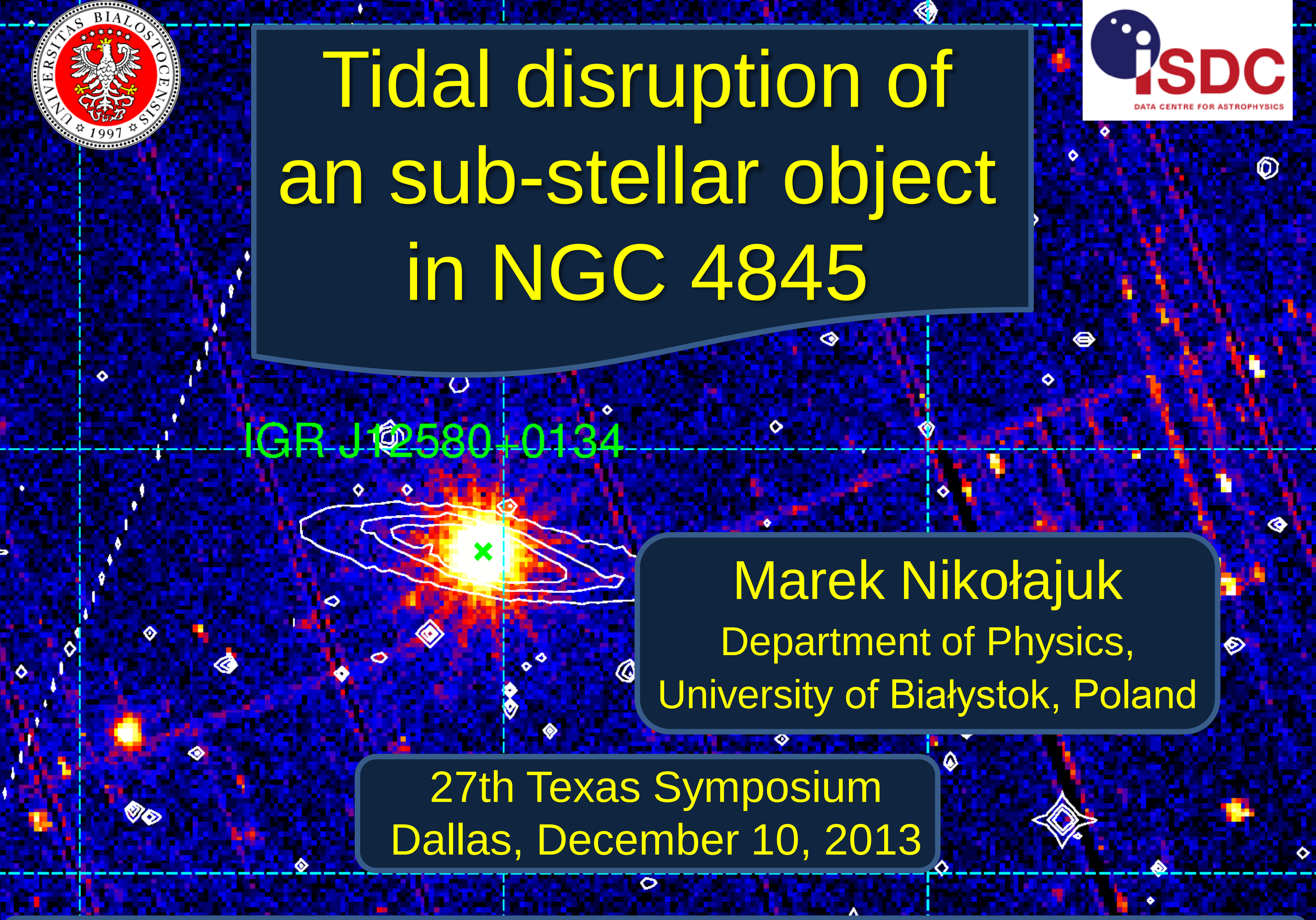
Tidal disruption of an sub-stellar object in NGC 4845



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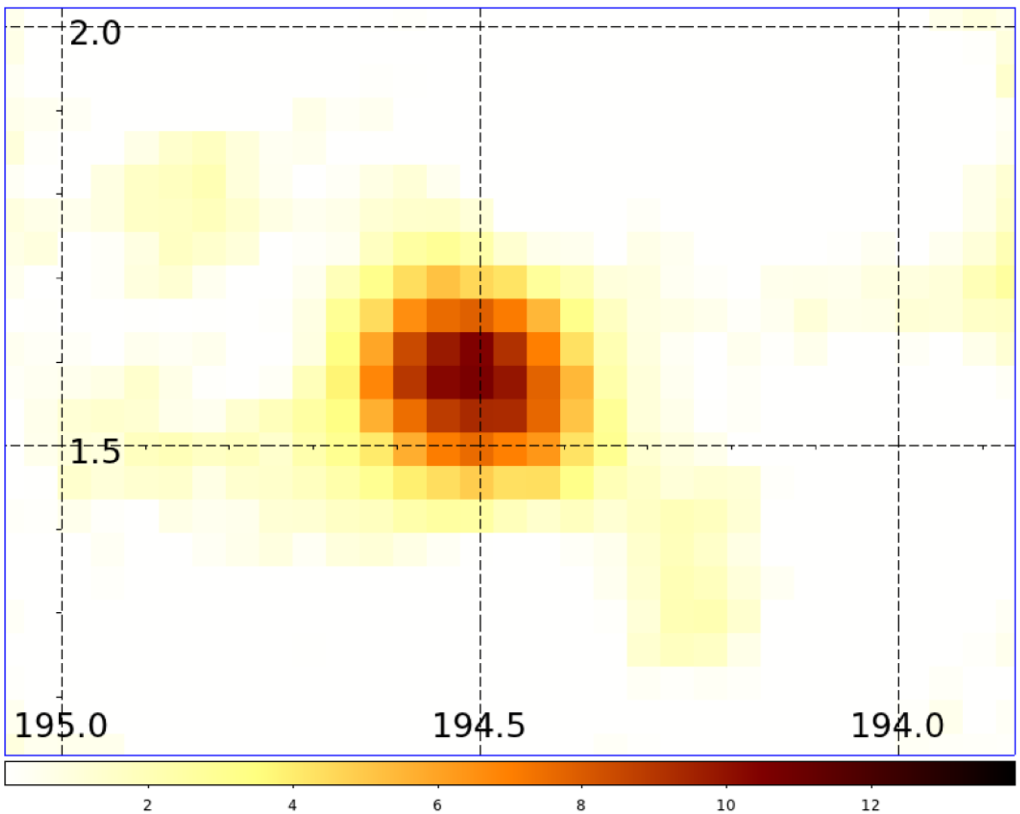
Department of Physics,
University of Białystok, Poland

27th Texas Symposium
Dallas, December 10, 2013

In collaboration with Roland Walter, ISDC, Universerté de Genève

Discovery -> IGR J12580+0134

- INTEGRAL satellite observed the Virgo cluster for the period of 10 yrs.
- In January 2011, INTEGRAL discovered a new source of hard X-rays in not previously detected region of the Virgo cluster.

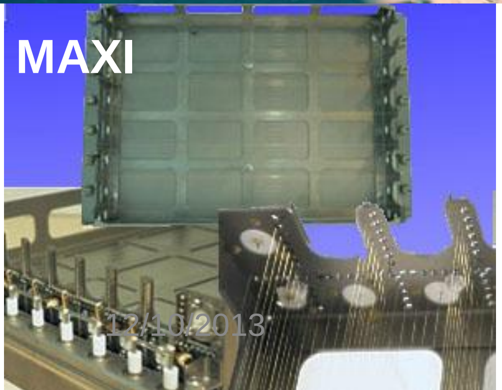


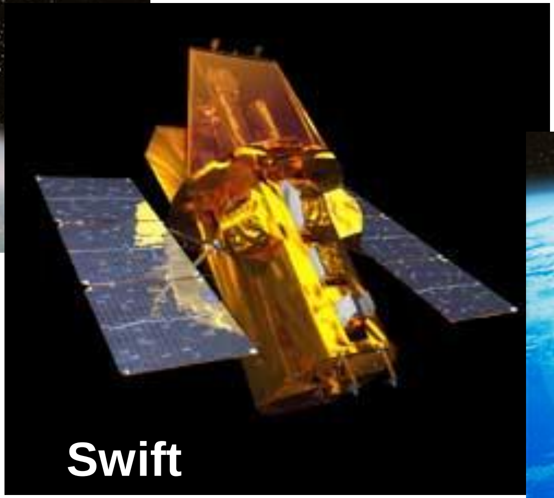
INTEGRAL/*ISGRI* (17.3-80 keV)
Observations: 2-11 Jan 2011
significance = 9σ

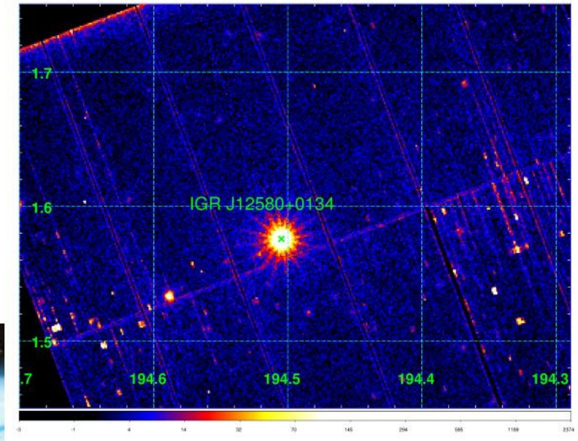
Observations

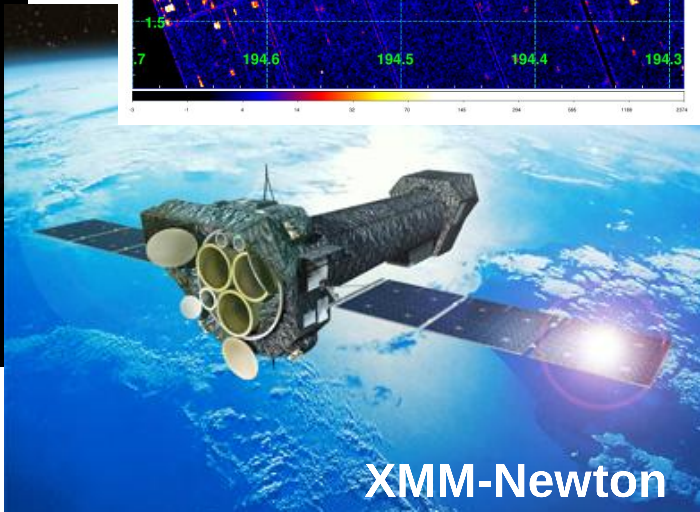
Detections were made by

- INTEGRAL (Jan-July 2011, Tot.Exp = 323 ksec)
- Swift (12-13 Jan 2011 & 29 Jun 2012, Tot.Exp = 8.5 ksec)
- XMM-Newton (22 Jan 2011, Tot.Exp = 14 ksec)
- MAXI on ISS (2011, Tot.Exp = 310 d)



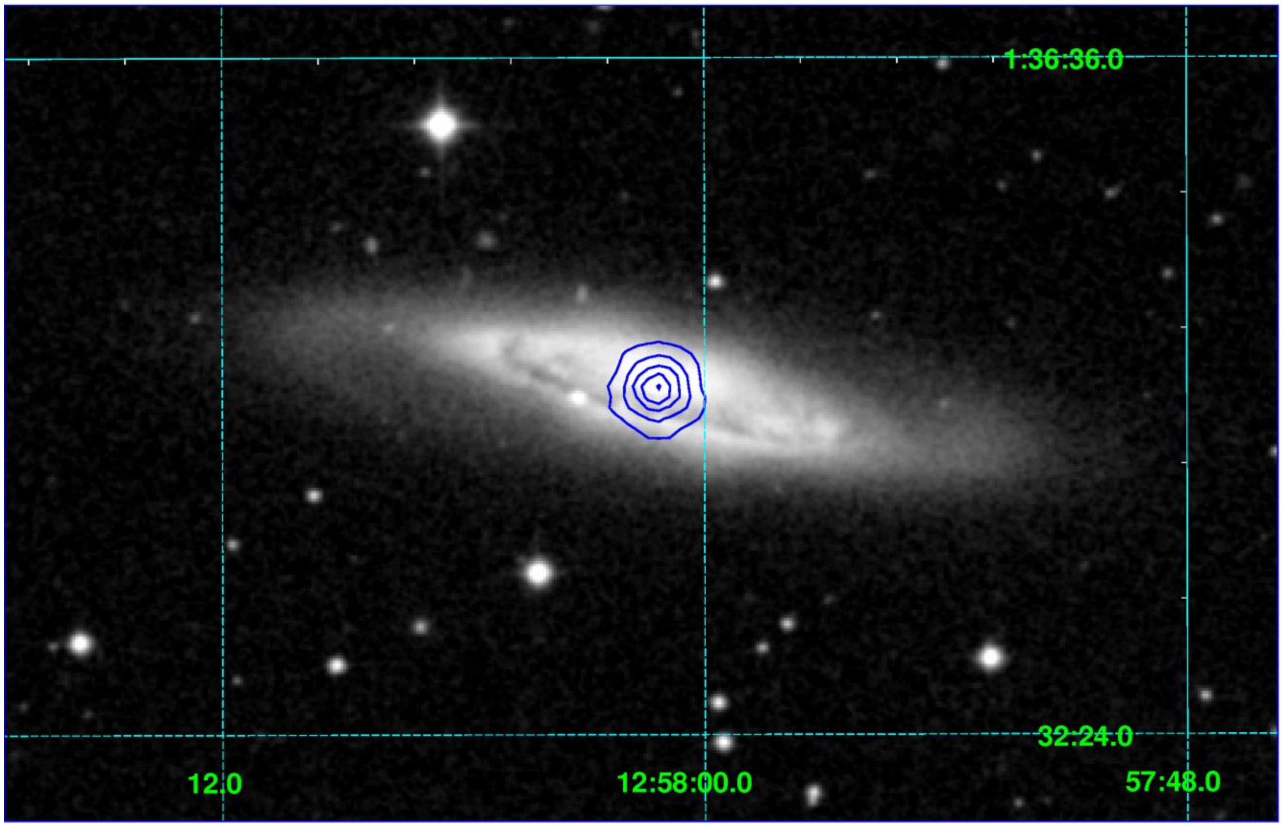






Location -> NGC 4845

Location of the new source -> center of NGC 4845
(Seyfert 2; Distance ≈ 14.5 Mpc
Shapley et al. 2001)

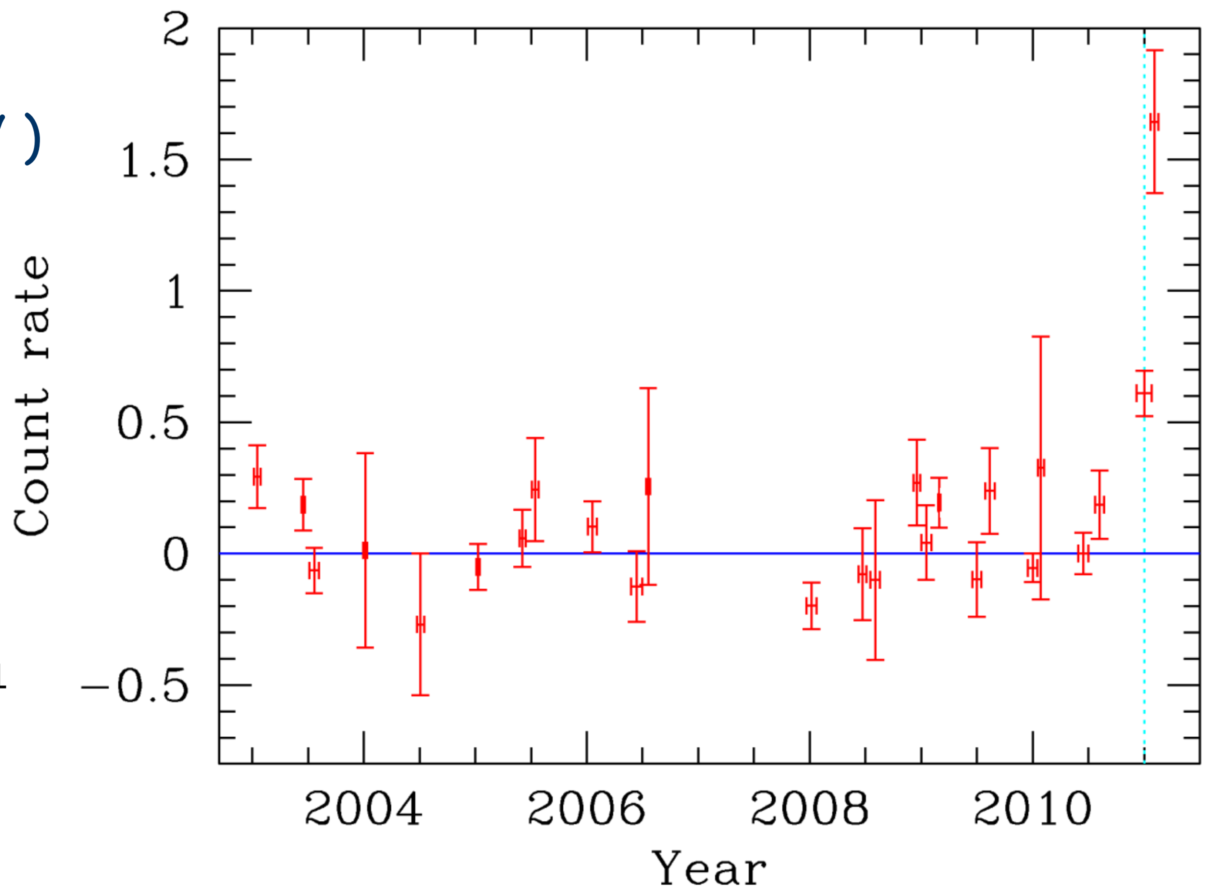


STSci-DSS (optics; in B&W) + XMM-Newton/*Epic-pn* (0.8-10 keV, blue isolines)

NGC 4845 in INTEGRAL (obs. 2003-2011)

IGR J12580 was not detected in the range 3-80 keV prior to 2011

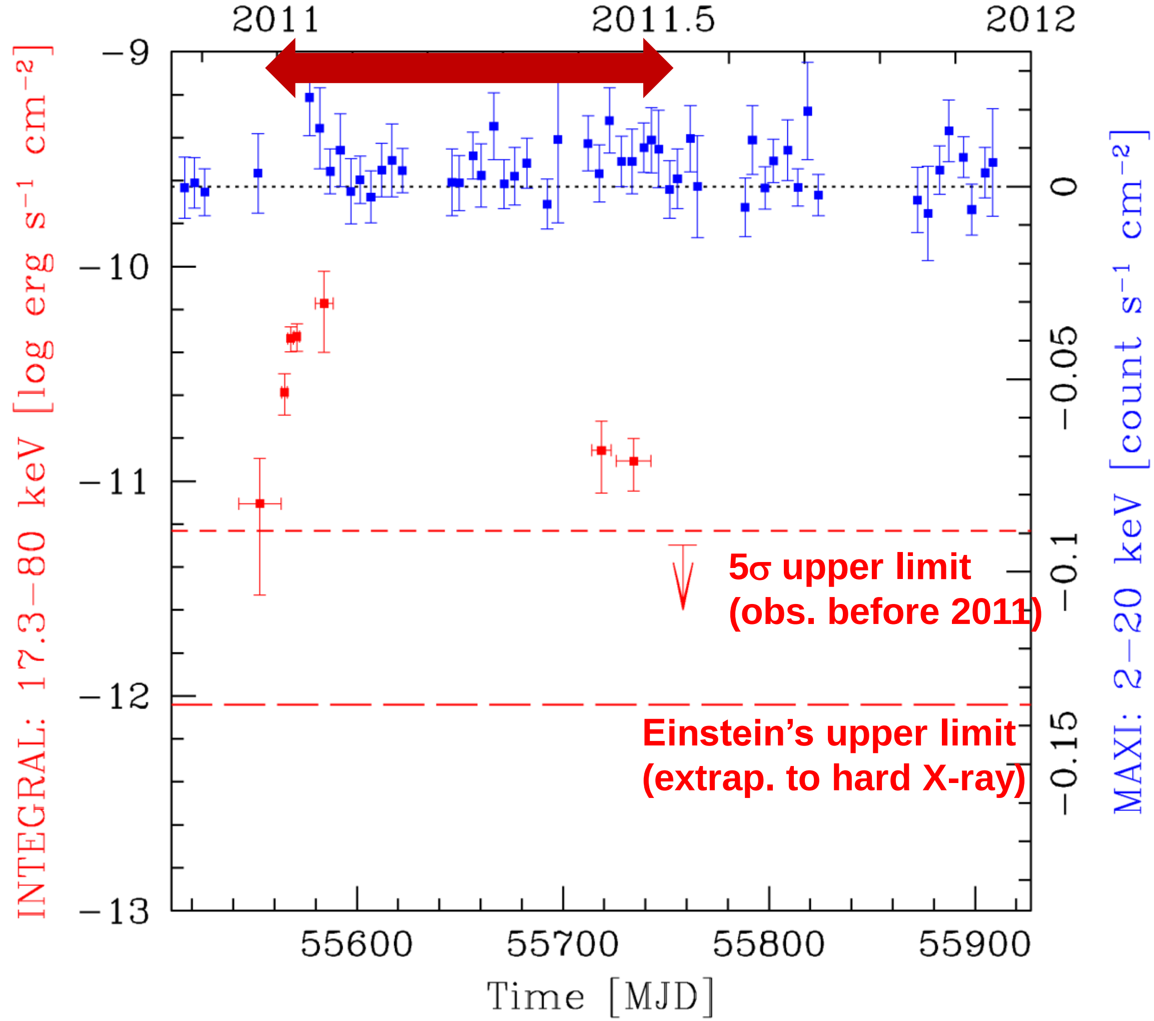
ISGRI/IBIS
(17.3-80 keV)



Mean flux:
0.014 ± 0.026 count s^{-1}

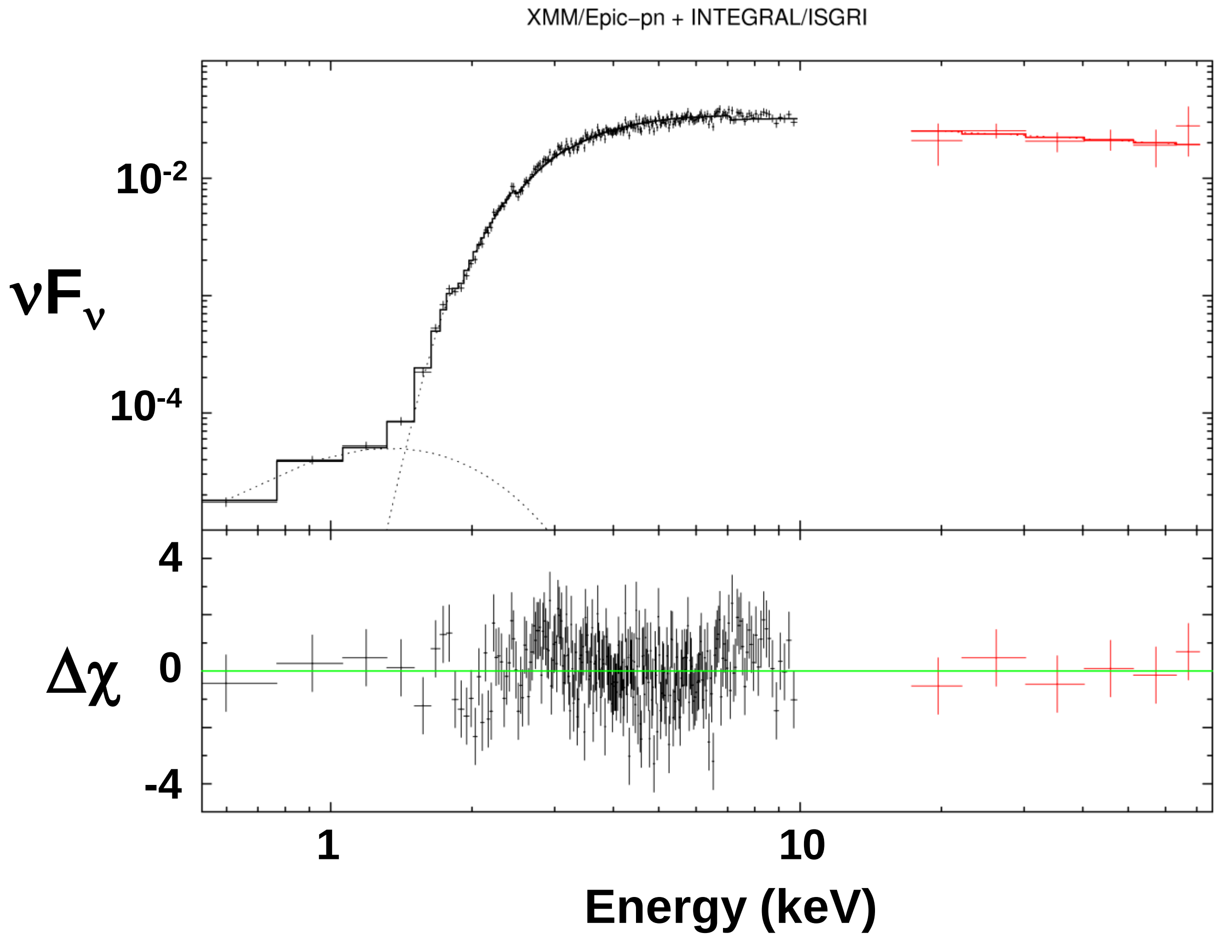
Decline of a flux

The flare span of around 6 months in the hard X-ray (17.3-80 keV).



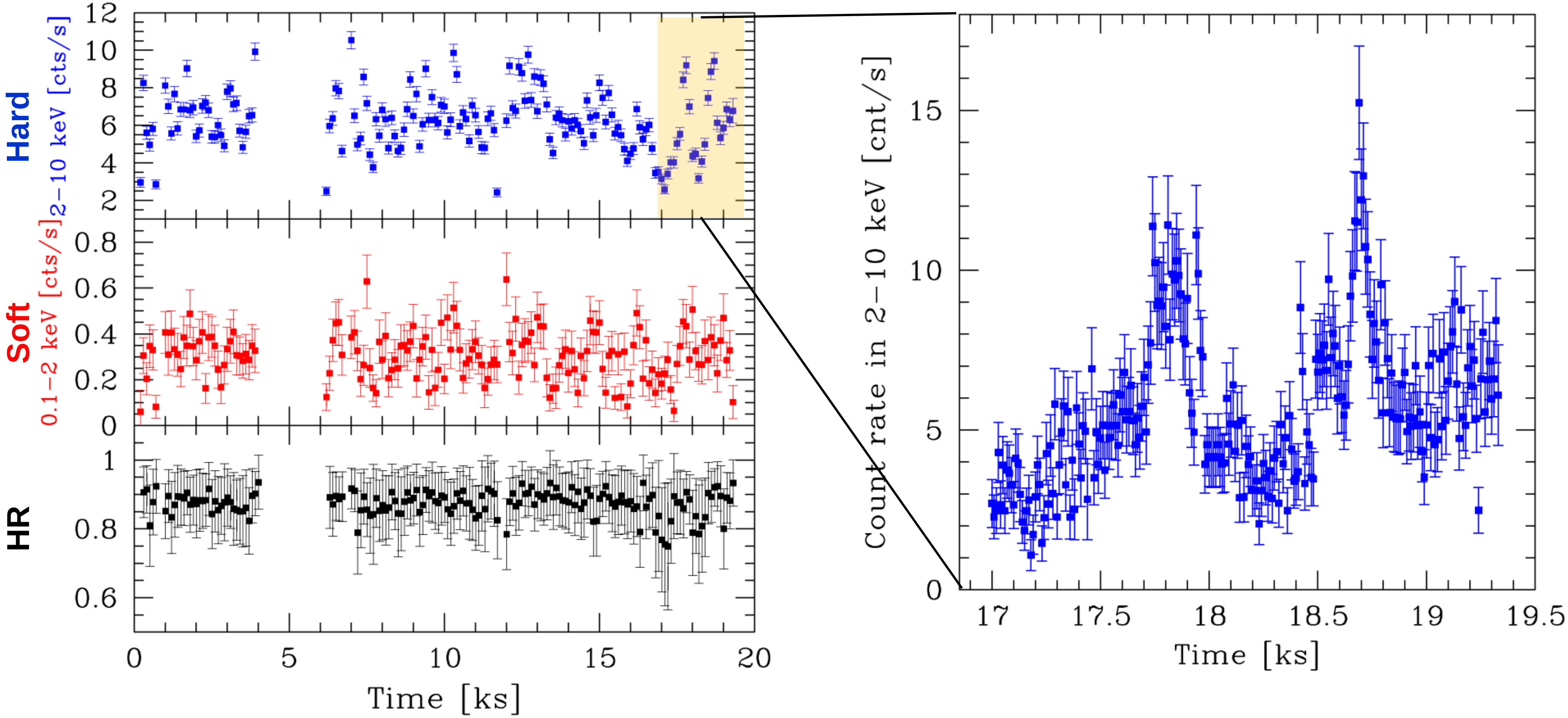
High-energy spectrum

The best-fit model: an absorbed power law ($\Gamma_{17\text{-}80\ keV}$ = 2.22±0.03 , N_H= (7.2 ± 0.1) × 10^{22} cm^{-1}) + an unabsorbed diffusion emission



Short term variability

Variability factor > 100



HR = (Hard – Soft)/(Hard + Soft)

XMM-Newton/*Epic-pn* (0.8-10 keV)
Obs. 01/22/2011

Origin of the flare

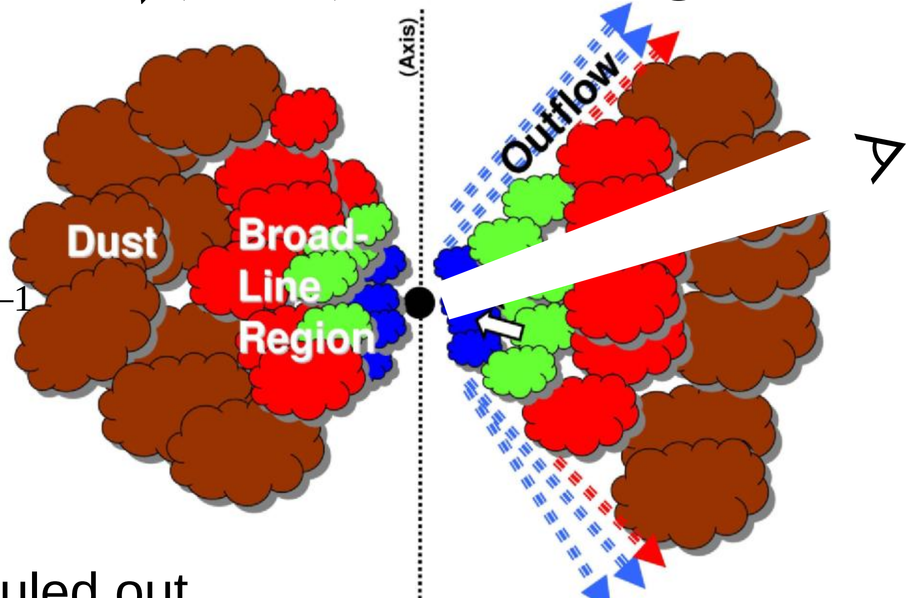
1. A hole in the AGN dusty torus
   - According to the [O III]$_{\lambda 5007 Å}$ – X-ray relationship

$$L_{(2-10\,\mathrm{keV})} \propto L_{[\mathrm{OIII}]}^{1.22\pm0.06}$$ (Panessa et al. 2006)

expected brightness of NGC 4845 is: $\nu F_\nu (2-10) \approx 6\times10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$

However, the observed brightness was

$$\nu F_\nu (2-10\,\mathrm{keV}) = 6.1\times10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$$



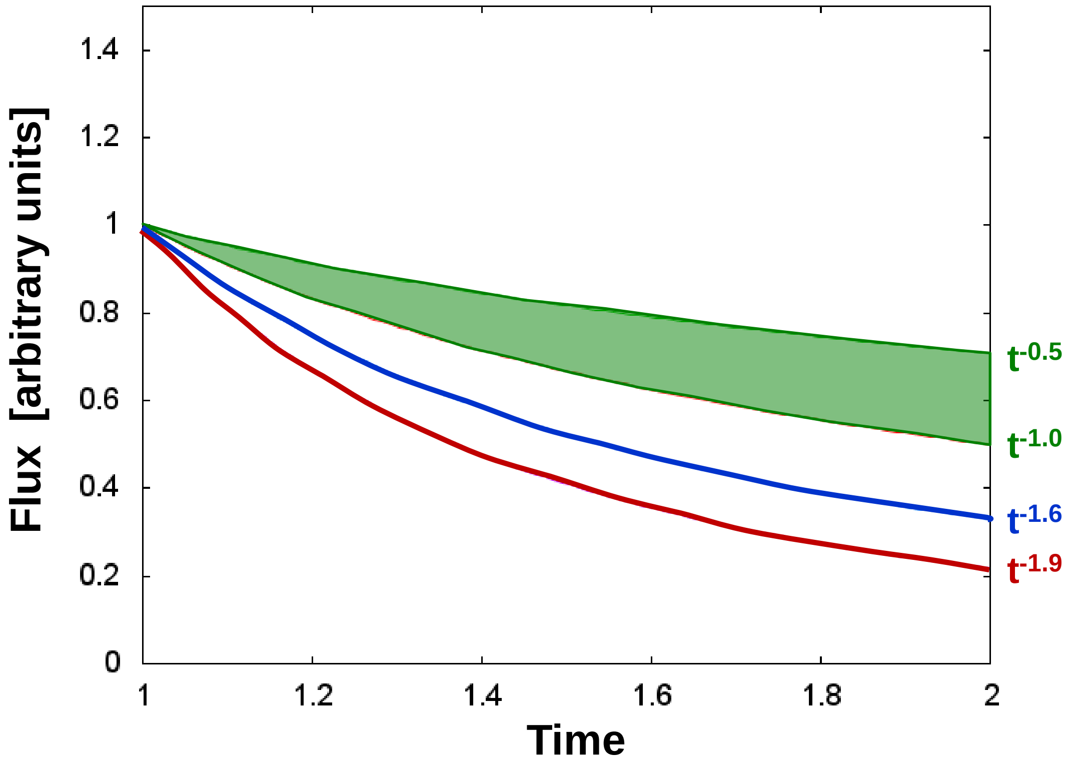
Creation of a hole in the cloudy torus – ruled out.

(mod. Fig. from Gaskell 2009)

Origin of the flare

2. Supernova

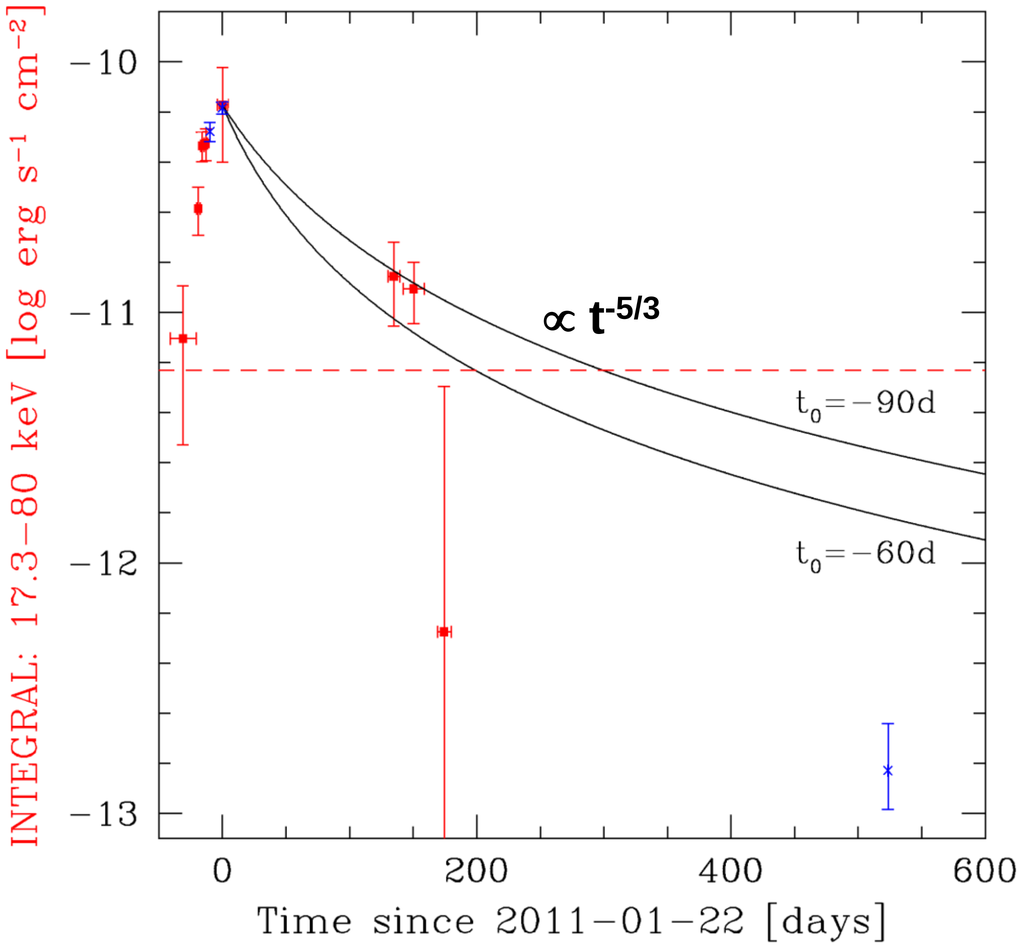
- A decline in the flux of the source ($\sim t^{-(1.6-1.9)}$) was faster than in cases among supernovas ($\sim t^{-(0.5-1)}$) (Immler & Lewin 2003, Chandra et al. 2009).



SN explosions – ruled out.

Origin of the flare

3. Tidal disruption by supermassive BH



$$E_{total} \approx 10^{50}\,\mathrm{erg} \Rightarrow E_{total} = \Delta M c^2 \Rightarrow \Delta M \approx 0.5 M_{Jup}$$

BH mass

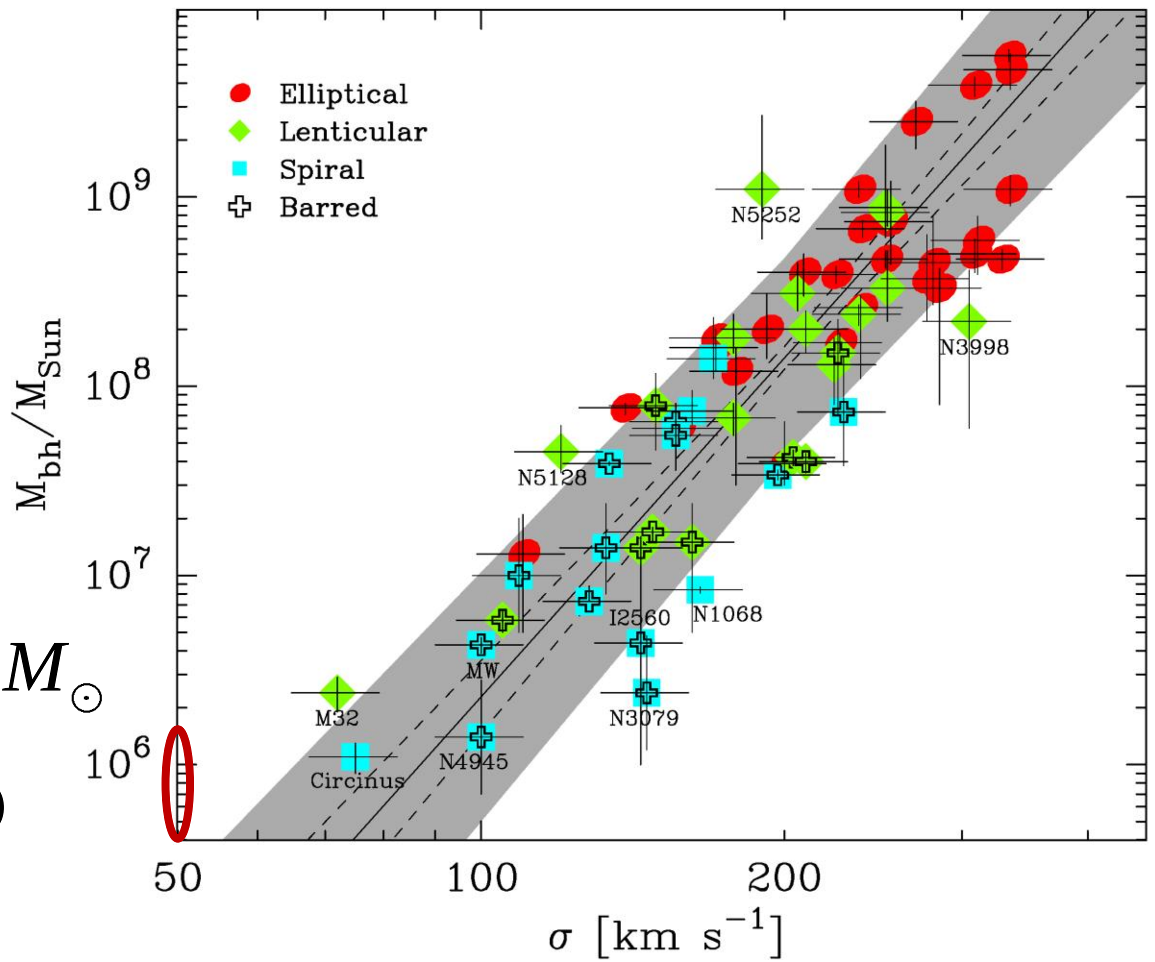
1. BH masses in AGNs from the stellar velocity dispersion method:

$$\sigma_*^{\mathrm{NGC4845}} \simeq 81 \pm 3\,\mathrm{km\,s^{-1}}$$

(Pizzella et al. 2005)

$$M_{\mathrm{BH}}(\sigma_*) \simeq 6.6^{+6.1}_{-4.7} \times 10^5 M_\odot$$

(Graham et al. 2011)



BH mass

2. The X-ray excess variance method:

The normalized excess variance , $\sigma_{nxs}^2 \equiv \sum_{i=1}^{N} [(x_i - \langle x \rangle)^2 - \sigma_{err}^2] \Big/ [N \langle x \rangle^2]$,

measures the real variability in an X-ray signal (e.g. Nandra et al. 1997).

$$\sigma_{nxs}^2 = 0.12_{-0.04}^{+0.09}$$ for IGR J12580 (in 2-10 keV)

The method uses the relationship between M_{BH} and σ^2_{nxs}, $M_{BH} \propto \frac{T_{durat} - 2bin}{\sigma_{nxs}^2}$
(Papadakis 2004, Nikolajuk et al. 2006)

$$M_{BH}\left(\sigma_{nxs}^2\right) = 2.3_{-1.0}^{+1.1} \times 10^5 M_\odot$$

• The errors, related to the calibration of the relationship, could be larger (O'Neill et al. 2005) and for this reason $M_{BH} = 10^4 - 10^6 M_\odot$.

BH mass

2. The X-ray excess variance method:

The normalized excess variance , $\sigma_{nxs}^2 \equiv \sum_{i=1}^{N}[(x_i - \langle x \rangle)^2 - \sigma_{err}^2] \Big/ [N \langle x \rangle^2]$,

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(Papadakis 2004, Nikolajuk et al. 2006)

$$M_{BH}\left(\sigma_{nxs}^2\right) = 2.3_{-1.0}^{+1.1} \times 10^5 M_{\odot}$$

The intermediate BH masses (Graham & Scott 2013,):
- dwarf galaxy Pox 52: log $M_{BH}/M_{\odot}$ = 5.3 ±0.9
- dwarf galaxy NGC 404: log $M_{BH}/M_{\odot}$ = 4.1 ± 1.1
- SAB(rs)cd galaxy NGC 1042 (AGN): log $M_{BH}/M_{\odot}$ = 3.3 ± 1.4
- NGC 4395 (Sy 1.8): log $M_{BH}/M_{\odot}$ = 2.6 ± 1.3

Comparison with hydro-simulations

Some facts about IGR J12580 :

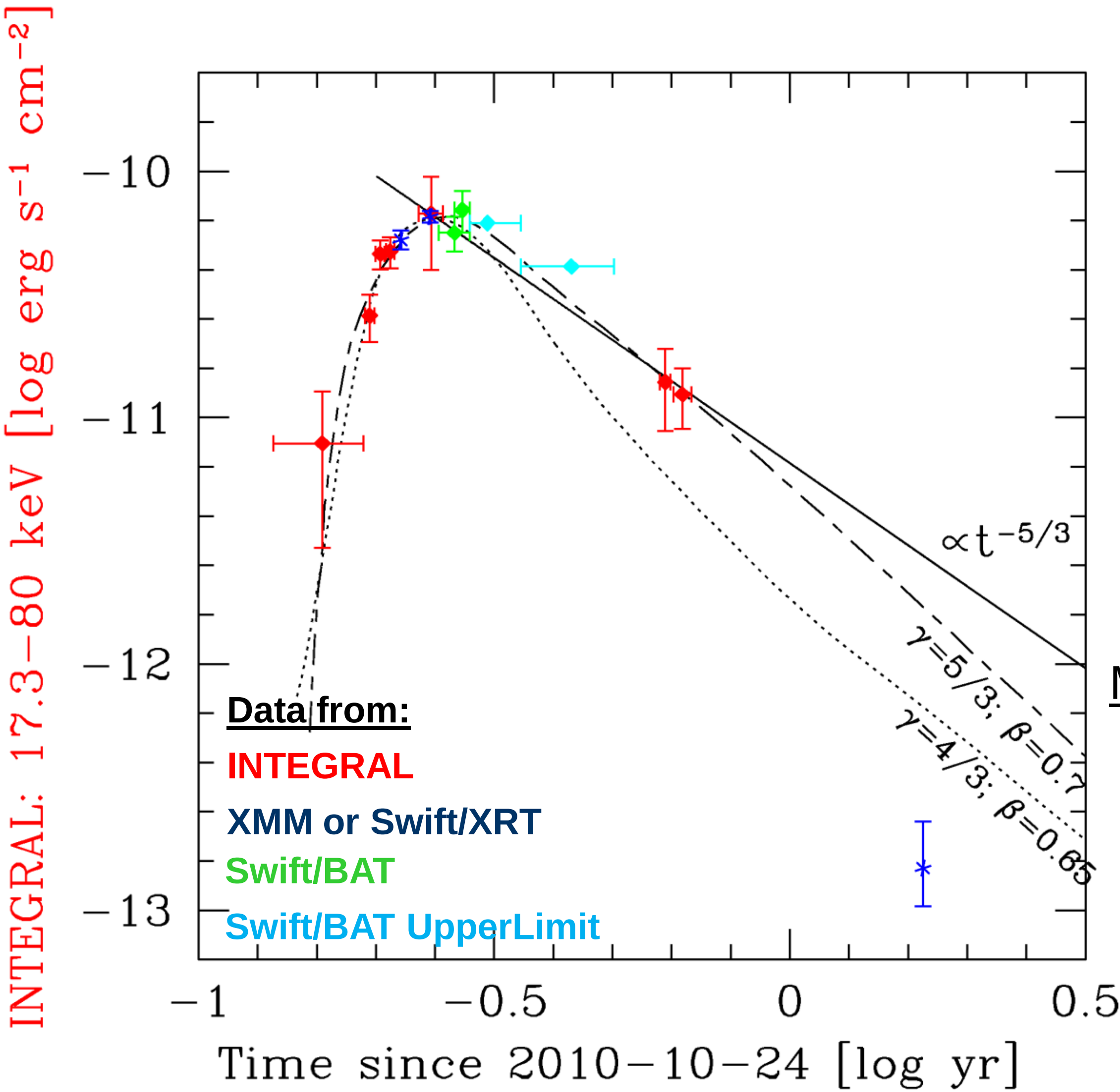
- $\nu L_{\nu,\mathrm{peak}}(17.3-80\,\mathrm{keV}) \simeq 1.4\times10^{42}\,\mathrm{erg\,s^{-1}}$
- $L_{\mathrm{peak}}/L_{\mathrm{Edd}} \simeq 0.6-0.1$ (for $M_{\mathrm{BH}} = 2.3\times10^{5}-10^{6}\,M_{\odot}$)
- $\boldsymbol{t}_{\mathbf{peak}} \sim 0.2\,\mathrm{yr}$ (the time of peak accretion)
- $\dot{\boldsymbol{M}}_{\mathbf{peak}} \sim 2.5\,M_{\mathrm{Jup}}/\mathrm{yr}$ (the peak accretion rate)

Hydro-simulations by Guillochon & Ramirez-Ruiz (2013)

$$\begin{cases} M_{*} = f(\dot{\boldsymbol{M}}_{\mathbf{peak}}, \boldsymbol{t}_{\mathbf{peak}}, M_{\mathrm{BH}}, R_{*}, \gamma) \\ \beta \equiv \dfrac{r_{\mathrm{tidal}}}{r_{\mathrm{peric}}} = g(\dot{\boldsymbol{M}}_{\mathbf{peak}}, \boldsymbol{t}_{\mathbf{peak}}, M_{\mathrm{BH}}, R_{*}, \gamma) \end{cases}$$

+ Relationship $R_{*} \propto M_{*}^{\alpha}$
(for MS stars,
brown dwarfs & planets)
(e.g. Chabrier & Baraffe 2000)

Comparison with hydro-simulations



$$M_{BH} = 2.3\times10^{5} - 10^{6} M_{\odot}$$

Substellar objects $\rightarrow \gamma = 5/3$

$$\Downarrow$$

$$M_{*} \approx 14 - 28 M_{Jup}$$

Main Sequence star $\rightarrow \gamma = 4/3$

$$\Downarrow$$

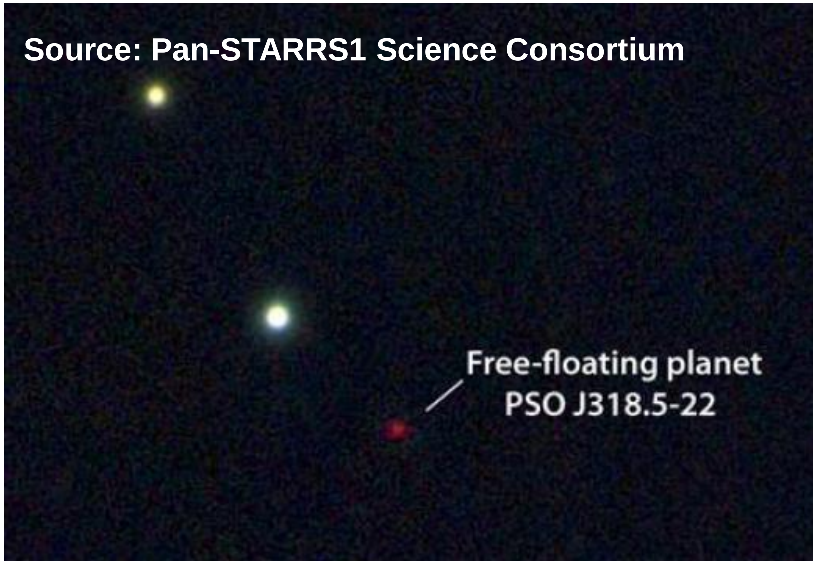
$$M_{*} \approx 1 - 15 M_{\odot}$$

Free-floating planets

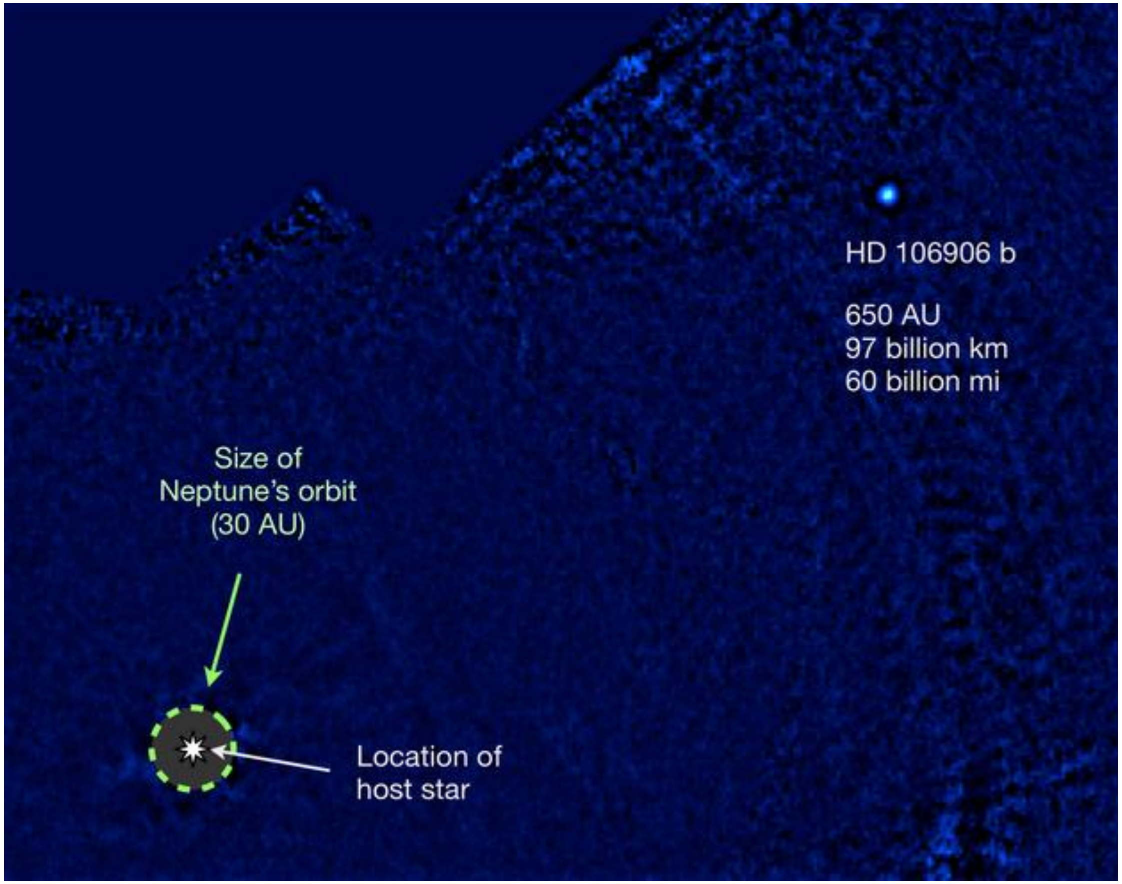
Gravitationally unbound planets in galaxies:

Gravitational instability during the formation of a planetary system could throw out giant planets (e.g. Veras et al. 2009).

- Free-floating planets:
  - 10 unbound Jupiter-mass planets – M=3-15M_{Jup} discovered by microlensing .experiments (Sumi et al. 2011);
  - PSO J318.5-22 – a planet with M=5-8M_J , distance ~80 l.yr in β Pic group of stars (Liu et al. 2013).



HD 106906b



$$M_{\text{planet}} = 11 \pm 2 M_{\text{Jup}}$$

Distance = 650 AU

$\text{Age}_{\text{planet}} = 13 \pm 2$ Myr

(Bailey et al. 2013)

Conclusions

- Regardless of how massive the BH in NGC 4845 would be (i.e. $< 10^7$ $M_\odot$), the tidally disrupted object is not a main sequence star. The object has mass of 14-28 Jupiters (i.e. brown dwarf or giant planet).

- The hard X-rays should come from a corona. Chronologically, this tidal disruption event is the first event where such a corona has been observed.

  (NGC 4845: 2 January 2011; Swift J1644+57: 28 March 2011 ; Swift J2058+05: 17 May 2011)

M. Nikolajuk & R. Walter,"Tidal disruption of a super-Jupiter by a massive black hole", 2013, A&A, 552, A75

Extra materials

IGR J12580+0134

IGRJ12580+0134, a flaring Seyfert 2 galaxy

ATel #3108; R. Walter, P. Bordas, E. Bozzo (ISDC, Geneva), V. Beckmann, S. De Jong (APC Paris), F. Panessa (IASF, Roma)
on ***14 Jan 2011; 17:27 UT***
Credential Certification: Roland Walter (Roland.Walter@unige.ch)

Subjects: X-ray, AGN

IGRJ12580+0134 was discovered by INTEGRAL during the observations of the 3C 273 field performed from 2011 January 2 to 11. The source was detected by IBIS/ISGRI (effective exposure time of 400 ks) at a significance level of 9.7 sigma (20-40 keV). The corresponding flux is 3.3+/-0.4 mCrab. IGRJ12580+0134 was also detected by JEMX in the soft energy band (3-10 keV), and the corresponding flux was 3.6+/-1.0 mCrab (effective exposure time 13 ks). The best determined position was found at: RA=194.5212 DEC=1.5738 (+/-2.3 arcmin, J2000), thus suggesting an association with the Seyfert 2 galaxy NGC 4845, which is not known as an X-ray source.

IGRJ12580+0134 was not detected during the observations of the same field performed previously from 2010 December 30 to 2011 January 2 nor from deep INTEGRAL observations of the field performed in the previous years and providing an upper limit of 0.3 mCrab in the 20-40 keV energy band. The source brightened by a factor >10, an unusual factor for a Seyfert 2. The ISGRI spectrum is very steep with a photon index of ~3.

A Swift XRT TOO observation performed on January 13 confirmed the association with the central regions of NGC 4845 with RA=194.5048 DEC=1.5753 (+/-3.6 arcsec, J2000). The Swift XRT spectrum can be modeled with an absorbed (NH ~ 8E22 cm-2) powerlaw (gamma ~ 3.3+/-0.3)

Diffusion emission

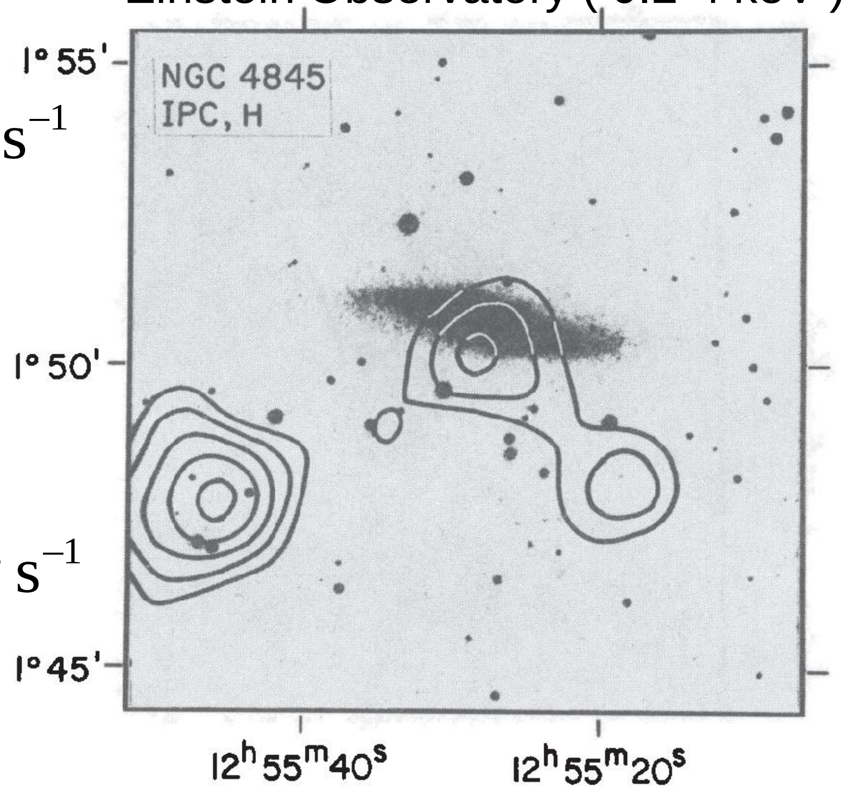
NGC 4845 had shown the diffusion emission in the energy band < 3.5keV

$$\nu F_\nu(\text{Einstein}) < \mathbf{2.5\times10^{-13}}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$$

IGR J12580 in Jan., 2011:

$$\nu F_\nu(2-10\text{keV}) \simeq 6.1\times10^{-11}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$$

Einstein Observatory (0.2-4 keV)



(Fabbiano, Kim & Trinchieri 1992)

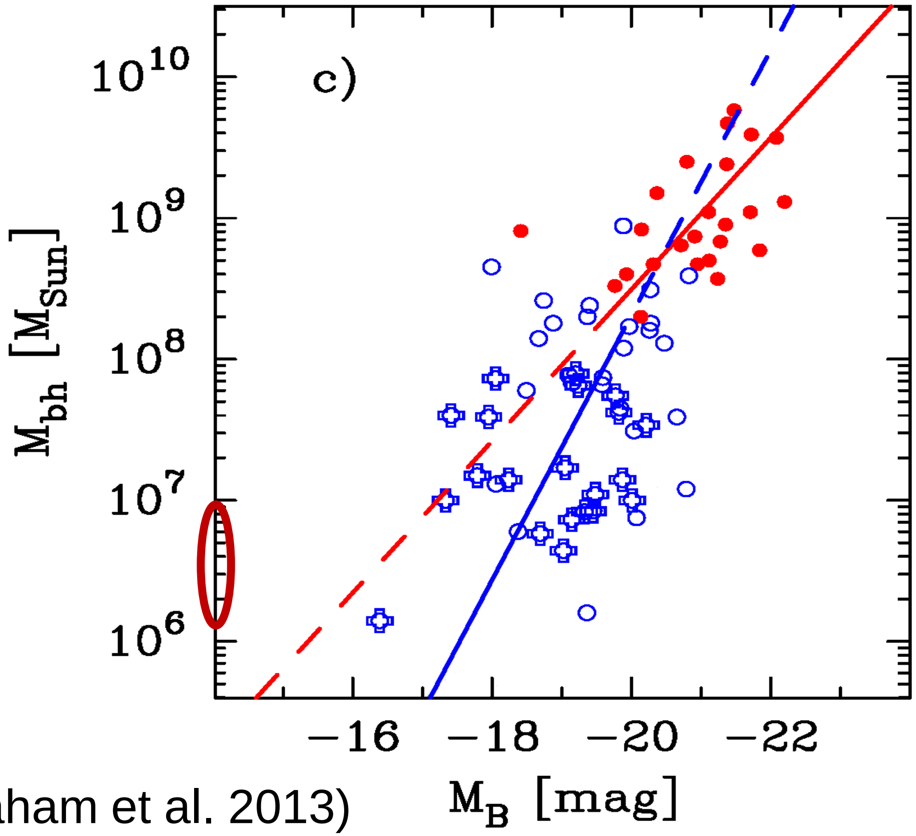
BH mass

The (BH mass)-(bulge luminosity) relation:

$$M_{\rm B}^{\rm bulge} \simeq -18.1$$

(Ho, Filippenko & Sargent 1997)

$$M_{\rm BH}\left(M_{\rm B}^{\rm bulge}\right) \lesssim 10^{7} M_{\odot}$$



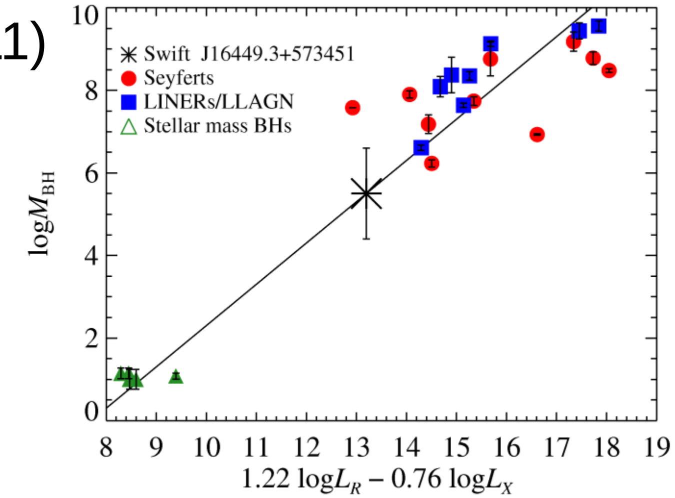
(Graham et al. 2013)

BH mass

The (BH mass)-(radio + X-ray luminosity) relationship:

$$\log L_{5\mathrm{GHz}} = (0.82 \pm 0.08)\log M_{\mathrm{BH}} + (0.62 \pm 0.10)\log L_{2\text{-}10\mathrm{keV}} + \mathrm{const}$$

(Mïller & Gültekin 2011)



For NGC 4845:

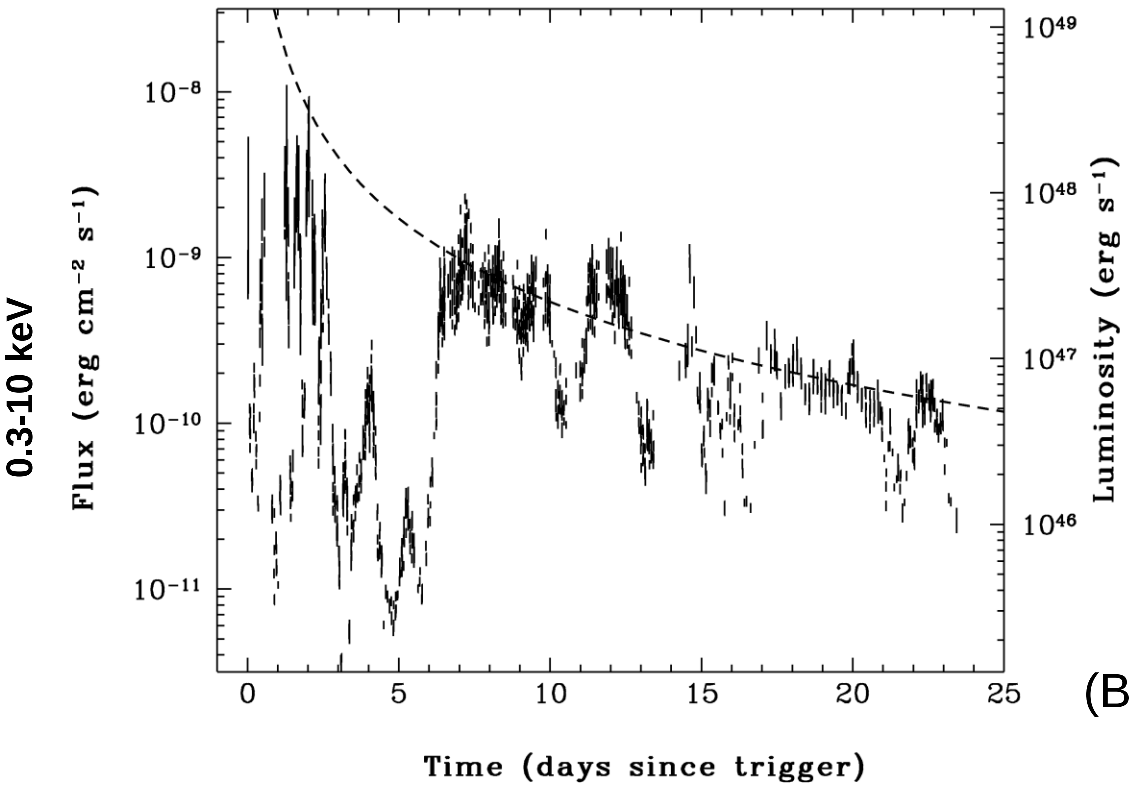
- $F_{1.4\mathrm{GHz}} = 43.3 \pm 1.4\,\mathrm{mJy}$
  (Condon et al. 1998)

- $\nu F_{\nu}(2-10\,\mathrm{keV}) \simeq 6.1\times10^{-11}\,\mathrm{erg\,s^{-1}cm^{-2}}$
(our paper; data from XMM-Newton)

$$\log M_{\mathrm{BH}} = 6.03 \pm 1.00$$

Swift J1644+57

Tidally disrupted WD by IMBH (Krolik & Piran 2011)
or MS star by SMBH (Levan et al. 2011, Zauderer et al. 2011)

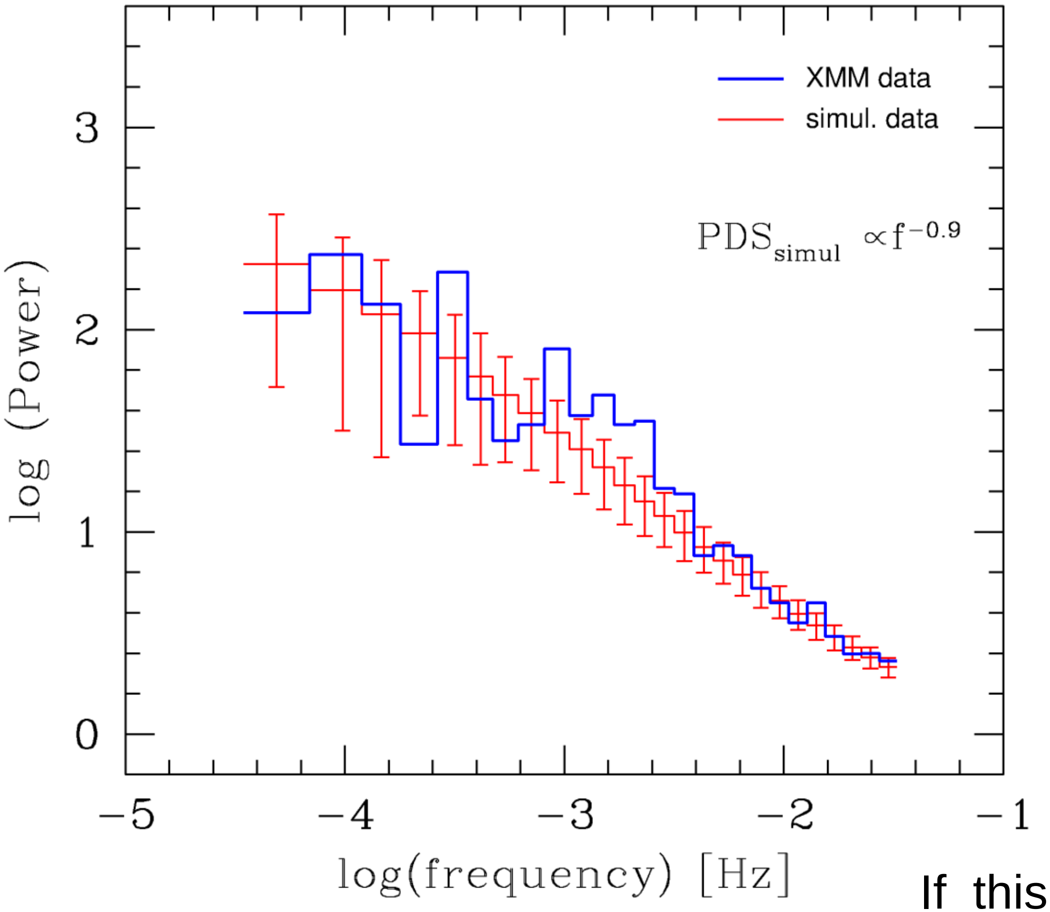


(Burrows et al. 2011)

$$\log M_{\mathrm{BH}} = 5.5 \pm 1.1$$

(Mïller & Gültekin 2011)

IGR J12580+0134



Excess of power near 10^{-3} Hz => QPO (?)

$$\begin{cases} \omega_{ISCO} = 2\pi\upsilon_{ISCO} \\ GM_{BH} / R^2_{ISCO} = \omega^2 R_{ISCO} \end{cases}$$

$$\upsilon_{ISCO} \propto \frac{\text{const}}{M_{BH}} \quad \text{Hz}$$

If this excess is connected with ISCO than

$$M_{BH} < 10^6 M_{\odot}$$

BH mass

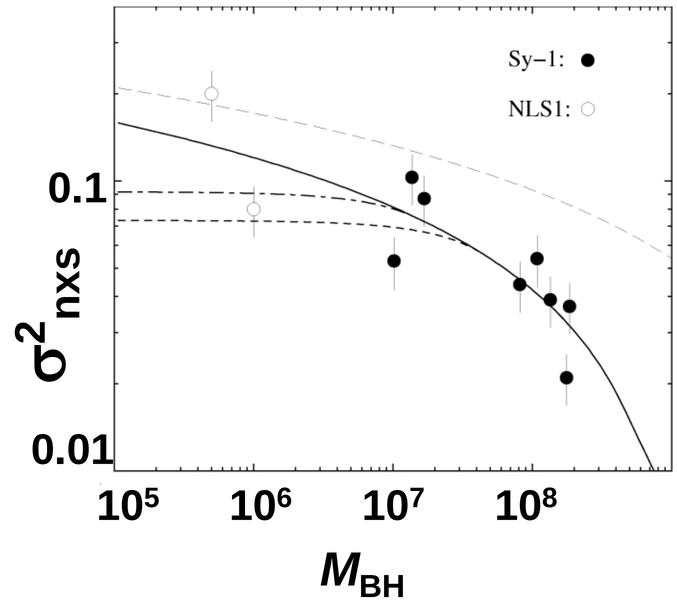
3. The X-ray excess variance method:

The normalized excess variance , $\sigma^2_{nxs} \equiv \sum_{i=1}^{N}[(x_i - \langle x \rangle)^2 - \sigma^2_{err}] \Big/ [N \langle x \rangle^2]$,

measures the real variability in an X-ray signal (e.g. Nandra et al. 1997).

$$\sigma^2_{nxs} = 0.12^{+0.09}_{-0.04}$$ for IGR J12580

$$M_{\rm BH}\left(\sigma^2_{nxs}\right) = 2.3^{+1.1}_{-1.0} \times 10^5 M_\odot$$



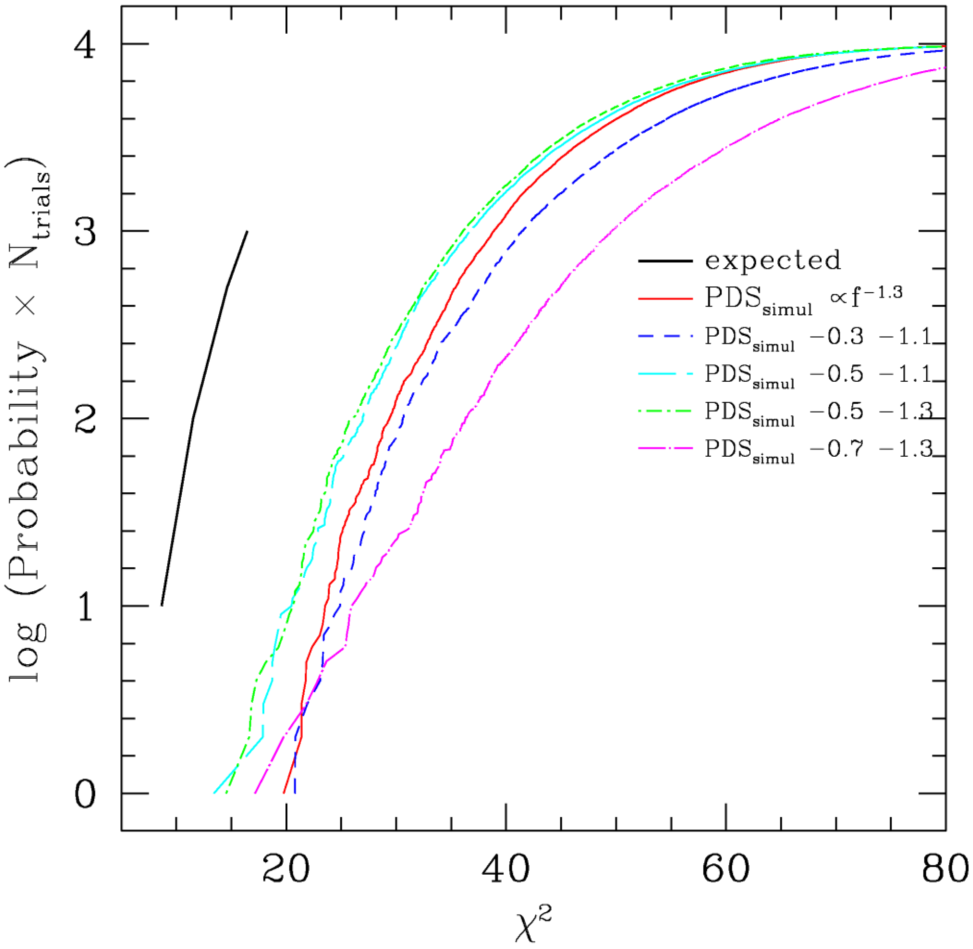
(Papadakis 2004)

Substellar objects:

$$R_* / R_\odot = 0.06 (M_* / M_\odot)^{-1/8} \quad (10 M_{\rm Jup} < M_* < 0.08 M_\odot)$$

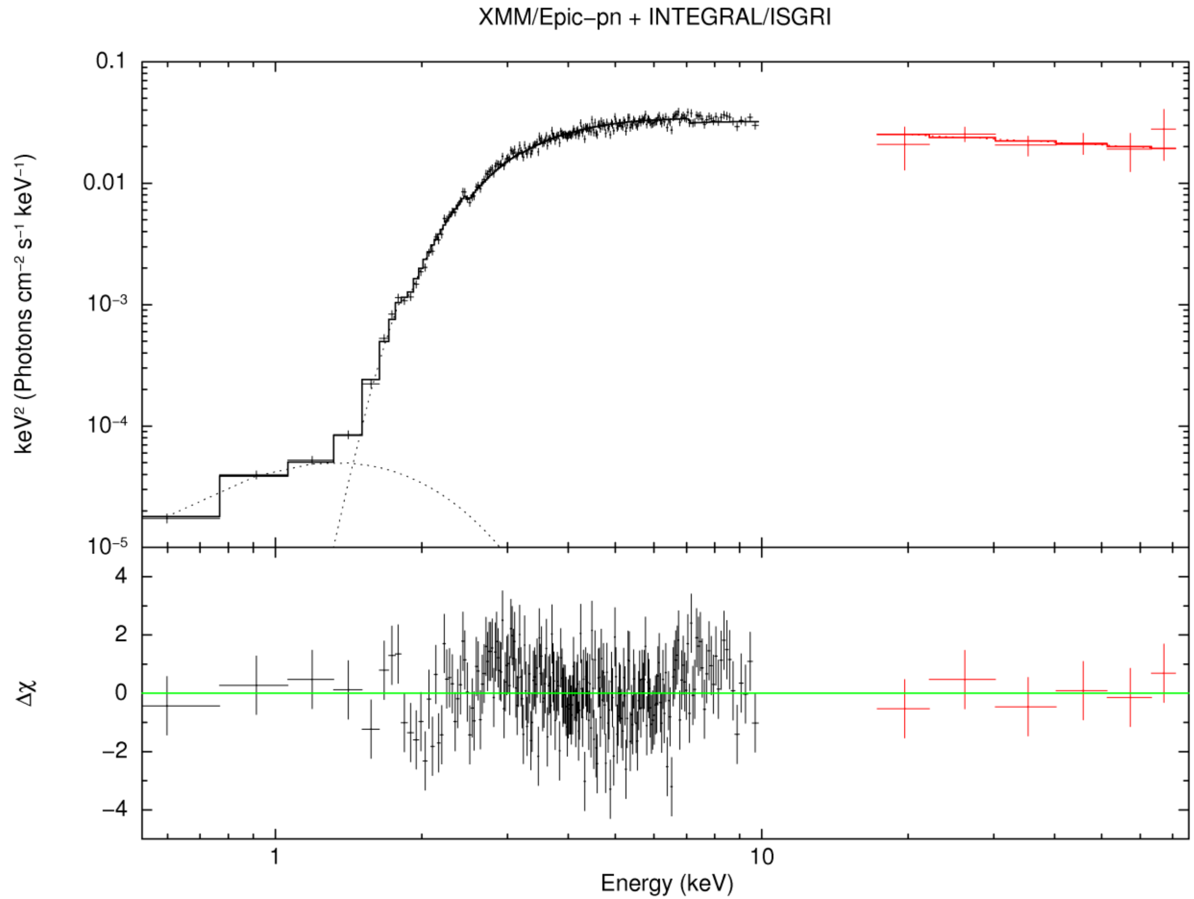
(Chabrier & Baraffe 2000)

IGR J12580+0134



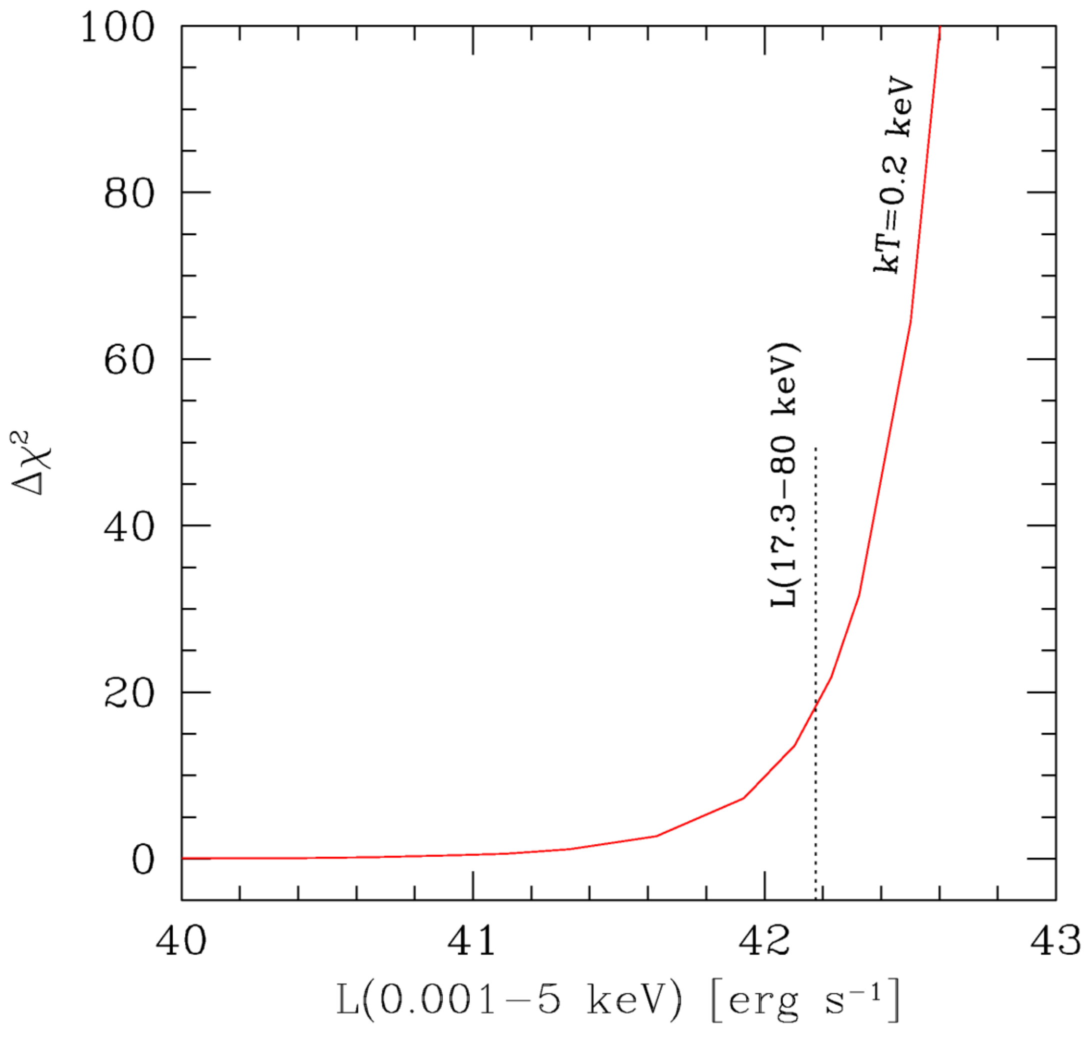
$$\nu F(\nu)^{\text{powerlaw}}_{17.3\text{–}80\,\text{keV}} =$$
$$5.44\times10^{-11}\,\text{erg cm}^{-2}\,\text{s}^{-1}$$

$$\nu F(\nu)^{\text{bbody}}_{0.5\text{–}4\,\text{keV}} =$$
$$1.1\times10^{-13}\,\text{erg cm}^{-2}\,\text{s}^{-1}$$

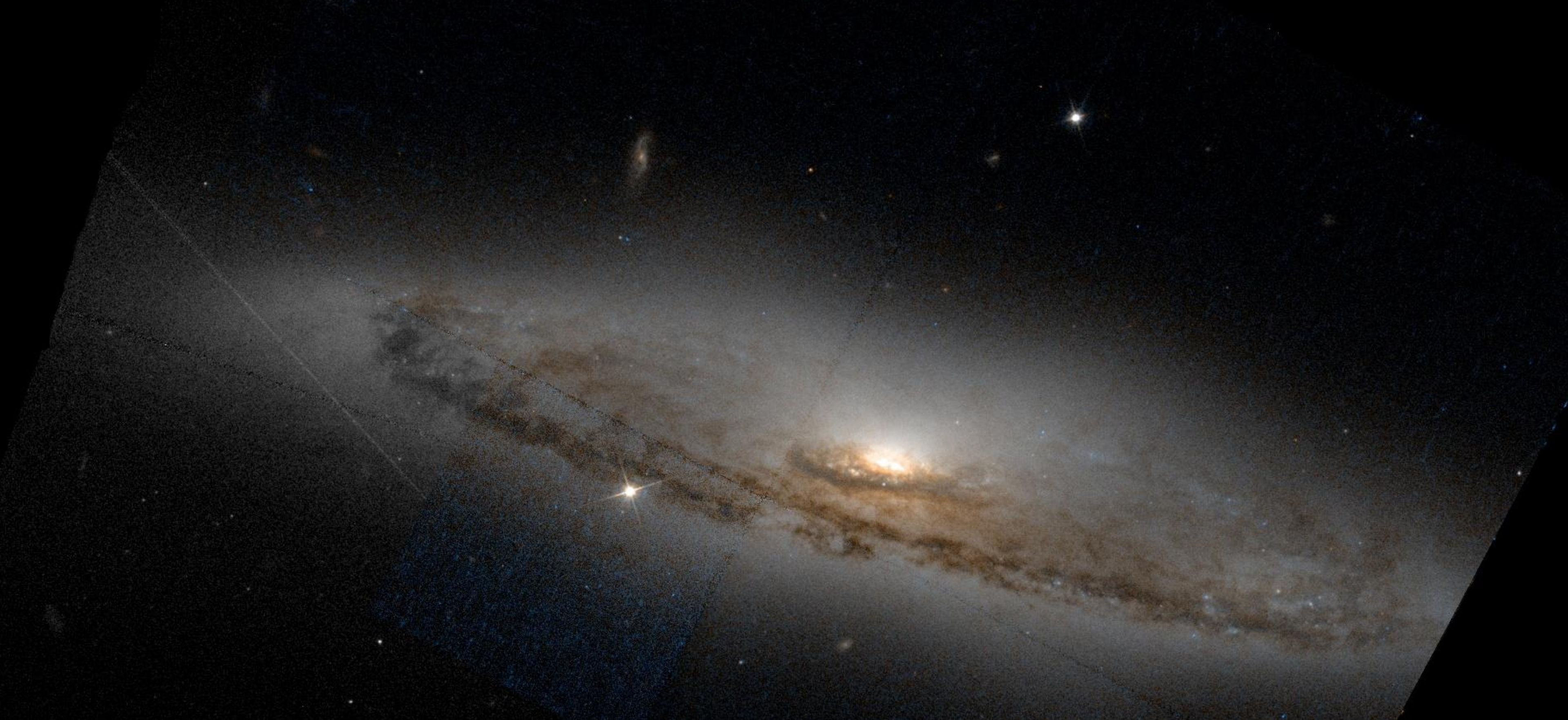


Model:
wabs*(bbody + wabs*powerlaw) /software: Xspec/

$$F(E) \propto E^{-(\Gamma-1)} \qquad \Gamma_{17\text{–}80\,\text{keV}} = 2.22 \pm 0.03$$


100
80
60
40
20
0
$\Delta\chi^2$
kT=0.2 keV
L(17.3−80 keV)
40
41
42
43
L(0.001−5 keV) [erg s^{-1}]

NGC 4845

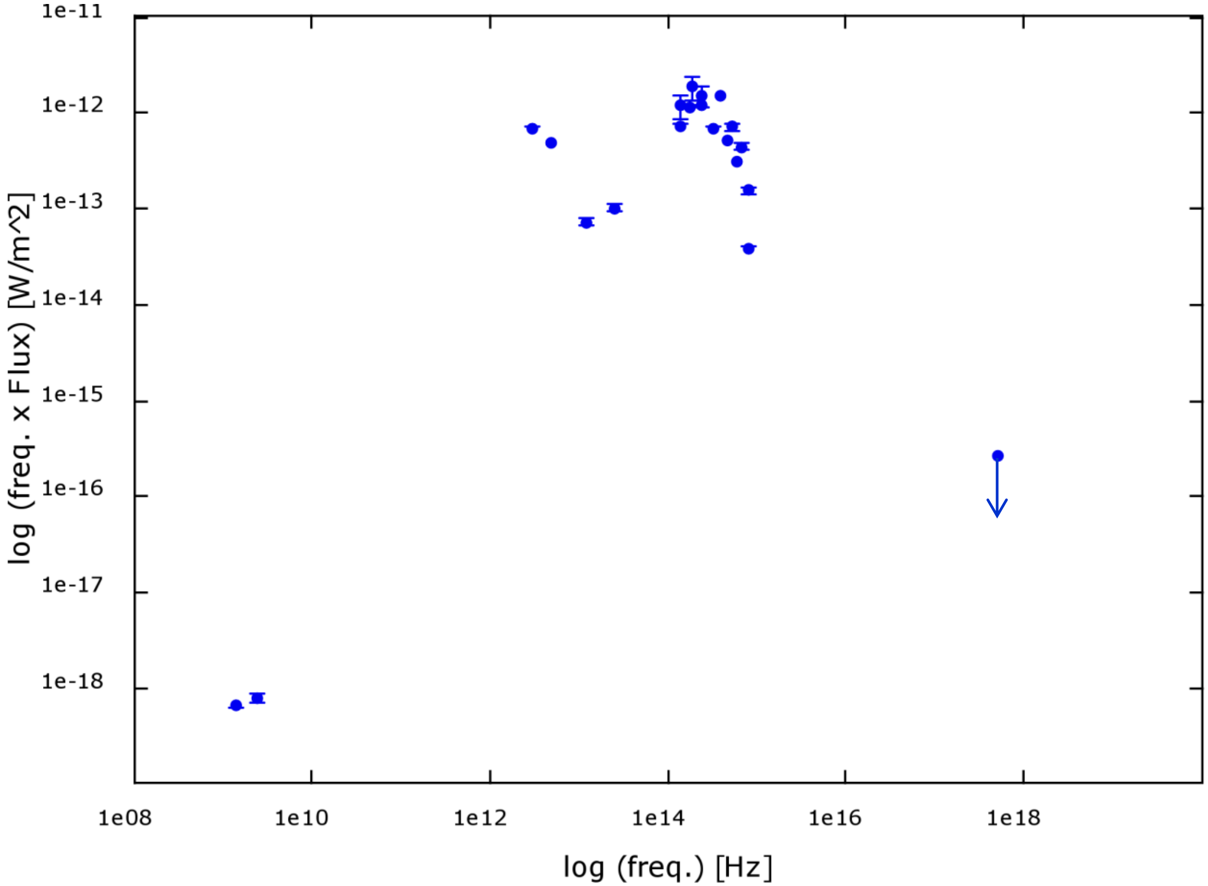


<u>Typ</u>: SA(s)ab sp   <u>Classification</u>: Sy2 (Veron-Cetty & Veron 2006)

<u>Inclination</u>: 76° (Pizzella et al. 2005)

<u>Distance</u>: 14.5 Mpc (Shapley et al. 2001)

Observations of NGC 4845



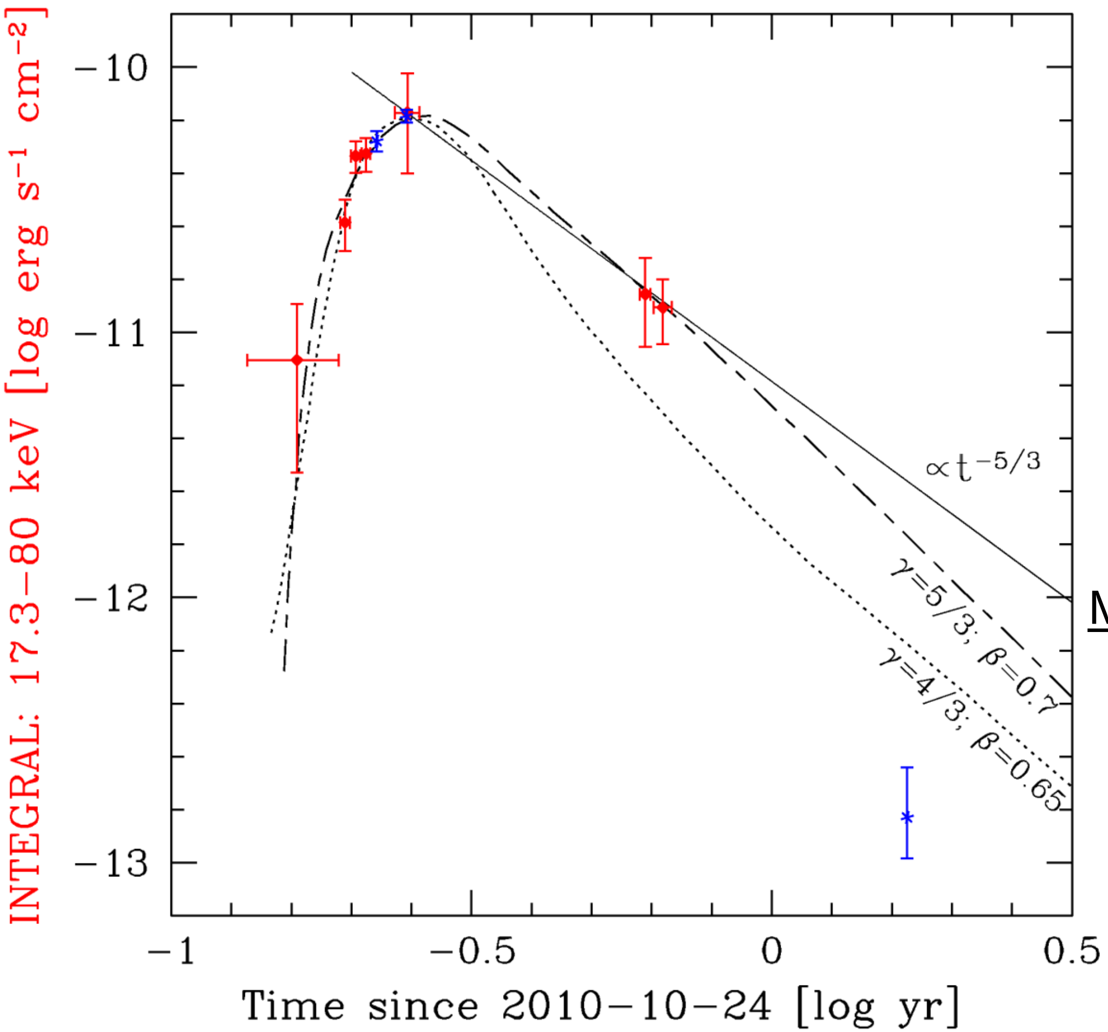
Observations in the range:

- **radio**: VLA, Green Bank Telescope (Condon et al.1998,2002,Filho et al.2000)
- **IR**: 2MASS, IRAS (Soifer et al.1989,Sanders et al. 2003,Jarrett et al. 2003)
- **optics**: SDSS, HST (Schneider et al. 2004, Merchan et al. 2005)
- **X-ray**: EINSTEIN/0.2-4.0 keV (Fabbiano et al. 1992)

Tidal disruption events by BH

Gal/Object	L_{max}	range
NGC 3599 (Esquej et al. 2007)	$L_X = 1x10^{41}$ erg/s	X
NGC 5905 (Bade et al. 1996)	$L_X = 3x10^{42}$ erg/s	X
RXJ J1242-1119 (Komossa & Greiner 1999)	$L_X = 9x10^{43}$ erg/s	X
SDSS J1201+30 (Saxton et al. 2012)	$L_X = 3x10^{44}$ erg/s	X
Swift J2058+05 (Cenko et al. 2011)	$L_X = 4x10^{47}$ erg/s	X,γ
Swift J1644+57 (Burrows et al. 2011)	$L_X > 10^{48}$ erg/s	radio,X,γ
Galex 1419+52 (Gezari et al. 2009)	$L_{Bol} = 1.3x10^{43}$ erg/s	UV,X
PS1-10jh (Gezari et al. 2012)	$L_{Bol} > 2.2x10^{44}$ erg/s	UV,

Comparison with hydro simulations



$$M_{\rm BH} = 2.3\times10^5 - 10^6 M_{Sun}$$

Low massive star $\rightarrow \gamma$ = 5/3

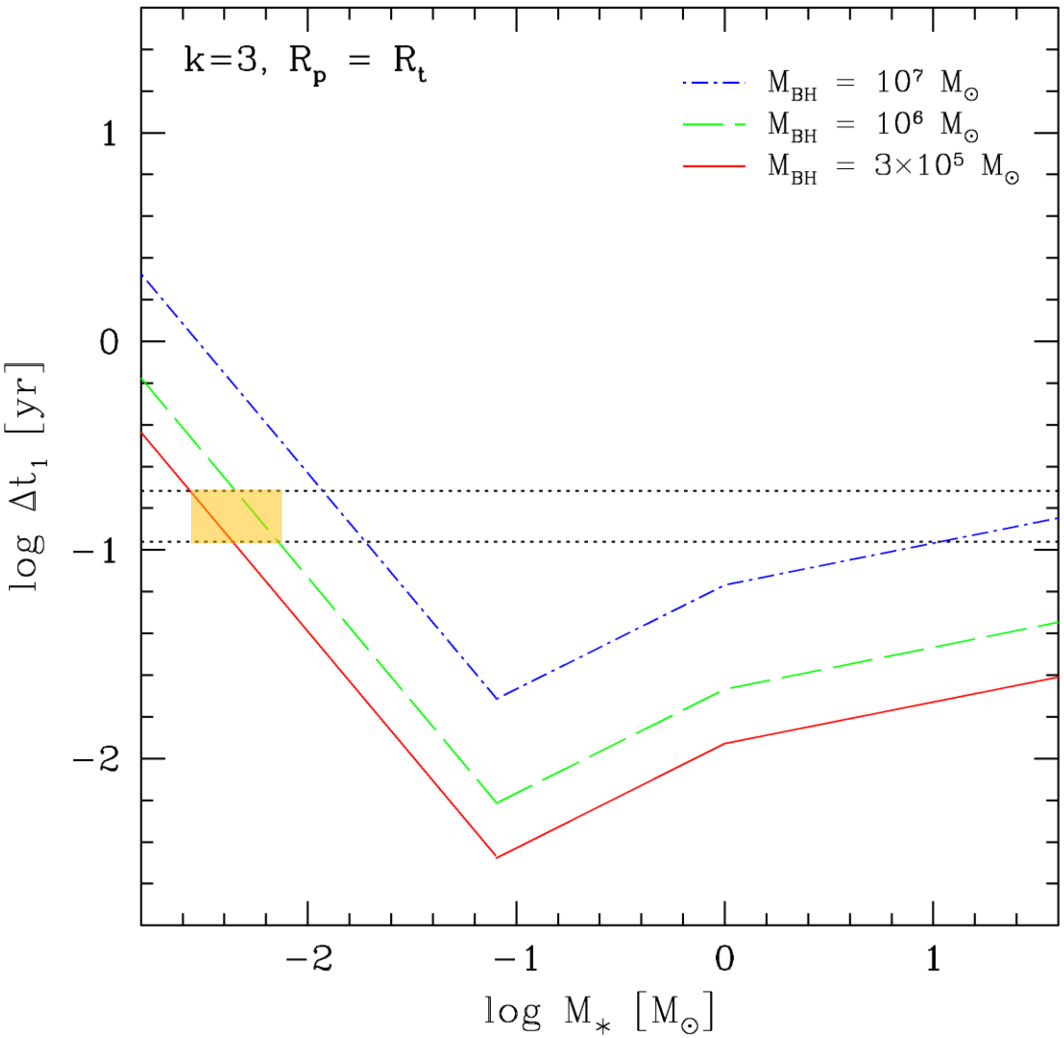
$\Downarrow$

$$M_* \approx 14 - 28 M_{\rm Jup}$$

Main sequence star $\rightarrow \gamma$ = 4/3

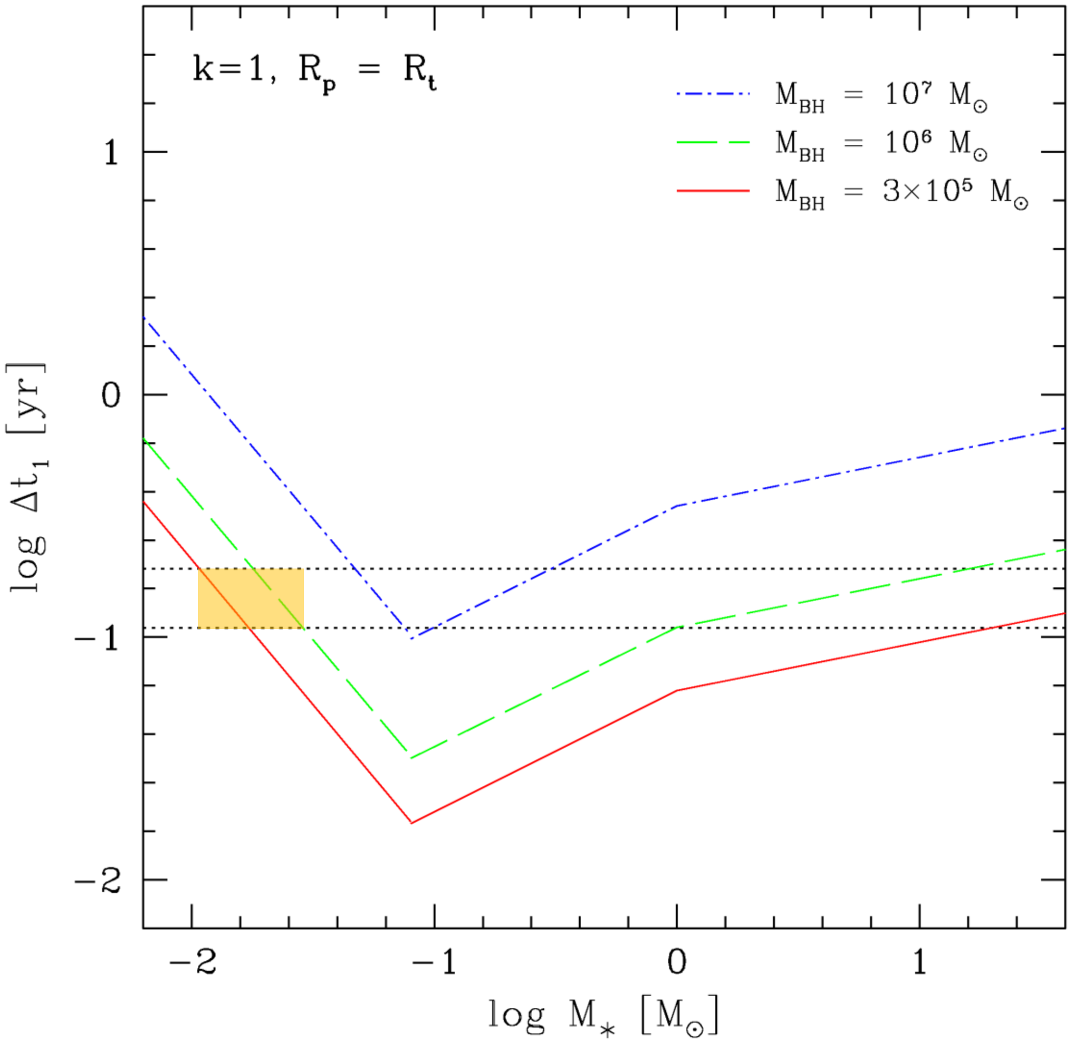
$\Downarrow$

$$M_* \approx 1 - 15 M_\odot$$



From theory
(Ulmer 1999, Li et al. 2002):

$$M_* \approx 3 - 20 M_{\rm Jup}$$



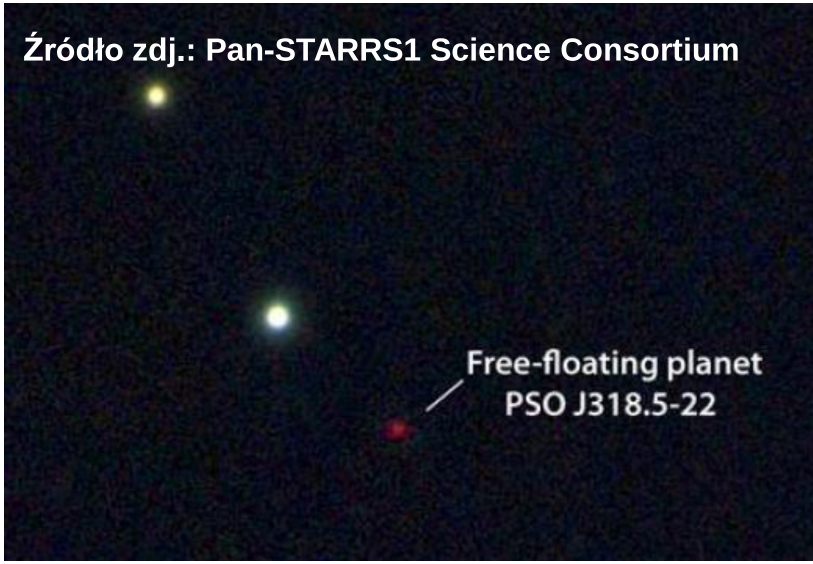
k=1, R_p = R_t
M_{BH} = 10^7 $M_\odot$
M_{BH} = 10^6 $M_\odot$
M_{BH} = 3×10^5 $M_\odot$
1
0
−1
−2
log Δt_1 [yr]
−2
−1
0
1
log M_* [$M_\odot$]

IGR J12580+0134 -> rozerwanie

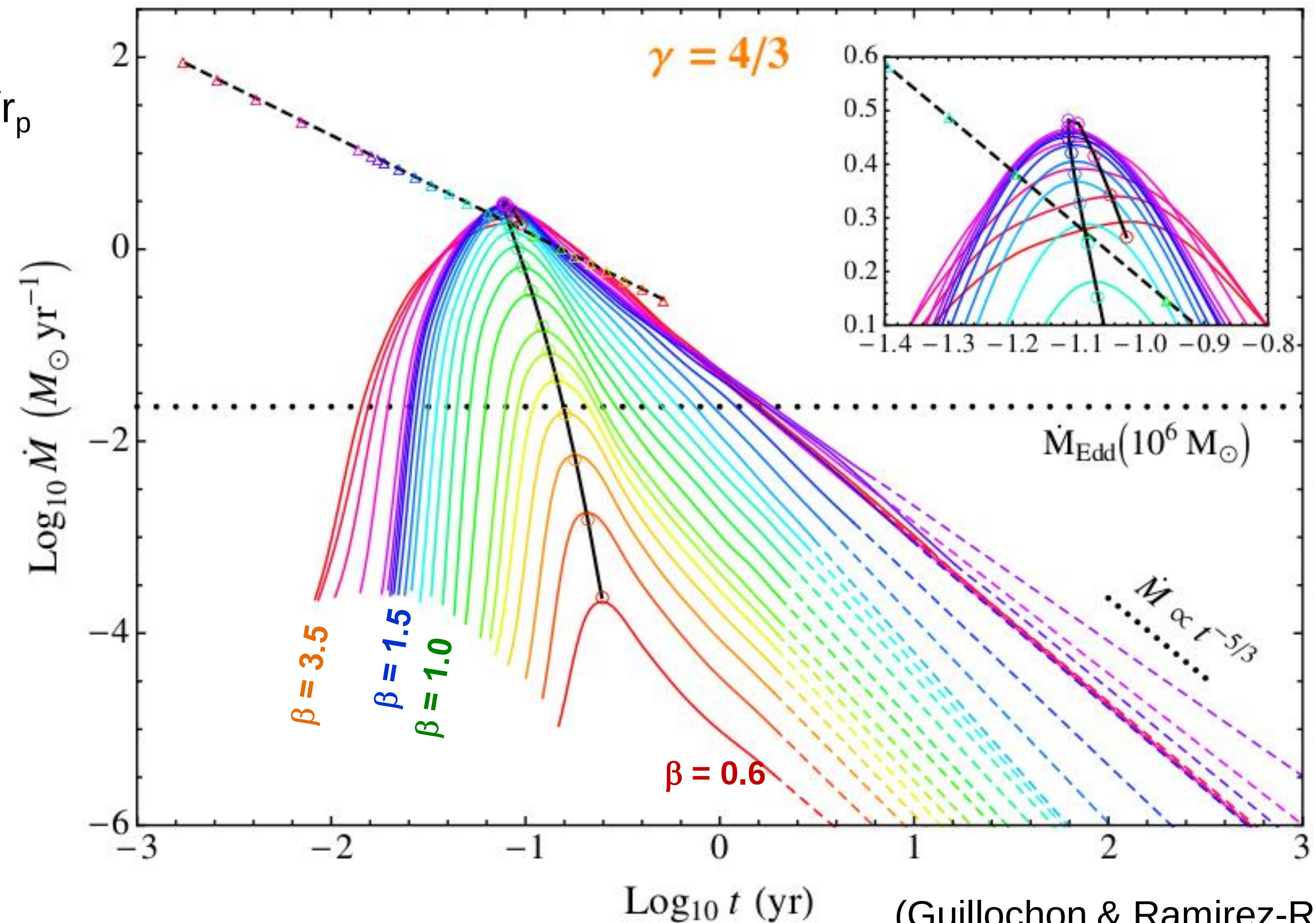
Skąd samotna planeta w galaktyce?

Podczas tworzenia się układu planetarnego z kilkoma gazowymi olbrzymami niektóre z nich byłyby wyrzucane z układu (np. Veras et al. 2009).

- Dowody obserwacyjne na istnienie samotnych planet:
  - 10 planet o $M \sim M_J$, bez gwiazd macierzystych (Sumi et al. 2011);
  - CFBDSIR2149-0403 – planeta o $M = 4\text{-}7 M_J$ odl. ok.100 l.św. od nas, uformowana 50-120 mln lat temu w grupie gwiazd AB Doradus (Delorme et al. 2012);
  - PSO J318.5-22 – planeta o $M = 5\text{-}8 M_J$ odl. ok.80 l.św. od nas w grupie gwiazd β Pic (Liu et al. 2013).



$\beta = r_t/r_p$



$M_{BH}=10^6 M_\odot$
$M_*=1 M_\odot$

(Guillochon & Ramirez-Ruiz 2013)