Dark Black Holes

Sarah Shandera

S. Shandera, D. Jeong, H.Grasshorn Gebhardt (1802.08206, PRL **120**, 2018)

R. Magee, A.S. Deutsch, P. McClincy, C. Horst, D. Meacher, C. Messick, S. Shandera, M. Wade (1808.04772, PRD **98**, 2018) (Chad Hanna's PSU group)

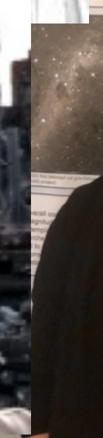
LIGO Scientific Collaboration, Virgo Collaboration and S. Shandera; (1808.04771, PRL **121**, 2018)

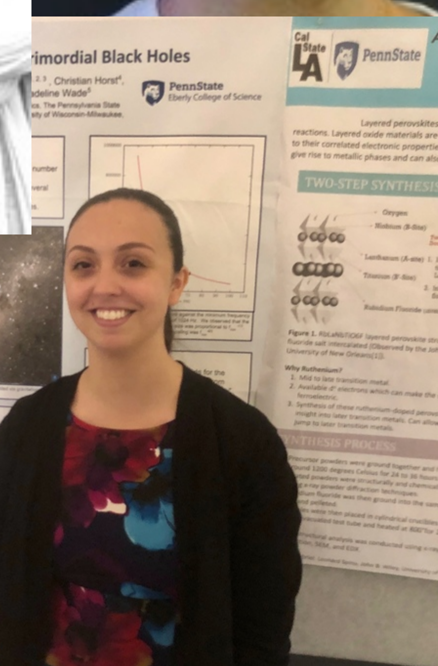
LIGO Scientific Collaboration, Virgo Collaboration and S. Shandera; (1904.08976 PRL **123**, 2019)

Dark Black Holes

Sarah Shandera

Work in progress: Michael Ryan, Divya Singh, Towsifa Akhter





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It is very early in the GW era

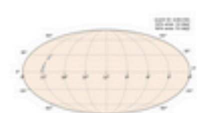
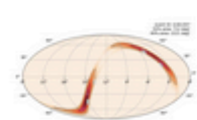
GraceDB — Gravitational-Wave Candidate Event Database

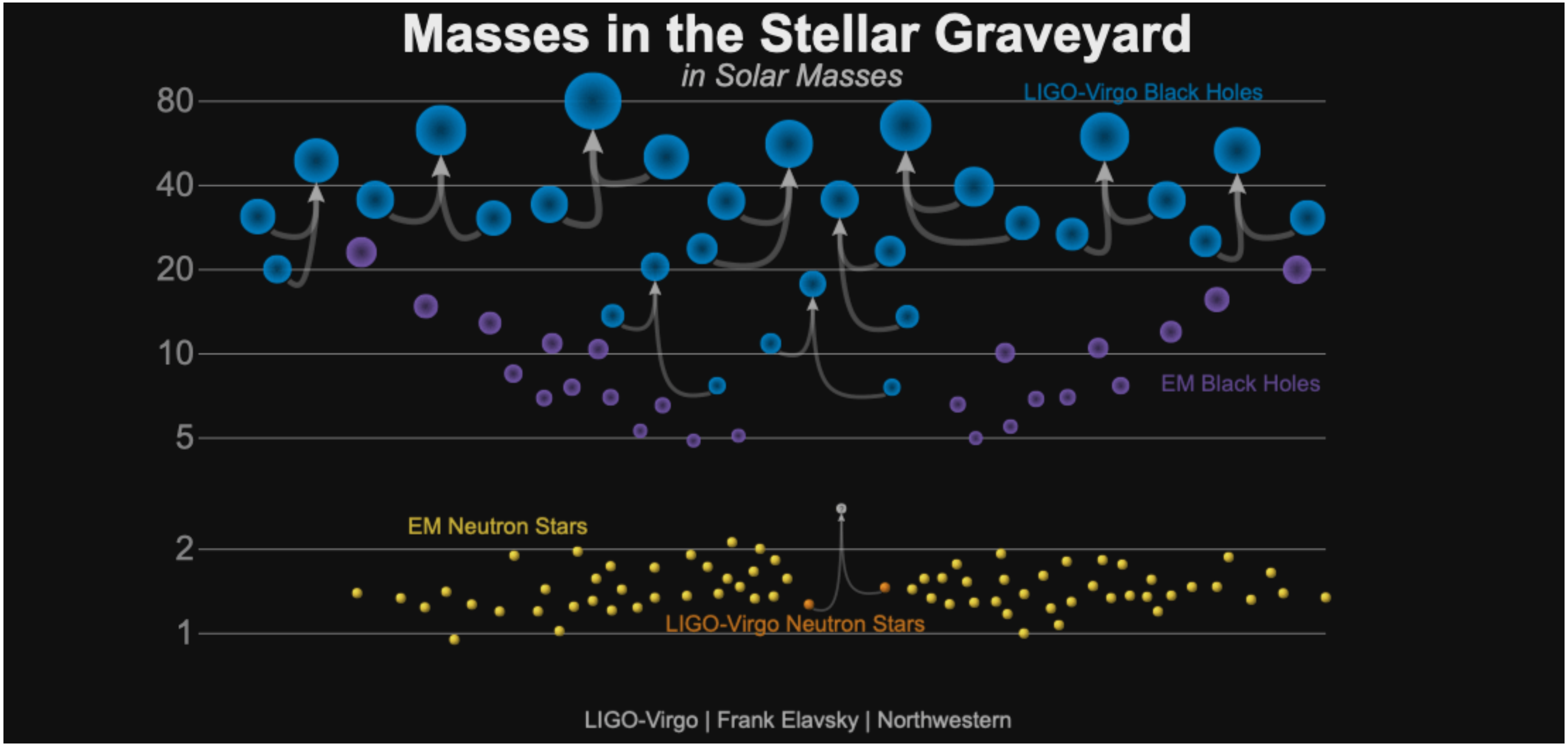
HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION | LOGIN

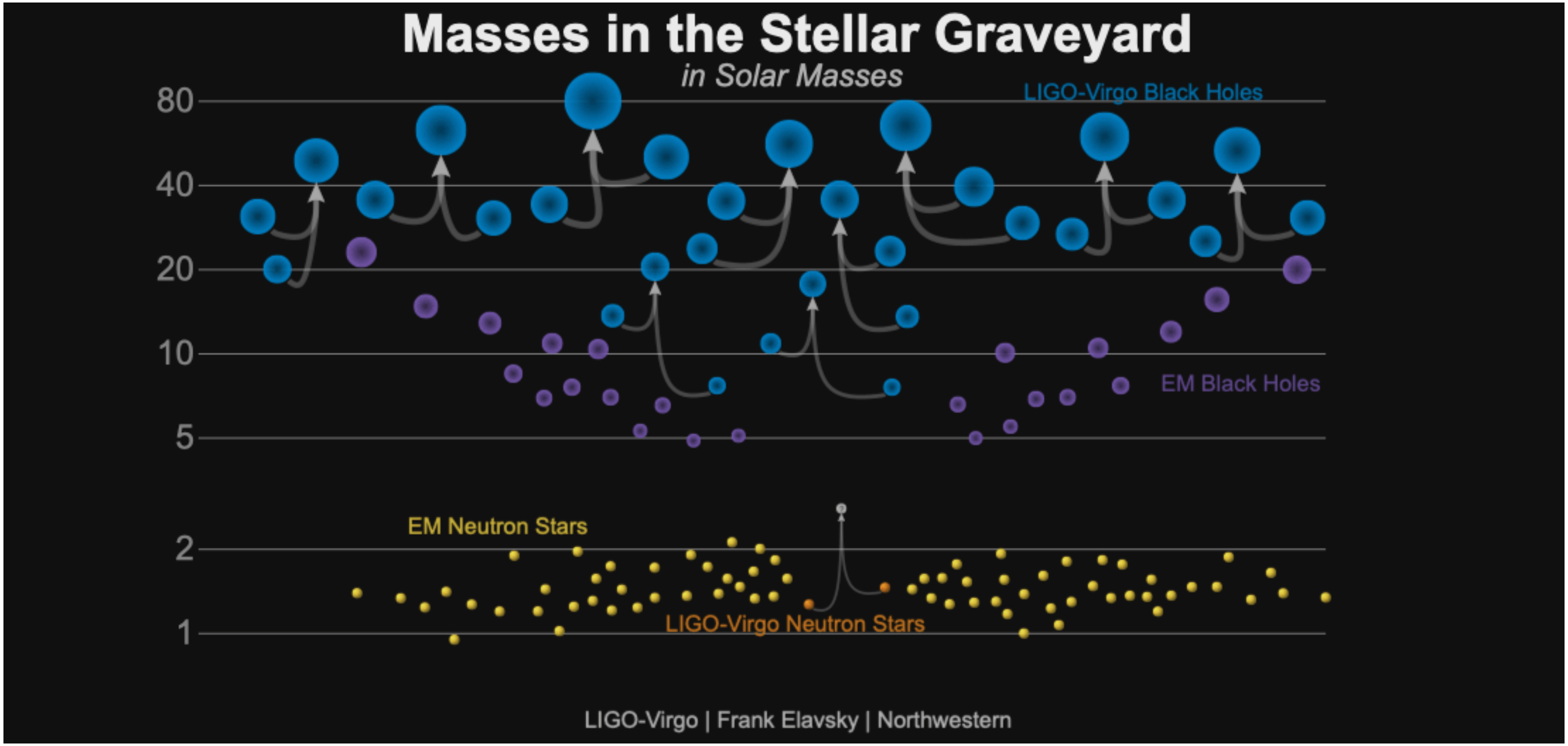
LIGO/Virgo O3 Public Alerts

Detection candidates: 48

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200129m	BBH (>99%)	Jan. 29, 2020 06:54:58 UTC	GCN Circulars Notices | VOE		1 per 4.7313e+23 years	
S200128d	BBH (97%), Terrestrial (3%)	Jan. 28, 2020 02:20:11 UTC	GCN Circulars Notices | VOE		1 per 1.9238 years	


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern



Where did LIGO's objects come from?

What else is out there?

Shandera, KITP, Feb 6 2020

A recently (re-)popular question….

Could black holes (made of normal matter) *be* the dark matter?

See talks by Dror, Kusenko, Profumo

A different question….

Can (new particle) dark matter make black holes?

A different question….

Can (new particle) dark matter make black holes?

Ask this question in the company of the right friends…

A different question….

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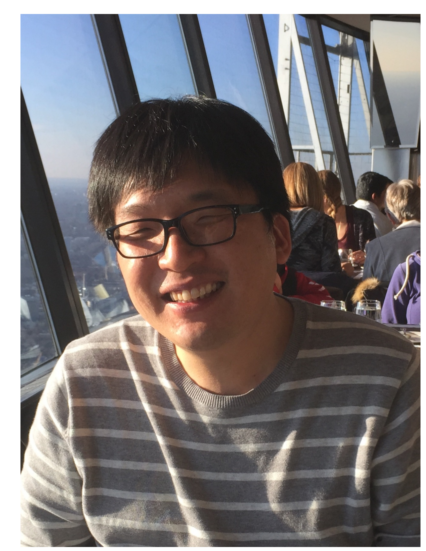
… Sure,

S. Shandera, D. Jeong,
H.Grasshorn Gebhardt
(1802.08206, PRL **120**, 2018)



A different question….

Can (new particle) dark matter make black holes?

Ask this question in the company of the right friends…

… Sure, and LIGO could find them.

S. Shandera, D. Jeong,
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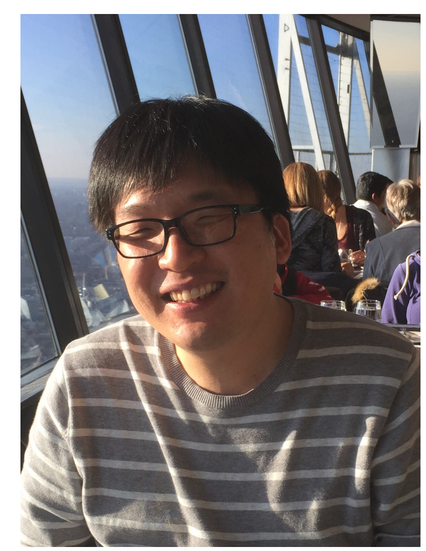

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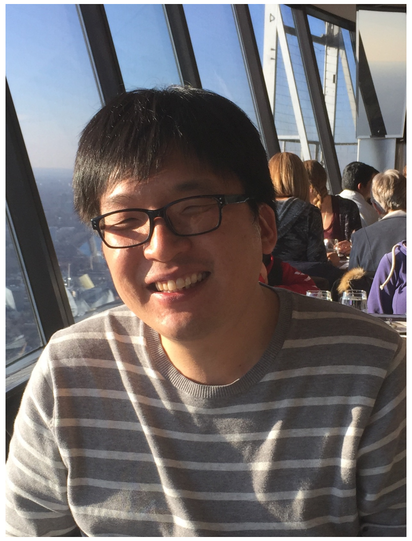


see also: d'Amico et al 1707.03419 (SMBH)
Choquette et al 1812.05088 (SMBH)
Essig et al 1809.01144, 1812.07000,
R. Foot ….

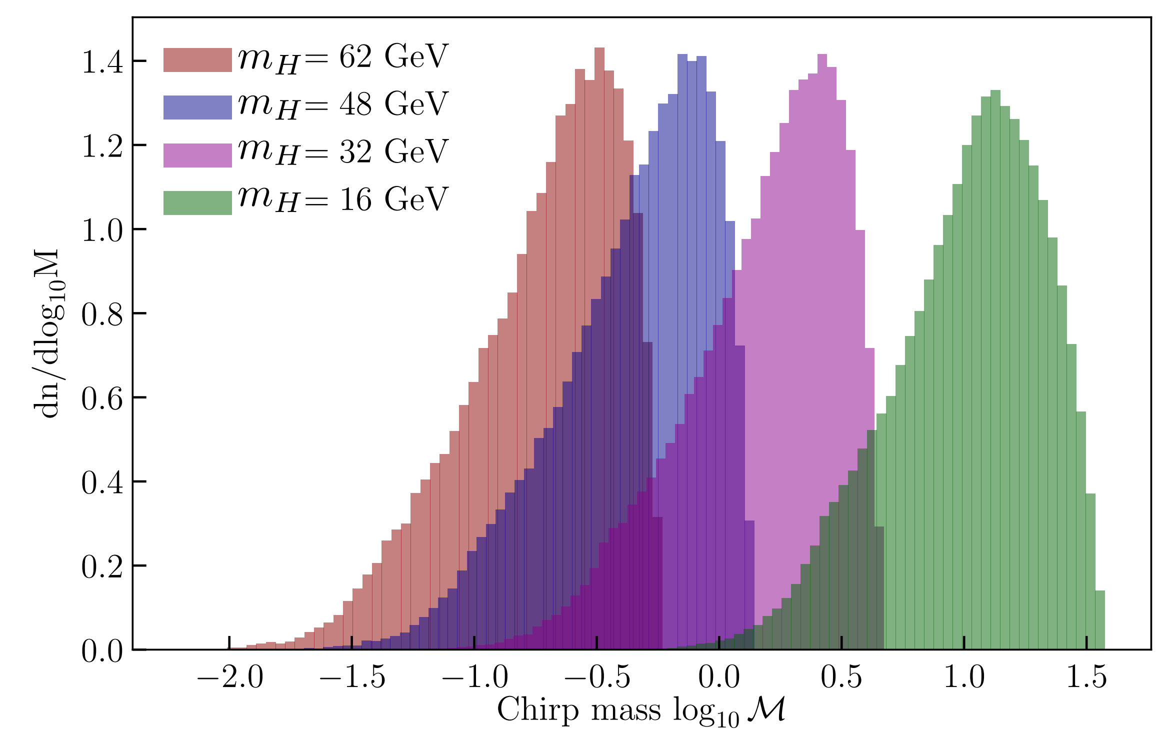
Three claims

(0) LIGO can provide clean new constraints on dark matter physics (with LIGO/VIRGO 1808.04771, 1808.04772, 1904.08976)

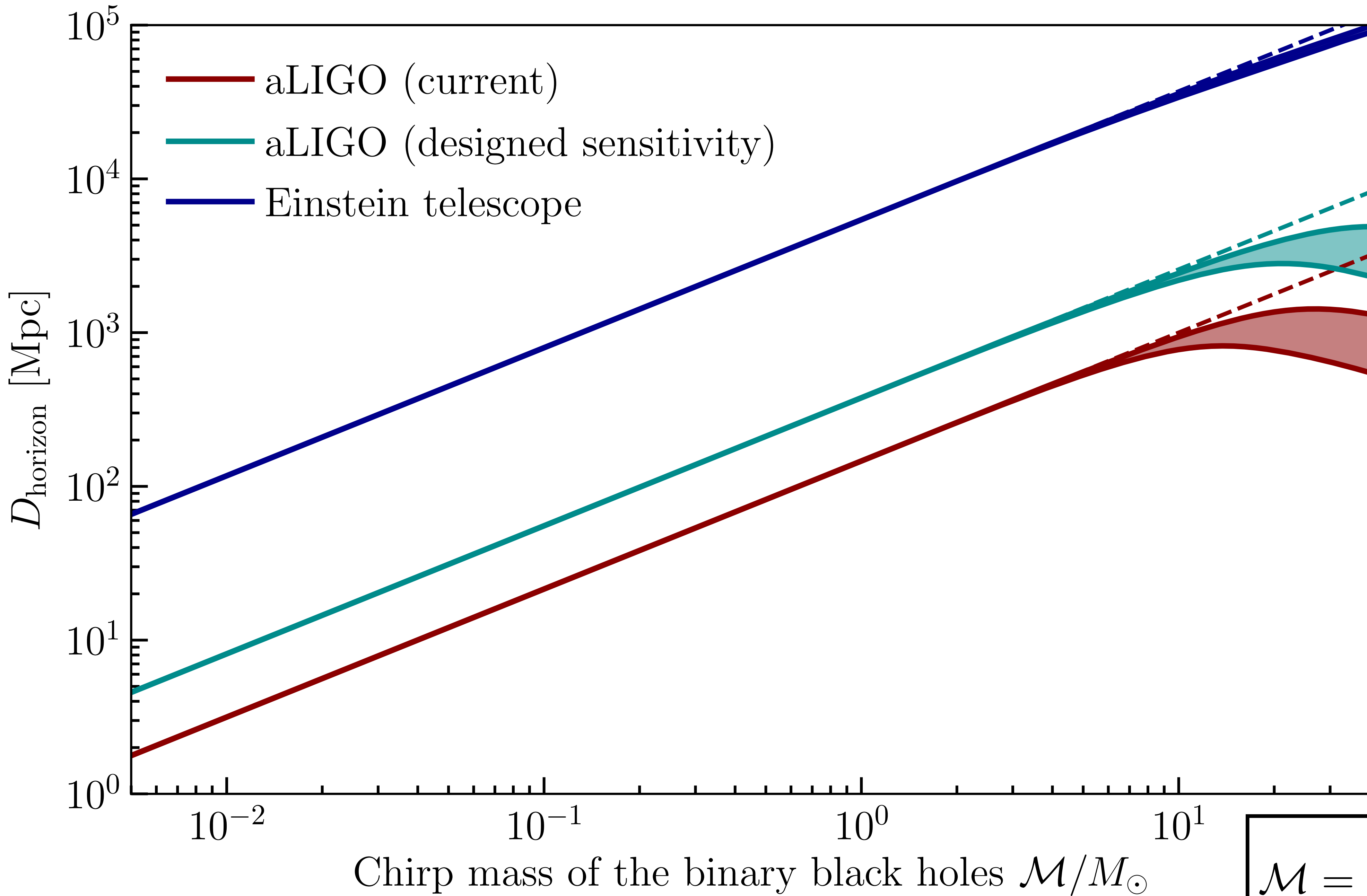
(1) No obvious obstruction to dark black hole formation by dissipative dark matter

(2) Back-of-the-envelope predicts populations accessible by Advanced LIGO

S. Shandera, D. Jeong, H. Gebhardt
1802.08206



(0) Clean new physics discovery space



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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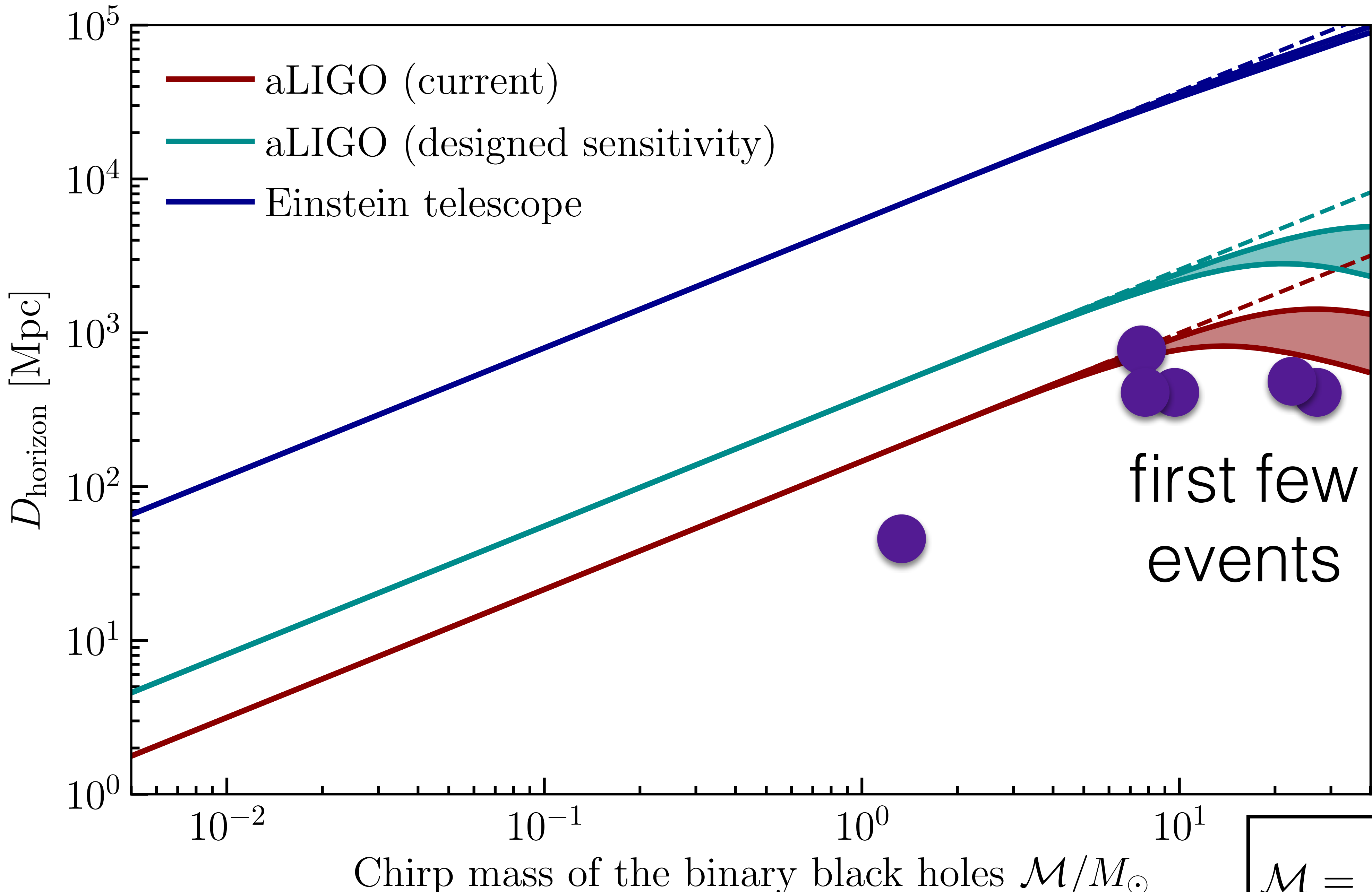

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Shandera, KITP, Feb 6 2020

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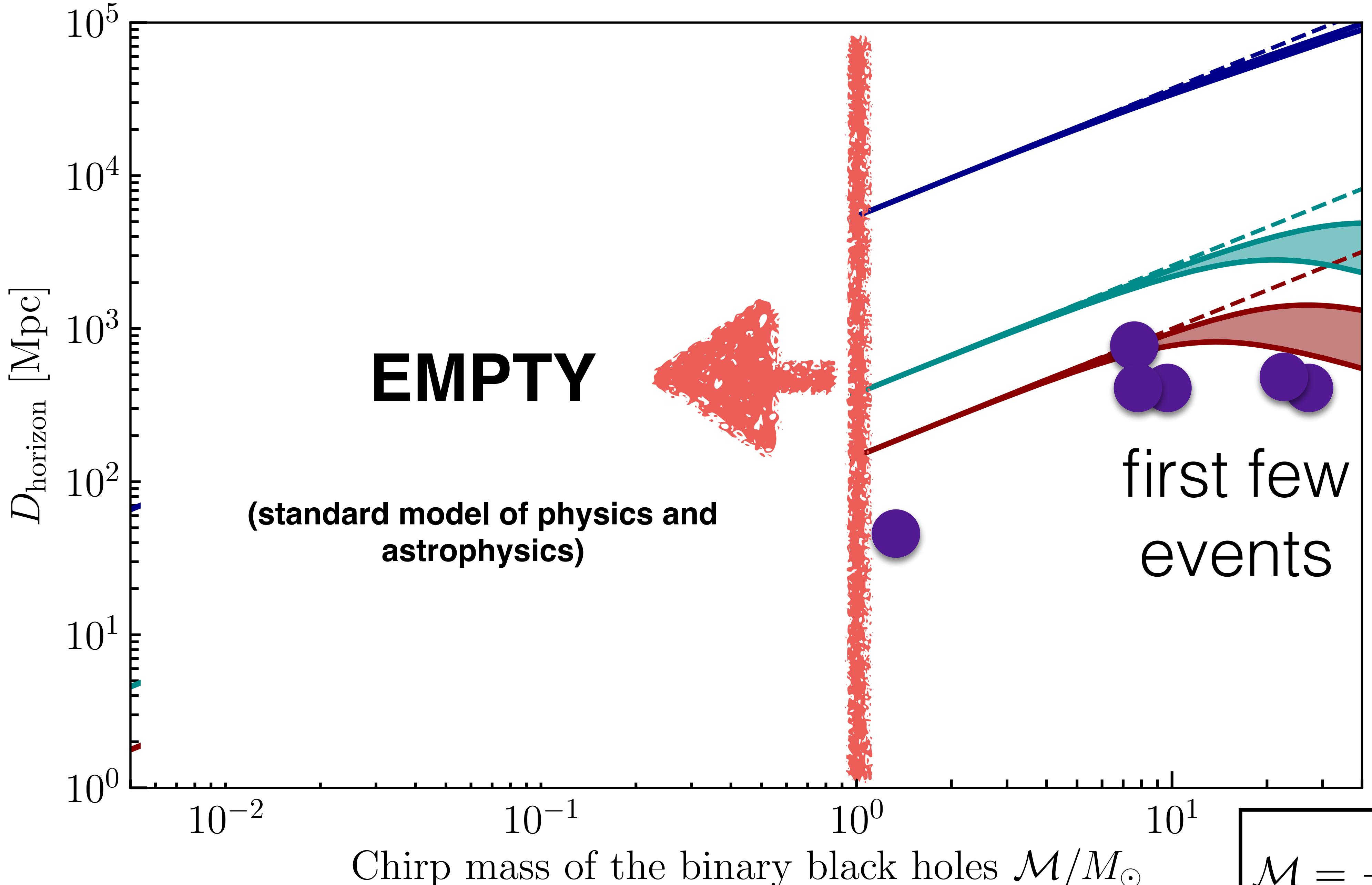

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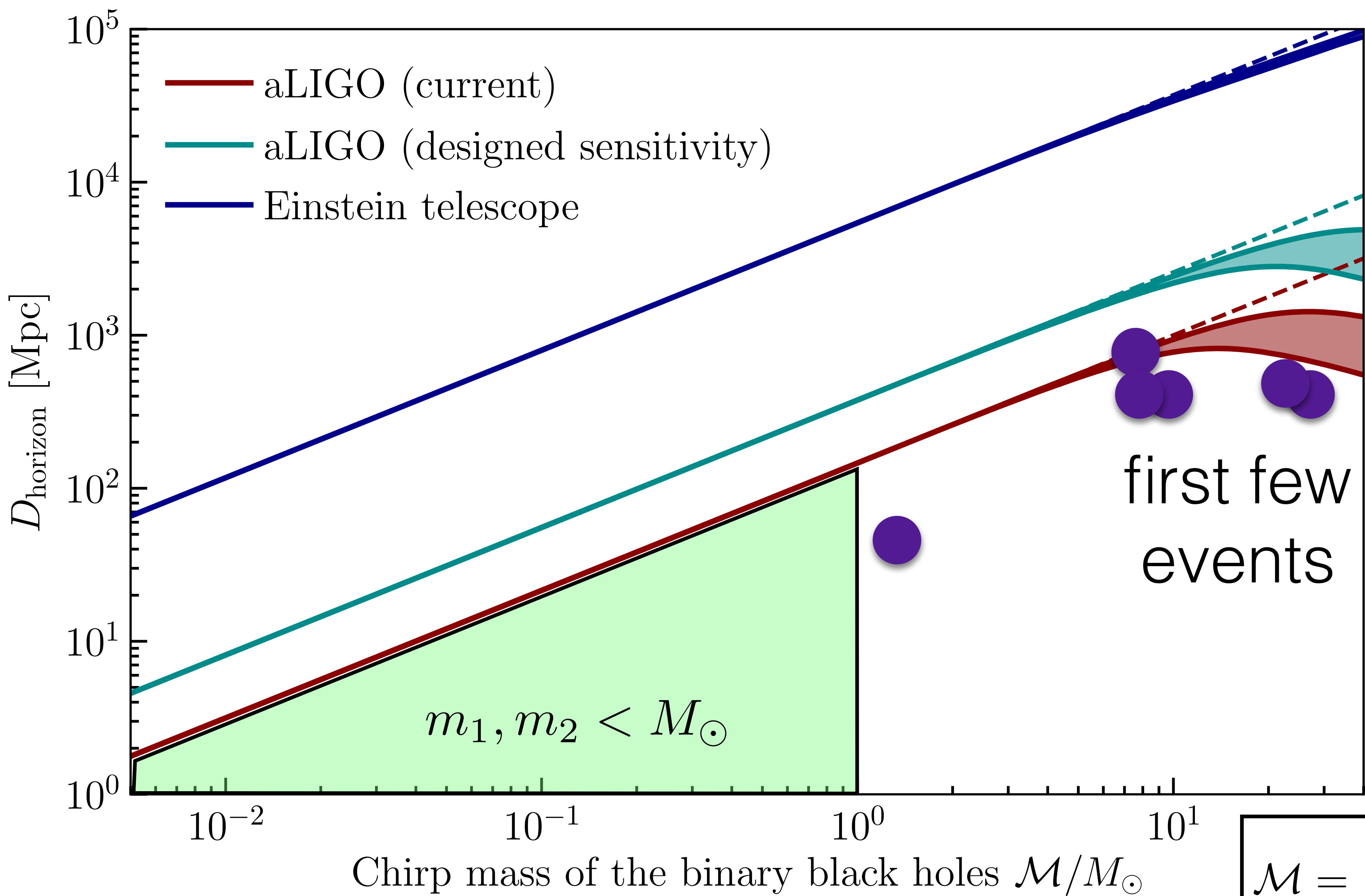

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Shandera, KITP, Feb 6 2020

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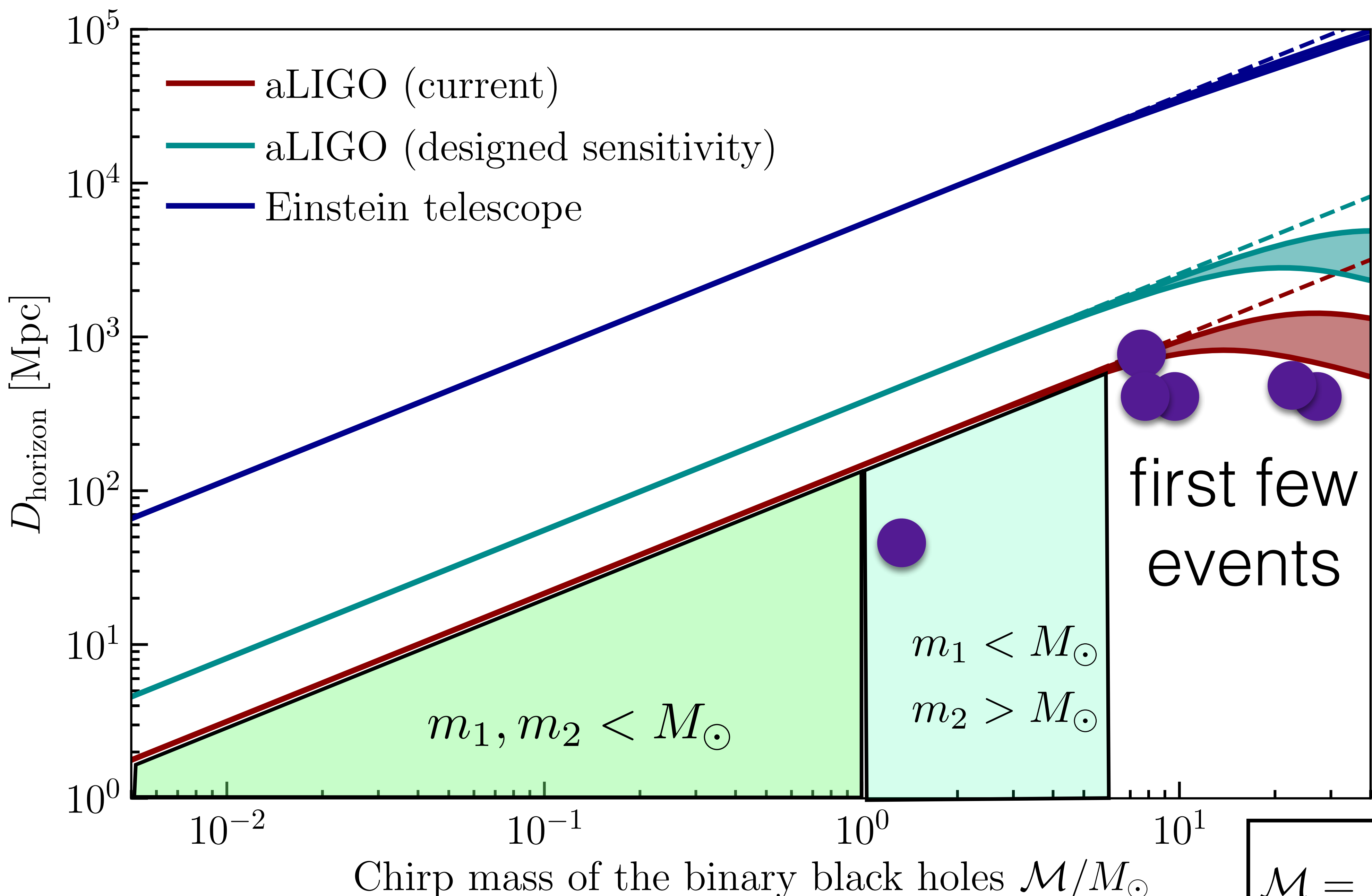

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Shandera, KITP, Feb 6 2020

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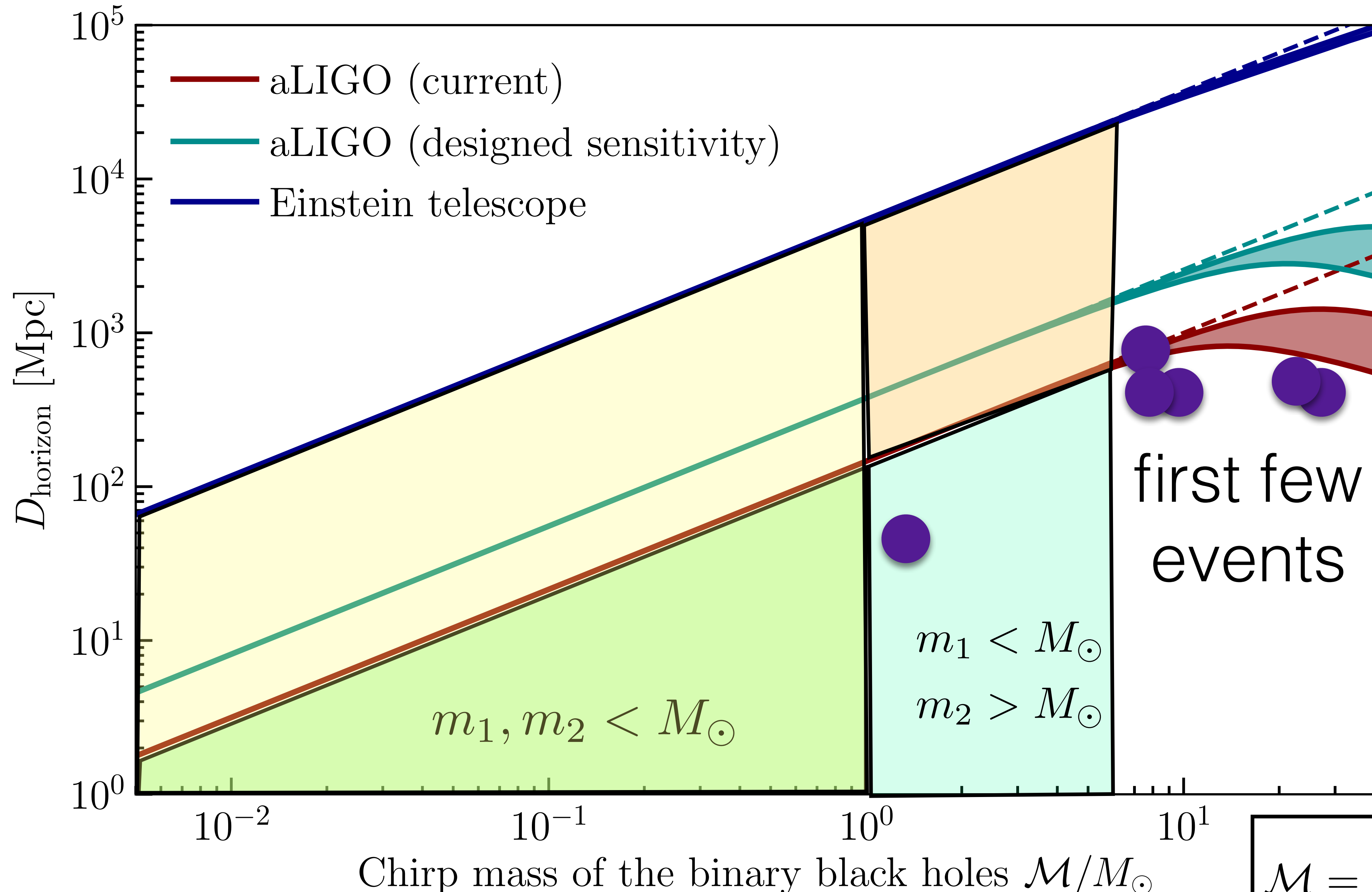

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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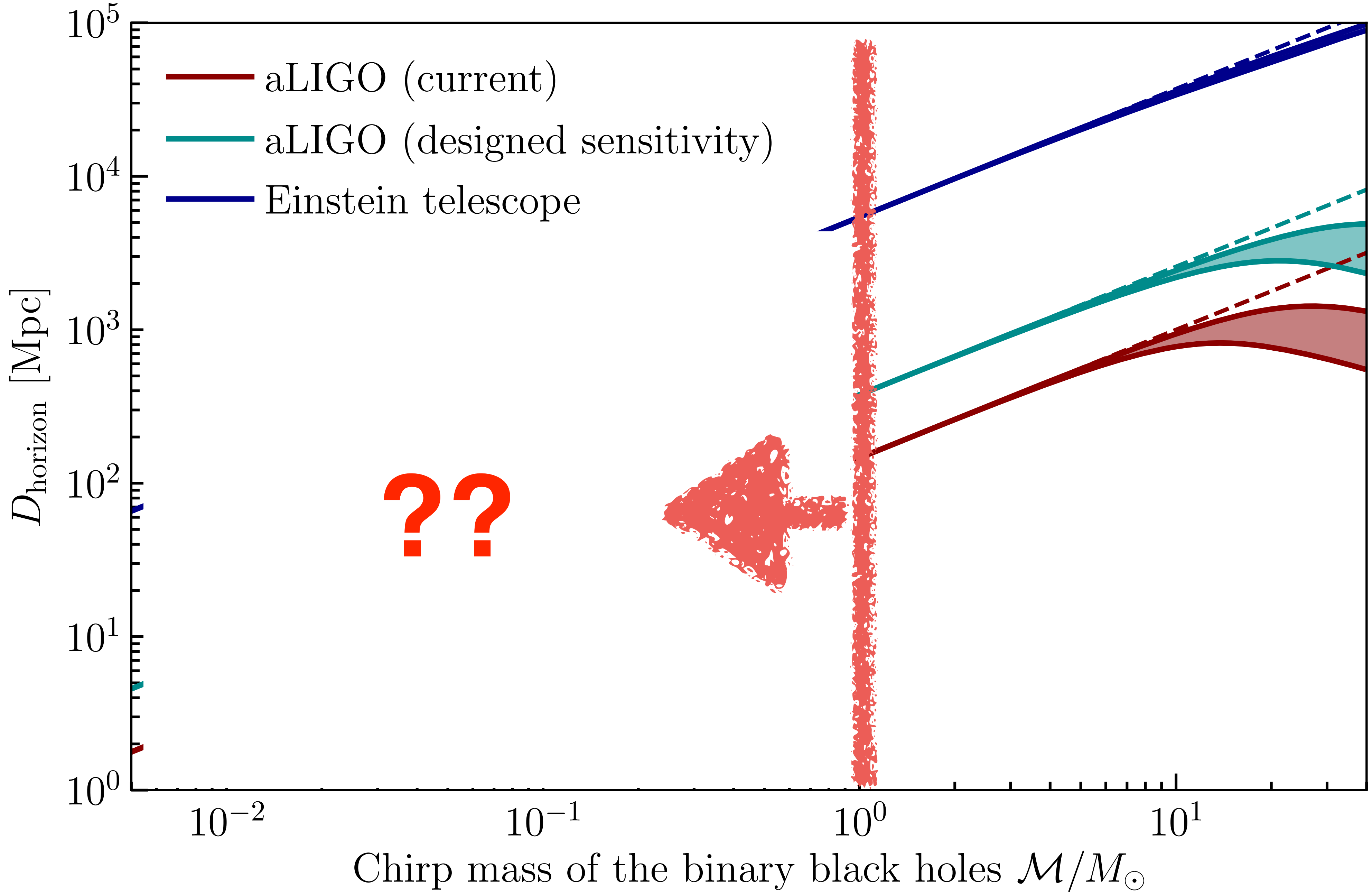
Could there be something there?



Data exists….doing the search takes time and resources

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LIGO and Dark Matter

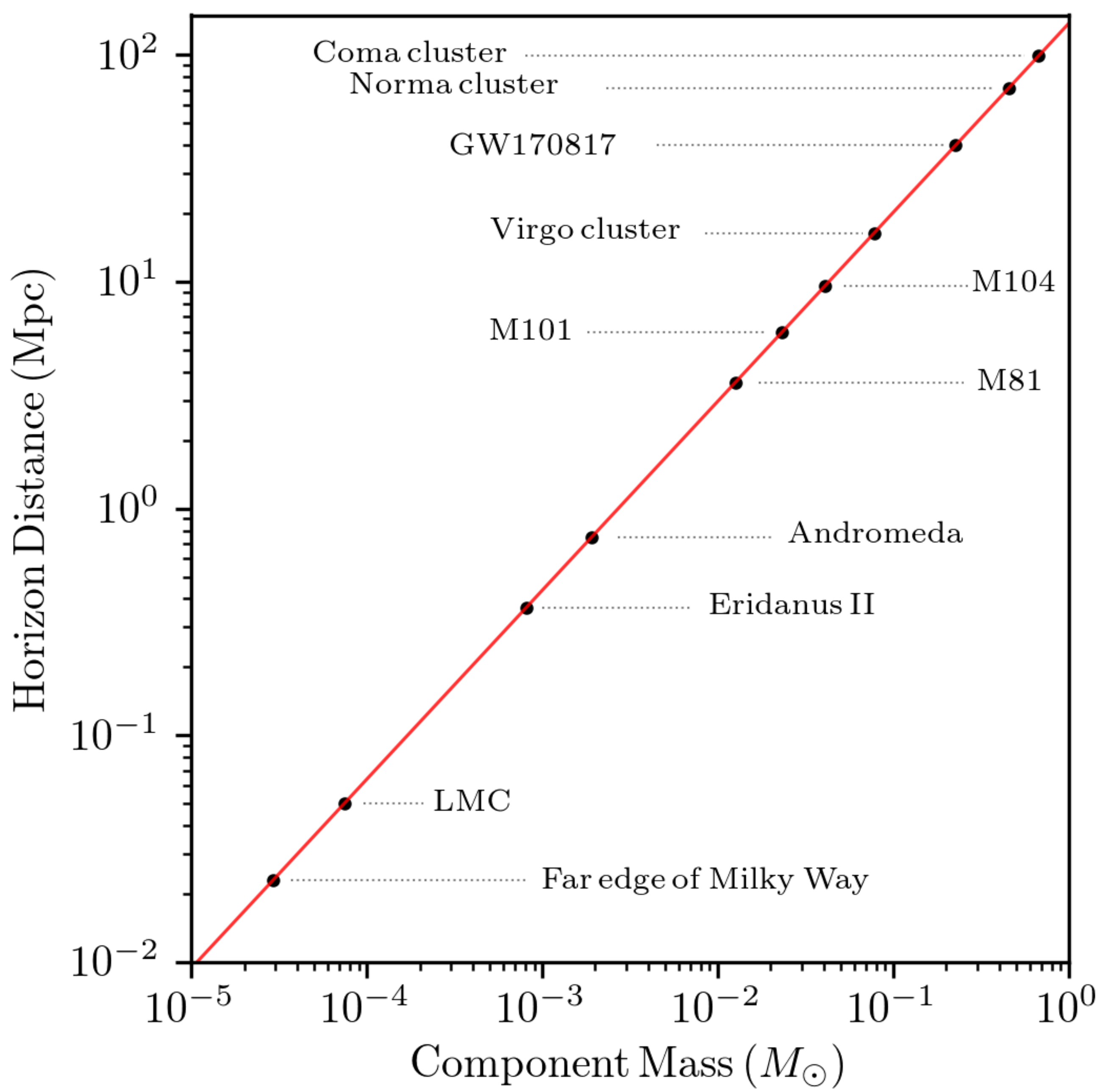


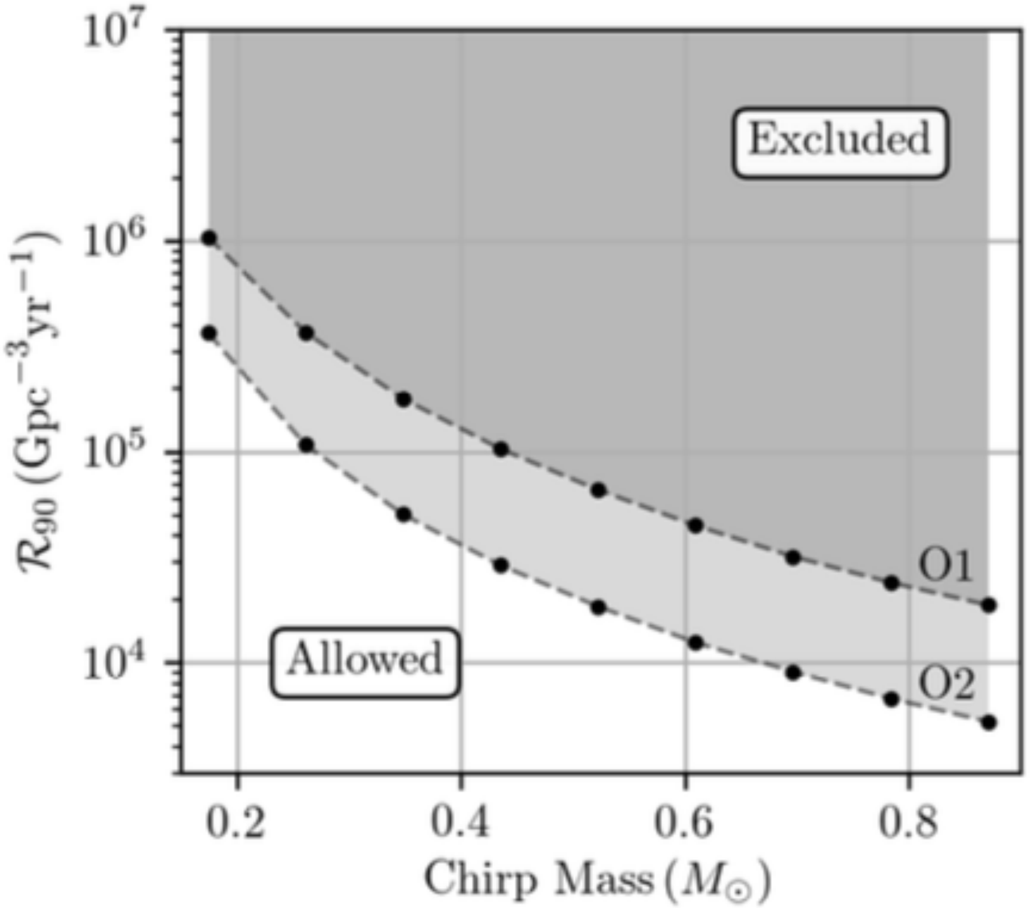
figure by Ryan Magee

Detections do not depend on particle physics

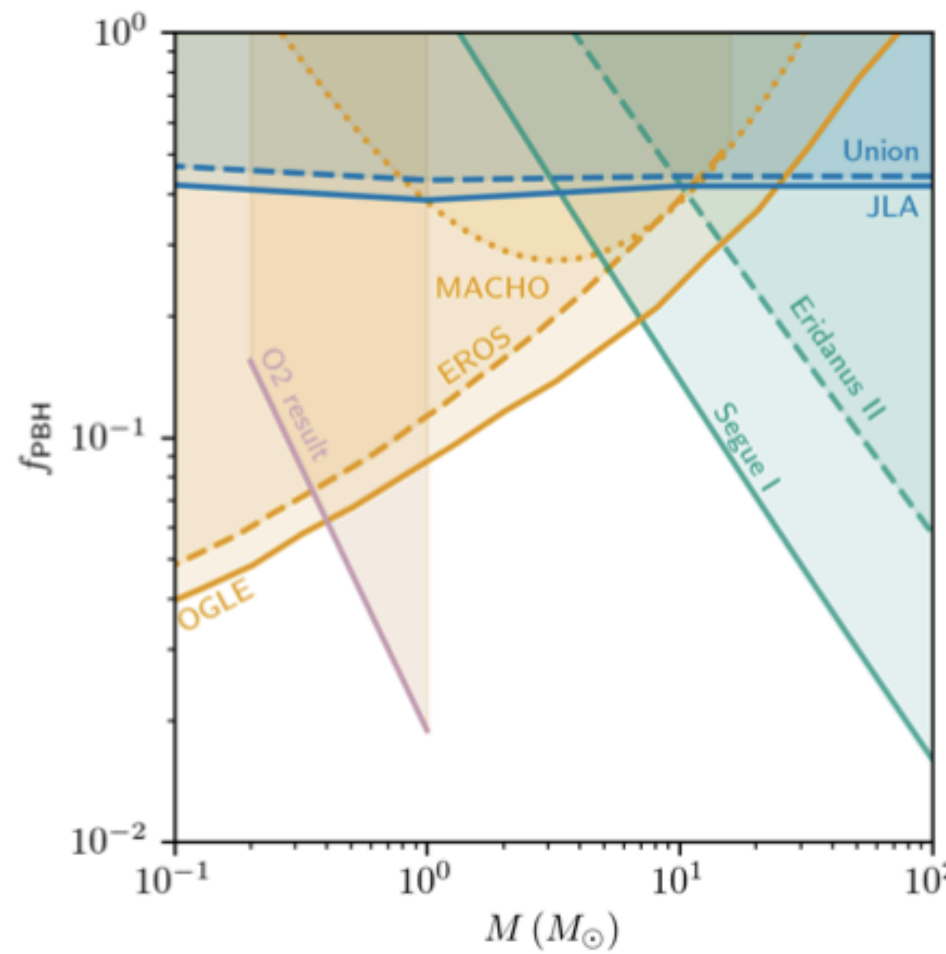
Existence of the objects does

No background/ foreground/ systematics

Sub-solar mass search



Data



PBH following Nakamura et al 1997

LIGO Scientific Collaboration, Virgo Collaboration and S. Shandera; (1904.08976 PRL **123**, 2019)

R. Magee, A.S. Deutsch, P. McClincy, C. Horst, D. Meacher, C. Messick, S. Shandera, M. Wade (1808.04772, PRD **98**, 2018)
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Shandera, KITP, Feb 6 2020

So why do astrophysical black holes form?

Gravitational collapse has to be able to win over all sources of pressure

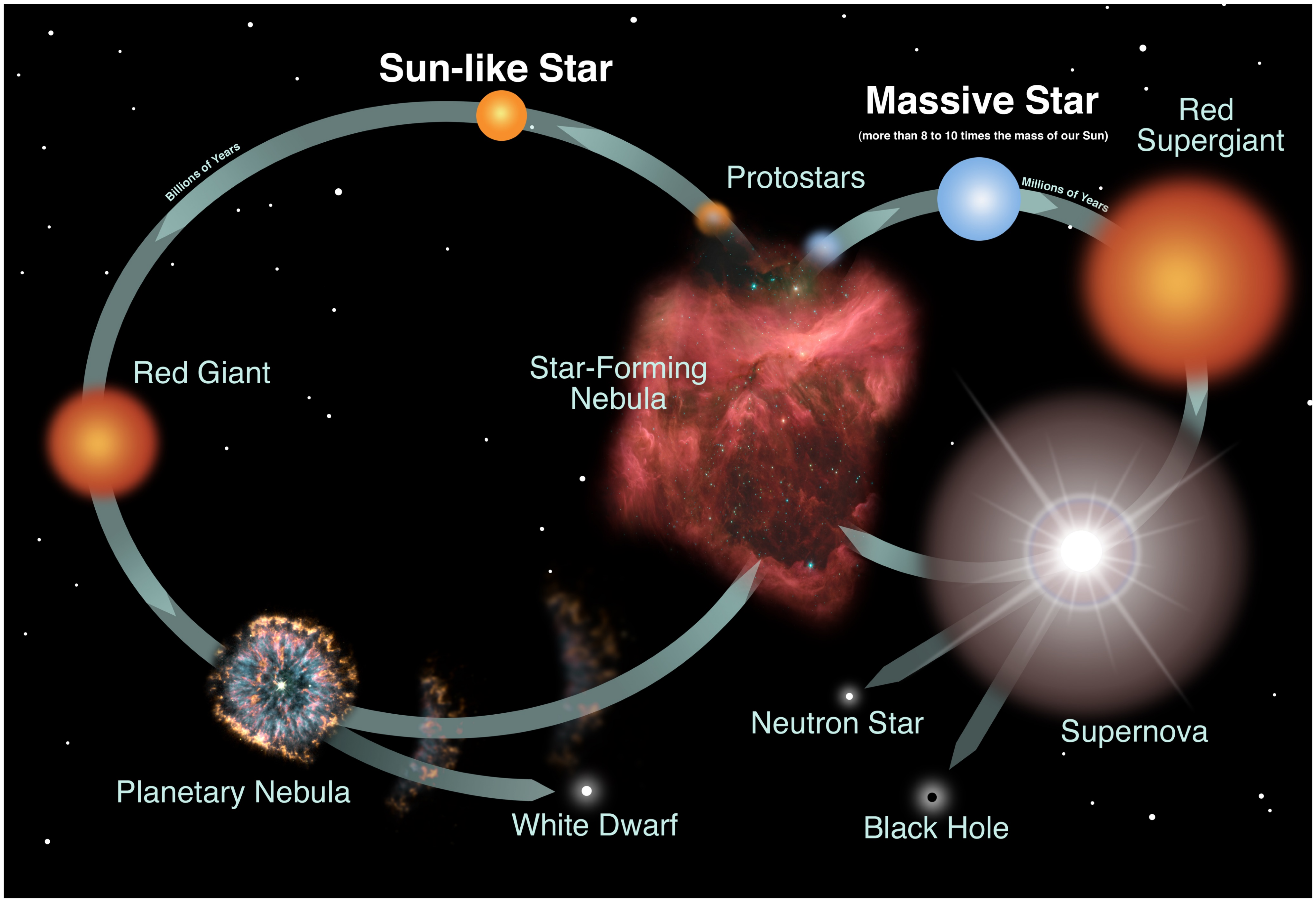
When does gravity win?

Minimal pressure is electron degeneracy pressure:

Chandrasekhar relation:

$$M \gtrsim 1.4 M_{\odot}$$

Okay, but astrophysical black holes:



NASA and Night Sky Network

Hmmm, nuclear physics is too complicated….
…let’s get rid of it

Primary obstacle to forming black holes from dark matter: it’s zipping around in high virial temperature halos

(1) A dark matter scenario

Dark “electron m_L

Dark “proton” (a fundamental particle) m_H

Dark “photon” $\xi = \frac{T_{\tilde{\gamma}}}{T_{\gamma,CMB}}$

Dark fine structure constant α_D

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Dark “electron m_L

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“atomic dark matter”
- Ackerman et al 0810.5126
- Feng et al 0905.3039
- Kaplan et al 0909.0753, 1105.2073
- Fan et al 1303.1521,1303.3271
- Cyr-Racine et al 1209.5752, 1310.3278

The minimum dark BH mass is

(while $m_H \gg m_L$)

$$M_{\rm Chand.}^{\rm Dark} \approx 1.4 M_\odot \left(\frac{m_p}{m_H}\right)^2$$

$m_p = 0.938 \text{ GeV}$

Constraints on parameter space?

$\frac{\sigma}{m} \lesssim 0.5 - 1\,\mathrm{cm}^2/\mathrm{g}$, But maybe $\frac{\sigma}{m} \neq 0$ helps with halo structure (cusp/core problem)

Boddy, Kaplinghat, Kwa, Peter, 1609.03592
also: Agrawal et al 1610.04611, etc
talk by Hai-bo You

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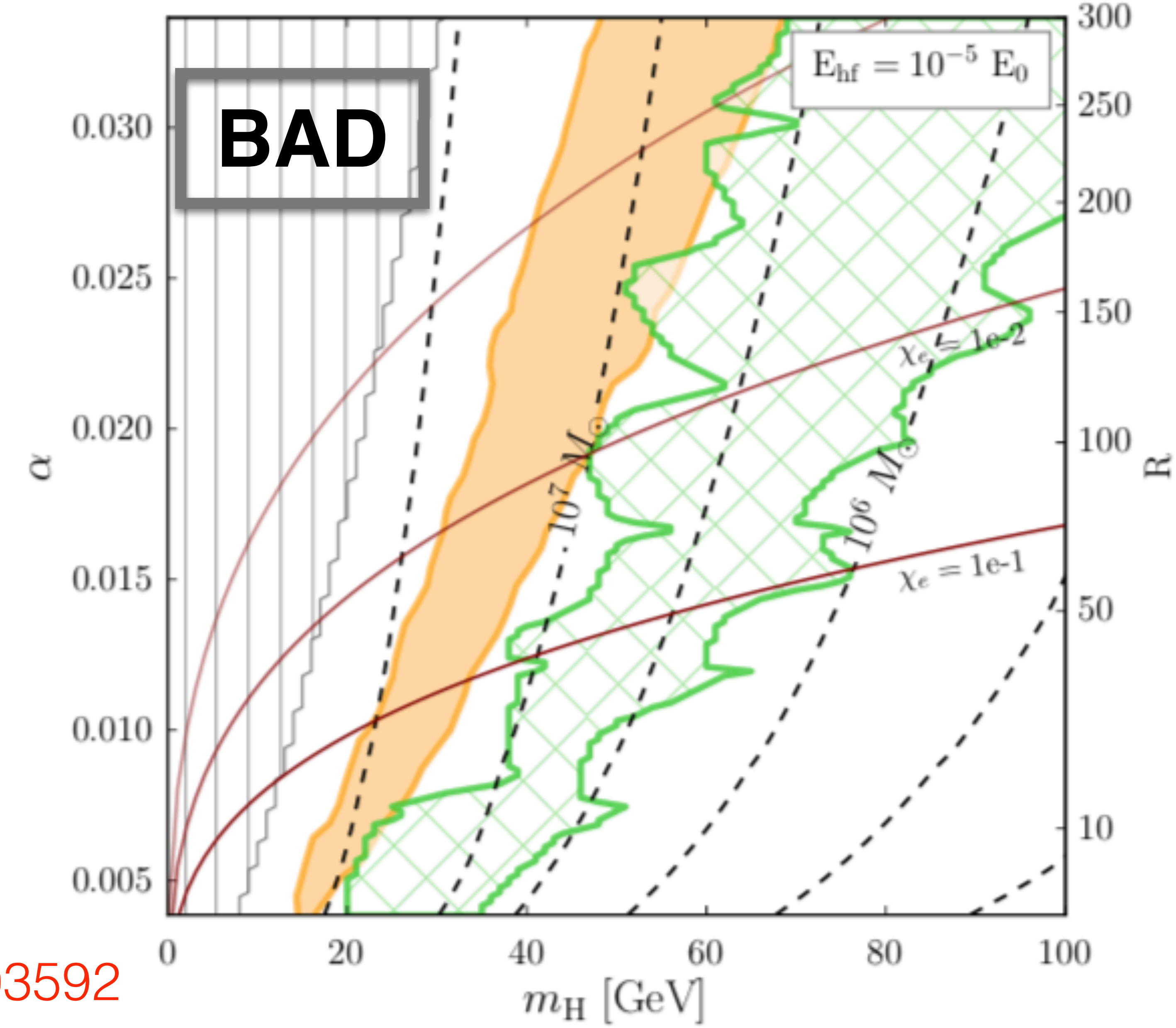

(assumes $\xi = 0.6$)

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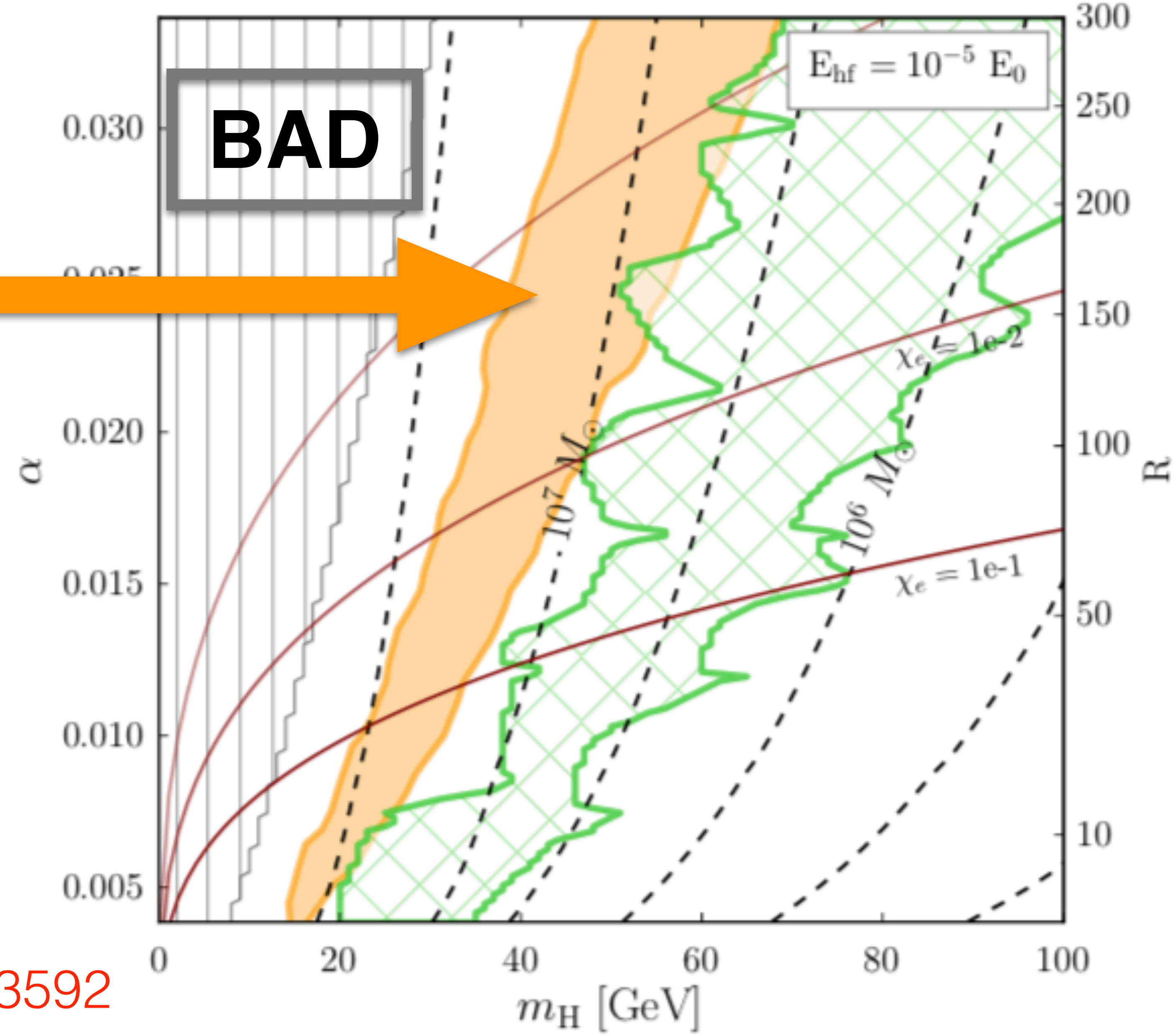
Best for cores in massive halos



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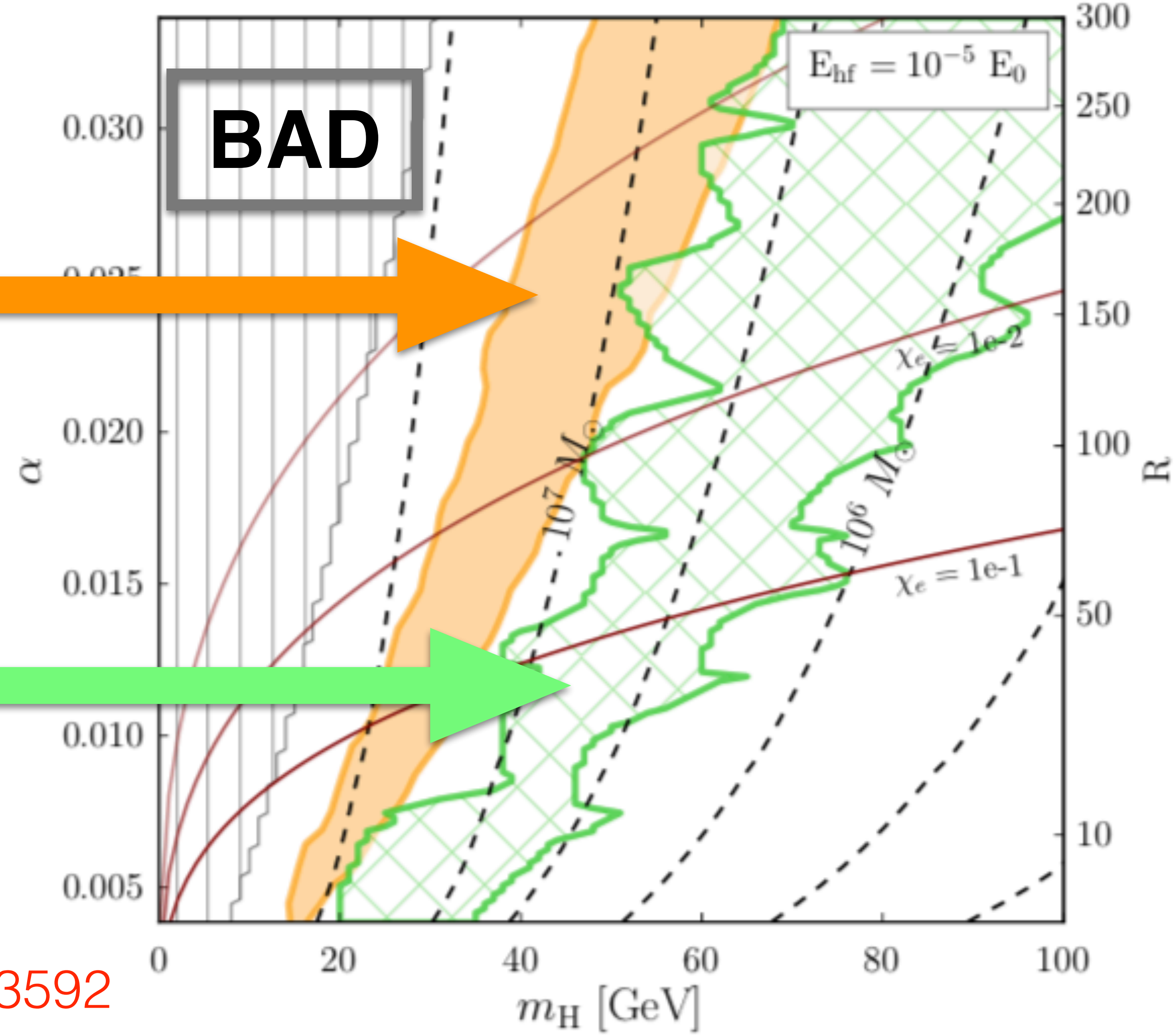

Best for cores in massive halos

Best for cores in low-mass halos

(assumes $\xi = 0.6$)

Boddy, Kaplinghat, Kwa, Peter, 1609.03592
also: Agrawal et al 1610.04611, etc
talk by Hai-bo You

Our benchmark model

Dark "electron" $m_L \sim 30 - 150 \text{ keV}$

Dark "proton" $m_H \sim 10 - 100 \text{ GeV}$

Dark "photon" $\xi = \frac{T_{\tilde{\gamma}}}{T_{\gamma,\text{CMB}}} = 0.02$

Dark fine structure constant $\alpha_D = 0.01$

These numbers come from considerations independent of the previous slide! Intriguing overlap…

A non-minimal dark matter scenario with distinct black holes

Dark "electron"

Dark "proton"

Dark "photon"

Dark fine structure constant

→

Interesting BH masses

A non-minimal dark matter scenario with distinct black holes

Dark "electron"

Dark "proton"

Dark "photon"

Dark fine structure constant

→ Interesting BH masses

Dark "hydrogen"

→ Cooling channels

A non-minimal dark matter scenario with distinct black holes

Dark “electron”

Dark “proton”

Dark “photon”

Dark fine structure constant

→ Interesting BH masses

Dark “hydrogen”

→ Cooling channels

→ Allows BHs to form dynamically from dark matter

Please Note:

1. The dark sector is very cold: how did it get that way?

$$\xi = \frac{T_{\tilde{\gamma}}}{T_{\gamma,\mathrm{CMB}}} = 0.02$$

2. No comment about relic abundance (but asymmetric dark matter has always been a good idea)

3. No comment about couplings to the standard model (maybe none?)

4. Particle content is designer to make calculations easy.

Related/contrasting ideas: talks by Heckman, Long, Shelton….work by Adshead, Cui, Shelton; Pearce,… ….

A non-minimal dark matter scenario with distinct black holes

Dark “electron”

Dark “proton”

Dark “photon”

Dark fine structure constant

→ Interesting BH masses

Dark “hydrogen”

→ Cooling channels

→ Allows BHs to form dynamically from dark matter

Still, can we form enough dark BHs for this to be interesting?

We need to check:

- Can dark matter cool sufficiently to collapse into black holes?

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Rosenberg and Fan, 1705.10341; Buckley and DiFranzo, 1707.03829

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- What is the merger rate today, detectable by LIGO?

Rosenberg and Fan, 1705.10341; Buckley and DiFranzo, 1707.03829

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opacity limit arguments from 1970's
+
Pop III star literature;

Parameterizing the coalescence rate

$\propto$ (number of black holes)$\times$(fraction in binaries)

$\times$ (merger rate of those binaries today)

S. Shandera, D. Jeong, H. Gebhardt 1802.08206

Parameterizing the coalescence rate

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$$\sim \quad \times f_{\rm binary} \times \left[\frac{dP(T_{\rm merge})}{dT_{\rm merge}}\right]\Bigg|_{T_{\rm merge}\sim 10^{10}{\rm yr}}$$

S. Shandera, D. Jeong, H. Gebhardt 1802.08206

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Depends on parameters of the binaries

S. Shandera, D. Jeong, H. Gebhardt 1802.08206

Parameterizing the coalescence rate

$\propto$ (number of black holes) $\times$ (fraction in binaries)

$\times$ (merger rate of those binaries today)

$$\sim \left(\frac{M_{\rm DM} \times f_{\rm cool} \times f_{\rm form.\,eff.}}{M_{DBH}} \right) \times f_{\rm binary} \times \left[\frac{dP(T_{\rm merge})}{dT_{\rm merge}} \right] \Bigg|_{T_{\rm merge} \sim 10^{10} {\rm yr}}$$

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S. Shandera, D. Jeong, H. Gebhardt 1802.08206

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Total DM mass available
How much is in BHs?

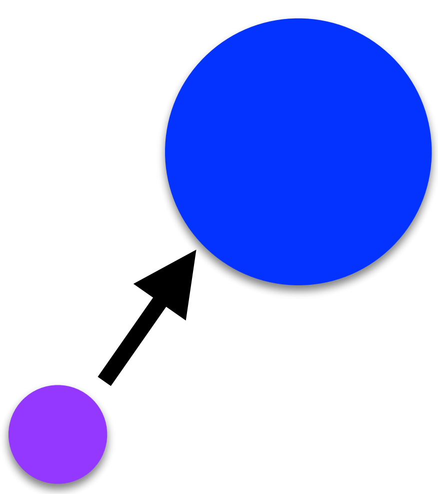
Depends on parameters of the binaries

S. Shandera, D. Jeong, H. Gebhardt 1802.08206

How much dark matter can cool?

Why is it cooling? Example: collisional excitation

dark hydrogen



(fast) dark electron

Detailed rates calculated by Rosenberg and Fan, 1705.10341;
BUT: molecular cooling should set minimum temperature of gas

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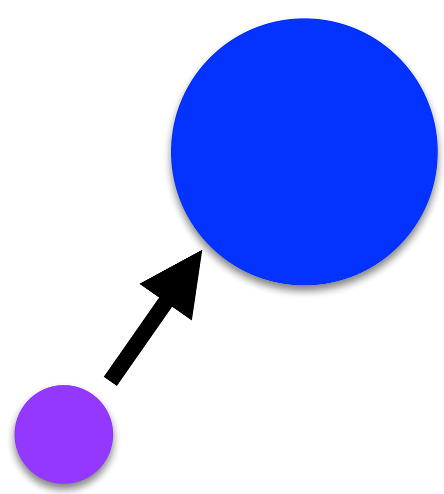
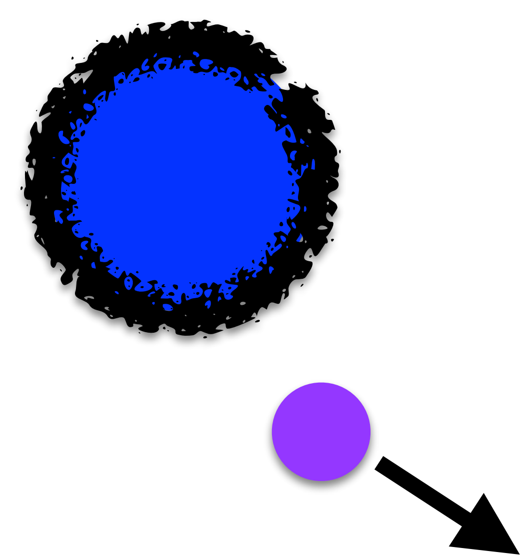


(fast) dark electron

dark hydrogen
excited state



slower dark electron

Detailed rates calculated by Rosenberg and Fan, 1705.10341;
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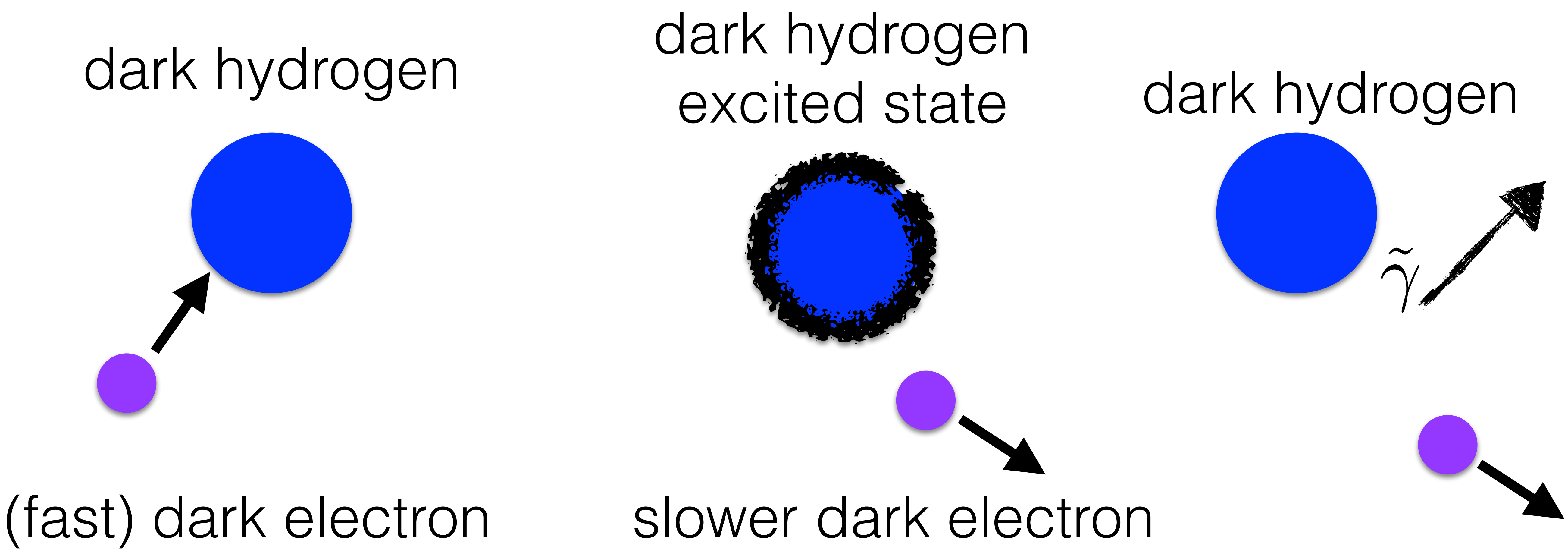


Detailed rates calculated by Rosenberg and Fan, 1705.10341;
BUT: molecular cooling should set minimum temperature of gas

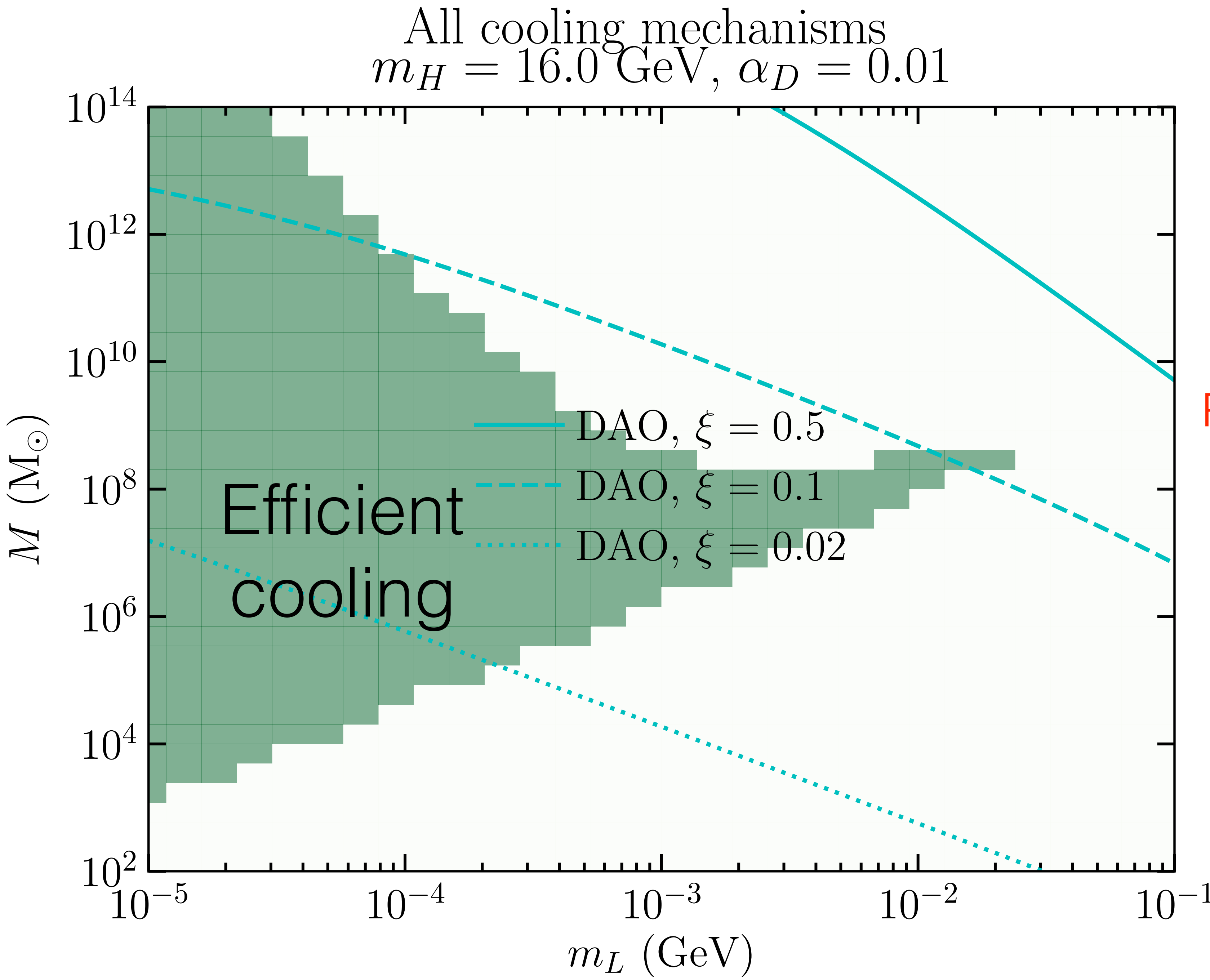
How much dark matter can cool?

$$\frac{dT}{dt}\text{(cooling processes)} > \frac{dT}{dt}\text{(kinematics in gravitational well)}$$

Cooling is more efficient for smaller dark matter halos: can maintain "cold dark matter" success on large scales

Buckley and DiFranzo, 1707.03829

How much dark matter can cool?



Plots: Henry Gebhardt

Rosenberg and Fan, 1705.10341; Buckley and DiFranzo, 1707.03829

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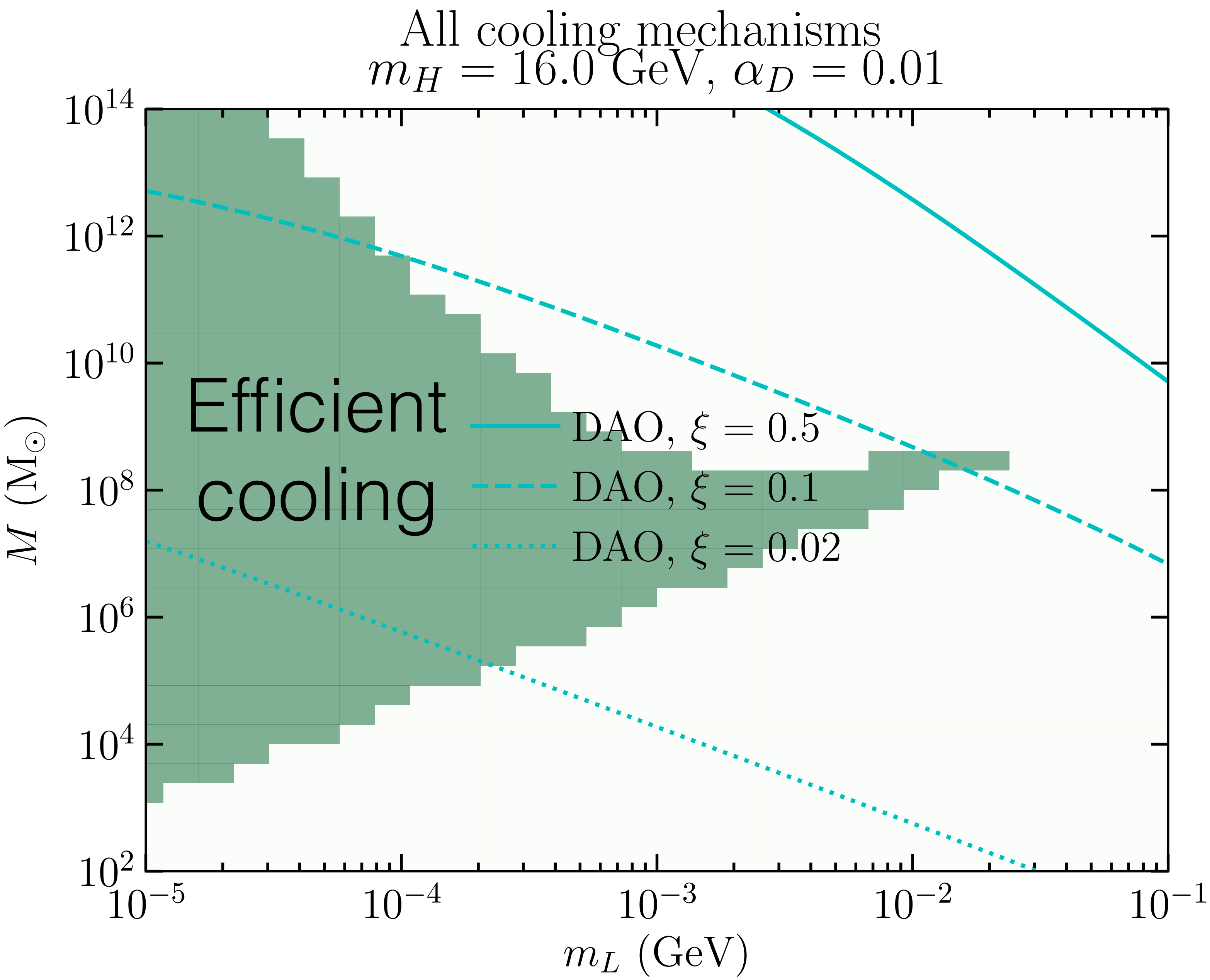
Cooling dark matter



Plot: Henry Gebhardt

This plot
+
sub-halo mass function:

$$f_{\rm cool} \sim 0.01$$

Rosenberg and Fan, 1705.10341;
Buckley and DiFranzo, 1707.03829

Shandera, KITP, Feb 6 2020

How much of the dark matter that can cool ends up in black holes?

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Star-to-gas ratio for Coma:

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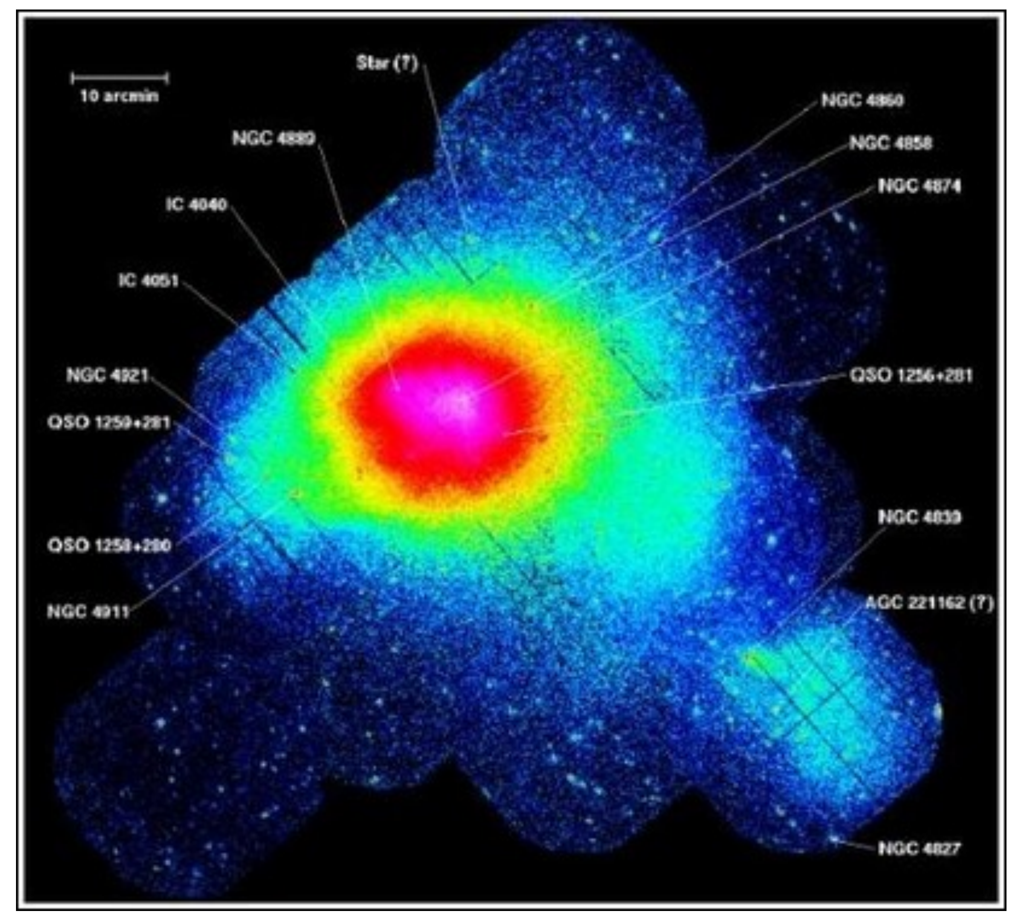
Star-to-gas ratio for Coma:



~2% of mass in stars

~10% of mass in gas

How much of the dark matter that can cool ends up in black holes?

Or, from literature on formation of first stars (in hydrogen gas, with a bit of helium):

$$f_{\rm form.\,eff.} \sim 10^{-3}$$

$$f_{\rm cool} \times f_{\rm form.\,eff.} \sim 10^{-5}$$

Optimistic: $$f_{\rm cool} \times f_{\rm form.\,eff.} \sim 10^{-3}$$

} Fraction of dark matter in black holes

What is the mass of black holes formed by collapse of "atomic" dark matter?

"opacity limit" argument (Rees; Lynden-Bell, 1976)

$$M_{\mathrm{J,min}} \propto \left(\frac{m_p}{m_H}\right)^{9/4} \left(\frac{T}{10^3 K}\right)^{1/4} M_\odot$$

Coefficient? Pop III star literature for proto-star masses:

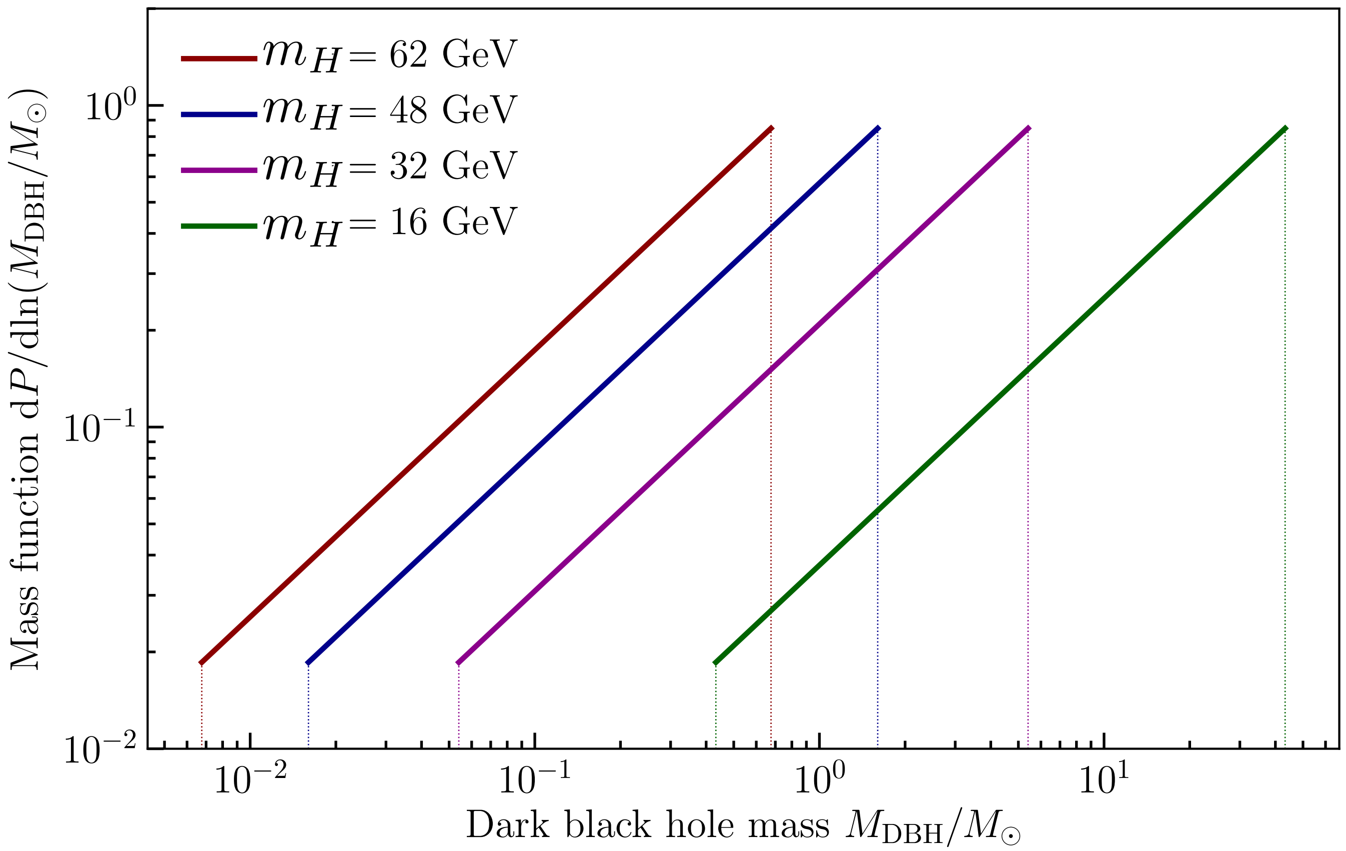
$$M_{\mathrm{DBH,min}} \sim \left(\frac{m_p}{m_H}\right)^{9/4} \left(\frac{T}{10^3 K}\right)^{1/4} 10^3 M_\odot$$

What is the spectrum of birth masses of these black holes?

$$dP_m \propto m^{-b} \qquad b = 0.17$$

up to two orders of magnitude above the minimum:

Stacey and Bromm, 2013



What are the binary parameters?

How many binaries? $f_{\rm binary} = 0.26$ Stacey and Bromm, 2013

Mass ratio in binaries? $P_q \propto q^{-0.55} dq$ $q = m_{\rm light}/m_{\rm heavy}$

Distribution of eccentricities? $dP_e \propto e de$ $0.1 < e < 1$

Semi-major axis? $dP_a \propto x^{-1/2} dx$ Hartwig et al, 2016

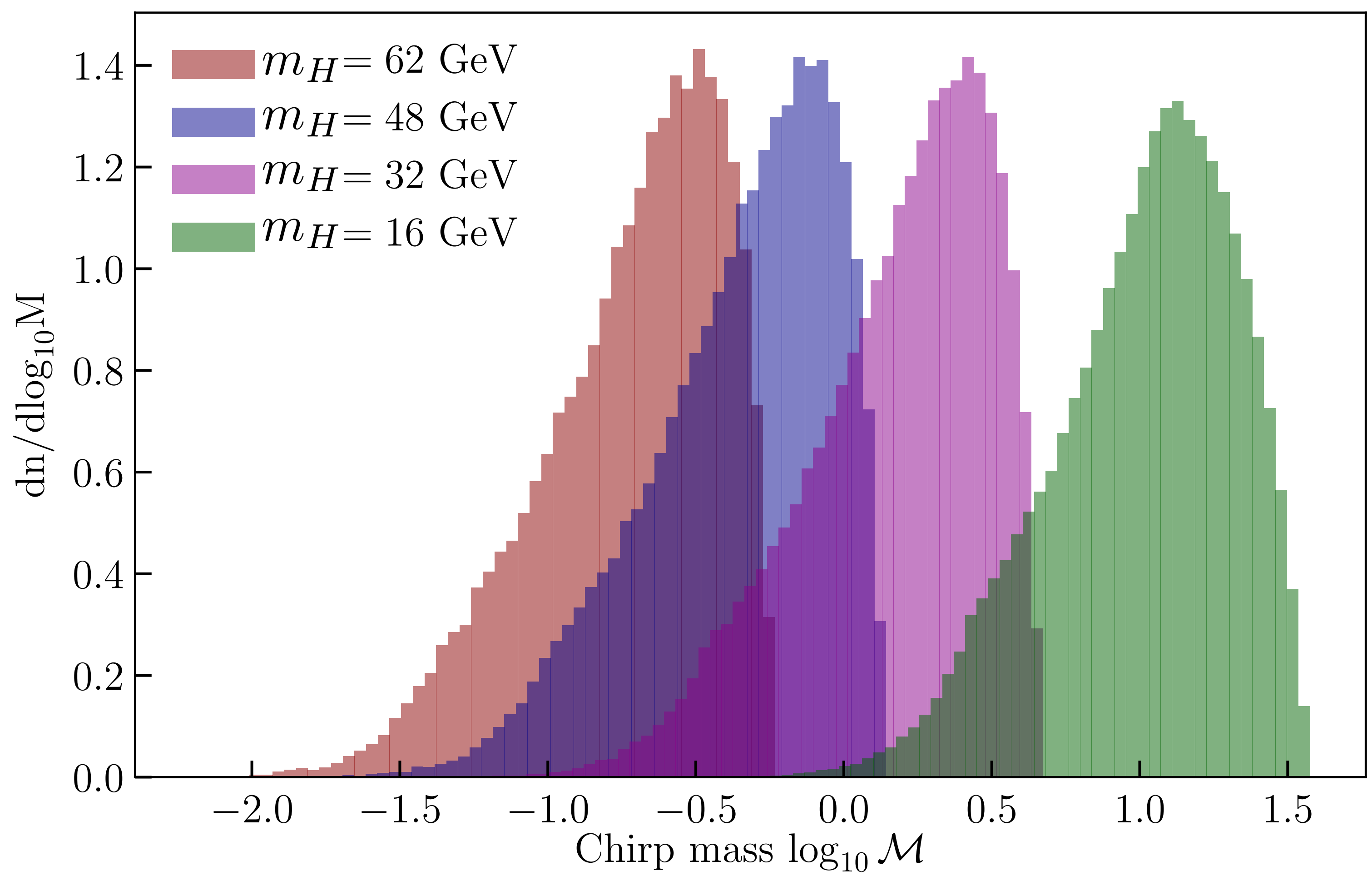
$x = {\rm Log}_{10}(a/a_*)$

For example: $0.06 < a < 2400$ AU $M_{\rm min} = 0.054\, M_\odot$

Are these black holes merging today?

$$T_{\rm merge} = \frac{(3\times 10^9 {\rm yr}) M_\odot^3}{m_1 m_2 (m_1+m_2)} \left(\frac{a}{0.01\ {\rm AU}}\right)^4 (1-e^2)^{7/2}$$

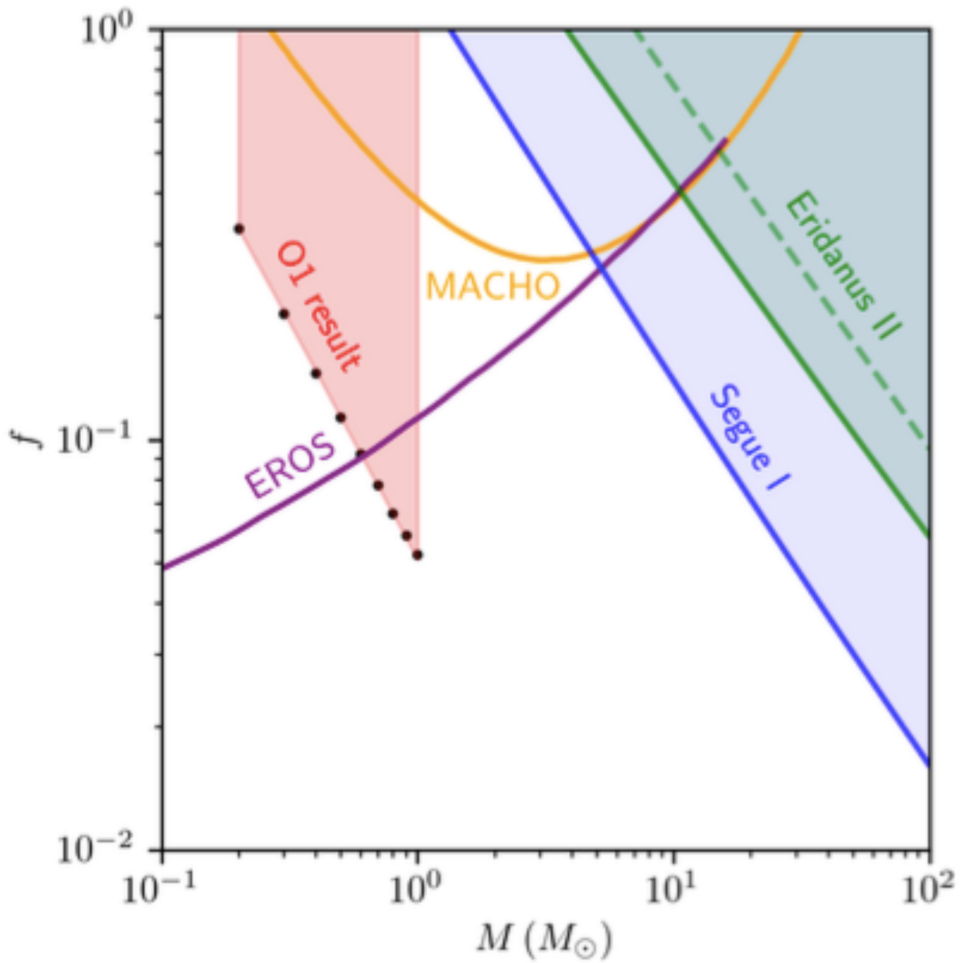
The spectrum of those that are:



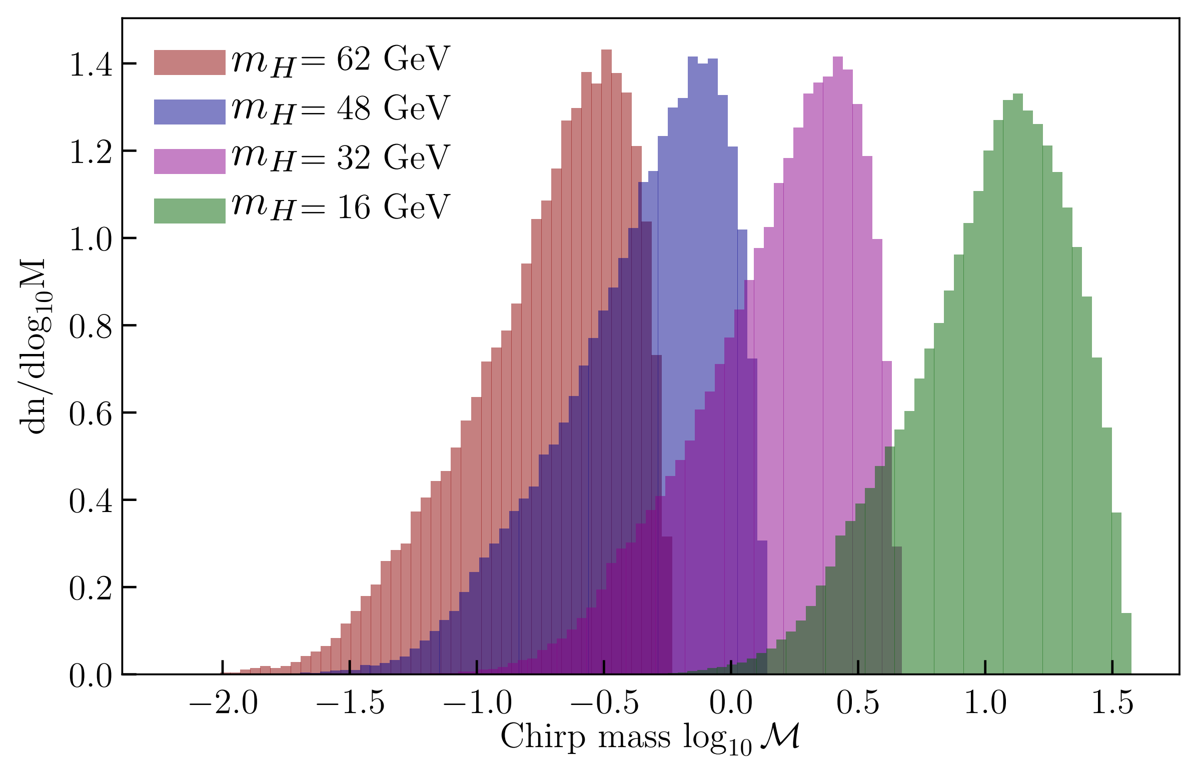
Estimated LIGO rates

m_X [GeV]	m_c [keV]	$M^{\rm dark}_{\rm Chand.}$ $[10^{-5} M_\odot]$	$M_{\rm DBH}$ $[M_\odot]$	Rates per year				$m_1 < 1.4$	$m_1, m_2 < 1.4$
				raw (MWEG^{-1})	aLIGO (current)	aLIGO (full)	Einstein T.	[%]	[%]
62	31	33	$0.0068 - 0.68$	$2.0\times10^{-6}(10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	$0.016 - 1.6$	$1.3\times10^{-6}(10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
32	70	125	$0.054 - 5.4$	$6.6\times10^{-7}(10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
16	140	500	$0.43 - 43$	$1.9\times10^{-7}(10^{-5})$	0.89 (89)	22 (2200)	92k (9200k)	9.8%	0.14%

To Do

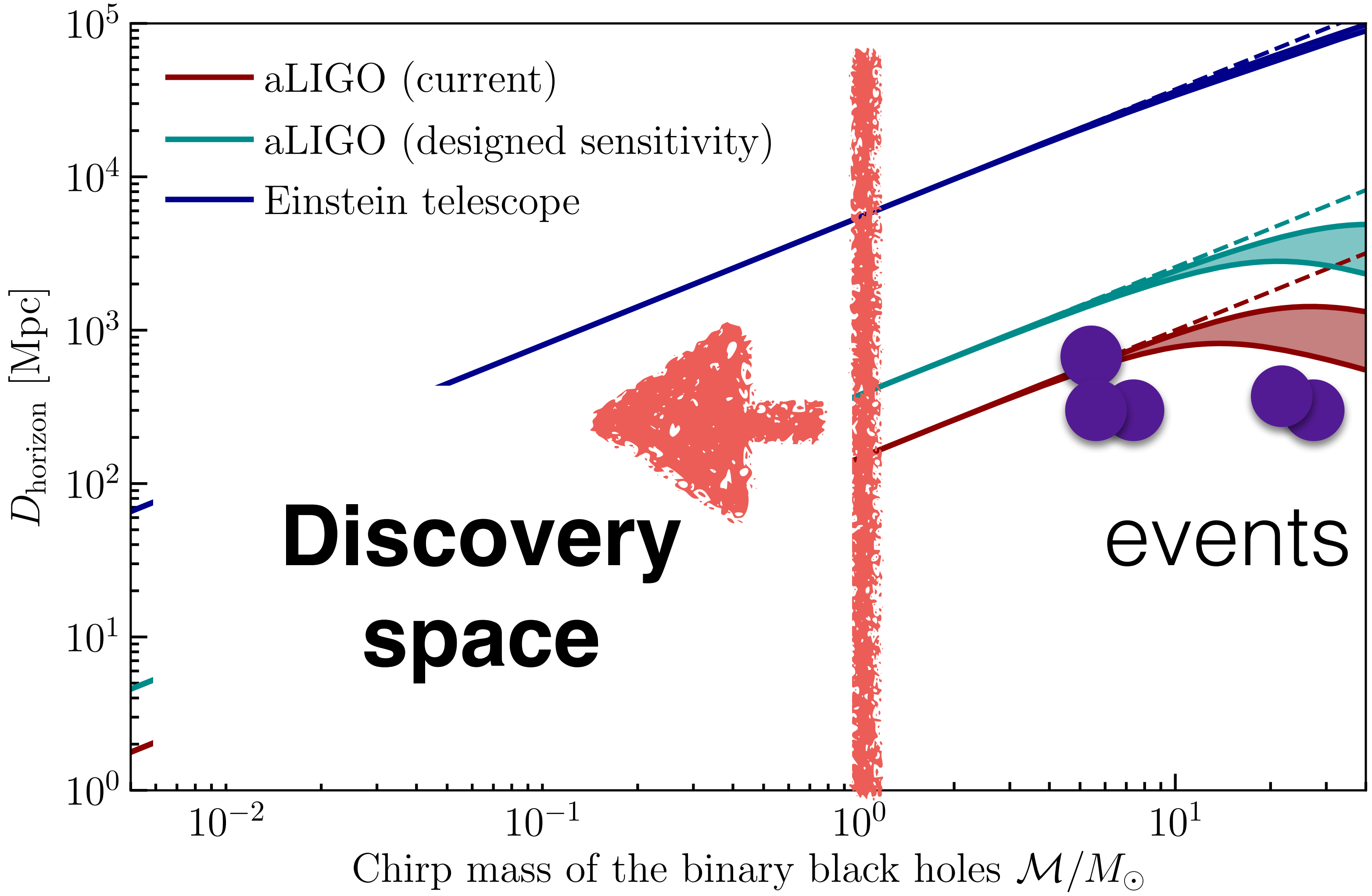


1. Keep looking…(O3 results…)
2. Improve the particle physics to black hole modeling (H_2 cooling, KROME)
3. Put existing results together for LIGO constrains
4. Connect to larger-scale structure
5. Explore particle models more broadly



Shandera, KITP, Feb 6 2020

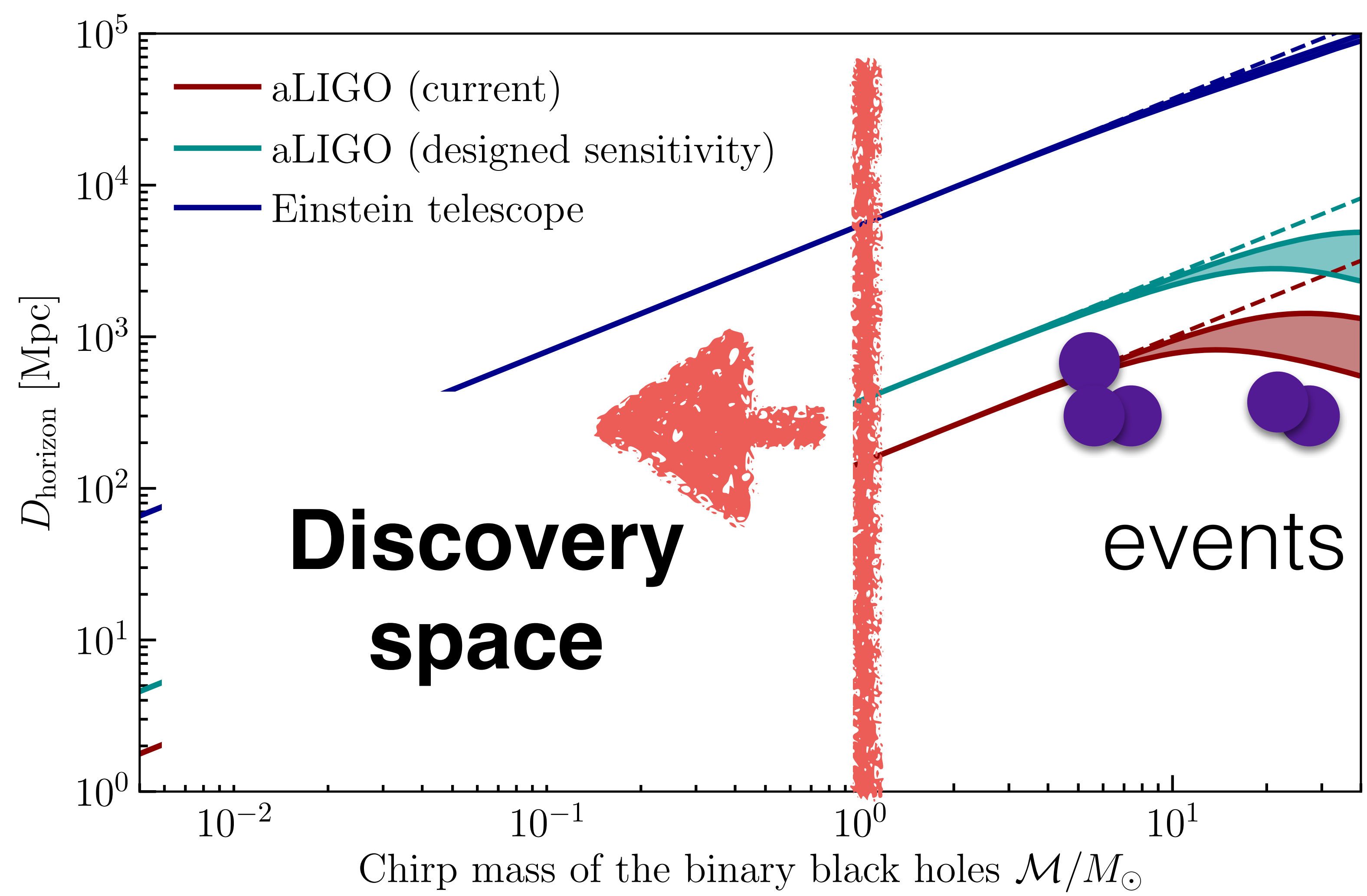
Summary



Shandera, KITP, Feb 6 2020

Summary

- Enough DM to make significant number of objects
- No obstruction for a simple example
- LIGO constrains cooling rate (chemistry!) of dark sector



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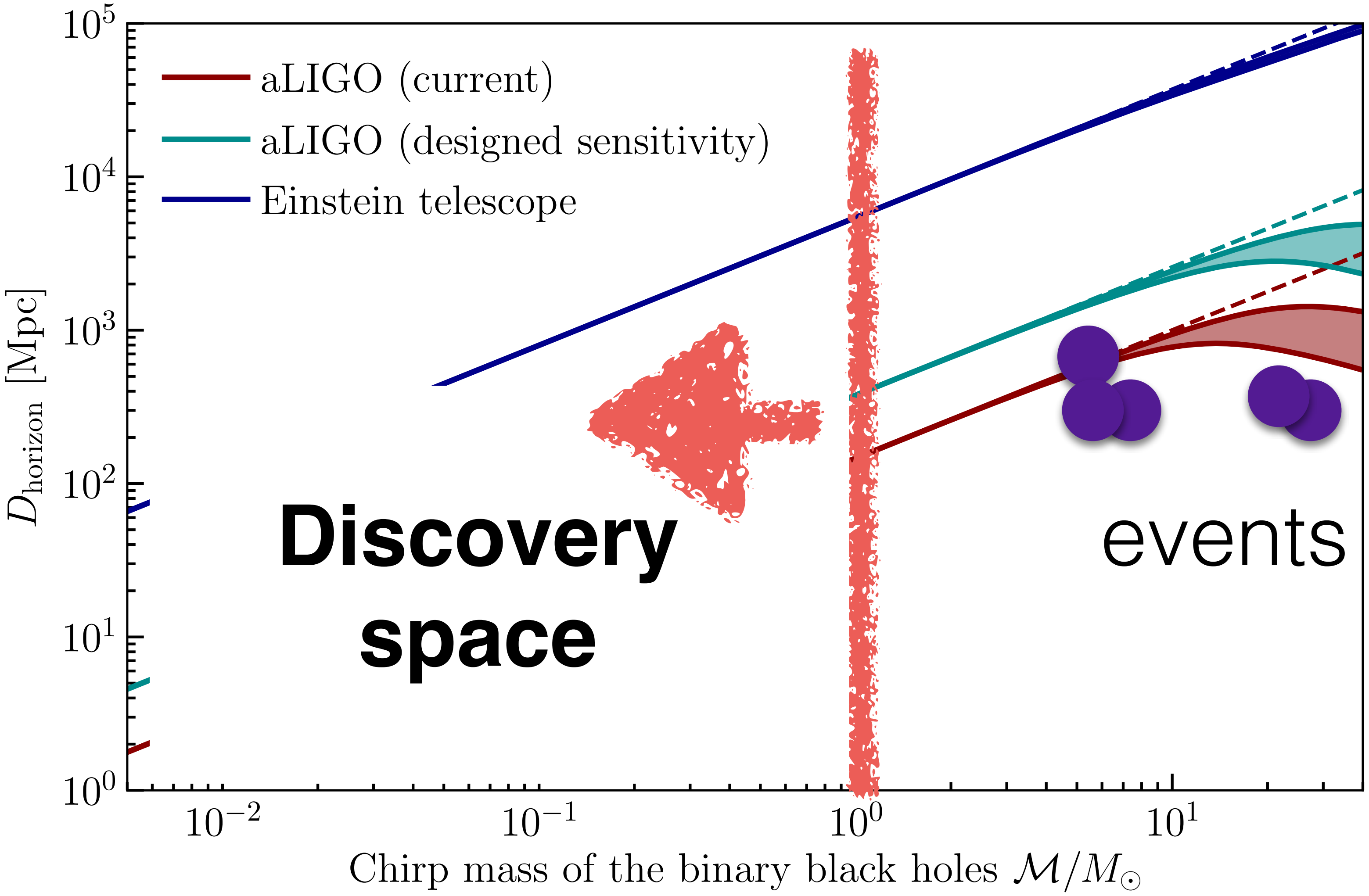

$$M^{\rm Dark}_{\rm Chand.} \approx 1.4 M_\odot \left(\frac{m_p}{m_H}\right)^2$$

Shandera, KITP, Feb 6 2020

Cosmology with extra cold dark matter

- Relativistic degrees of freedom not very constraining:

$$\left[g_{*\mathrm{Dark}}\xi^4\right]\big|_{\mathrm{CMB}} \leq \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} \Delta N_{\mathrm{eff}}^{BBN}$$

- Far fewer dark photons per dark baryon vs SM:

$$\eta_{D,10} \approx 2 \times 10^5 \qquad \eta_{D,10} = 10^{10} n_{Db}/n_{\tilde{\gamma}}$$

- Dark recombination and decoupling is early:

$$z_{\mathrm{dec}} \approx 32,000 \qquad X_{De}^{\mathrm{freeze}} \approx 5 \times 10^{-8}$$

- Damping scale is larger than DAO scale:

$$k_{\mathrm{d}}^{-1} \sim 0.24\ \mathrm{Mpc} > d_{\mathrm{DAO}} \approx 0.02\ \mathrm{Mpc}$$