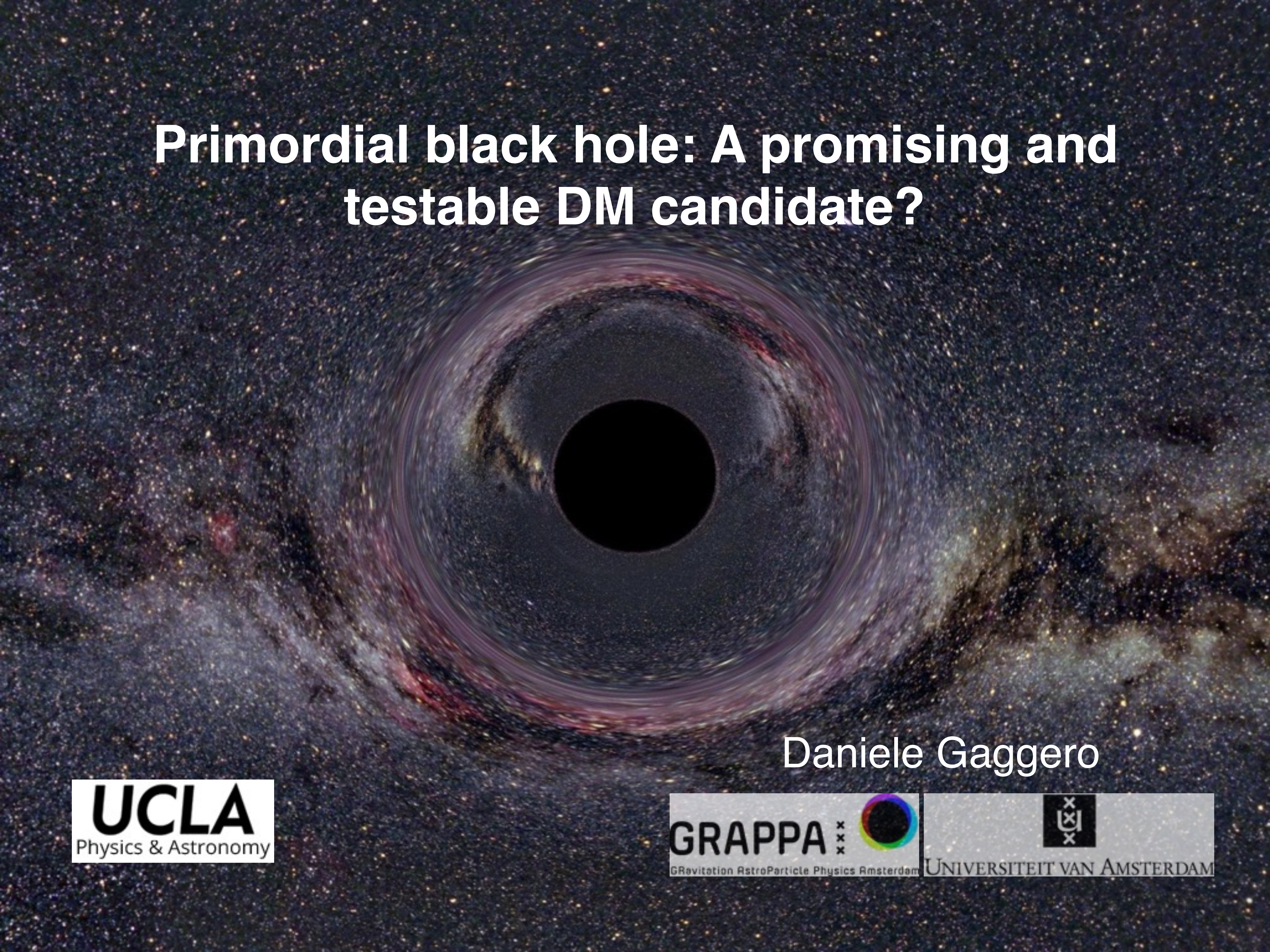
Primordial black hole: A promising and testable DM candidate?



Daniele Gaggero

UCLA Physics & Astronomy

GRAPPA GRavitation AstroParticle Physics Amsterdam

Universiteit van Amsterdam

DM candidates: ~90 orders of magnitude in mass

10^{-22} eV

Axion-like particles

1 GeV   1 TeV

10^{19} GeV (10^{-5} g)

10^{57} GeV (10^{33} g)

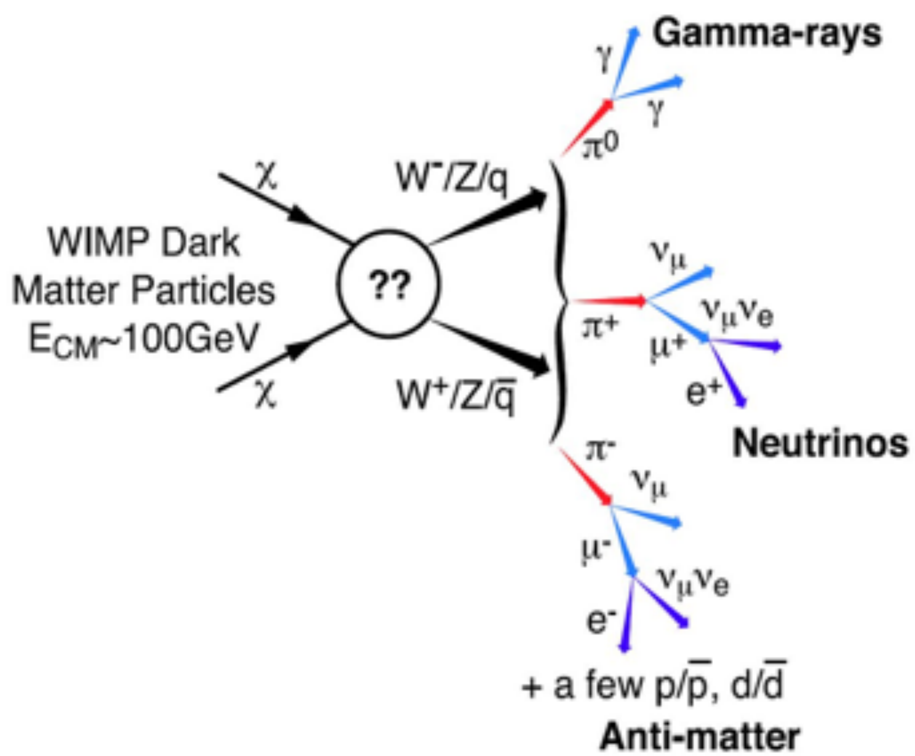
"Fuzzy" Dark Matter

λ_{dB} ~ 1 kpc ~ size of a dSph Galaxy

[Hui, Ostriker, Tremaine, Witten 2016]

Weakly interacting massive particles (WIMPS)

e.g. lightest neutralino state in MSSM



Primordial black holes (PBHs)

[Zeld'ovich and Novikov 1966, Hawking 1971]

many constraints from lensing, wide binaries, Galactic disk stability; became less popular after MACHO project *[Alcock 2001]*

future radio and X-ray observations can provide strong constraints on the presence of a population of heavy PBHs (e.g. GHz radio emission due to accretion of gas in the inner Galaxy)

Part 1: LIGO, PBHs and DM

Brief summary on primordial black holes as DM candidate

[see yesterday talk by A. Green]

PBHs can form in the early universe from large-amplitude small-scale density perturbations formed during inflation, and other mechanisms.

PBHs can span an extremely large mass range

- collapse at Planck time (10^{-43} s) -> Planck mass (10^{-5} g),
- collapse at ~1 s -> $10^5\ M_\odot$

if the mass is too low, PBHs have enough time to evaporate (Hawking-Bekenstein radiation)

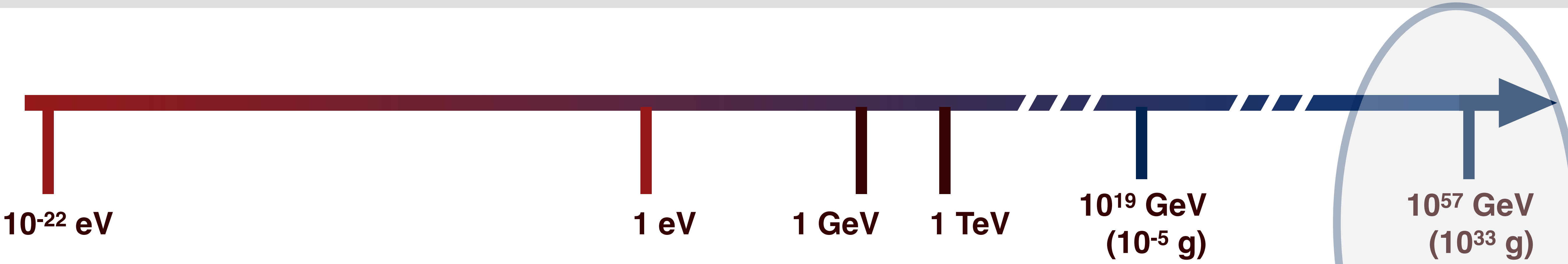
$$t_{\mathrm{evaporation}}[\mathrm{s}] = 10^{71}\left(\frac{M}{M_\odot}\right)^3$$

G. Chapline was among the first to suggest **PBHs as a DM candidate** [G. F. Chapline, Nature **253**, 251 (1975)]

Typical ranges for a PBH as DM candidate:

M ~ 10^{16} g ($10^{-17}\ M_\odot$) — 10^{39} g ($10^5\ M_\odot$)
size ~ 10^{-13} cm — 10^{10} cm
number in our Galaxy ~ 10^{29} — 10^6

LIGO, PBHs and DM



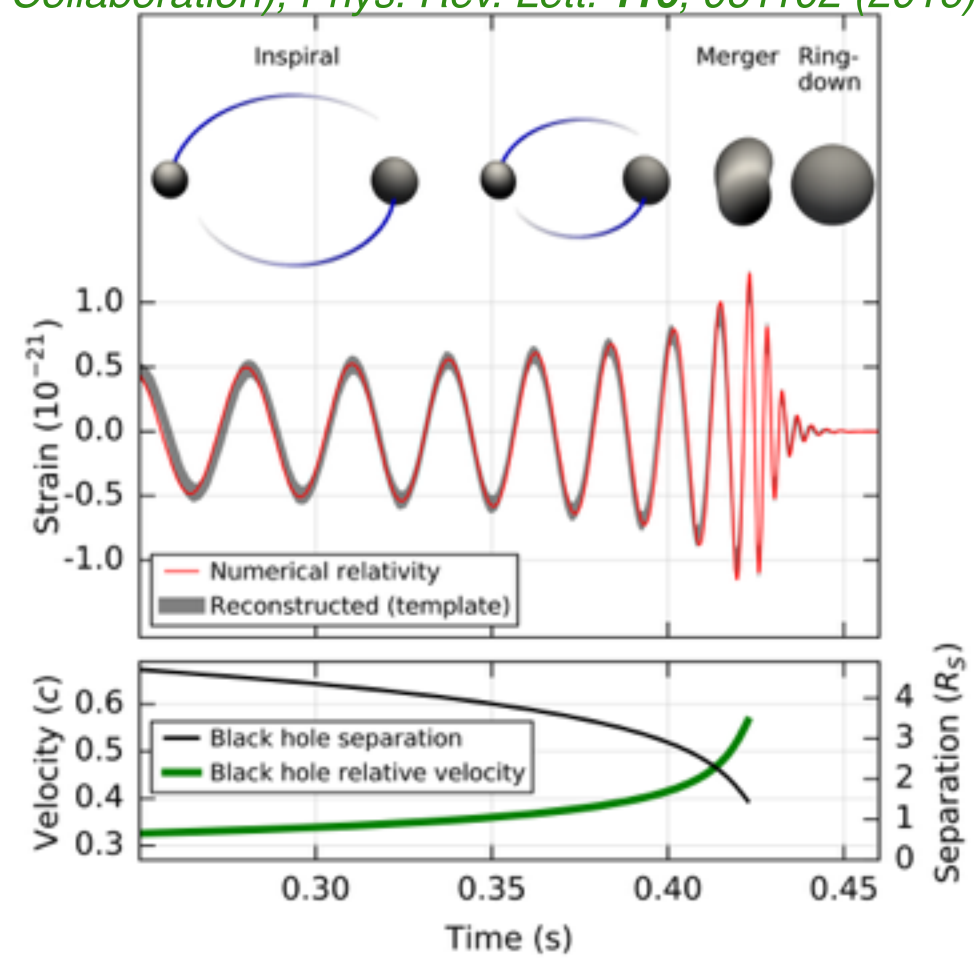
- Amazing detections in this mass window: The ***first direct detections of gravitational wave signals from black hole mergers!***

- The ***first direct detections of binary black hole systems***

- The ***first direct detections of stellar-mass black holes with M as large as 30 $M_\odot$***

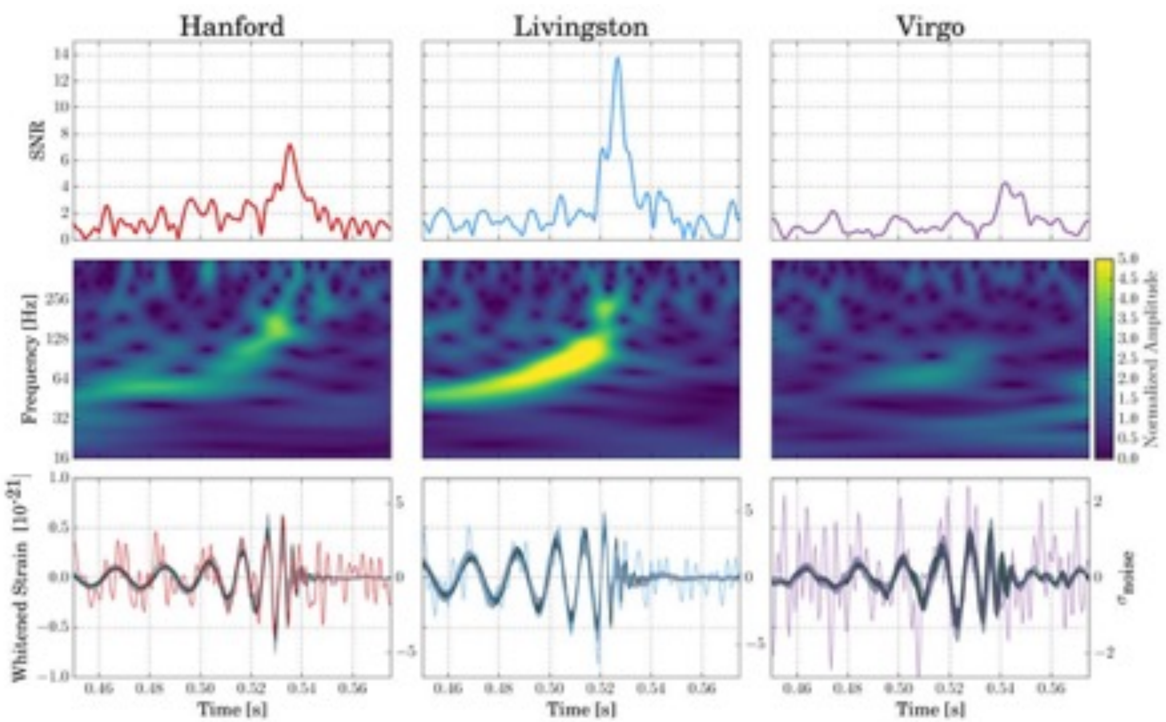
(stellar-mass black holes discovered so far are in X-ray binaries. BH masses ranging from ~3 to ~15 solar masses; e.g. GRS 1915+105, M = 14±4 Msun, *arXiv:0111540*)

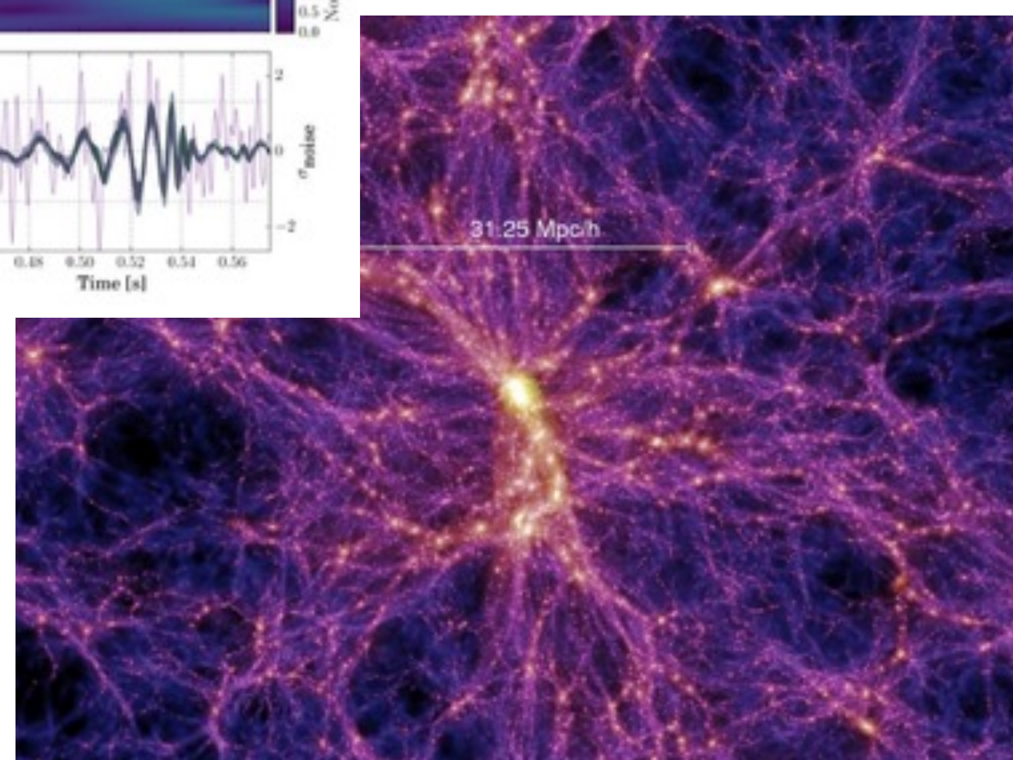
Abbott et al. (LIGO Collaboration, Virgo Collaboration), Phys. Rev. Lett. ***116****, 061102 (2016)*

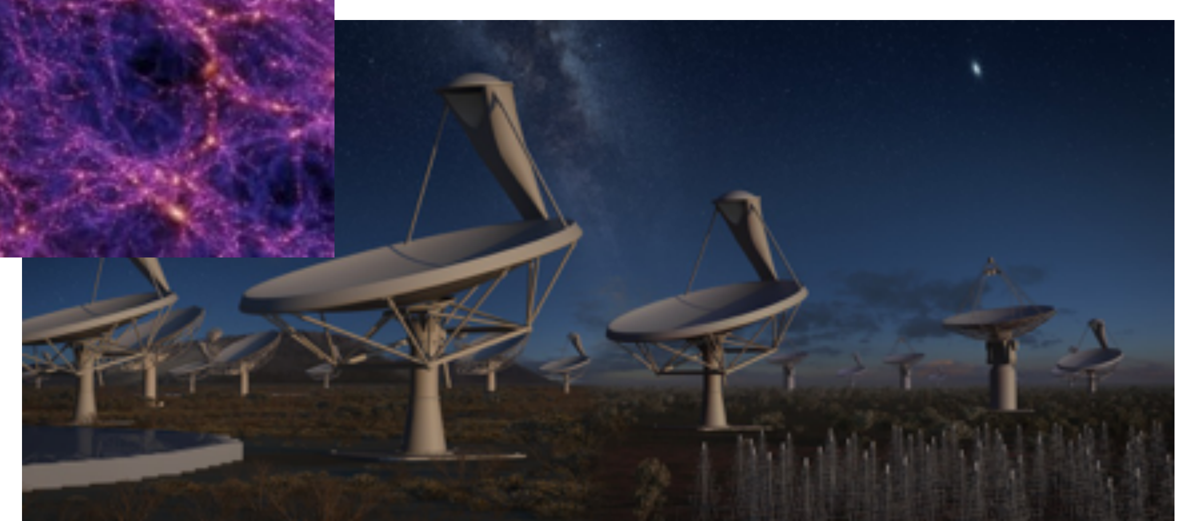


LIGO, VIRGO, PBHs and DM

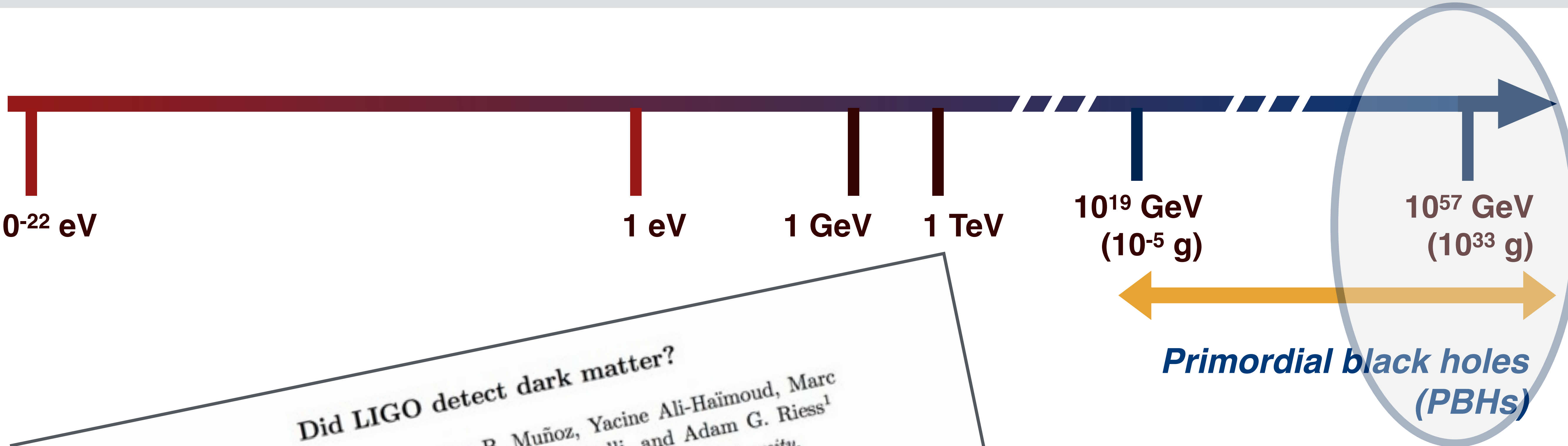
How can we exploit the connections between GW physics, dark matter, and radio astronomy?

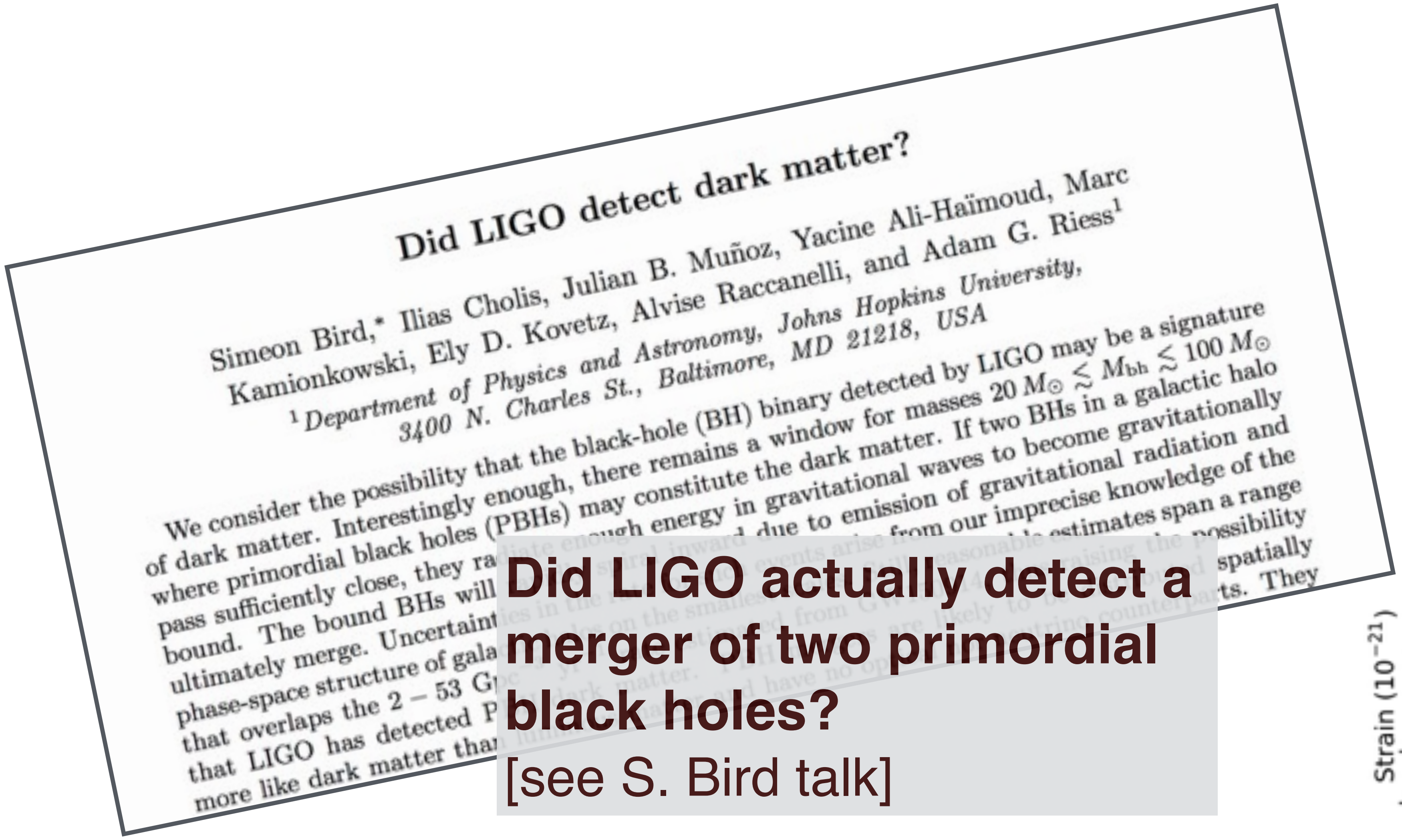






LIGO, PBHs and DM





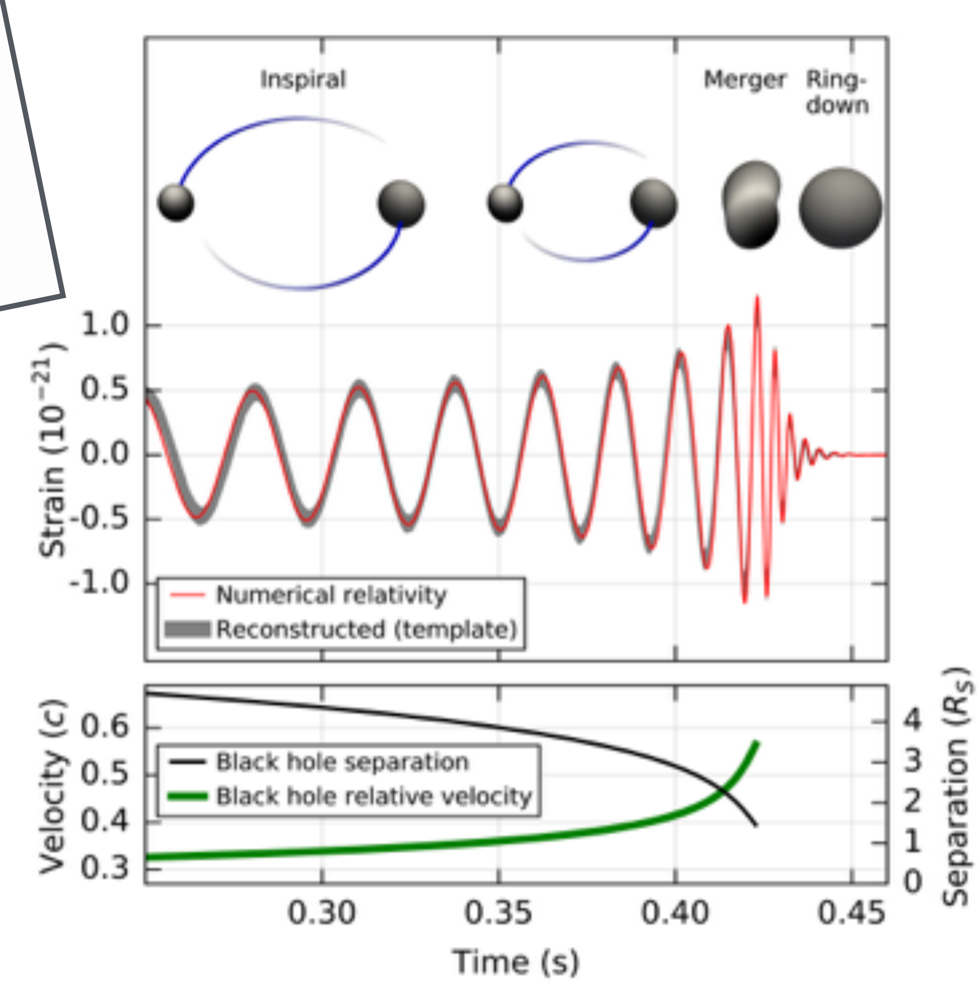
Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo

Did LIGO actually detect a merger of two primordial black holes?
[see S. Bird talk]



*Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, Adam G. Riess, Phys. Rev. Lett. **116**, 201301 (2016)*

*Sebastien Clesse, Juan García-Bellido, Physics of the Dark Universe **10** (2016) 002*

LIGO, PBHs and DM

An argument based on rates: the predicted merger rate is (roughly) compatible with the one inferred by LIGO and VIRGO

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, Adam G. Riess, Phys. Rev. Lett. ***116****, 201301 (2016)*

$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\,{\rm pc}^2$$

$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2}\left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}}\right)^2 \langle \sigma v_{\rm pbh}\rangle\, dr$$

$$\mathcal{V} = \int (dn/dM)(M)\,\mathcal{R}(M)\,dM.$$

$$\mathcal{V} = 2\,f(M_c/400\,M_\odot)^{-11/21}\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$$

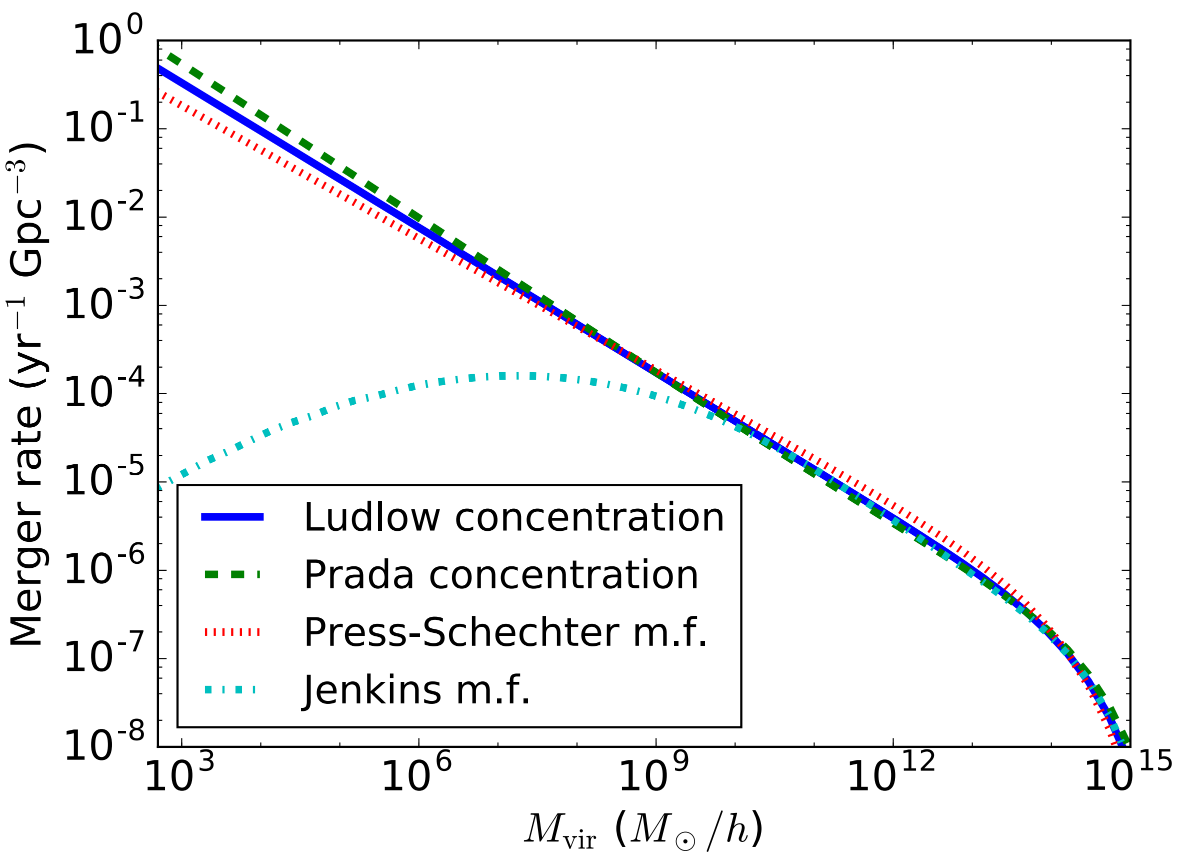
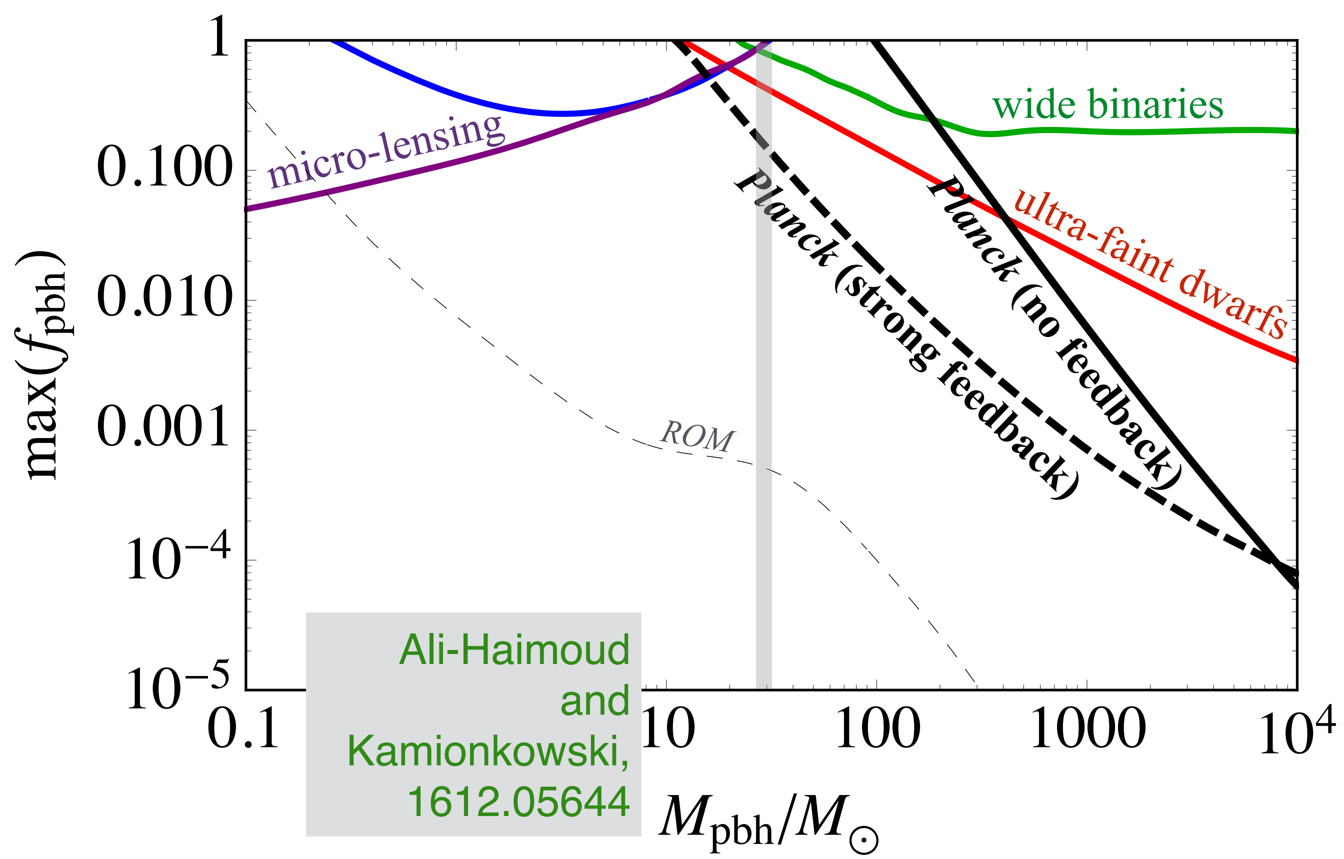


FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

is DM made of PBHs? existing constraints

Existing constraints on DM as PBHs



- **Dynamical constraints**

green line: disruption of wide binaries [*1406.5169*]
red line: ultra-faint dwarf [*Brandt 1605.03665*], constraint based on a recently discovered star cluster near the center of the ultra-faint dwarf galaxy Eridanus II. MACHO dark matter would lead it to higher velocity dispersions until it dissolves into its host galaxy

- **Lensing constraints**

blue line: MACHO project [*Alcock et al. 2000*]: search for micro-lensing events towards the Large Magellanic Cloud. 13-17 short-duration events reported no long-duration (> 150 days) events -> constraints up to 30 Msun

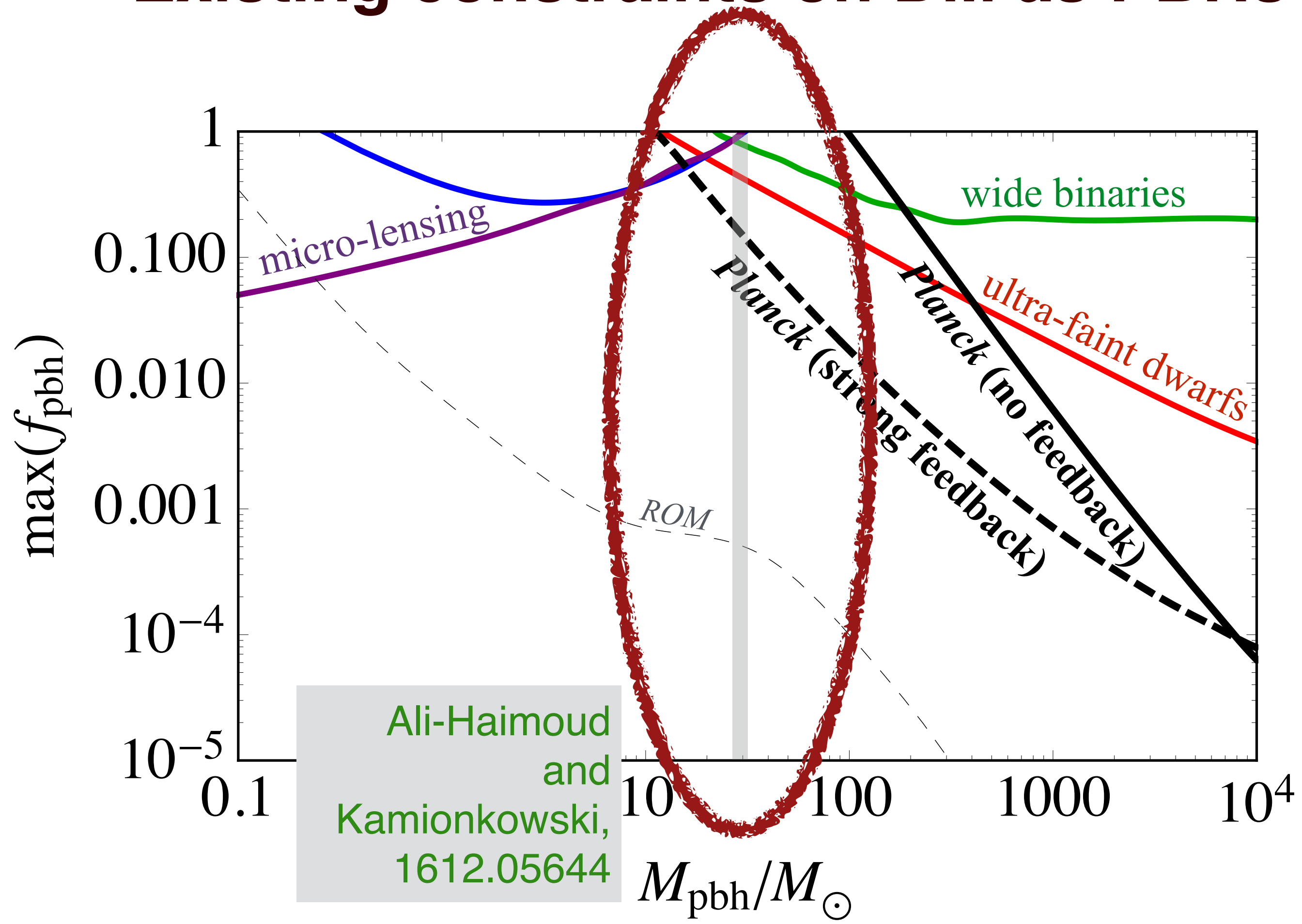
purple line: EROS project [*Tisserand et al. 2007*]; similar strategy, based on a 7-year monitoring of ~10^6 bright stars in the LMC and SMC

- **Early universe constraints:**

PBHs, if present in the early Universe, would accrete, radiate, heat up and partially reionize the Universe
(strong-feedback case assumes that the local gas is entirely ionized due to the PBH radiation)

is DM made of PBHs? existing constraints

Existing constraints on DM as PBHs



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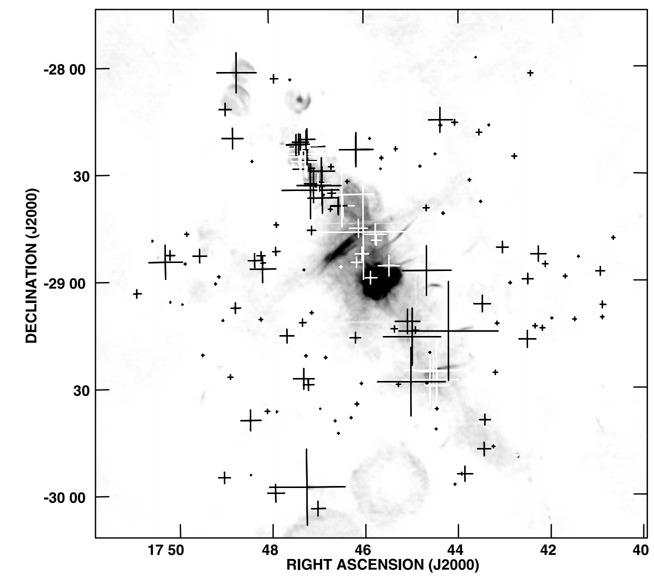
Our idea: why not looking at radio and X-ray data?

based on: *D. Gaggero, G. Bertone, F. Calore, R. Connors, M. Lovell, S. Markoff, E. Storm, "Searching for Primordial Black Holes in the radio and X-ray sky", arXiv:1612.00457, PRL 2017*

- If ~$30M_\odot$ PBHs are the DM —> **~10^{11} objects of this kind in the Milky Way, and ~10^8 in the Galactic bulge**.
  (*compare to ~10^8 astrophysical stellar-mass black holes in our Galaxy, Fender et al. arXiv:1301.1341*)

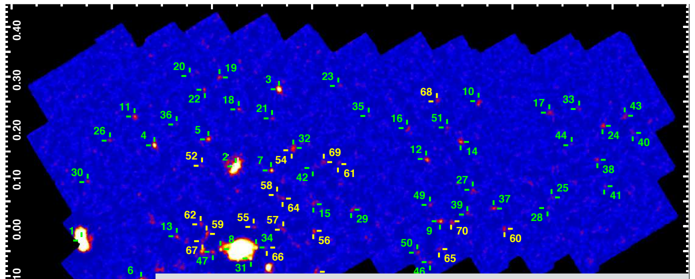


1.4 GHz, VLA, *Lazio & Cordes 2008*

- Given the large amount of gas in the inner Galaxy, **how easy is it to hide such a large population of black holes?**

- Given conservative estimates of the accretion rate and radiative efficiency, **is this population of PBHs compatible with current radio (VLA) and X-ray (NuStar, Chandra) observations?**

- **Will future radio facilities such as SKA have the capability to detect a population of PBHs** in our Galaxy if they are all the DM, or maybe a subdominant population of them?



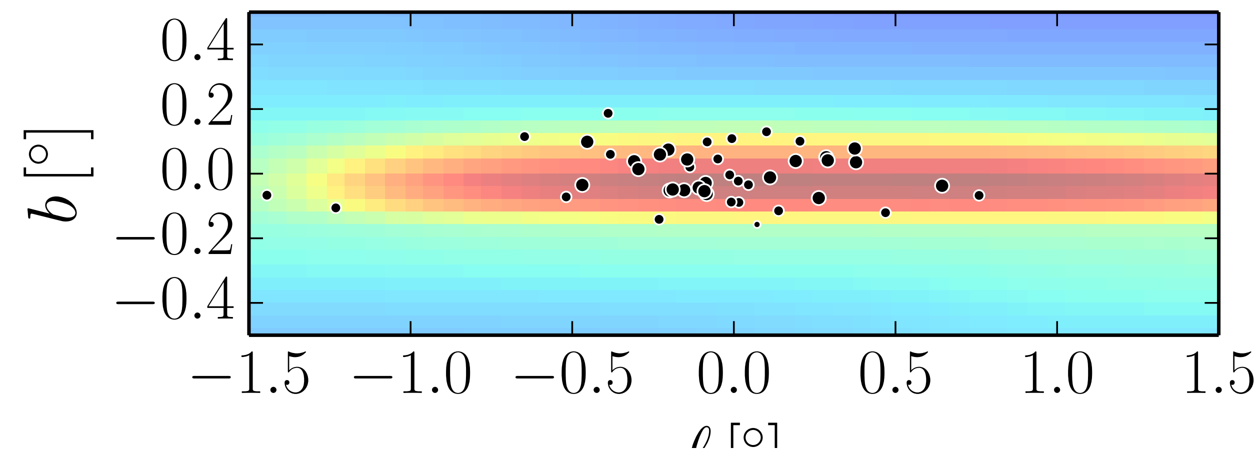
10-40 keV, NuStar catalog, *Hong et al. 2016*

Astronomical constraints: our simulation

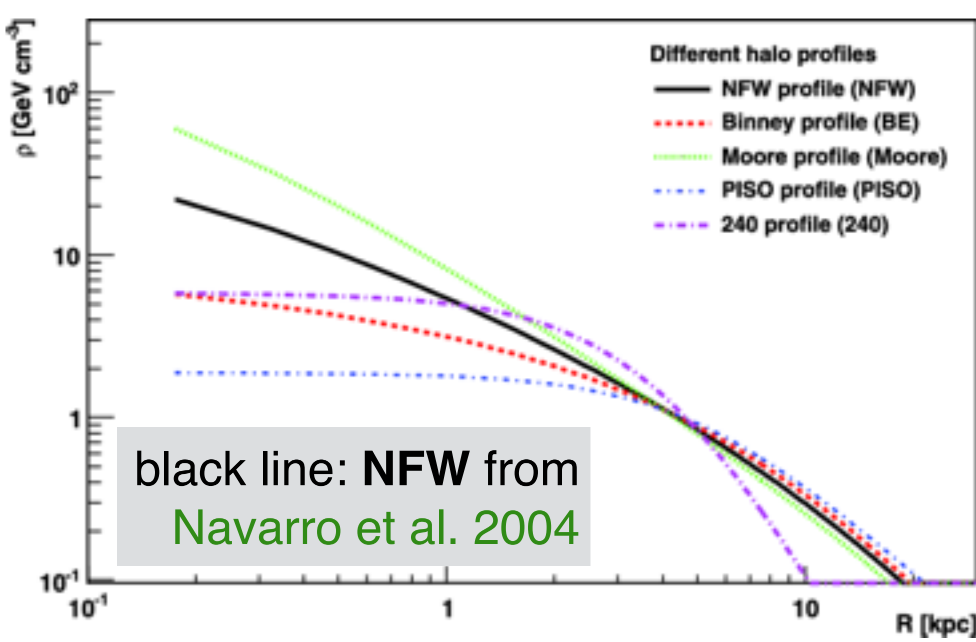
— We set up a MC simulation

— **We populate the Galaxy with PBHs**, and compute the predicted X-ray and radio luminosity

— **We produce simulated maps of predicted bright X-ray and radio sources**



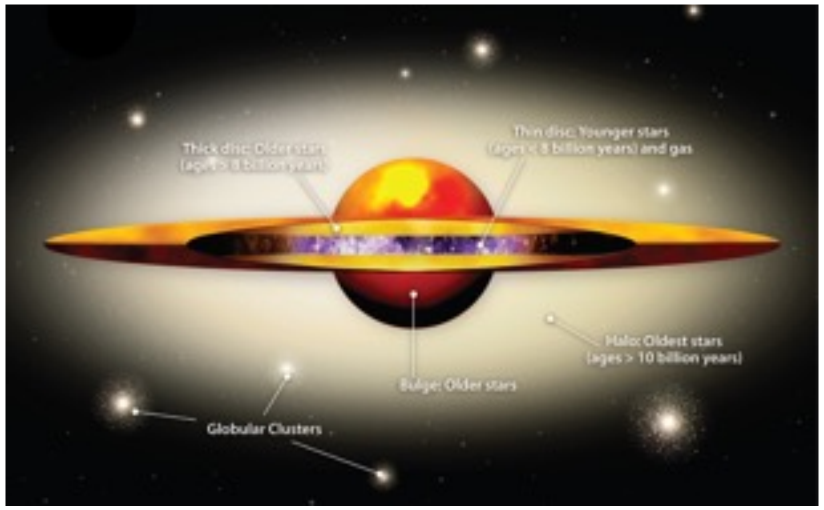
Spatial distribution of PBHs: We consider as a benchmark the NFW distribution.
We also consider other variations, based on numerical simulations with baryons (*see F. Calore et al., arXiv: 1509.02164*)



black line: **NFW** from Navarro et al. 2004

Velocity distribution: we consider, for each radius R, a Maxwell-Boltzmann distribution centered on v = $\sqrt{(G\,M(<R)/R)}$.

We use a spherical average of a mass model of the Milky Way M(R) from *McMillian 1608.00971 (2016)*, including DM halo and baryonic structures (bulge, thin and thick stellar disk, gas distribution).



Astronomical constraints: physics of BH accretion

- A crucial ingredient is the physics of gas accretion on BHs

—> what is a *conservative estimate* of the accretion rate?

—> what is a *conservative estimate* of the radio and X-ray emission?

1) Accretion rate: a small fraction of the Bondi-Hoyle rate:

$$\dot{M} = 4\pi\lambda(GM_{BH})^2\rho\left(v_{BH}^2 + c_s^2\right)^{-3/2}$$

- ***λ ~ 0.02*** **(conservative value)**

isolated neutron star population estimates and studies of active galactic nuclei accretion

R. Perna, et al., ApJ 598, 545 (2003), astro-ph/0308081
S. Pellegrini, ApJ 624, 155 (2005), astro-ph/050203

2) We assume radiative inefficiency

$$L_B = \eta\dot{M}c^2 \qquad \eta = 0.1\dot{M}/\dot{M}_{\rm crit} \text{ for } \dot{M} < \dot{M}_{\rm crit}$$

- Physical picture: *advection-dominated accretion* in which the gas cooling timescales greatly exceed the dynamical timescales

Narayan and Yi 1994, *"Advection-Dominated Accretion: A Self-Similar Solution"*
Blanford and Begelman 1998: "On the Fate of Gas Accreting at a Low Rate onto a Black Hole"

Astronomical constraints: comparison with data

X-rays:

- 30% of the bolometric luminosity in the 2-10 keV band [*Fender 2013*]

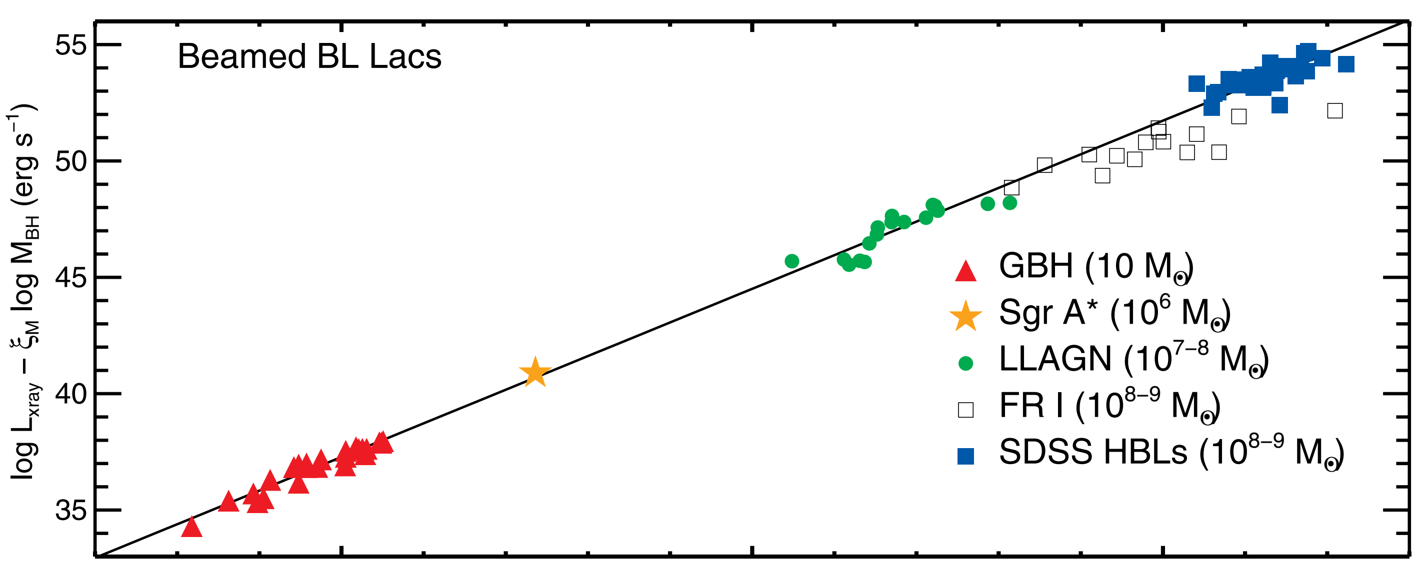
- We extrapolate to the **10-40 keV** band assuming a hard power-law (index 1.6)
- We compare to the **NuStar catalog** [*Hong et al. 2016*] data in the 10-40 keV band *(threshold: 8 * 10 ^{32} erg/s; ROI: -0.9° < l < 0.3°; -0.1° < b < 0.4°)* and to the **Chandra** catalog in the 0.5-8 keV band

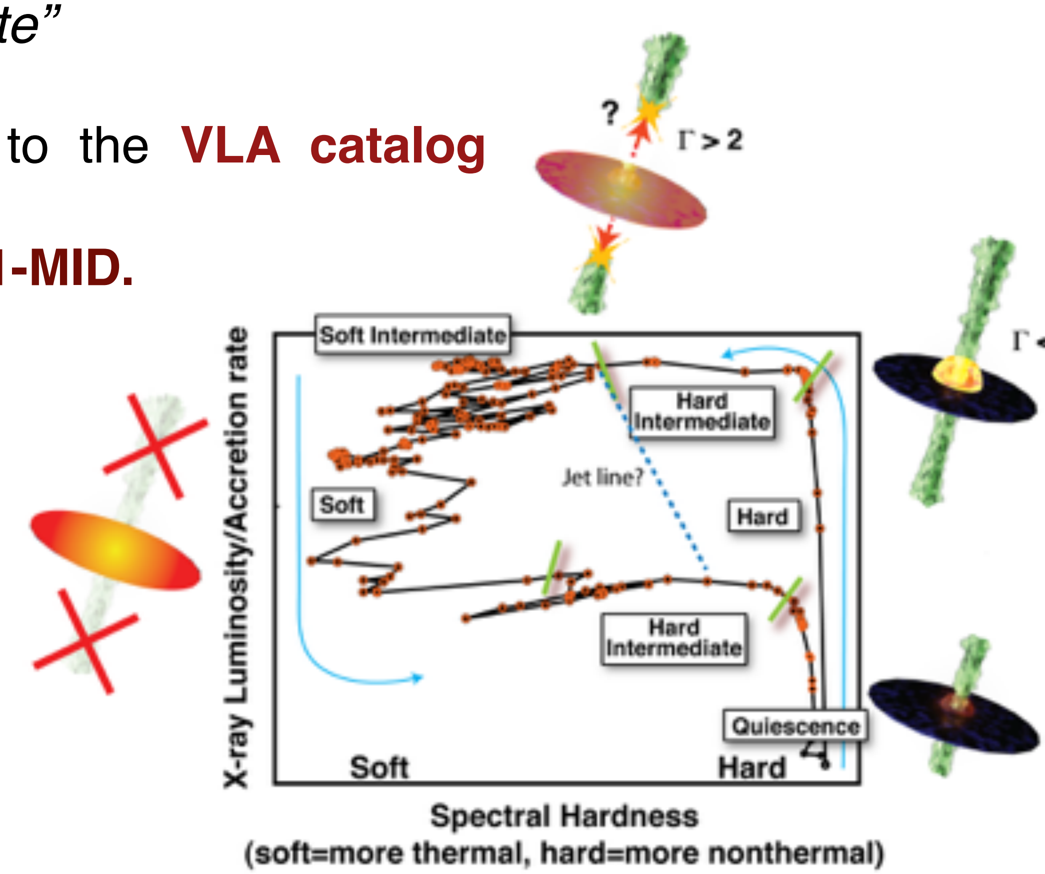
Radio:

- We use *fundamental plane relation* between soft X-ray and radio luminosity *[Plotkin et al. 2013]*

- *We are assuming that the BH launches a jet, and is in the "hard state"*

- We convert X-ray fluxes into radio fluxes (**1 GHz**) and compare to the **VLA catalog** (threshold ~1 mJy; ROI: -0.5° < l < 0.5°; |b| < 0.4°)
- **We also compute the number of point sources detectable by SKA1-MID.**





Astronomical constraints: our results

X-rays:

- Prediction: more than **3000 bright X-ray sources**
- *Observed sources in the ROI by Chandra: **~400***

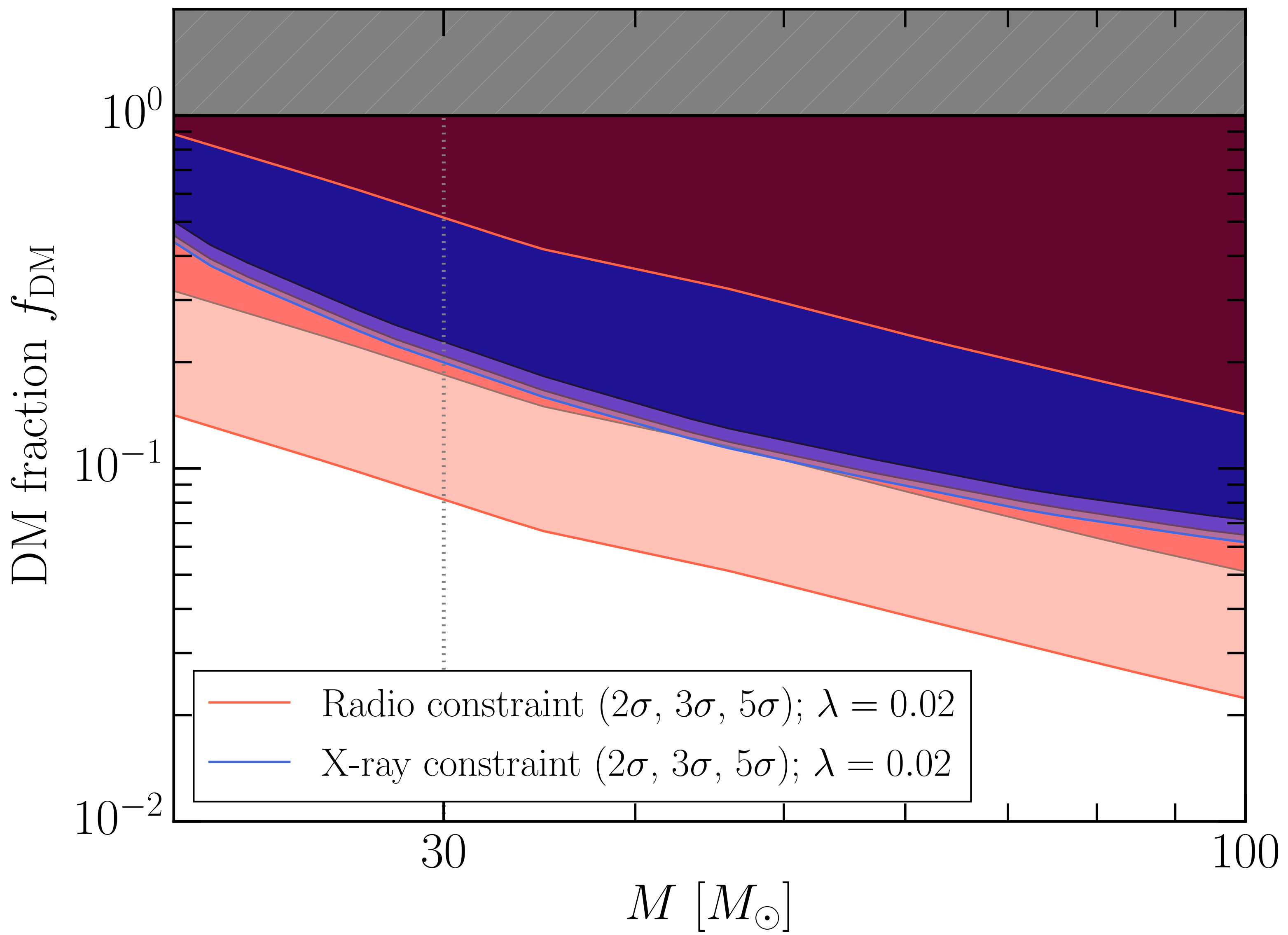
(40% are cataclysmic variables)

Radio:

- Prediction **40±6 bright radio sources** in the ROI
- Observed radio sources in the ROI: 170
- N*umber of candidate black holes in the ROI: **0***

assuming BHs obey the Fundamental Plane relation

(i.e. no radio source in the ROI have a X-ray counterpart compatible with the FP relation they cannot be BHs accreting in the hard state)



Our results compared to other constraints

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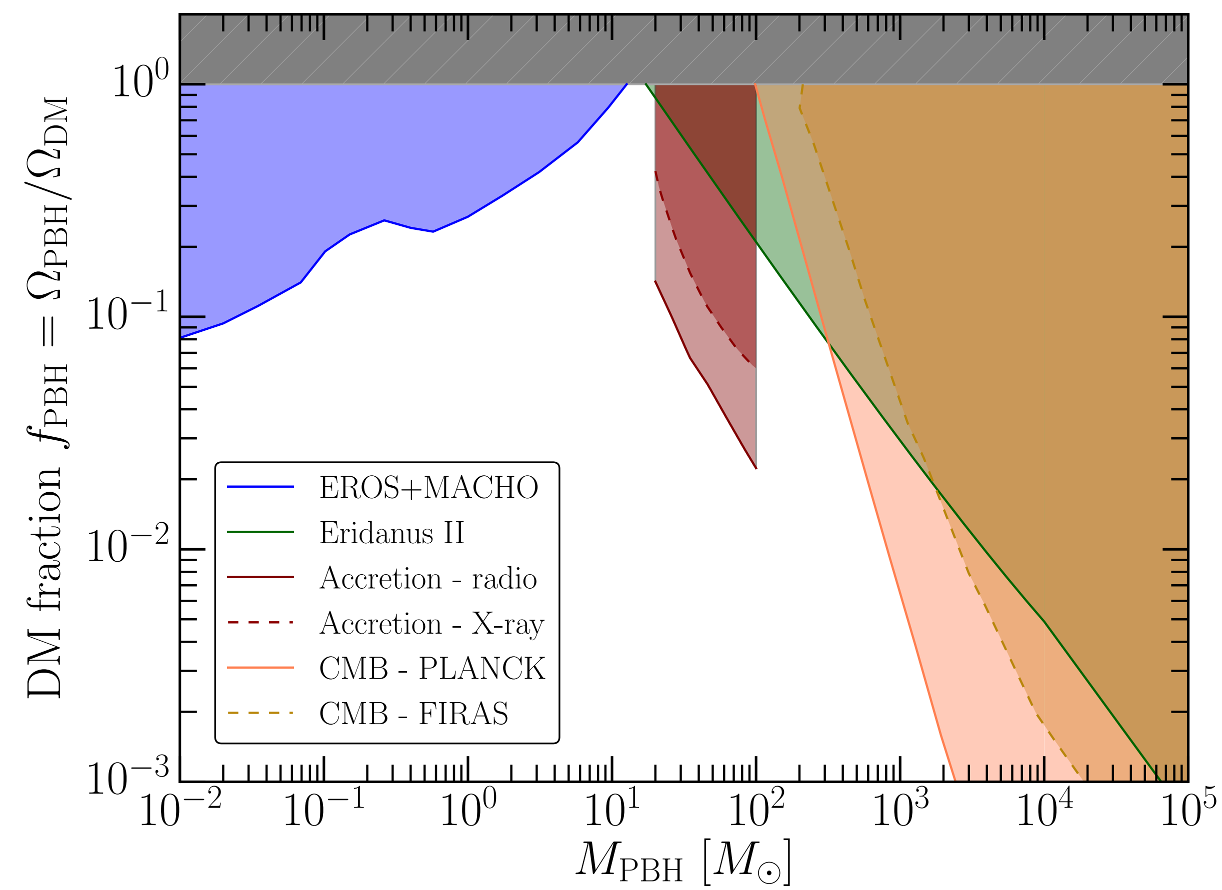
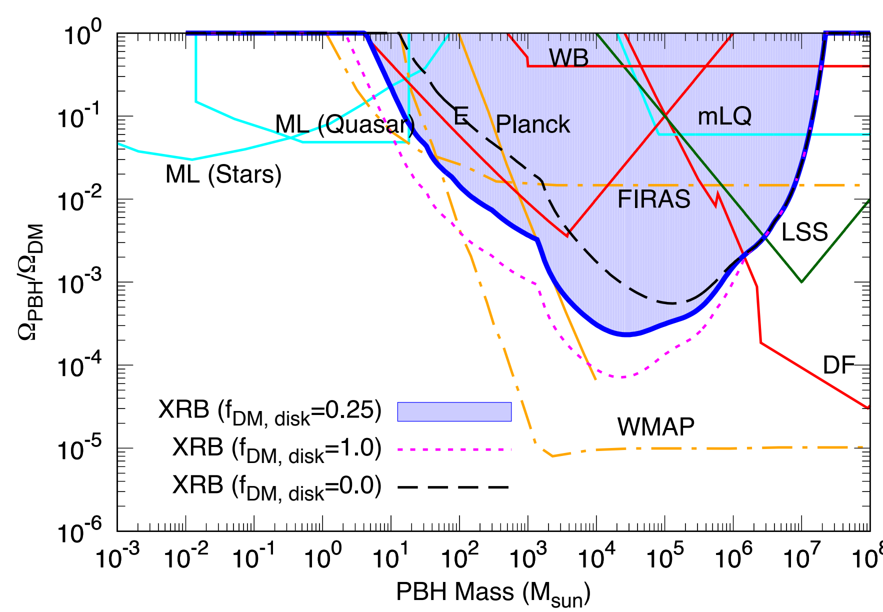


Inoue&Kusenko 2017



Astronomical constraints: our results

X-rays:

- Prediction: **160±12 bright X-ray sources**

- *Observed sources in the ROI: **70***
(40% of those are cataclysmic variables)

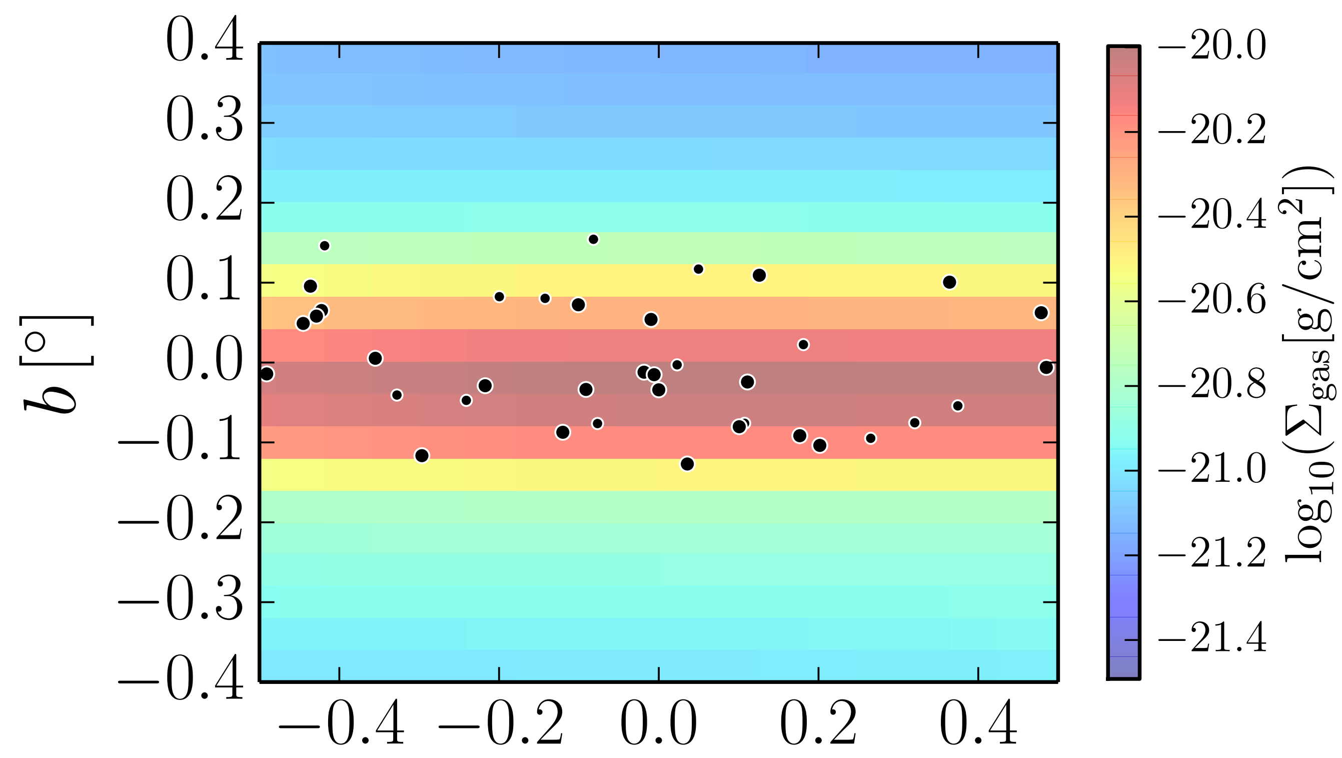
Radio:

- Prediction **40±6 bright radio sources** in the ROI

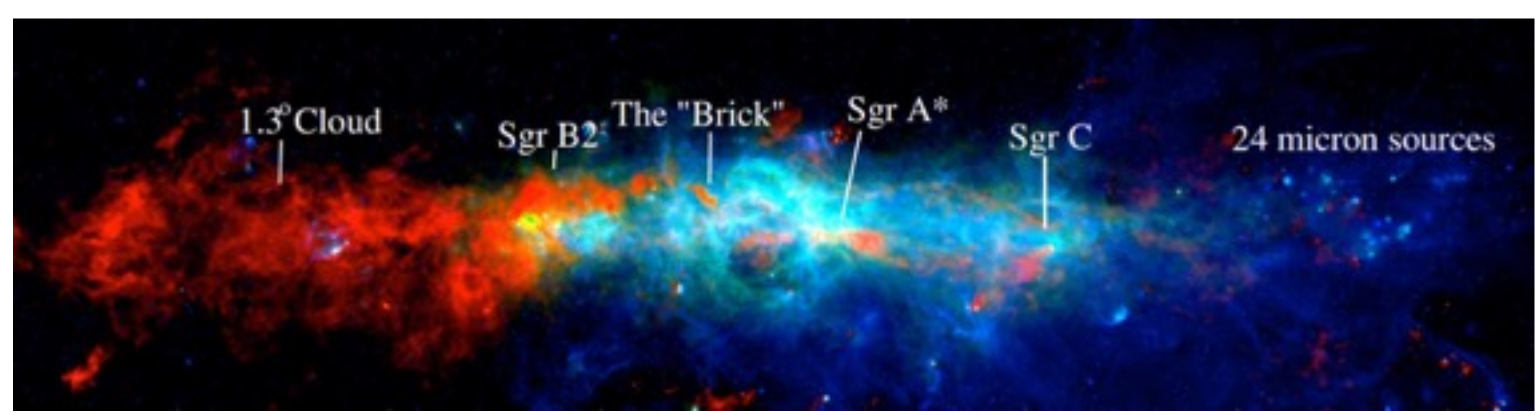
- Observed radio sources in the ROI: 170

- N*umber of candidate black holes in the ROI: **0**, assuming that BHs obey the Fundamental Plane relation*

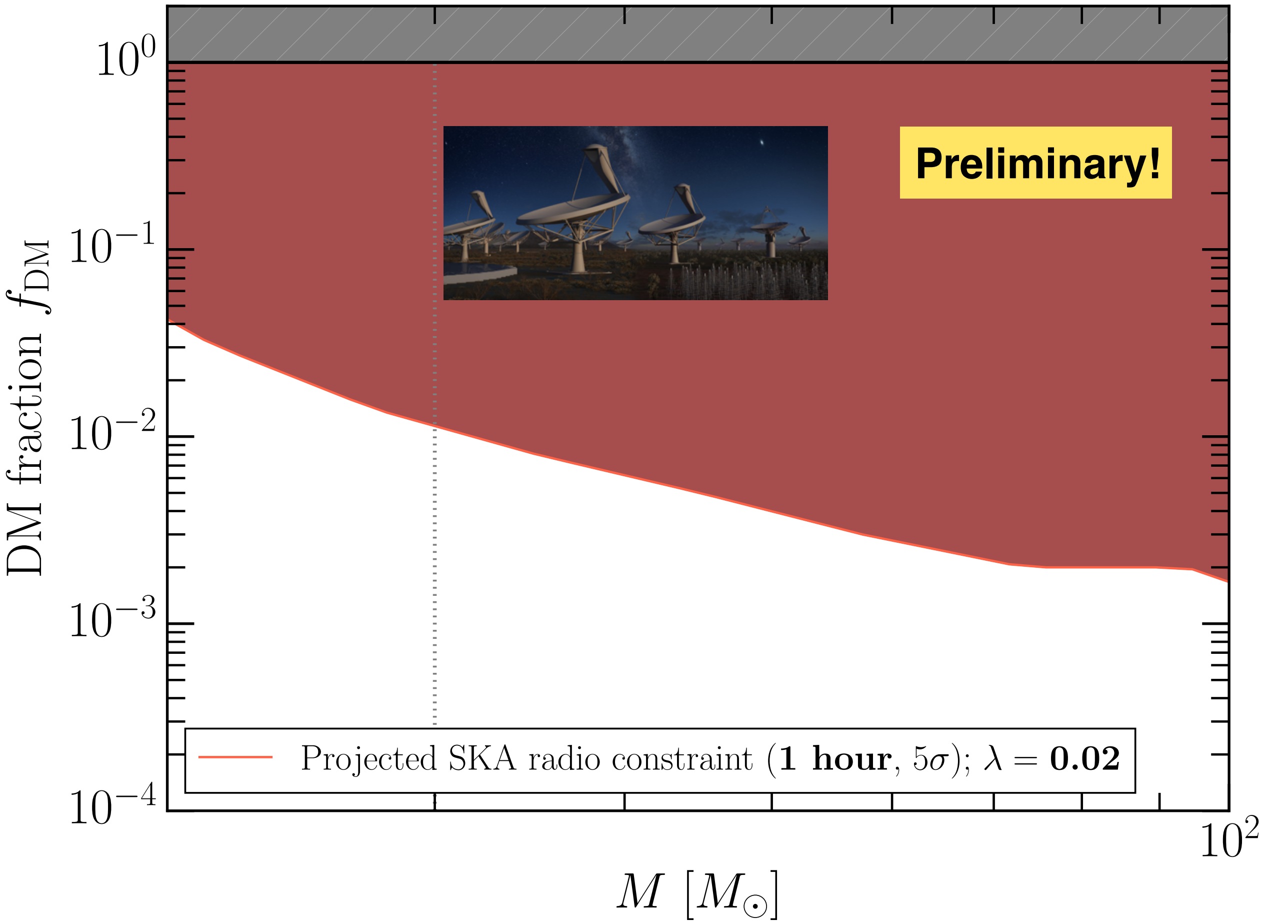
(i.e. no radio source in the ROI have a X-ray counterpart compatible with the FP relation they cannot be BHs accreting in the hard state)

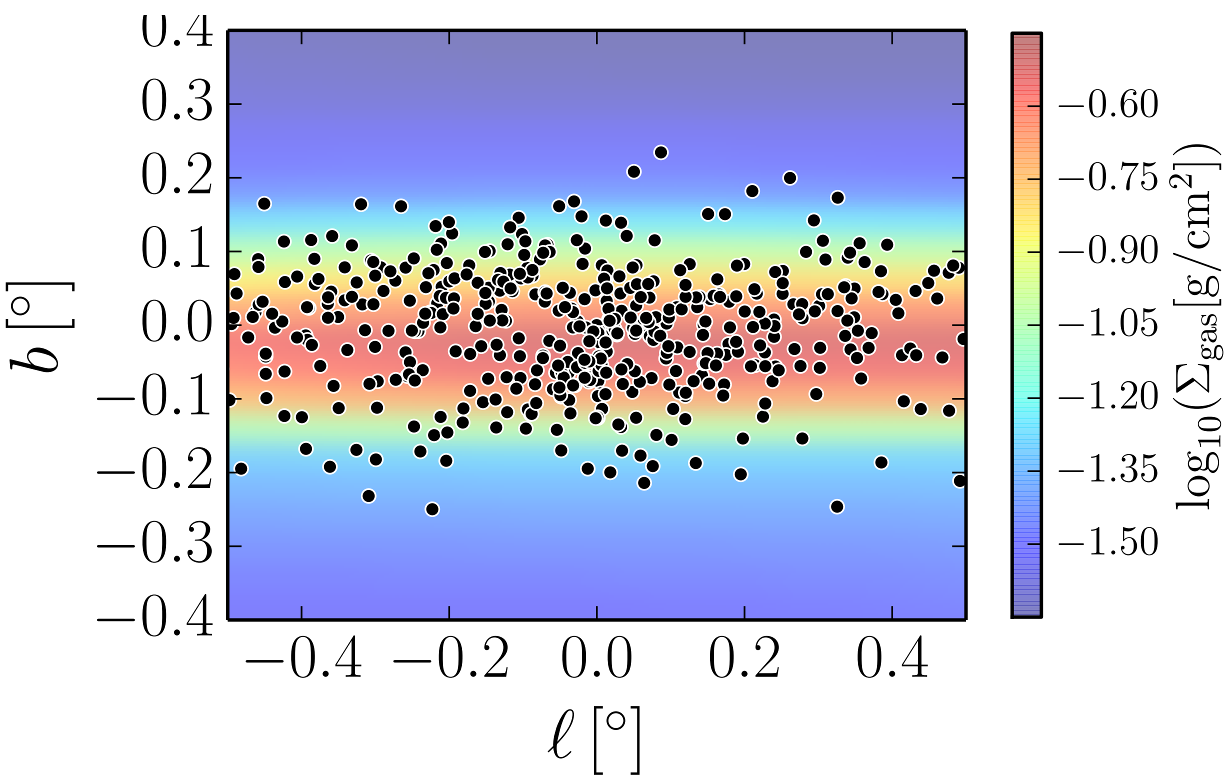


The constraining power mainly comes from BHs in the low-velocity tail of the BH distribution (v < 10 km/s) accreting gas in the Central Molecular Zone (a compact, very dense region in the inner Galactic bulge)



The role of SKA: A window of detection

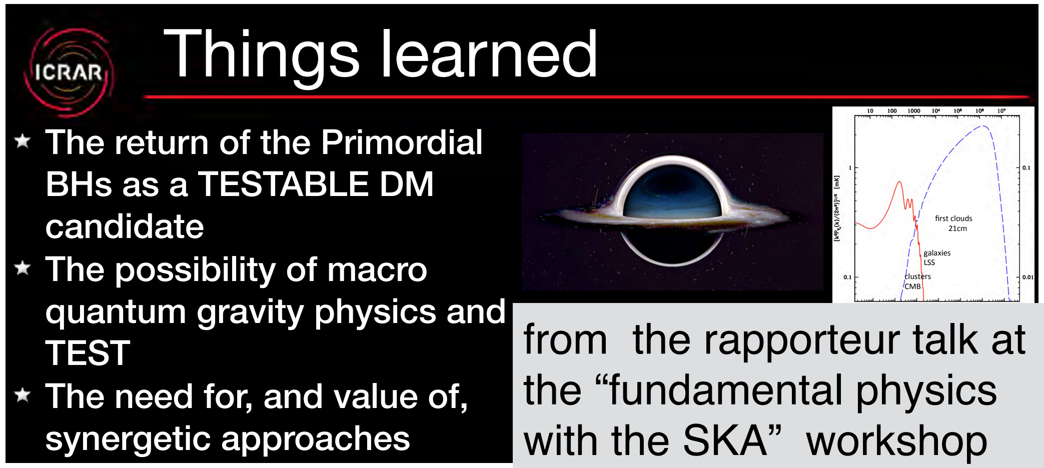




With the **SKA1-MID** (band 2, 0.95-1.76 GHz) point-source sensitivity, we predict to detect **~2000** sources in our ROI (<1° away from the GC) for *1 hour* of exposure, **if PBHs are the DM and λ ~ 0.02**.

Assuming no candidate BH sources, with SKA data we can place a stringent bound
If a subdominant population of PBHs is present, SKA can detect it (even for a DM fraction at the percent level)

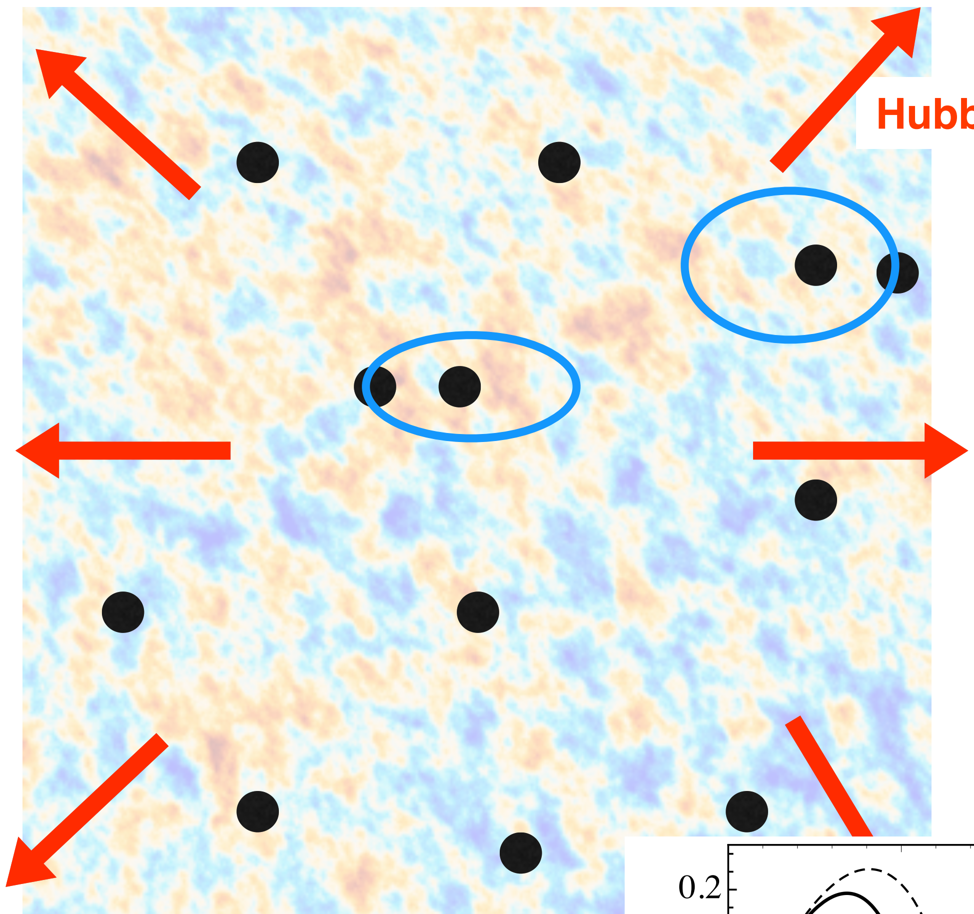
PBHs seem a testable DM candidate!



from the rapporteur talk at the “fundamental physics with the SKA” workshop

Part II: A closer look to merger rates

A) Binaries formed in the early Universe



Sasaki+ PRL 2017
Ali-Haimoud+ 2017

$$\ddot{r} - (\dot{H} + H^2)r + \frac{2M}{r^2}\frac{r}{|r|} = 0,$$

- If most of the DM is made of PBHs, **most pairs decouple from the Hubble flow and form a binary** deep in the radiation era.

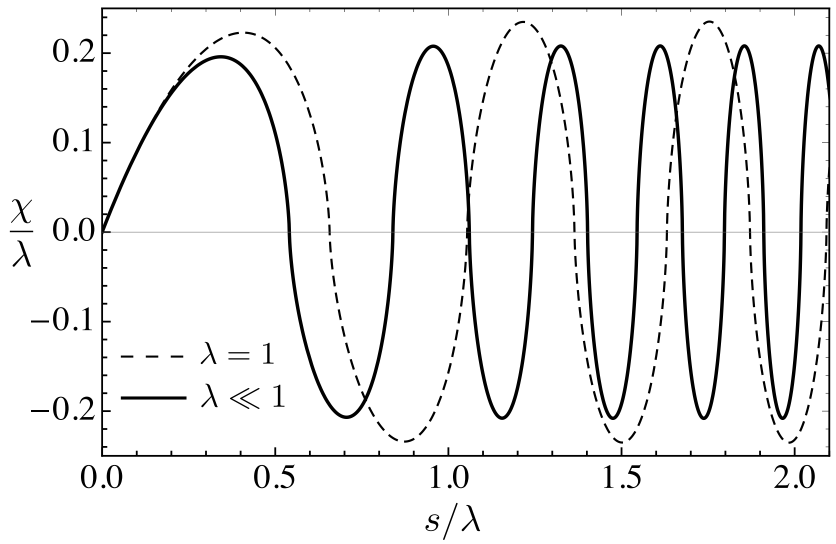
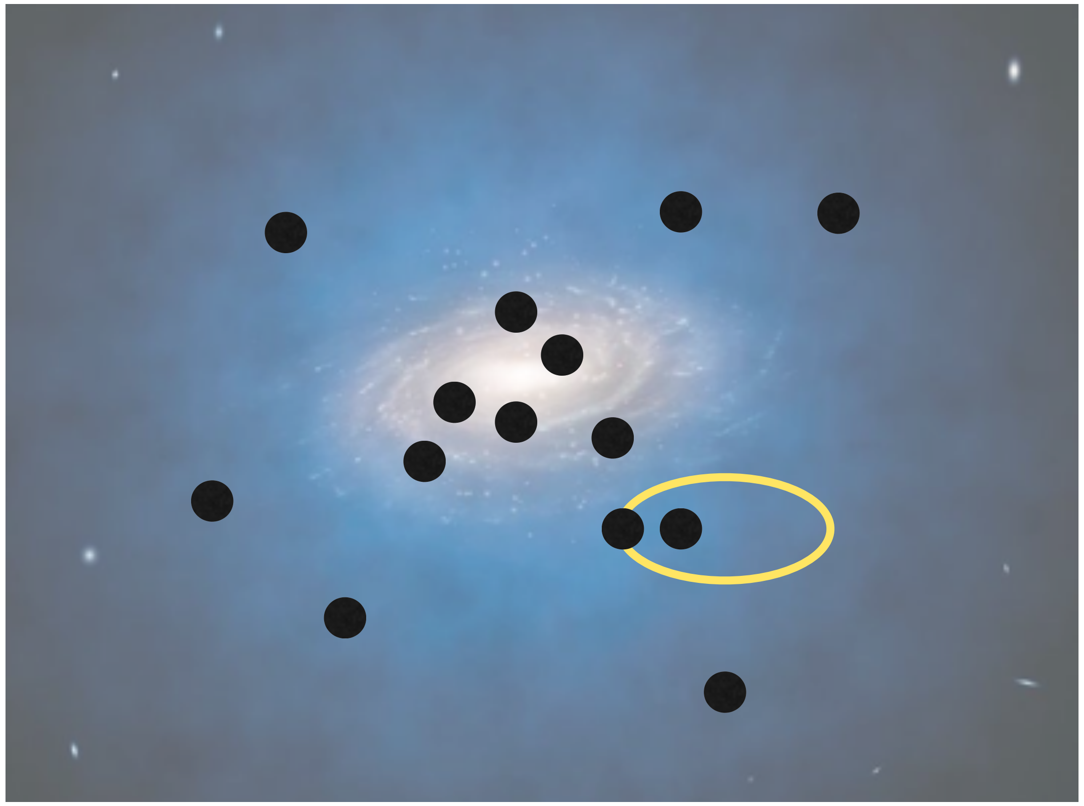


FIG. 1. Dimensionless separation $\chi = r/x$ of two point masses, rescaled by the parameter $\lambda = \frac{1}{f}(x/\overline{x})^3$, as a function of the rescaled scale factor s/λ, in the limit $\lambda \ll 1$ (solid) and for $\lambda = 1$ (dashed).

B) Binaries formed after close encounters within a DM halo



$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
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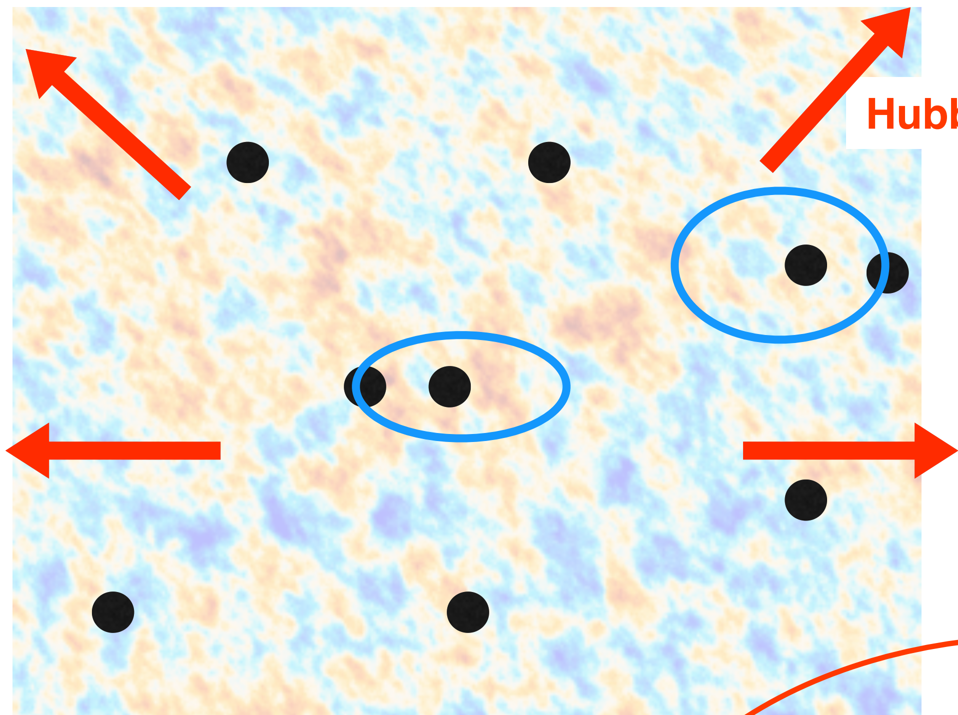
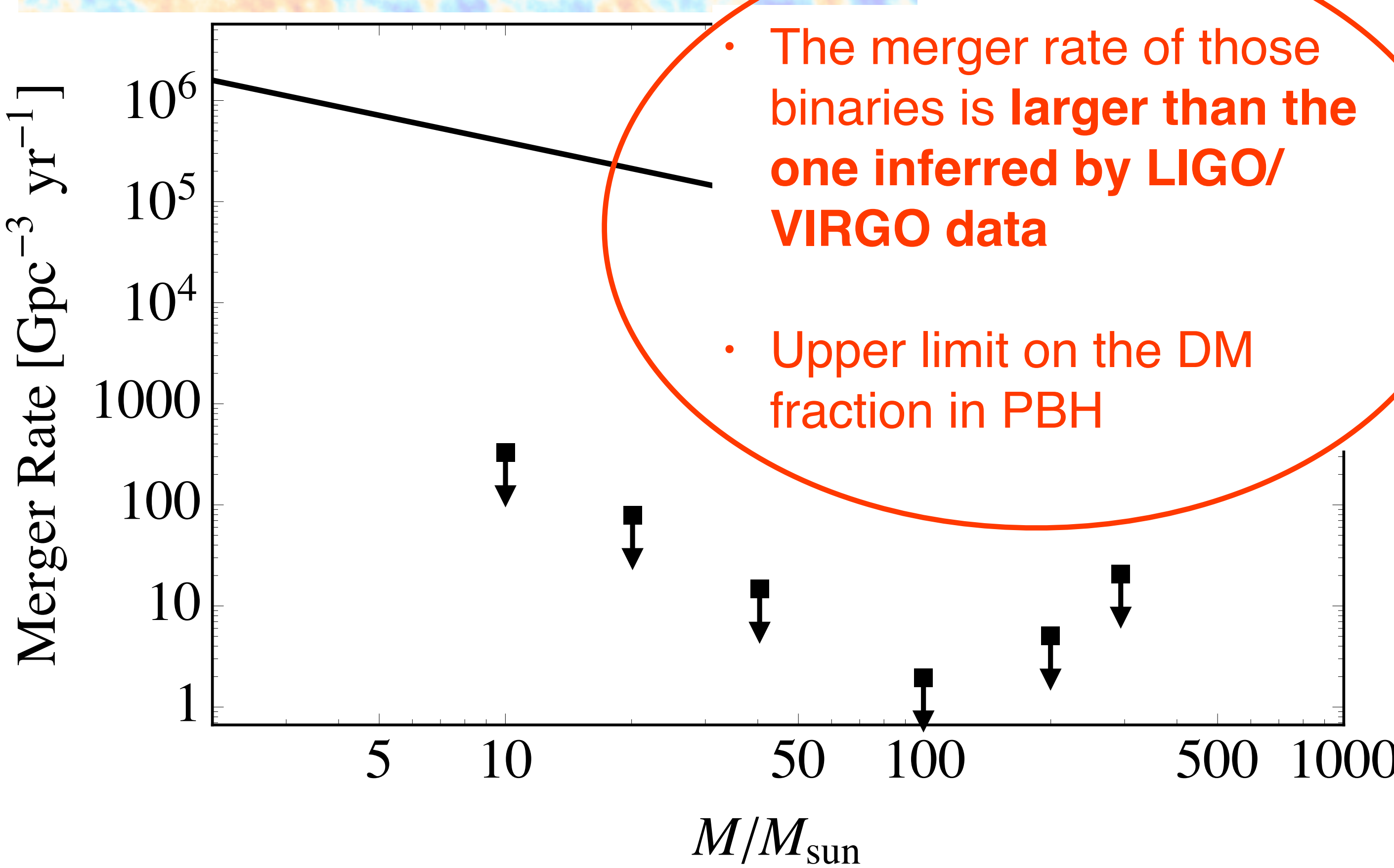
Bird+ PRL 2017

Part II: A closer look to merger rates

A) Binaries formed in the early Universe

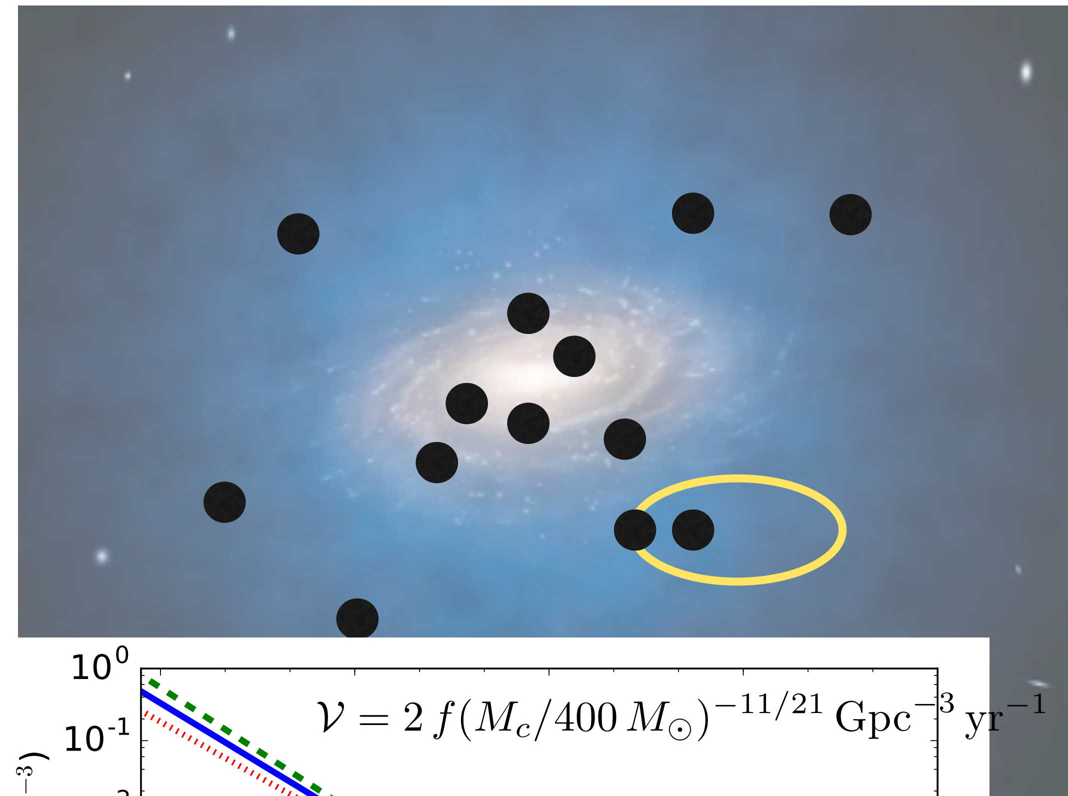


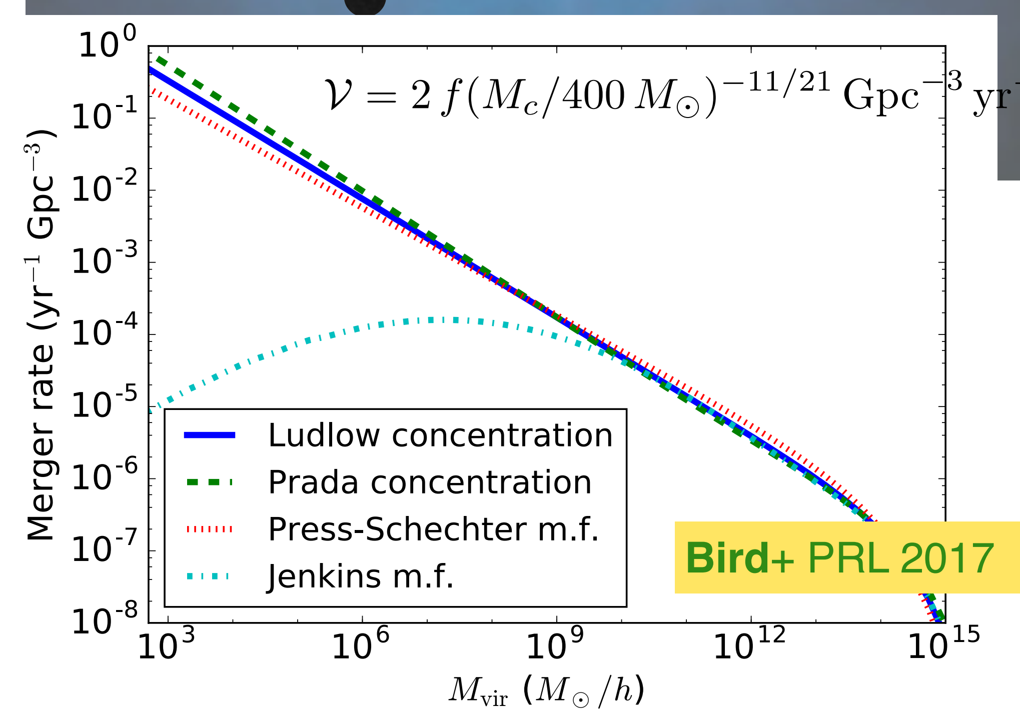
Ali-Haimoud+ 2017



- The merger rate of those binaries is **larger than the one inferred by LIGO/VIRGO data**
- Upper limit on the DM fraction in PBH

B) Binaries formed after close encounters within a DM halo





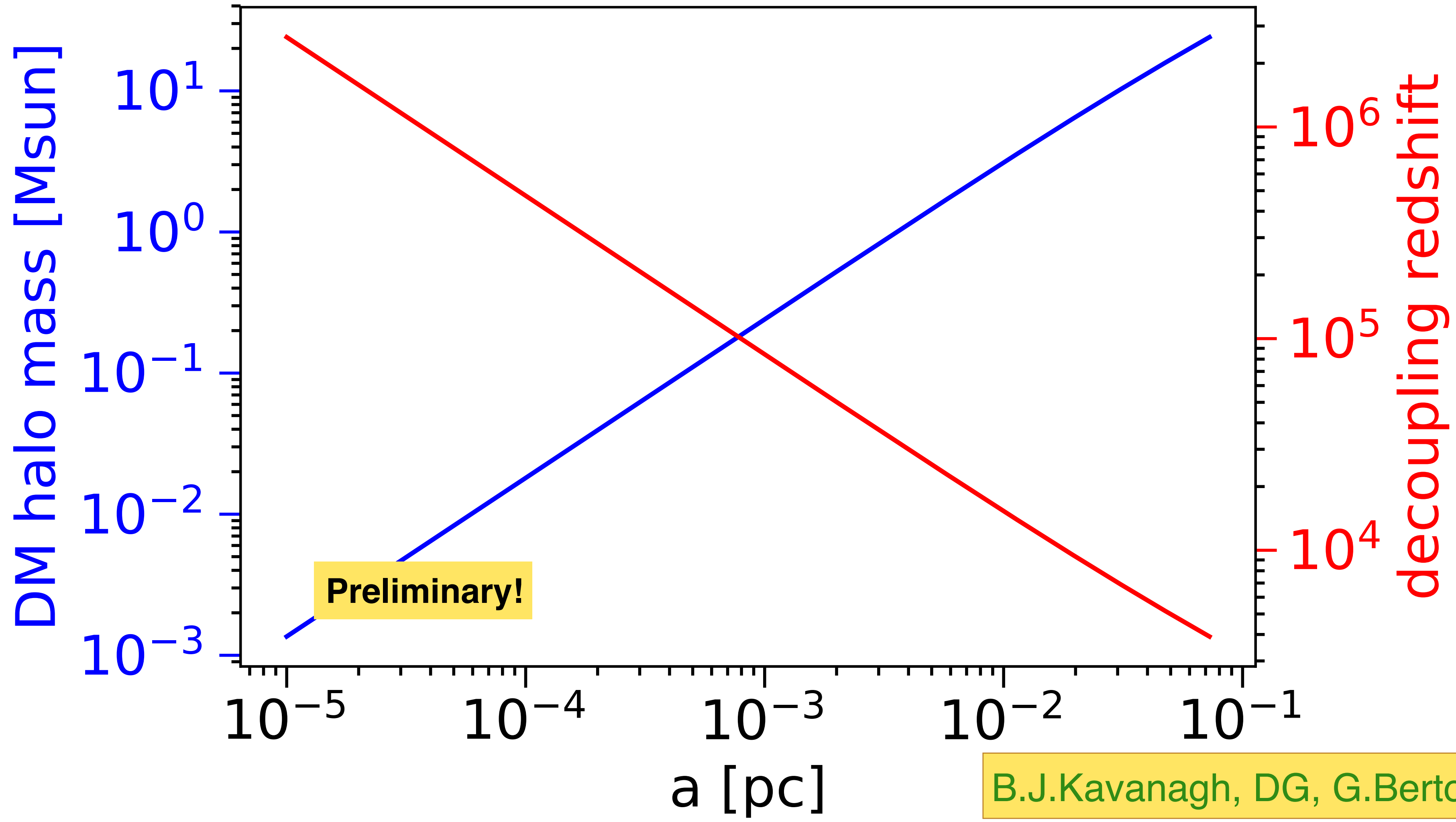
Bird+ PRL 2017

FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

Part II: A closer look to merger rates

According to Ali-Haimoud et al. 2017, if $f_{PBH} \sim 0.01$ the merger rate (at present time) of these binaries is compatible with the one inferred by LIGO.
What is the impact of the other form(s) of DM?

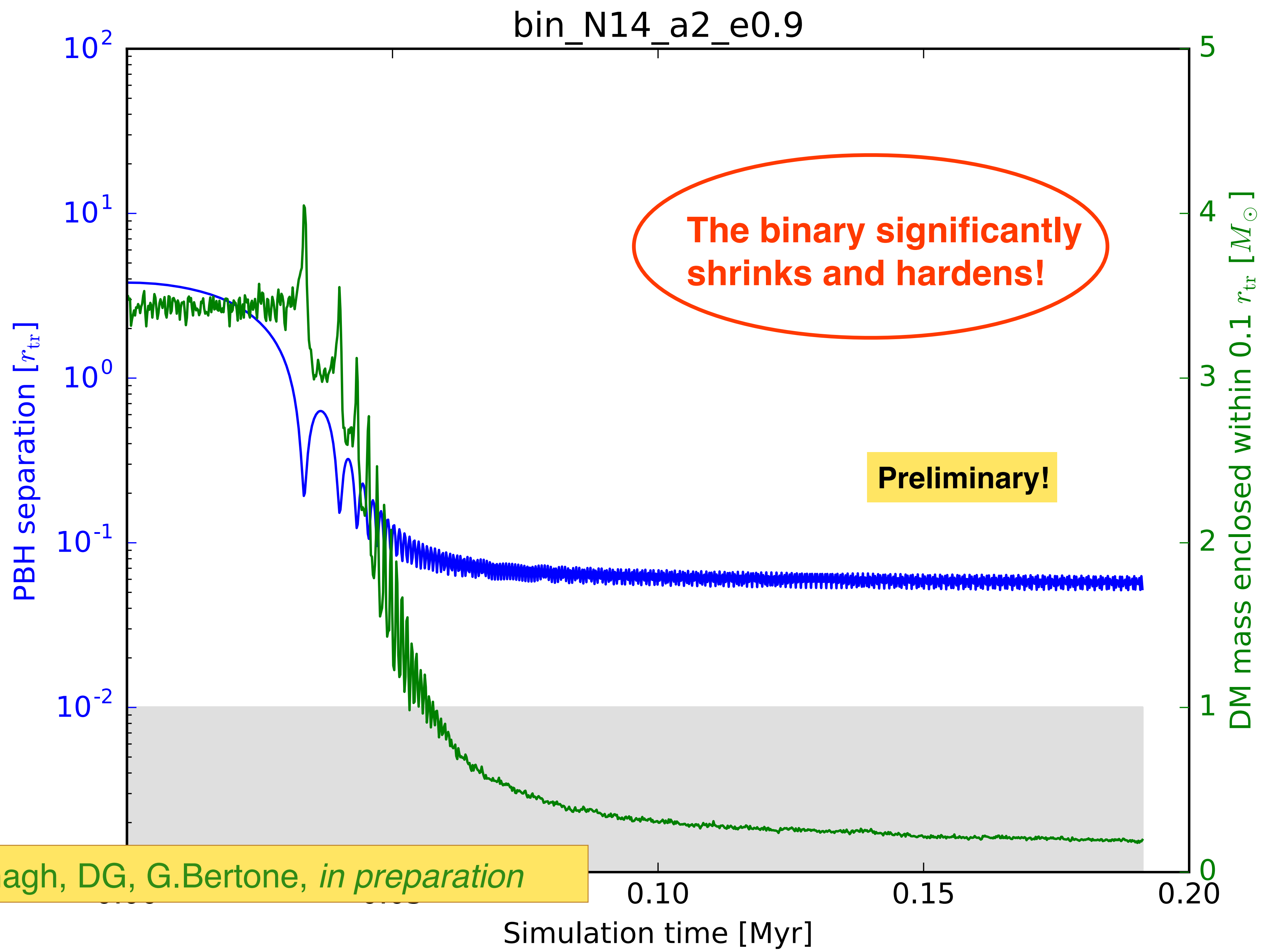
The PBH binaries *with large semi-major axis*, that decouple near matter-radiation equality, have enough time to **accrete a significant DM halo around them!**



B.J.Kavanagh, DG, G.Bertone, *in preparation*

Part II: A closer look to merger rates

- The PBH binaries *with large semi-major axis*, that decouple near matter-radiation equality, have enough time to **accrete a significant DM halo around them!**
- **Gravitational "friction"** due to the DM mini-halos can significantly change the properties of those binaries —> major **impact on the merger rate**



B.J.Kavanagh, DG, G.Bertone, *in preparation*

Conclusions

1) The idea that PBHs are the DM (quite popular, e.g., in the 1980s) has recently been discussed again in the DM community, after the LIGO discovery of several massive BBH systems

2) Several constraints exist on this scenario, from lensing, dynamical arguments, early-universe studies.

3) We asked ourselves: If the PBHs are the DM, **how easily can they be hidden in the Galaxy?** We set up a MC simulation to predict the number of bright X-ray and radio sources we should see in a tiny ROI around the GC, if PBHs are the bulk of the DM.

5) Despite all the caveats and uncertainties, **we got a significant constraint** in this mass window!

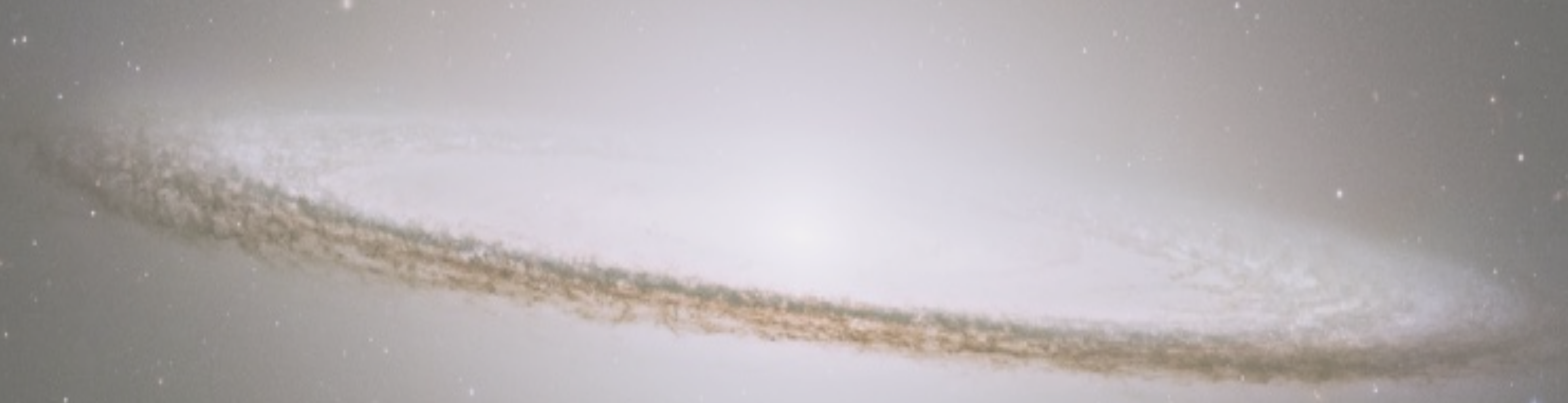
7) SKA has the capability to either make the constraint much stronger, and extend it to very low accretion rates, or detect a population of PBHs peaked at the GC

8) **The merger rate is a key observable.** The merger rate of PBH binaries formed in the early Universe seems to be 2 orders of magnitude larger than the one inferred from LIGO

9) The DM fraction in PBHs seems to be severely constrained then. However, for low DM fractions in PBHs, **the formation of DM mini-halos around them can significantly impact the merger rate** (work in progress)

10) **Discussion point:** How to discriminate astrophysical from primordial PBHs?

Thank you for your attention!



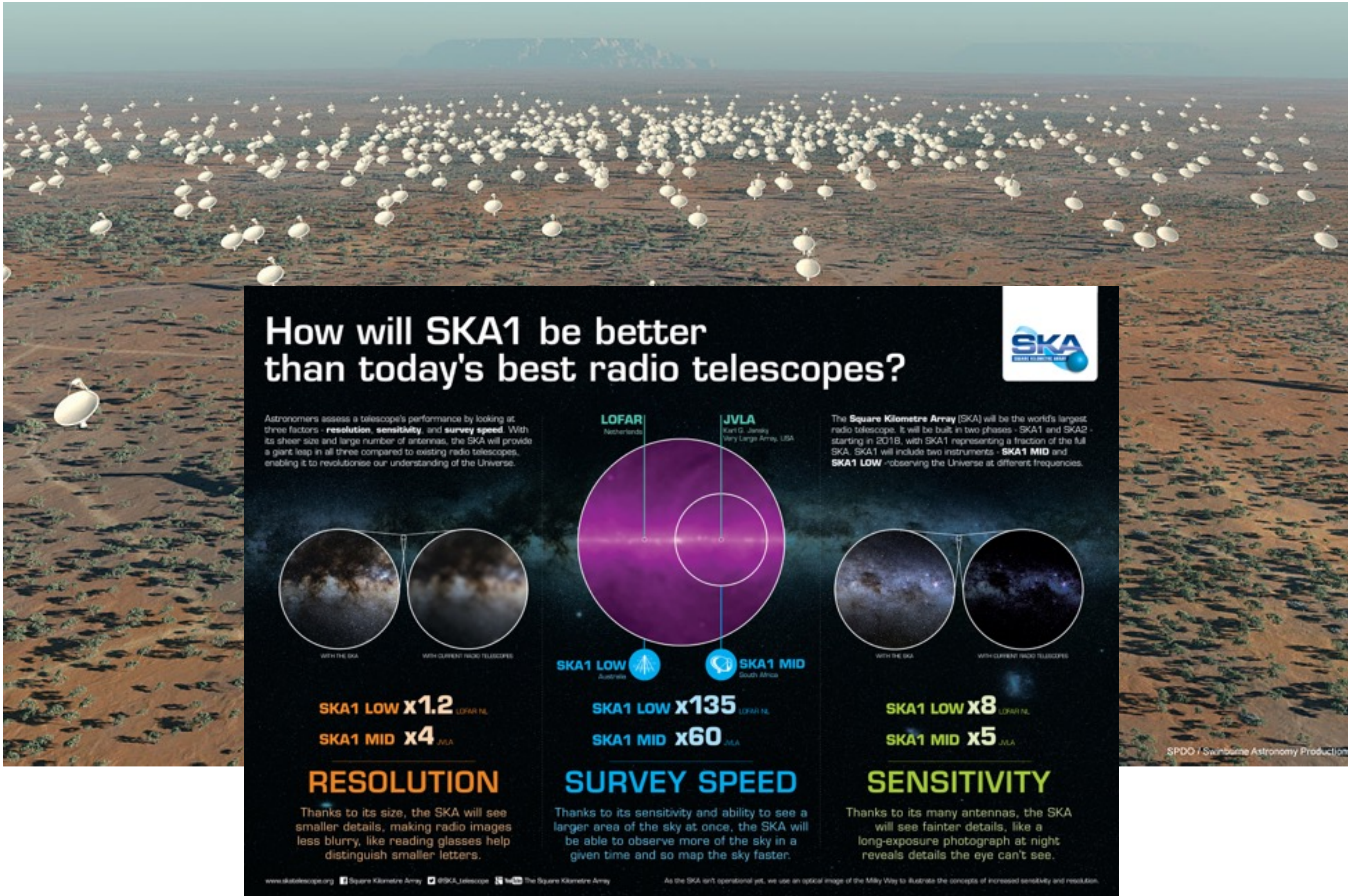
Daniele Gaggero

GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITEIT VAN AMSTERDAM

Backup Slides

The role of SKA



Part 1: LIGO, PBHs and DM

GW150914 and its implications: did LIGO detect a merger of two primordial black holes?

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, Adam G. Riess, *Phys. Rev. Lett.* **116**, 201301 (2016)

Sebastien Clesse, Juan García-Bellido, *Physics of the Dark Universe* **10** (2016) 002

M. Sasaki et al., Phys. Rev. Lett. 117, 061101 (2016)

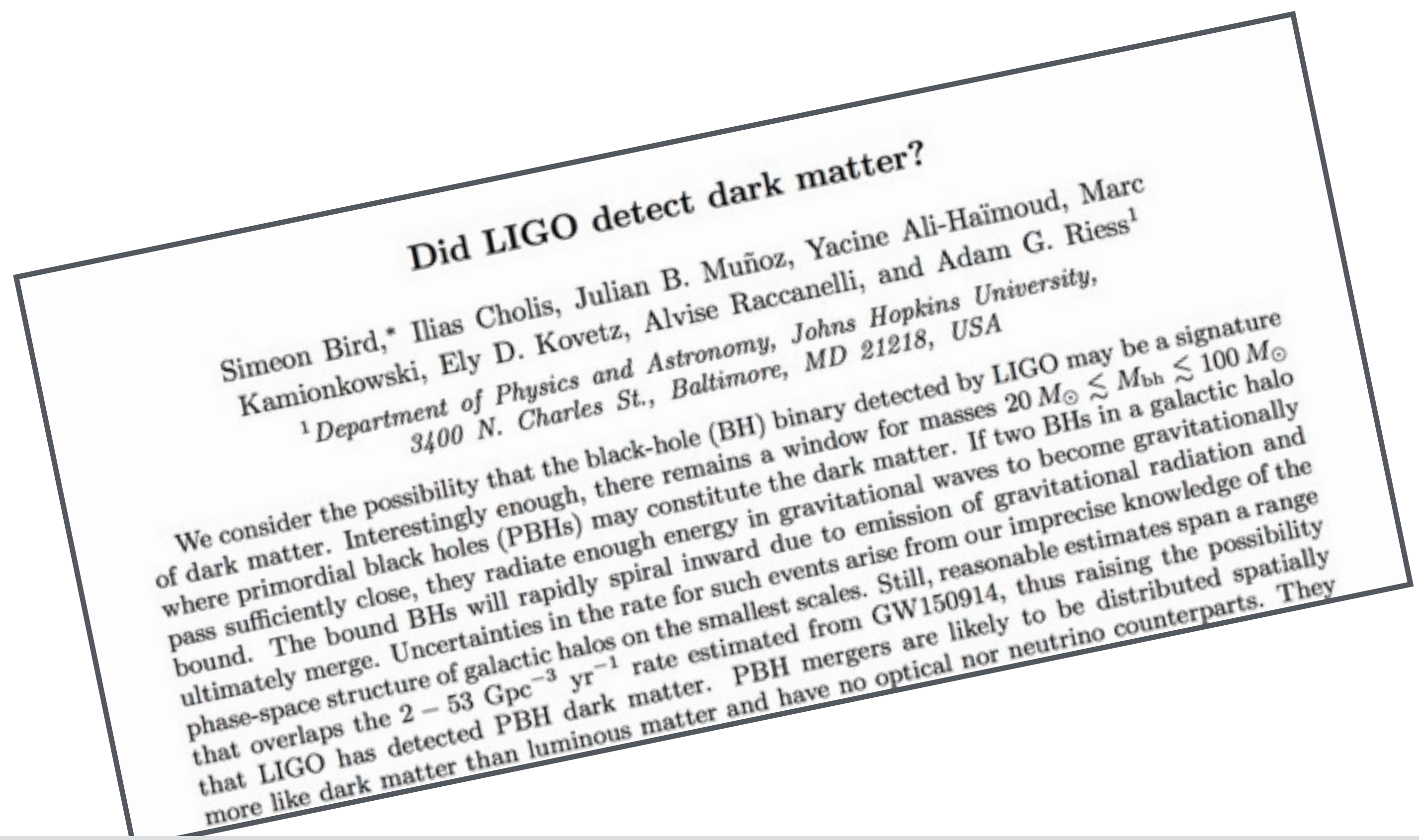
- The "crazy idea" proposed by the Johns Hopkins team: ***did LIGO detect the DM*?** **(in the form of primordial black holes)**

- As we will see, *the hypothesis that DM is made of PBHs is currently not well constrained in the mass window explored by LIGO*!

- **Most of the argument in *Bird et al.* is based on *estimates on rates:***

☆ 30 $M_\odot$ BH merging rate estimated by the LIGO collaboration: **2 - 53 Gpc^{-3} yr^{-1}**

☆ What would be the *merging rate of primordial black holes*, if they are the bulk of the Dark Matter in the Universe?



Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses 20 $M_\odot \lesssim M_{bh} \lesssim 100\, M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They

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- What would be the *merging rate of primordial black holes*, if they are the bulk of the Dark Matter in the Universe?

$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\, {\rm pc}^2$$

$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2} \left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}}\right)^2 \langle \sigma v_{\rm pbh} \rangle \, dr$$

$$\mathcal{V} = \int (dn/dM)(M)\,\mathcal{R}(M)\,dM.$$

$$\mathcal{V} = 2\, f (M_c/400\, M_\odot)^{-11/21}\, {\rm Gpc}^{-3}\, {\rm yr}^{-1}$$

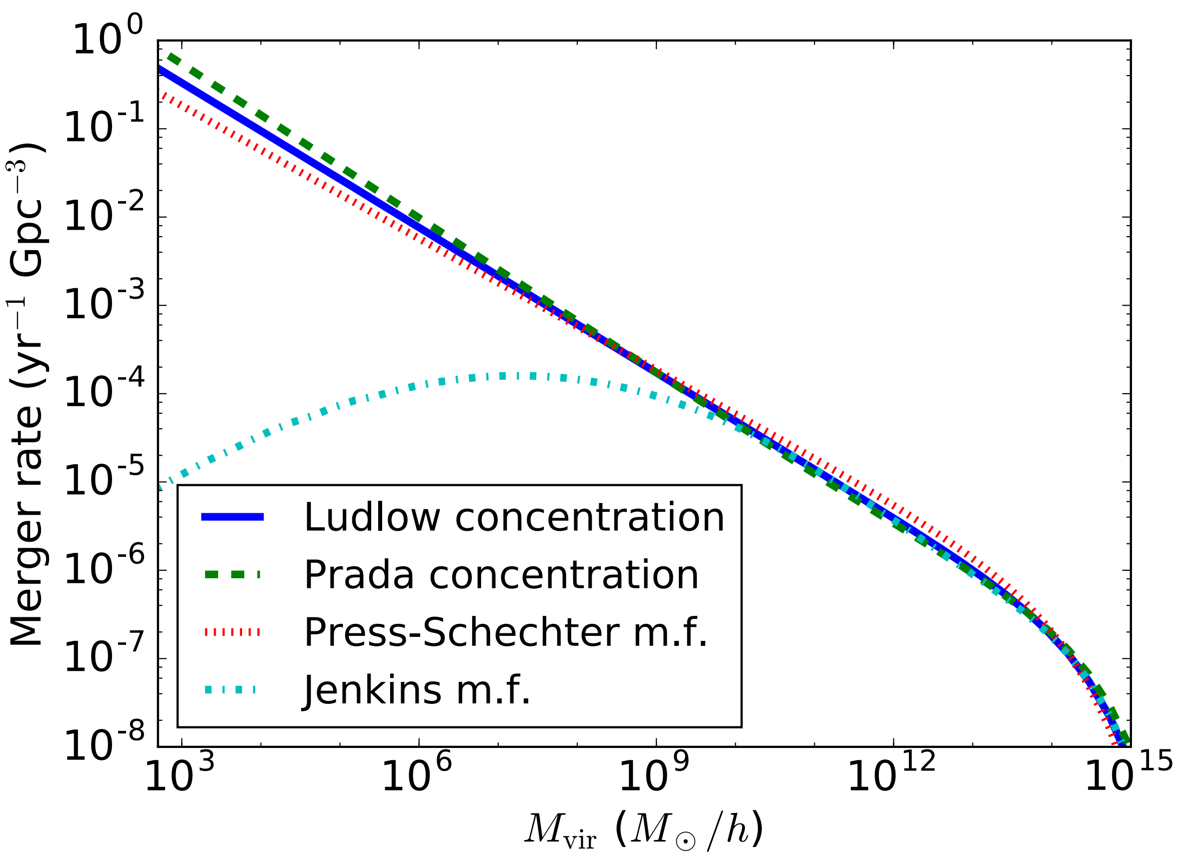

FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

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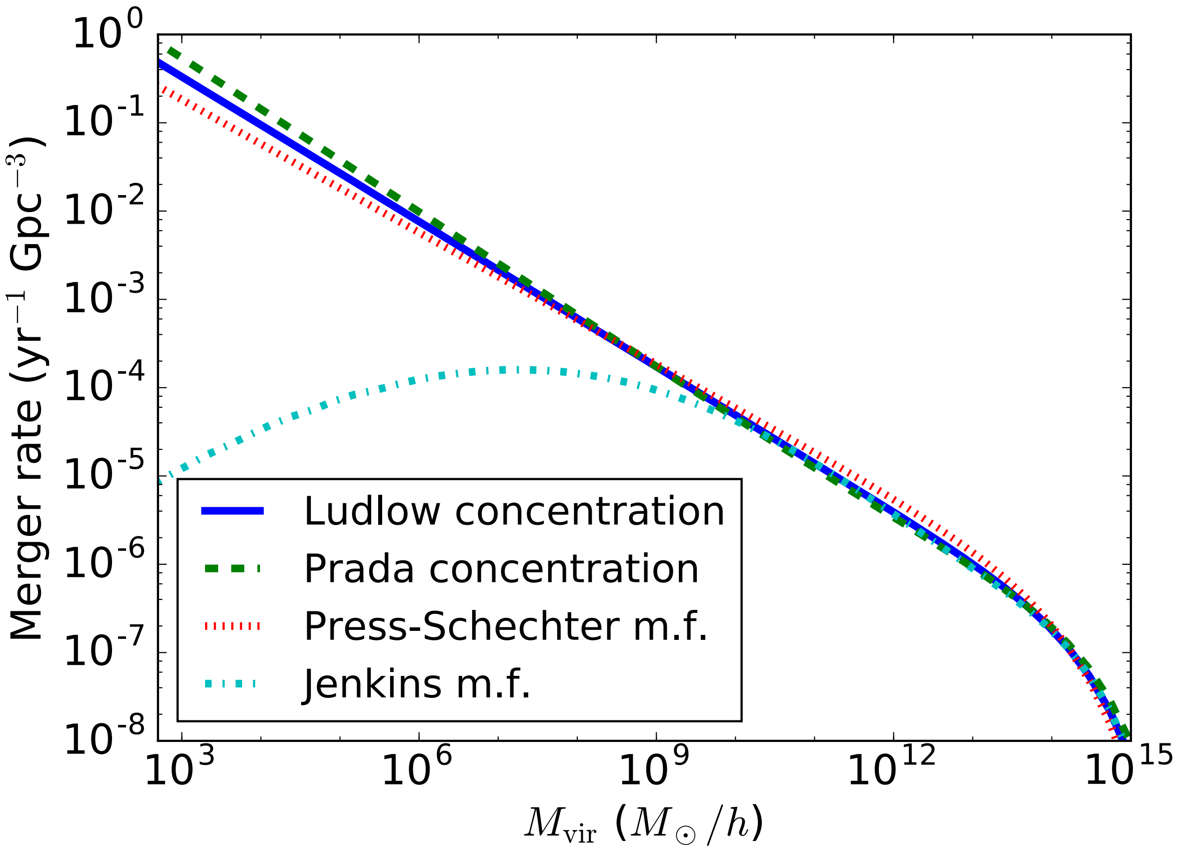
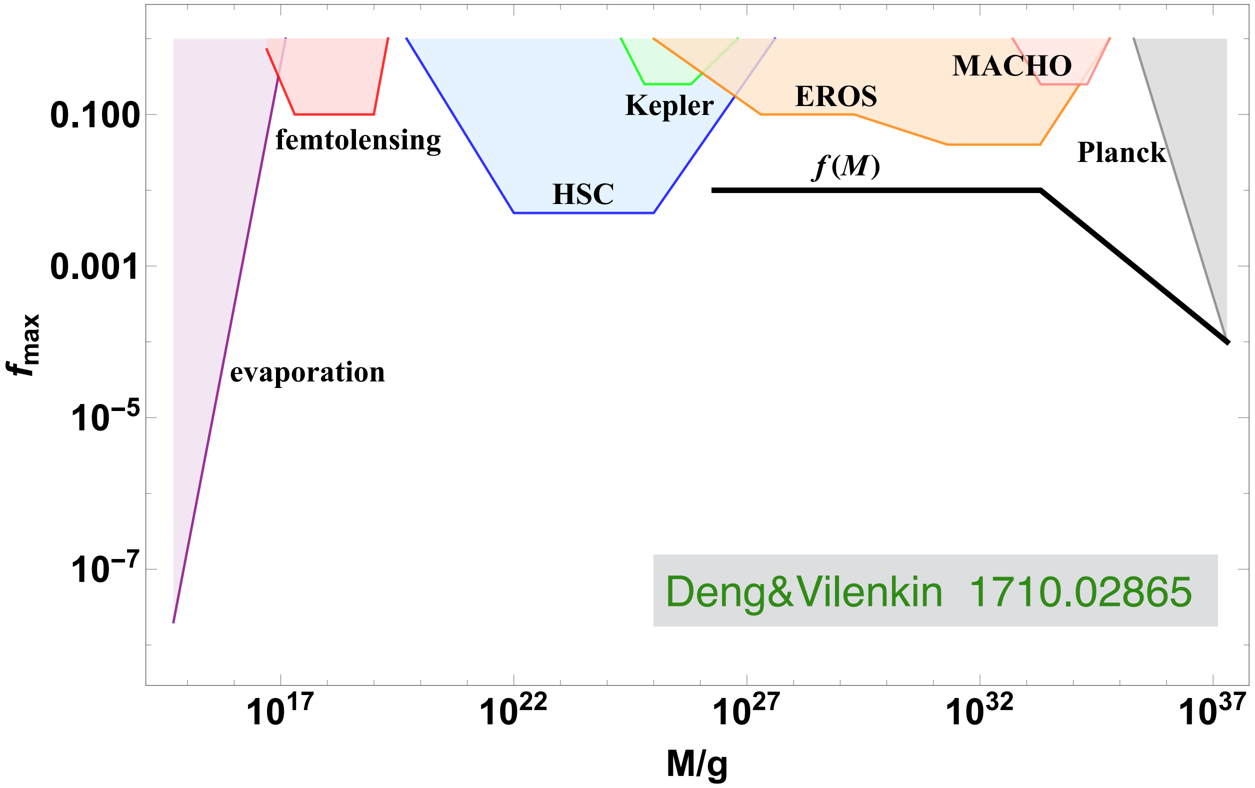


Compatible with the rate inferred by the LIGO collaboration!

What about generic mass functions?



- Most of the constraints discussed so far rely on the **assumption of a delta function** for the PBH mass distribution!
- A broad mass function could evade all those bounds!

- It is therefore crucial to **recompute the bounds for more general mass functions**
- A remapping procedure has been recently presented in Bellomo et al. 2017

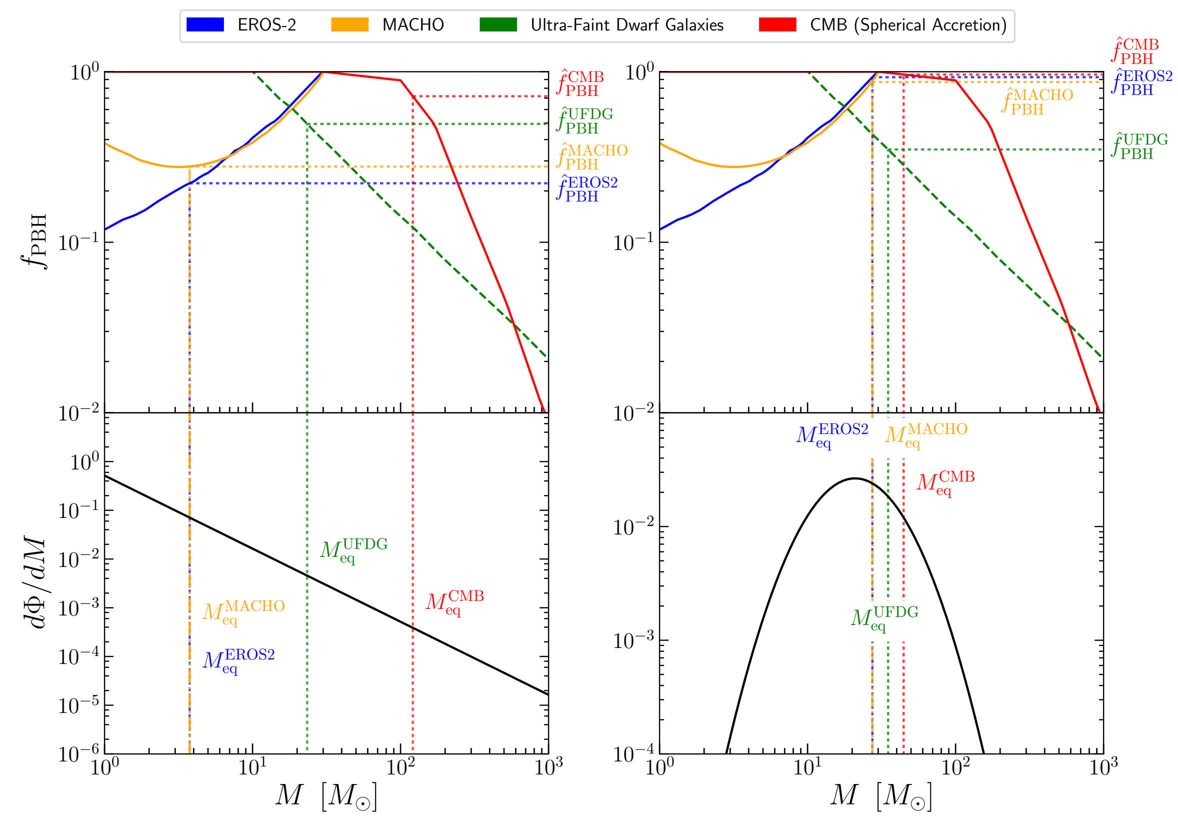
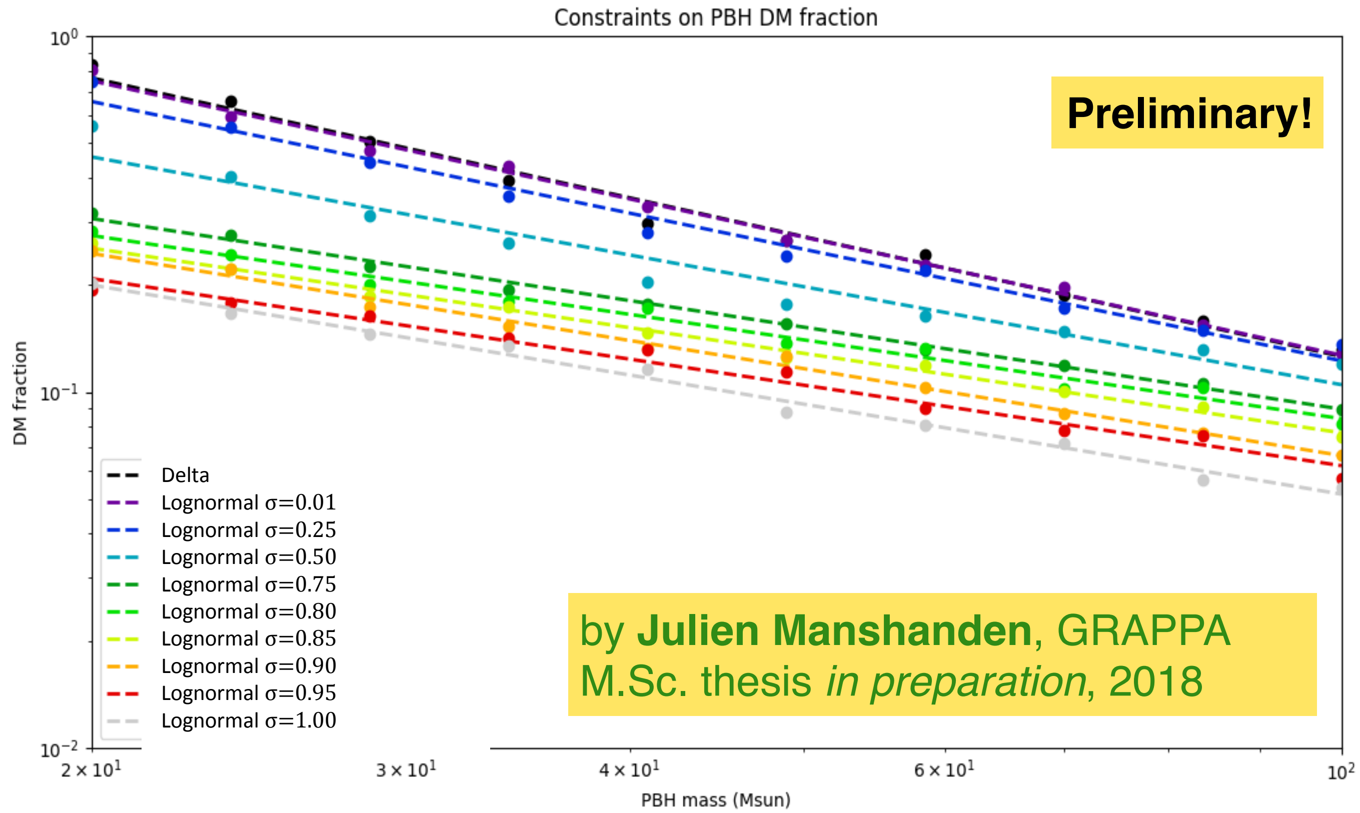


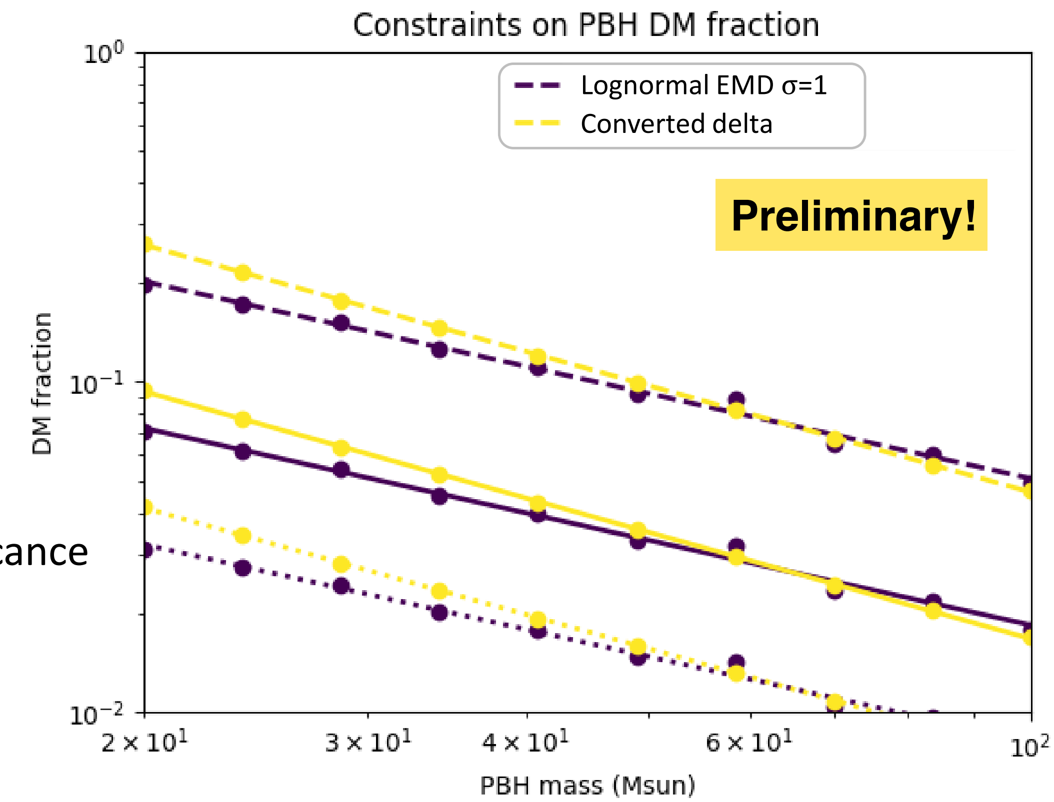
Figure 1: Illustration of the new method proposed in this paper. *Upper Panels*: Microlensing (EROS-2, MACHO), ultra-faint dwarf galaxies (UFDG) and cosmic microwave background (CMB) constraints for MMD. Solid lines are used for constraints generally considered robust to astrophysical assumptions, while dashed lines are used for constraints which robustness has yet to be fully discussed in the literature. *Lower Panels*: Examples of Power Law (on the left) and Lognormal (on the right) mass distributions. The vertical dotted lines highlight the position of the equivalent mass for each observable, calculated from Equations 3.12, 3.16 and 3.20. From their intersection with the corresponding constraint in the upper panels, we extract the set of four maximum PBHs allowed fractions $\hat{f}_{\rm PBH}$. The fraction of PBHs that

N. Bellomo, J.L. Bernal, A. Raccanelli, L. Verde, arXiv:1709.07467

What about generic mass functions?



- What about our astronomical constraint? How does it change for generic mass functions?
- Work in progress…



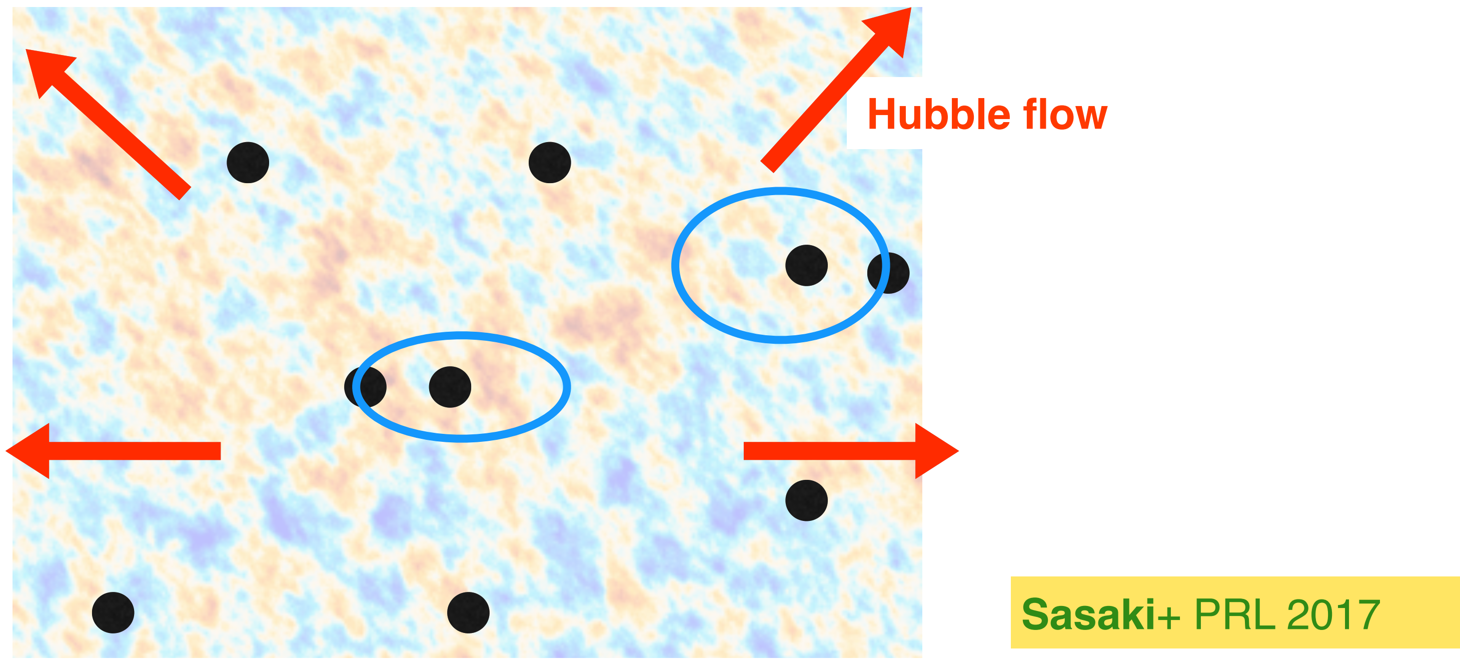
5σ significance

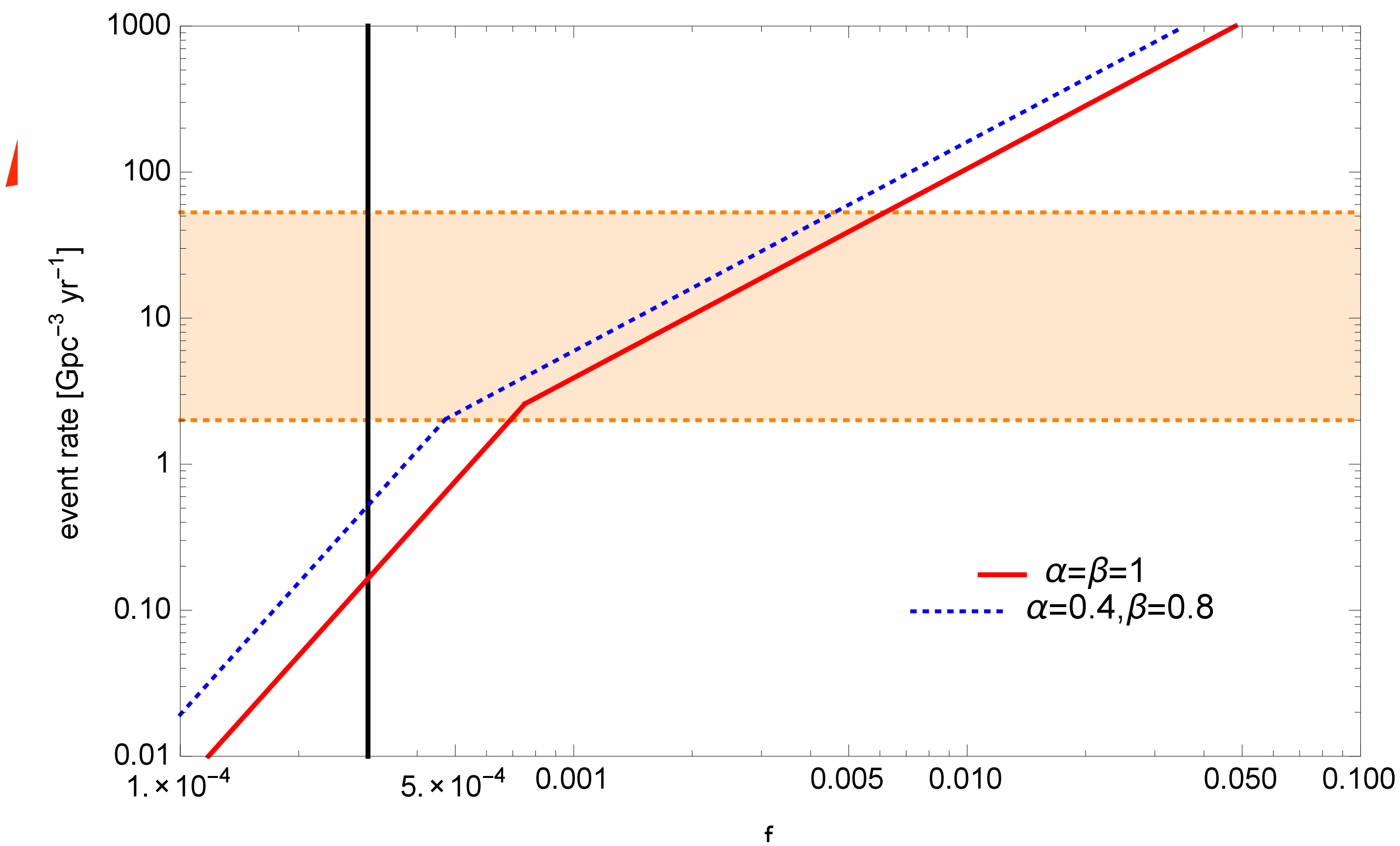
3σ significance

2σ significance

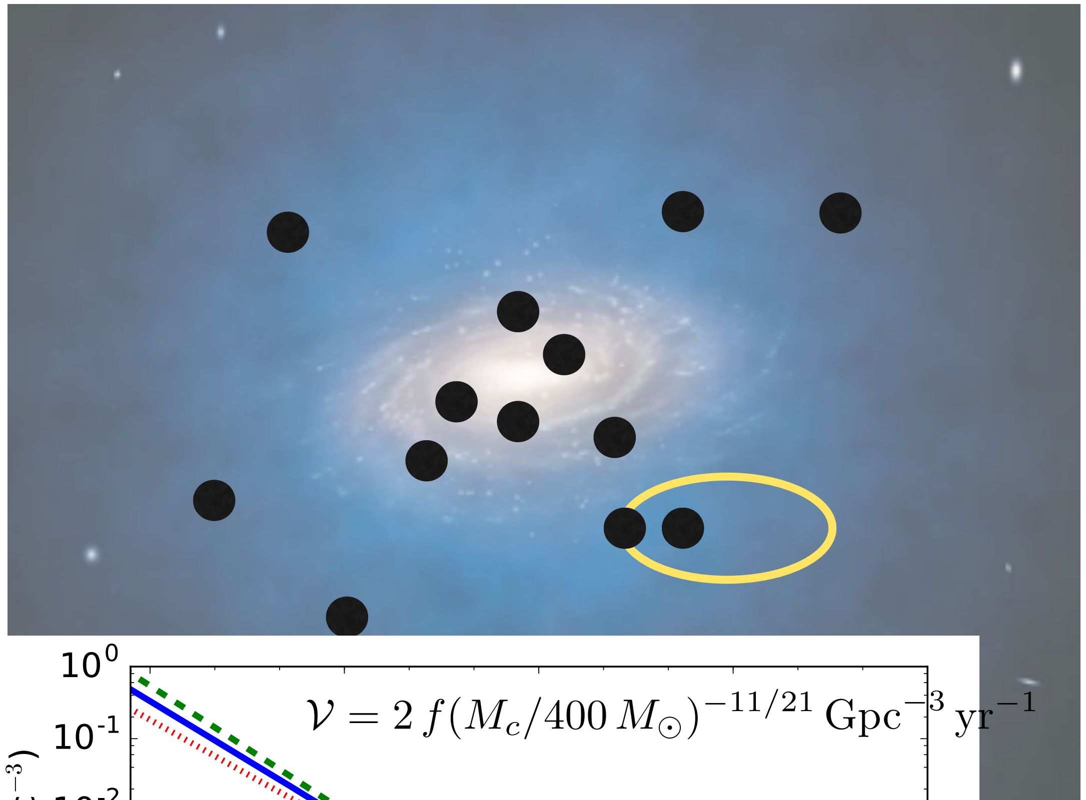
Part II: A closer look to merger rates

A) Binaries formed in the early Universe





B) Binaries formed after close encounters within a DM halo



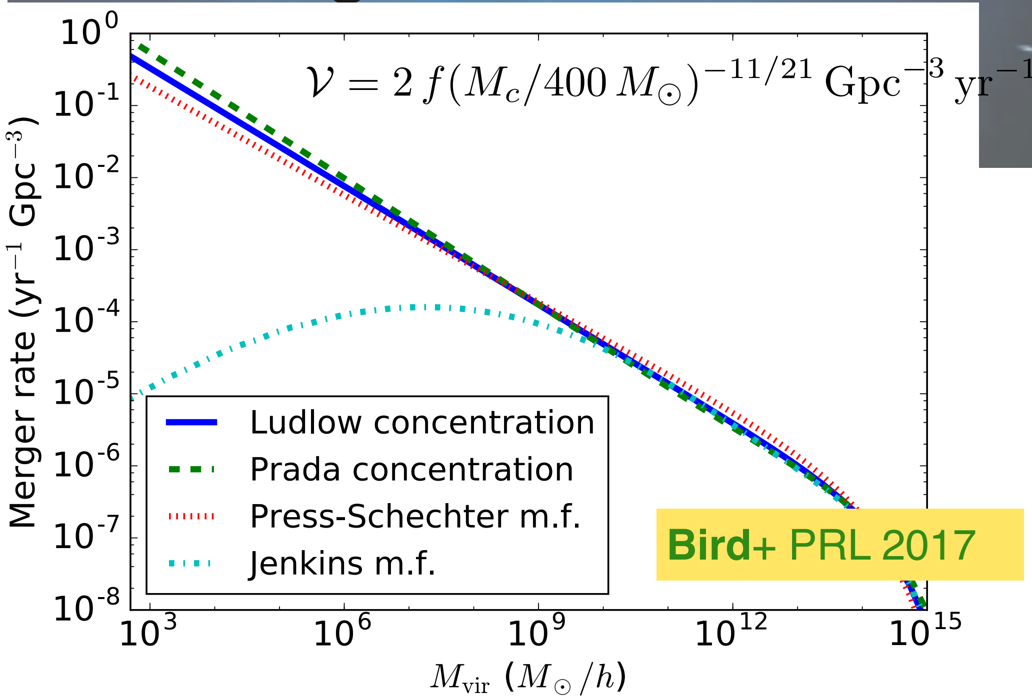


FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

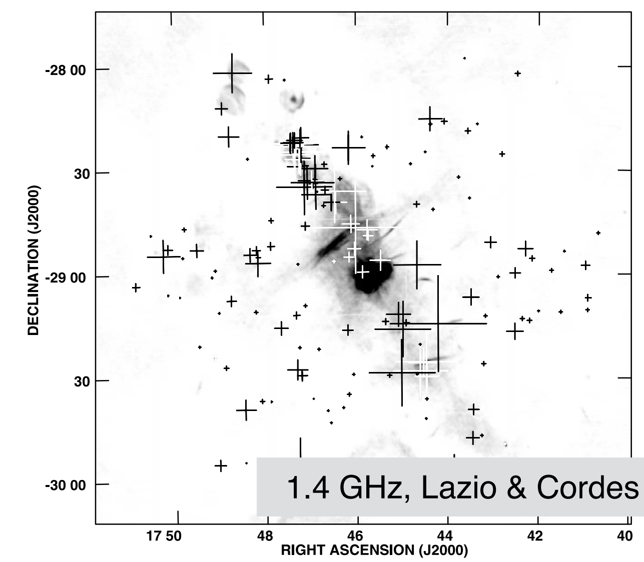
Part 1: LIGO, PBHs and DM

Our idea: why not using current astronomical observations in the radio and X-ray band?

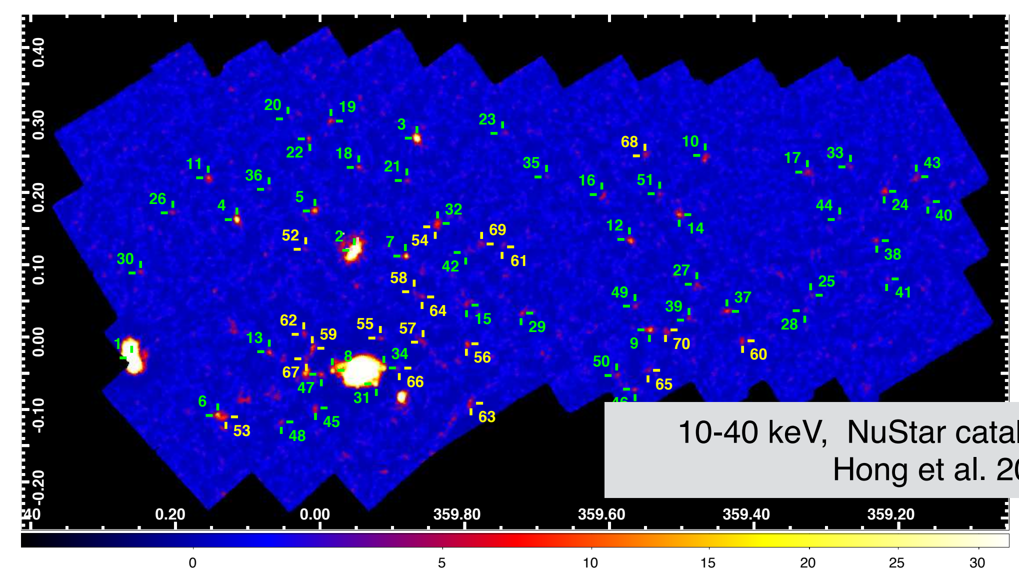
see D. Gaggero, G. Bertone, F. Calore, R. Connors, M. Lovell, S. Markoff, E. Storm, “Searching for Primordial Black Holes in the radio and X-ray sky”, arXiv:1612.00457

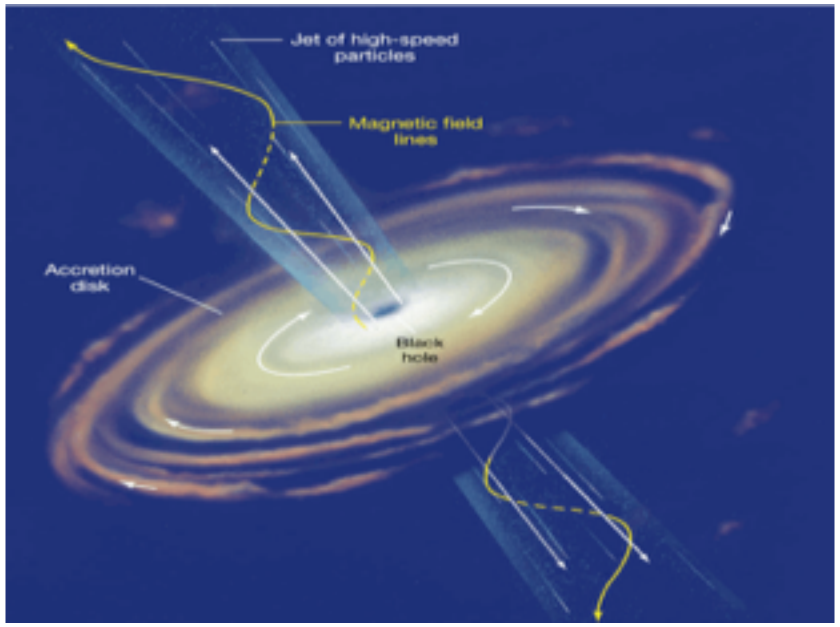
- If ~30M$_\odot$ PBHs are the DM, there should be **~10^{11} objects of this kind in the Milky Way, and ~10^{8} in the Galactic bulge**. (*as a comparison, we expect ~10^{8} astrophysical stellar-mass black holes in our Galaxy, see e.g. Fender et al. 1301.1341 “The closest black holes”*)

- The question is: given the large amount of gas in the inner Galaxy, **how easy is it to hide such a large population of black holes?** Given conservative estimates of the accretion rate and radiative efficiency, **is this population of PBHs compatible with current radio and X-ray observations?**



1.4 GHz, Lazio & Cordes 2008


10-40 keV, NuStar catalog, Hong et al. 2016



Accretion on isolated BHs

- The relevant pieces of information we need are:

—> what is a *conservative estimate* of the accretion rate
of an isolated BH in the Galaxy,
given its velocity and the local density
of the interstellar medium?
—> what is a *conservative estimate* of the radio and X-ray emission?

Very complicated phenomenology, high uncertainties. We had to parametrize the problem and adopt simplified, **conservative** assumptions.

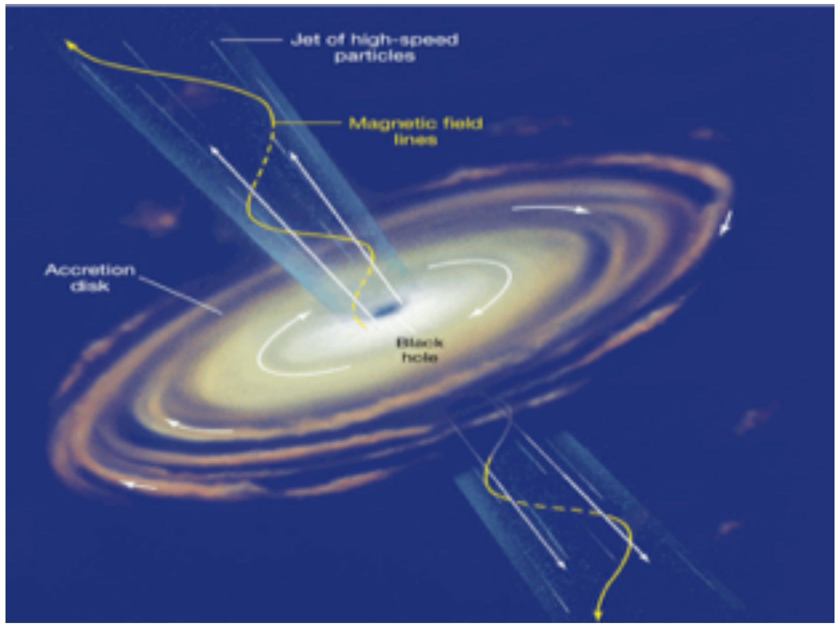
1) we parametrize the accretion rate as a fraction of the Bondi-Hoyle rate:

$$\dot{M} = 4\pi\lambda(GM_{BH})^2\rho\left(v_{BH}^2 + c_s^2\right)^{-3/2}$$

we choose **a conservative value *λ = 0.01***, inspired by isolated neutron star population estimates and studies of active galactic nuclei accretion. Larger values would imply a large population of bright X-ray sources corresponding to nearby isolated neutron stars.
Caveat: it can be even smaller, see final discussion!

R. Perna, et al., ApJ 598, 545 (2003), astro-ph/0308081
S. Pellegrini, ApJ 624, 155 (2005), astro-ph/050203, "Nuclear Accretion in Galaxies of the Local Universe: Clues from Chandra Observations"

Accretion on isolated BHs



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of the interstellar medium?

—> what is a *conservative estimate* of the radio and X-ray emission?

Very complicated phenomenology, high uncertainties. We had to parametrize the problem and adopt simplified assumptions.

2) We parametrize the radiative efficiency: given the low accretion rate, **we conservatively assume radiative *inefficiency***, and a non-linear scaling of this kind

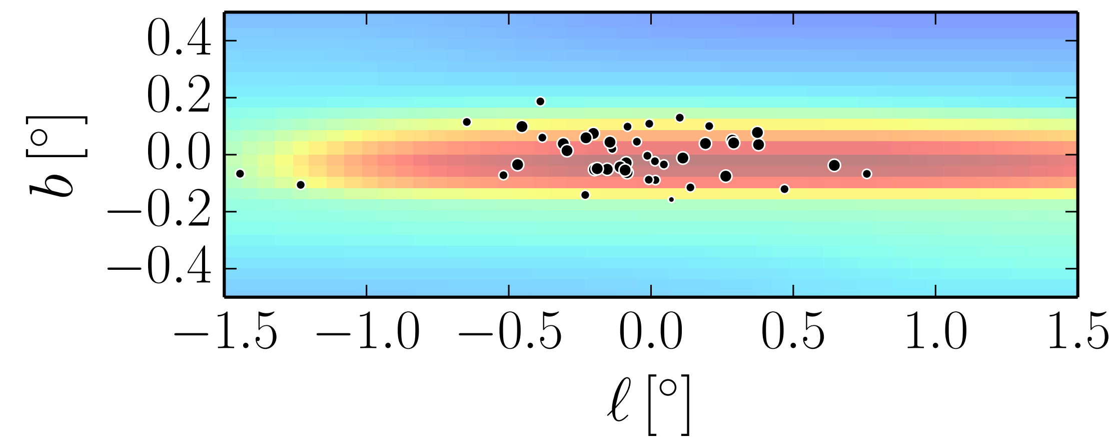
$$L_B = \eta \dot{M} c^2 \qquad \eta = 0.1 \dot{M}/\dot{M}_{\rm crit} \text{ for } \dot{M} < \dot{M}_{\rm crit}$$

Physical picture: *advection-dominated accretion* in which the gas cooling timescales greatly exceed the dynamical timescales; mass loss from the disc or internal convective flows.

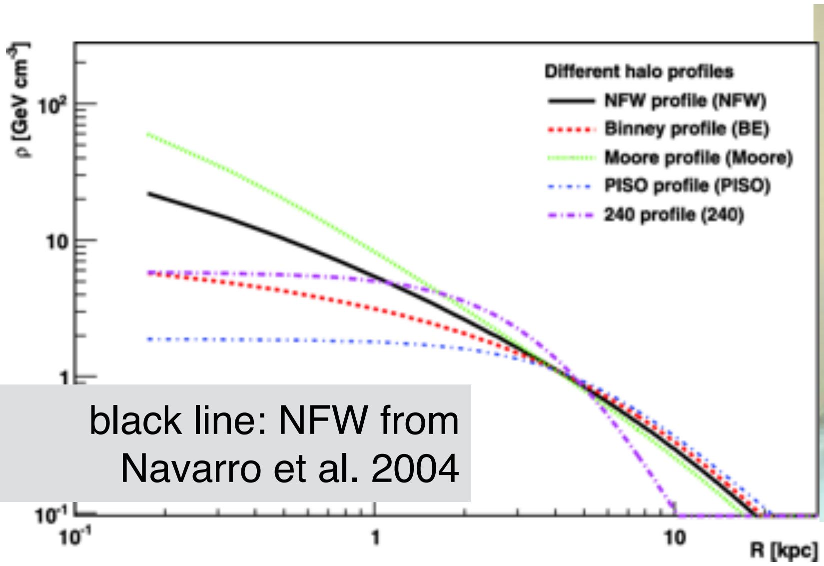
see ***Narayan and Yi 1994***, *"Advection-Dominated Accretion: A Self-Similar Solution"*
and also *Blanford and Begelman 1998: "On the Fate of Gas Accreting at a Low Rate onto a Black Hole"*

Our MC simulation

We set up a MC simulation in which **we populate the Galaxy with PBHs**, and compute the predicted X-ray and radio luminosity; then **we produce simulated maps of predicted bright X-ray and radio sources**

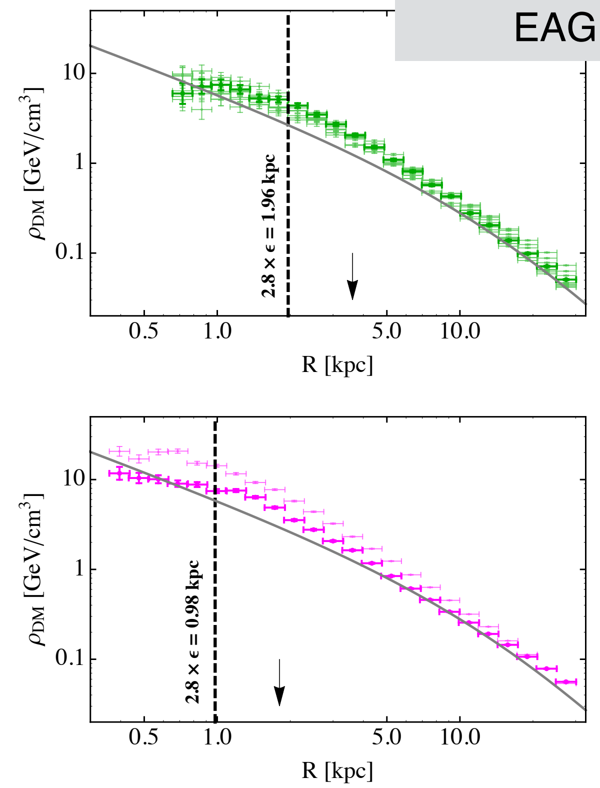


Spatial distribution of PBHs: We consider as a benchmark the NFW distribution.
We also consider other variations, based on numerical simulations with baryons (*see F. Calore et al., arXiv:1509.02164*)



black line: NFW from Navarro et al. 2004

F. Calore et al., arXiv: 1509.02164, based on EAGLE simulations



Part 1: LIGO, PBHs and DM

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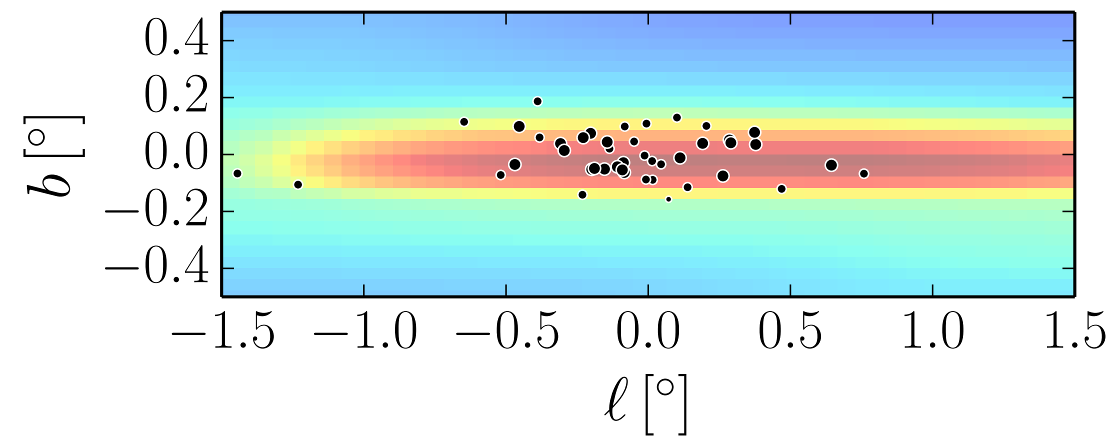
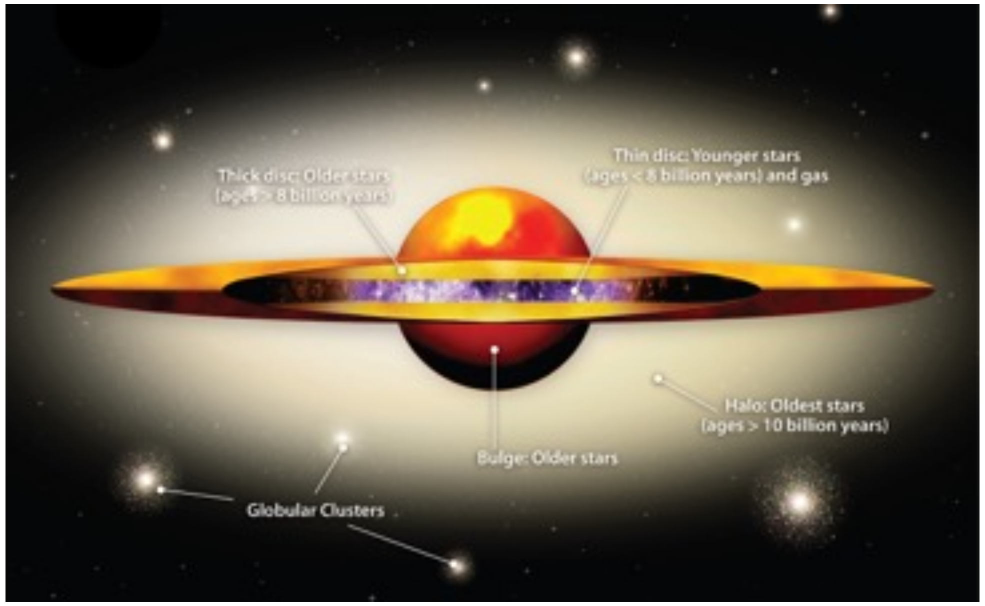


Velocity distribution: we consider, for each radius R, a Maxwell-Boltzmann distribution centered on v = $\sqrt{(G\,M(<R)/R)}$.

We use a spherical average of a mass model of the Milky Way M(R) from *McMillian 1608.00971 (2016)*, including DM halo and baryonic structures (bulge, thin and thick stellar disk, gas distribution).



Our simplified treatment, in the low-v tail, is compatible with the more accurate Eddington formalism, which holds under the assumption of spherical symmetry and isotropy

$$F_h(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{d^2\rho_h}{d\Psi^2}\frac{d\Psi}{\sqrt{\mathcal{E}-\Psi}} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{d\rho_h}{d\Psi}\right)_{\Psi=0}\right]$$

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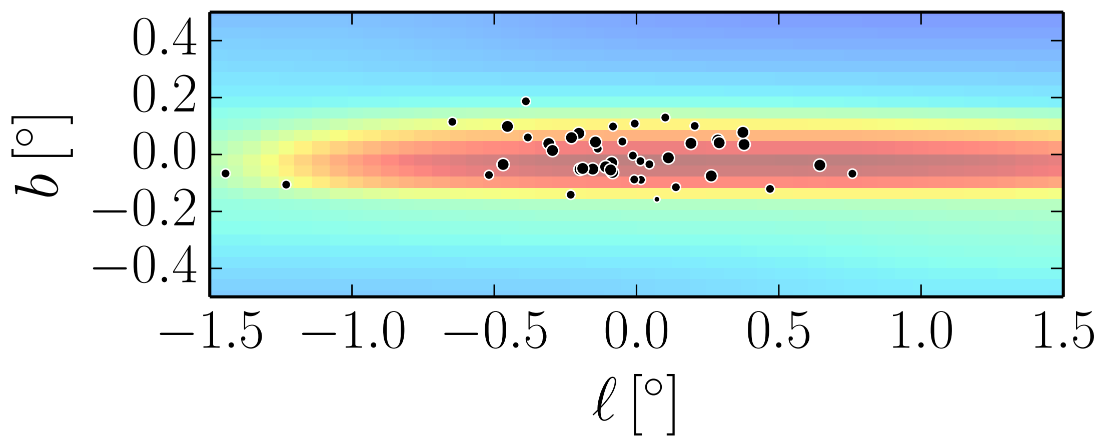
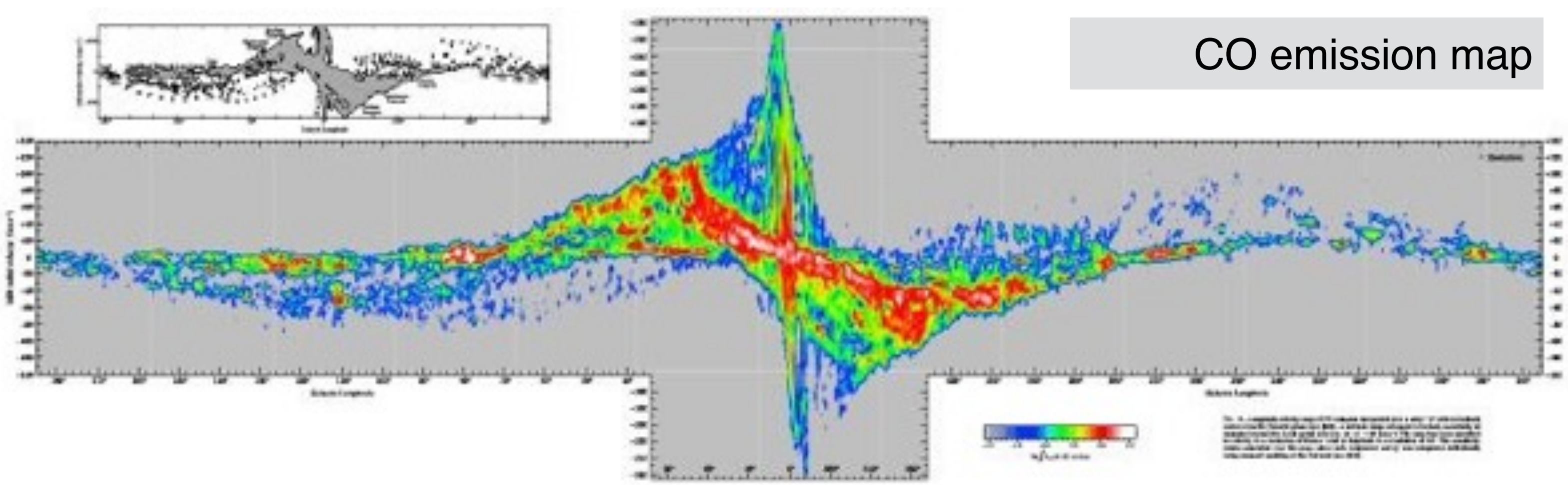
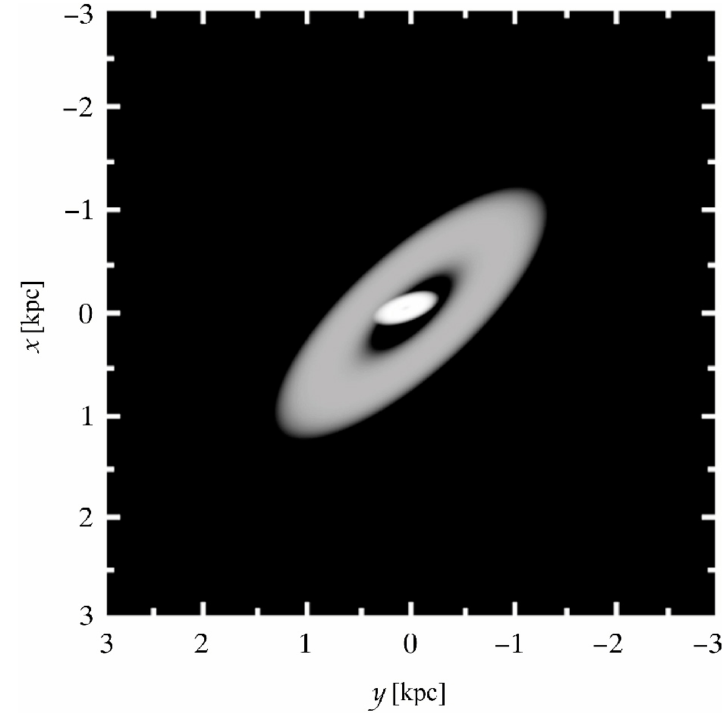


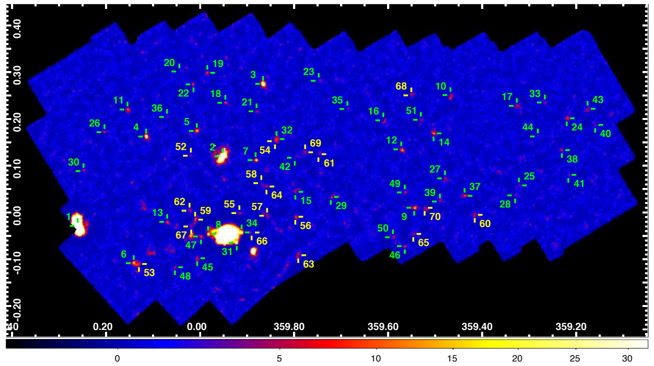
Gas distribution: we consider the state-of-the-art models by K. Ferrière (Ferrière 2001, Ferrière 2007)
very accurate models of the 3D gas distribution in the inner bulge, based on CO observations



CO emission map

Zoomed-in analytical 3D model of the distribution of interstellar gas in the inner Galactic bulge, from K. Ferrière 2007





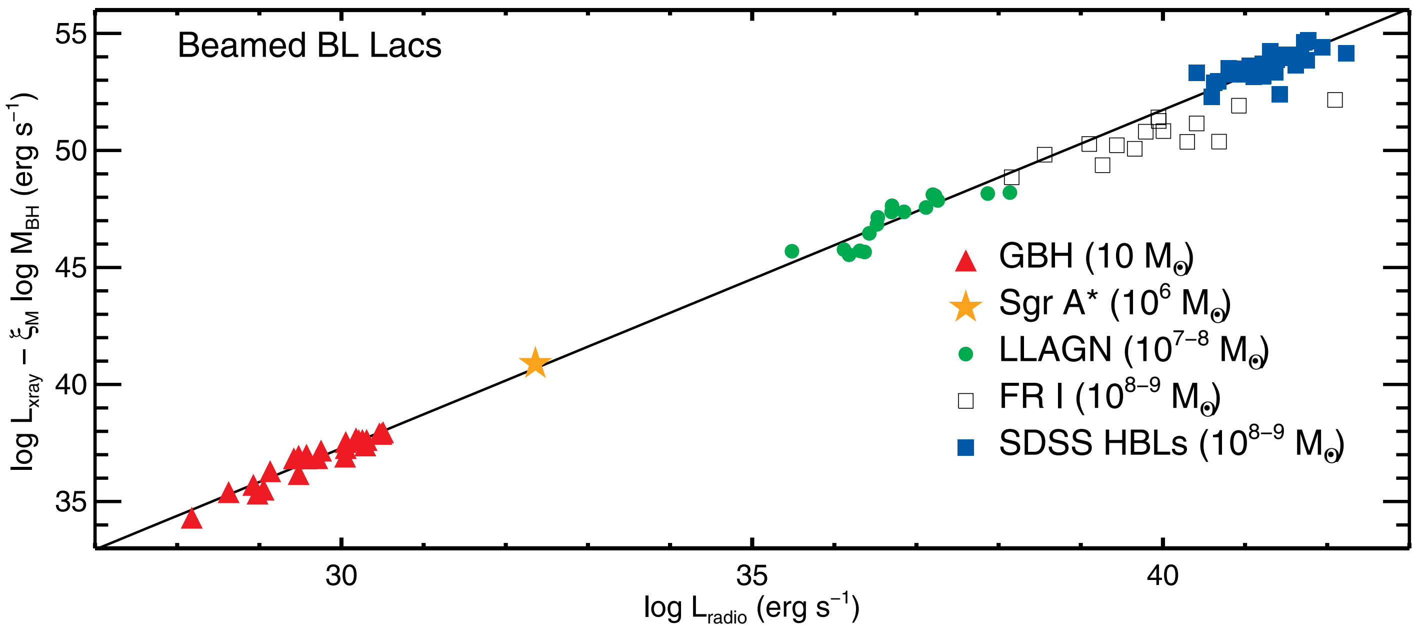
Comparison with the X-ray and radio data

X-rays:

We assume that 30% of the bolometric luminosity lies in the 2-10 keV band (*Fender 2013*)
We extrapolate to the 10-40 keV band assuming a hard power-law (index 1.6)

We compare against
the **NuStar catalog** (*Hong et al. 2016*)
data in the 10-40 keV band

*threshold: 8 * 10 ^{32} erg/s*
ROI: -0.9° < l < 0.3°; -0.1° < b < 0.4°



Radio:

Here the prediction is even more complicated

We rely on the empirical *fundamental plane relation* between soft X-ray and radio luminosity *[see e.g. Plotkin et al. 2013]*

We convert X-ray fluxes into radio fluxes (1 GHz) and compare to the number of predicted point sources to the **VLA catalog** (threshold ~1 mJy; we consider the ROI: -0.5° < l < 0.5°; lbl < 0.4°)

Our predictions for SKA (very optimistic scenario)

It is possible to get a strong bound (or detect a population of sources) ***even for much lower values of λ*** (as low as 10^{-3}),
but **a much larger integration time is needed**: O(1000 h)

compare to other projected bounds (e.g. pulsar timing, 21 cm fluctuations)