Where do cosmic rays go to die?

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Nomenclature

- "CR" = cosmic ray (proton)
- "CGM" = circumgalactic medium = "halo gas"
- "MW" = Milky Way

We know cosmic rays leak out of star-forming galaxies

- In the Milky Way: B/C and other measures => spallation grammage is far below the hadronic destruction depth
- Measured gamma-ray luminosities of Milky Way and nearby galaxies show they are not hadronic calorimeters
- The gamma-ray budget of the the universe (informed by the isotropic gamma-ray background) cannot accommodate most star-forming galaxies being calorimeters

So what happens to the CRs that escape into the CGM?

Some hints about CRs in the CGM

- Extended gamma-ray emission around M31 (Andromeda) out to $\lesssim$200 kpc impact parameter has been claimed (e.g., Karwin et al.); $u_c(r)$ in Milky Way from, e.g., GalProp (see Yang+2016)

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- Detailed CGM modelling informed by X-ray emission and UV absorption lines points to need for a "non-thermal" pressure component in MW and other galaxy CGMs (e.g., Faerman+2017)

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- CGM CRs cannot easily escape the CGM unless they diffuse very fast, $D \gtrsim 10^{30}$ cm^2 s^{-1}

How does nature compromise?

- CRs in the CGM must achieve some delicate balance between accumulation, energy loss to streaming, energy loss to pp, and escape.

- Where the balance sits is determined by the diffusion coefficient ***D, but we don't know what that is***.

- IDEA: instantiate a transport model parameterised by ***D*** and scan across that parameter.

- Check empirical constraints for that ***D***.

Transport equation

$$\frac{\partial u_{\rm c}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_{\rm c}}{\partial r}\right] - \frac{u_{\rm c}}{t_{\rm pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_{\rm c}}{\partial r}\right|$$

Diffusion term

Hadronic collisional losses

Streaming losses

Boundary conditions

- Inner:

$$M_{\rm h}(z) \rightarrow M_{\star}(z) \rightarrow {\rm SFR}$$

$$\epsilon_c \equiv 10^{50}\ {\rm erg}/(90\ M_{\odot})$$

$$\dot{E}_{\rm c,inj}(z) = (1 - f_{\rm cal})\ \epsilon_c\ {\rm SFR}(z)$$

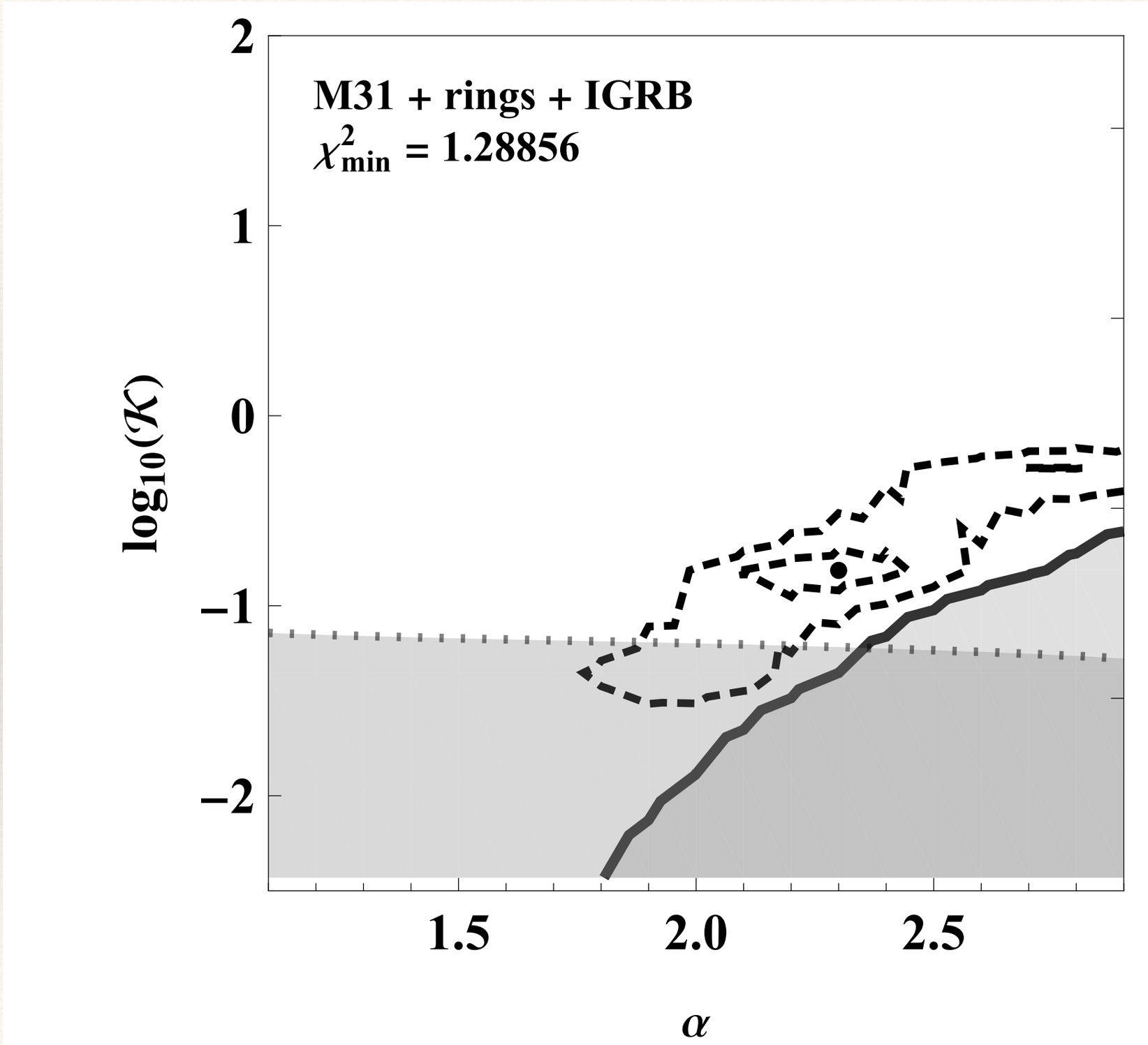
- Outer:

Trapping (virial shock) or free escape

(*I will show results for free escape*)

Results

Parameter space scan



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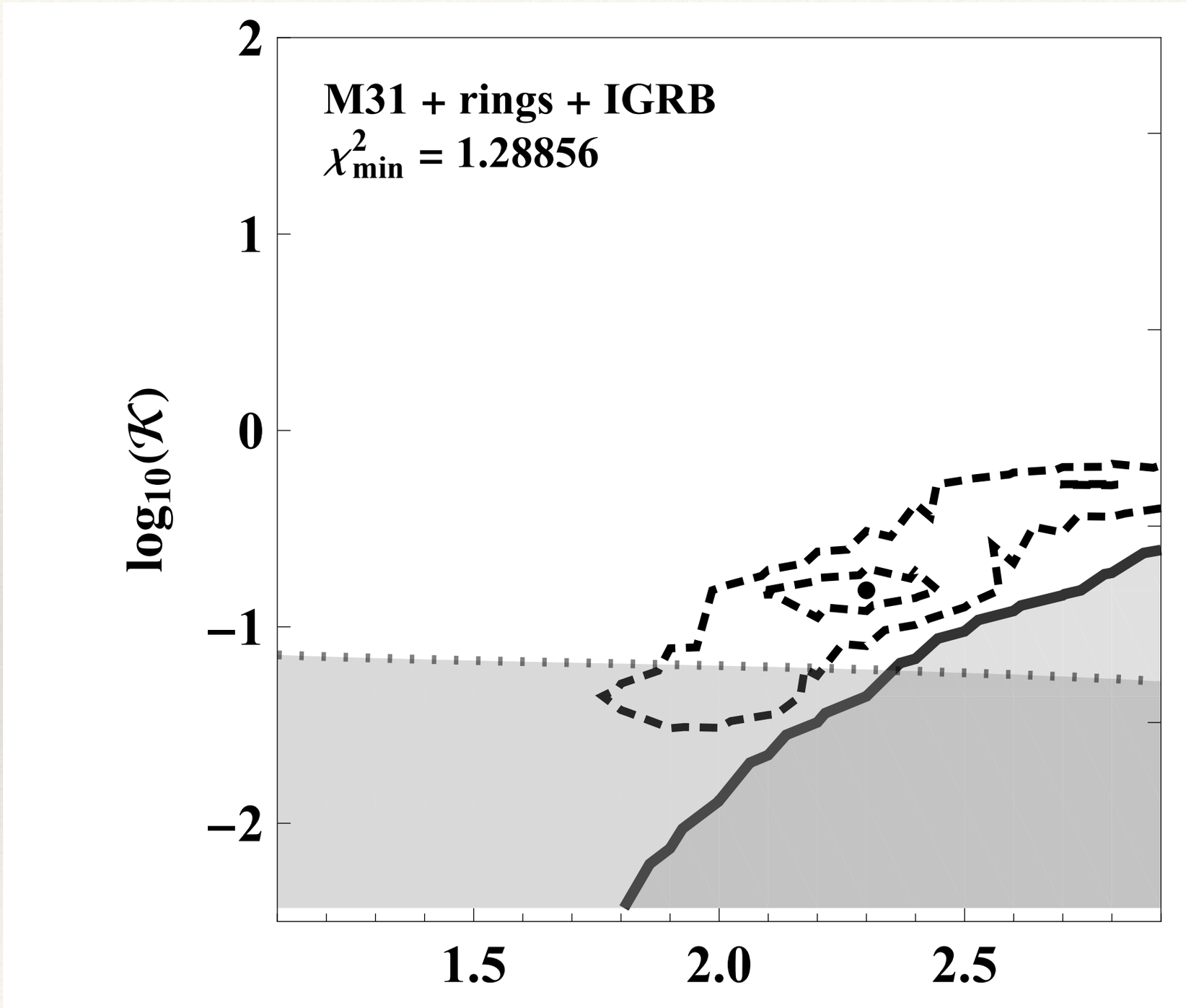
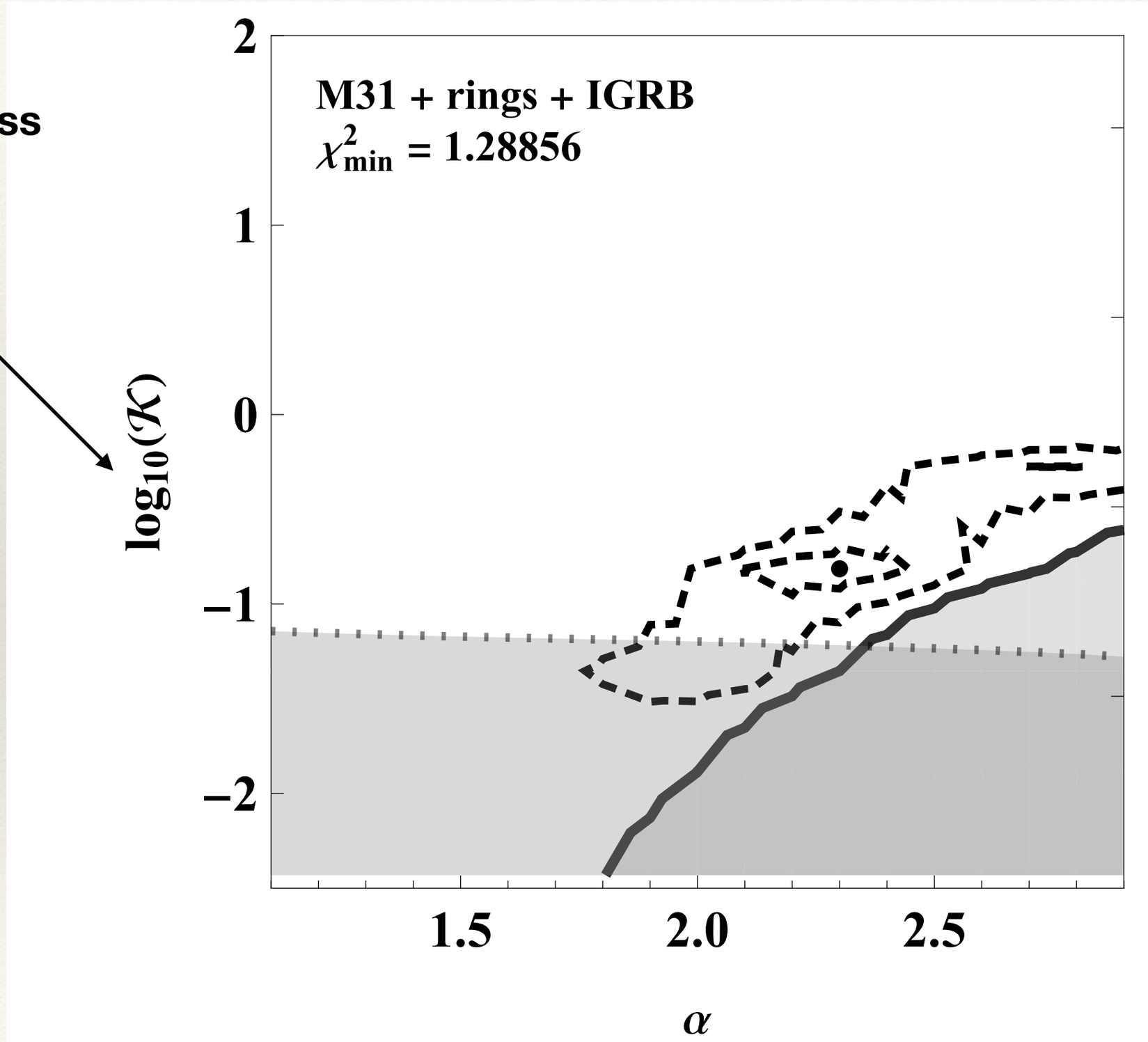


CGM gas density profile (also poorly known)

Parameter space scan



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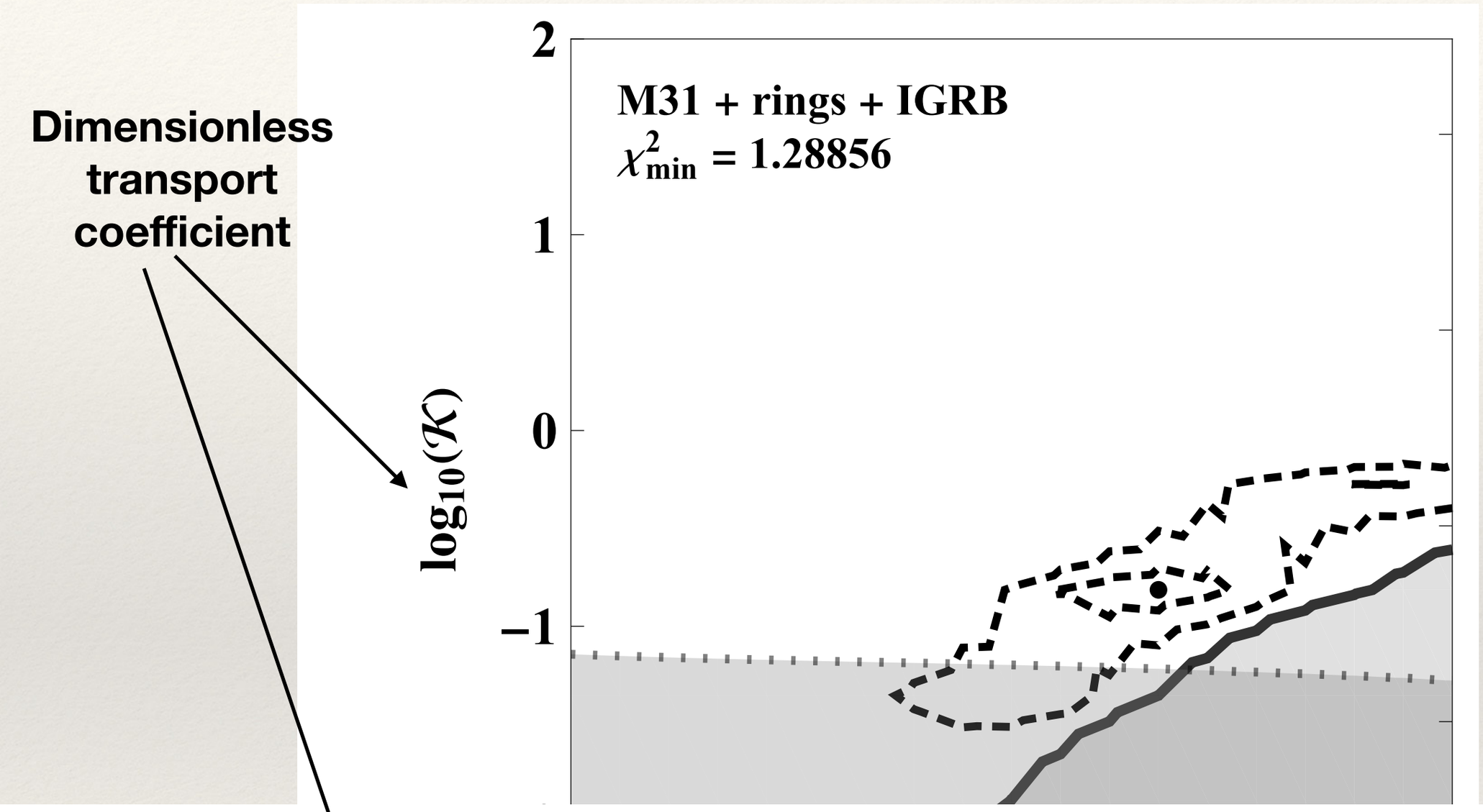

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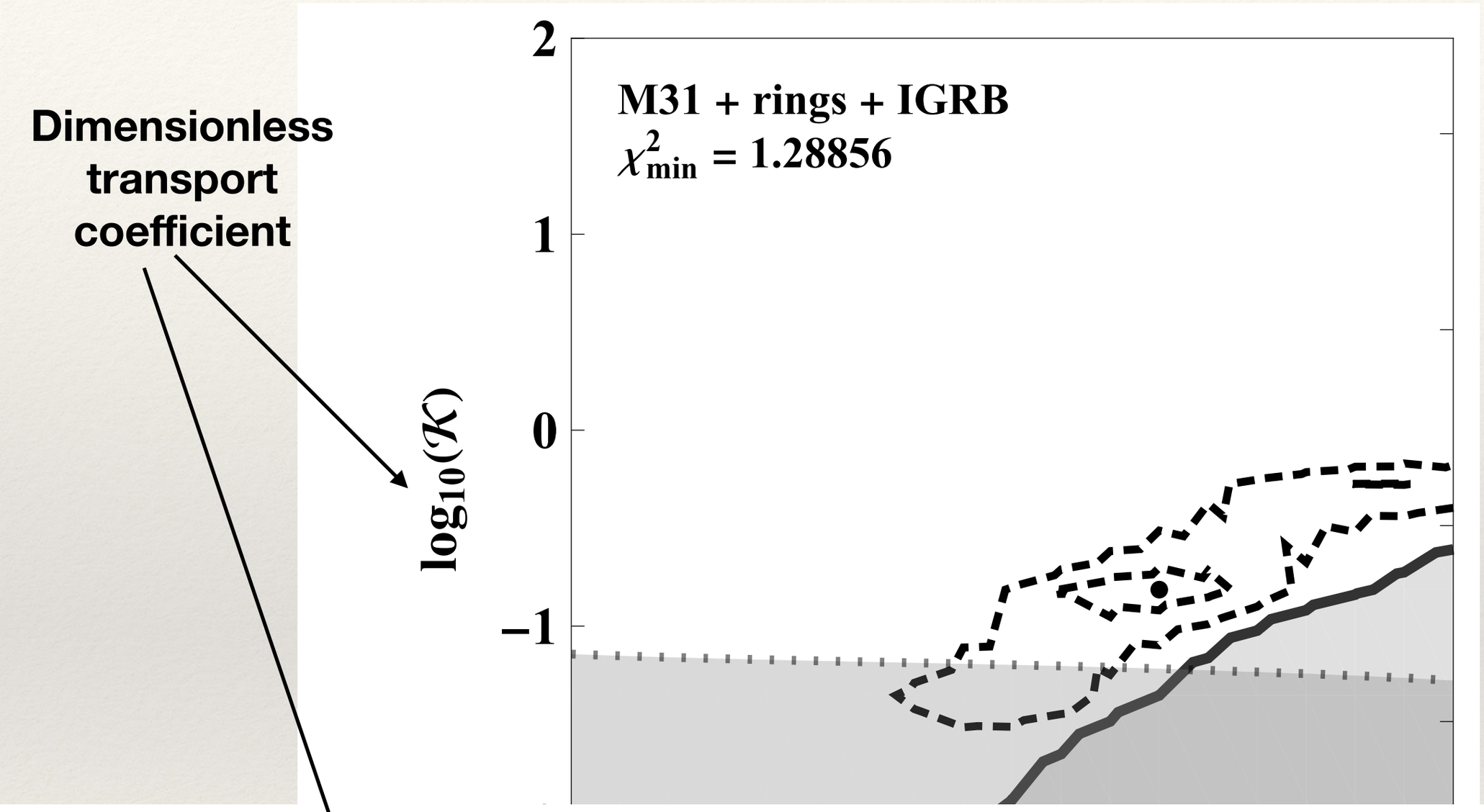

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virial radius ✖ sound speed

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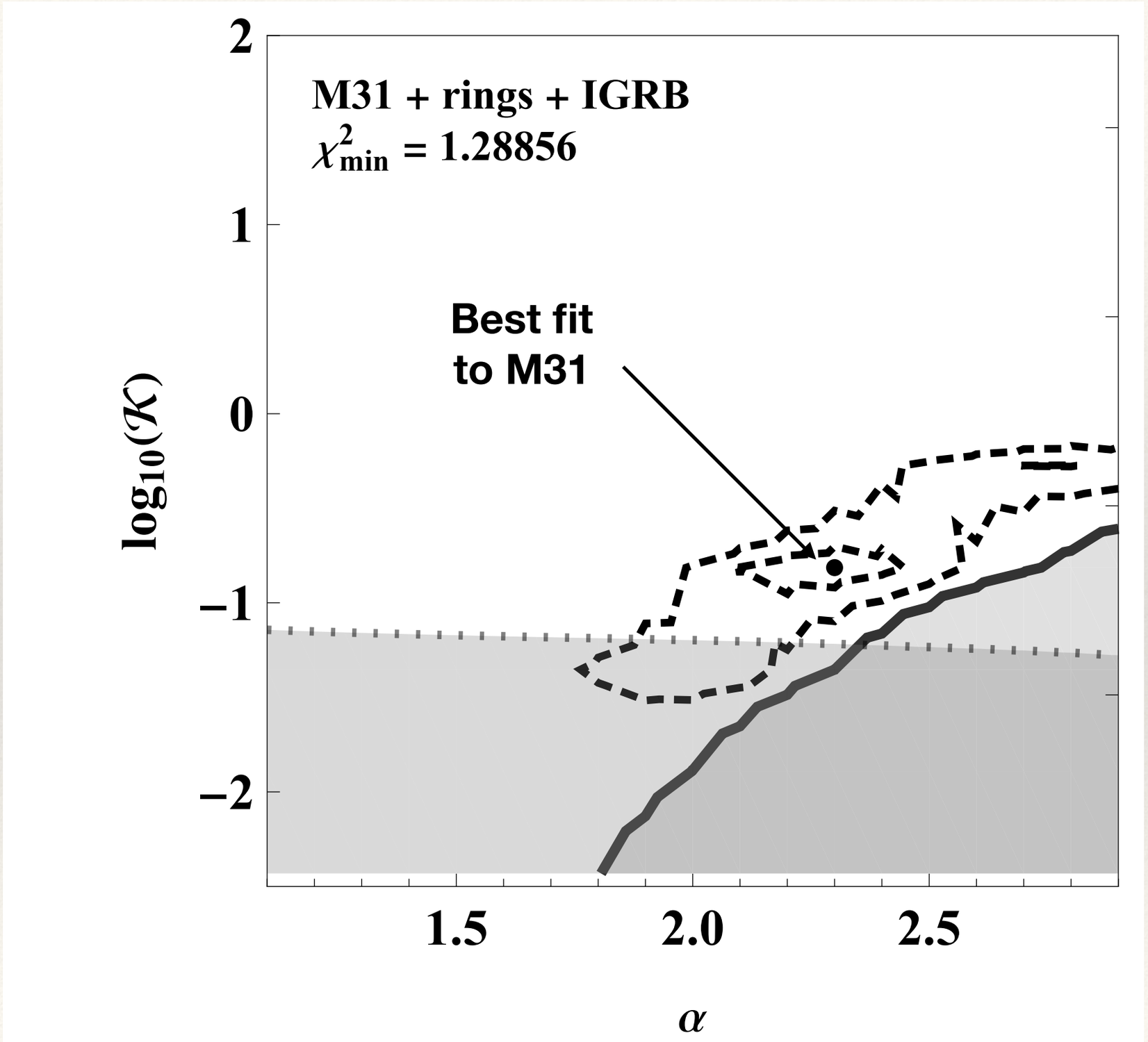

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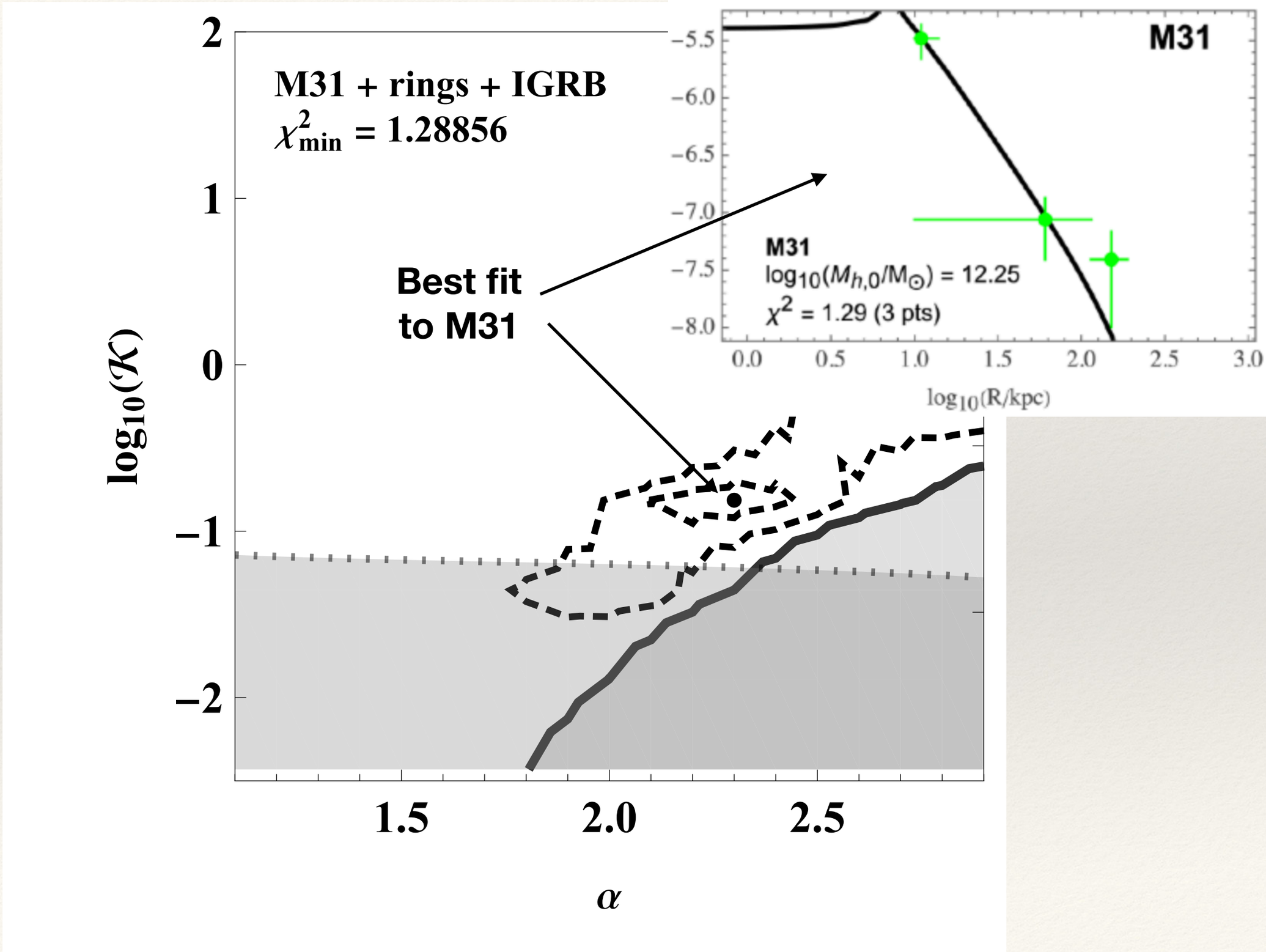

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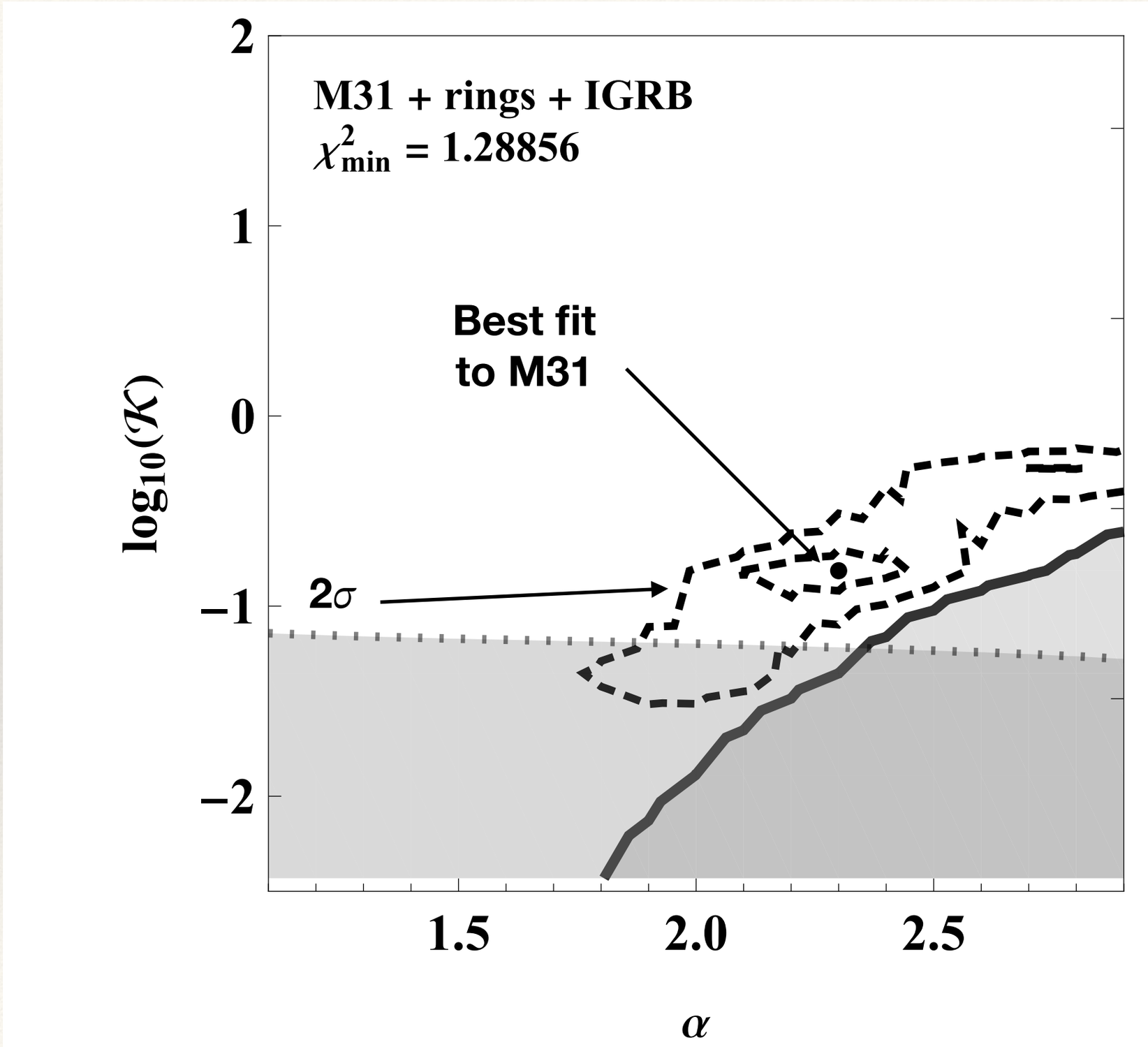

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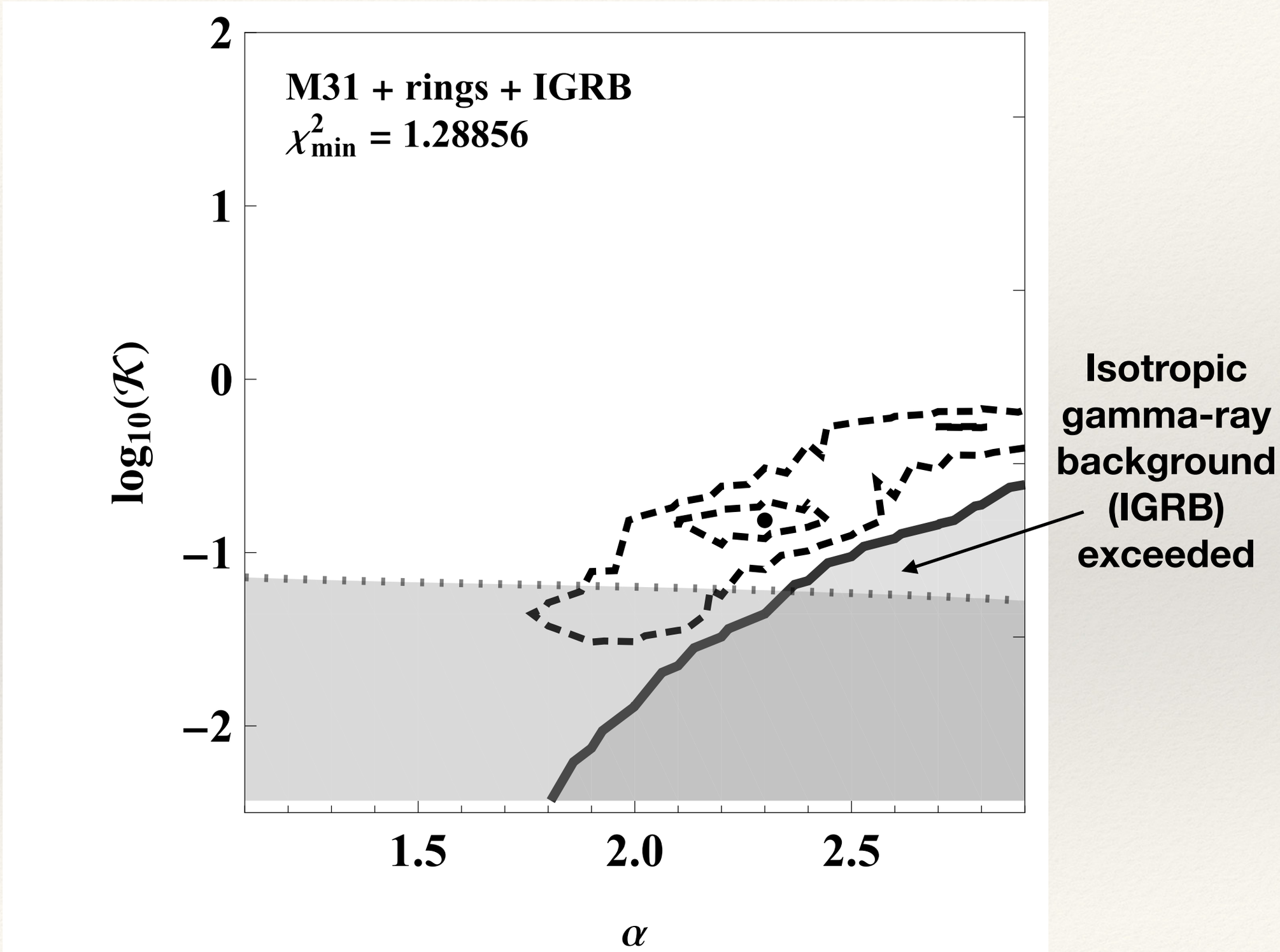

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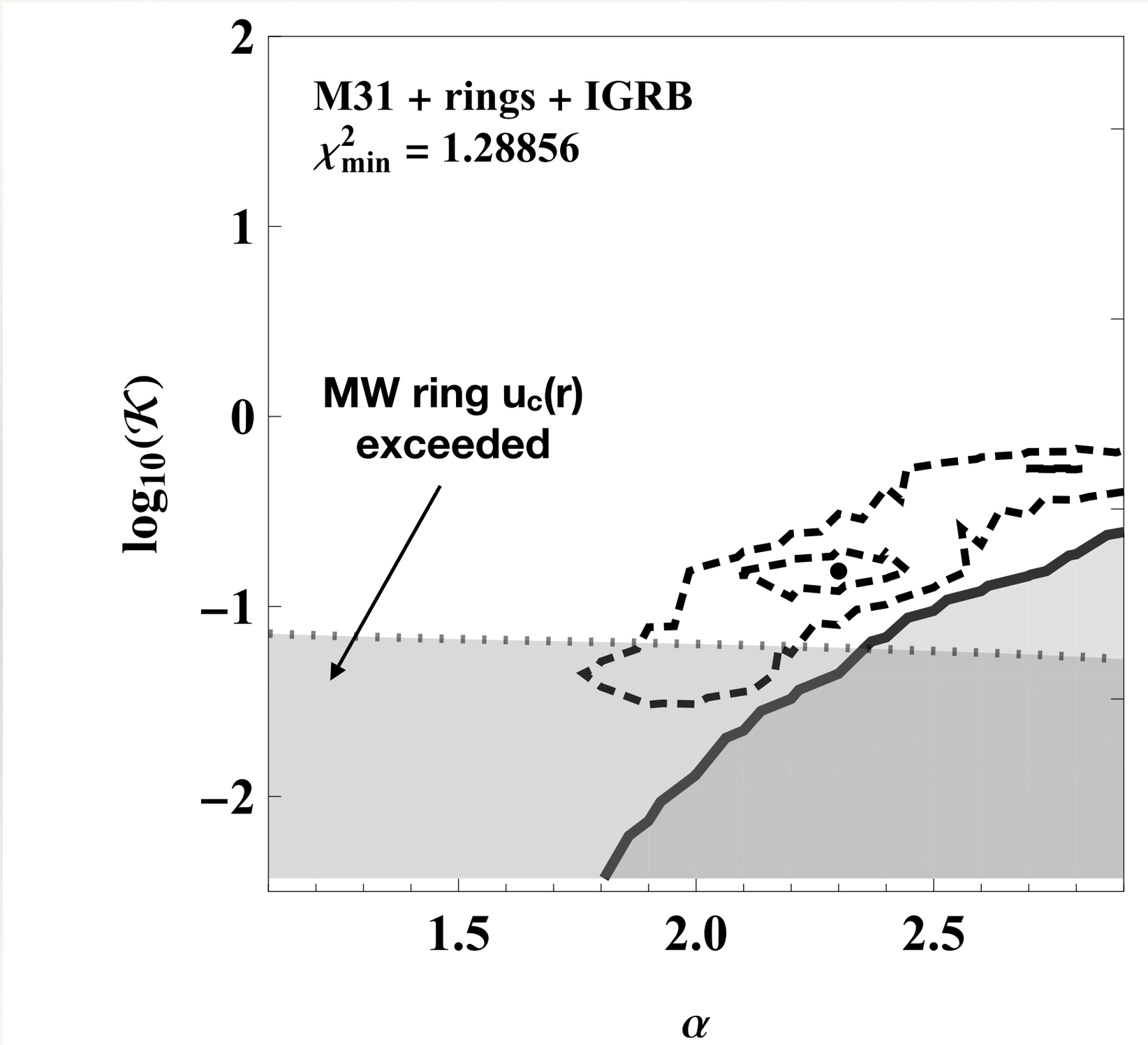

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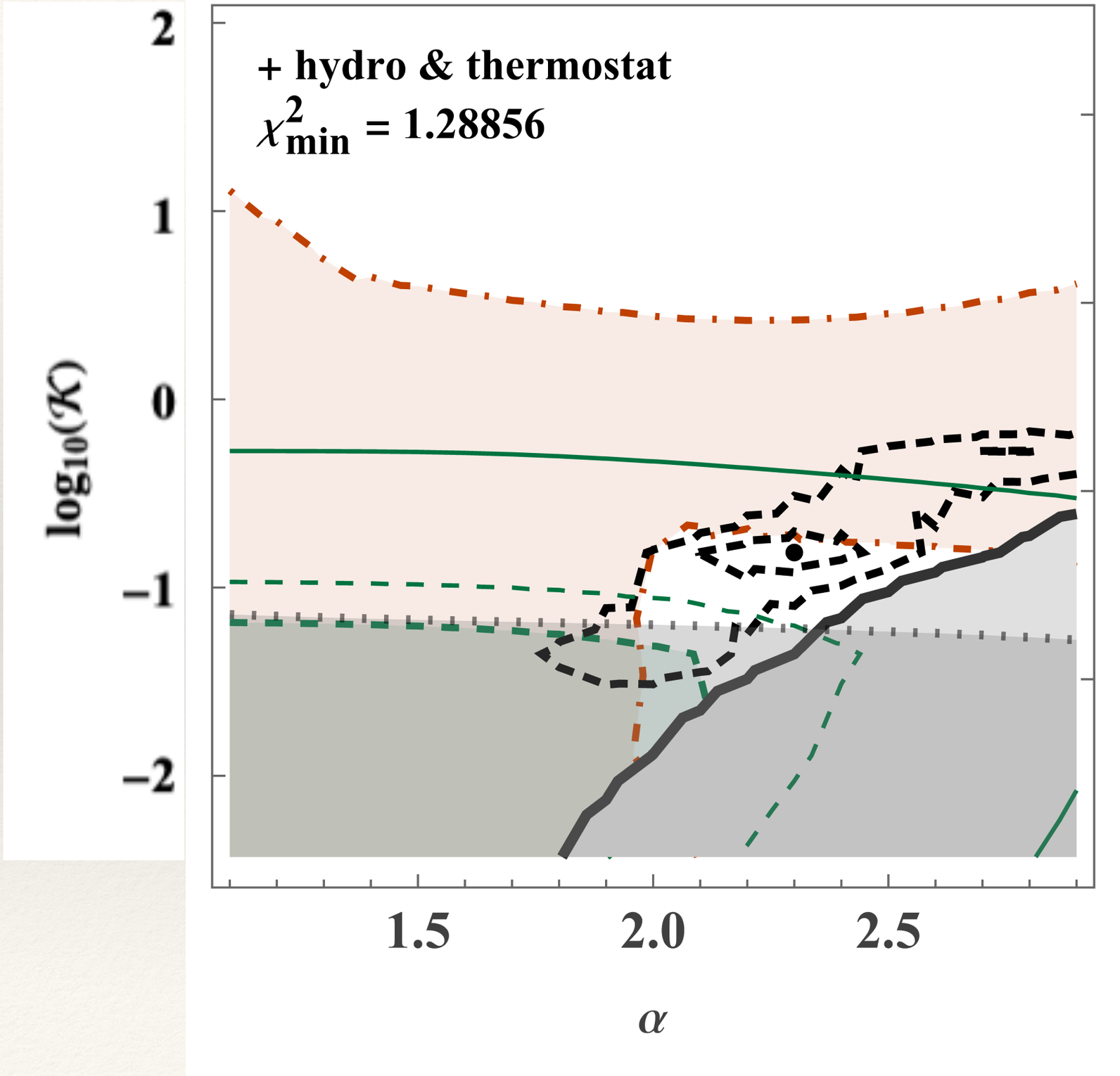

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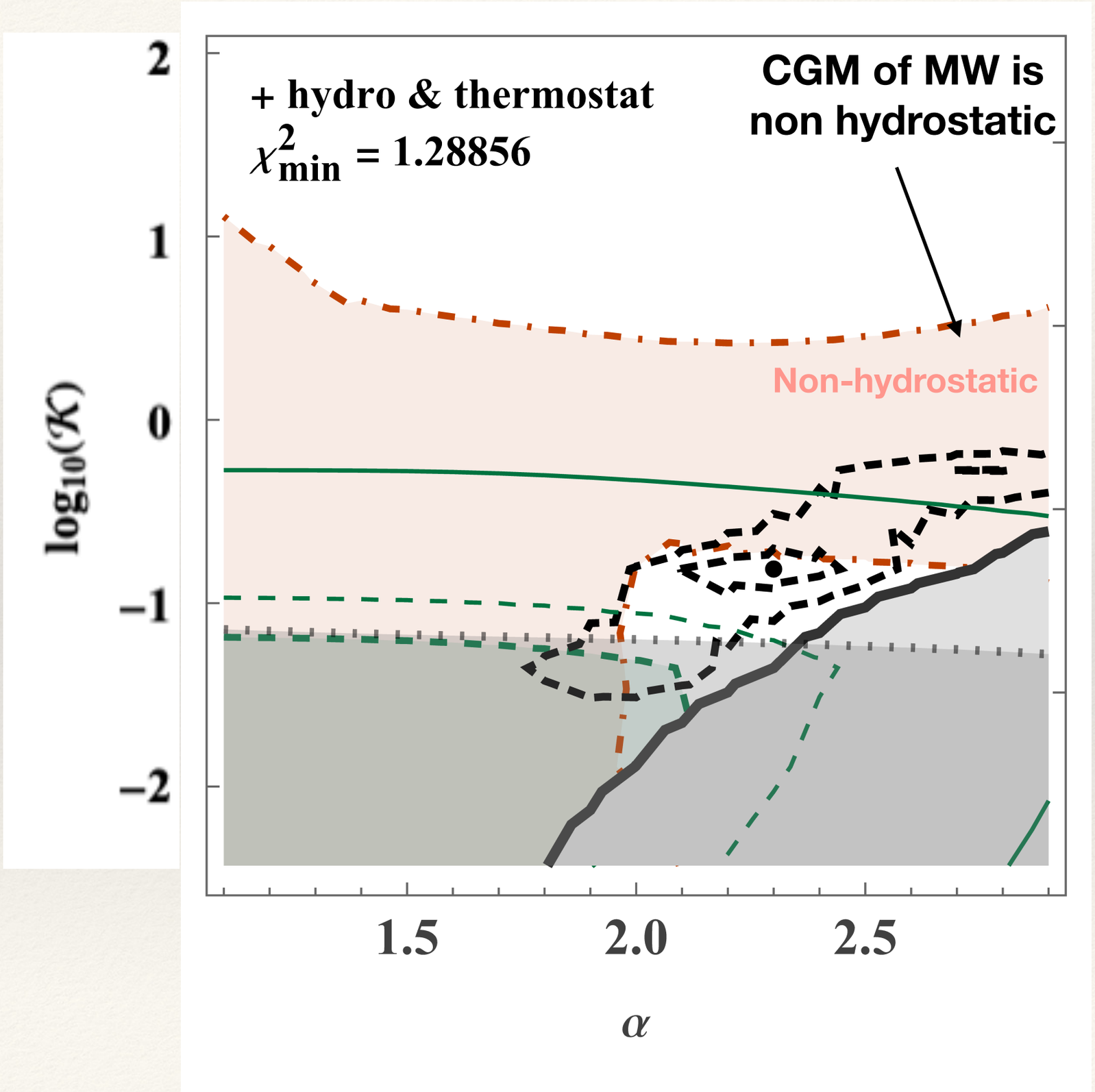

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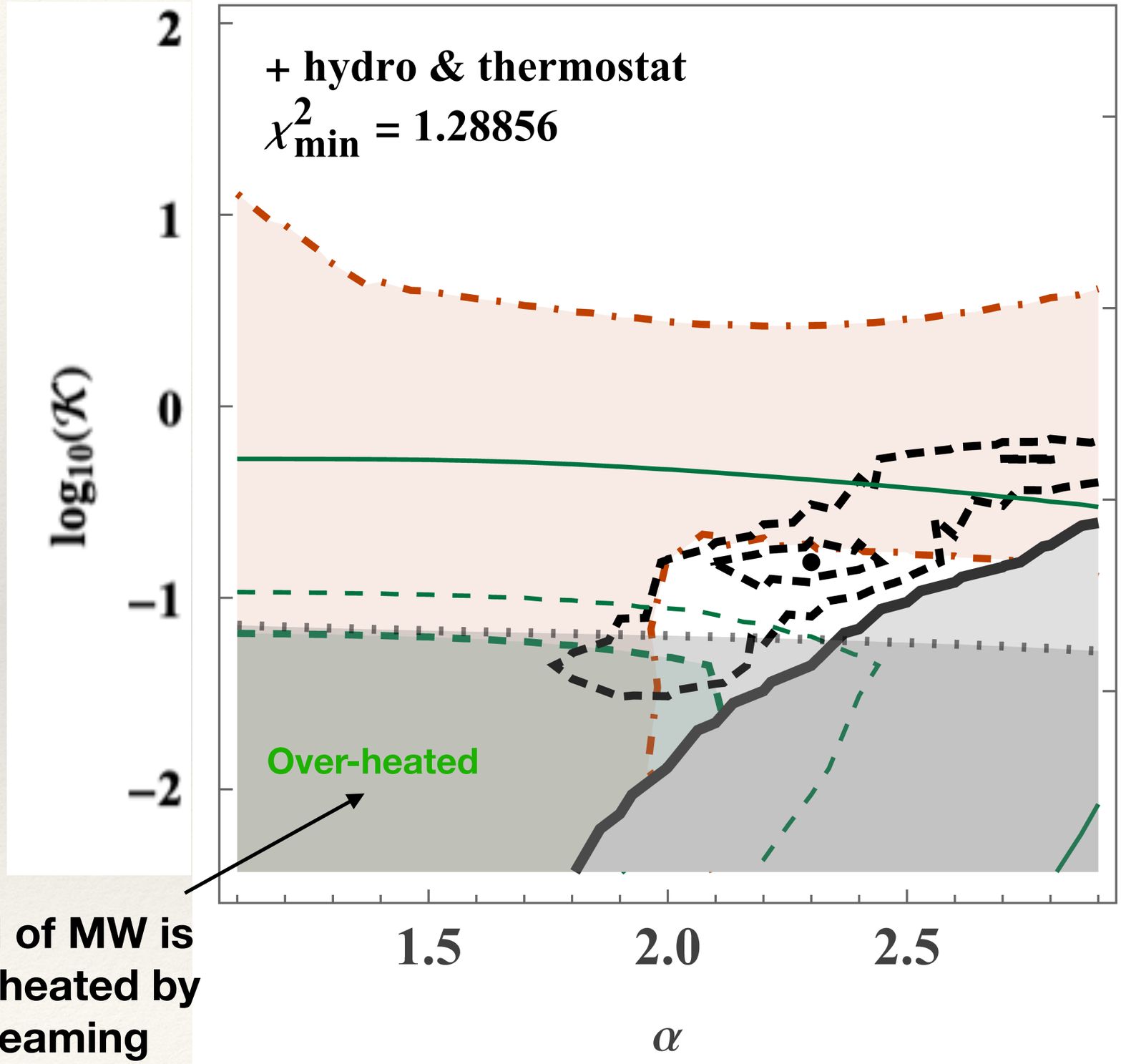

CGM of MW is over-heated by streaming

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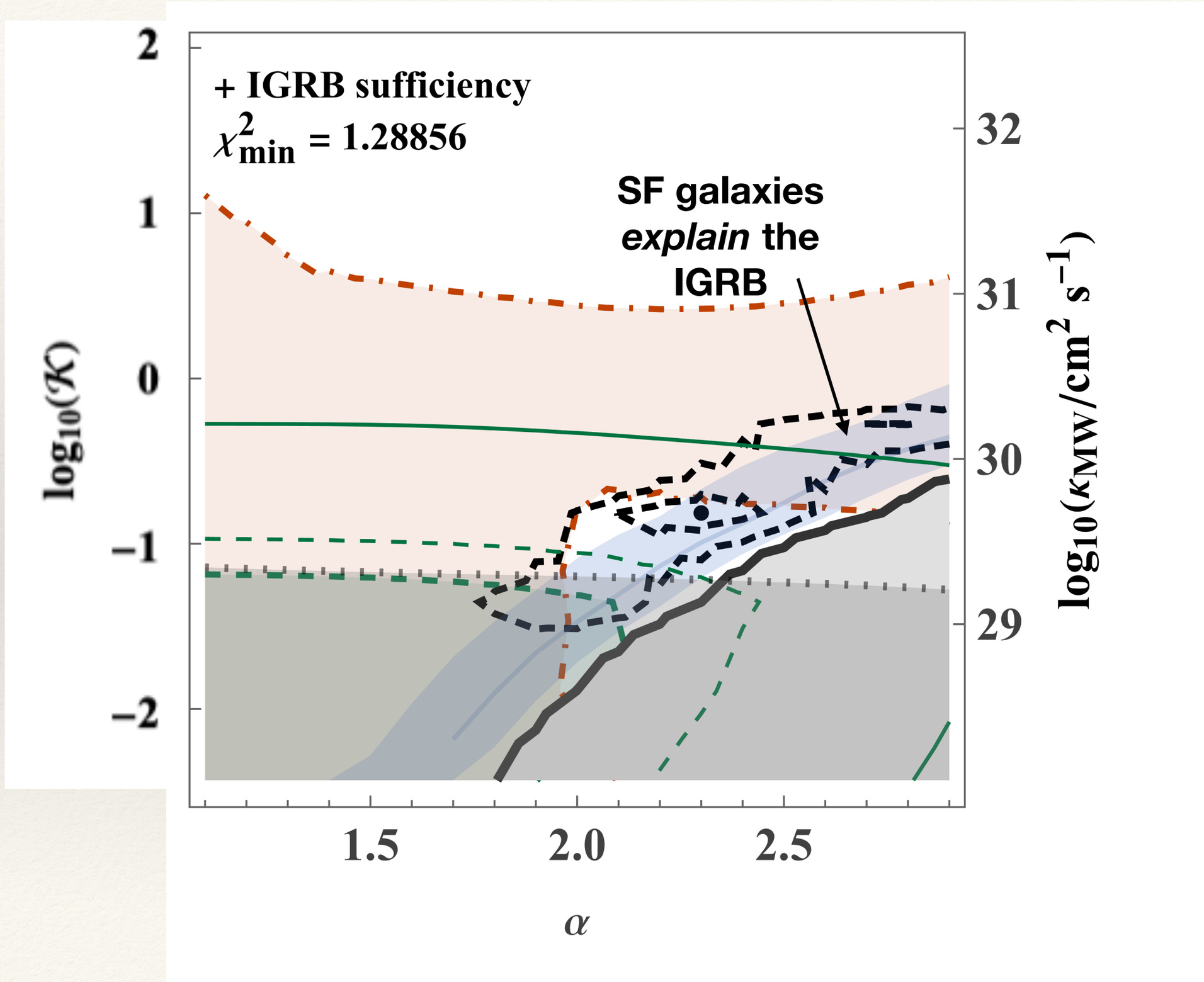

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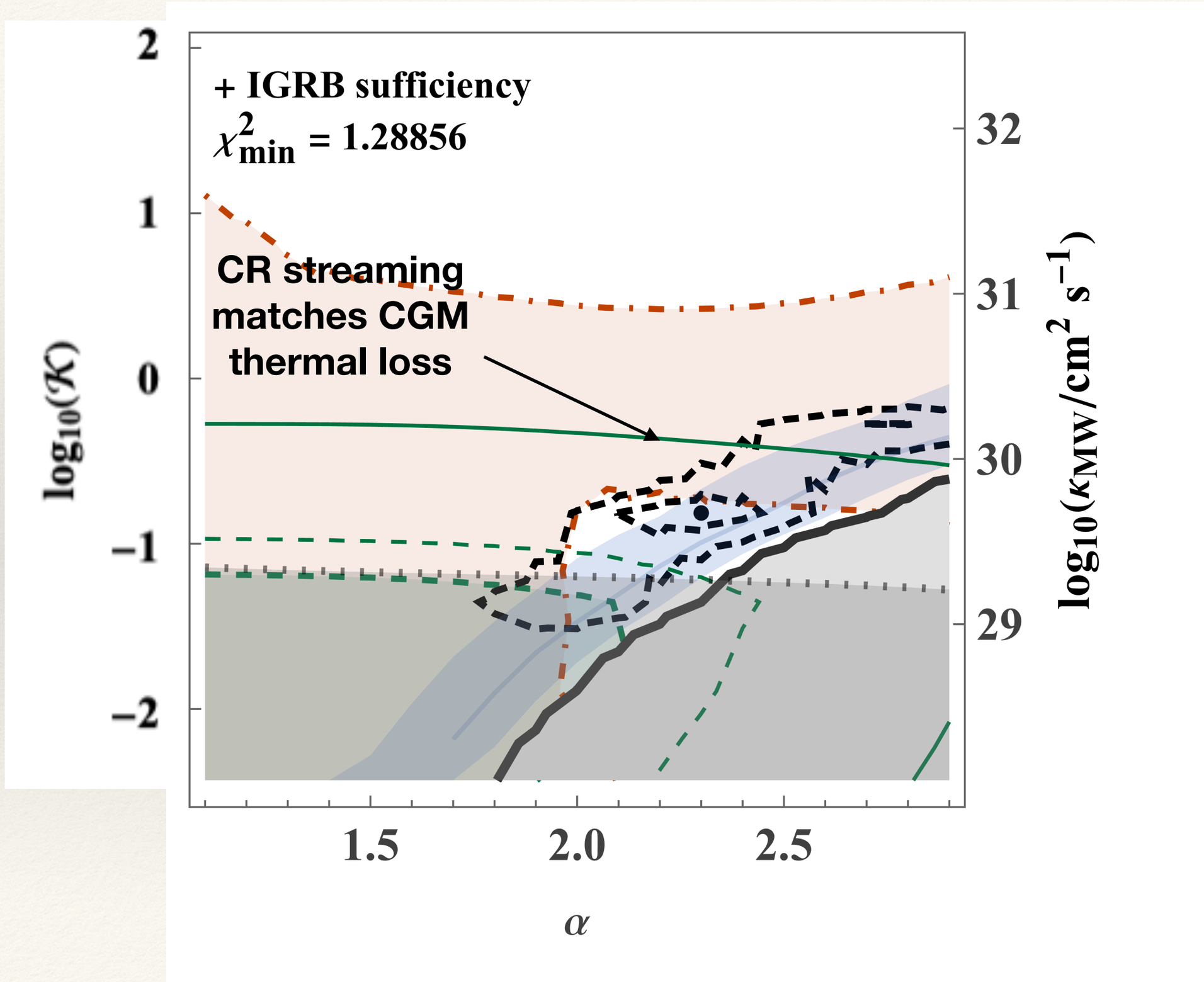

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- CR streaming can maintain temperature of MW-like haloes

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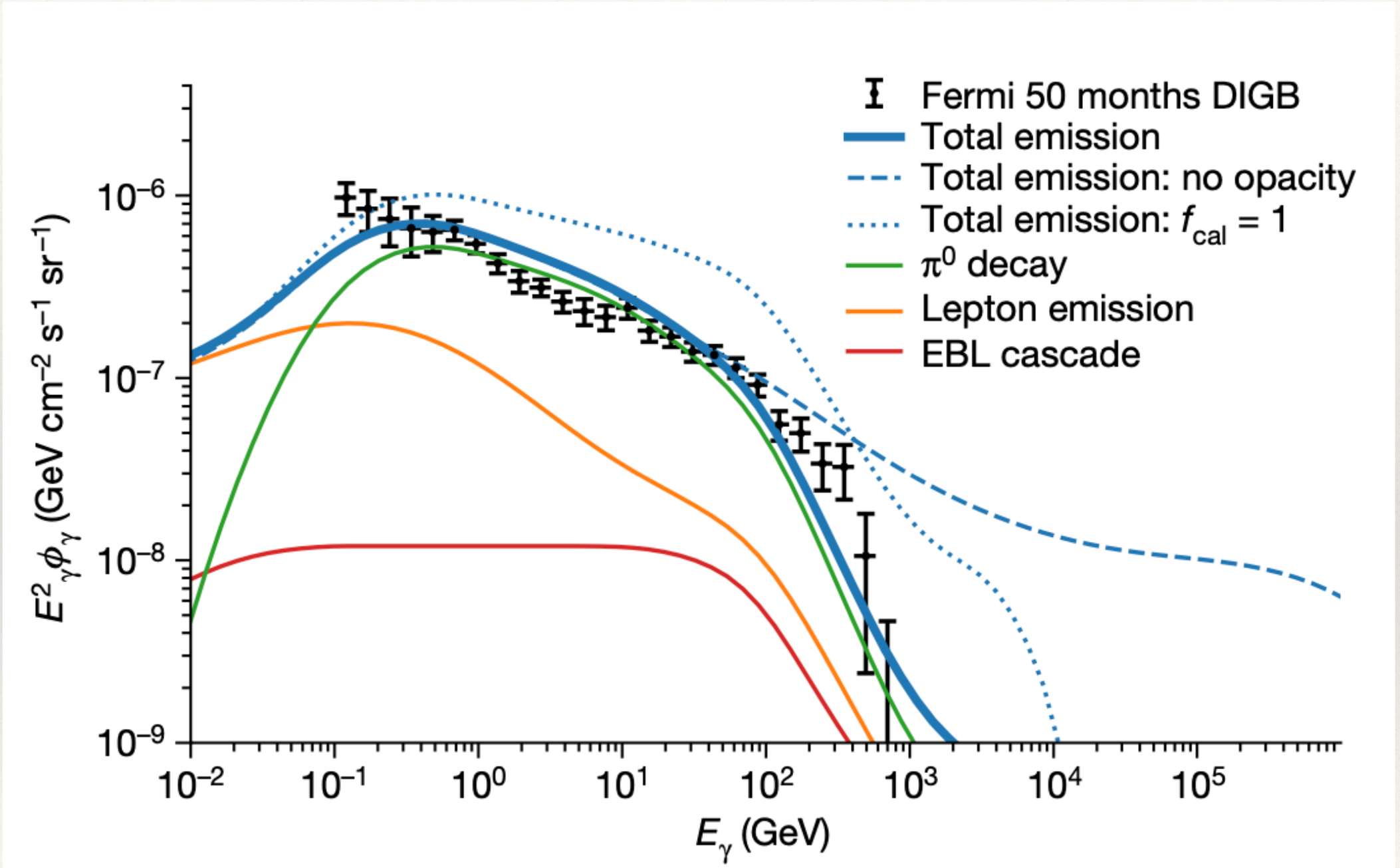
- SF galaxies generate the IGRB including a non-negligible MW CGM contribution 15% with 5% from external CGMs

Extra slides

CONGRuENTS applied to all SF galaxies through cosmic time (CANDELS survey)



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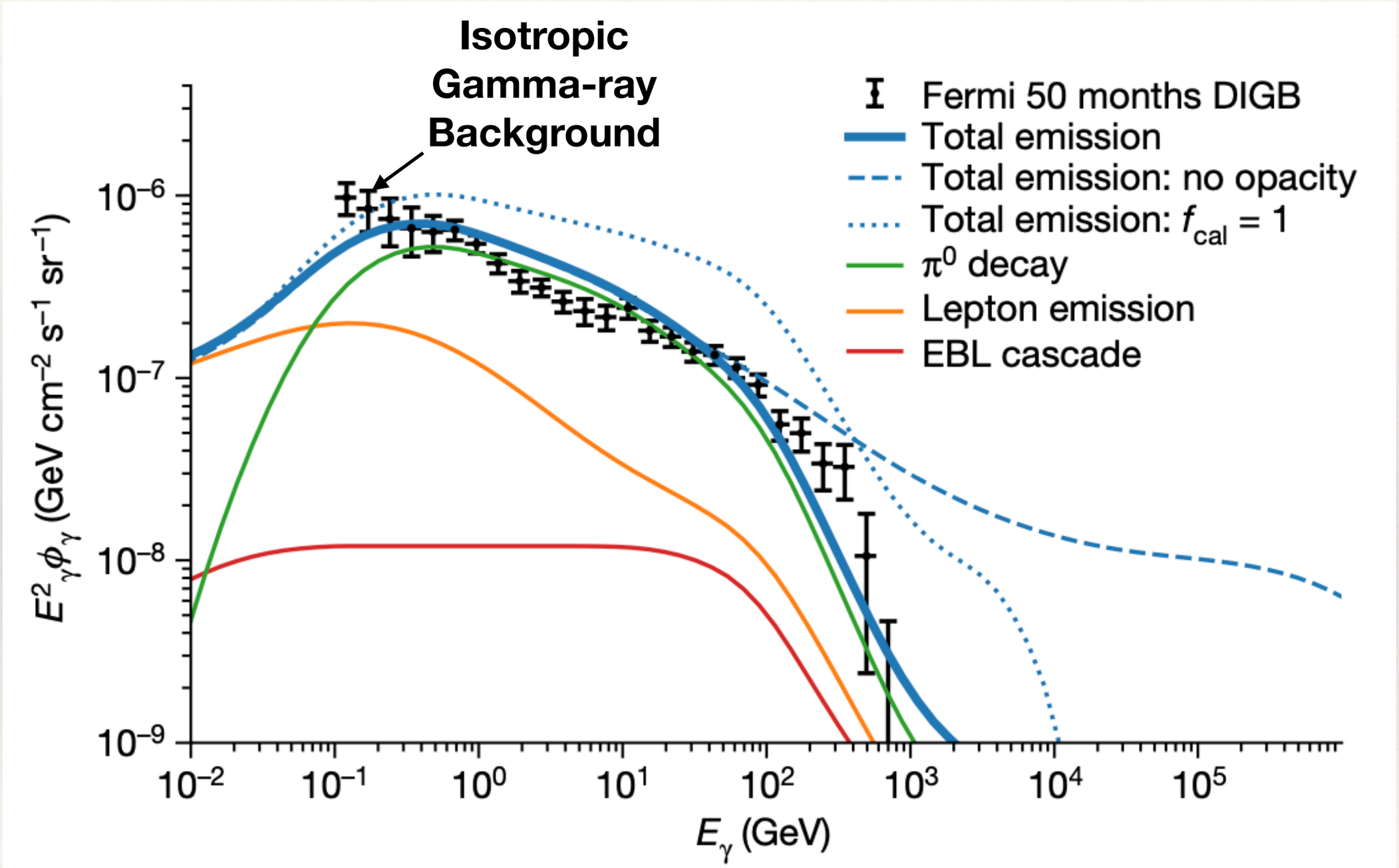

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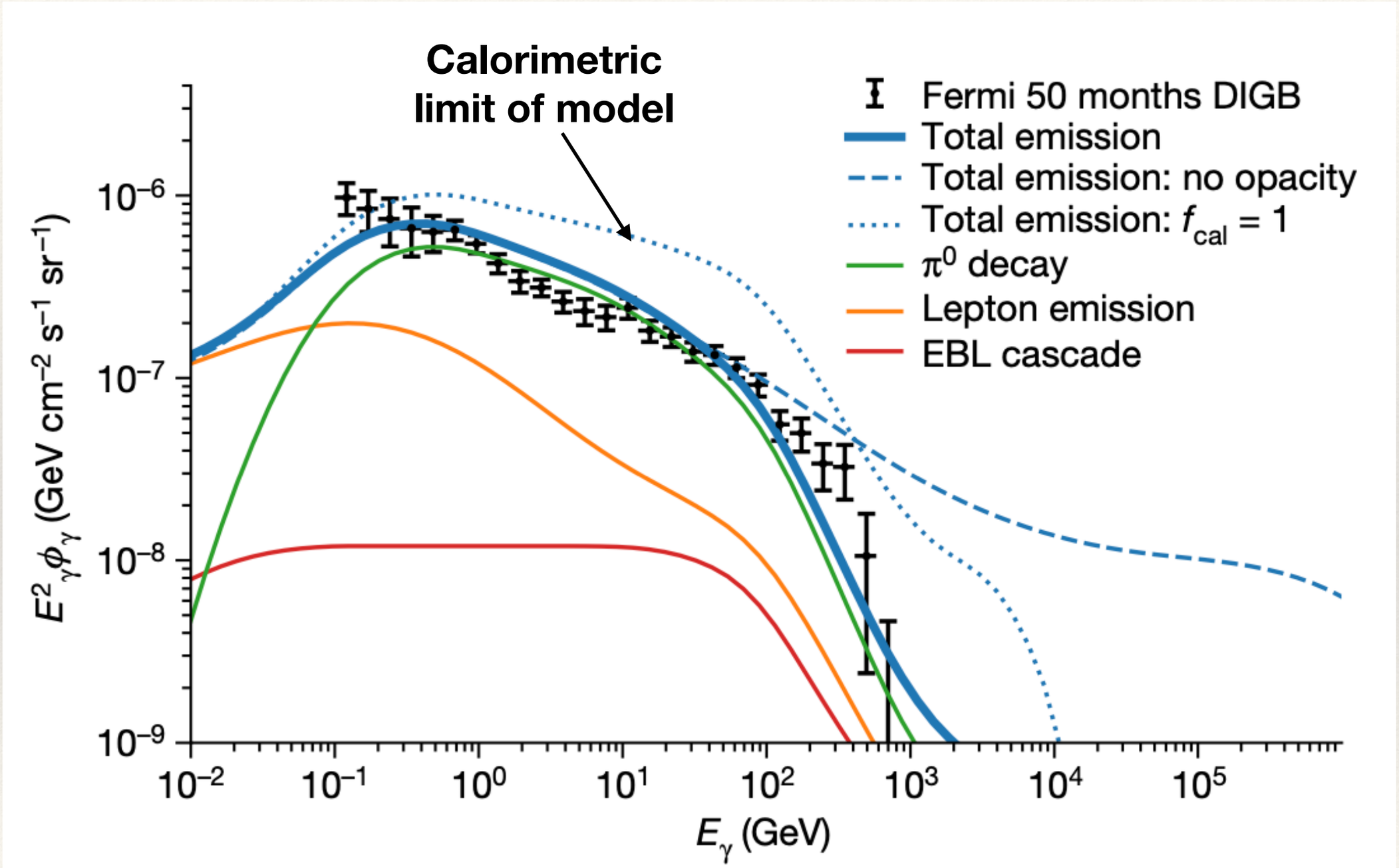

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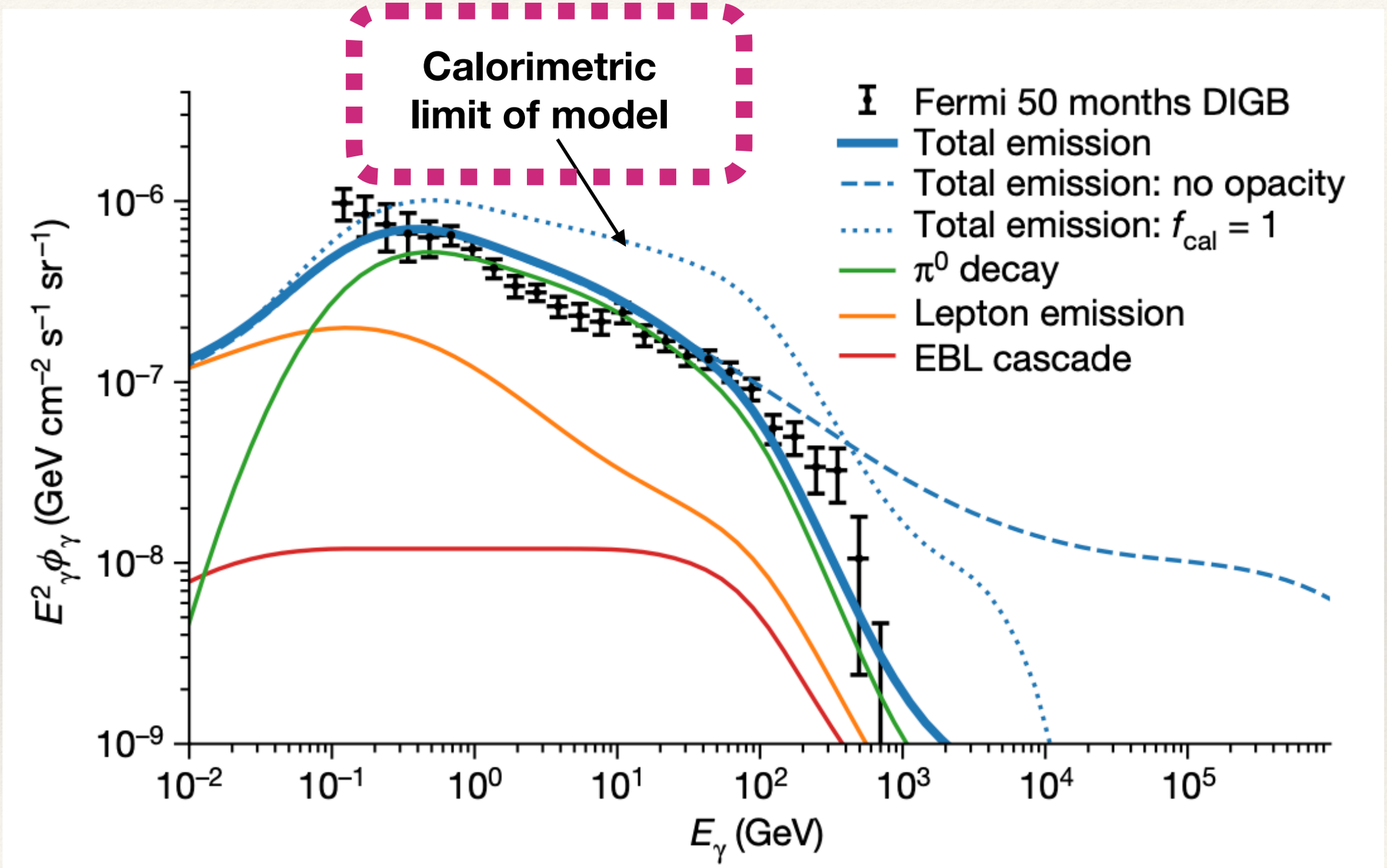

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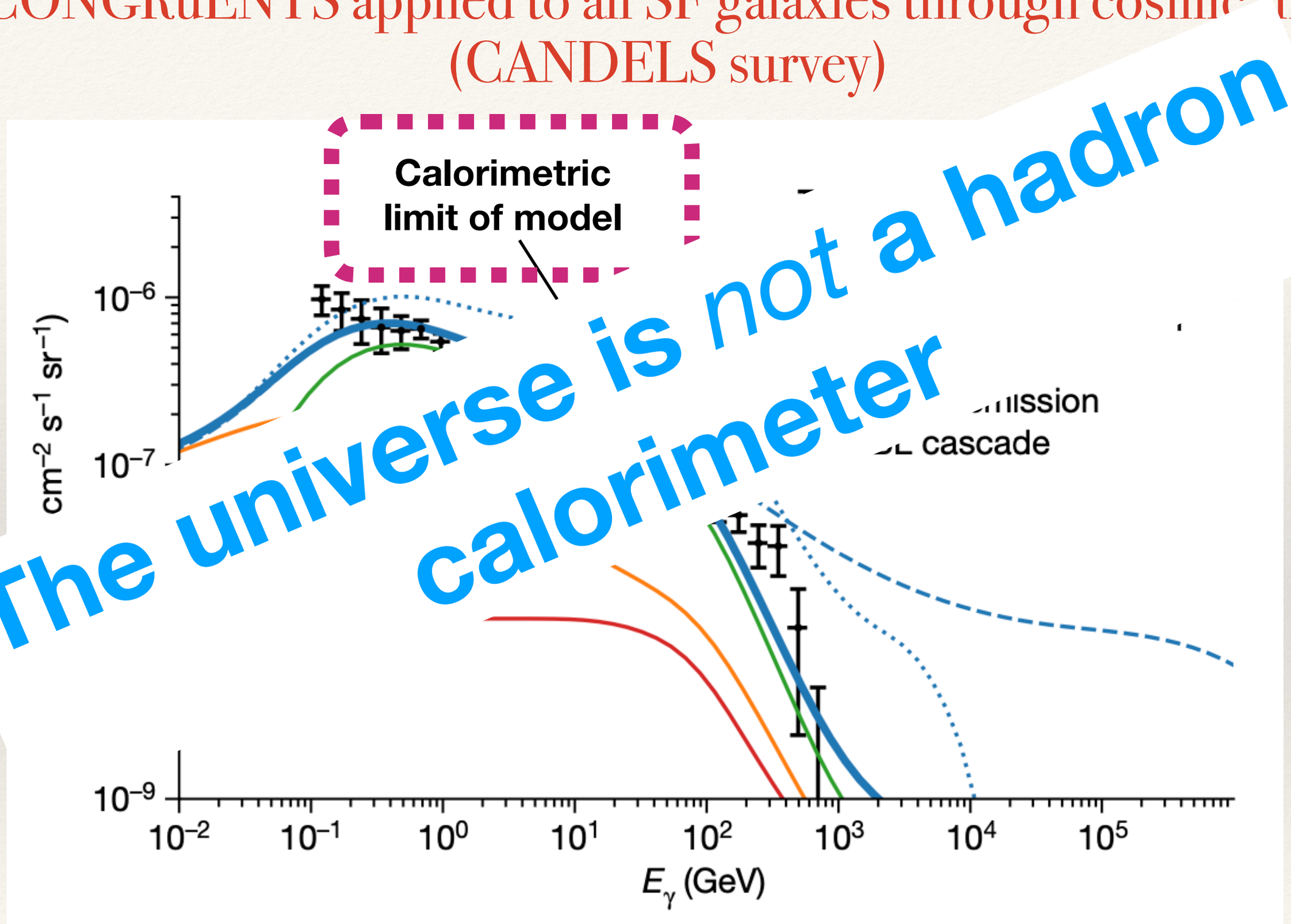

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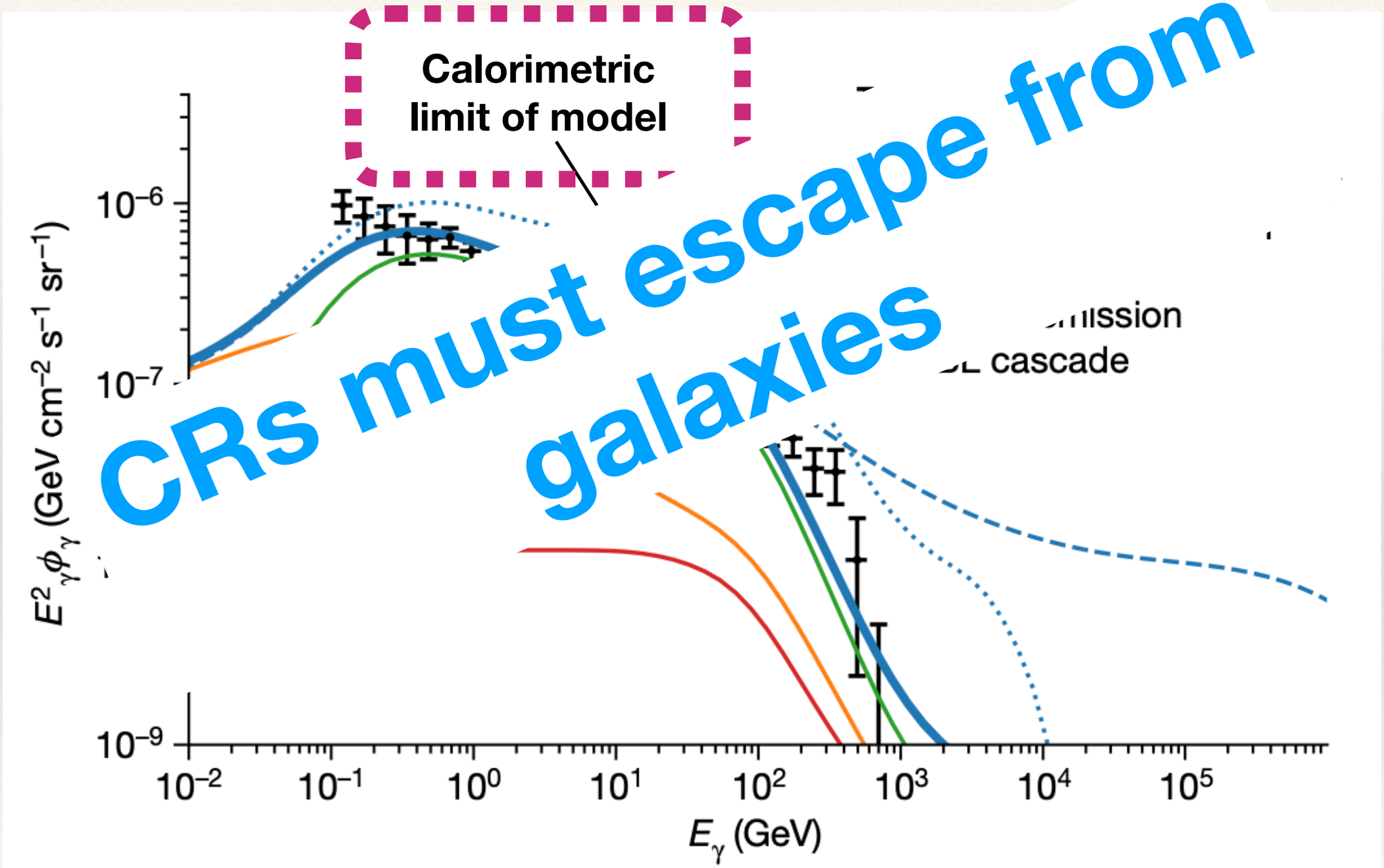

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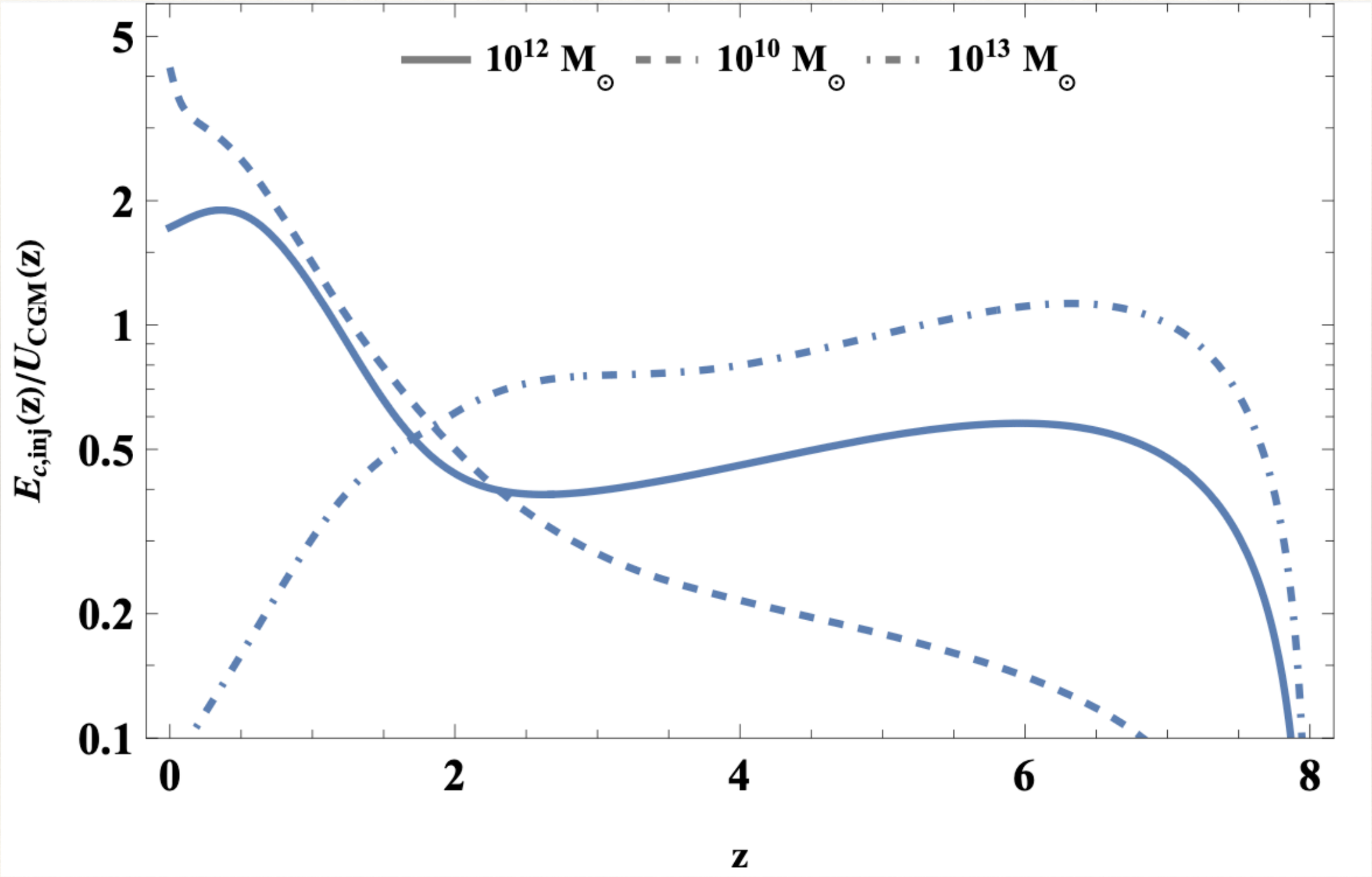
Evolution of the ratio of CR to CGM gas binding energy



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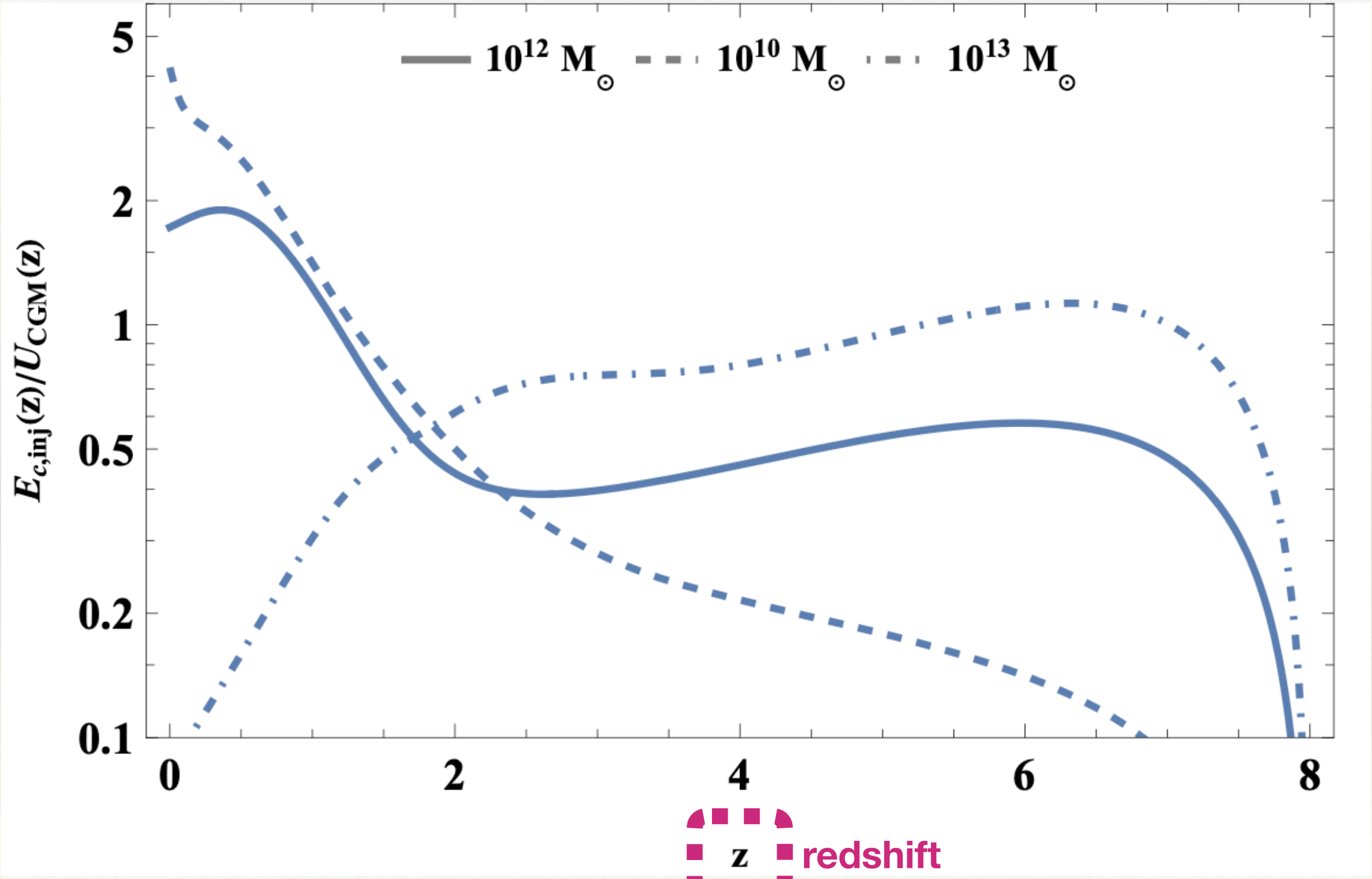

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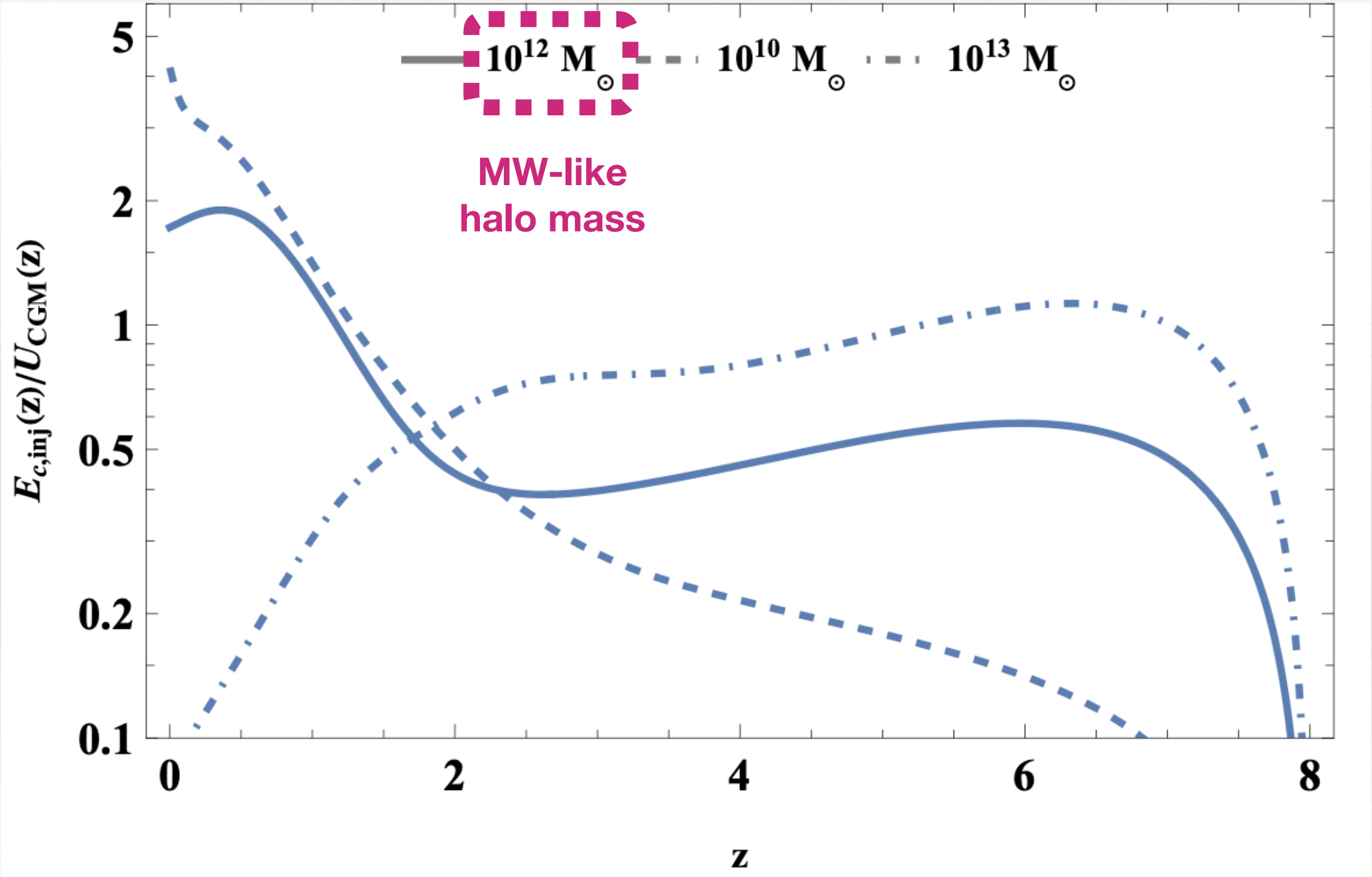

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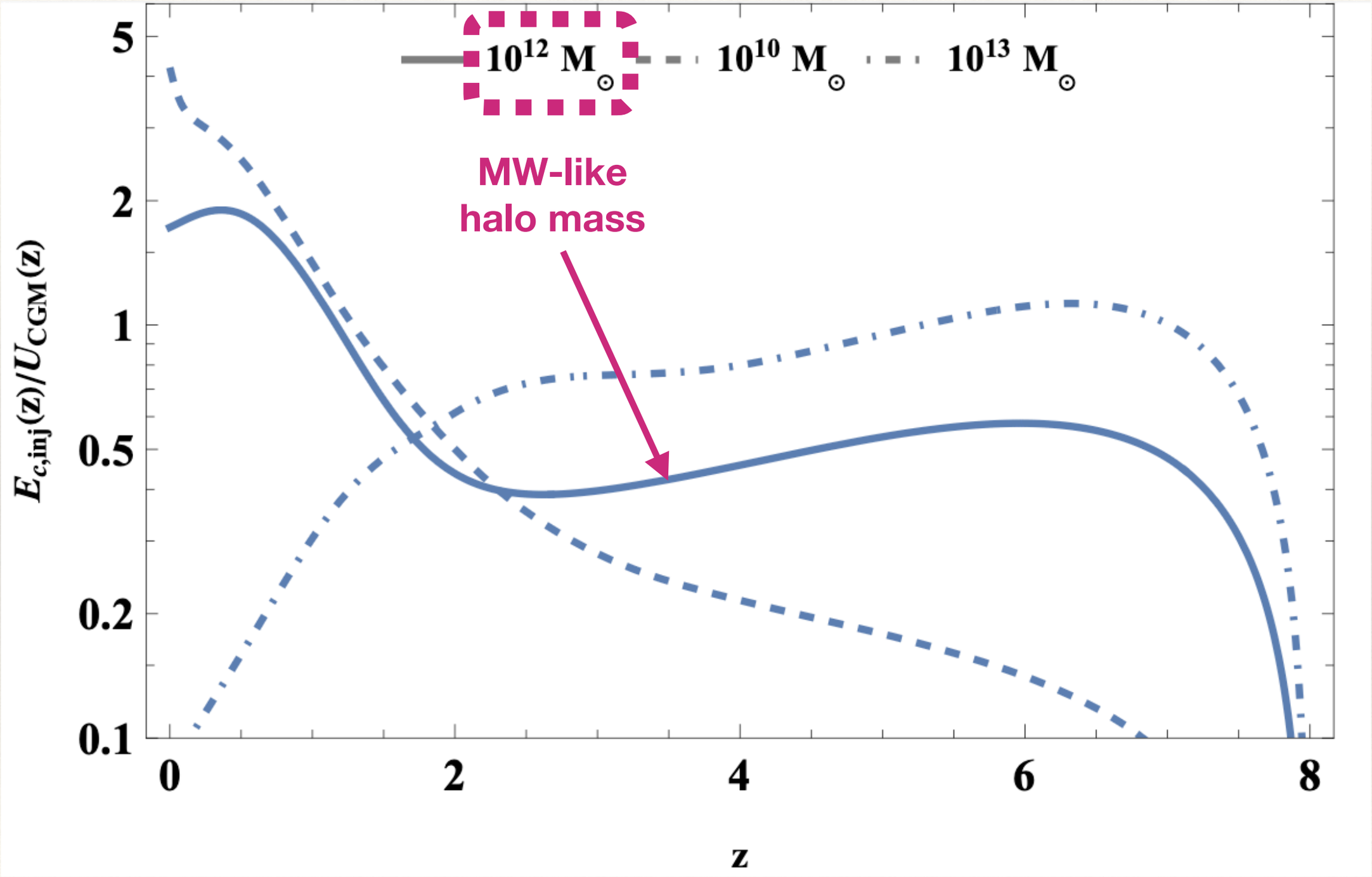

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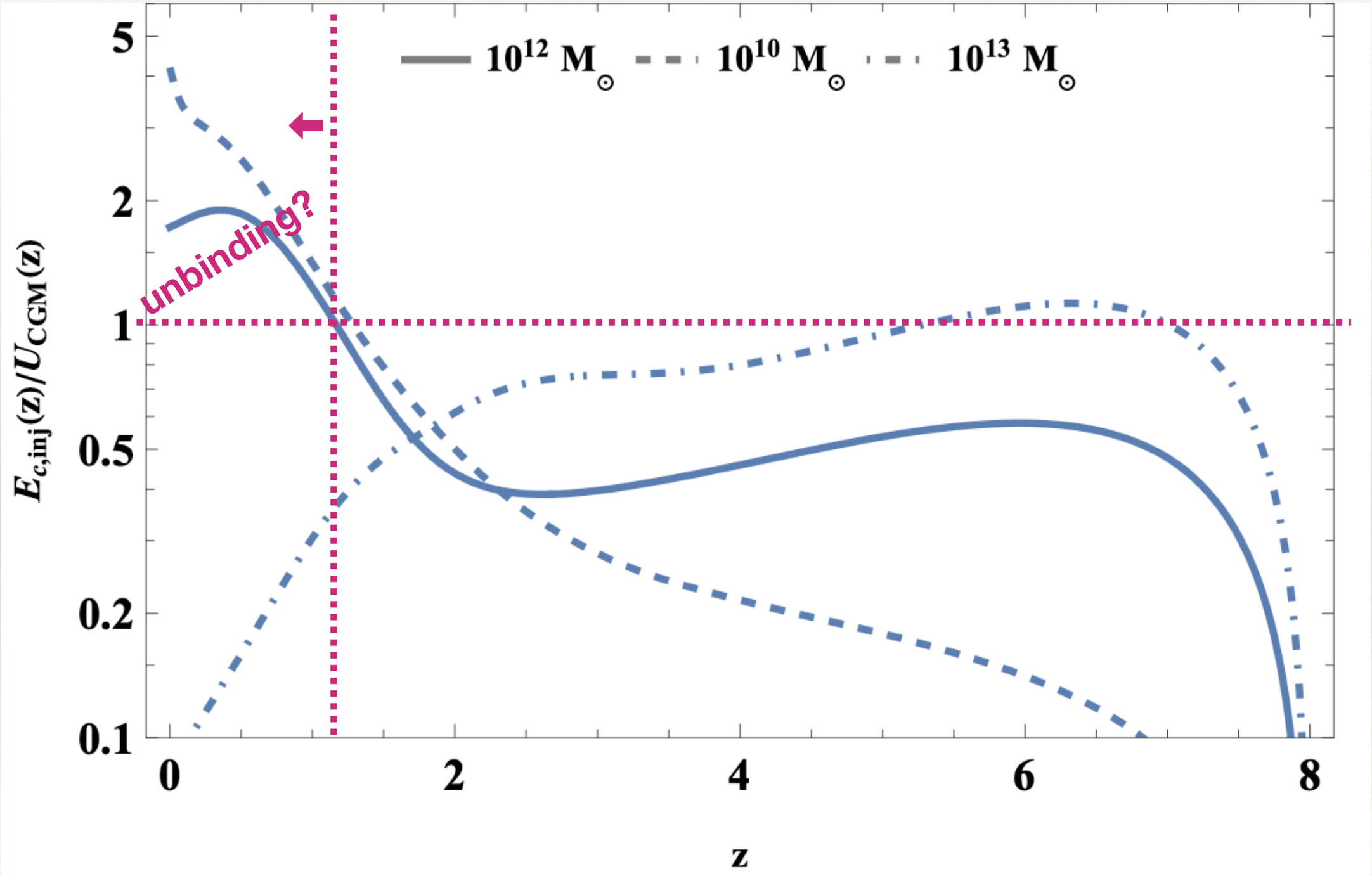

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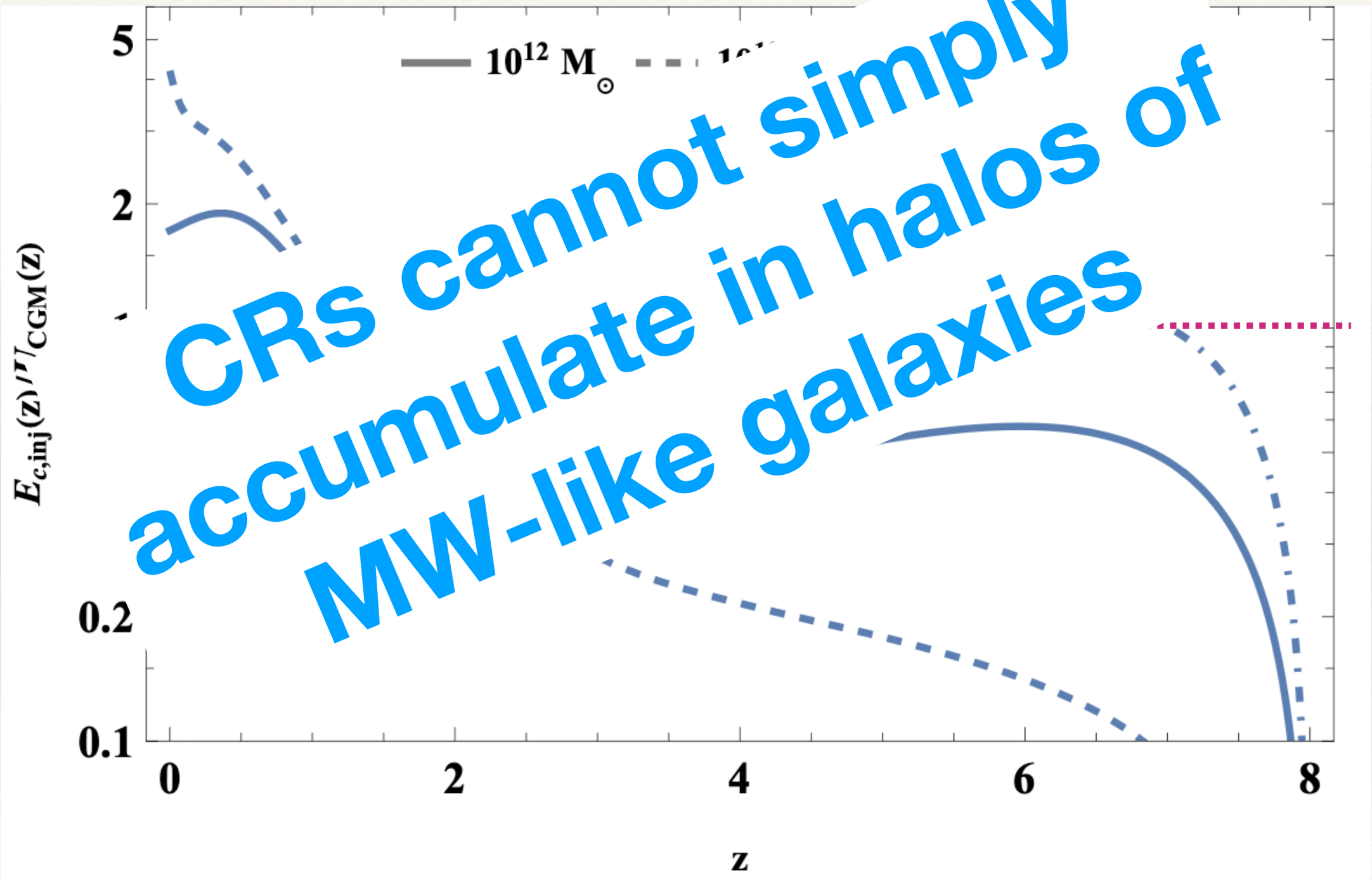
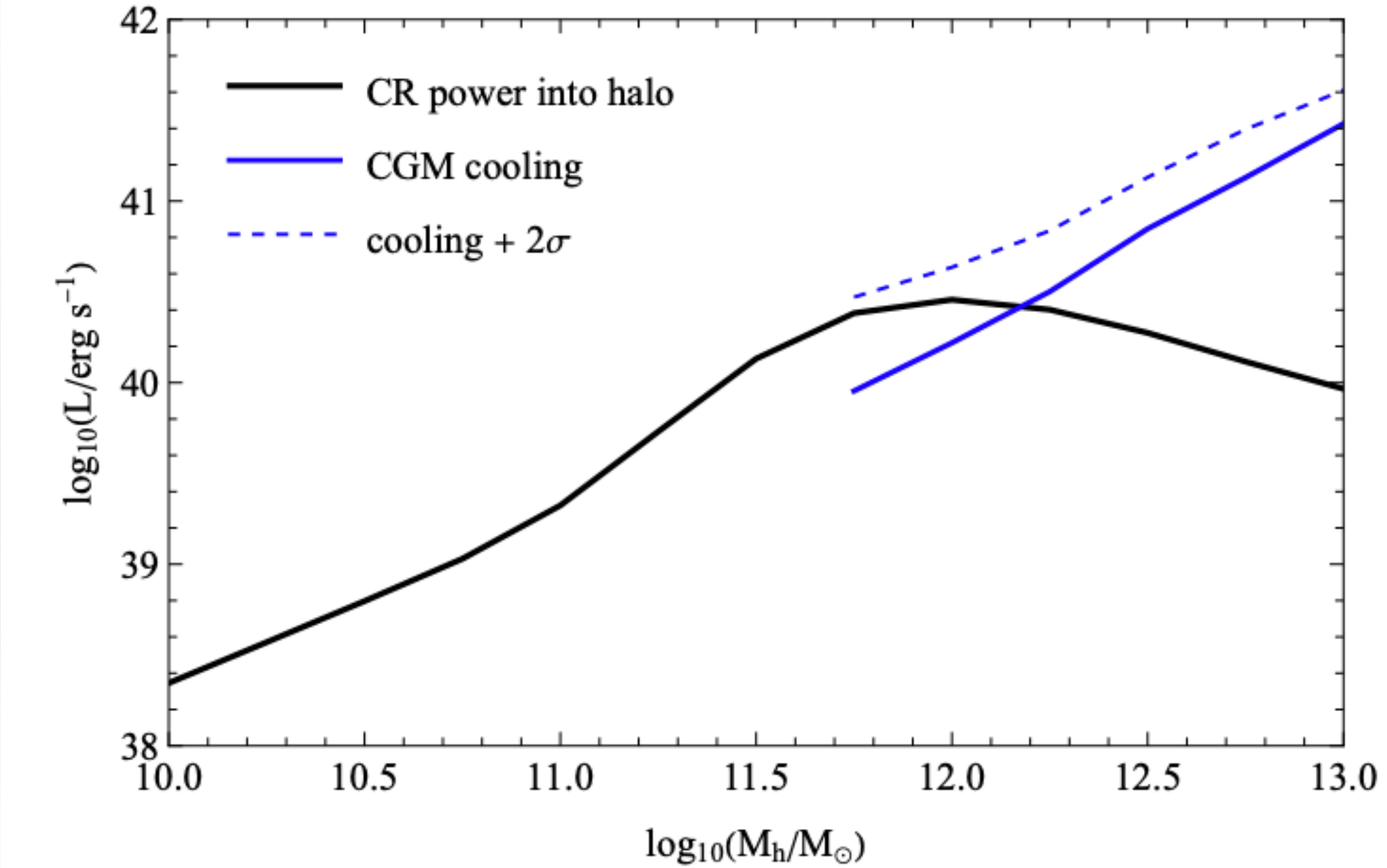


Ratio of CR power injected into halo to bolometric cooling luminosity of CGM at z = 0



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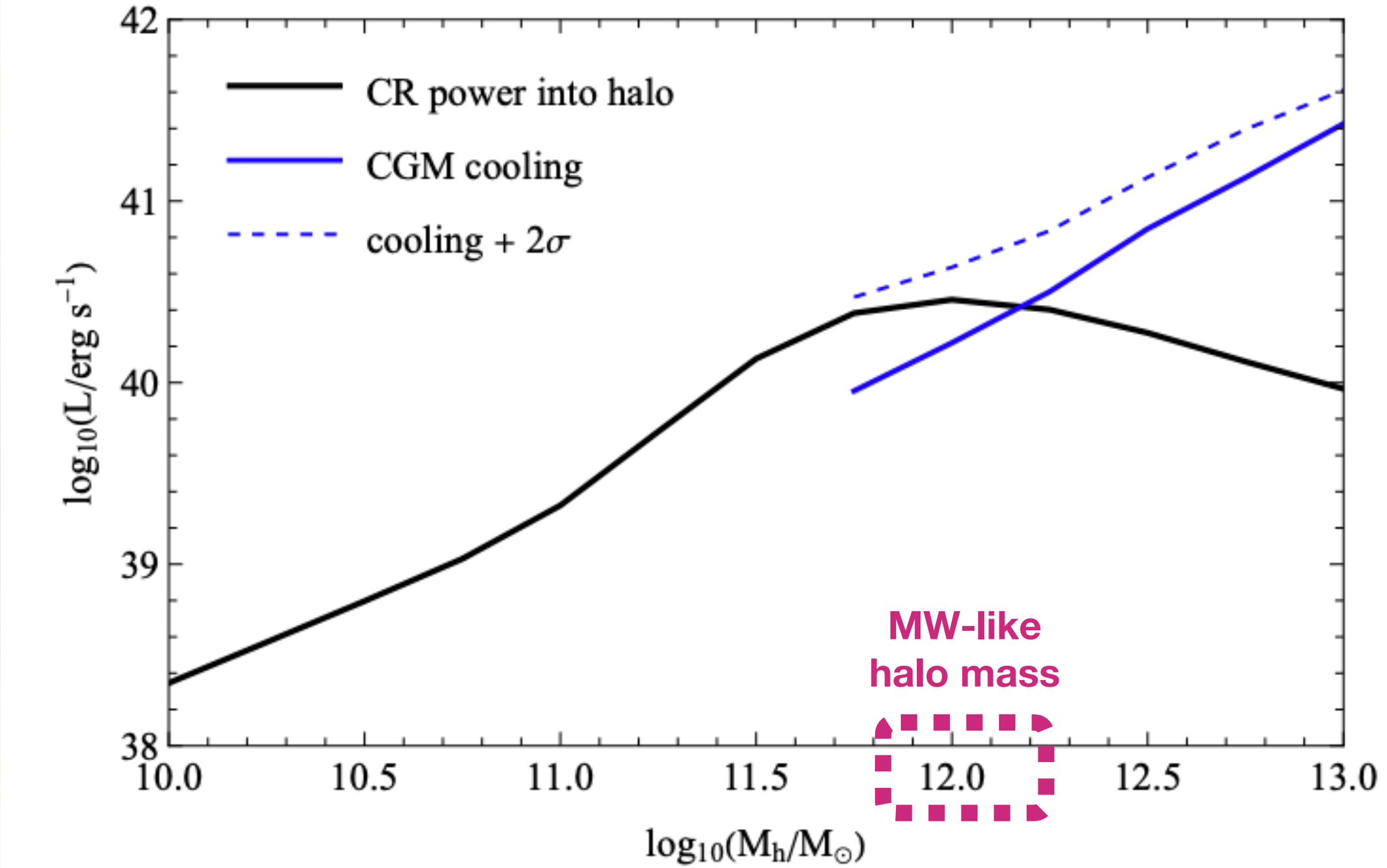

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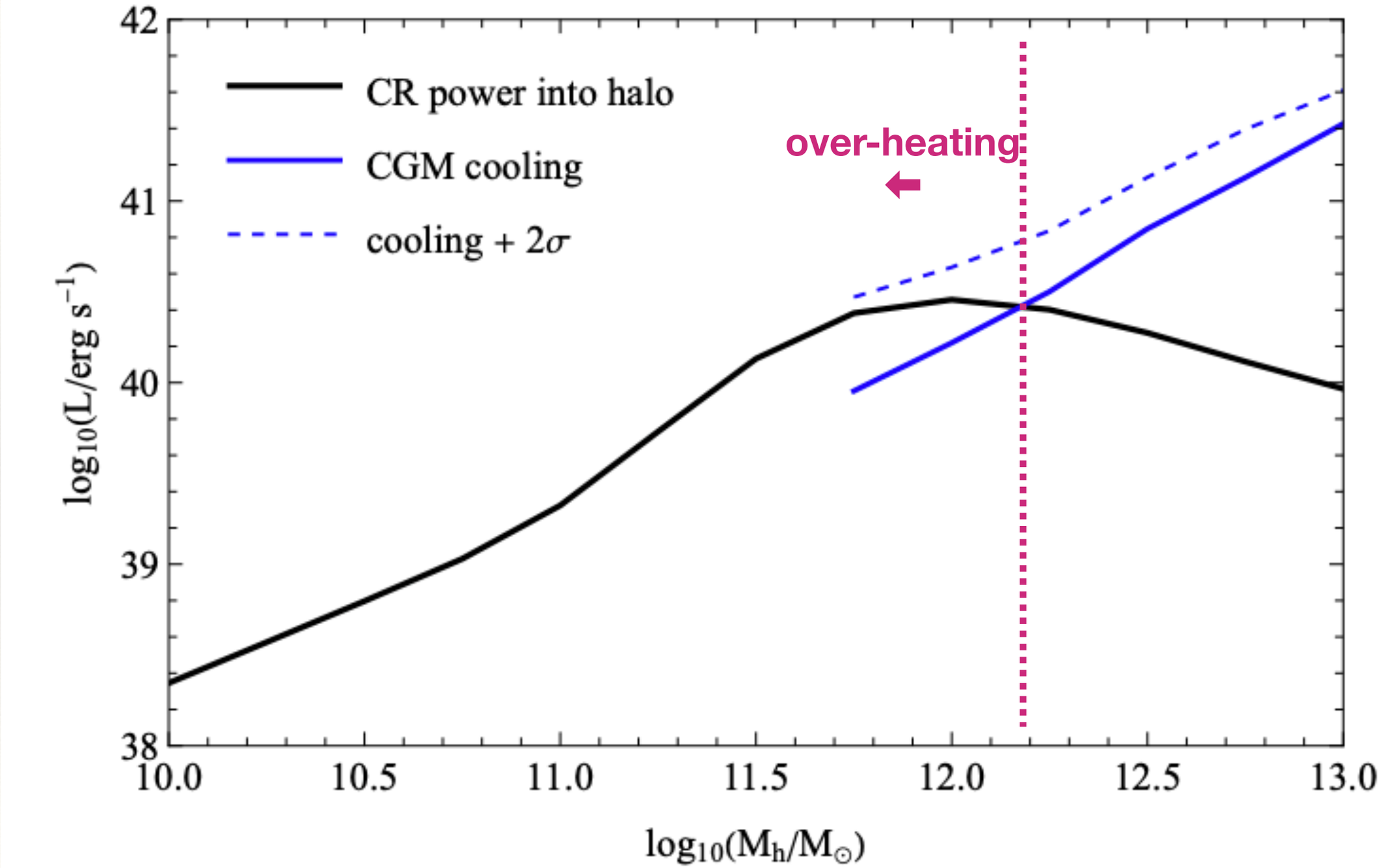

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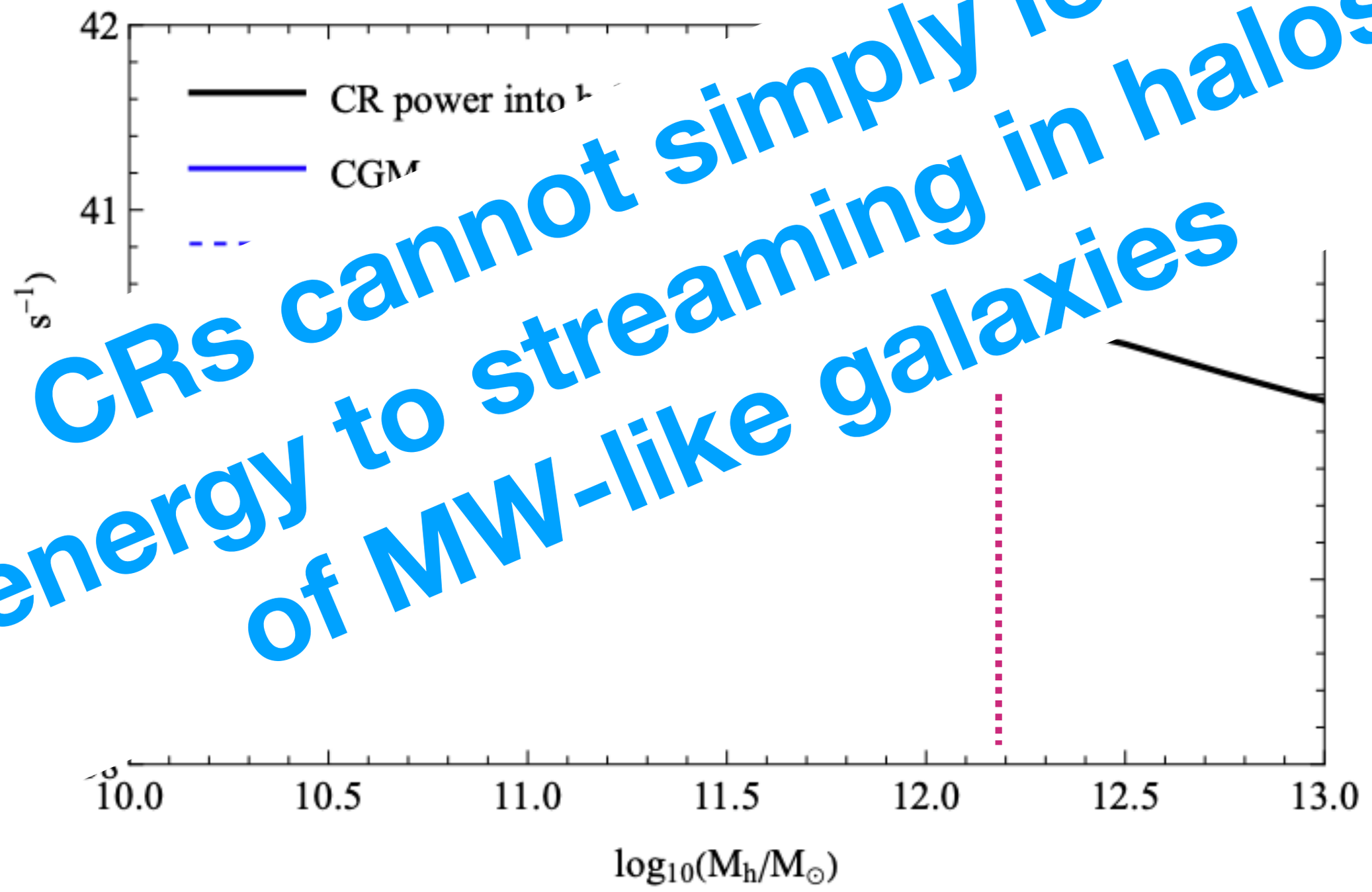
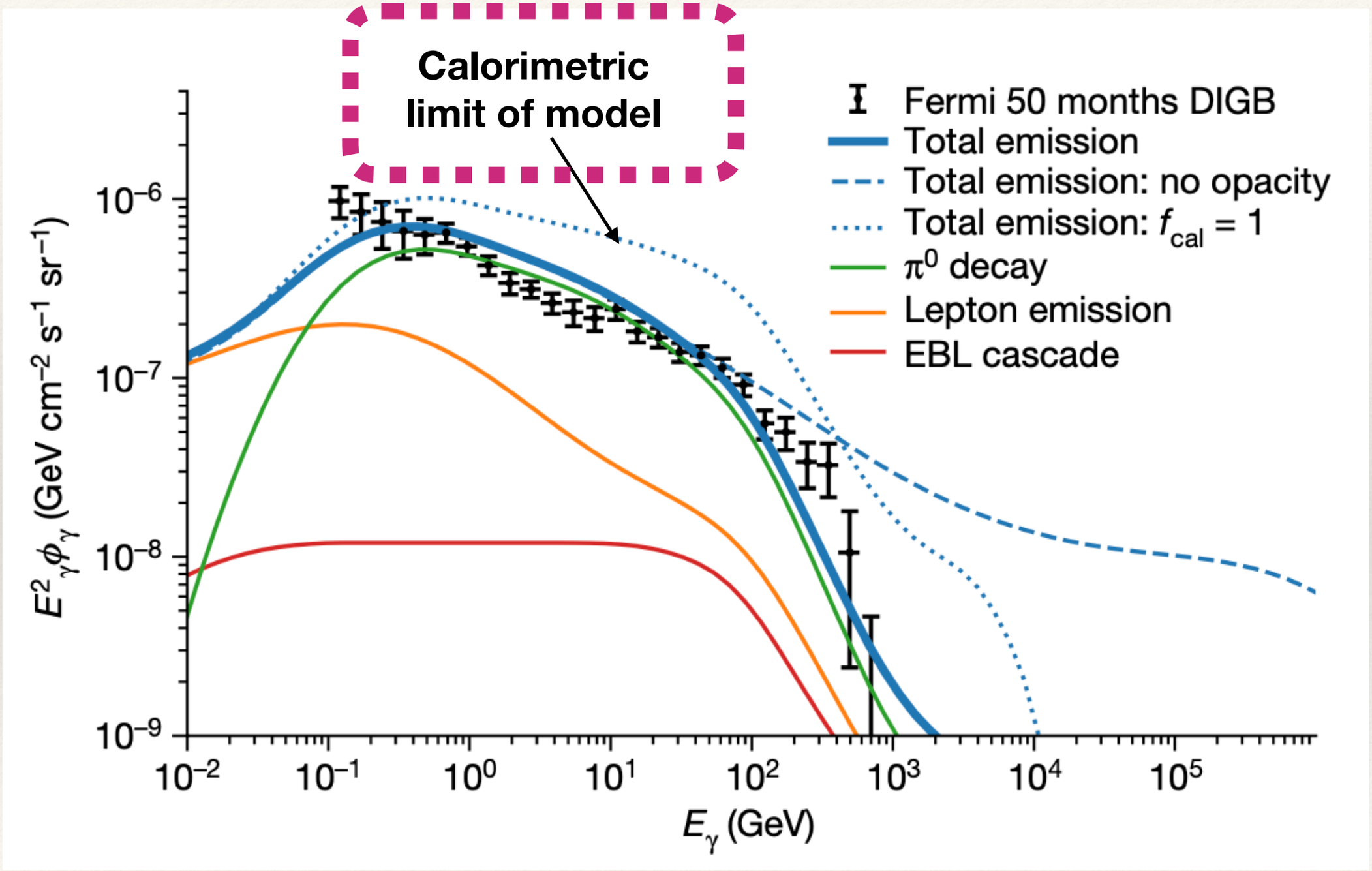


CRs cannot simply lose energy to streaming in halos of MW-like ga galaxies

CONGRuENTS applied to all SF galaxies through cosmic time (CANDELS survey)



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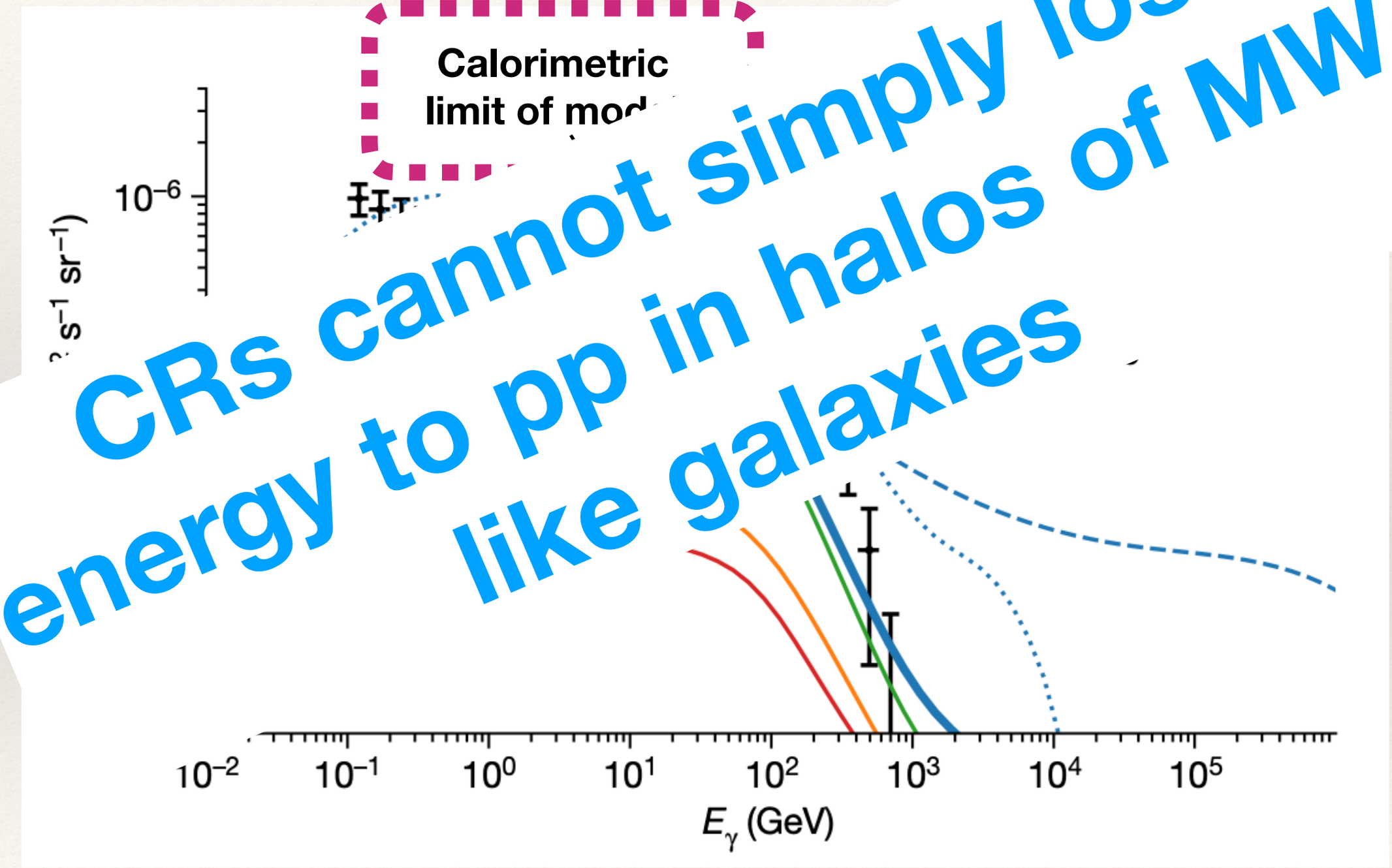

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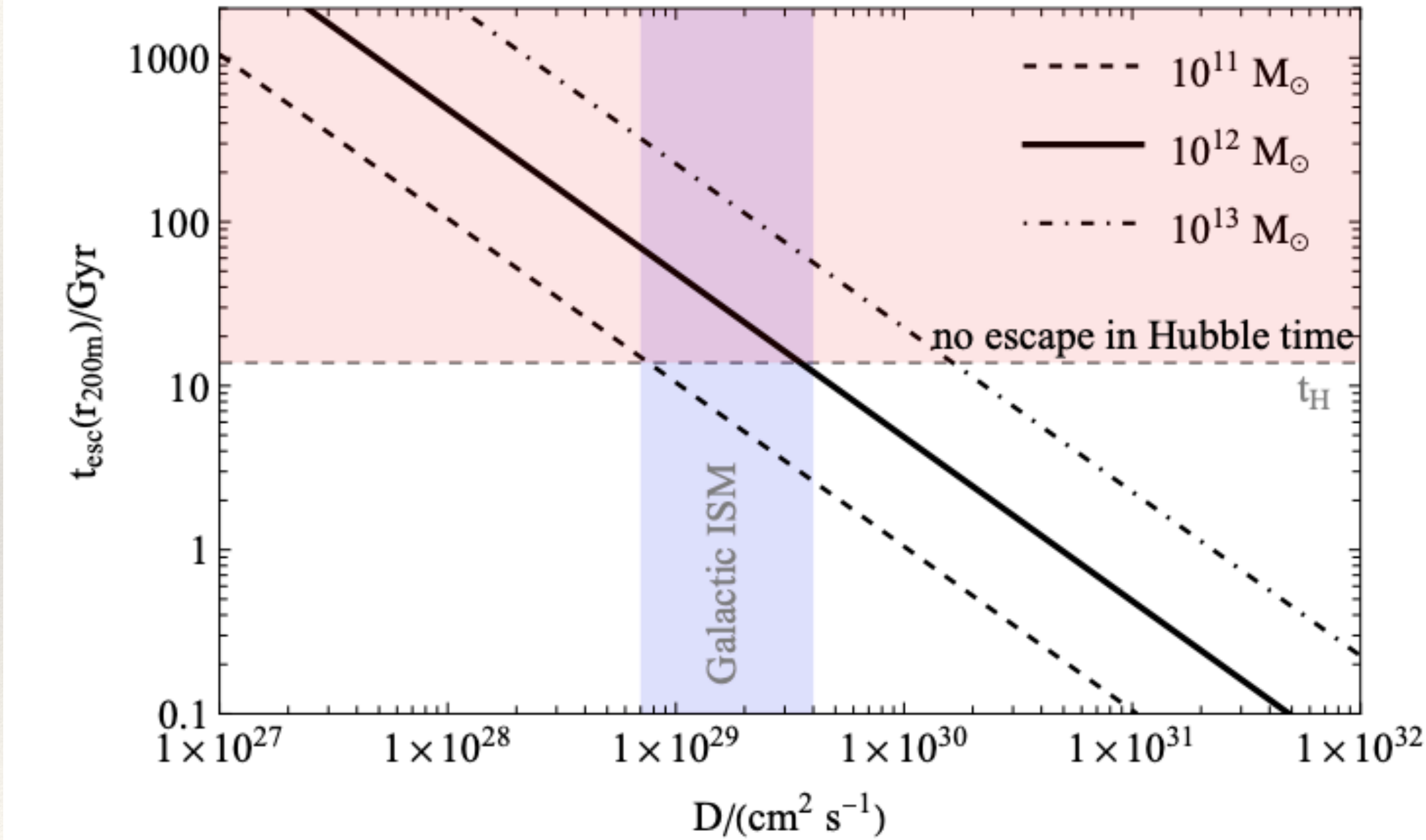
Escape time to virial radius at z = 0 as function of diffusion coefficient



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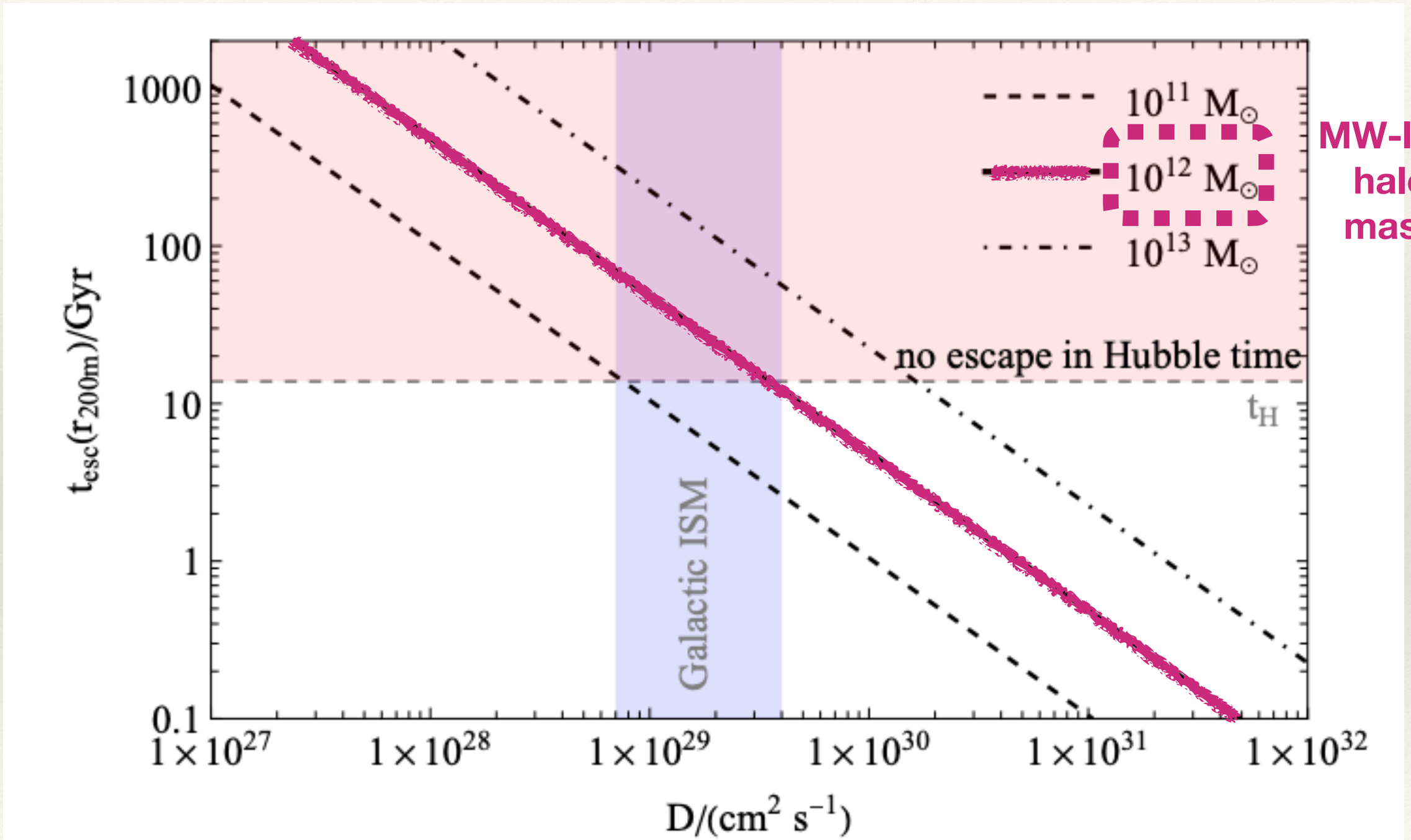

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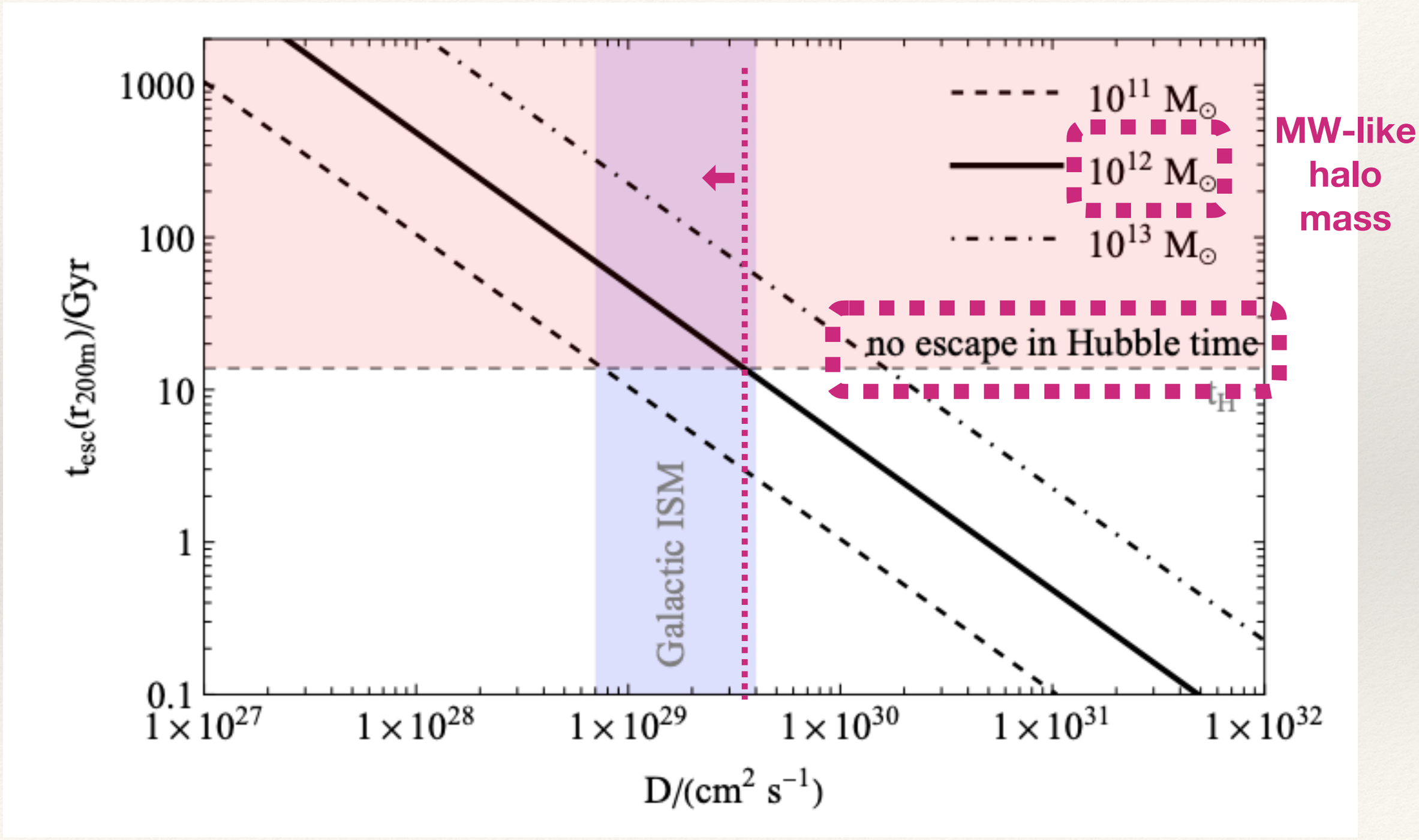

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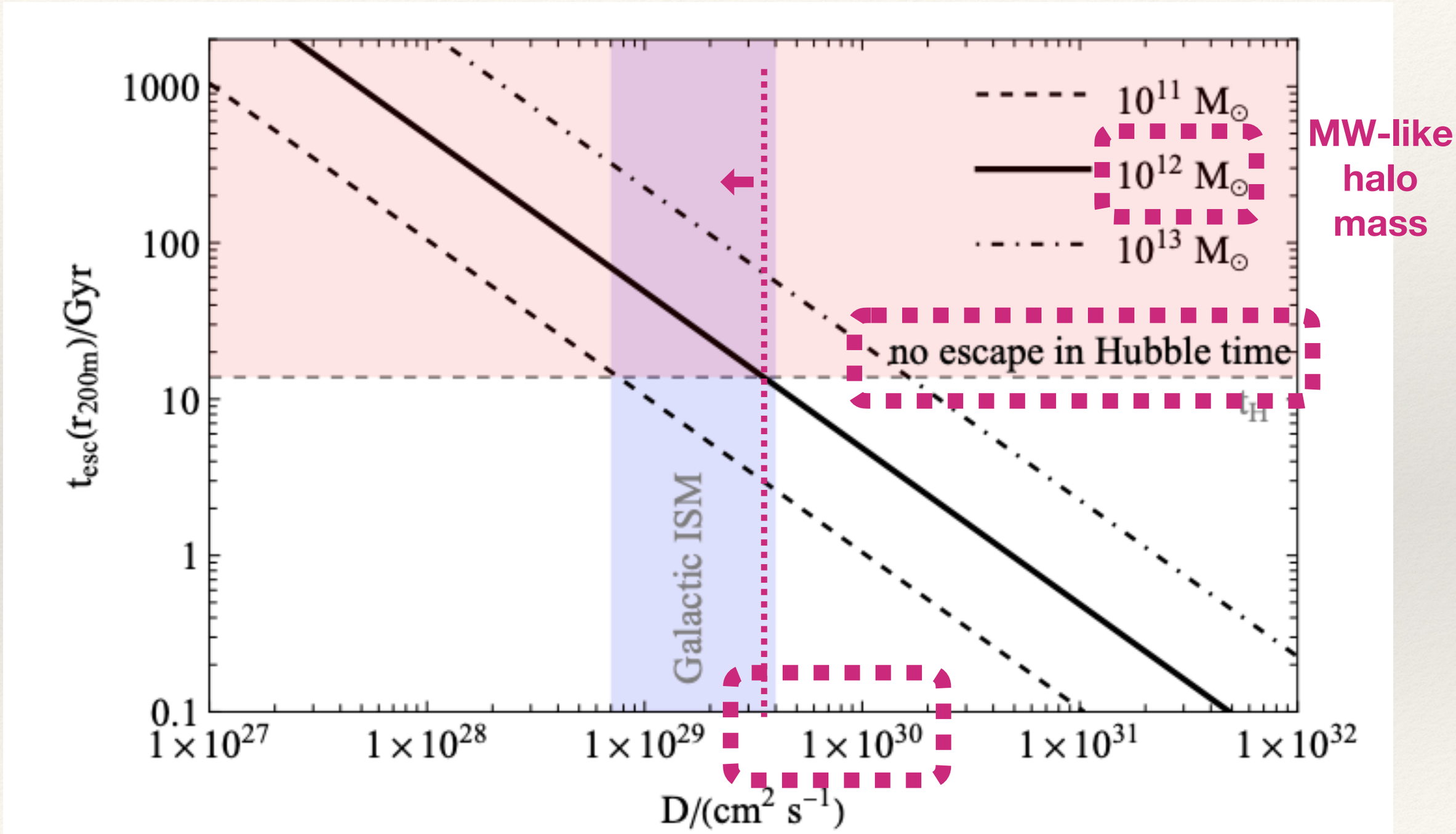

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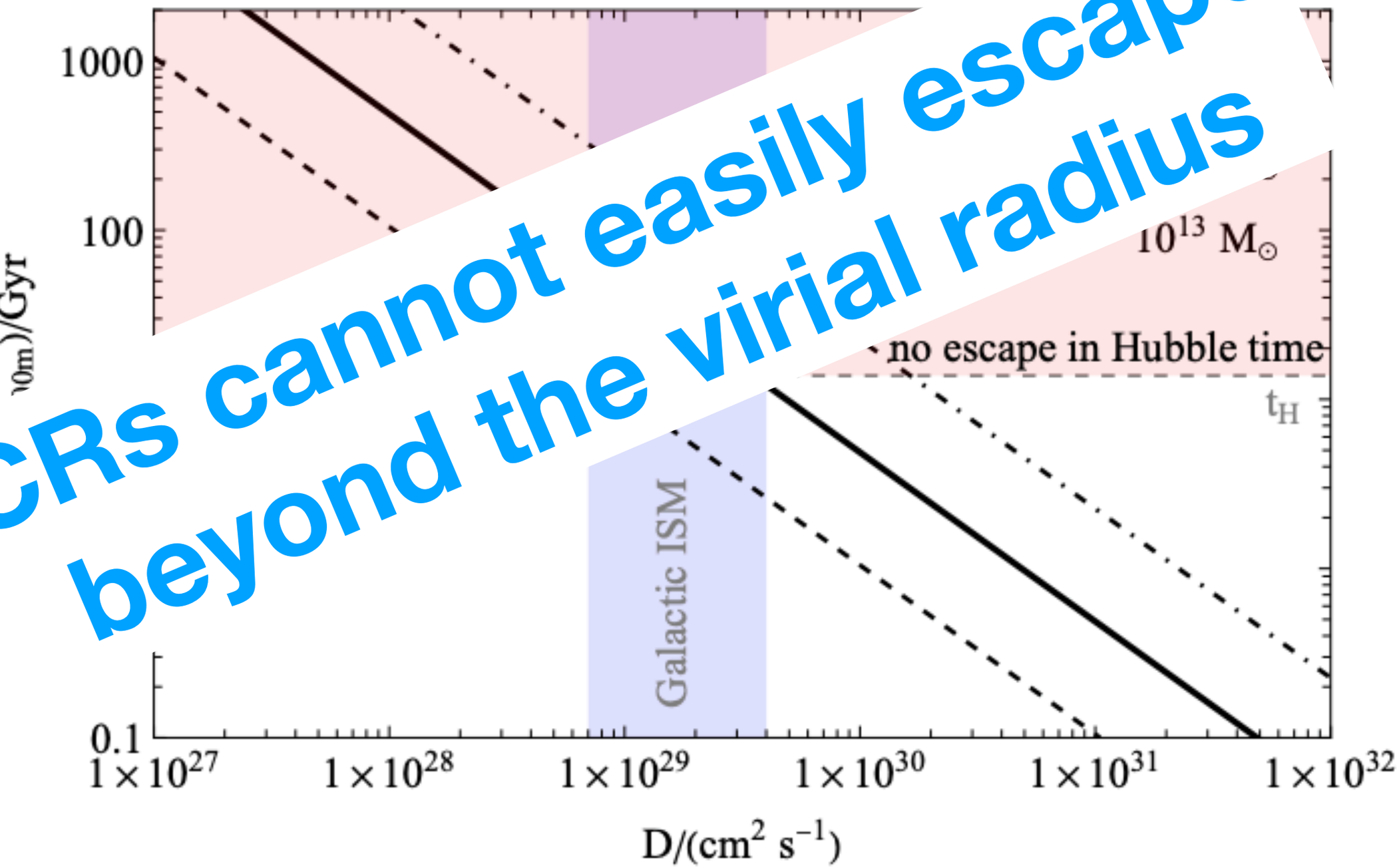
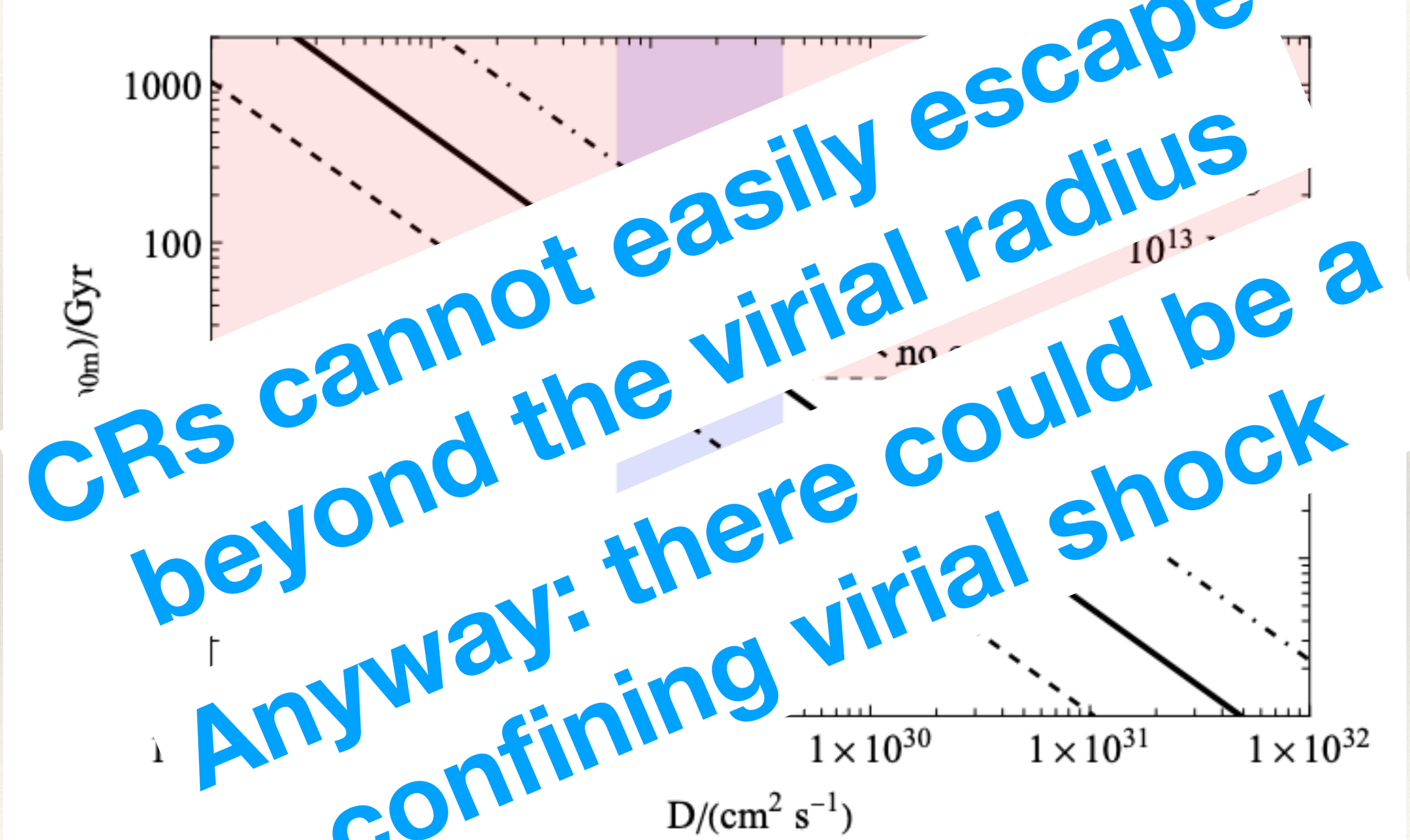


Escape time to virial radius at z = 0 as function of diffusion coefficient



CRs cannot easily escape beyond the virial radius

Anyway: there could be a confining virial shock

Conclusions

- CR transport in the CGM is fast: $\kappa_{\rm MW,CGM} \sim 10^{29} - 10^{30}$ cm^2 s^{-1} (at z ~ 0 and $M_h \sim 10^{12}\ M_\odot$); cf. Butsky+23
- This corresponds to $\mathcal{K} \sim \mathcal{O}$**(0.1)**

$$\Rightarrow \mathbf{t_{diff}(r_{vir}) \sim (r_{vir})^2/(0.1\ r_{vir}\ c_s) \sim 10\ r_{vir}/\ c_s \sim 10\ t_{dyn} \sim t_{Hubble}}$$

In words: the system conspires so that ***the diffusion time to the virial radius is about the Hubble time***

- Combined constraints locate us in part of parameter space where CRs are both dynamically important ($P_c \sim P_{\rm hydro}$) *and* can provide significant heating via streaming ($\dot{E}_{\rm str} \sim L_{\rm therm,CGM}$) *and* SF galaxies generate the IGRB including a non-negligible MW CGM

Transport equation

$$\frac{\partial u_c}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_c}{\partial r}\right] - \frac{u_c}{t_{pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_c}{\partial r}\right|$$

Transport equation

***r*: radius within halo**

$$\frac{\partial u_{\rm C}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_{\rm C}}{\partial r}\right] - \frac{u_{\rm C}}{t_{\rm pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_{\rm C}}{\partial r}\right|$$

***t*: cosmological time**

Transport equation

$$\frac{\partial u_c}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_c}{\partial r}\right] - \frac{u_c}{t_{pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_c}{\partial r}\right|$$

Diffusion term

$$D(z) = \mathcal{K}\,\kappa_{nat}(z), \qquad \kappa_{nat}(z) \equiv \frac{1}{3}\,r_\star(z)\,c_s(z)$$

Transport equation

$$\frac{\partial u_{\rm c}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_{\rm c}}{\partial r}\right] - \frac{u_{\rm c}}{t_{\rm pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_{\rm c}}{\partial r}\right|$$

Diffusion term

Hadronic collisional losses

Streaming losses

Transport equation

$$\frac{\partial u_{\rm c}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_{\rm c}}{\partial r}\right] - \frac{u_{\rm c}}{t_{\rm pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_{\rm c}}{\partial r}\right|$$

Reference length
$=r_{vir}$

$$D(z) = \mathcal{K}\,\kappa_{\rm nat}(z), \qquad \kappa_{\rm nat}(z) \equiv \frac{1}{3}\,r_{\star}(z)\,c_s(z)$$

Transport equation

$$\frac{\partial u_{\mathrm{c}}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_{\mathrm{c}}}{\partial r}\right] - \frac{u_{\mathrm{c}}}{t_{\mathrm{pp}}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_{\mathrm{c}}}{\partial r}\right|$$

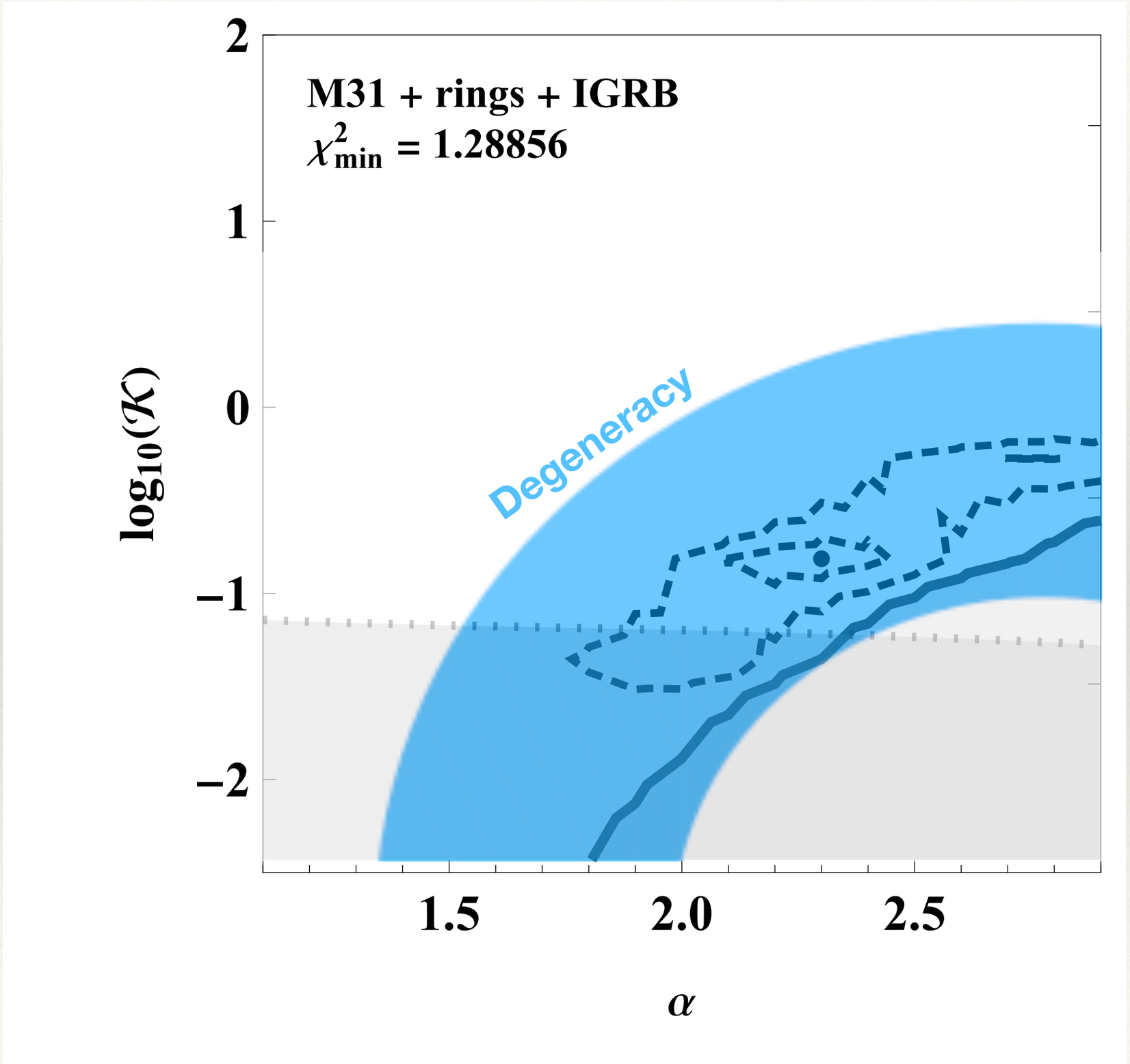
Hadronic collisional losses

Transport equation

$$\frac{\partial u_c}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(z)\frac{\partial u_c}{\partial r}\right] - \frac{u_c}{t_{pp}(r,z)} - \frac{v_A}{3}\left|\frac{\partial u_c}{\partial r}\right|$$

Streaming losses

Mathematical details

- $t \rightarrow z$
- Non-dimensionalise
- moving boundaries given $r_{vir} = r_{vir}(z)$
- inner boundary: in-coming flux given by (1 - f_{cal}) $\dot{E}_c$ from CONGRuENTS
- outer boundary: either trapping or free-escape
- PDEs parameterised by: {boundary mode, v_A, M_{h0}, α, $\mathcal{K}$}
- numerically solve each PDE to find z and r dependent CR energy density profiles $u_c = u_c(r,z)$

Parameter space scan