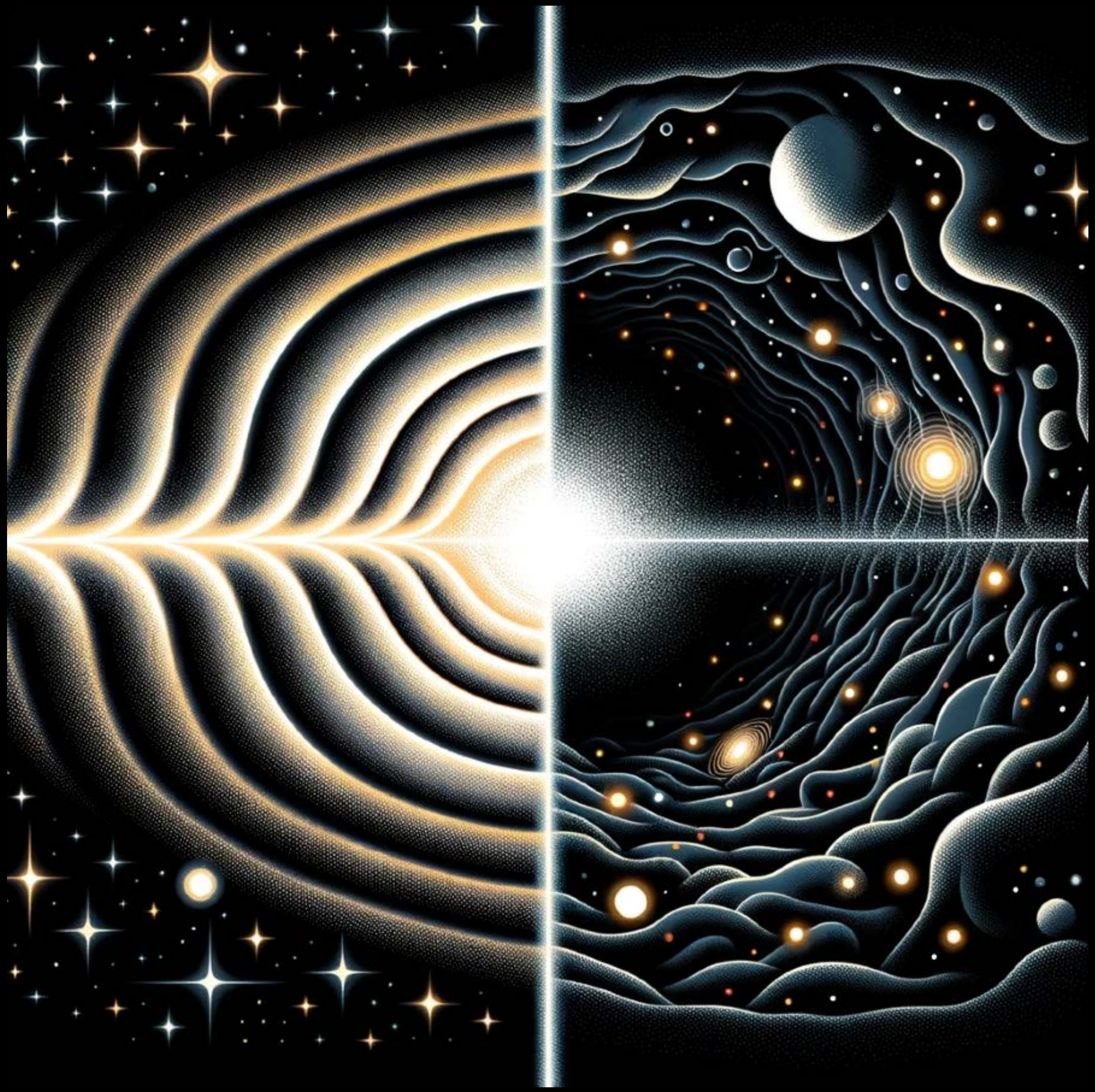
Gravitational Wave Probes of Dark Matter



Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

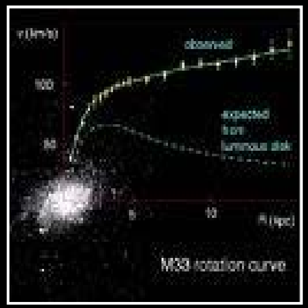
GEMMA 2 @ La Sapienza — September 16, 2024

Plan of the talk:

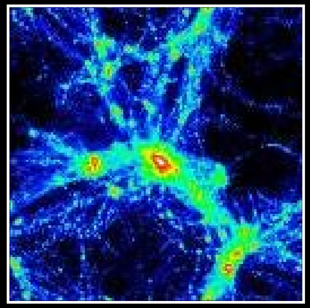
- Why study DM in strong gravity?
- The DM-BH connection
- Gravitational Wave probes of DM

What is the Universe made of?

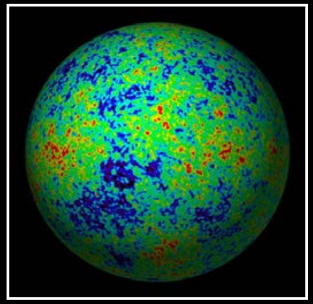
OBSERVATIONS



- Rotation Curves



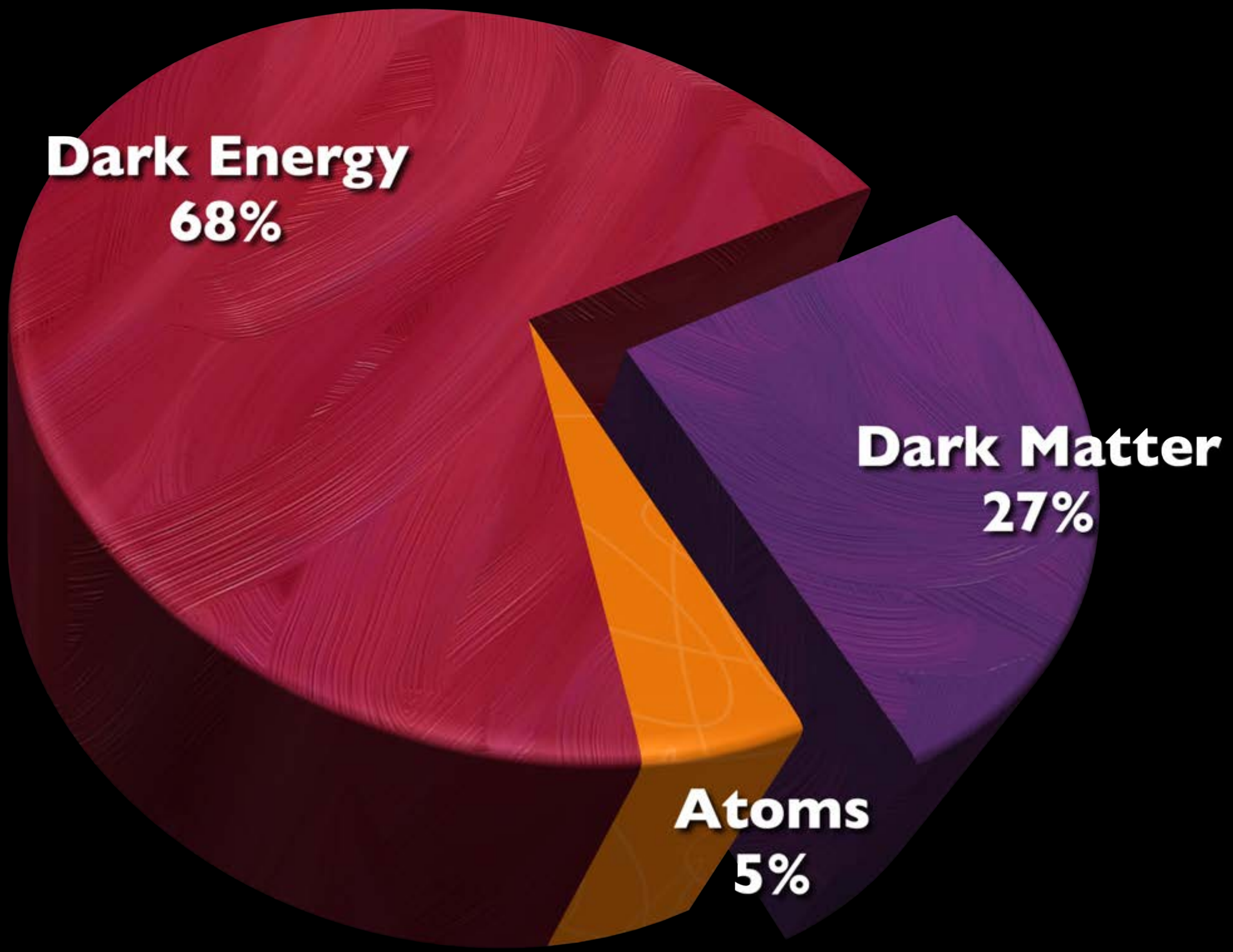
- Clusters of galaxies



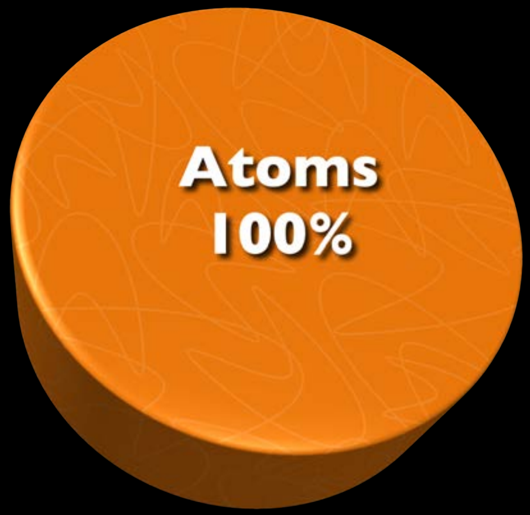
- CMB

- Type Ia Supernovae

...

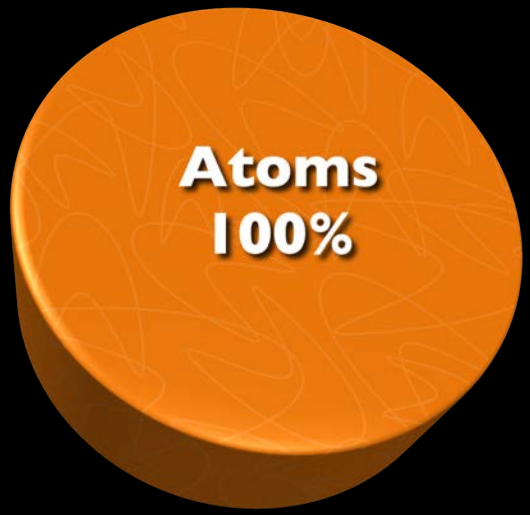


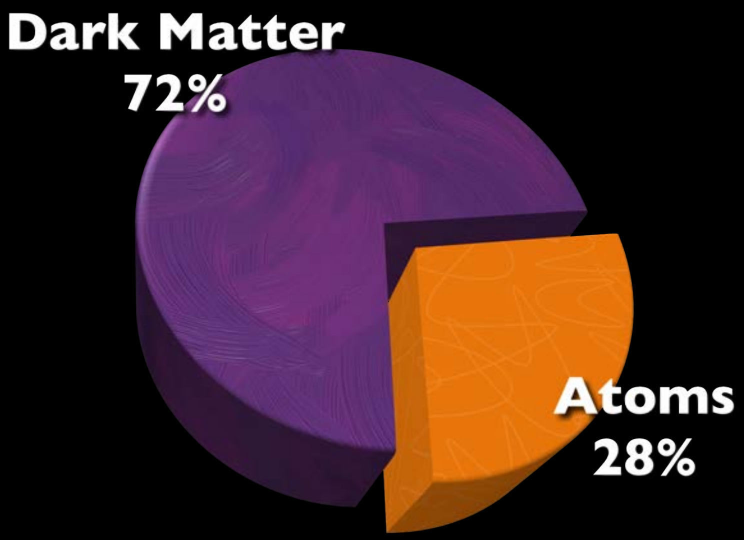
How is DM distributed?



How is DM distributed?

Posti & Helmi, A&A 621, A56 (2019)





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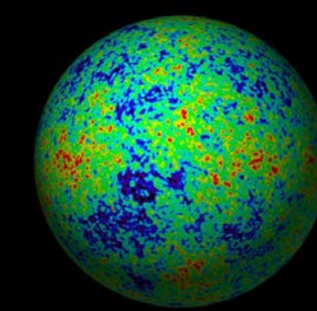
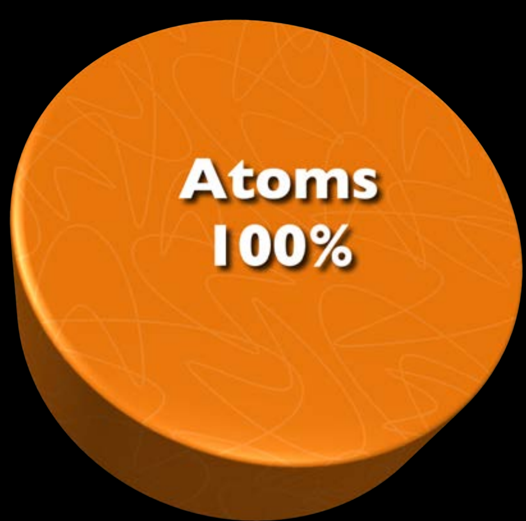
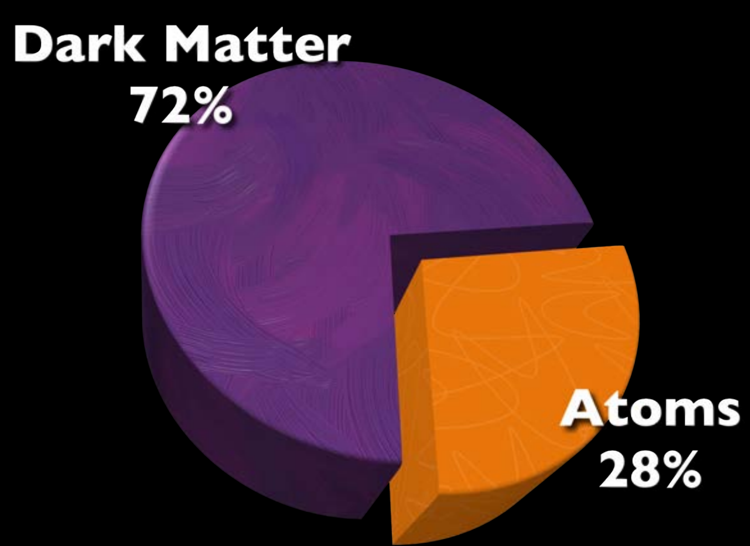
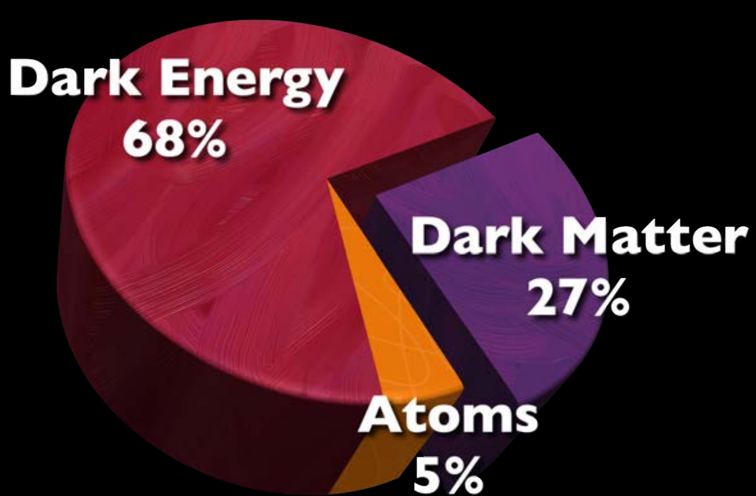


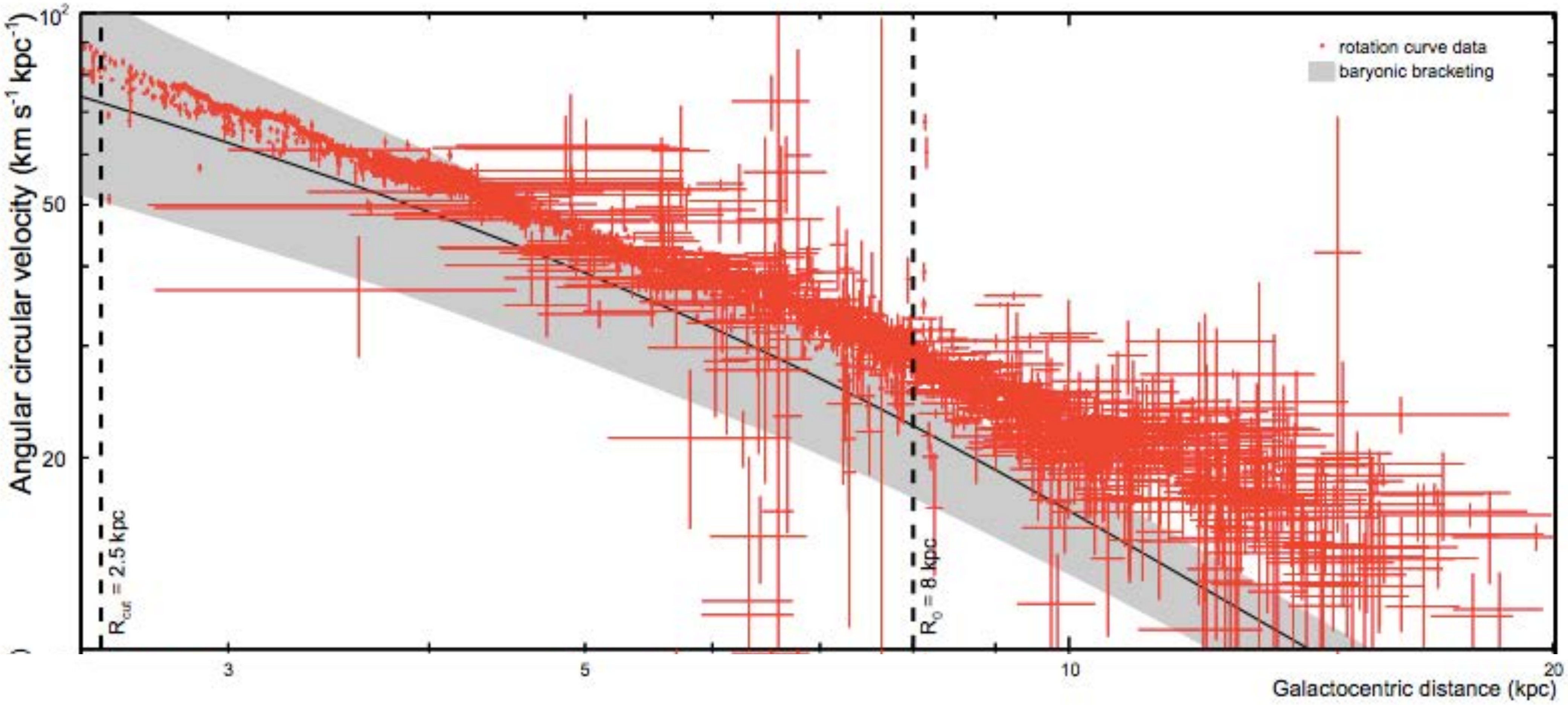
Planck collaboration (2018)







Rotation curve of the Milky Way



Iocco, GB et al. 2015: http://www.nature.com/nphys/journal/v11/n3/full/nphys3237.html

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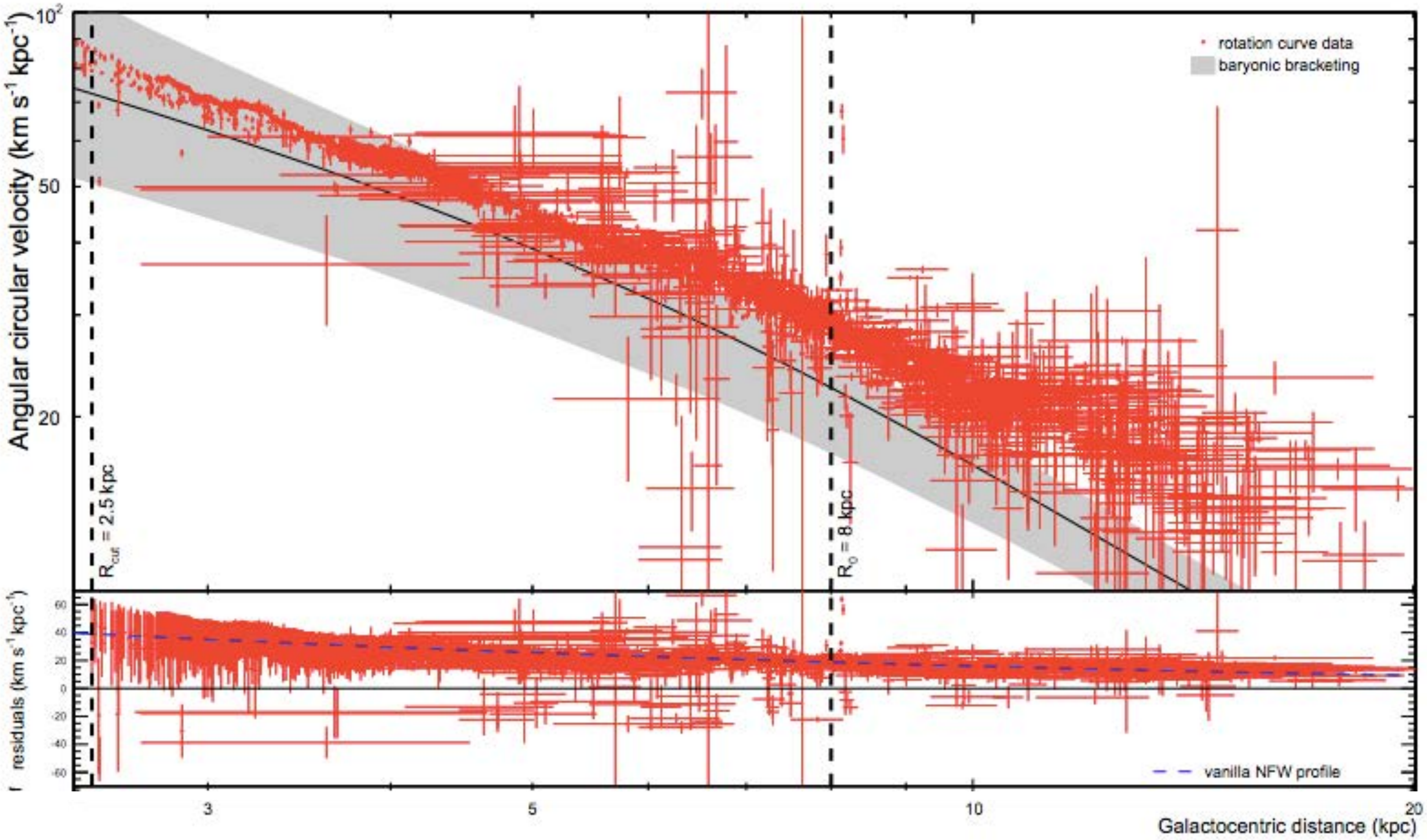

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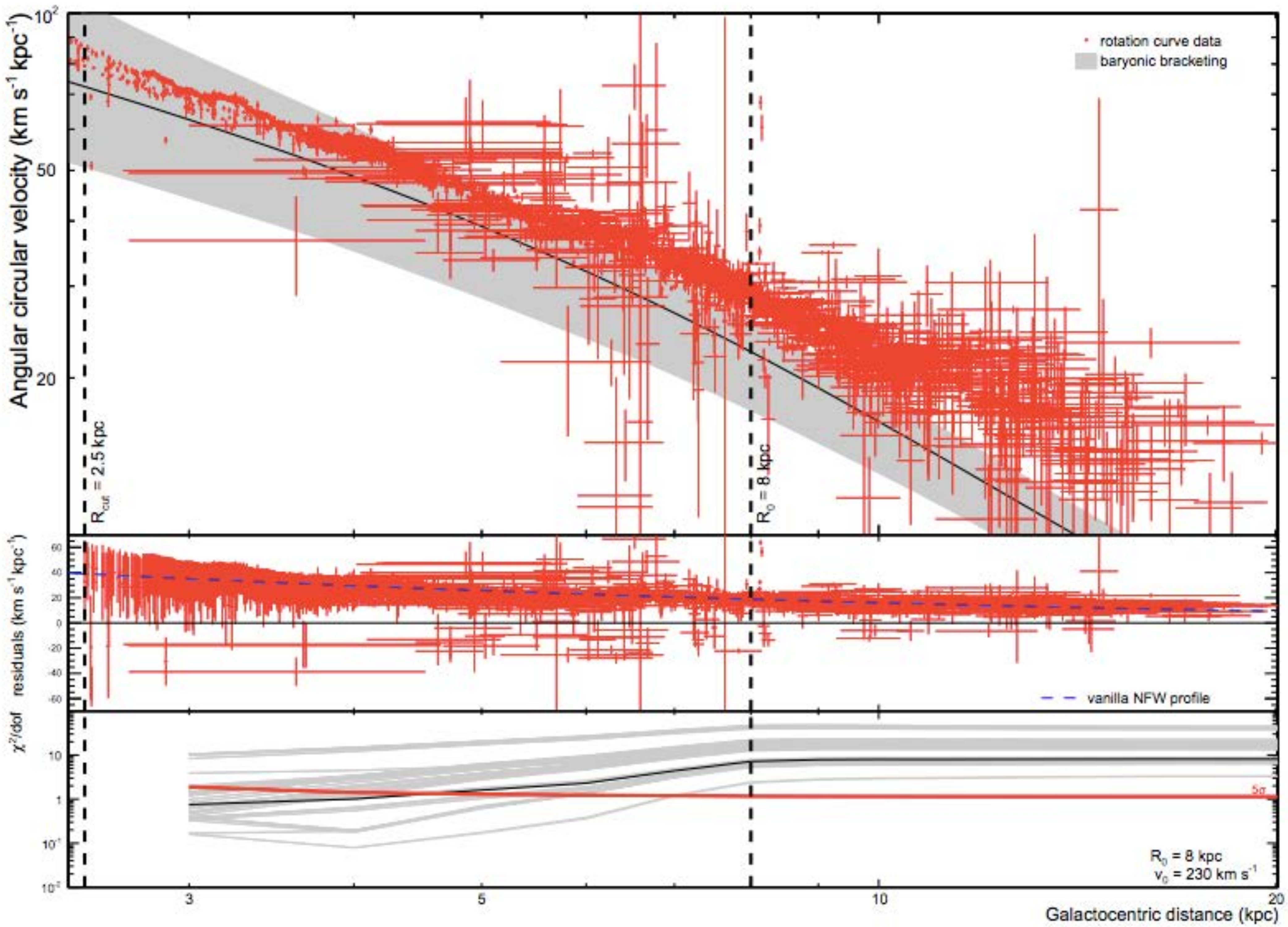

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Assuming DM is cold and collisionless:

http://www.illustris-project.org/media/

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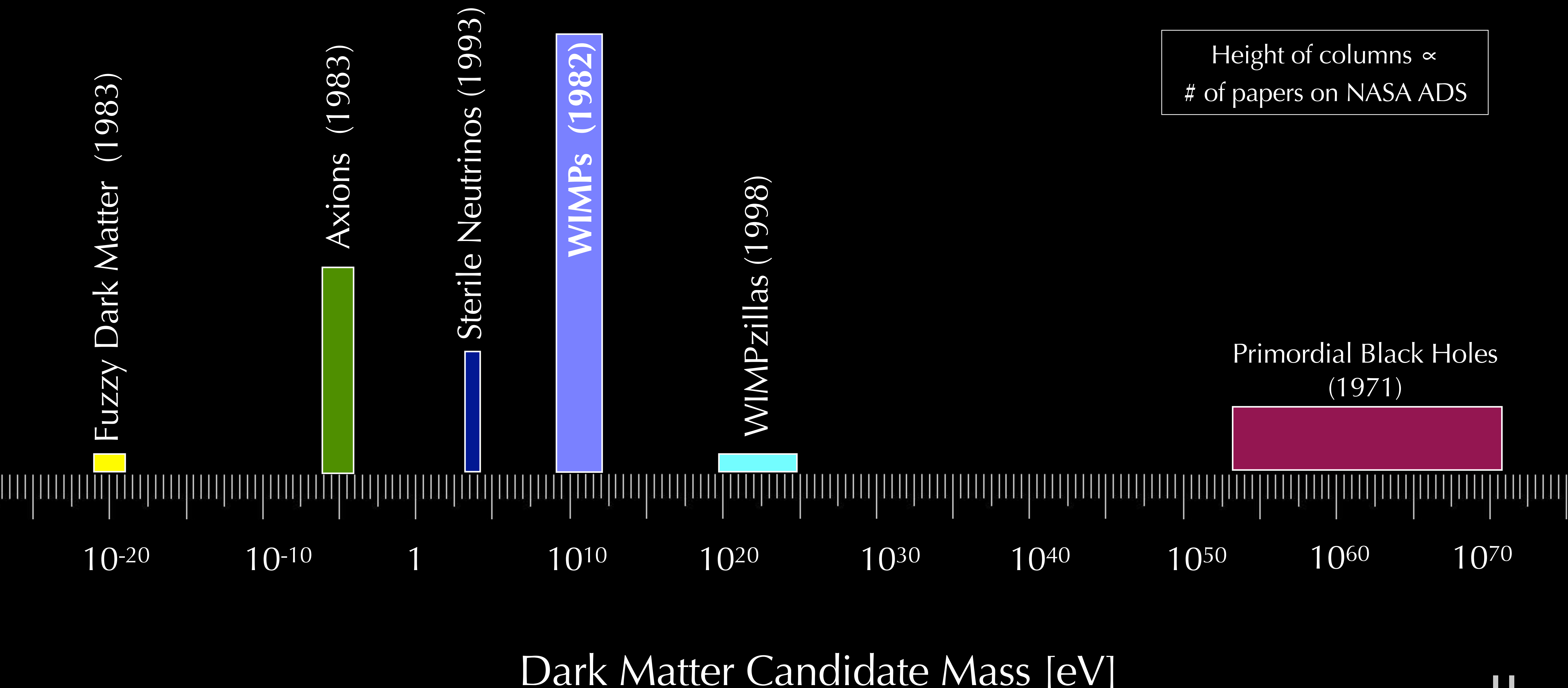
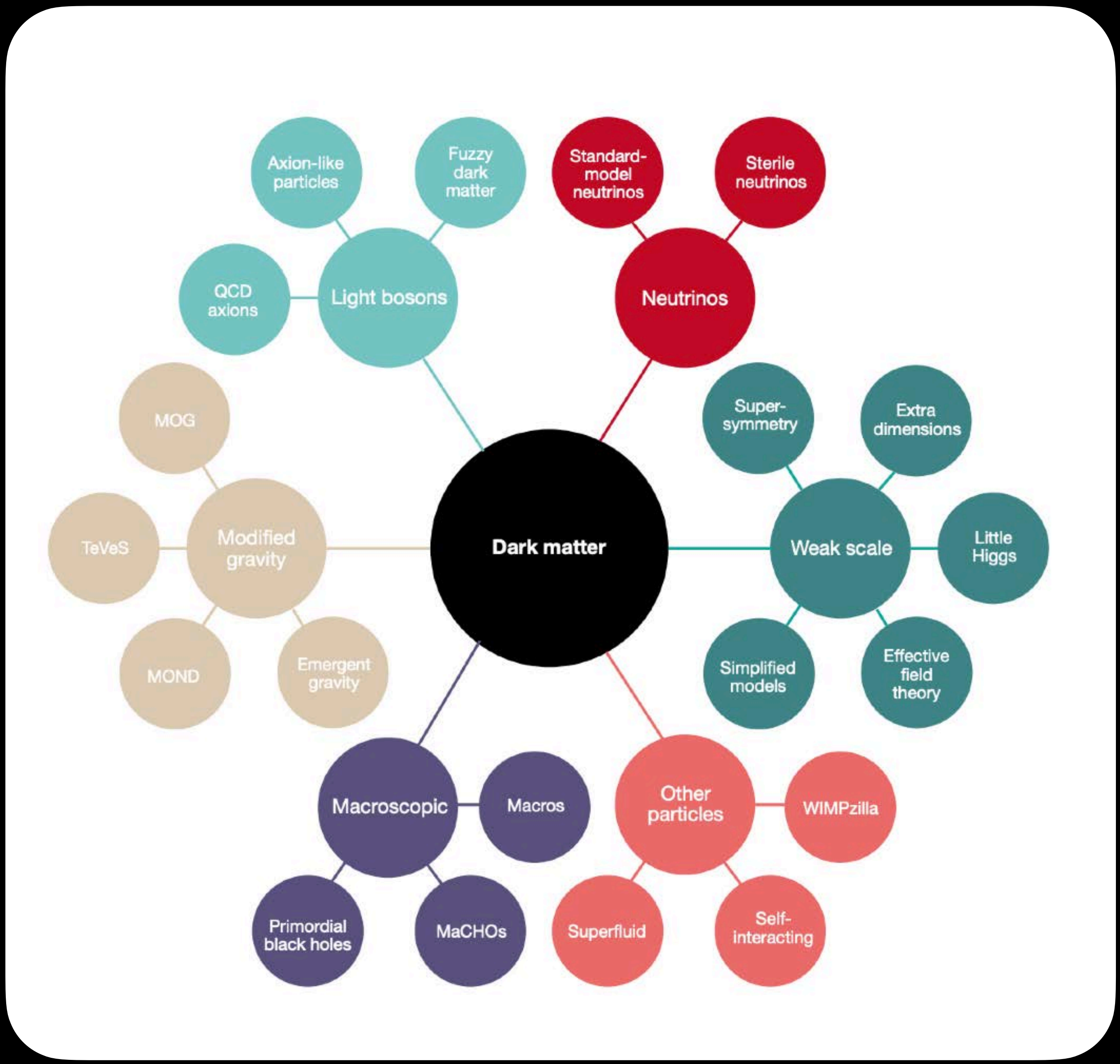
Candidates

- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



Why study DM in Strong Gravity



GB, Tait, *Nature (2018) 1810.01668*

- Identifying DM = discriminating among hundreds of DM candidates
- DM candidates differ in terms of:
    - small-scale distribution
    - Scattering rate: $\Gamma_{\chi n} \sim \sigma_{\chi n} n_\chi n_n$
    - Self-annihilation rate: $\Gamma_{\chi\chi} \sim < \sigma v > n_\chi^2$
- Idea: study DM phenomenology in strong gravity = very small scales, very high-densities

The team


Pippa Cole


Adam Coogan


Daniele Gaggero


Bradley Kavanagh


Thomas Spieksma


Gimmy Tomaselli

+ Ismini Andrianou, Leon Kamermans, Theophanes Karydas, David Nichols, Renske Wierda, …

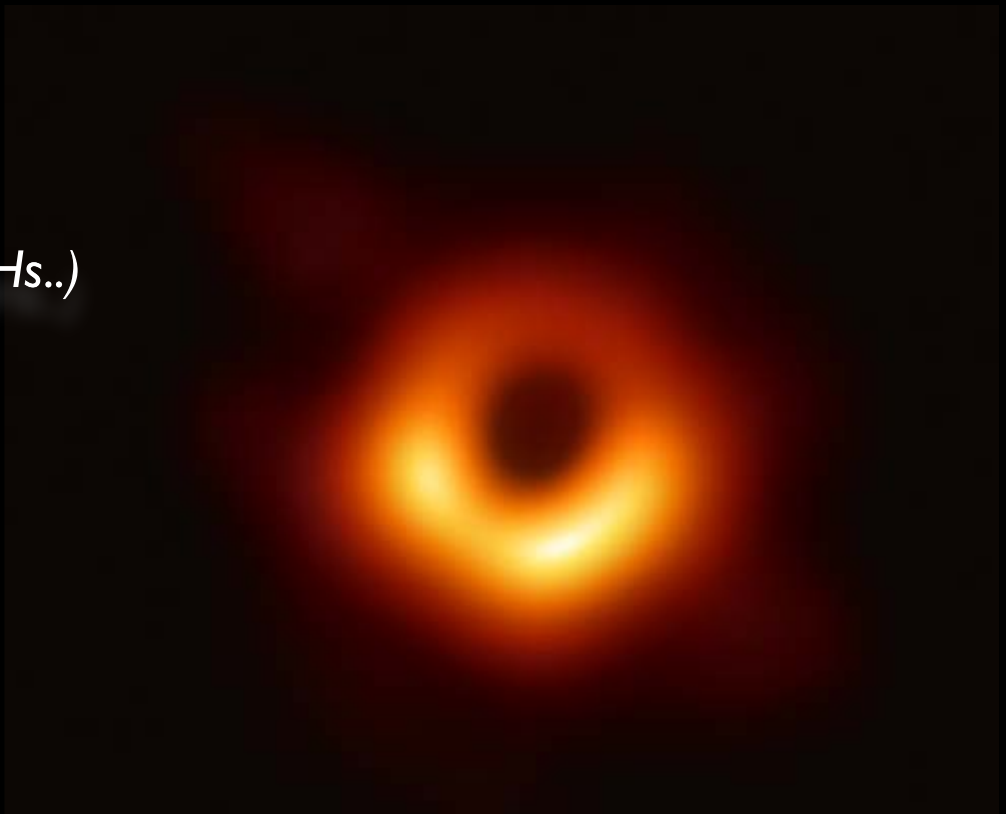
Plan of the talk:

- Why study DM in strong gravity?
- The DM-BH connection
- Gravitational Wave probes of DM

Black Holes

- In GR, *completely* described by (M, L, q)

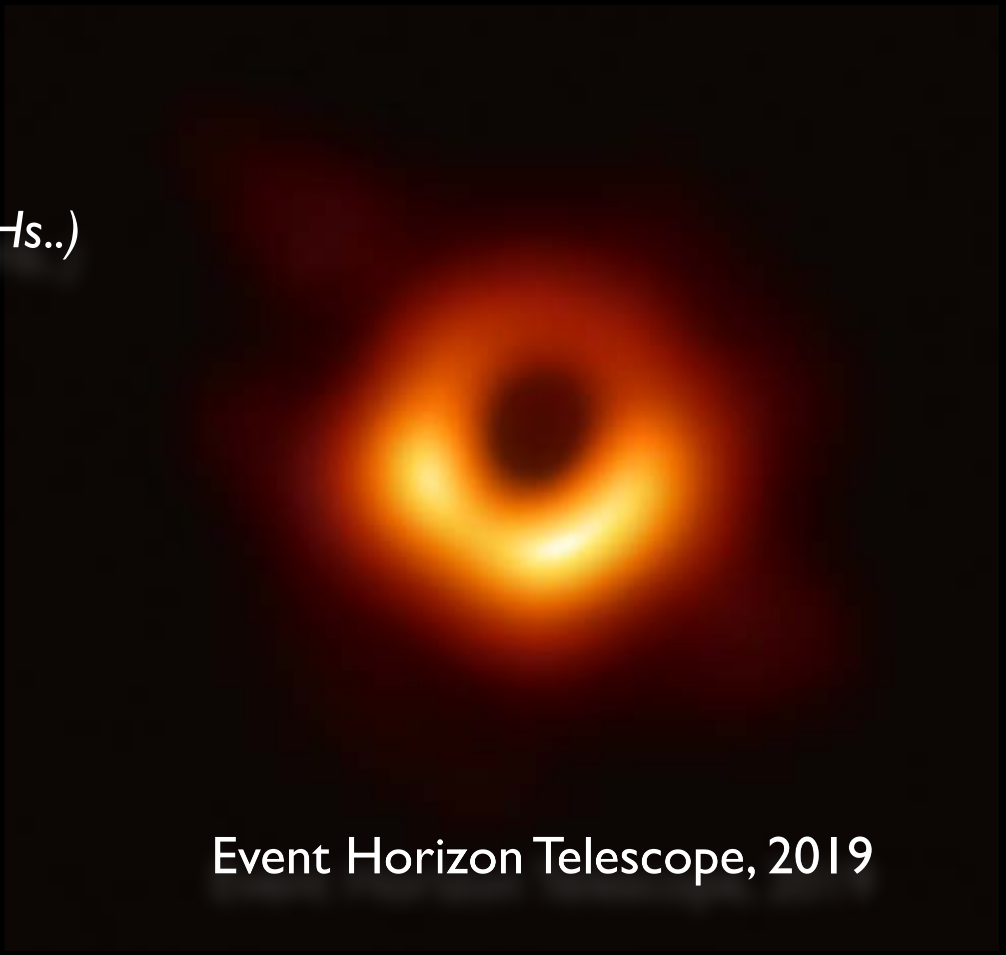
- BUT observed $(M, L, q; z)$ drawn from probability distribution that carries information about history *(PBHs..)*



Event Horizon Telescope, 2019

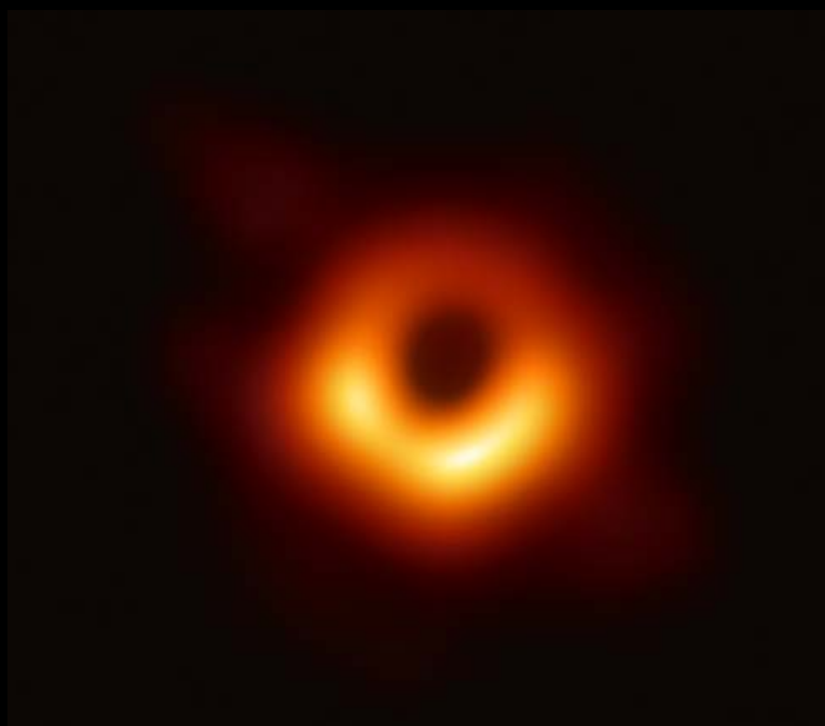
Black Holes

- In GR, *completely* described by (M, L, q)
- BUT observed $(M, L, q; z)$ drawn from probability distribution that carries information about history *(PBHs..)*
- Don't exist in vacuum. Environment:
  - Enables EM detection
    (direct imaging of accretion discs, dynamical M from stars, ..)
  - Affects $P(M, L, q; z)$
    (q=0, formation scenario, merger rate history, …)
  - Alters GW signals
    (dephasing, caracteristic features,…)

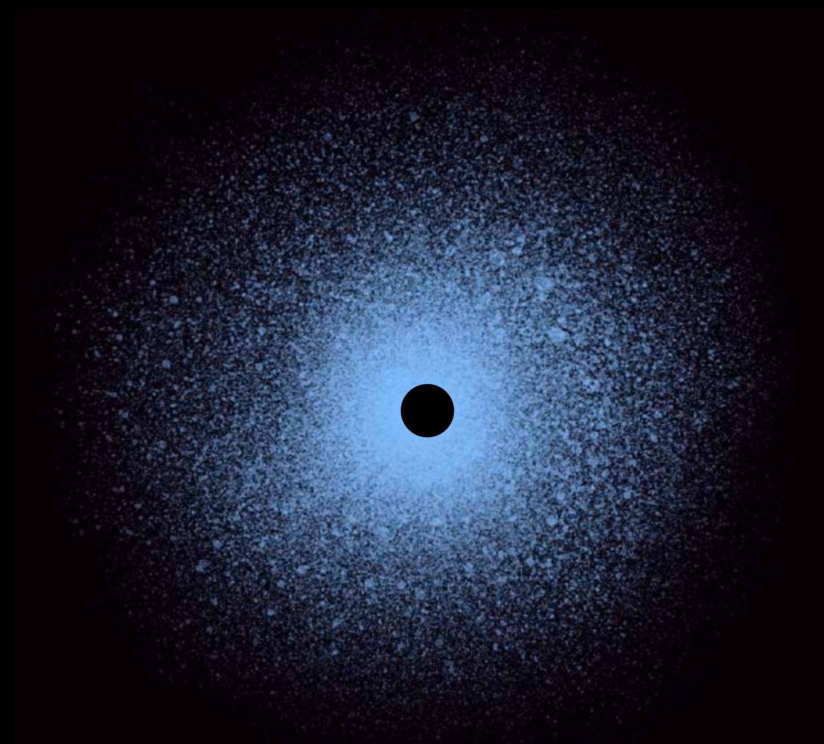


Event Horizon Telescope, 2019

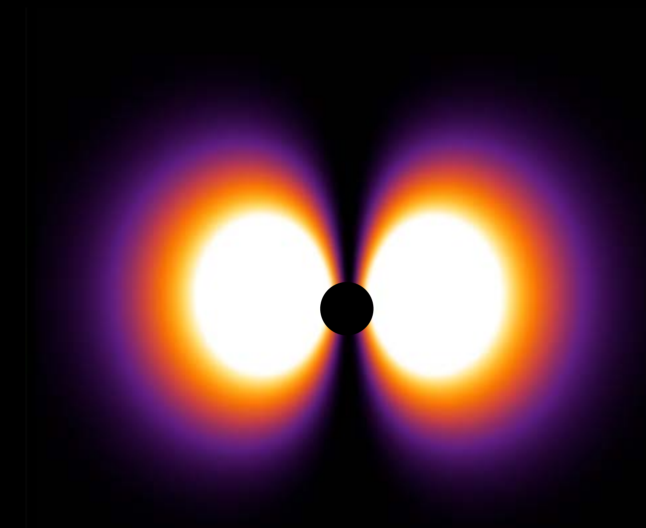
BH environments



Accretion discs

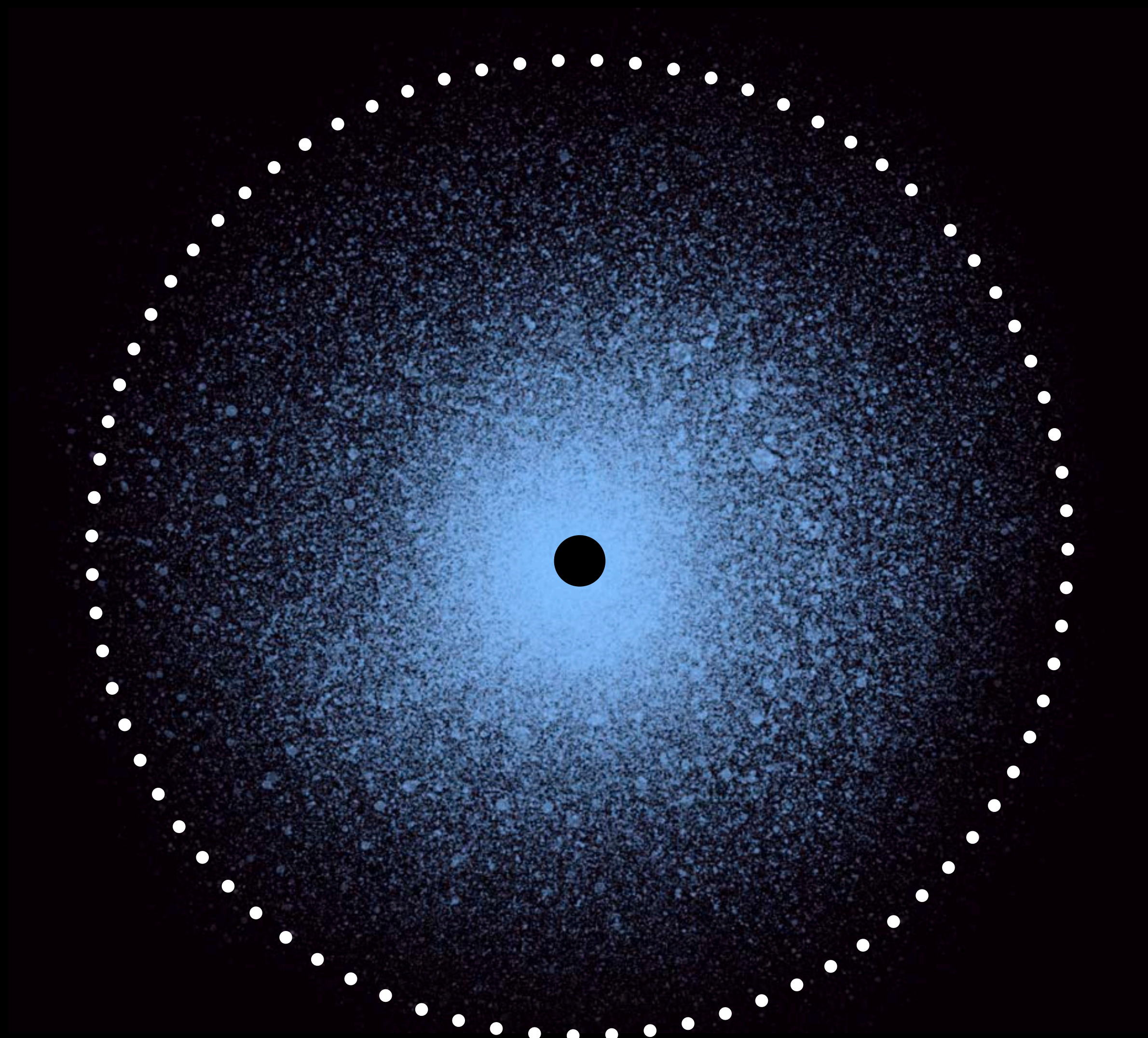


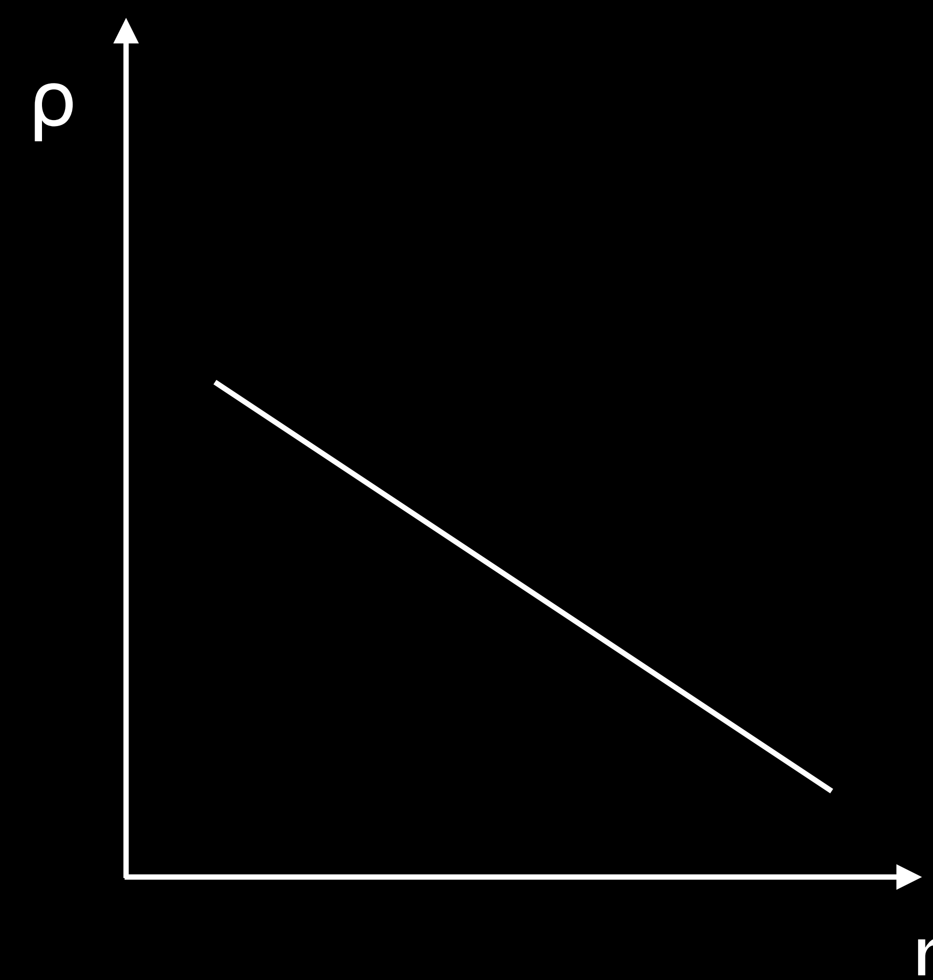
DM ‘spikes’



Gravitational atoms

Adiabatic compression of DM around BHs





Conservation of adiabatic invariants:

$$I_i(E_i, L) = I_f(E_f, L) \quad \rightarrow \quad f_f(E_f, L) = f_i(E_i, L) \quad \rightarrow \quad \rho_f(r) = \frac{4\pi}{r^2} \int_{E_f^{\min}}^{0} dE_f \int_{L_f^{\min}}^{L_f^{\max}} dL_f \frac{L_f}{v_r} f_f(E_f, L_f) \, .$$

(Peebles 1972, Young 1980, Quinlan, Hernquist and Sigurdsson 1995, Gondolo and Silk 2000, …)

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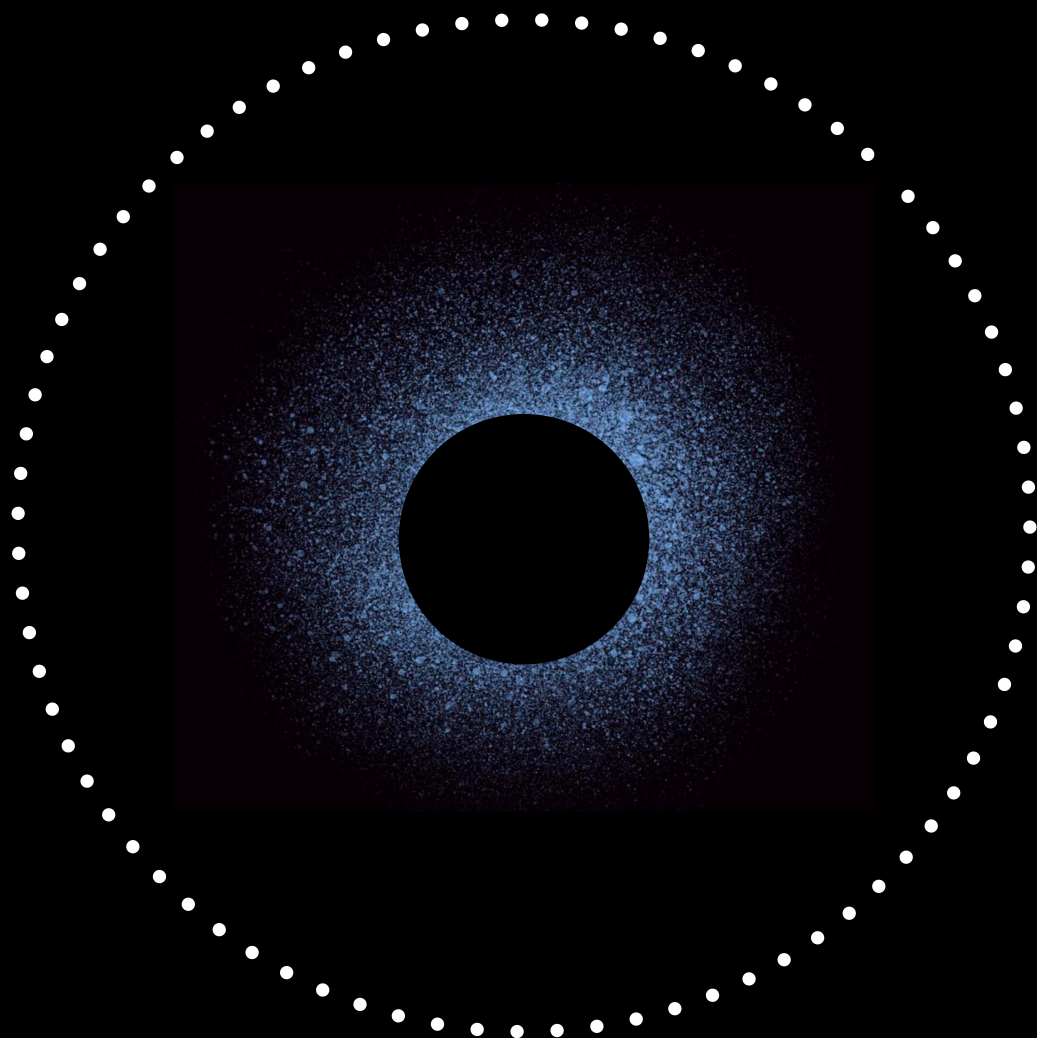

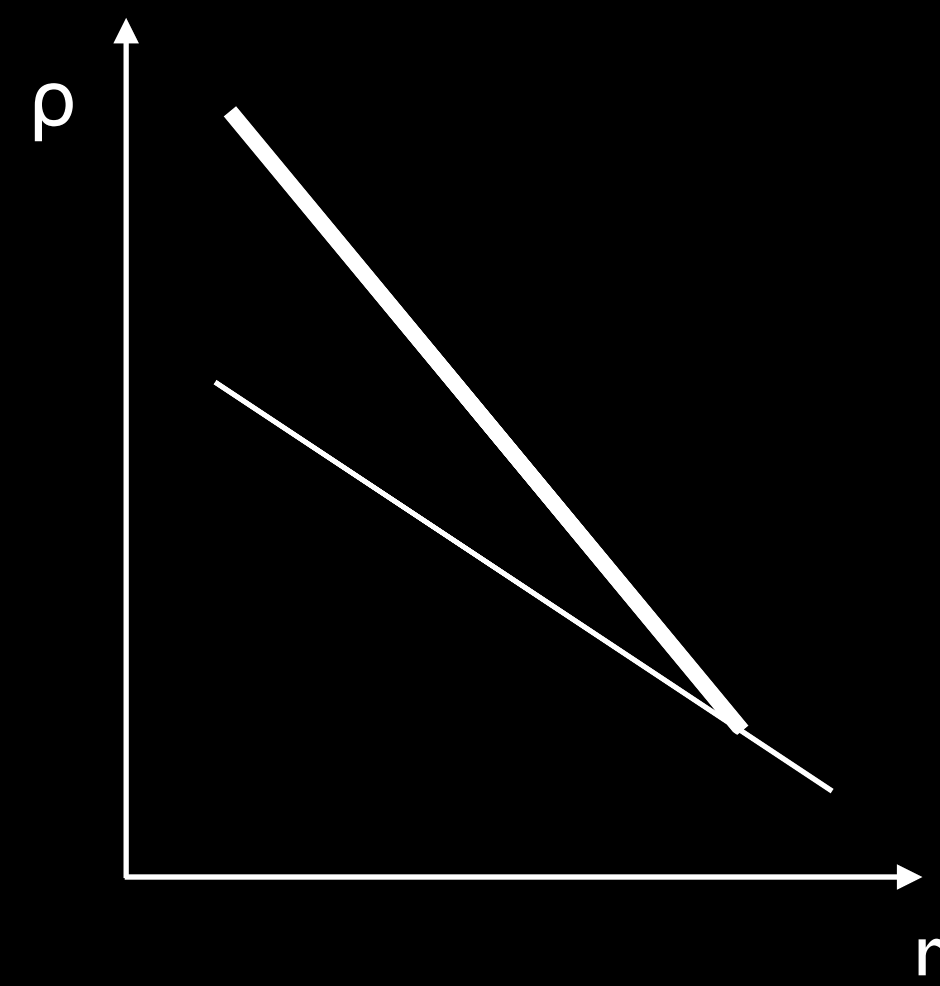

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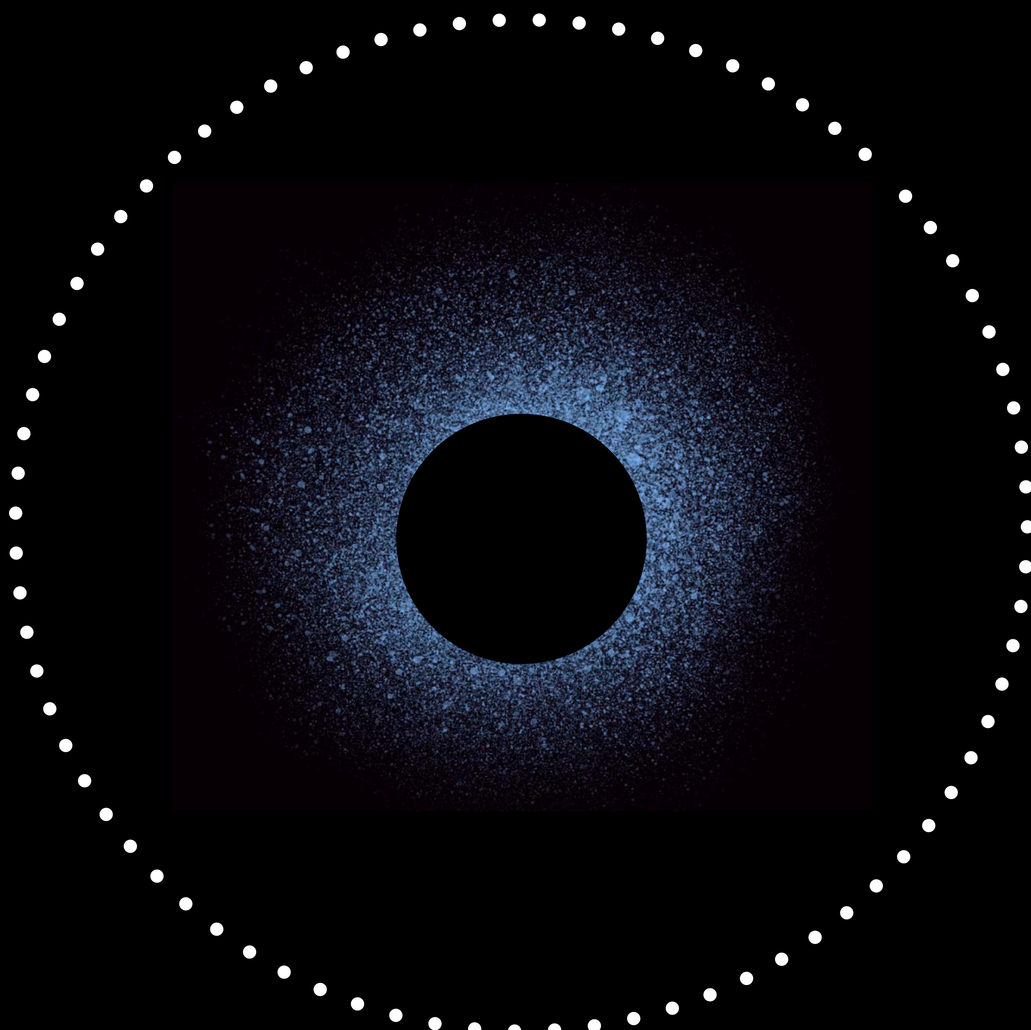

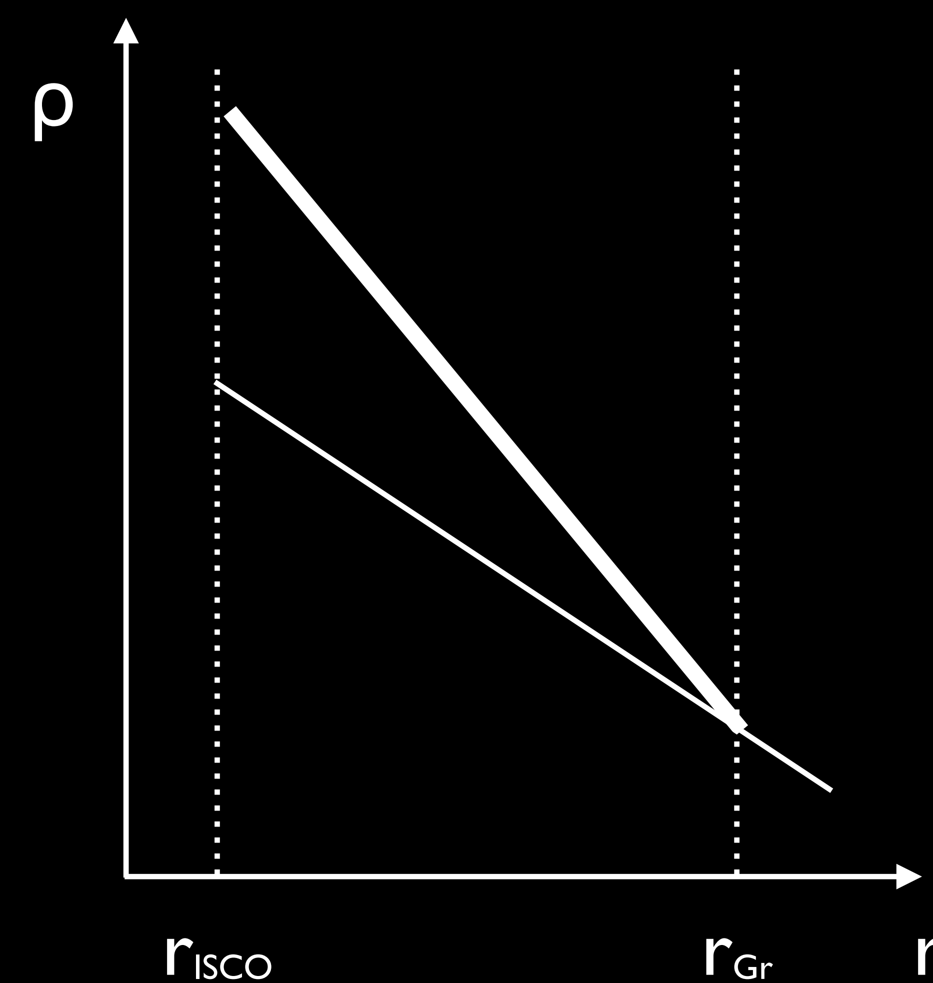

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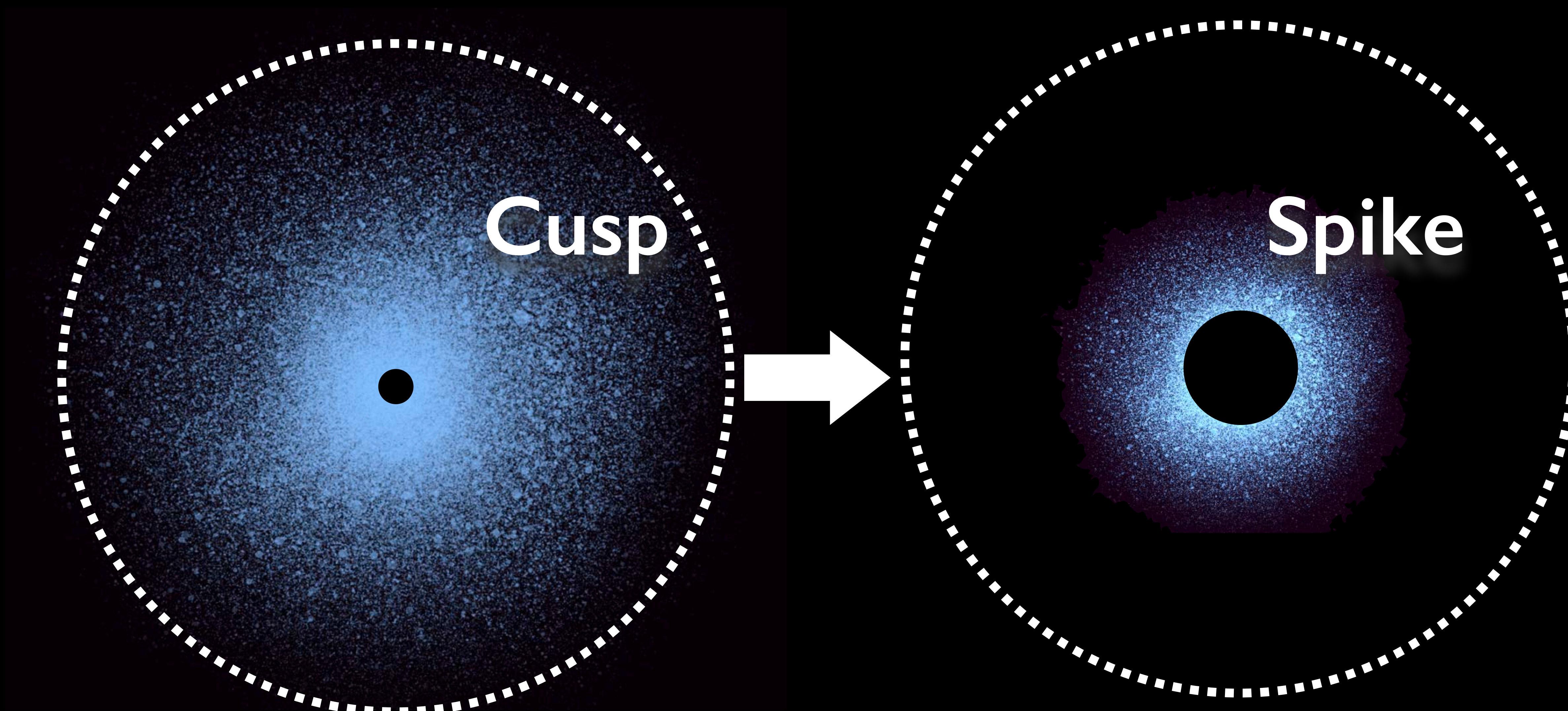

$$\rho_{\rm cusp}(r) \sim r^{-\gamma}$$

$$(\mathrm{NFW}: \gamma = 1)$$

$$\rho_{\rm spike}(r) \sim r^{-\gamma_{\rm sp}}\ ,\ \gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$

$$(\gamma = 1 \rightarrow \gamma_{sp} = 7/3)$$

Gondolo and Silk 2000

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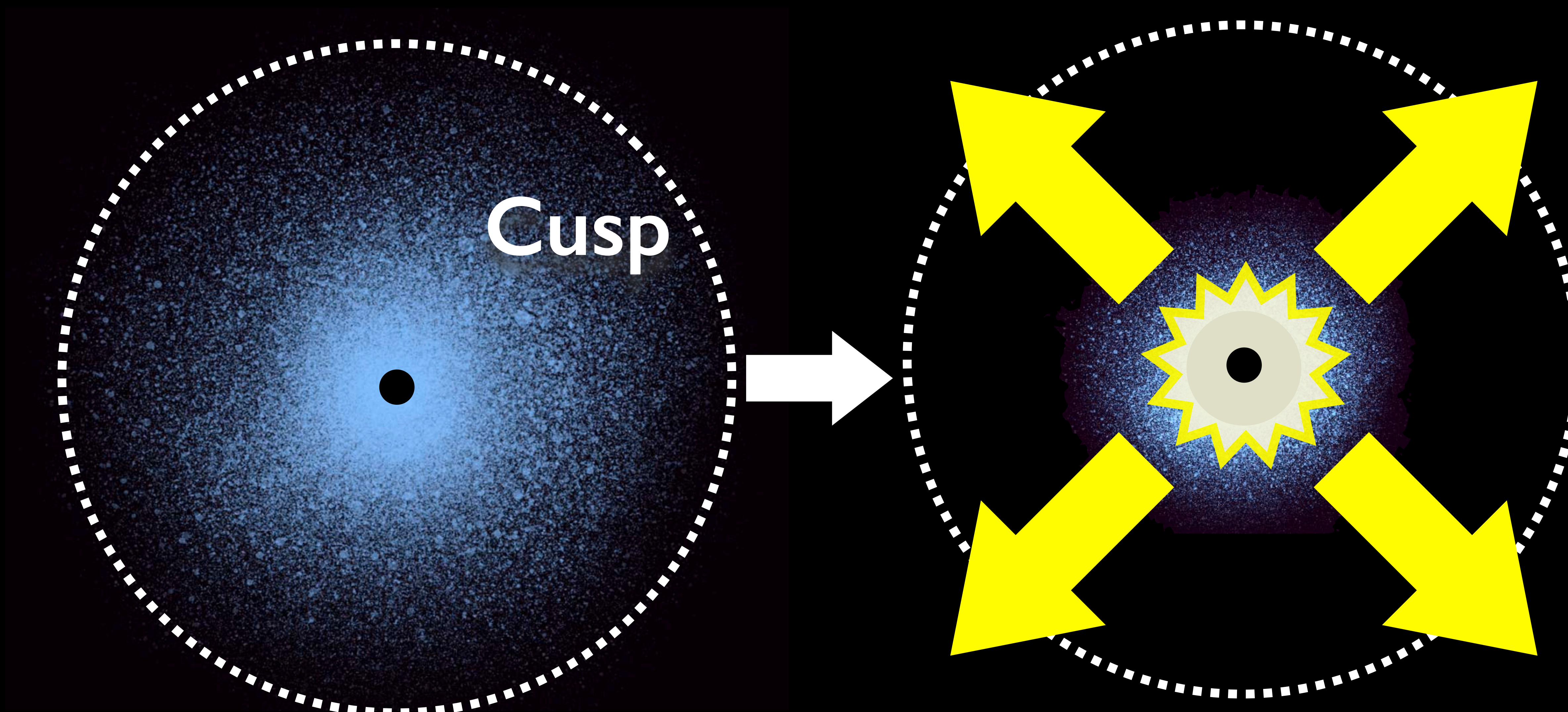

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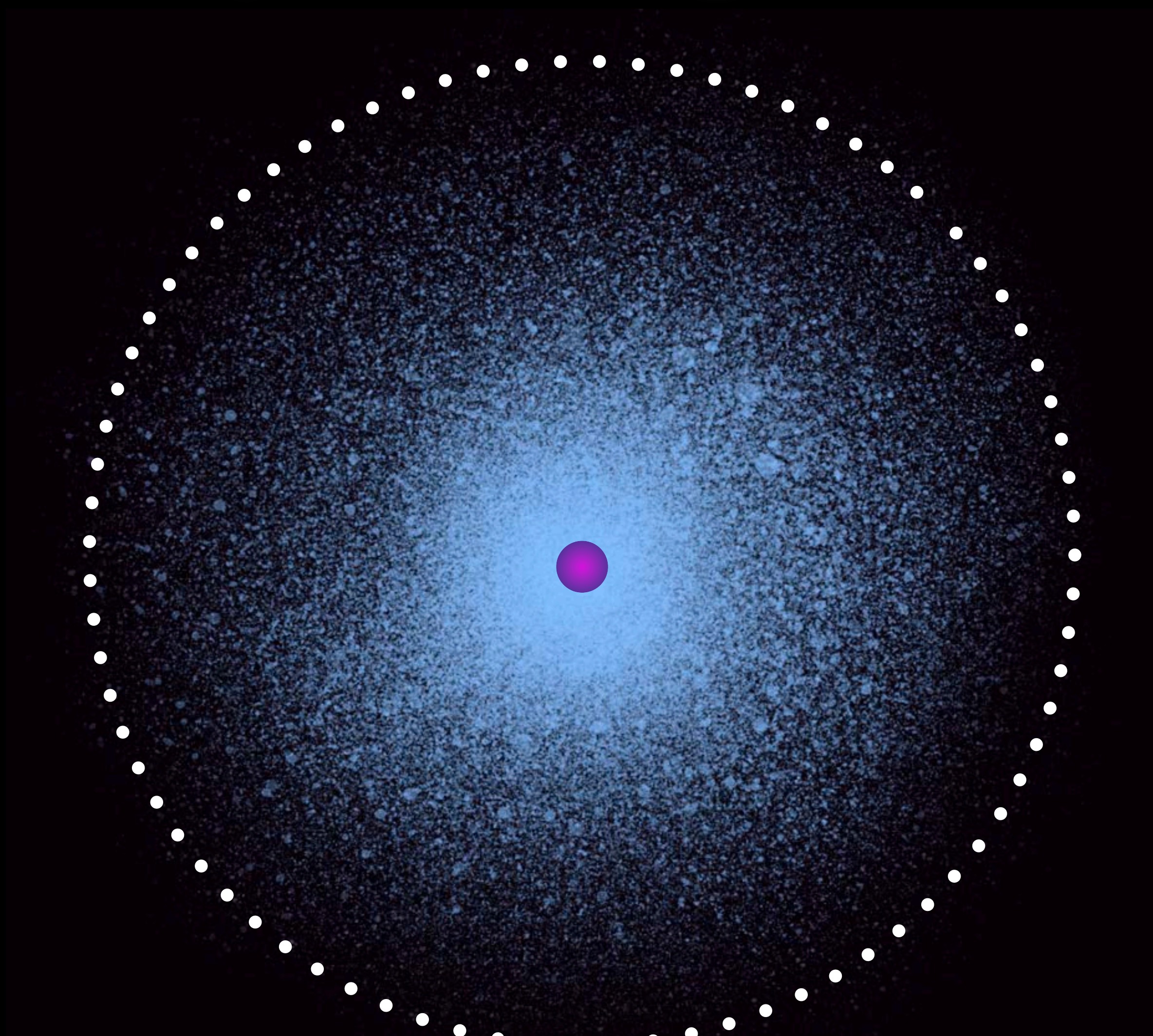
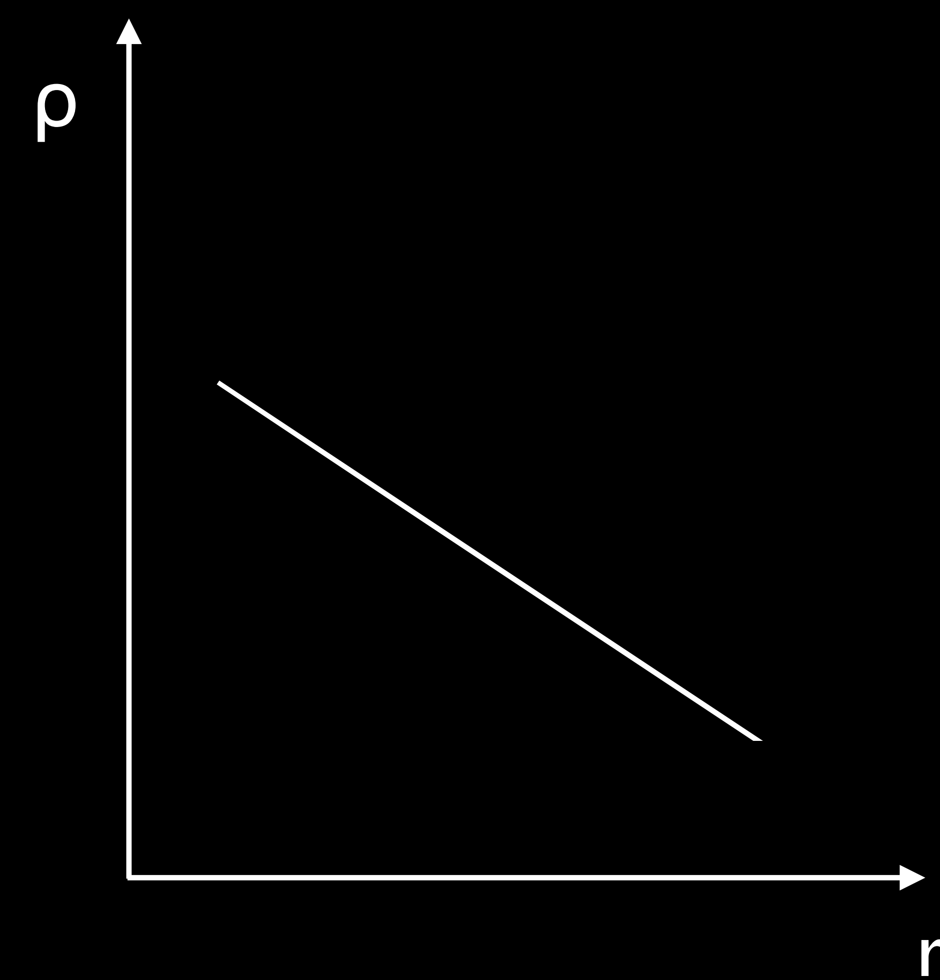
3 steps: SMS growth, Collapse, BH growth





- I - Adiabatic growth on extended stellar object
  Blumenthal 1986; Young 1980; Spolyar, Freese, Gondolo 2007; Freese et al. 2008

- II - Collapse to BH on free-fall timescale
  E.g. Ullio, Zhao, Kamionkowski 2001 (circular orbits)

- III - Growth of BH from seed to final mass
  Gondolo & Silk 2000

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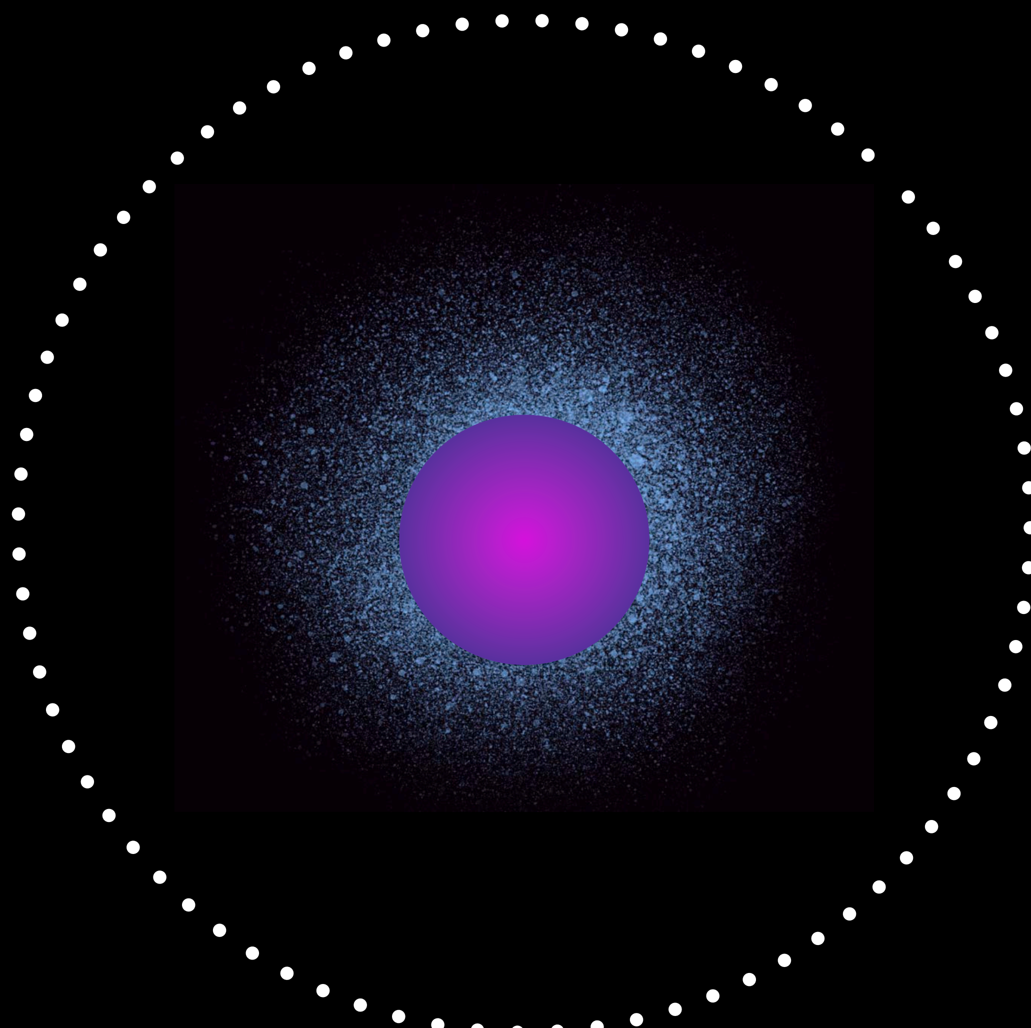

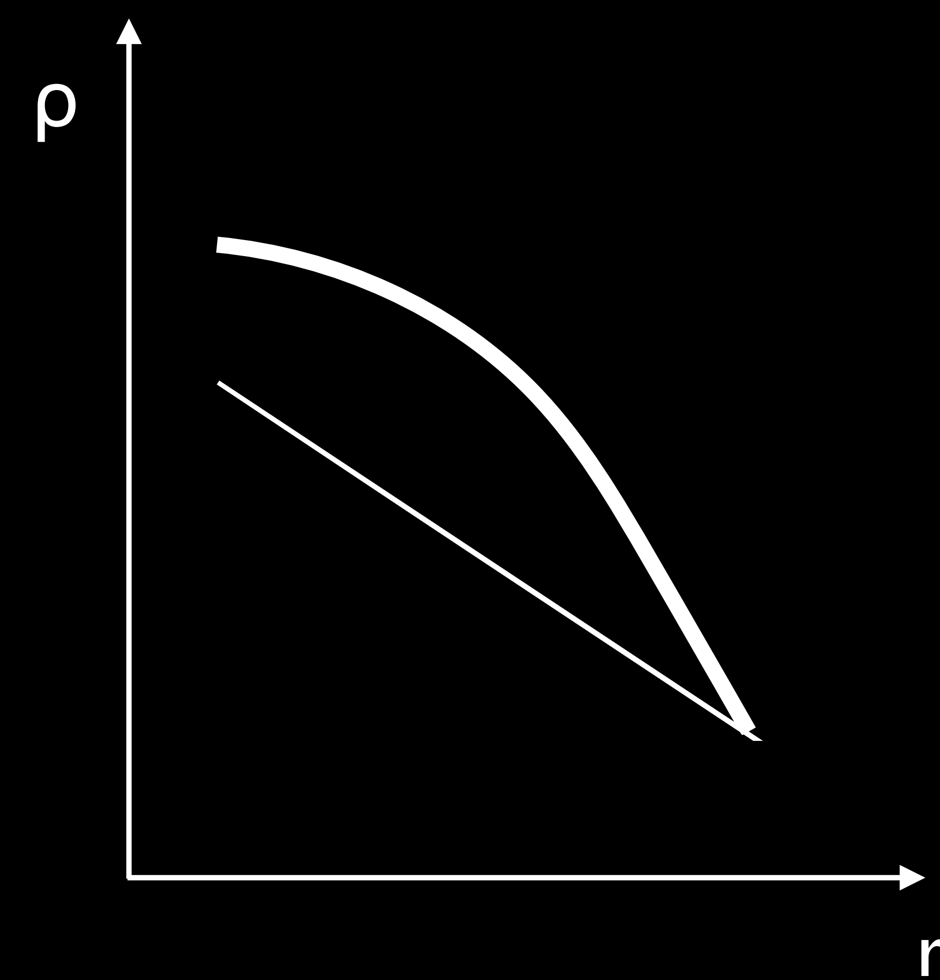

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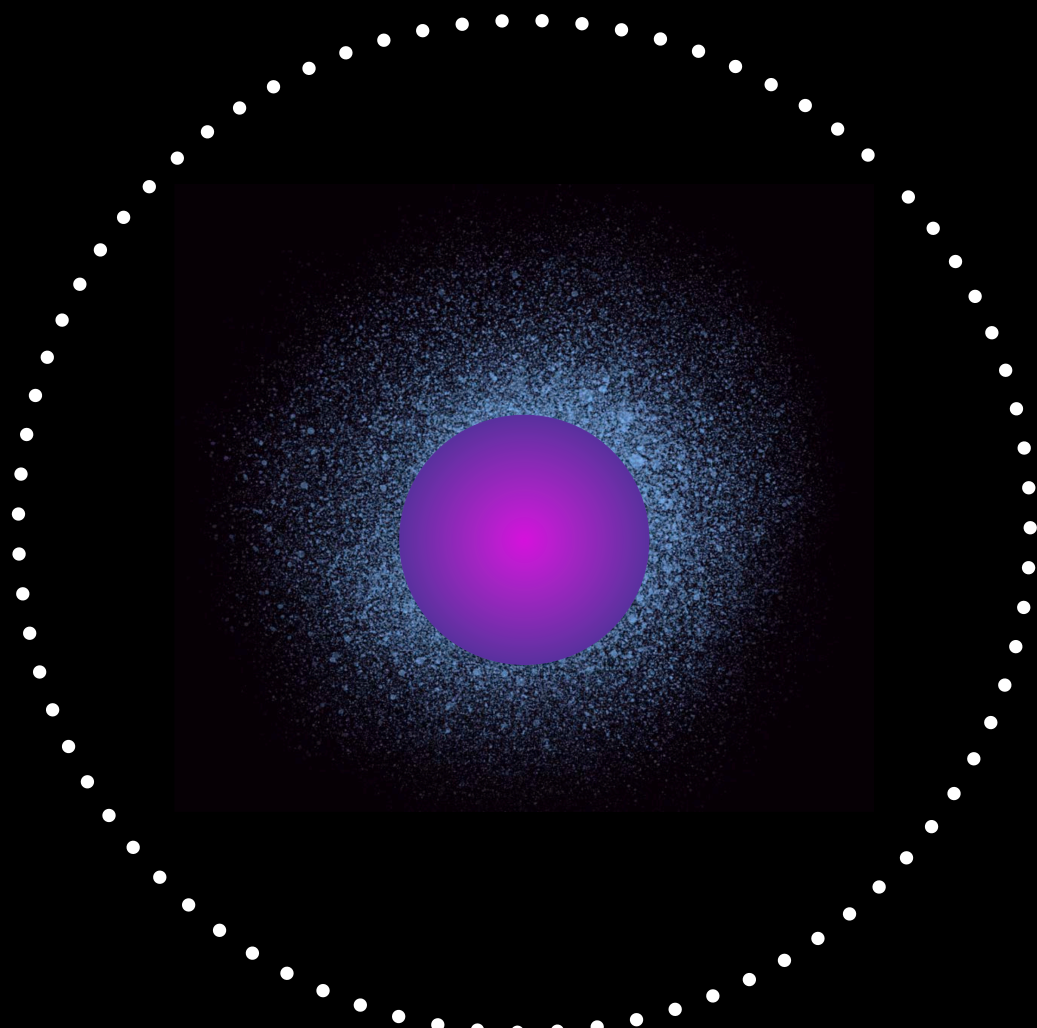

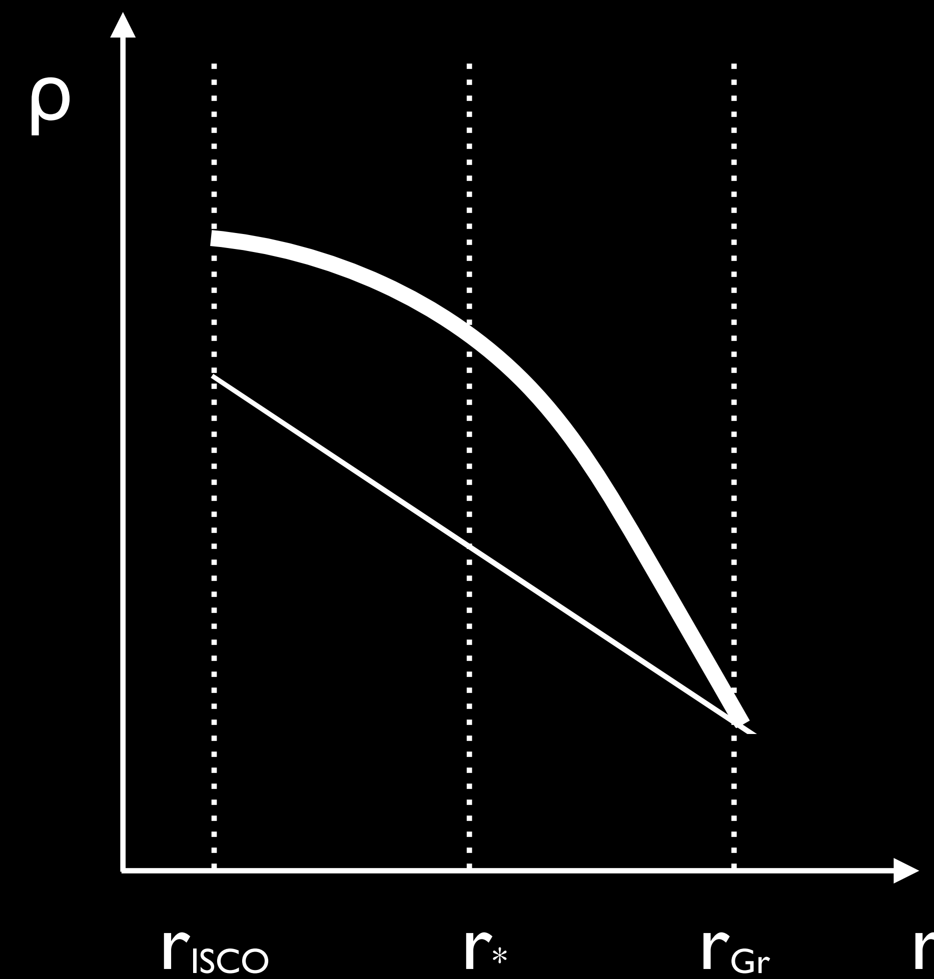

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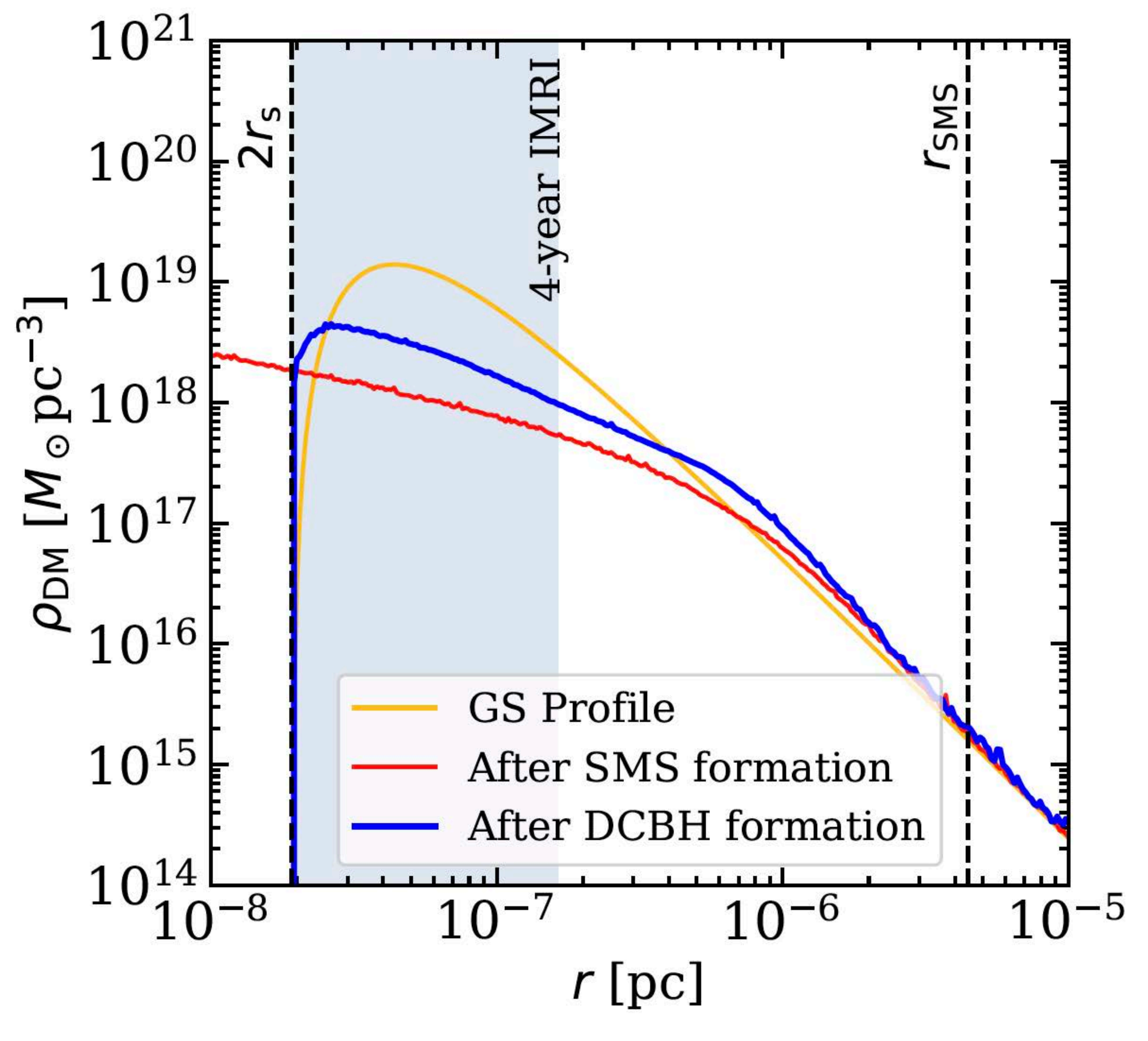
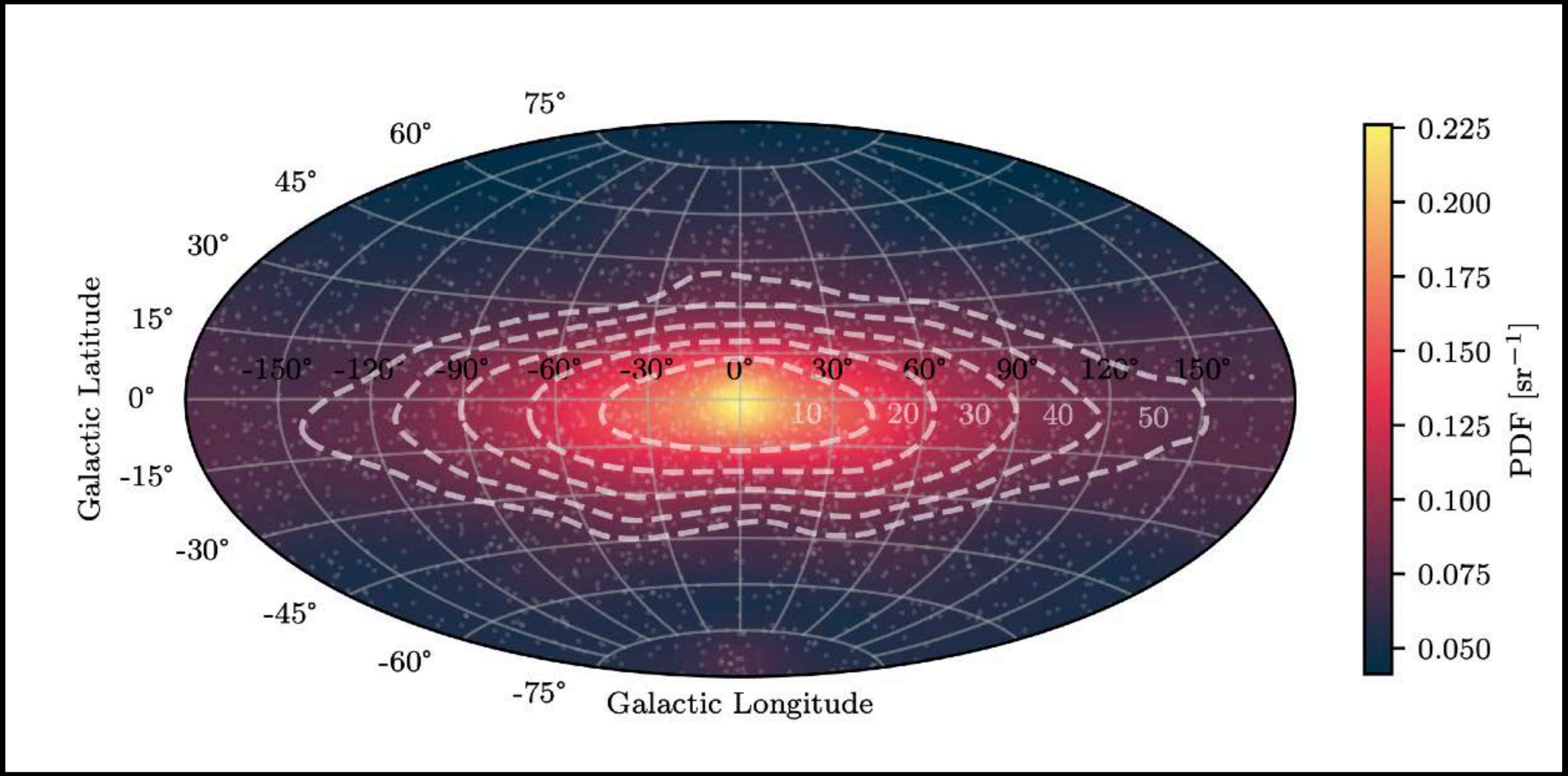
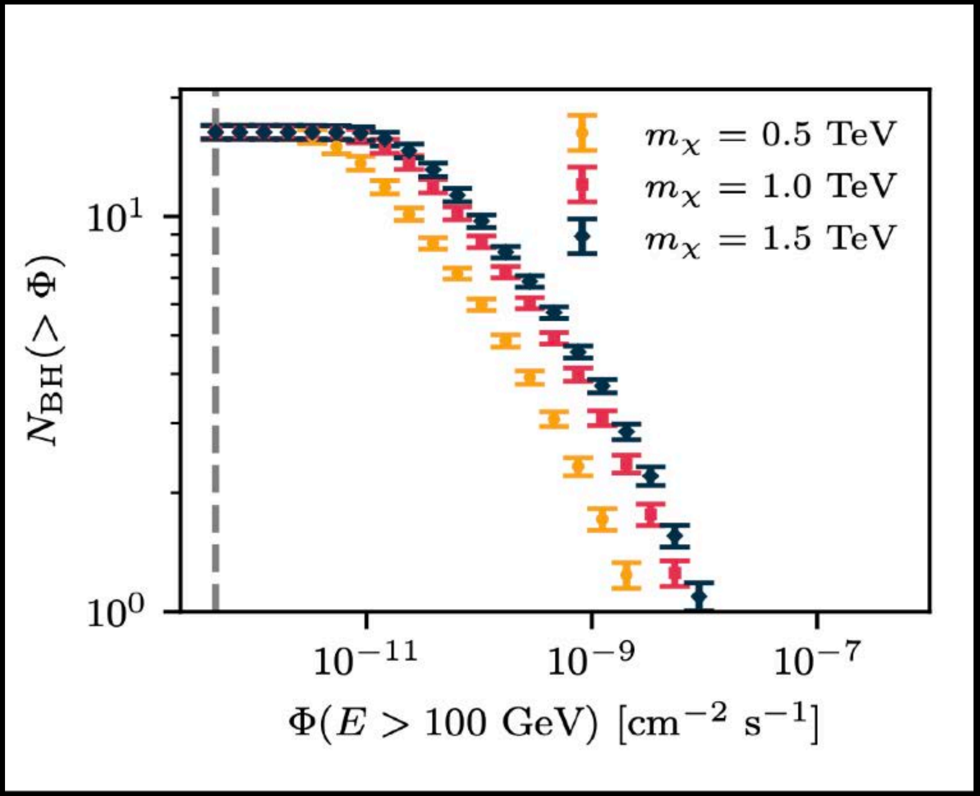
Realistic dark matter overdensities around BHs



GB, Wierda, Gaggero, Kavanagh, Volonteri, Yoshida - 2404.08731

γ-rays from DM spikes in EAGLE simulations

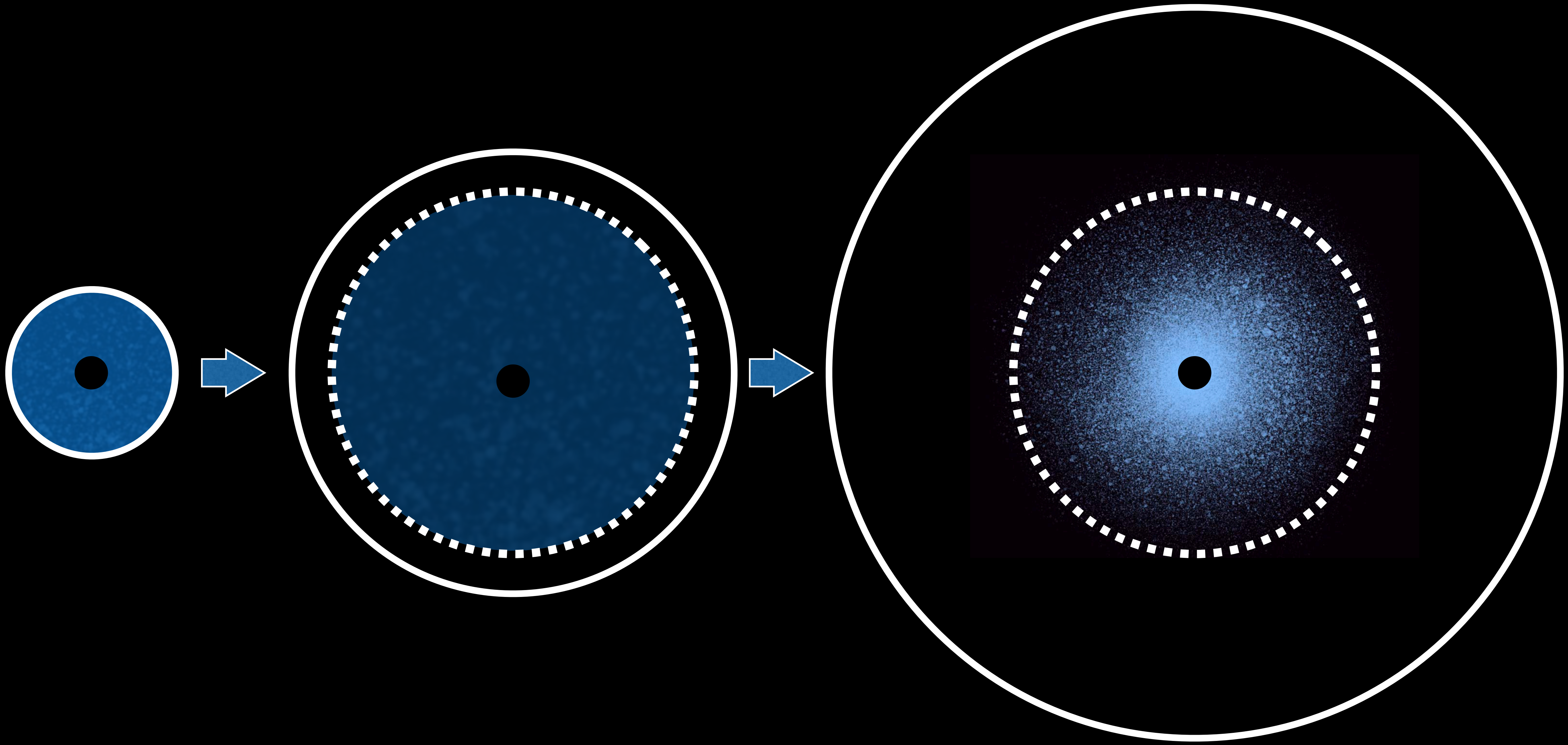




Aschersleben, GB et al JCAP09(2024)005

Fermi-LAT, H.E.S.S. and CTAO sensitive to dark matter self-annihilation around IMBHs well below thermal relic cross section

DM overdensities around PBHs



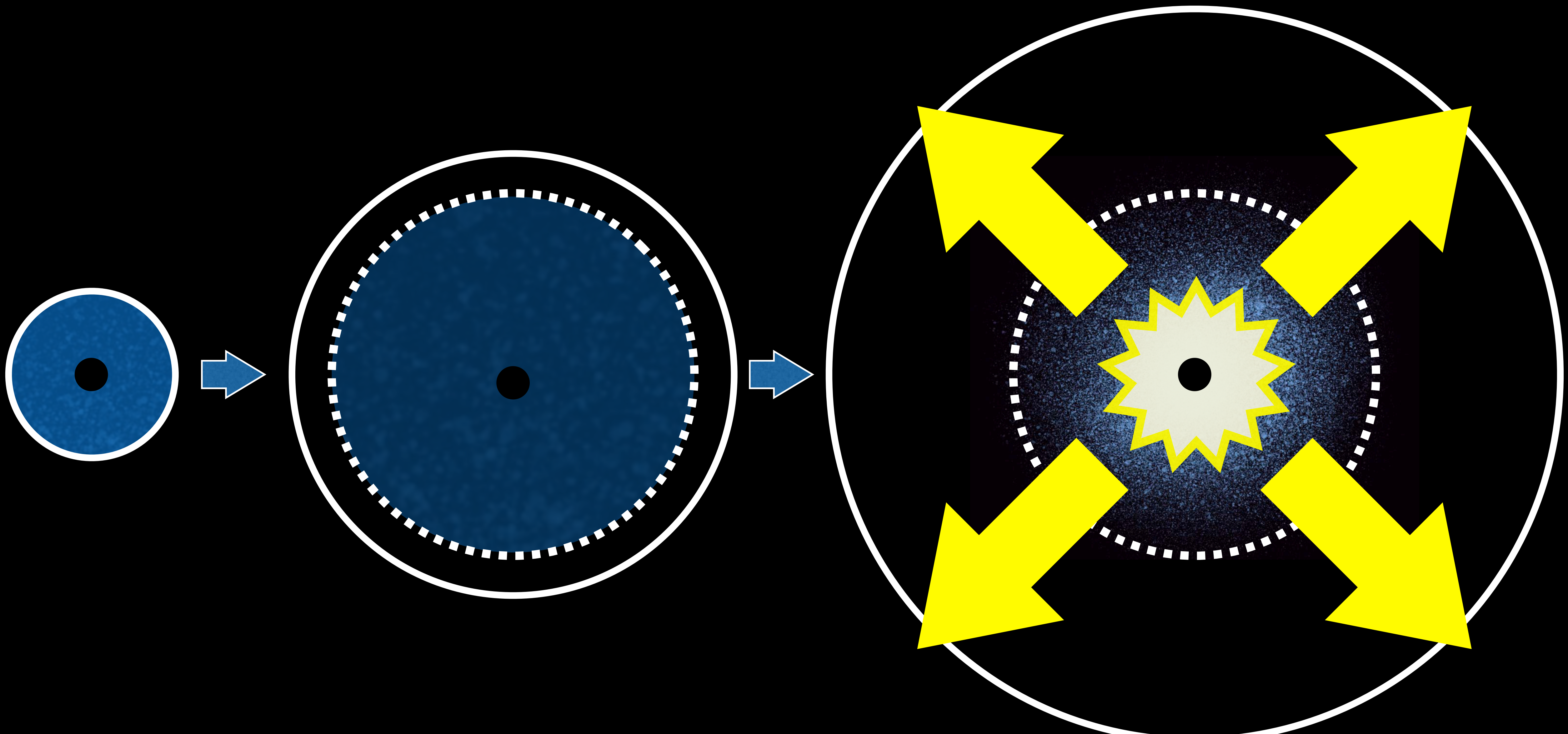
PBH

'Turnaround' point, when particles decouple from expansion

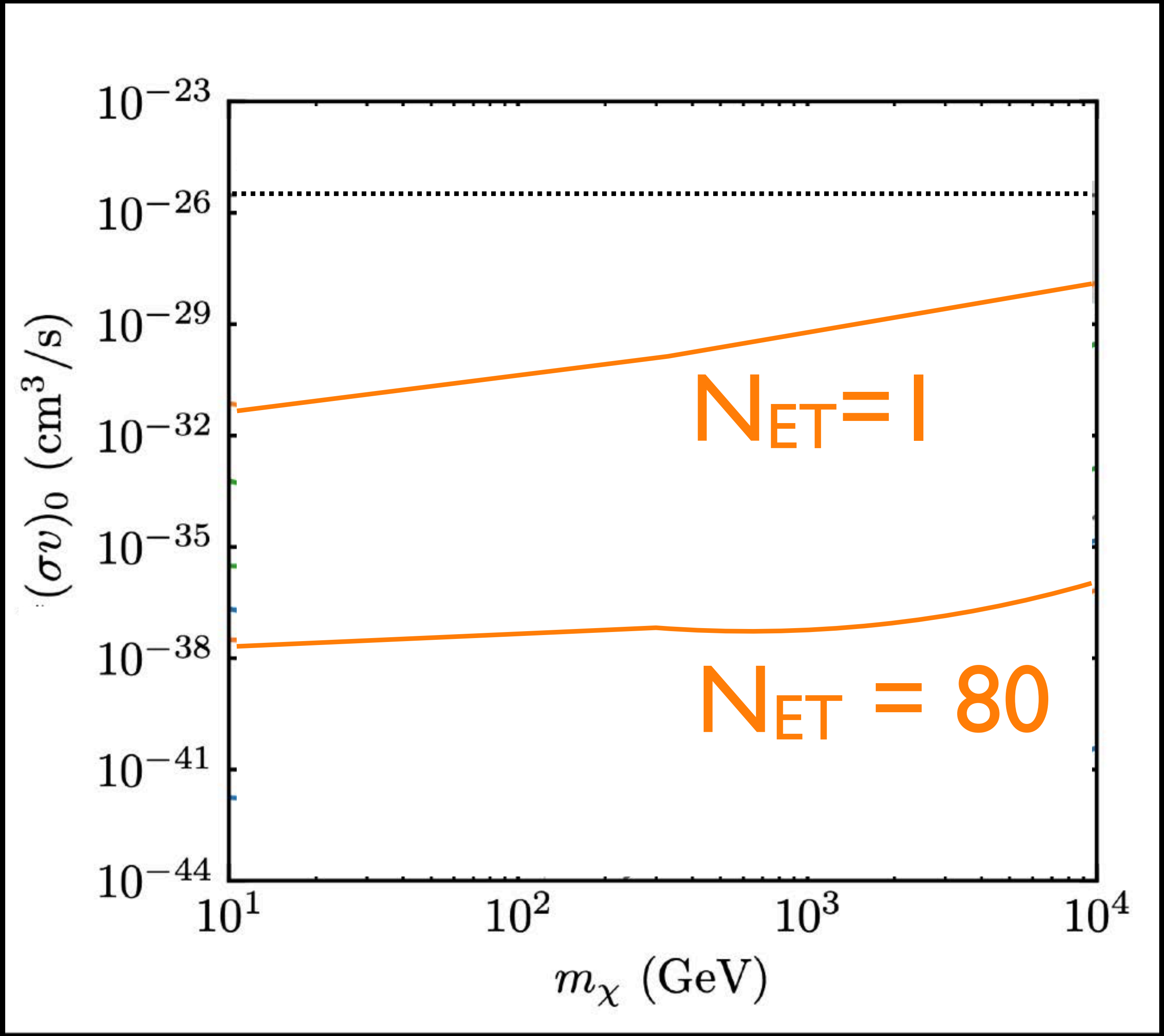
$$\rho_{\rm DM}(r) \sim r^{-9/4}$$

Adamek+ 1901.08528, Boudaud+ 2106.07480

If DM=WIMPs, large annihilation flux!



If (subdominant) PBHs discovered: Extraordinarily stringent constraints on new physics at the weak scale!



GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

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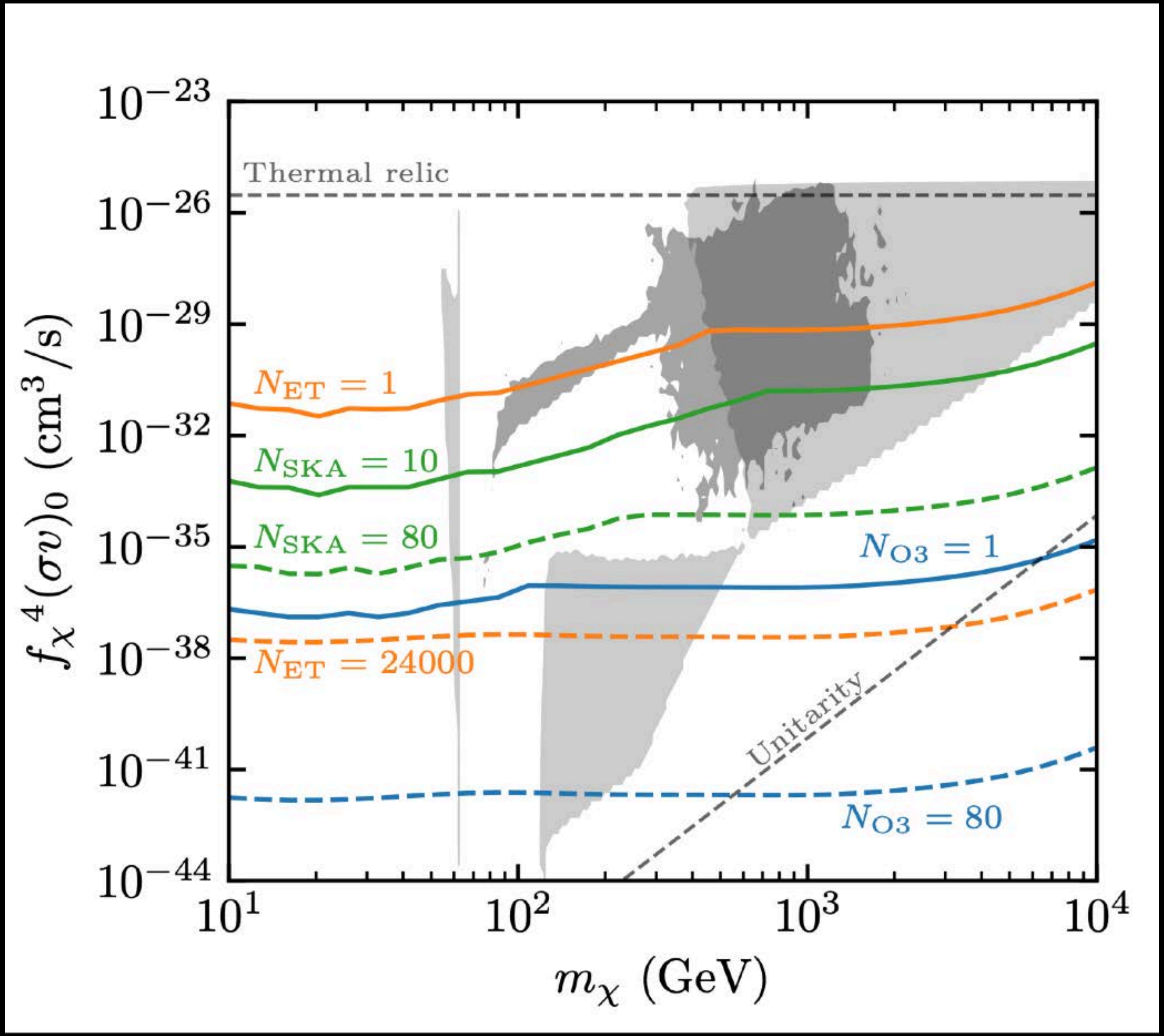


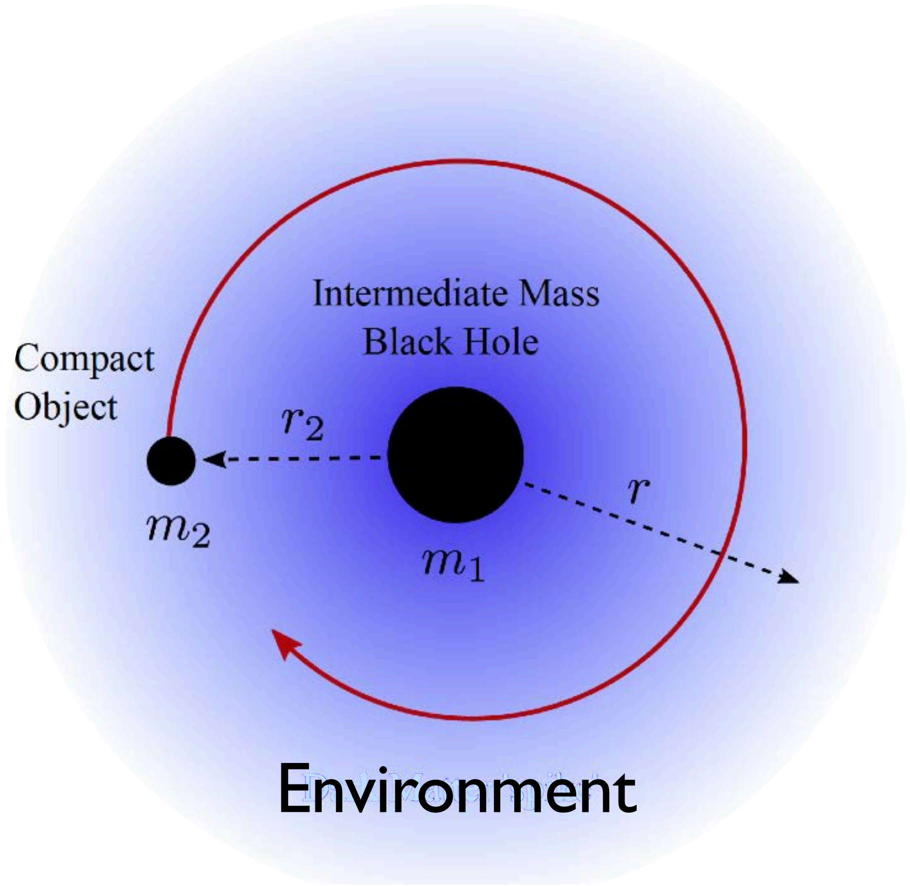
GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

- Detecting a subdominant PBHs with the Einstein Telescope would essentially rule out not only WIMPs, but entire classes of BSM models (even those leading to subdominant DM!)

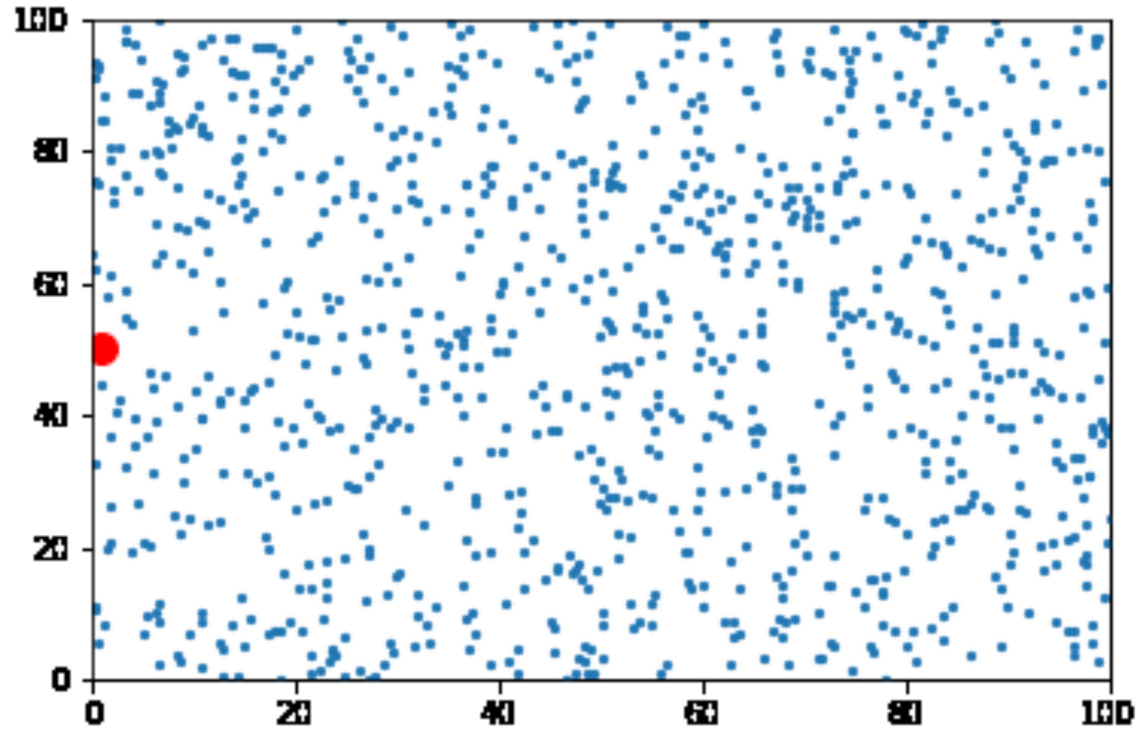
Plan of the talk:

- Why study DM in strong gravity?
- The DM-BH connection
- Gravitational Wave probes of DM

Phenomenology of DM in Strong Gravity



Dynamical Friction



(Classical paper: Chandrasekhar 1931)

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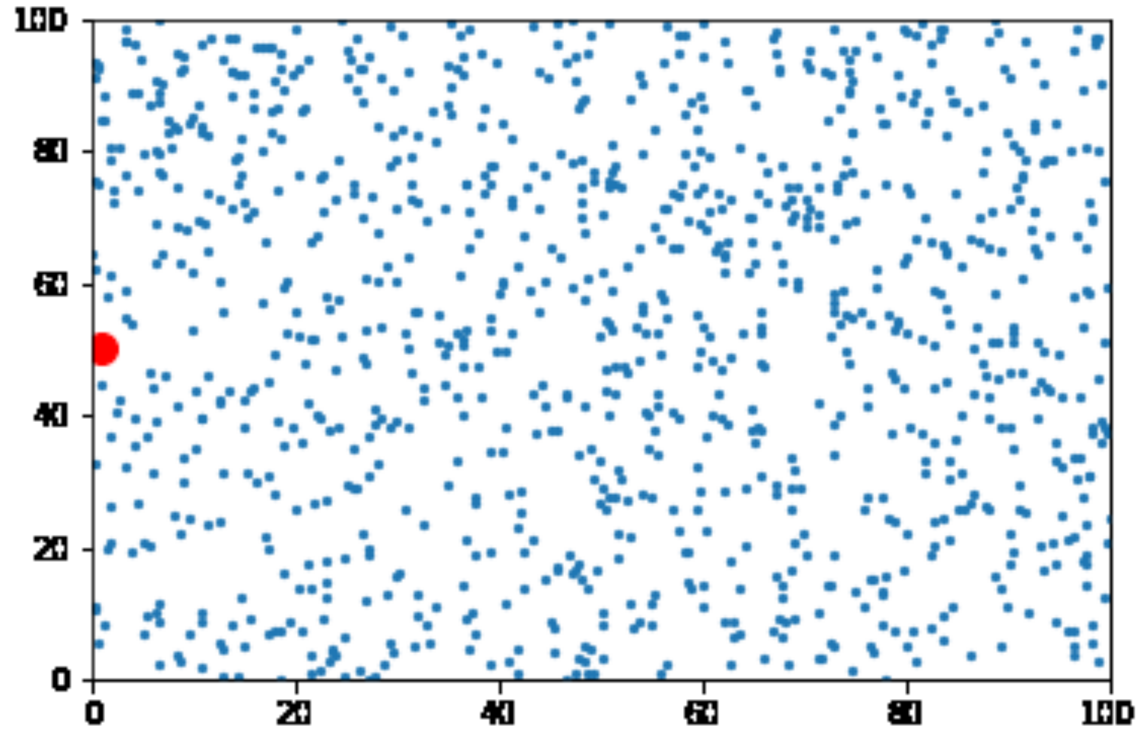

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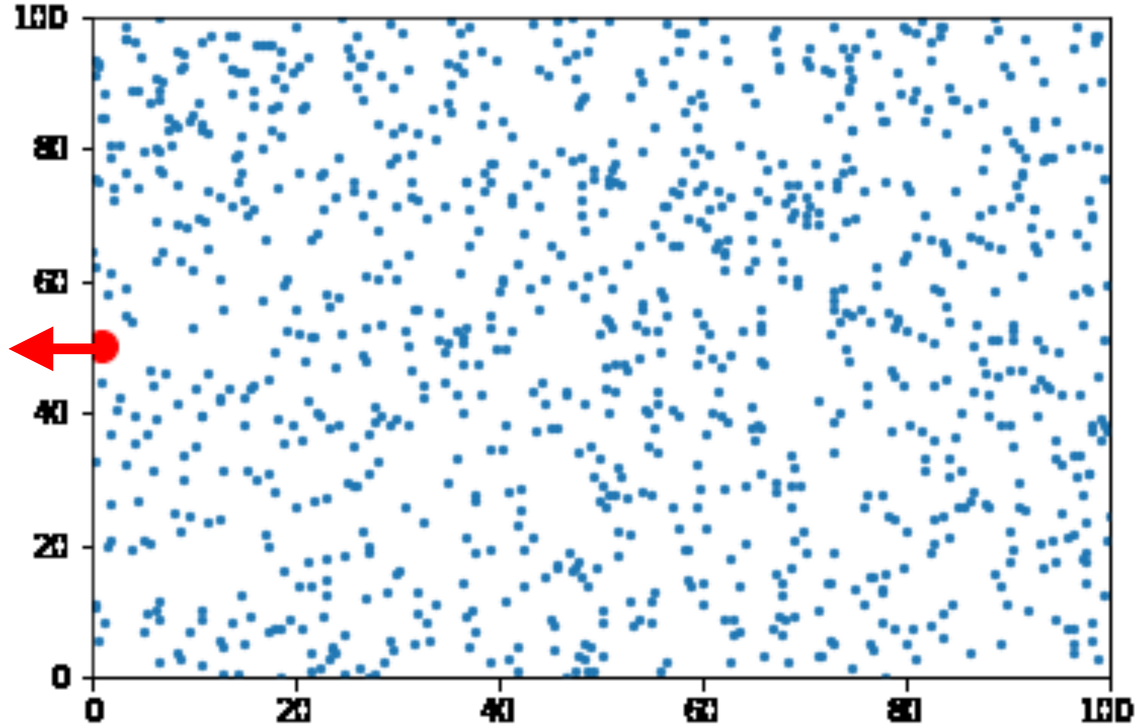

Additional energy loss term: $\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$

Evolution of binary separation:

$$\dot{r}_2 = -\frac{64\,G^3\,M\,m_1\,m_2}{5\,c^5\,(r_2)^3} - \frac{8\pi\,G^{1/2}\,m_2\,\log\Lambda r_2^{5/2}\,\rho_{\rm DM}(r_2)}{\sqrt{M}m_1}$$

Easy, right?

(Eda+ 2013, 2014)

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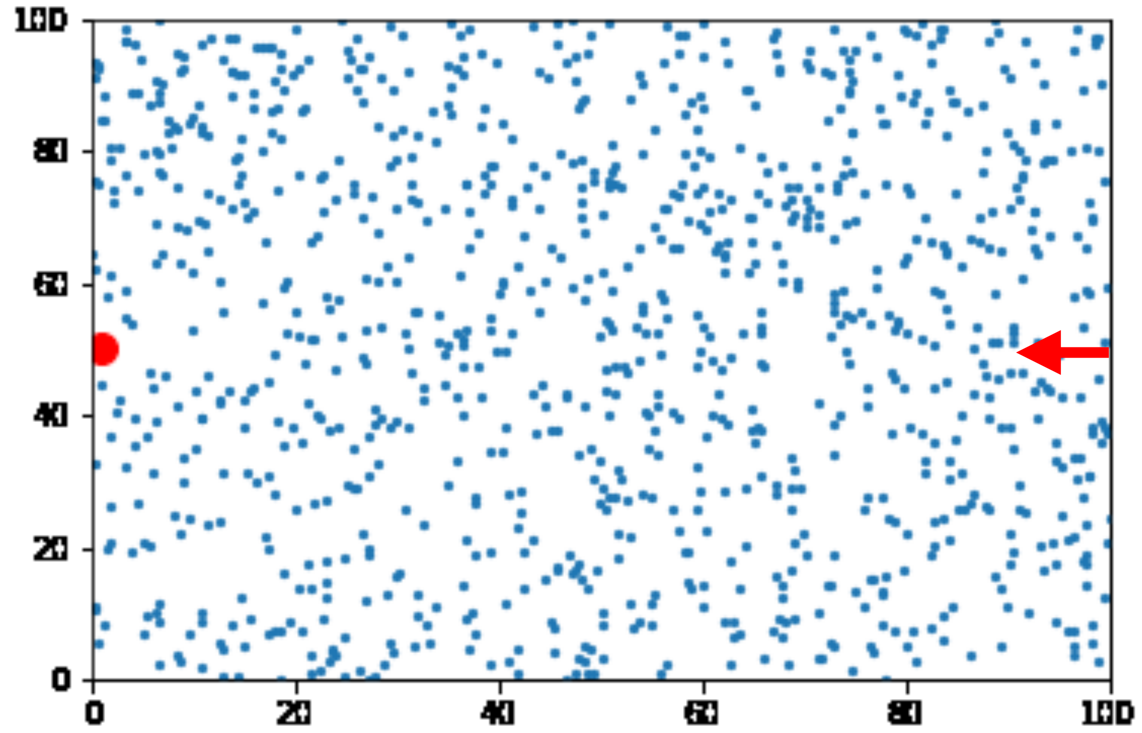

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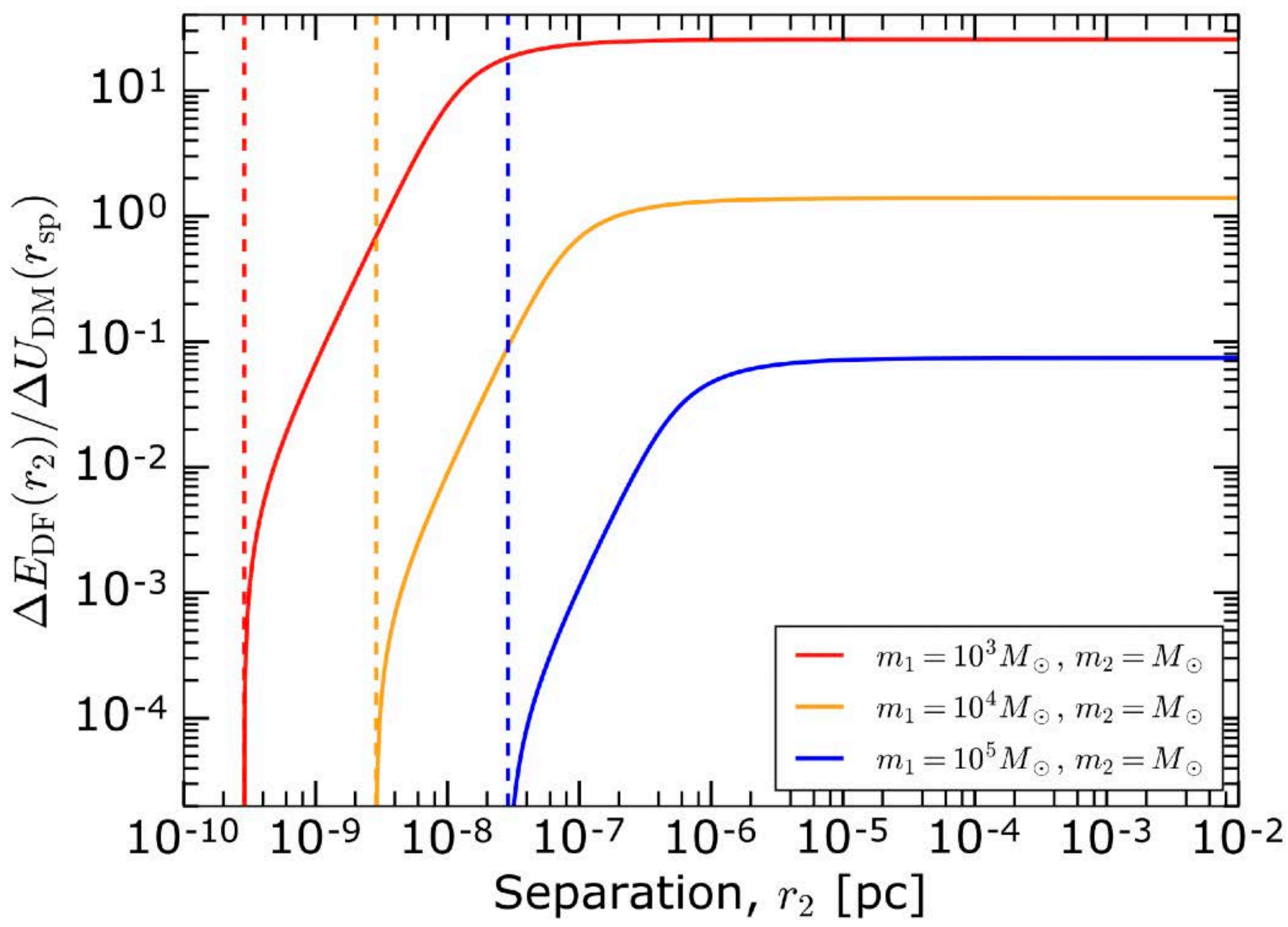
(Eda+ 2013, 2014)

Not so fast..

DM distribution is *heated:* $$\Delta E_{\rm DF}(r_{\rm i}, r_{\rm f}) = -\int_{r_{\rm i}}^{r_{\rm f}} \frac{{\rm d}E_{\rm DF}}{{\rm d}t}\left(\frac{{\rm d}r_2}{{\rm d}t}\right)^{-1}\,{\rm d}r_2$$

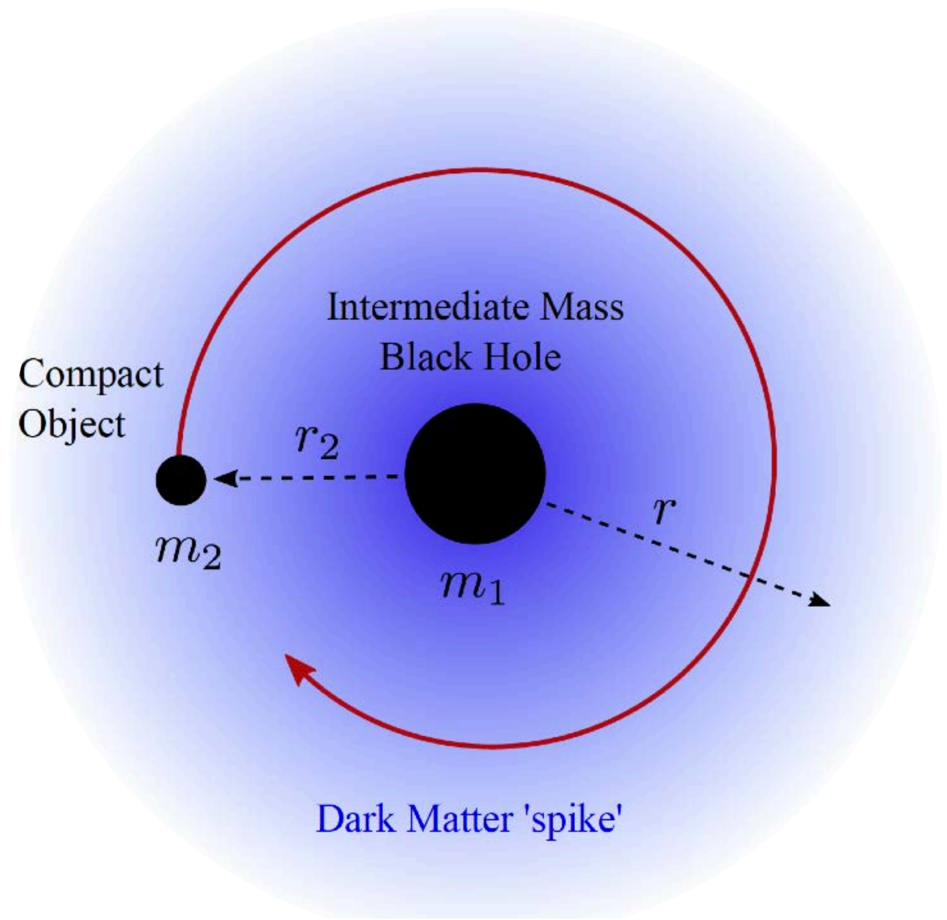


Not so fast II…

DM medium NOT homogenous

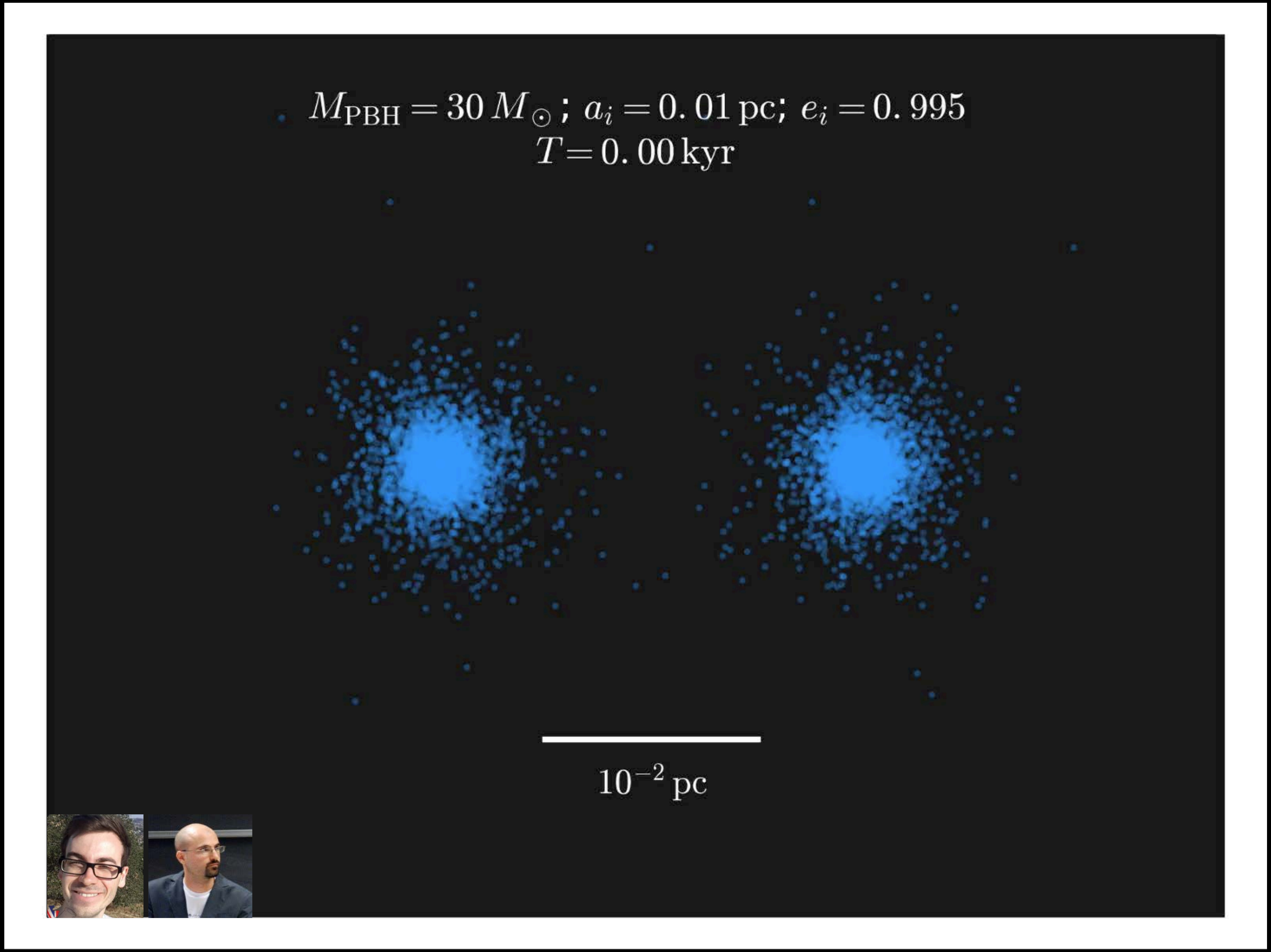
Scattered particles are in a ~ torus around the secondary object orbit

Ellipticity, high-v particles, relativistic corrections, accretion etc..



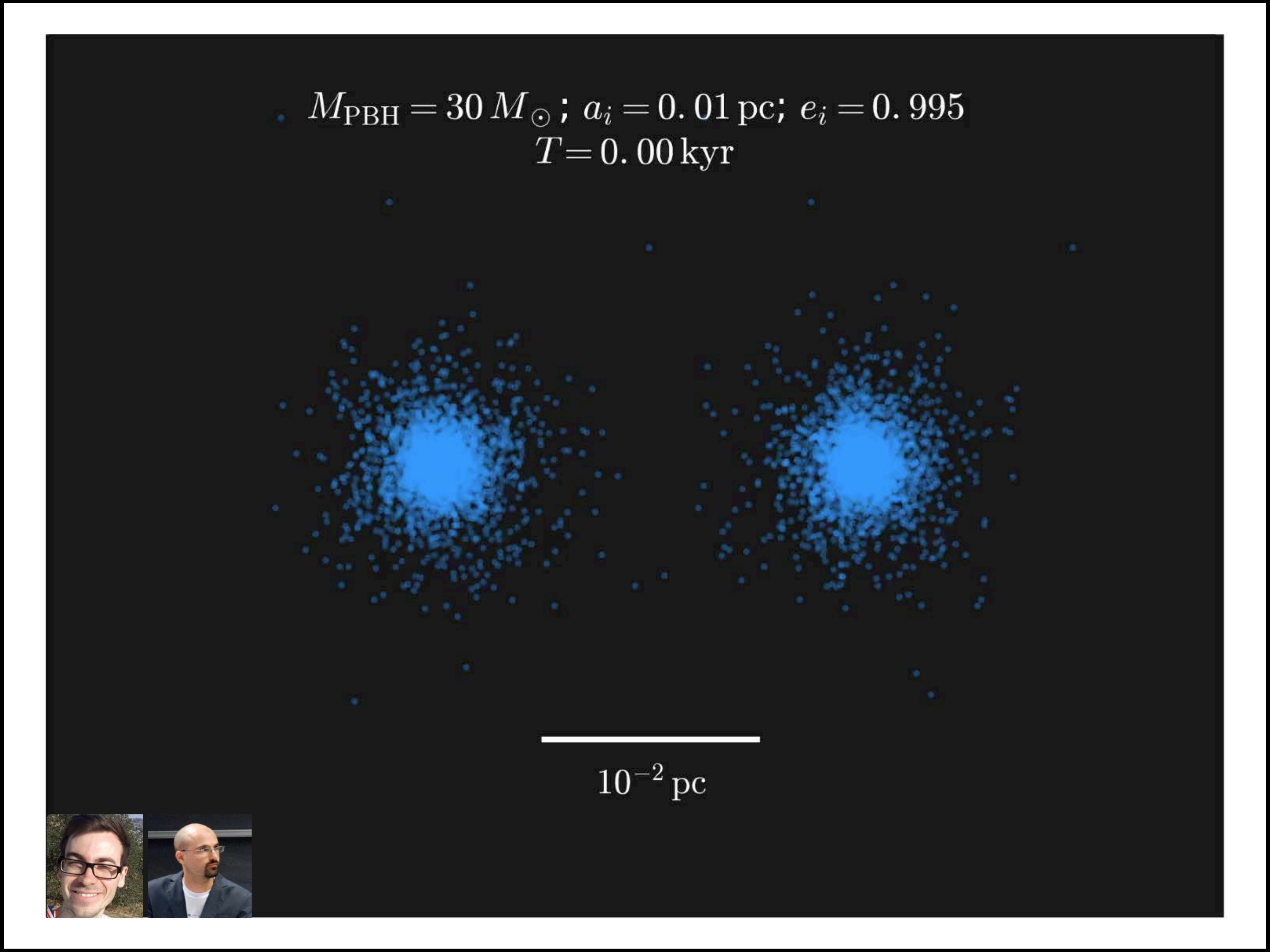
(Kavanagh, GB et al. 2002.12811, Becker+ 2112.09586, Dosopoulou 2305.17281, …)

Equal-mass 'Dressed' BH-BH merger



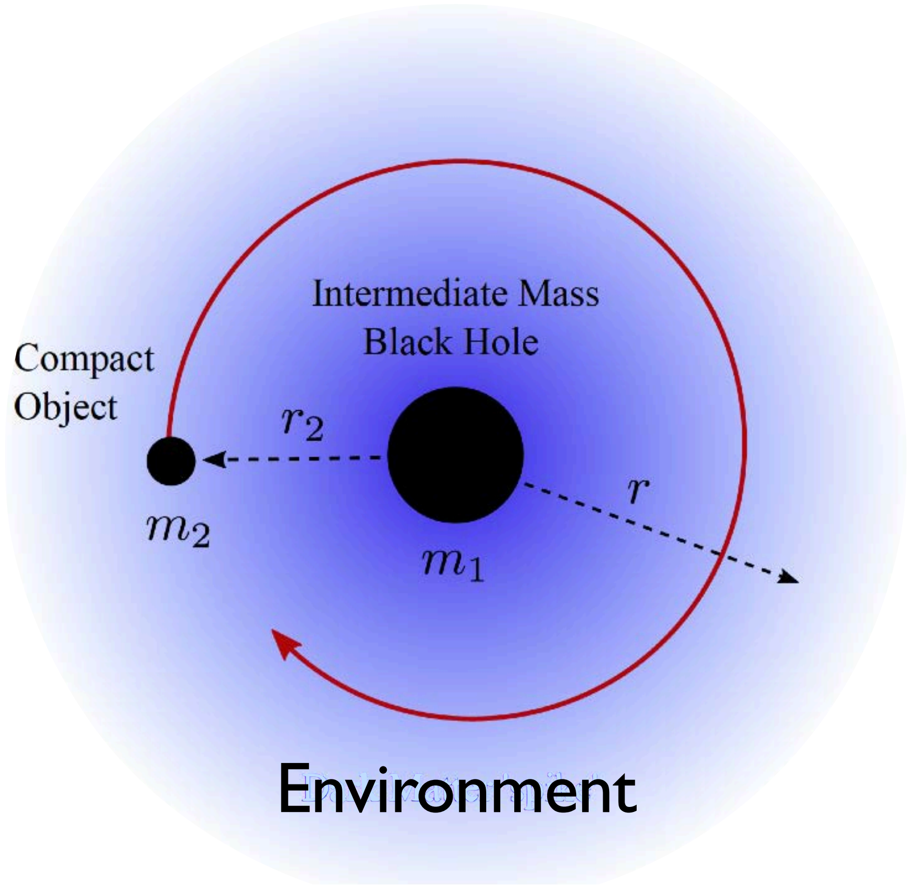
Kavanagh, Gaggero & GB, arXiv:1805.09034

Equal-mass 'Dressed' BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

EMRIs = Extreme Mass Ratio Inspirals



$$m_1 \gg m_2$$

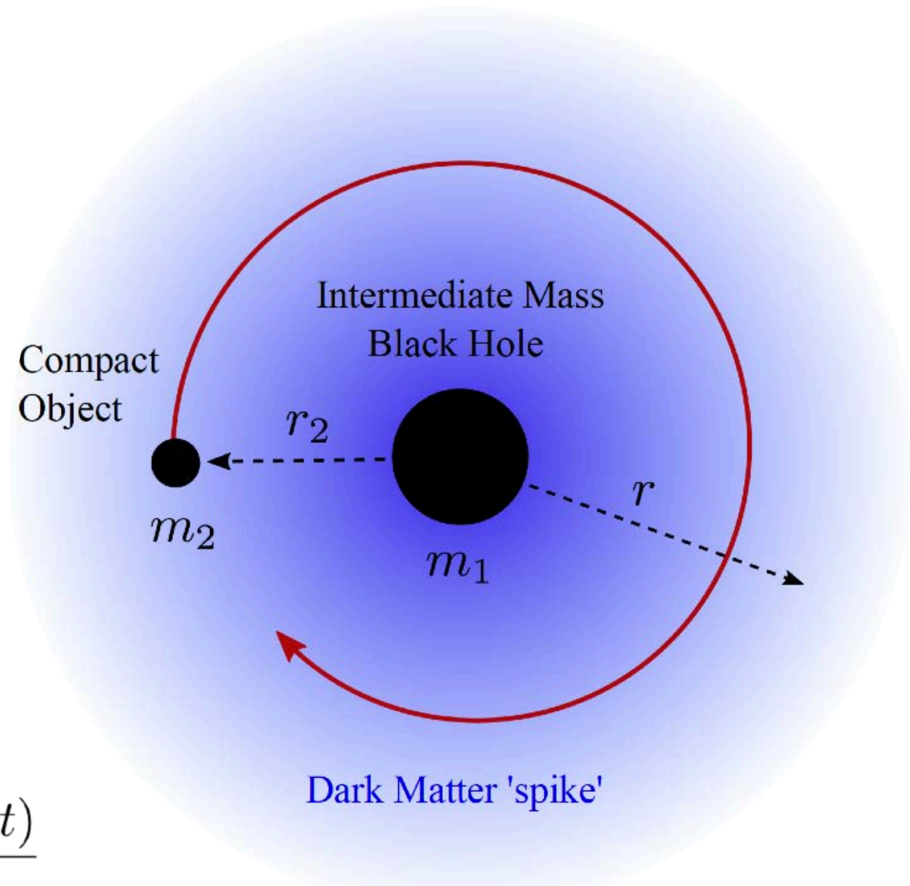
Co-evolution of binary and DM distribution

Energy losses due to dynamical friction:

$$\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$$

Evolution of binary separation:

$$\dot{r}_2 = -\frac{64\,G^3\,M\,m_1\,m_2}{5\,c^5\,(r_2)^3} - \frac{8\pi\,G^{1/2}\,m_2\,\log\Lambda r_2^{5/2}\,\rho_{\rm DM}(r_2,t)\,\xi(r_2,t)}{\sqrt{M}m_1}$$

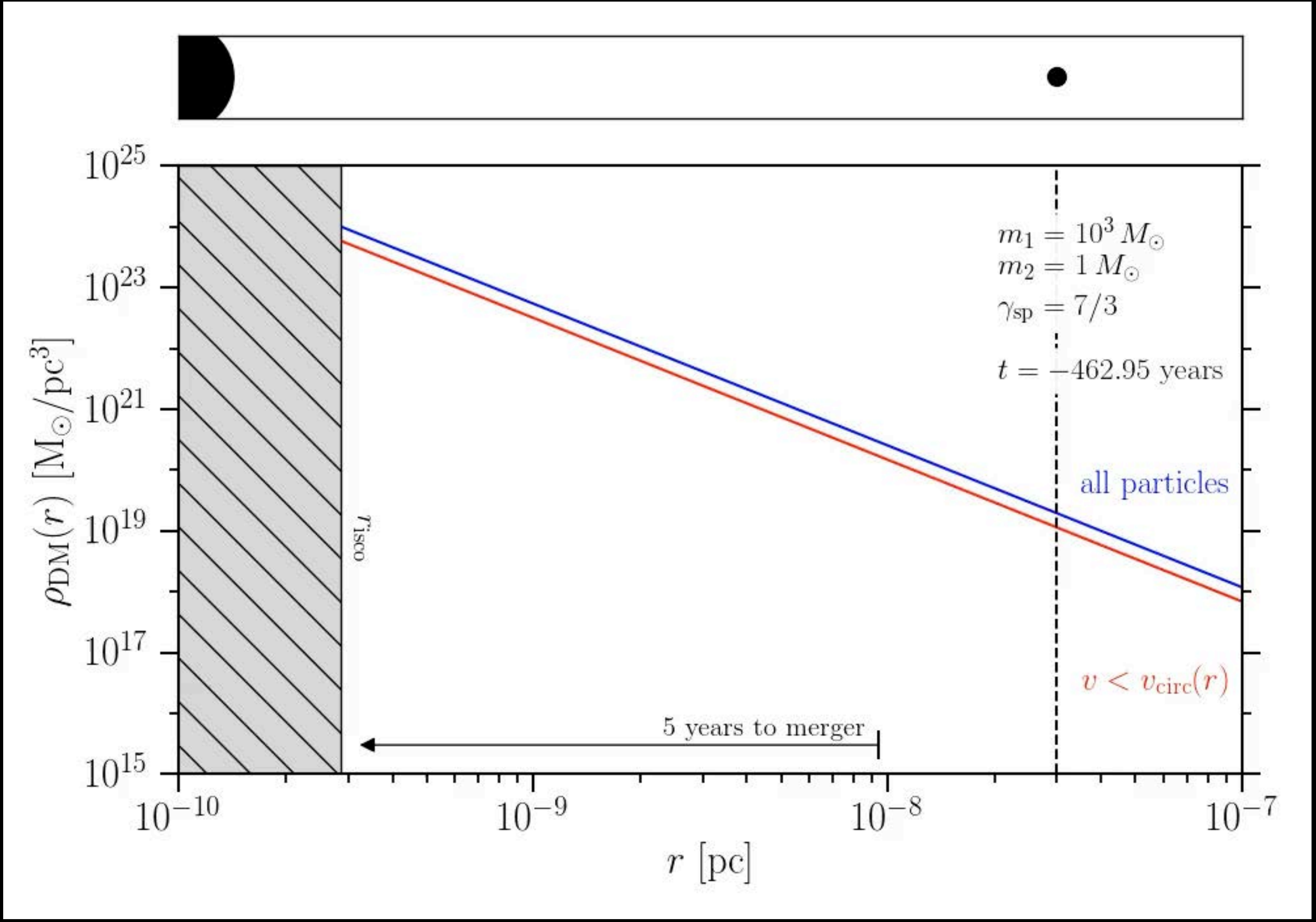


Time-dependent dark matter phase space density:

$$T_{\rm orb}\frac{\partial f(\mathcal{E},t)}{\partial t} = -p_{\mathcal{E}}\,f(\mathcal{E},t) + \int\left(\frac{\mathcal{E}}{\mathcal{E}-\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E},t)P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$$

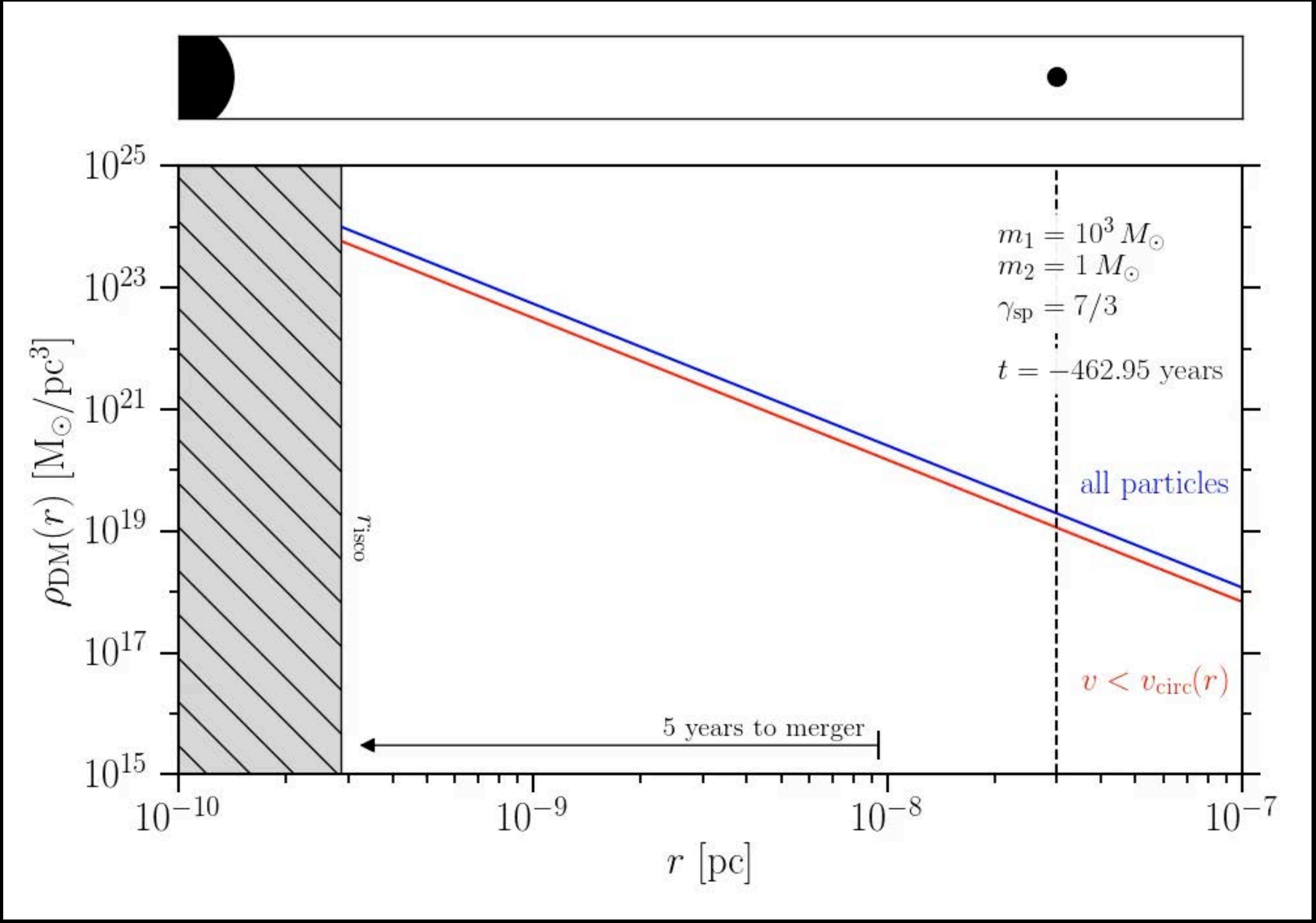
Kavanagh, GB et al. 2002.12811
[see also Trestini's talk]

Time-dependent dark matter density profile



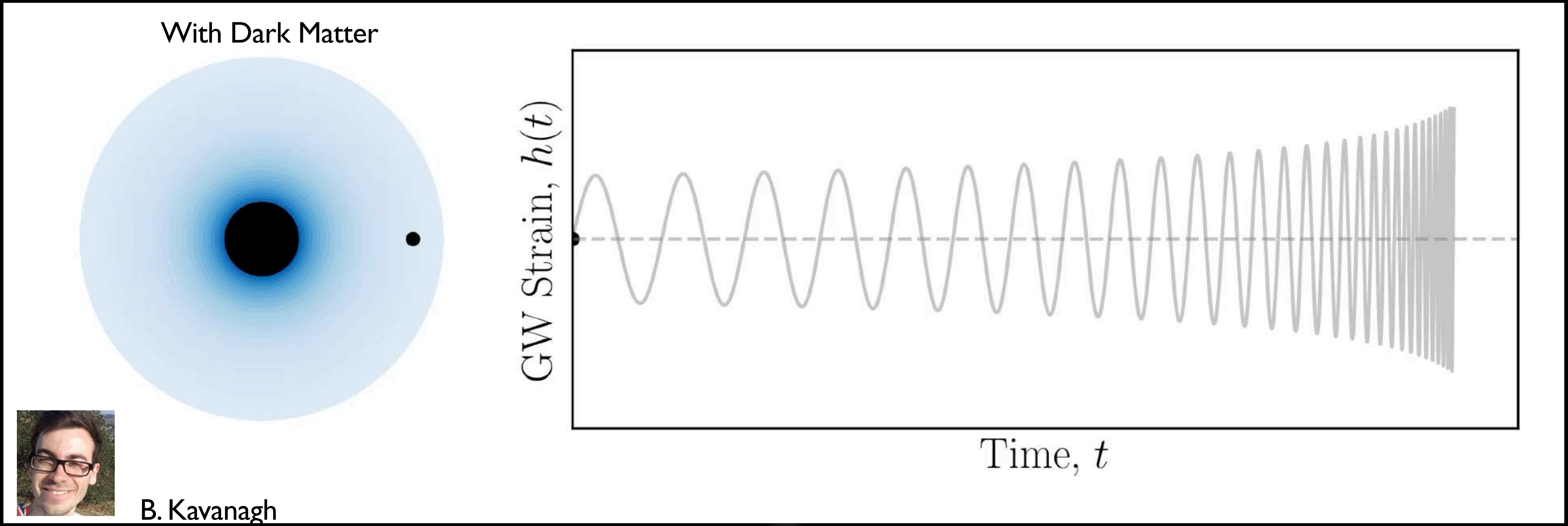
Kavanagh, GB et al 2002.12811, https://doi.org/10.6084/m9.figshare.11663676

Time-dependent dark matter density profile



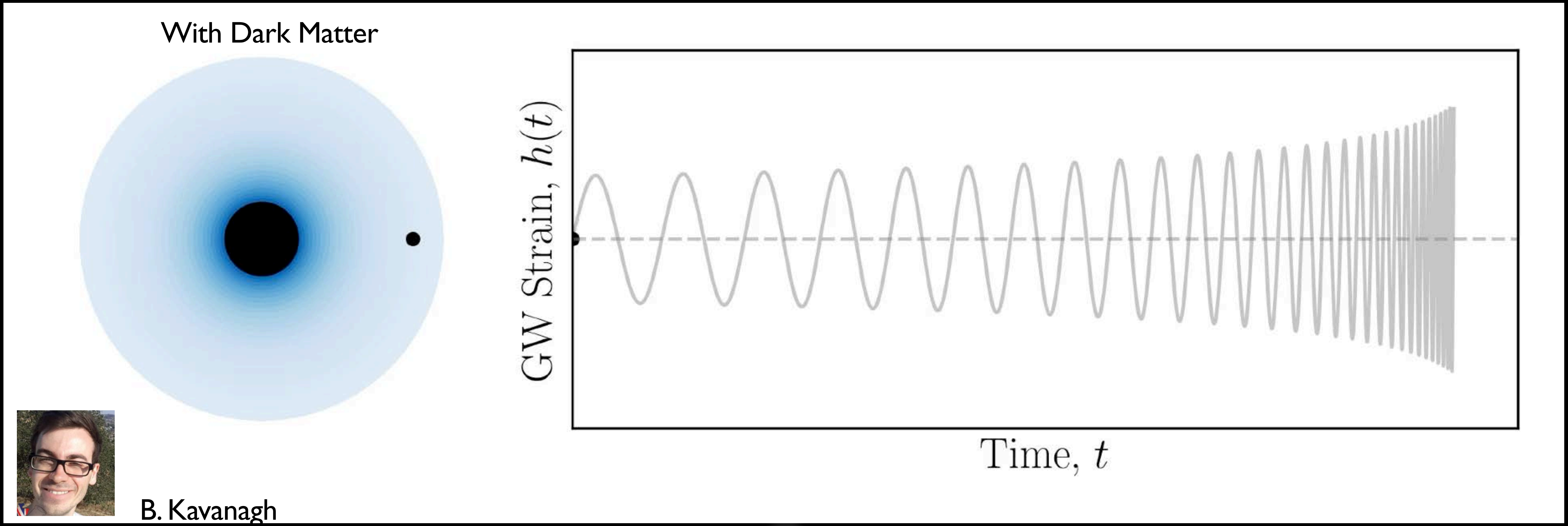
Kavanagh, GB et al 2002.12811, https://doi.org/10.6084/m9.figshare.11663676

Effect of the environment on the waveform



- Waveforms are *dephased,* with a characteristic $\Delta\phi(f)$
- Additional energy loss → shorter time to merger

Effect of the environment on the waveform



- Waveforms are *dephased*, with a characteristic $\Delta\phi(f)$
- Additional energy loss → shorter time to merger

Gravitational Waveform dephasing

- Calculate the number of cycles including the effect DM

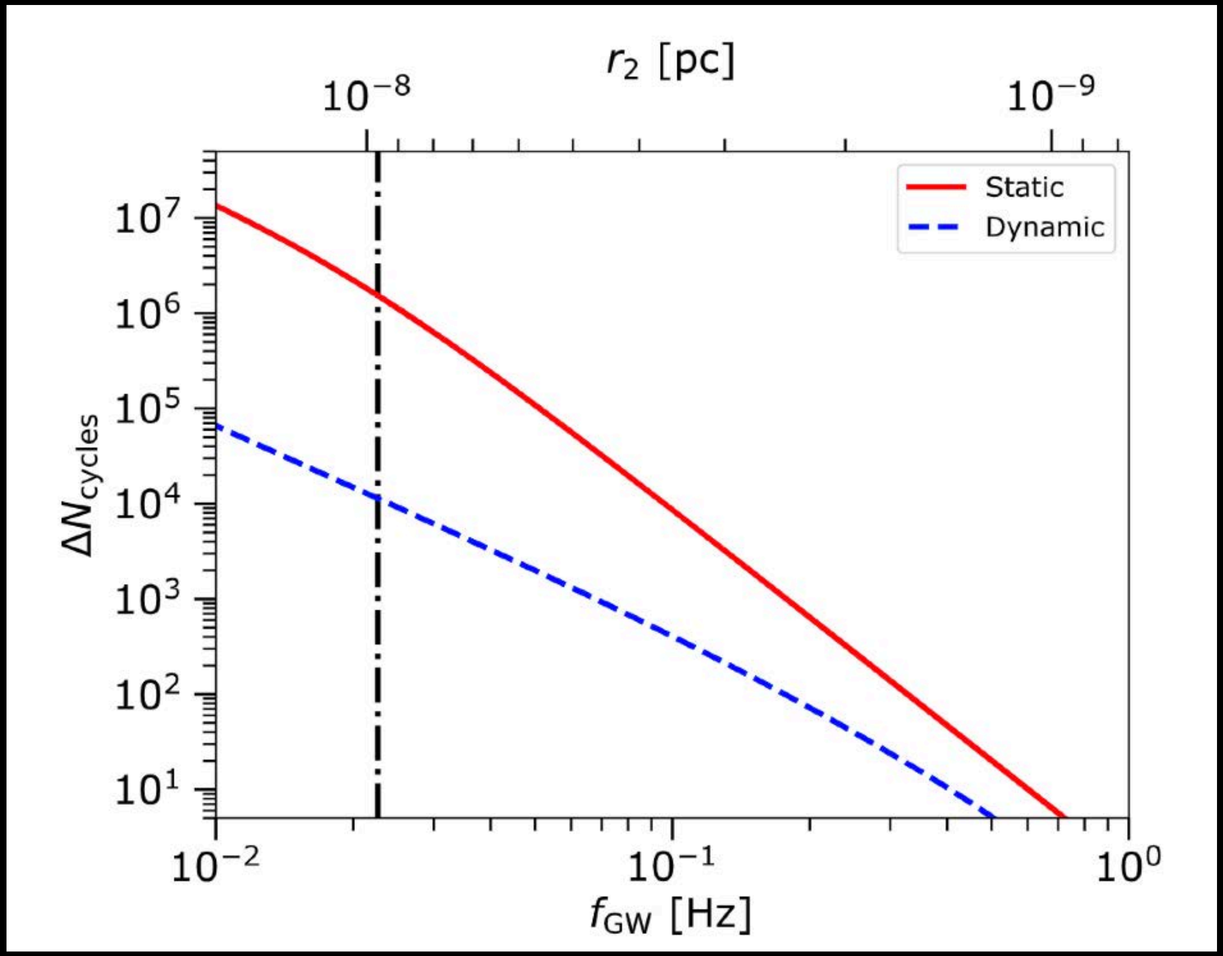
$$N_{\mathrm{cycles}}(t_{\mathrm{f}}, t_{\mathrm{i}}) = \int_{t_{\mathrm{i}}}^{t_{\mathrm{f}}} f_{\mathrm{GW}}(t)\mathrm{d}t$$

- Calculate difference wrt vacuum

$$\Delta N_{\mathrm{cycles}} = N^{\mathrm{vac}}_{\mathrm{cycles}}(f_{\mathrm{GW,f}}, f_{\mathrm{GW,i}}) - N^{\mathrm{DM}}_{\mathrm{cycles}}(f_{\mathrm{GW,f}}, f_{\mathrm{GW,i}})$$

- Static: Assuming DM fixed (Eda+ 2013, 2014)

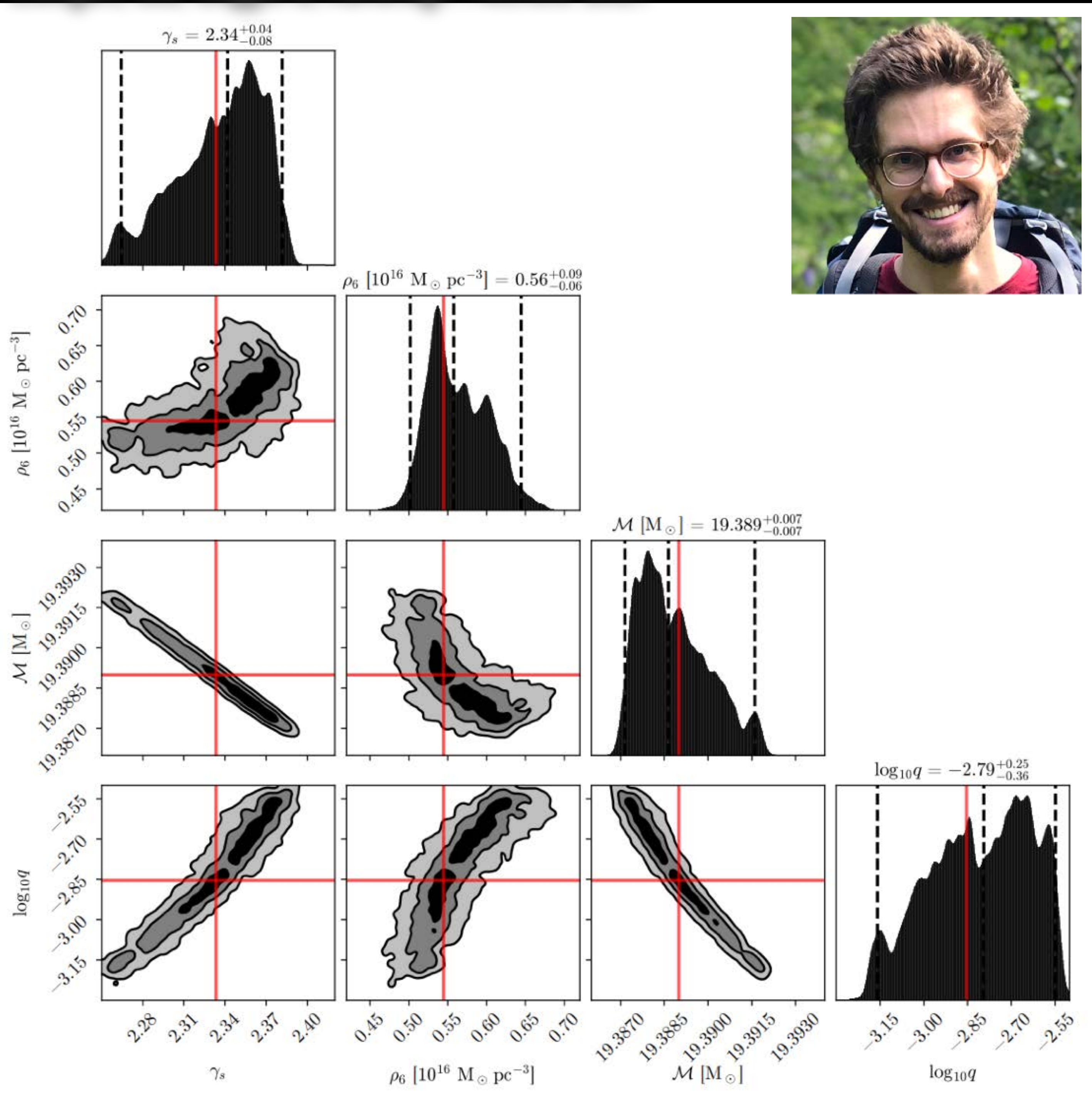
- Dynamic: including evolution of DM phase space (2002.12811)



Kavanagh, GB et al. 2002.12811

Detecting / discovering / Measuring DM with GWs

Coogan, GB, Gaggero, Kavanagh Nichols 2021



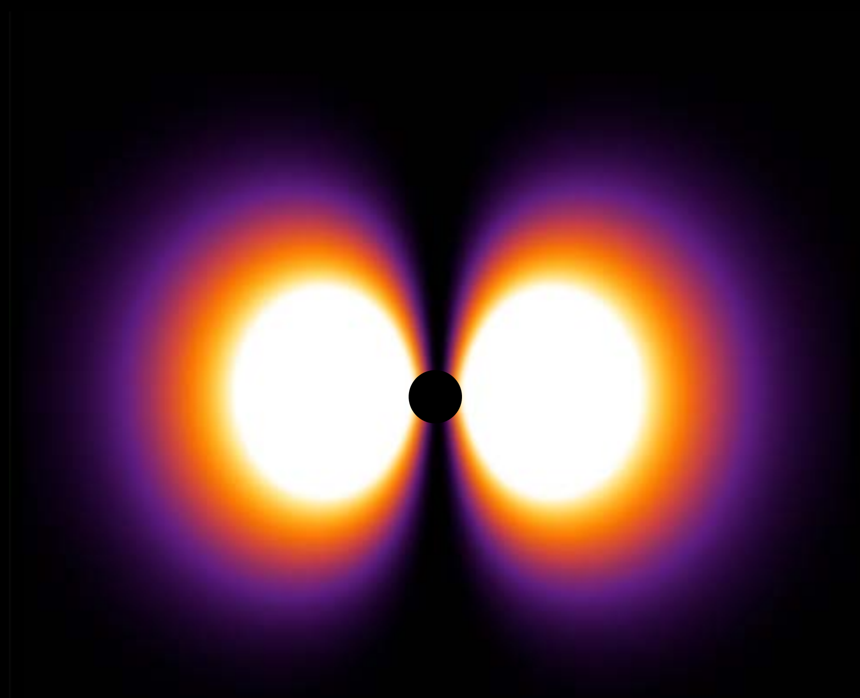
Spike Slope | Normalisation | Chirp Mass | Mass ratio

- Dark dresses within ~ 100 Mpc are <u>detectable</u> with Lisa
- Can discover that fiducial systems are <u>not</u> <u>GR-in-vacuum</u> (in terms of Bayes factor)
- Can <u>measure</u>:
  - DM density profile
    - normalization
    - slope
  - mass ratio

OK, but can we *identify* DM with GW observations?

Can we tell e.g. WIMPs from ultra-light DM, WDM, self-interacting DM, etc..?

Gravitational atoms

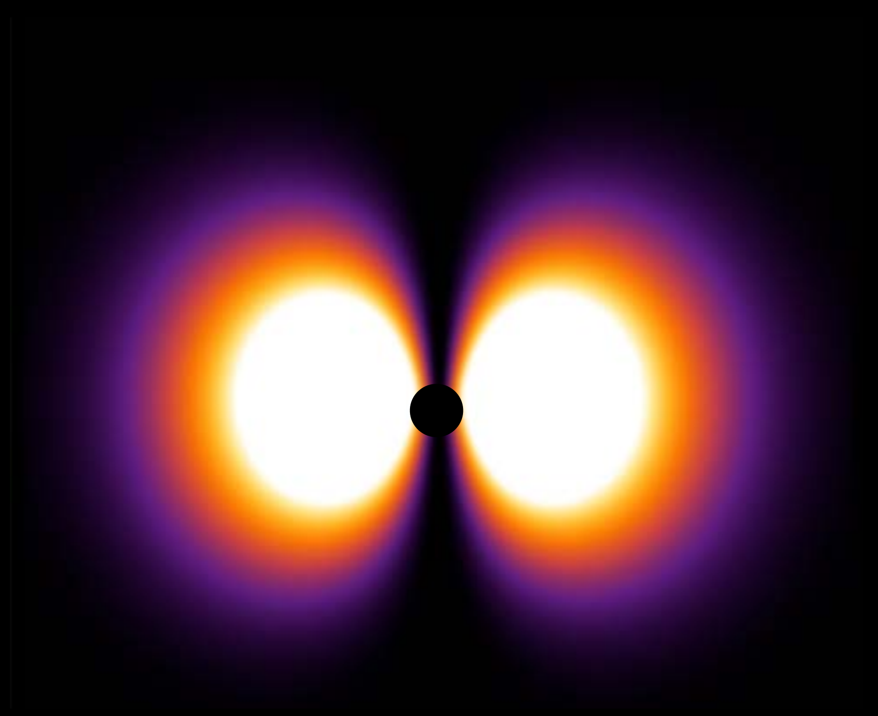


Y. Zel'Dovich (1971,1972); C. Misner (1972); A. Starobinsky (1973); Detweiler (1980); W. East and F. Pretorius (2017); and many many others, see e.g. the review by R. Brito, V. Cardoso, and P. Pani (2015)

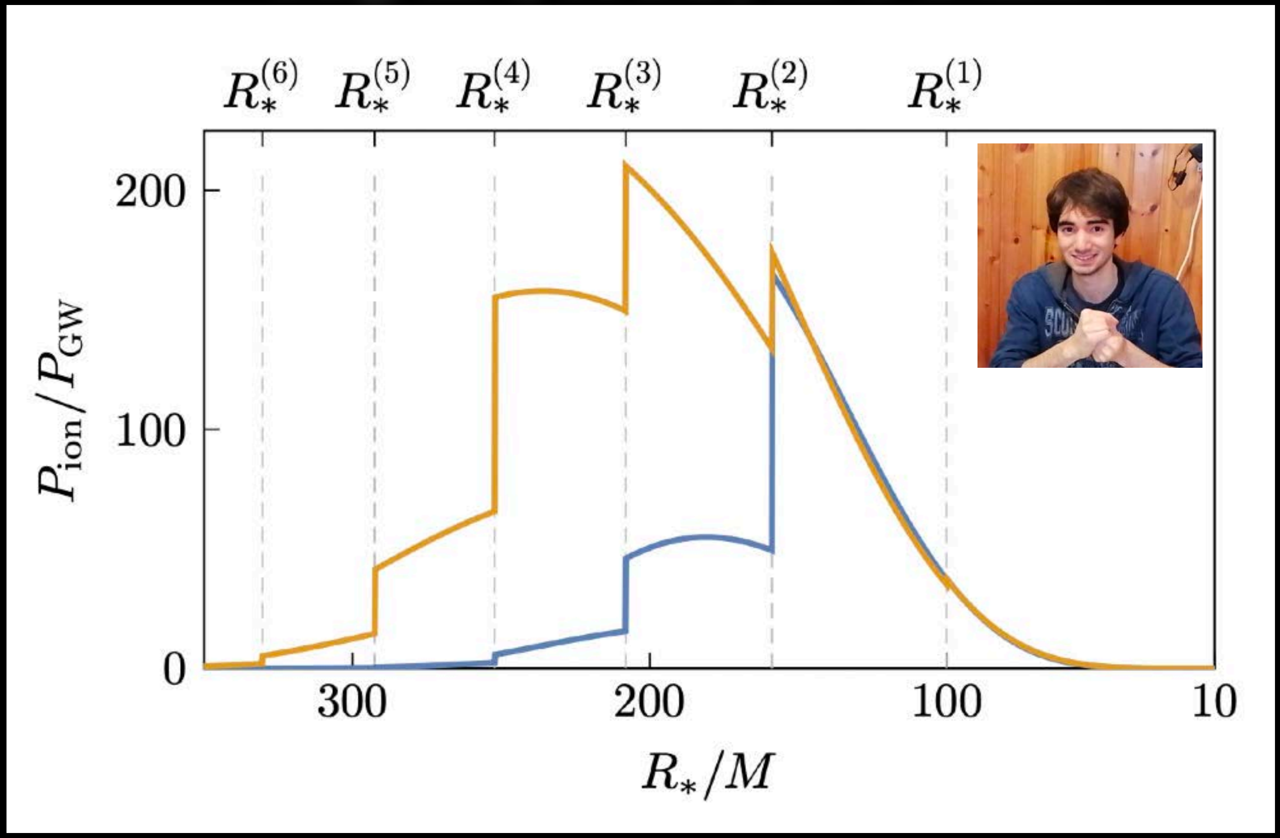
- If ultra-light bosons exist, they can be produced around rotating black holes through S**uperradiance**
- Extraction of mass and angular momentum → **cloud** of the bosonic field
- BH + boson cloud = **gravitational atom.** Bound states $|nlm\rangle$ in analogy with proton + electron structure in H atom

See talk by Cristina Mondino

EMRIs in presence of Gravitational Atoms



Energy lost by the binary due to 'ionisation'

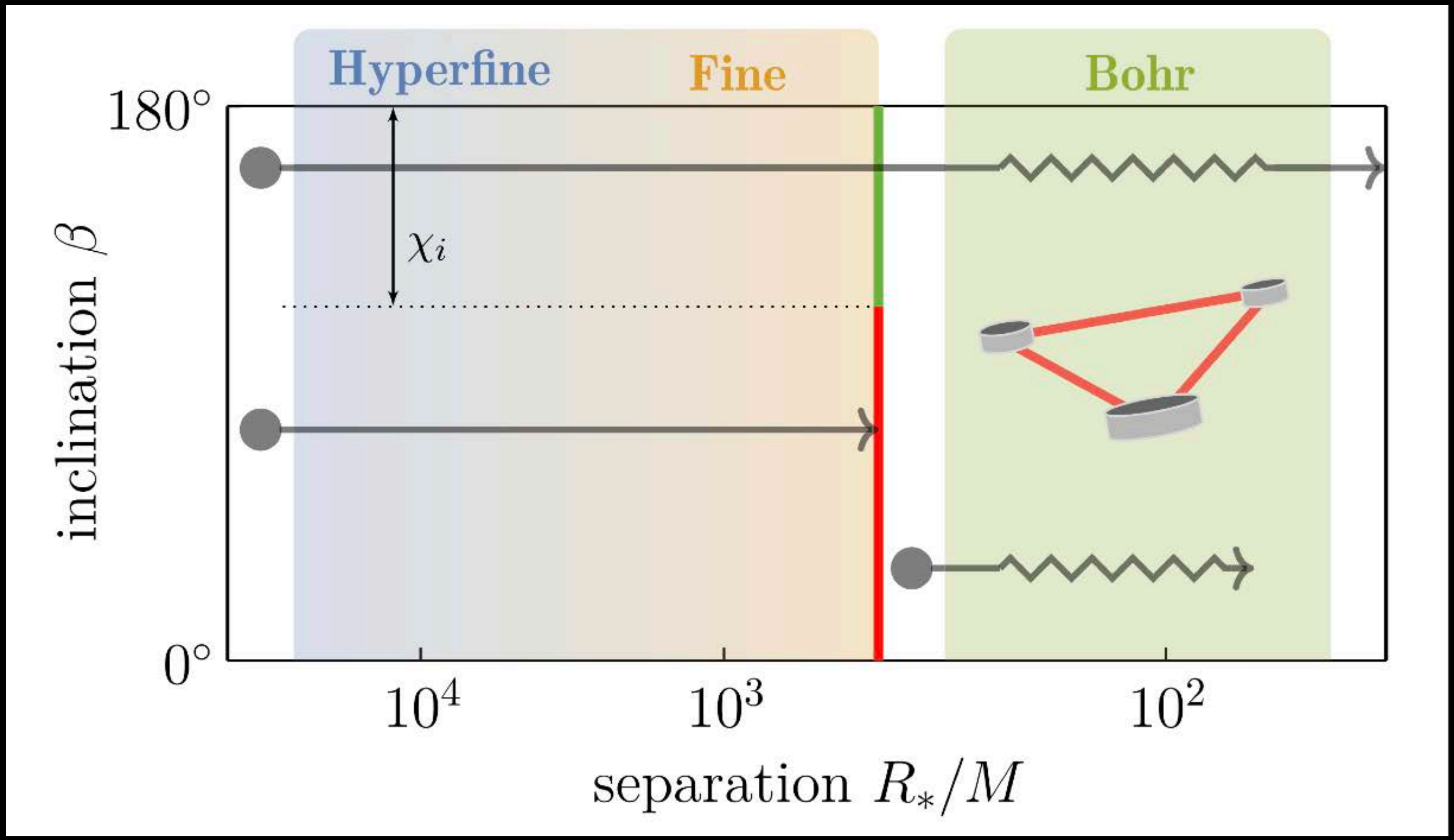


- 'Resonances' due to transitions between bound states $< a | V_*(t) | b >$
  Baumann, Chia, Porto, arXiv:1804.03208

- 'Ionization', i.e. transitions to continuum $< a | V_*(t) | klm >$
  Baumann, GB, Stout, Tomaselli Phys.Rev.Lett. 128 (2022) 22, 221102

- Role of accretion on companion, eccentricity, inclination
  Baumann, GB, Stout, Tomaselli 2112.14777, Tomaselli, Spieksma, GB 2305.15460, 2403.03147

Published yesterday:

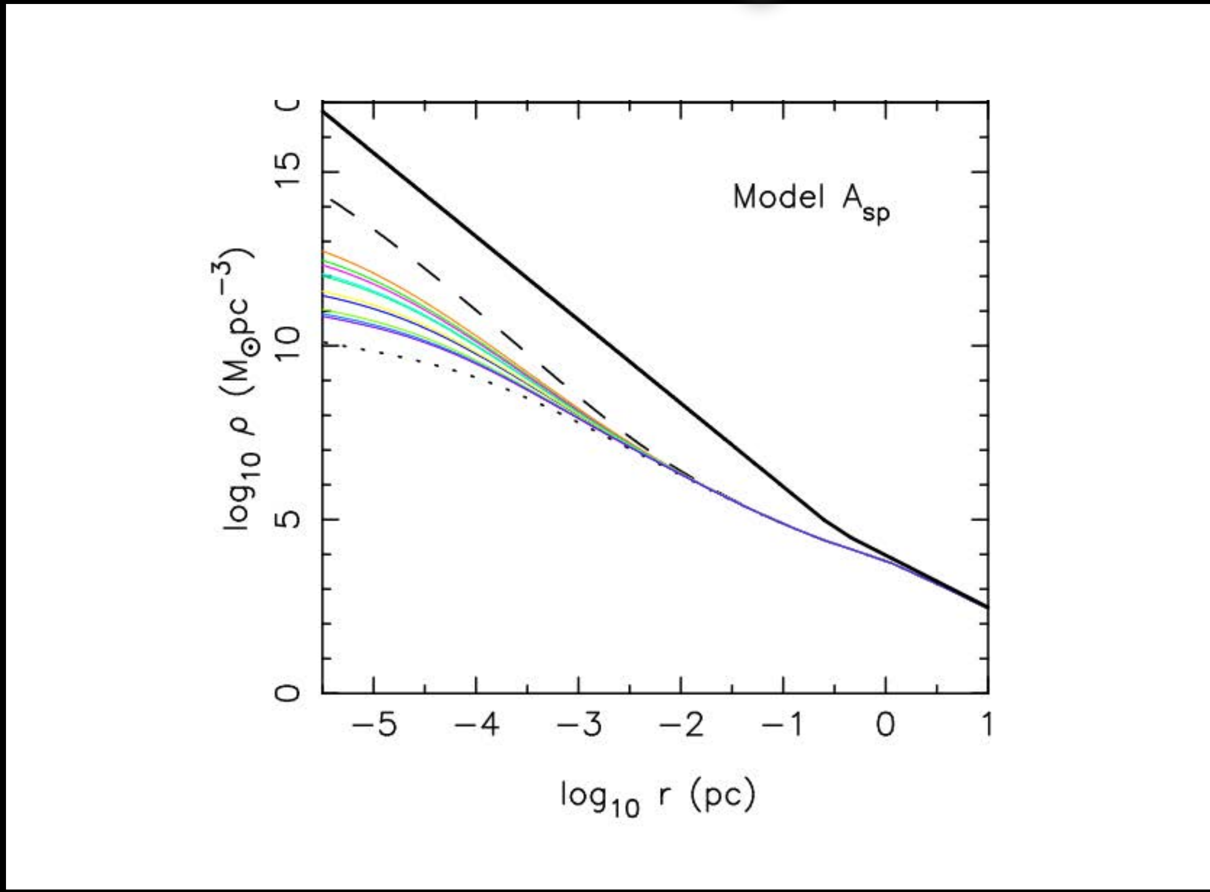


- Phys. Rev. Lett. 133, 121402
-

- When inclination angle falls inside angular interval χ_i around a counterrotating configuration, the cloud survives all the resonances, becoming observable late in the inspiral
- Otherwise, cloud is destroyed (red line), leaving a distinctive mark on the orbital parameters.
- Binaries that form at small radii are an exception: They may skip the destructive (hyper)fine resonances.

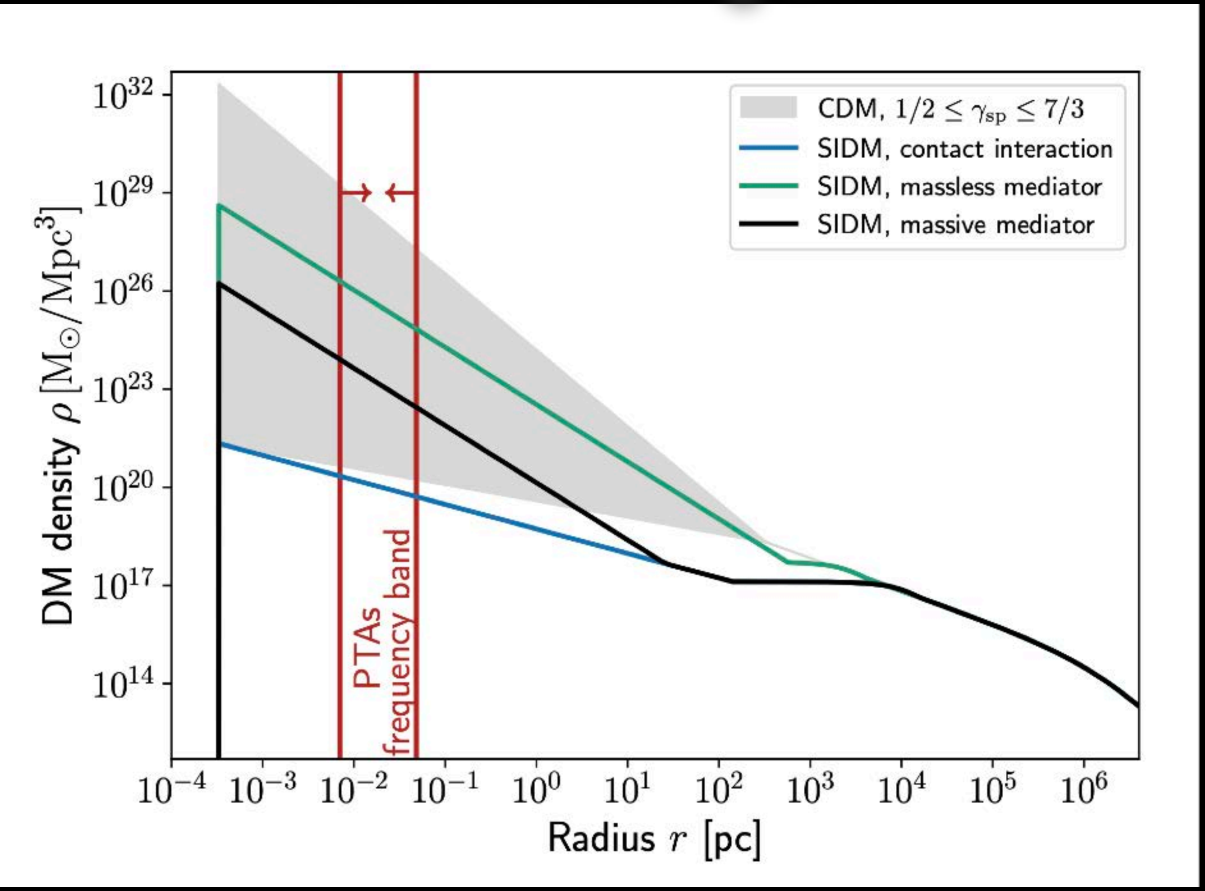
Density profiles depend on the DM properties

Self-annihilating DM



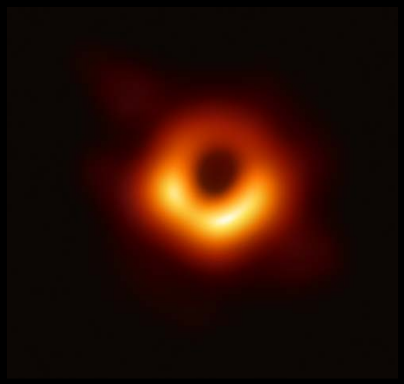
[GB & Merritt astro-ph/0504422, Shapiro & Shelton1606.01248]

Self-interacting DM

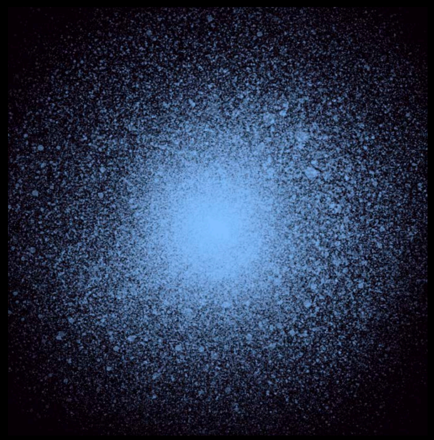


[Alonso-Alvarez+ 2401.14450]

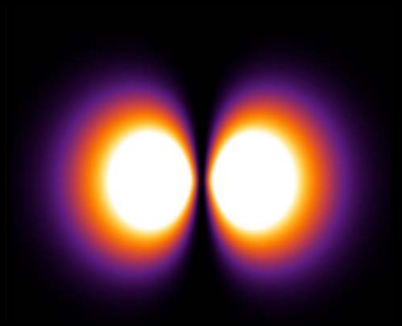
In case of detection, how well can we reconstruct parameters?



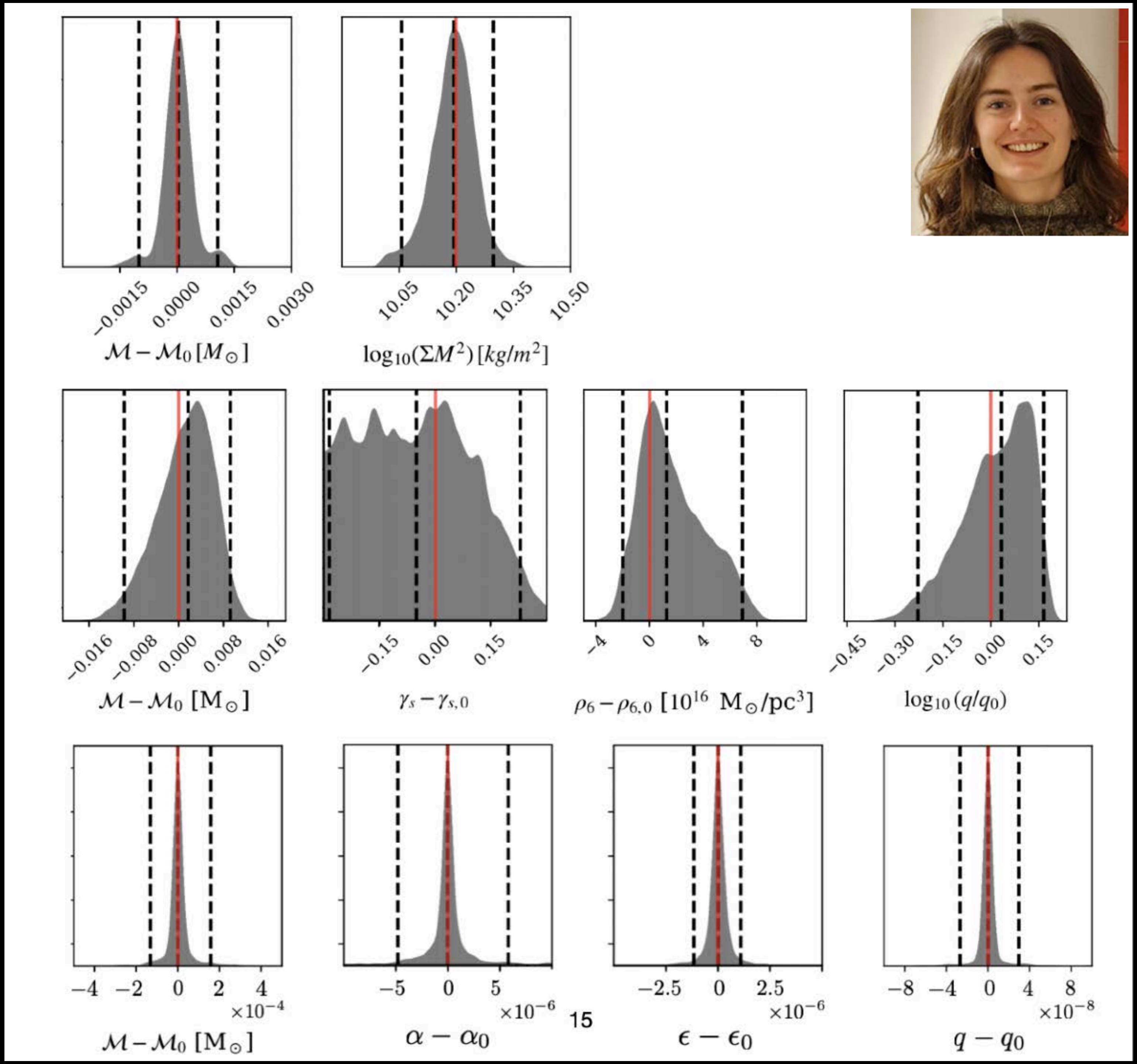
Accretion disc



Dark Matter Spike



Gravitational Atom



Cole, GB et al. Nature Astron. 7 (2023) 8, 943-950

New results/Work in progress

- Realistic spike formation scenarios, via formation and collapse of **Supermassive Stars** (2404.08731)

- **Refined modeling** of eccentricity, accretion, torques, etc
  (2402.13053, 2402.13762, 2403.03147)

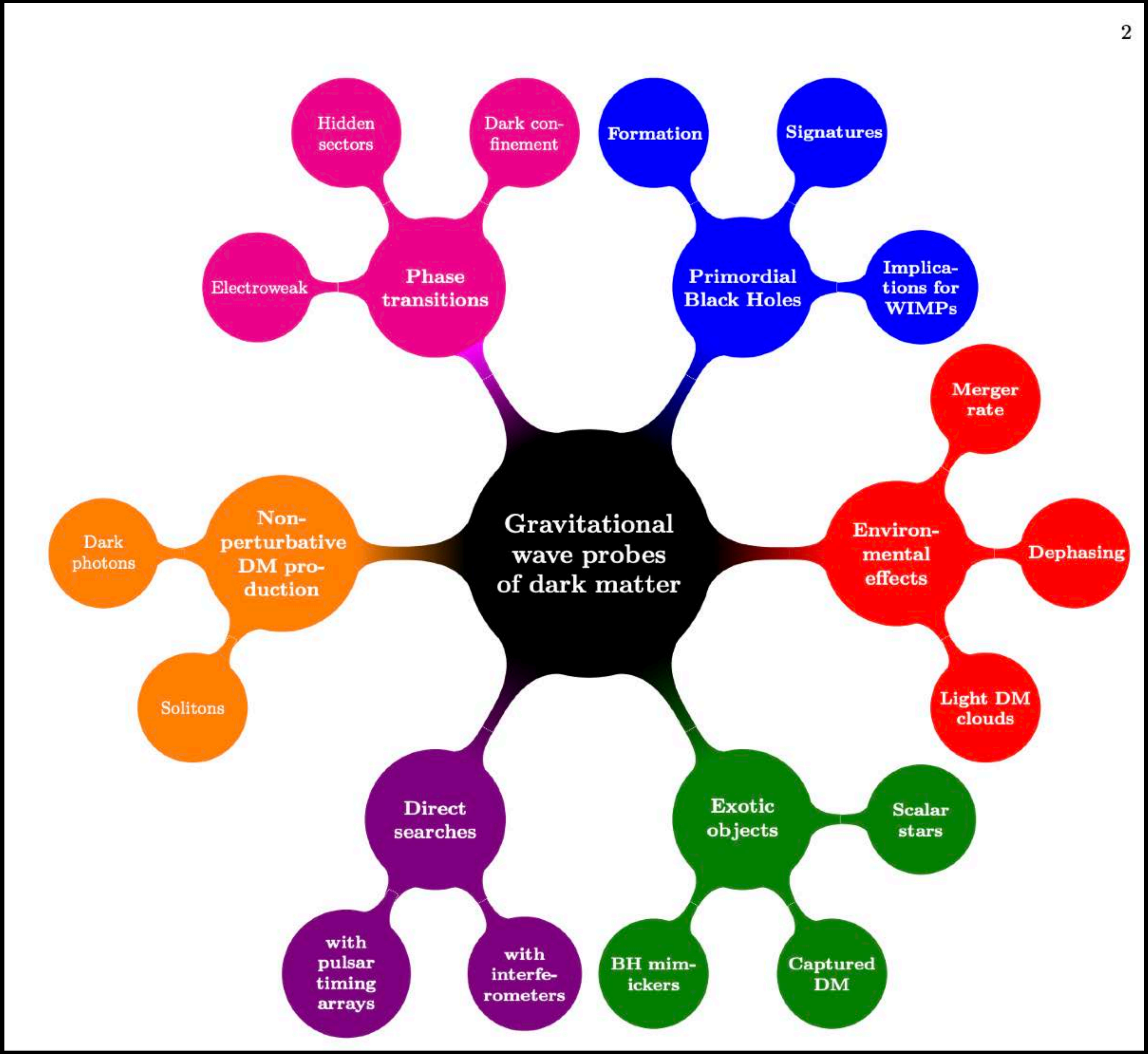
- **Relativistic** effects

- Fast statistical inference of environments w/ machine learning

- Imprint of DM particle properties on the waveform

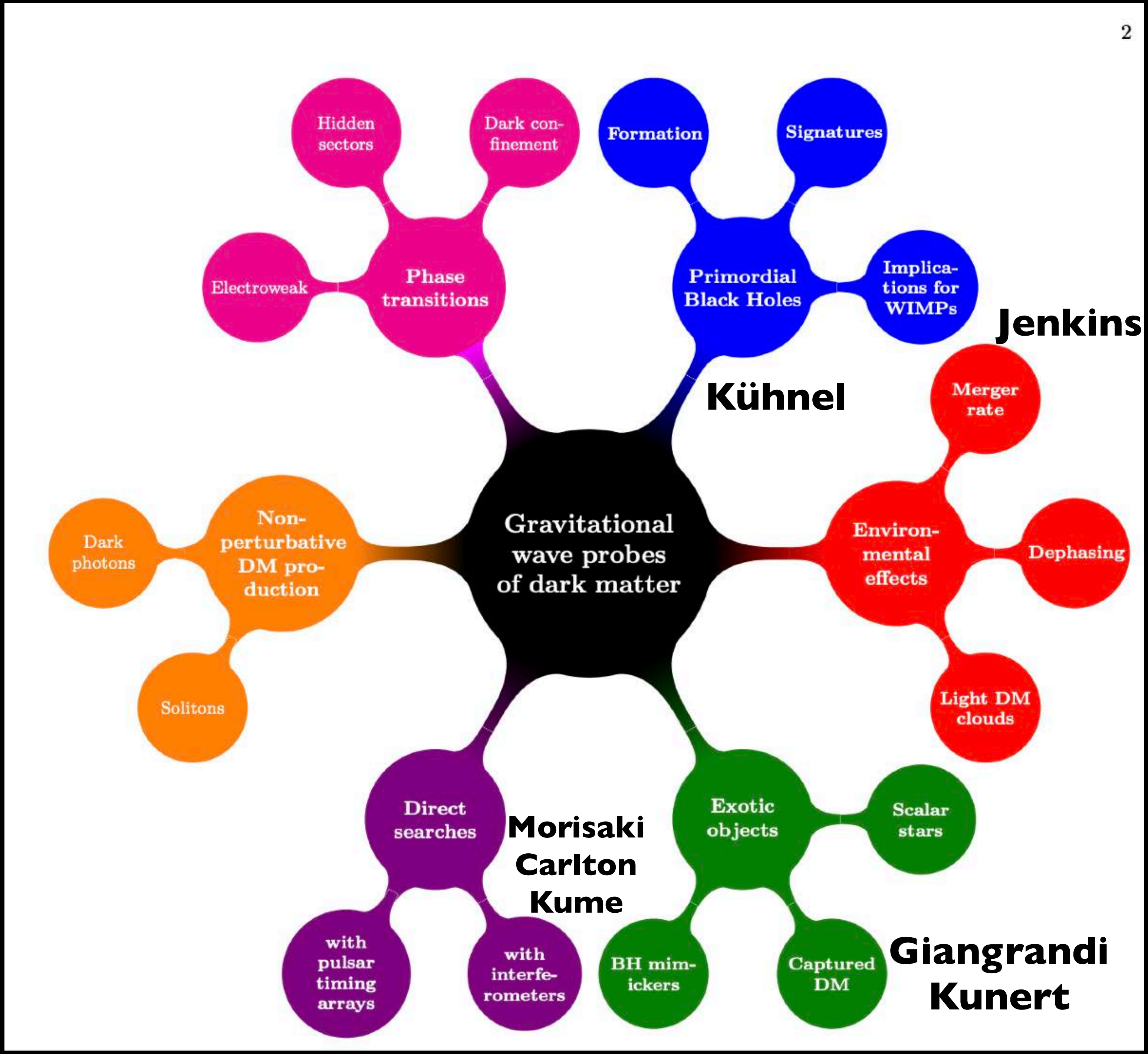
- Population studies, Merger rates, etc

Gravitational wave probes of DM



"Gravitational wave probes of dark matter: challenges and opportunities"
GB, Croon, et al. 1907.10610

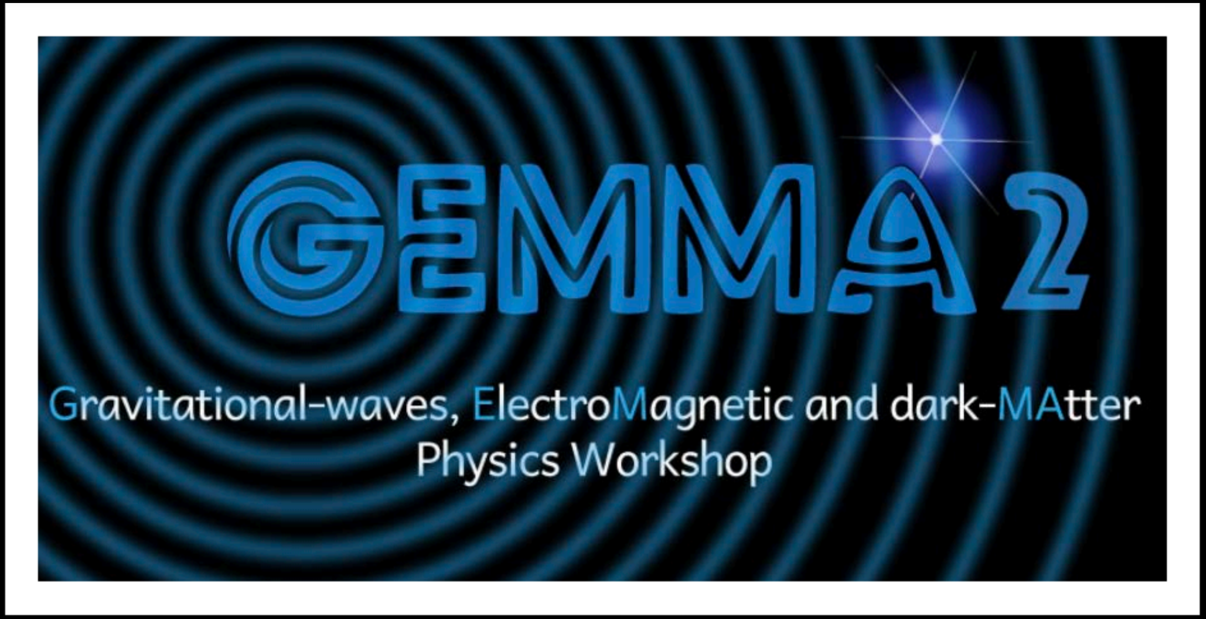
Gravitational wave probes of DM



"Gravitational wave probes of dark matter: challenges and opportunities"
GB, Croon, et al. 1907.10610

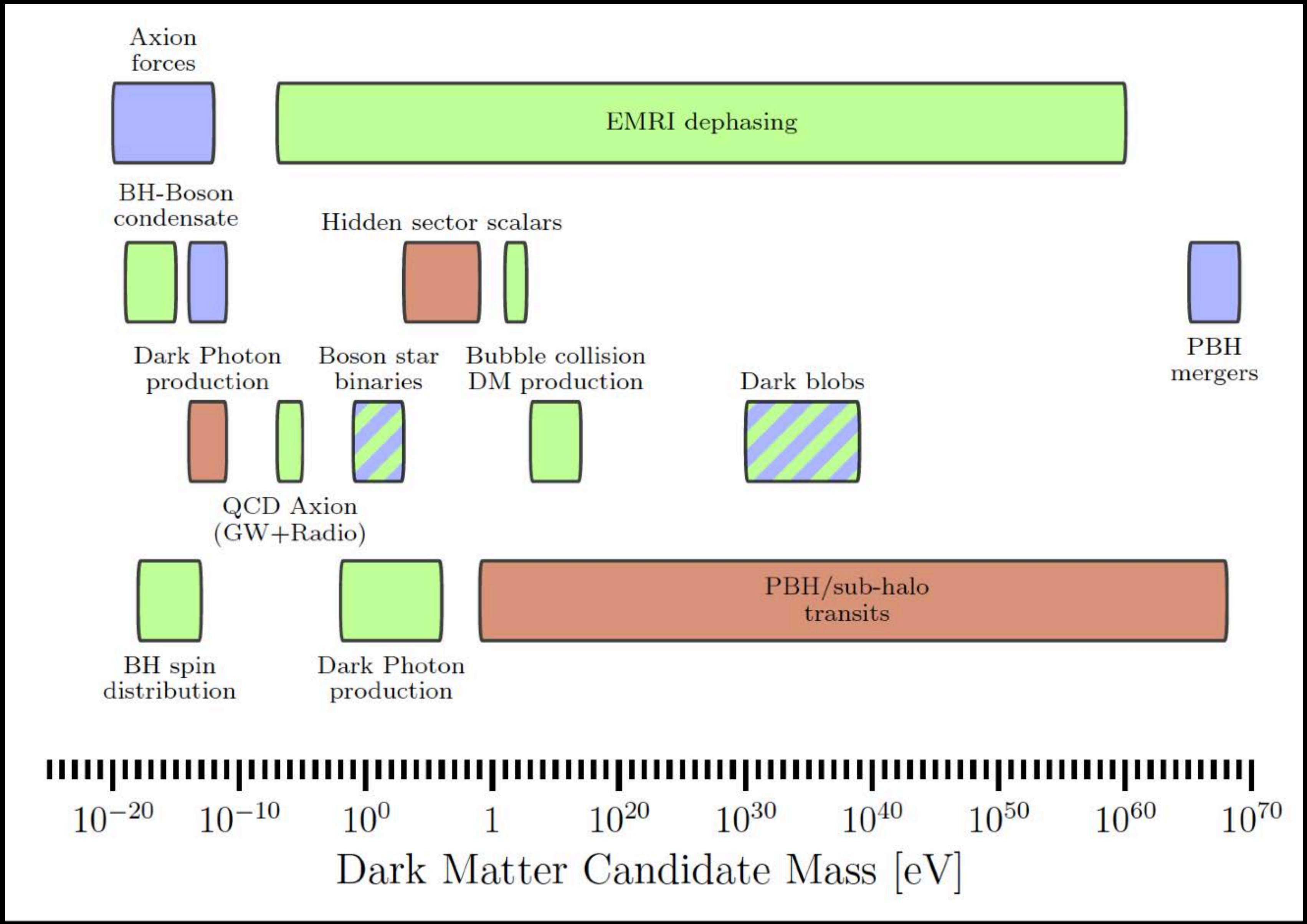
Conclusions

- Studying DM in strong gravity opens new opportunities to identify it
- DM can reach very high density around BHs
- We can probe these very high densities with (γ-rays and) GWs



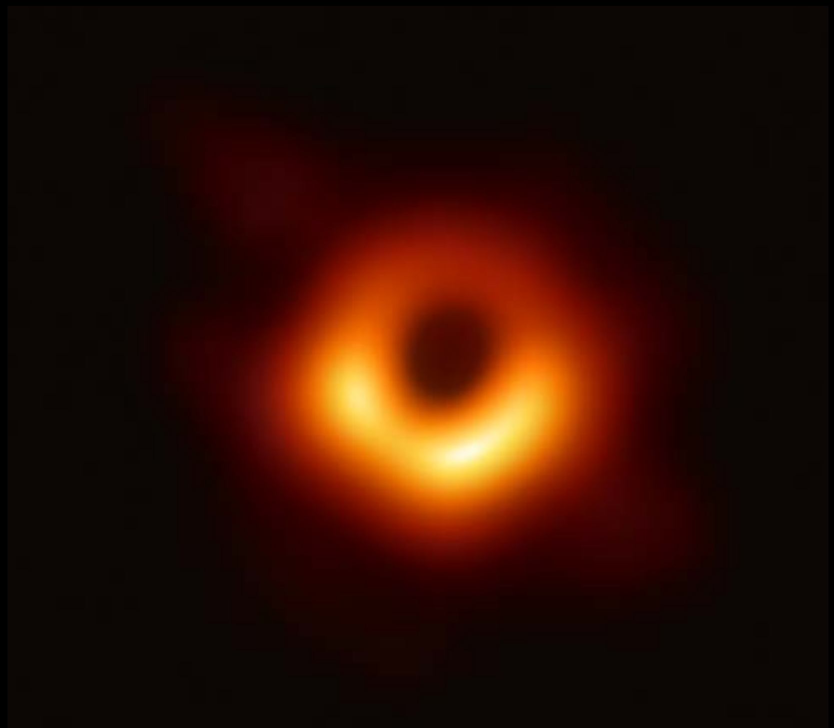
Supplementary material

Further GW-DM connections:

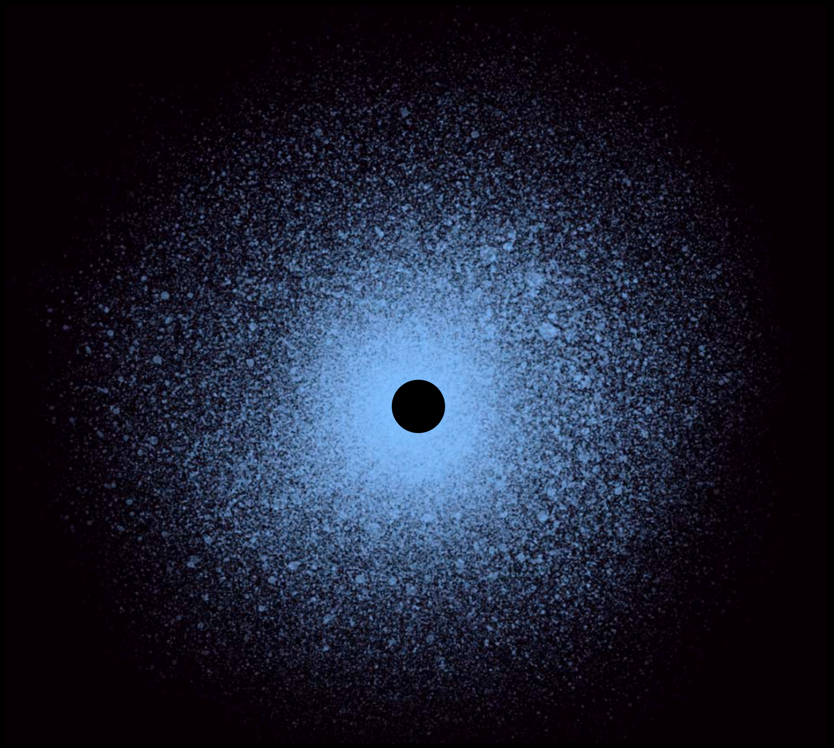


"Gravitational wave probes of dark matter: challenges and opportunities"
GB, Croon, et al. 1907.10610

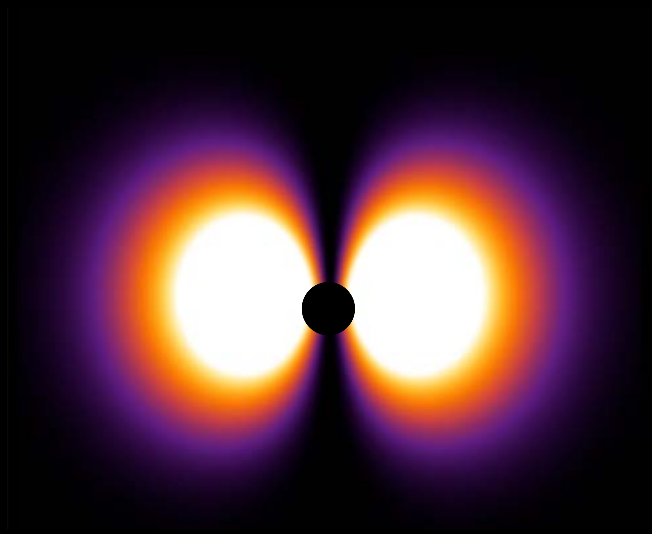
BH environments



Accretion discs

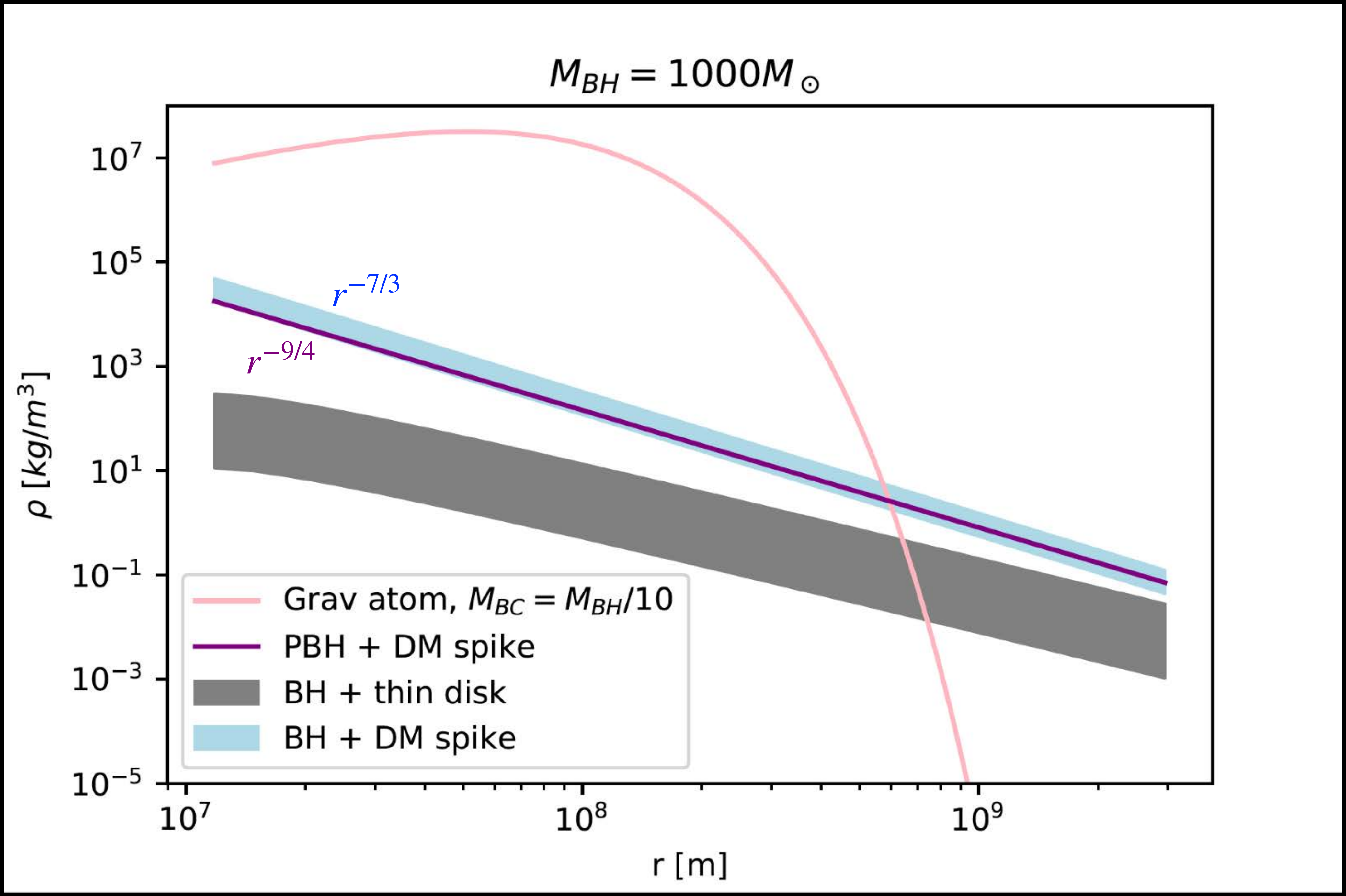


DM ‘spikes’



Gravitational atoms

Other environments



Pippa Cole, GB + 2302.03351