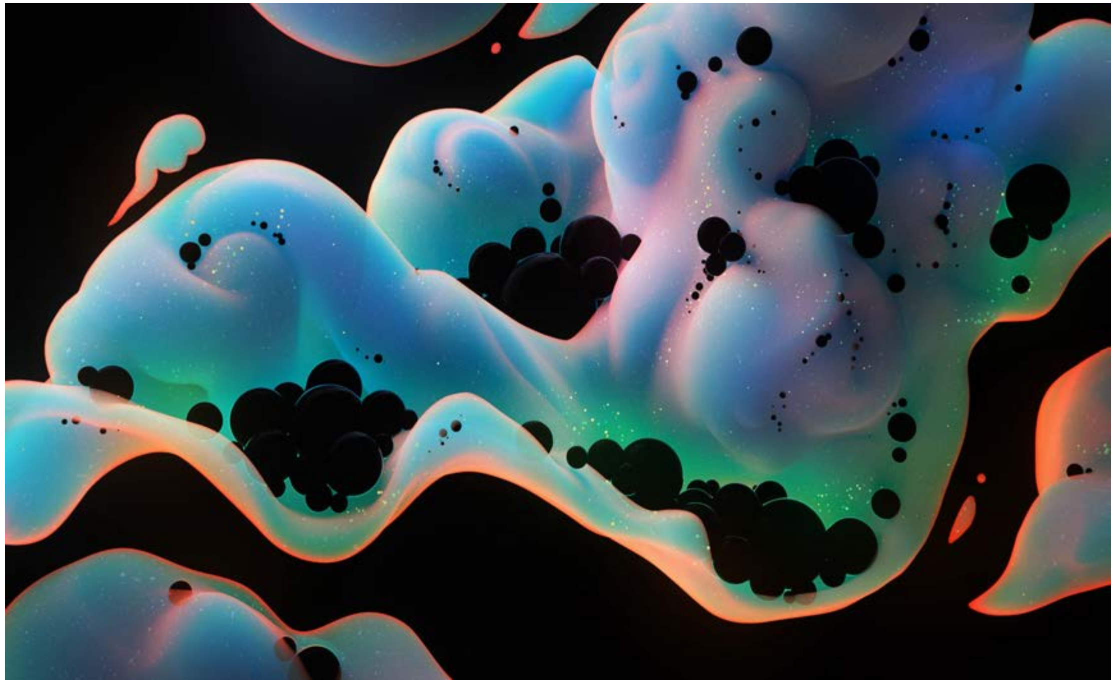
Stefano Profumo
University of California, Santa Cruz
Santa Cruz Institute for Particle Physics

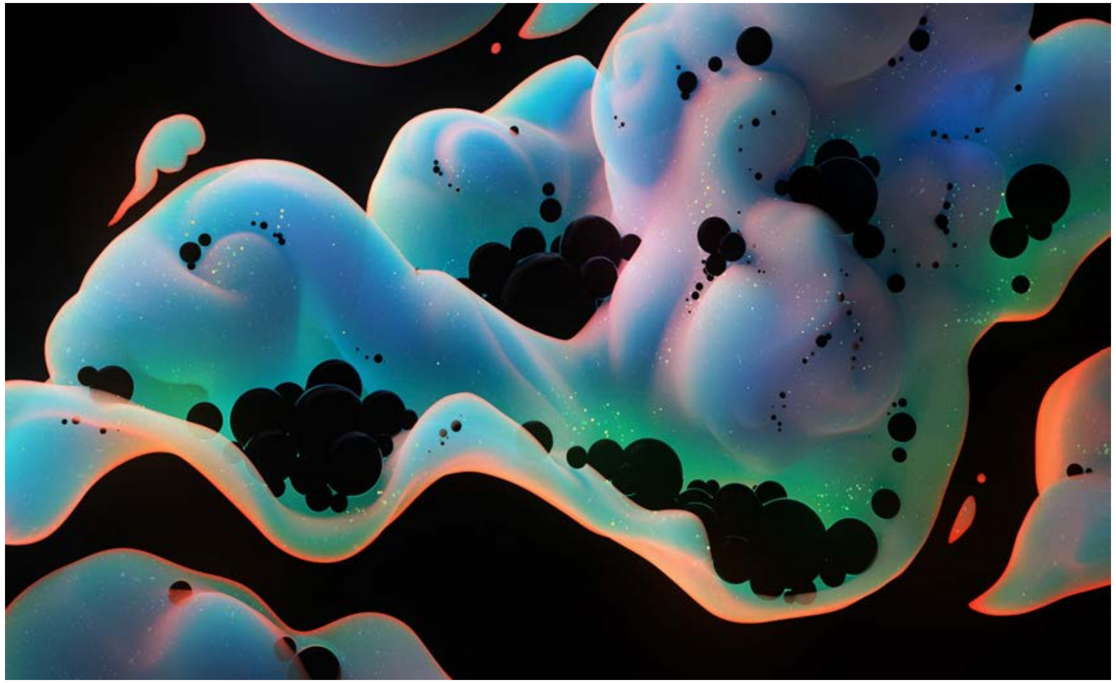
Non-Stellar Black Holes and Exotic Astrophysics



PACIFIC 2024

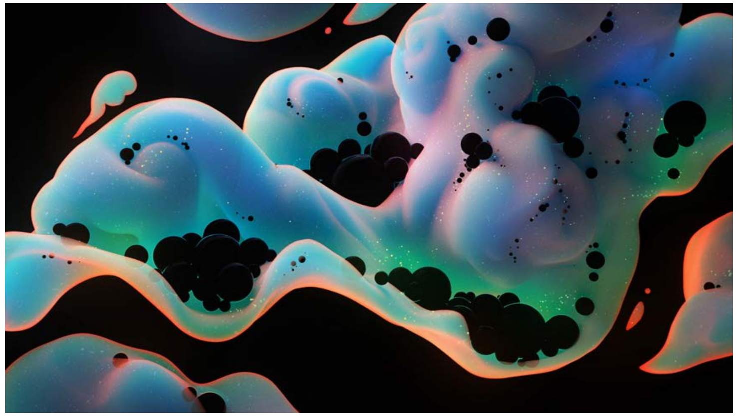
Moorea, PF, Wednesday, August 28, 20204

*art by Olena Shmahalo
Quanta Magazine



*art by Olena Shmahalo
Quanta Magazine

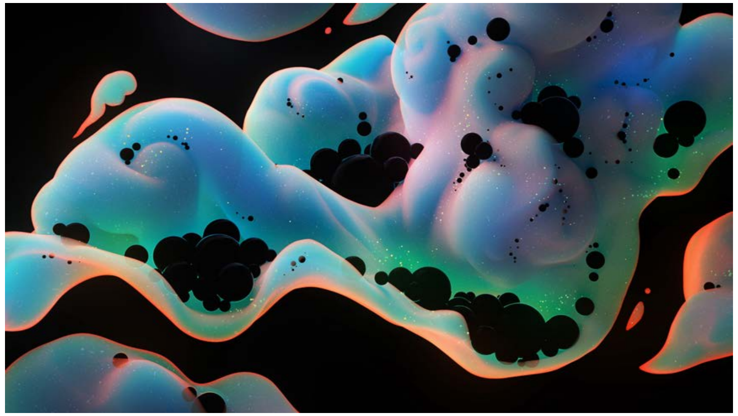
Black Holes of
non-stellar origin



- Dark Matter
- Baryon Asymmetry
- Both of the above

➢ Exotic astrophysical phenomena

Black Holes of non-stellar origin



- *G* objects, no-GW kilonovae, FRBs,…
- ✅ Black Hole "Explosions"
- ✅ Anomalous cosmic- and gamma-rays
- ✅ Neutron-star "Implosions"
- ✅ Tidal heating & Star cluster disruption
- 🏁 Early Pop III star formation
- 🏁 High-redshift SMBH seeds

[highly incomplete and very partial list!]

A field theory defined on a black-hole background is in a **thermal** state whose temperature at infinity is

$T=M_P^2/M_{BH}$

Black holes radiate (~)like any **black body**, and, as such, shed their mass at a rate

$$\frac{dM}{dT} \propto A(T)T^4 \propto \frac{M^2}{M^4} \propto M^{-2}$$

[Stefan-Boltzmann]

The resulting runaway evaporation process gives a lifetime

"**Black Hole Explosion**"*

$$\tau \approx 407\left(\frac{f(M)}{15.35}\right)^{-1} M_{10}^3 \text{ s.}$$

[10^{10} grams units]

Black holes formed in the early universe, with a mass **M_U~ 5x10^{14} grams**, **T~100 MeV** are exploding **today****

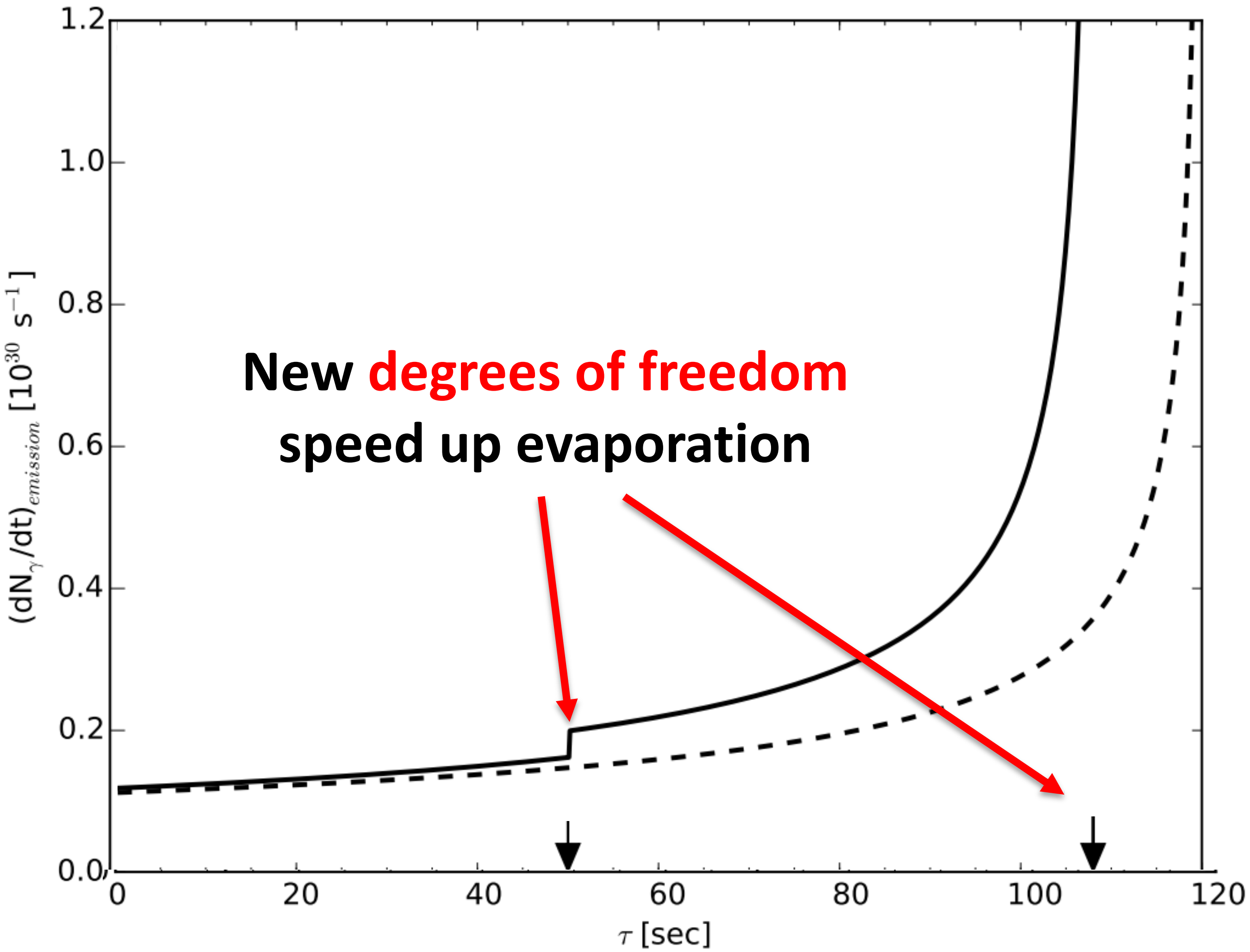
*Hawking, 1974

****or lighter, and formed later!**

The (universal*) Black Hole Light-curve

Universal Luminosity
→ perfect
"standard candle"

"Backwards"
Gamma-Ray Burst

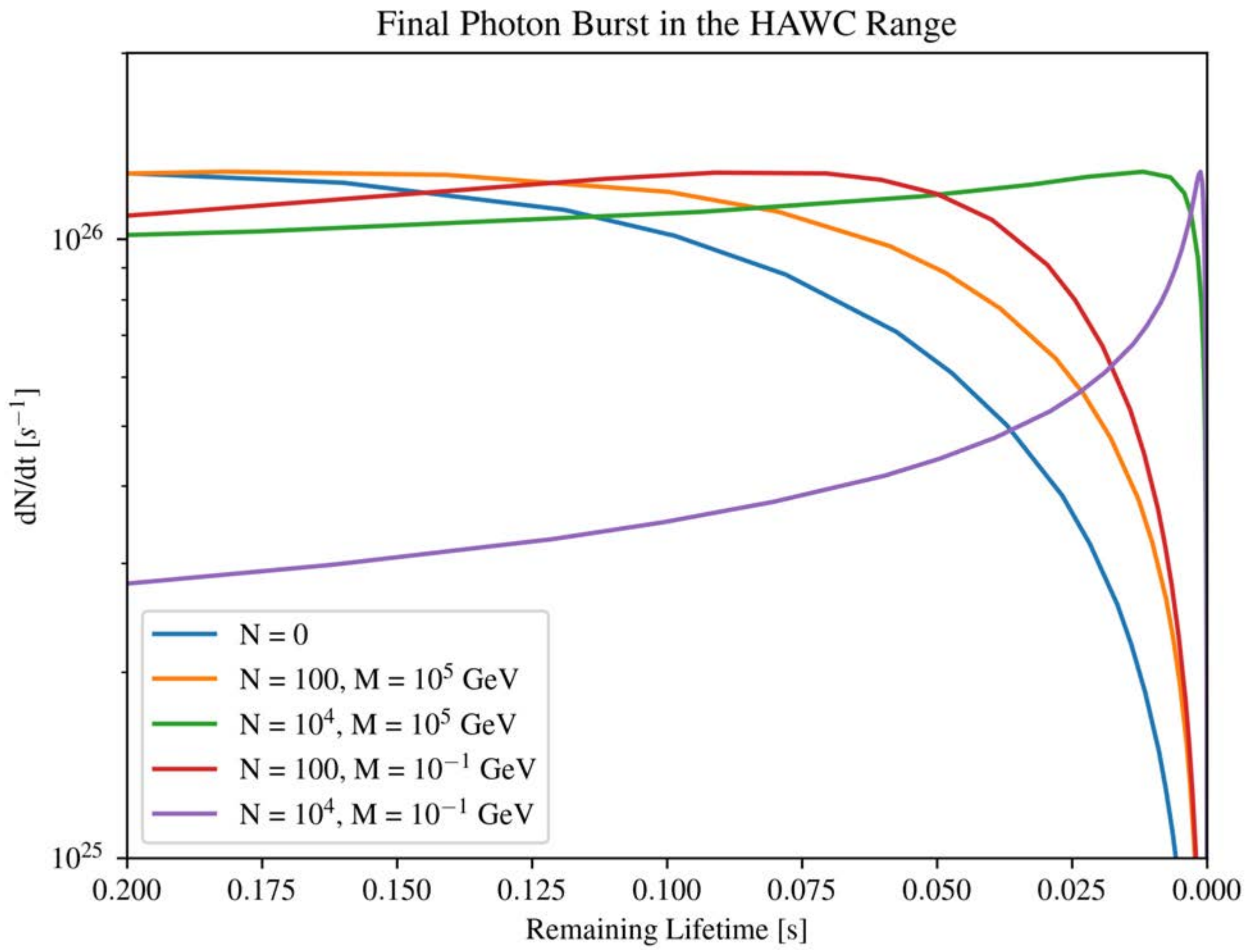


No afterglow
(BHs don't form a photosphere or chromosphere)

*for a given spin/charge, and evaporating d.o.f

The (non-universal) Black Hole Light-curve

Photon Emission Rate



Time to Explosion

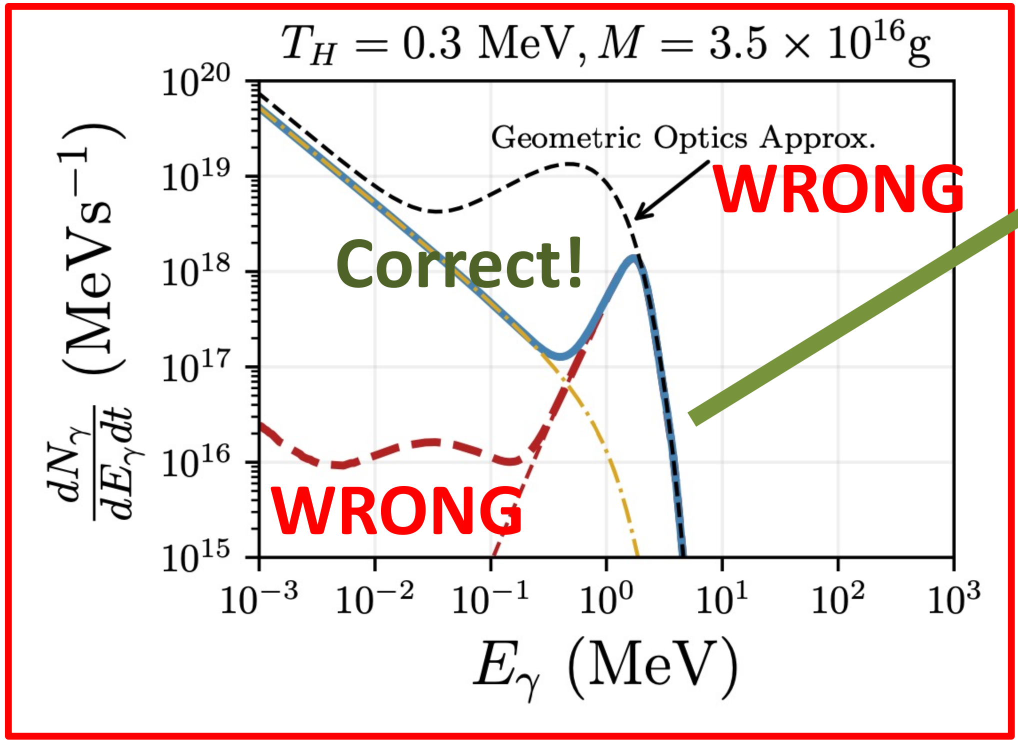
 # new degrees of freedom

Mass-scale of new d.o.f

SM emission from new d.o.f

K. Fedrico and S. Profumo, in preparation

Evaporation products (gamma rays, cosmic-ray positrons) are **detectable**, constraining the **fraction** of light PBH that can be the DM



Direct Detection of Hawking Radiation from Asteroid-Mass Primordial Black Holes

Adam Coogan,[1,*] Logan Morrison,[2,†] and Stefano Profumo[2,‡]

[1] *GRAPPA, Institute of Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands*

[2] *Department of Physics, University of California, Santa Cruz, CA 95064, USA*

(Dated: October 13, 2020)

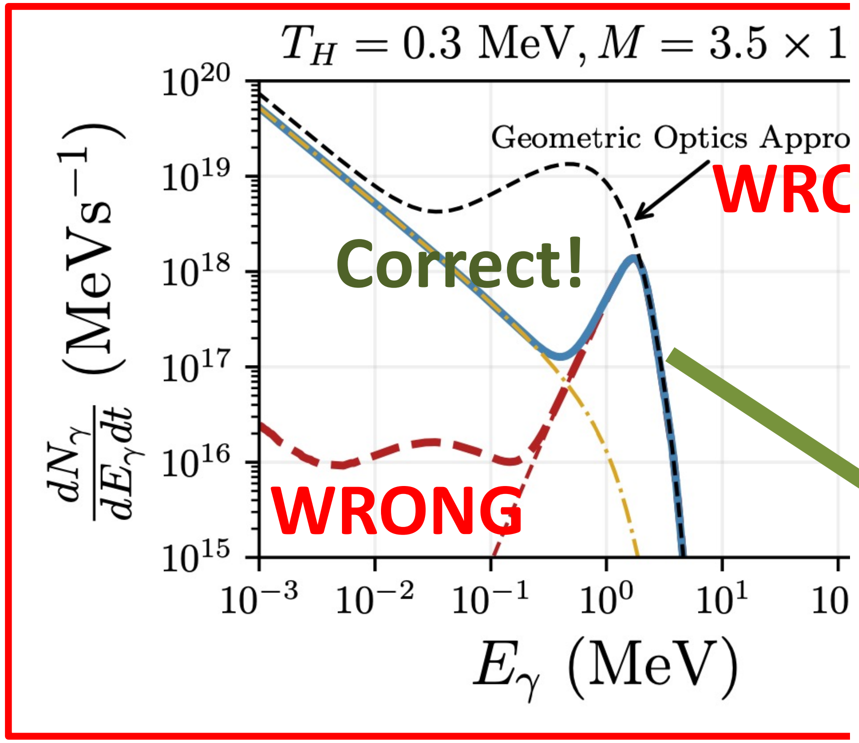
Light, asteroid-mass primordial black holes, with lifetimes in the range between hundreds to several millions times the age of the universe, are well-motivated candidates for the cosmological dark matter. Using archival COMPTEL data, we improve over current constraints on the allowed parameter space of primordial black holes as dark matter by studying their evaporation to soft gamma rays in nearby astrophysical structures. We point out that a new generation of proposed MeV gamma-ray telescopes will offer the unique opportunity to directly detect Hawking evaporation from observations of nearby dark matter dense regions and to constrain, or discover, the primordial black hole dark matter.

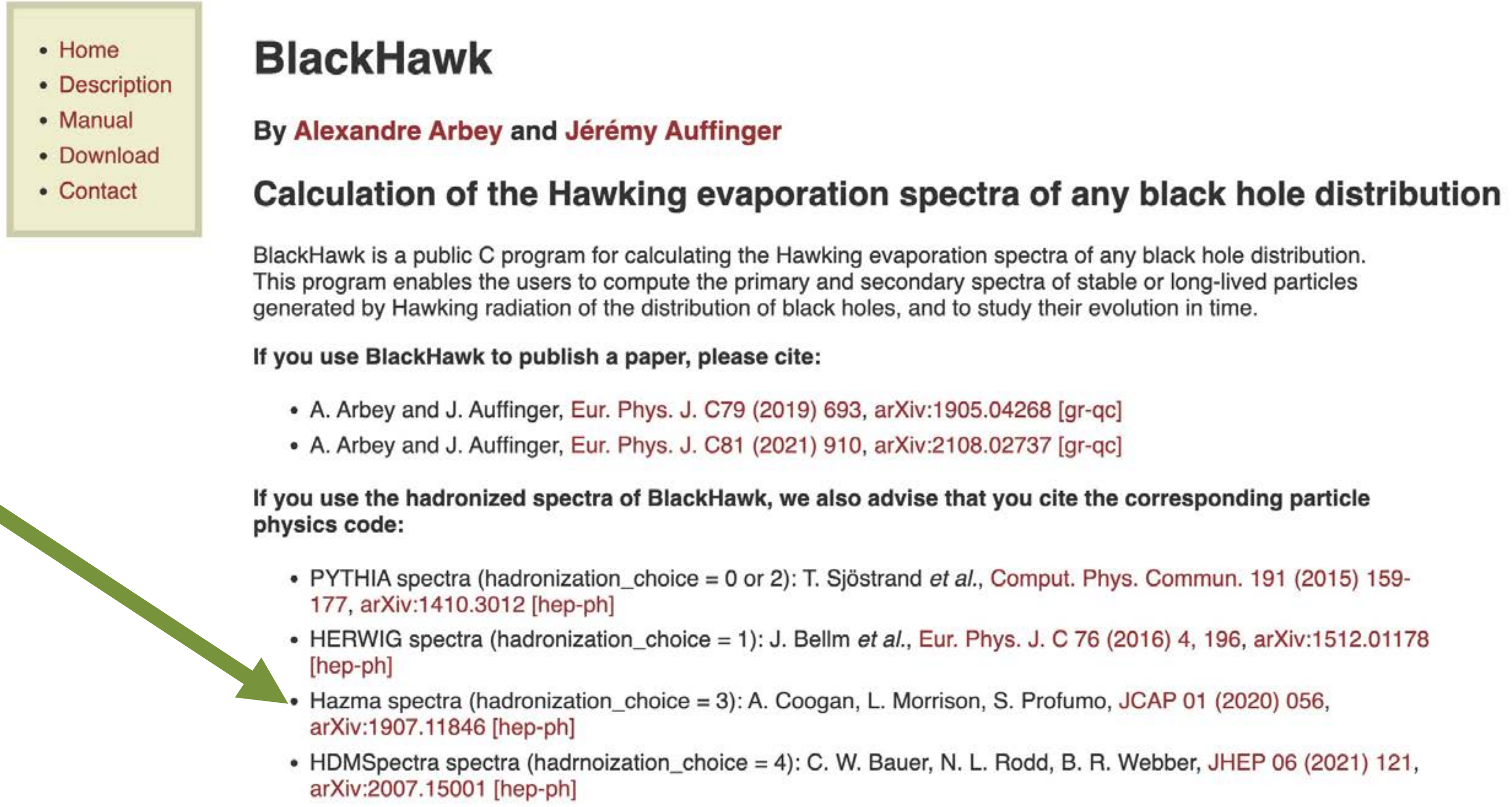
- **Chiral Perturbation Theory**
- **Vector Meson Dominance**
- **Hadronic Form Factors**

GALACTIC COMPTON AND
GECCO
CODED APERTURE MASK EXPLORER

Coogan, Morrison and Profumo, 2010.04797, PRL 126 (2021) 17, 171101

Evaporation products (gamma rays, cosmic-ray positrons) are detectable, constraining the fraction of light PBH that can be the DM





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BlackHawk

By Alexandre Arbey and Jérémy Auffinger

Calculation of the Hawking evaporation spectra of any black hole distribution

BlackHawk is a public C program for calculating the Hawking evaporation spectra of any black hole distribution. This program enables the users to compute the primary and secondary spectra of stable or long-lived particles generated by Hawking radiation of the distribution of black holes, and to study their evolution in time.

If you use BlackHawk to publish a paper, please cite:

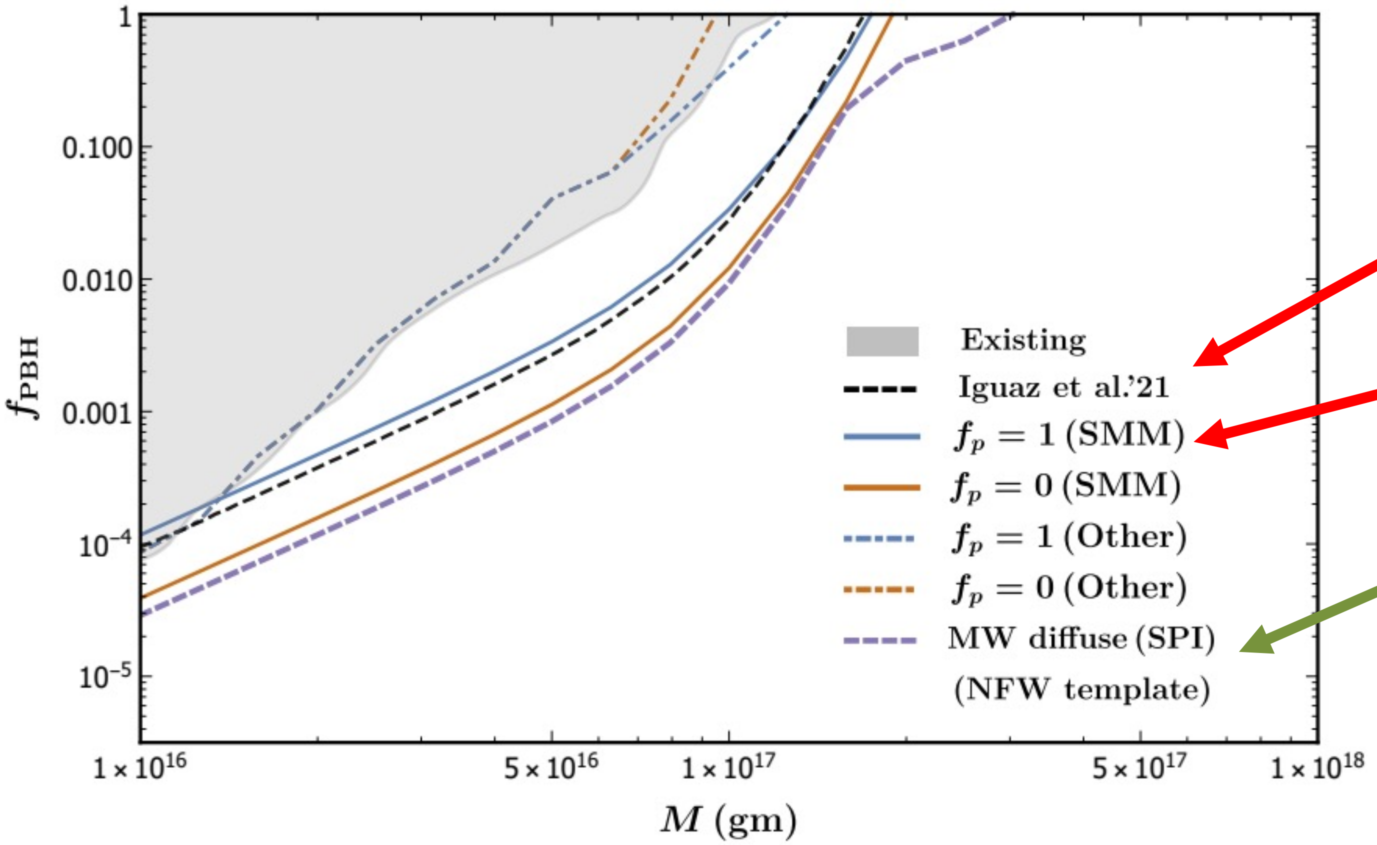
- A. Arbey and J. Auffinger, Eur. Phys. J. C79 (2019) 693, arXiv:1905.04268 [gr-qc]
- A. Arbey and J. Auffinger, Eur. Phys. J. C81 (2021) 910, arXiv:2108.02737 [gr-qc]

If you use the hadronized spectra of BlackHawk, we also advise that you cite the corresponding particle physics code:

- PYTHIA spectra (hadronization_choice = 0 or 2): T. Sjöstrand *et al.*, Comput. Phys. Commun. 191 (2015) 159-177, arXiv:1410.3012 [hep-ph]
- HERWIG spectra (hadronization_choice = 1): J. Bellm *et al.*, Eur. Phys. J. C 76 (2016) 4, 196, arXiv:1512.01178 [hep-ph]
- Hazma spectra (hadronization_choice = 3): A. Coogan, L. Morrison, S. Profumo, JCAP 01 (2020) 056, arXiv:1907.11846 [hep-ph]
- HDMSpectra spectra (hadrnoization_choice = 4): C. W. Bauer, N. L. Rodd, B. R. Webber, JHEP 06 (2021) 121, arXiv:2007.15001 [hep-ph]

Coogan, Morrison and Profumo, 2010.04797, PRL 126 (2021) 17, 171101

Strongest constraints to date: MW diffuse gamma-ray emission from Integral-SPI, including the 511 keV line



wrong by factor 2

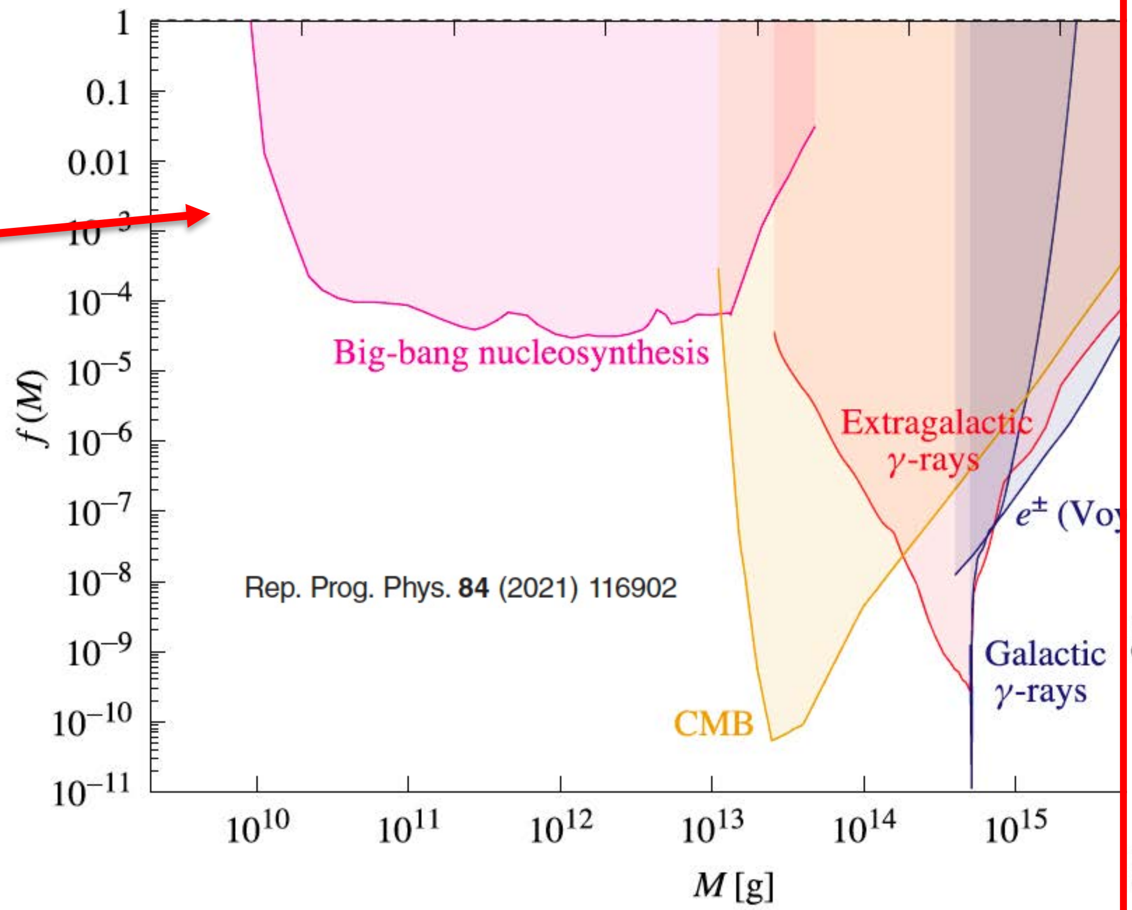
unreliable data

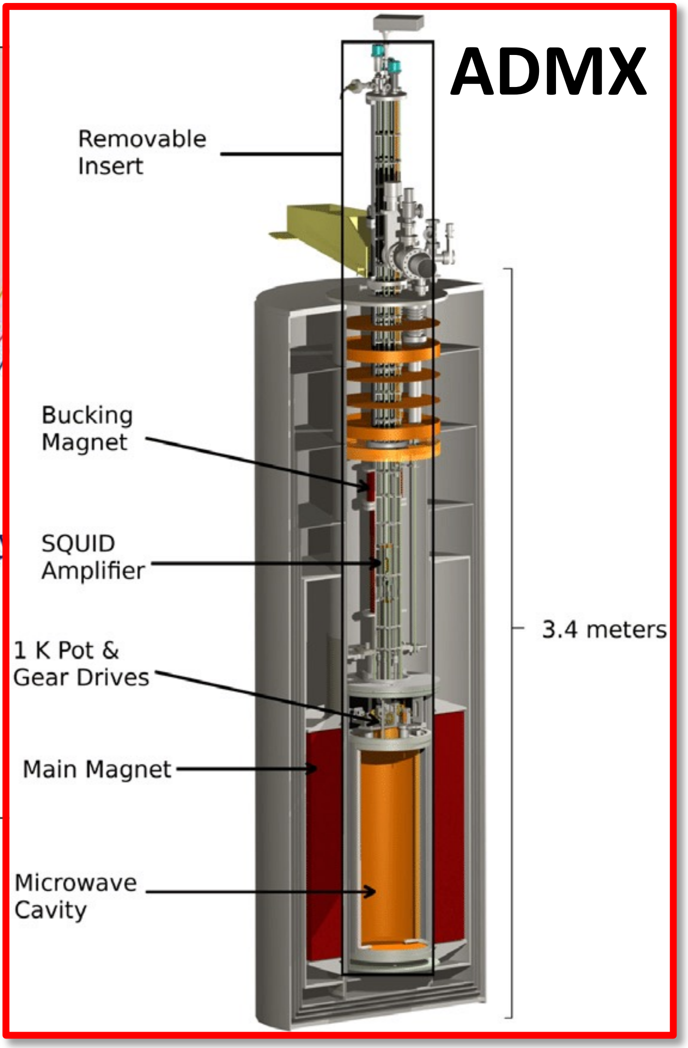
use this!

Korwar and Profumo, 2302.04408, JCAP

At earlier times, evaporation perturbs BBN, CMB

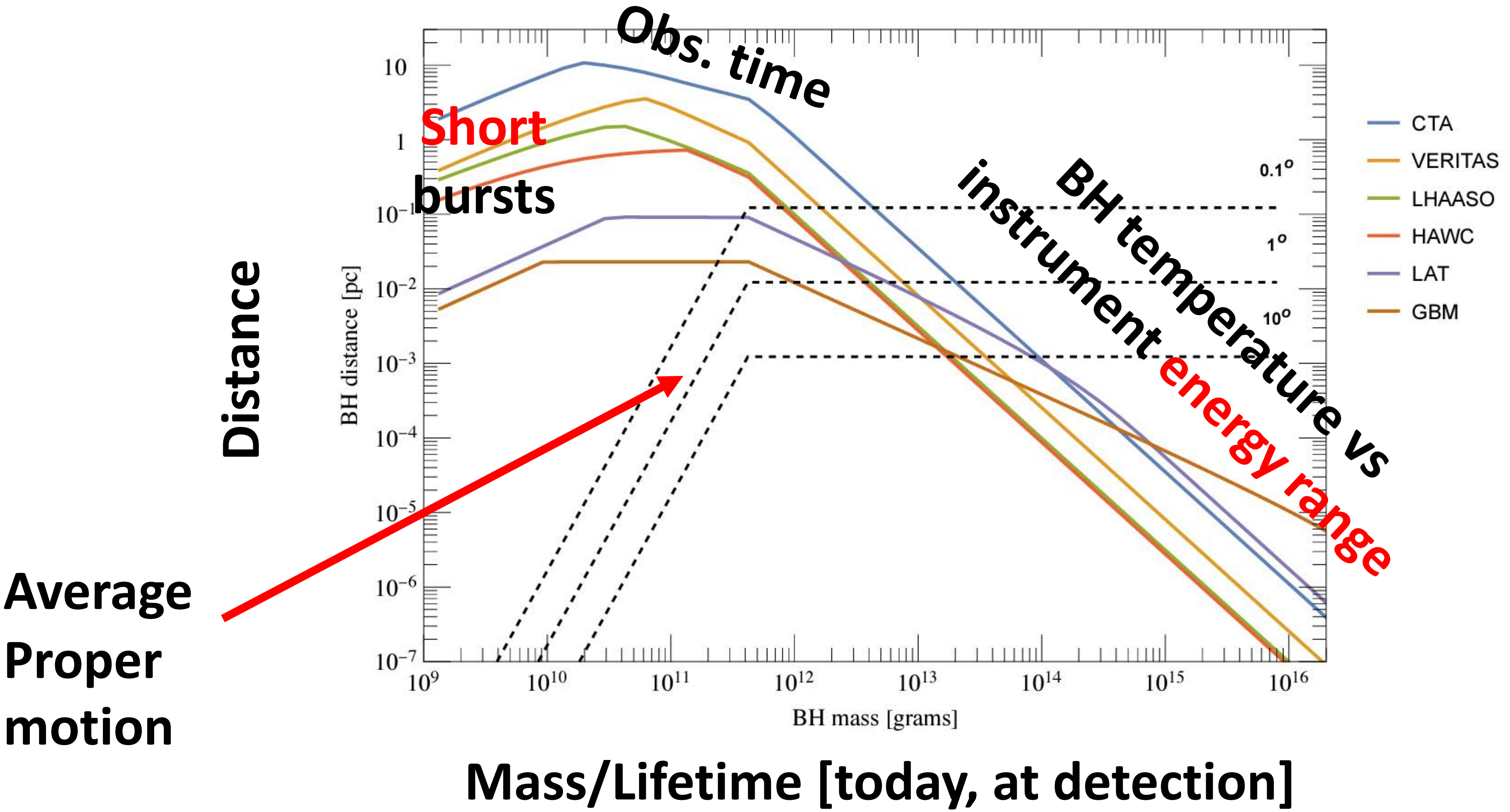
Here, perhaps, gravity waves! (but very high frequency!)*





*Ireland, Profumo and Scharnhorst, 2302.10188 (PRD), 2312.08508 (JCAP)

How can we search for PBH explosions today?



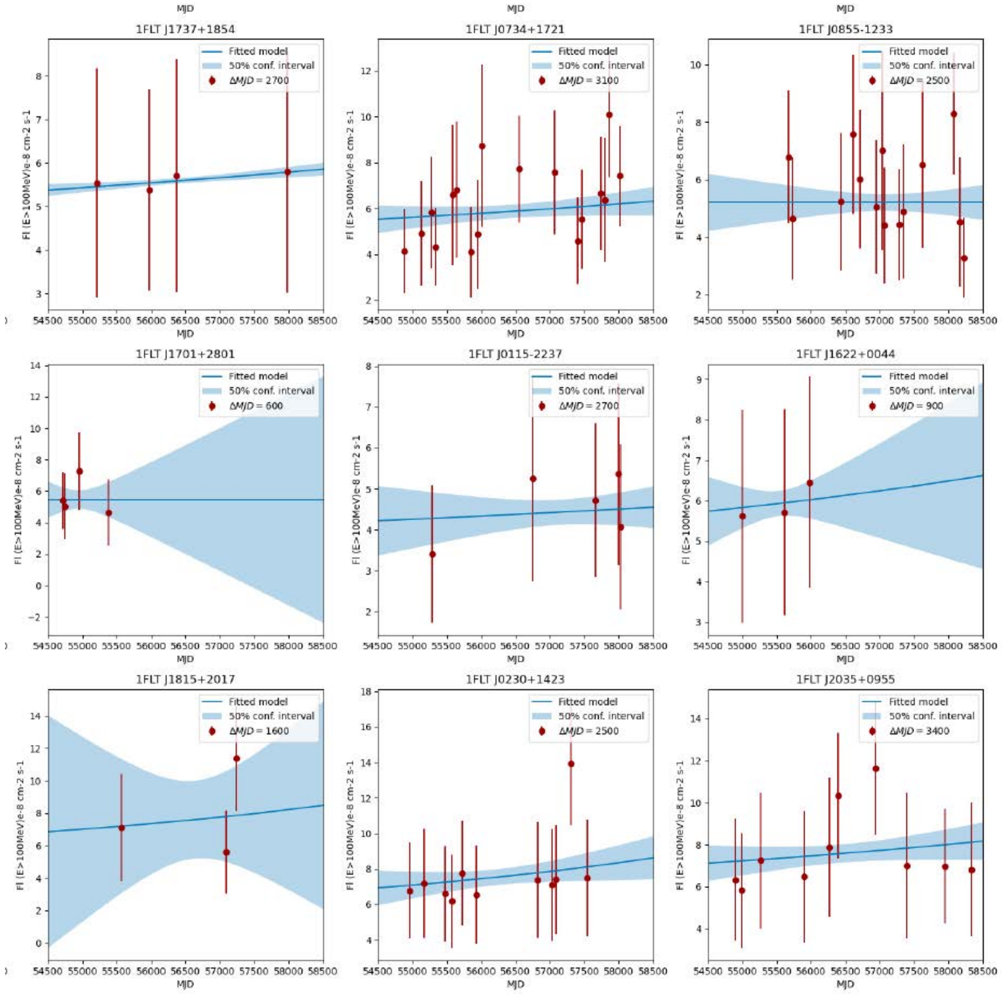
*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

Where to look:
LAT and GBM Gamma-ray burst catalog

- Lightcurve (flux as a function of time)
- Absolute brightness (“luminosity distance”)
- Spectrum (flux as a function of energy)
- Sky distribution

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

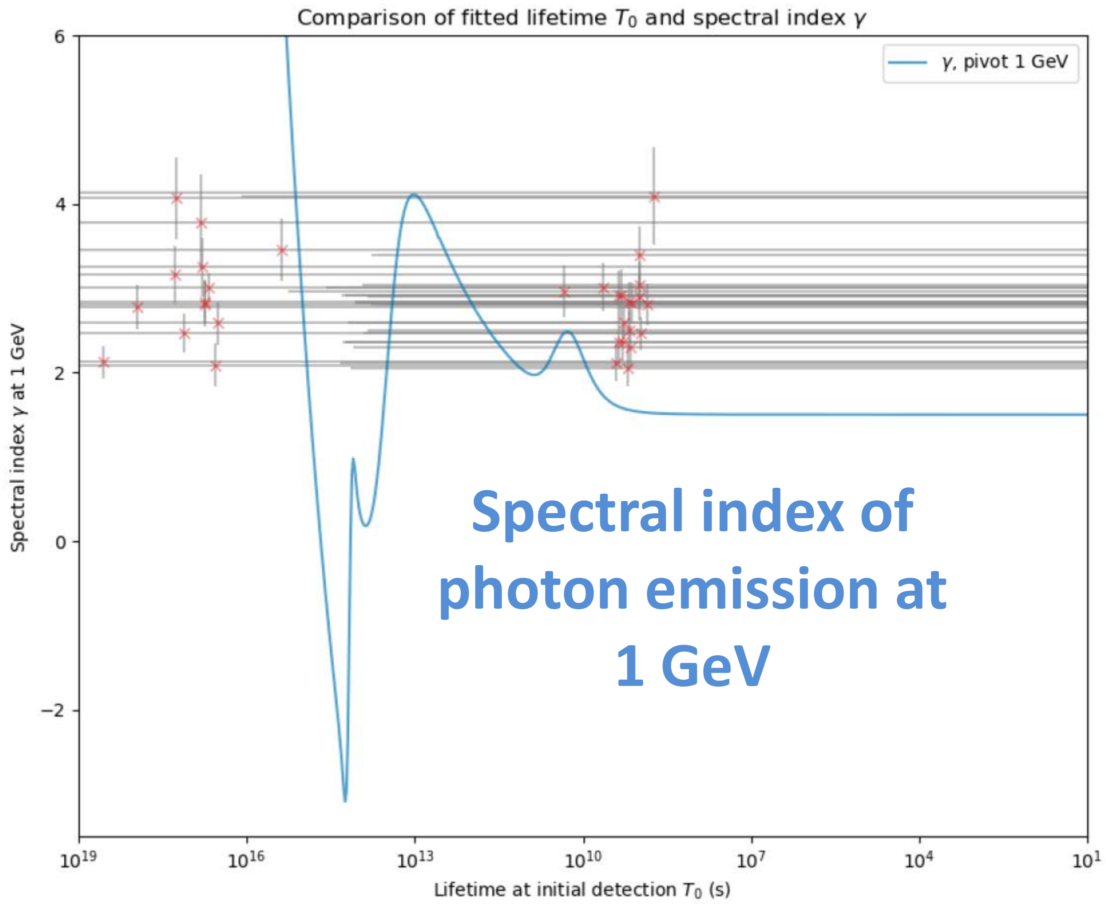
LAT and GBM Gamma-ray burst catalog
(1) LAT variable sources



time

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

LAT and GBM Gamma-ray burst catalog
(2) LAT variable sources: spectral fit

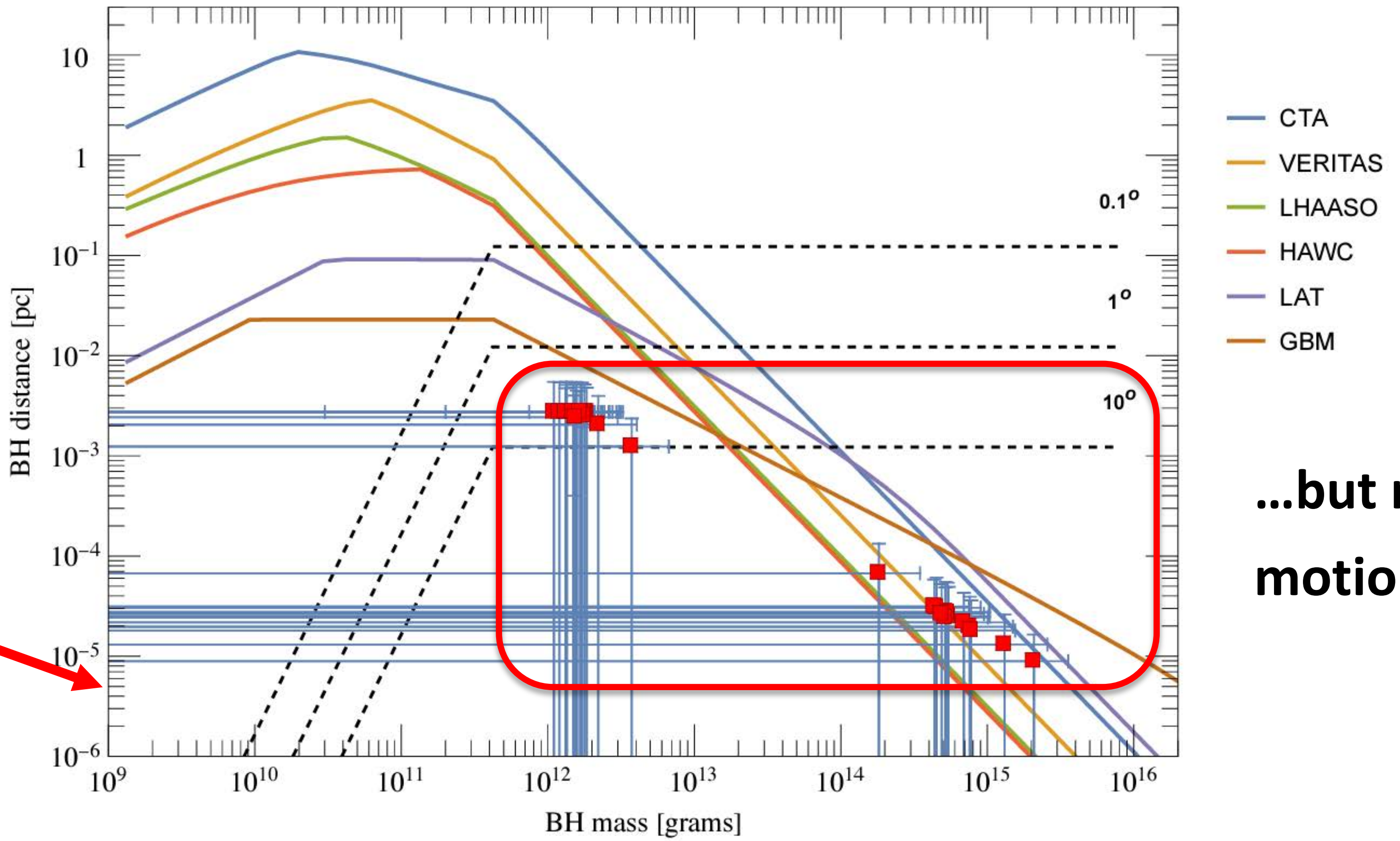


Time-to-explosion

***Profumo, Boluna, Ble, Hennings, 2023 (JCAP)**

LAT and GBM Gamma-ray burst catalog
(3) LAT variable sources: distance-age fit

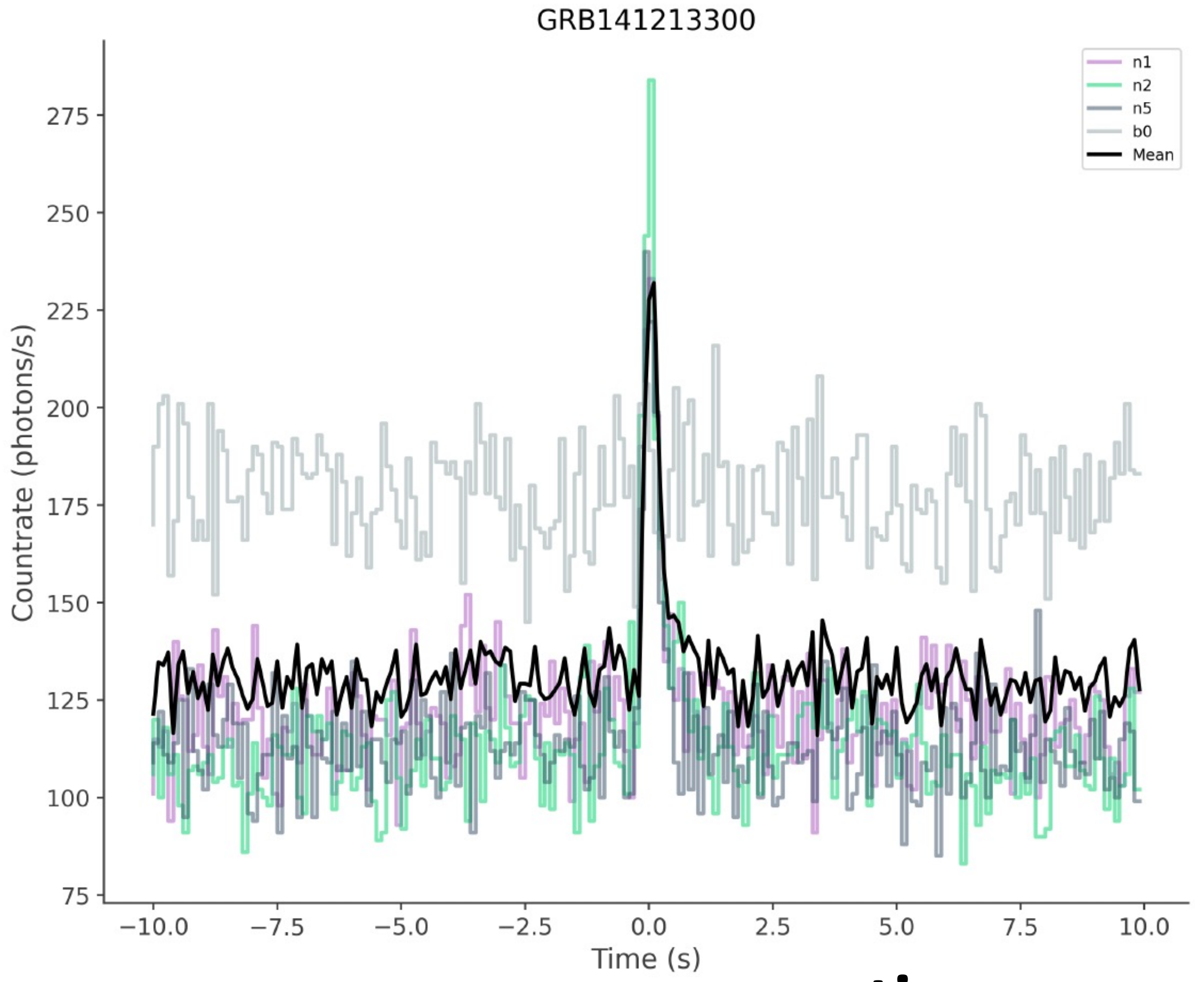
~1 A.U.



…but no proper motion detected 😢

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

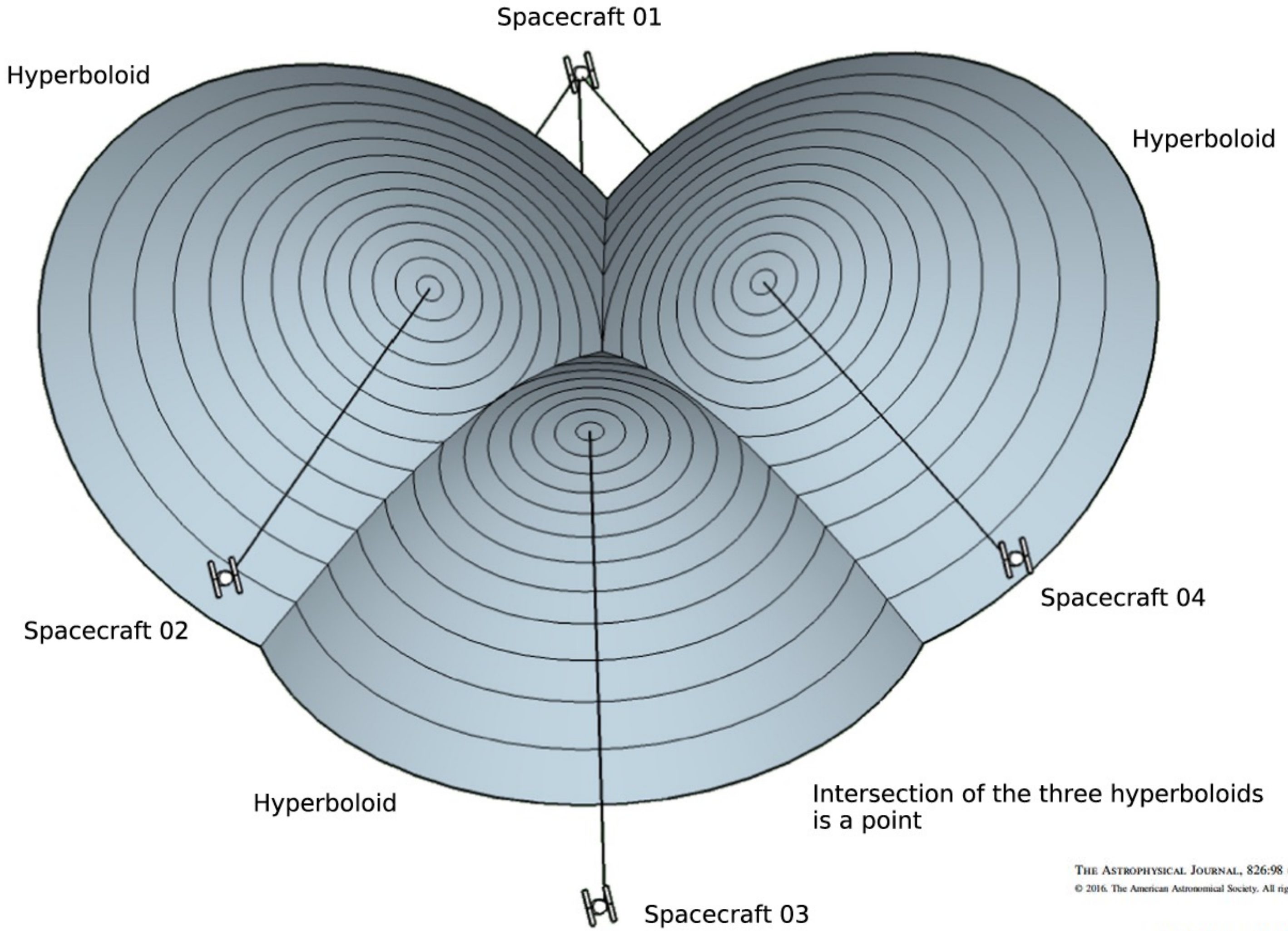
LAT and GBM Gamma-ray burst catalog
(4) Short duration: light curve



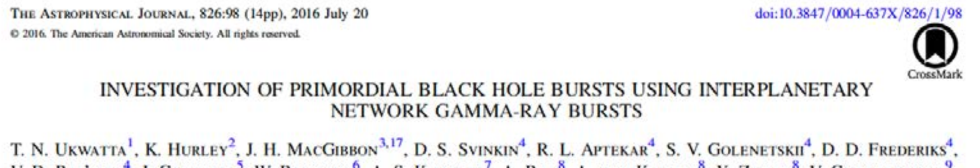
time

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

LAT and GBM Gamma-ray burst catalog
(5) Interplanetary GRB monitors network (IPN)



Timing resolution distinguishes cosmological vs local events!


The Astrophysical Journal, 826:98 (14pp), 2016 July 20
doi:10.3847/0004-637X/826/1/98

INVESTIGATION OF PRIMORDIAL BLACK HOLE BURSTS USING INTERPLANETARY NETWORK GAMMA-RAY BURSTS

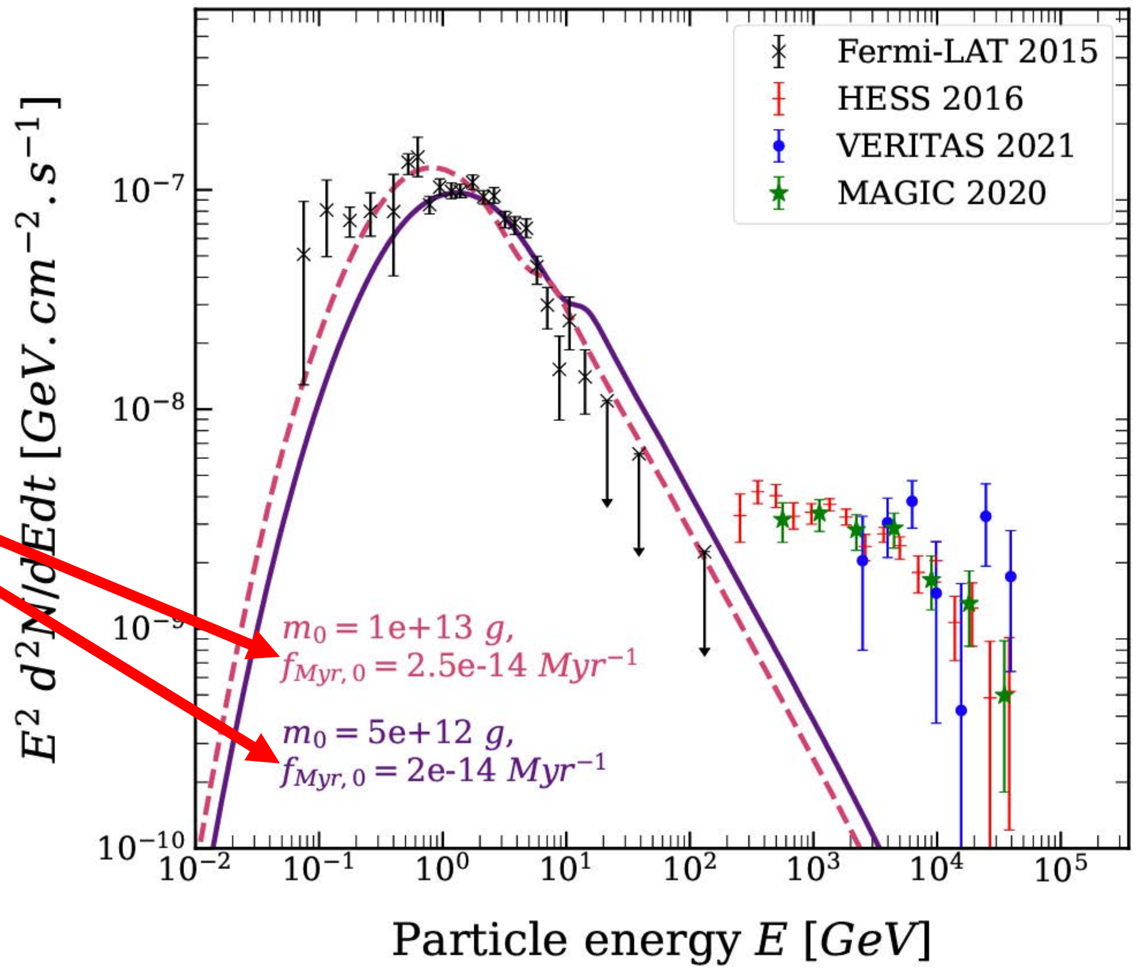
T. N. Ukwatta[1], K. Hurley[2], J. H. MacGibbon[3,17], D. S. Svinkin[4], R. L. Aptekar[4], S. V. Golenetskii[4], D. D. Frederiks[4],

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

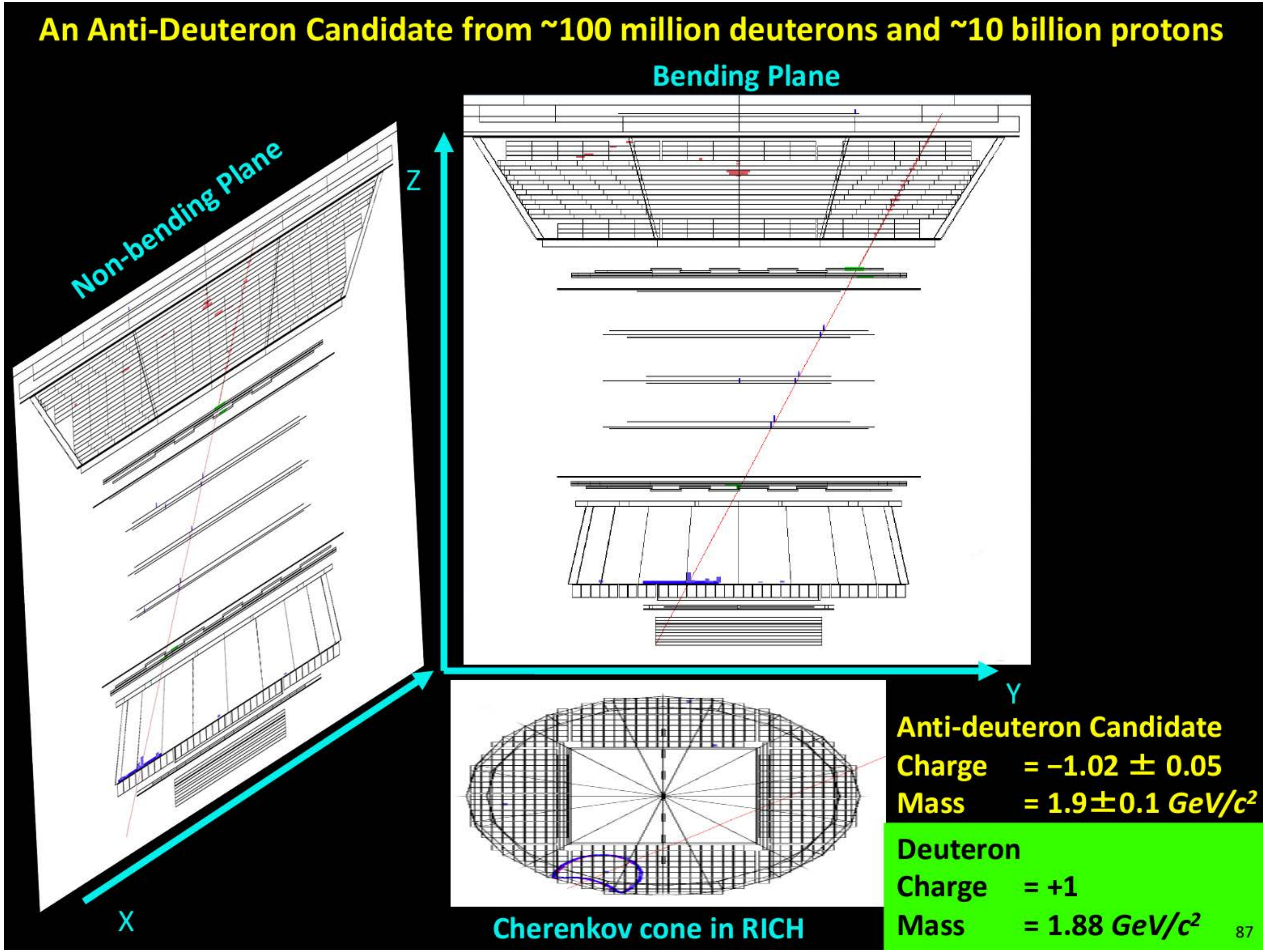
- Detection of Hawking radiation would be momentous!
- Unique opportunity to discover dark sectors!
- Number of handles to discriminate against GRBs
  - ✓ Light-curve
  - ✓ Spectrum
  - ✓ Distance
  - ✓ Afterglow

Anomalous Cosmic-ray and Gamma-ray Signals from late-forming PBH

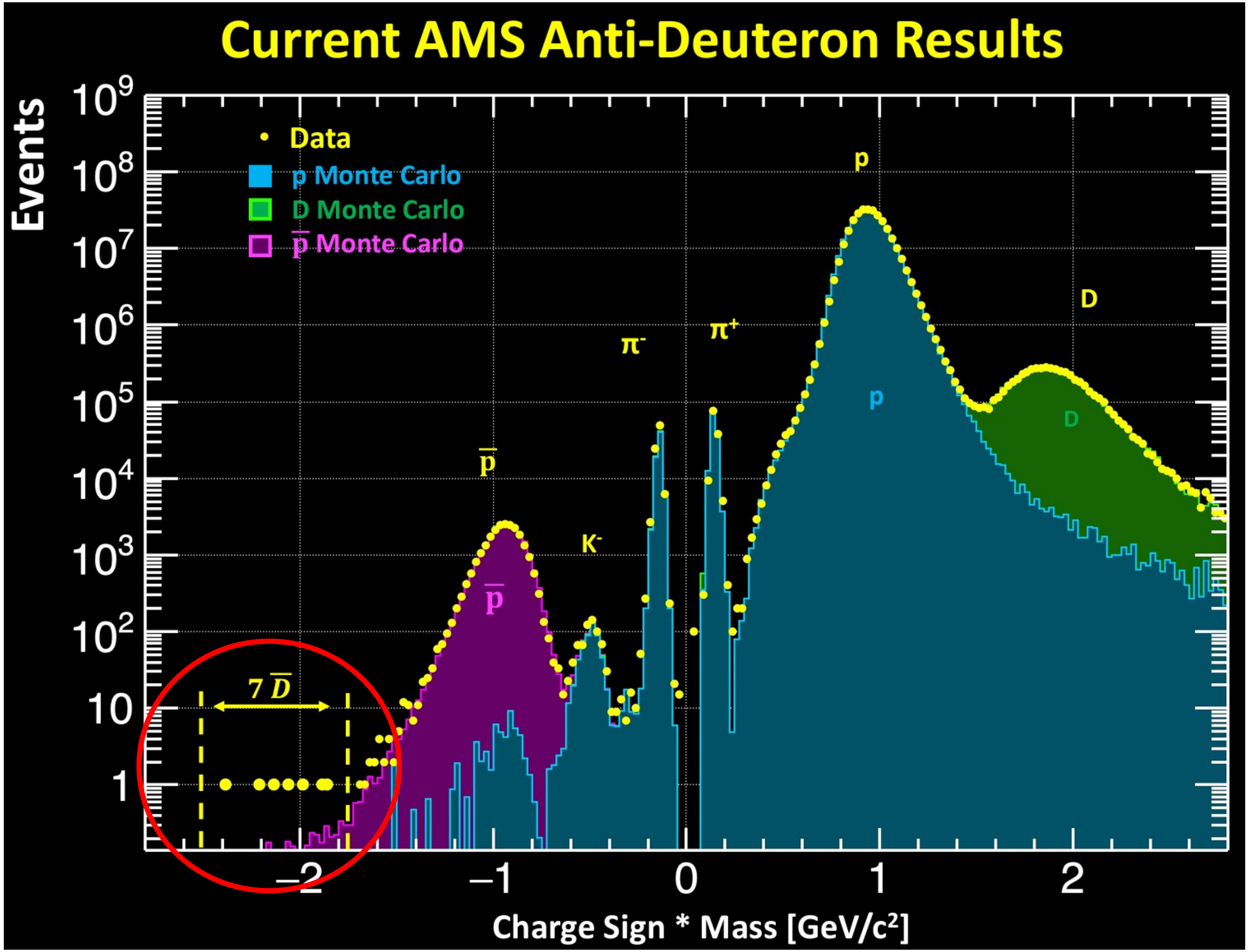
Rate of BH "injection" (per Myr, per fraction of cosmological DM density)



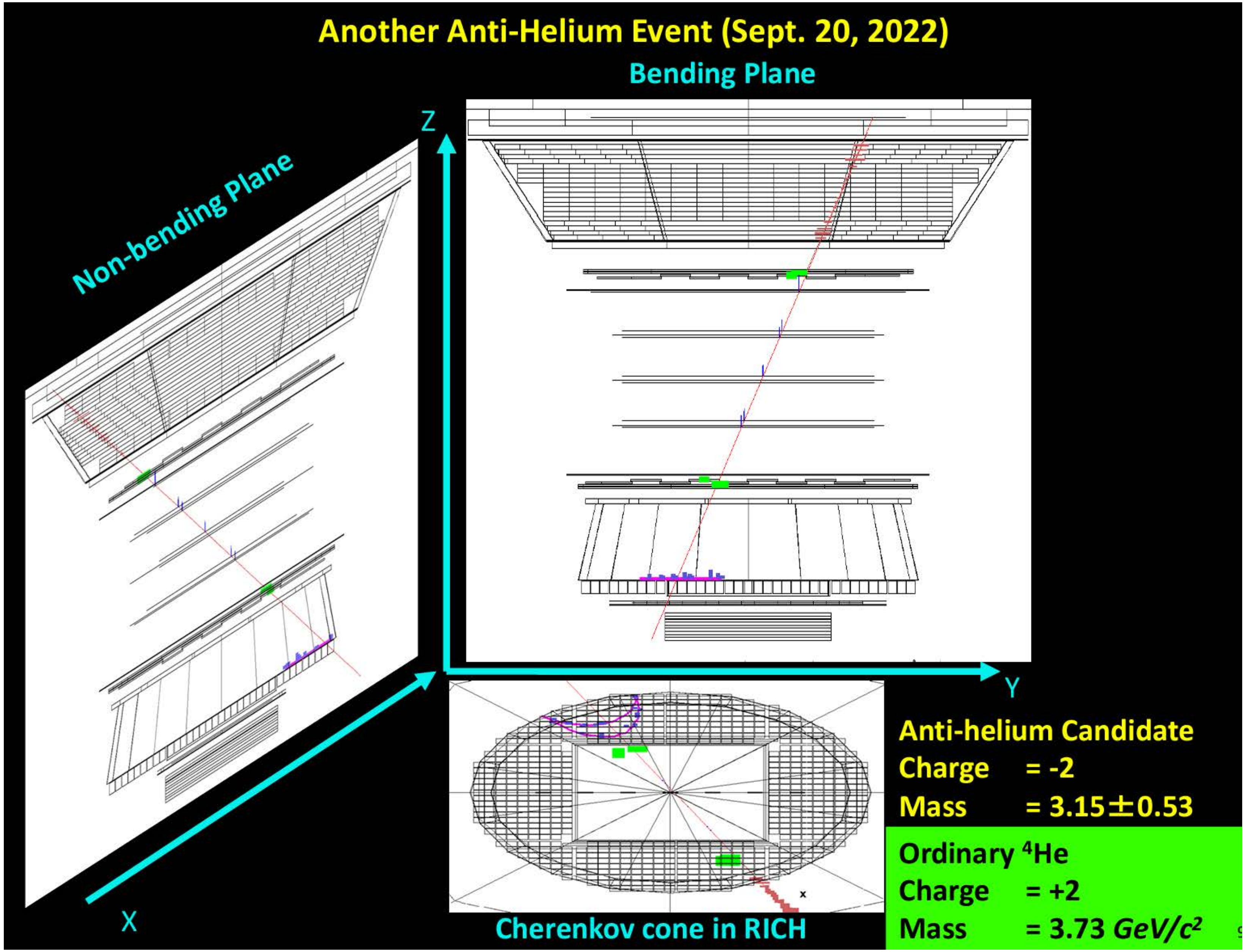
* Picker and Kusenko, 2023 *Phys.Lett.B* 845 (2023) 138175



Sam Ting, 2023 CERN Colloquium

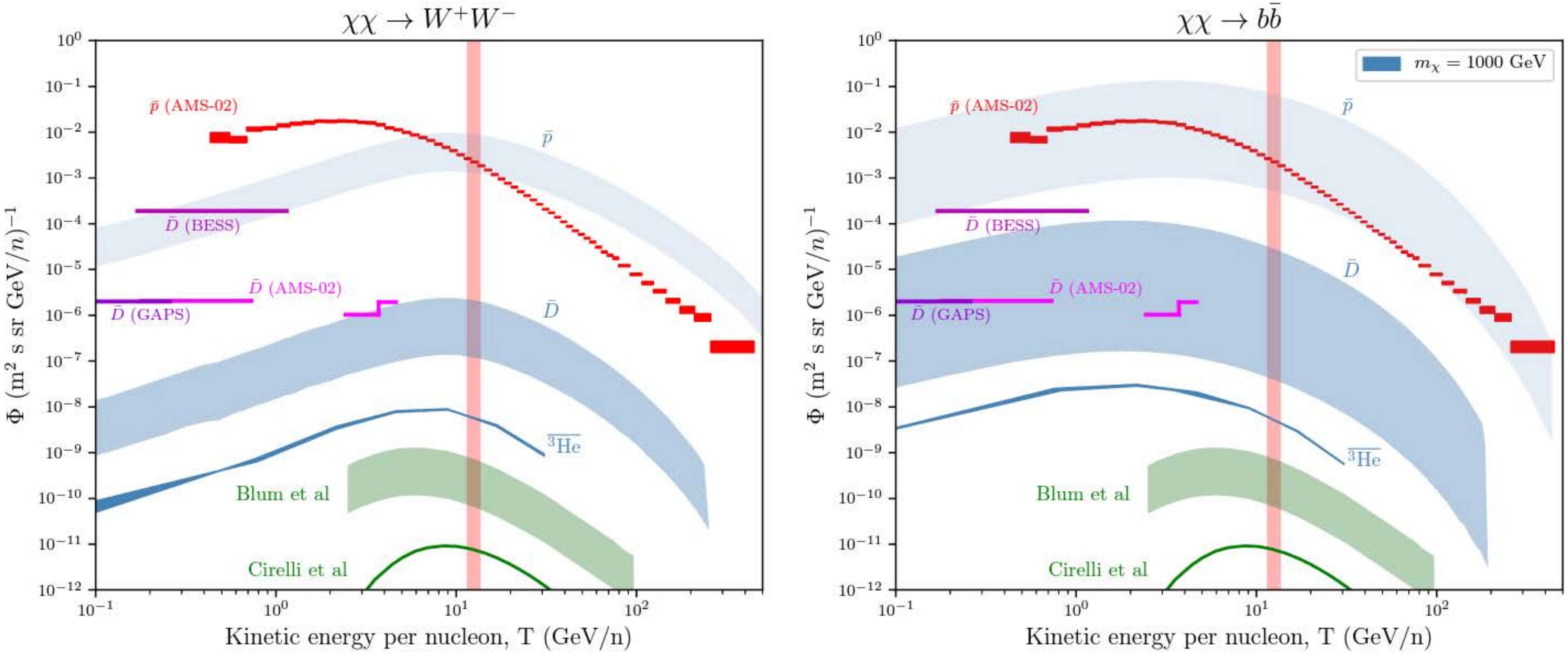


Sam Ting, 2023 CERN Colloquium



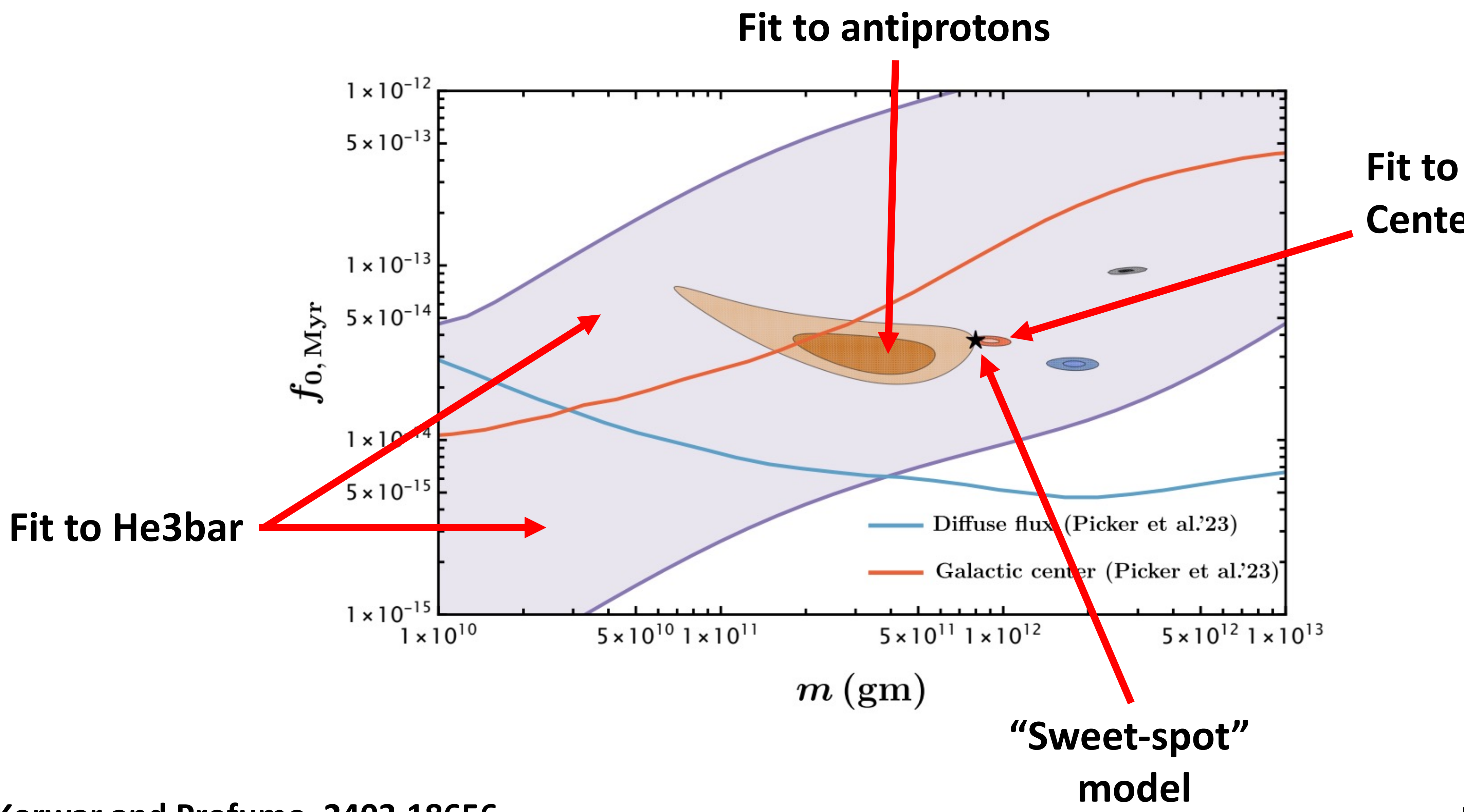
Sam Ting, 2023 CERN Colloquium

Annihilating Dark Matter remains a possibility, albeit very constrained!



*Coogan and Profumo., *Phys.Rev.D* 96 (2017) 8, 083020

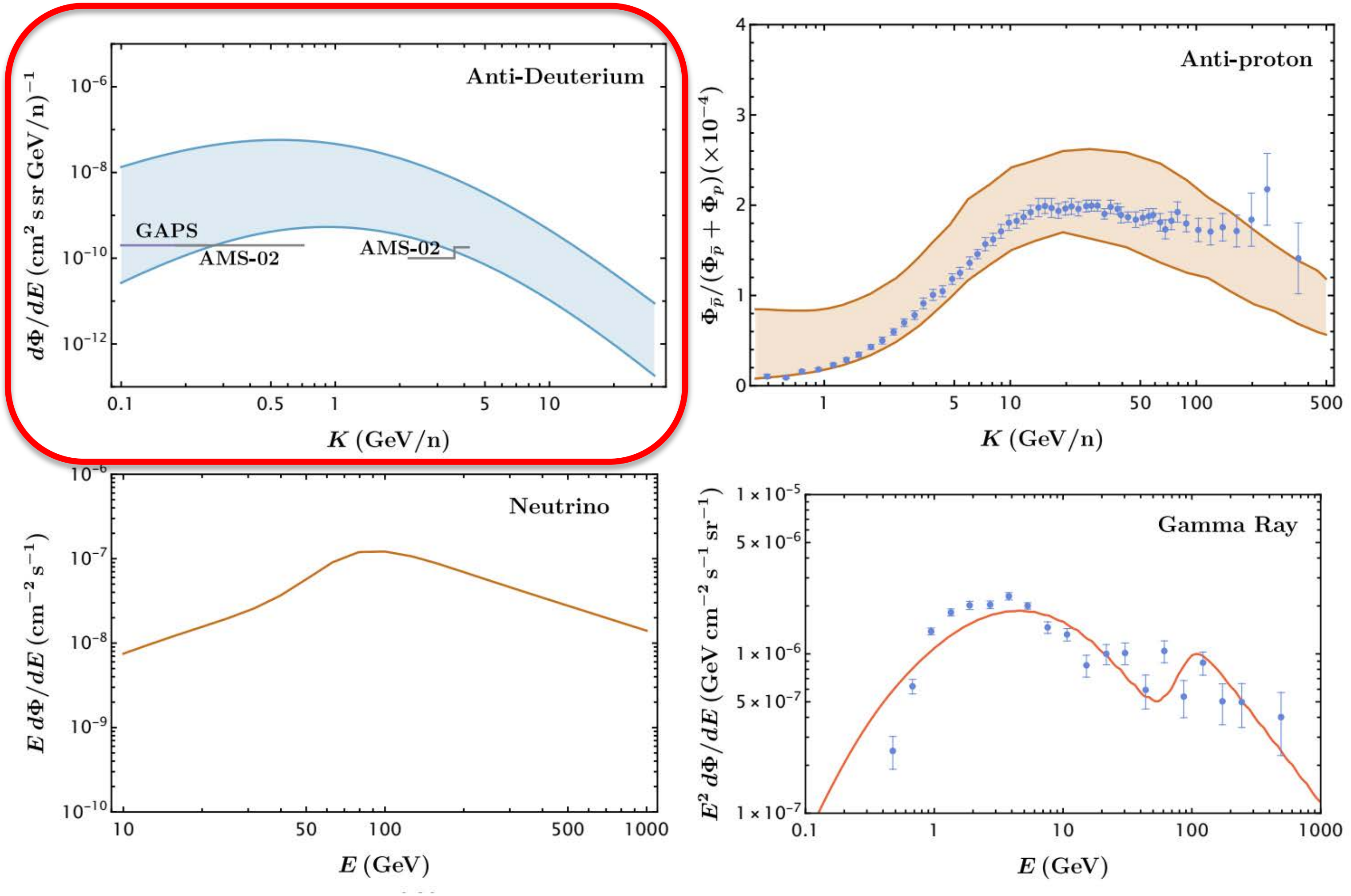
Microstructure BH are ideal candidates to explain 3Hebar and Dbar



Mrunal Korwar

*Korwar and Profumo, 2403.18656

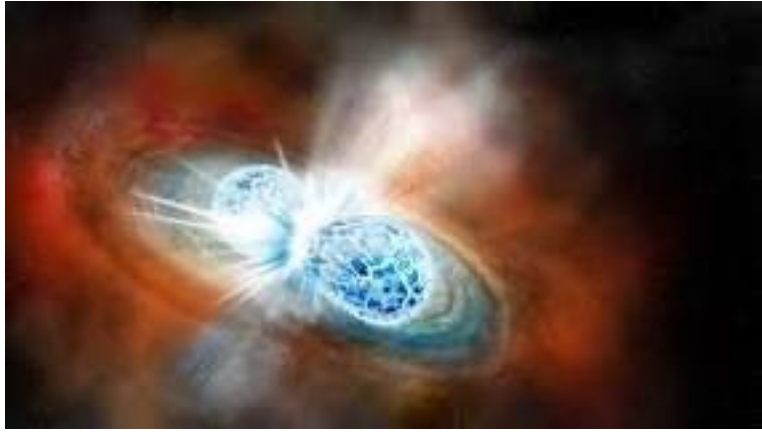
Microstructure BH are ideal candidates to explain 3Hebar and Dbar



Mrunal Korwar

*Korwar and Profumo, 2403.18656

Neutron Star "Implosions"



Dark matter can be captured in celestial bodies via repeated scattering off of ordinary matter

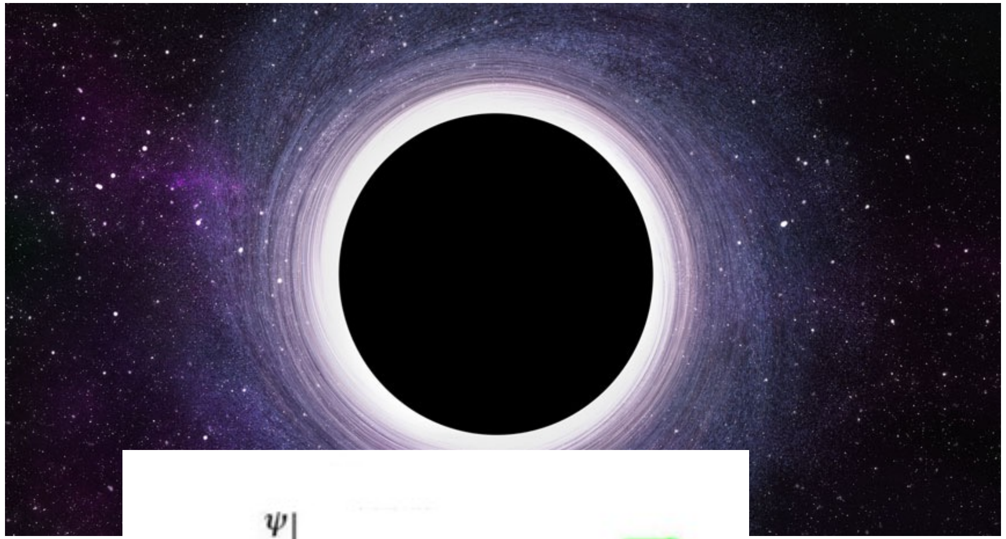
Out-of-equilibrium, rare invisible neutron decay can also accrete over time dark particles*

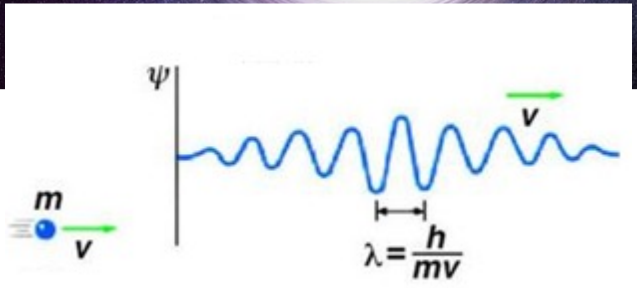
If dark matter cannot pair-annihilate, it will accrete over time, possibly thermalize, form a condensate, and eventually collapsing into a black hole

The black hole can either evaporate away, or swallow and destroy the neutron star

*Roy and Profumo, in prep.

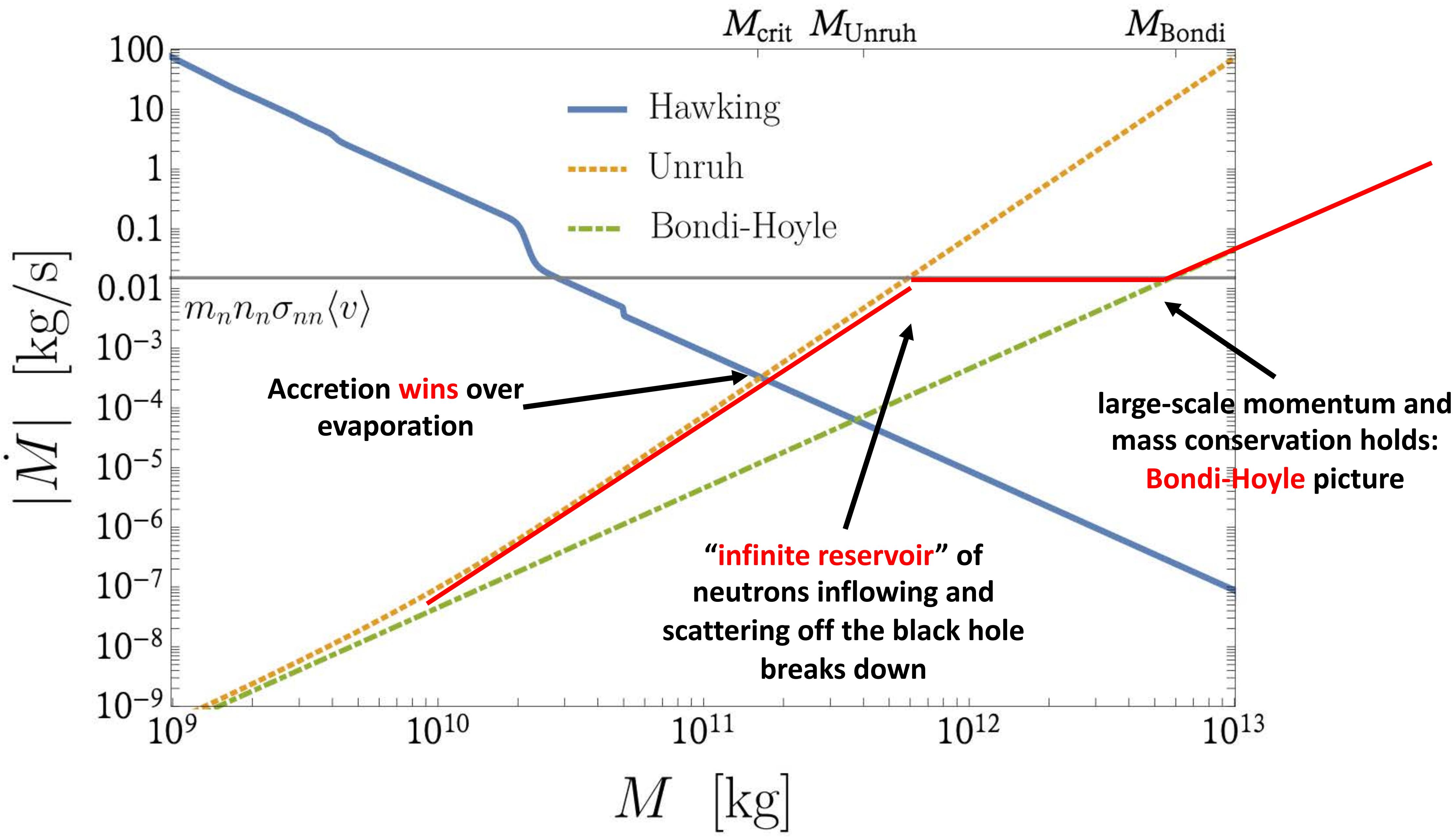
what if the black hole size (its Schwarzschild radius) is smaller than the neutron star constituents?





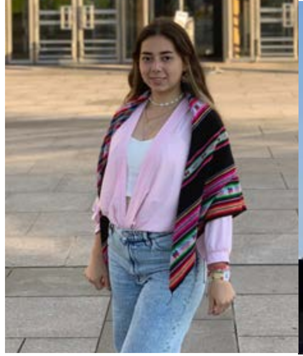
the description of matter accretion must necessarily use quantum mechanics and not (classical) fluid dynamics (massless point particles)!

Giffin, Lloyd, McDermott, Profumo, *Phys.Rev.D* 105 (2022) 12, 123030



Giffin, Lloyd, McDermott, Profumo, *Phys.Rev.D* 105 (2022) 12, 123030

Full Numerical Treatment of Dynamical Constraints on Massive PBHs



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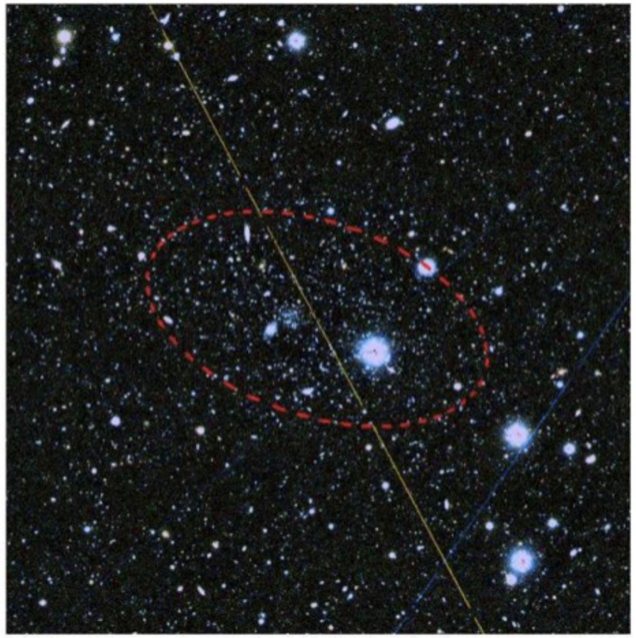
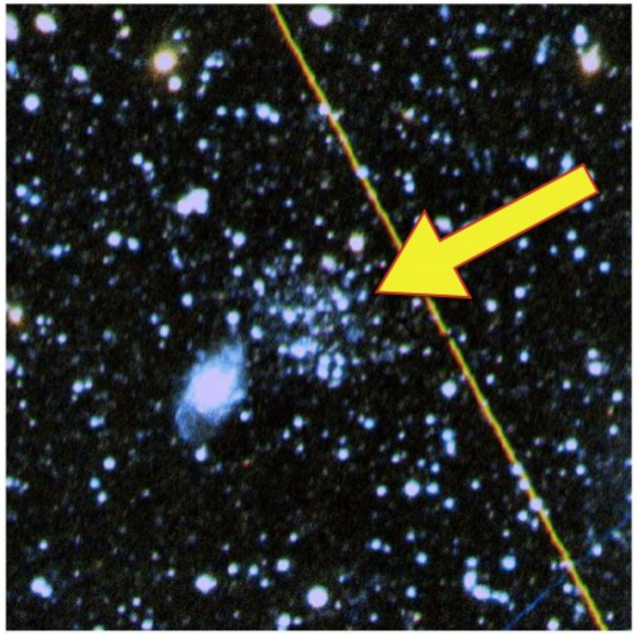
Nolan Smyth

New ultra-faint dwarf galaxies (discovered via DES+PanSTARRS) provide strong constraints on the abundances and masses of massive compact objects → constraints can be derived by looking at the survival of a star cluster within the Eridanus II galaxy (Eri II)





Stellar tidal disruption can be modeled* as a diffusion problem

$$D[(\Delta v)^2] = \frac{4\sqrt{2}\pi G^2 f_{\mathrm{DM}}\rho m_a \ln\Lambda}{\sigma}\left[\frac{\mathrm{erf}(X)}{X}\right] \qquad \frac{dr_{\mathrm{h}}}{dt} = \frac{4\sqrt{2}\pi G f_{\mathrm{DM}} m_a \ln\Lambda}{\sigma}\left(\frac{\alpha M_*}{r_{\mathrm{h}}^2\rho} + 2\beta r_{\mathrm{h}}\right)^{-1}$$

-$\boldsymbol{m_a}$: MACHO mass

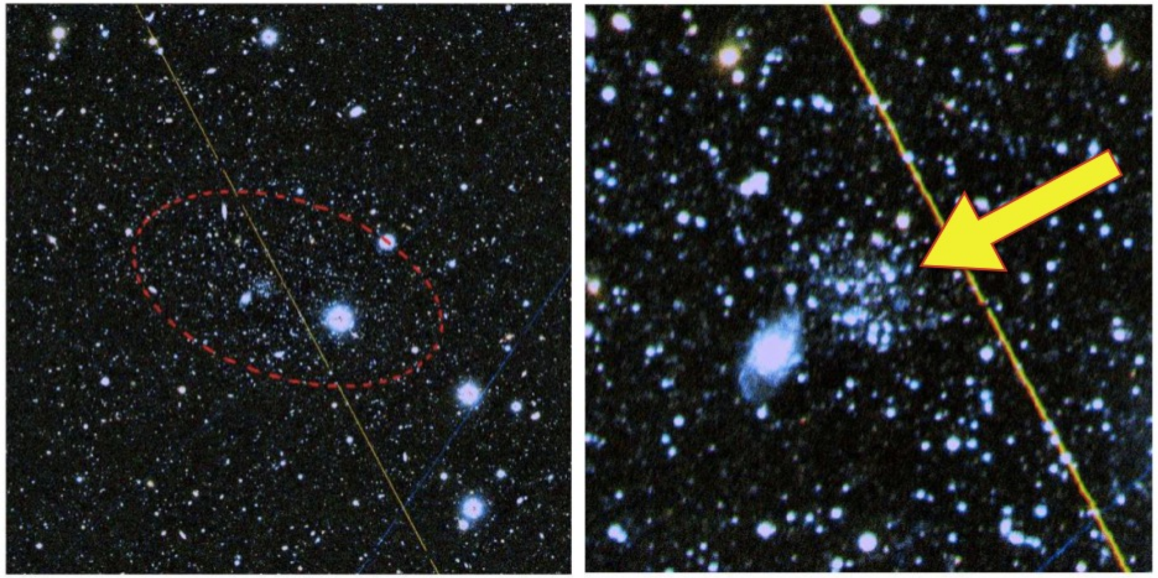
-$\boldsymbol{\rho}$: total DM density

-$\boldsymbol{\sigma}$: MACHO velocity dispersion

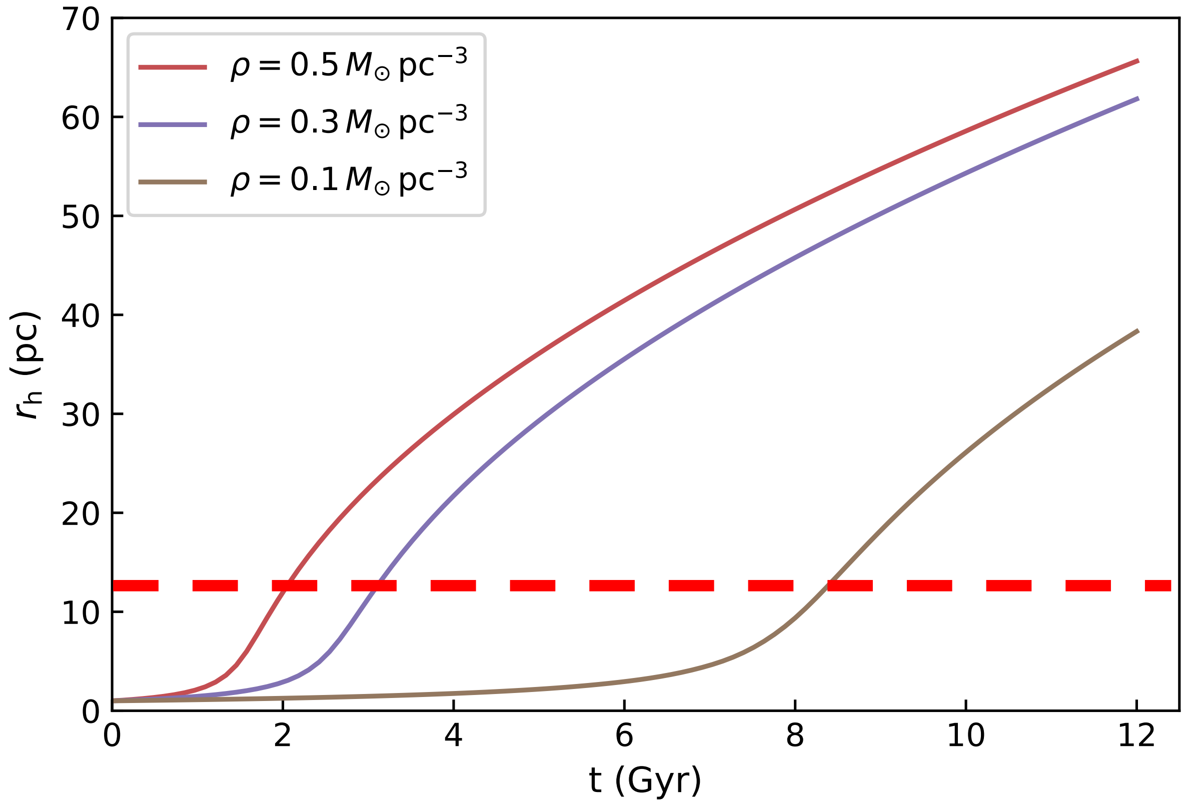
-ln$\boldsymbol{\Lambda}$: Coulomb-Logharithm

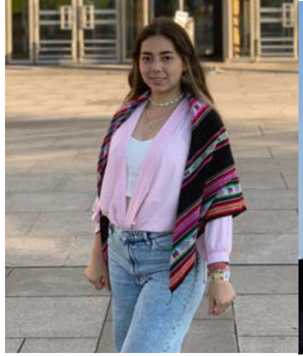
-$\boldsymbol{f_{DM}}$: fraction of DM in MACHOs

-$\boldsymbol{X \equiv v_*/(\sqrt{2}\sigma)}$: ratio of the stellar velocity to the velocity of the MACHOs



*Timothy D. Brandt 2016 *ApJL* **824** L31





Julia Koulen Nolan Smyth

-MACHOs with mass $m_a = 30\ M_\odot$ and velocity dispersion $\sigma = 5\,\frac{\mathrm{km}}{\mathrm{s}}$

-stellar mass $M_* = 6000\ M_\odot$

-initial half-light radius $r_h = 1\ \mathrm{pc}$

-current radius $r_h = 13\ \mathrm{pc}$

Koulen, Profumo, Smyth 2024

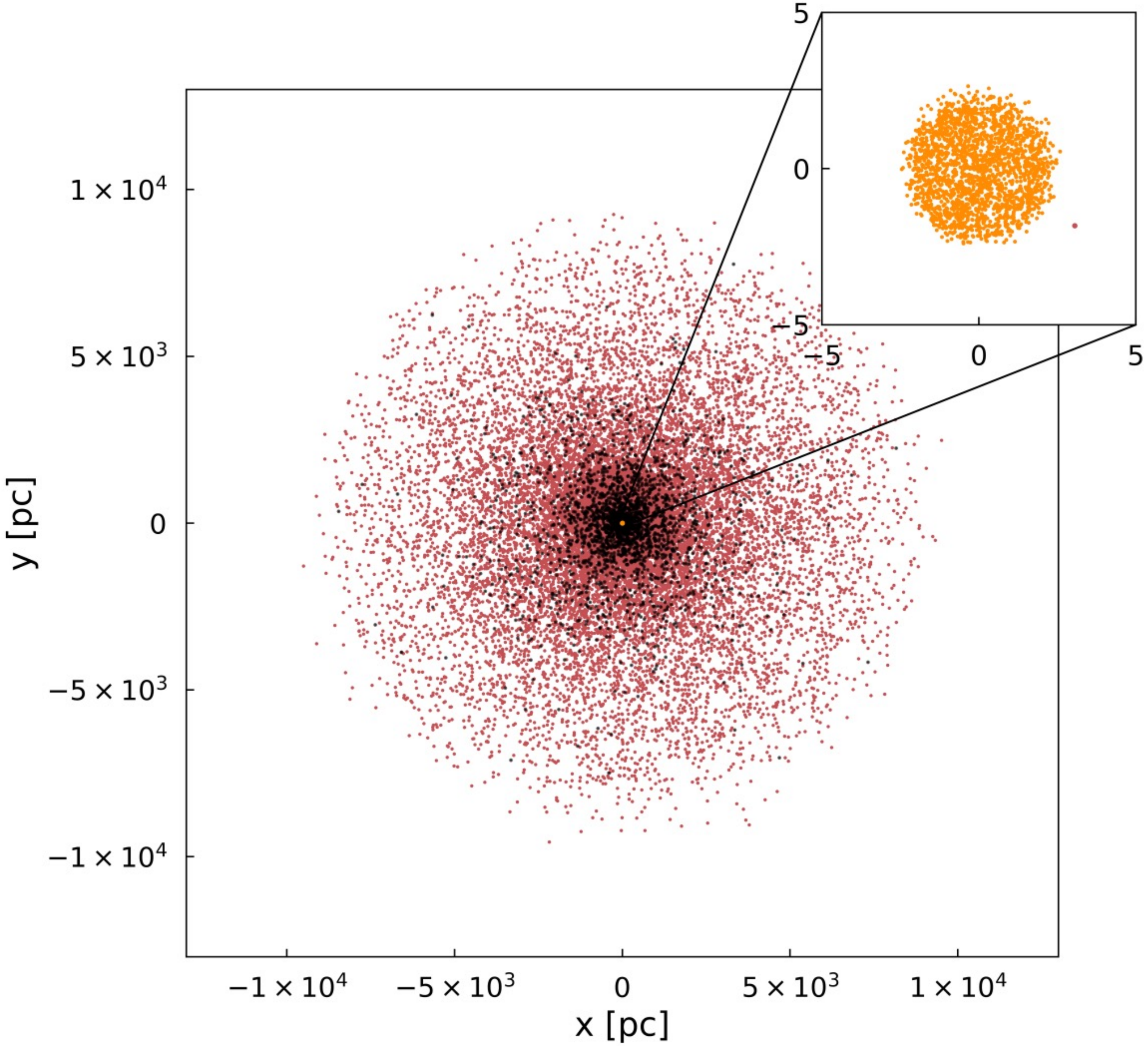
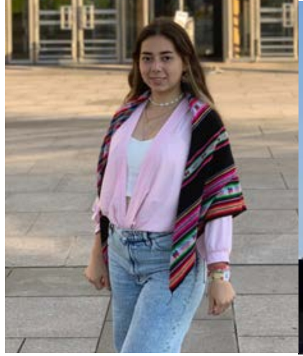


Figure 3. **Snapshots of the initial condition state of the Eridanus II galaxy for $f_{\mathbf{PBH}} = 0.1$ and $m_{\mathrm{PBH}} = 10,000\ M_{\odot}$.** Snapshot of the simulation in the xy-plane. Background DM particles are indicated in red, PBH in black, and stars in yellow. Upper right panel: Zoom-in snapshot of the simulation in the x-y plane. Both snapshots are at $t = 0.0\,\mathrm{Gyr}$.



Julia Koulen

Nolan Smyth

Koulen, Profumo, Smyth 2024

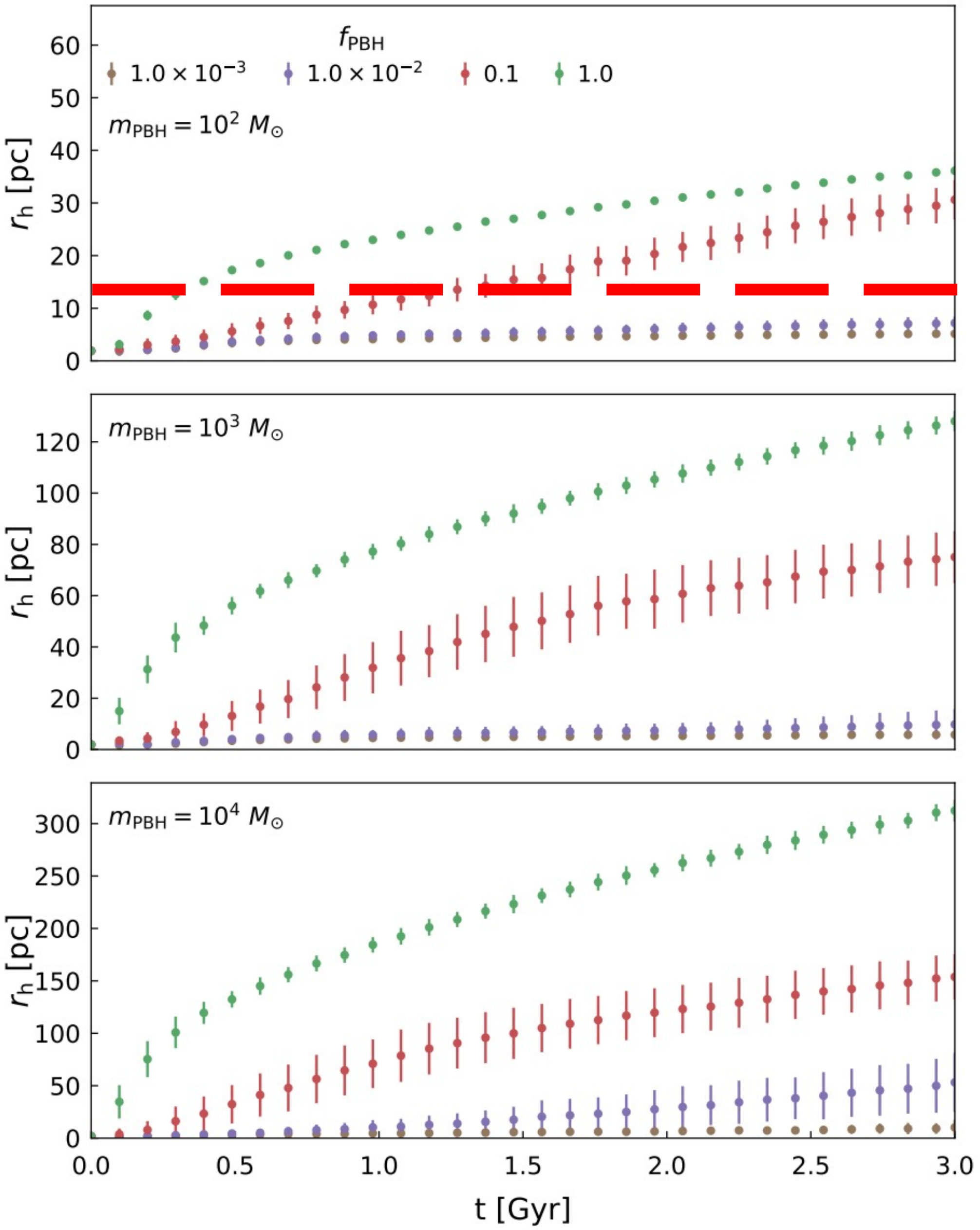
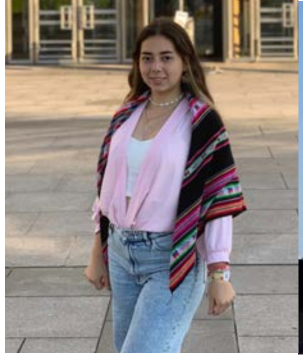


Figure 4. **Evolution of the half-mass radius over 3 Gyr for different PBH masses.** At each timestep and for each value of f_{PBH}, the half-mass radius values are averaged over 50 simulations.

Current radius of stellar cluster



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Nolan Smyth

Koulen, Profumo, Smyth 2024

Reliable **constraints** on large-mass PBHs

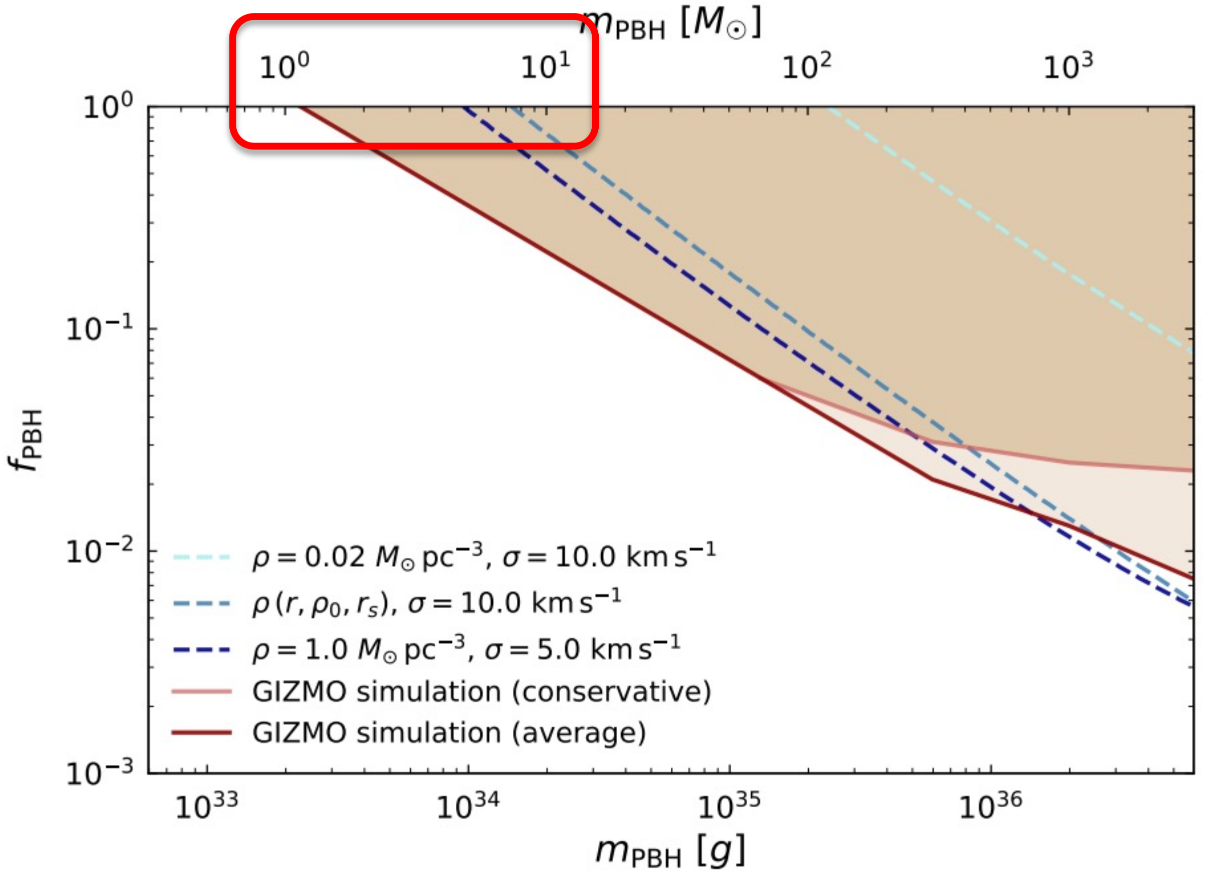
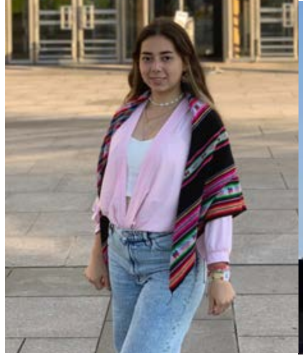


Figure 5. **Constraints on $f_{\rm PBH}$ as a function of $m_{\rm PBH}$.** Limits are derived using the average $r_{\rm h}$ over 50 simulations for each mass. Also shown is a conservative case using $r_{\rm h}$ one standard deviation below the mean. The dashed lines are the semi-analytically derived constraints.



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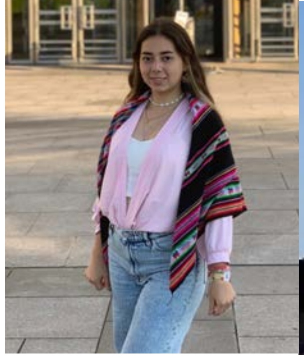
Koulen, Profumo, Smyth 2024

Early Pop III Star Formation



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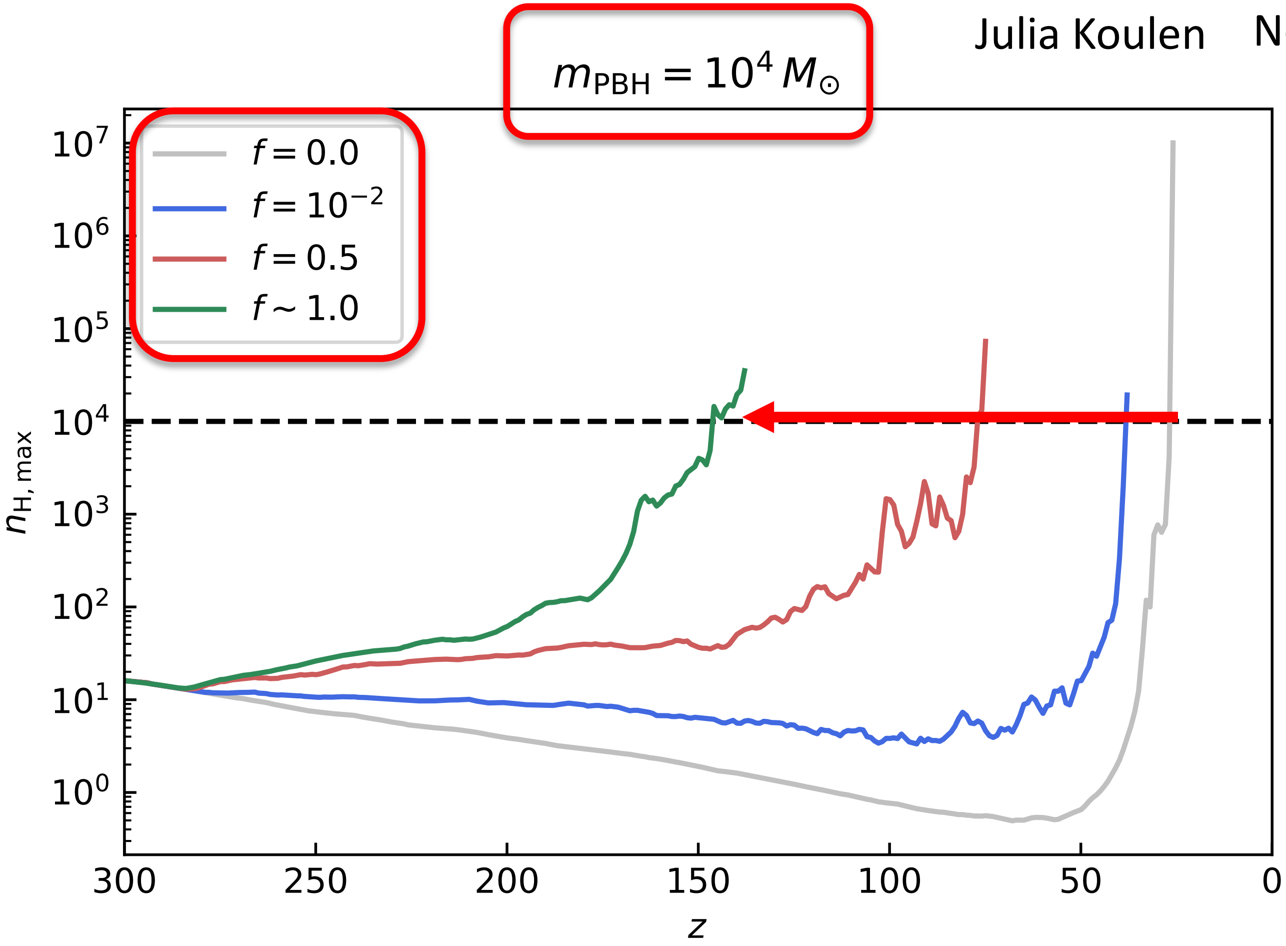
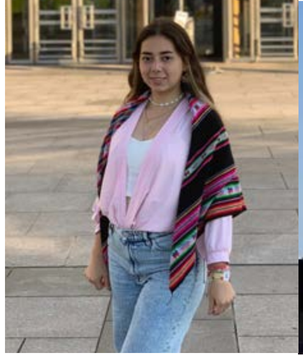


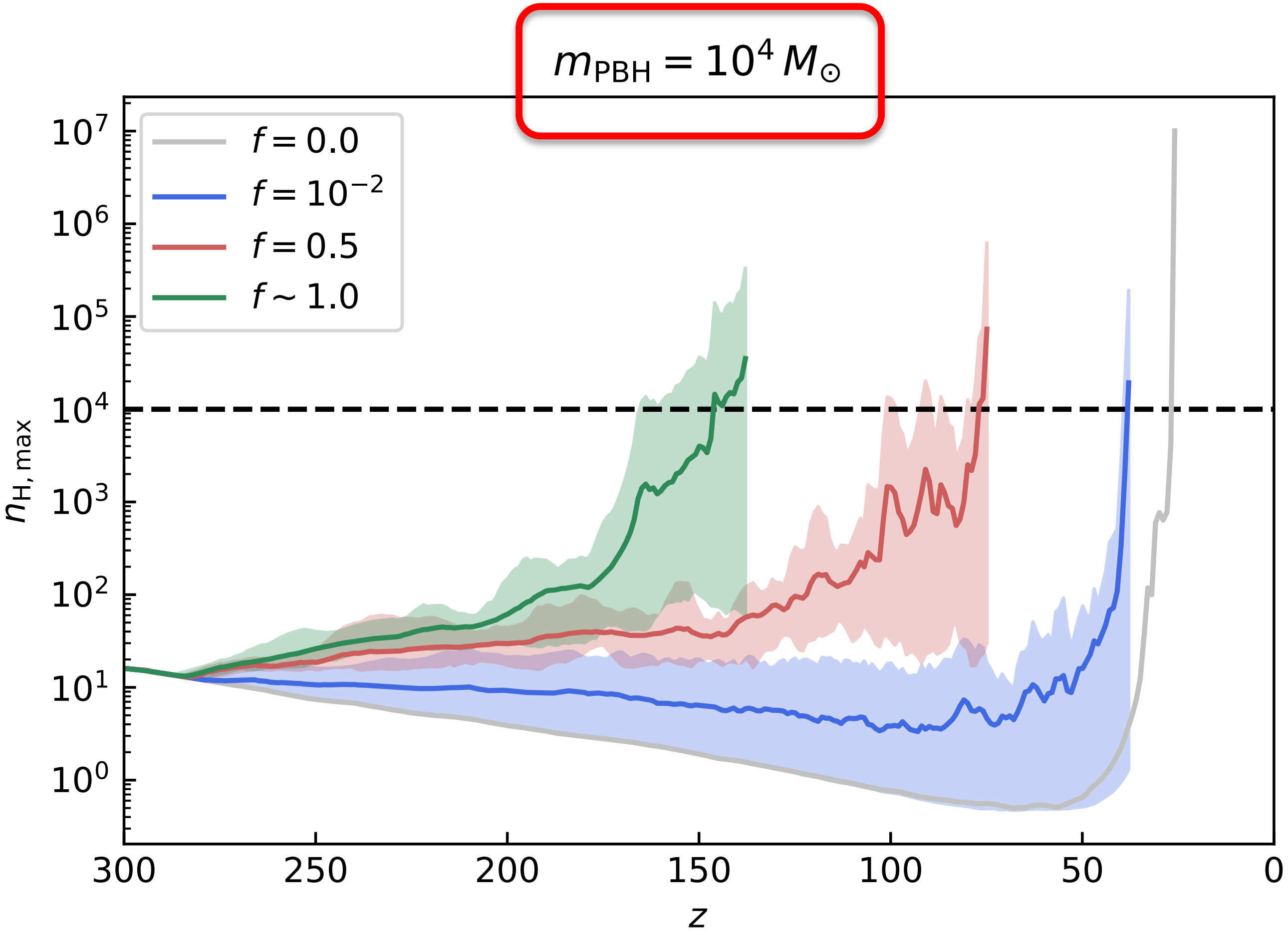
GIZMO+MUSIC+GRACKLE

Early Pop III Star Formation



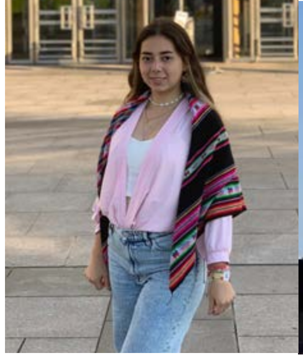
Julia Koulen

Nolan Smyth



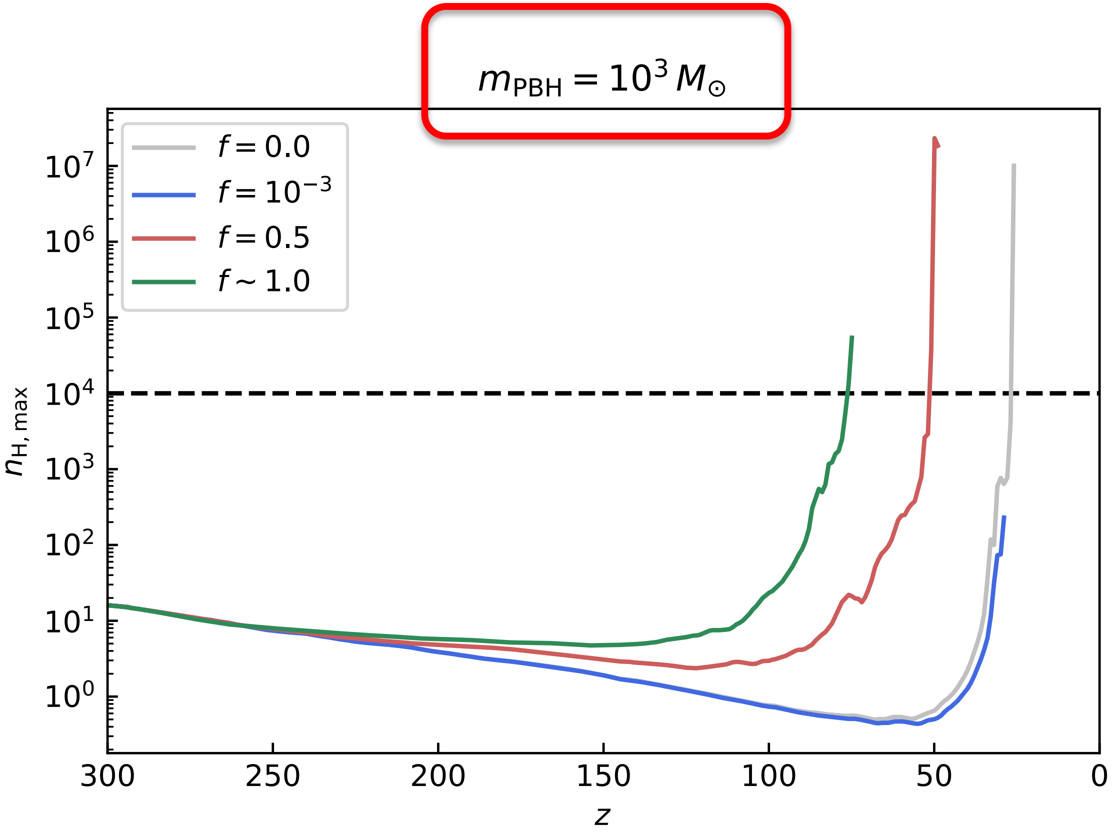
statistics from ~100 simulations

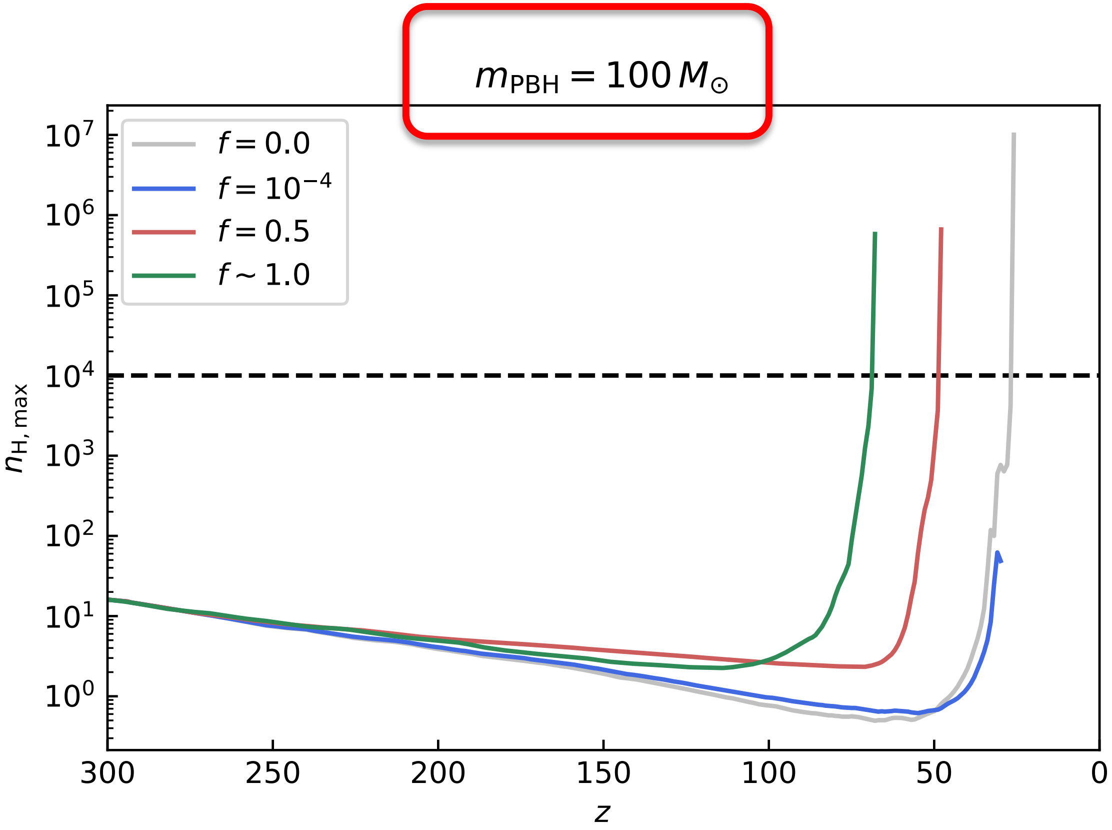
Early Pop III Star Formation



Julia Koulen

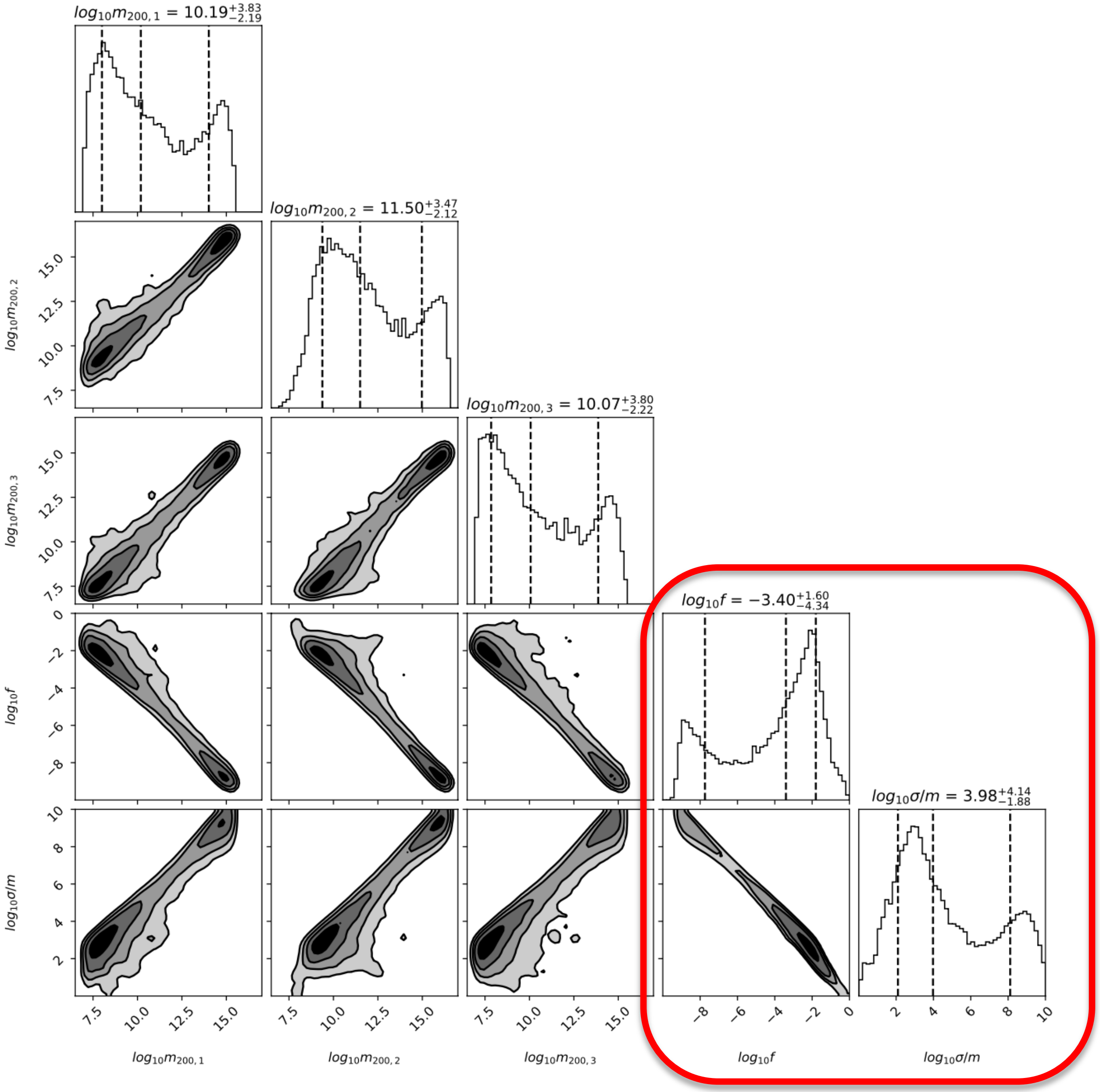
Nolan Smyth



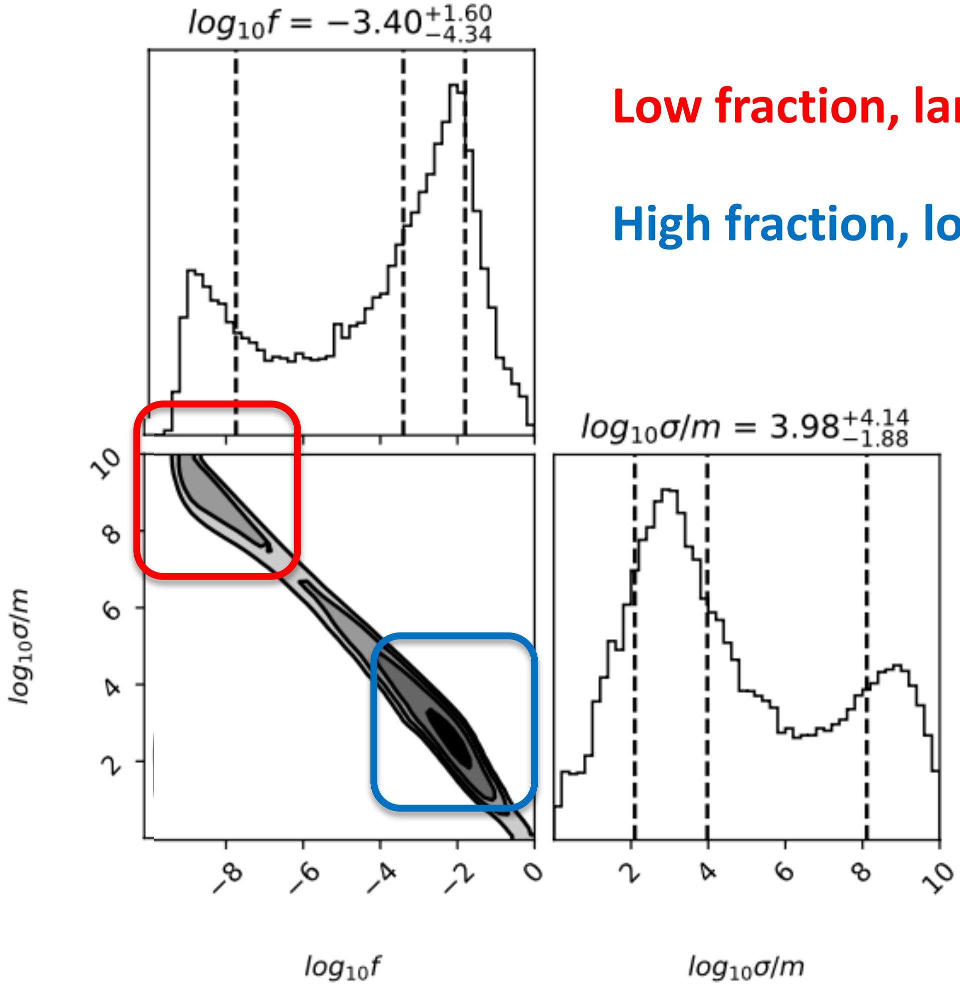


High-redshift Super-Massive BH Formation

Grant M. Roberts +
Lila Braff & Aarna Garg
Tesla Jeltema



High-redshift Super-Massive BH Formation

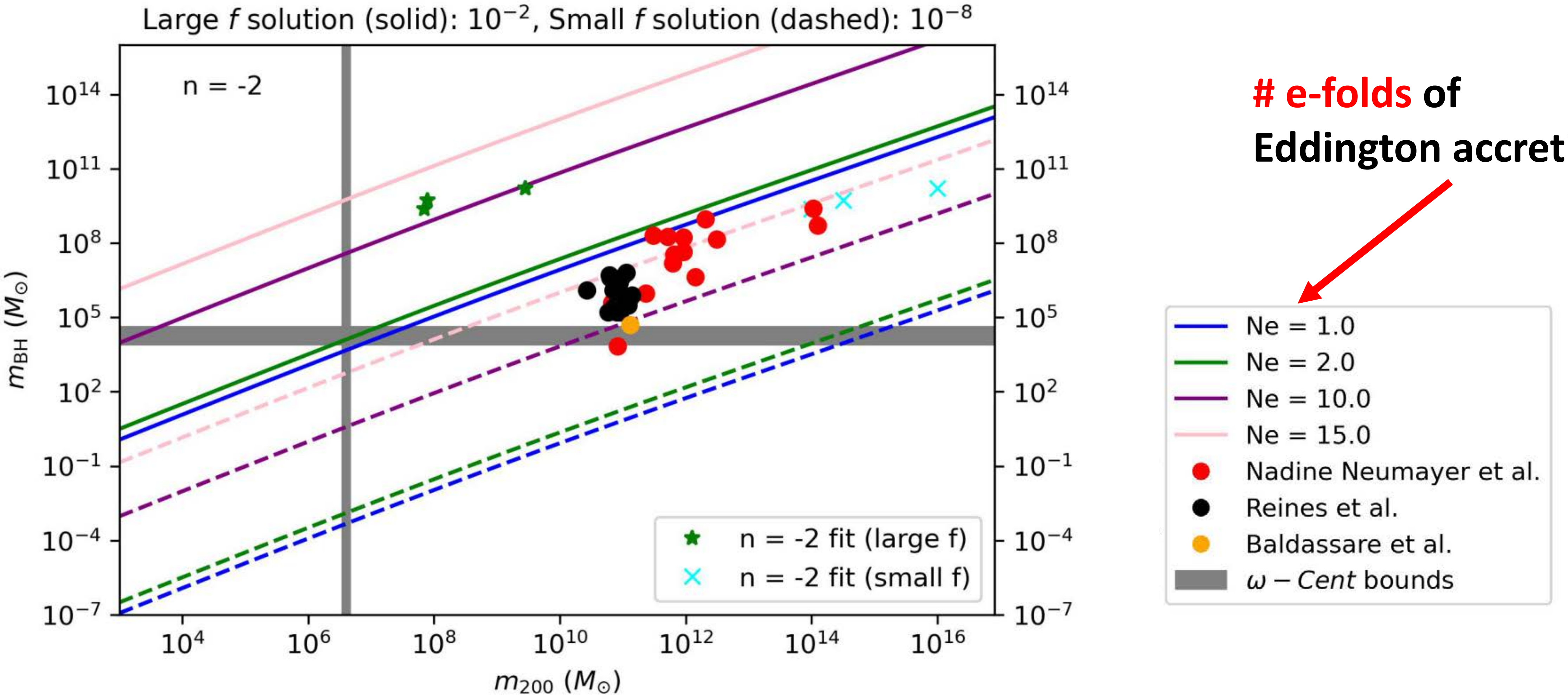


Low fraction, large X-sec

High fraction, low X-sec

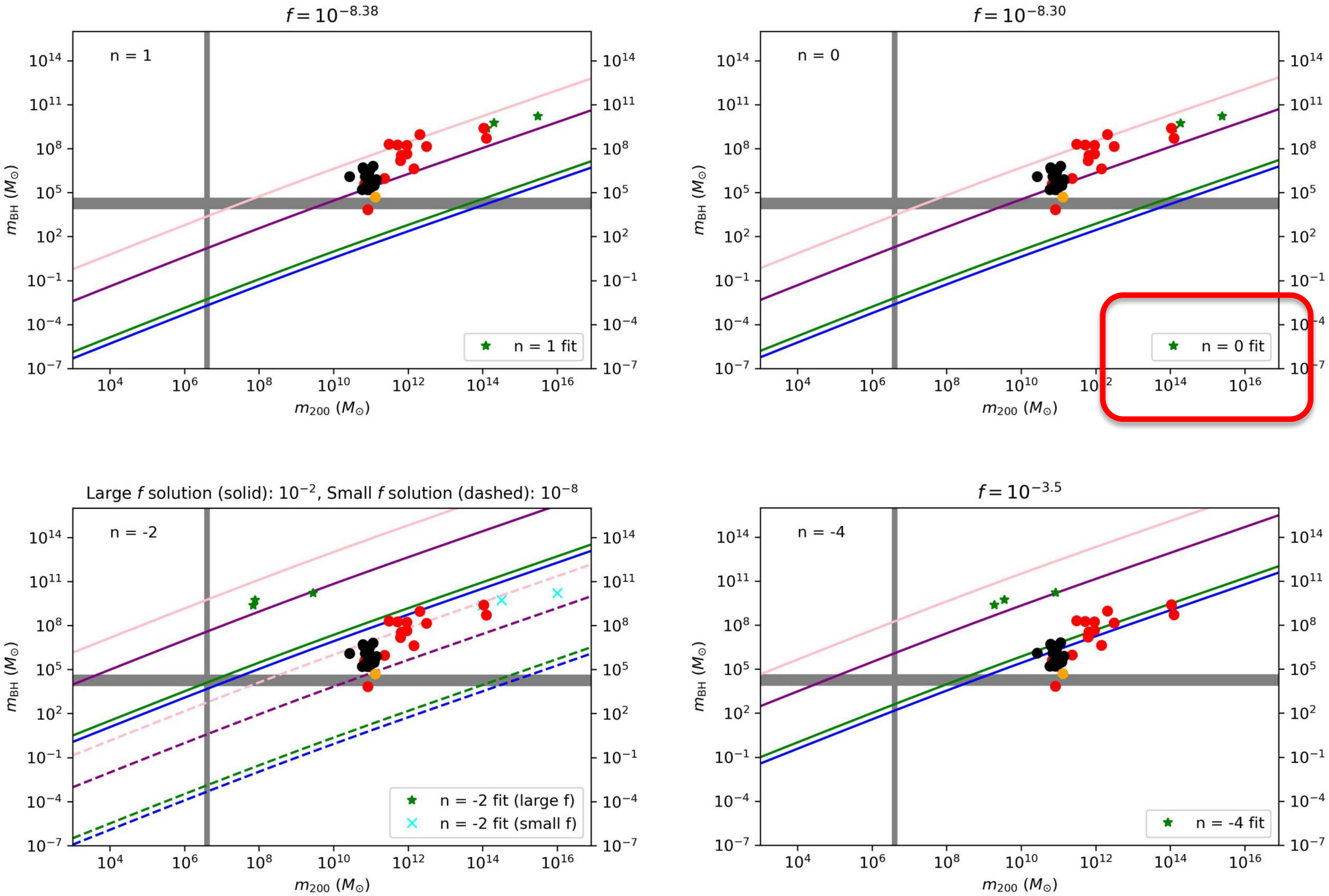
Grant M. Roberts +
Lila Braff & Aarna Garg
Tesla Jeltema

High-redshift Super-Massive BH Formation



 # e-folds of Eddington accretion

High-redshift Super-Massive BH Formation



Different velocity dependences prefer one or the other solution

Some solution imply excessively large host halo sizes

- Black Hole “Explosions”
- Anomalous cosmic- and gamma-rays
- Neutron-star “Implosions”
- Tidal heating & Star cluster disruption
- Early Pop III star formation
- High-redshift SMBH seeds