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ダークマター候補 Primordial Black Hole, axion, WIMP の問題点

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Candidate of Dark Matter
My favorite DMs (推しダークマター)

- WIMP
- Axion

- Primordial Black Hole

- …

Why PBHs?

- We need 30 $M_\odot$ BHs to explain LIGO/VIRGO GW events
- We do not know the origin of 30 $M_\odot$ BHs to be astrophysical or cosmological.
- PBHs should be a good candidate for Cold Dark Matter (CDM)
- Some inflation modes predict PBHs formed at small scales in the early Universe (much before 1 sec)
- Scenarios have been constrained by BBN, CMB, lensing、gamma-ray, and so on.
- In future, scenarios can be investigated further by PIXIE-like satellite (CMB μ-distortion), SKA/Ominiscope (21cm), CTA (gamma-ray), DECIGO (Gravitational Wave), …

How to produce the binary black hole with masses of O(10) $M_\odot$?

- Have binaries originated from Pop III or Pop II stars collided within cosmic time? [astrophysically model-dependent]

- Primordial black holes (PBHs) formed through collapses of perturbations produced by Inflation

  [Cosmologically model-dependent]

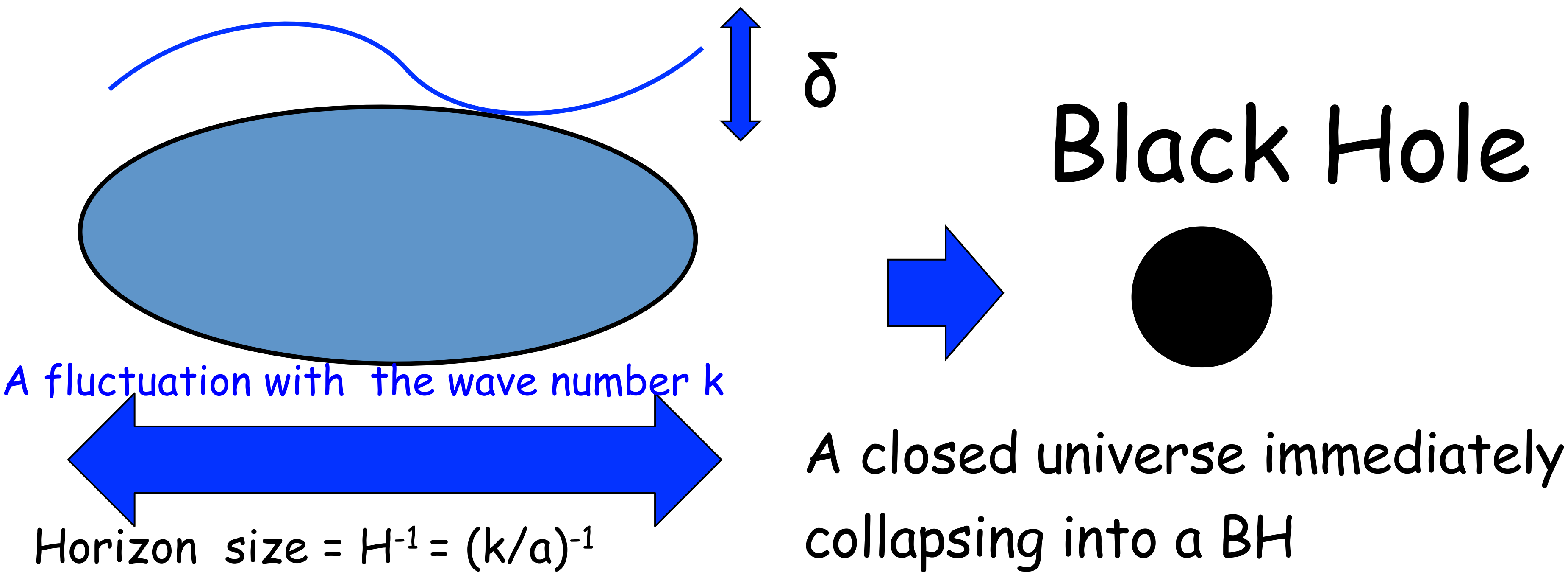
Conditions for a PBH formation in Radiation dominated (RD) Universe

Zel'dovich and Novikov (1967), Hawking (1971), Carr (1975)

Harada, Yoo and KK (2013)

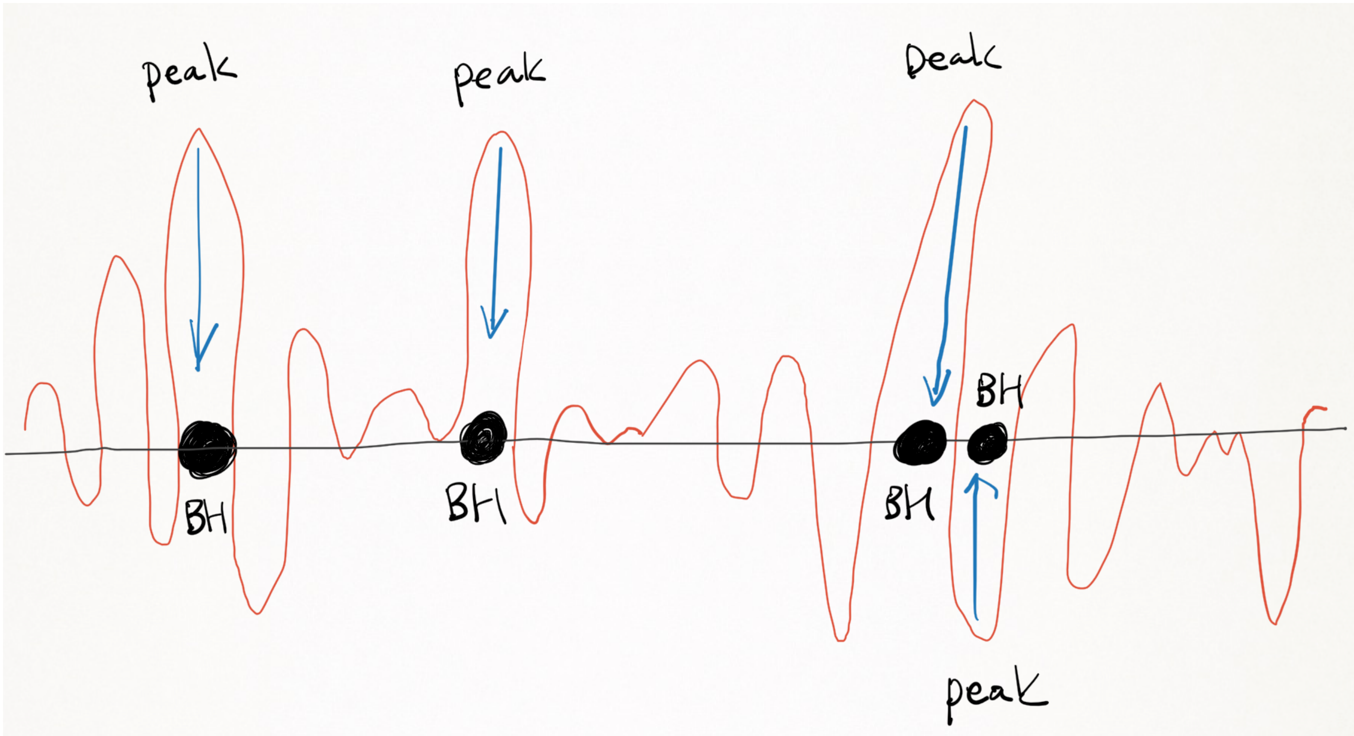
- Gravity could be stronger than pressure

$$\delta > \delta_c \sim p/\rho \sim c_s^2 = w = 1/3$$



Primordial Black Hole (PBH)

- Large perturbation at small scales was produced by Inflation at around > 10^{-36} second



P_ζ (k) and PBH abundance β(M)

$$\Omega_{PBH} = \rho_{PBH} / \rho_{tot}$$

- Fraction of PBH to the total at its formation epoch with Gaussian fluctuation.

$$\beta(M) \equiv \frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}} = 2\int_{\delta_{\rm th}}^{\infty} d\delta \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\delta^2}{2\sigma^2}\right) = {\rm erfc}\left(\frac{\delta_{\rm th}}{\sqrt{2}\sigma}\right)$$

δ_{th} ~ 0.3 – 0.4

- Finally we have a relation between β and fluctuation σ (or β and Ω)

$$\beta(M) \sim {\rm erfc}\left(\frac{\delta_{\rm th}}{\sqrt{2}\sigma}\right) \simeq \sqrt{\frac{2}{\pi}} \frac{\sigma}{\delta_{\rm th}} \exp\left(-\frac{\delta_{\rm th}^2}{2\sigma^2}\right)$$

$$= 1.5 \times 10^{-18} \left(\frac{m_{PBH}}{10^{15} g}\right)^{1/2} \left(\frac{\Omega_{PBH} h^2}{0.13}\right)$$

$\sigma^2 \sim P_\zeta$

Typical quantities of PBHs in RD

- Mass (horizon mass $=\rho(t_{form})\,H(t_{form})^{-3}$)

$$M_{PBH} \sim \rho(H^{-1}_{form})^3 \sim M^2_{pl} t_{from} \sim \frac{M^3_{pl}}{T^2_{form}} \sim 10^{15} g \left(\frac{T_{form}}{3\times 10^8 GeV}\right)^{-2} \sim 30 M_\odot \left(\frac{T_{form}}{40 MeV}\right)^{-2}$$

- Lifetime

$$\tau_{PBH} \sim \frac{M^3_{PBH}}{M^4_{pl}} \sim 4\times 10^{17}\, sec \left(\frac{M_{PBH}}{10^{15} g}\right)^3 \sim 3\times 10^{68} yrs \left(\frac{M_{PBH}}{30 M_\odot}\right)^3$$

- Hawking Temperature

$$T_{PBH} \sim \frac{M^2_{pl}}{M_{PBH}} \sim 0.1 MeV \left(\frac{M_{PBH}}{10^{15} g}\right)^{-1} \sim 3\times 10^{-11} K \left(\frac{M_{PBH}}{30 M_\odot}\right)^{-1}$$

- Wave number of horizon length

$$k = aH \sim 10^5 Mpc^{-1} \left(\frac{M_{PBH}}{10^4 M_\odot}\right)^{-1/2} \sim 10^5 Mpc^{-1} \left(\frac{T_{form}}{MeV}\right)^{+1}$$

- Fraction to CDM

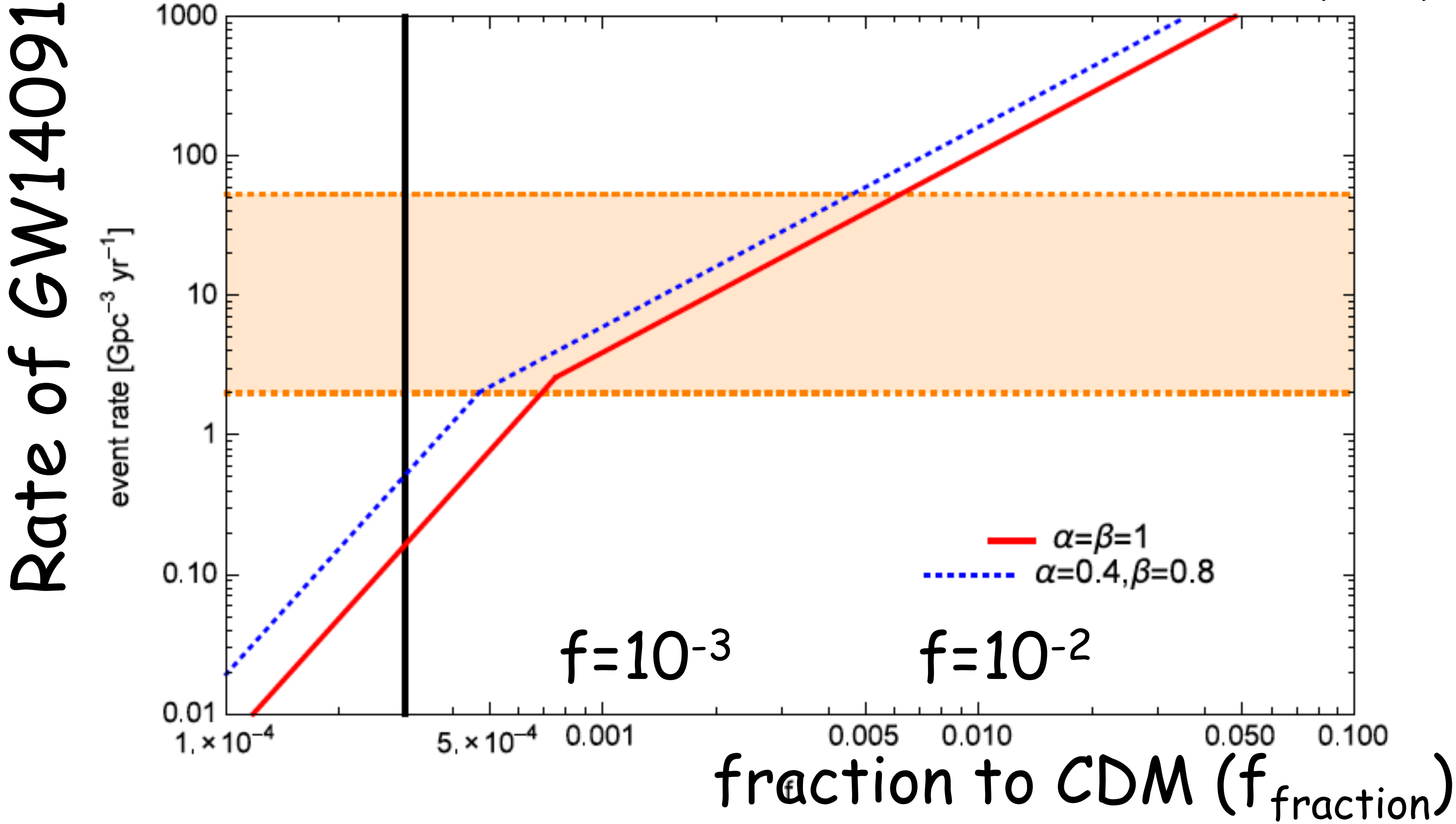
$$f_{fraction} \equiv \frac{\Omega_{PBH}}{\Omega_{CDM}} \sim \left(\frac{\beta}{10^{-18}}\right) \left(\frac{M_{PBH}}{10^{15} g}\right)^{-1/2} \sim \left(\frac{\beta}{10^{-8}}\right) \left(\frac{M_{PBH}}{30 M_\odot}\right)^{-1/2} \sim 10^8 \left(\frac{M_{PBH}}{30 M_\odot}\right)^{-1/2} \sqrt{P_\delta}\, \exp\left[-\frac{1}{18 P_\delta}\right]$$

GW150914 and its merger rate

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama (2016).

3-body is important for the BBH formations

See also, Ali-Haimound, Kovetz and Kamionkowski (2017)



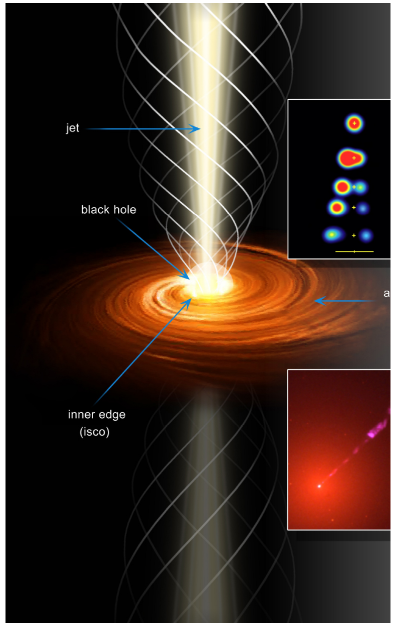
CMB bound on PBHs by disk-accretion in the late MD epoch

Poulin, Serpico, Calore, Clesse, KK (2017)

- A non-spherical accretion disk (ADAF(slim) + Standard disk) around a PBH caused by an angular momentum emits radiation

$$\dot{M}_{\rm HB} \equiv 4\pi\lambda\,\rho_\infty v_{\rm eff} r_{\rm HB}^2 \equiv 4\pi\lambda\,\rho_\infty \frac{(GM)^2}{v_{\rm eff}^3}$$

$$l \simeq \omega\, r_{\rm HB}^2 \simeq \left(\frac{\delta\rho}{\rho} + \frac{\delta v}{v_{\rm eff}}\right) v_{\rm eff} r_{\rm HB}$$

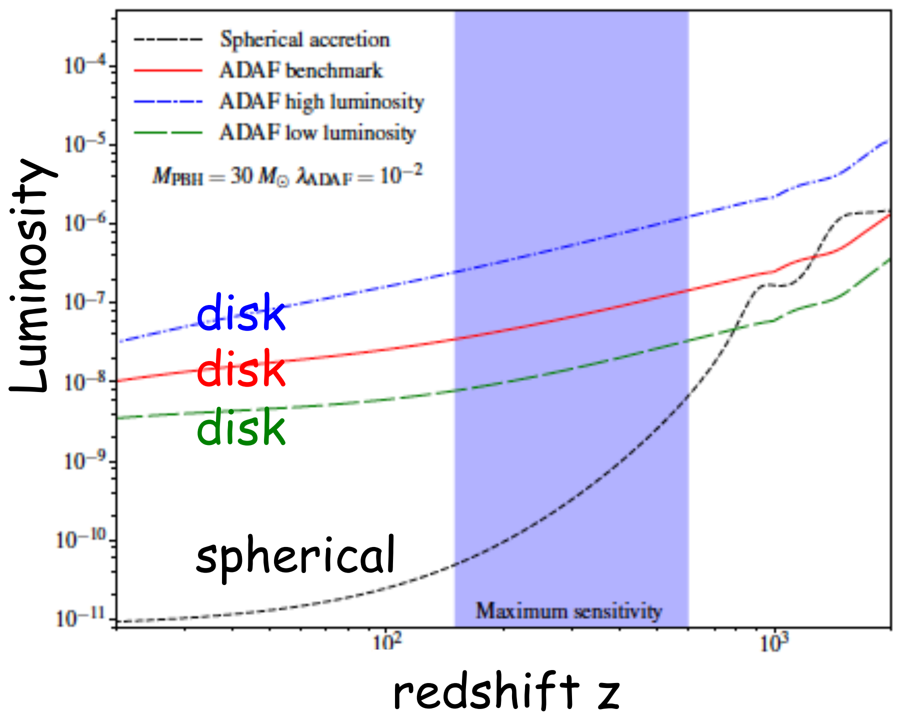


- CMB anisotropies are affected

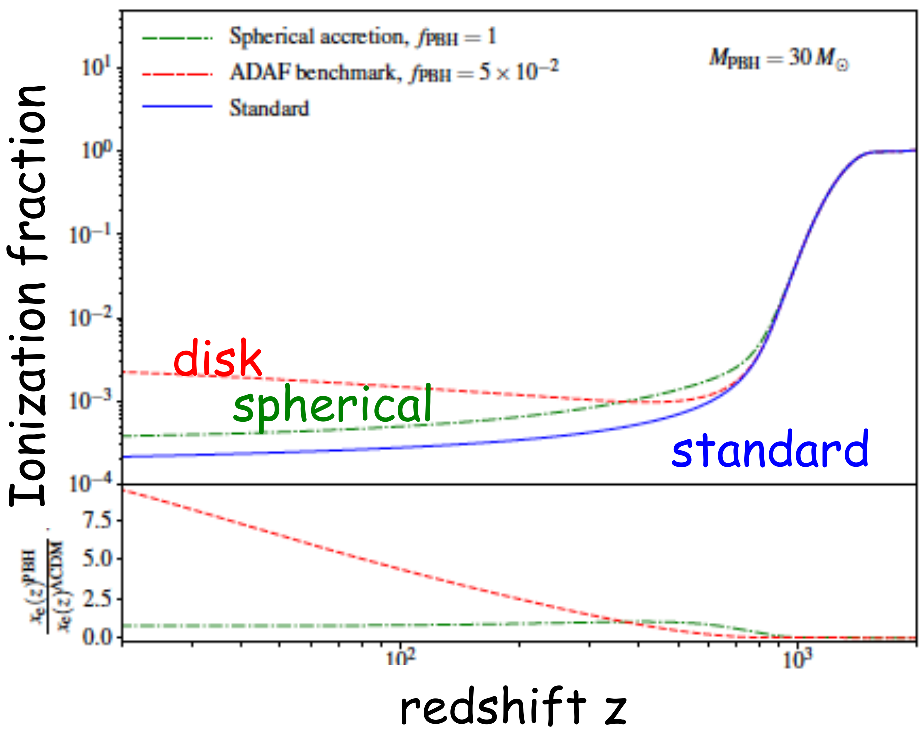
- From observations, we can constrain the number density of PBHs.

Modified CMB anisotropy

Poulin, Serpico, Calore, Clesse, Kohri (2017)



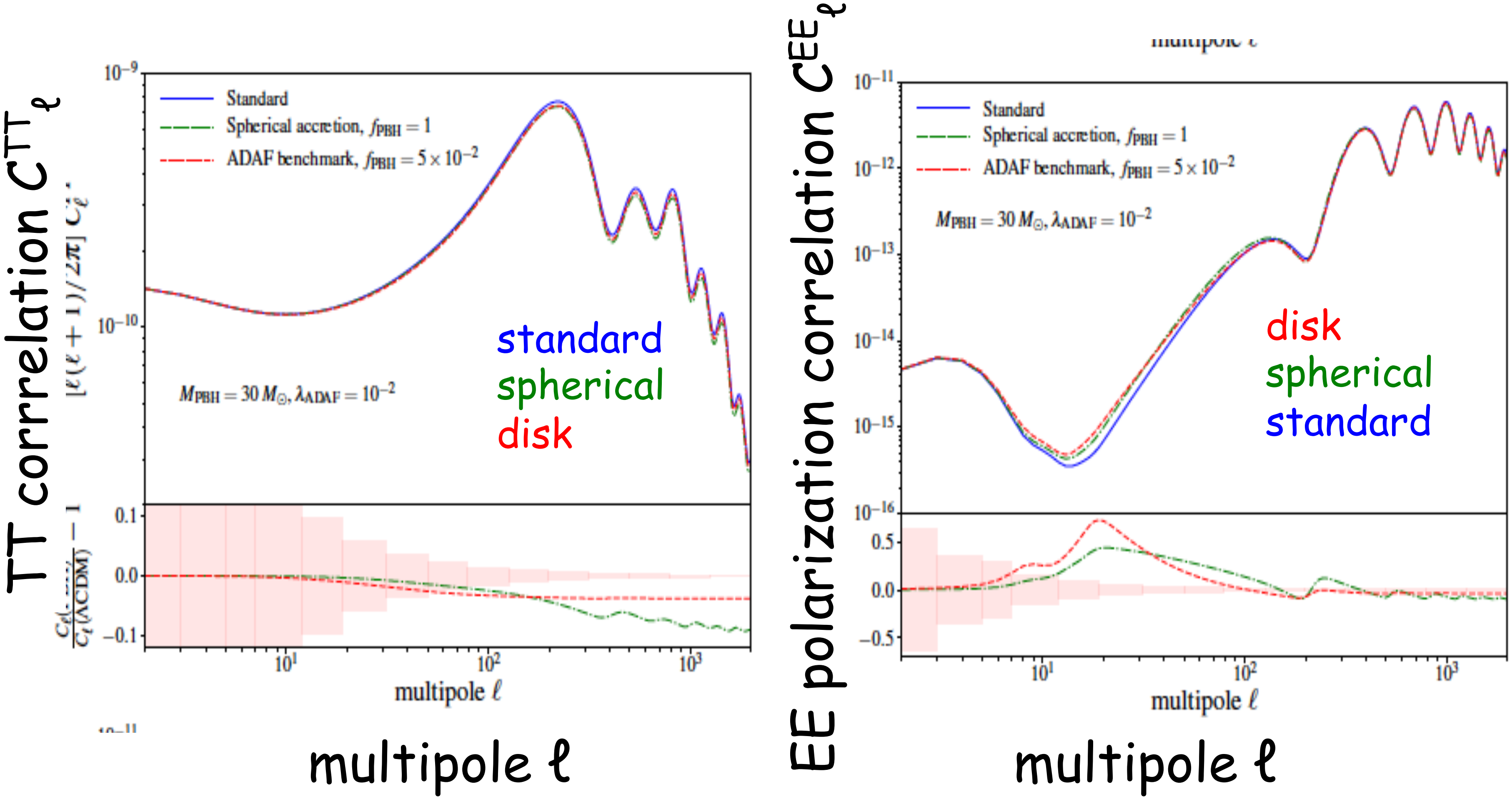
Luminosity



Ionization fraction

Modified CMB anisotropy

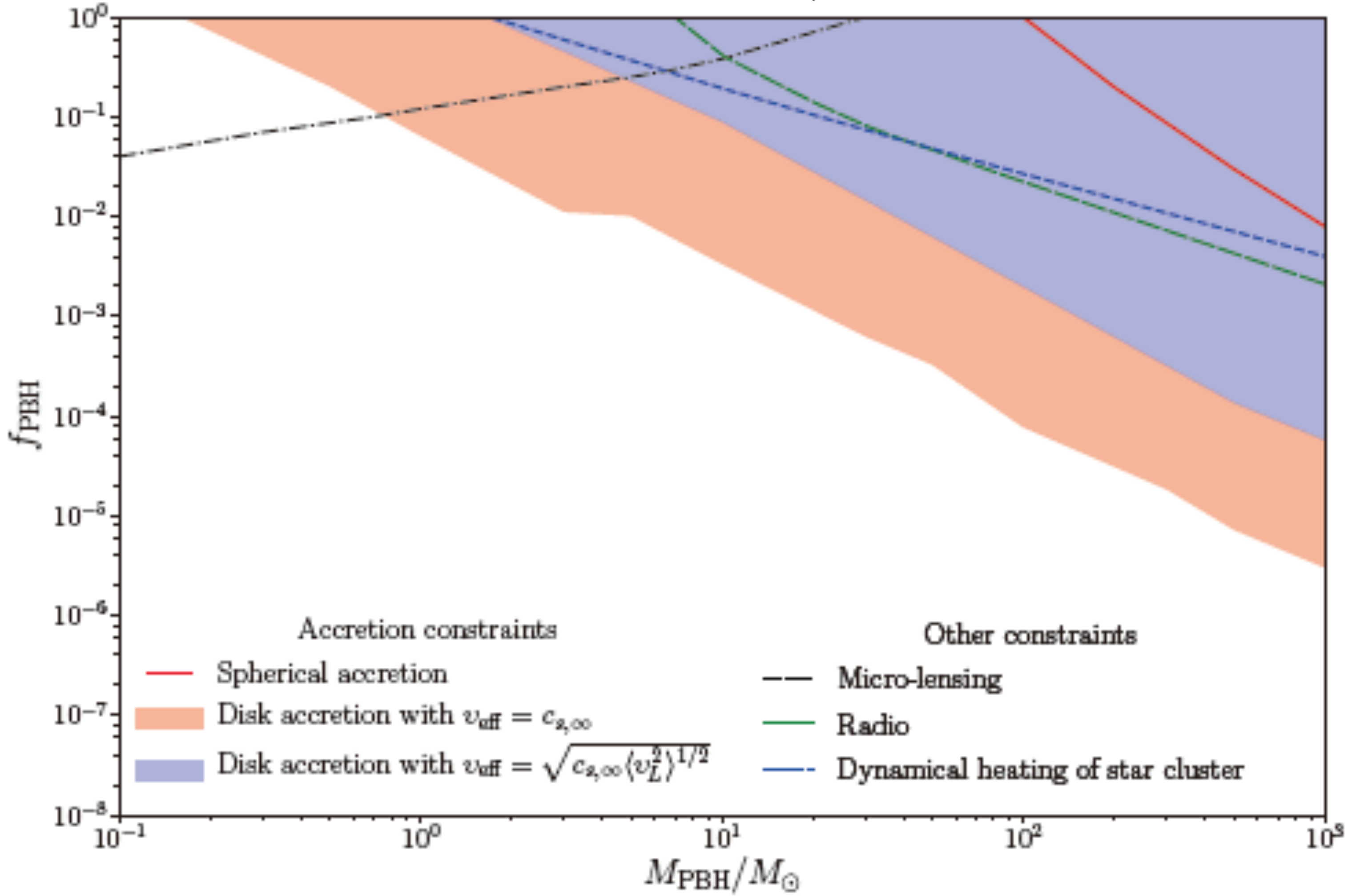
Poulin, Serpico, Calore, Clesse, Kohri (2017)



CMB bound by disk-accretion in the latest MD epoch

Poulin, Serpico, Calore, Clesse, KK (2017)

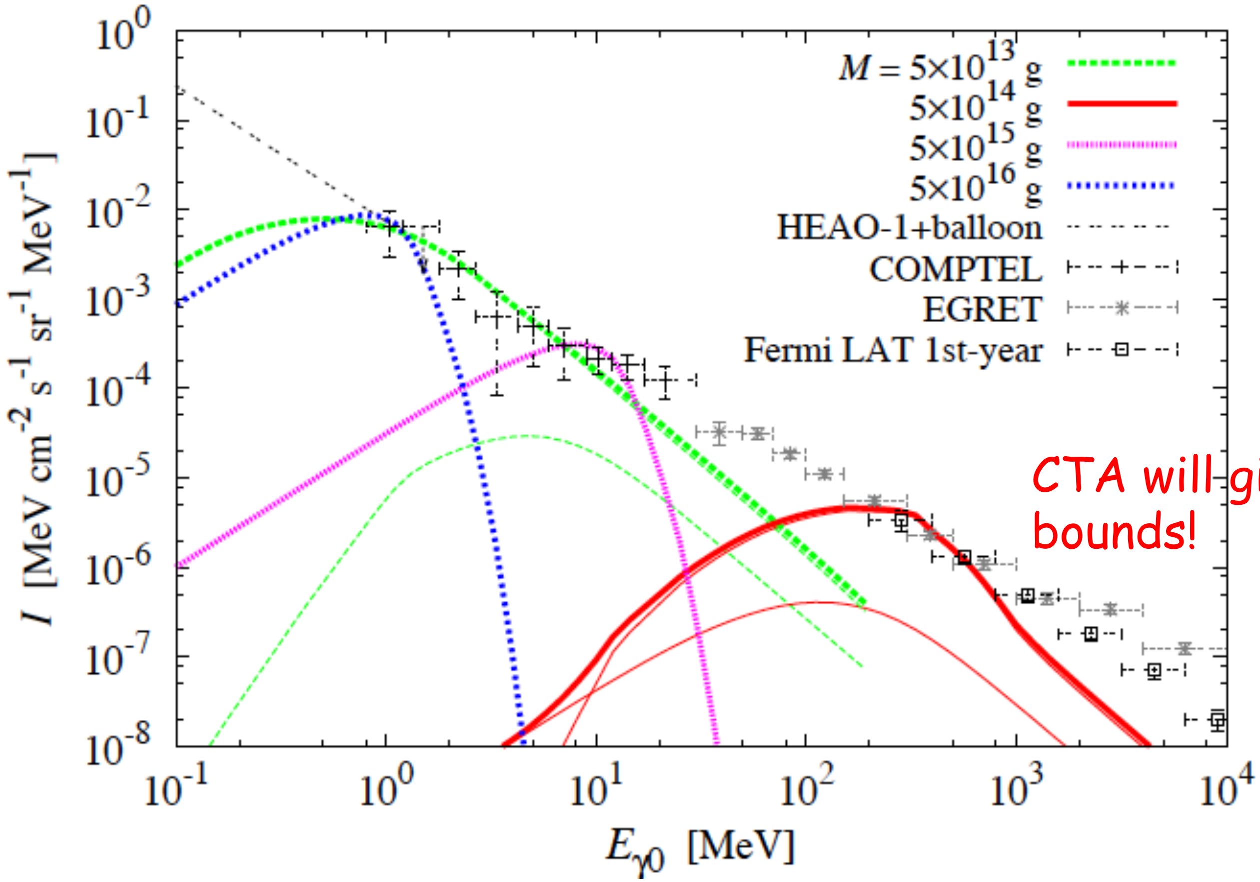
Fraction to CDM



Evaporating PBHs due to Hawking Process

$$d\dot{N}_s = \frac{dE}{2\pi} \frac{\Gamma_s}{e^{E/T_{BH}} - (-1)^{2s}}$$

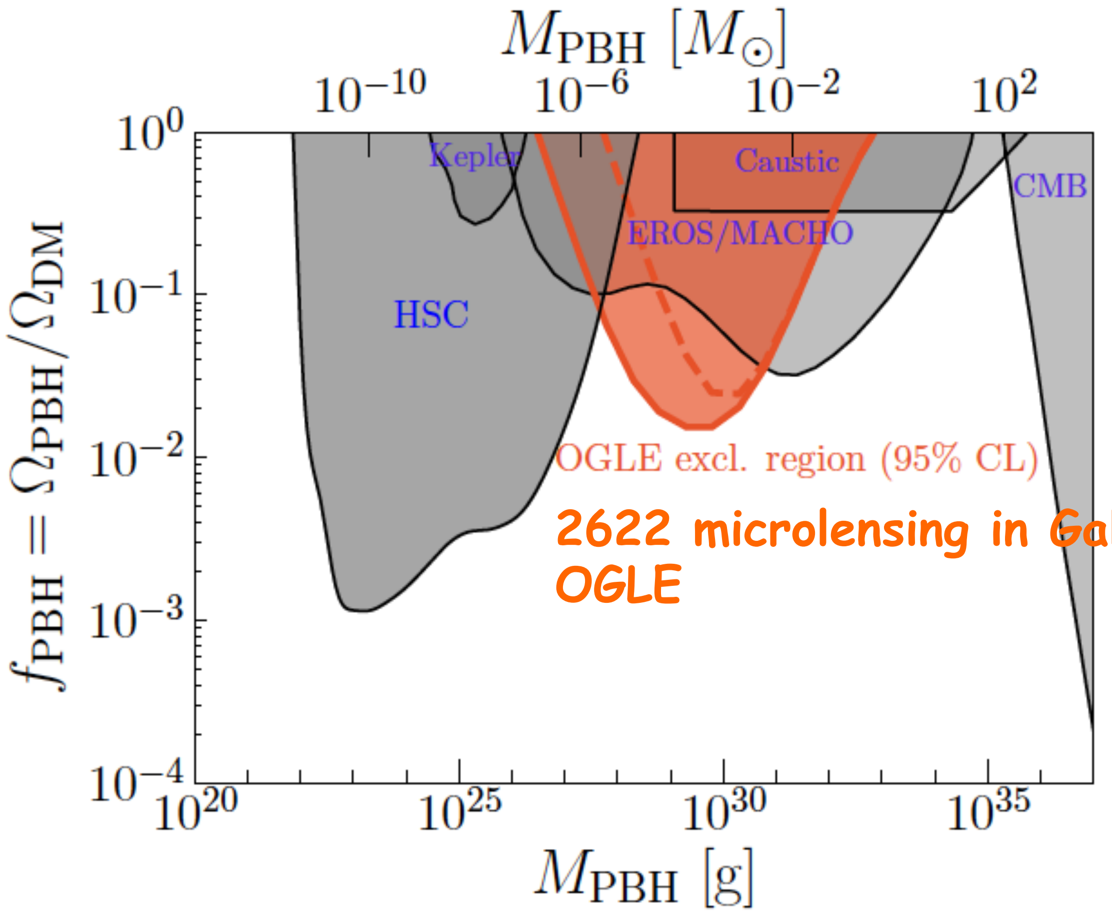
Carr, Kohri, Sendouda and Yokoyama (2010)



CTA will give stronger bounds!

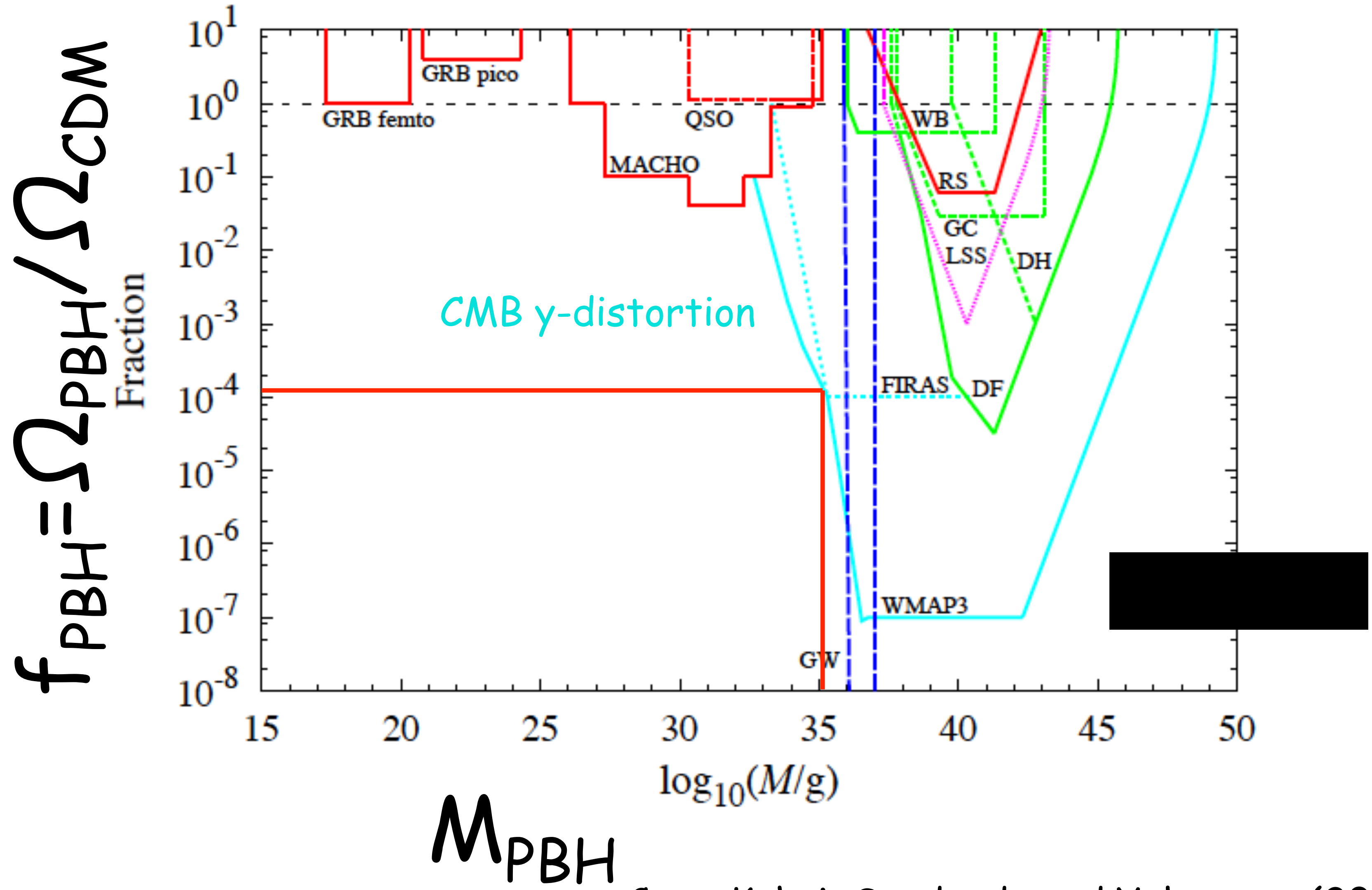
Gravitational lensing constrains on PBHs

Hiroko Niikura, Masahiro Takada, Shuichiro Yokoyama, Takahiro Sumi, Shogo Masaki,
arXiv:1901.07120 [astro-ph.CO]



2622 microlensing in Galactic bulge by OGLE

Upper bounds on the fraction to CDM

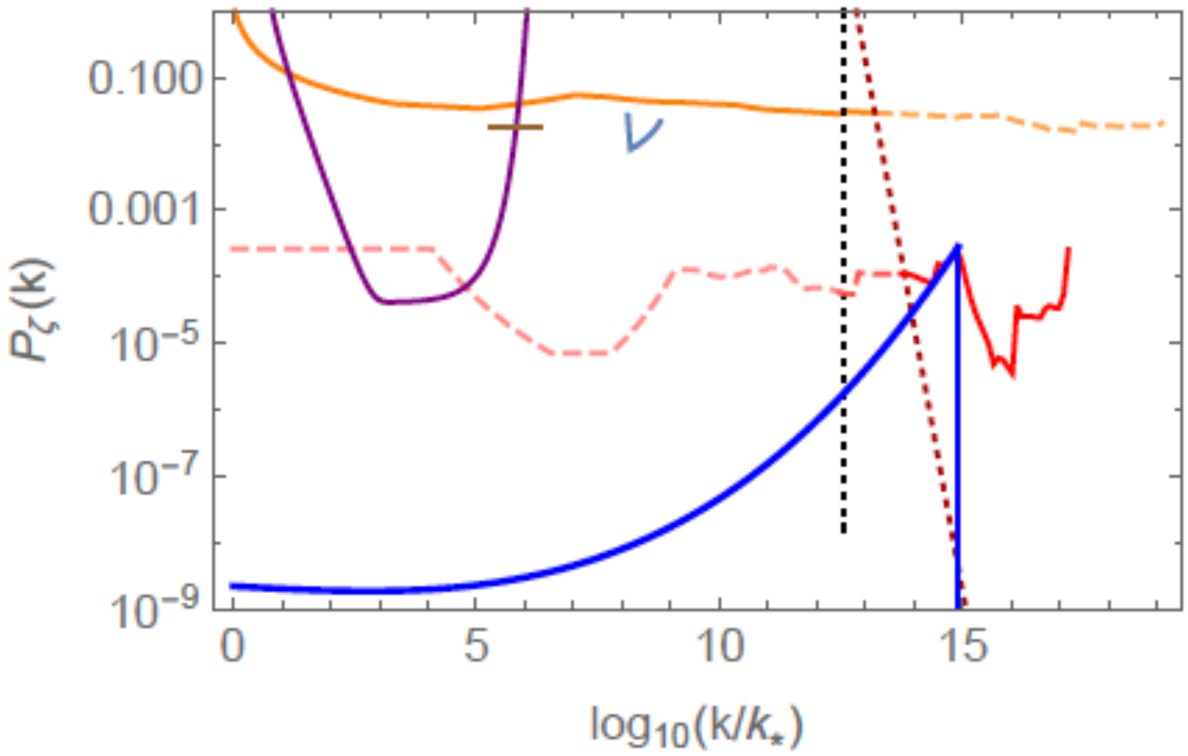


Carr, Kohri, Sendouda and Yokoyama (2010)

100 % Dark Matter by PBHs

KK and T.Terada, 2018

$$n_s = 0.96, \alpha_s = 0, \beta_s = 0.0019485.$$



black dotted line shows
$T_R = 10^4$GeV.

Axion
or
Axion-Like
Particle (ALP)

Oscillation probability

- Probability

$$P_{a\leftrightarrow\gamma} = \frac{1}{1+\left(\frac{\mathrm{E}_*}{\mathrm{E}_\gamma}\right)^2}\sin^2\left[\frac{g_{a\gamma}Br}{2}\sqrt{1+\left(\frac{\mathrm{E}_*}{\mathrm{E}_\gamma}\right)^2}\right]$$

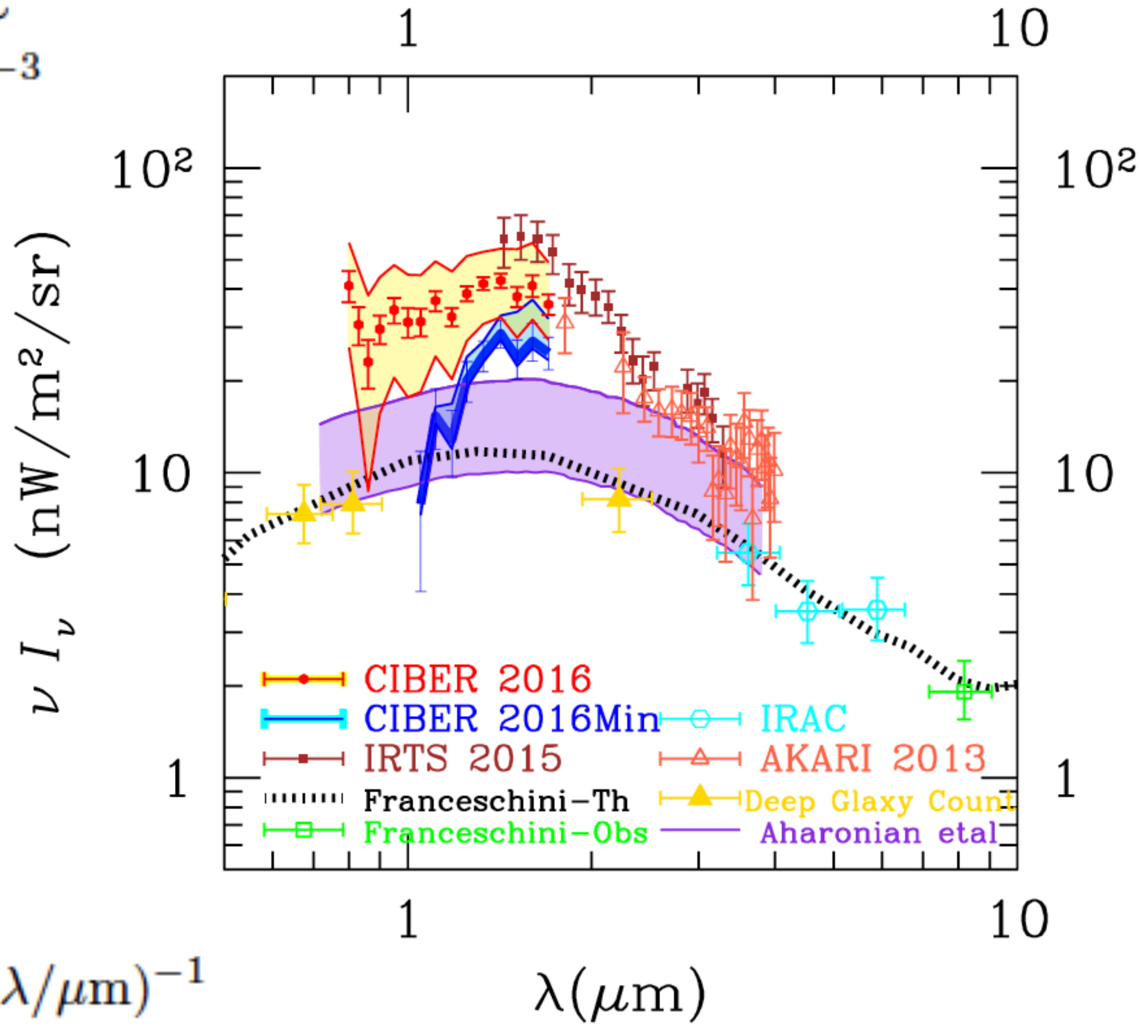
- For efficient oscillation,

$$E_\gamma > E_* = \frac{m_a^2}{2g_{a\gamma}B} \quad \text{and} \quad r \geq r_{Ha} \equiv \frac{2}{g_{a\gamma}B}$$

Cosmic Infrared Background (CIB) by CIBER 2016, IRTS 2013, Akari 2013

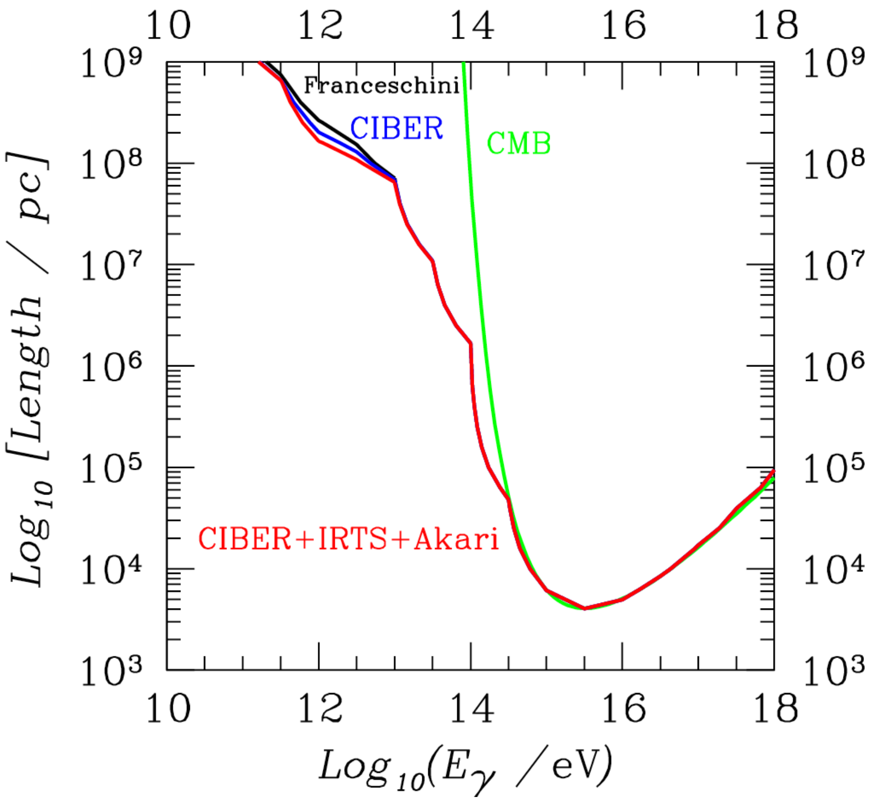
S. Matsuura *et al.* [CIBER Collaboration], Astrophys. J. 839, 7 (2017)

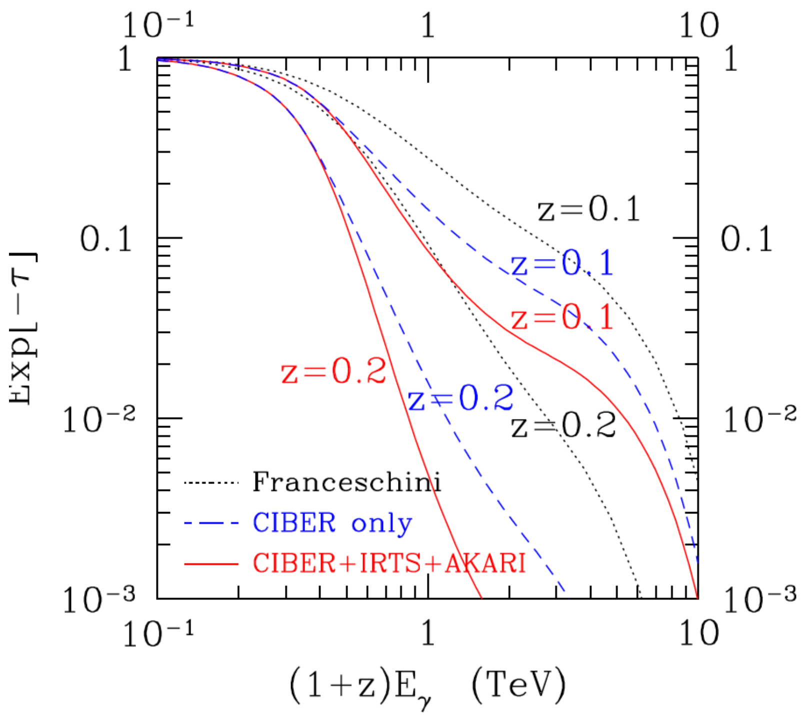
$10\text{nWcm}^2\text{sr}^{-1} \sim 2 \times 10^{-3}\text{eVcm}^{-3}$



$E_{\gamma BG} \sim 1.23\ \text{eV}(\lambda/\mu\text{m})^{-1}$

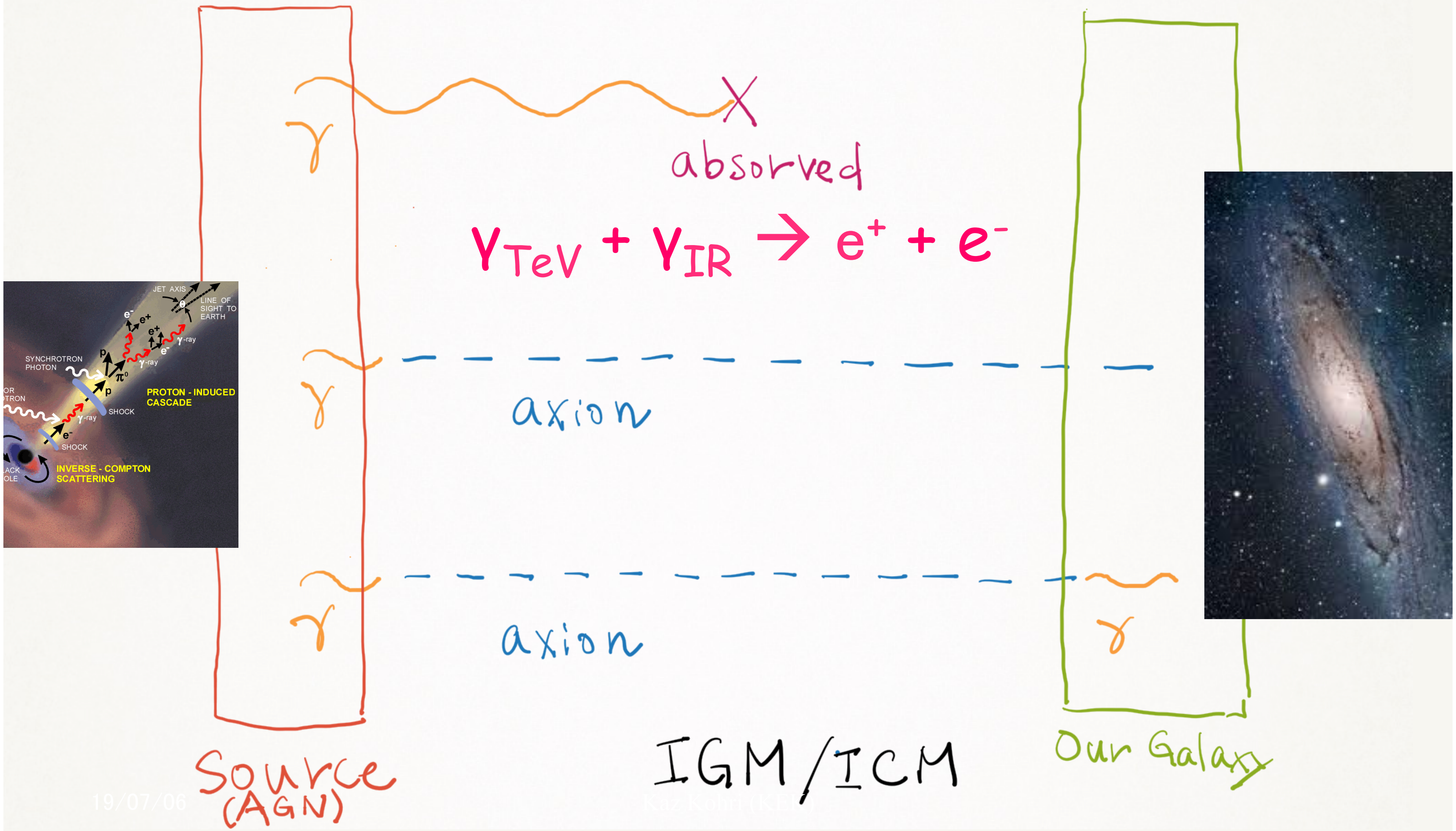
Gamma-ray horizon





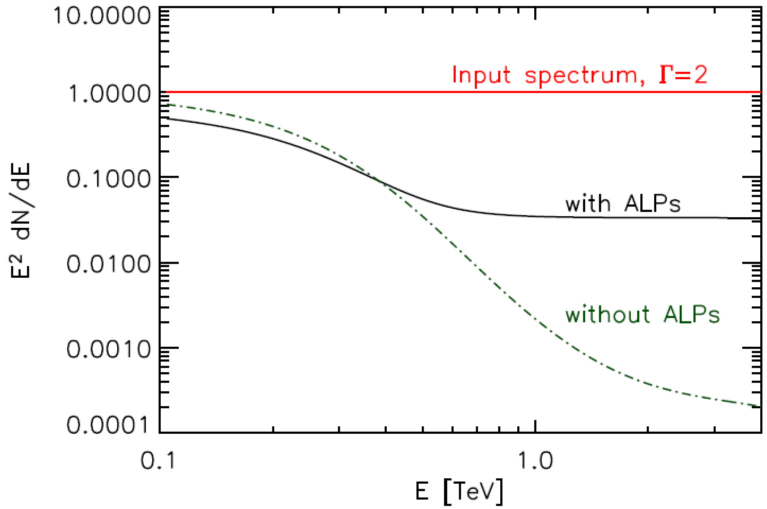
Kohri and Kodama, arXiv:2017.05189

γ (AGN) →axion (IGM)→γ (Milky-Way)



Spectrum reduction by axion mixing

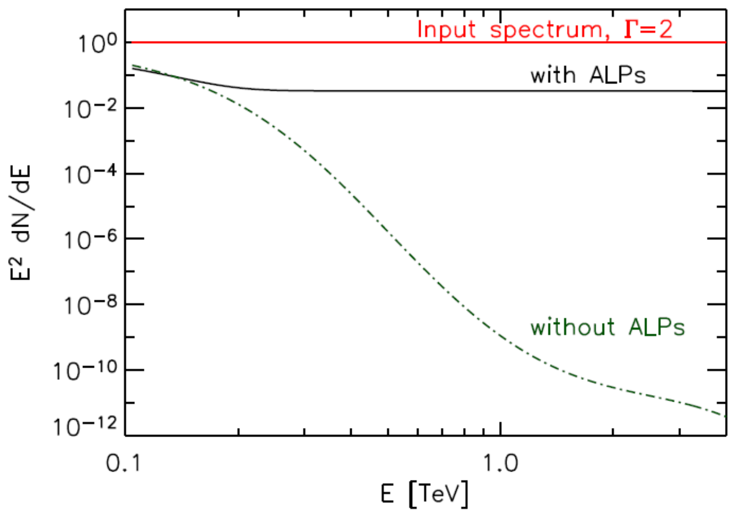
Shimet, Hooper, Serpico (08)



H 2356-309

z=0.165

r=610Mpc



1ES1101-232

z=0.186

r=680Mpc

We need axion or ALPs

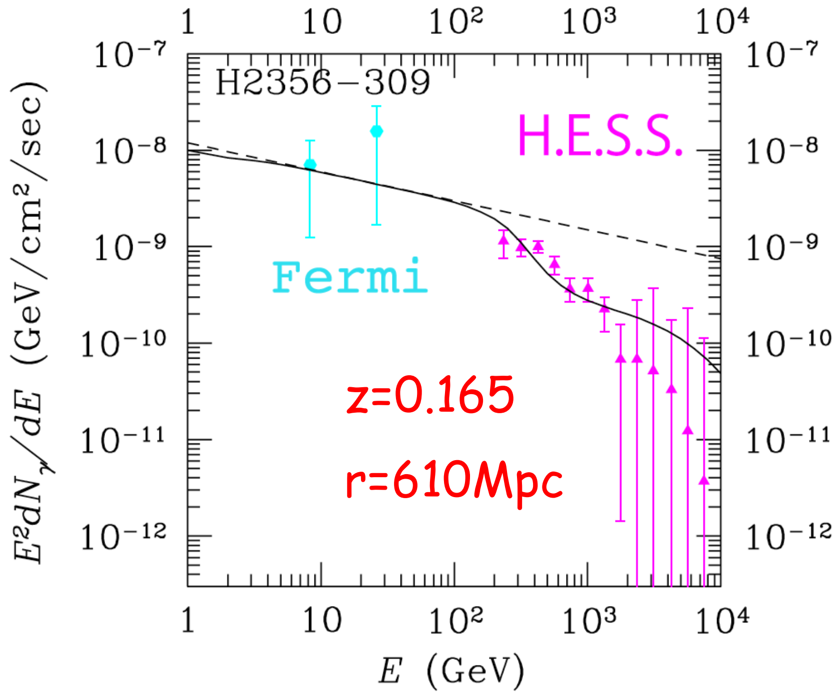


FIG. 3: Gamma-ray spectrum fitted to the data of H2356 309 (the redshift is $z = 0.165$ which gives the distance ~ 610 Mpc). Here, we adopted $g_{a\gamma} = 3.2 \times 10^{-11}\mathrm{GeV}^{-1}$ and $m_a = 3.2 \times 10^{-9}$ eV. The reduced χ^2 is estimated to be $\chi^2/\mathrm{d.o.f} = 1.1$, which is improved from the case without axion $\chi^2/\mathrm{d.o.f} = 2.2$. The fitted value of the photon index is $\Gamma_s = 2.3$. We followed

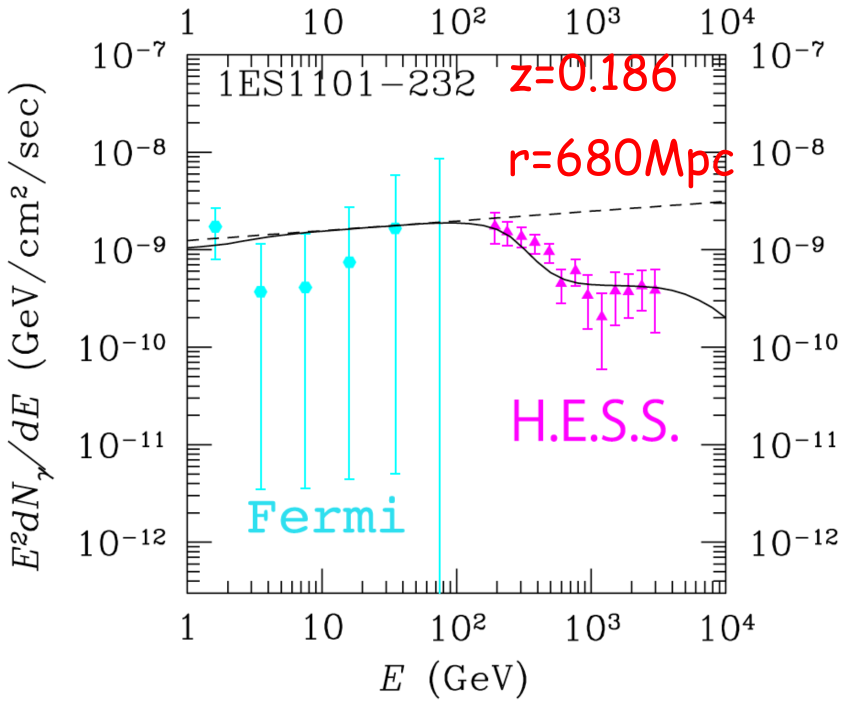
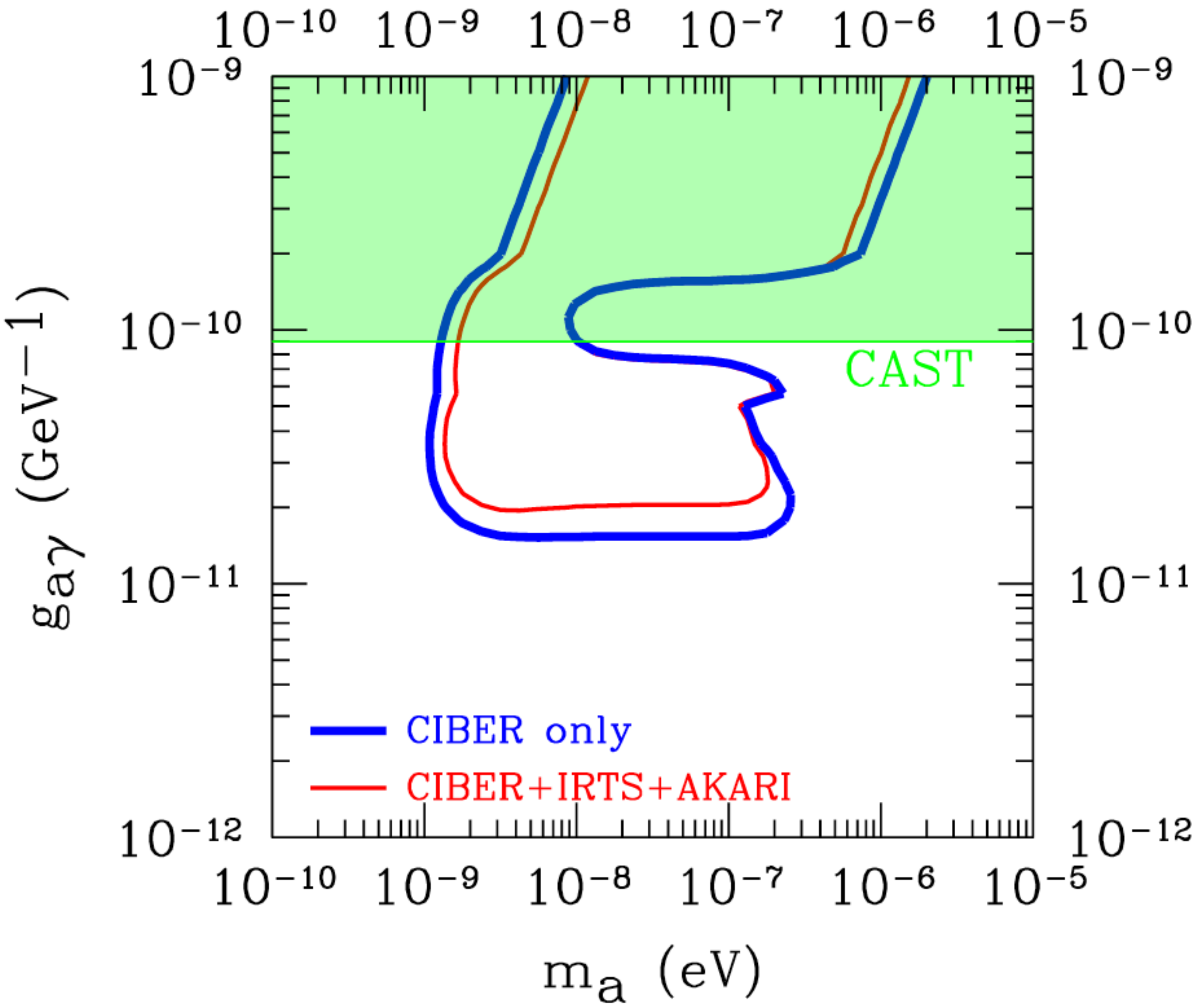


FIG. 4: Sames as Fig. 3, but for 1ES1101 232 (the redshift is $z = 0.186$ which gives the distance ~ 680 Mpc.). The reduced χ^2 is estimated to be $\chi^2/\mathrm{d.o.f} = 0.69$, which is improved from the case without axion $\chi^2/\mathrm{d.o.f} = 2.0$. The fitted value of the photon index is $\Gamma_s = 1.9$.

Kohri and Kodama, arXiv:2017.05189

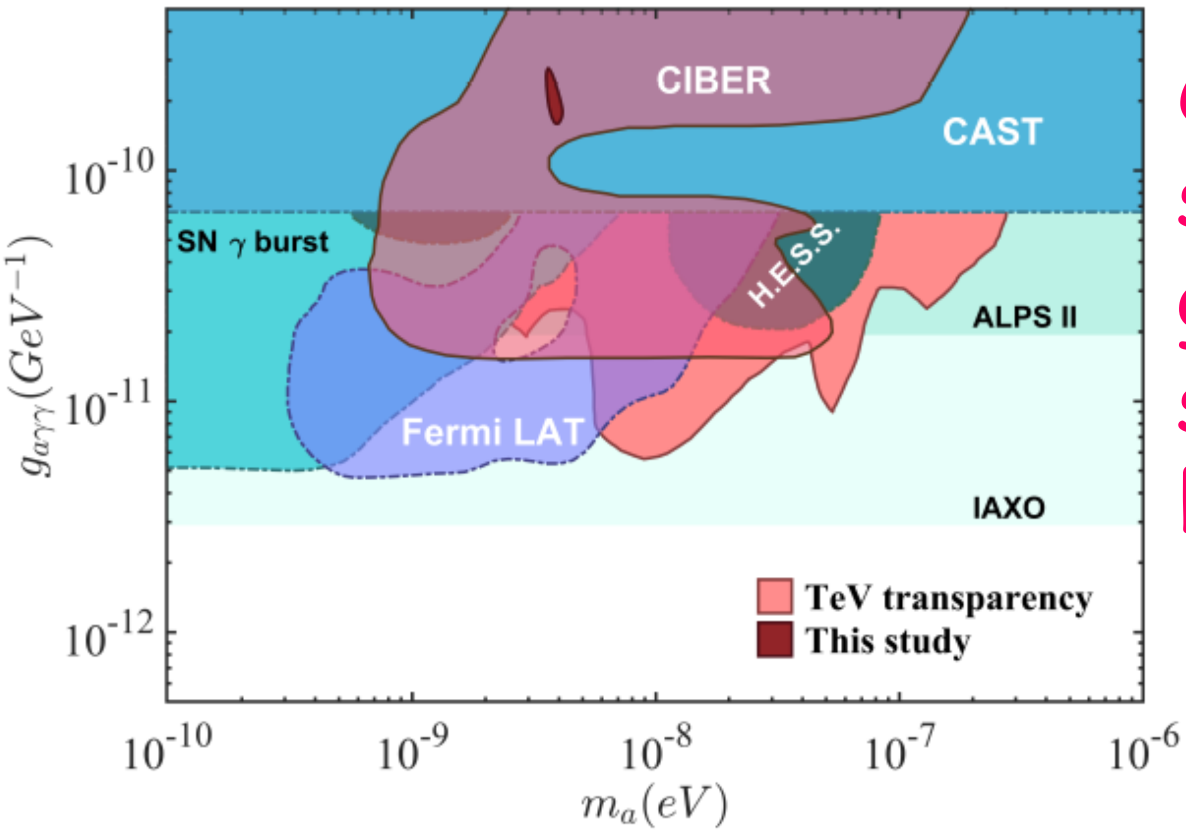
An axion solution



Kohri and Kodama, arXiv:2017.05189

Photon–axion mixing through gamma-ray emission from 6 galactic pulsars

Jhilik Majumdar, Francesca Calore, Dieter Horns, arXiv: 1801.08813 [hep–ph]



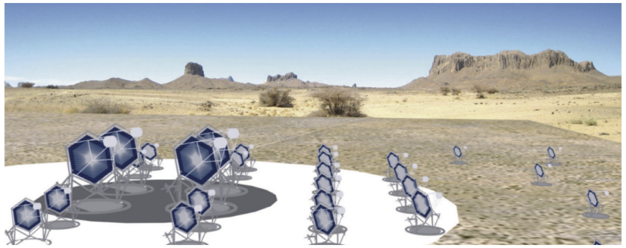
CTA should give us stronger bound

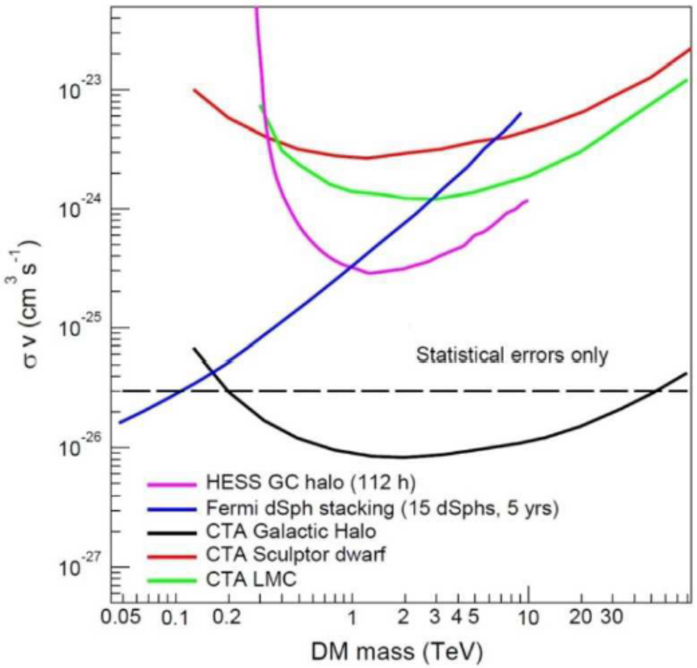
CIBER : Femi+HESS+CIBER, Kohri and Kodama (2017)

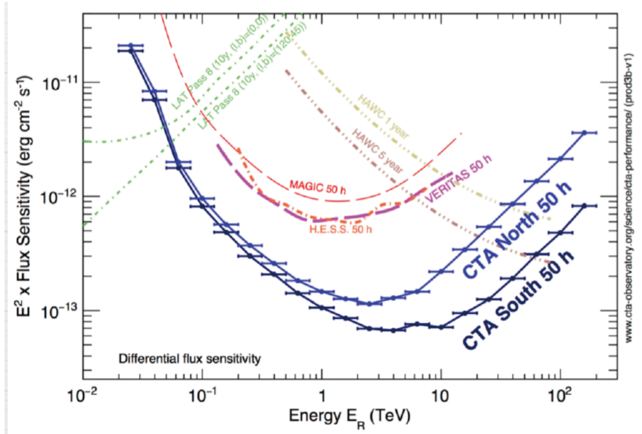
WIMP

Future TeV-gamma observation
Cherenkov Telescope Array (CTA)

One order of magnitude better sensitivity at TeV





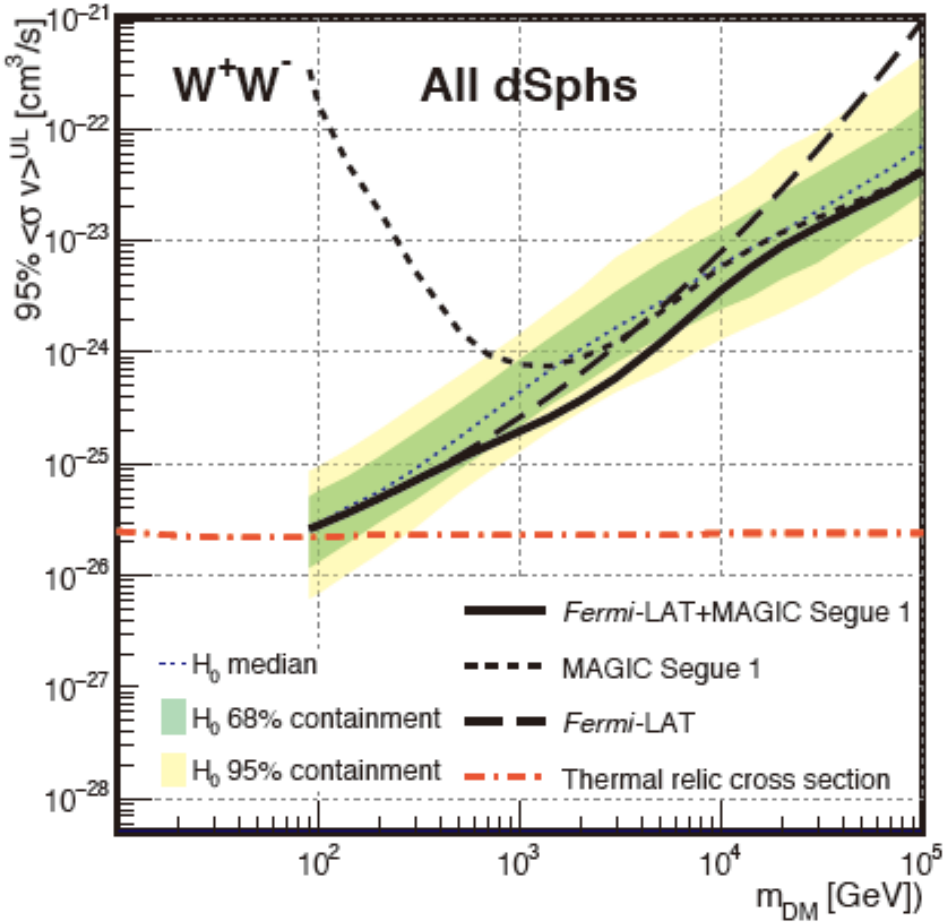


← Uncertainties at galactic center?

 (KEK)

Fermi bounds on annihilation into WW

M. L. Ahnen et al., MAGIC and Fermi-LAT Collaborations, arXiv:1601.06590 [astro-ph.HE]

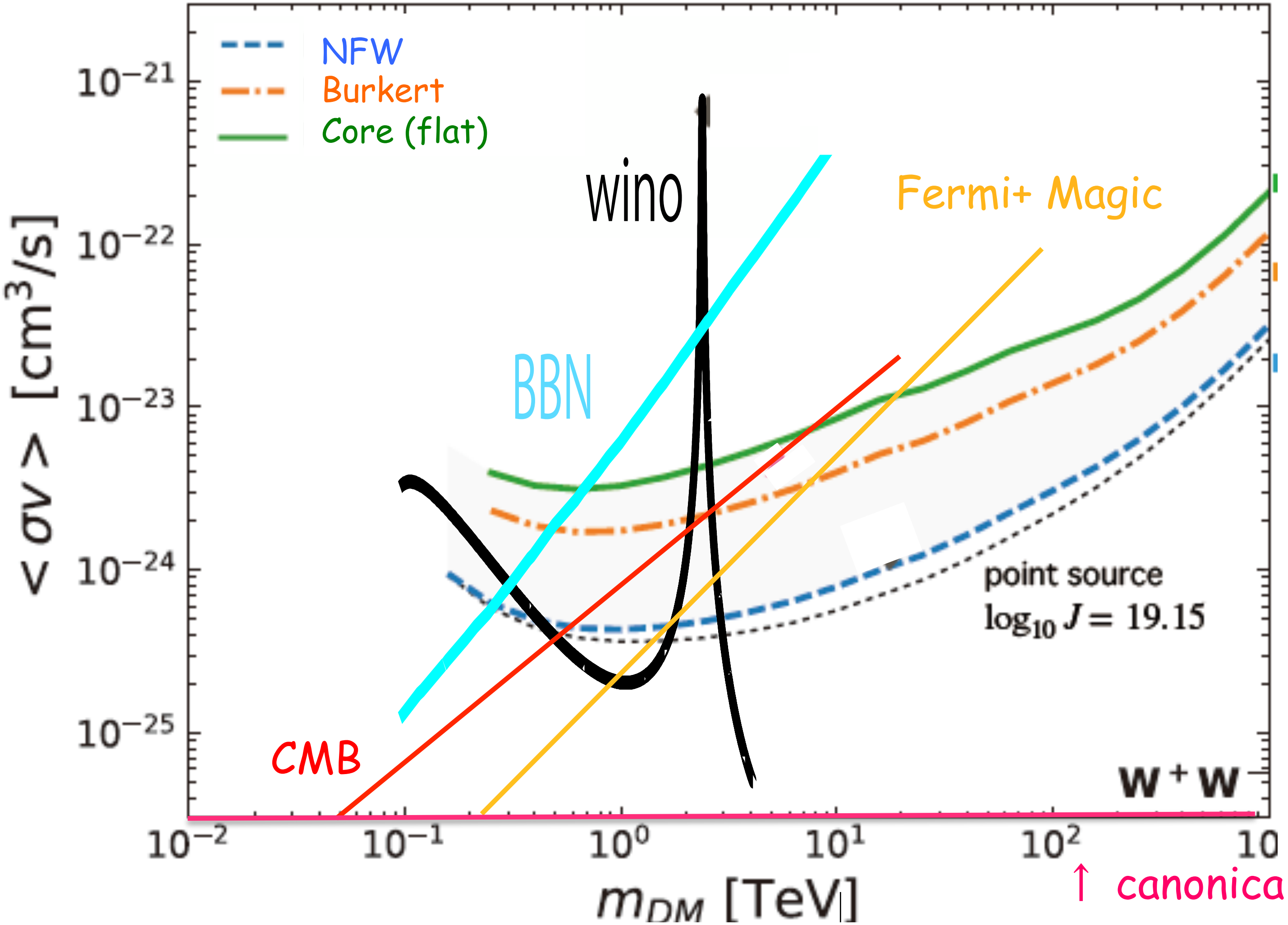


Point source or Diffusive source?

- However, Fermi observed each dwarf Spheroidal galaxy to be a point source in O(0.1°) x O(0.1°)
- CTA can resolve the spatial structure much better in future, e.g., in 0.03° x 0.03°
- The limit should have been stronger by measuring it to be a point source

Future limits on cross section by Draco dwarf spheroidal with some density profiles

N.Hiroshima, M.Hayashida, and KK, arXiv:1905.12940 [astro-ph.HE]



Big uncertainties due to a variety of density profiles

Should we stick to canonical σ?

$\sigma > \sigma_{\text{canonical}}$

- Such a smaller relic density can be replaced by non-thermally-produced DM e.g, by massive-decaying particles (moduli, gravitino, ...)

$\sigma < \sigma_{\text{canonical}}$

- Such a larger relic density can be diluted by entropy production e.g, by massive-decaying particles (moduli, gravitino, ...)

We may allow even a decaying DM with lifetime of > 10^{26} sec through another interactions or a parity violation (e.g., R-parity violation in SUSY)

Summary

- PBHs can be dark matter, which is related with inflation
- We need axion-like particle with its mass of O(1) – O(10^2) neV and a coupling with photon to be $g_{a\gamma\gamma} = O(10^{-11})$ GeV^{-1} to agree with both IR (CIBER) and gamma-ray (HESS &Fermi) observations
- CTA can resolve the spatial structure of dwarf spheroidal to constrain WIMP dark matter for the first time. Then, we definitely need information for density profiles of dSphs