GW150914-like Black Holes as Galactic High Energy Sources

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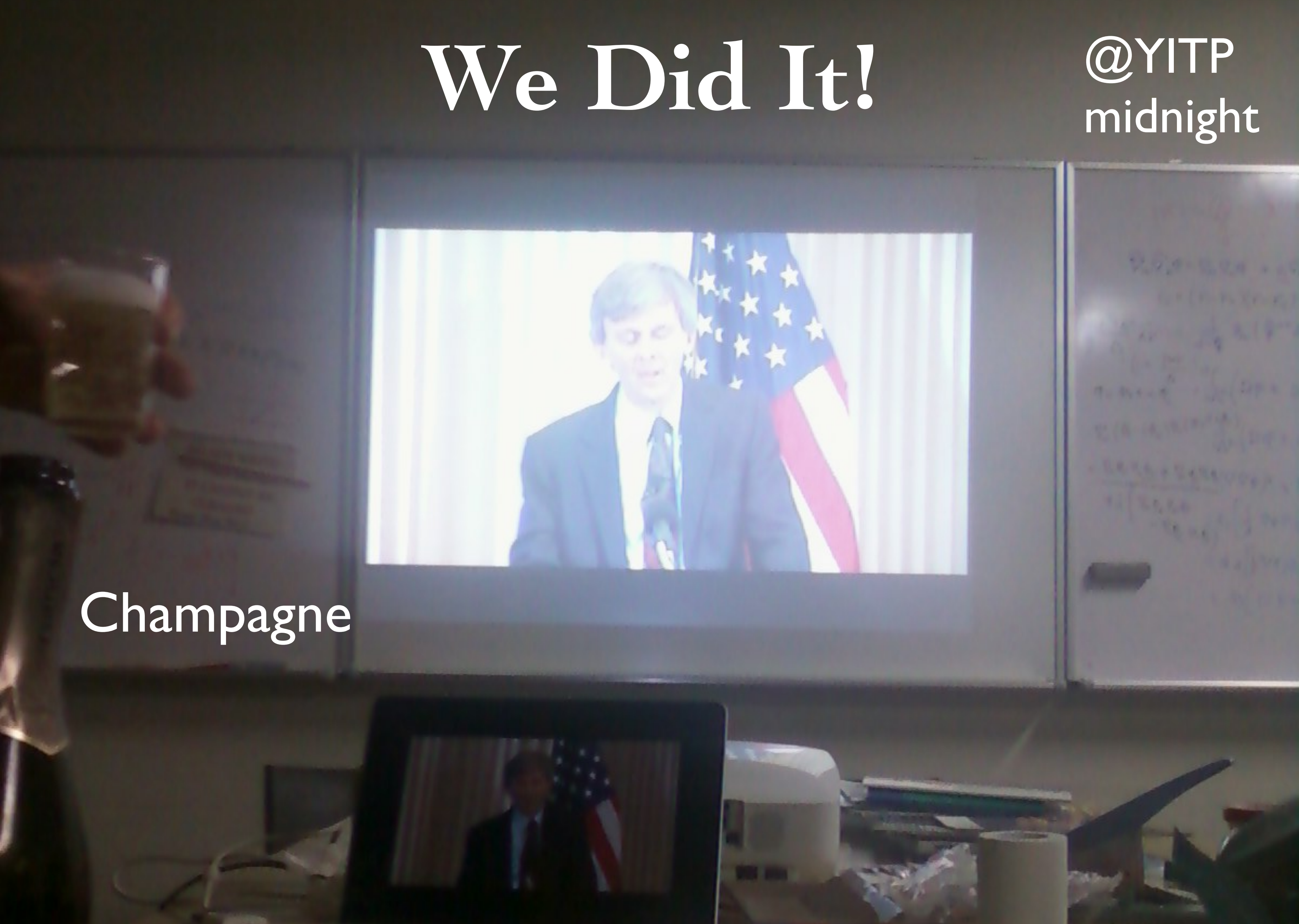
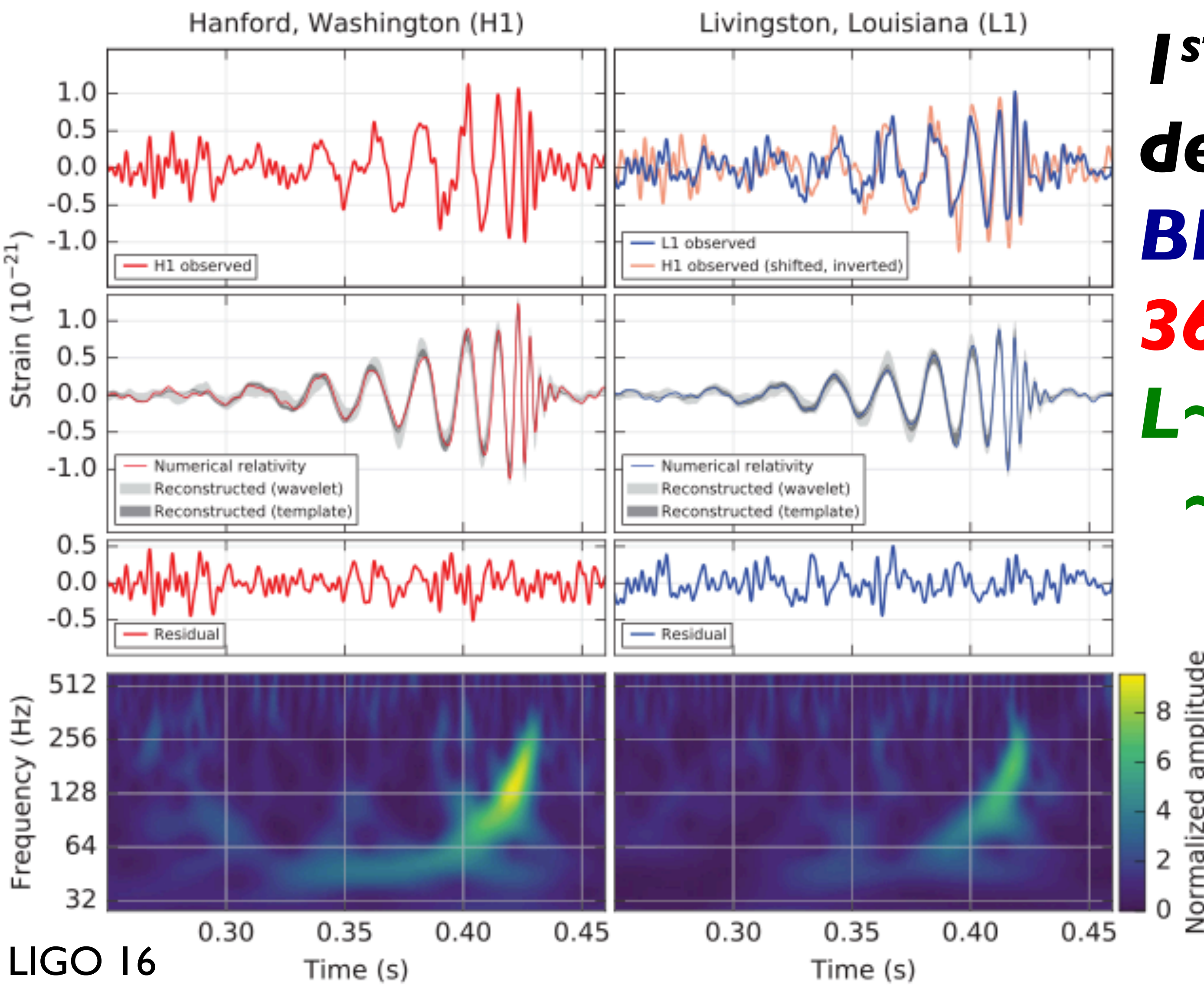
KI, Matsumoto, Teraki,
Kashiyama & Murase
arXiv:1612.03913

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

We Did It!



GW150914



1^{st} direct detection

BH-BH

$36M_\odot+29M_\odot$

$L\sim200M_\odot c^2/s$
$\sim10^{-3}\ c^5/G$

30-350Hz bandpass
First at L1
6.9+0.5-0.4ms
later at H1

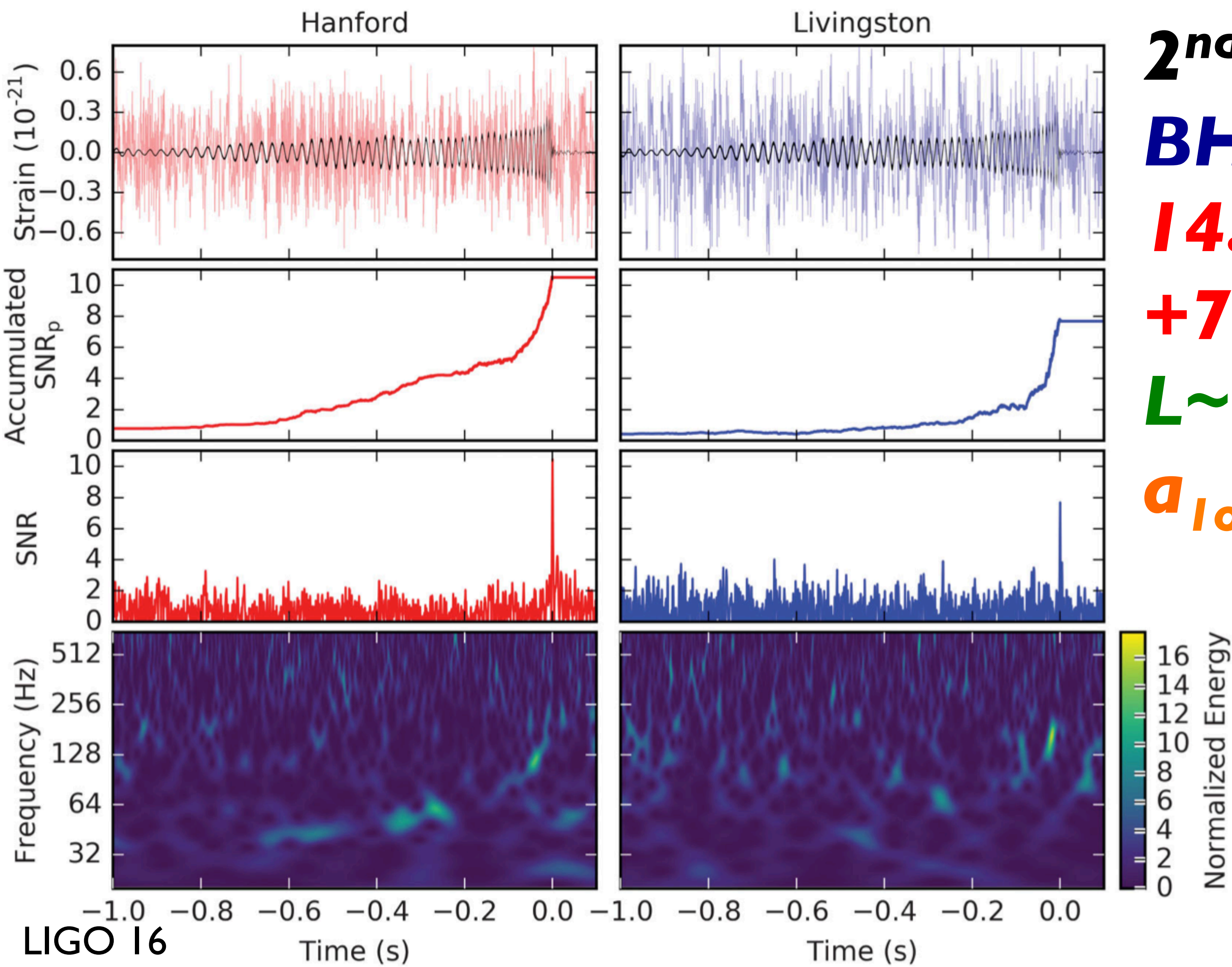
LIGO 16

The Most Luminous in the Universe

- Total radiated mass
  $M \sim 3.0{+0.5}{-0.5}\ M_\odot$
- Energy $E=Mc^2 \sim 6\times10^{54}$ erg
- $L_{peak} \sim 3.6{+0.5}{-0.4} \times 10^{56}$ erg/s
  $\sim 200{+30}{-20}\ M_\odot c^2/s$
  $\sim 10^{-3}\ c^5/G$
- $> L_{Gamma\text{-}Ray\ Bursts} \sim 10^{50\text{-}54}$ erg/s

Solar mass is radiated within ~0.01sec!

GW151226



LIGO 16

2nd event

BH-BH

$14.2 M_\odot + 7.5 M_\odot$

$L \sim 170 M_\odot c^2/s$

$a_{1or2} > 0.2$

LVT151012

$R_{GW} \sim 9$-240 events $Gpc^{-3}\ yr^{-1}$

Galactic BHs

$70\ \mathrm{Gpc^{-3}\ yr^{-1}} \div 0.01\ \mathrm{galaxy\ Mpc^{-3}} \times 10^{10}\ \mathrm{yr}$

~ 70000 Merged BHs/galaxy

Galactic BHs

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~ 70000 Merged BHs/galaxy

Old Problem

- Eddington 20's
- Hoyle & Lyttleton 39
- Bondi & Hoyle 44
- Bondi 52
- Zel'dovich 64
- Salperter 64
- Lynden-Bell 69
- Shvartsman 71
- Michel 72
- Shapiro 73
- Shakura & Sunyaev 73
- Meszaros 75
- Ipser & Price 77, 82, 83
- Grindlay+ 78
- Carr 79
- McDowell 85
- Campana & Pardi 93
- Heckler & Kolb 96
- Fujita+ 98
- Popov & Prokhorov 98
- Armitage & Natarajan 99
- Agol & Kamionkowski 02
- Chisholm+ 03
- Barkov+ 12
- Motch & Pakull 12
- Fender+ 13

GWs put a lower limit on #(spinning BHs)

Spin Energy

$$E_{\rm spin} = \left(1 - \sqrt{\frac{1+\sqrt{1-a_*^2}}{2}}\right) Mc^2$$

$$\cong 7\% \times Mc^2 \sim 1 \times 10^{54}\,{\rm erg}\left(\frac{M}{10 M_\odot}\right)$$

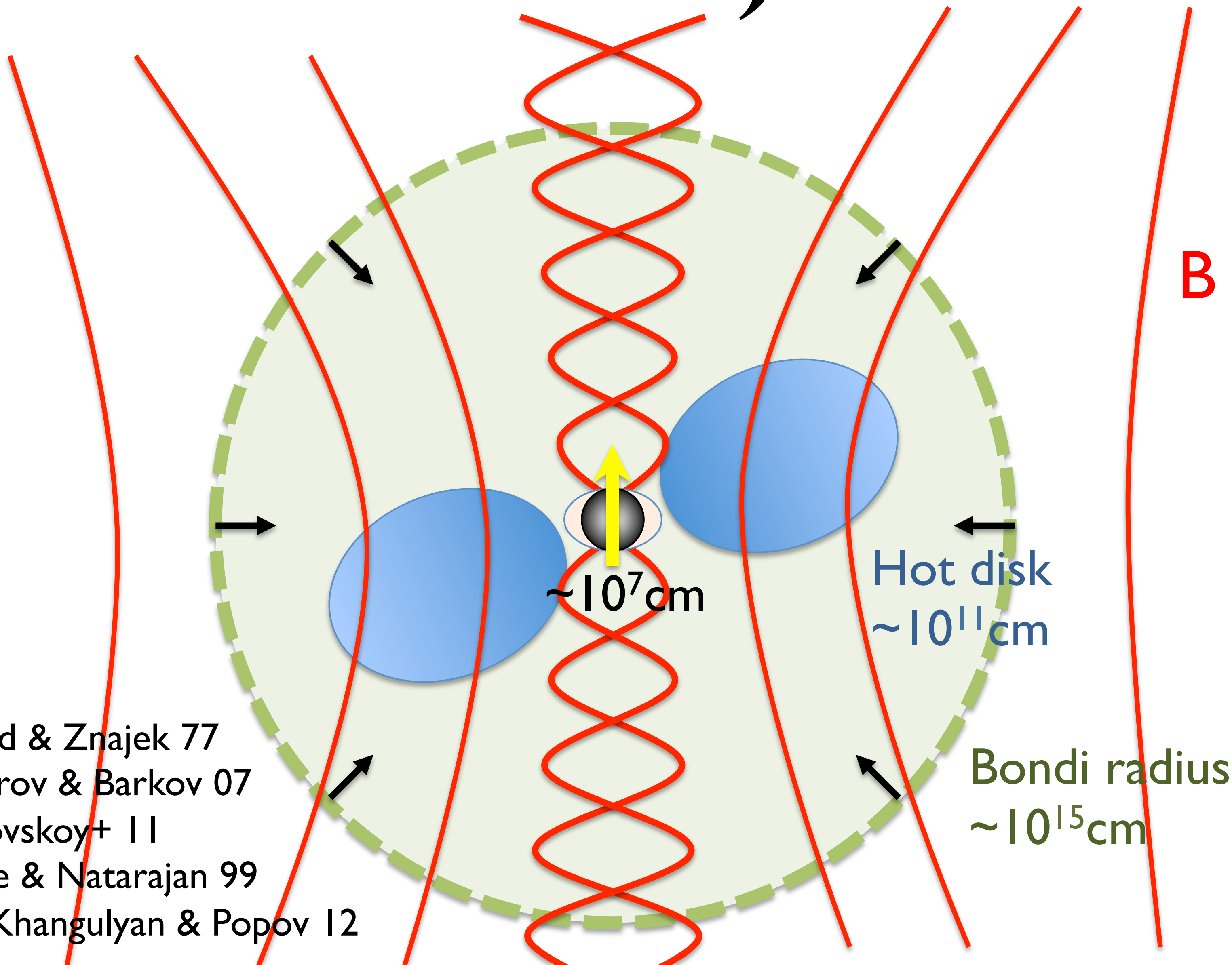
$$E_{\rm tot} \sim N_{BH} E_{\rm spin} \sim 7 \times 10^4 \ {\rm BHs} \times 1 \times 10^{54}\,{\rm erg}$$

$$\sim 9 \times 10^{58}\,{\rm erg}$$

$$\sim \frac{10^{10}\,{\rm yr}}{100\,{\rm yr}} \ \text{supernovae}$$

Comparable to supernovae ever happened!

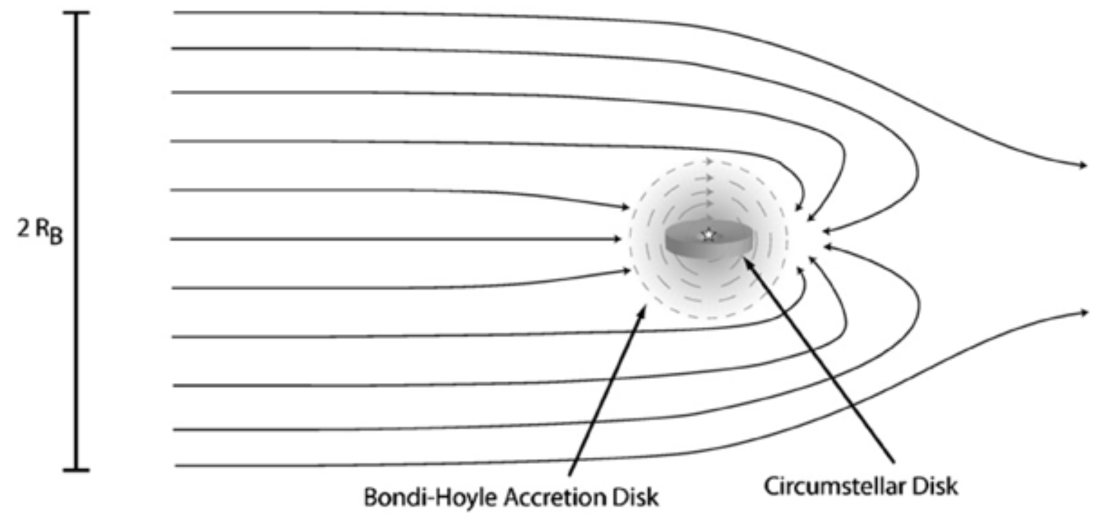
Blandford-Znajek Effect



Blandford & Znajek 77
Komissarov & Barkov 07
Tchekhovskoy+ 11
Armitage & Natarajan 99
Barkov, Khangulyan & Popov 12

Bondi Accretion

$$r_B \sim \frac{GM}{V^2} \sim 1\times 10^{15}\,\mathrm{cm} \times \left(\frac{M}{10M_\odot}\right)\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-2}$$



$$V = \sqrt{c_s^2 + v^2 + v_{\mathrm{GW}}^2}$$

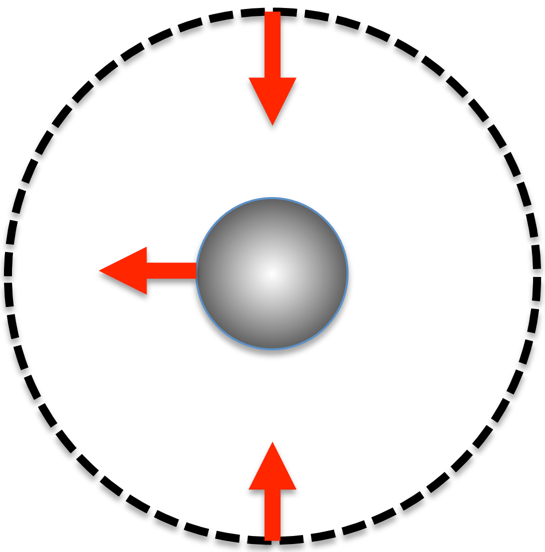
$$\dot{M} \sim 4\pi r_B^2 V \rho$$

$$\sim 5\times 10^{35}\,\mathrm{erg\ s^{-1}}\left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10M_\odot}\right)^2\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$

$$\sim 4\times 10^{-4}\,\frac{L_{Edd}}{c^2}\left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10M_\odot}\right)\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$

Bondi & Hoyle 44

Disk



$$\frac{\delta\rho}{\rho} \sim \left(\frac{L}{6\times10^{18}\,\mathrm{cm}}\right)^{1/3}$$

$$\ell \sim \frac{1}{4}\frac{\delta\rho}{\rho} v r_B$$

$$\ell_K \sim \sqrt{GMr_{\mathrm{disk}}}$$

$$\Rightarrow \frac{r_{\mathrm{disk}}}{r_S} \sim 2\times10^5 \left(\frac{M}{10M_\odot}\right)^{2/3} \left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-10/3}$$

Fujita+ 98
Agol & Kamionkowski 02

$\Rightarrow$ Disk formation

Disk axis fluctuates with $\Delta t \sim \dfrac{r_B}{V} \sim 40\ \mathrm{yr}$

ADAF (Hot, Thick Disk)

Advection Dominated Accretion Flow

$$L_{\rm disk} \sim \frac{\alpha_{\rm QED}}{\alpha^2} \frac{m_e}{m_p} \frac{\dot{M}c^2}{L_{\rm Edd}} \dot{M}c^2 \sim 10^{-11} L_{\rm Edd} \left(\frac{\dot{M}c^2 / L_{Edd}}{10^{-4}} \right)^2 \sim 10^{29} \,{\rm erg\ s^{-1}}$$

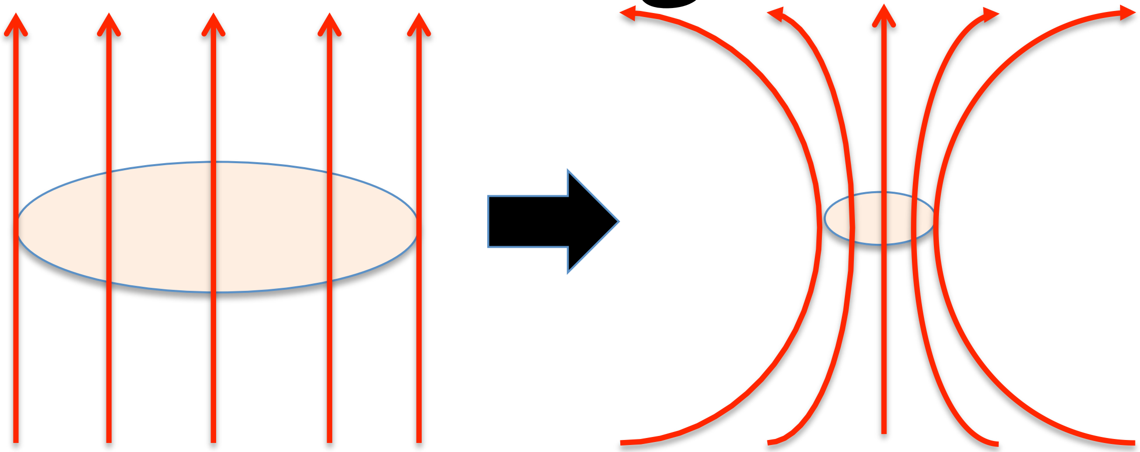
$$\frac{10^{29}\,{\rm erg\ s^{-1}}}{4\pi ({\rm kpc})^2} \sim 10^{-15}\,{\rm erg\ s^{-1}\ cm^{-2}}$$

Nearby BH disks might be observable

Also Hirotani-san's talk

Ichimaru 77, Narayan & Yi 94
Fujita, Inoue, Nakamura, Manmoto, Nakamura 98
Matsumoto+ in preparation

Magnetic Field



$$B \propto R^{-2}$$

$$3\mu\text{G} \rightarrow 3\times 10^{10}\,\text{G}$$

But B is saturated so that $p_B < p_{disk}$

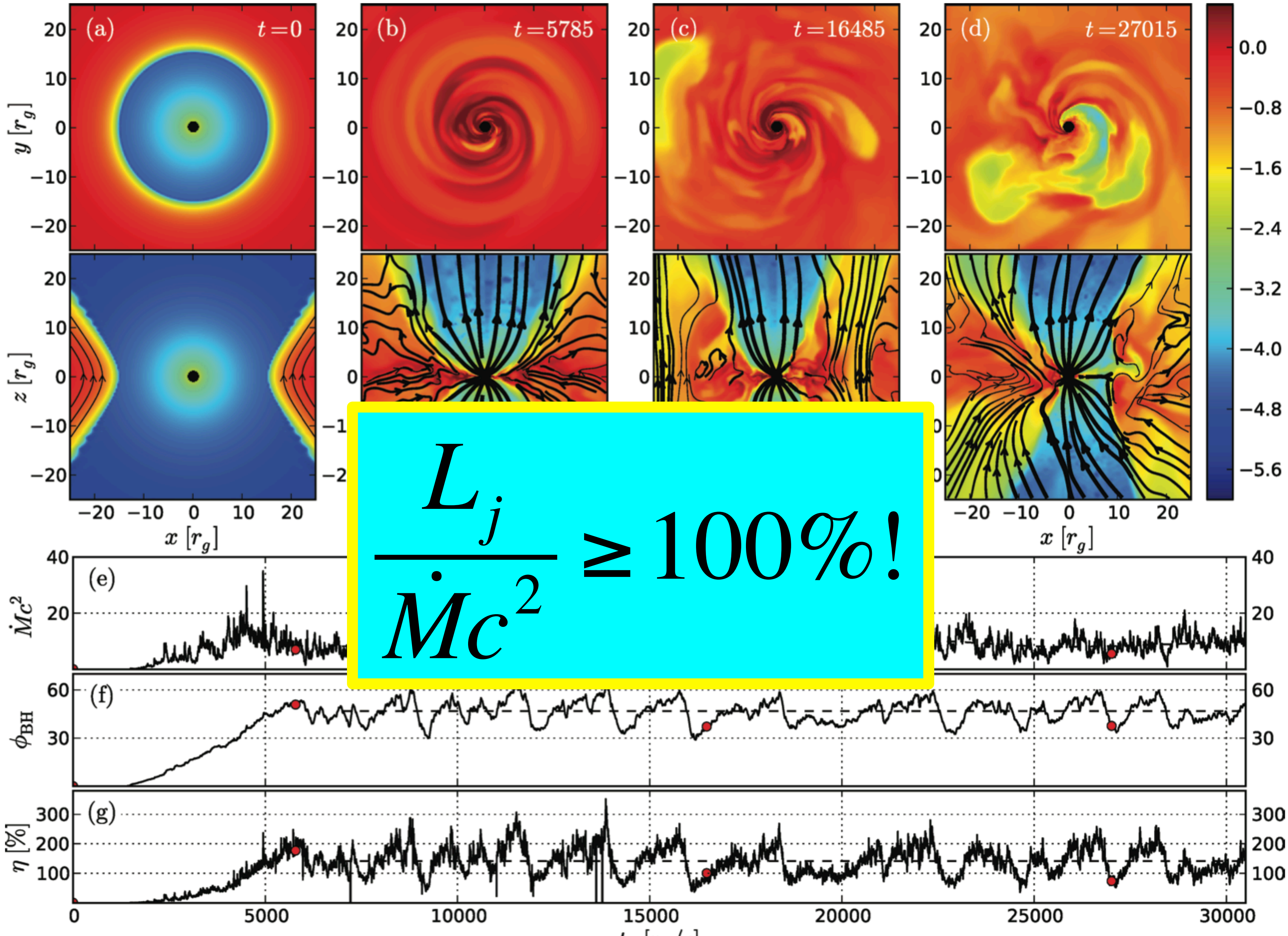
$$p_B = \frac{B^2}{8\pi}$$

$$p_a = \frac{GM\Sigma}{r^2} \sim \frac{GM\dot{M}}{2\pi r^3 v_r}$$

Magnetically Arrested Disk (MAD)

Bisnovatyi-Kogan & Ruzmaikin 76
Narayan+ 03

$$B_H \sim \left.\sqrt{\frac{4GM\dot{M}}{r^3 v_r}}\right|_{r=r_H} \sim 4\times 10^7\,\text{G}\left(\frac{n}{10\ \text{cm}^{-3}}\right)^{1/2}\left(\frac{V}{10\ \text{km s}^{-1}}\right)^{-3/2}$$



$$\frac{L_j}{\dot{M}c^2} \geq 100\%!$$

Tchekhovskoy+ 11, McKinney+ 12

Bardeen-Petterson Effect

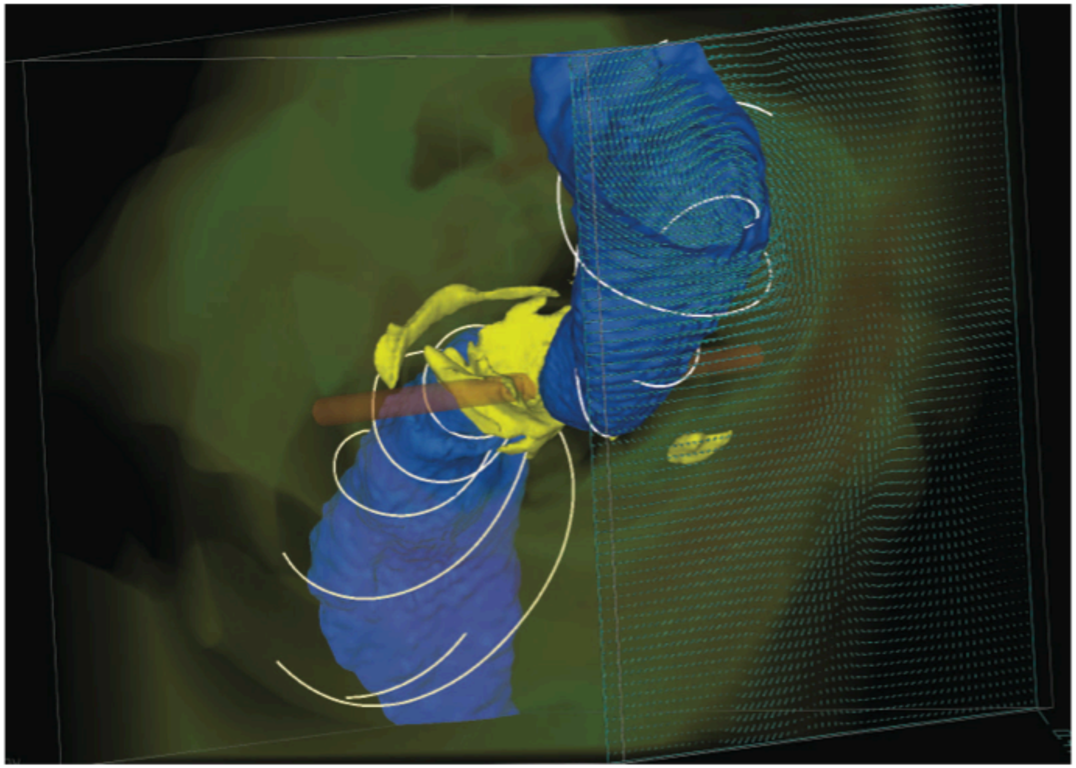


Fig. 1. 3D snapshot for an evolved model with $j = 0.99$, initial relative tilt $\theta_{tilt,0} \approx 90°$, and disk thickness $H/R \sim 0.3$. The rotating BH sits at the center of the box of size $r = -40r_g$ to $r = +40r_g$ in each dimension. The snapshot shows the disk near the BH (yellow isosurface, which is mostly flat in the figure plane), the highly magnetized jet region (blue isosurface, with magnetic energy per unit rest-mass energy equal to about 70), the rotational axis of the disk both initially and at large distances (orange cylinder), outer disk (green-yellow volume rendering, more aligned with disk rotational axis at large distances), magnetic field vectors (like iron filings on that surface) for a cross section of the jet (cyan vectors), and jet magnetic field lines (white lines) that trace from the BH out to large distances. The disk and jet near the BH are aligned with the BH spin axis and point mostly in and out of the figure plane, whereas at larger distances the jet points roughly halfway between the BH spin axis and the disk's rotational axis (pointing along the orange cylinder).

BH spin axis
// Disk axis
"Bardeen-Petterson effect"
// B axis
"Magneto-spin alignment"

Bardeen & Petterson 75
McKinney+ 13

Luminosity Function

$$\frac{dN}{d\dot{M}} = N_{\rm BH} \int dm_1 \frac{dp(m_1)}{dm_1} \int dm_2 \frac{dp(m_2|m_1)}{dm_2} \int dv \frac{df(v)}{dv} \int dn \frac{d\xi(n)}{dn} \times h(m_1, m_2, v) \delta\left[\dot{M}(n, m_1, m_2, v) - \dot{M}\right],$$

Agol & Kamionkowski 12
KI+ 16

BH mass: m_1: Salpeter, m_2: Flat, $5M_\odot < m_2 < m_1 < 50M_\odot$

Velocity: Maxwell distribution
+ GW recoil + ISM sound velocity

Density: 5 phases of ISM

Phase	n_1 [cm^{-3}]	n_2 [cm^{-3}]	β	ξ_0	c_s [km s^{-1}]	H_d
Molecular clouds	10^2	10^5	2.8	10^{-3}	10	75 pc
Cold $\rm H_I$	10	10^2	3.8	0.04	10	150 pc
Warm $\rm H_I$	0.3	–	–	0.35	10	0.5 kpc
Warm $\rm H_{II}$	0.15	–	–	0.2	10	1 kpc
Hot $\rm H_{II}$	0.002	–	–	0.4	150	3 kpc

Luminosity Function

$$\frac{dN}{d\dot{M}} = N_{\rm BH}\int dm_1 \frac{dp(m_1)}{dm_1}\int dm_2 \frac{dp(m_2|m_1)}{dm_2}\int dv \frac{df(v)}{dv}\int dn \frac{d\xi(n)}{dn} \times h(m_1,m_2,v)\delta\left[\dot{M}(n,m_1,m_2,v)-\dot{M}\right],$$

Mass function

Agol & Kamionkowski 12

$$\frac{dp(m_1)}{dm_1} = Cm_1^{-2.35}, \quad \frac{dp(m_2|m_1)}{dm_2} = \frac{1}{m_1 - M_{\rm min}}, \quad 5M_\odot \le m_2 \le m_1 \le 50M_\odot$$

Velocity distribution

$$\frac{df(v)}{dv} = \sqrt{\frac{2}{\pi}}\frac{v^2}{\sigma_v^3}\exp\left(-\frac{v^2}{2\sigma_v^2}\right)$$

σ_v=40km/s: isolated binary

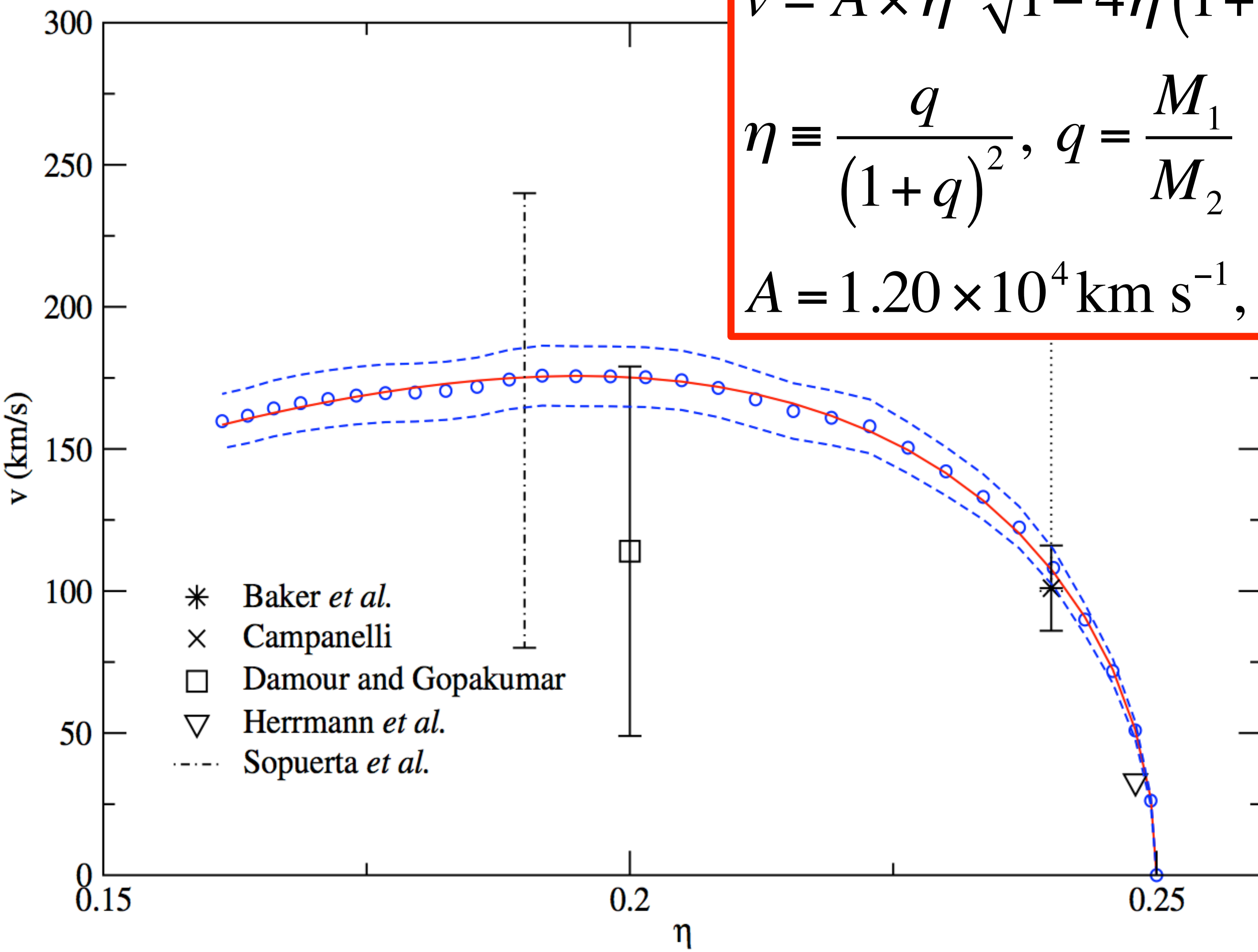
σ_v=200km/s: stellar cluster

GW Recoil Velocity

$$v = A \times \eta^2 \sqrt{1-4\eta}\,(1+B\eta) \cong 62\ \mathrm{km\ s^{-1}}$$

$$\eta \equiv \frac{q}{(1+q)^2},\quad q = \frac{M_1}{M_2}$$

$$A = 1.20 \times 10^4\,\mathrm{km\ s^{-1}},\ B = -0.93$$



We assume $a_* \sim 0$

Gonzalez+ 07

Density Distribution

$$\frac{d\xi(n)}{dn} = D\xi_0 n^{-\beta}$$

Volume filling fraction

Scale height

Phase	n_1 [cm^{-3}]	n_2 [cm^{-3}]	β	ξ_0	c_s [km s^{-1}]	H_d
Molecular clouds	10^2	10^5	2.8	10^{-3}	10	75 pc
Cold H_I	10	10^2	3.8	0.04	10	150 pc
Warm H_I	0.3	–	–	0.35	10	0.5 kpc
Warm H_{II}	0.15	–	–	0.2	10	1 kpc
Hot H_{II}	0.002	–	–	0.4	150	3 kpc

$$h(m_1, m_2, v) = \min\left(1, \frac{H_d}{H(v_z)}\right), \quad v_z^2 = \frac{1}{3}\left(v^2 + v_g^2\right)$$

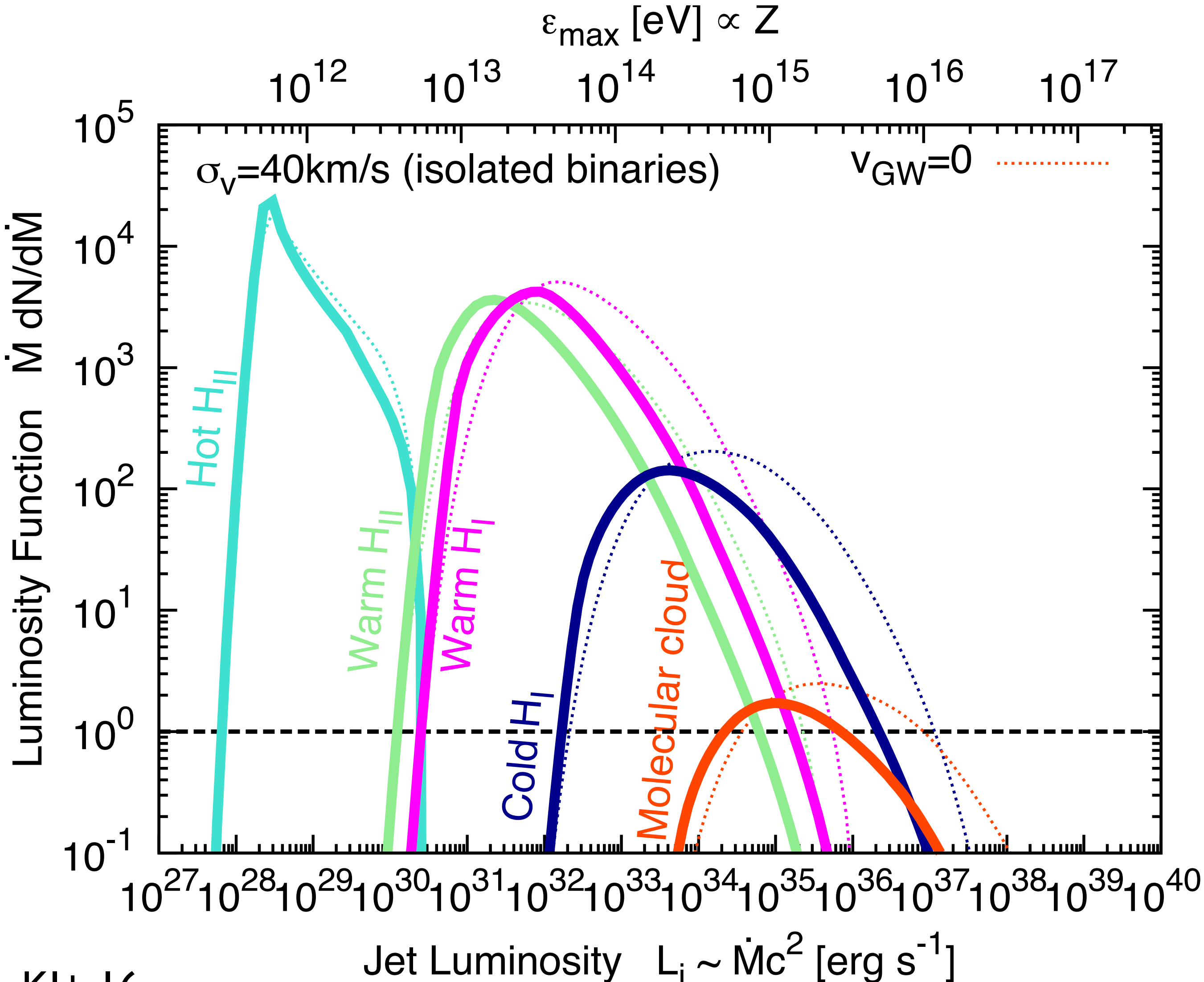
$$\frac{1}{2}v_z^2 = \Phi_z\left[H(v_z)\right], \quad \frac{\Phi_z(z)}{2\pi G} = K\left(\sqrt{z^2 + Z^2} - Z\right) + Fz^2$$

Z~180pc

K=48M$_\odot$/pc^2

F=0.01M$_\odot$/pc^3

Luminosity Function

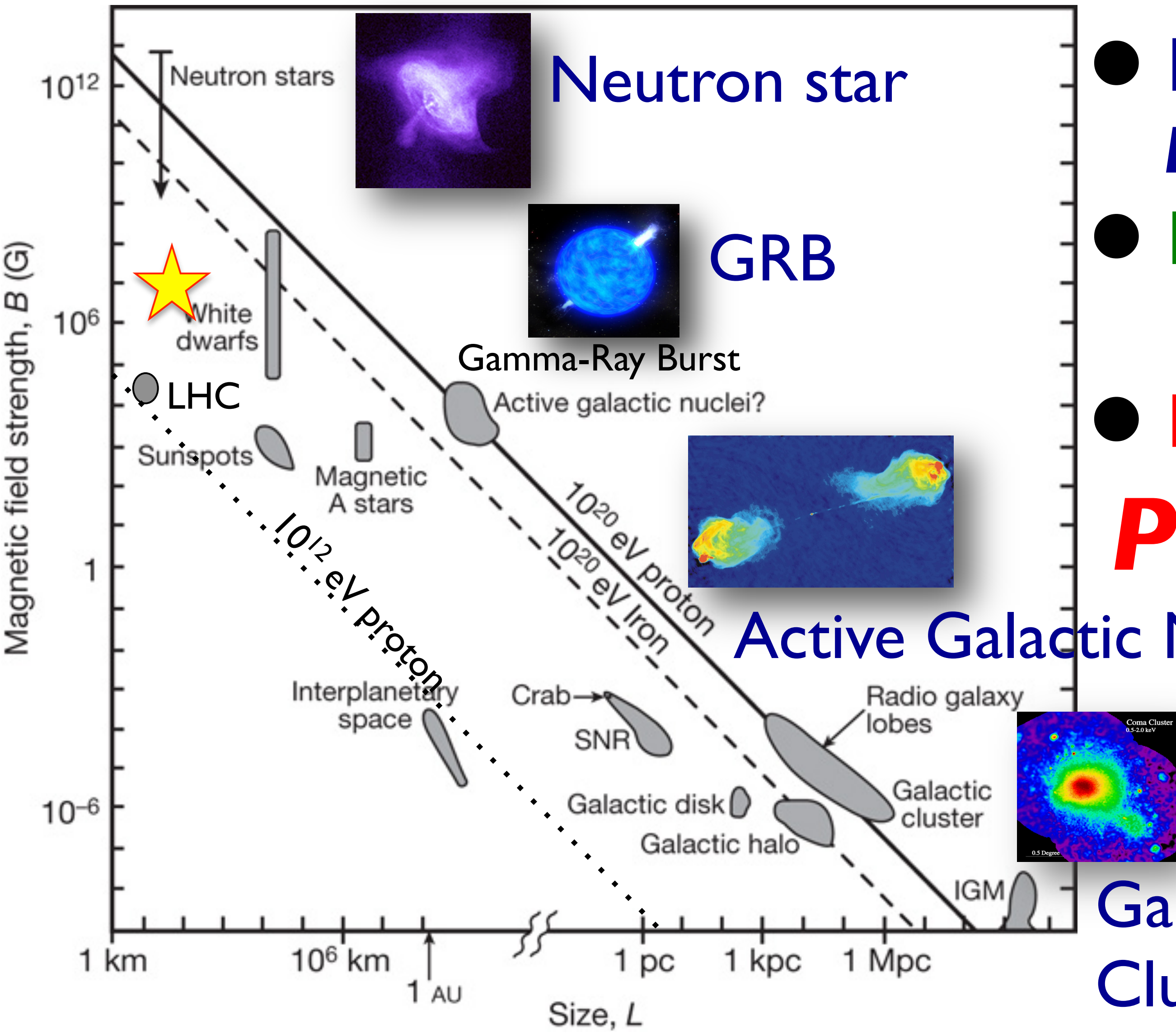


KI+ 16

The most luminous BH jet is $\sim 10^{36}$ erg/s in cold H_I

v_{GW} reduces L_j by ~10

Particle Acceleration



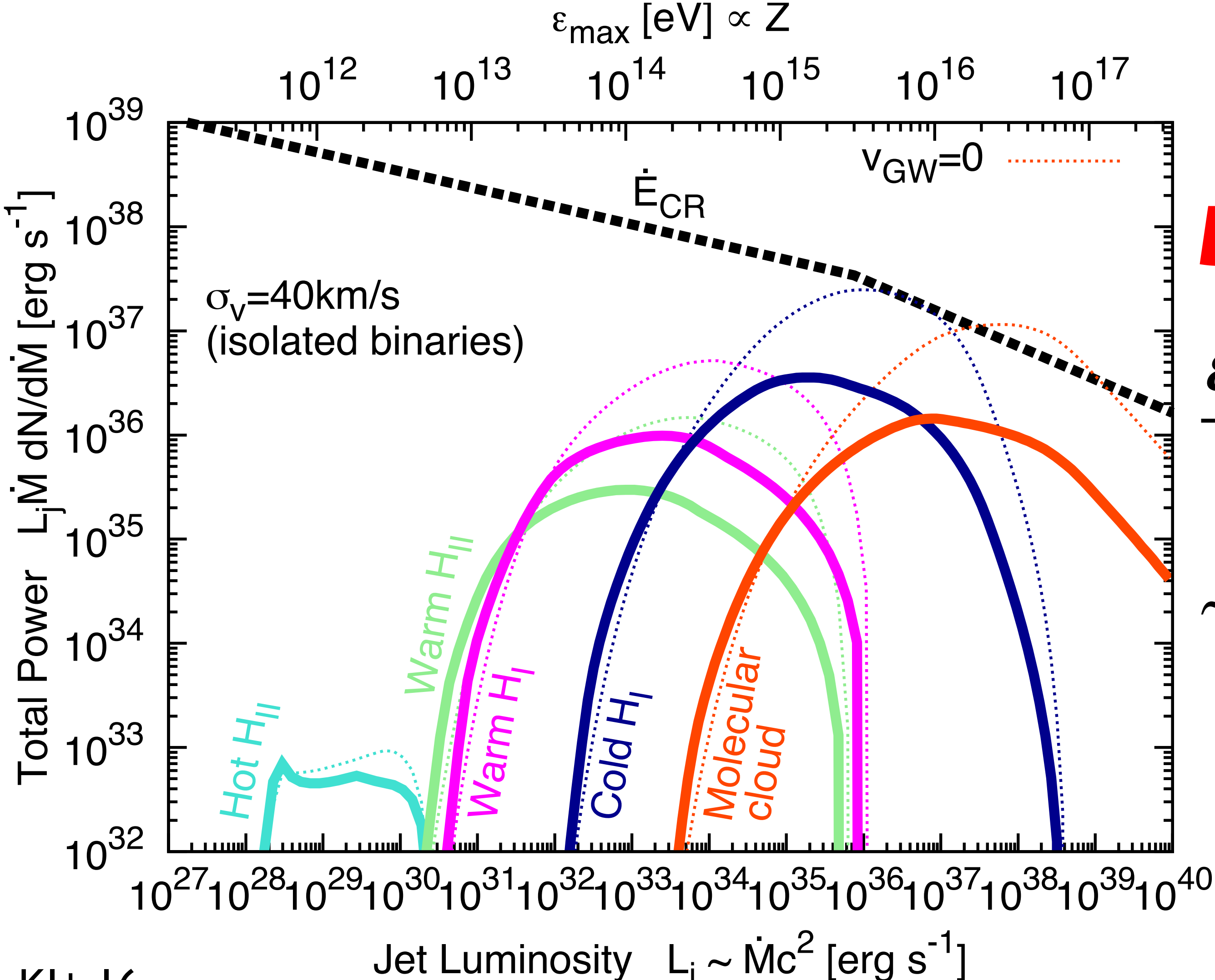
- Hillas condition
  E<ZqBR
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\boldsymbol{\propto (BR)^2}$ Blandford 00, Waxman 04
- E_{max}>PeV

PeVatron!!!

Barkov+ 12
KI+ 16

Dark Matter?

Total Power



KI+ 16

BHs ⇔ Cosmic rays beyond PeV?

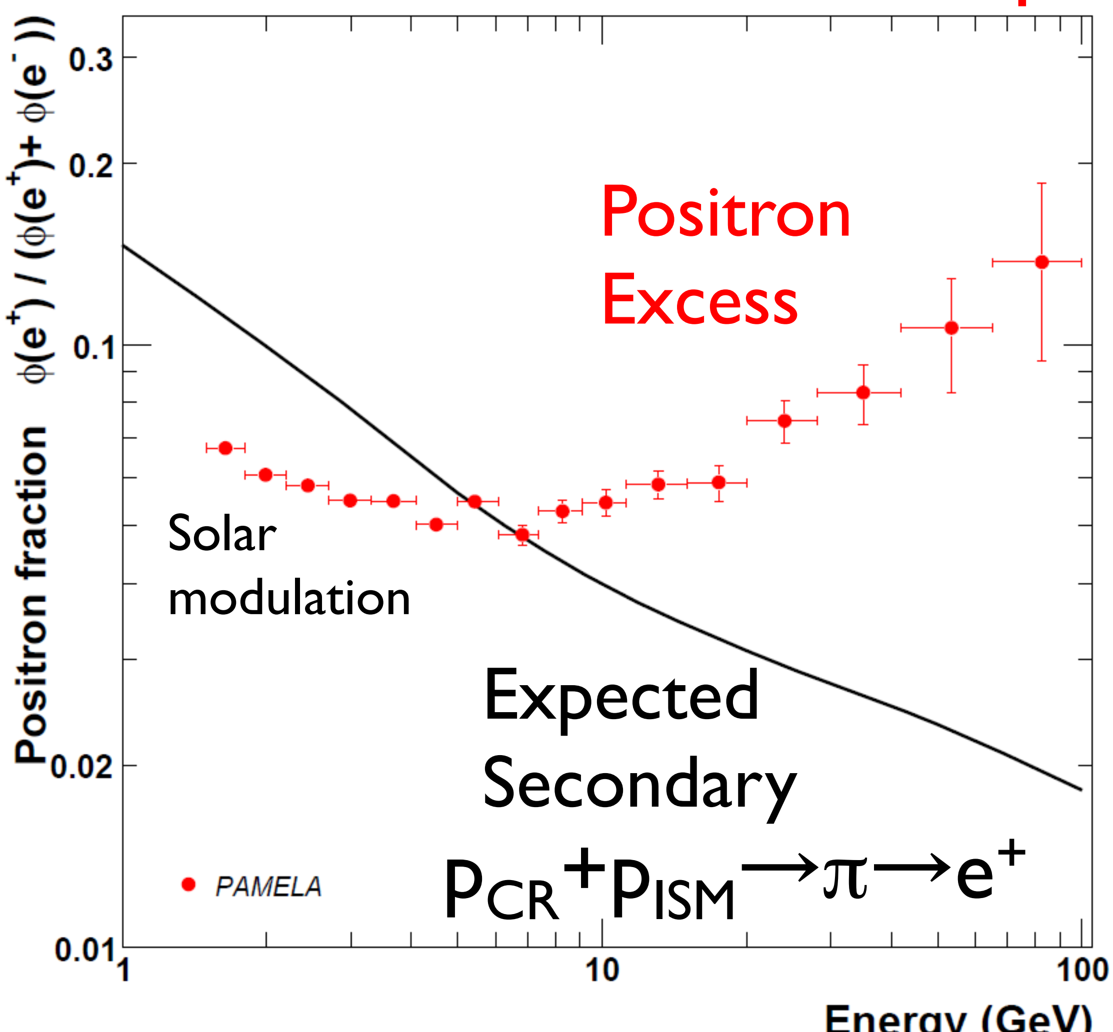
$$\frac{\varepsilon_{CR} E_{SN}}{100\mathrm{yr}}$$

$$\sim 3\times 10^{40} \text{ erg s}^{-1}$$

If leptonic ⇔ $e^{\pm}$ excess?

PAMELA

Positron excess above the predicted secondary



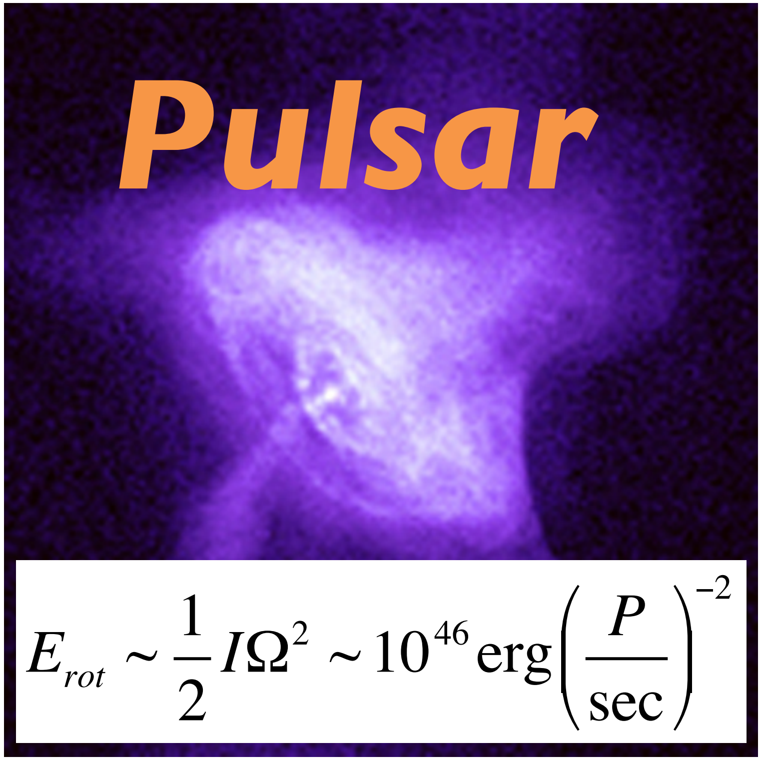
Adriani+ 08, 10

⇒ New sources
- Dark Matter?
- Astrophysical?

⇒ Many papers $>10^3$

Jul 06 - Feb 08
151672 e-, 9430 e+

Astrophysical Models



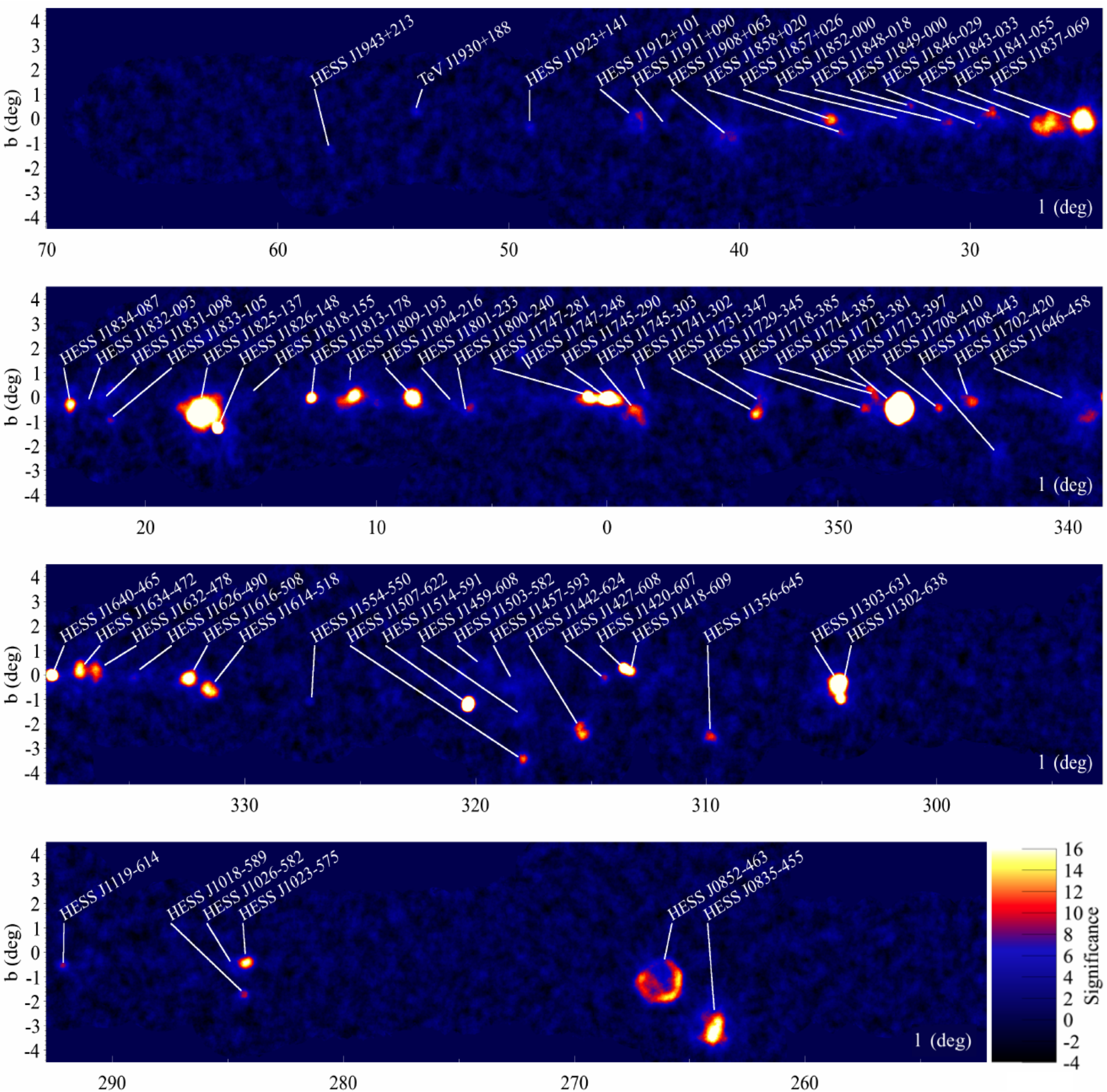
$$E_{rot} \sim \frac{1}{2} I\Omega^2 \sim 10^{46}\,\mathrm{erg}\left(\frac{P}{\mathrm{sec}}\right)^{-2}$$

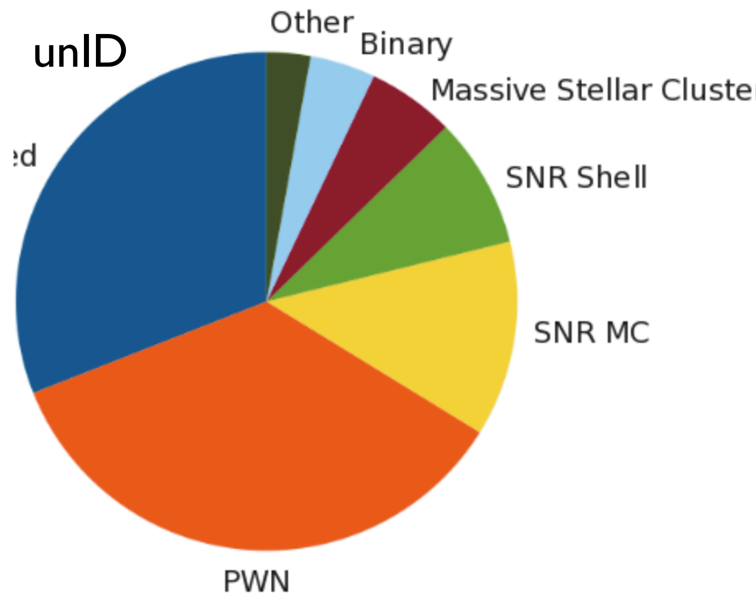
Energy required for $e^{\pm}$ excess

$$R_{e^+} \sim \frac{\rho_{e^+}}{\rho_p} \frac{t_{\mathrm{esc}}}{t_{\mathrm{cool}}} R_p \sim \frac{10^{46}\,\mathrm{erg}}{100\,\mathrm{yr}}$$

TeV Gamma-Ray Sky

HESS 1307.4690





unIDs dominate TeV γ-ray sky

Spatially extended

$$R \sim \theta d \sim 3\mathrm{pc}\left(\frac{\theta}{0.2^\circ}\right)\left(\frac{d}{\mathrm{kpc}}\right)$$

TeV unID

Disk ⇒ Galactic origin d~1-10kpc

$$F \sim 10^{-11} - 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$$

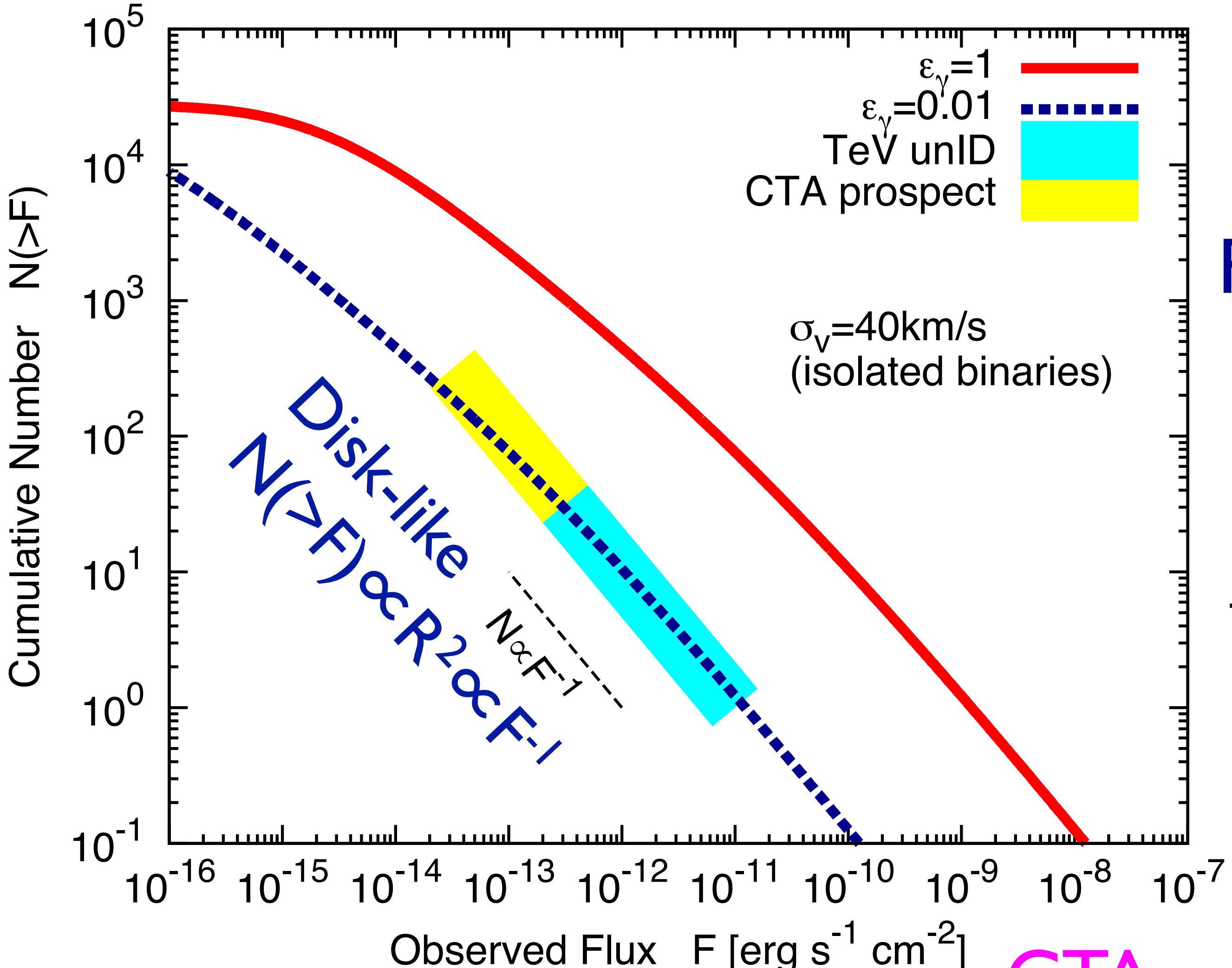
$$L = 4\pi d^2 F \sim 10^{34-35}\,\mathrm{erg\,s^{-1}} \left(\frac{d}{10\mathrm{kpc}}\right)^2$$

$$N \sim 10 - 100$$

Extended

$$R \sim \theta d \sim 30\mathrm{pc} \left(\frac{\theta}{0.2^\circ}\right)\left(\frac{d}{10\mathrm{kpc}}\right)$$

Log N – Log F



KI+ 16

BHs ⇔ TeV unIDs?

Flux dis. is similar

BH nebula size:

$$\frac{L_j}{4\pi r_h^2 \theta^2 c} \sim \rho V^2$$

$$\Rightarrow \quad r_h \sim 3 \text{ pc}$$

CTA will see ~300 BHs

BH Jet Nebula

Poynting jet
⇒ Dissipation
~ Pulsar wind nebula

Jet termination radius

$$\frac{L}{4\pi R_h^2 \theta^2 c} \sim \rho c_s^2$$

$$R_h \sim 10^{19}\,\mathrm{cm} \sim 3\,\mathrm{pc}$$

Model Uncertainties

	Number $N_{\rm BH}$	Velocity σ_v [km s^{-1}]	Spin a_*^i	Disk s	Duty cycle $\mathscr{D}$	Total power $P_{\rm tot}$ [erg s^{-1}]
Isolated binary (fiducial)	7×10^4	40	0	0	1	$\sim 10^{37}$
High spin	10^8	–	0.2	–	–	$\sim 10^{37} \times 10^3$
Stellar cluster	–	200	–	–	–	$\sim 10^{37} \times 10^{-2}$
Wind	–	–	–	1	–	$\sim 10^{37} \times 10^{-2}$
Feedback	–	–	–	1	10^{-1}	$\sim 10^{37} \times 10^{-3}$

KI+ 16

$$\dot{M}_{BH} \sim \dot{M} \left(\frac{20 r_S}{r_{\rm disk}} \right)^s \text{ for } r_{\rm disk} > 20 r_S$$

Blandford & Begelman 99
Yuan+ 16

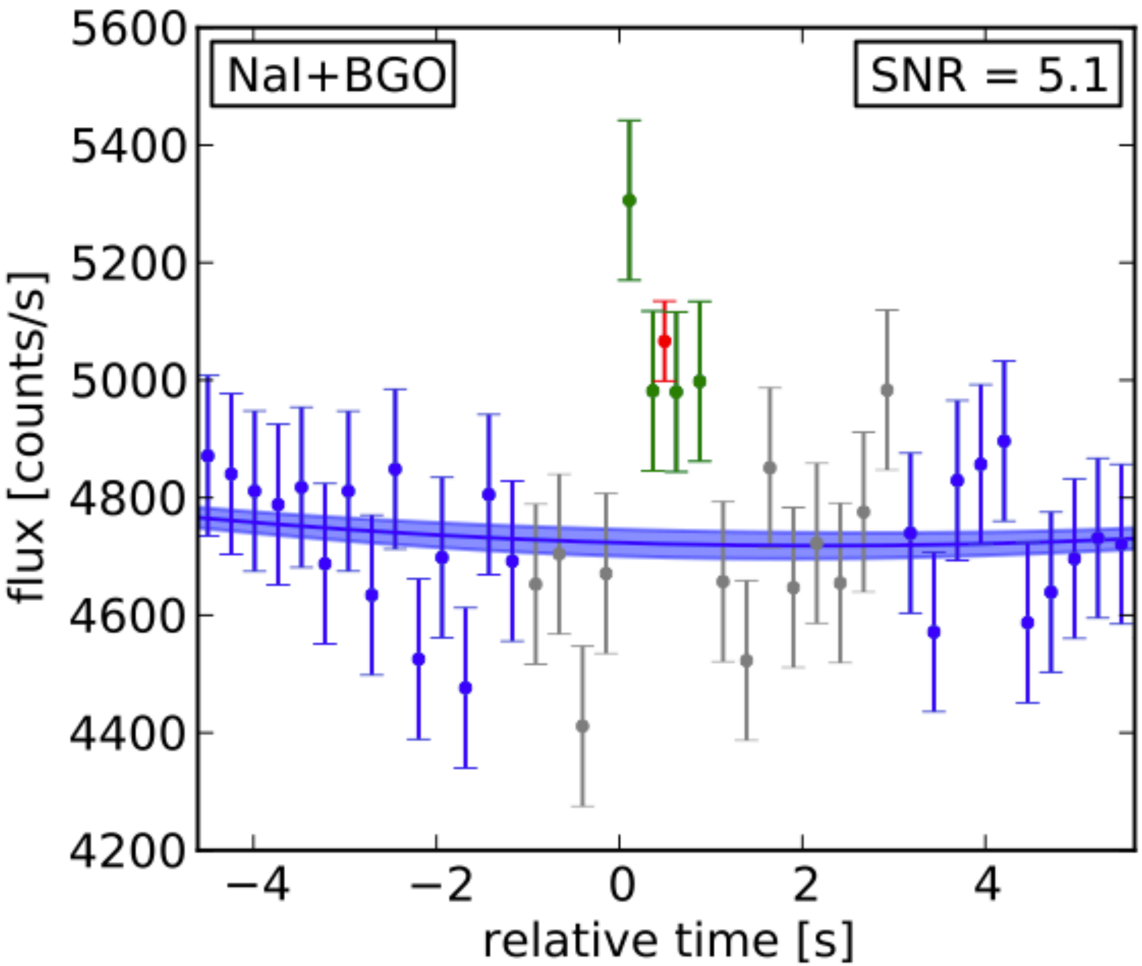
$$\text{Duty cycle} \sim \frac{t_{\rm active}}{t_{\rm dormant}} \sim \frac{\text{Accretion time@}r_{\rm Bondi}}{\text{Nebula lifetime}} \sim 10^{-1}$$

Uncertainties in total power ~ $\times 10^{\pm 3}$

Tip of Iceberg

Fermi γ-ray Burst Monitor

GBM detectors at 150914 09:50:45.797 +1.024s



>50keV

0.4s after GW

T~1sec

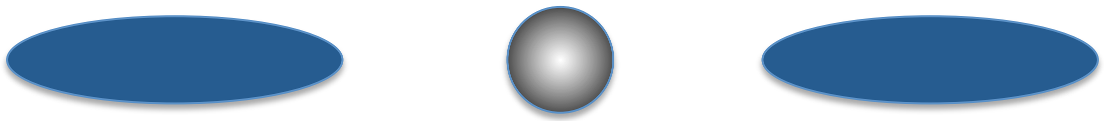
False alarm~0.0022

$L \sim 1.8^{+1.5}_{-1.0}$e49erg/s

Short GRB!?

Fermi+ 16

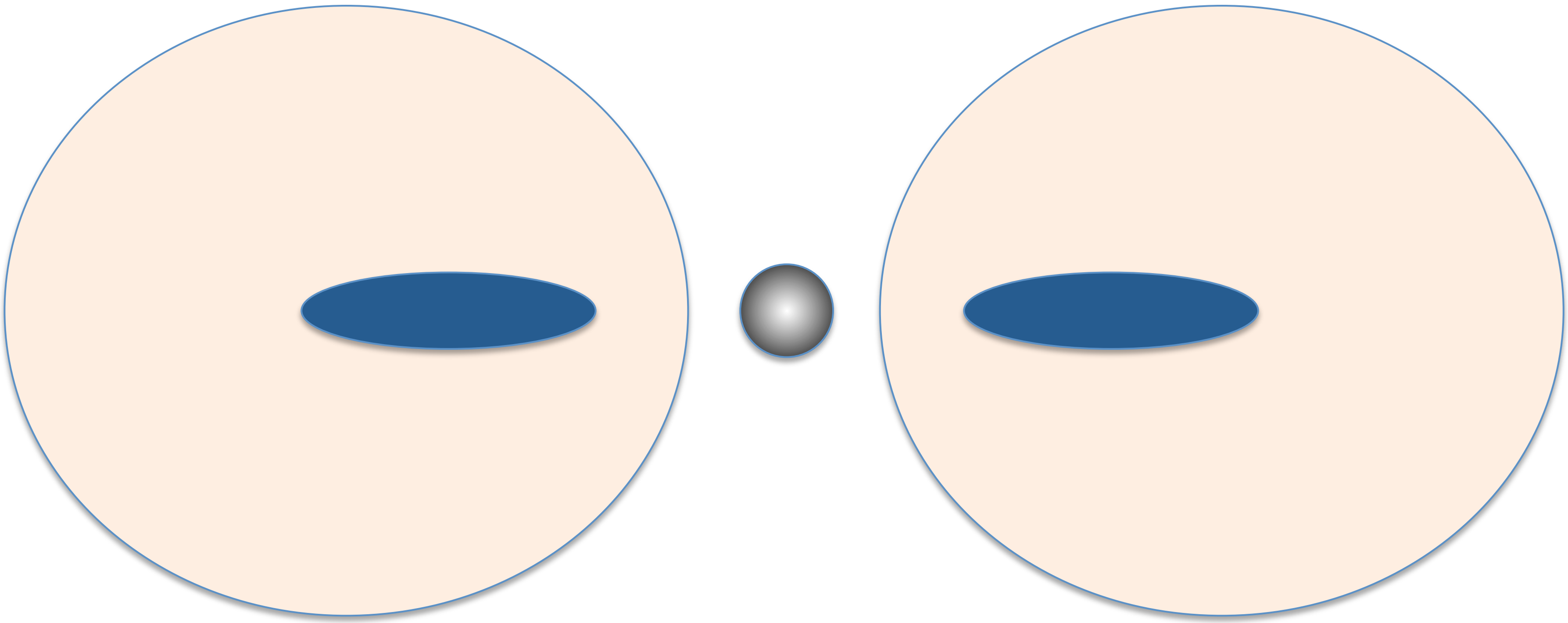
Dead Disk



Cold neutral disk
No MRI, No accretion
Accretion only at merger

Perna+ 15

Dead Disk Evaporation



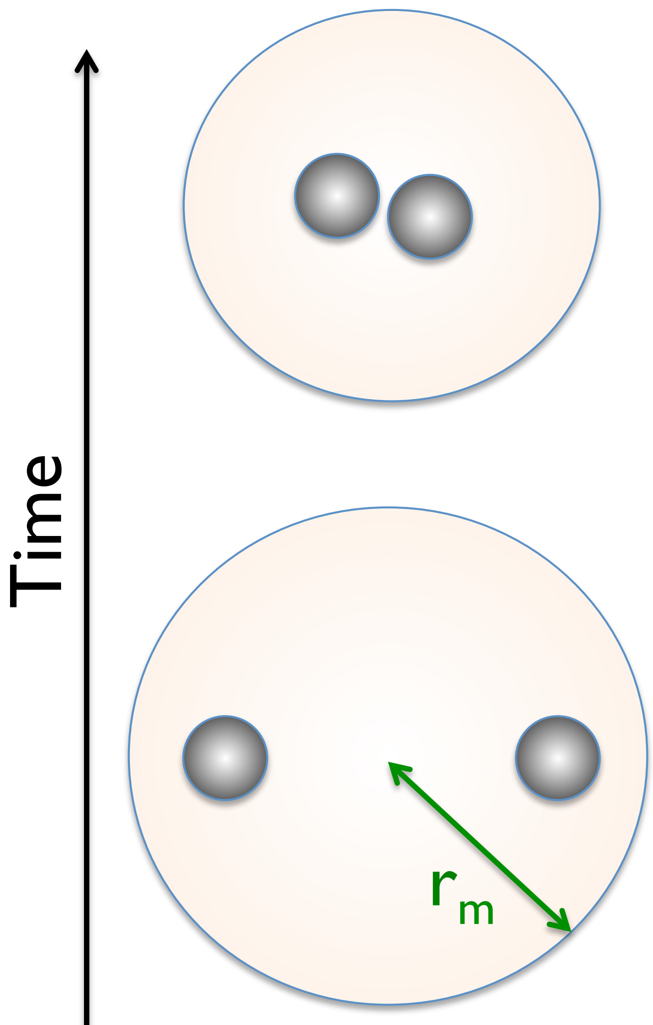
ISM accretion ⇒ Hot disk ⇒ Evaporation

$$\dot{M}_{\rm eva} \sim 2\pi r^2 n_i v_i m_p \sim 1 \times 10^{15}\,{\rm g\,s^{-1}} \left(\frac{r}{10^{12}\,{\rm cm}}\right)^{-5/2} \left(\frac{M}{60 M_\odot}\right)^4 \left(\frac{n}{1\,{\rm cm^{-3}}}\right)^{5/2} \left(\frac{V}{40\,{\rm km\,s^{-1}}}\right)^{-9/2}$$

$t_{\rm eva} \sim 10^6$ yr for $M_{\rm dead\ disk} \sim 10^{-5} M_\odot$

KI+ 16

No-Go?



Going back time
by say t_b~1000 sec

$$r_m \sim 10^{10}\,\mathrm{cm}\left(\frac{t_b}{10^3\,\mathrm{sec}}\right)^{2/3}$$

$$\frac{E_{\mathrm{binding}}}{M_m c^2} = \frac{GMM_m/r_m}{M_m c^2}$$

$$\sim 10^{-3}\left(\frac{t_b}{10^3\,\mathrm{sec}}\right)^{-2/3}$$

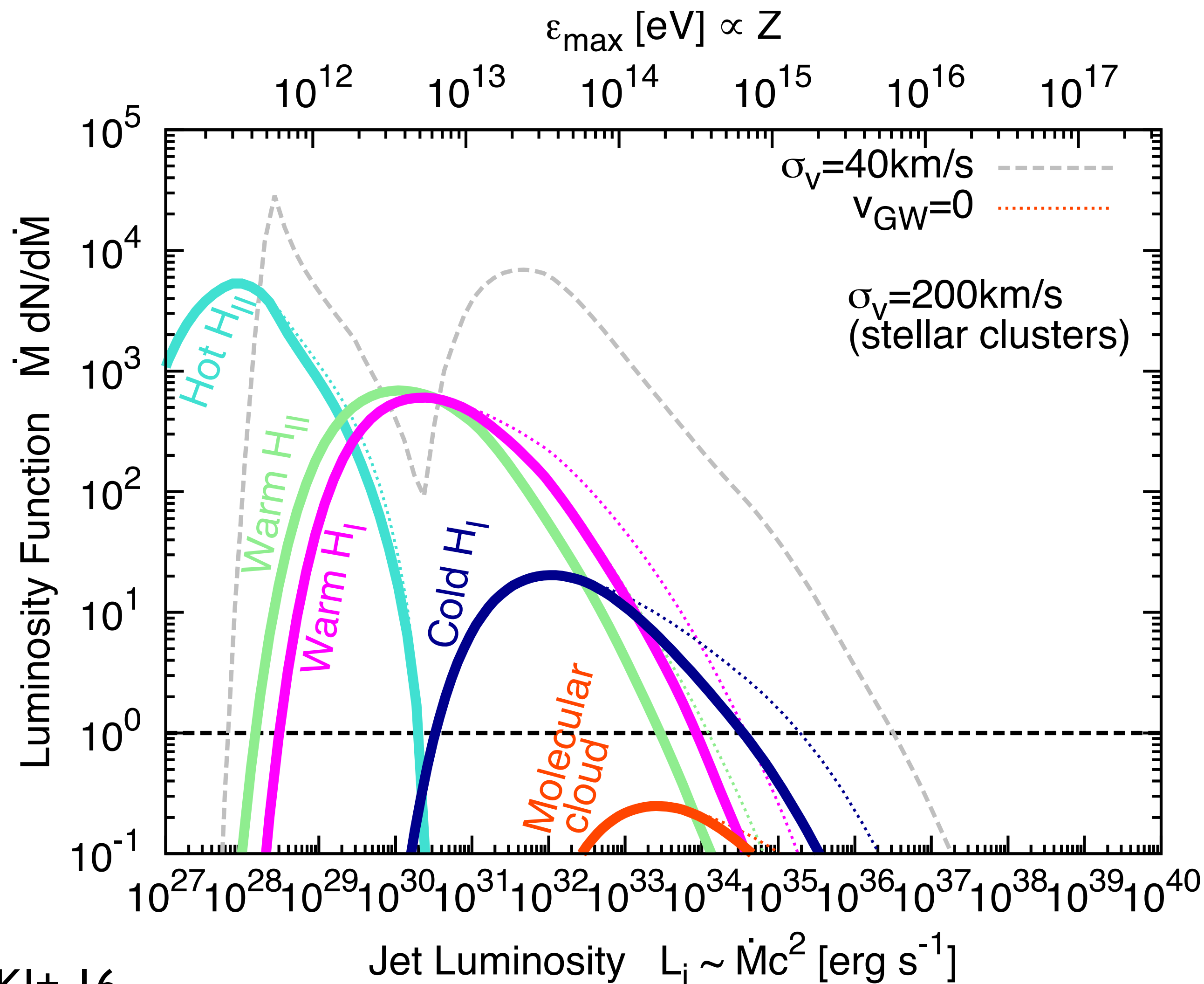
Accretion occurred ⇒ Super Edd. outflow ⇒ Unbound

Summary

- ***Merged BHs have huge energy***
- ***E_{rot} is extracted by B***
  - ADAF, MAD
  - Blandford-Znajek jet ⇒ Luminosity function
- ***PeVatron***
- ***High energy remnant like PWN***
  - >PeV CRs
  - TeV unID
  - Positron excess …

CTA could detect +300 BH nebulae!!

Dependence on Binary Formation Scenario

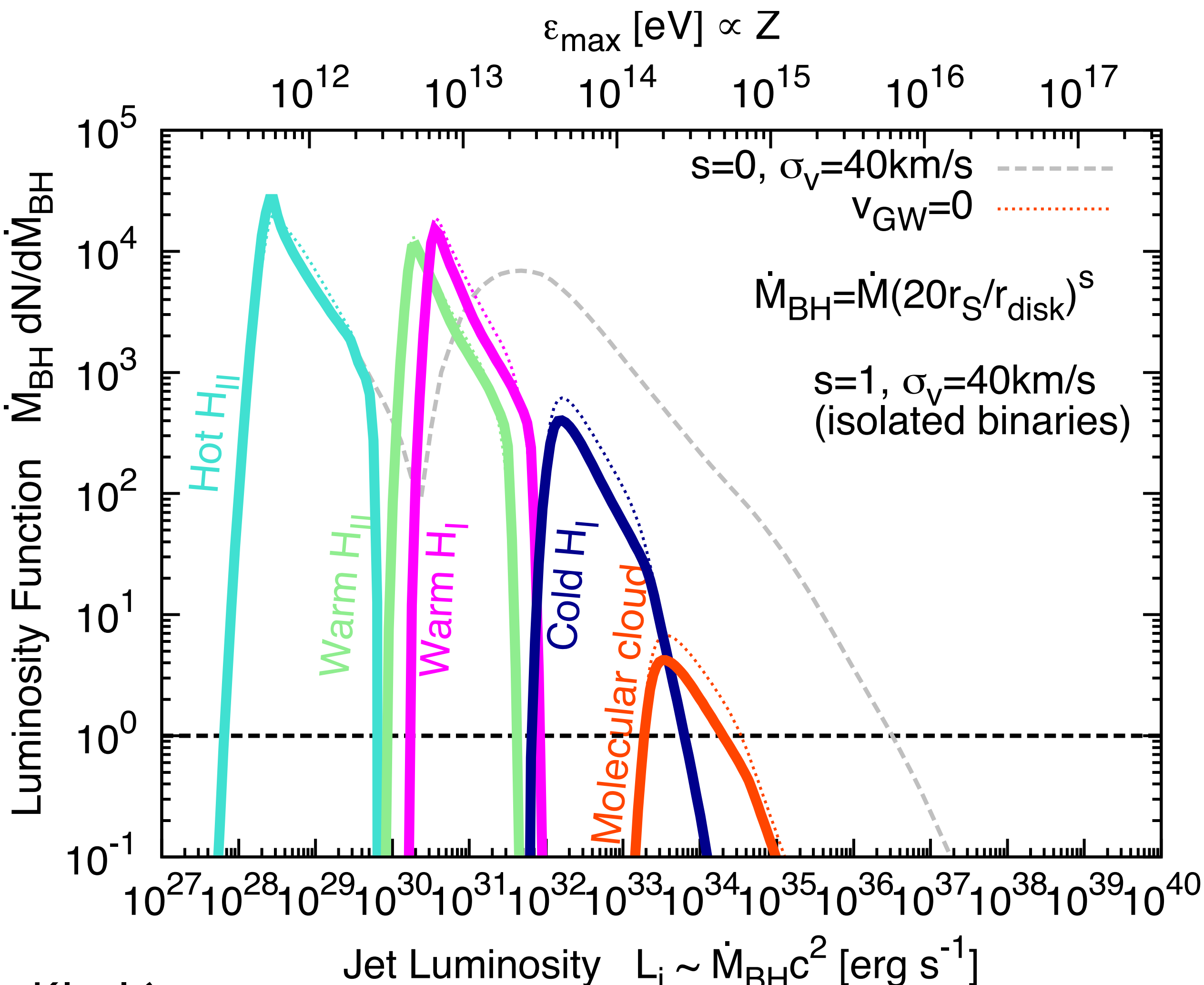


KI+ 16

$$\dot{M} \propto V^{-3} \sim \left(\frac{40\ \mathrm{km\ s^{-1}}}{200\ \mathrm{km\ s^{-1}}}\right)^3 \sim \frac{1}{100}$$

Still relevant to TeV unIDs

Dependence on Accretion Disk Model



KI+ 16

Adiabatic inflow-outflow solution (ADIOS)

$$\dot{M}_{\rm BH} \approx \dot{M}\left(\frac{20r_S}{r_{\rm disk}}\right)^s$$

Yuan+ 15

Most ISM does not accrete to BH

c_s & v

- c_s(ISM)~10 km s^{-1}
- Formation channel
  - Massive binary
    - Direct collapse ⇒ Little kick
    - SN kick, if v ∝ p

$$\sigma_{BH} \sim \frac{M_{NS}}{M_{BH}} \sigma_{NS} \sim \frac{1.4}{60} \times 300 \sim 7 \text{ km s}^{-1}$$

  - 3 body in clusters
    - Escape velocity ~50km s^{-1}
    - $v \sim v_{Galaxy}$~200 km s^{-1}
- Obs. of BH candidates
  - few tens of km s^{-1} or less

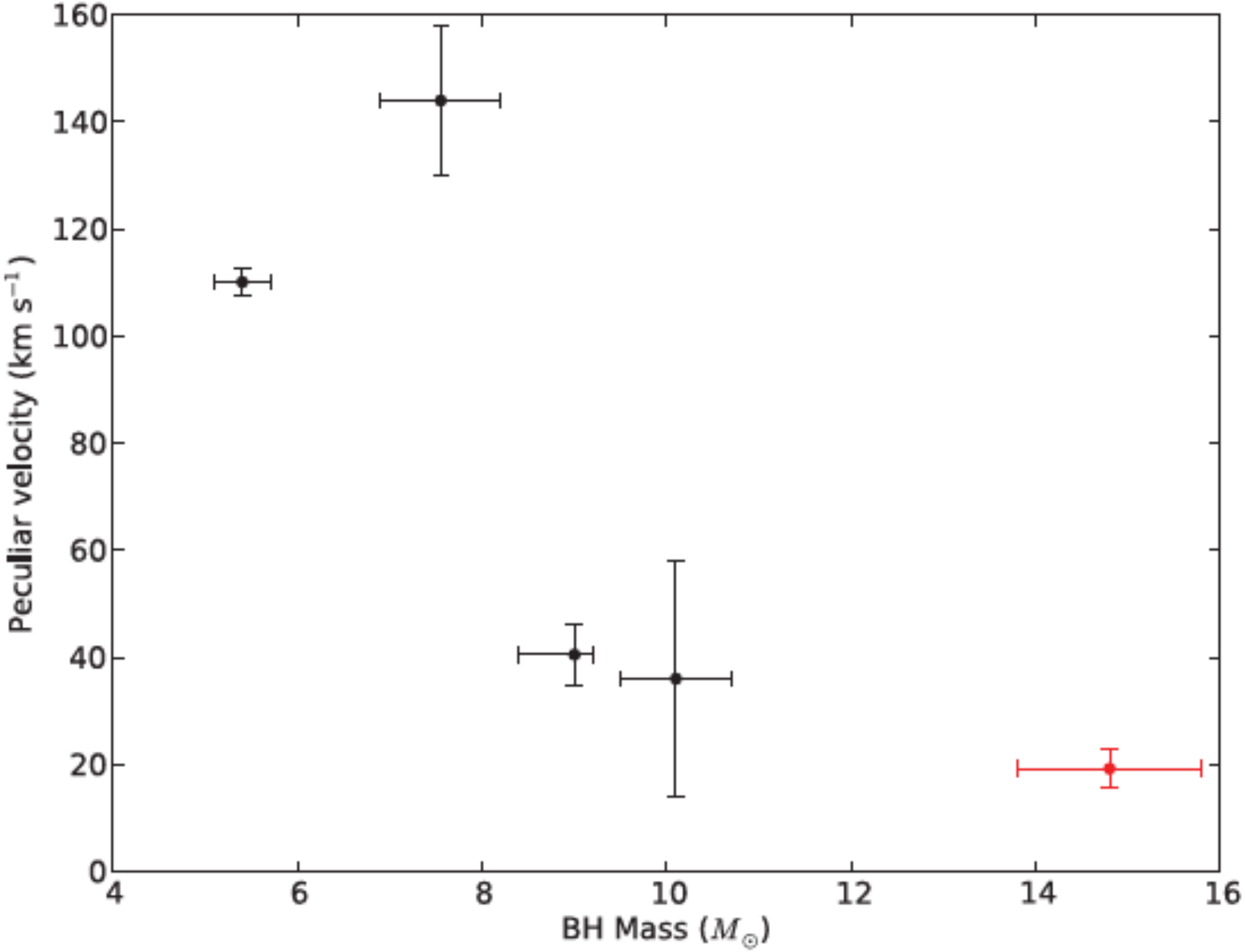


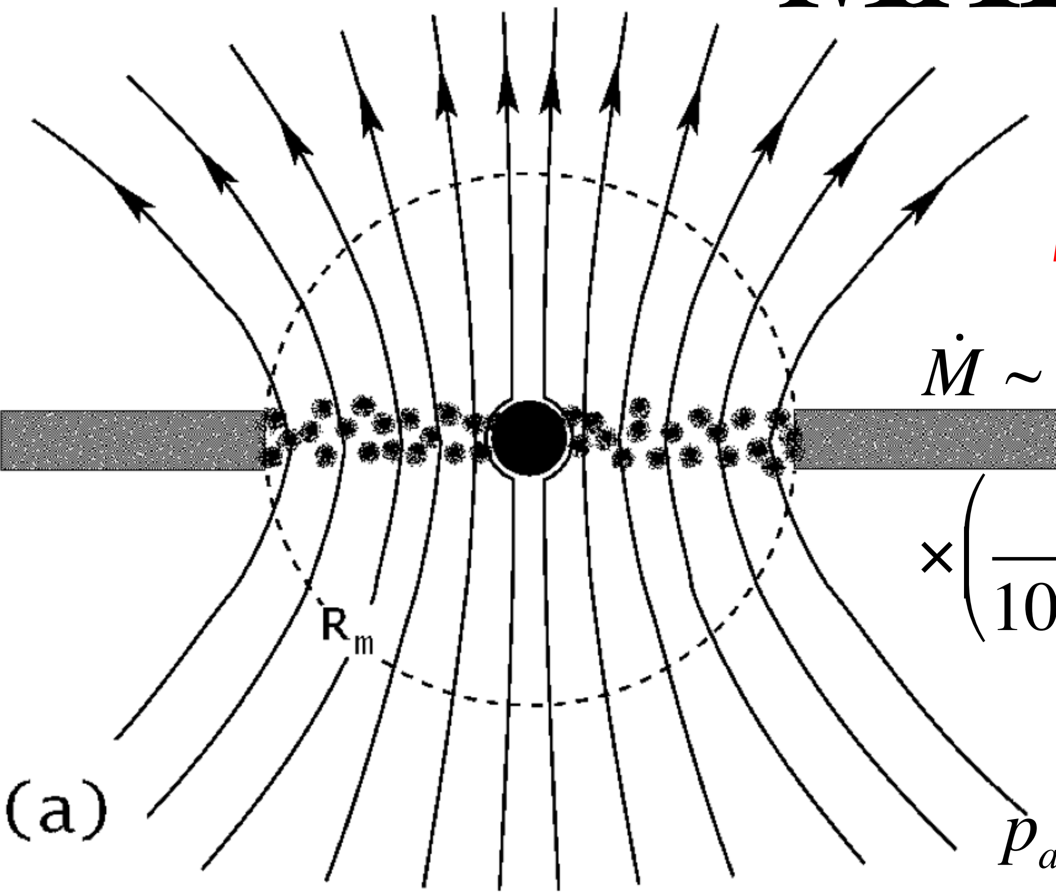
Figure 3. Inferred peculiar velocity as a function of black hole mass. Black points denote low-mass X-ray binaries, and the red point represents the high-mass X-ray binary Cygnus X-1. A larger sample is required to make robust inferences about any potential correlation between black hole (or companion) mass and natal kicks.

Miller-Jones 14

MAD

Magnetically Arrested Disk

B-flux saturation



Bisnovatyi-Kogan & Ruzmaikin 76
Narayan+ 03

$$\dot{M} \sim 4\pi r_B^2 V \rho \sim 5\times10^{35}\,\mathrm{erg\ s^{-1}} \times\left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10 M_\odot}\right)^2\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$

$$p_a = \frac{GM\Sigma}{r^2} \sim \frac{GM\dot{M}}{2\pi r^3 v_r} \Leftrightarrow p_B = \frac{B^2}{8\pi}$$

$$B_H \sim \sqrt{\frac{4GM\dot{M}}{r^3 v_r}}\Bigg|_{r=r_H} \sim 4\times10^7\,\mathrm{G}\left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)^{1/2}\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3/2}$$

BZ Luminosity

$$L_{BZ} = \frac{\kappa}{4\pi c}\Omega_{BH}^2 \Psi_{BH}^2$$

$$= \frac{\kappa}{4\pi c}\left(\frac{a_* c}{2 r_H}\right)^2 \left(\pi r_H^2 B_H\right)^2$$

$$= \frac{\pi\kappa}{16} c a_*^2 r_H^2 B_H^2$$

$$\sim \left(\frac{\kappa}{\varepsilon}\sqrt{\frac{\pi^3}{12}\frac{GM}{c^2 r_H}}\right) a_*^2 \dot{M} c^2$$

$$\sim \dot{M} c^2$$

$$\kappa \sim 0.05$$

$$p_B \sim p_a$$

$$B_H \sim \left.\sqrt{\frac{4GM\dot{M}}{r^3 v_r}}\right|_{r=r_H}$$

$$v_r = \varepsilon v_{ff} = \varepsilon\sqrt{\frac{3GM}{4\pi r}}$$

$$\varepsilon \sim 0.05$$

Source Parameters

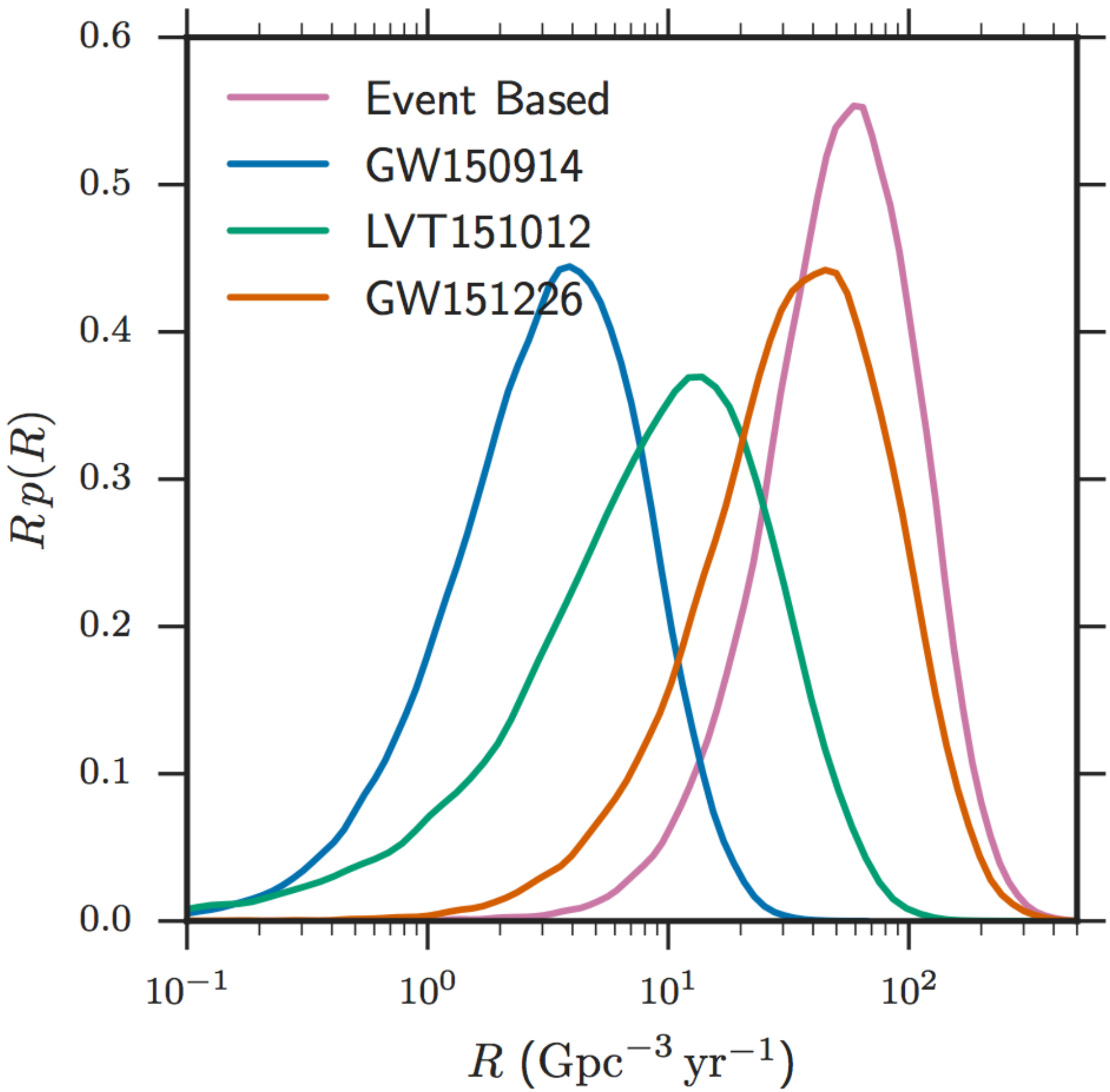
TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

TABLE I. Source parameters for GW151226. We report median values with 90% credible intervals that include statistical and systematic errors from averaging results of the precessing and nonprecessing spin waveform models. The errors also take into account calibration uncertainties. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [61]. The spins of the primary and secondary black holes are constrained to be positive. The source redshift assumes standard cosmology [62]. Further parameters of GW151226 are discussed in [5].

Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_\odot c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	440^{+180}_{-190} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Event Rate



9-240 Gpc^{-3} yr^{-1}

70 Gpc^{-3} yr^{-1}
÷ ~0.01 galaxy Mpc^{-3}
× ~10^{10} yr

~ 7×10^{4} BHs/galaxy

Black Hole Candidates

BH candidates are discovered as X-ray novae

Half of them have no counterpart

Table 1 Twenty confirmed black holes and twenty black-hole candidates[a]

Coordinate Name	Common[b] Name/Prefix	Year[c]	Spec.	P_{orb} (hr)	$f(M)$ $(M_\odot)$	M_1 $(M_\odot)$
0422+32	(GRO J)	1992/1	M2V	5.1	1.19 ± 0.02	3.7–5.0
0538–641	LMC X–3	–	B3V	40.9	2.3 ± 0.3	5.9–9.2
0540–697	LMC X–1	–	O7III	93.8[d]	0.13±0.05[d]	4.0–10.0:[e]
0620–003	(A)	1975/1[f]	K4V	7.8	2.72 ± 0.06	8.7–12.9
1009–45	(GRS)	1993/1	K7/M0V	6.8	3.17 ± 0.12	3.6–4.7:[e]
1118+480	(XTE J)	2000/2	K5/M0V	4.1	6.1 ± 0.3	6.5–7.2
1124–684	Nova Mus 91	1991/1	K3/K5V	10.4	3.01 ± 0.15	6.5–8.2
1354–64[g]	(GS)	1987/2	GIV	61.1[g]	5.75 ± 0.30	–
1543–475	(4U)	1971/4	A2V	26.8	0.25 ± 0.01	8.4–10.4
1550–564	(XTE J)	1998/5	G8/K8IV	37.0	6.86 ± 0.71	8.4–10.8
1650–500[h]	(XTE J)	2001/1	K4V	7.7	2.73 ± 0.56	–
1655–40	(GRO J)	1994/3	F3/F5IV	62.9	2.73 ± 0.09	6.0–6.6
1659–487	GX 339–4	1972/10[i]	–	42.1[j,k]	5.8 ± 0.5	–
1705–250	Nova Oph 77	1977/1	K3/7V	12.5	4.86 ± 0.13	5.6–8.3
1819.3–2525	V4641 Sgr	1999/4	B9III	67.6	3.13 ± 0.13	6.8–7.4
1859+226	(XTE J)	1999/1	–	9.2:[e]	7.4 ± 1.1:[e]	7.6–12.0:[e]
1915+105	(GRS)	1992/Q[l]	K/MIII	804.0	9.5 ± 3.0	10.0–18.0
1956+350	Cyg X–1	–	O9.7Iab	134.4	0.244 ± 0.005	6.8–13.3
2000+251	(GS)	1988/1	K3/K7V	8.3	5.01 ± 0.12	7.1–7.8
2023+338	V404 Cyg	1989/1[f]	K0III	155.3	6.08 ± 0.06	10.1–13.4

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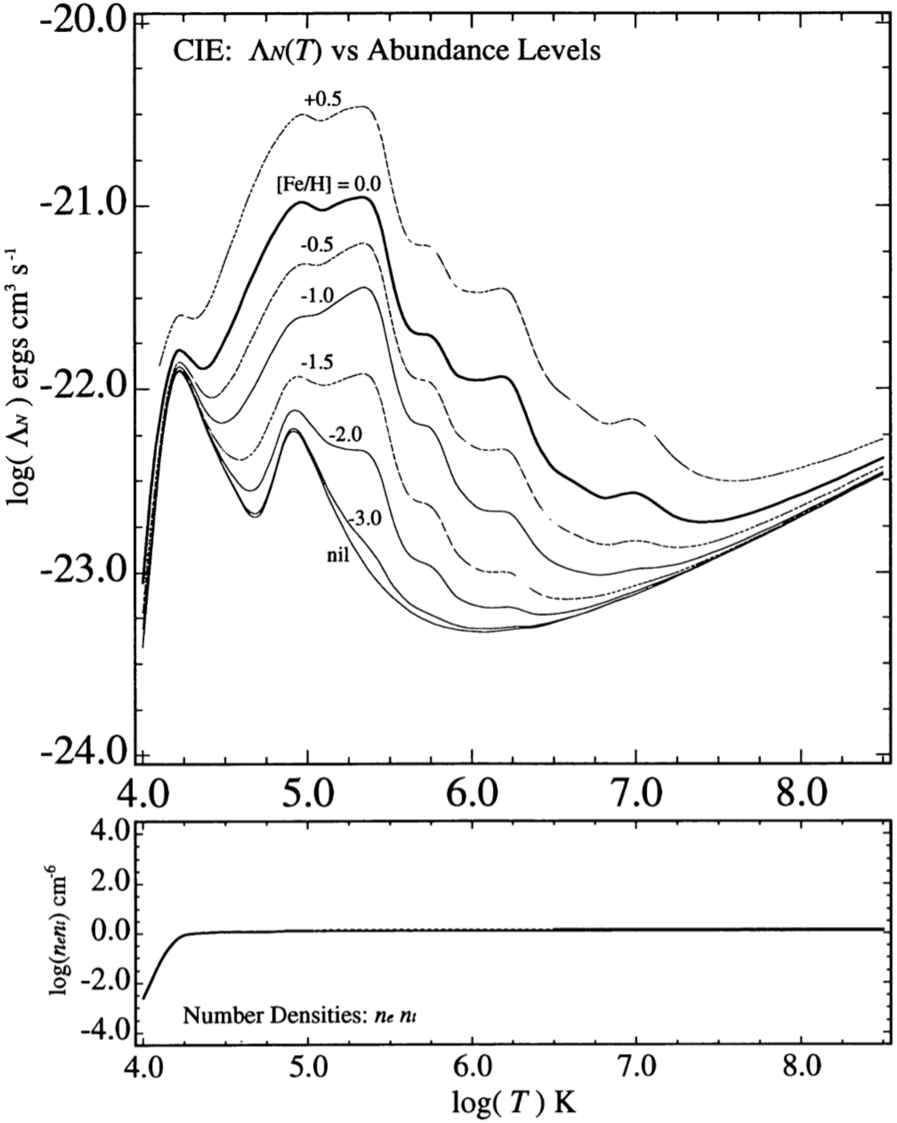
1524–617	(A)	1974/2	–	–	–	–
1630–472	(4U)	1971/15	–	–	–	–
1711.6–3808	(SAX J)	2001/1	–	–	–	–
1716–249	(GRS)	1993/1	–	14.9	–	–
1720–318	(XTE J)	2002/1	–	–	–	–
1730–312	(KS)	1994/1	–	–	–	–
1737–31	(GRS)	1997/1	–	–	–	–
1739–278	(GRS)	1996/1	–	–	–	–
1740.7–2942	(1E)	–	–	–	–	–
1743–322	(H)	1977/4	–	–	–	–
1742–289	(A)	1975/1	–	–	–	–
1746–331	(SLX)	1990/2	–	–	–	–
1748–288	(XTE J)	1998/1	–	–	–	–
1755–324	(XTE J)	1997/1	–	–	–	–
1755–338	(4U)	1971/Q[l]	–	4.5	–	–
1758–258	(GRS)	1990/Q[l]	–	–	–	–

(*Continued*)

Table 1 Twenty confirmed black holes and twenty black-hole candidates[a]

Coordinate Name	Common[b] Name/Prefix	Year[c]	Spec.	P_{orb} (hr)	$f(M)$ $(M_\odot)$	M_1 $(M_\odot)$
1846–031	(EXO)	1985/1	–	–	–	–
1908+094	(XTE J)	2002/1	–	–	–	–
1957+115	(4U)	–	–	9.3	–	–
2012+381	(XTE J)	1998/1	–	–	–	–

Cooling Function



$$\Lambda \sim 10^{-22} \text{erg cm}^3 \text{ s}^{-1}$$

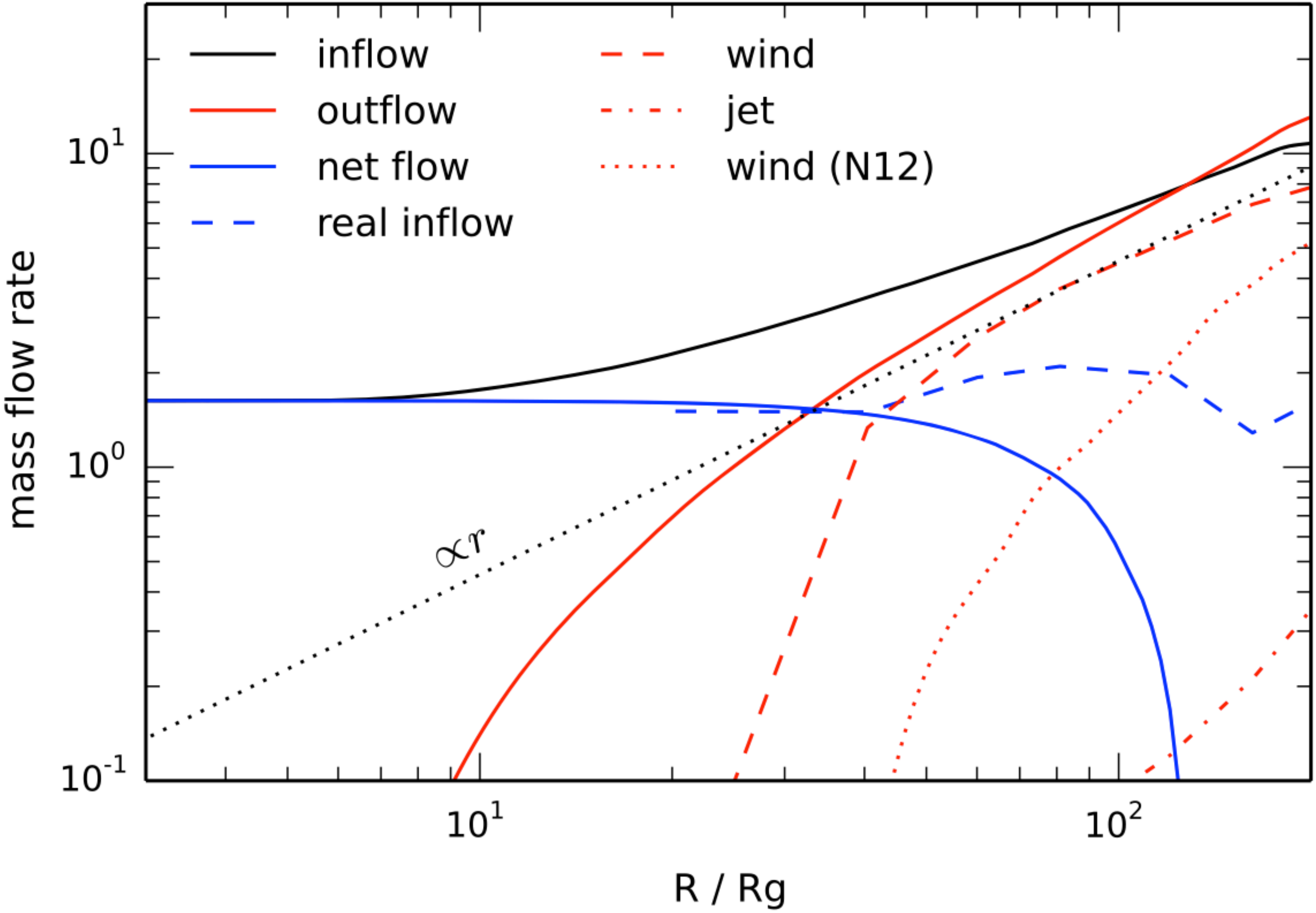
$$\Lambda \cdot n^2 \cdot \frac{4\pi}{3} R^3 \sim L$$

$$R \sim 10^{19} \text{cm} \left(\frac{L}{10^{36} \text{erg s}^{-1}} \right)^{1/3} n^{-2/3}$$

$$\sim 3 \text{ pc}$$

ISM can tolerate the energy injection

Sutherland & Dopita 93


inflow
outflow
net flow
real inflow
wind
jet
wind (N12)
$\propto r$
mass flow rate
10^1
10^0
10^{-1}
10^1
10^2
R / Rg

Recoil with Spin

$$v_k = \sqrt{v_m^2 + 2 v_m v_\perp \cos\zeta + v_\perp^2 + v_{//}^2}$$

$$v_m = A\eta^2 \frac{1-q}{1+q}(1+B\eta)$$

$$v_\perp = H\eta^2 \Delta_{//}$$

$$v_{//} = 16\eta^2 \left[\Delta_\perp \left(V_{11} + 2V_A \tilde{\chi}_{//} + 4V_B \tilde{\chi}_{//}^2 + 8V_C \tilde{\chi}_{//}^3\right) + 2\tilde{\chi}_\perp \Delta_{//}\left(C_2 + 2C_3 \tilde{\chi}_{//}\right)\right]\cos\Theta$$

$$q = \frac{m_2}{m_1}$$

$$M = m_1 + m_2$$

$$\eta = \frac{m_1 m_2}{M^2} = \frac{q}{(1+q)^2}$$

$$S_i = m_i^2 \chi_i$$

$$\Delta = \frac{q\chi_2 \hat{\mathbf{S}}_2 - \chi_1 \hat{\mathbf{S}}_1}{1+q}$$

$$\tilde{\chi} = \frac{q^2 \chi_2 \hat{\mathbf{S}}_2 + \chi_1 \hat{\mathbf{S}}_1}{(1+q)^2}$$

$$\tilde{\chi}_{//} = \tilde{\chi} \cdot \hat{\mathbf{L}}$$

$$\tilde{\chi}_\perp = \left|\tilde{\chi} \times \hat{\mathbf{L}}\right|$$

$$A = 1.2 \times 10^4 \text{ km s}^{-1}$$

$$B = -0.93$$

$$H = 6.9 \times 10^3 \text{ km s}^{-1}$$

$$V_{11} = 3677.76 \text{ km s}^{-1}$$

$$V_A = 2481.21 \text{ km s}^{-1}$$

$$V_B = 1792.45 \text{ km s}^{-1}$$

$$V_C = 1506.52 \text{ km s}^{-1}$$

$$C_2 = 1140 \text{ km s}^{-1}$$

$$C_3 = 2481 \text{ km s}^{-1}$$

$$\zeta = 145^\circ$$

$q \sim 1$, $\chi_2 \sim 0.2$

$v_\perp \sim 40$km/s

$v_{||} \sim 260$km/s