Constraining Primordial Black Holes with High-energy Astrophysics

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Solvay Workshop

THE DARK SIDE OF BLACK HOLES

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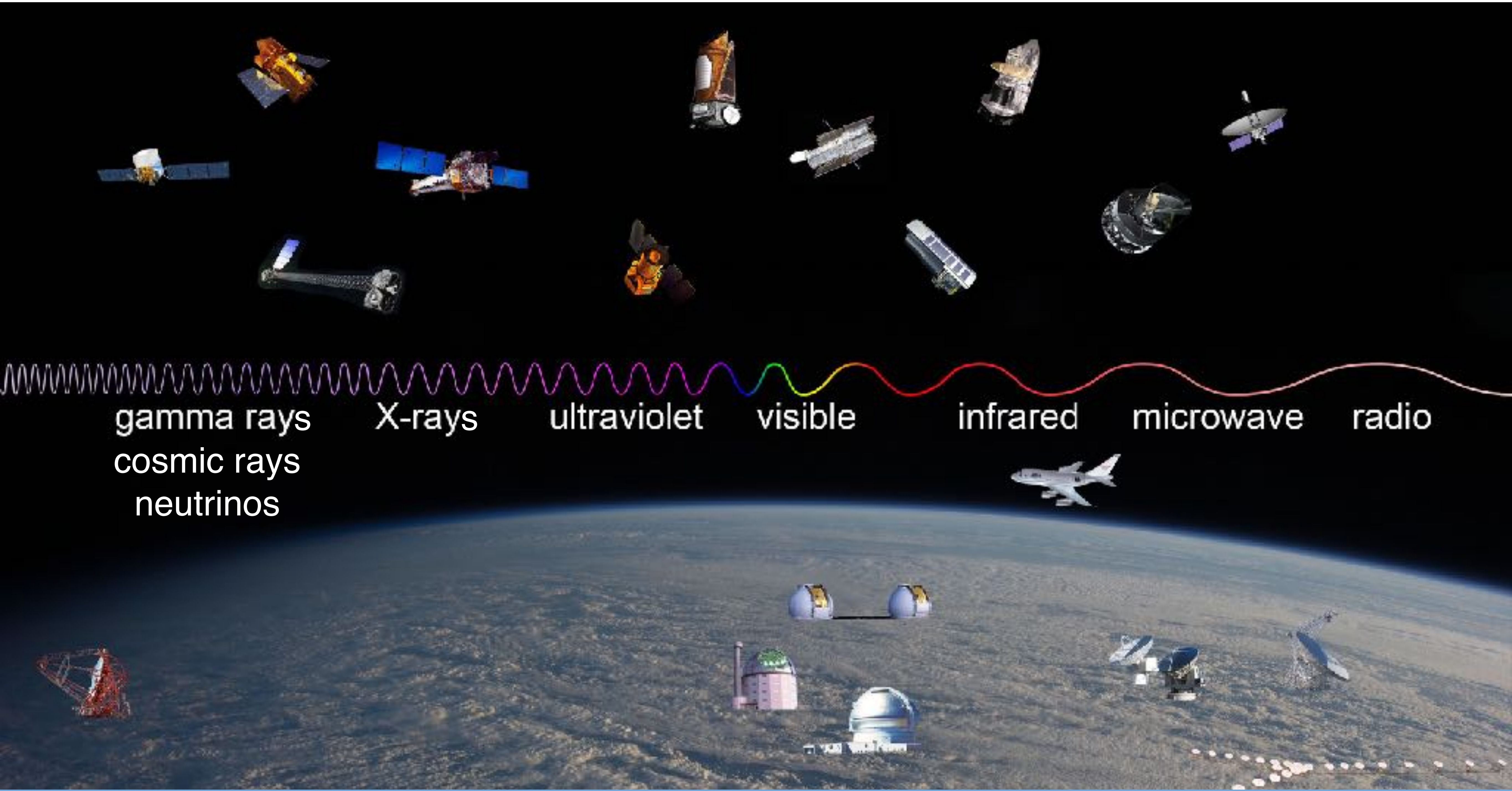
Bruxelles

The astronomical data landscape

Ground-based telescopes and **space-borne instruments** dedicated to detection of electromagnetic radiation, cosmic rays and HE neutrinos



Constraints from HE astrophysics

B. Carr talk

"High"(Stellar)-mass PBH

$$10 - 100\, M_\odot$$

Mechanism: Gas accretion onto (P)BH*

Probes: Radio (GHz), X rays (keV)

Exp: VLA, Chandra, NuSTAR

Low-mass PBH

$$10^{-19} - 10^{-16}\, M_\odot$$

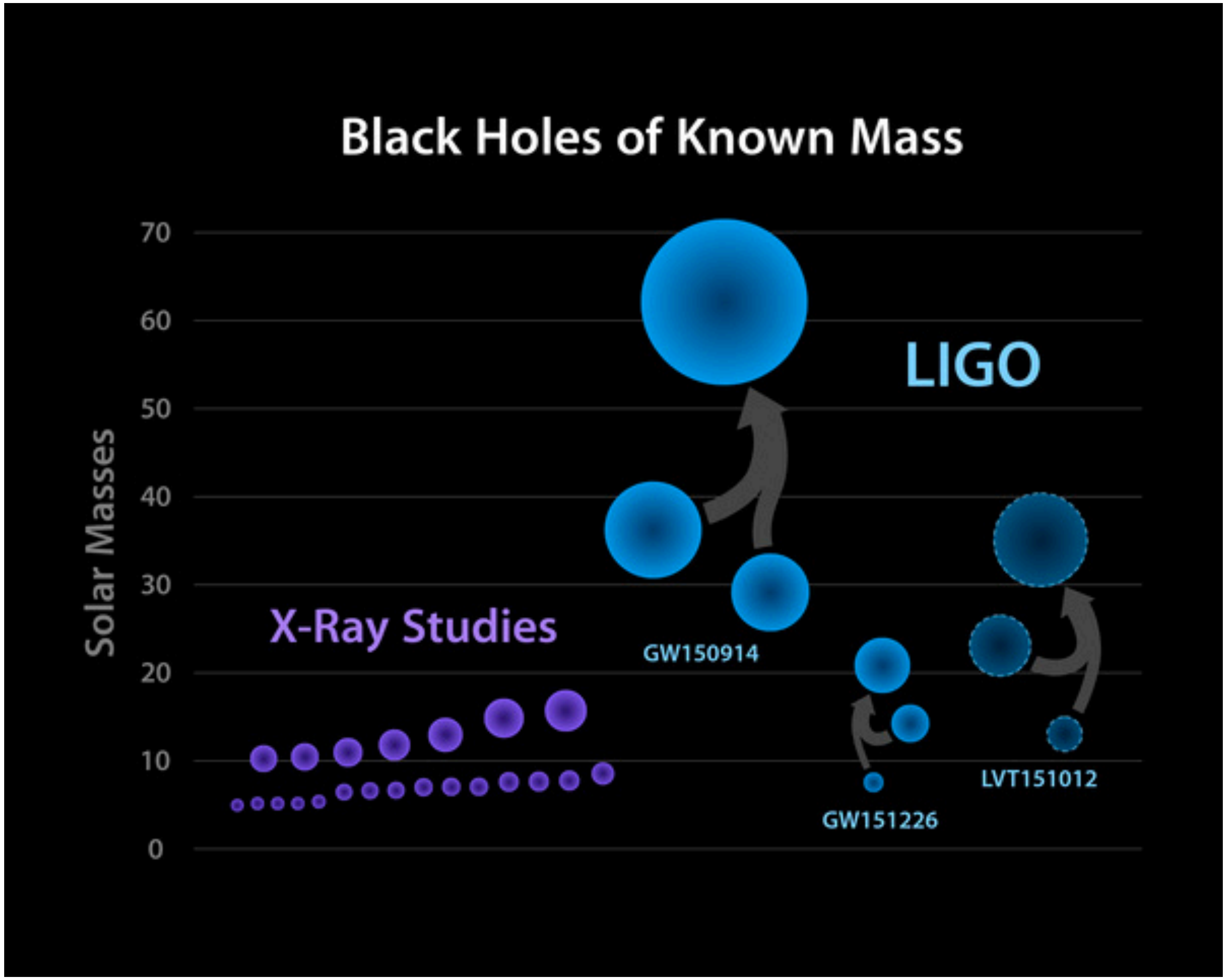
Mechanism: Emission of charged cosmic rays and photons at low energies via Hawking radiation*

Probes: Extragalactic gamma rays, electron/positron yields (sub-GeV)

Exp: EGRET, Voyager, AMS02, Fermi-LAT

* Complementary to CMB and other cosmological bounds

Stellar-mass BH distribution



- Stellar-mass BH in X-ray binaries [*arXiv:0111540*]
- GW detection of stellar mass BH with mass as high as 40 M_{Sun} [*Abbott+ PRL'16*]

High-mass PBH constraints (end ’16)

Lensing constraints:

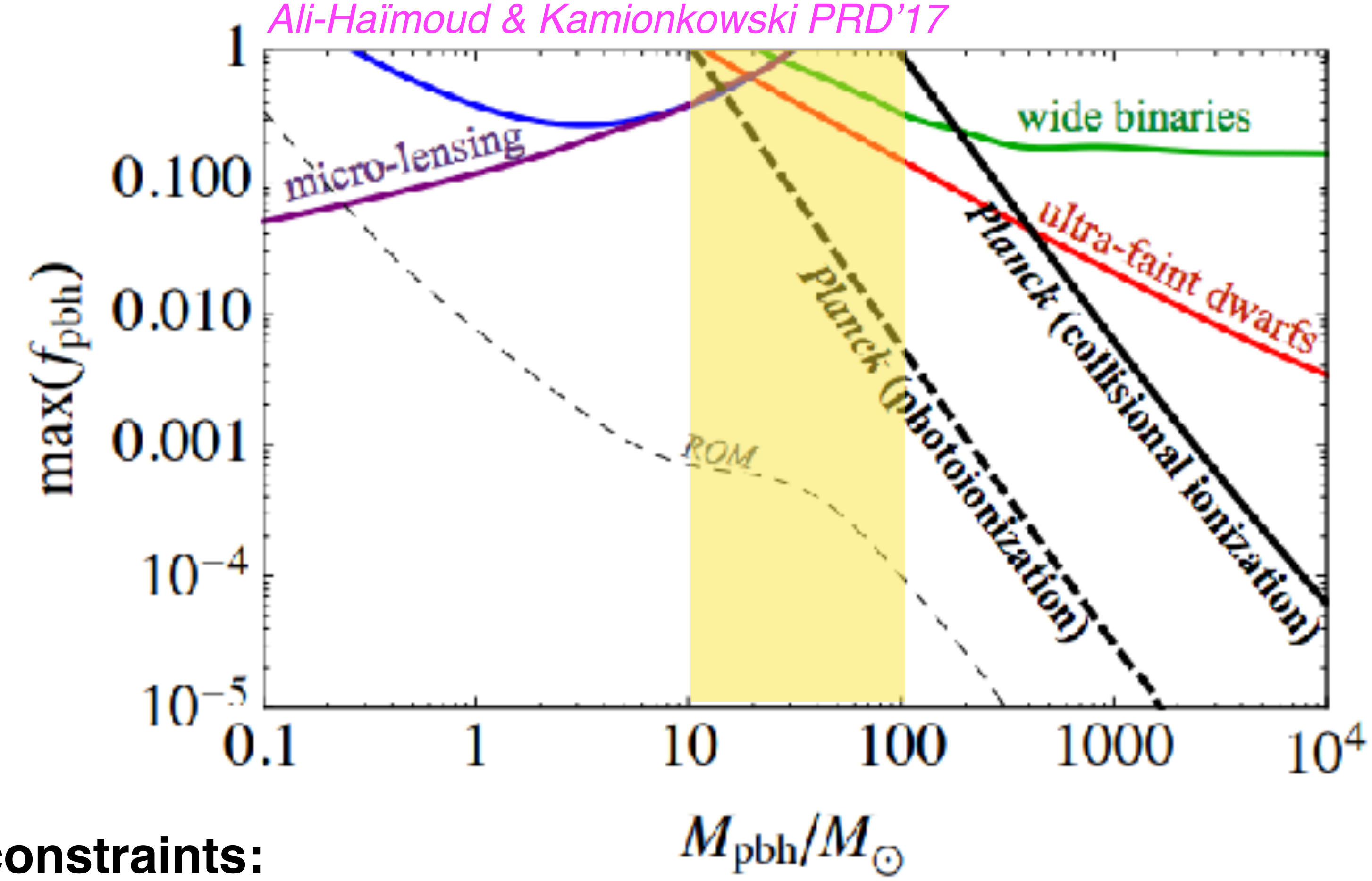
* **MACHO project** [*Allsman+ ApJ’01*]: micro-lensing events towards the Large Magellanic Cloud
* **EROS project** [*Tisserand+ A&A'07*]: 7-year monitoring millions of bright stars in the LMC and SMC

A. Green talk

Dynamical constraints:

* **Disruption of wide binaries** [*Monroy-Rodriguez+ ApJ'14*]
* **Ultra-faint dwarfs** [*Brandt ApJ’16*]: constraint from existence of star cluster at the center of Eridanus II

Ali-Haïmoud & Kamionkowski PRD’17



Early Universe constraints:

* Exploiting **accretion of gas onto PBH** at very early times [e.g. *Ali-Haïmoud & Kamionkowski PRD’17*]
* **21 cm line** brightness temperature fluctuations: how PBH do alter the reionisation history [*Gong+JCAP'18*]

Y. Ali-Haïmoud talk

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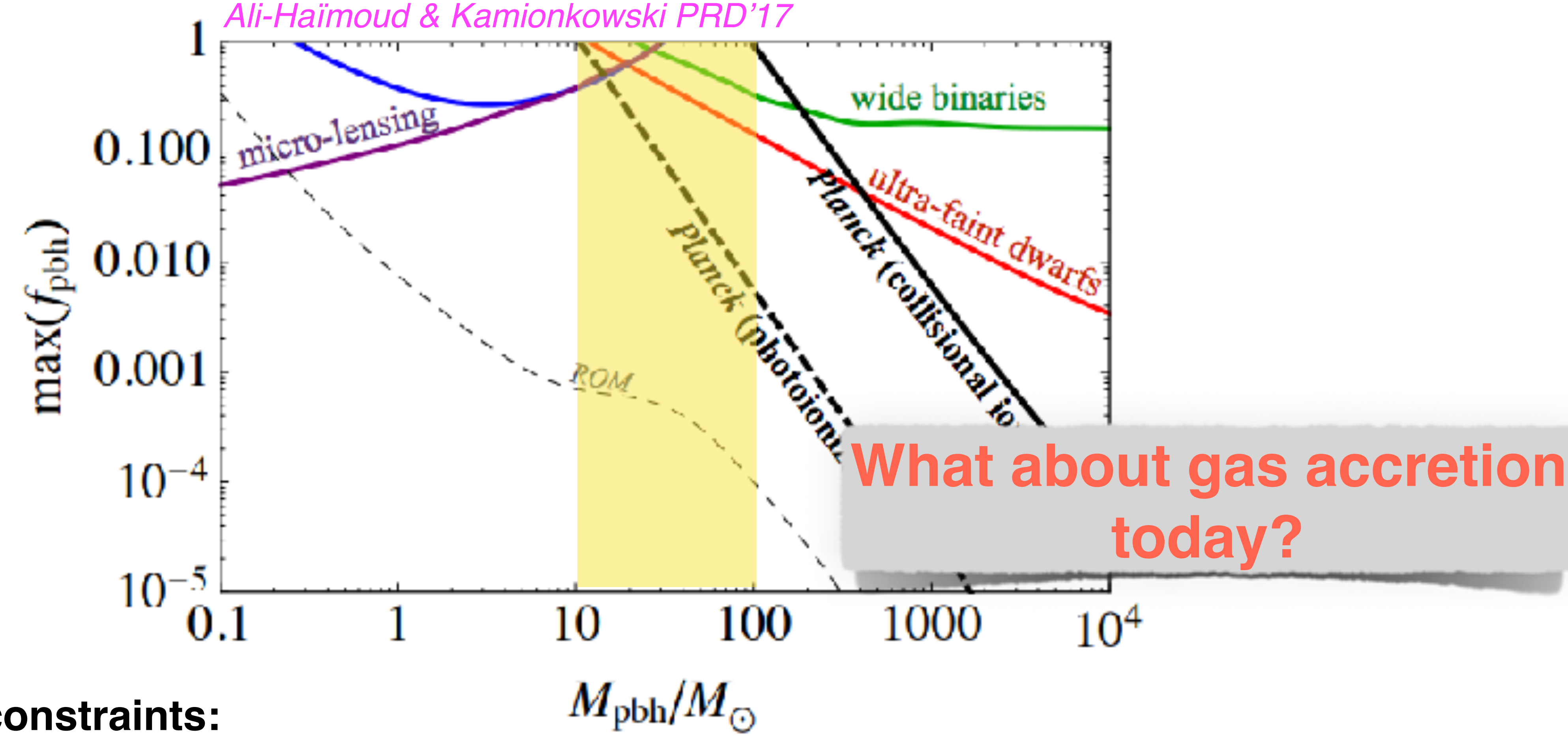

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Y. Ali-Haïmoud talk

Gas accretion onto (P)BH

- Isolated black holes should all accrete at some level from the local interstellar medium (ISM)
- Because of BH gravitational potential the gas inspires towards the event horizon and heats up, emitting **non-thermal X rays**
- In the presence of a jet, **radio emission** from synchrotron emission is expected.

Emission mechanisms targeted by traditional searches for astrophysical stellar-mass BH

Fender+ MNRAS'13

Idea: can we look for (P)BH candidates accreting today in radio and X-ray point-source catalogues

Gaggero, FC+ PRL'17
Hektor+A&A'18, Manshanden+ 1812.07967

Astro BH & PBH in the MW bulge

Astro BH

- From the star formation history of the MW and the local mass density of stellar remnants, the total number of isolated, stellar-mass, black holes in our galaxy is estimated to be **~10⁸** [e.g. *Shapiro & Teukolsky 1983; van den Heuvel 1992*]
- Isotropic distribution in MW of **5×10^5 BH per kpc³**, with a mean separation of just over **10 pc**.

Primordial (DM) BH

- Assuming that all DM is made of PBH, and adopting the mass model from *Portail+2015*, one can estimate **~10⁸ PBH in the Galactic bulge**

$$M_{\rm Bulge} = (1.84 \pm 0.07) \times 10^{10}\, M_\odot$$

$$M_{DM} \sim 40\% M_{\rm Bulge}$$

$$R_{\rm Bulge} \sim 2{\rm kpc},\ {\rm M_{PBH}} = 30{\rm M_\odot}, {\rm f_{DM}} = 1$$

$$\rightarrow N_{PBH} \sim 10^8, n_{PBH} \sim 10^7\,{\rm kpc}^{-3}$$

At least $f_{DM} < 0.01$ to be comparable in number in the Galactic bulge

Some questions

- Given the large amount of gas in the inner Galaxy, **how bright is this large population of DM PBH** thanks to accretion?
- Is this population **compatible with current X-ray (Chandra, NuSTAR) and radio (VLA) point-source catalogues**?
- Will **future** radio (ngVLA, SKA) and X-ray **facilities be able to detect such PBH population**? What is the level of “background" expected by the astrophysical BH population?

The accretion rate

Bondi-Hoyle-Lyttleton accretion formalism

Hoyle & Lyttleton '39; Bondi & Hoyle ’44

$$\dot{M} \equiv \lambda \dot{M}_B = 4\pi\lambda \frac{G^2 M_{BH}^2 n_{\rm gas}}{(\sqrt{v_{BH}^2 + c_s^2})^3}$$

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Accretion efficiency relative to the Bondi accretion rate

- Numerical parameter quantifying non-gravitational forces, pressure, viscosity, radiation feedback, disk formation
- Benchmark value for λ = 0.02, consistent with neutron star population estimates and studies of AGN [*Perna+ ApJ'03; Pellegrini ApJ'05*]

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Gas density and sound speed

- **n_{gas}**: 3D distribution of molecular, atomic and ionised gas in the inner bulge, notably in the Central Molecular Zone (CMZ), within 300 pc from GC [*Ferrière+ AAP'07*]; ~0.1 g/cm^2
- Constraint on isothermal sound speed **c_s ~ 0.5-0.9 km/s**, from mapping of CMZ temperature *Ginsburg+'15*
- Effect of radiative feedback and formation of ionisation bubble around PBH; if gas fully ionised with **c_s = 10 km/s**

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BH space velocity

Mass modelling of the MW and derivation of phase-space velocity distribution

Accretion rate and luminosity

The maximum luminosity of a source in hydrostatic equilibrium is the Eddington luminosity

$$L_{edd} = 1.2 \times 10^{38} \left(\frac{M}{M_\odot}\right) \quad \mathrm{erg/sec}$$

If the luminosity exceeds the Eddington limit, then the radiation pressure drives an outflow.
For a 100 M_{Sun} BH:

$$\dot{M}_\mathrm{B} \sim 10^{-4} \frac{n_\mathrm{gas}}{\mathrm{cm}^{-3}} \dot{M}_\mathrm{Edd} \qquad \dot{M}_\mathrm{B} \ll \dot{M}_\mathrm{Edd}$$

Sub-Eddington accretion rate (if < 0.01 **radiatively inefficient accretion**)
e.g. Sgr A* in weak accretion regime

In the **weak accretion limit**, the luminosity scales non-linearly with the accretion rate:

$$L_B = \eta \dot{M} c^2 \quad \text{with} \quad \eta = 0.1 \frac{\dot{M}}{\dot{M}_\mathrm{crit}}, \ \dot{M}_\mathrm{crit} = 0.01 \dot{M}_\mathrm{Edd}$$

Fender+ MNRAS'13

Some observational evidence in *Koerding, Fender & Migliari 2006*

X-ray and radio emission

X rays

Hard X-ray luminosity obtained from the bolometric L by assuming a photon index α = 1.6 from 10^{13} Hz up to 100 keV in line with observations of X-ray binaries @ low accretion rates

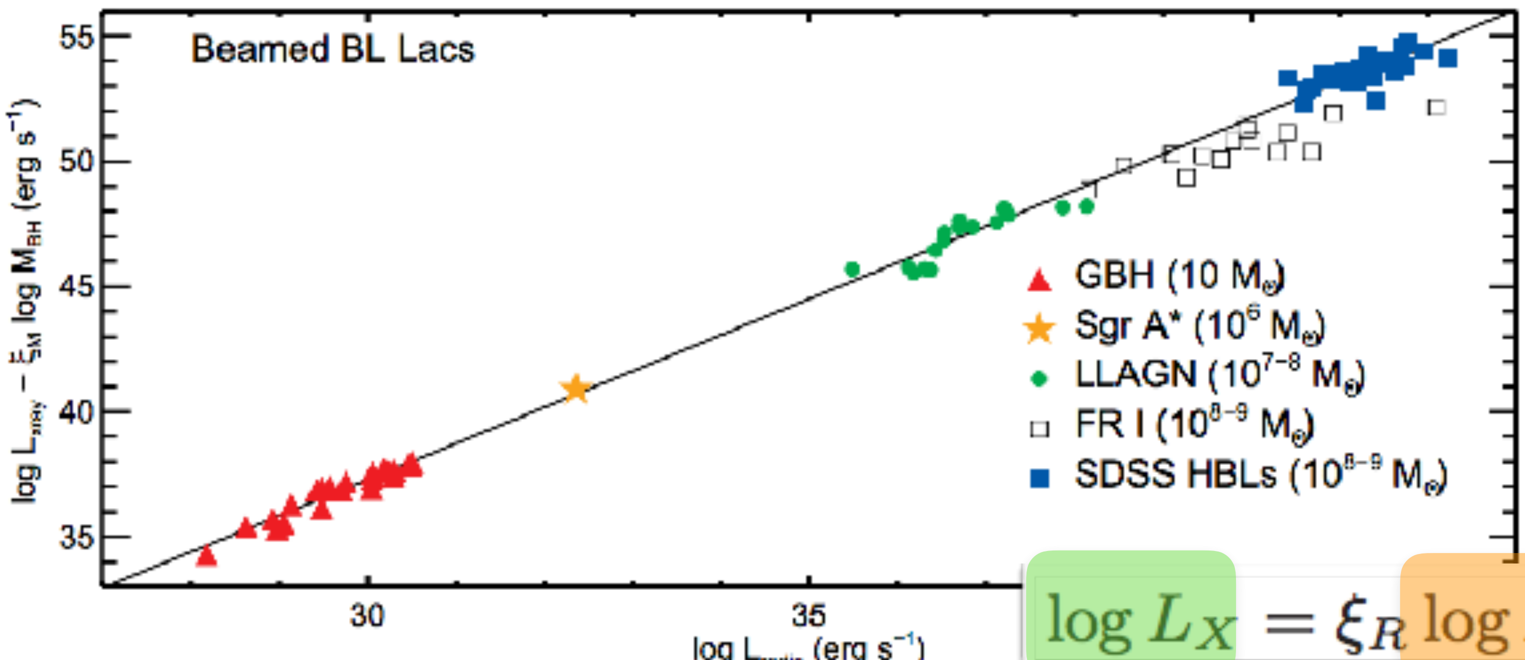
Hong+ ApJ'16

$$L_X \sim 0.3 L_B$$ **2-10 keV**

radio

Radio emission from jet electron population: main hp jet formation, with flat, optically thick, spectrum [*Fender+ 2001*]
Advantage of radio: More successful than X-ray in detecting isolated BH since jet kinetic power should dominate the total accretion with decreasing L [*Maccarone MNRAS'05*]

To convert from hard X rays to radio, we make use of the **Fundamental Plane** [*Plotkin+MNRAS'13*]: Universal scaling relation for low-accretion BH between **hard X rays** and **radio @ 5GHz**

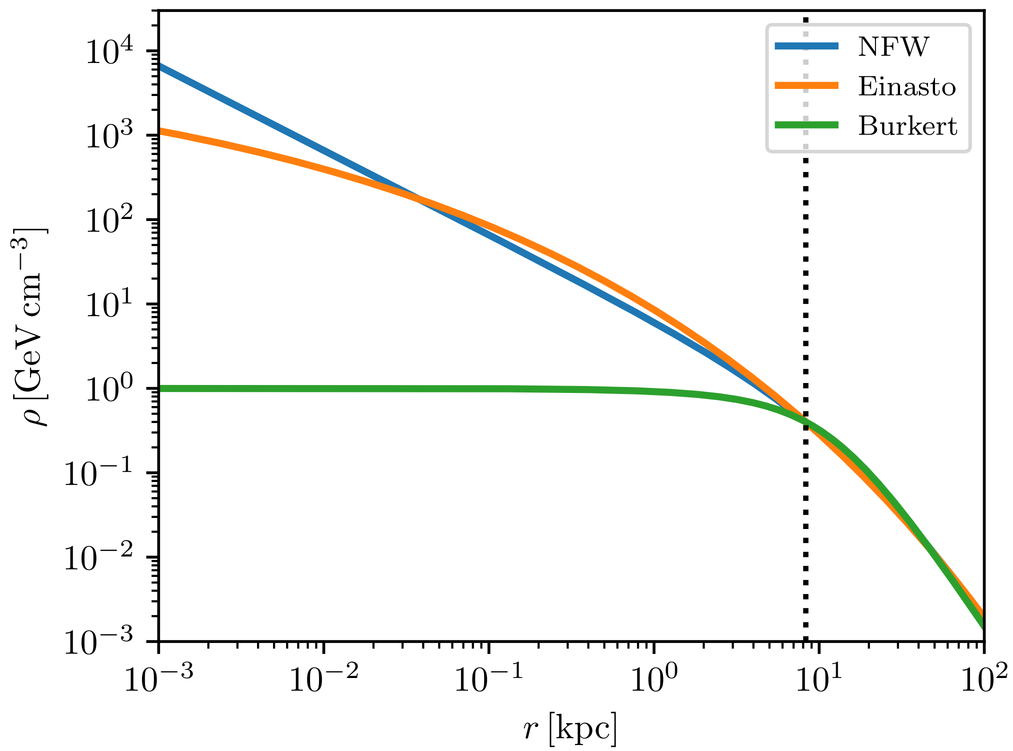


$$\log L_X = \xi_R \log L_R + \xi_M \log M_{BH} + B$$

PBH population

(M_{BH}, v_{BH}) **Monte Carlo simulation** of PBH distribution in the Galactic bulge

* **Mass distribution:** Monochromatic mass distribution
* **Spatial distribution:** Follows the Navarro-Frenk-White DM space density distribution (benchmark)*
* **Velocity distribution:** Follows the Maxwell-Boltzmann distribution with position-dependent 1D velocity dispersion, derived from the spherical average of a MW mass model distribution [*McMillan MNRAS'17*]**



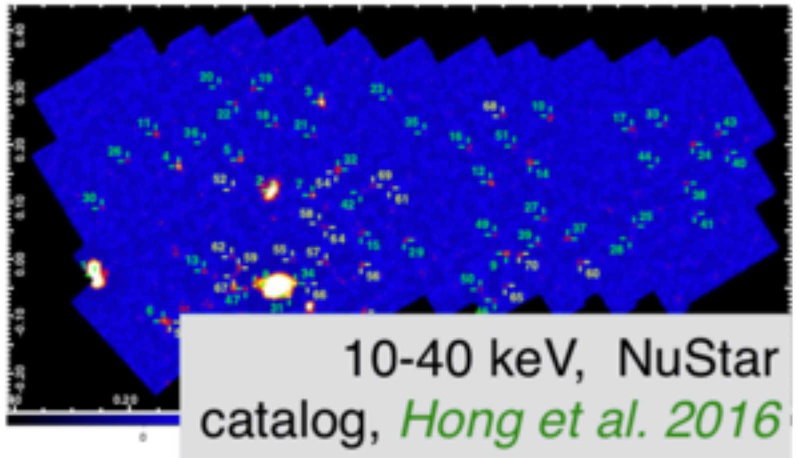
$$v_{MB} = \sqrt{GM(<r)/r}$$

~50 km/s @ 60 pc
~74 km/s @ 100 pc
~138 km/s @ 500 pc

* We tested shallower DM profiles with inner slope ~-0.6 [*Calore+JCAP'15*], and a Burkert with 1 kpc core
** Maxwell-Boltzmann characteristic velocities are consistent with v distribution derived by applying the Eddington formalism (agreement in the low-velocity tails)

X-ray and Radio catalogues

X rays



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

Chandra 0.5-8 keV [*Muno+ApJ'09*]

$-0.9^\circ < l < 0.7^\circ \ \& \ |b| < 0.3^\circ$ $\qquad 2 \times 10^{-6}\,\mathrm{ph/cm^2/s}$

483 likely Galactic X-ray sources => **291 BH candidates**

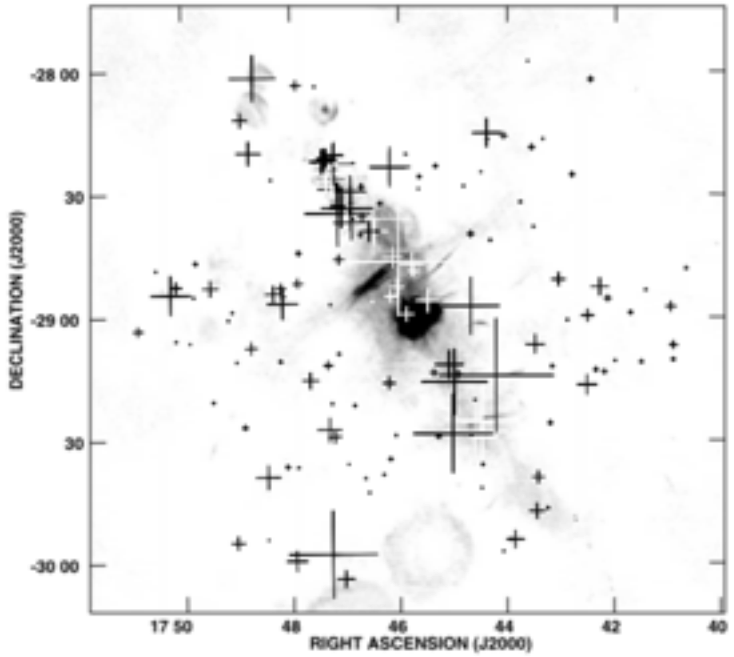
NuSTAR 10-40 keV [*Harrison+ApJ'13*]

$-0.9^\circ < l < 0.3^\circ \ \& \ -0.1^\circ < b < 0.4^\circ$ $\qquad 8 \times 10^{32}\,\mathrm{erg/s}$

70 sources => **42 BH candidates**

Prediction: More than **3000 (160) bright X-ray sources**

radio



1.4 GHz, VLA, *Lazio & Cordes 2008*

VLA @ 1.4 GHz [*Lazio & Cordes ApJ'08*]

170 source in 1 deg^2

1 mJy sensitivity threshold

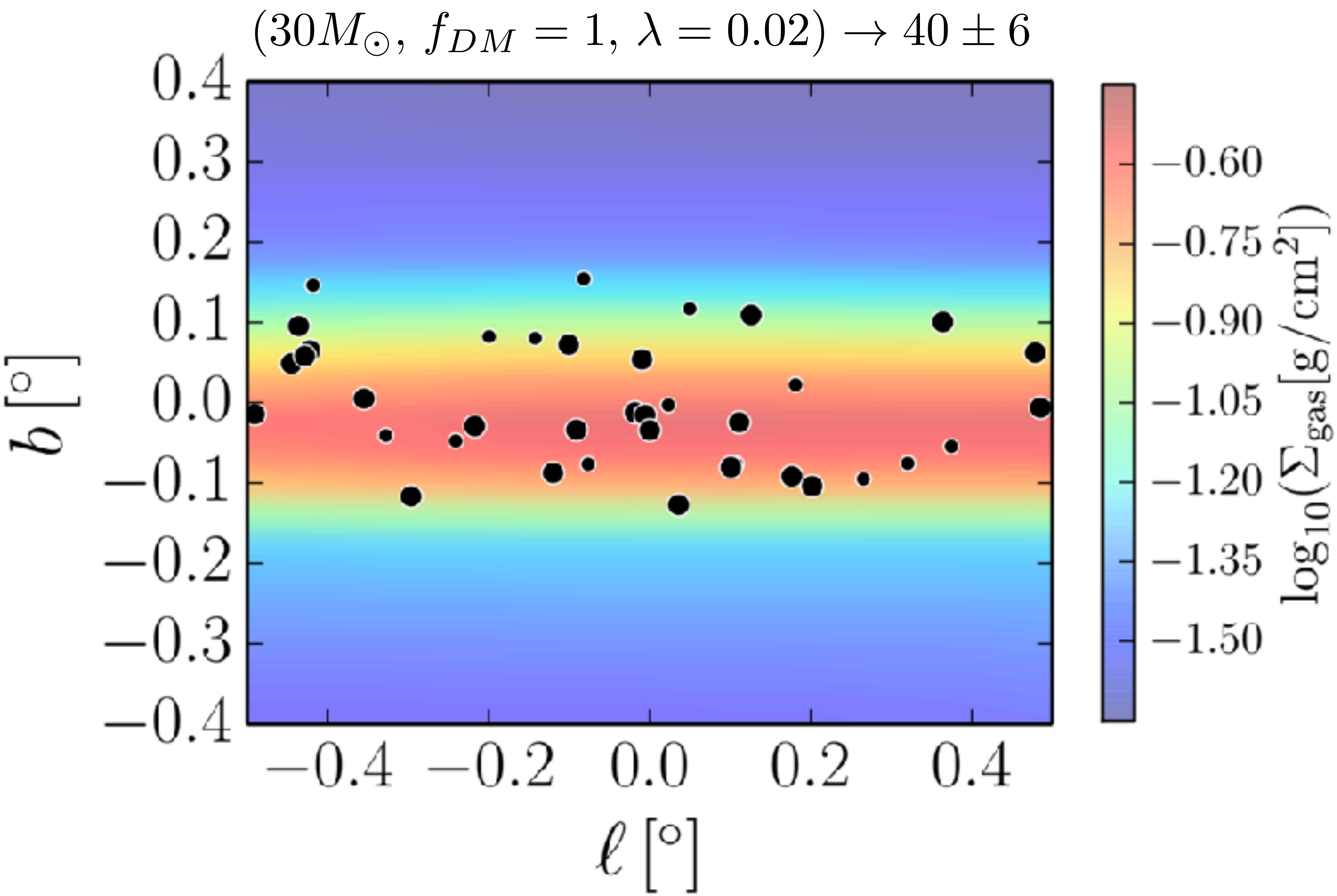
We search for spatial coincidence (10") with *Chandra* catalogue => **24 sources** (9 likely foreground)

If accreting BH, they should lie on the FP (10–100 Msun): the FP X-ray flux is 3-7 o.d.m. lower than what measured => **No BH candidate in radio survey**

Prediction: for 30 M_{Sun} and f_{DM} = 1 we expect ~41 PBH detectable

Constraints on PBH DM abundance

Gaggero, FC+ PRL'17



Example of the distribution of **30 M⊙ PBHs detectable by VLA** in the ROI, for one Monte Carlo realisation.

Detectable **PBH velocity in the range 0.3 – 3 km/s**.

The constraints arise from the very low-velocity tail of the distribution and high gas column densities (CMZ).

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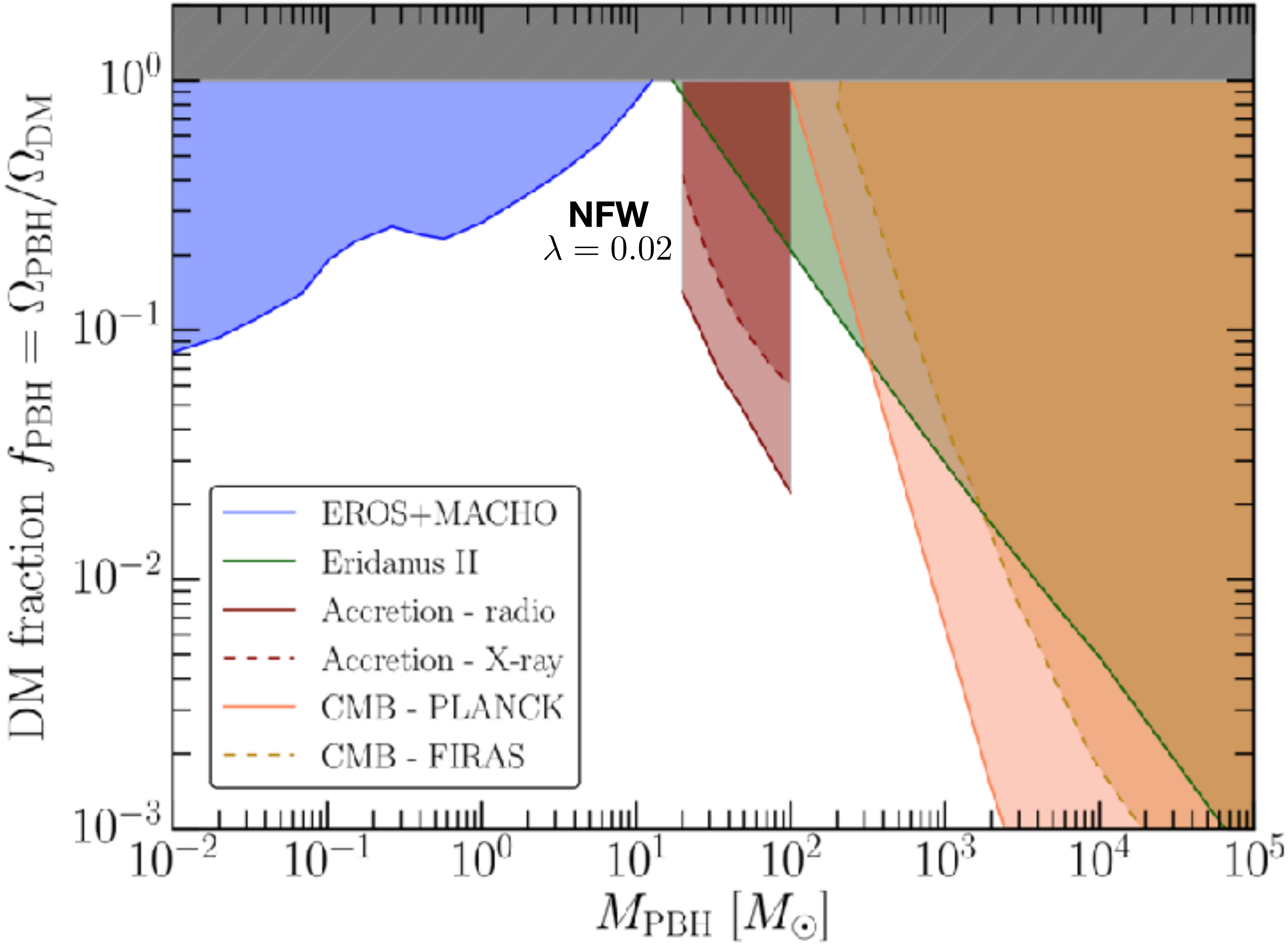
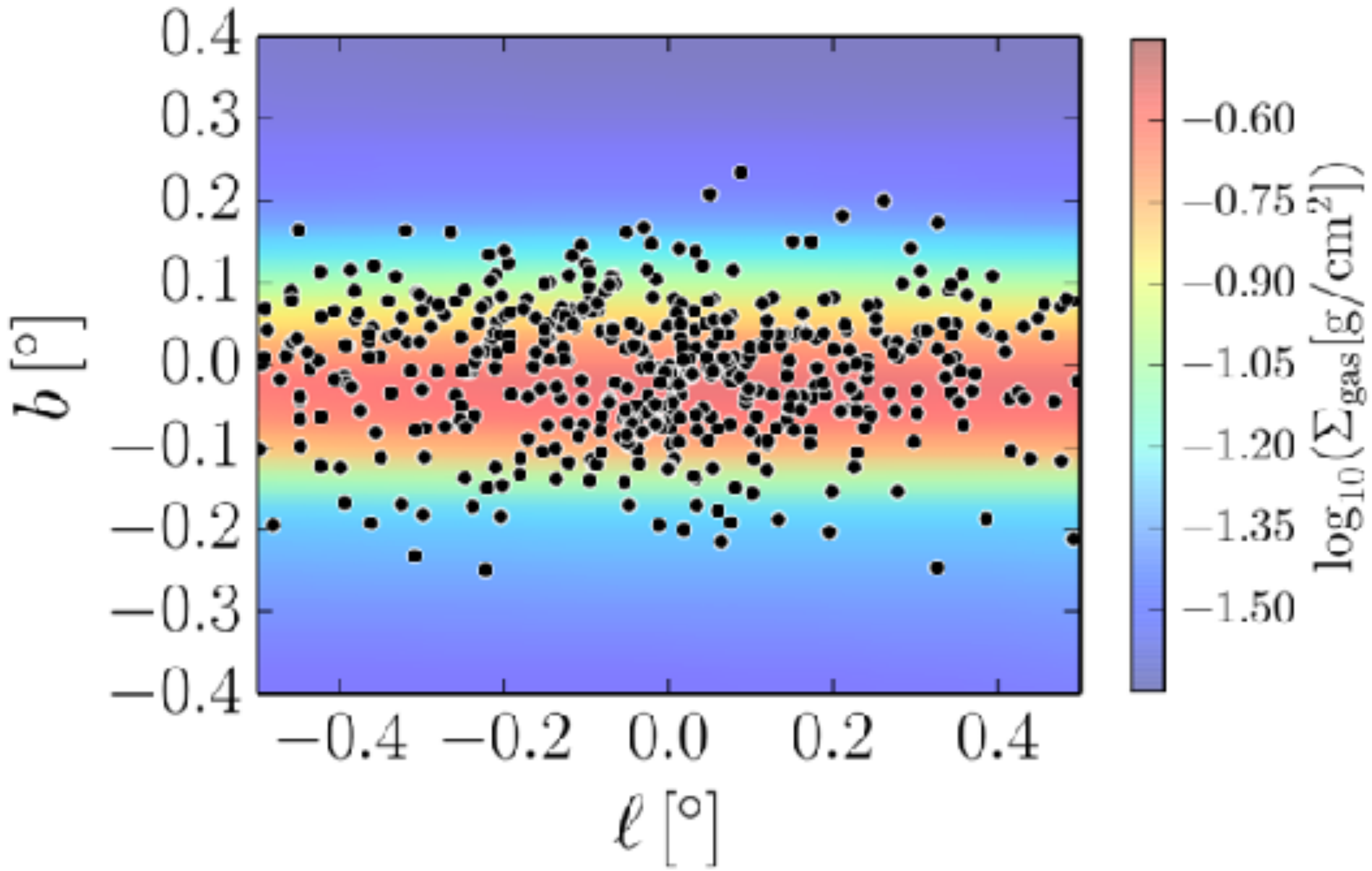


Limits from 100 MC realisations of the PBH population, 10—100 $M_{\rm Sun}$, for $f_{\rm DM} = 1$

$\langle N_{\rm PBH} \rangle$ proportional to $f_{\rm DM}$

The limit vanish for $\lambda < 2 \times 10^{-3}$

Outlook: SKA



Radio sources above the SKA1-Mid point source sensitivity, for 1000 hours of data taking, if PBHs are ~ 1% of the DM

MeerKAT (data taking)

0.01 mJy sensitivity

Detectable PBH

$(30M_\odot,\ f_{DM}=1,\ \lambda=0.001) \rightarrow 88 \pm 11$

$(30M_\odot,\ f_{DM}=0.1,\ \lambda=0.01) \rightarrow 99 \pm 9$

SKA1-MID configuration

2.7 micro-Jy (1 hr, shallow survey)

~2000 detectable PBH

- ➡ no BH candidates => Very strong limit
- ➡ BH candidate => Great potential for detection*

Deep field continuum observation (1000h)

87nJy sensitivity => Strong constraints placed even if lambda ~0.001

SKA could allow the discovery of PBHs, even if they represent a subdominant contribution to DM

* For $f_{DM} < 0.001$, searches must include the modelling of the comparably abundant population of astrophysical BHs

Caveats & Questions

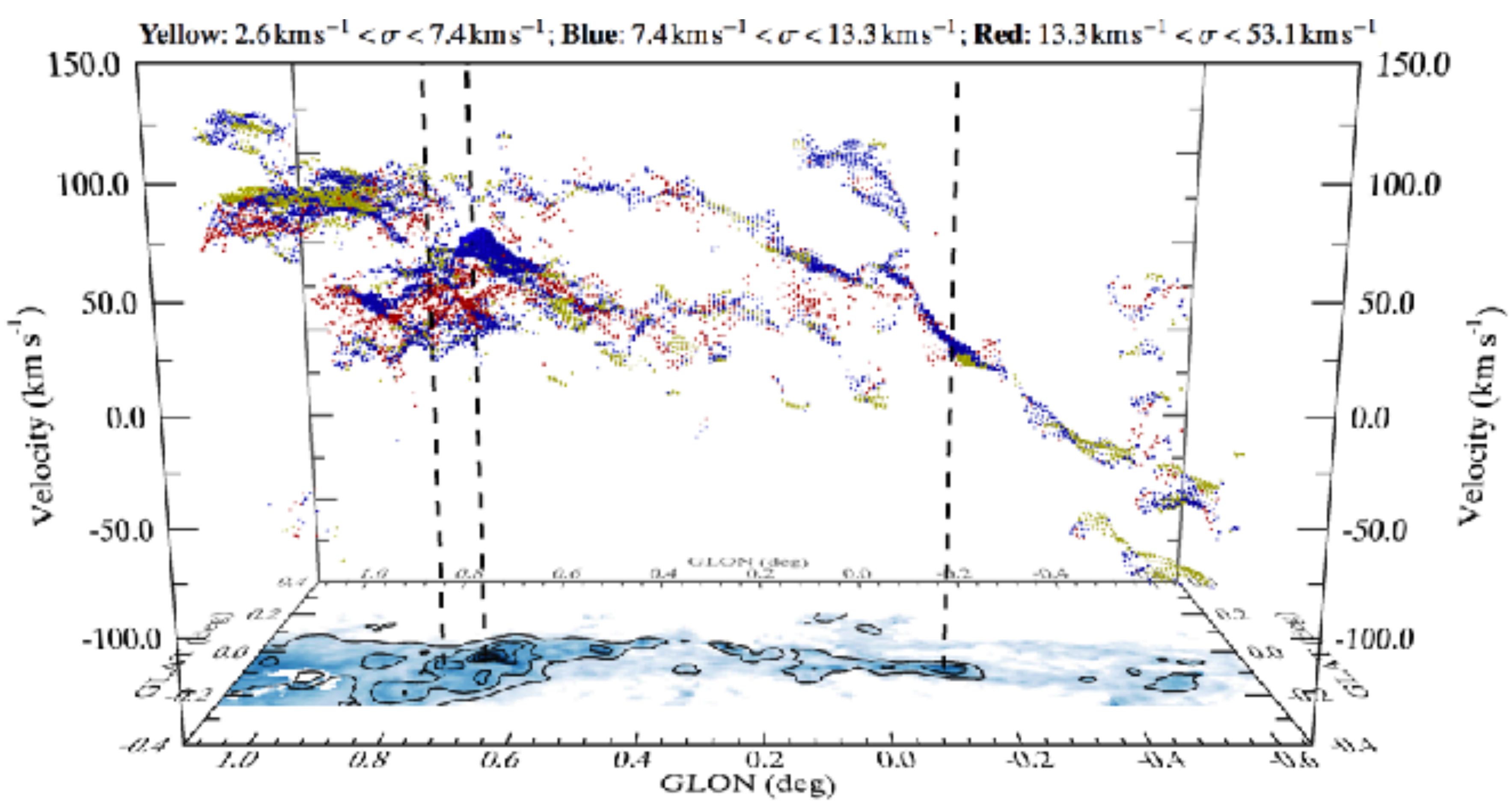
- Effective accretion rate **lambda parameter is highly uncertain**. We rely on current UL for weak accretors. If < 0.01 bounds vanish
- **Accretion spectrum** is largely unknown: a) Rely on observed spectra (photon index ~1.6-2); b) Spectrum from accretion models (e.g. ADAF)
- Significant **impact of the DM profile**: e.g. for a cored profile, the bound is non-vanishing for lambda = 1
- The bound is very sensitive to the **velocity distribution** (which is probably also degenerate with lambda): Limits here come from low-velocity tail of the distribution. A careful treatment of gas turbulent motion is required
- What is the impact of the **gas fine structure** in dense molecular clouds?
- Radio bounds rely on the assumption that a **jet is triggered** (spin, magnetic fields, etc.)
- What is the effect of an **extended mass function**? [*Manshanden+1812.07967*]
- Is the **Fundamental Plane** relation robust? [*Inoue+ApJ'17*]

* Disk can form in the early Universe, strongest constraints from CMB anisotropy [*Poulin,FC+PRD'17*]

Turbulent gas motion

The relative velocity between BH and gas can be affected by the turbulent motion of the gas*
How to estimate impact of **turbulent gas motion** in the CMZ?

Molecular gas kinematics within the central 250 pc of the Milky Way
[*Henshaw+ MNRAS'16*]
Velocity dispersions range from 2.6 km/s < σ < 53.1 km/s
A median dispersion of 9.8 km/s



- Evidence for non-thermal gas motions inherently supersonic (Mach number ~10-60)
- "This should be taken as an *upper bound* on the level of turbulent motion"
- Importance of turbulence in the suppression of star formation [*Kruijssen+MNRAS'13*] and in setting the initial distribution of masses for star formation [*Rathborne+ApJ'14*] in the environment of the CMZ
- Driving mechanism for the increased turbulence in CMZ clouds is not conclusively identified

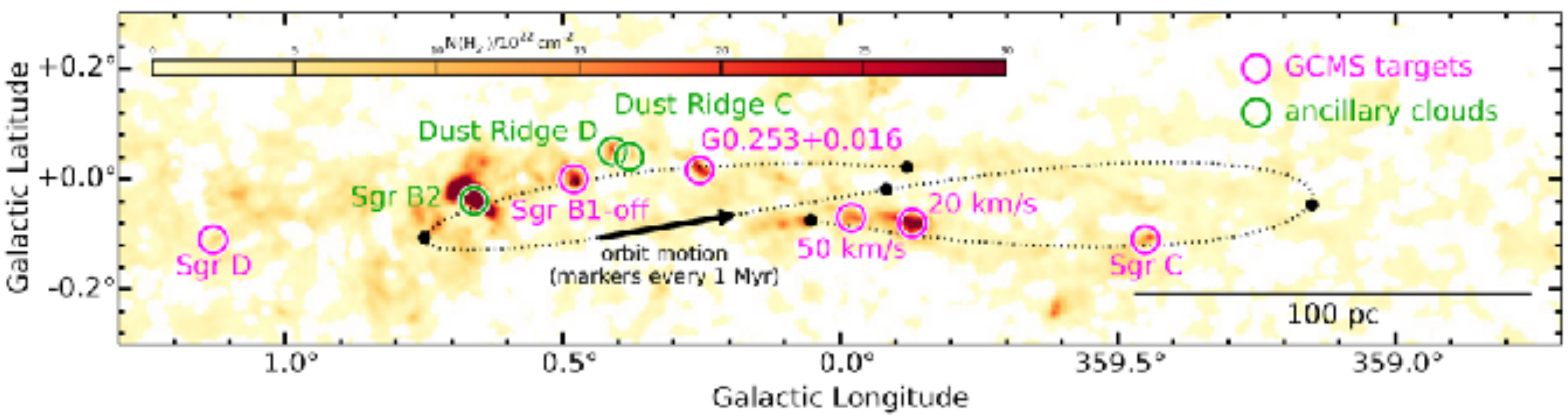
* Only relevant for UL, if those depend on low-velocity tails of v distribution

Gas small-scale structure

On top of the mean gas density, the ISM is finely structured in molecular clouds

CMZ molecular clouds have unusually high mean H2 densities ~10^4/cm^3
Clouds reside at a distance of 8.34 ± 0.16 kpc [*Reid et al. 2014*]
They seem to lie on a well-organized common orbit [*Molinari et al. 2011,Kruijssen et al. 2015*] along which clouds might also systematically evolve [*Longmore et al. 2013*]

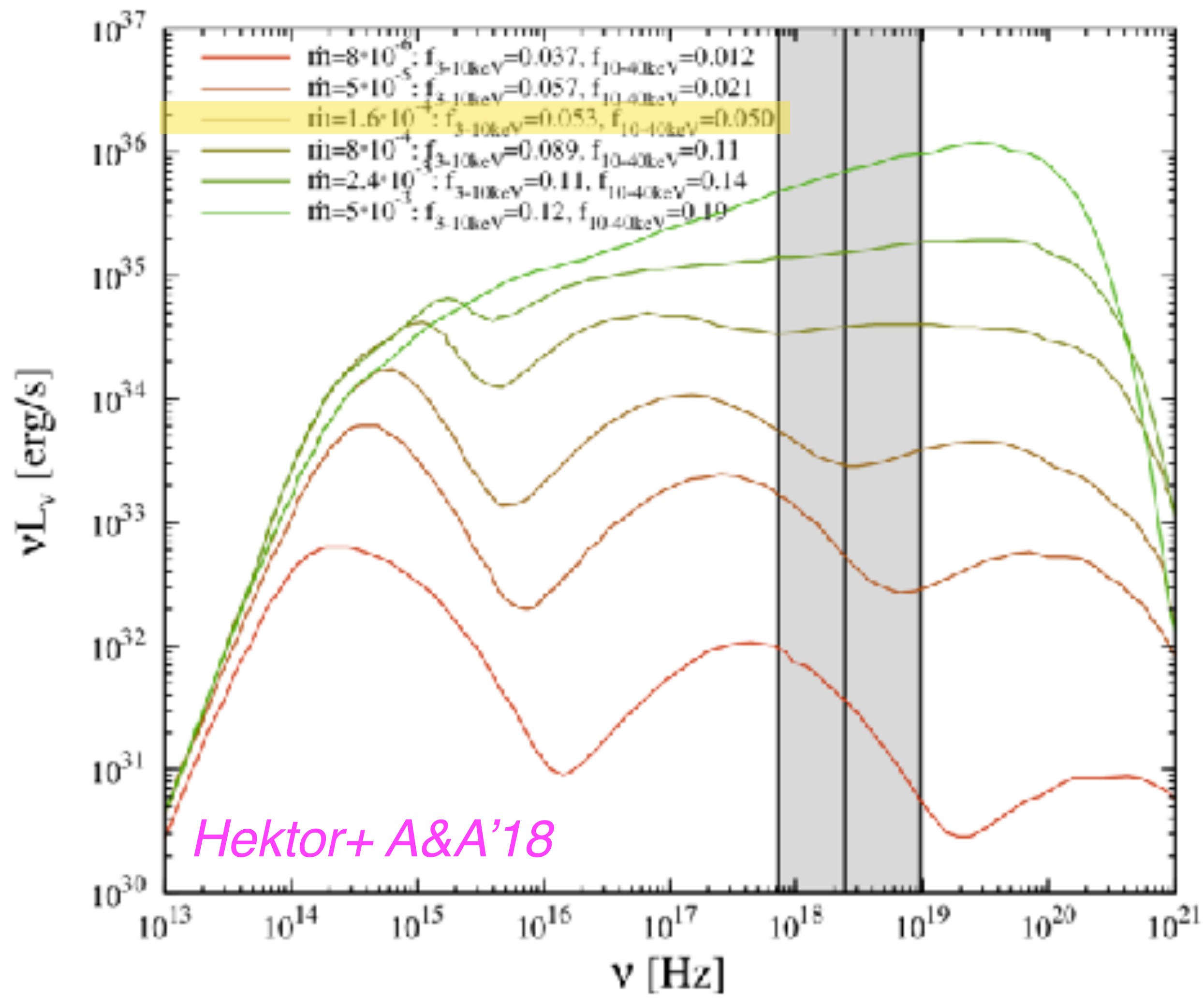
Galactic Center Molecular Cloud Survey (GCMS)
First systematic study resolving all major CMZ molecular clouds at interferometer angular resolution [*Kauffmann+A&A'17*]

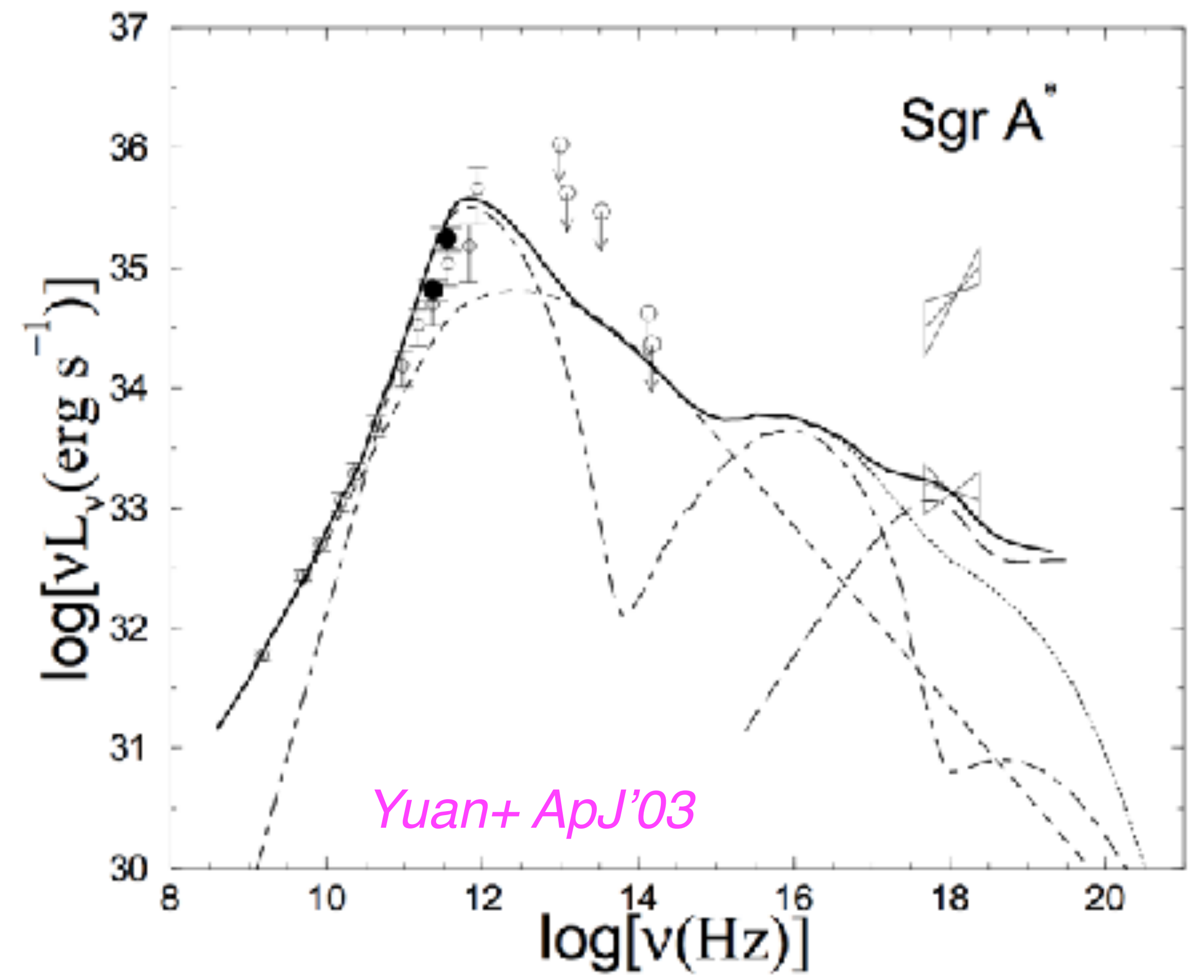


Impact on PBH abundance bounds: In case v_{turb}=0 the number of detectable sources does not depend on the gas small-scale structure; $v_{turb} > 0$ the small-scale gas density distribution function improves the limits

Hektor+ A&A'18

Accretion spectrum





ADAF model [*Yuan & Narayan A&A'14*]

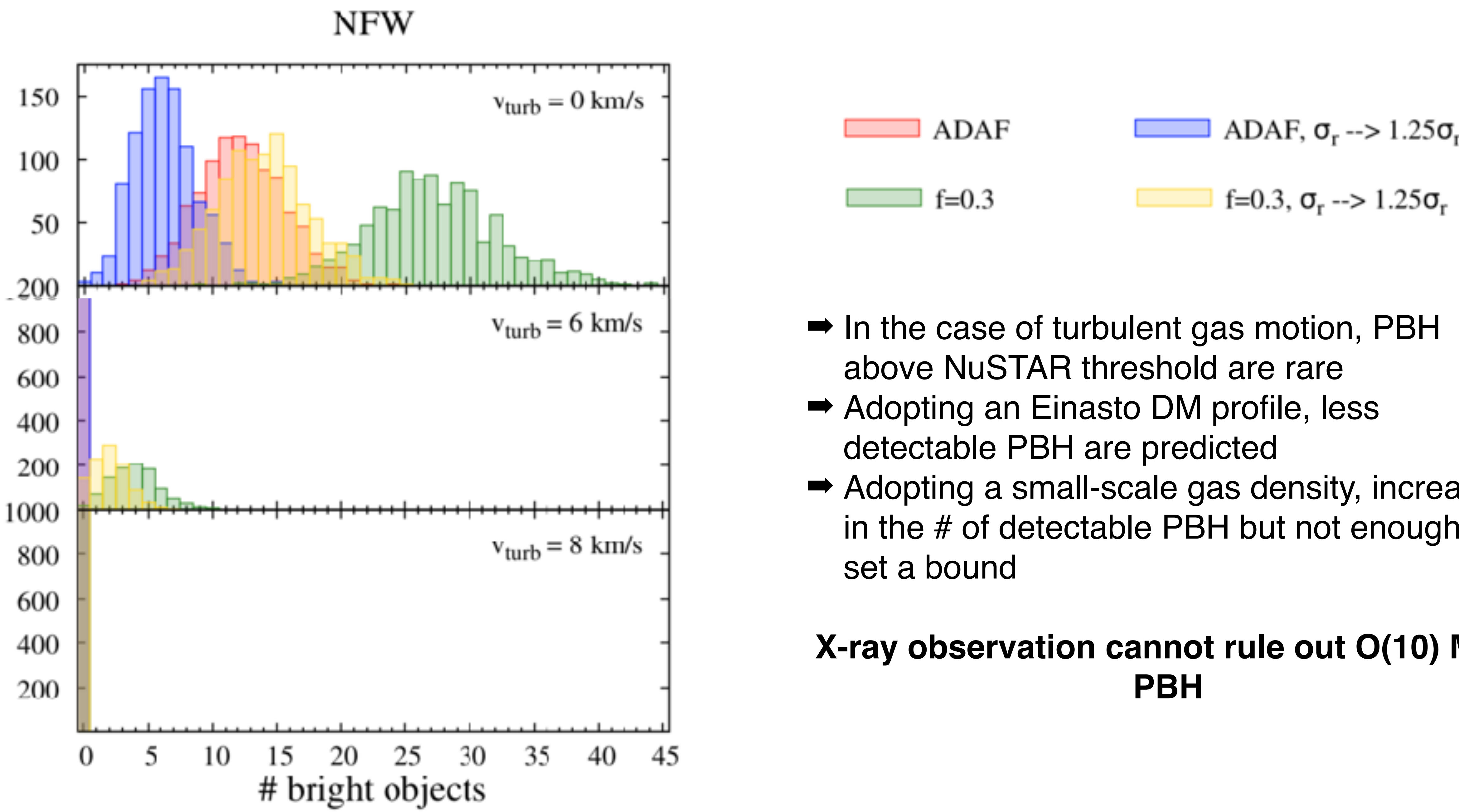
- Depends on several parameters (e.g. viscosity, magnetisation, etc)
- In the case of a non-thermal electron component (e.g. jet) the IC bumps are smoothed out. Required e.g. to explain Sgr A* data [*Yuan+ ApJ'03*]

NuSTAR constraints revised

Hektor+ A&A'18

What's new:

* Include turbulent gas motion (probably overestimating v_{turb})
* Effect of small-scale gas distribution (power-law pdf with slope 2.8)
* Advection dominated accretion flow (ADAF) spectrum (w/o adjusting for Sgr A* observation)
* Limits from NuSTAR 70 PS (w/o considering contamination from Galactic sources, e.g CV)



➡ In the case of turbulent gas motion, PBH above NuSTAR threshold are rare

➡ Adopting an Einasto DM profile, less detectable PBH are predicted

➡ Adopting a small-scale gas density, increasing in the # of detectable PBH but not enough to set a bound

X-ray observation cannot rule out O(10) M_{Sun} PBH

Improving on accretion modelling

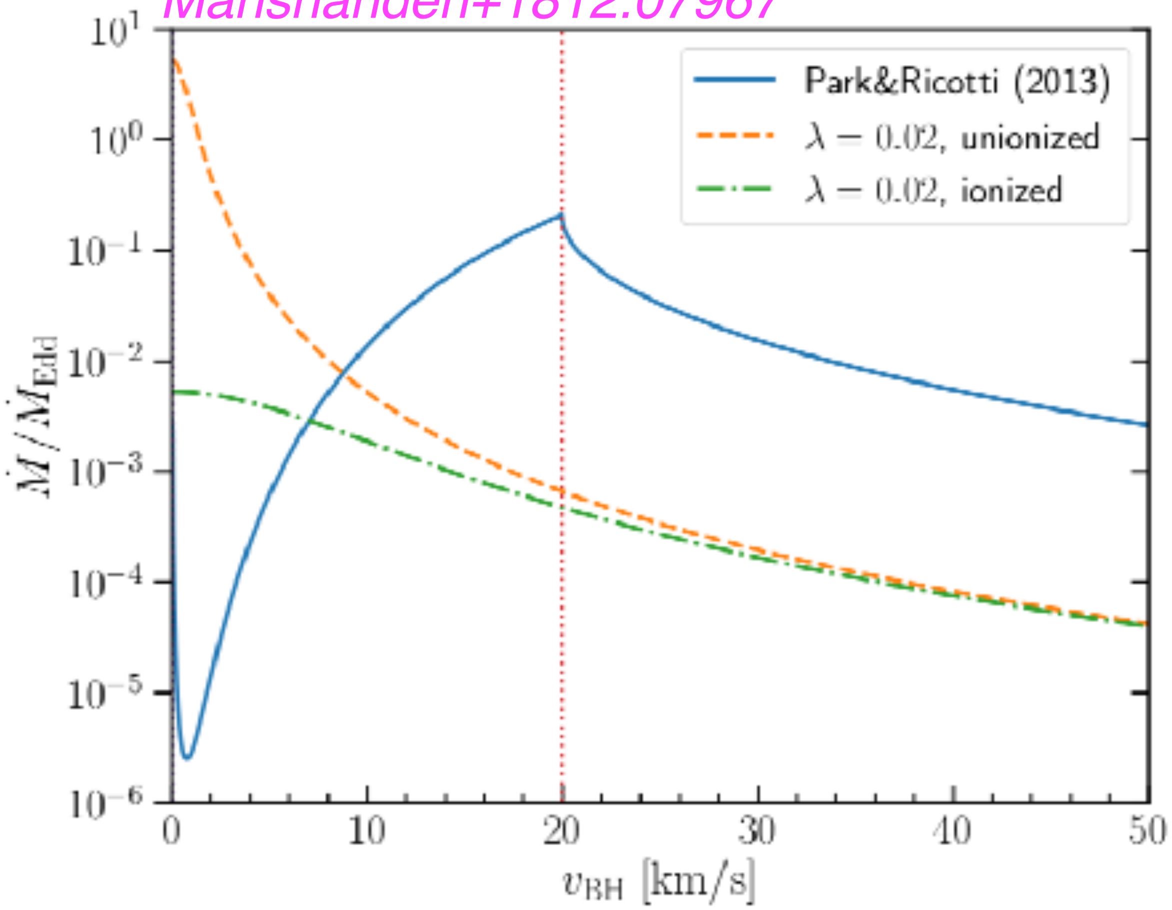
Weak accretion onto e.g. Sgr A* => Models for **radiatively inefficient accretion flows** (RIAFs)

Traditionally adopted **factorised parametrisation**:

1) lambda: encodes our ignorance on gas energetics in the accretion flow
2) eta: efficiency of converting gravitational potential energy into radiation depending on c_s (gas phase)

Going beyond: Self-consistent estimate of how the accretion rate depends on the BH velocity in the presence of radiative feedback => radiation-(non-rel)-hydrodynamic simulations [e.g. *Park & Ricotti ApJ'13*]

Manshanden+1812.07967

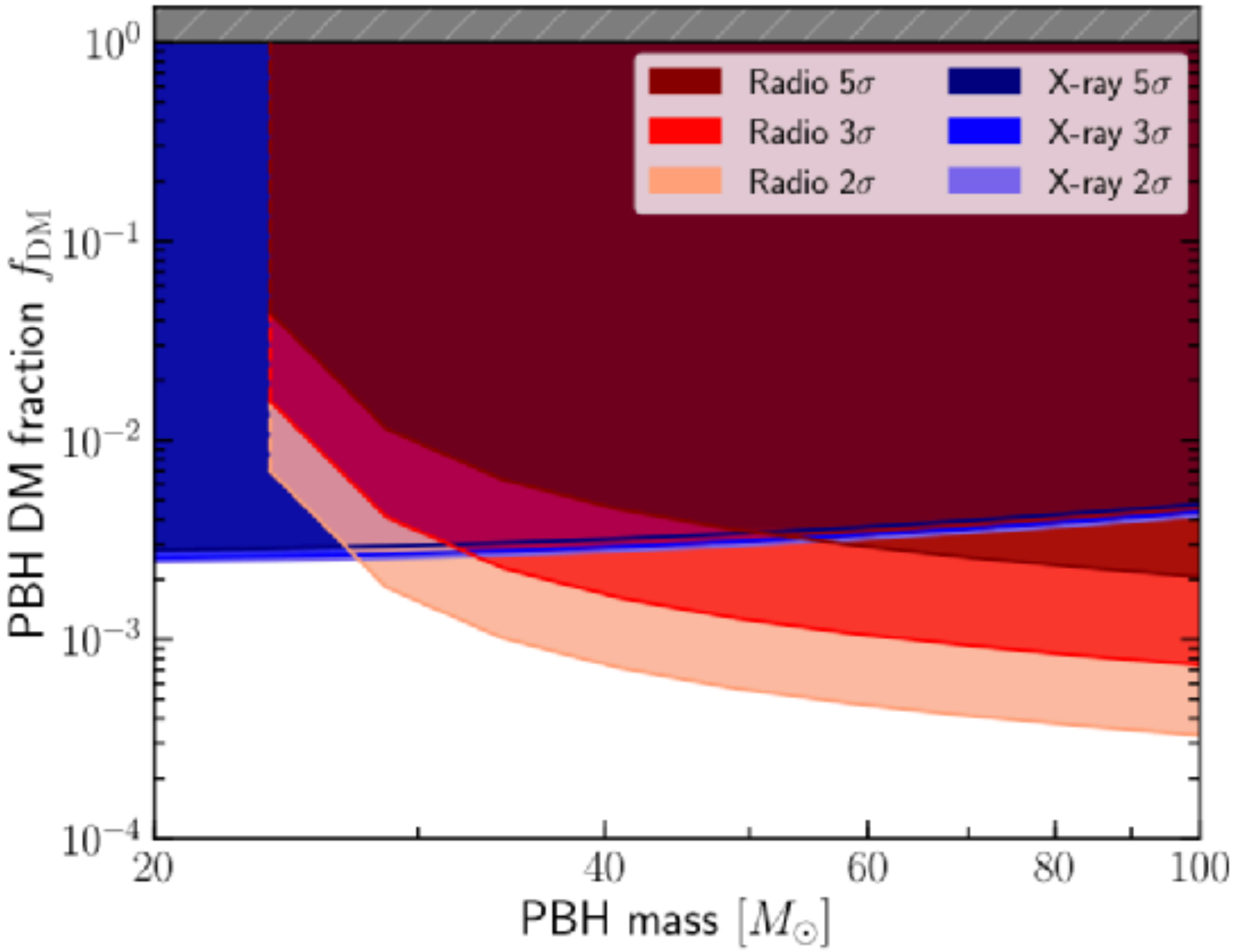


- **Factorised formalism:**
  Simple, monotonic decrease of accretion rate with increasing BH velocity
- **Full simulation**:
  If *BH velocity below M_{crit}*, a bow shock forms developing a dense ionisation front behind the shock with lower downstream density (and gas velocity) => *accretion rate increases with v*
  If *BH above M_{crit}*, the ionisation front is rarefied => the *accretion rate decreases with v*

* Radio jet not included in the hydrodynamic simulation while can have dynamical and radiative implications

Latest X-ray and radio constraints

Manshanden+1812.07967



- Accretion rate of low-v PBH is suppressed => They no longer contribute to the constraints
- Accretion rate of high-v PBH is enhanced => Those objects are more likely to radiate above threshold
- The bounds originate from PBH with v~20 km/s (peak of accretion rate)
- Limit O(100) stronger than *Gaggero,FC+ PRL'17*

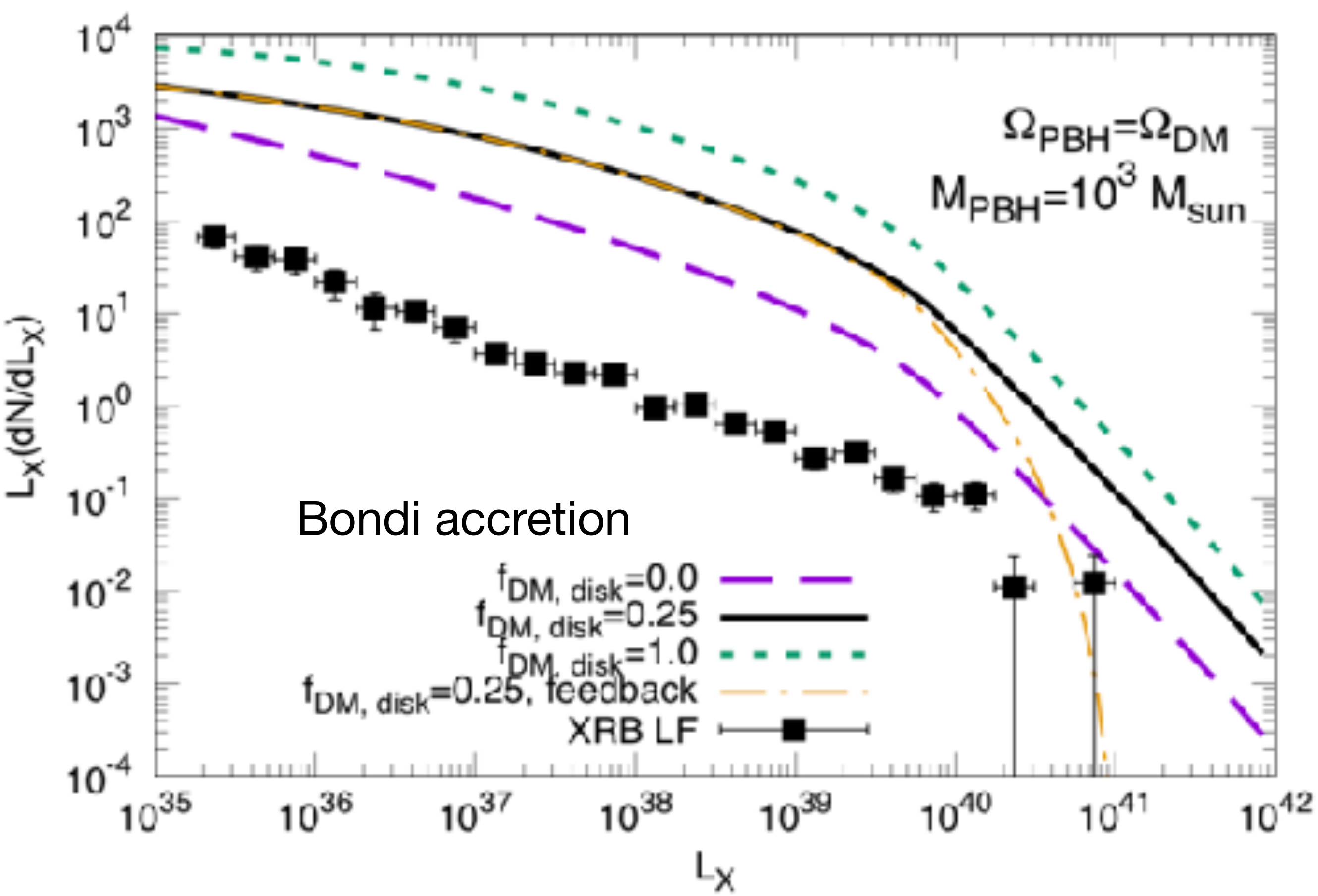
* Bounds still present at 5 sigma even with a 2 kpc core of the DM distribution

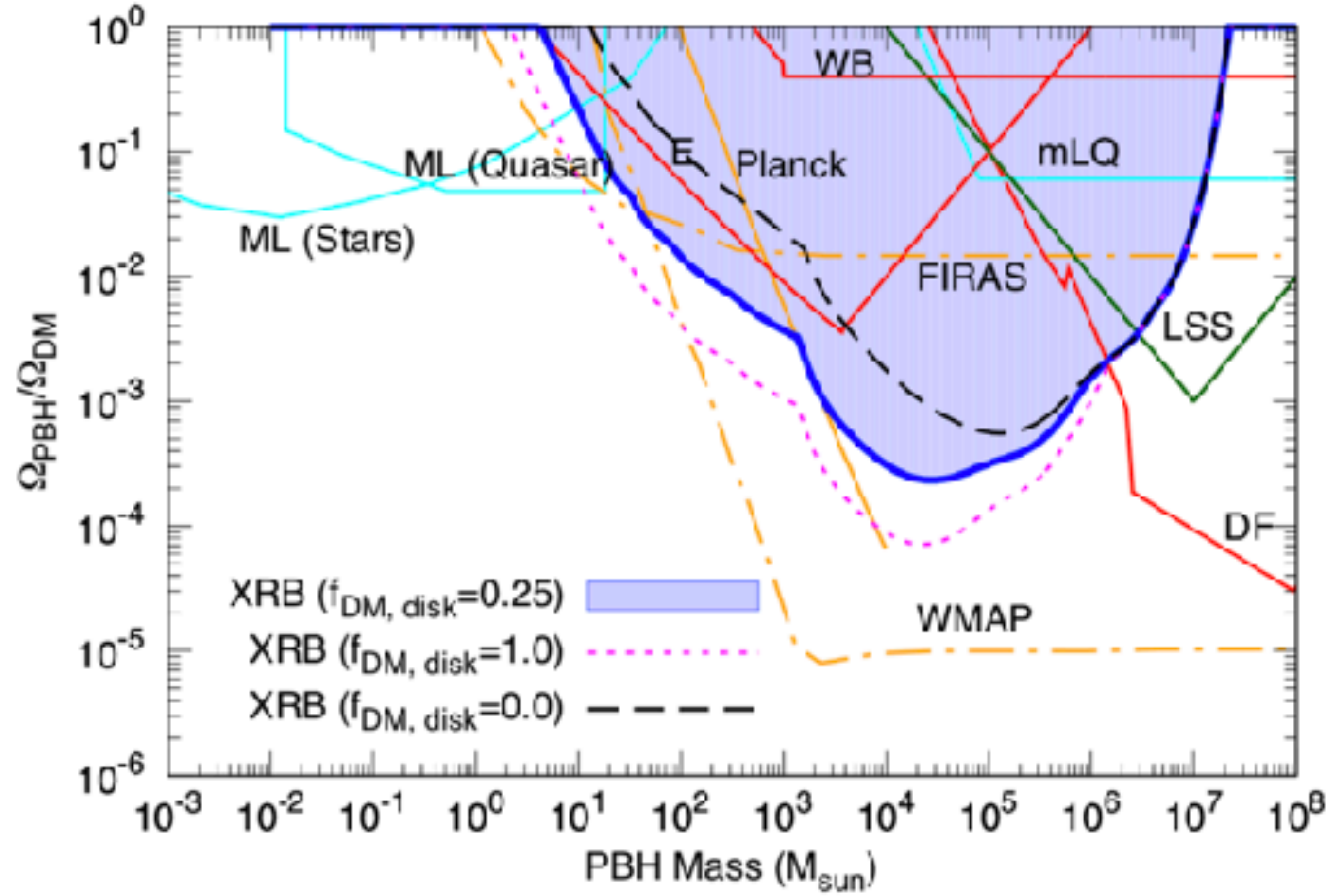
XRB luminosity function

Inoue & Kusenko JCAP'18

Limits from **observed number density of X-ray binaries** (XRB)

$$\frac{dN}{dL_X} = \frac{dN}{d\dot{M}}\frac{d\dot{M}}{dL_X}$$





X-ray emission from free-floating BHs interacting with ISM gas is similar to XRBs.
How to disentangle the two? Ionisation bubble around accreting (P)BHs, emission of iron K-alpha fluorescent light

Low-mass PBH

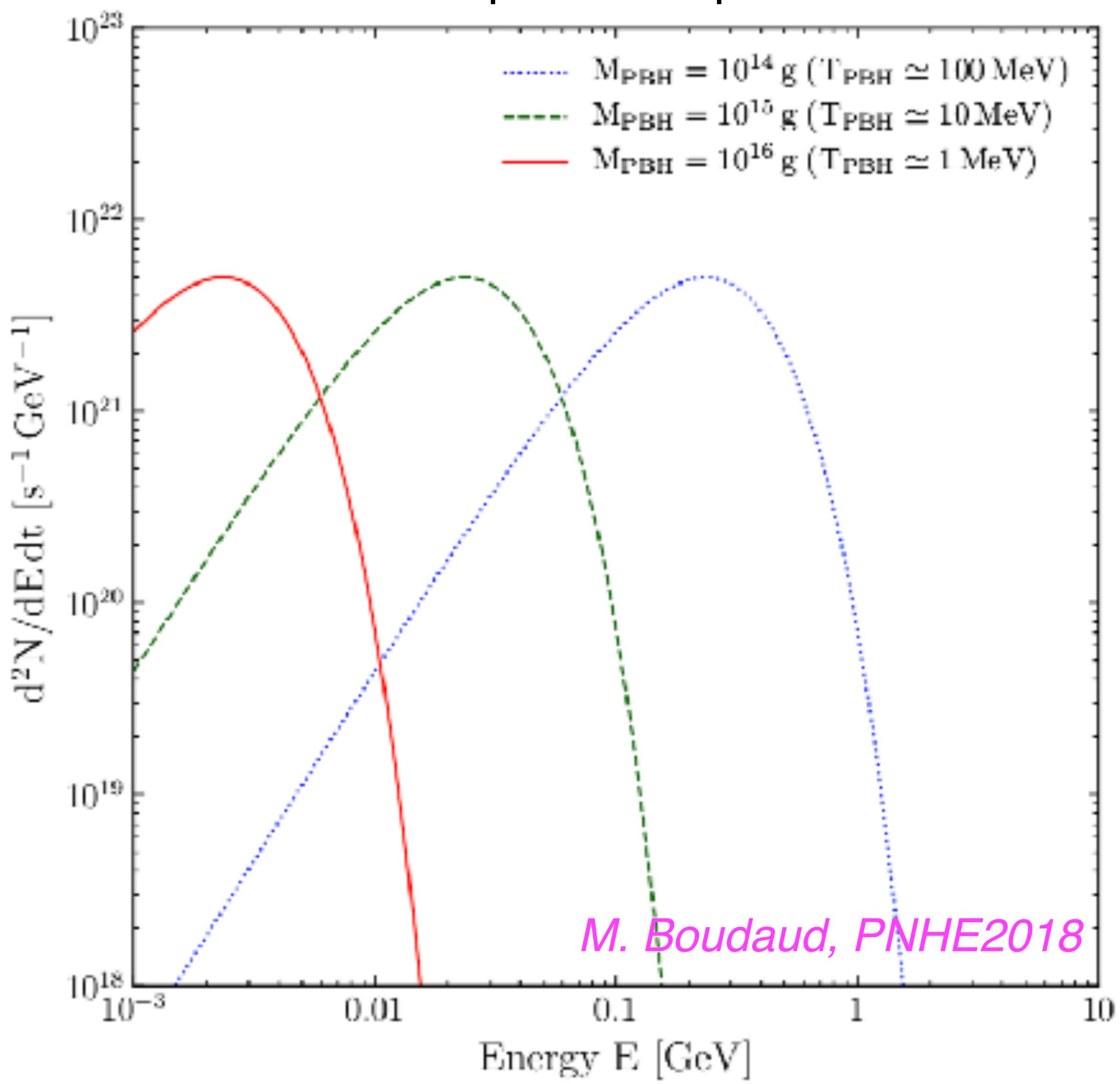
How to constrain PBH which are evaporating at the present epoch (10^{14} - 10^{17} g)?

Hawking radiation is emitted in all available (SM) particle species, the total emitted power and therefore the lifetime of a PBH depends on the number of available particle states

BHs lose mass radiating particles with the rate:

$$\frac{dM}{dt} \simeq -5.25 \times 10^{25} f(M) \left(\frac{\mathrm{g}}{M}\right) \mathrm{g\,s^{-1}}$$

electron/positron spectrum



M. Boudaud, PNHE2018

Almost-black body (grey) emission

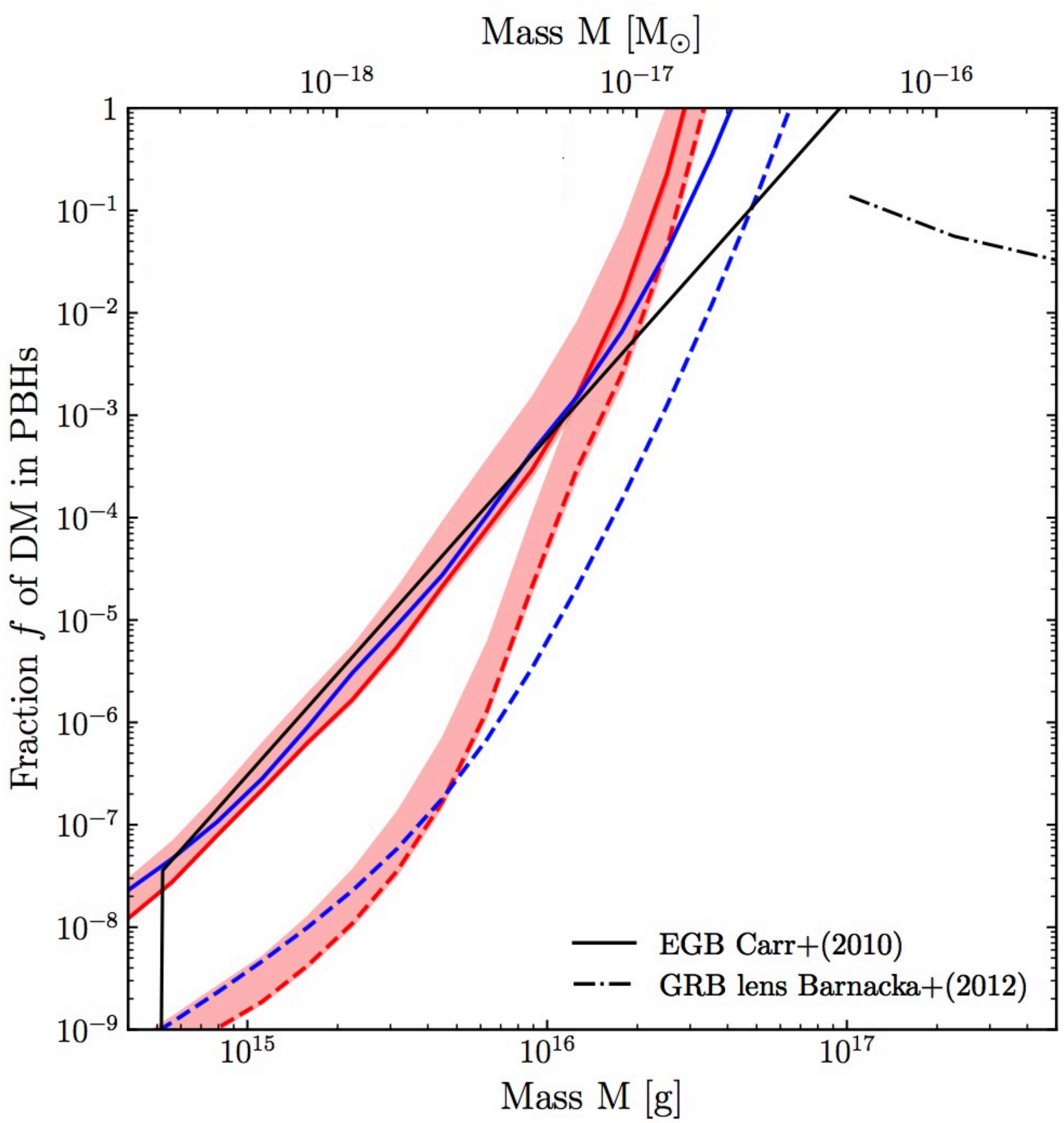
$$\frac{dN}{dt\,dE} = \frac{27}{128}\frac{\hbar^2 c^6}{\pi^3}\frac{x^2}{e^x + 1} \qquad x = \frac{E}{T}$$

$$T = \frac{1}{8\pi G M} \simeq 1.06 \left(\frac{10^{13}\,\mathrm{g}}{M}\right) \mathrm{GeV}$$

Spectrum of emitted particles is centered at MeV-a few GeV energies

Page & Hawking ApJ'76;
Carr & MacGibbon Phys. Rep.'98

Low-mass PBH constraints



✓ Extragalactic diffuse background limits on the mean cosmological number density, by integrating the flux from PBHs over the lifetime of the Universe

Carr+ PRD'10

✓ Searching for diffuse emission from PBHs in the halo of the Milky Way galaxy => Constraints from the Galactic diffuse background (EGRET)

Lehoucq+ A&A'09

✓ Strongest constraints from Voyager I electron/positron data

Boudaud&Cirelli PRL'18

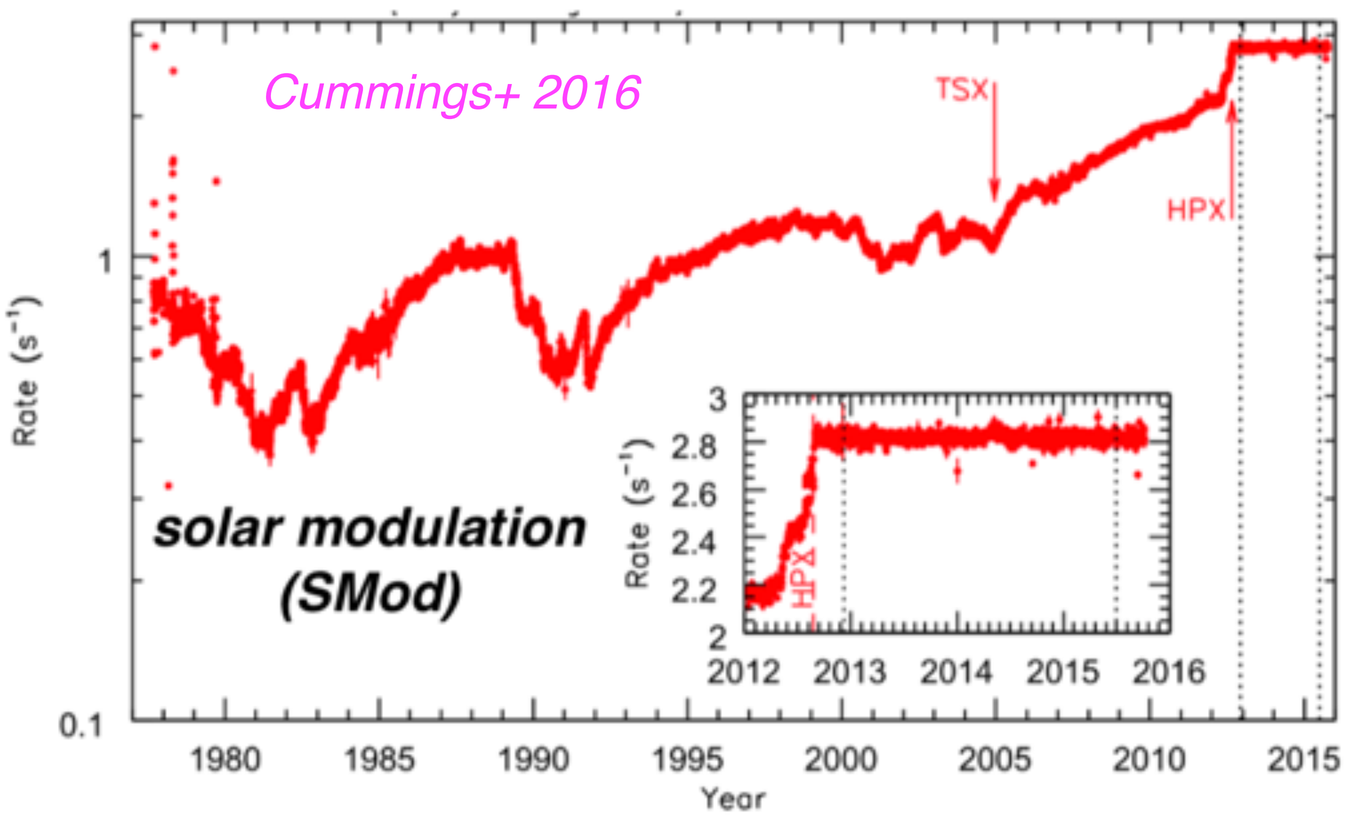
[Femtolensing constraints: **J. Kopp talk**]

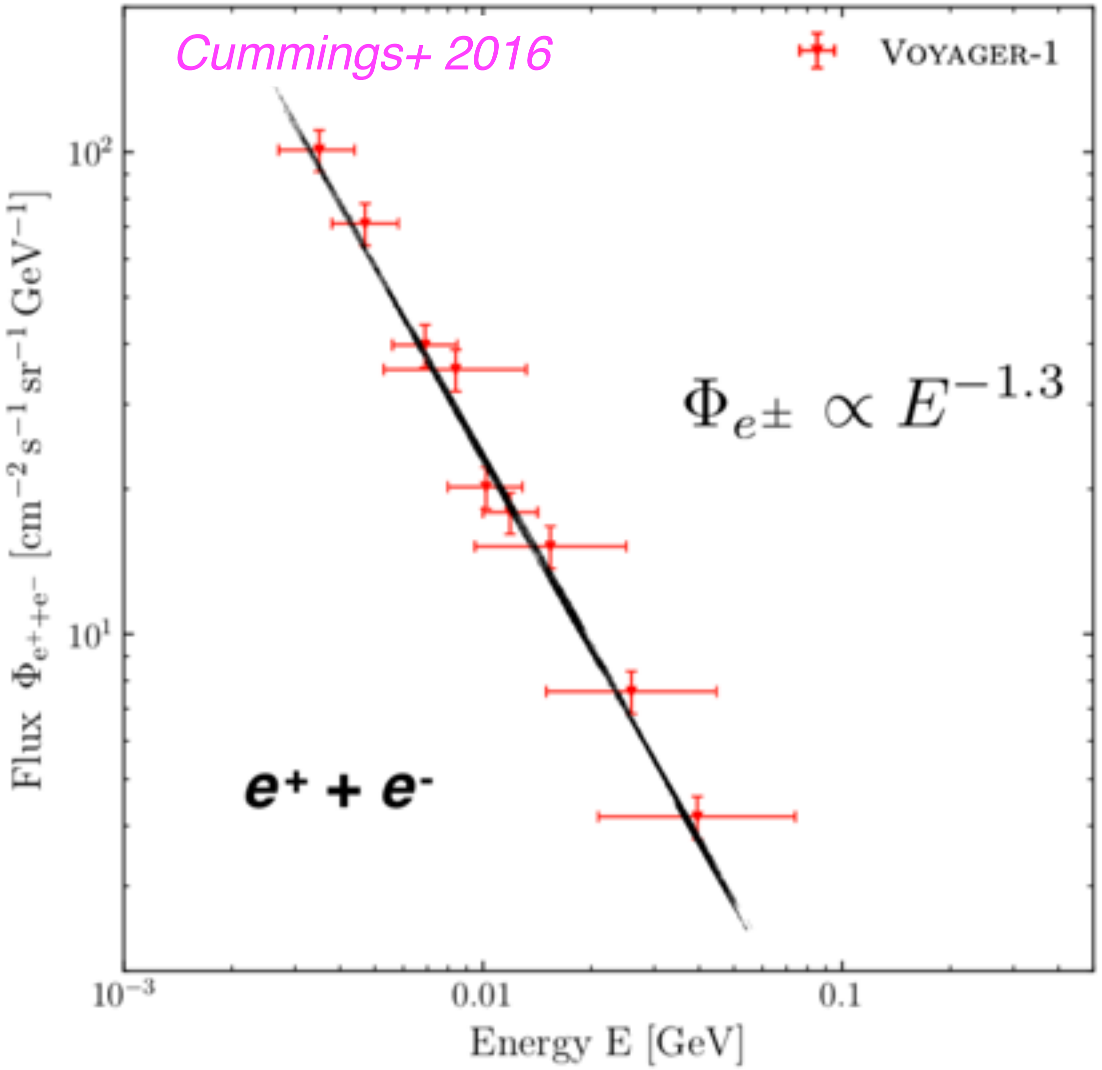
Voyager I: The local ISM

Sub-GeV interstellar cosmic rays cannot reach detectors orbiting the Earth, because they are stopped by the heliopause (Solar wind)

Voyager-1 crossed the heliopause in August 2012 and probes now the local interstellar medium

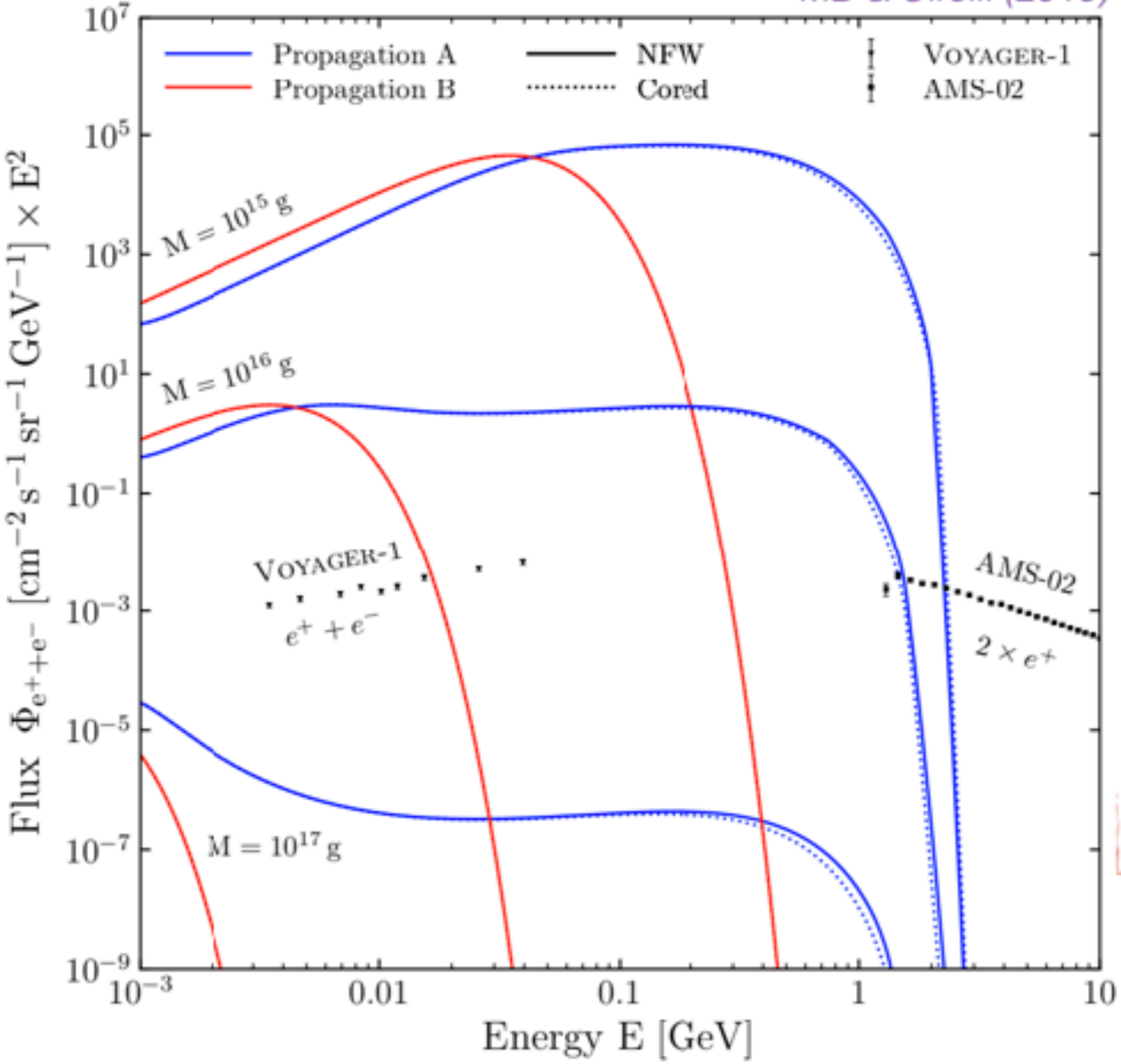
=> **First sub-GeV interstellar CRs**





Electrons/positrons from PBH radiation

MB & Cirelli (2018)



Propagation A: strong reacceleration

$V_A = 117.6\,\mathrm{km/s}$ *Maurin+(2001)*

Propagation B: no reacceleration

$V_A = 0\,\mathrm{km/s}$ *Reinert & Winkler(2018)*

DM distribution from *McMillan(2016)* (**NFW/cored**)

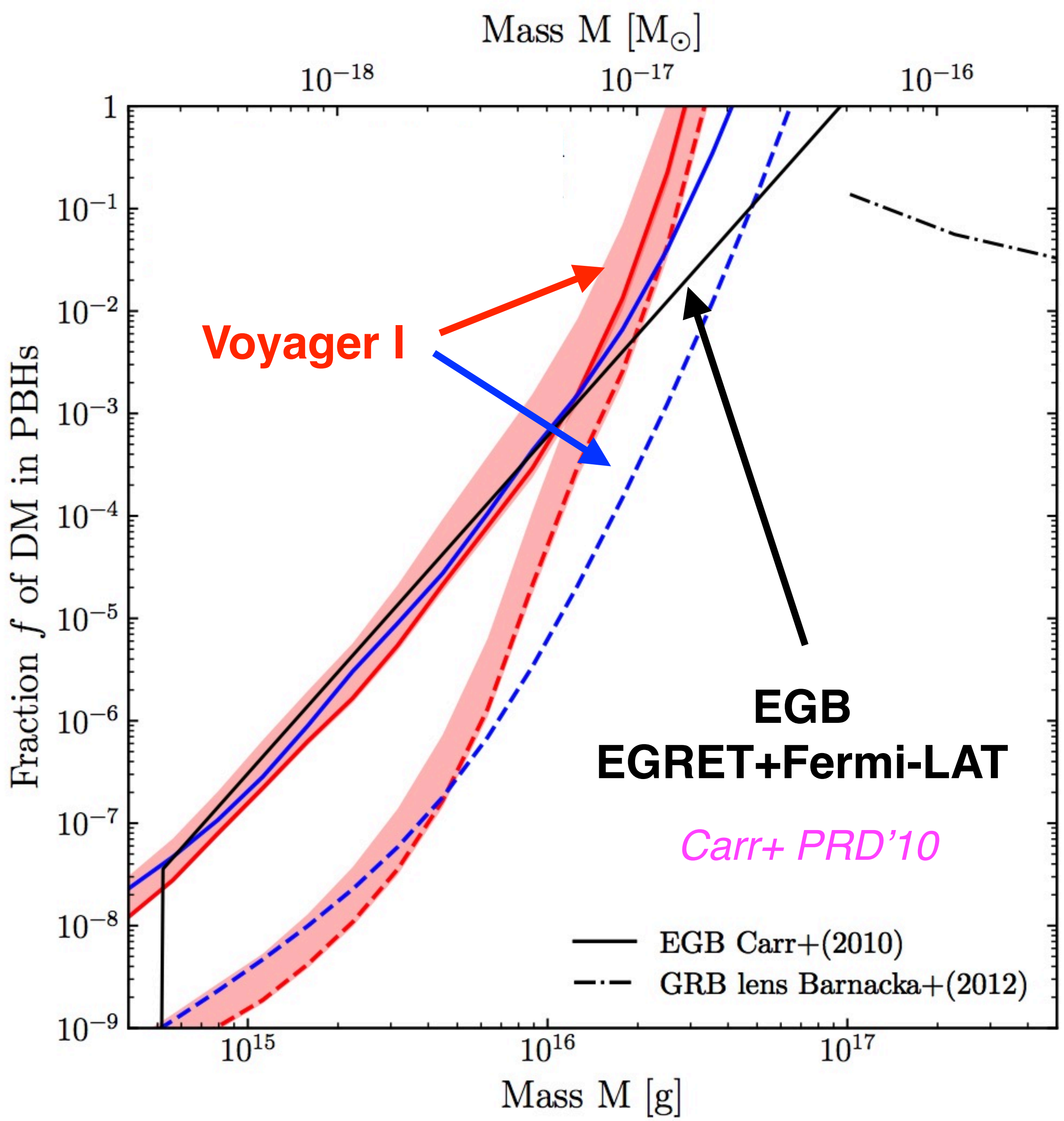
$$\rho_{\odot}^{\mathrm{DM}} = 0.4\,\mathrm{GeV cm^{-3}}$$

Voyager-1 probes PBHs with mass up to ~10^{17} g

- Voyager-1 is sensitive local PBHs (~1kpc) because of $e^{\pm}$ energy losses (ISM ionisation) $\Longrightarrow$ signal **not sensitive** to the DM halo profile
- strong reacceleration (**A**) enables to detect a signal above 1 GV $\Longrightarrow$ AMS-02 probes PBHs with $M < 10^{16}$ g

Voyager-1 data $\Longrightarrow$ upper limit for $f = \rho_{PBH}/\rho_{DM}$

Constraints from Voyager I



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- ✓ **Competitive with EGB limits** up to 10^{16} g
- ✓ **Independent on DM density profile** — probe only local flux of CRs (< 1kpc)
- ✓ Largest **uncertainty** related to **CRs propagation**, e.g. magnetic halo size (red band)
- ✓ Very **conservative limits** (signal only) => Improve by more than a factor of 10 if the astrophysical bkg of electrons/positrons is considered

Fermi-LAT PBH search

Fermi-LAT Clb ApJ'18

Search for evidence of gamma rays produced by the Hawking radiation of low-mass, high-temperature PBHs in the Fermi-LAT data

PBHs with the remaining lifetime of months to years

Would appear as **Fermi-LAT unassociated sources with proper motion**

- Differential point-source sensitivity in 4 yr (3FGL) of observations is most sensitive to PBHs with temperature $T_{BH} \sim 16$ GeV, i.e. with a remaining lifetime of ~4 yr.
- Detectable up to 0.03 pc, very local sources
- Expected proper motion of 1 deg, vs localisation error of 0.1 deg
- **Smoking-gun signature**: A moving unassociated source with a hard spectrum of gamma rays

No PBH candidate found in the 3FGL

➡ Set limits **on PBH evaporation rate** $\dot{\rho}_{\rm PBH} < (7.2^{+8.1}_{-2.4}) \times 10^3\ {\rm pc}^{-3}\ {\rm yr}^{-1}$

➡ Constraint on **local mass density** $\Omega^{\rm loc}_{\rm pbh} \leq (3.6^{+4.1}_{-1.2}) \times 10^2$

➡ **Average PBH density** $\Omega_{\rm pbh} \leq (1.5^{+1.7}_{-0.5}) \times 10^{-3}$

* Several orders of magnitude less constraining than the limits obtained from extragal. and Galactic gamma-ray backgrounds

Conclusions & Outlook

- ✓ **Solar-mass PBHs** can be bright in **radio** and **X rays**
- ✓ How much, it depends on the **modelling of gas accretion onto BH**. Latest results based on hydro simulations show that a sizeable number of detectable PBHs is predicted above current radio and X-ray survey thresholds
- ✓ Radio and X-ray bounds nicely complements other constraints in the PBH solar-mass range
- ✓ Future radio facilities (**SKA, ngVLA**) have the potential to either set very strong constraints on PBH abundance or to detect a population of PBHs at the GC
- ✓ **Low-mass PBHs** can be probed by **sub-GeV particles**: photons and cosmic rays.Strong and robust constraints from Voyager I electron/positron data
- ✓ **Future** (proposed) **gamma-ray missions @ sub-GeV** can push further down the limits on PBH abundance from diffuse photon observations, e.g. Amego

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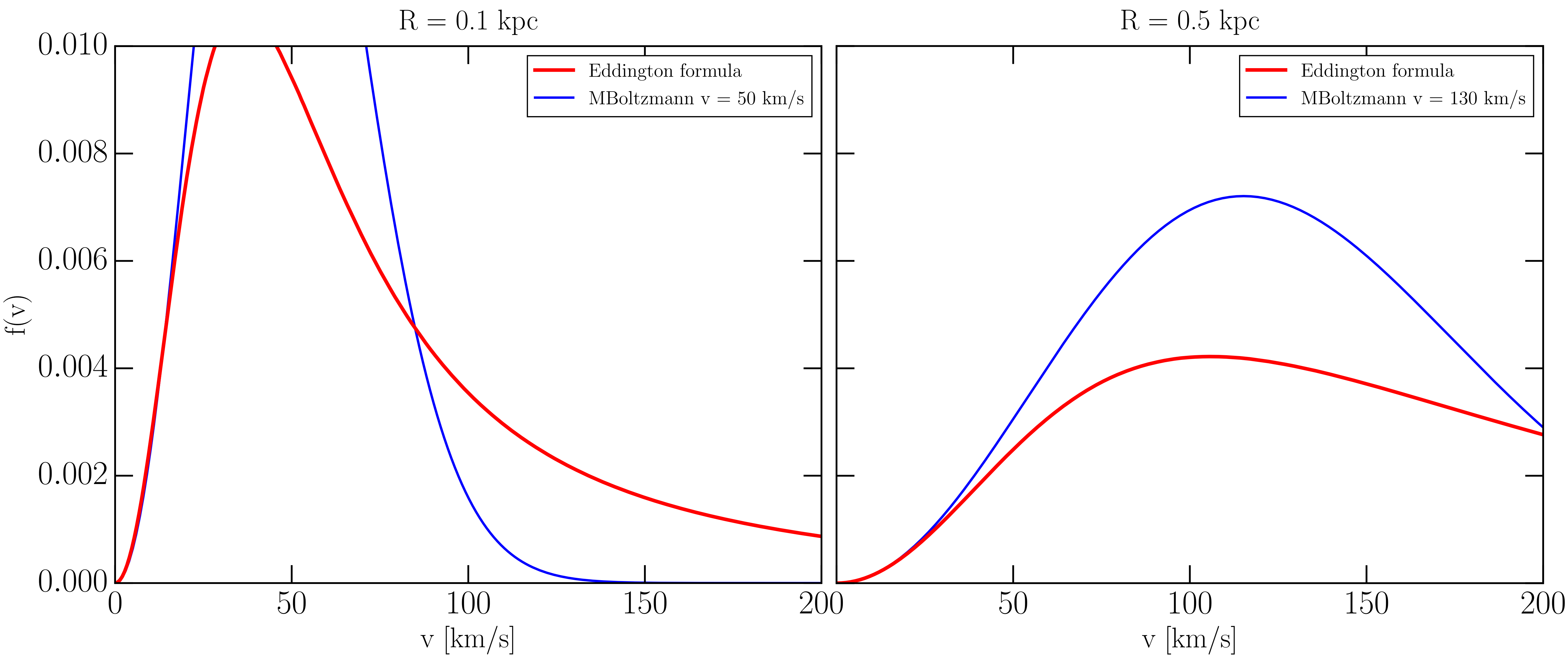
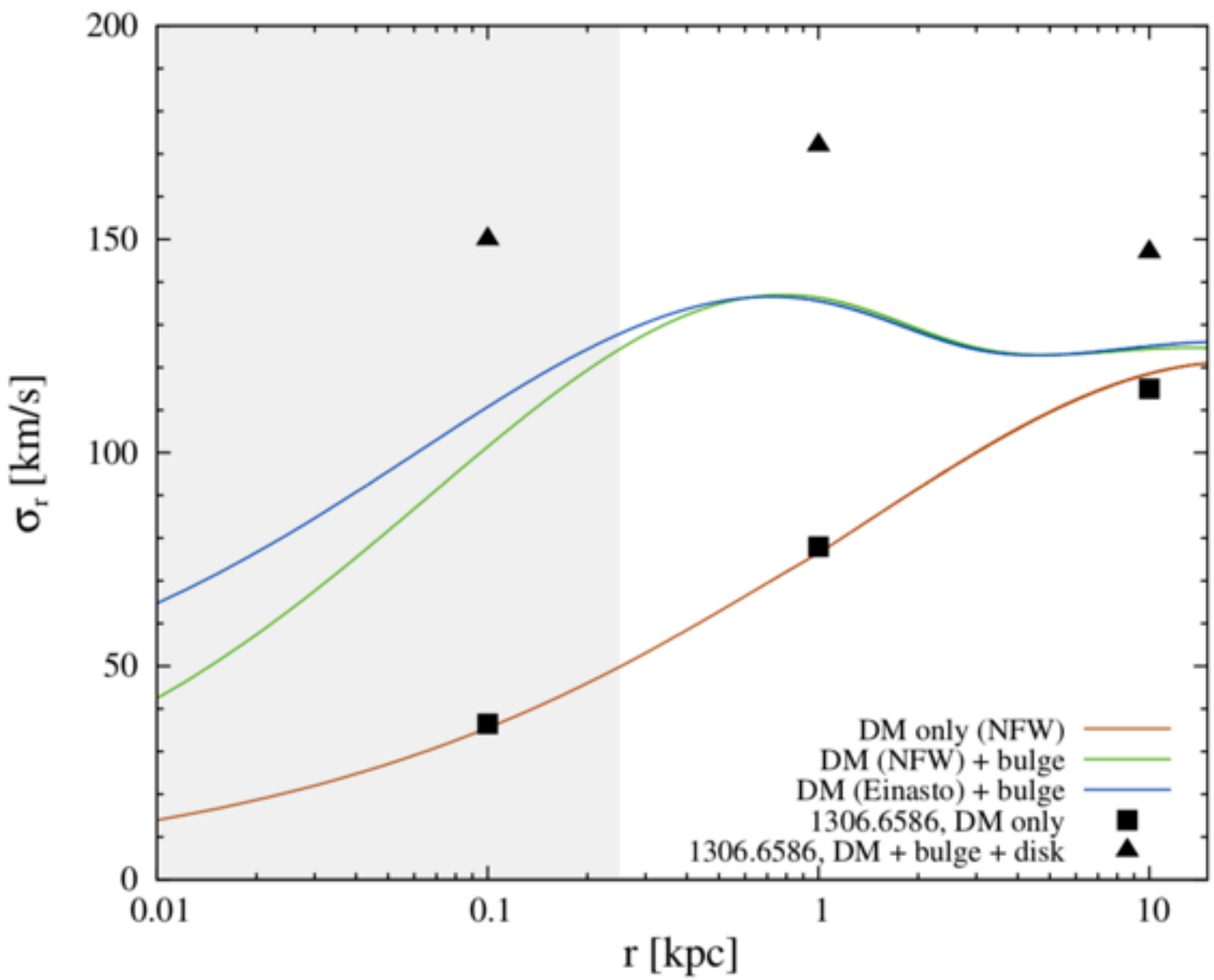
Thank you for your attention!

PBH velocity distribution



MB centered at 50 km/s at 60 pc, 74 km/s at 100 pc and 138 km/s at 500 pc in our computation

PBH velocity distribution



~50 km/s @ 60 pc

~74 km/s @ 100 pc

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The SKA

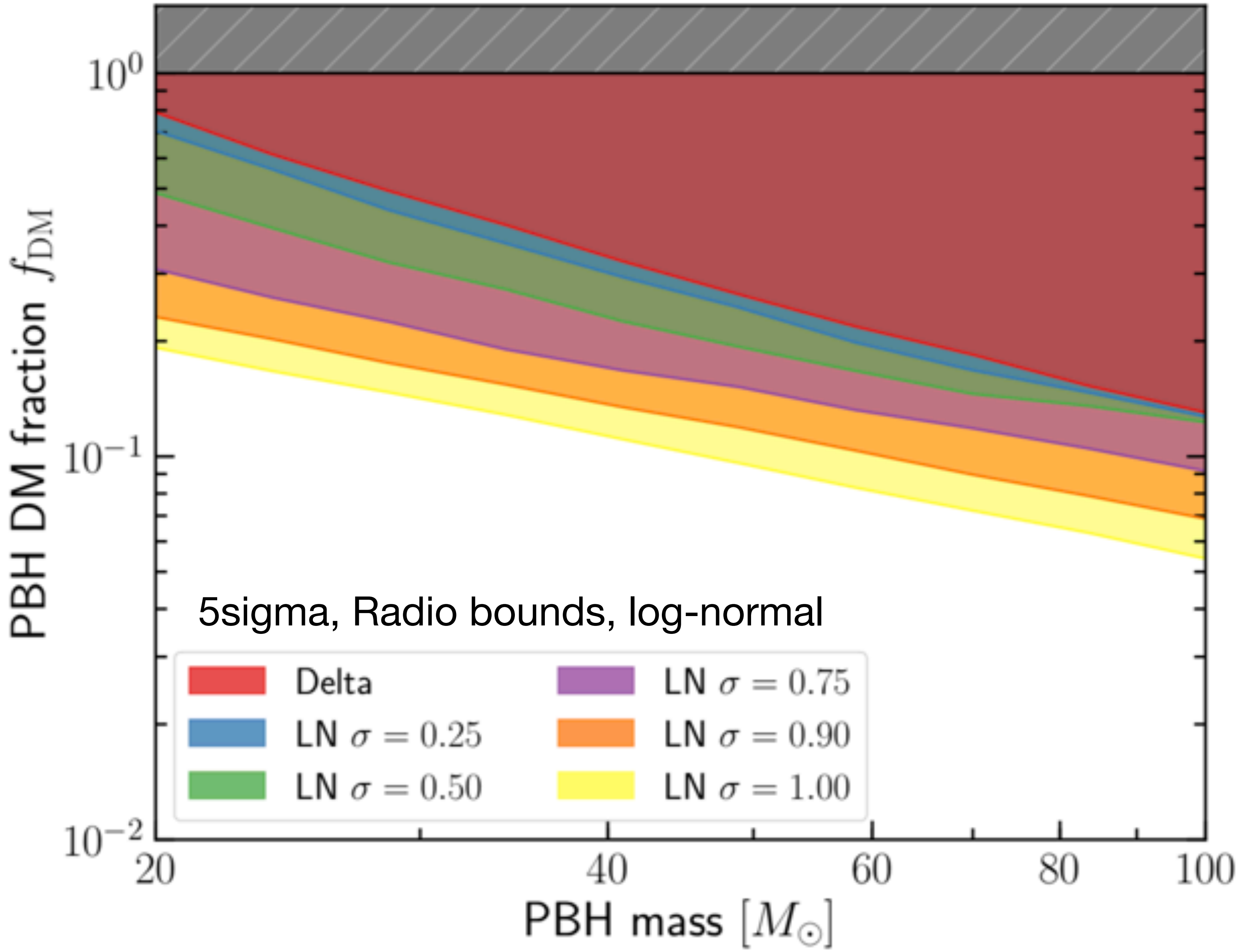
SPDO / Swinburne Astronomy Productions
How will SKA1 be better
than today's best radio telescopes?
SKA
Astronomers assess a telescope's performance by looking at three factors - resolution, sensitivity, and survey speed. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.
LOFAR
Netherlands
JVLA
The Square Kilometre Array (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.
SKA1 LOW
Australia
SKA1 MID
South Africa
SKA1 LOW x1.2
SKA1 MID x4
SKA1 LOW x135
SKA1 MID x60
SKA1 LOW x8
SKA1 MID x5
RESOLUTION
Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.
SURVEY SPEED
Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.
SENSITIVITY
Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

The gas distribution in the MW

Phase	Volume Fraction	Mass Fraction	N (cm^{-3})	T (K)	c_s ($\times 10^5$ cm s^{-1})
Molecular Clouds	0.005	0.4	1000	10–30	0.6
Diffuse Clouds	0.05	0.4	100	80	0.9
Intercloud Medium	0.4	0.2	1	8000	9
Coronal Gas	0.5	0.001	0.001	10^6	100

Extended mass distribution

Manshanden+1812.07967

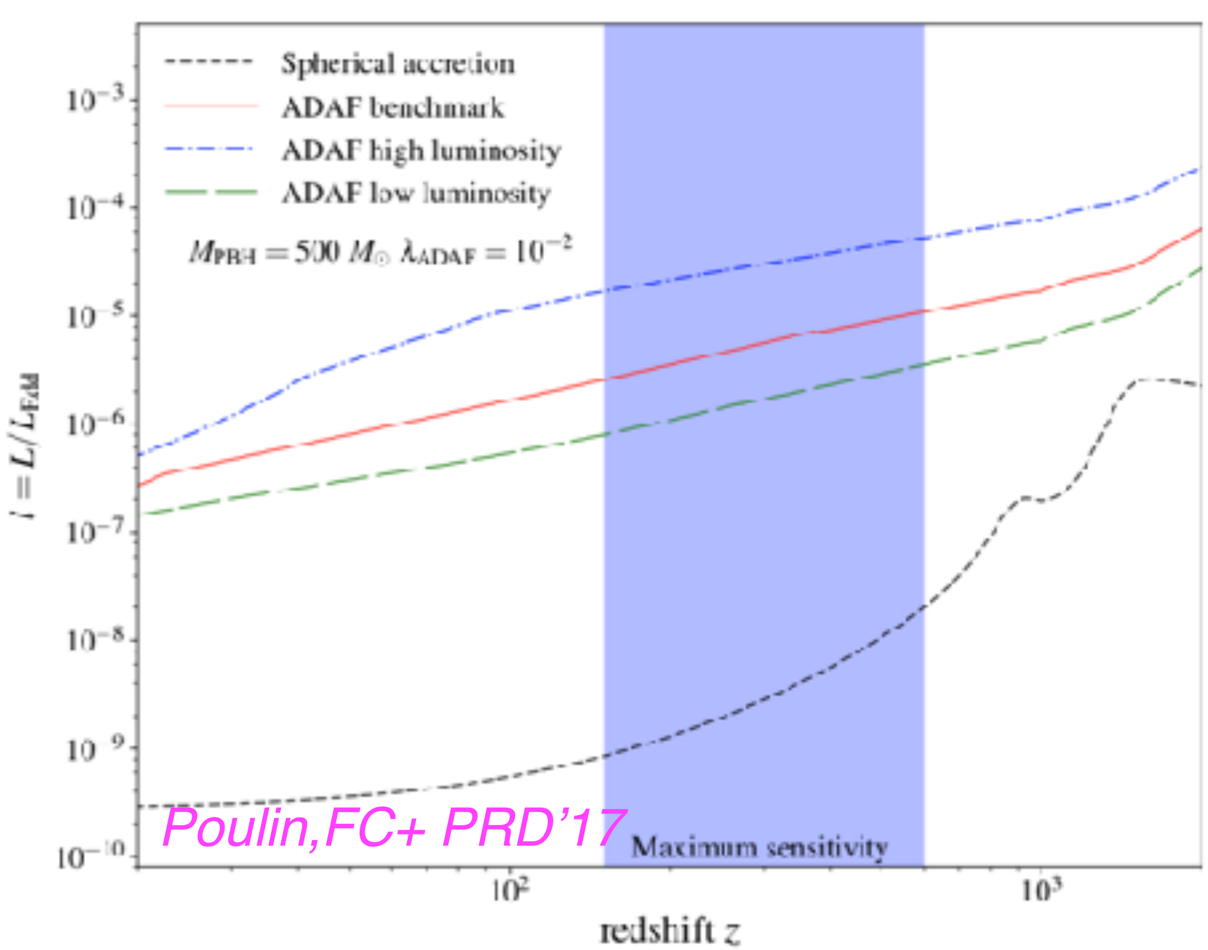


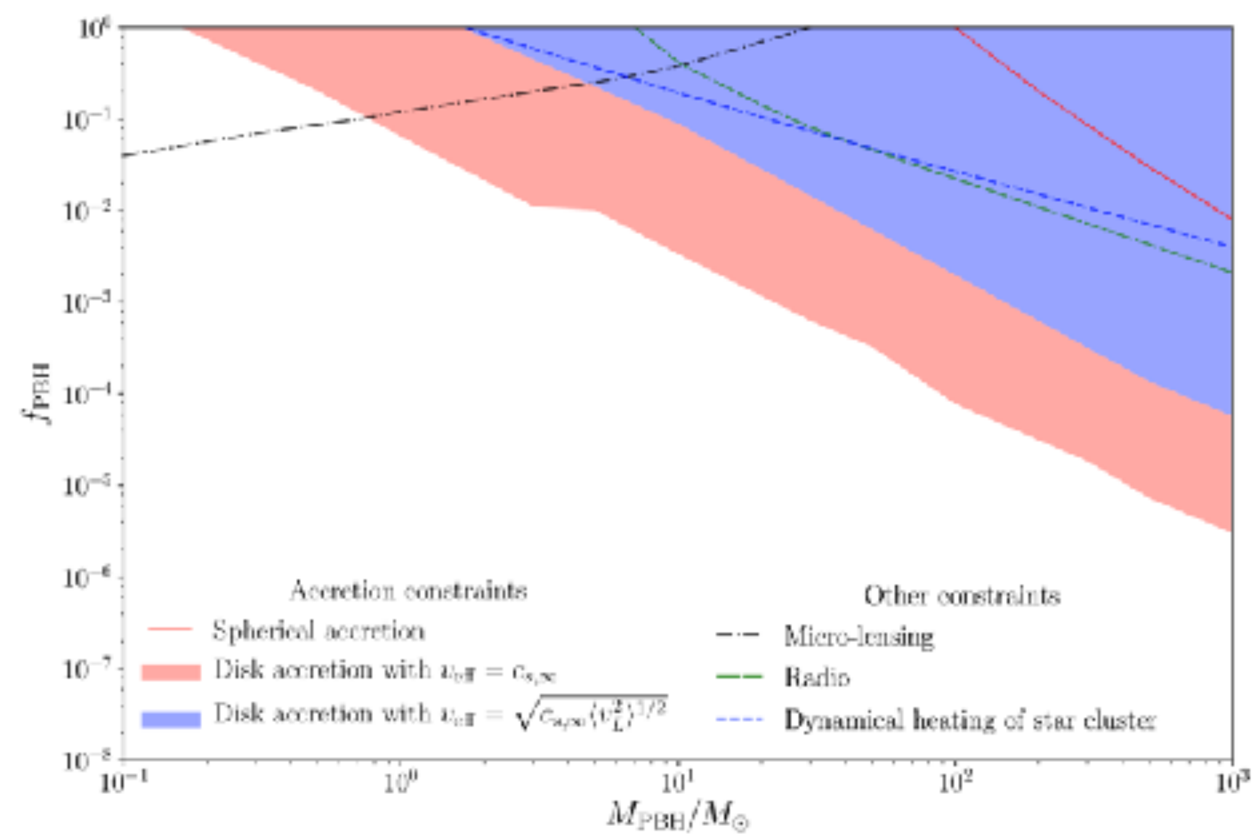
Power-law: can give bounds as strong as $f_{DM} = 0.05$

Relevance of disk-like accretion

CMB anisotropy constraint on PBH abundance

An accretion disk generally form in dark ages between recombination and reionisation





* Disk not resolved in hydro simulation [*Park&Ricotti ApJ’13*]

** The disk formation can drive thermal instabilities leading to outbursts [*Agol&Kamionkowski MNRAS’02*]