X-ray bound on primordial black holes density

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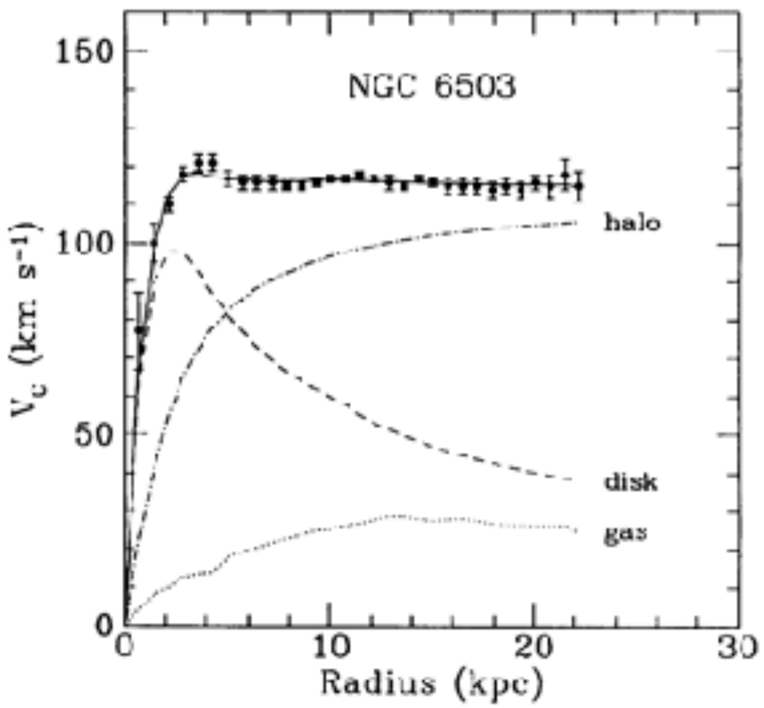
Focus week on primordial black holes @Kavli-IPMU, 2017-11-15

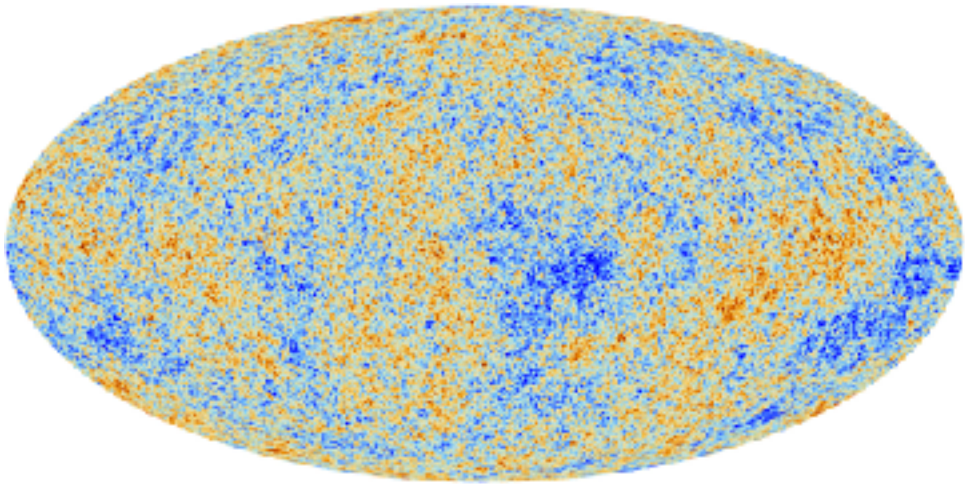
Evidence for Dark Matter

Rotation Curve



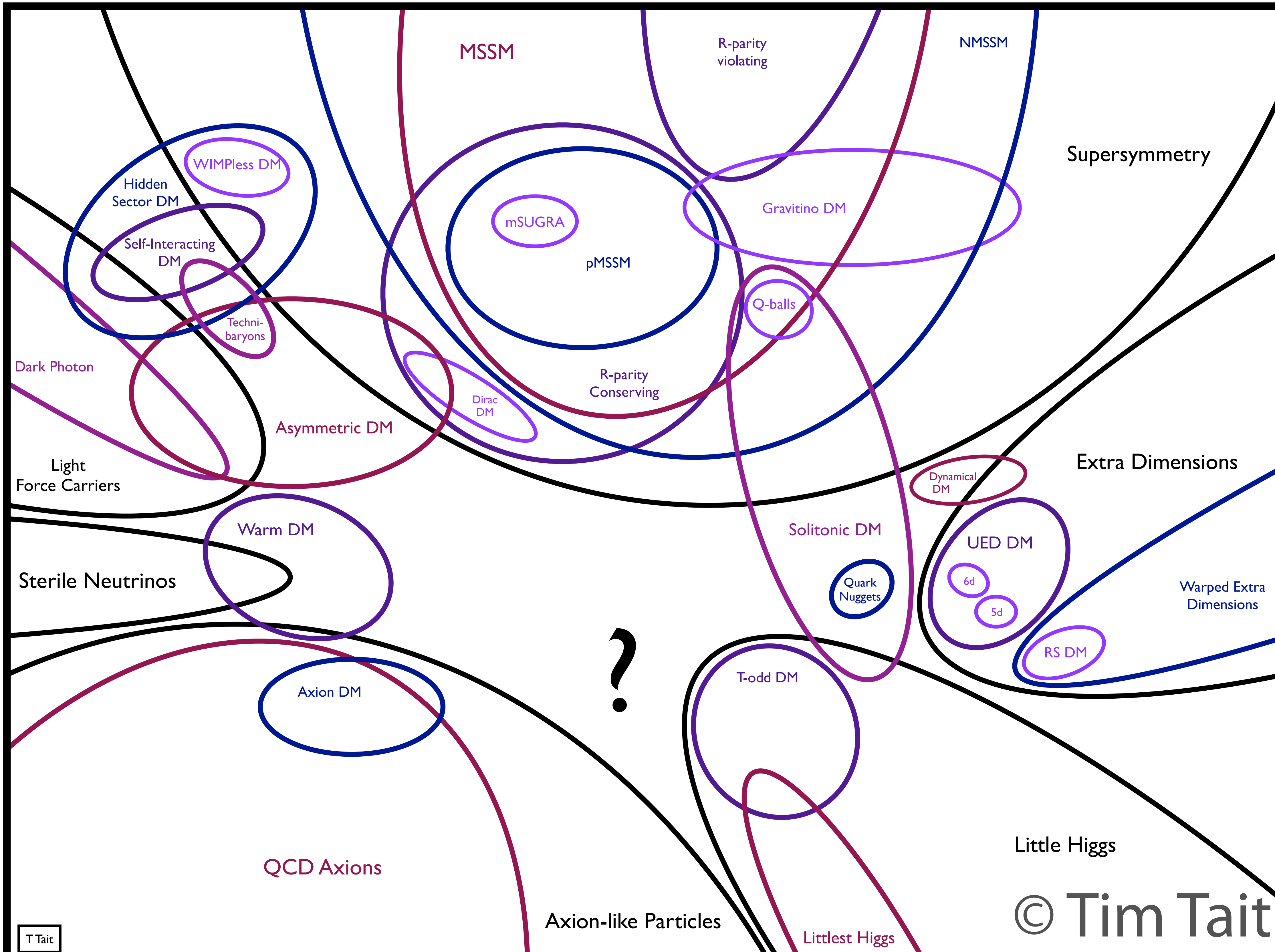
Merging Cluster

Cosmic Microwave Background

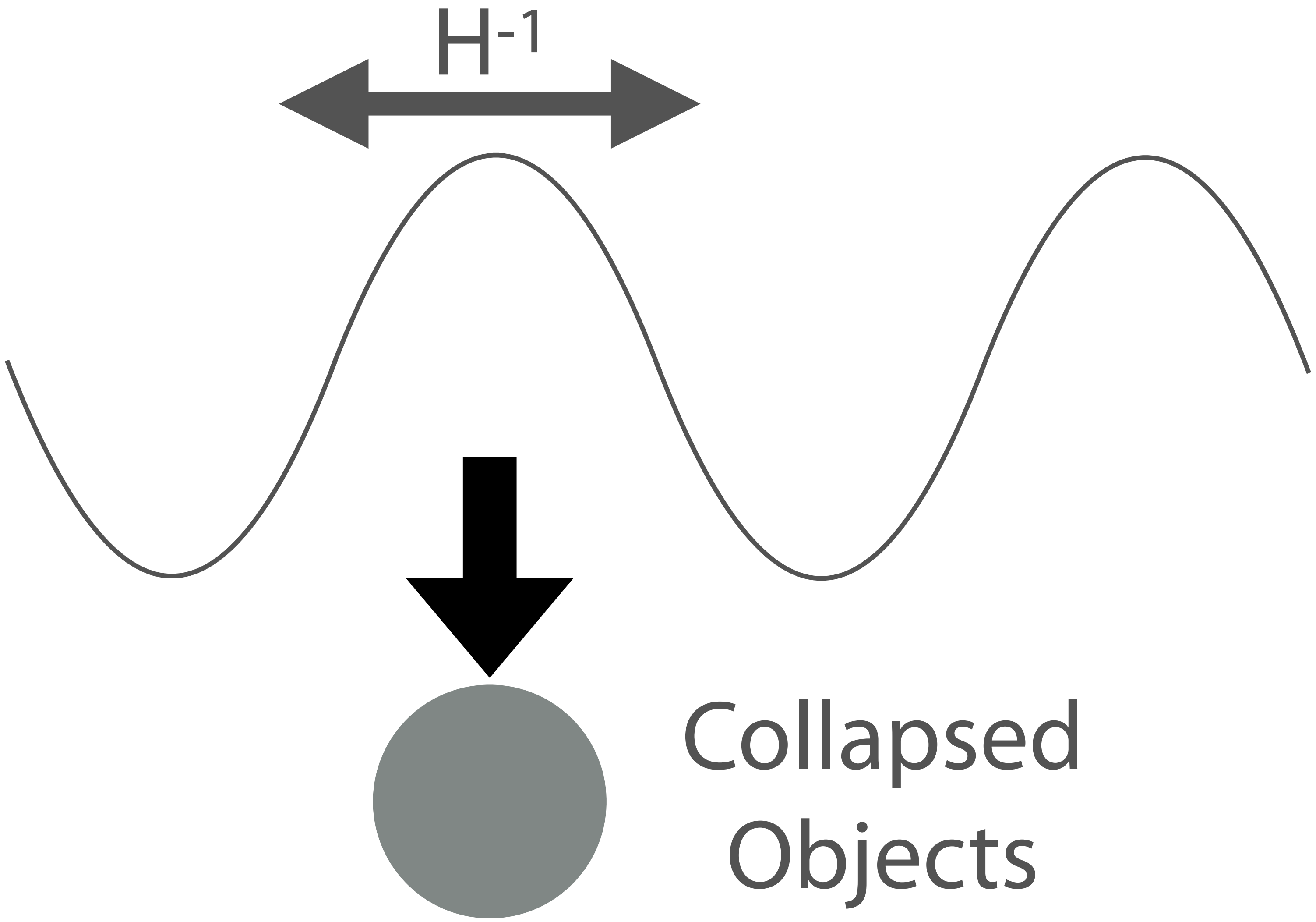


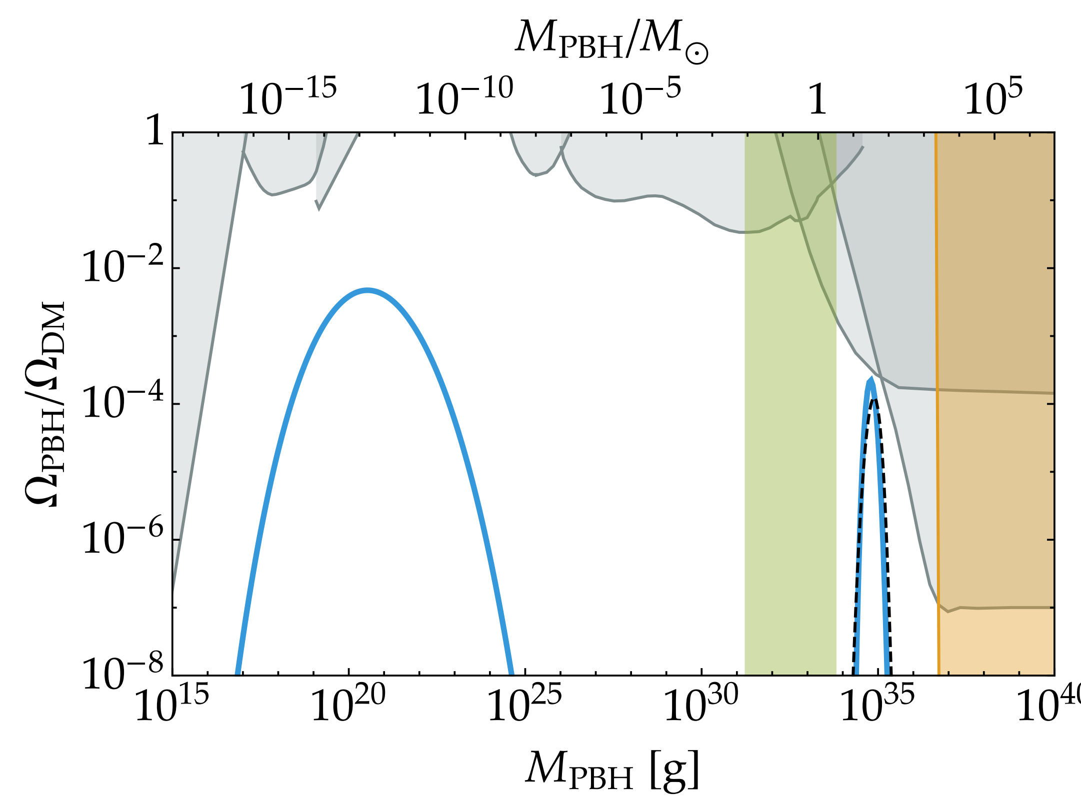
- Multiple evidence of dark matter in various scales
- Cosmological simulations also require dark matter
- What is dark matter?

Dark Matter Candidates from Particle Physics



Primordial Black Holes

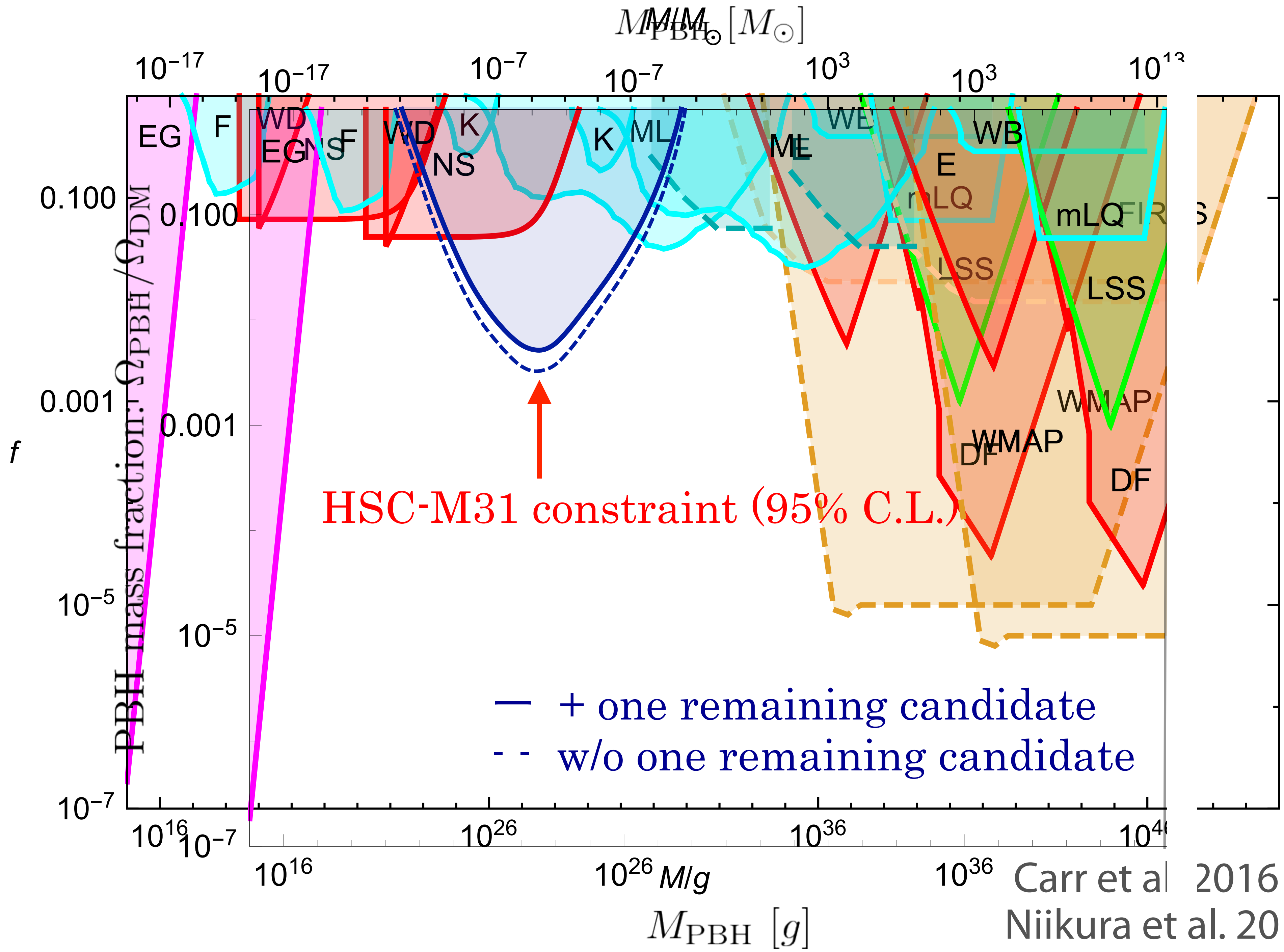




Inomata et al. 2016

- Collapse of Hubble patch: $M \sim 4\pi/3\ \rho H^{-3} \sim 10^{15}\ (t/10^{-23}\ s)$ g
- Many PBH forming scenarios (e.g., Carr & Hawking 1974; Kawasaki et al. 2012; Inomata et al. 2016; and more)

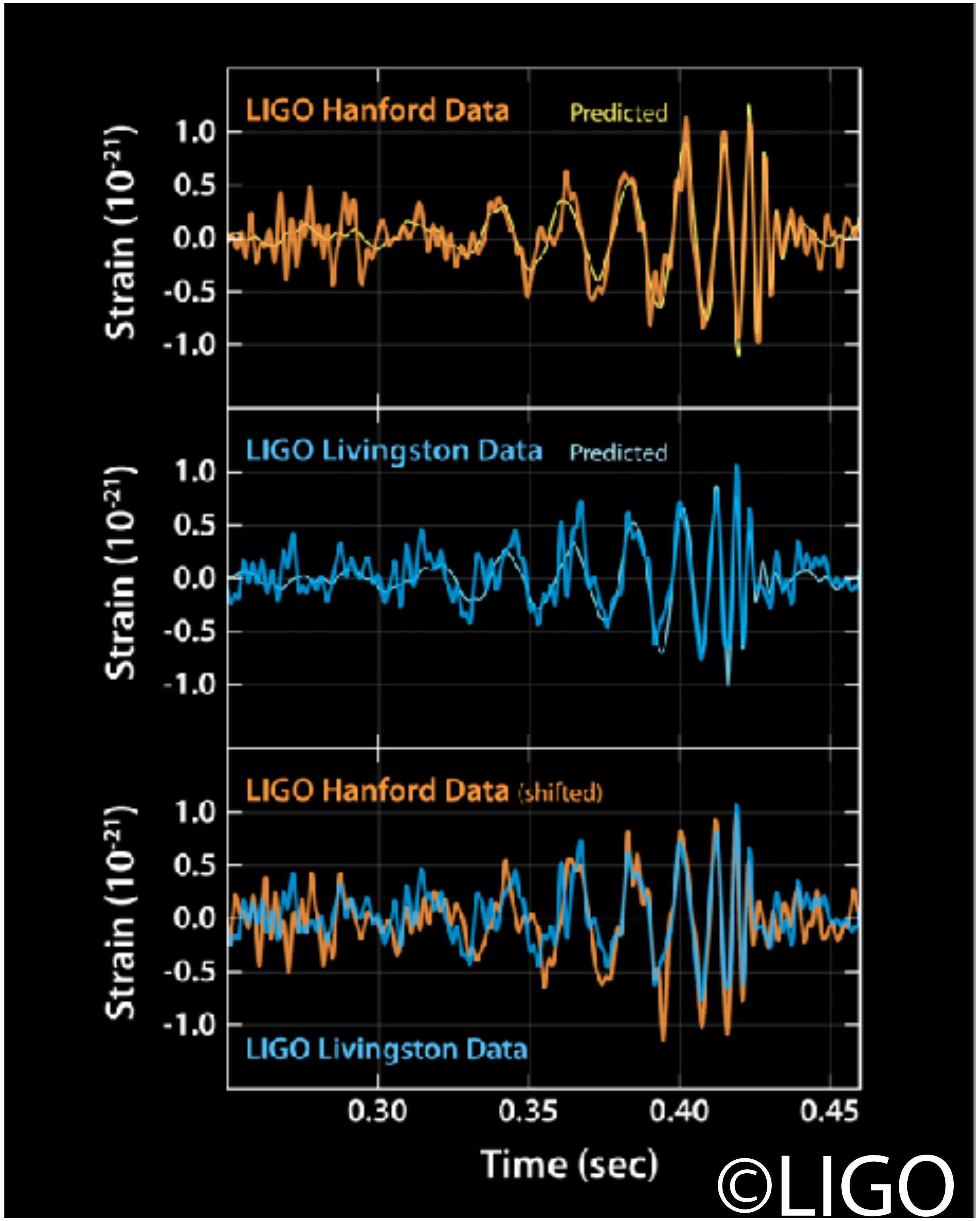
Constraints on Primordial Black Holes



Carr et al. 2016
Niikura et al. 2017

- constraints on PBHs from various observations and theory.

The GW150914 Event



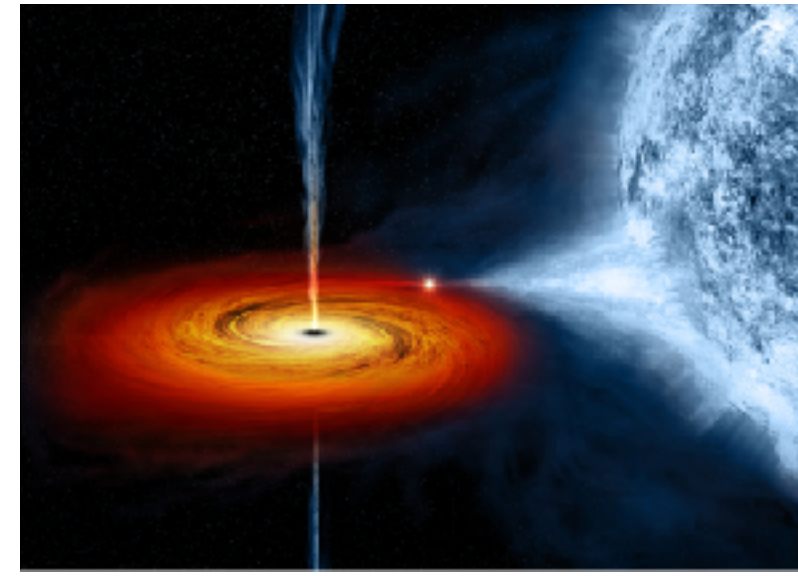
- Binary black hole system with 36 and 29 solar mass BHs.
  - 62 solar mass BH is formed.

  ➡Evidence of intermediate mass BHs.

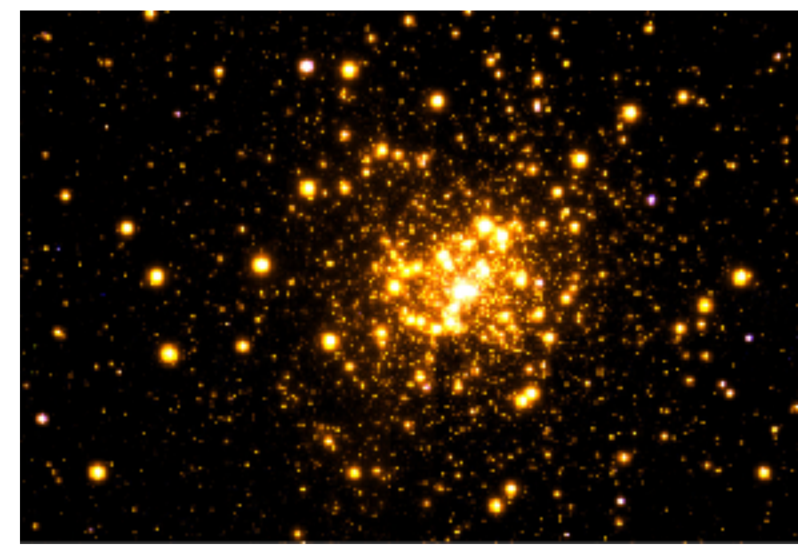
- Why such massive?

Various Scenarios

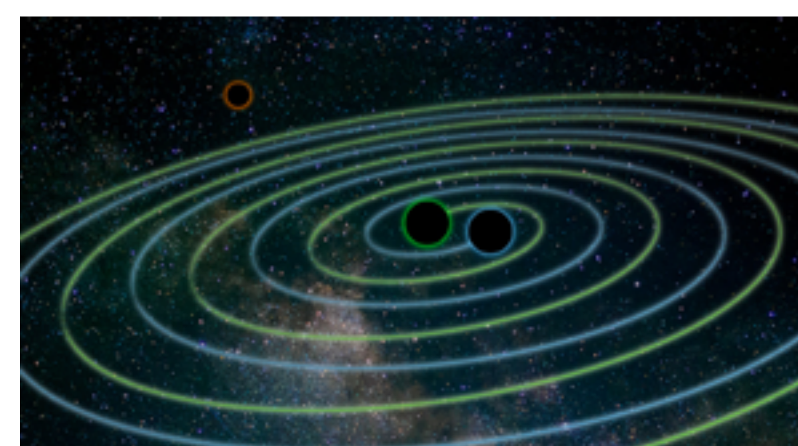
- isolated binary (e.g. Belczynski et al. 2011; Kinugawa et. al. 2014)
    - Evolution from binary massive stars.



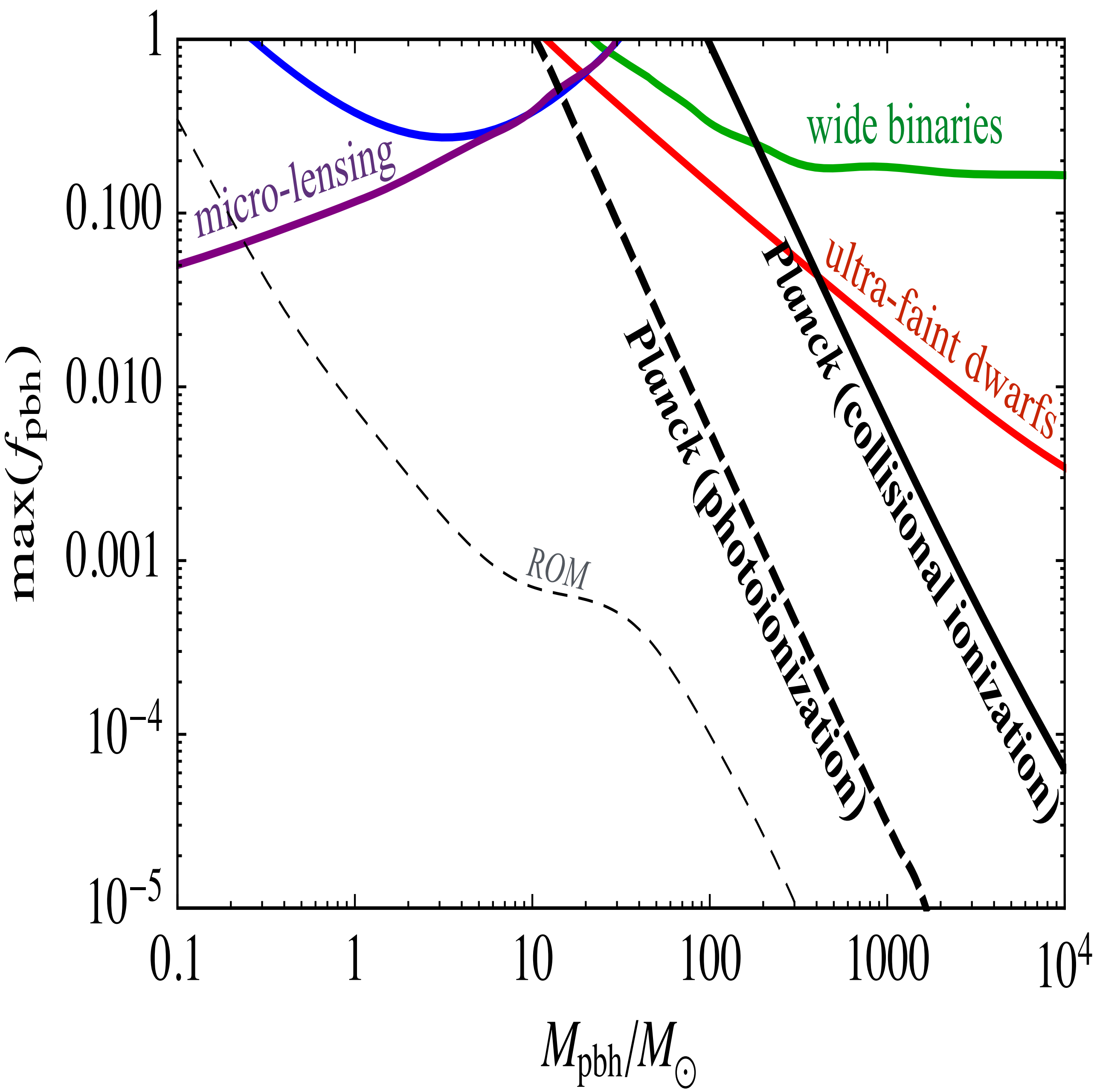
- dense stellar system (e.g. Rodoriguez et al. 2015)
    - Dynamical interaction between BH systems.



- primordial black hole binary (e.g. Bird et al. 2016; Sasaki et al. 2016; Clesse & Garcia-Bellido 2017)



Closer Look at 1-10^3 M_{sun}

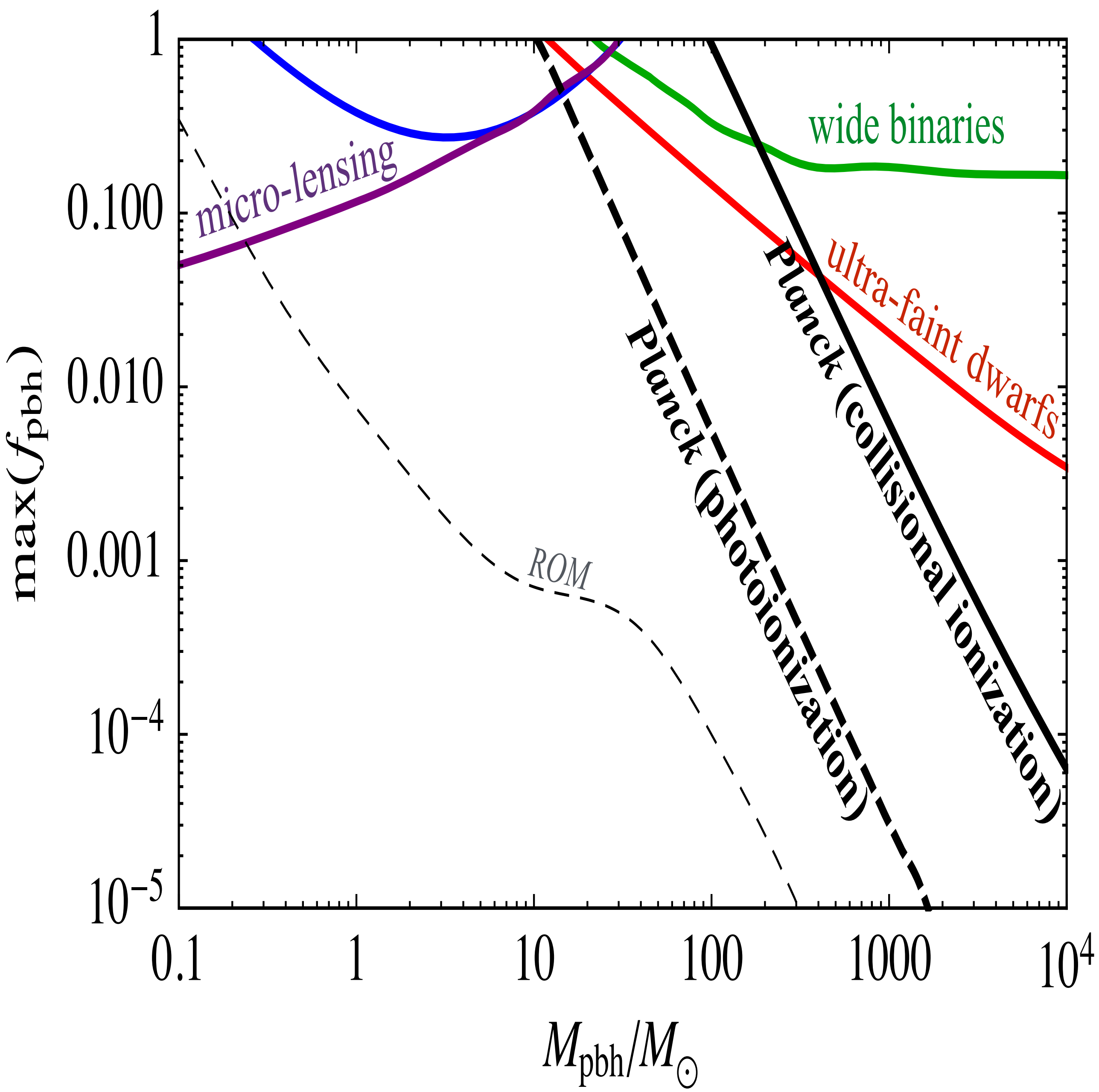


Ali-Hamoud & Kamionkowski 2017

- Lack of MACHO events
  (e.g., Tisserand et al. 2007)
- wide binary star systems are not disrupted
  (e.g., Monroy-Rodoriguez & Allen 2014)
- heating of primordial plasma due to accretion onto PBHs

➡distortion in CMB
(e.g., Ricotti et al. 2007, Ali-Hamoud & Kamionkowski 2017)

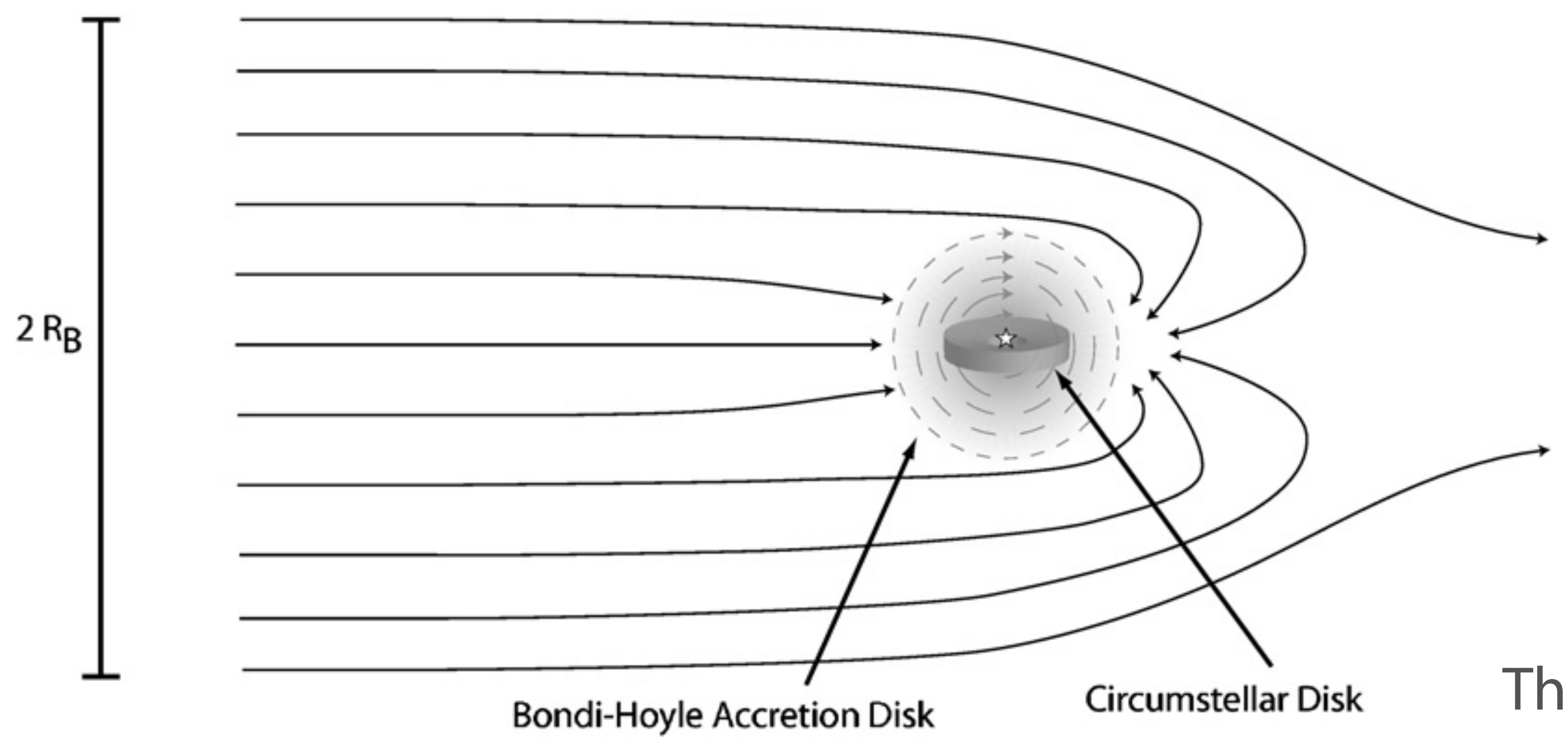
Another new constraint?



Ali-Hamoud & Kamionkowski 2017

- All the constraints need assumptions.
  - complex accretion systems
  - complex IGM heating,,,
- Constraints from X-ray observations
  (Carr 1979; Barrow & Silk 1979; Gaggero et al. 2017; Inoue & Kusenko 2017)

Bondi-Hoyle-Lyttleton Accretion



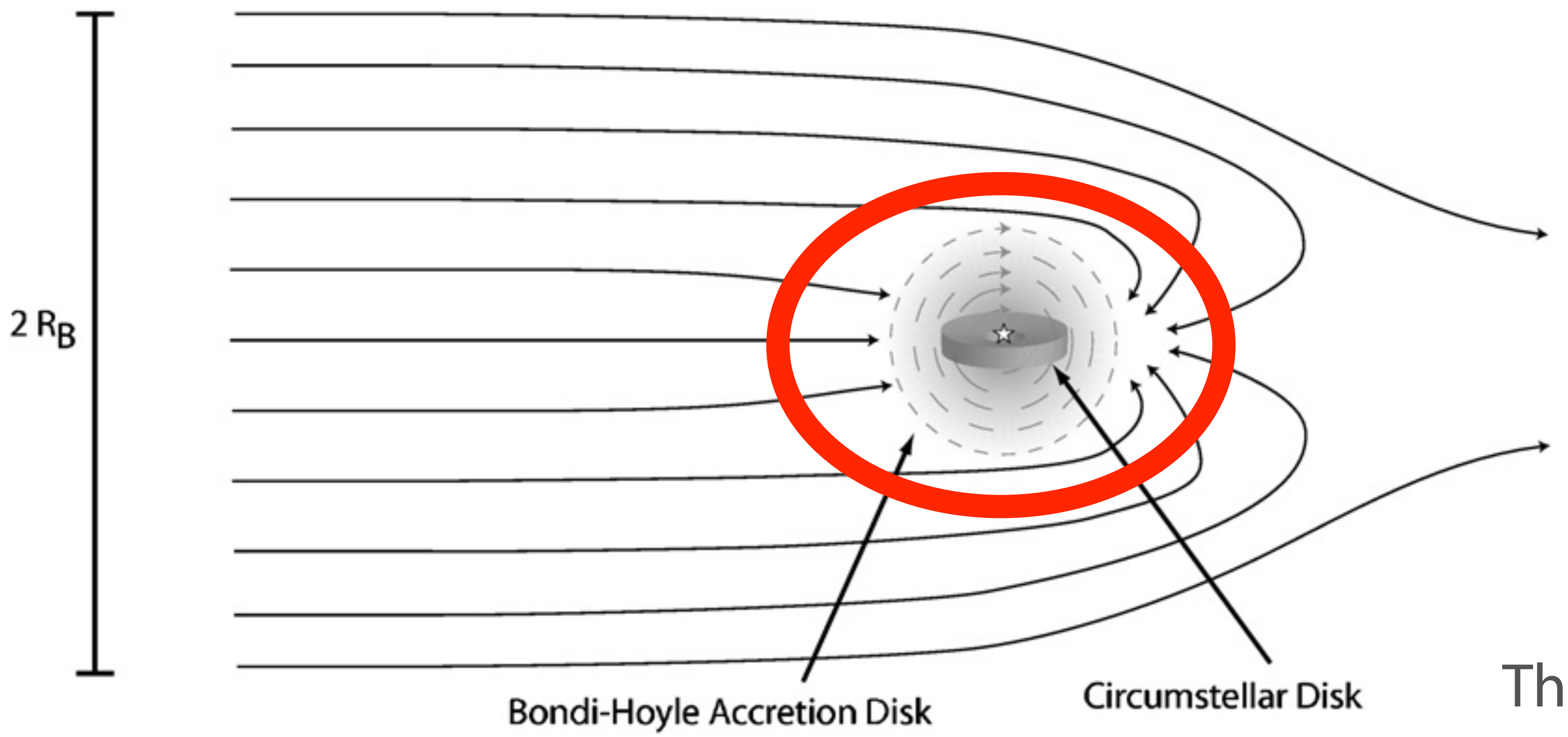
Throop & Bally 2008

- If a black hole freely floats, it may interact with interstellar medium (ISM) gas via Bondi-Hoyle-Lyttleton accretion
  (e.g., Ipser & Price 1977; Fujita et al. 1998; Agol & Kamionkowski 2002; Mii & Totani 2005; Ioka et al. 2017; Matsumoto et al. 2017)

- Accretion rates scale with n & v^{-3} :

$$\dot{M} = 4\pi r_B^2 \tilde{v} \rho = \frac{4\pi G^2 M_{\rm BH}^2 n\, \mu\, m_p}{\tilde{v}^3}$$

Accretion Disk Formation



Throop & Bally 2008

- Perturbations in the ISM gas density/velocity will form a disk (Shapiro & Lightman 1976; Fujita et al. 1998; Agol & Kamionkowski 2002)

- Density fluctuation in ISM gas (Armstrong et al. 1995):

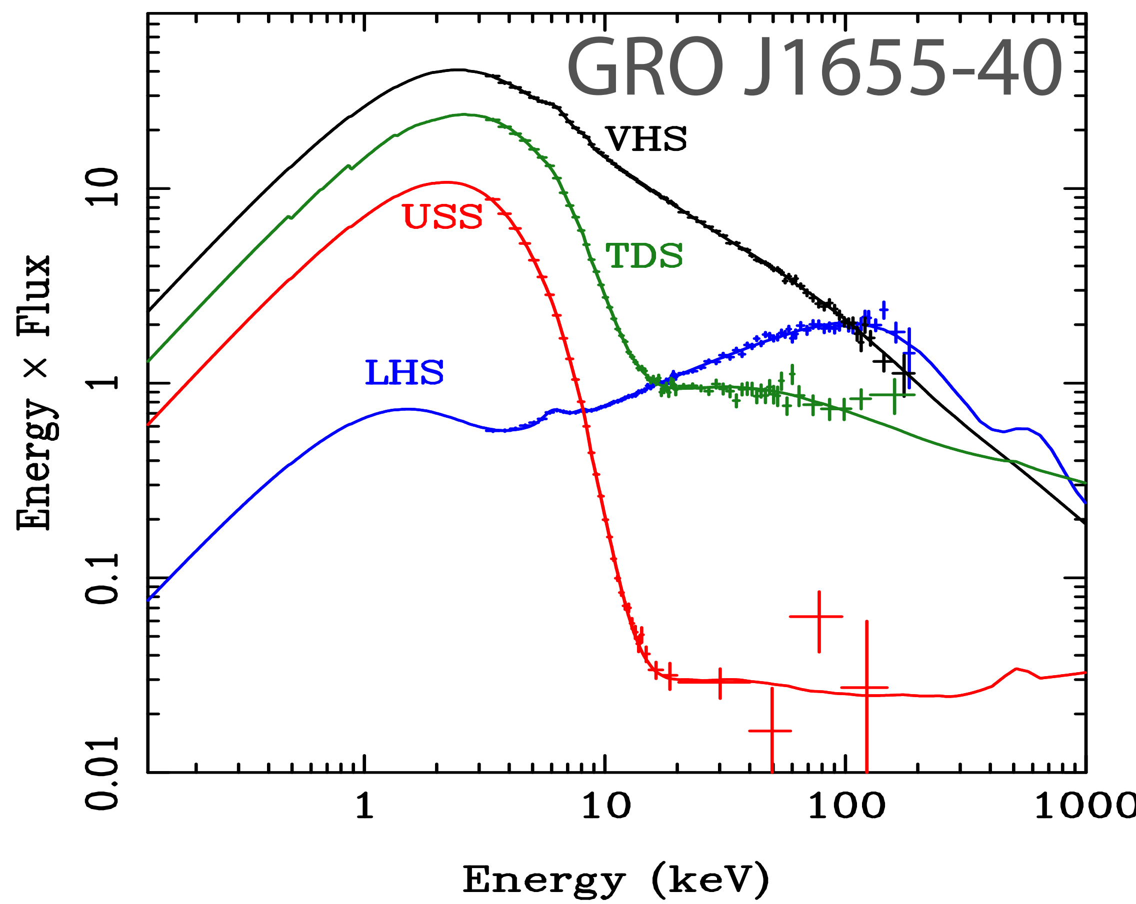
$$\delta\rho/\rho \sim (L/10^{18}\ \mathrm{cm})^{1/3}$$

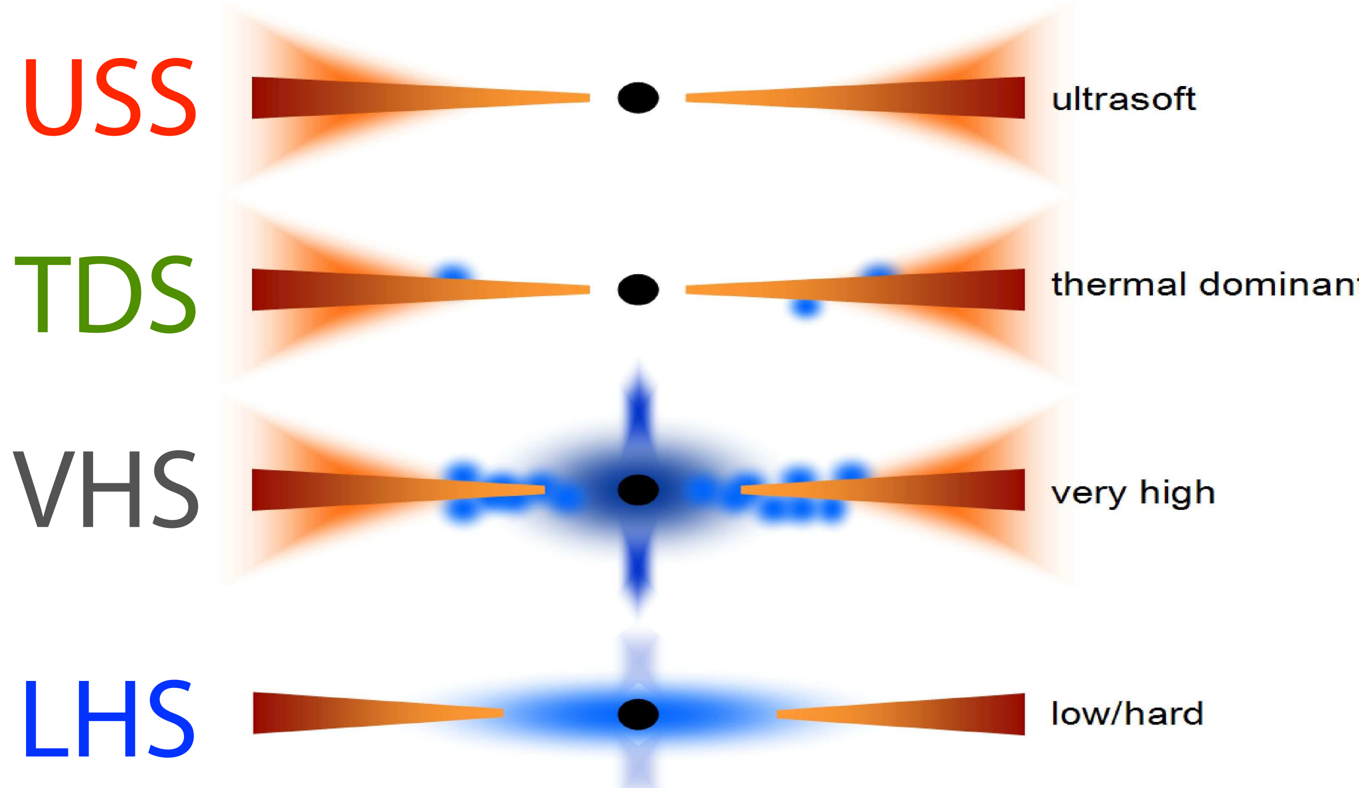
- Accretion disk size:

$$\frac{r_{\rm disk}}{r_s} = \frac{1}{16}\left(\frac{\delta\rho}{\rho}\Big|_{L=2r_B}\right)^2 \frac{r_B}{r_s}$$

$$\simeq 2.5\times10^6\left(\frac{M_{\rm BH}}{100M_\odot}\right)^{2/3}\left(\frac{\tilde{v}}{10\ \mathrm{km\ s^{-1}}}\right)^{-10/3}$$

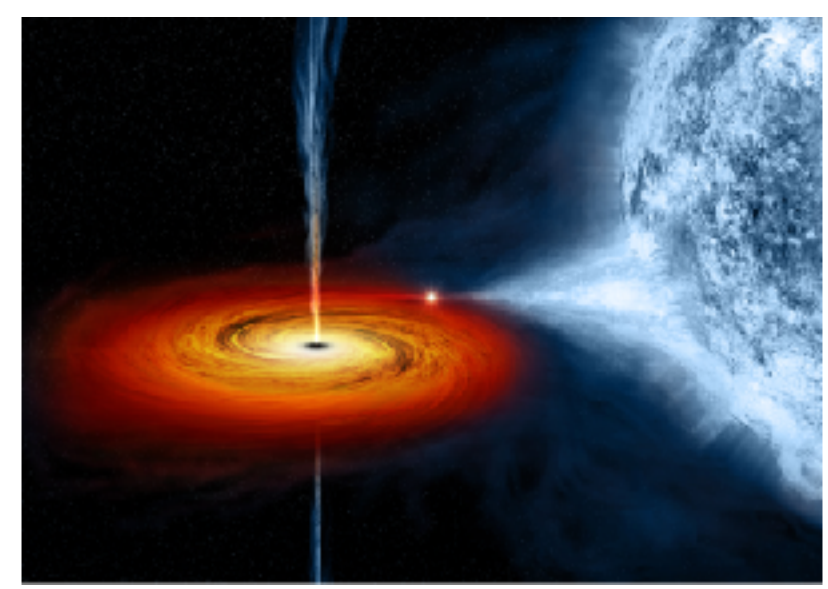
Emission from X-ray Binary Accretion Disks





Done, Gierlinski & Kubota 2008

- X-ray binary (XRB):
  - mass accretion from companion stars
  - significant emission in X-ray



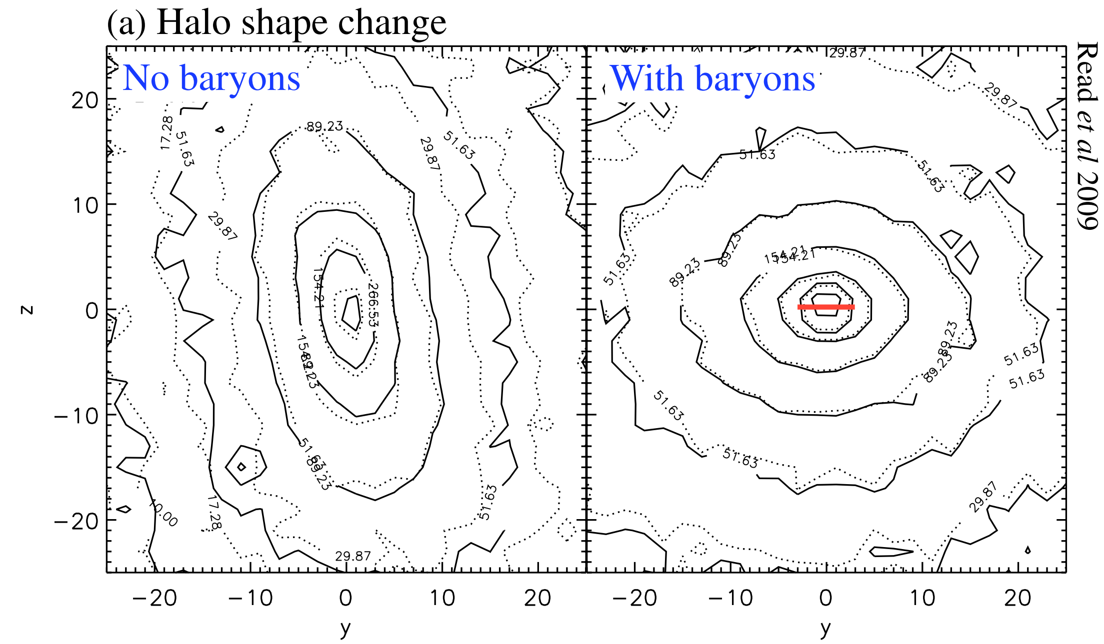
Number density of X-ray emitting PBHs

$$\frac{dN}{d\dot{M}} = N_{\mathrm{PBH,disk}} \int_{n_{\min}}^{n_{\max}} dn \int_0^{\infty} dv \frac{df_n}{dn} \frac{df_v}{dv} \delta[\dot{M}(n,v) - \dot{M}]$$

Agol & Kamionkowski 2002

- To compare X-ray binary number density with X-ray emitting PBHs,
  - we need mass accretion rate (or luminosity) function.
    - N_{PBH}: Number of PBHs in a galactic disk
    - df_n/dn : ISM gas distribution
    - df_v/dv : PBH velocity distribution

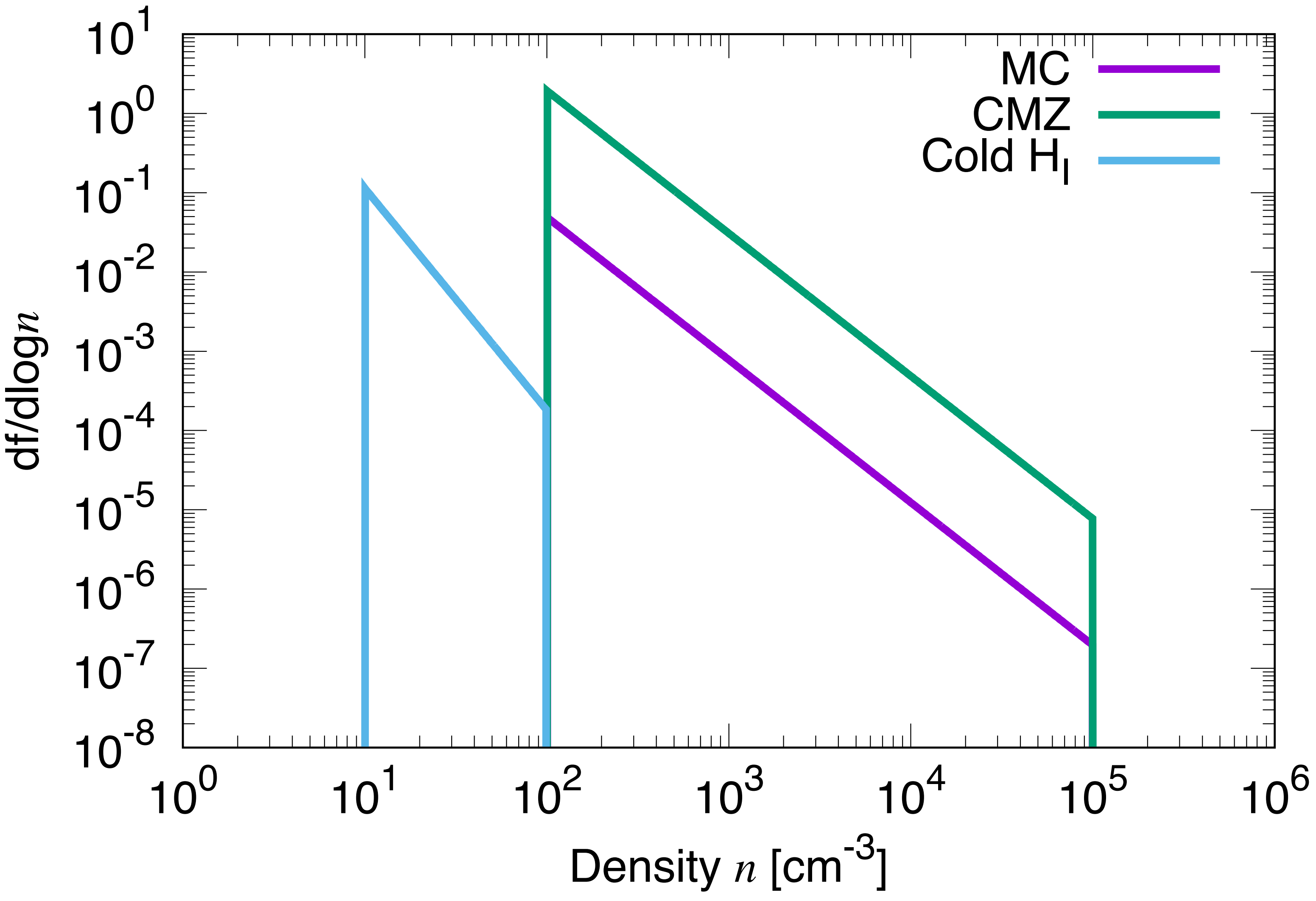
PBH Density and Velocity Distribution



Read 2014

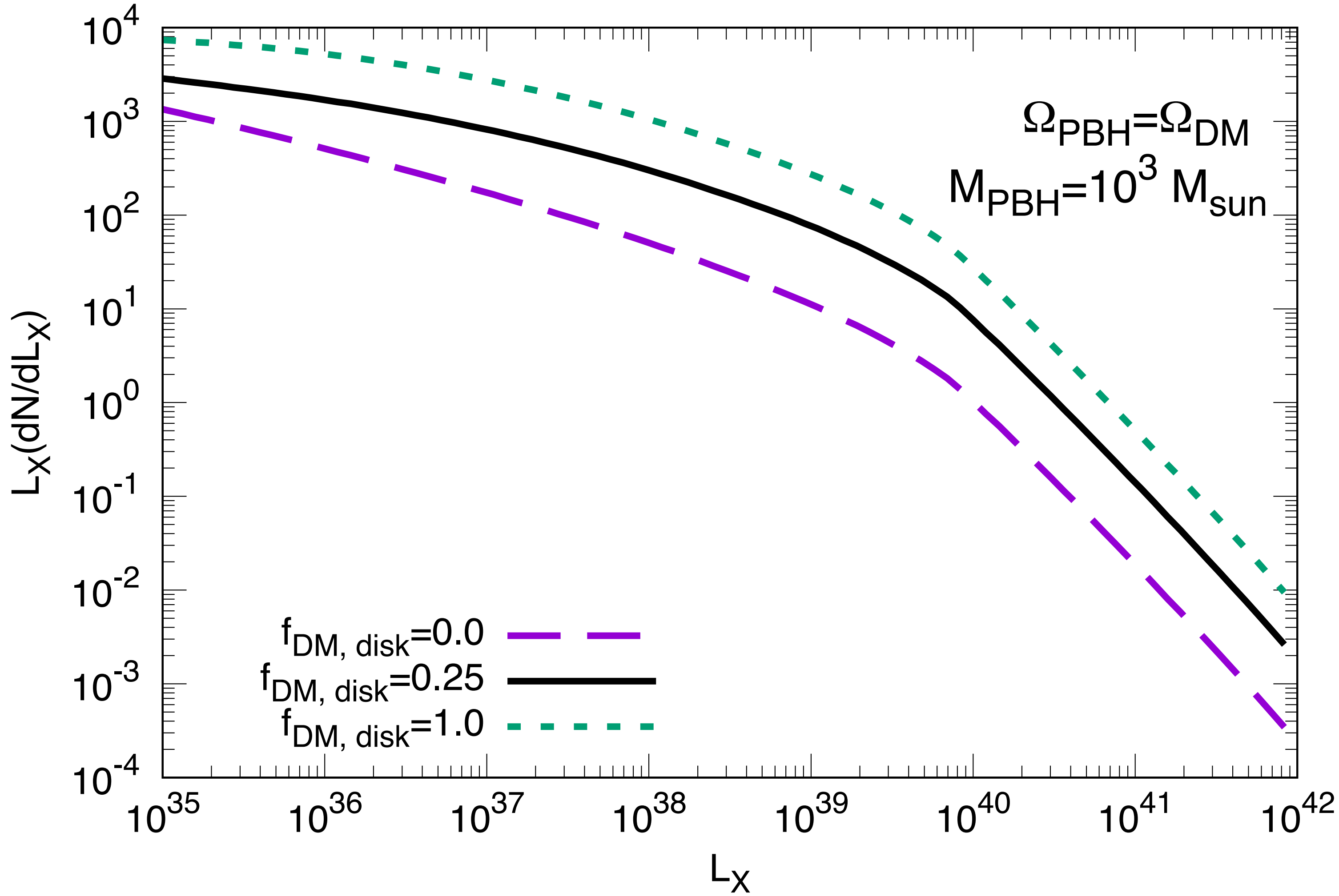
- Navarro-Frenk-White (NFW) profile
- Assume Maxwellian distribution for velocity
  - w/ velocity dispersion of 150 km/s (Ling et al. 2010a)
- Galaxy mergers may form a "dark matter" disk (Read et al. 2008, 2009)
  - density of dark disk: 0.25-1.5 of the non-rotating DM density
  - with low velocity dispersion 50 km/s (Read et al. 2008, 2009; Bruch et al. 2009; Ling 2010b)

ISM Gas Distribution



- We need the volume of the Galaxy filled by gas
- We consider molecular gas, HI gas, central molecular zone (CMZ)
  - We assume power-law distribution (e.g., Berkhuijsen 1999)

Expected Luminosity Function



- We assume radiative efficiency scales with accretion rate as

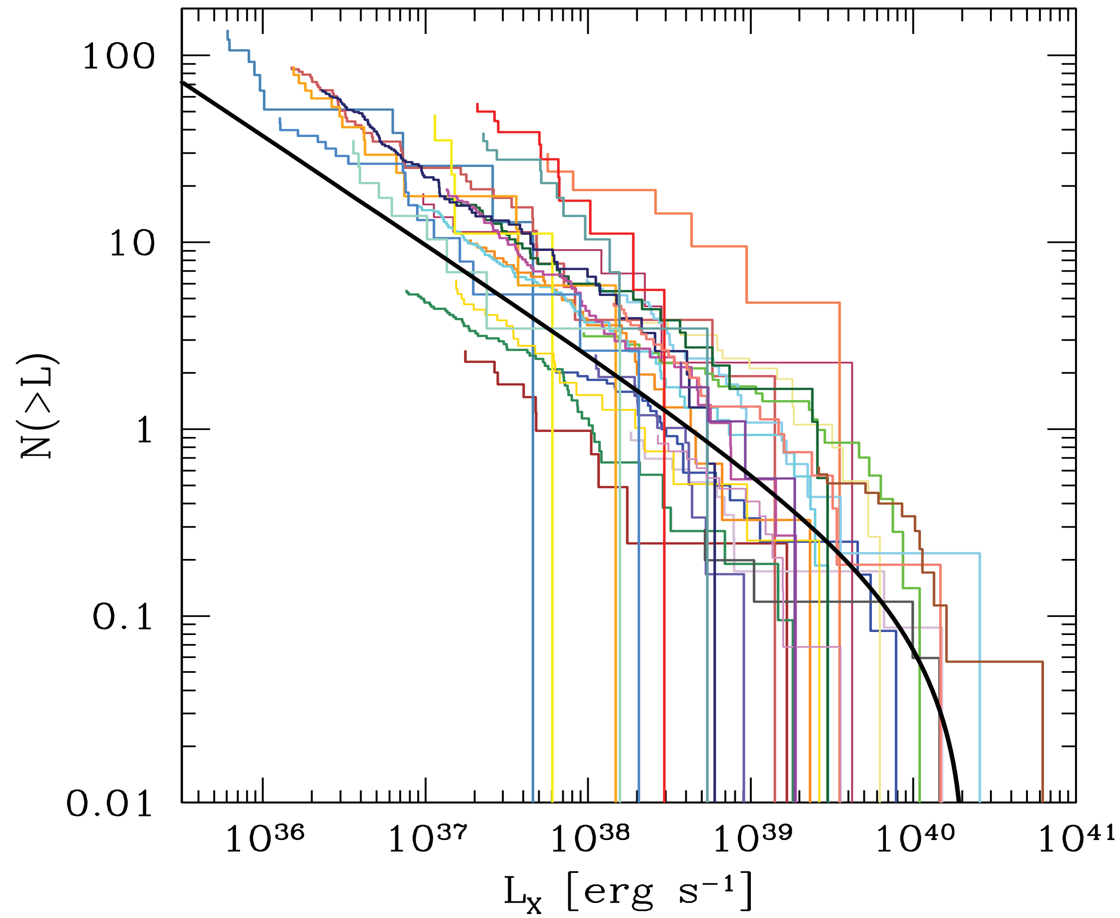
$$\epsilon(\dot{M}) = 0.1/[1.0 + (\dot{M}/0.01\dot{M}_{\rm Edd})^{-1}]$$

- Broken power-law shape is expected due to radiative efficiencies and ISM distributions.

- However, PBH X-ray luminosity function should not overproduce observed XRBs.

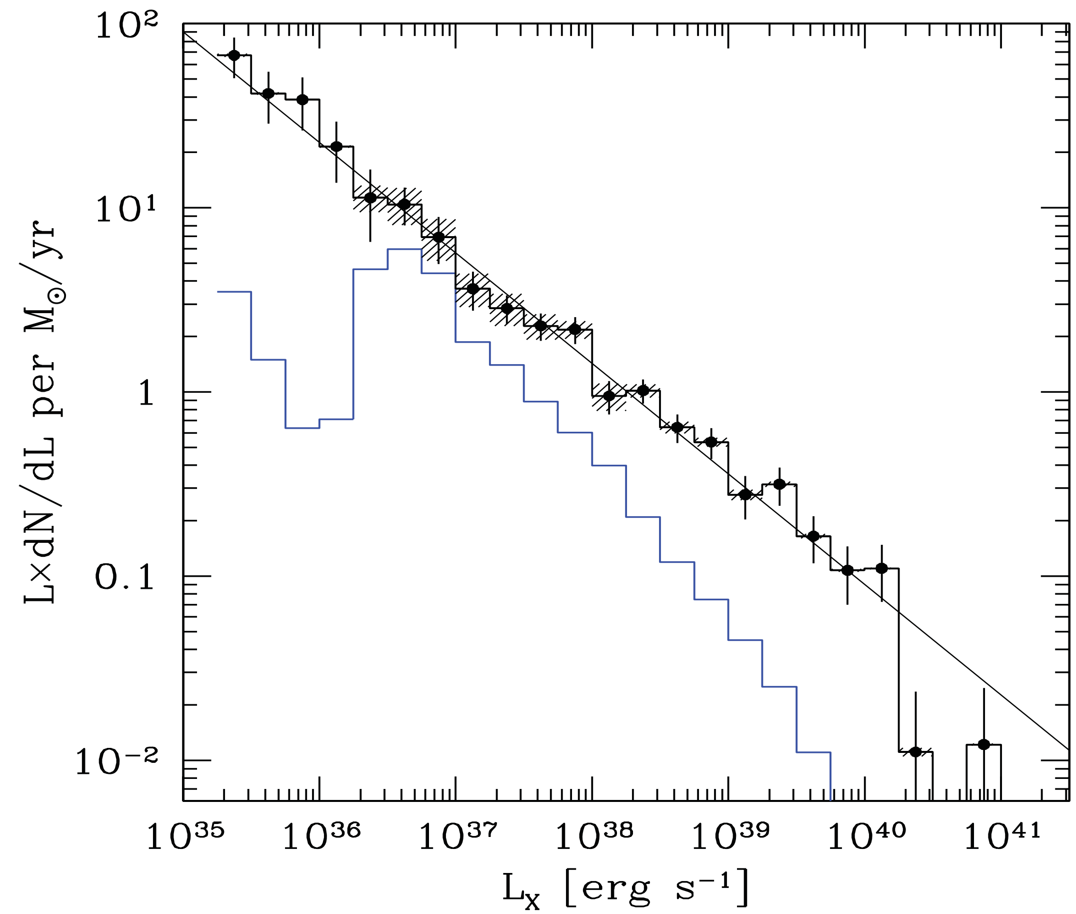
Distribution of X-ray Binaries

XRBs in each galaxy



Mineo et al. 2012

SFR normalized XRB LF



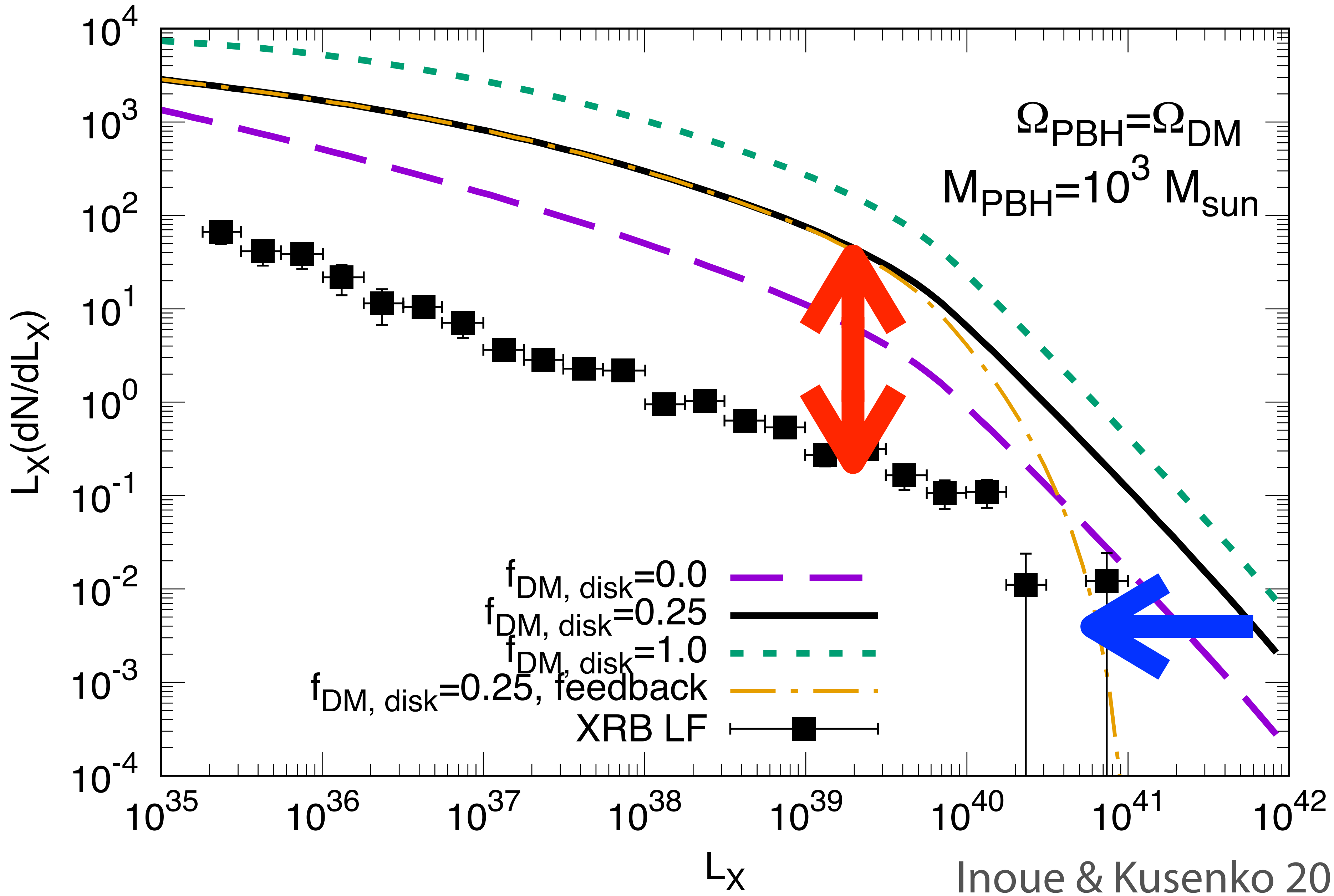
Mineo et al. 2012

- XRB luminosity function is known to be correlated with star formation rate (e.g., Mineo et al. 2012)

- A simple power-law (γ~1.6) + cutoff (10^{40} erg/s)

(e.g. Grimm et al. 2003; Swartz et al. 2011; Walton et al. 2011; Mineo et al. 2012).

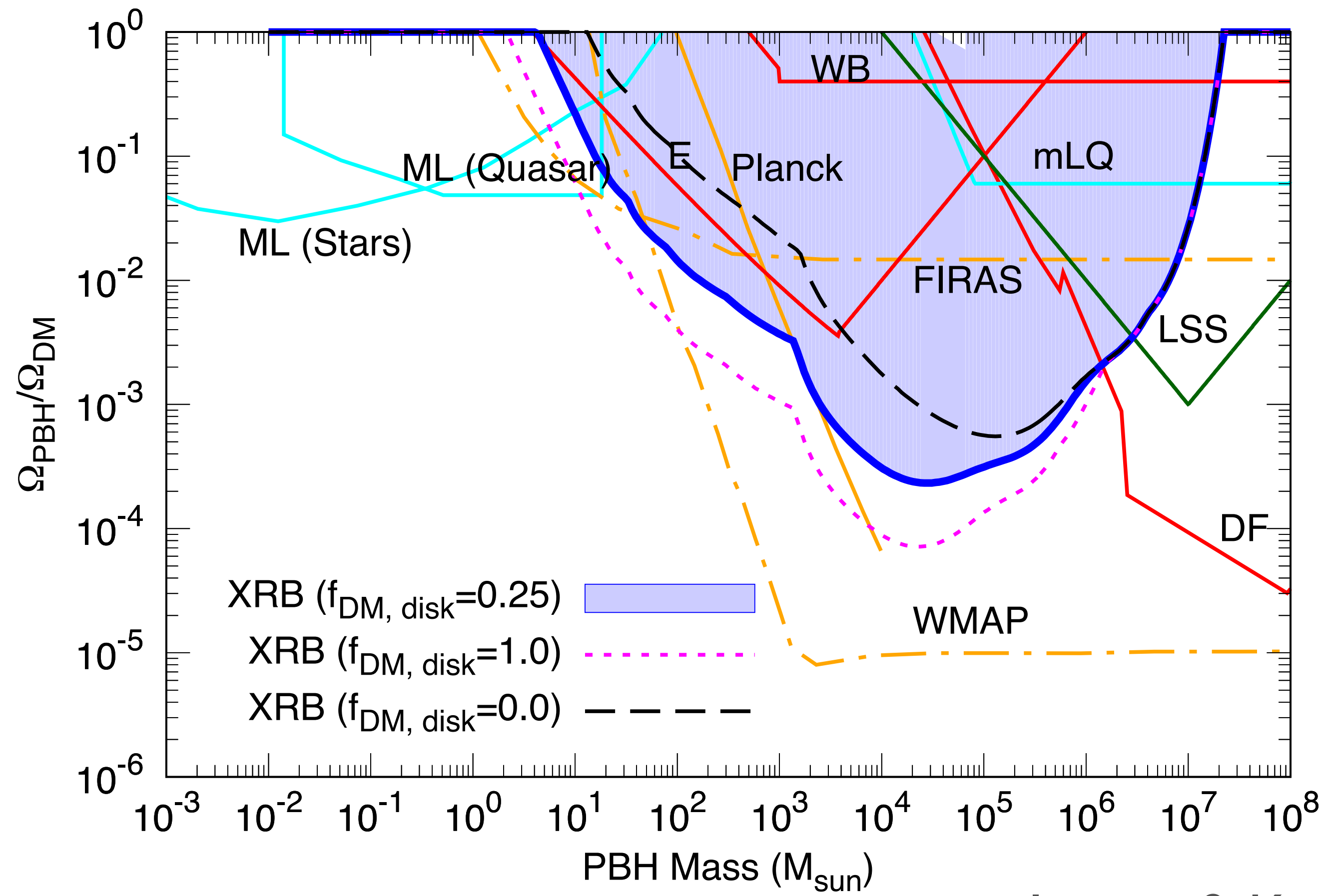
Comparison with XRB Luminosity Function



Inoue & Kusenko 2017

- Assume the Milky way (SFR = 1 M_{sun}/yr)
- constraints come from high luminosities
  - radiation feedback (e.g., Fukue & Ioroi 1999) will loosen constraints, but only at ~L_{Edd}

New Constraint on PBHs from X-ray

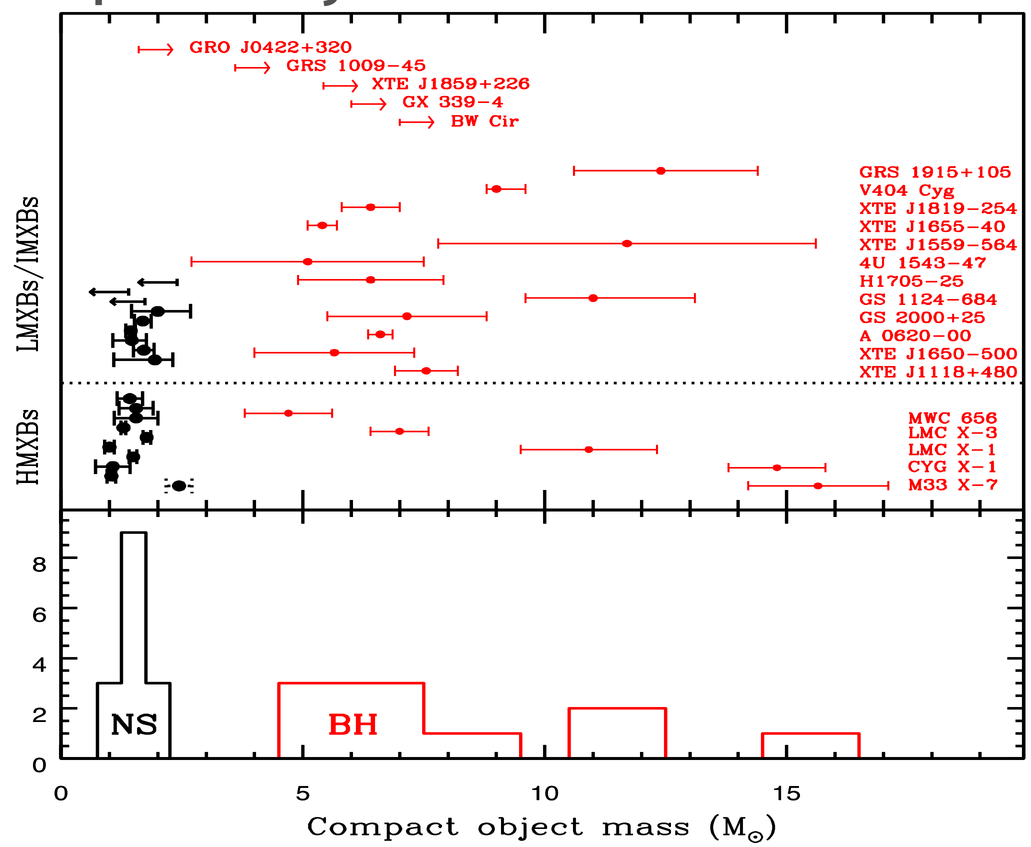


Inoue & Kusenko 2017

- $\Omega_{PBH} = \Omega_{DM}$ is excluded at stellar and intermediate mass ranges
  - PBHs scenarios for LIGO events are still viable (see e.g., Sasaki et al. 2017)
- Similar constraints are obtained by independent study by Gaggero et al. 2017

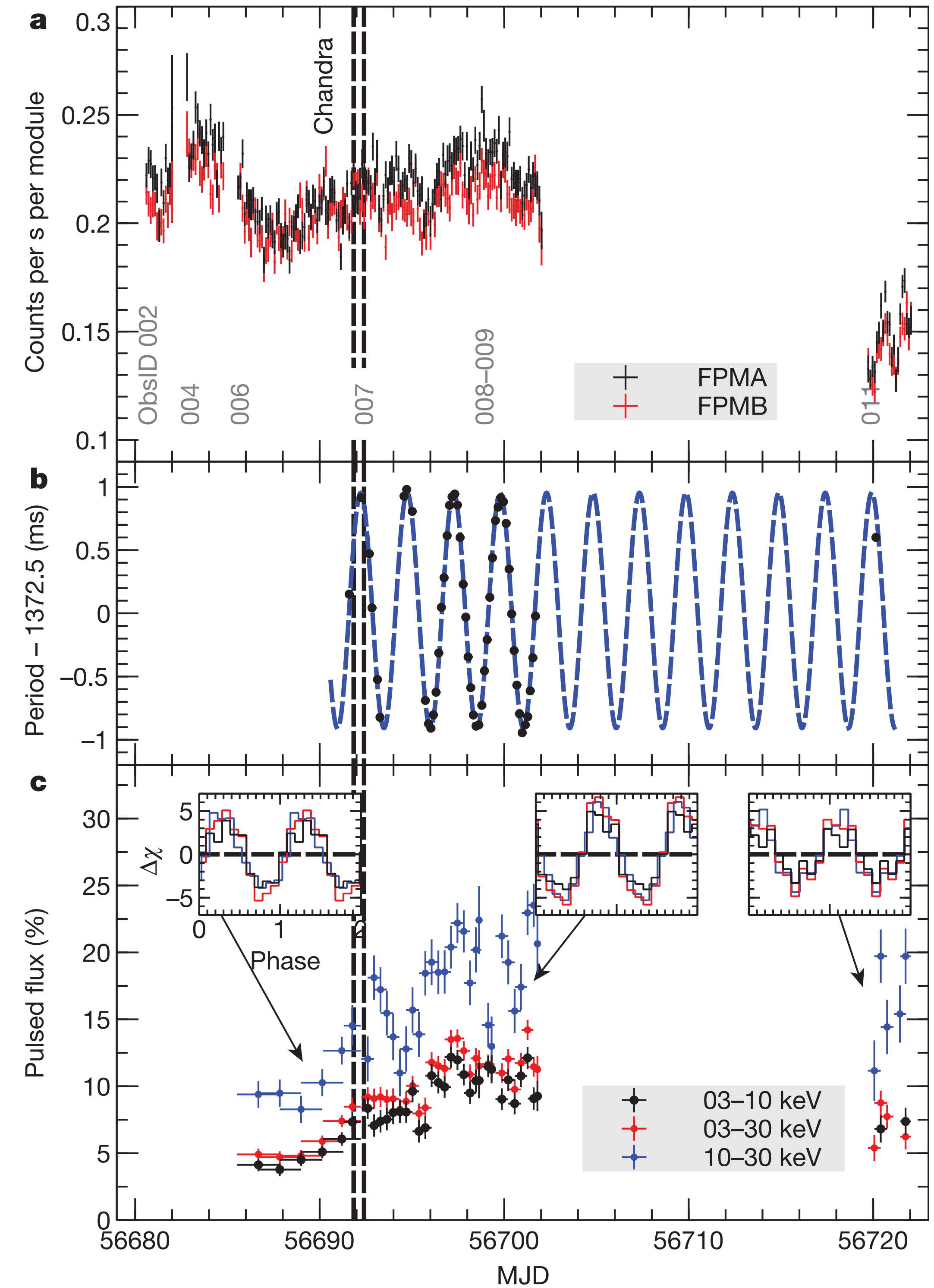
Contamination of Neutron Stars

Compact object mass distribution of XRBs



Casares et al. 2017

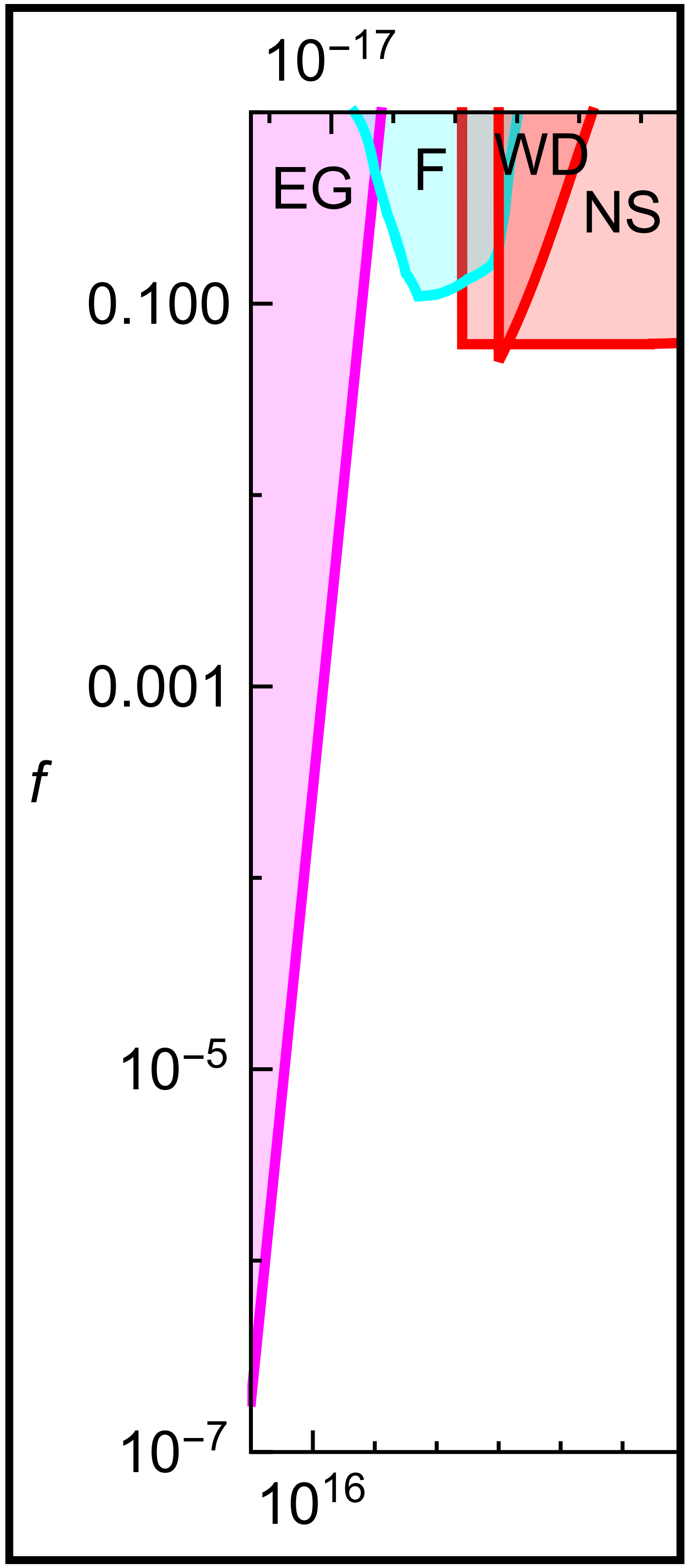
Pulsar powered ULX



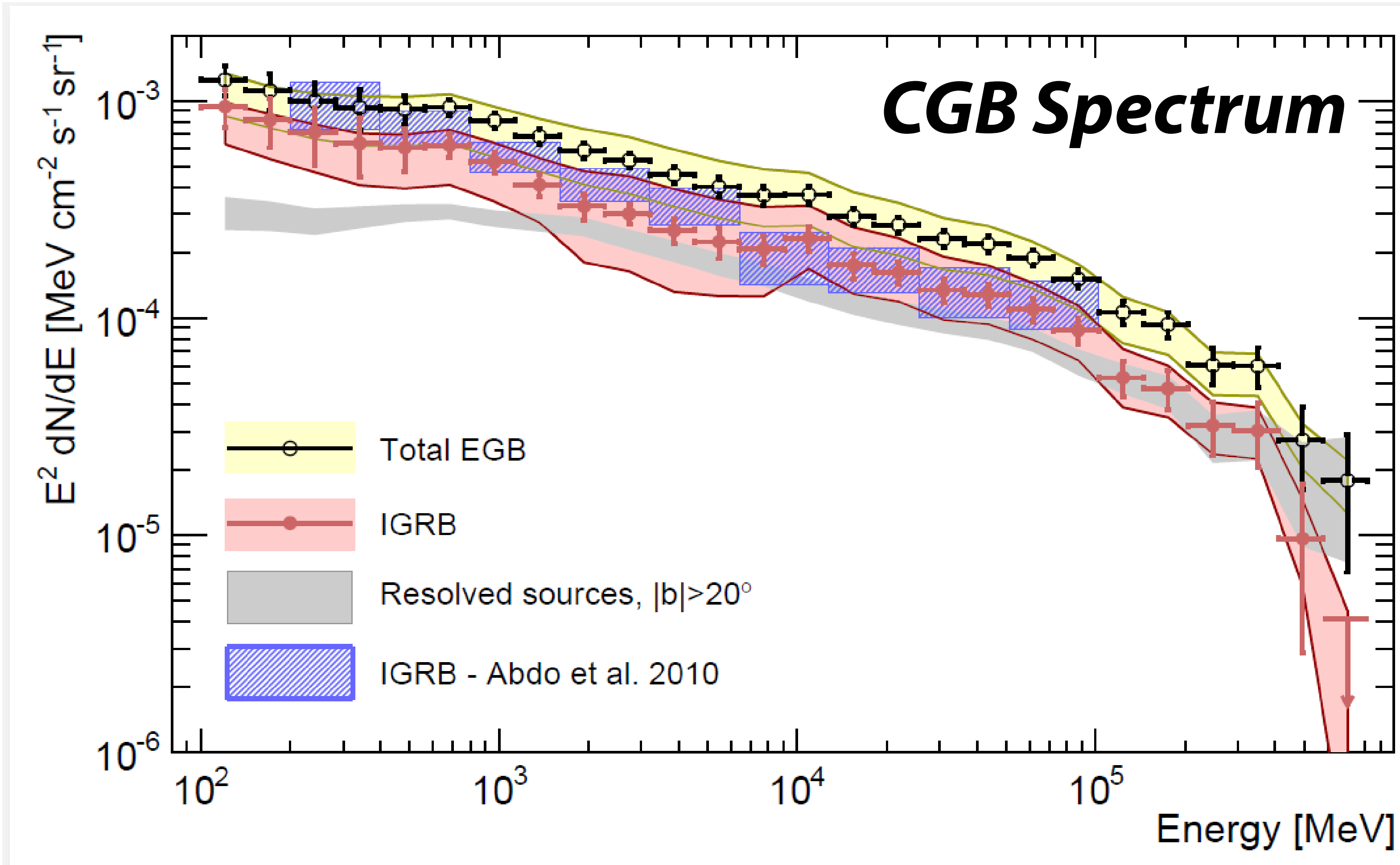
Bachetti et al. 2014

- Some XRBs are hosted by neutron stars.
  - 3 ULXs powered by pulsars (Bachetti et al. 2014; Israel et al. 2016a,b, Fuerst et al. 2016).
- need to understand the "BH" XRB population.

Cosmic Gamma-ray Background



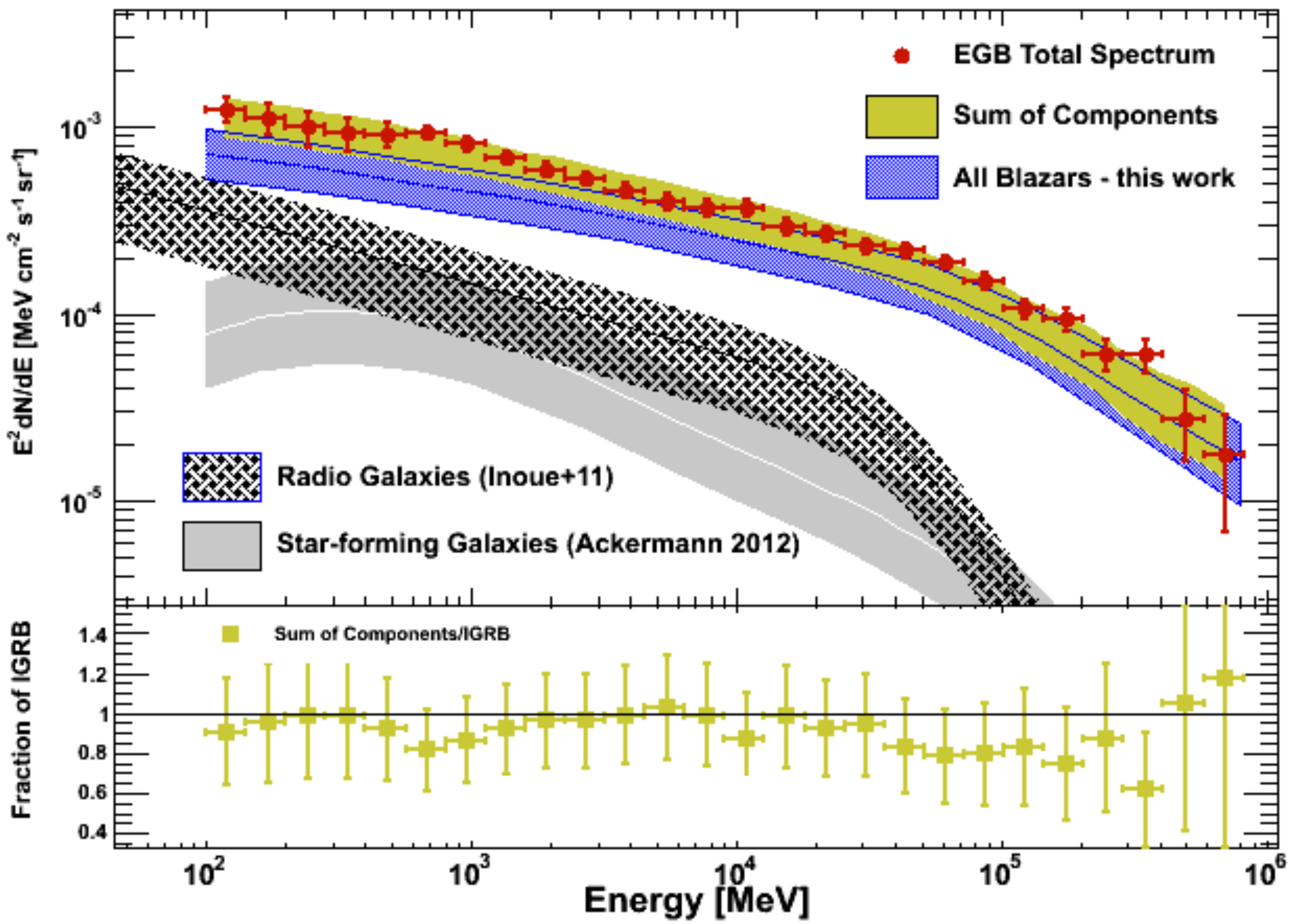
Carr et al. 2016



Ackerman+'15

- Fermi has resolved 30% of the CGB at ~1 GeV and more at higher energies.
- Current constraint on PBHs are based on the measured total (or unresolved) CGB spectrum.

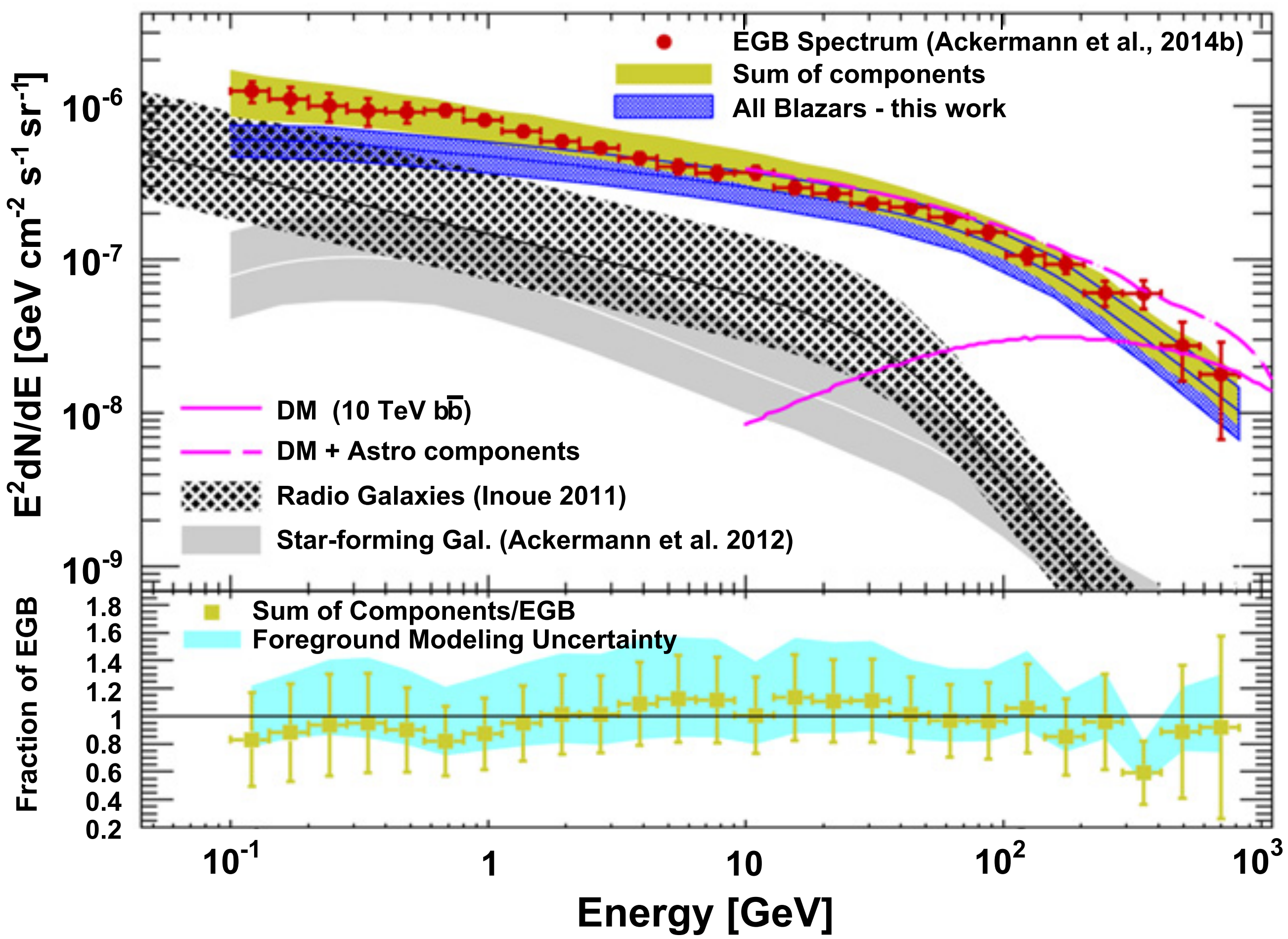
Components of Cosmic Gamma-ray Background



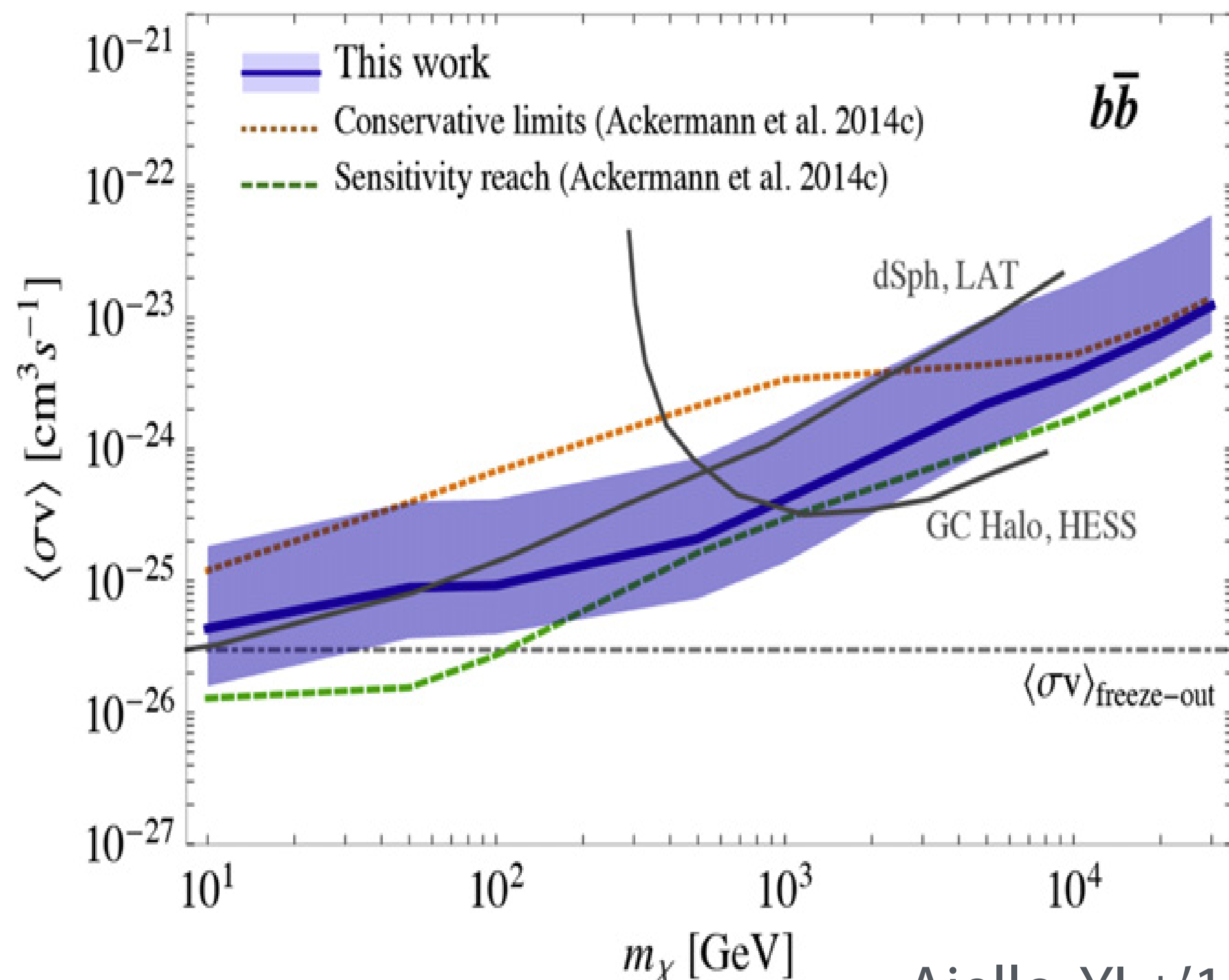
Ajello, YI +'15

- FSRQs (Ajello+'12), BL Lacs (Ajello+'14), Radio gals. (YI'11), & Star-forming gals. (Ackermann+'12) makes ~100% of CGB from 0.1-1000 GeV.

CGB spectrum from DM particles



Ajello, YI +'15



Ajello, YI +'15

- DM annihilation creates a feature in the spectrum.
  - comparable to constraints from dwarfs by Fermi
  - Similar exercise for PBHs (x10 times stronger constraint)

Summary

- Primordial black holes will shine in X-ray through the Bondi-Hoyle-Lyttleton accretion process.
  - X-ray binary observations put constraints on the PBH abundance.
  - $\Omega_{PBH} = \Omega_{DM}$ is excluded at stellar and intermediate mass ranges.
    - PBH scenarios for LIGO events are still viable.
- Composition of cosmic gamma-ray background is now understood: blazars, radio galaxies, star forming galaxies
  - x10 better constraints will be obtained for PBHs.