Primordial black holes as a dark matter candidate?

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Outline

- Introduction. The Dark Matter puzzle

- Dark Matter searches at all scales. Interplay with astrophysics.

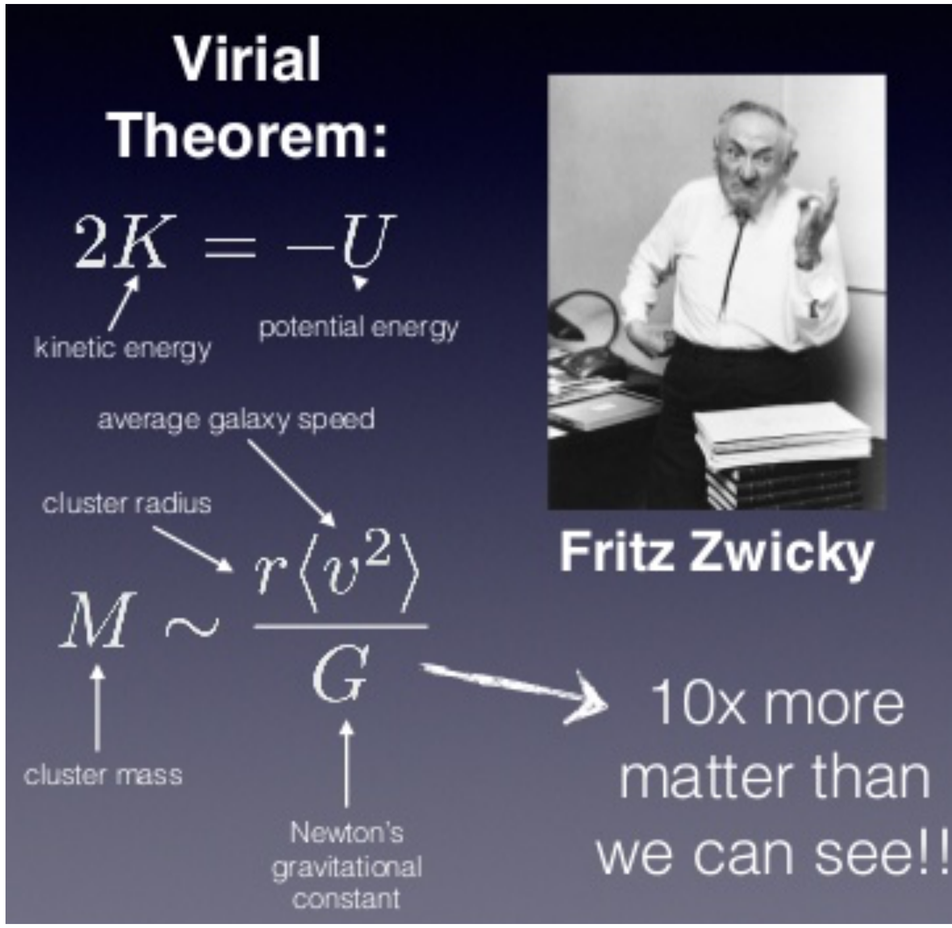
PART 1 - Primordial Black Holes and Gravitational Waves

- GW150914
- The “crazy idea”: *did LIGO detect Dark Matter*?
- Basic concepts on primordial black holes
- How to constrain the PBH scenario
- Other indirect signatures of (primordial and astrophysical) BHs: radio and X-ray emission
- Our simulation
- Our results
- Discussion
- Future perspectives: SKA, MeerKAT…

PART 2 - The GC gamma-ray excess: a case of WIMP annihilation?

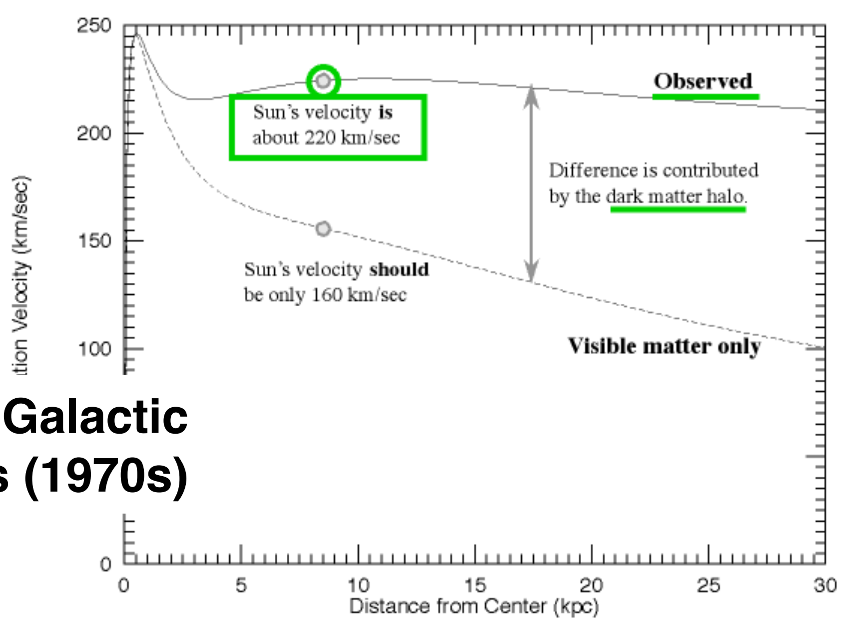
- Is there an anomalous emission from the inner Galaxy?
- The template fitting and its limits
- The importance of the background
- Our analysis: no more GC excess
- Other interpretations

Introduction: The Dark Matter puzzle



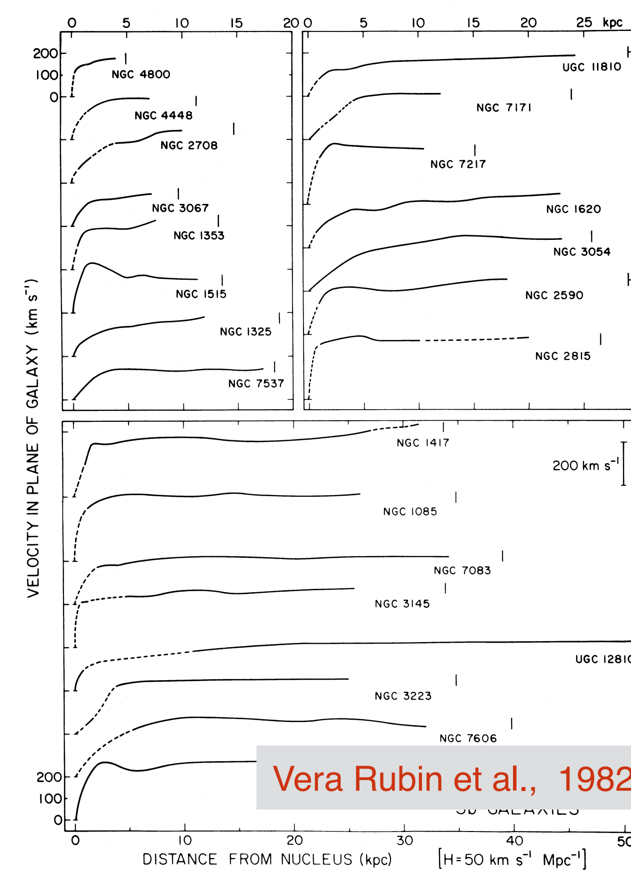
The coma cluster (APOD website)

Dark Matter at Galaxy cluster scales (anomalous mass-to-light ratio, 1930s)



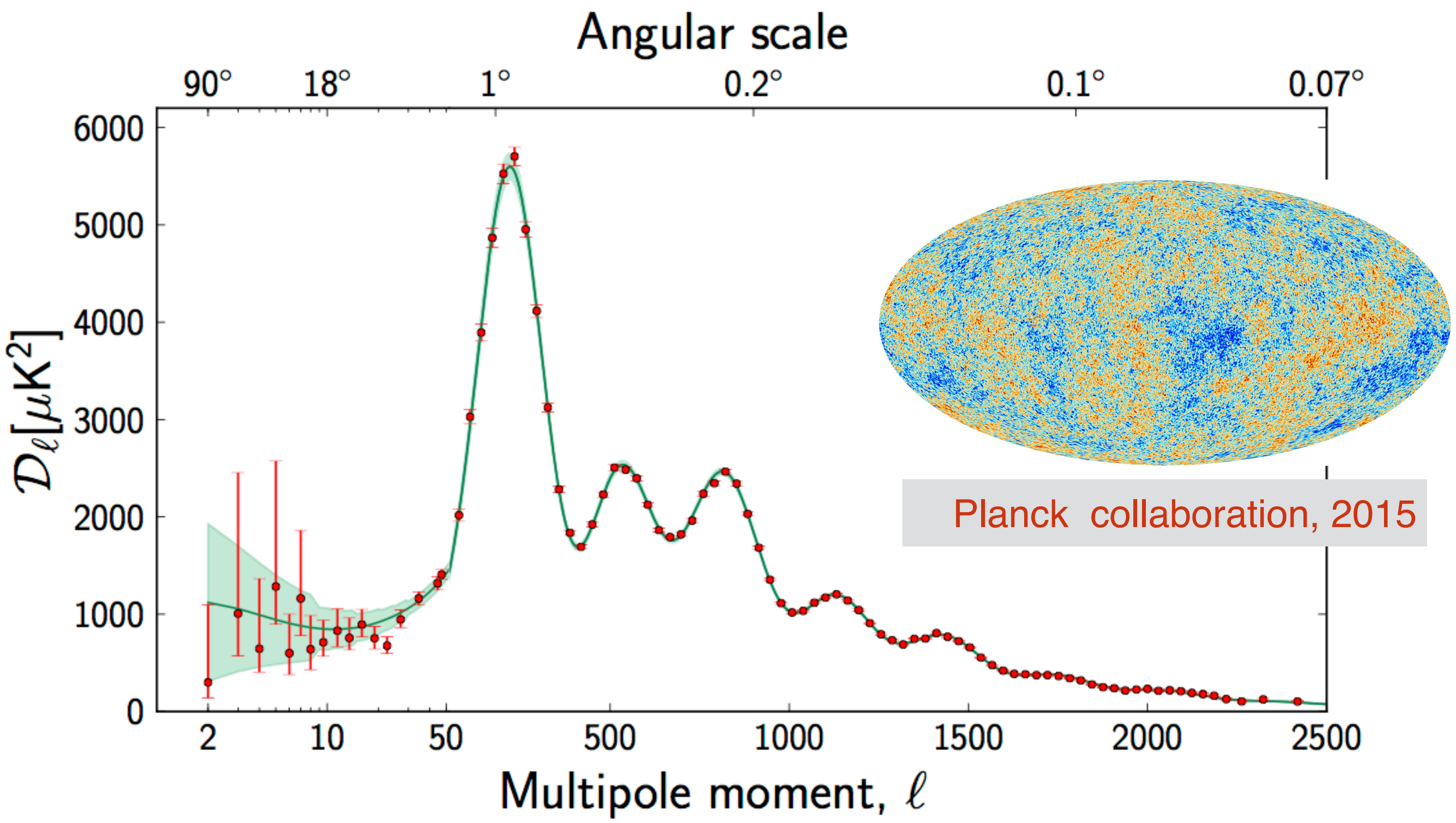
Dark Matter at Galactic scales (1970s)

Vera Rubin (1928-2016)



Vera Rubin et al., 1982

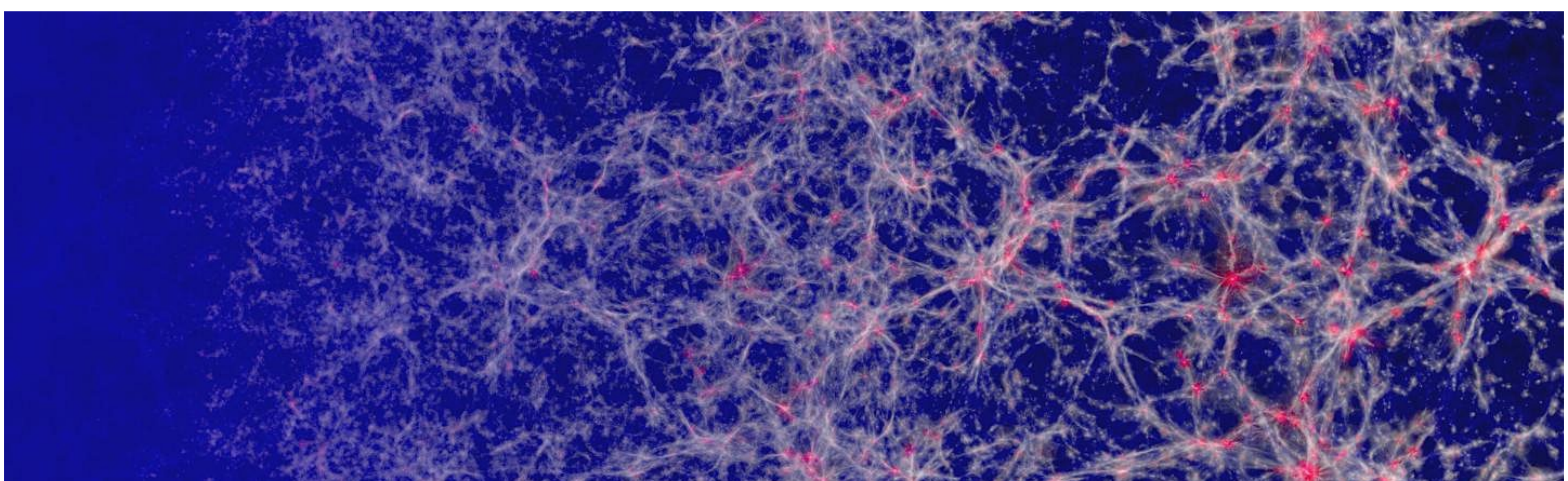
Introduction: The Dark Matter puzzle



Planck collaboration, 2015

Dark Matter at cosmological scales

Dark Matter as a crucial ingredient in structure formation

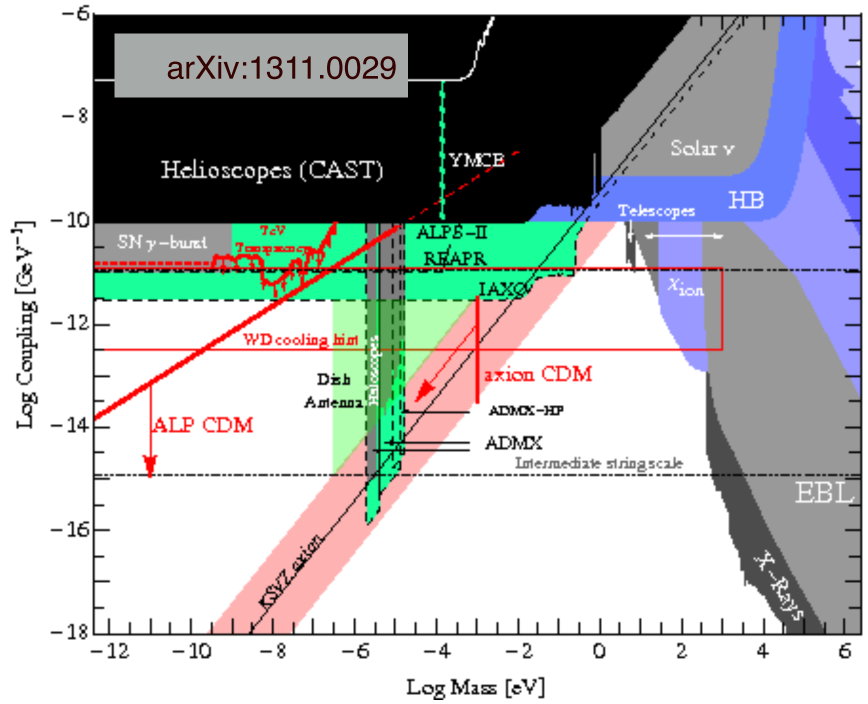


courtesy of the EAGLE collaboration

Dark Matter candidates

10^3 eV

— Axion-like particles



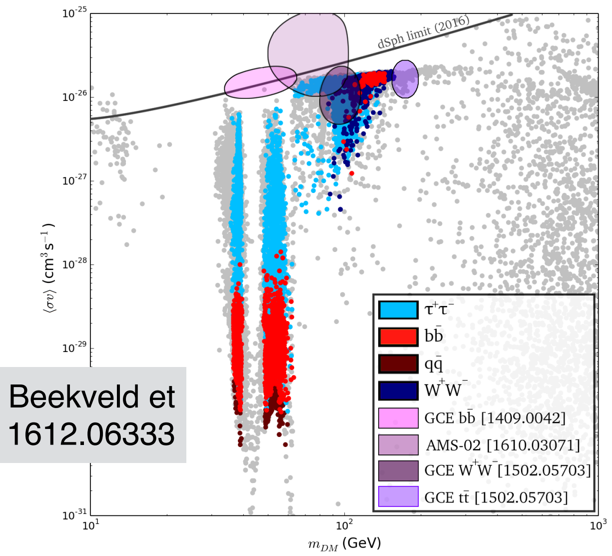
— Fuzzy Dark Matter

Fornax dSph seen from San Esteban (Chile) - 14Dec2003

λ_{dB} ~ 1 kpc ~ size of a dSph Galaxy
[see recent paper: Hui, Ostriker, Tremaine, Witten 2016]

10^{-22} eV

Dark Matter candidates



van Beekveld et al., 1612.06333

10^{12} eV

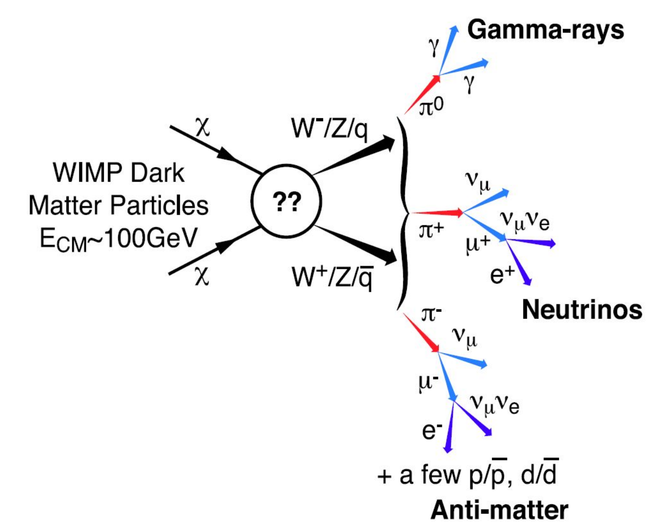
— Weakly interacting massive particles (WIMPS) e.g. neutralino in MSSM

10^{9} eV

very large parameter space

strong limits from direct detection

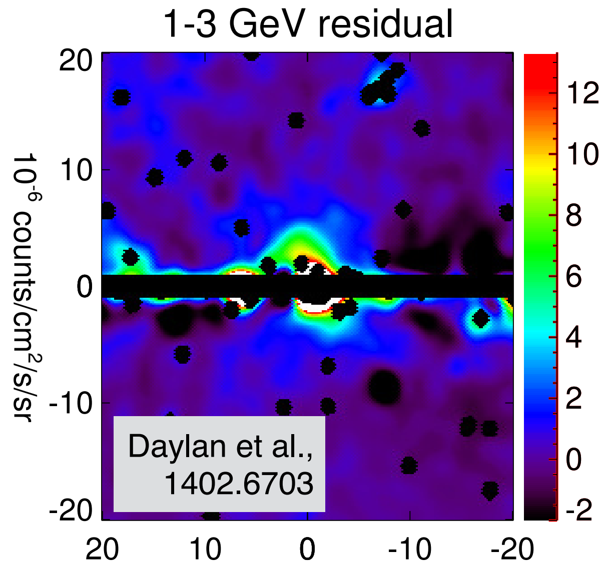
indirect detection channels: gamma rays (from dSph, from inner Galaxy, line features); CR antiprotons, positrons anti-deuterium, anti-helium; neutrinos from WIMP capture in the Sun…



a recent **tentative claim** of detection: “*γ-ray GeV excess*”

V. Vitale et al., 2009 [arXiv:0912.3828]; L Goodenough and D. Hooper, 2009; T. Daylan et al., 2014 [arXiv:1402.6703]; F. Calore et al., 2014 [arXiv:1409.0042]

(probably due to mis-modeling of the background: see D. Gaggero et al. 2015, E. Carlson et al. 2015)

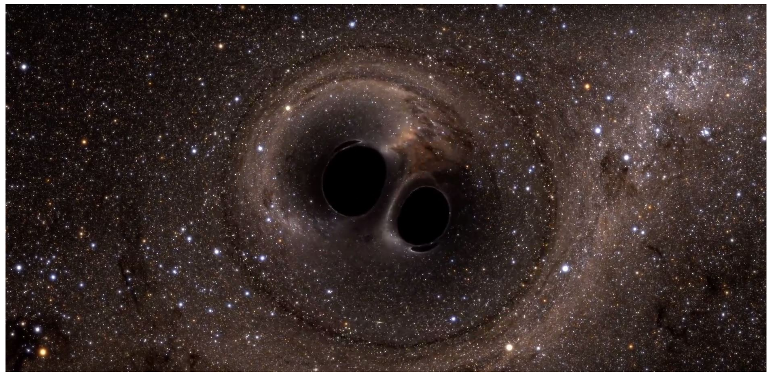


Daylan et al., 1402.6703

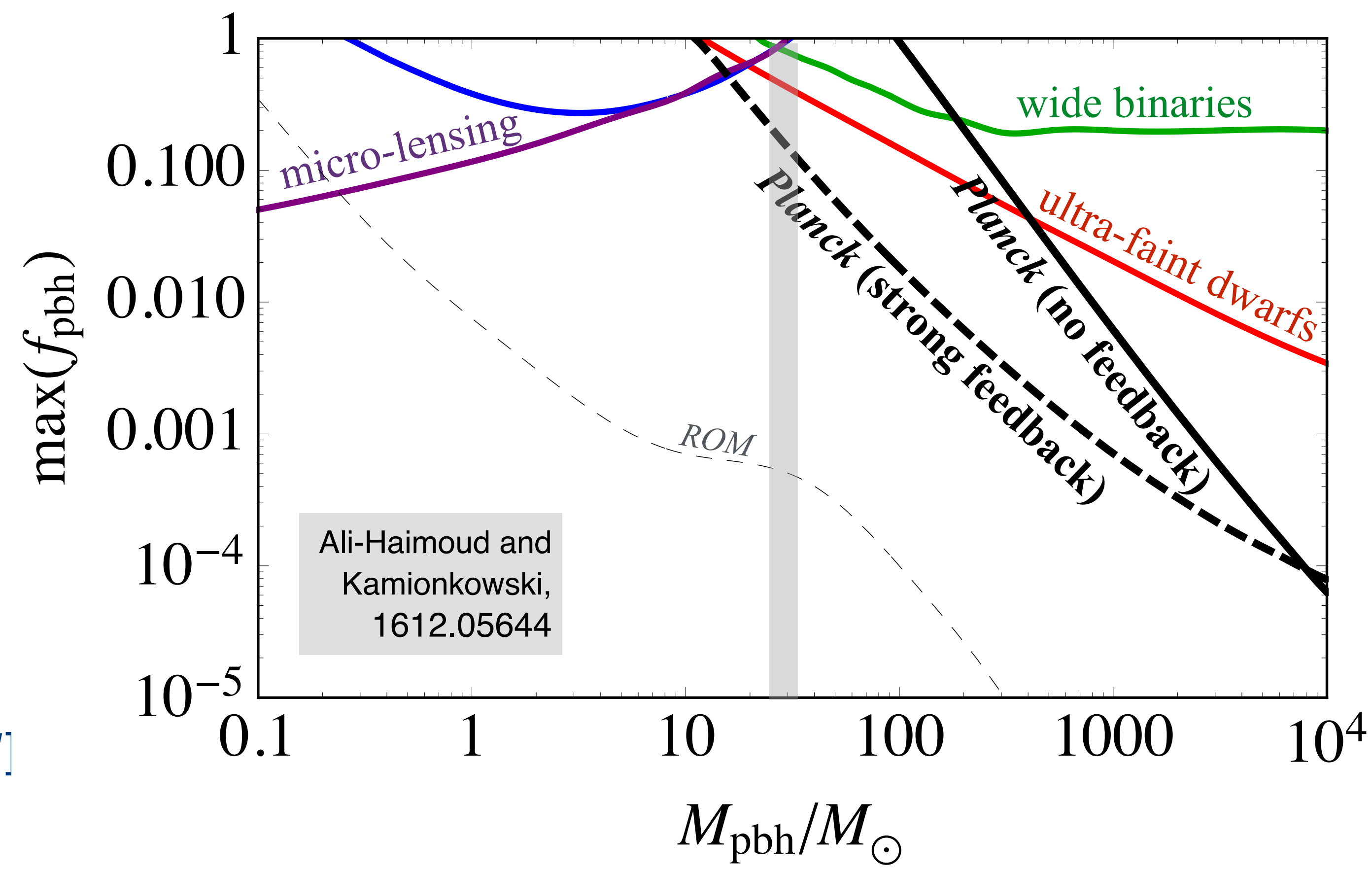
10^{3} eV

— Warm dark matter (e.g. sterile neutrinos)

Dark Matter candidates



10^{57} **GeV ~** 10^{33} **g ~ 1 Msun**



— Primordial black holes (PBHs)

[*Zeld'ovich and Novikov 1966, Hawking 1971*]
— large mass range
— should have formed before BBN
— **many constraints** from lensing, wide binaries, Galactic disk stability
— very popular in the 80s, less considered after MACHO project (Alcock 2001)

— WIMPs

1 GeV

Credit for the BBH system: Bohn et al. (see http://www.black-holes.org/lensing

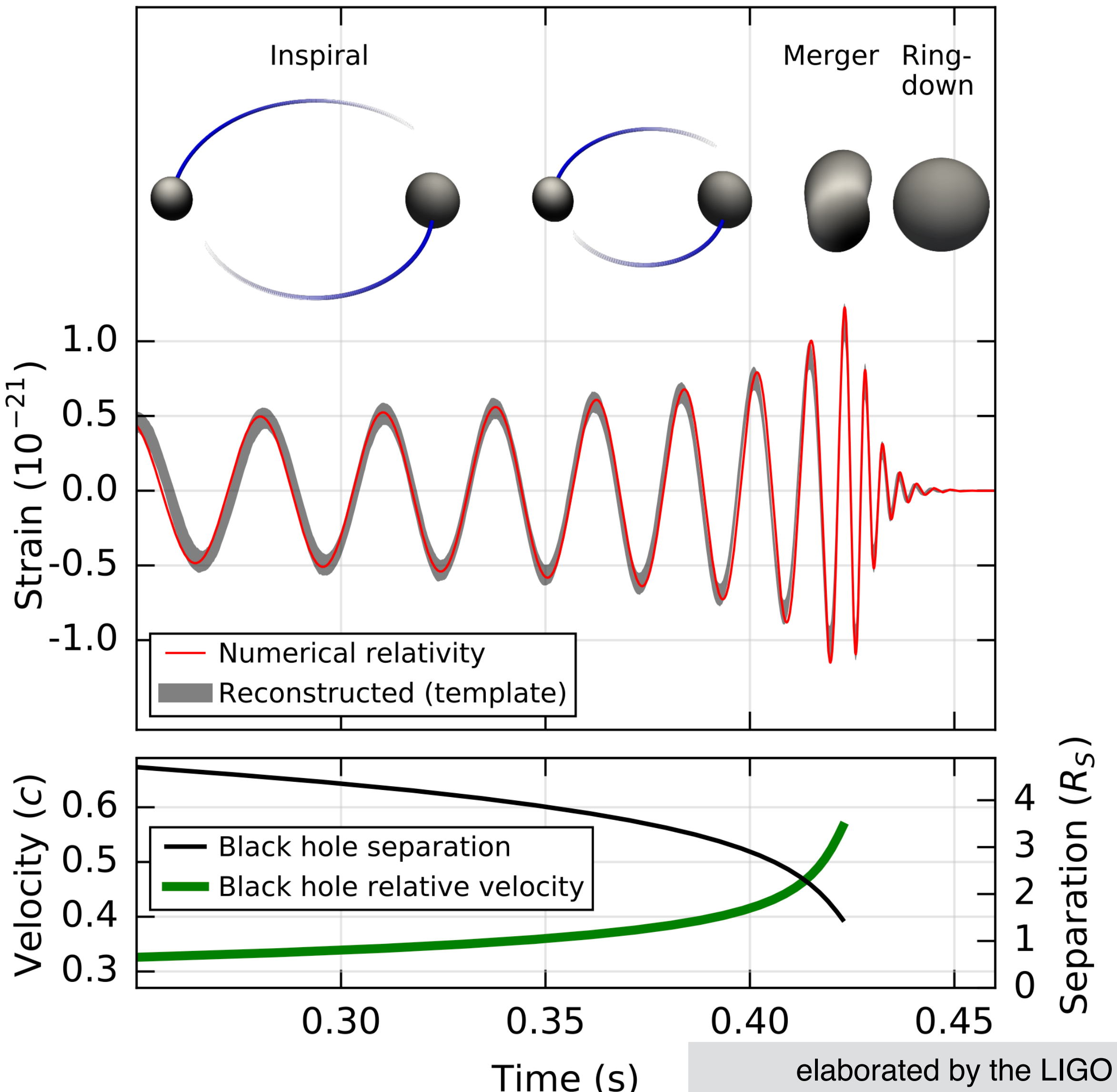
GW150914 and its implications

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

B. P. Abbott et al. (LIGO Collaboration, Virgo Collaboration), "An improved analysis of GW150914 using a fully spin-precessing waveform model", *Phys. Rev. X* **6**, 041014 (2016)

- The ***first direct detection of a gravitational wave signal***
- The waveform is compatible with a merging of two massive black holes
- A recent accurate estimate of the parameters (arXiv:1606.01210):

Source-frame total mass $M^{\rm source}/{\rm M}_\odot$	$65.6^{+4.1}_{-3.8}$
Source-frame chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$28.3^{+1.8}_{-1.7}$
Source-frame primary mass $m_1^{\rm source}/{\rm M}_\odot$	$35.6^{+4.8}_{-3.4}$
Source-frame secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$30.0^{+3.3}_{-4.4}$
Source-frame final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.5^{+3.7}_{-3.4}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	440^{+160}_{-180}
Source redshift z	$0.094^{+0.032}_{-0.037}$



elaborated by the LIGO collaboration

Part 1: LIGO, PBHs and DM

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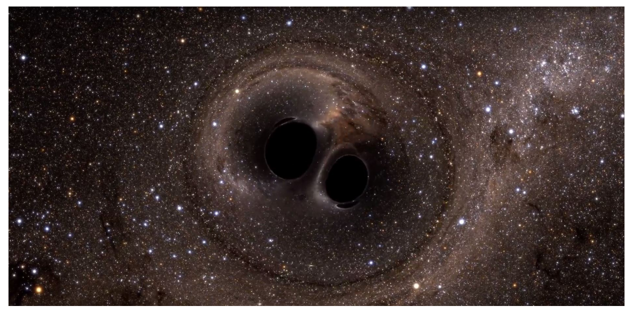
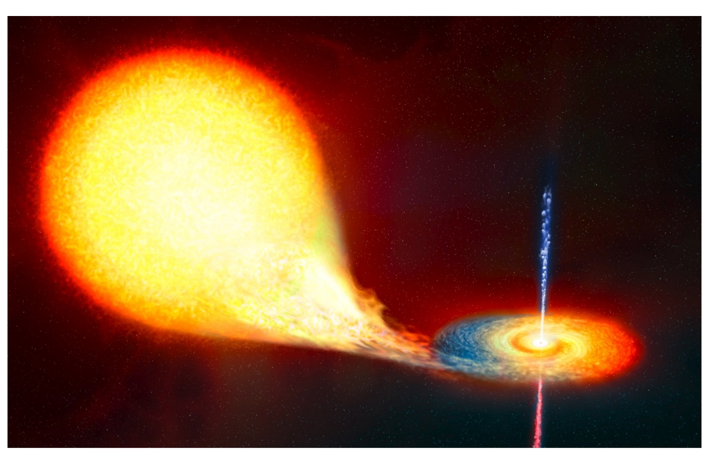
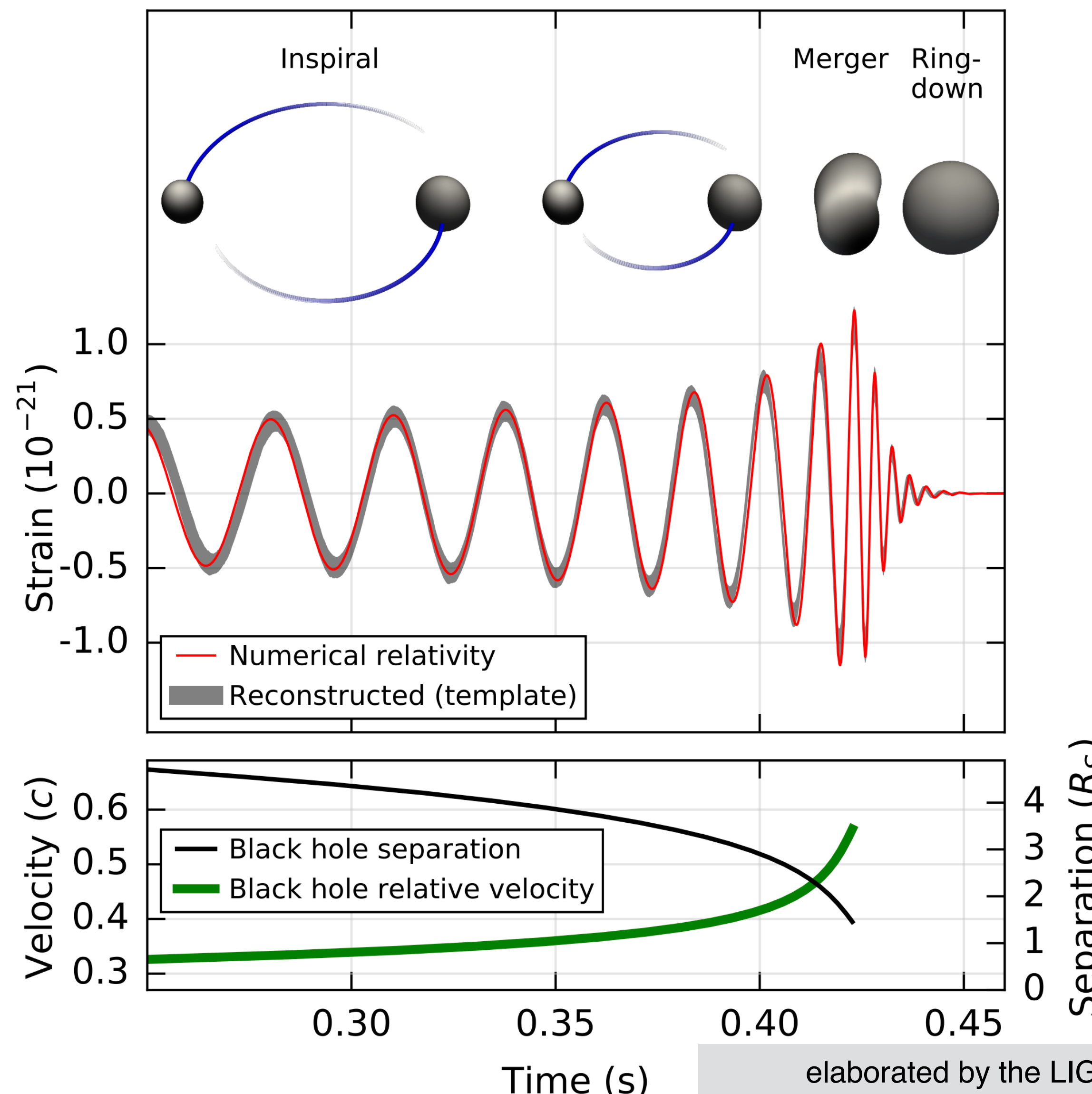
- The ***first direct detection of a binary black hole system***



- The ***first direct detection of stellar-mass black holes with M as large as 30 M☉***

(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*)





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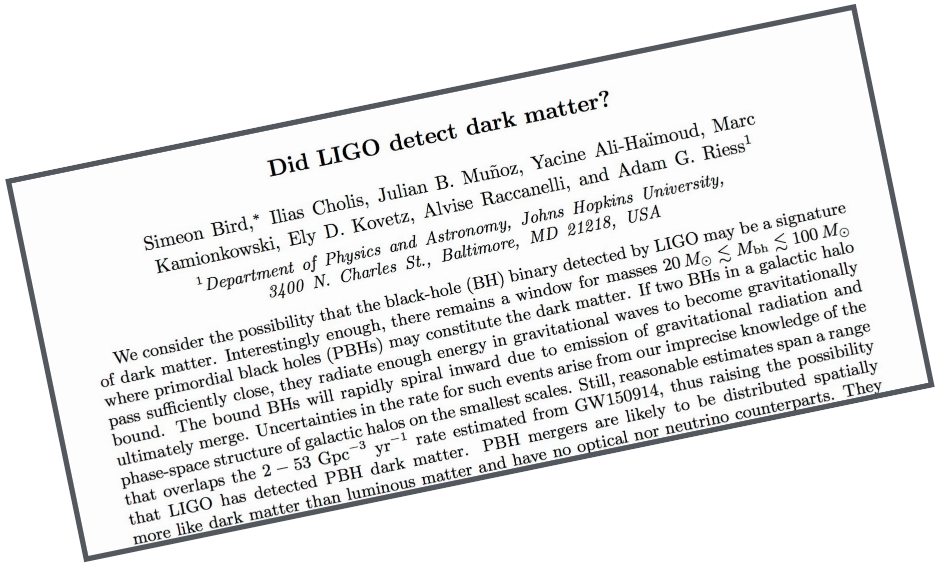
GW150914 and its implications: did LIGO detect a merger of two primordial black holes?

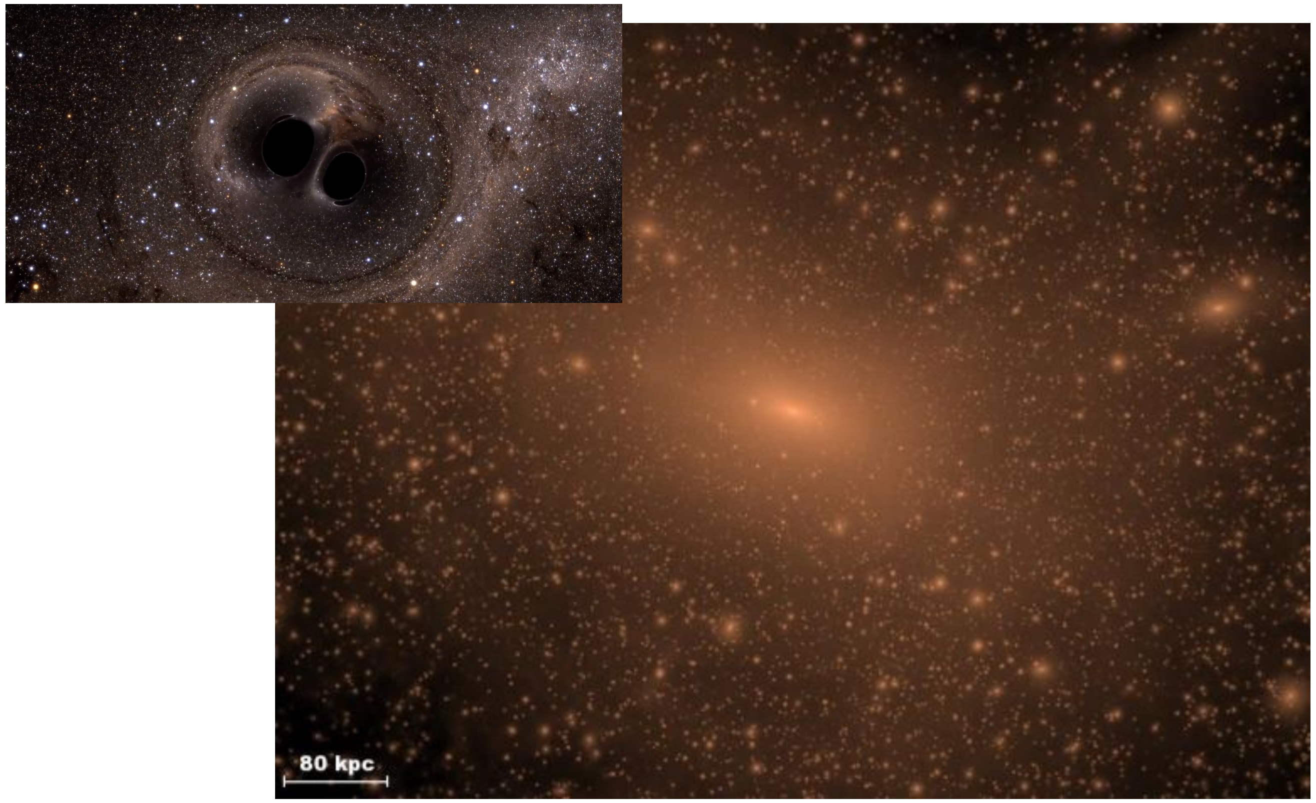


Did LIGO detect dark matter?

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

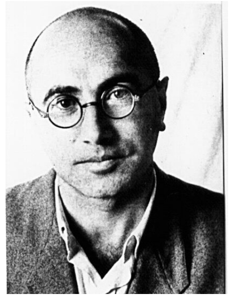


- The “crazy idea” proposed by the Johns Hopkins team: ***did LIGO detect the dark matter*** **(in the form of primordial black holes)?**

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

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)]

Astrophysical black holes: ~10^9 $M_\odot$ down to ~1 $M_\odot$

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

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

Low-mass primordial black holes can form at early times (<< 1 s)

PBHs can form at early times when the Jeans length scale and the Schwarzschild length are comparable

Part 1: LIGO, PBHs and DM

Brief summary on primordial black holes as DM candidate

in general, **PBHs can span an enormous mass range**
—> those formed at the Planck time (10^{-43} s) would have the Planck mass (10^{-5} g),
—> those formed at 1 s would be as large as $10^5\ M_\odot$

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

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

- Chapline was among the first to suggest the PBHs as a DM candidate [G. F. Chapline, Nature (London) 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

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

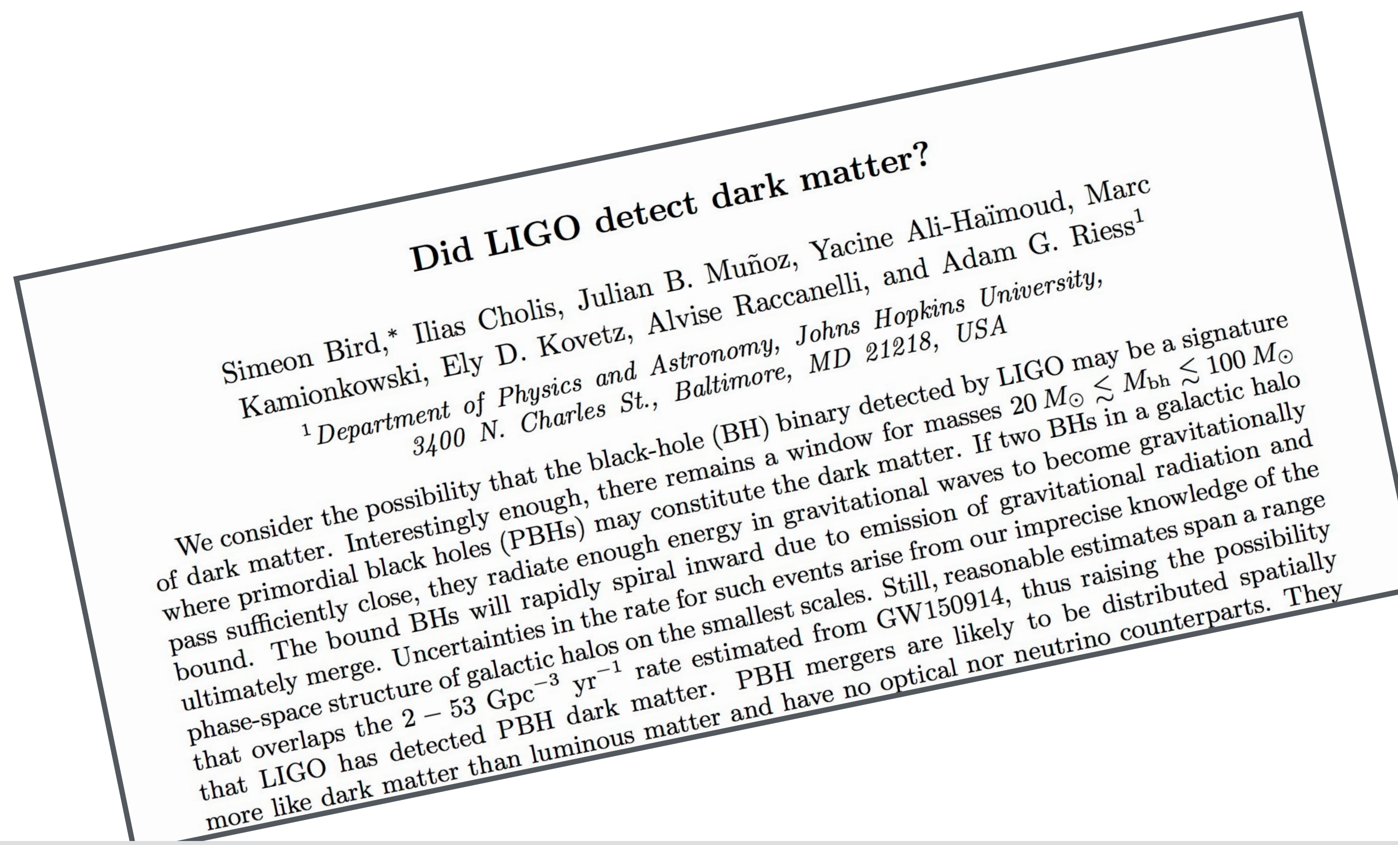
- The “crazy idea” proposed by the Johns Hopkins team: ***did LIGO detect the DM*?** **(in the form of primordial black holes)**

- 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?



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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?

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

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

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

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

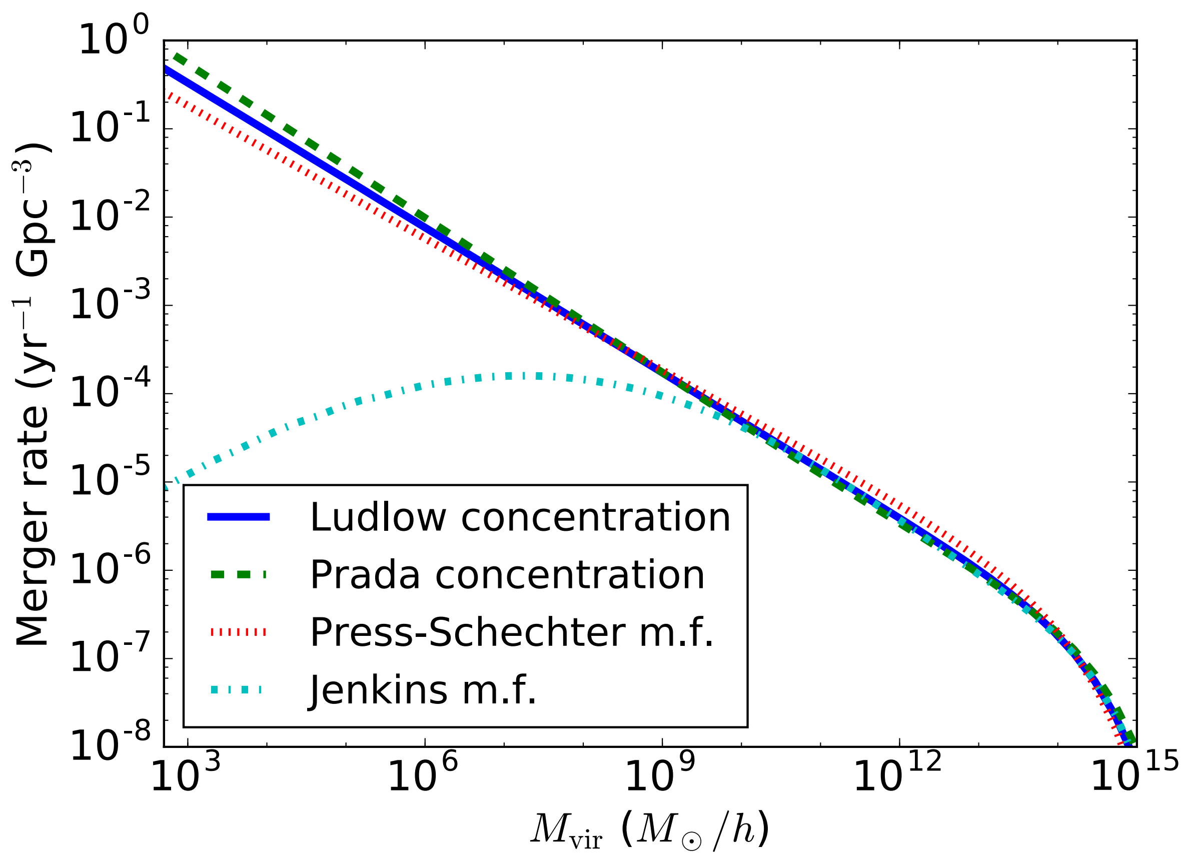

FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

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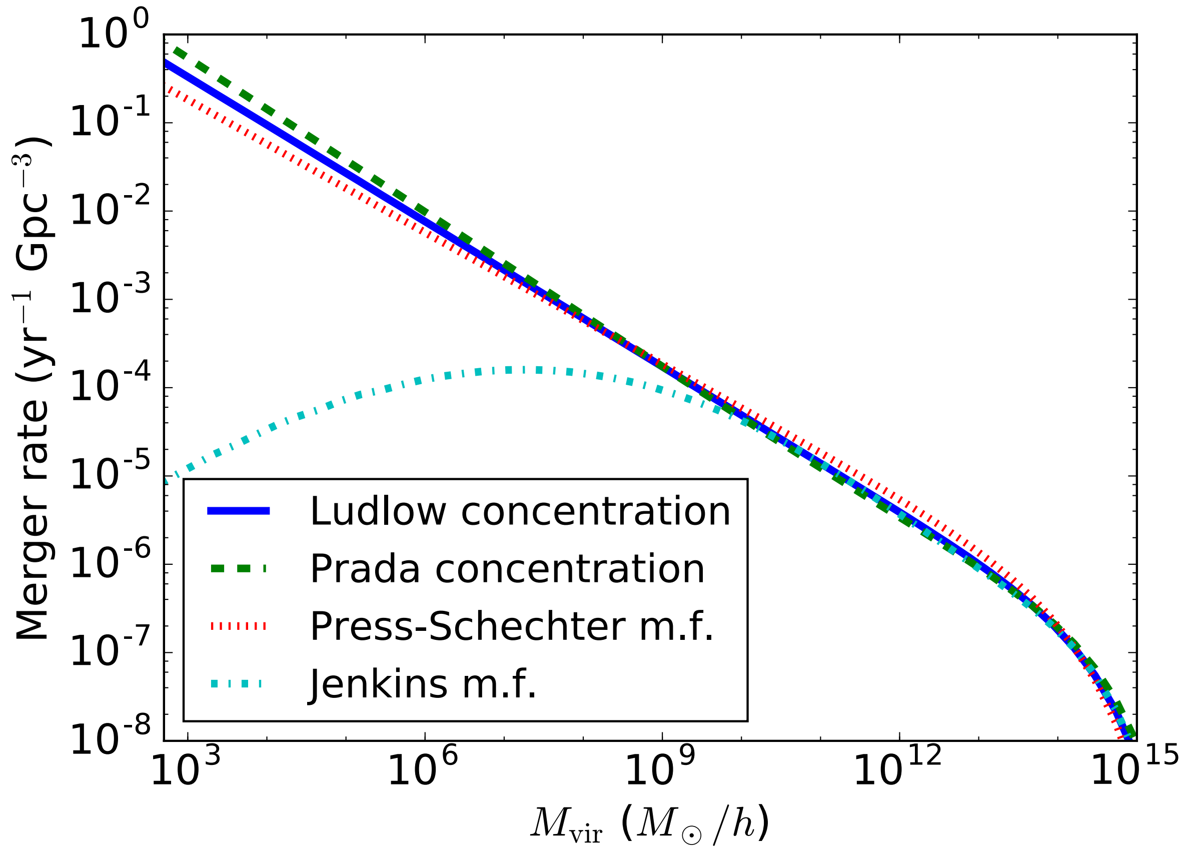
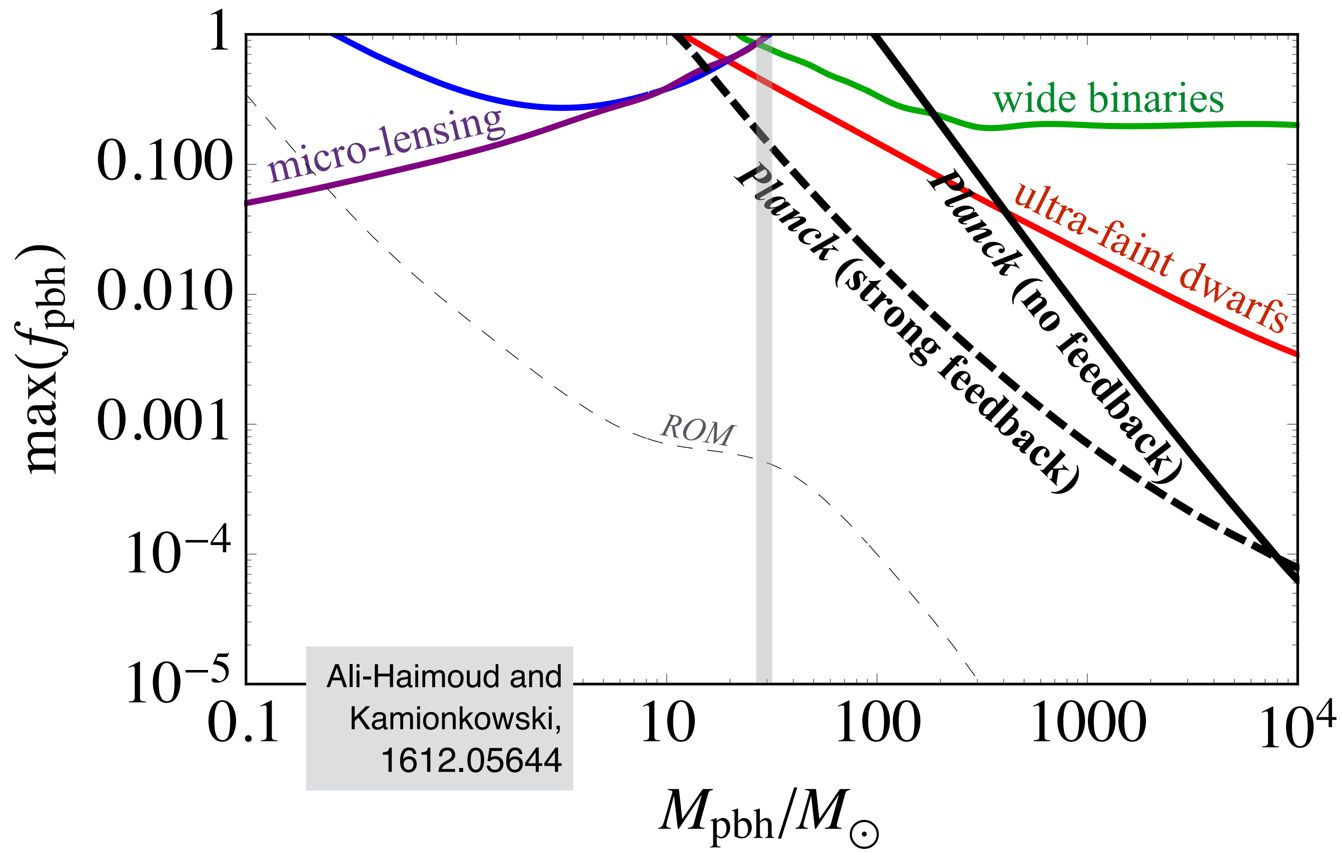


Compatible with the rate inferred by the LIGO collaboration!

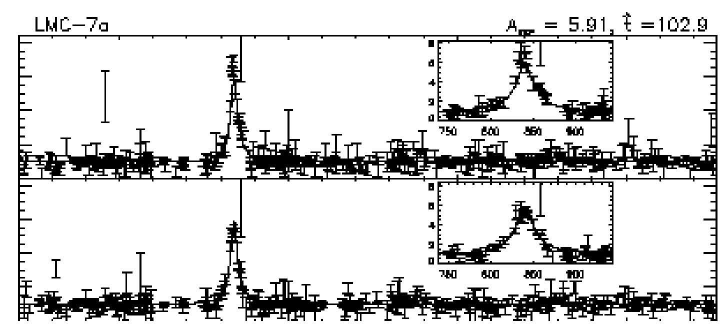
Part 1: LIGO, PBHs and DM

Existing constraints on DM as PBHs



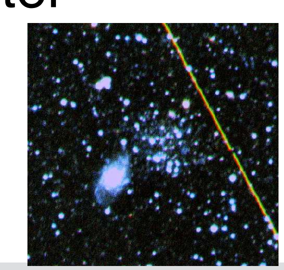
- **Lensing constraints**

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



- **Dynamical constraints**

green line: disruption of wide binaries [*1406.5169*]
red line: ultra-faint dwarfs [*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



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

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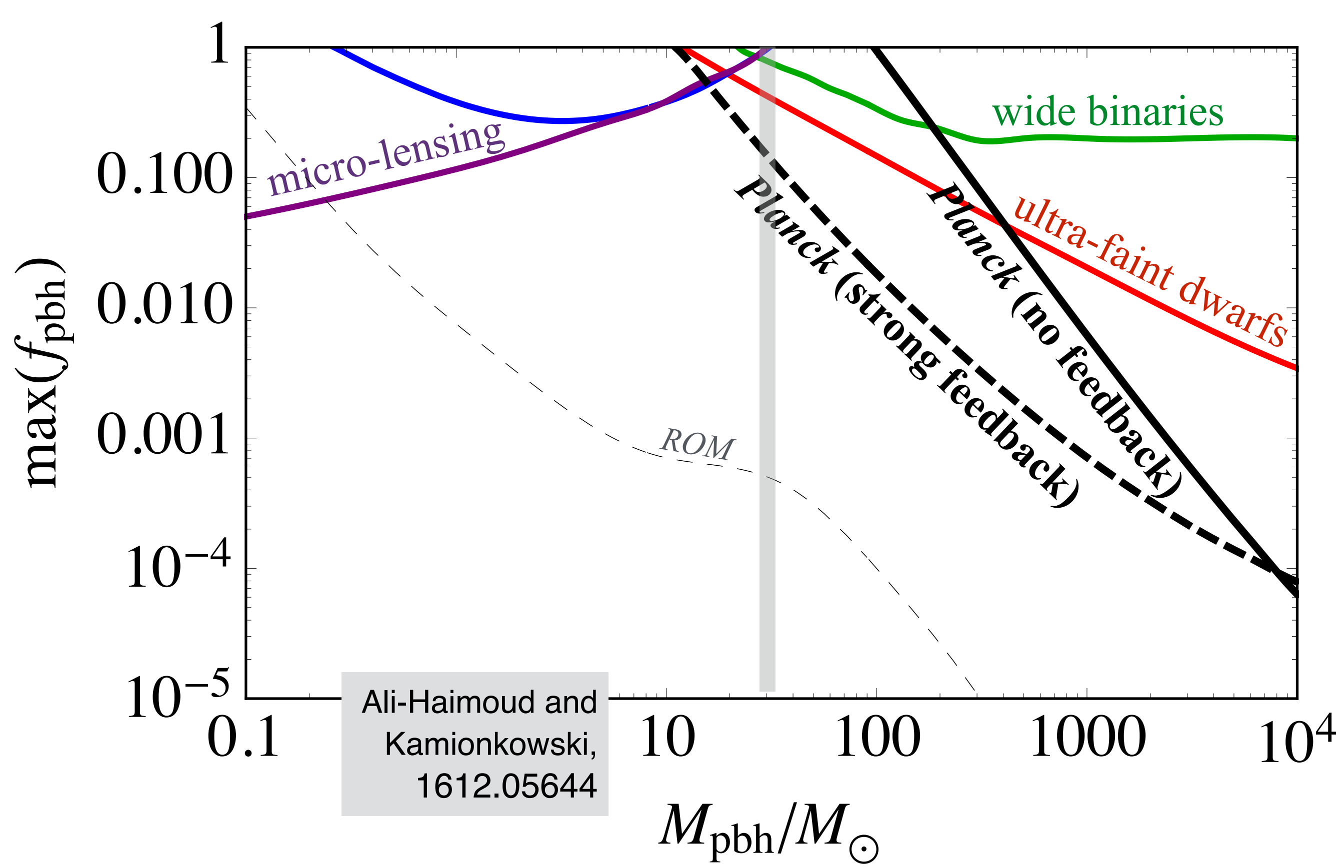


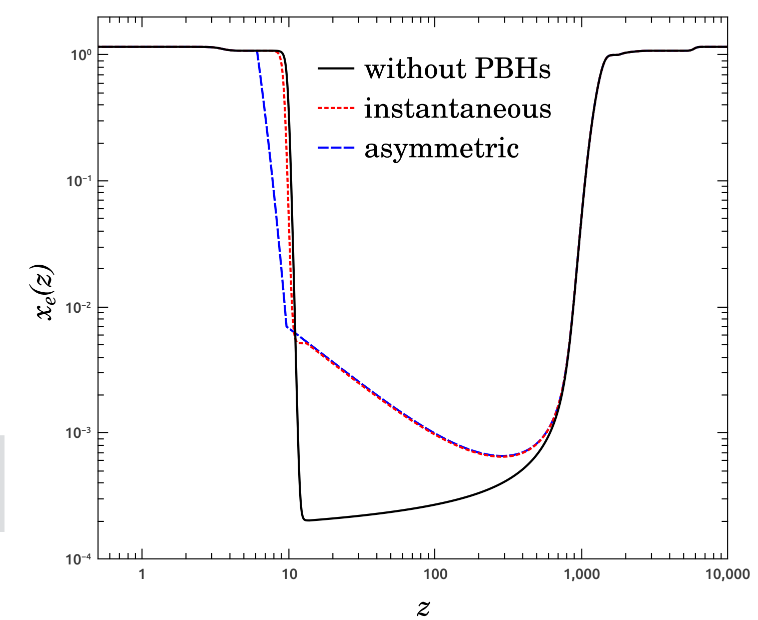
Ali-Haimoud and Kamionkowski, 1612.05644

- **Early universe constraints:**

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

Such an increase in the free-electron abundance would change the CMB temperature and polarization power spectra.

Planck measurements do not allow for large deviations from the standard recombination history —> tight bounds for large and luminous PBHs



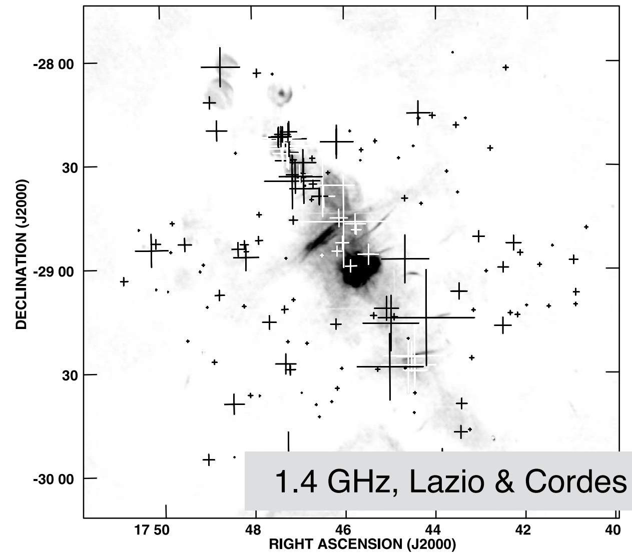
Chen et al. 1608.02174

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

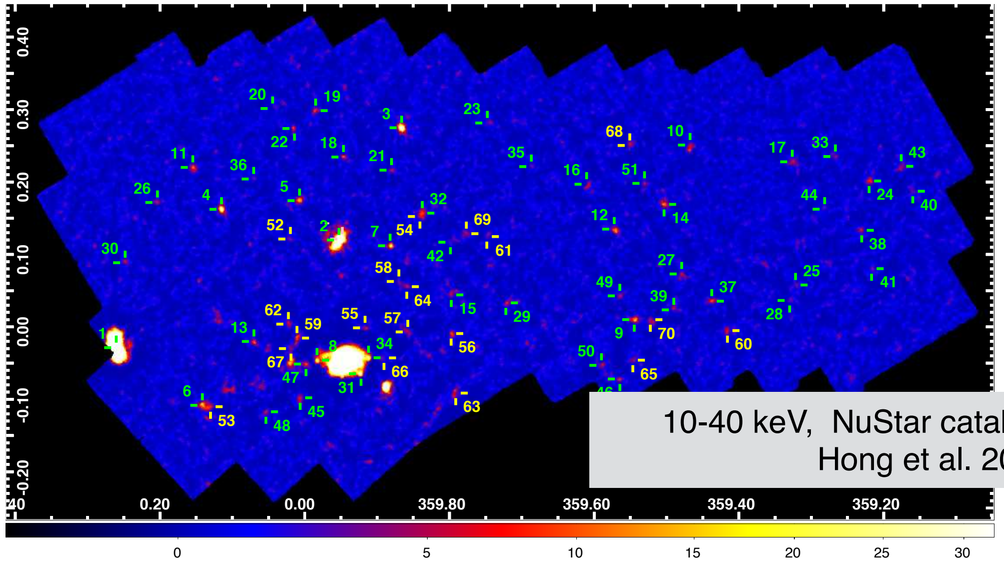
see D. Gaggero, G. Bertone, F. Calore, R. Connors, M. Lovell, S. Markoff, E. Storm, “Searching for Primordial Black Holes in the radio and X-ray sky”, arXiv:1612.00457

- If ~30$M_\odot$ 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”*)

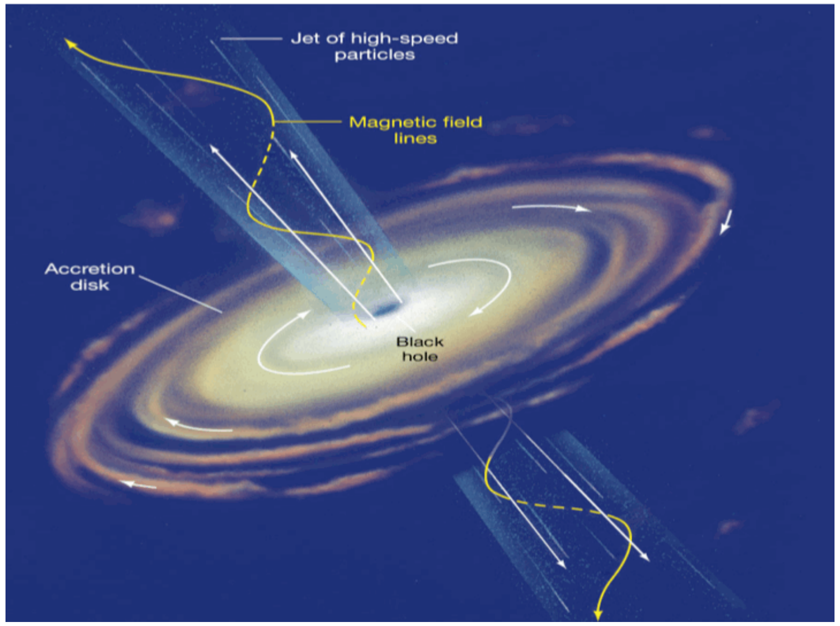
- The question is: given the large amount of gas in the inner Galaxy, **how easy is it to hide such a large population of black holes?** Given conservative estimates of the accretion rate and radiative efficiency, **is this population of PBHs compatible with current radio and X-ray observations?**



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?

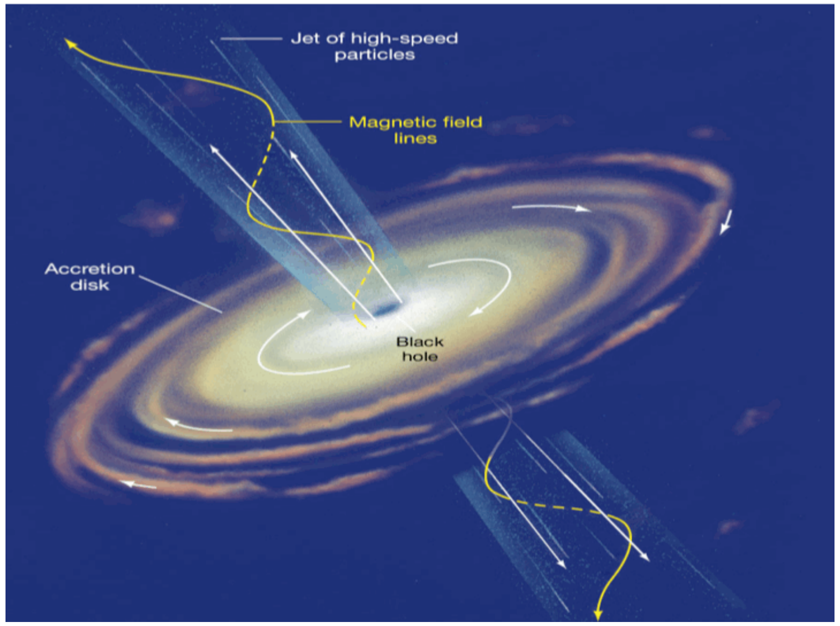
Very complicated phenomenology, high uncertainties. We had to parametrize the problem and adopt simplified, **conservative** assumptions.

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"



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—> 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

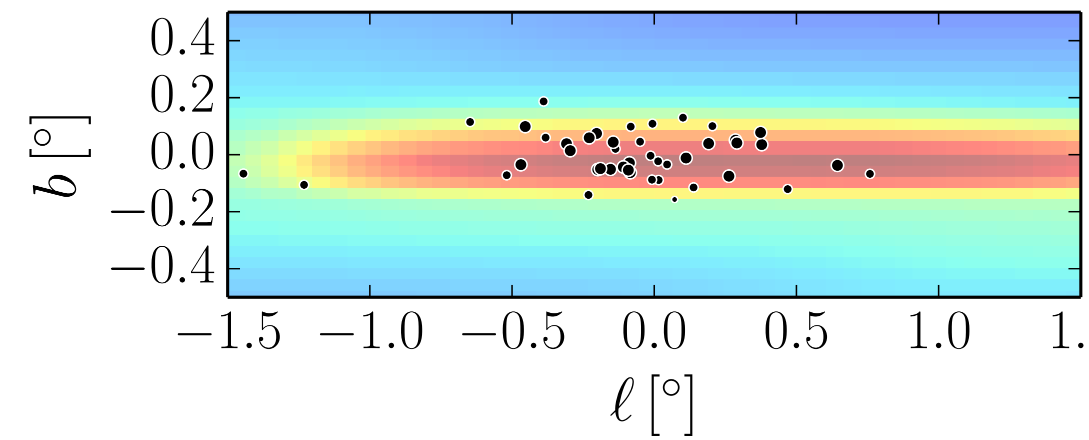
$$L_B = \eta \dot{M} c^2 \qquad \eta = 0.1 \dot{M}/\dot{M}_{\rm crit} \text{ for } \dot{M} < \dot{M}_{\rm crit}$$

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.

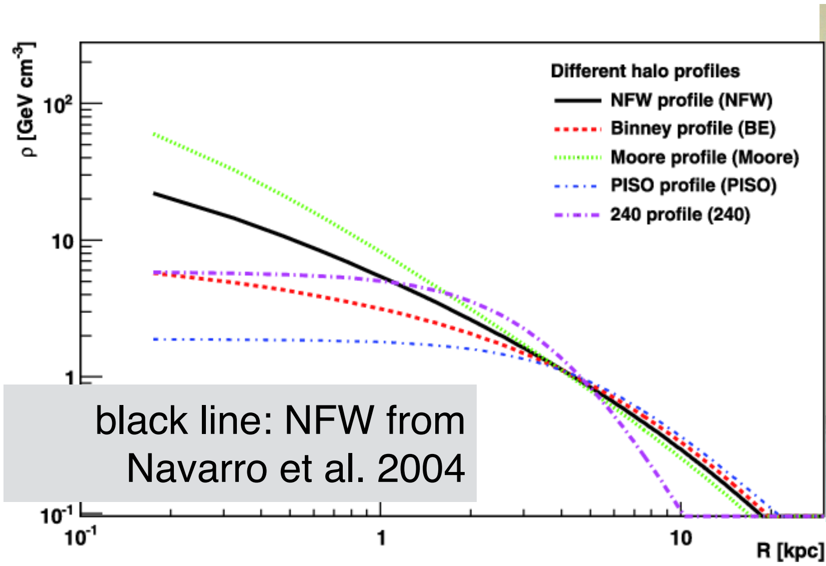
see *Narayan and Yi 1994, “Advection-Dominated Accretion: A Self-Similar Solution”*
and also *Blanford and Begelman 1998: “On the Fate of Gas Accreting at a Low Rate onto a Black Hole”*

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**

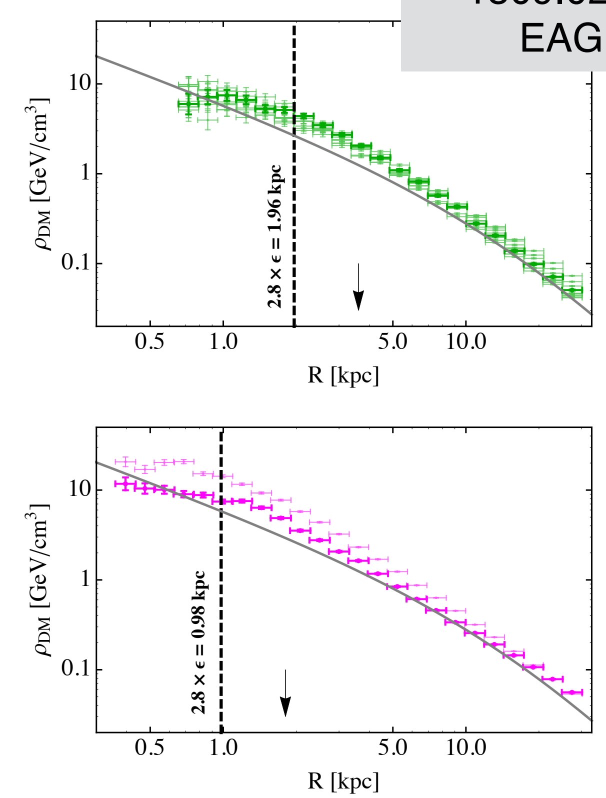


Spatial distribution of PBHs: We consider as a benchmark the NFW distribution.
We also consider other variations, based on numerical simulations with baryons (*see F. Calore et al., arXiv:1509.02164*)



black line: NFW from Navarro et al. 2004

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



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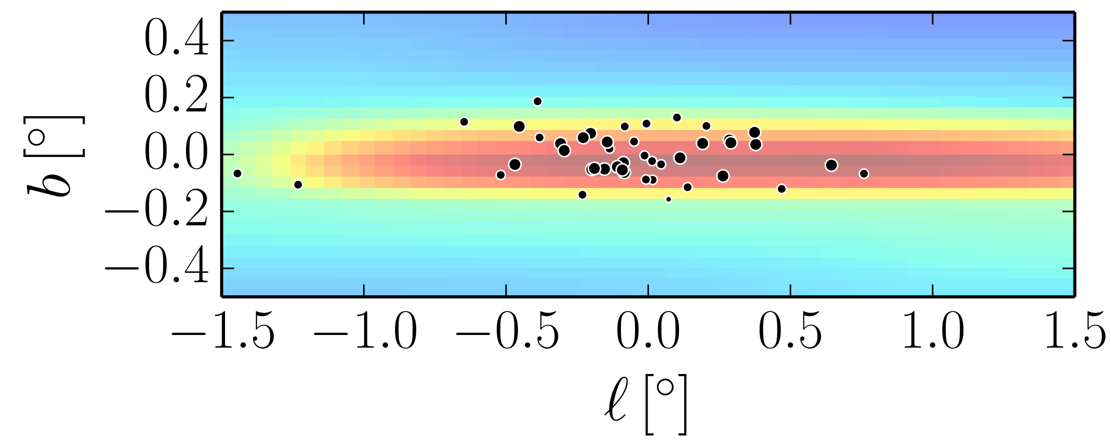
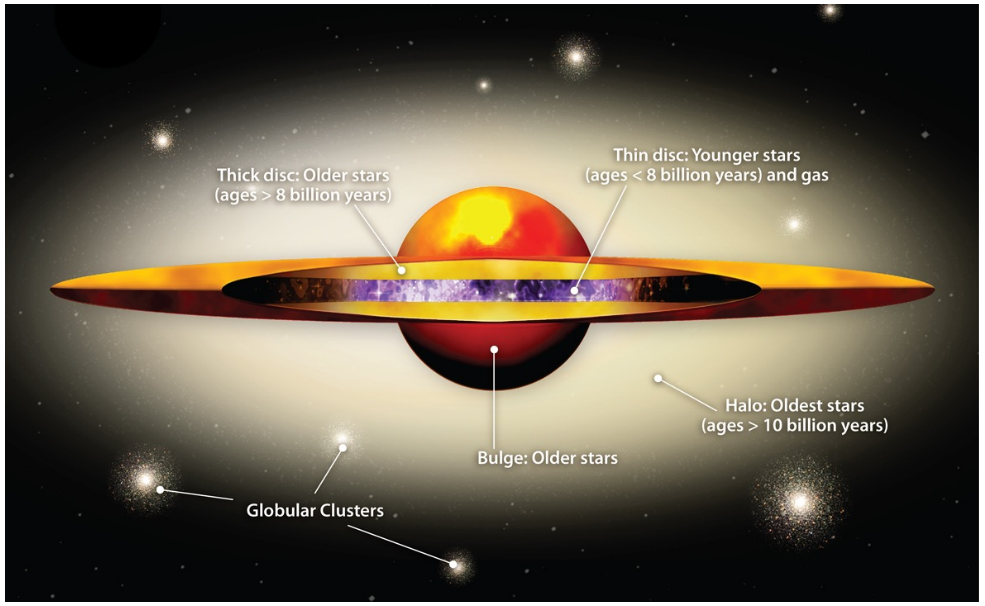


Velocity distribution: we consider, for each radius R, a Maxwell-Boltzmann distribution centered on v = $\sqrt{(G\,M(<R)/R)}$.

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).

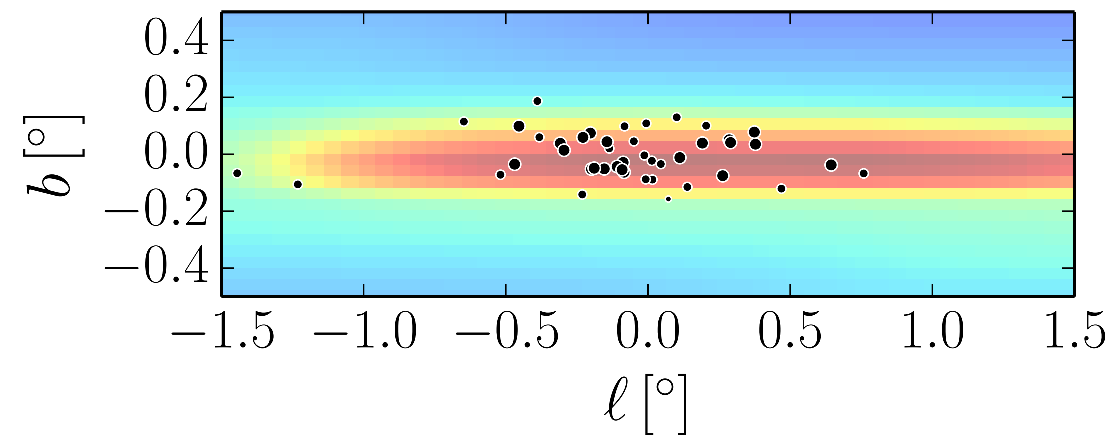


Our simplified treatment, in the low-v tail, is compatible with the more accurate Eddington formalism, which holds under the assumption of spherical symmetry and isotropy

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

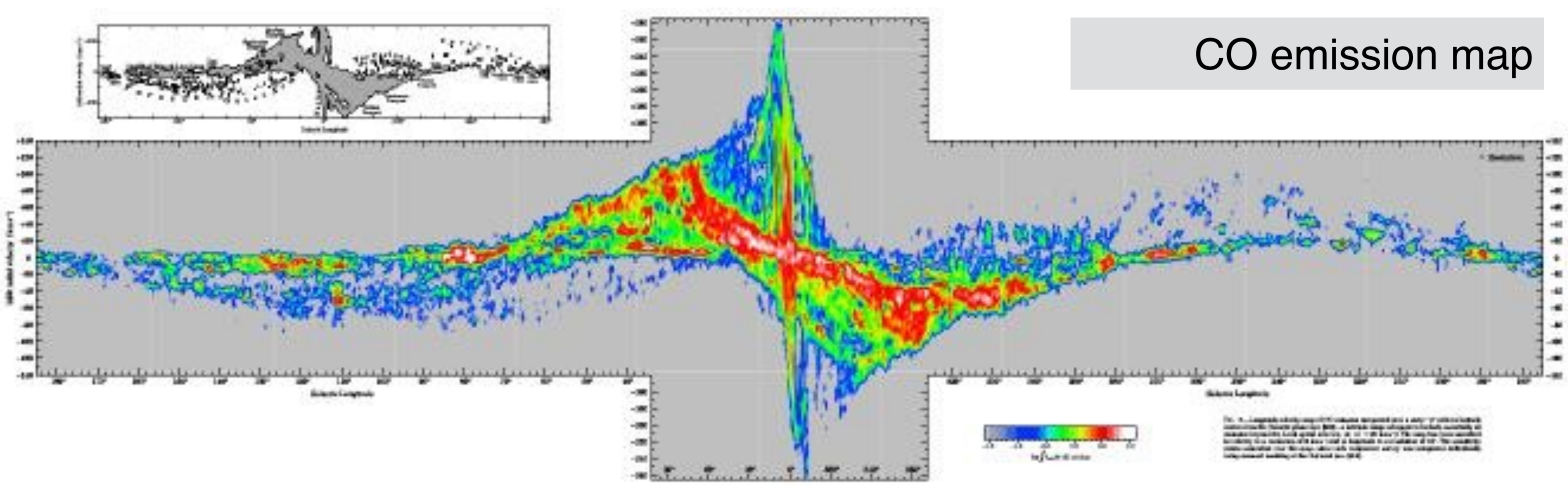
Our MC simulation

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**

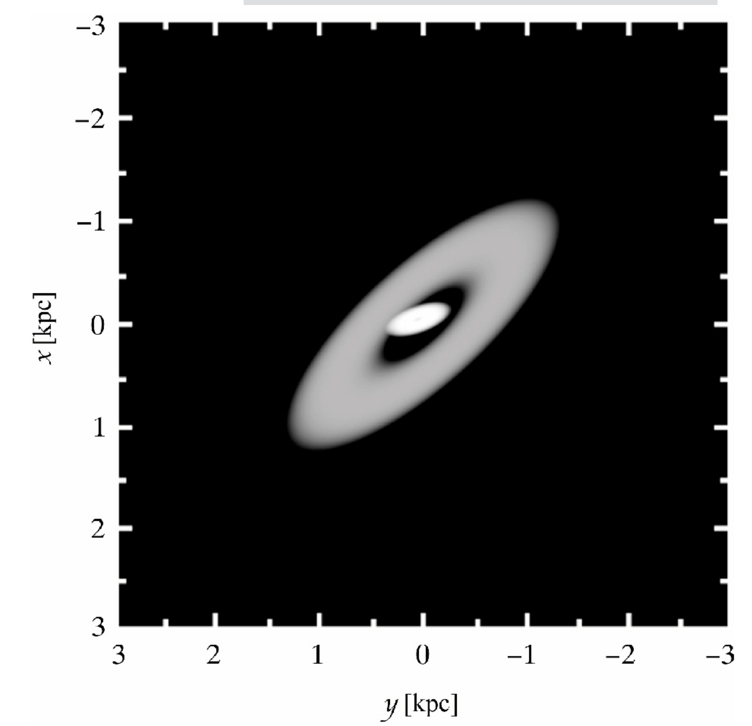


Zoomed-in analytical 3D model of the distribution of interstellar gas in the inner Galactic bulge, from K. Ferrière 2007

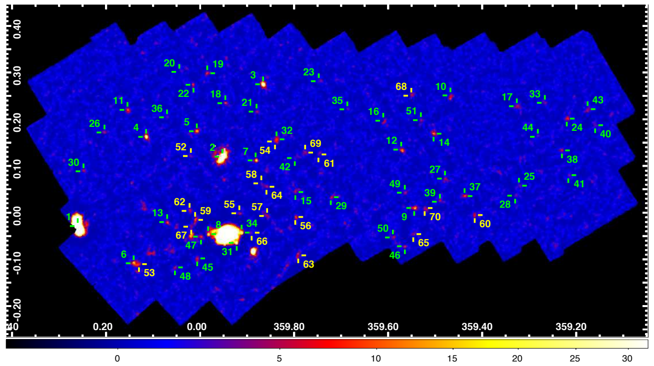
Gas distribution: we consider the state-of-the-art models by K. Ferrière (Ferrière 2001, Ferrière 2007)
very accurate models of the 3D gas distribution in the inner bulge, based on CO observations



CO emission map



Part 1: LIGO, PBHs and DM



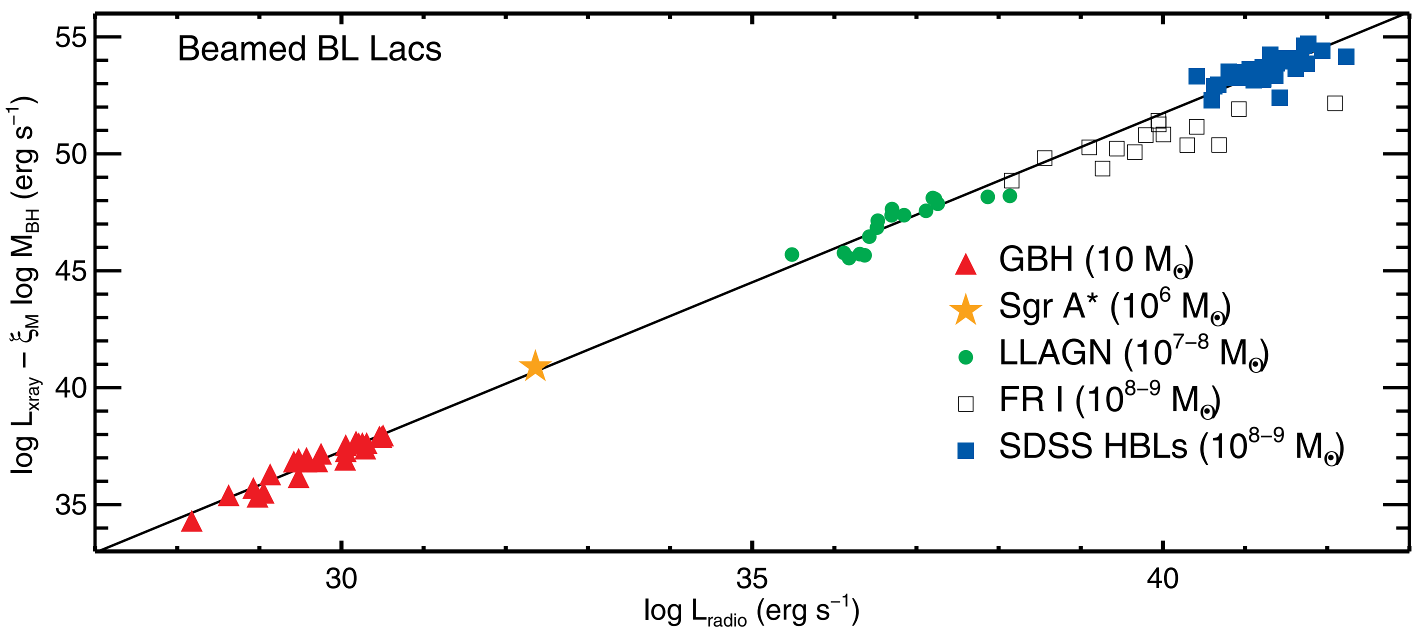
Comparison with the X-ray and radio data

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: $-0.5° < l < 0.5°$; $|b| < 0.4°$)

Results and discussion

X-rays:

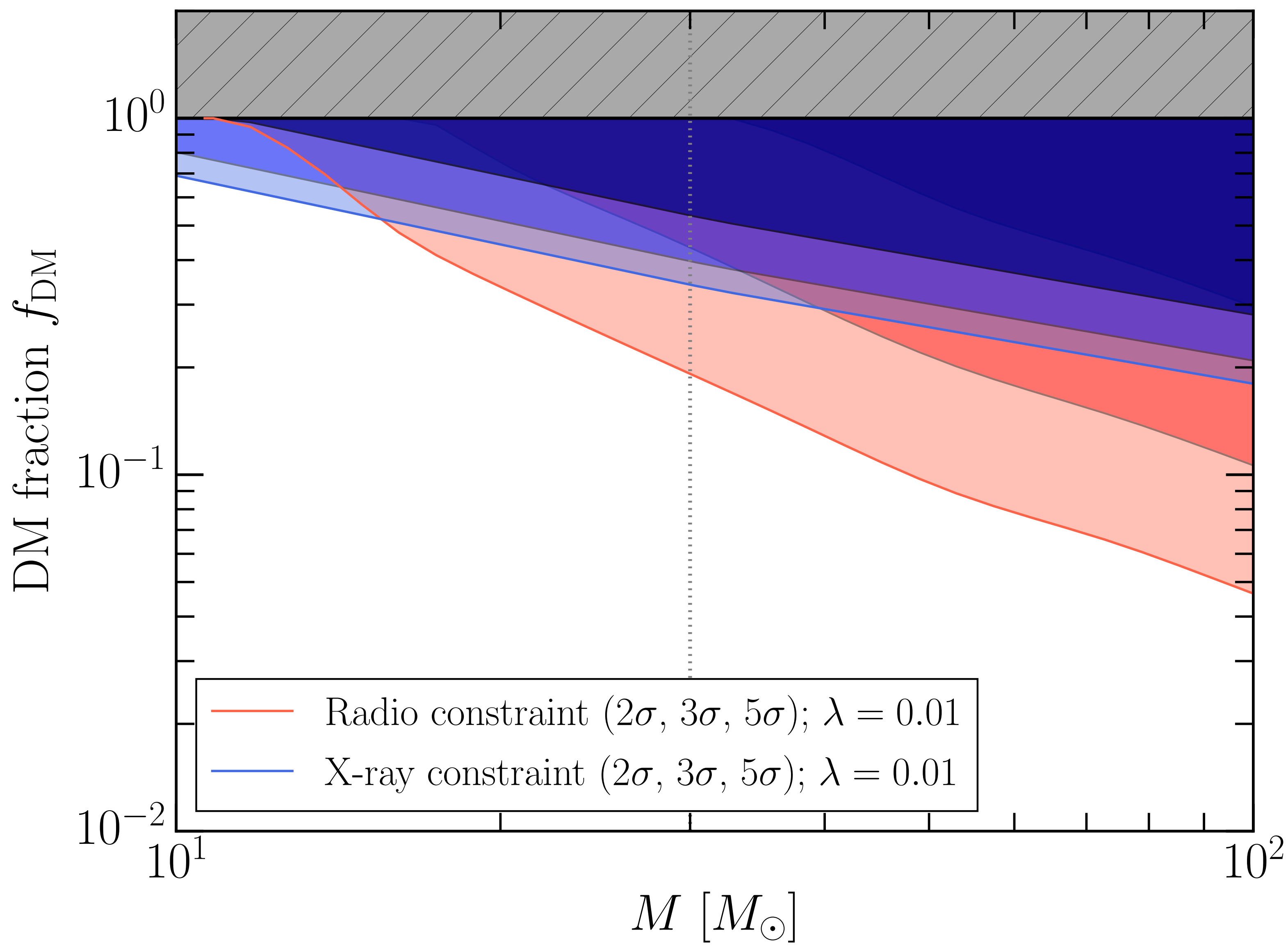
We predict **170±13 bright X-ray sources**, *given the assumptions we discussed*

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

Radio:

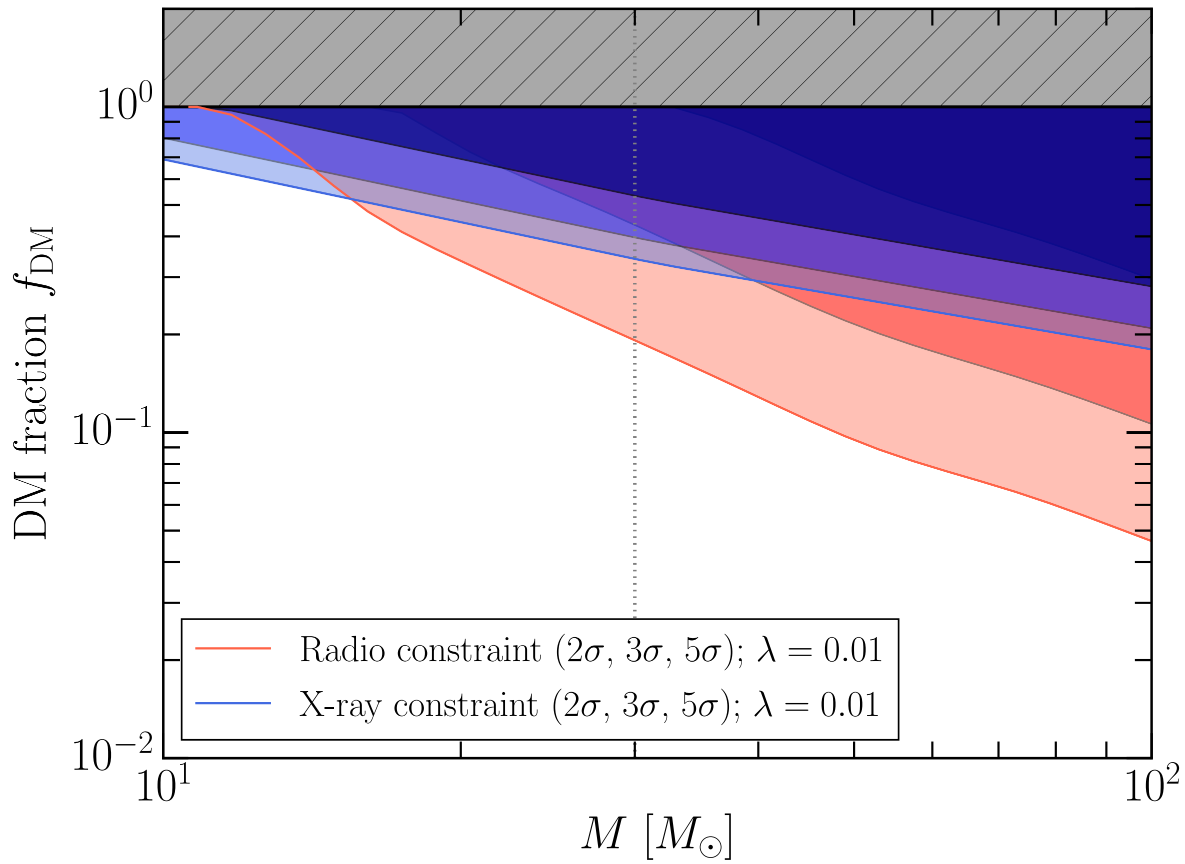
We predict **21±5 bright radio sources** in the ROI

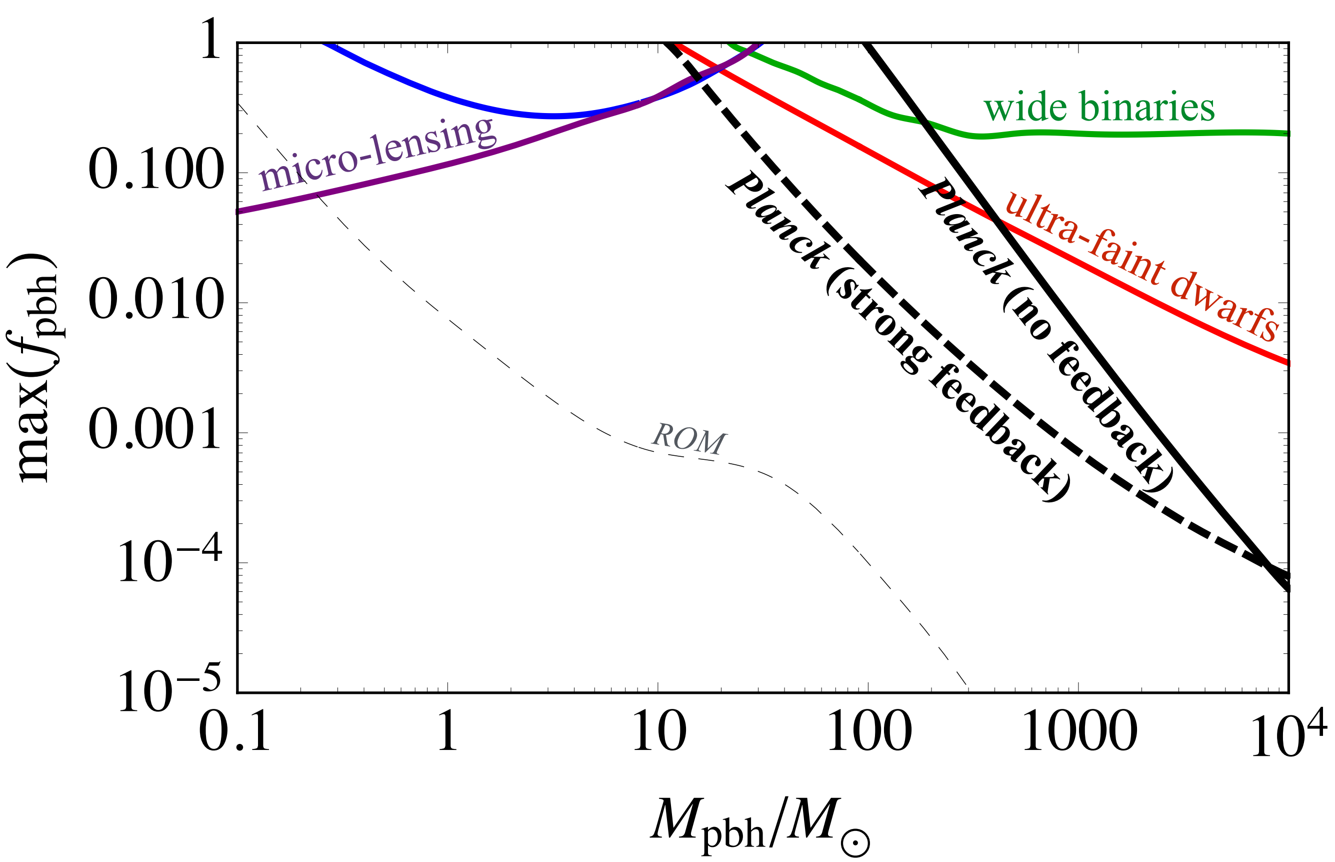
total number of radio sources in the ROI: 170
number of candidate black holes in the ROI: 0, assuming that BHs obey the Fundamental Plane relation



Results and discussion

Our constraints compared to other constraints (from lensing, CMB, stellar dynamics)

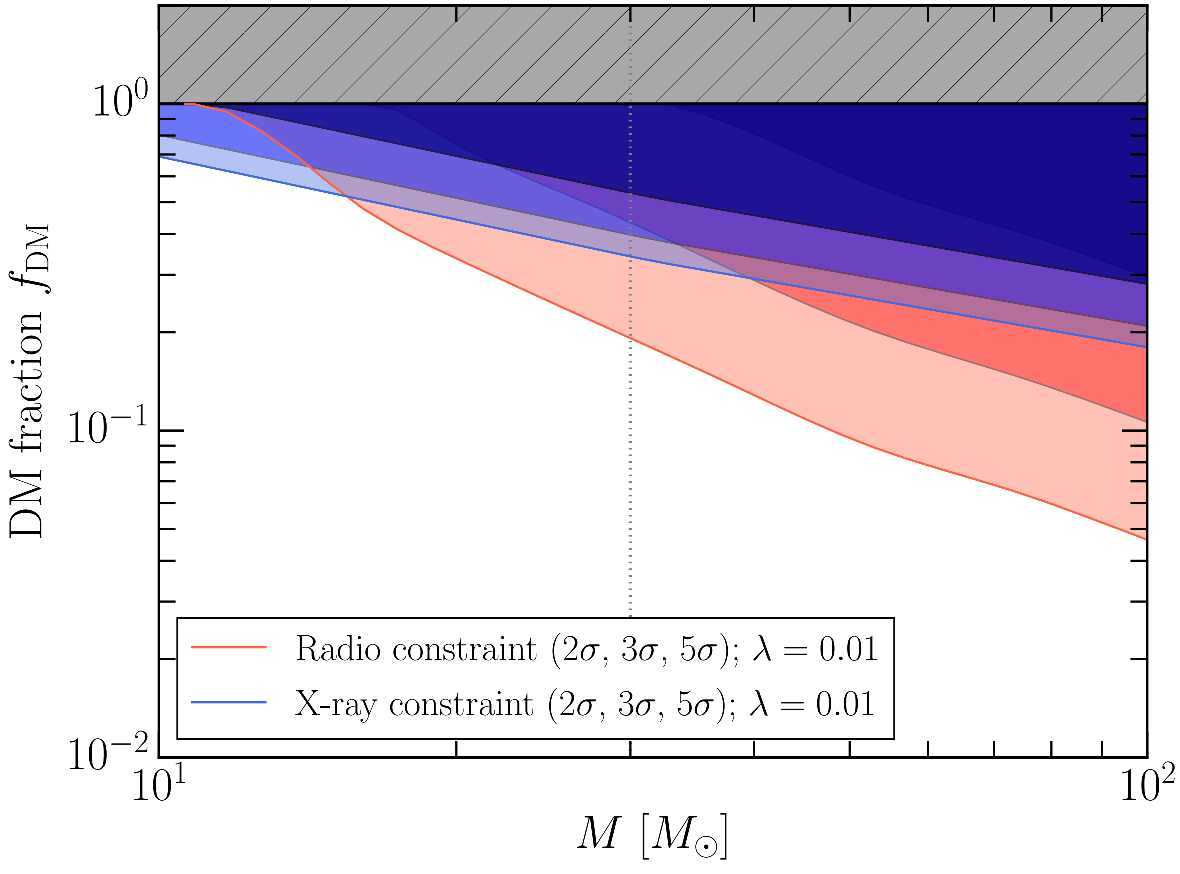


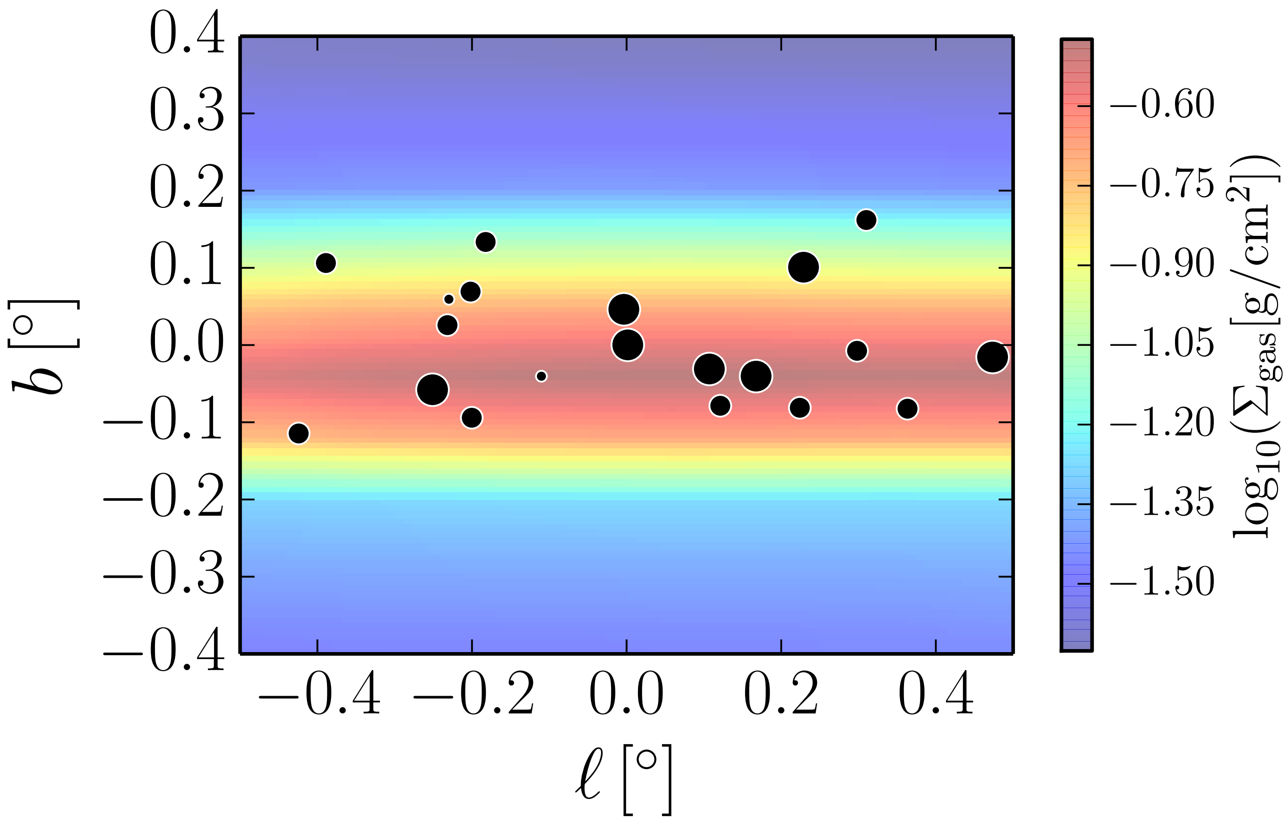


Results and discussion

Where does the constraining power comes from?

Only the low-velocity (< 10 km/s) black holes crossing the high-density regions matter!
A very tiny fraction of the BHs are bright (above NuStar or VLA threshold) sources.





Conclusions of Part 1

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.

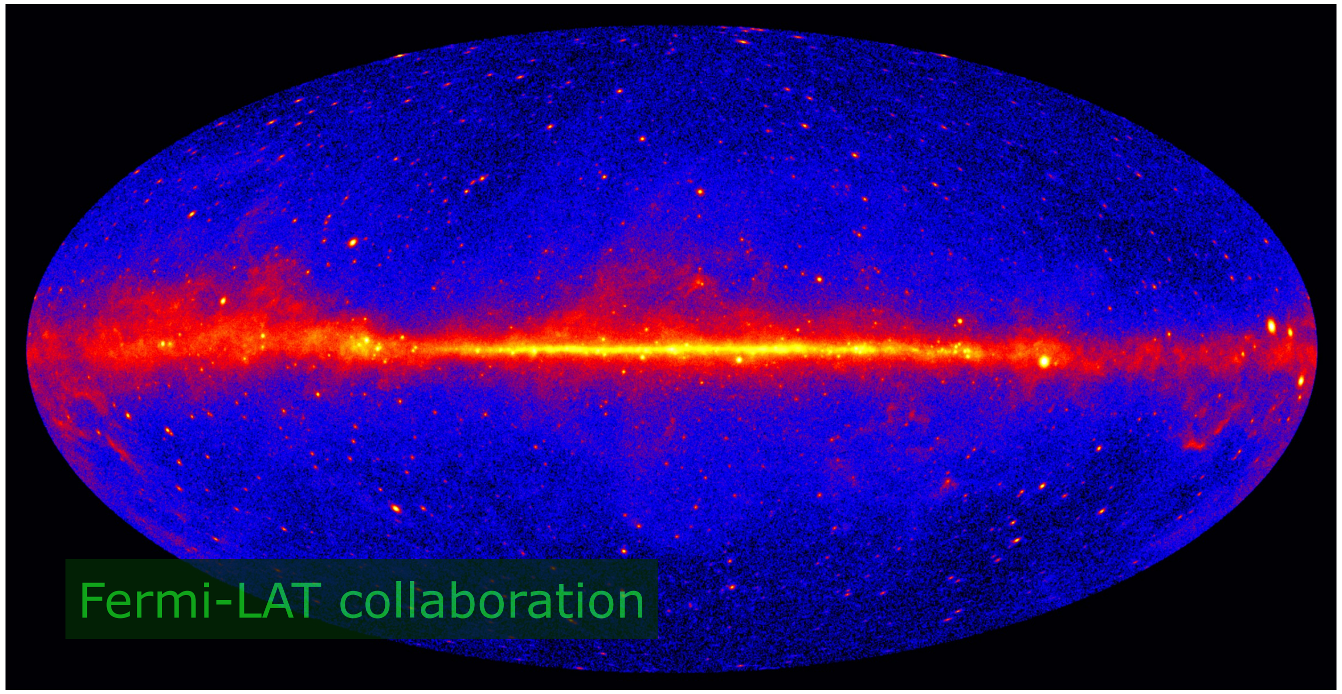
5) We considered a very conservative scenario (much more conservative than many papers on CMB constraints)

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

7) **The idea that PBHs are the DM is unlikely in our opinion**

Part 2: The γ-ray inner Galaxy excess

Searching for signatures of WIMP dark matter annihilation in gamma-ray maps

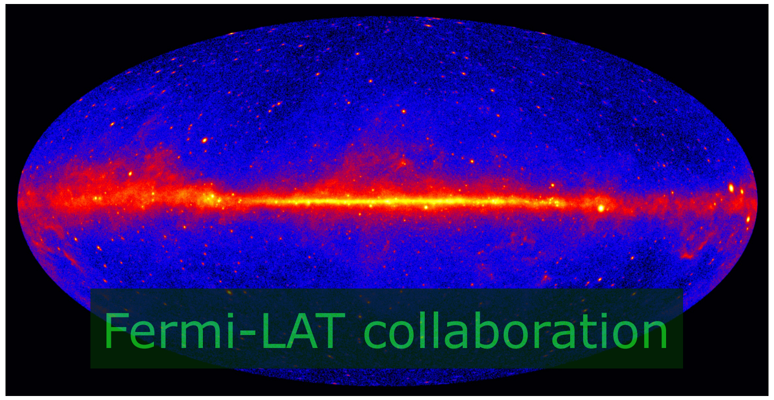


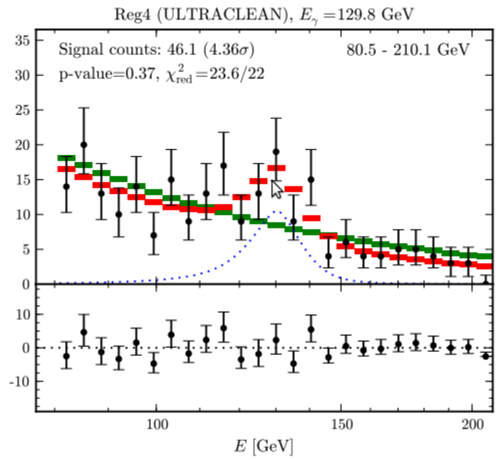
The diffuse gamma rays are a precious tool in the astroparticle community since they are able to track the CR distribution in different positions of the Galaxy

Main processes: *pion decay, Inverse Compton scattering, bremsstrahlung*

300 MeV up to >300 GeV —> **Fermi-LAT** has been providing the most accurate maps ever

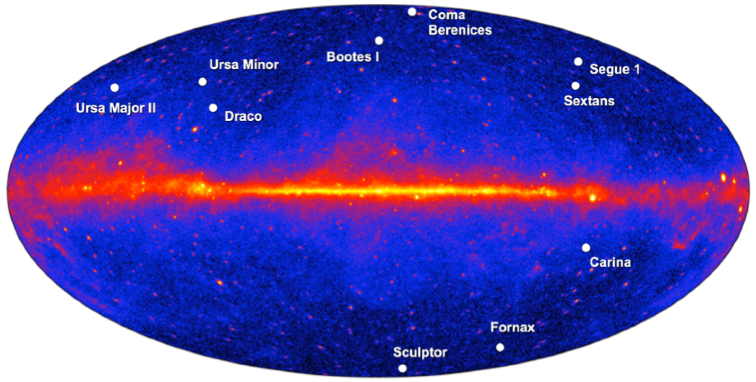
Searching for signatures of WIMP dark matter annihilation in gamma-ray maps





Interesting features relevant for DM searches

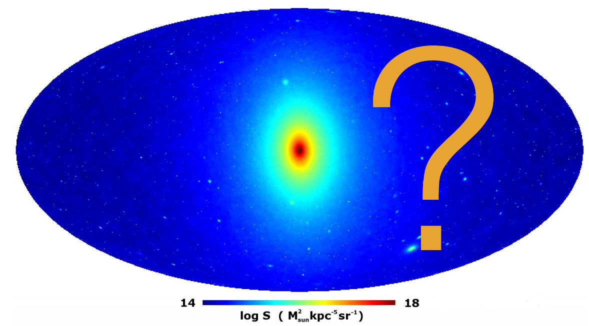
- **gamma-ray line**? *no detection yet*

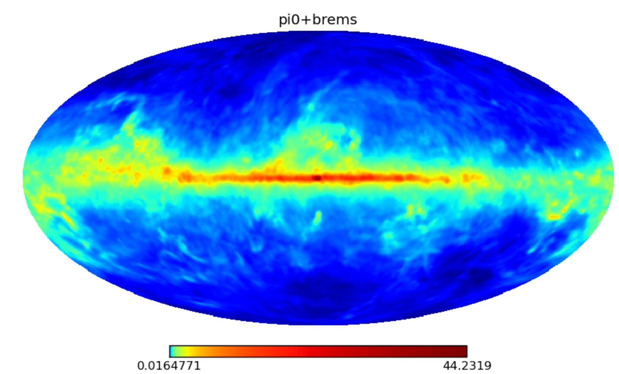


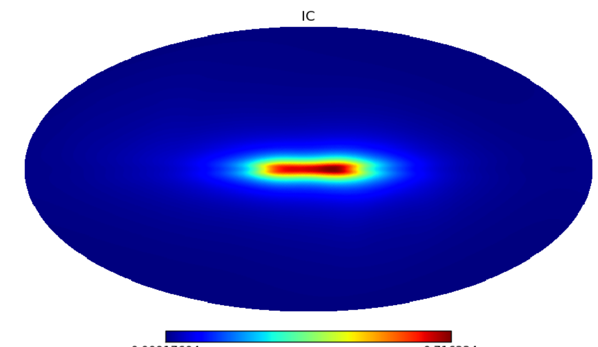
- *significant* gamma-ray emission from **dwarf spheroidal Galaxies**? *no detection yet*

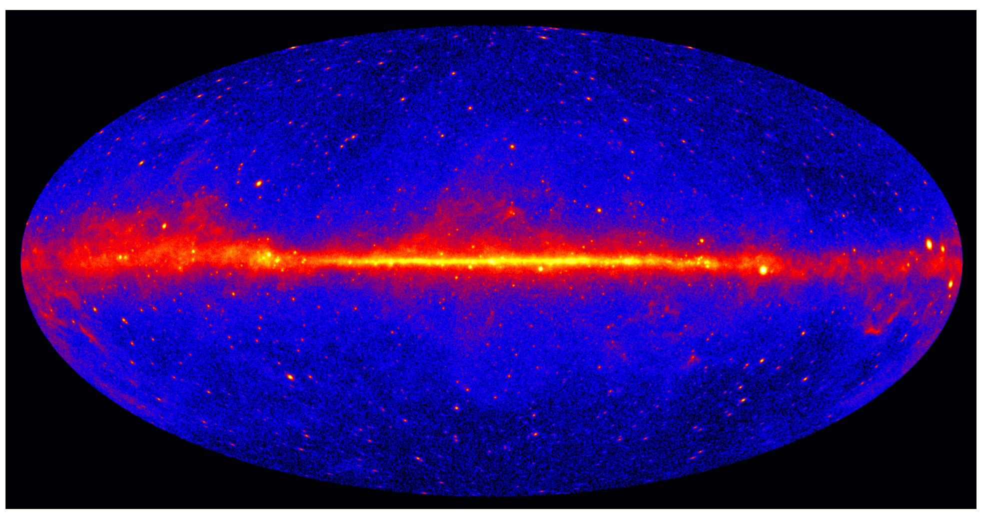
- **gamma-ray excesses** from inner Galaxy? There's a tentative claim to be discussed

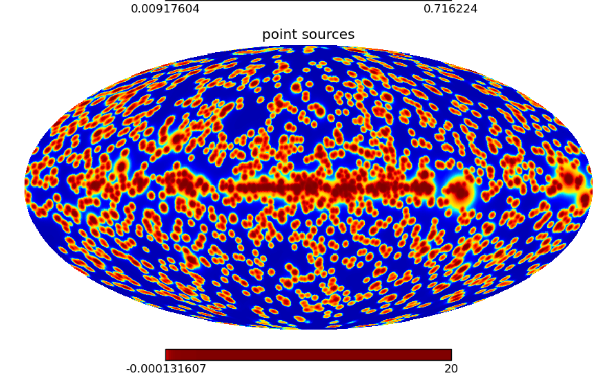
Does a NFW template improve the fit of the Fermi-LAT data?

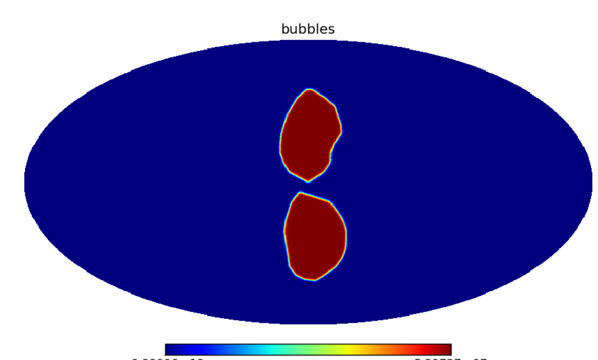












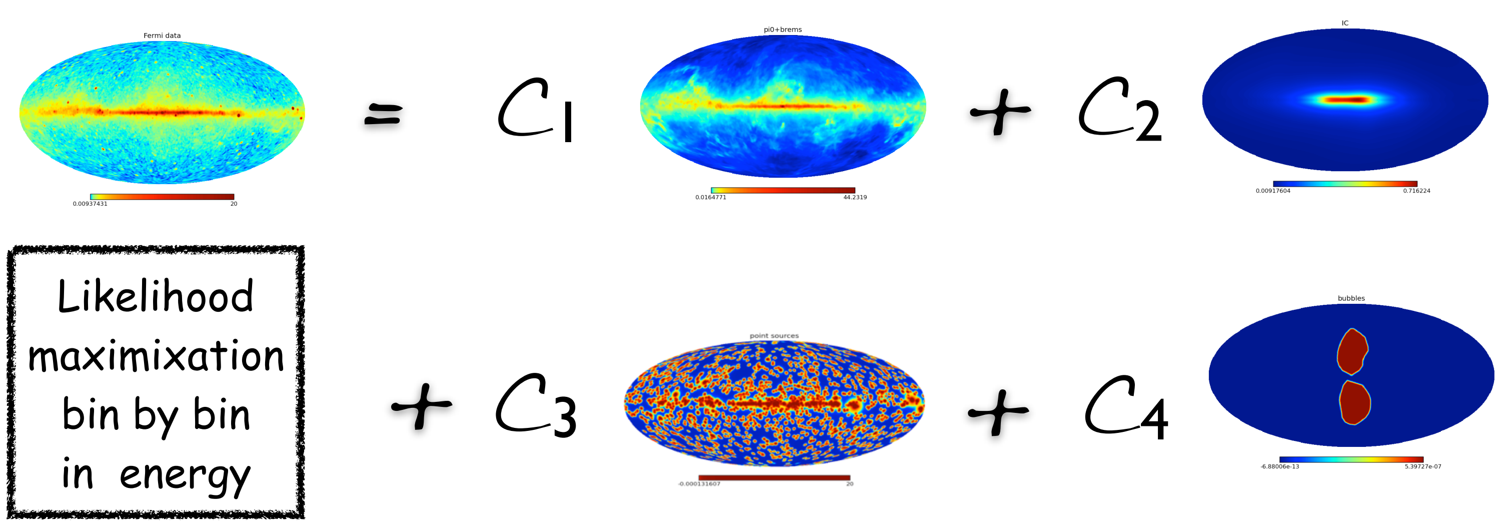
yes, according to a long series of papers

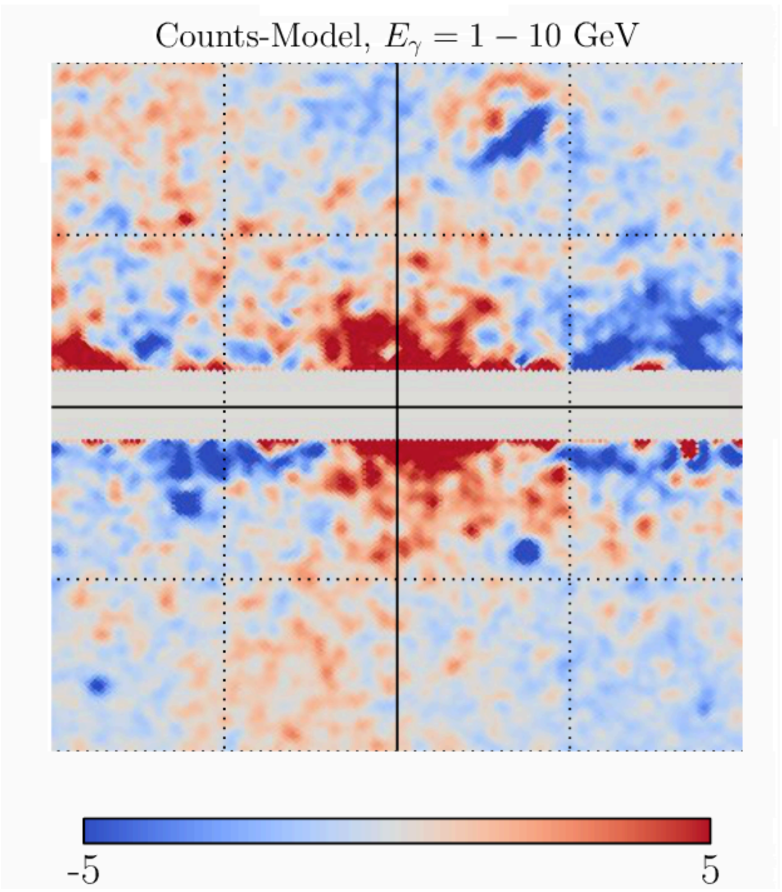
D. Dixon et al. 1998 [arXiv:9803237]; V. Vitale et al. 2009 [arXiv:0912.3828]; L Goodenough and D. Hooper, 2009; D. Hooper and L. Goodenough, 2010 D. Hooper and T. Linden, 2011; K. N. Abazajian and M. Kaplinghat, 2012 D. Hooper and T. R. Slatyer, 2013; C. Gordon and O. Macias, 2013 T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden; S. Portillo, N. L. Rodd and T. R. Slatyer, 2014 [arXiv:1402.6703]; F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]; F. Calore et al. 2015 [arXiv;1411.4647]

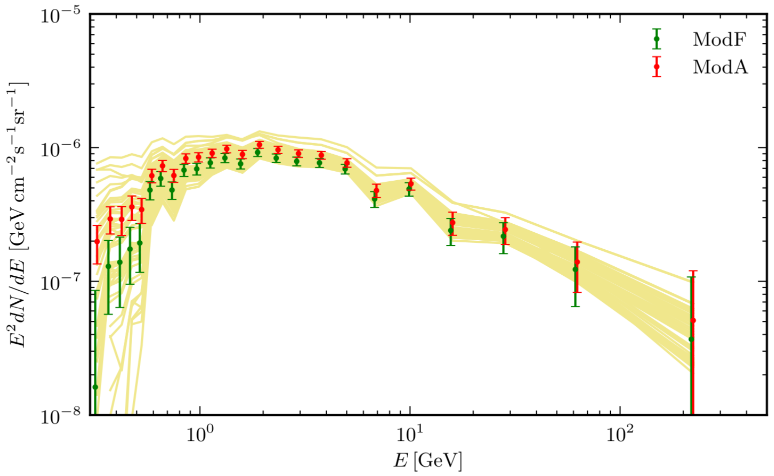
Part 2: The γ-ray inner Galaxy excess

Does a NFW template improve the fit of the Fermi-LAT data?

If you try to model the gamma-ray emission taking into account the diffuse emission from π0 decay, the Inverse Compton emission, and all the other known gamma-ray sources, you end up missing something in the inner Galaxy



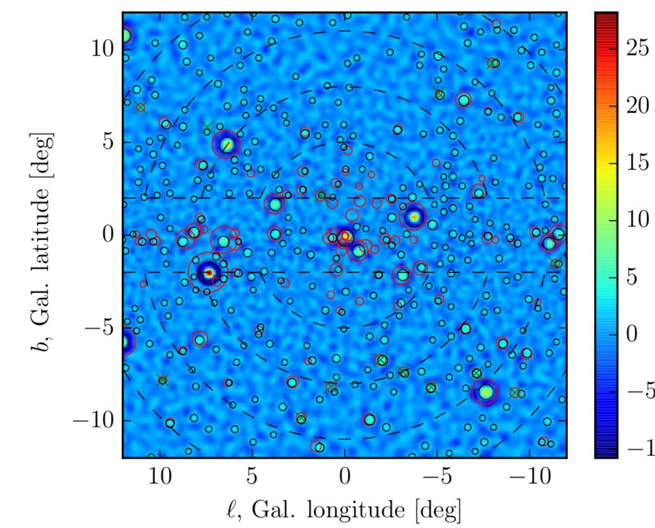




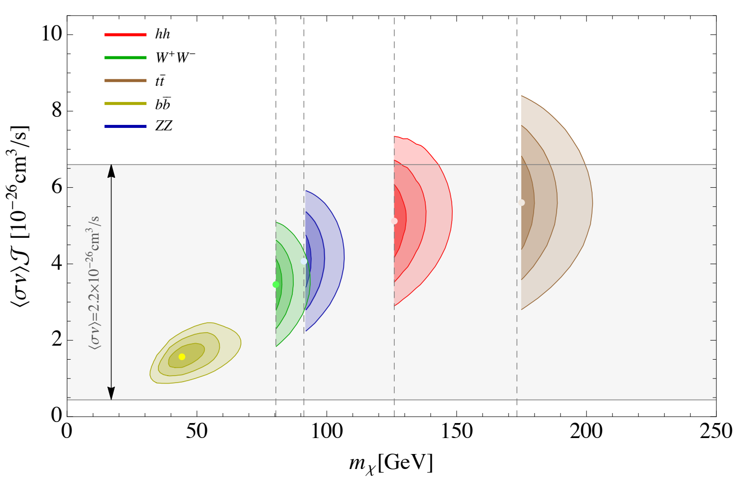
Calore et al 2015

The spectrum of the signal is compatible with 40 GeV DM annihilating in conventional channels, with the reference thermal cross section!

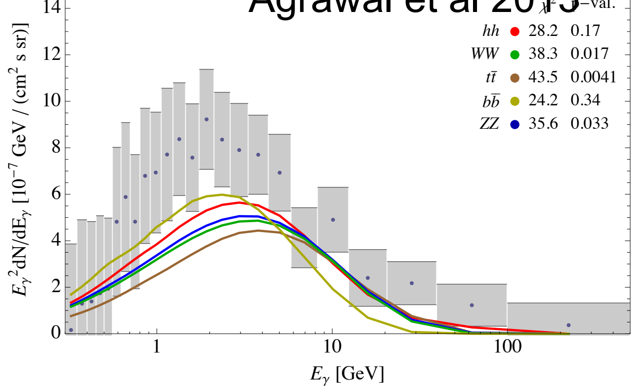
A “compelling case of dark matter detection”, a new class of sources, or maybe a mis-modeling of the background?



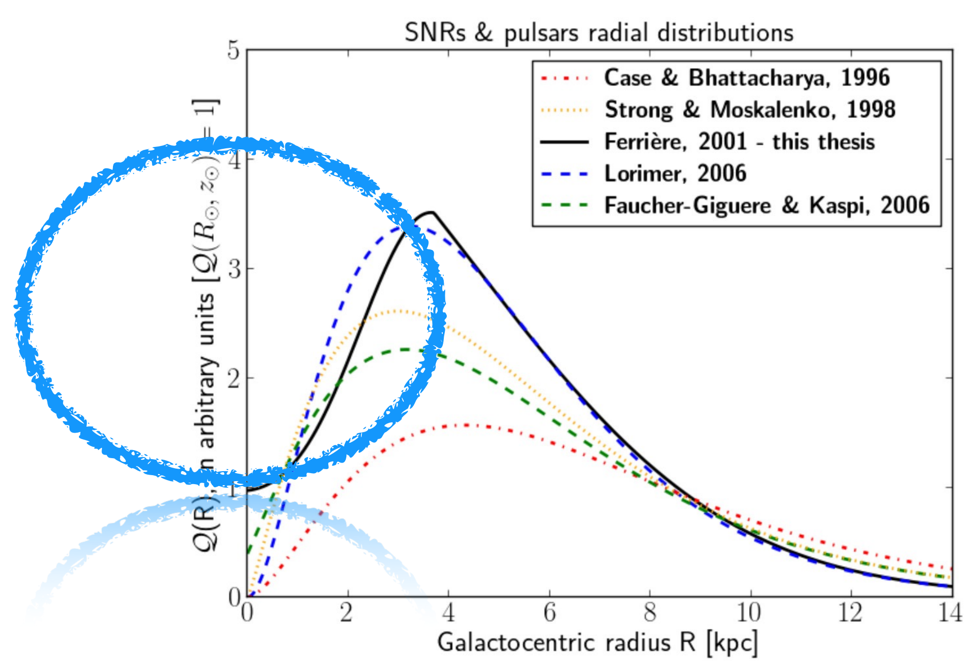
Bartels et al 2016



Agrawal et al 2015

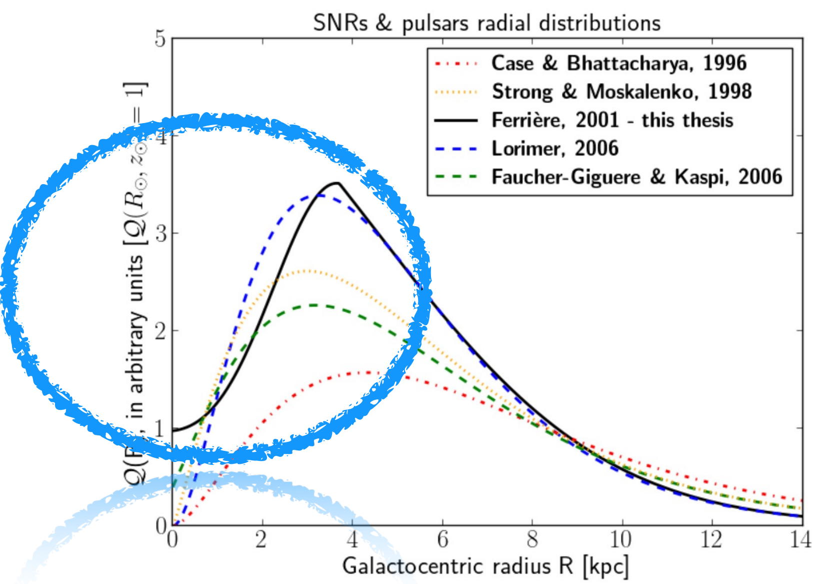


The background models assume no sources in the center… is that reasonable?



(a) *Radial profile of the distribution functions of the CRs sources*

Astrophysical interpretations



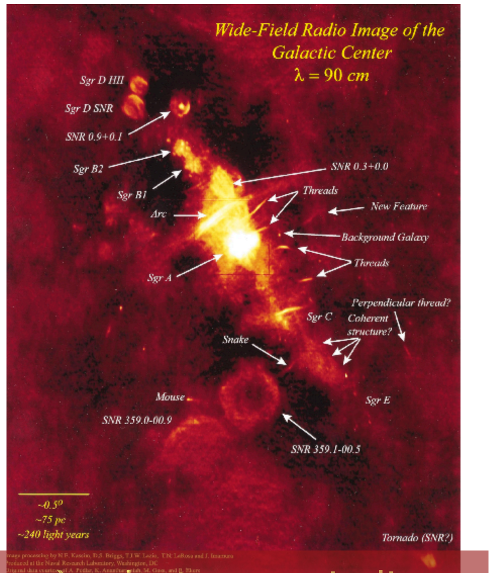
(a) *Radial profile of the distribution functions of the CRs sources*

The background models assume no sources in the center… is that reasonable?

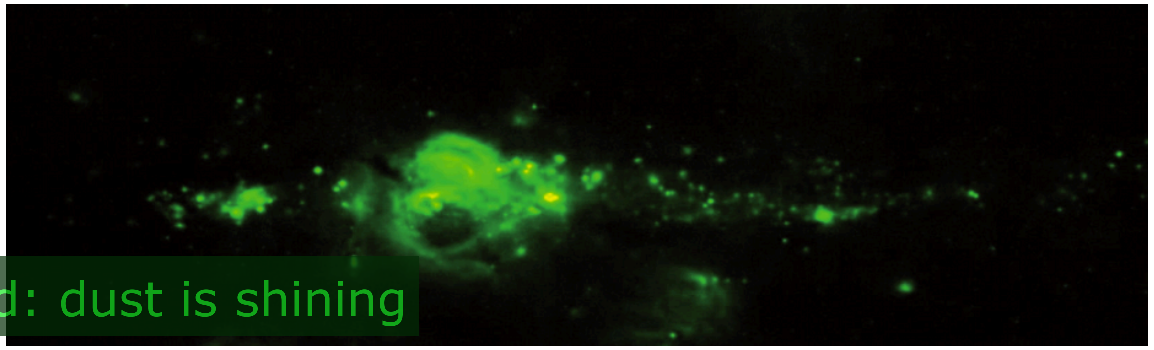
Probably it's not realistic: A very efficient star formation is going on

According to [Figer et al. 2004 ApJ 581 2002] 1% of the total SFR takes place in the inner 2-300 pc

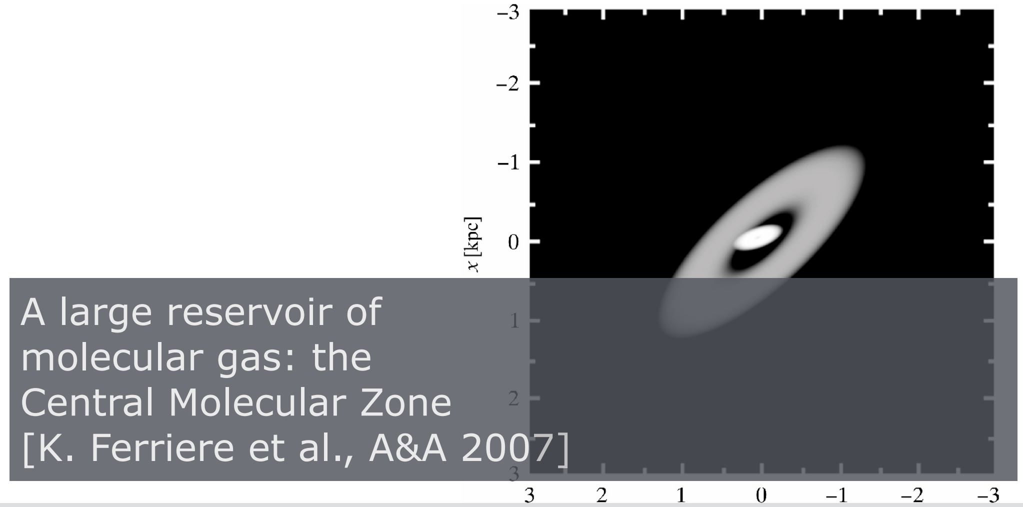
(2 order of magnitude more than the average); see also [Longmore et al. 1208.4256]



Radio (90 cm): electrons spiraling in a higly magnetized environment are shining. Nonthermal filaments, SNRs… [LaRosa et al. ApJ 119 2000]



Infrared: dust is shining

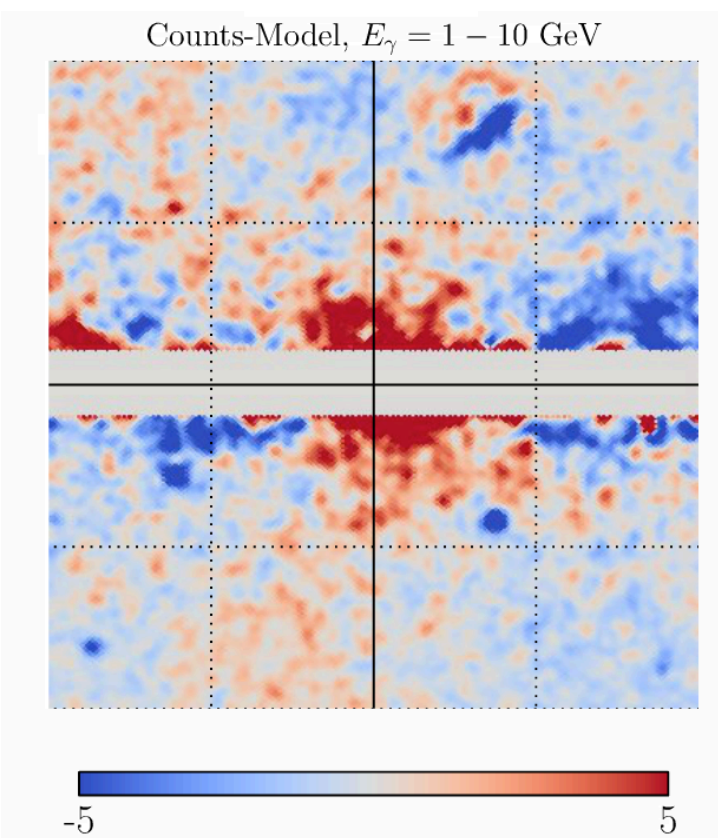


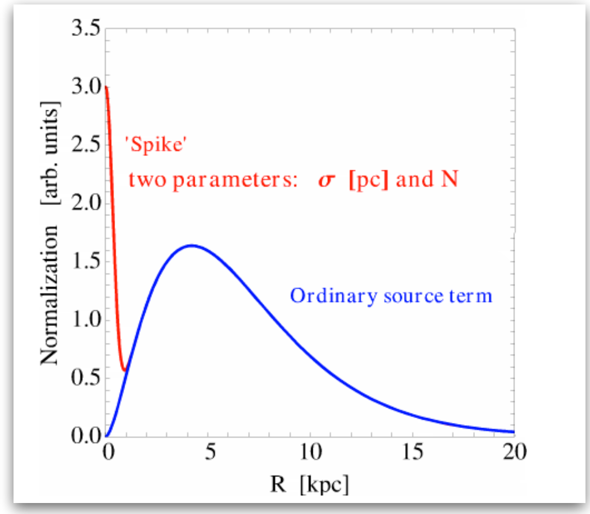
A large reservoir of molecular gas: the Central Molecular Zone [K. Ferriere et al., A&A 2007]

Part 2: The γ-ray inner Galaxy excess

A modified source term in the center, compatible with the astronomical observations, reabsorbs the excess!

[D. Gaggero et al. 2015]
[E. Carson and S. Profumo 2016]

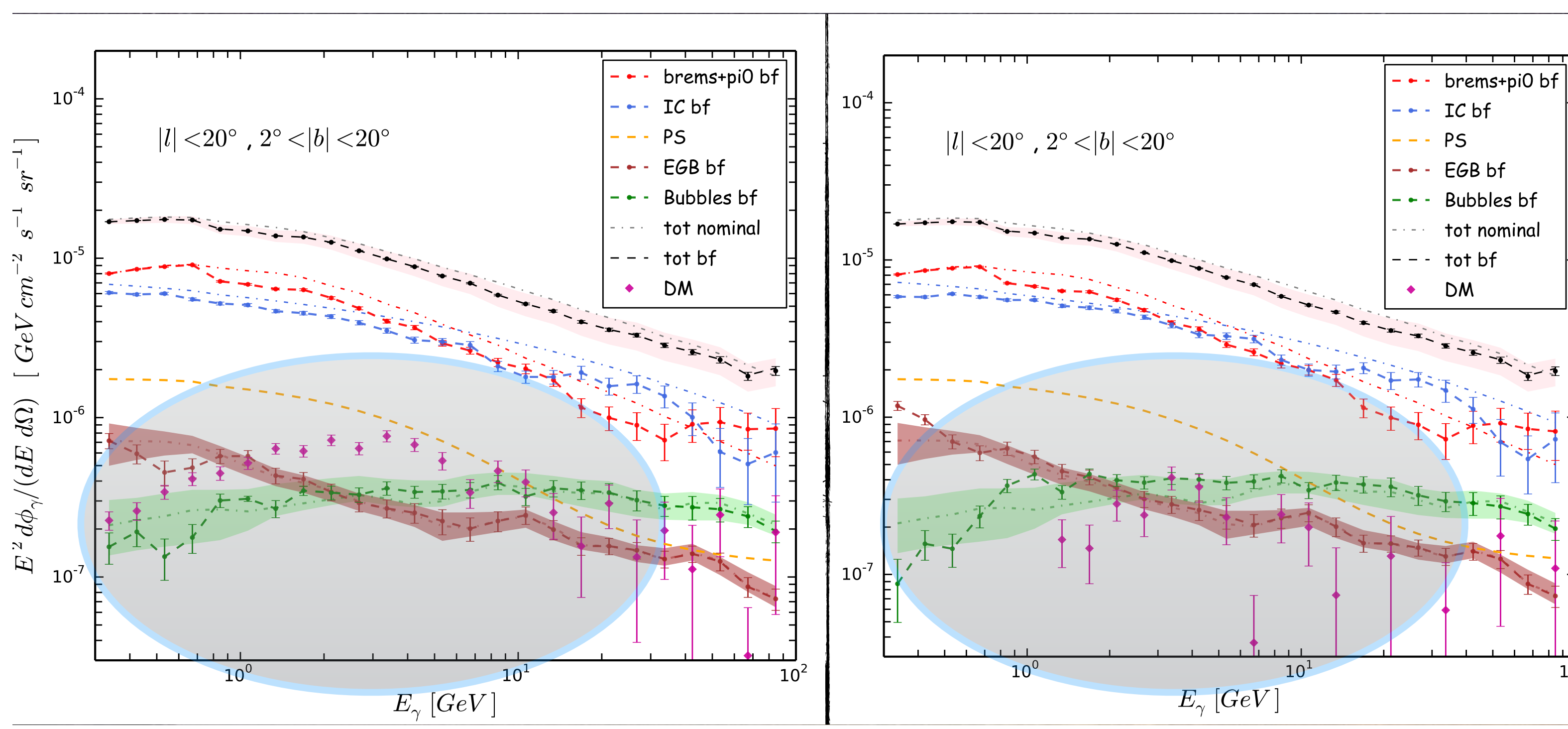




$$Q(x,y,z) = \mathcal{N} \exp\left(-\frac{x^2+y^2+z^2}{\sigma^2}\right)$$

normalization compatibly with star formation rate estimate @ the GC

spike extension roughly matching CMZ one, i.e. O(100) pc



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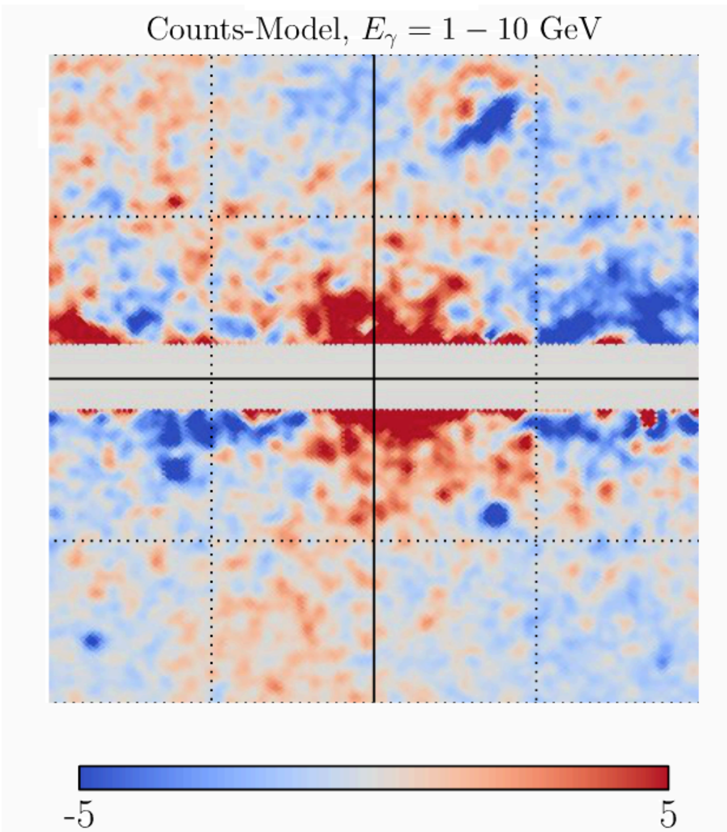

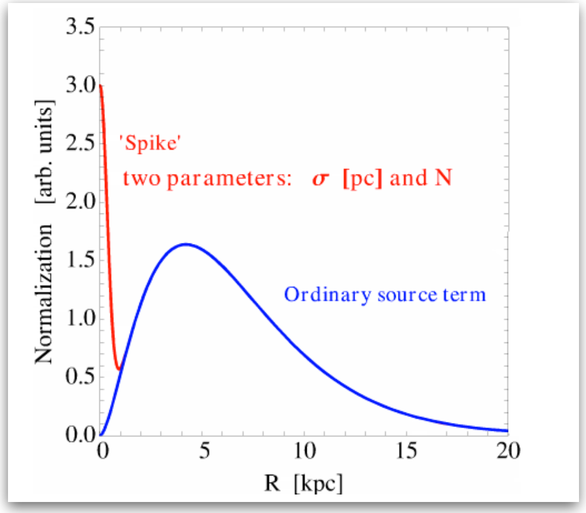

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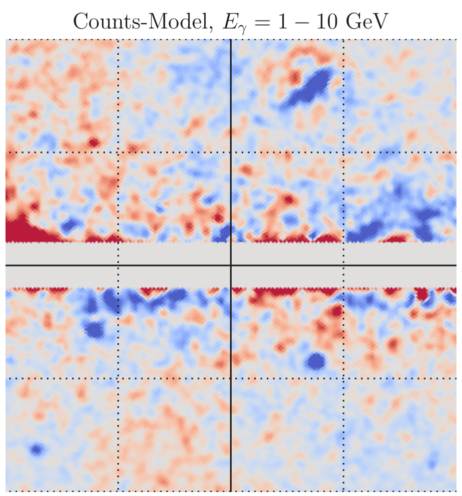
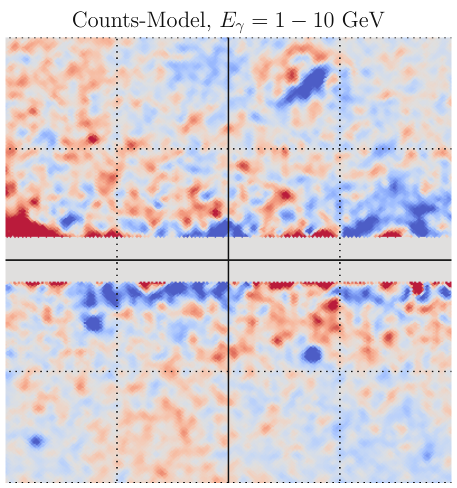
Model+DM



Model+spike



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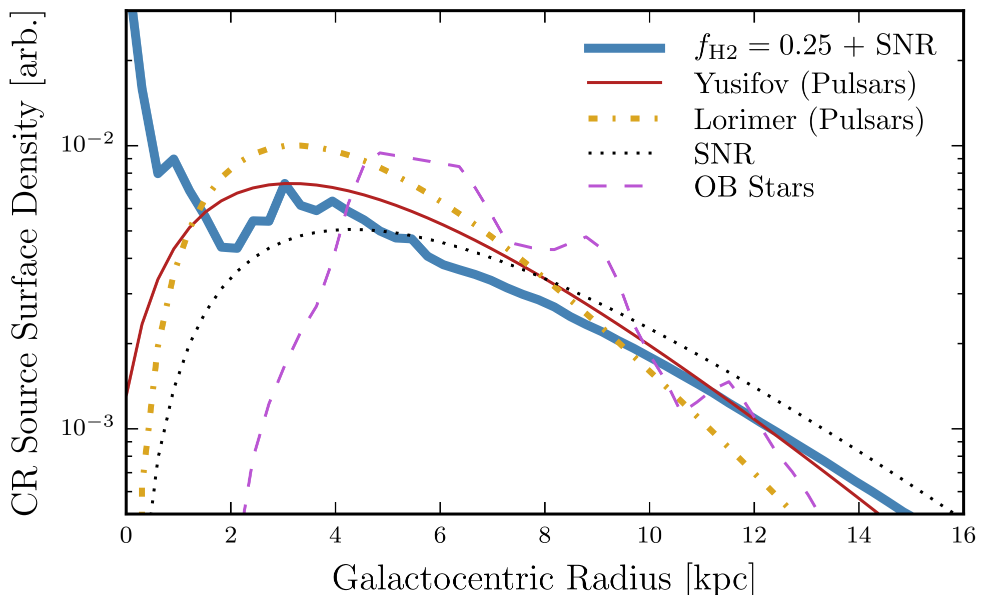

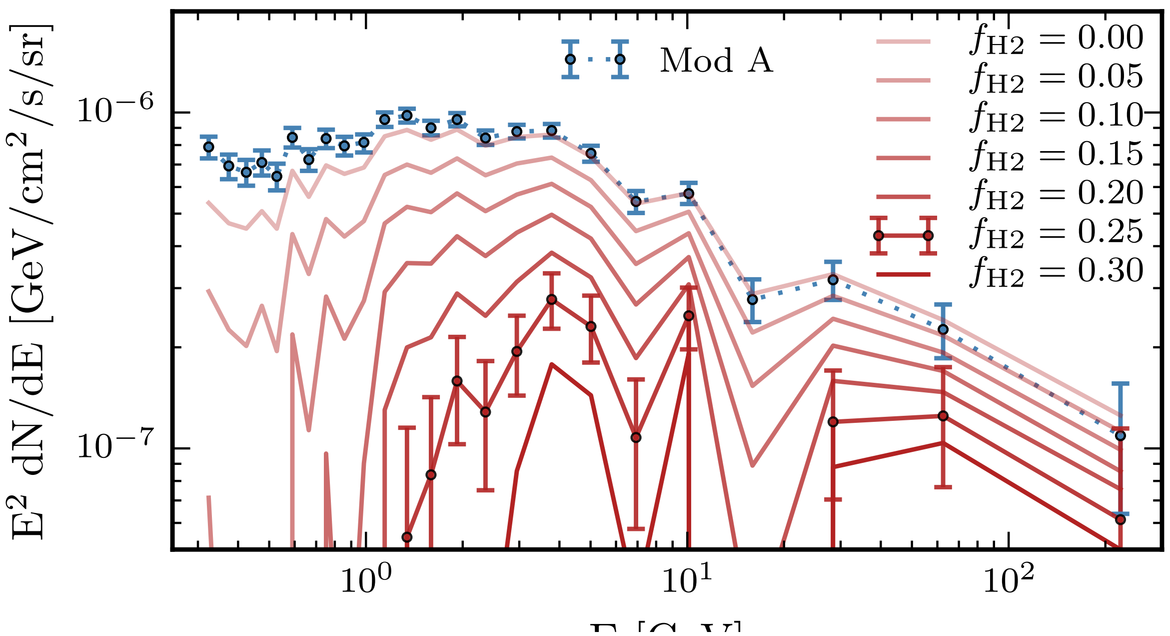

Conclusions of Part 2

1) The gamma-ray maps are interesting for WIMP DM searches

2) A tentative claim of a GeV excess from the inner Galaxy exists

3) Many astrophysical explanations exist

4) The claim triggered an interesting debate —> **It became clear that most CR propagation models are not adequate to describe the inner Galaxy!**

Thank you for your attention!

Daniele Gaggero

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