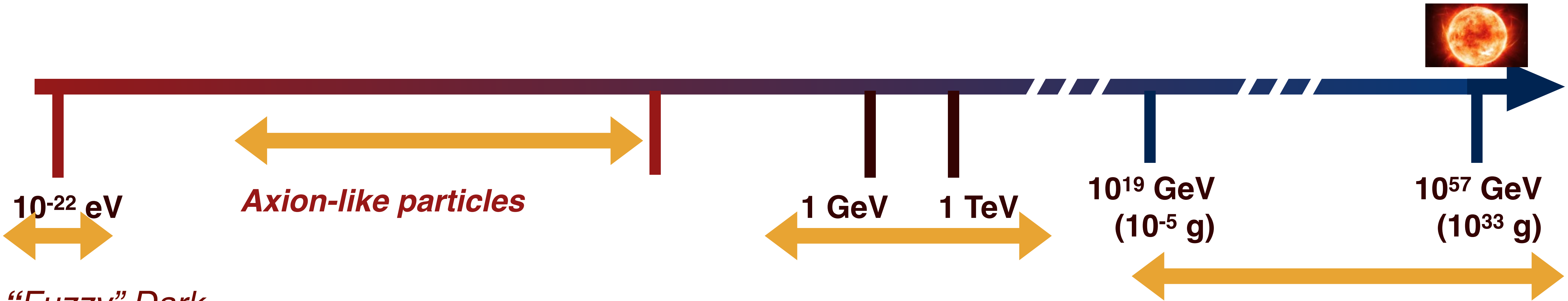
Searching for primordial black holes in the X-ray and radio sky

APS/LAPS/CAPS/SLAP
meeting
October 12th, 2017

Daniele Gaggero

GRAPPA
GRavitation AstroParticle Physics Amsterdam
Universiteit van Amsterdam

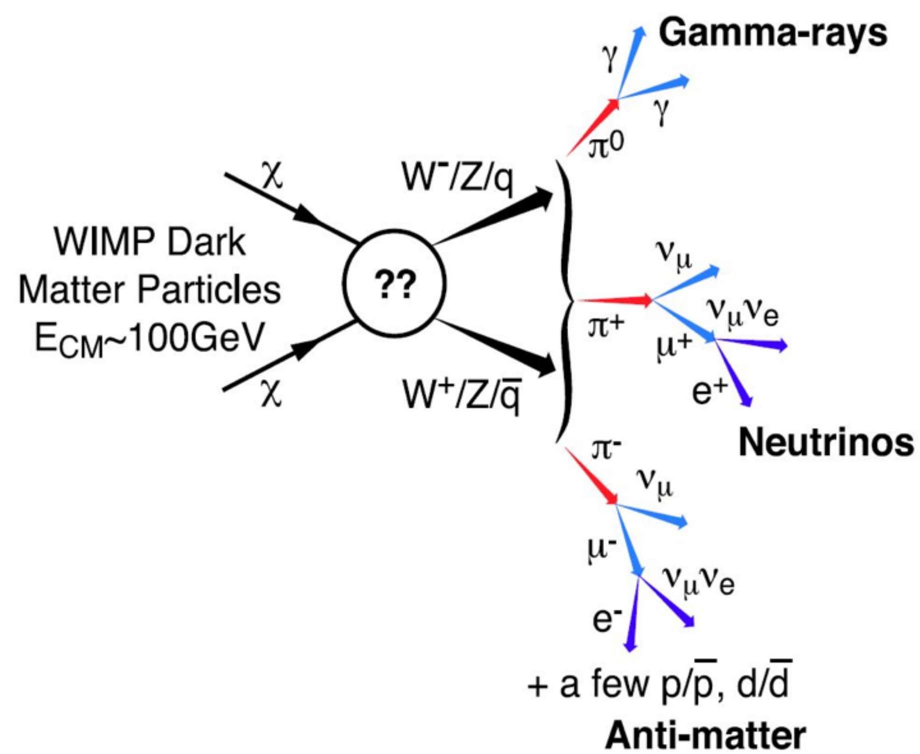
DM candidates: 90 orders of magnitude in mass



"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



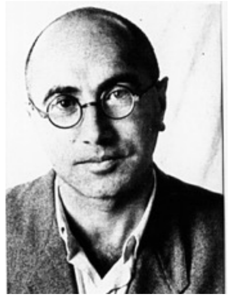
Primordial black holes (PBHs)

[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)

Brief summary on primordial black holes as DM candidate



- Primordial black holes first proposed by Zel’dovich and Novikov [*Y. B. Zel’dovich and I. D. Novikov, Soviet Astronomy 10, 602 (1967)*]

- Hawking proposed that early-Universe fluctuations could lead to the formation of PBHs with masses *down to the Planck mass* [*S. Hawking*, Mon. Not. R. Astron. Soc. 152, 75 (1971)]; see also [*Carr and Hawking*, MNRAS 168 (1974)]

density: $$\rho_S = 10^{18}\left(\frac{M}{M_\odot}\right)^{-2}\frac{\mathrm{g}}{\mathrm{cm}^3}$$

compare to early-Universe density: $$\rho_C = 10^{6}\left(\frac{t}{\mathrm{s}}\right)^{-2}\frac{\mathrm{g}}{\mathrm{cm}^3}$$

- **The early universe (t < 1 s) was an ideal environment for black hole formation:** the Jeans length scale and the Schwarzschild length scale were comparable

- **It is possible to build models of inflation providing peaks in the power spectrum compatible with the formation of PBHs in a given mass range** (e.g. Clesse&Garcia-Bellido *arXiv:1501.07565*, Garcia-Bellido&Morales *arXiv:1702.03901*)

Part 1: LIGO, PBHs and DM

Brief summary on primordial black holes as DM candidate

In general, **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, the PBHs have enough time to evaporate (Hawking-Bekenstein radiation)

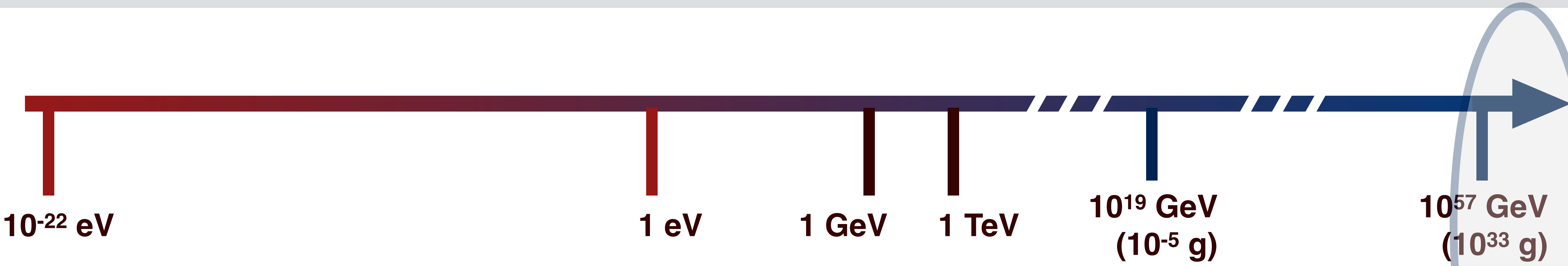
$$t_{\mathrm{evaporation}}[\mathrm{s}] = 10^{71}\left(\frac{M}{M_\odot}\right)^3$$

- 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:

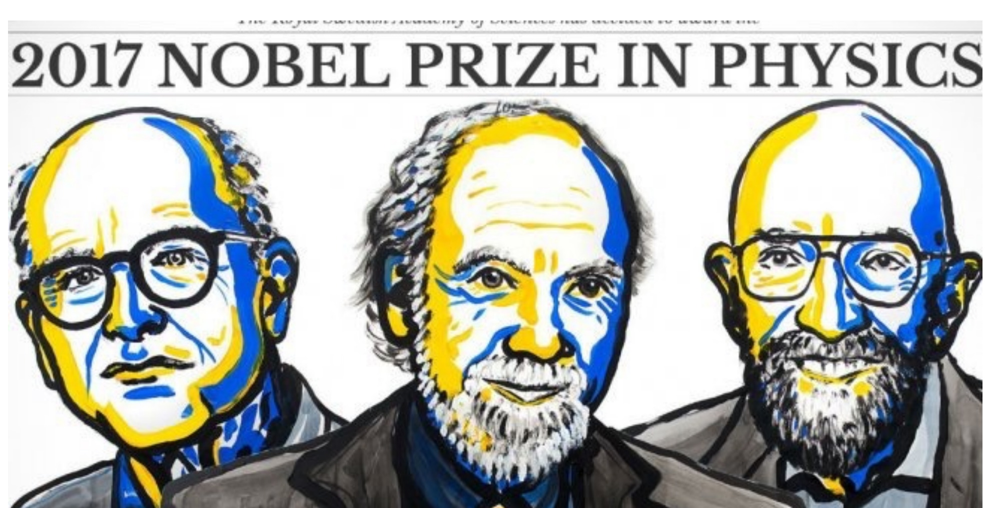
M ~ 10^{16} g (10^{-17} $M_\odot$) — 10^{39} g (10^5 $M_\odot$)
size ~ 10^{-13} cm — 10^{10} cm
number in our Galaxy ~ 10^{29} — 10^6

LIGO, PBHs and DM

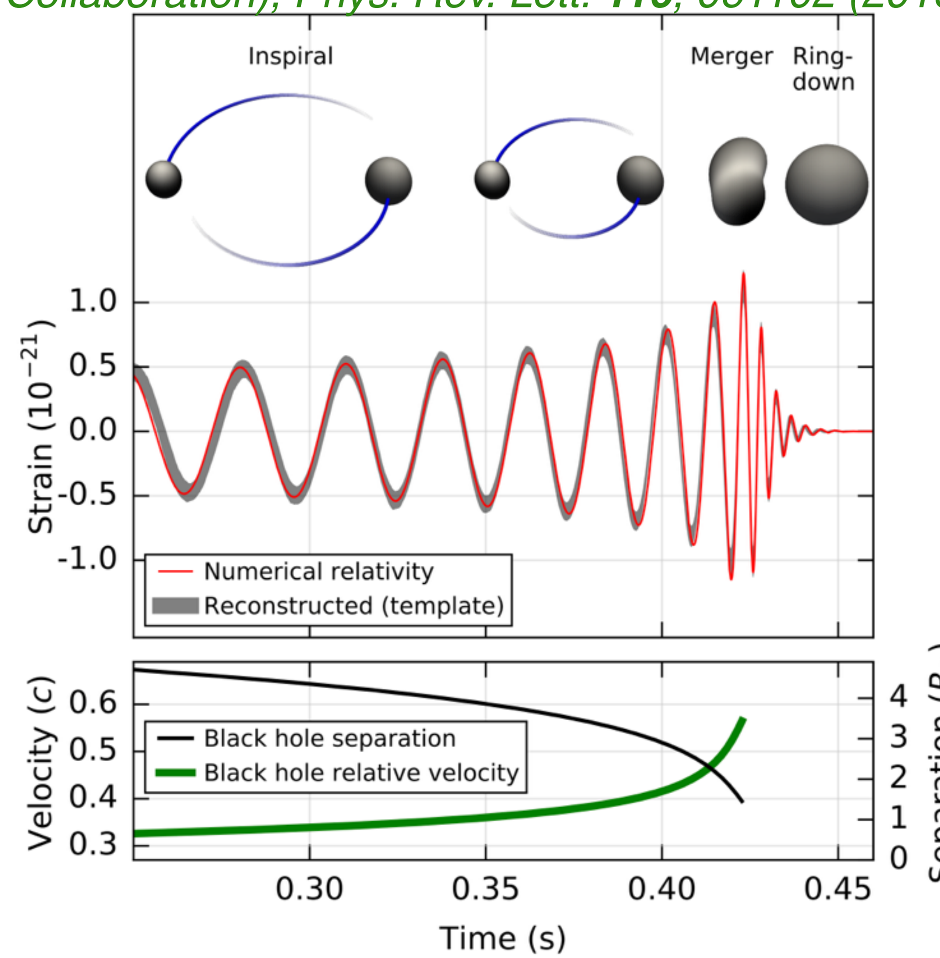


- Amazing detections in this mass window: The ***first direct detections of gravitational wave signals from black hole mergers!***
- The ***first direct detections of binary black hole systems***
- The ***first direct detections of stellar-mass black holes with M as large as 30 $M_\odot$***

(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*)



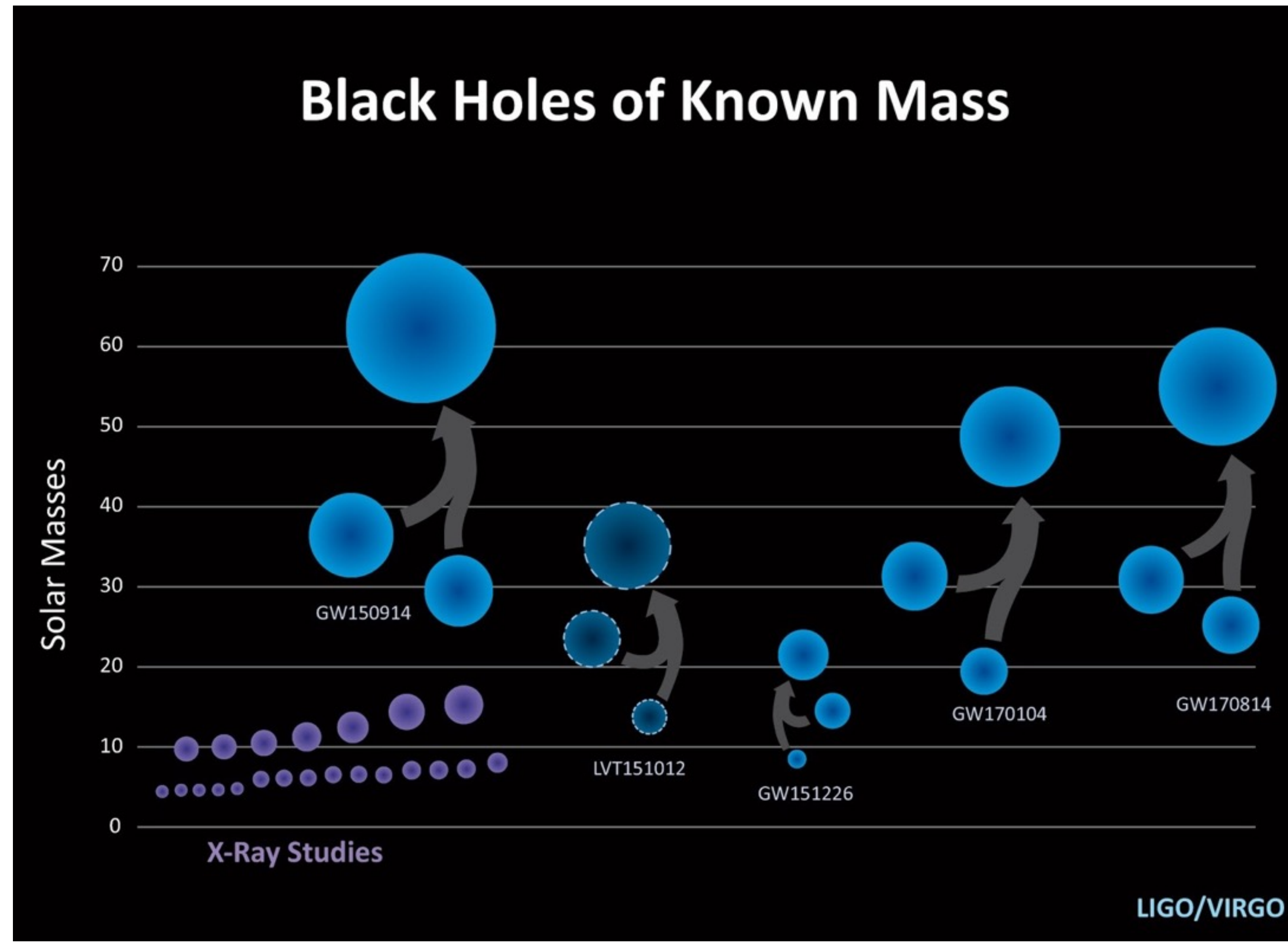
*Abbott et al. (LIGO Collaboration, Virgo Collaboration), Phys. Rev. Lett. **116**, 061102 (2016)*



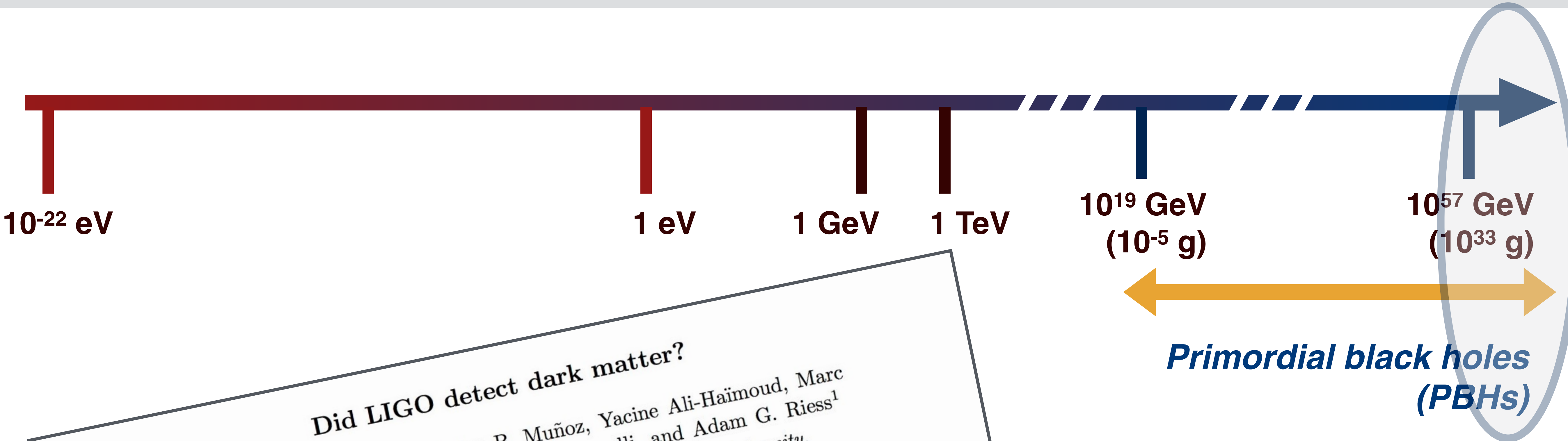
LIGO, VIRGO, PBHs and DM

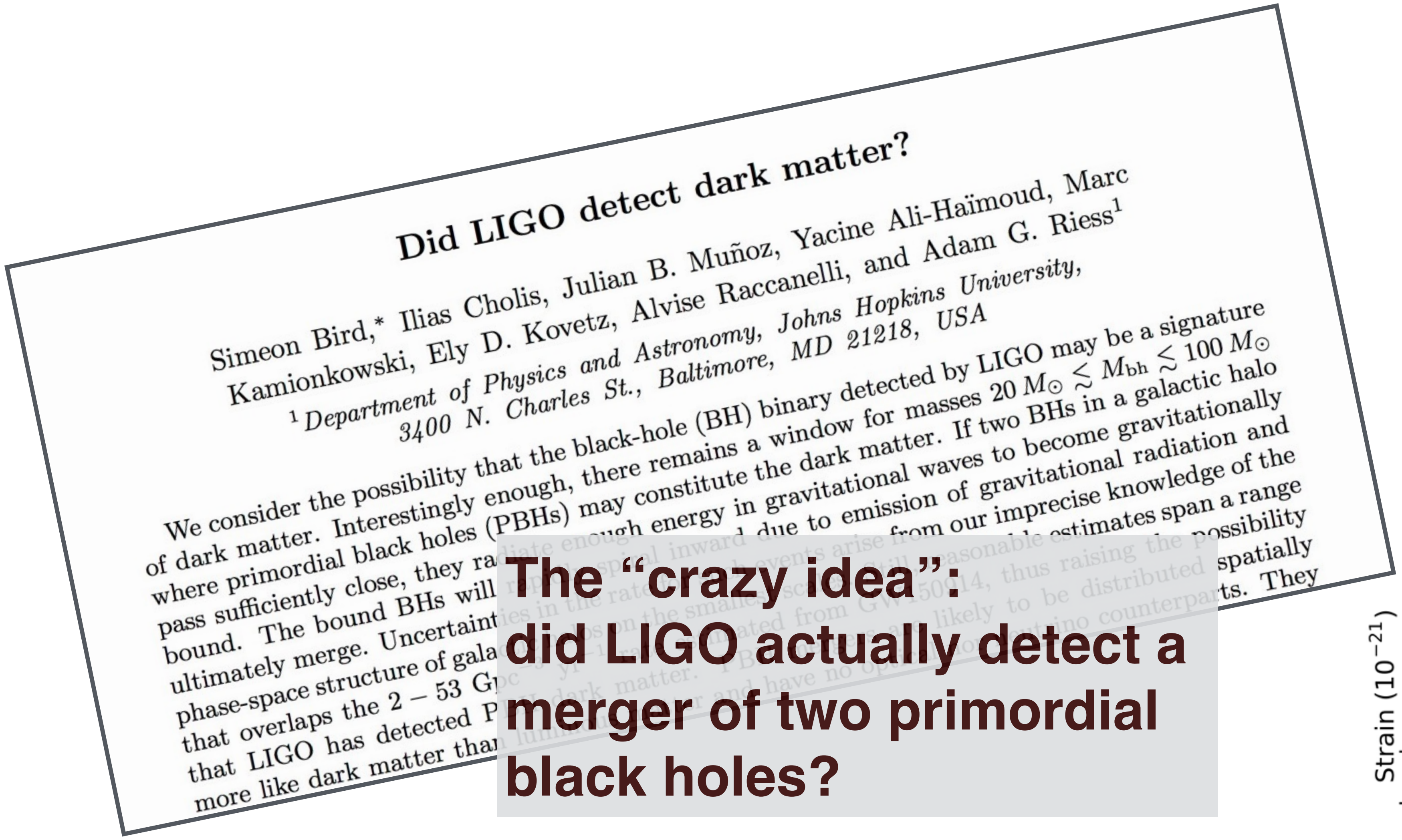
- Another event recently announced by the LIGO and VIRGO collaborations

*Abbott et al. (LIGO Collaboration, Virgo Collaboration), Phys. Rev. Lett. **119**, 141101 (2017)*



LIGO, PBHs and DM



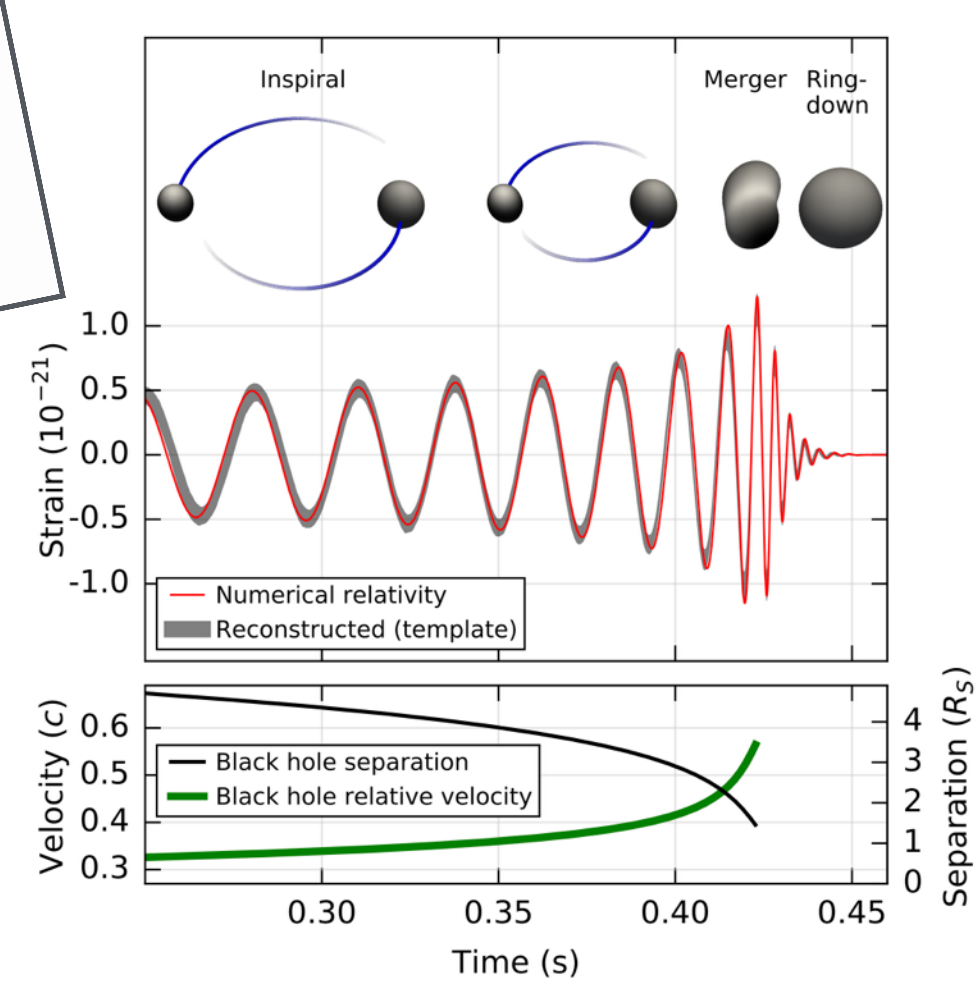

Did LIGO detect dark matter?

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 pass sufficiently close, they ra[...] enough energy in gravitational waves to become gravitationally bound. The bound BHs will [...] due to emission of gravitational radiation and ultimately merge. Uncertaint[...] from our imprecise knowledge of the phase-space structure of gala[...] estimates span a range that overlaps the 2 − 53 Gp[...] the possibility that LIGO has detected P[...] spatially more like dark matter than [...] counterparts. They

The "crazy idea": did LIGO actually 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*

LIGO, PBHs and DM

An argument based on rates: the predicted merger rate is compatible with the one inferred by LIGO…

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)*

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

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

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

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

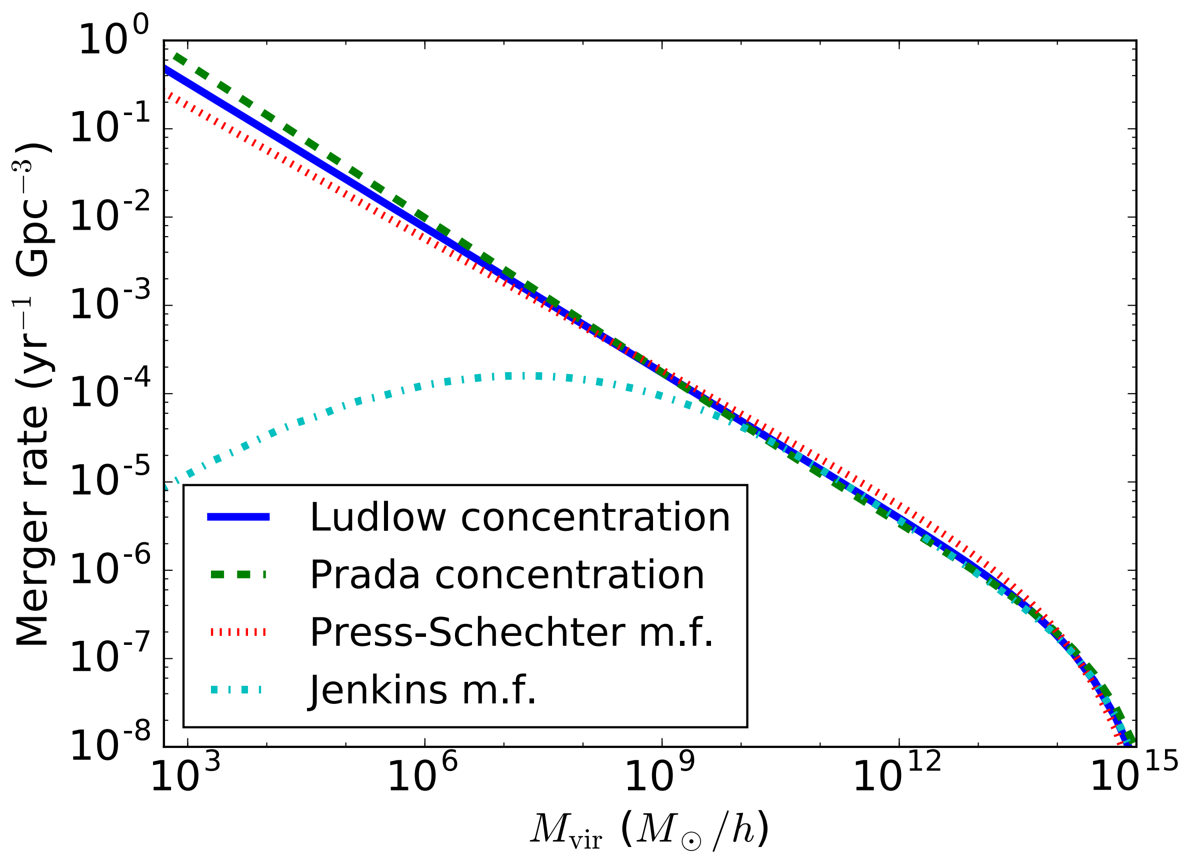
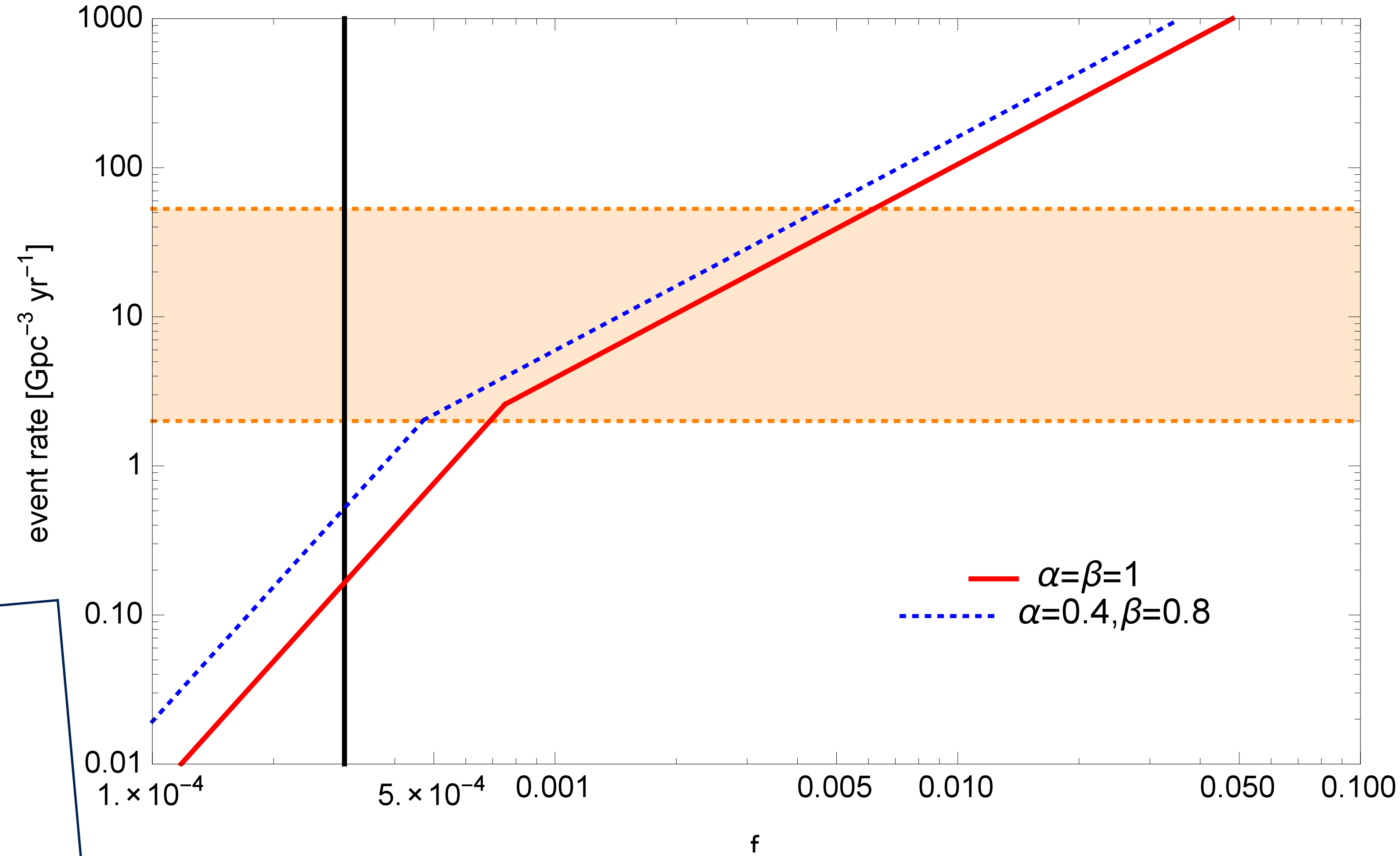


FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

LIGO, PBHs and DM

…unless one considers the pairs formed at matter-radiation equality

*Sasaki et al., Physical Review Letters, Volume **117**, Issue 6, id.061101 (2016)*



Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

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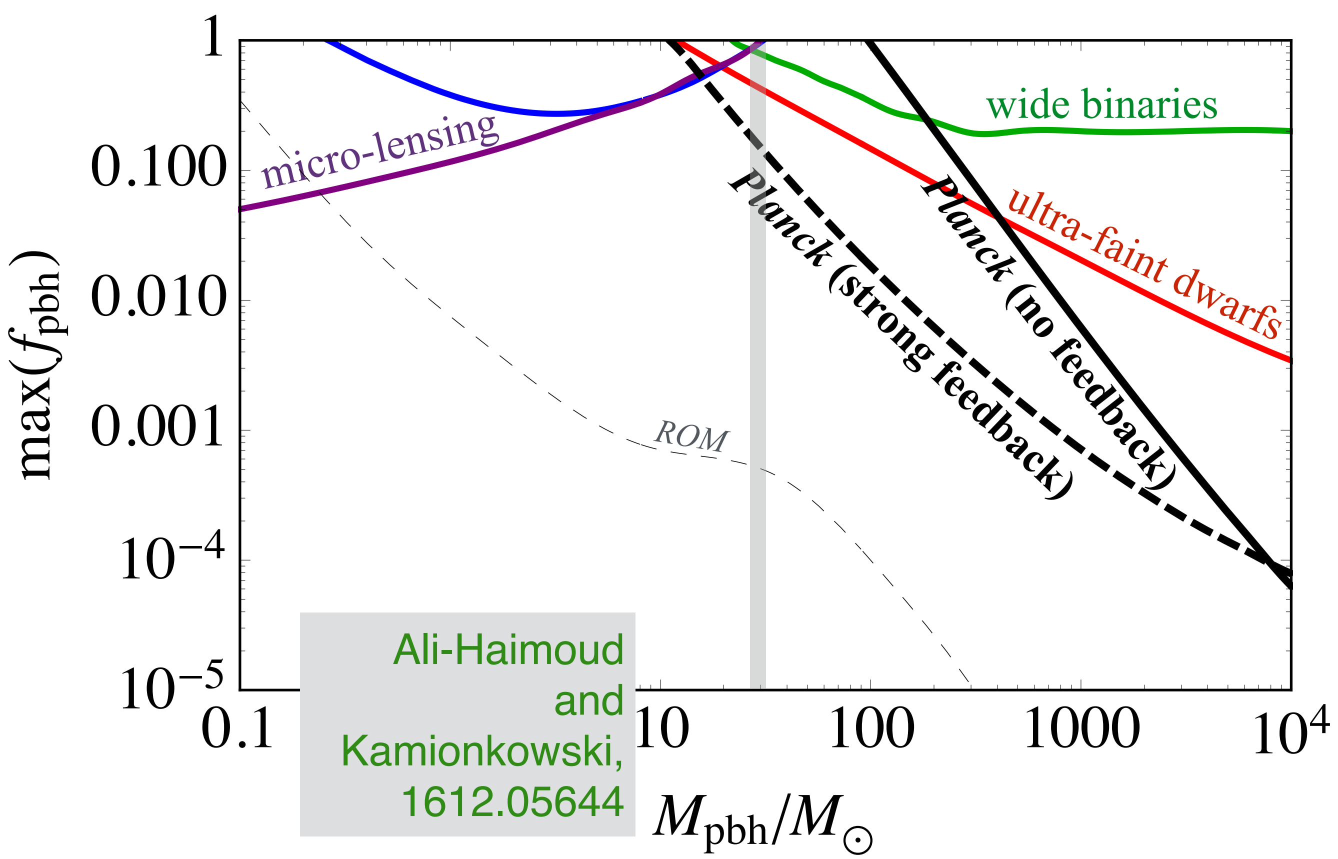
[d] Department of Physics, Rikkyo University, Tokyo 171-8501, Japan

Abstract

We point out that the gravitational-wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO Scientific Collaboration and the Virgo Collaboration if PBHs were the dominant component of dark matter, while it can be made compatible if PBHs constitute a fraction of dark matter. Intriguingly, the abundance of PBHs required to explain the suggested lower bound on the event rate, > 2 events Gpc^{-3}yr^{-1}, roughly coincides with the existing upper limit set by the nondetection of the cosmic microwave background spectral distortion. This implies that the proposed PBH scenario may be tested in the not-too-distant future.

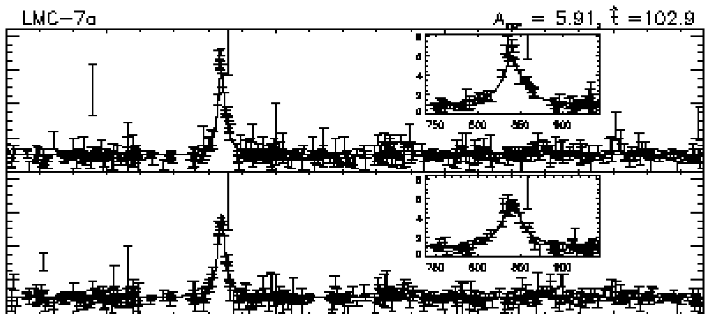
is DM made of PBHs? existing constraints

Existing constraints on DM as PBHs



- **Lensing constraints**

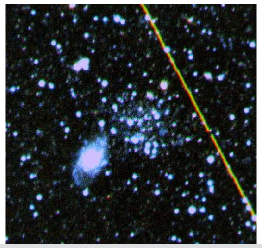
blue line: MACHO project [*Alcock et al. 2000*]: search for micro-lensing events towards the Large Magellanic Cloud. 13-17 short-duration events reported no long-duration (> 150 days) events -> constraints up to 30 Msun



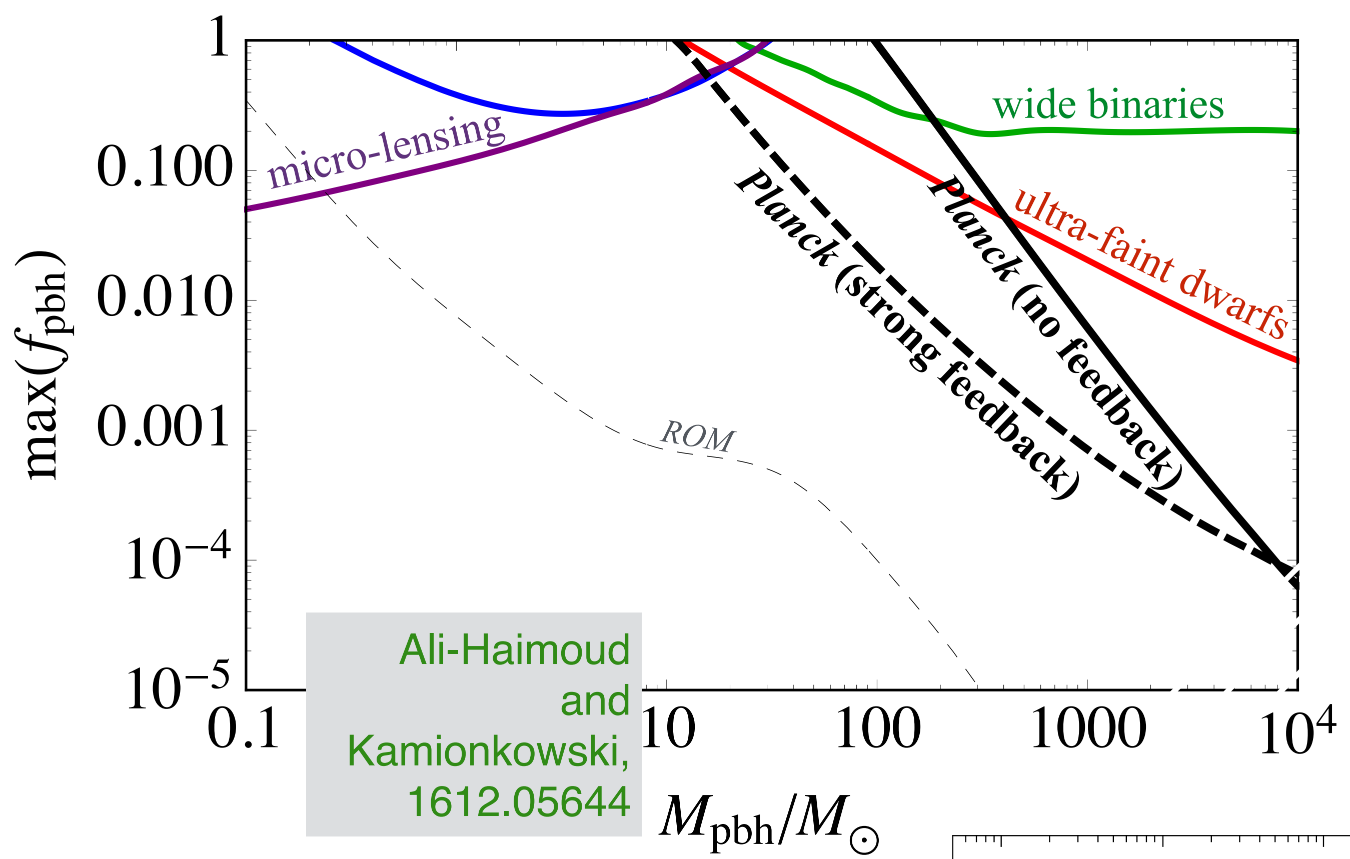
purple line: EROS project [*Tisserand et al. 2007*]; similar strategy, based on a 7-year monitoring of ~10^6 bright stars in the LMC and SMC

- **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



Existing constraints on DM as PBHs



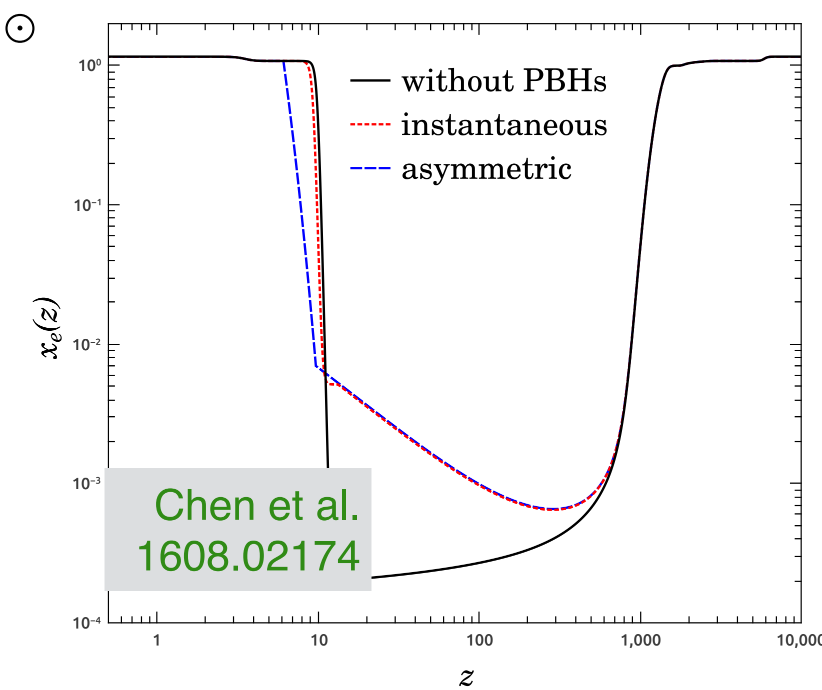
Ali-Haimoud and Kamionkowski, 1612.05644

- **Early universe constraints:**

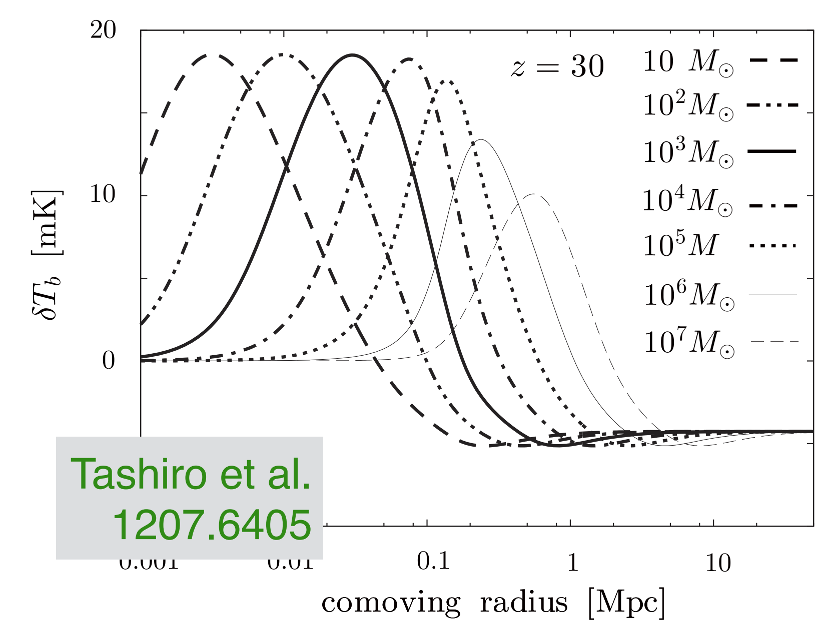
PBHs, if present in the early Universe, would accrete, radiate, heat up and partially reionize the Universe
(strong-feedback case assumes that the local gas is entirely ionized due to the PBH radiation)

Current bounds are under debate, and based on WMAP and PLANCK data.

***SKA** has the opportunity to probe the altered reionization history induced by PBHs looking at 21 cm brightness temperature fluctuations*



Chen et al. 1608.02174

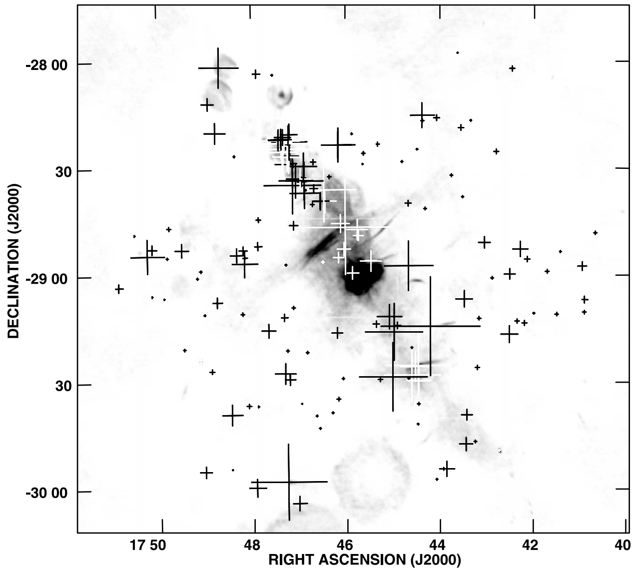


Tashiro et al. 1207.6405

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 ~30$M_\odot$ 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*)

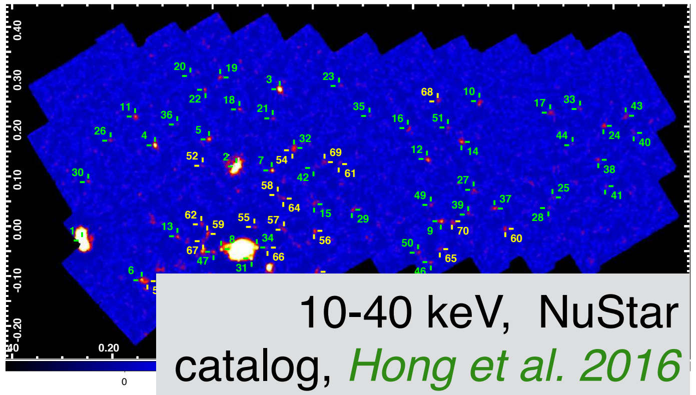


1.4 GHz, VLA, *Lazio & Cordes 2008*

- 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 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?



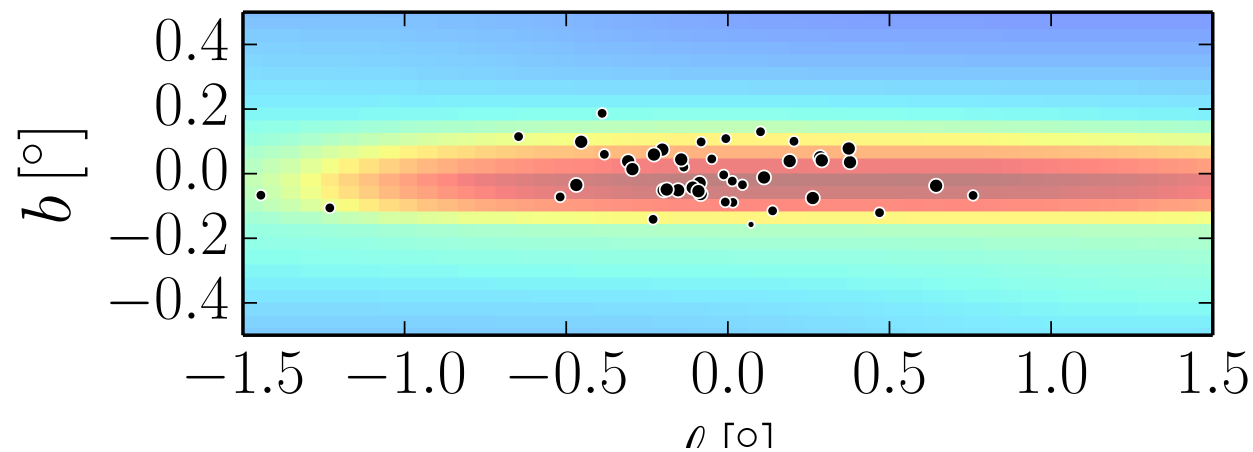
10-40 keV, NuStar catalog, *Hong et al. 2016*

Astronomical constraints: our simulation

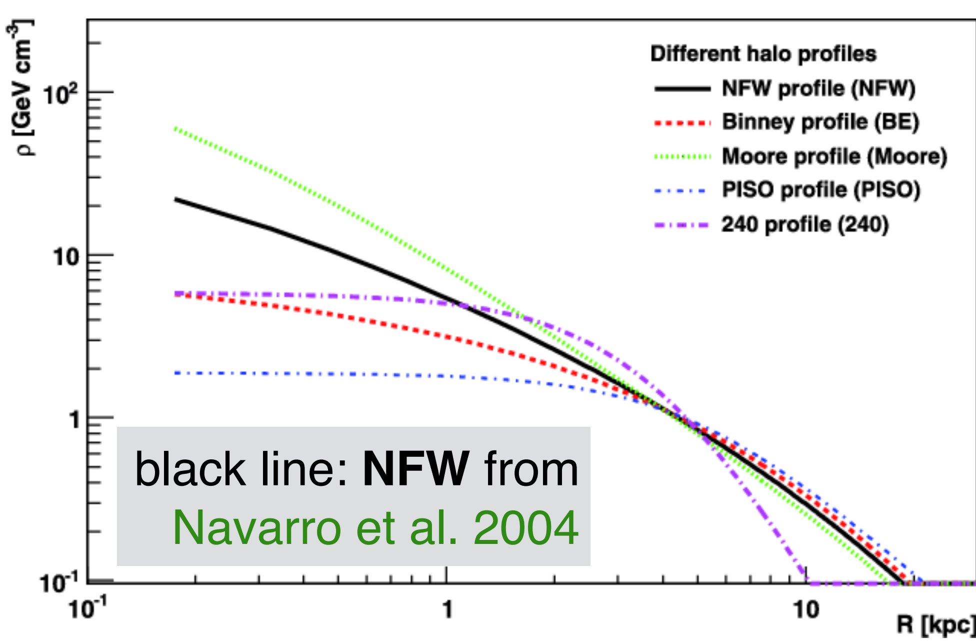
— We set up a MC simulation

— **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**

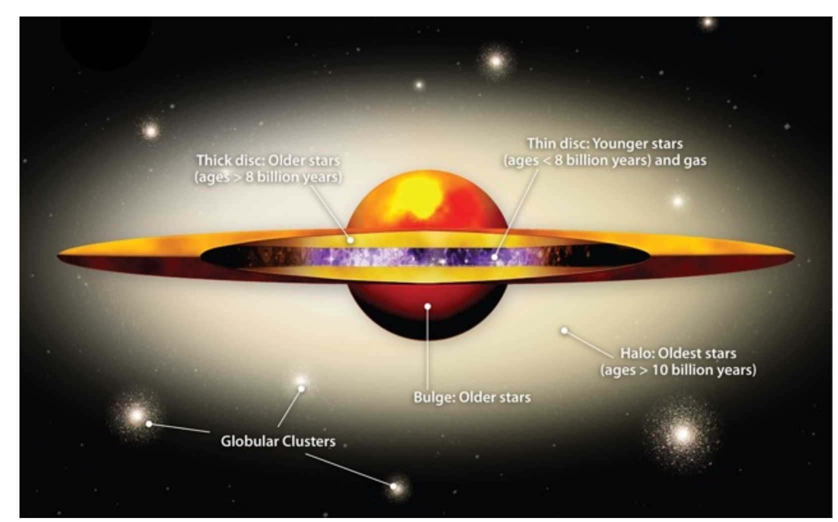


Spatial distribution of PBHs: We consider as a benchmark the NFW distribution.
We also consider other variations, based on numerical simulations with baryons (*see F. Calore et al., arXiv: 1509.02164*)



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*]

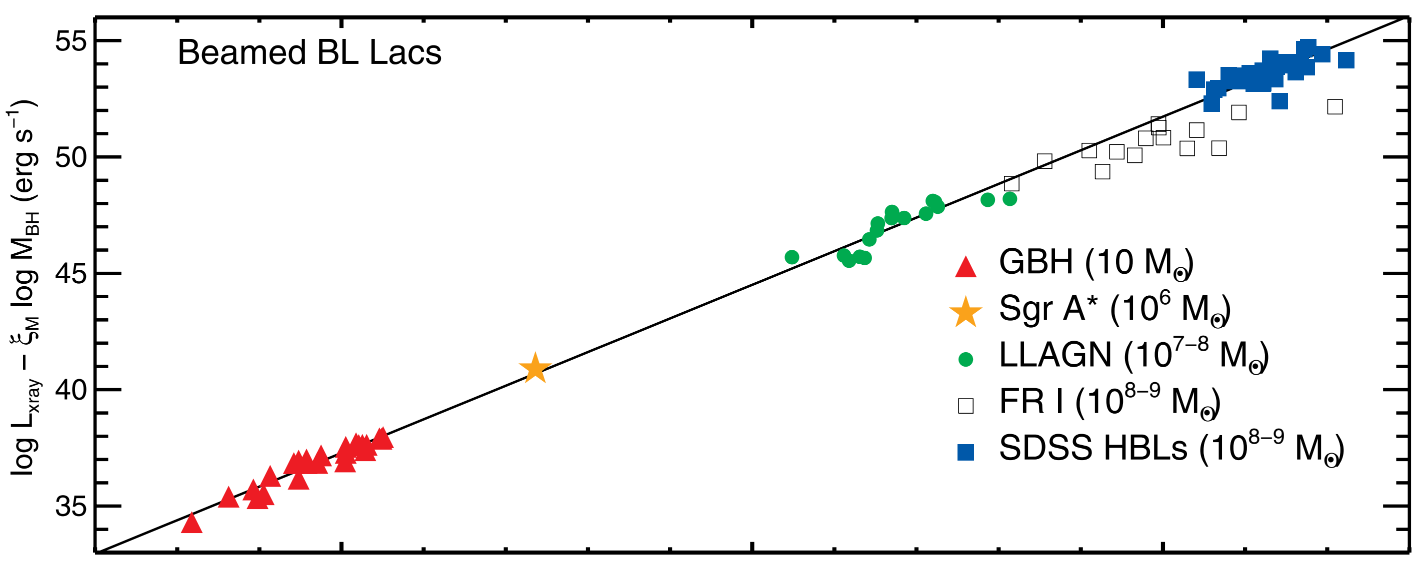
- We extrapolate to the **10-40 keV** band assuming a hard power-law (index 1.6)
- We compare to the **NuStar catalog** [*Hong et al. 2016*] data in the 10-40 keV band *(threshold: 8 * 10 ^{32} erg/s; ROI: -0.9° < l < 0.3°; -0.1° < b < 0.4°)* and to the **Chandra** catalog in the 0.5-8 keV band

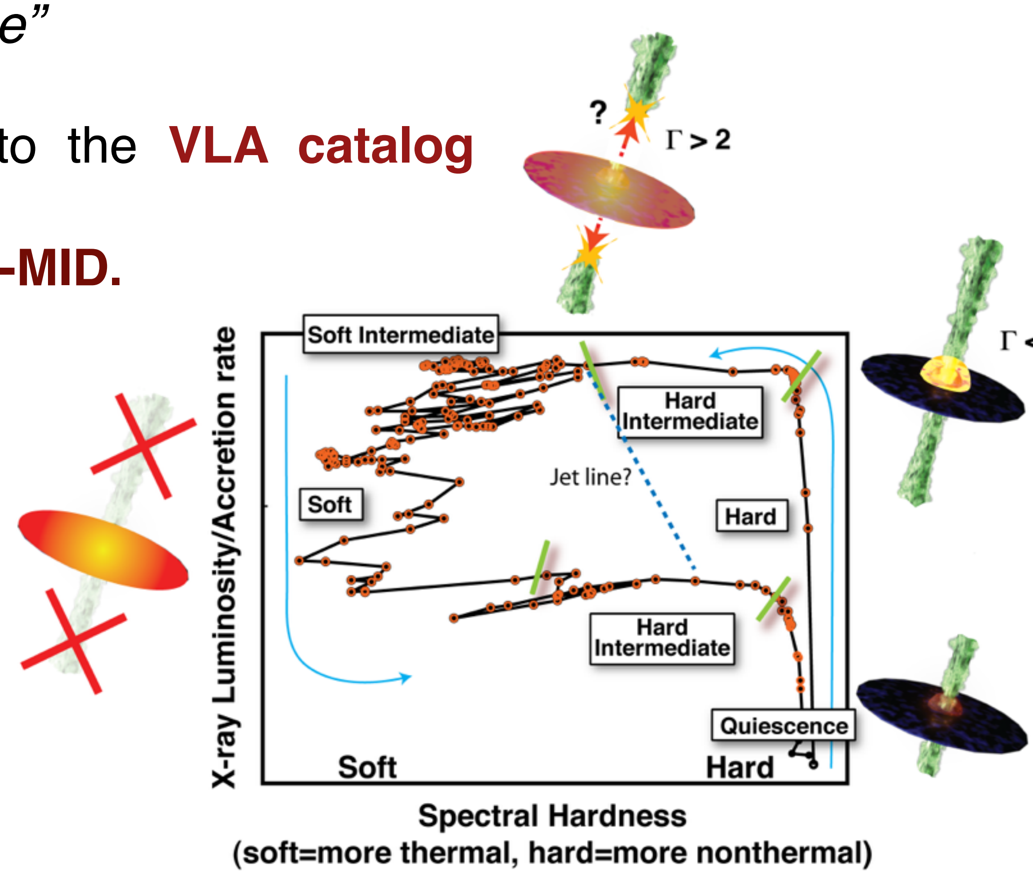
Radio:

- 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***

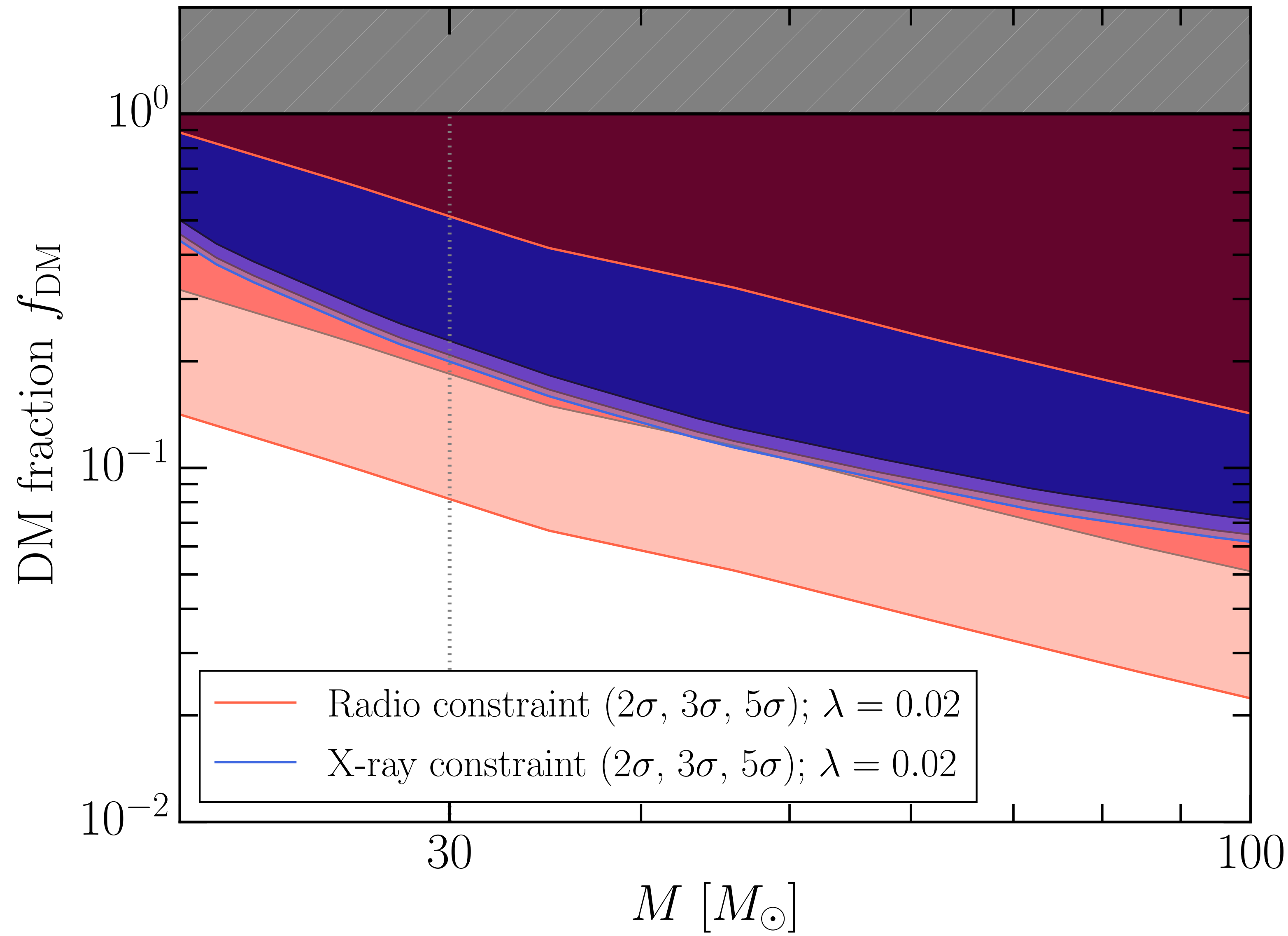
(40% are cataclysmic variables)

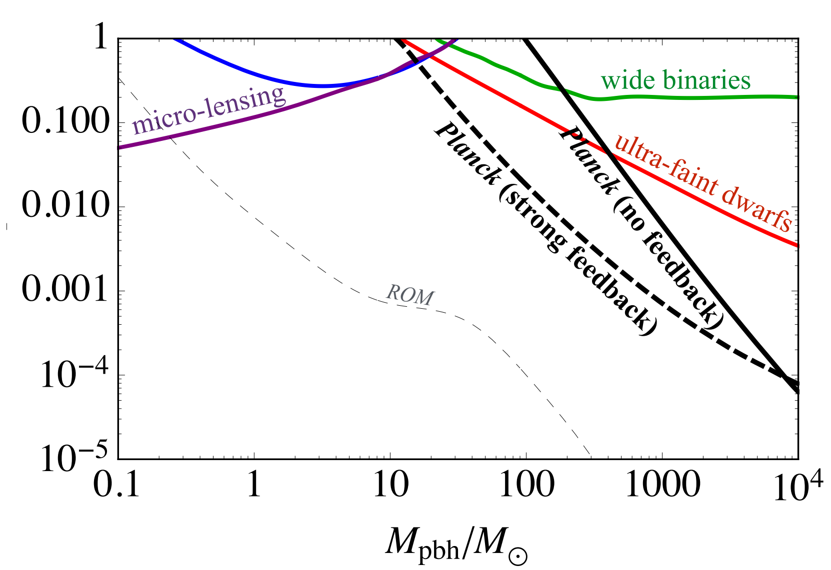
Radio:

- 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)





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)

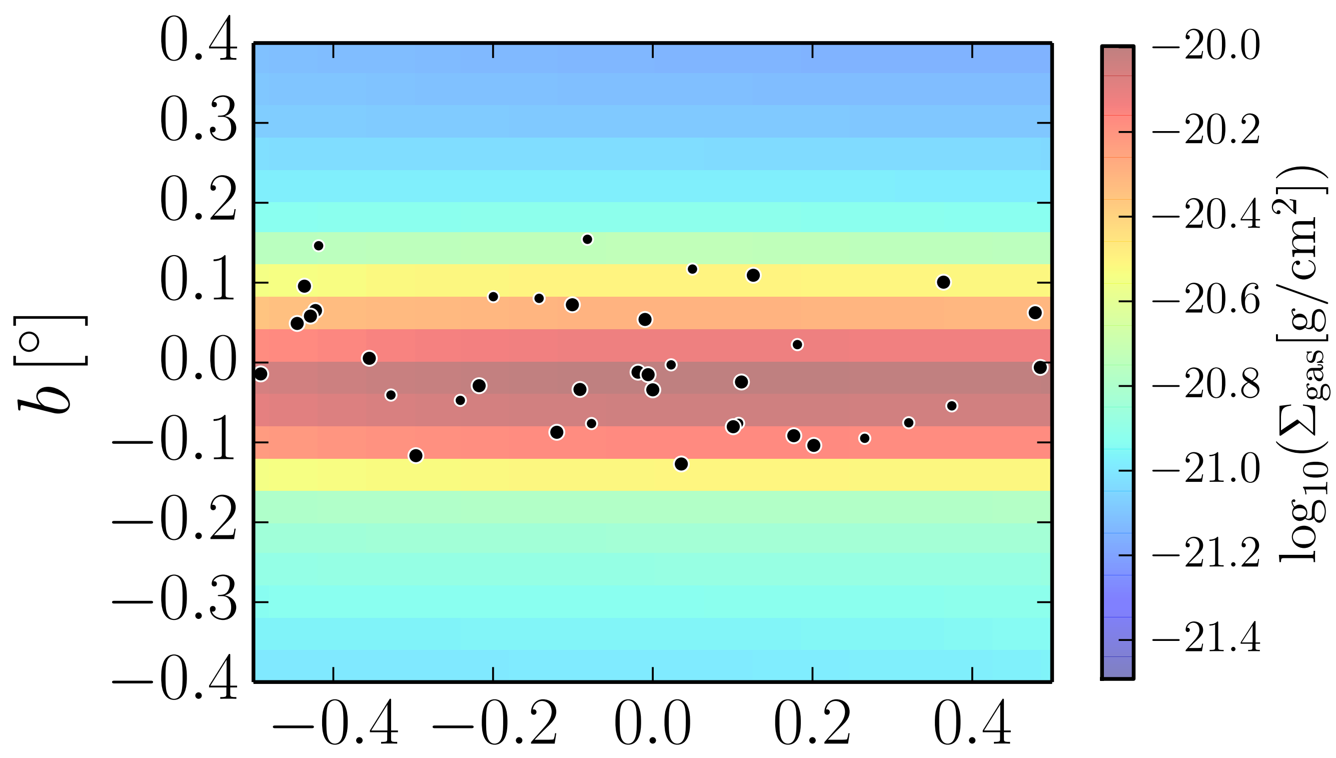
Radio:

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

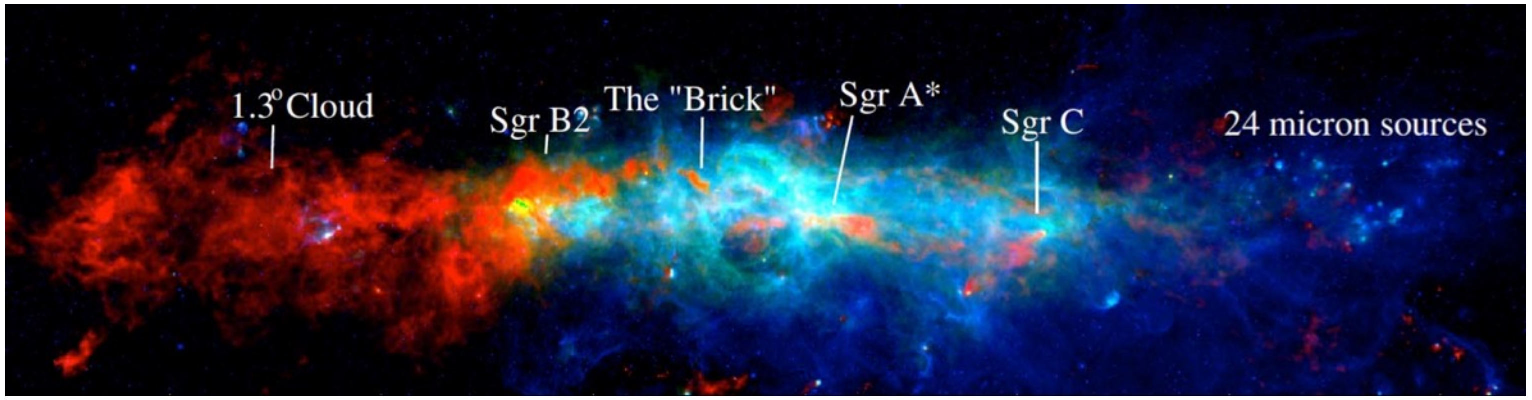
- Observed radio sources in the ROI: 170

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

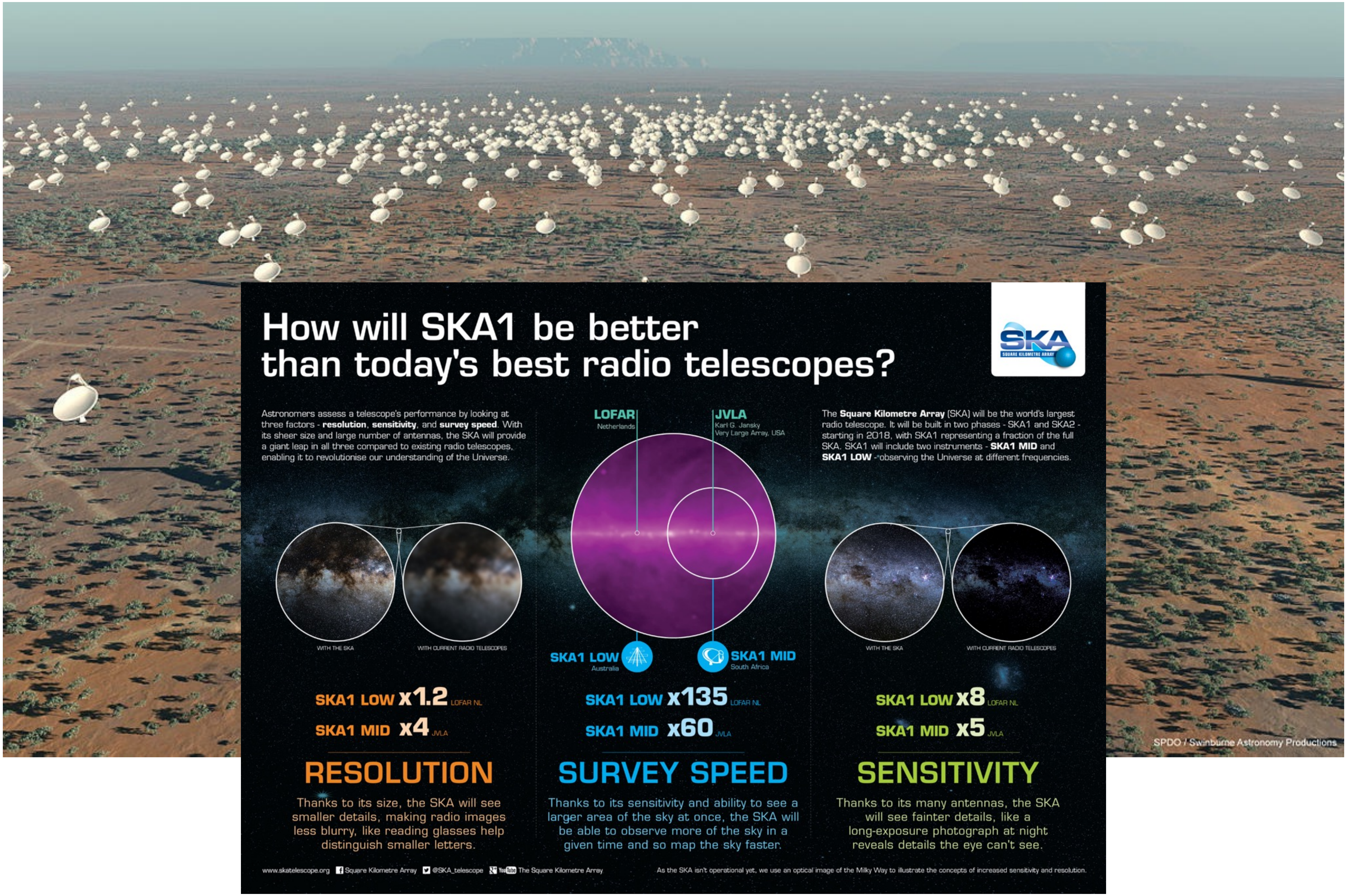
(i.e. no radio source in the ROI have a X-ray counterpart compatible with the FP relation they cannot be BHs accreting in the hard state)



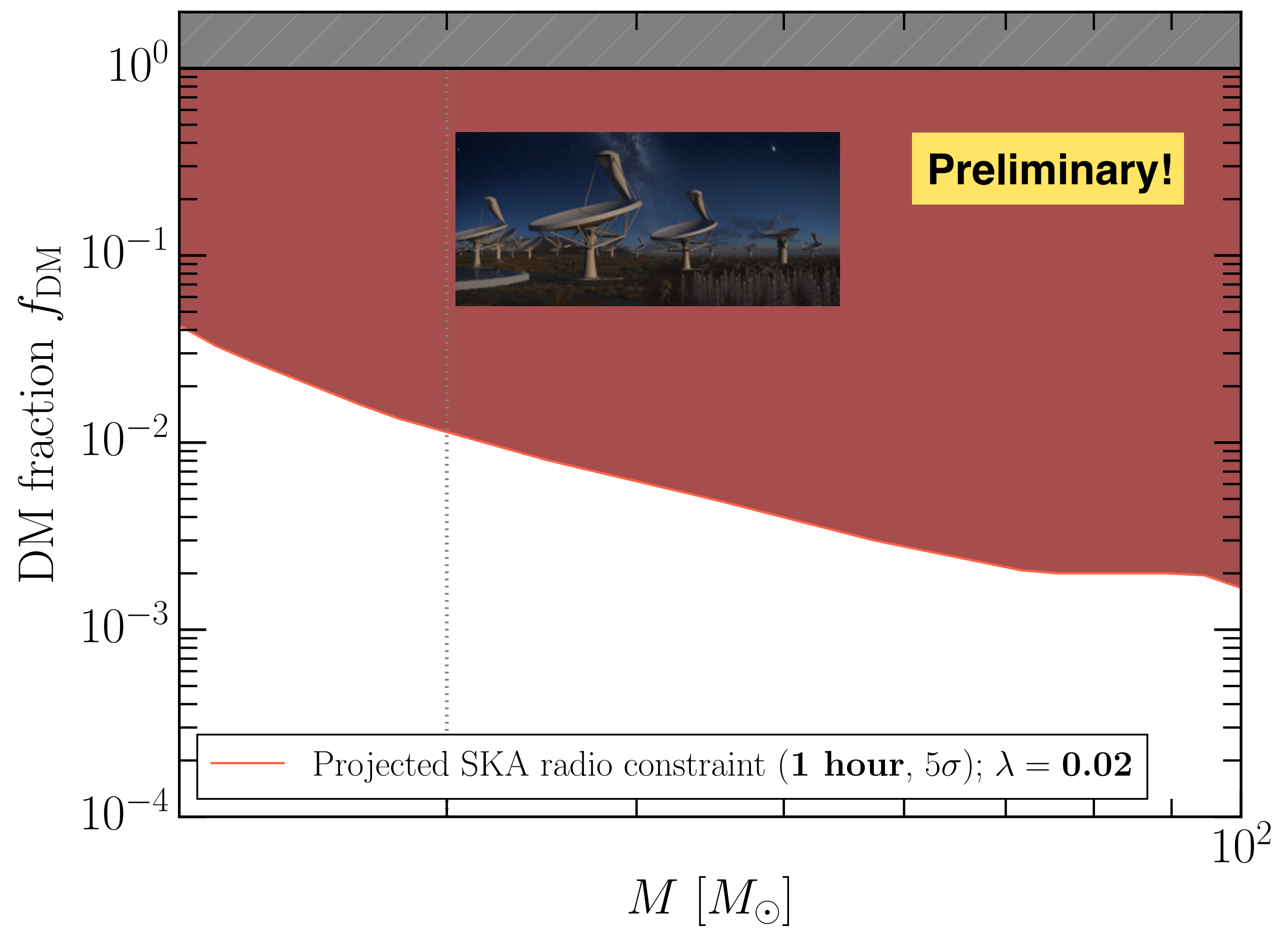
The constraining power mainly comes from BHs in the low-velocity tail of the BH distribution (v < 10 km/s) accreting gas in the Central Molecular Zone (a compact, very dense region in the inner Galactic bulge)

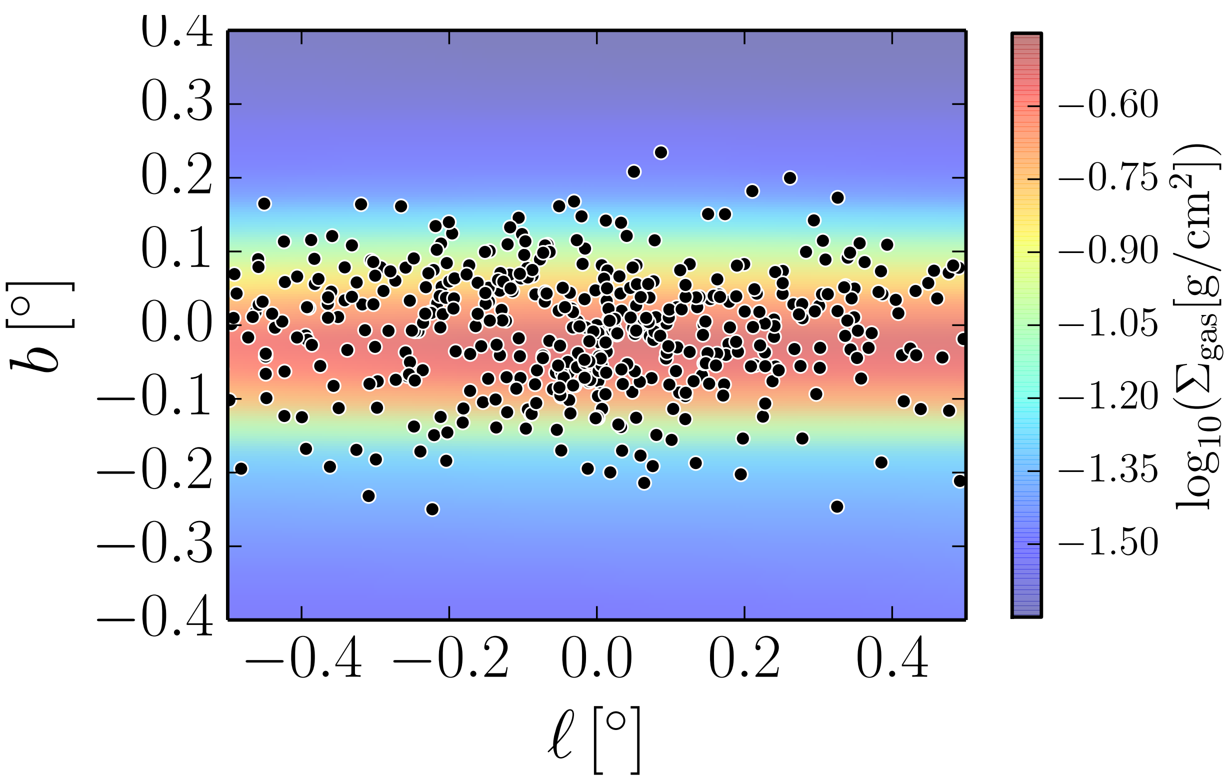


The role of SKA



The role of SKA



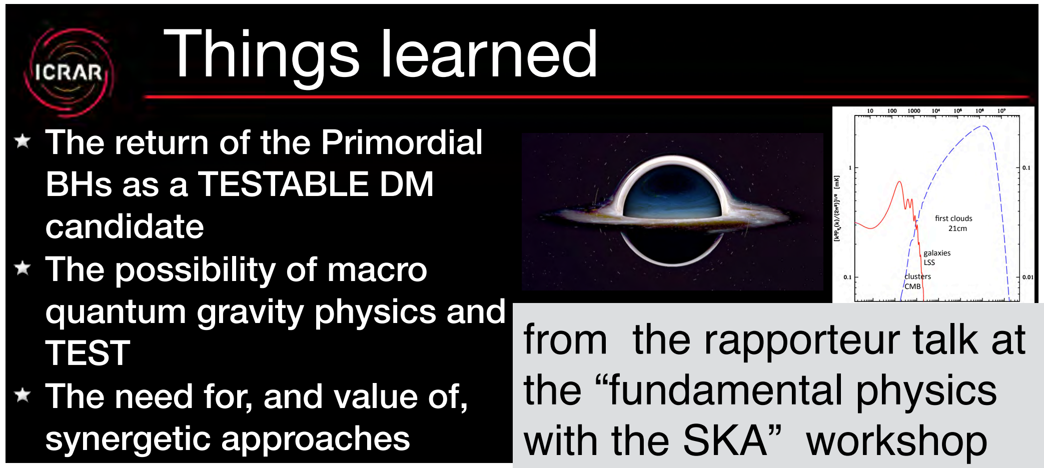


With the **SKA1-MID** (band 2, 0.95-1.76 GHz) point-source sensitivity, we predict to detect ~**2000** sources in our ROI (<1° away from the GC) for *1 hour* of exposure, **if PBHs are the DM and λ ~ 0.02**.

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

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 a massive BBH system

2) **Several constraints exist** on this scenario, from lensing, dynamical arguments, early-universe studies. The 10-50 Msun window is very weakly constrained though.

3) We asked ourselves: If the PBHs are the DM, **how easily can they be hidden?**

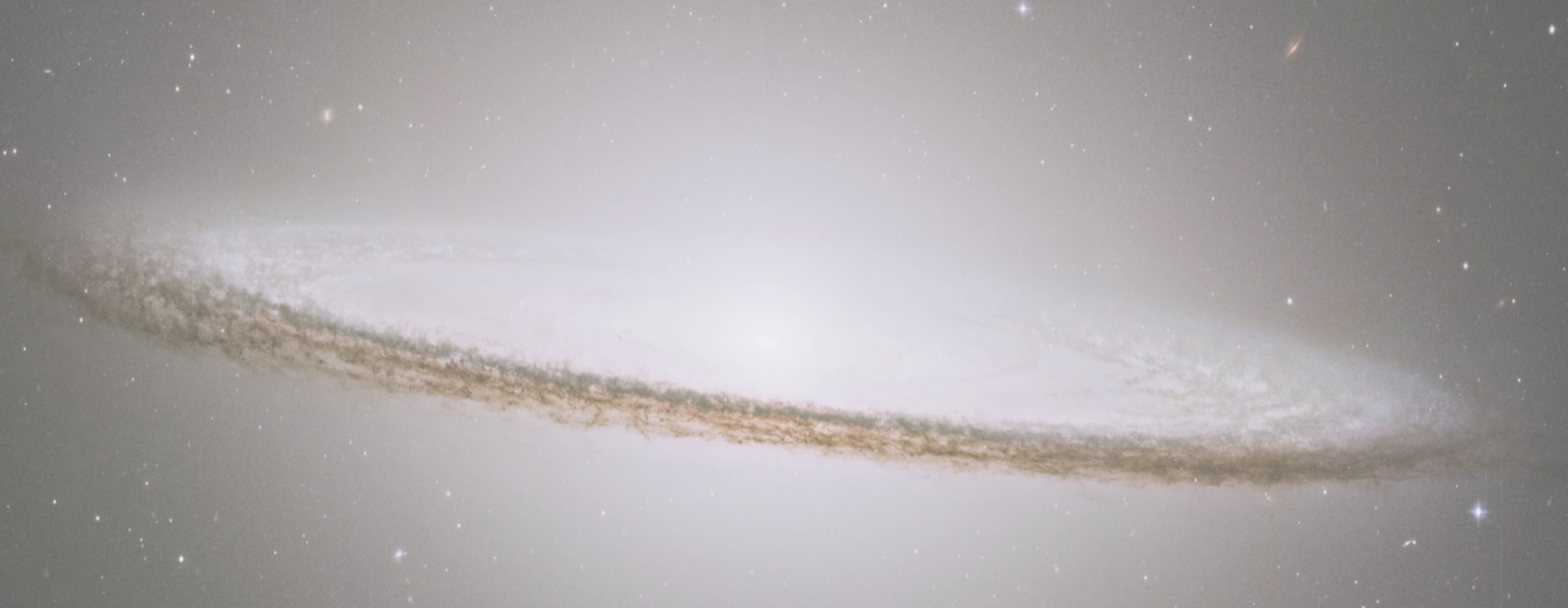
4) **We set up a MC simulation** to predict the number of bright X-ray and radio sources we should see in a tiny ROI around the GC, if PBHs are the bulk of the DM.

5) We considered a very conservative scenario (much more conservative than many papers on CMB constraints)

6) 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**

Thank you for your attention!



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Backup Slides

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?

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

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

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

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

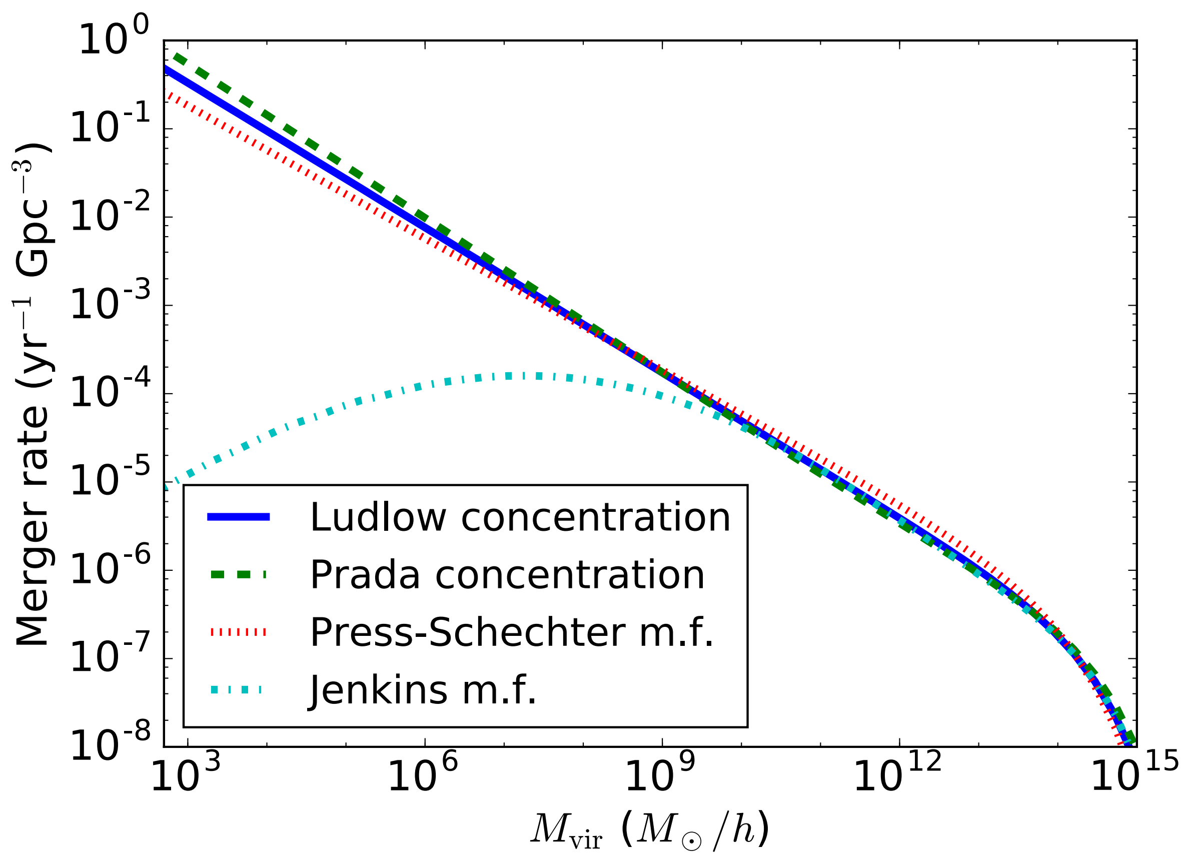

FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

Part 1: LIGO, PBHs and DM

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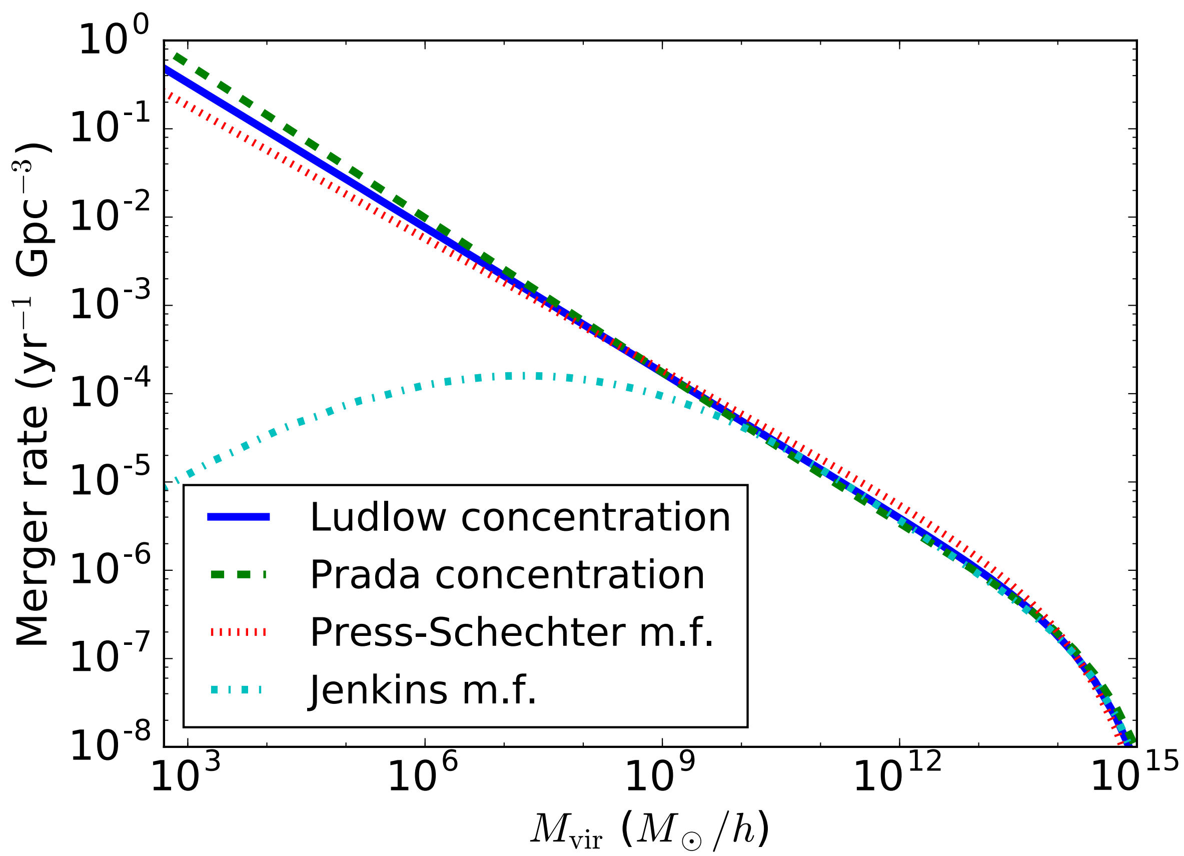
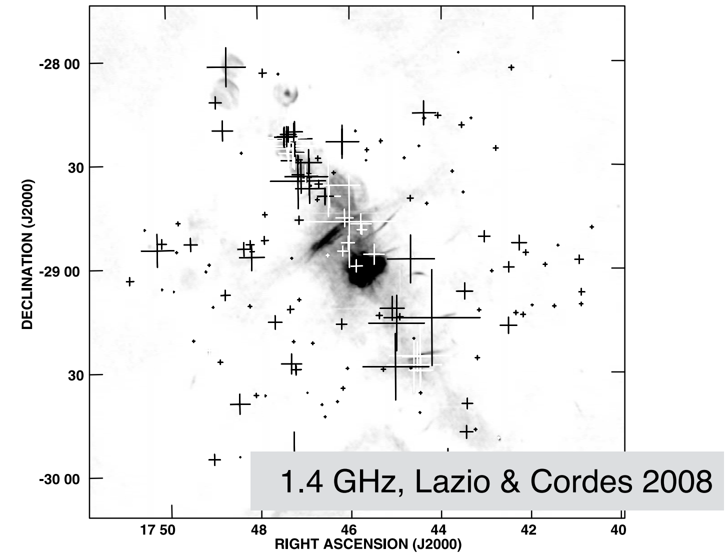


Compatible with the rate inferred by the LIGO collaboration!

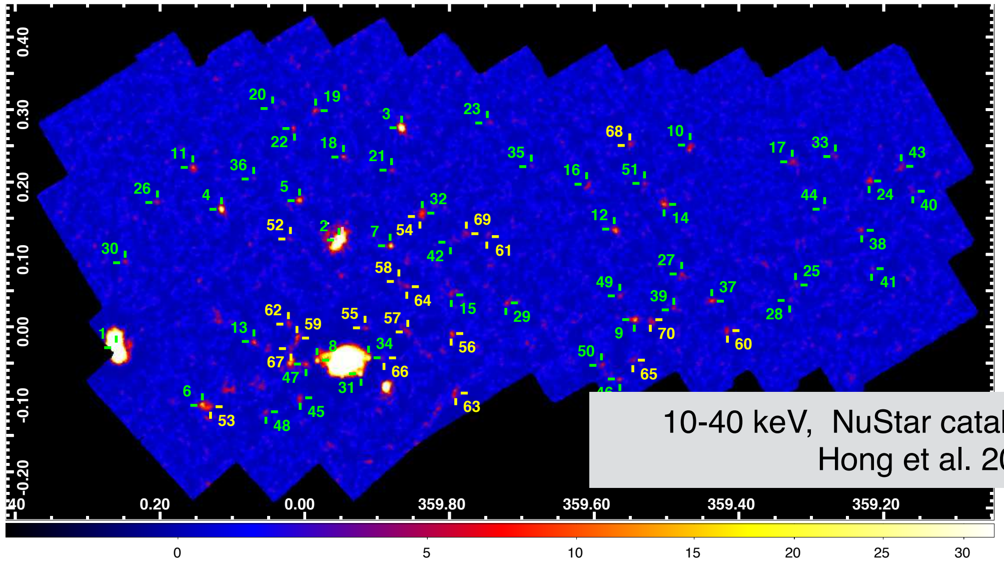
Our idea: why not using current astronomical observations in the radio and X-ray band?

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

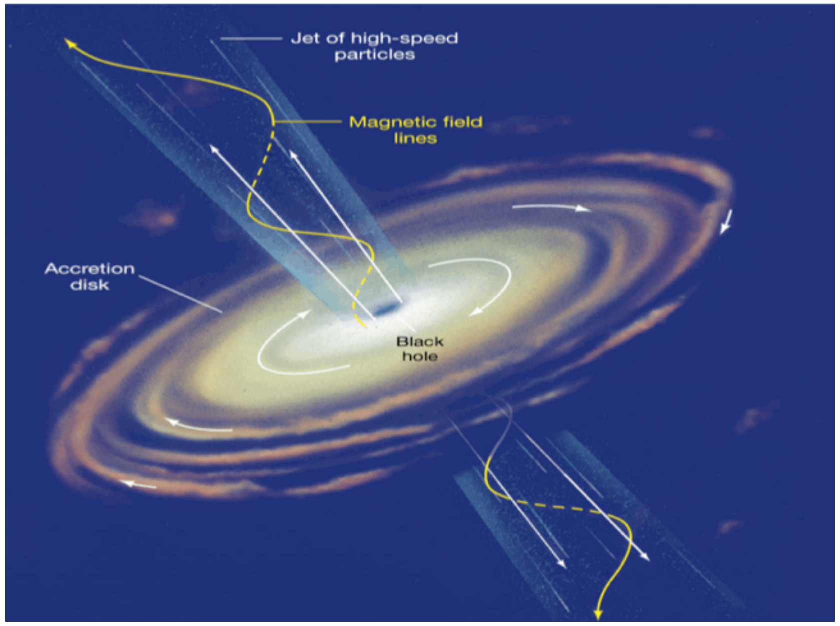
- If ~$30M_\odot$ PBHs are the DM, there should be **~10^{11} objects of this kind in the Milky Way, and ~10^{8} in the Galactic bulge**. (*as a comparison, we expect ~10^{8} astrophysical stellar-mass black holes in our Galaxy, see e.g. Fender et al. 1301.1341 “The closest black holes”*)
- The question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

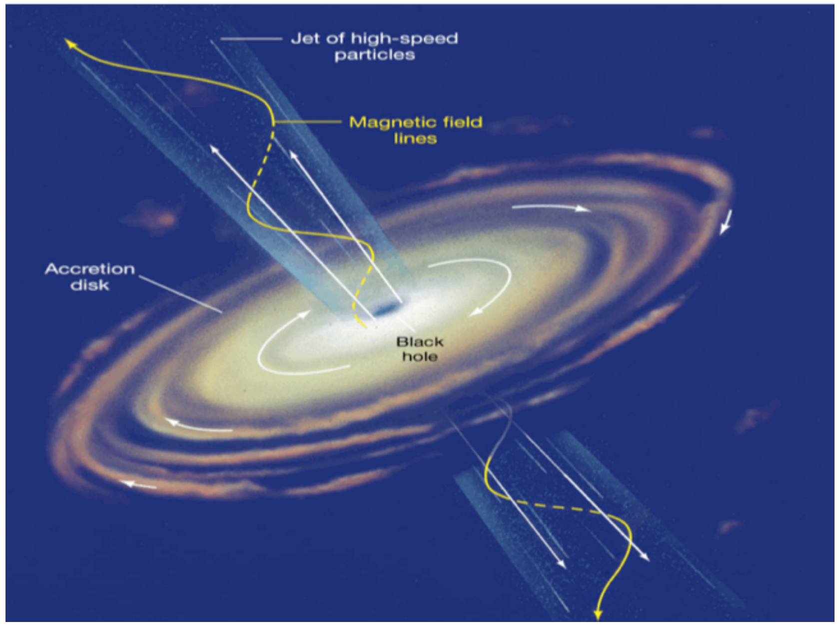
1) we parametrize the accretion rate as a fraction of the Bondi-Hoyle rate:

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

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

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

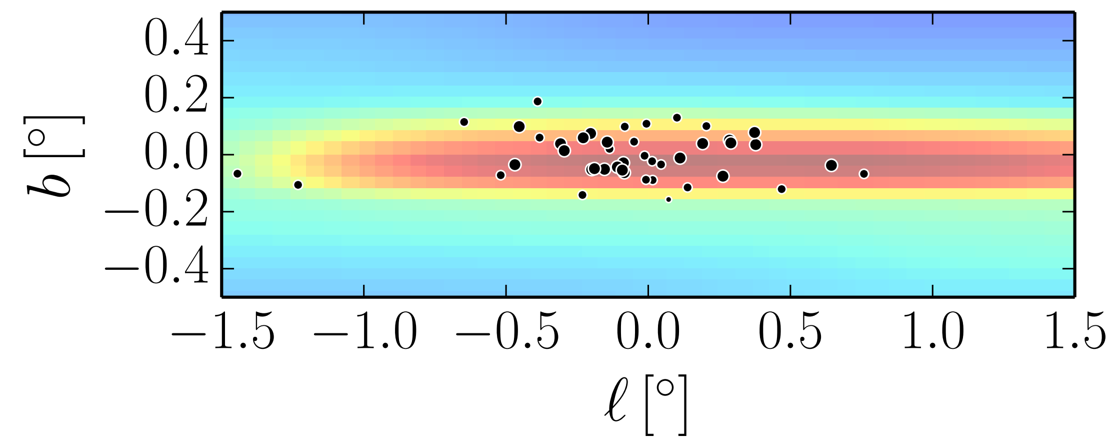
Physical picture: *advection-dominated accretion* in which the gas cooling timescales greatly exceed the dynamical timescales; mass loss from the disc or internal convective flows.

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"*

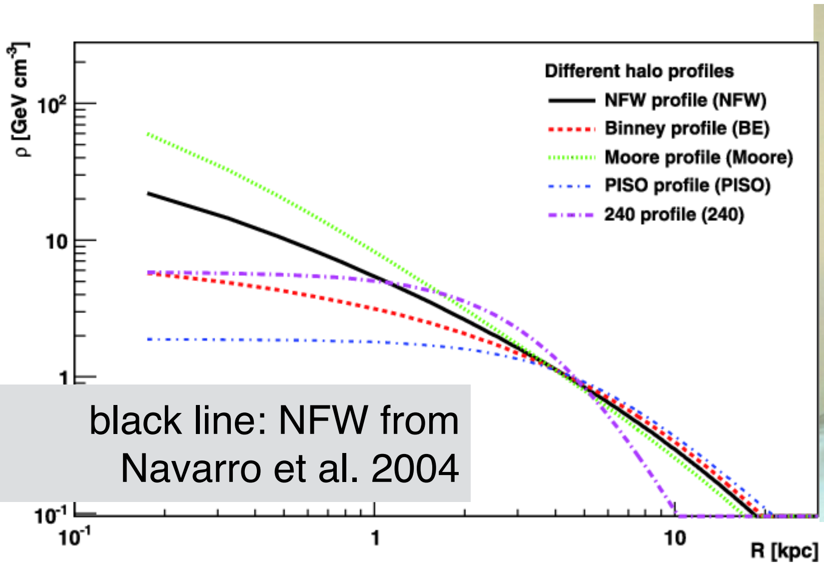
Part 1: LIGO, PBHs and DM

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**

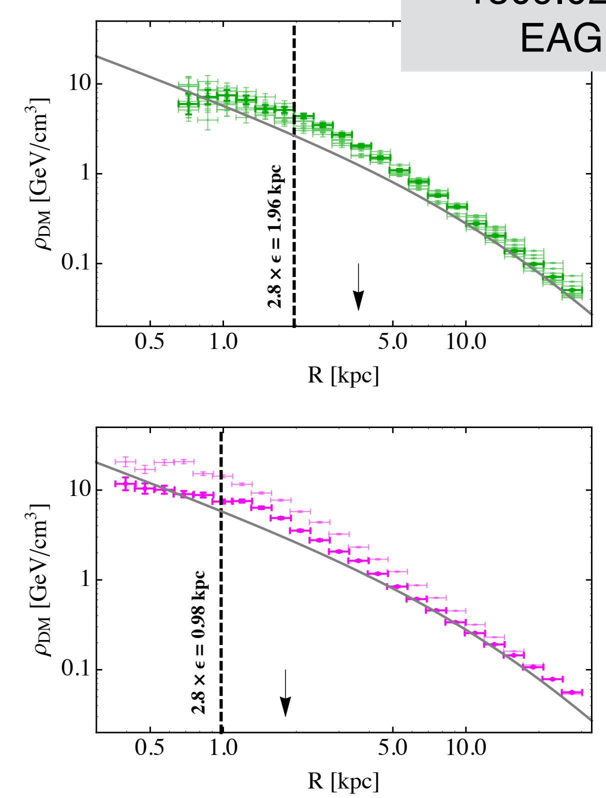


Spatial distribution of PBHs: We consider as a benchmark the NFW distribution.
We also consider other variations, based on numerical simulations with baryons (*see F. Calore et al., arXiv:1509.02164*)



black line: NFW from Navarro et al. 2004

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



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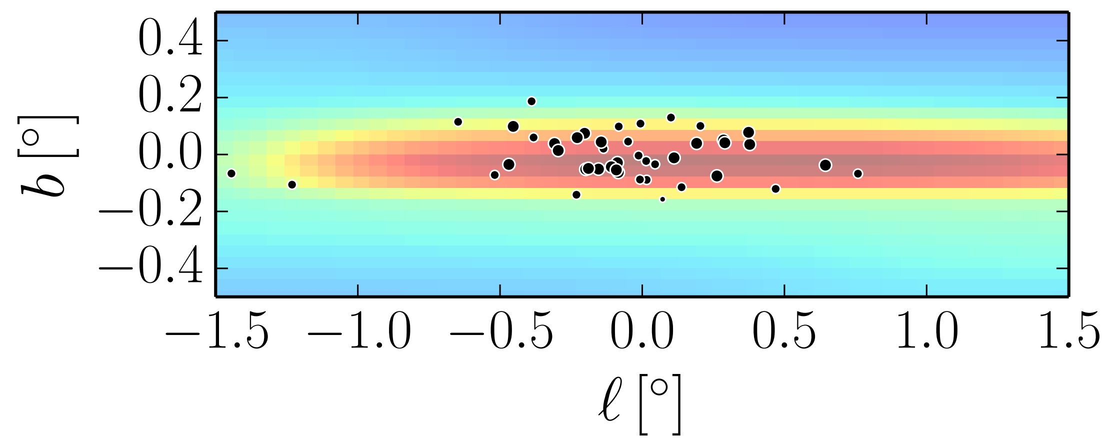
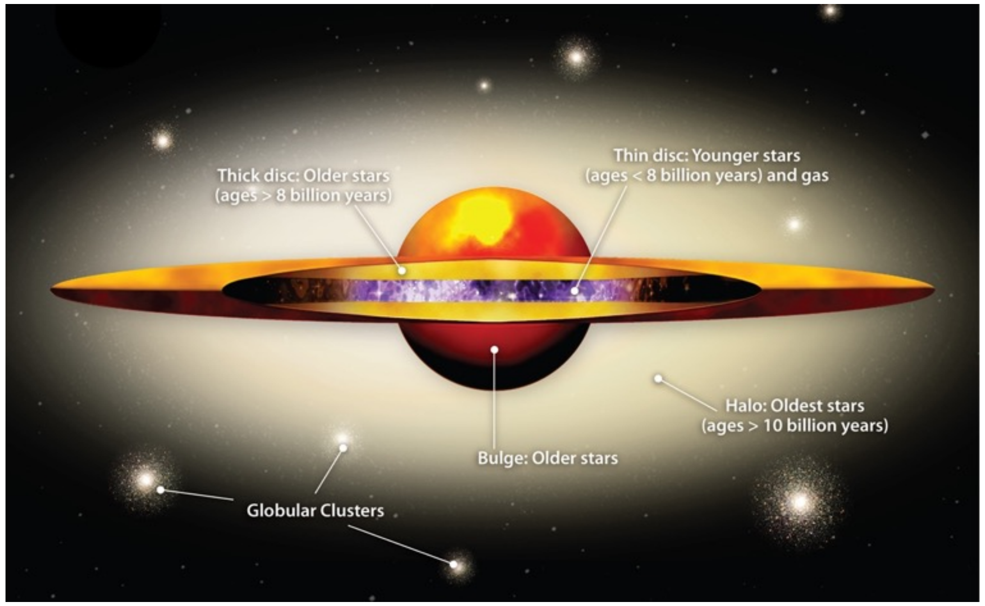


Velocity distribution: we consider, for each radius R, a Maxwell-Boltzmann distribution centered on v = $\sqrt{(G\,M(<R)/R)}$.

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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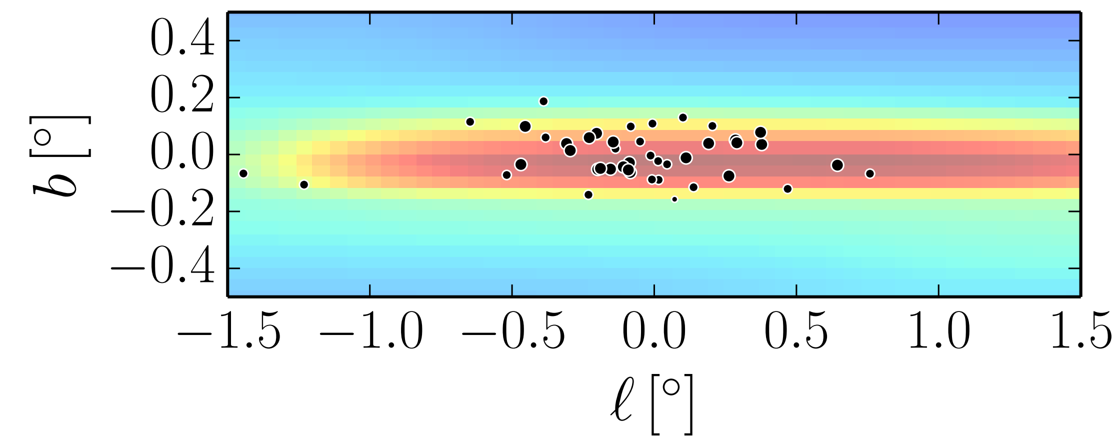
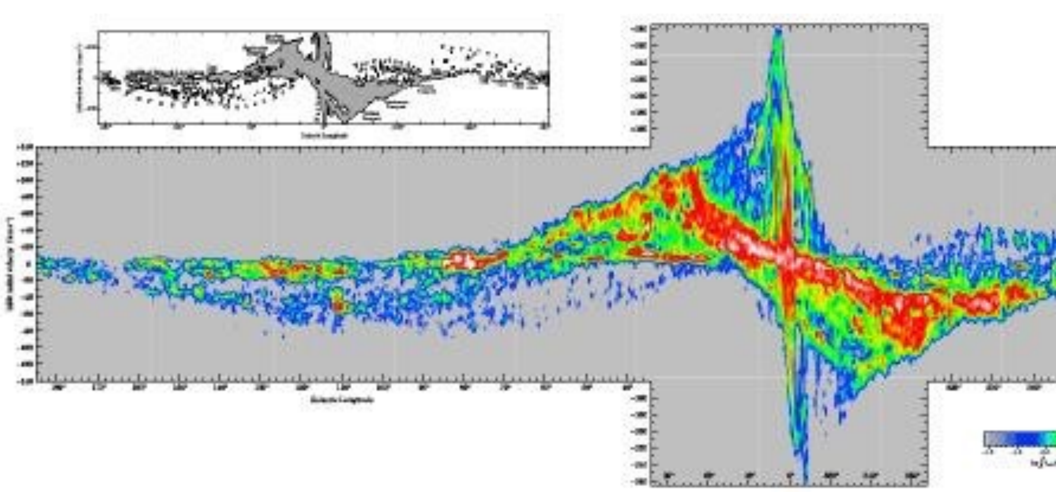
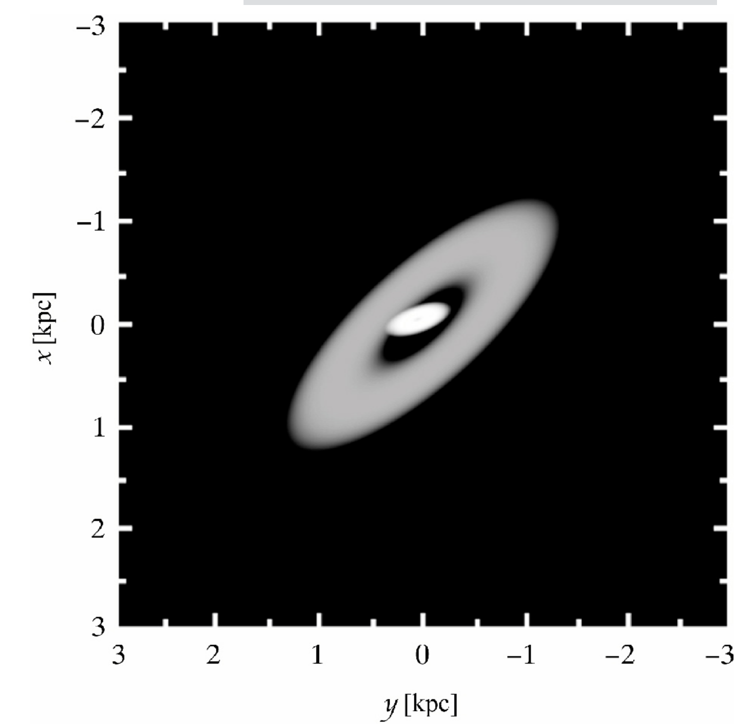


Gas distribution: we consider the state-of-the-art models by K. Ferrière (Ferrière 2001, Ferrière 2007)
very accurate models of the 3D gas distribution in the inner bulge, based on CO observations



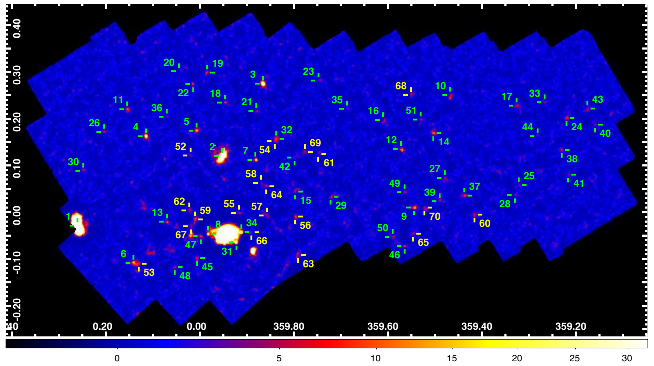
CO emission map

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



Part 1: LIGO, PBHs and DM

Comparison with the X-ray and radio data

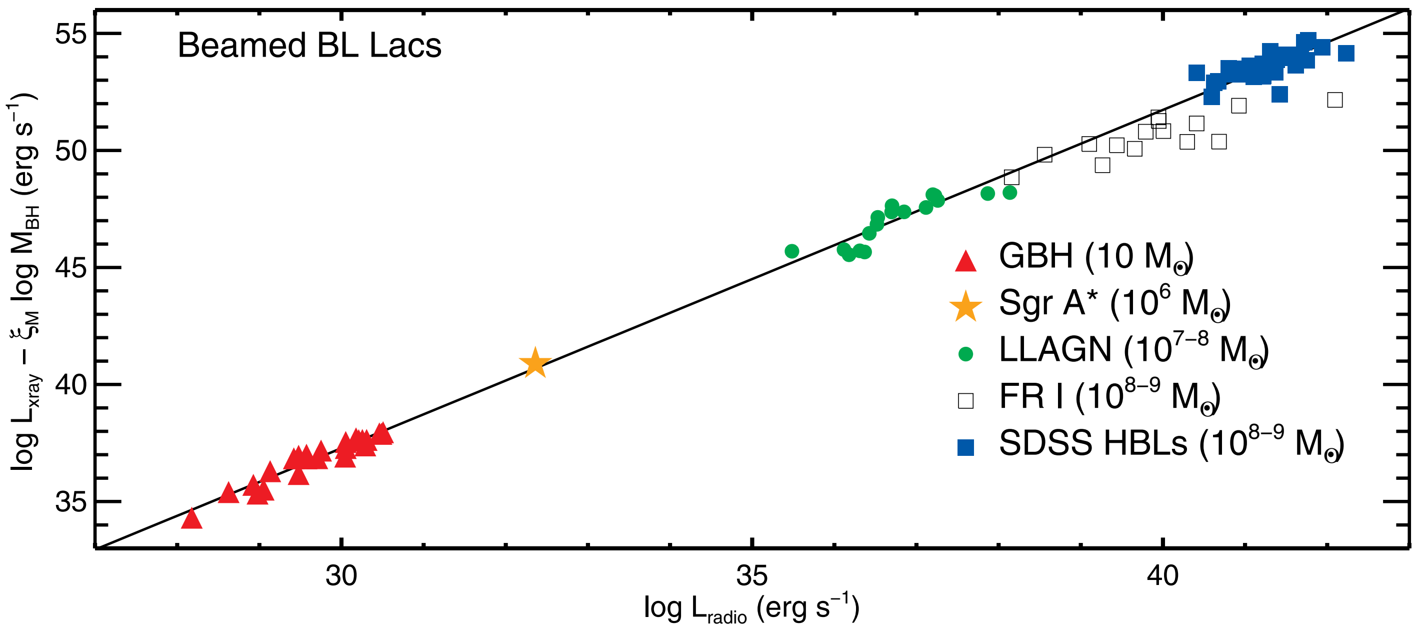


X-rays:

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°; |b| < 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)