p and time-span of the variability $T_{\Delta\beta}$
- precession cone β and change of precession cone $\Delta\beta$

E. Kun, K. Gabányi, S. Britzen, Gopal-Khrisna. P. L. Biermann, L. Á. Gergely: *in preparation* (2012)

GW measurements give

- time when SNR=10 (or any reasonable other value), T_{SNR10}
- time when GW signal stops T_{merger} ≈ time of the inspiral

→**Location , redshift + 6 measurements**

GW signal expressed in terms of location, redshift + 5 astrophysical variables:

dominant spin magnitude and
inclination, mass ratio,
total mass, PN parameter at emission

separation, GW frequency at emission

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β from jets, the other 4 variables expressed as function of (T_{SNR10}, T_{merger}, T_p, $T_{\Delta\beta}$ / $\Delta\beta$)

→ <u>source parameters fully recovered</u> !!!

Summary

Combined EM, particle physics and GW measurements worth to pursue!