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Cosmic ray feedback across the sequence of star-forming galaxies

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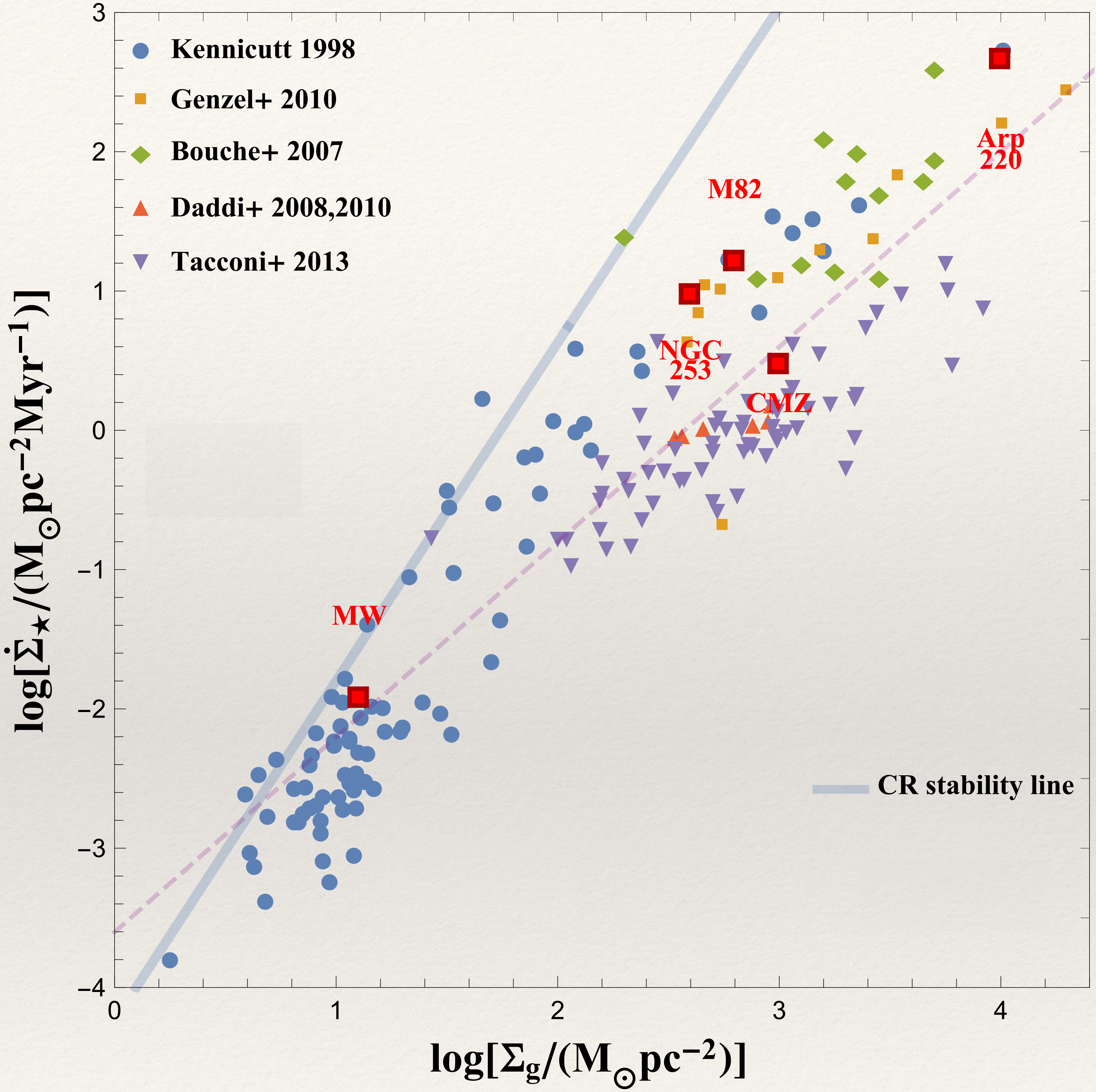
Australian National University

Referencing work done in collaboration with:

Mark Krumholz, Todd Thompson, Matt Roth,
Siyao Xu, Alex Lazarian, & Silvia Celli

Claim:

A correct understanding of cosmic ray transport in (relatively) dense, partially ionised (but largely neutral) gas that sustains star formation in galaxies allows us to understand the empirical upper limit to the star formation efficiency of ‘normal’ galaxies



Kennicutt 1998
Genzel+ 2010
Bouche+ 2007
Daddi+ 2008,2010
Tacconi+ 2013
CR stability line
MW
NGC 253
M82
CMZ
Arp 220
$\log[\dot{\Sigma}_\star/(M_\odot pc^{-2} Myr^{-1})]$
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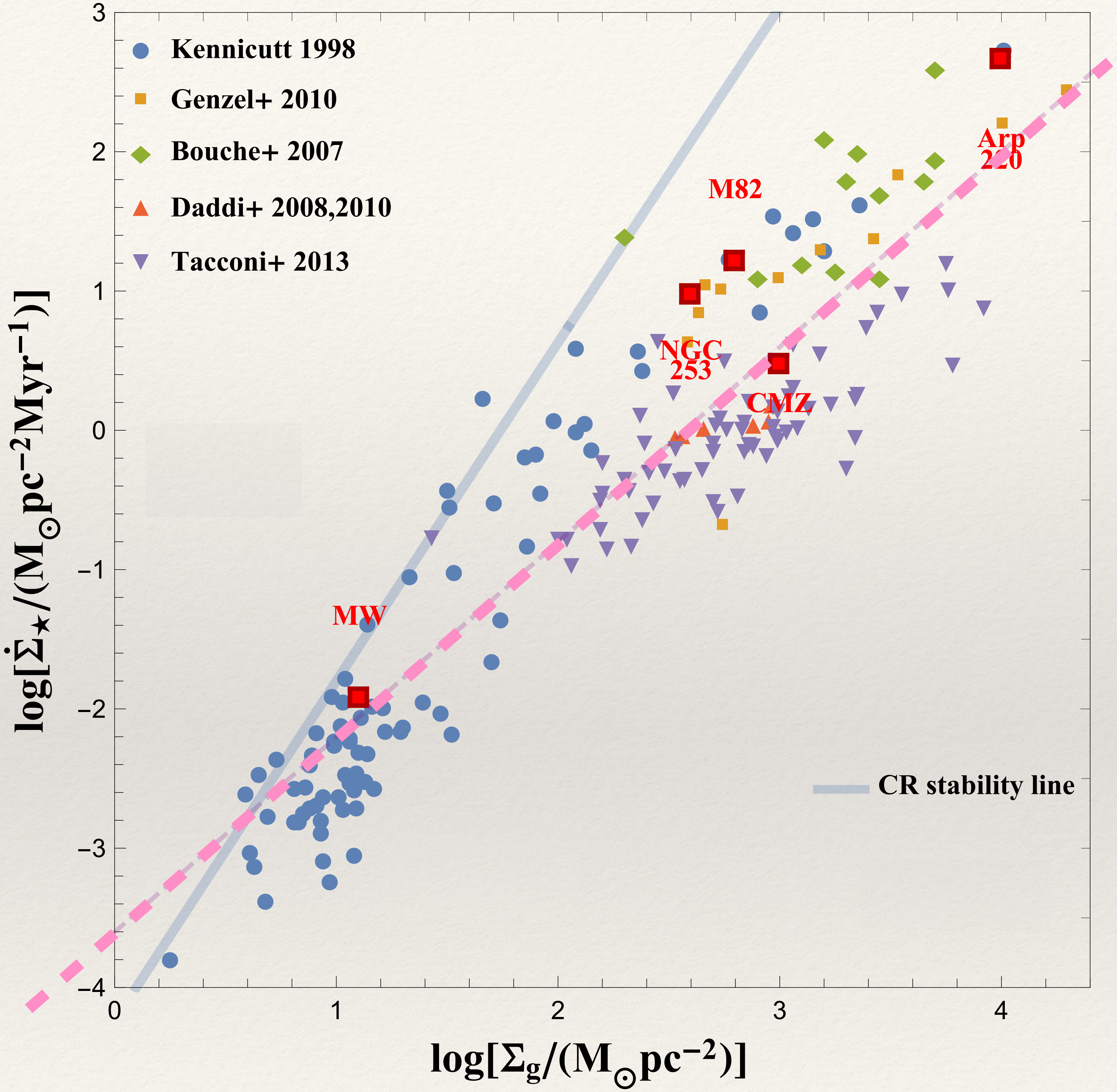
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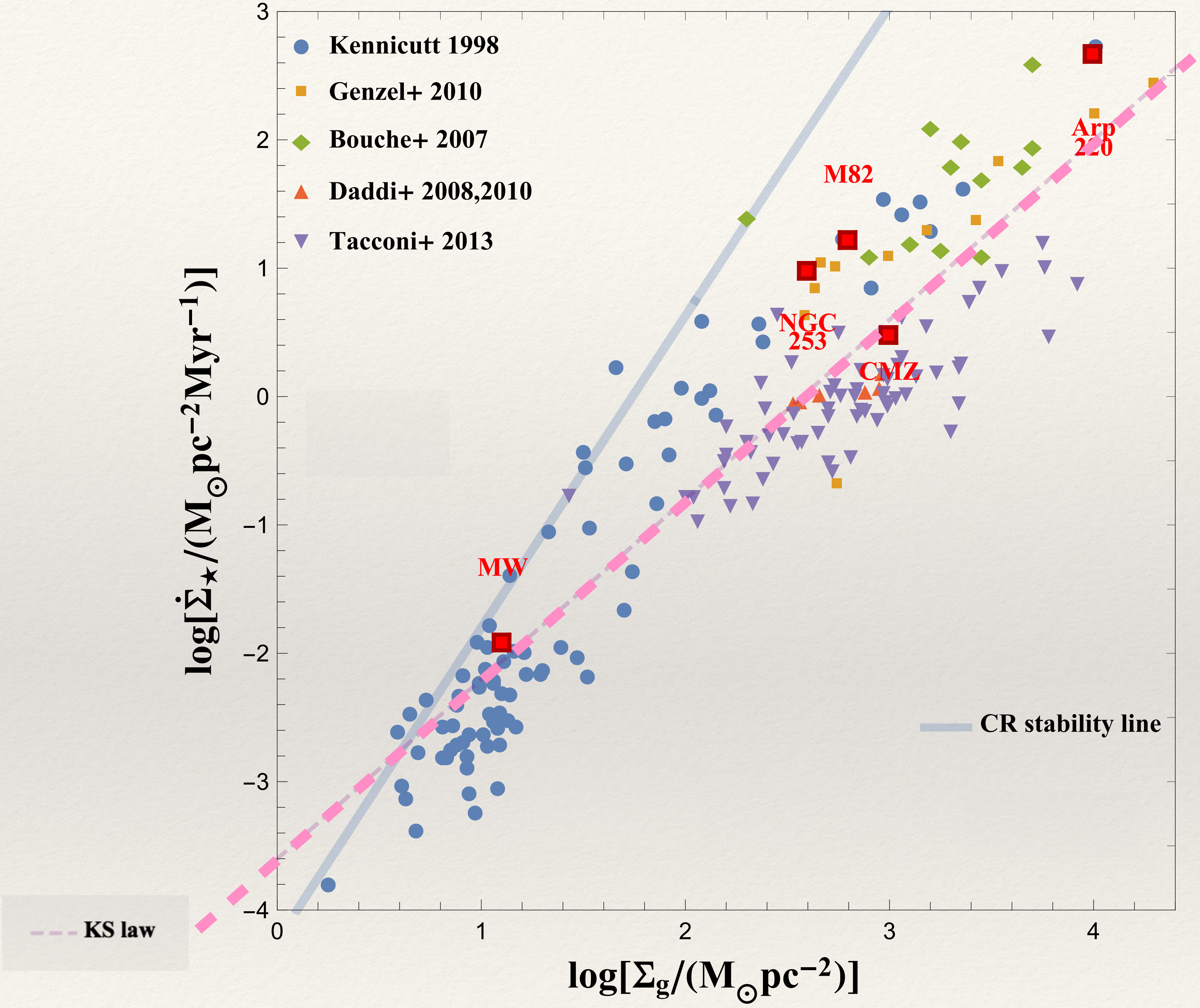
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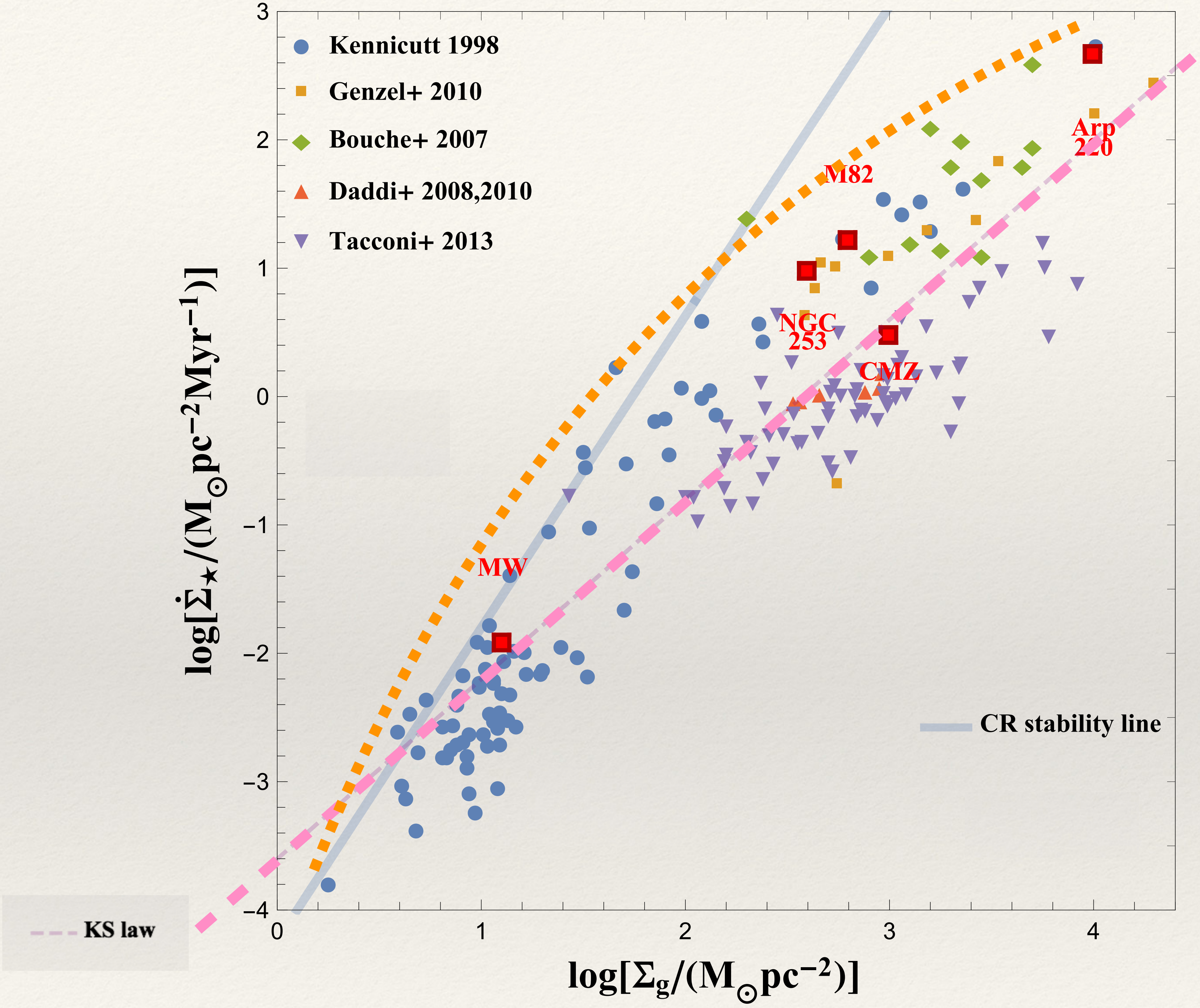
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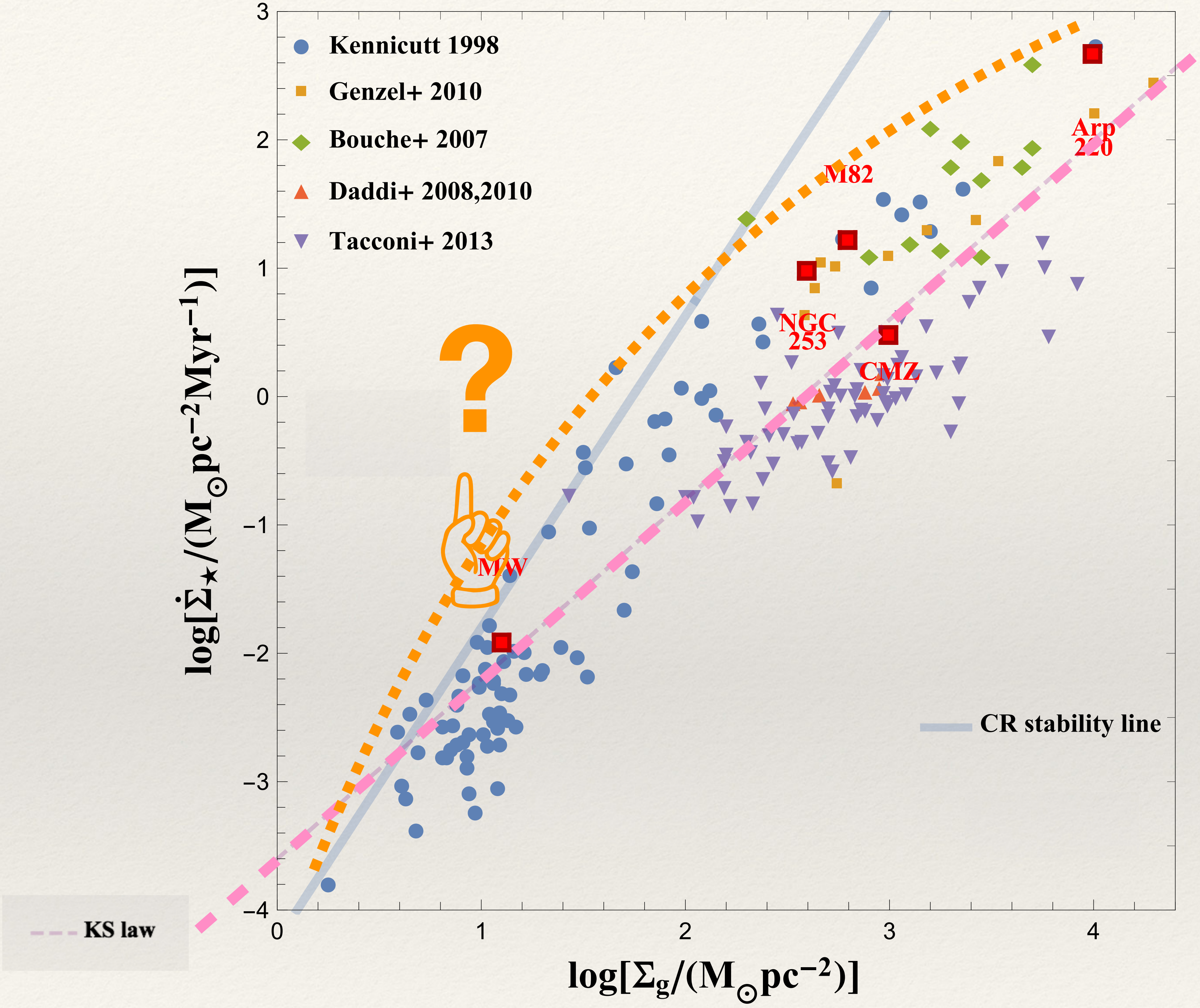

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CRs are dynamically important in galaxies:

- Cosmic rays can be measured locally and their presence throughout the Galactic disk and in local group galaxies can be inferred from gamma-ray emission
- As CRs scatter on B field they exchange momentum with the B field
- ⇒ they exert an effective pressure to the gas into which the B field is “frozen in”
- in the Milky Way, CRs provide energy density/pressure equivalent to other ISM phases (Boulares & Cox 1990)

⇒ CRs help to support the scale height of the gaseous disk

Cosmic ray transport

- Dynamically dominant ~GeV CRs have ~10^{-6} pc gyro radii in ISM of galaxies
- The classical picture of CRs scattering on extrinsic magnetic field turbulence that has cascaded down to this ~10^{-6} pc size scale does NOT work in the largely neutral gas phase where star forms
- Instead, in this phase, CRs generate themselves the turbulence on which they scatter via the streaming instability
- Putting streaming and ion-neutral damping into balance, it turns out that **CRs stream at the ION Alfven speed** in the partially ionised (but largely neutral), star-forming gas
- The CRs execute a **field line random walk** streaming along the turbulent-dynamo-generated magnetic field

- Can now estimate the effective macroscopic diffusion coefficient (Yan & Lazarian 2008) for CRs:

Streaming velocity equal to the ION Alfven velocity:

$$v_s \simeq v_{A,i}$$

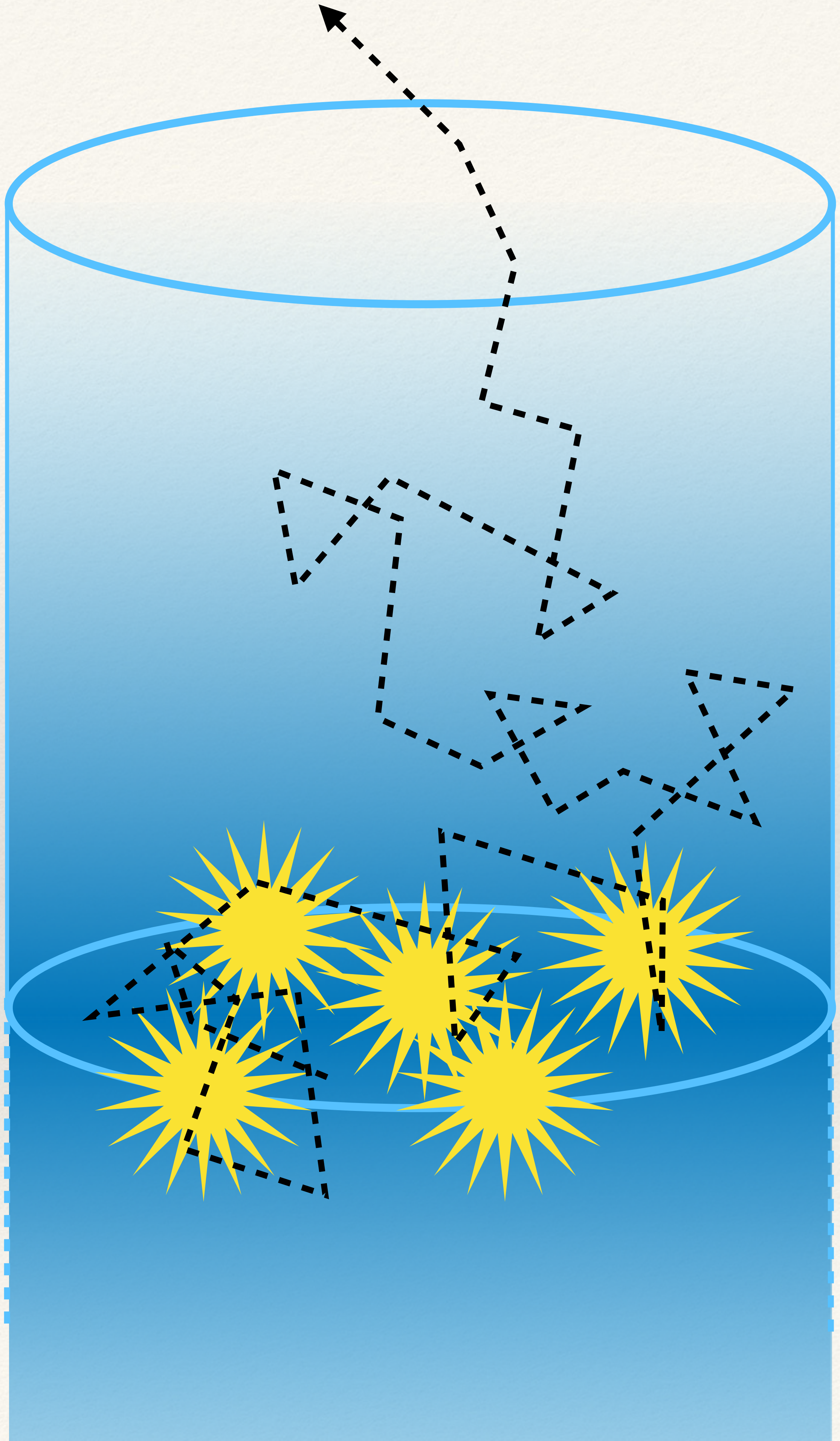
FLRW scattering length = B field coherence length:

$$l_{\mathrm{coh,B}} \simeq \frac{z_*}{M_{\mathrm{A}}^3},$$

So effective diffusion coefficient is:

$$\kappa \simeq v_{A,i} \frac{l_{\mathrm{coh,B}}}{3}.$$

Application: stability of star-forming gas column subject to CR flux



Midplane star formation

Coupled ODEs:

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4{\tau_s}^2\left(\frac{ds}{d\xi}\right)^{\beta}p_c - \tau_{\mathrm{path}}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

Transport/loss equation

diffusive transport

Fermi-II

hadronic losses

streaming losses

$$\frac{dp_c}{d\xi} + \xi_{\mathrm{turb}}\frac{d^2 s}{d\xi^2} = -\left(1 - f_{\mathrm{gas}}\right)\frac{ds}{d\xi} - f_{\mathrm{gas}}s\frac{ds}{d\xi}$$

Hydrostatic balance

CR pressure gradient

turbulent pressure gradient

stellar gravity

gas self gravity

+ 4 BCs

Coupled ODEs:

ξ: height

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4{\tau_s}^2\left(\frac{ds}{d\xi}\right)^{\beta} p_c - \tau_{\rm path}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

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s: gas column (ds/dξ: gas density), p_c: cosmic ray pressure

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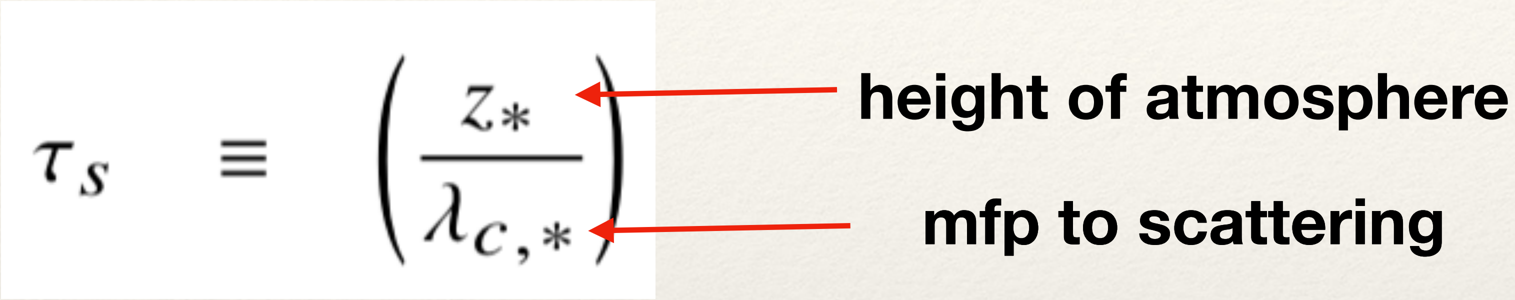


$$\tau_s \equiv \left(\frac{z_*}{\lambda_{c,*}}\right)$$

height of atmosphere

mfp to scattering

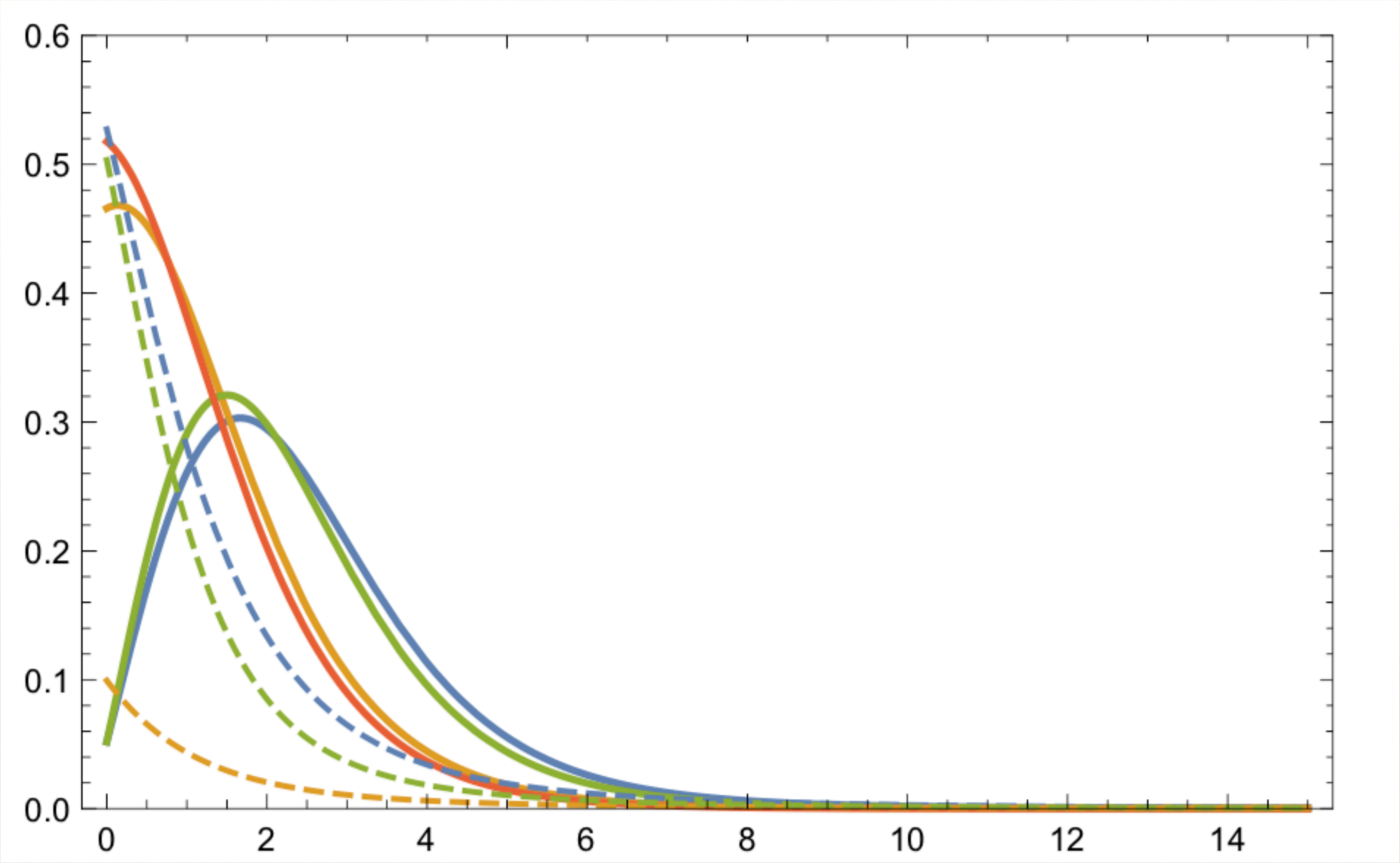
optical depth to scattering

$$\tau_{\rm path} \equiv \frac{\tau_s \tau_{\rm pp}}{\beta_{A,i}}$$

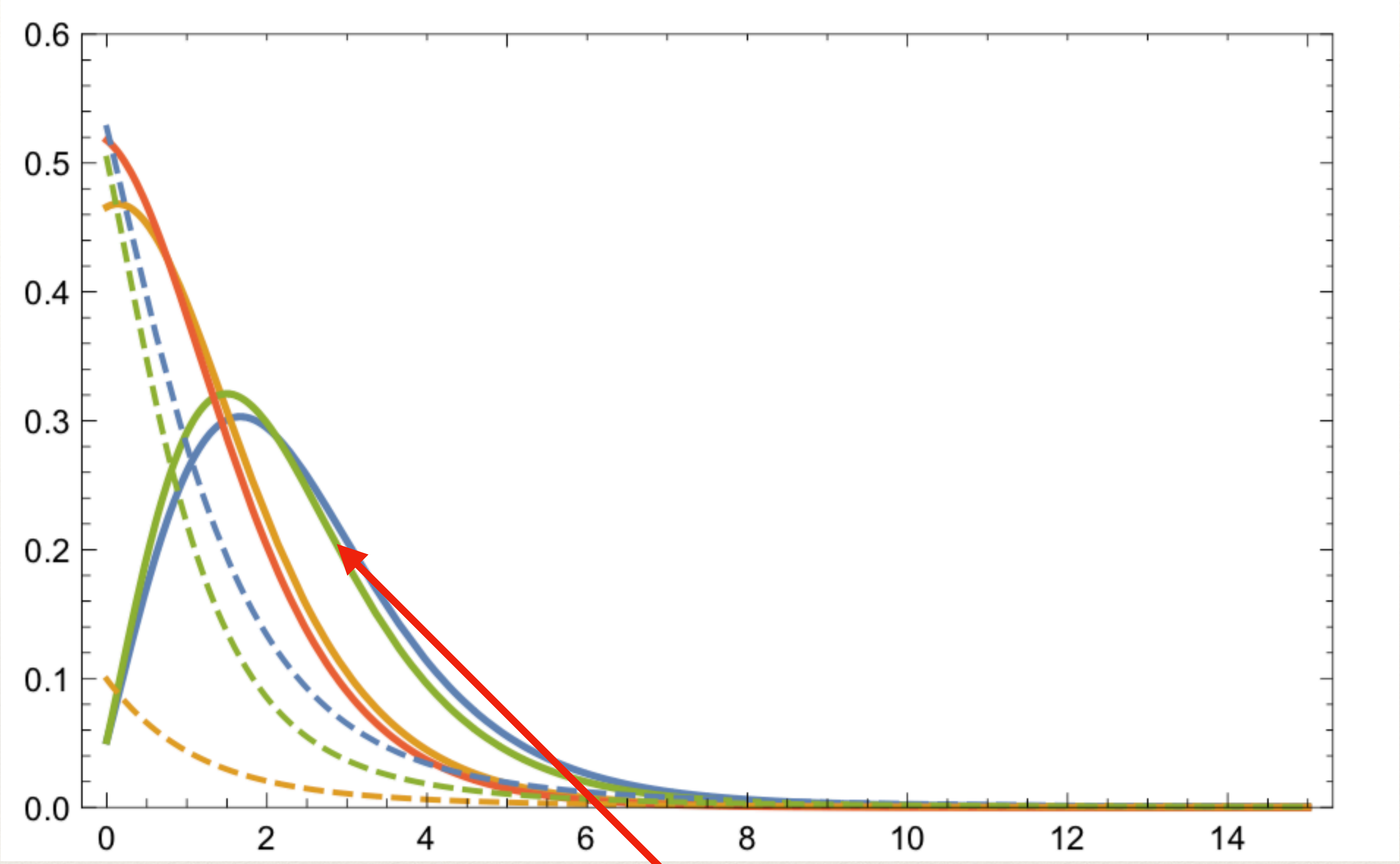
rectilinear optical depth

ion Alfven speed

optical depth to absorption over path



Numerical solutions give gas number density and cosmic ray pressure profiles



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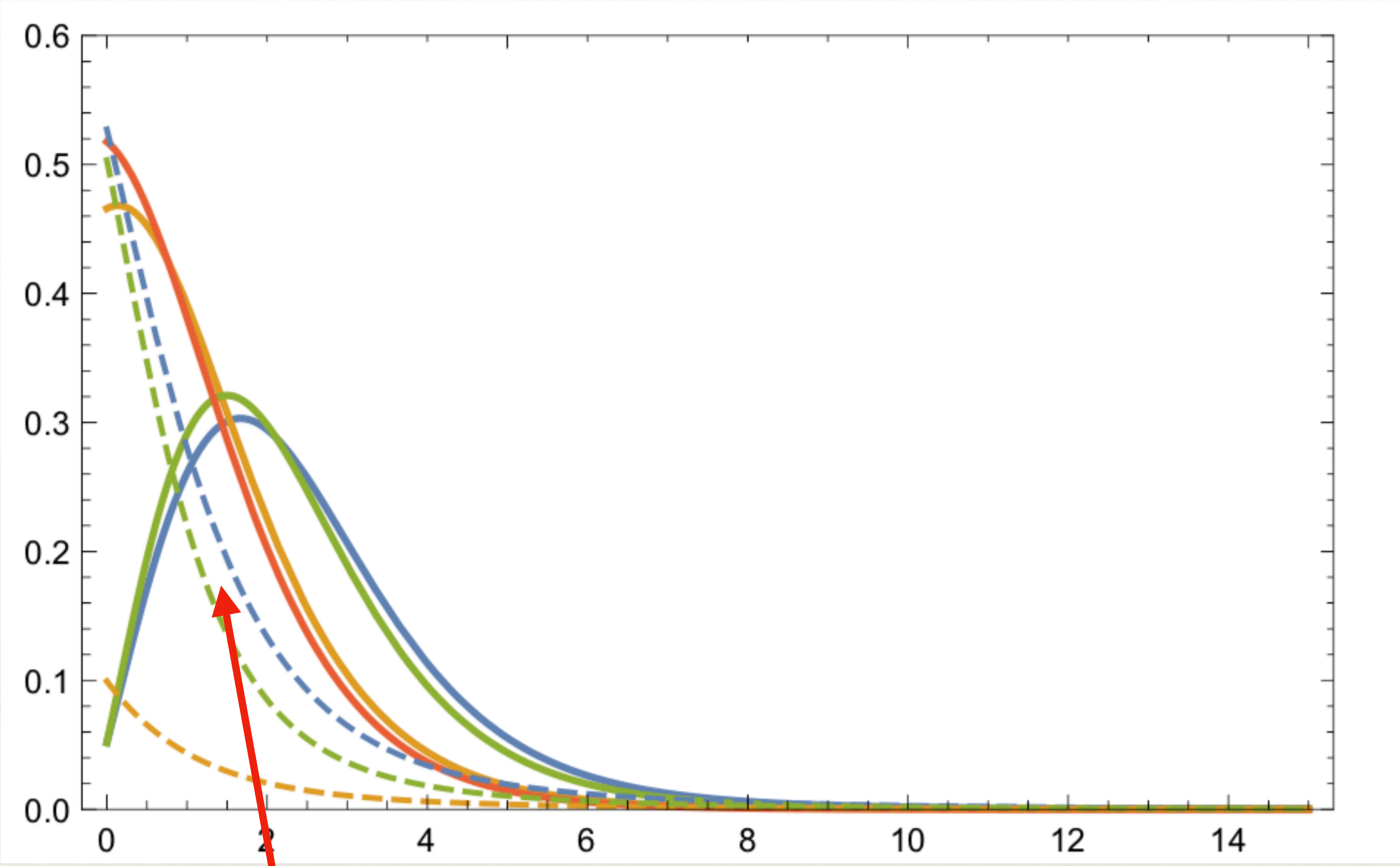

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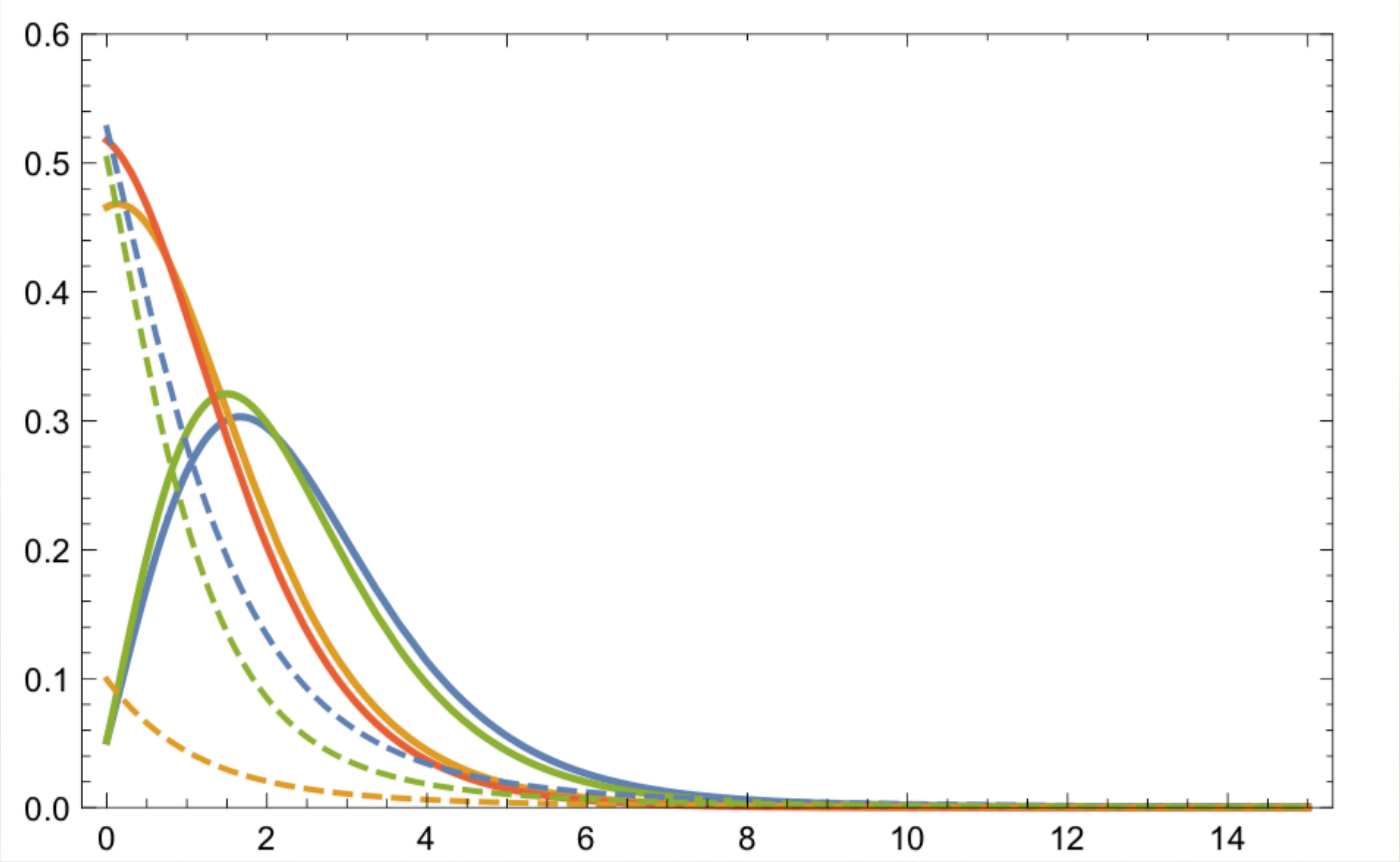

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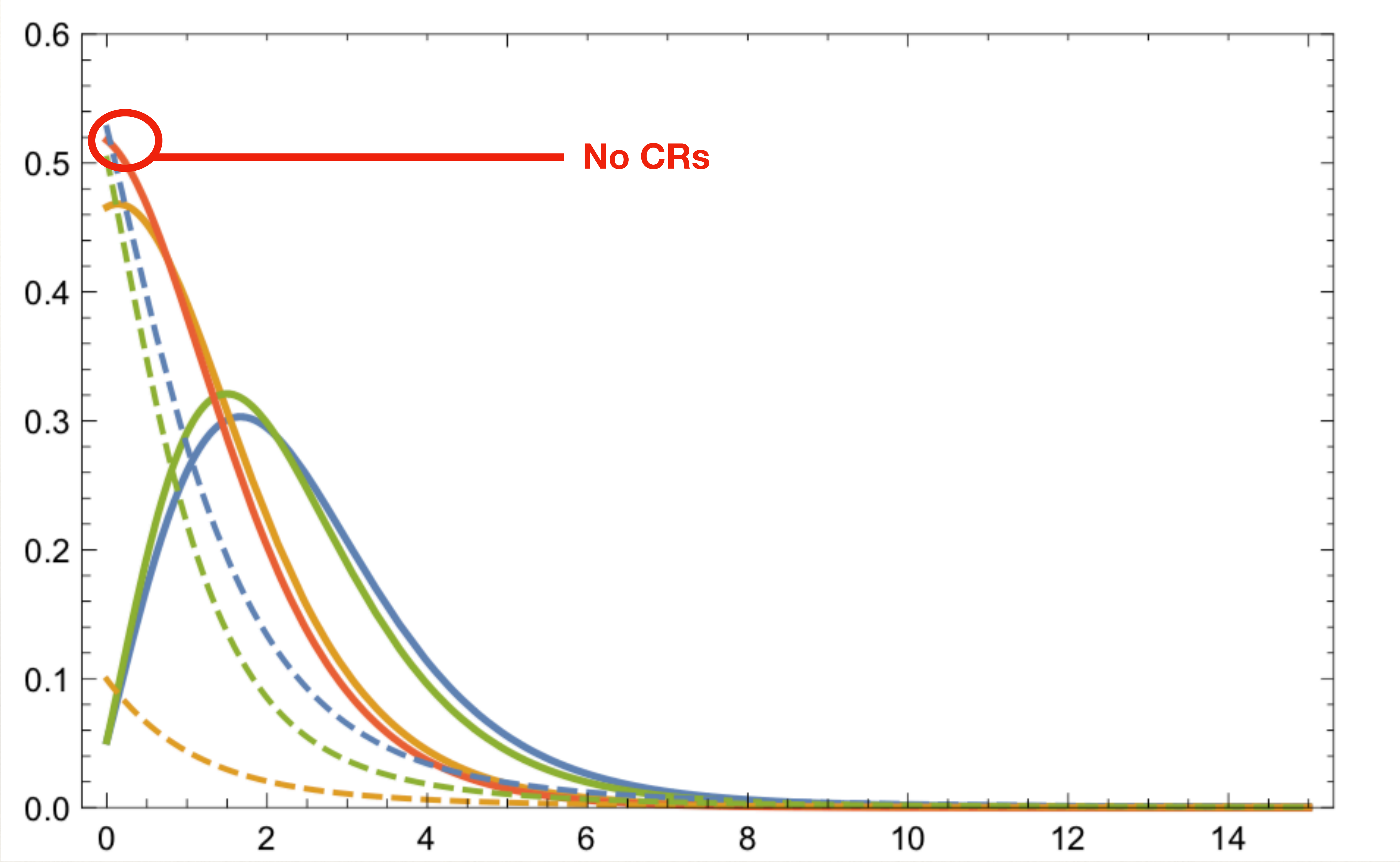

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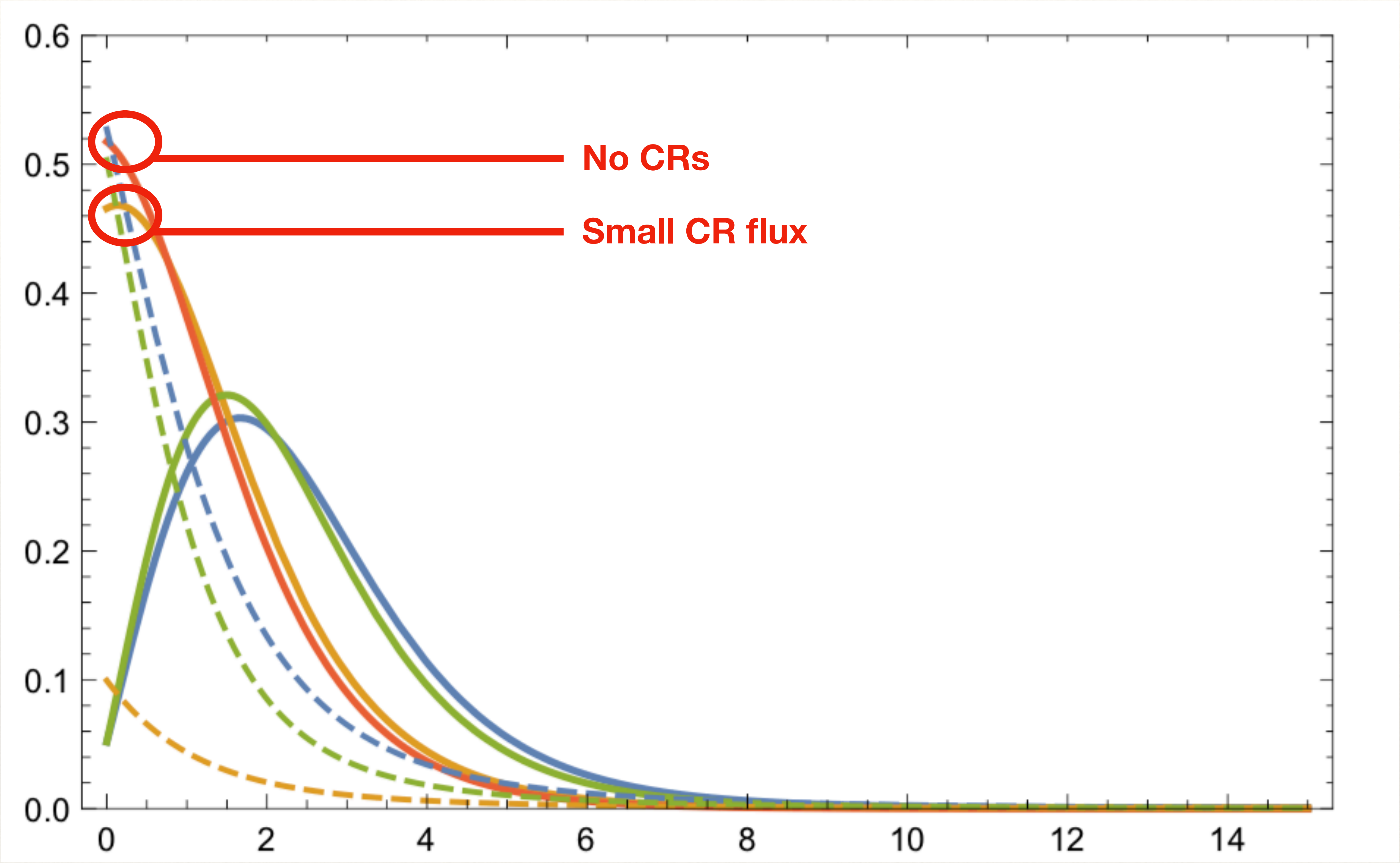

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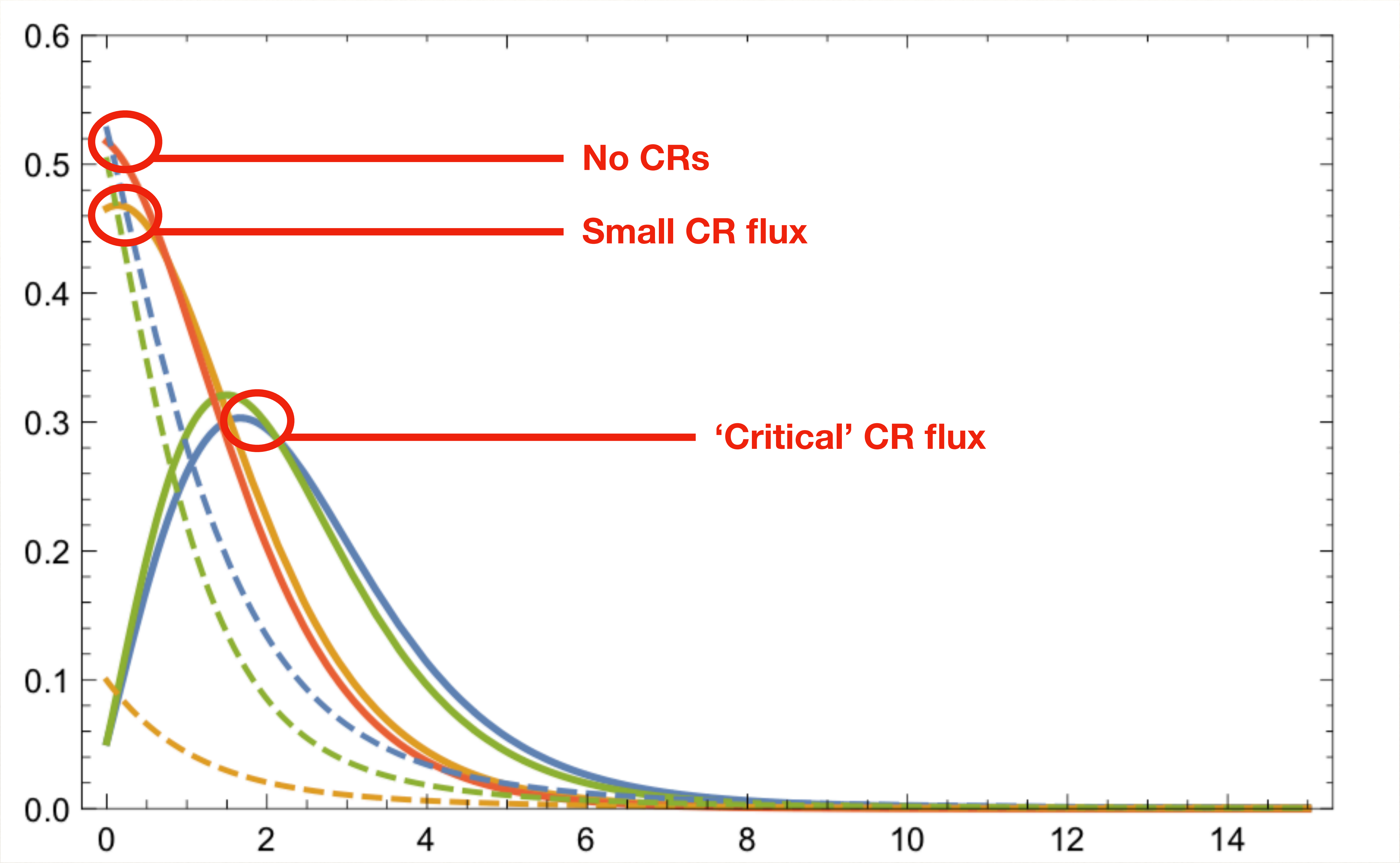
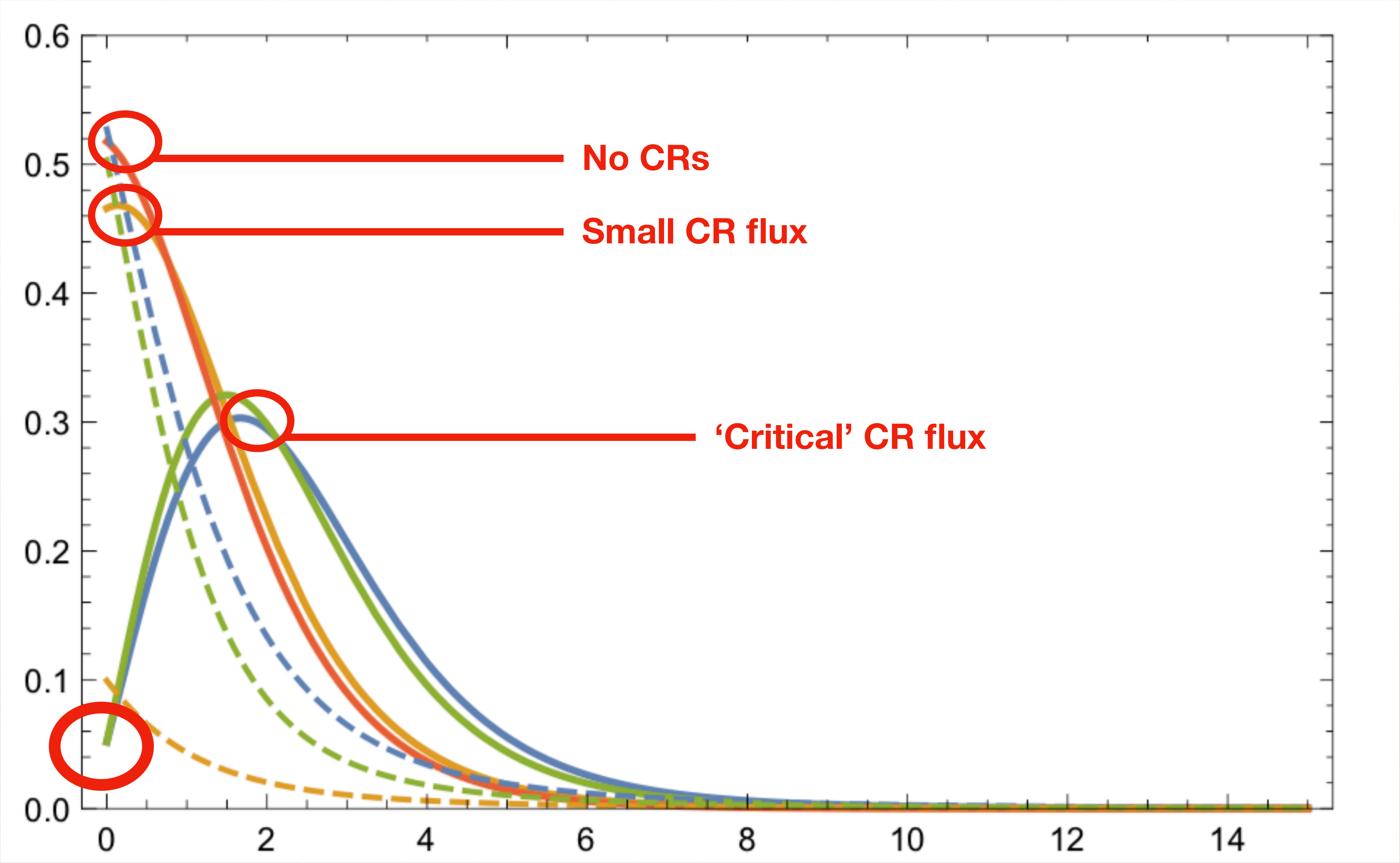


No CRs

Small CR flux

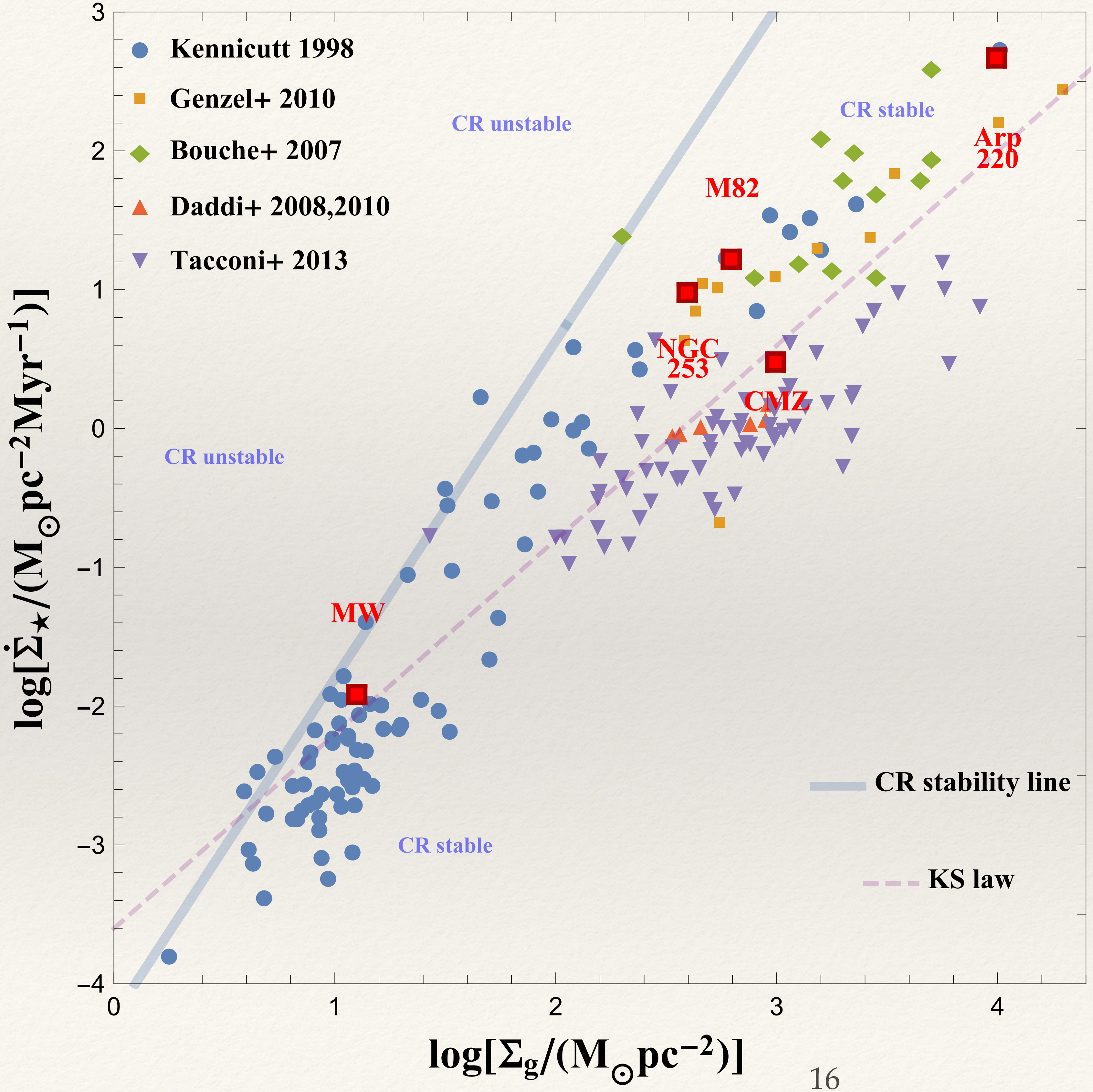
'Critical' CR flux

Numerical solutions give gas number density and cosmic ray pressure profiles



Numerical solutions give gas number density and cosmic ray pressure profiles

CR stability curve in physical parameter space:



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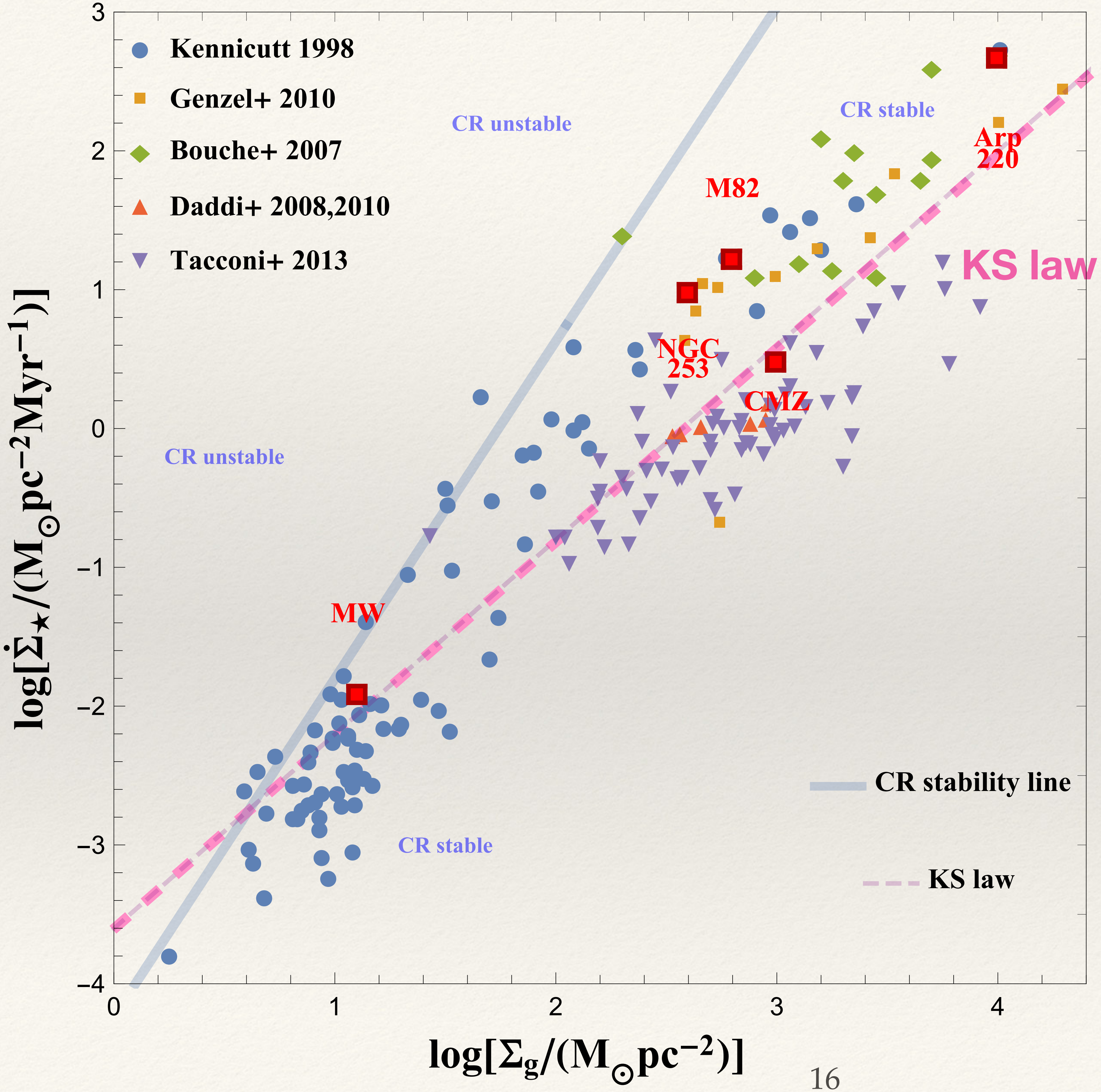

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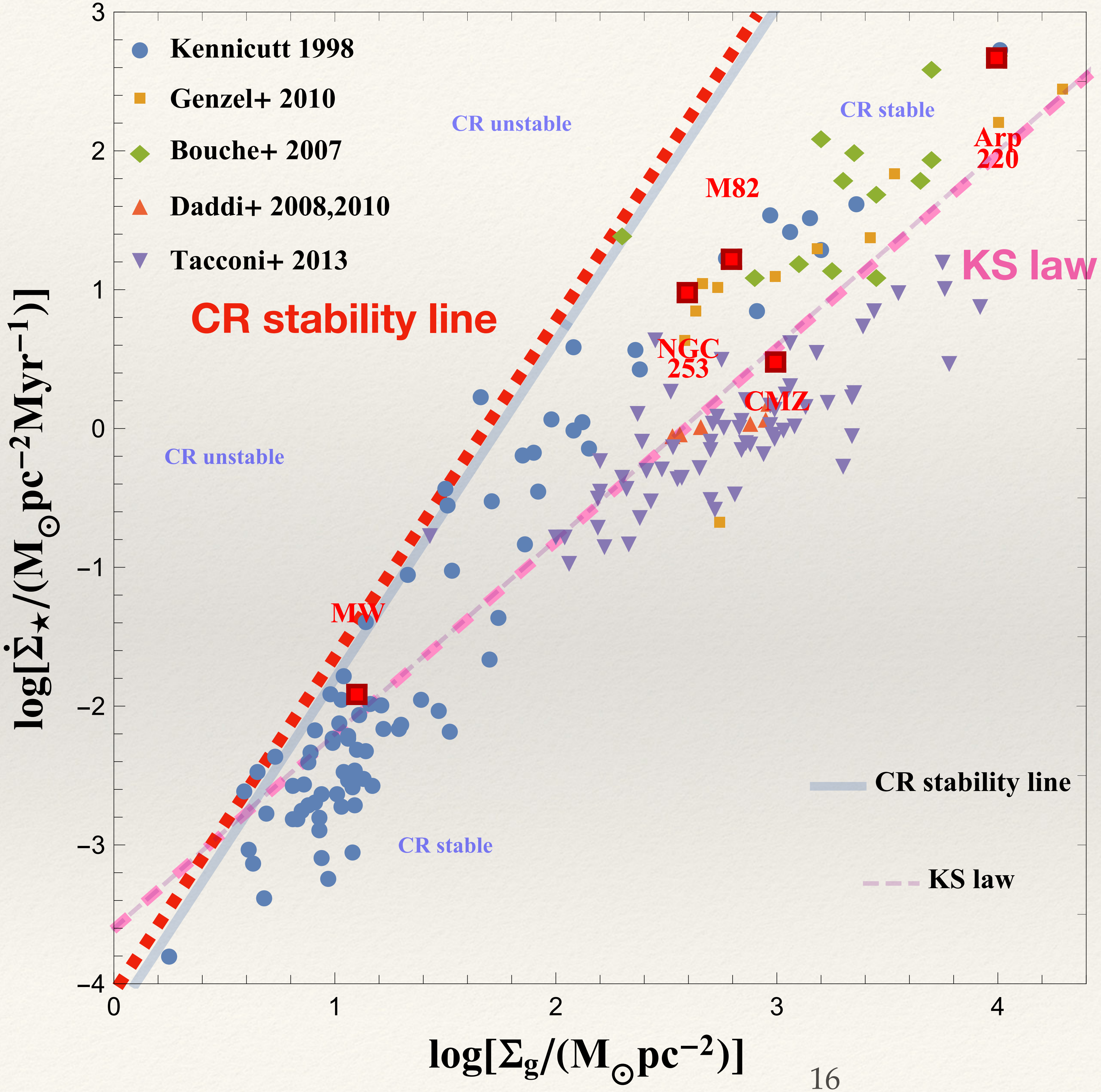

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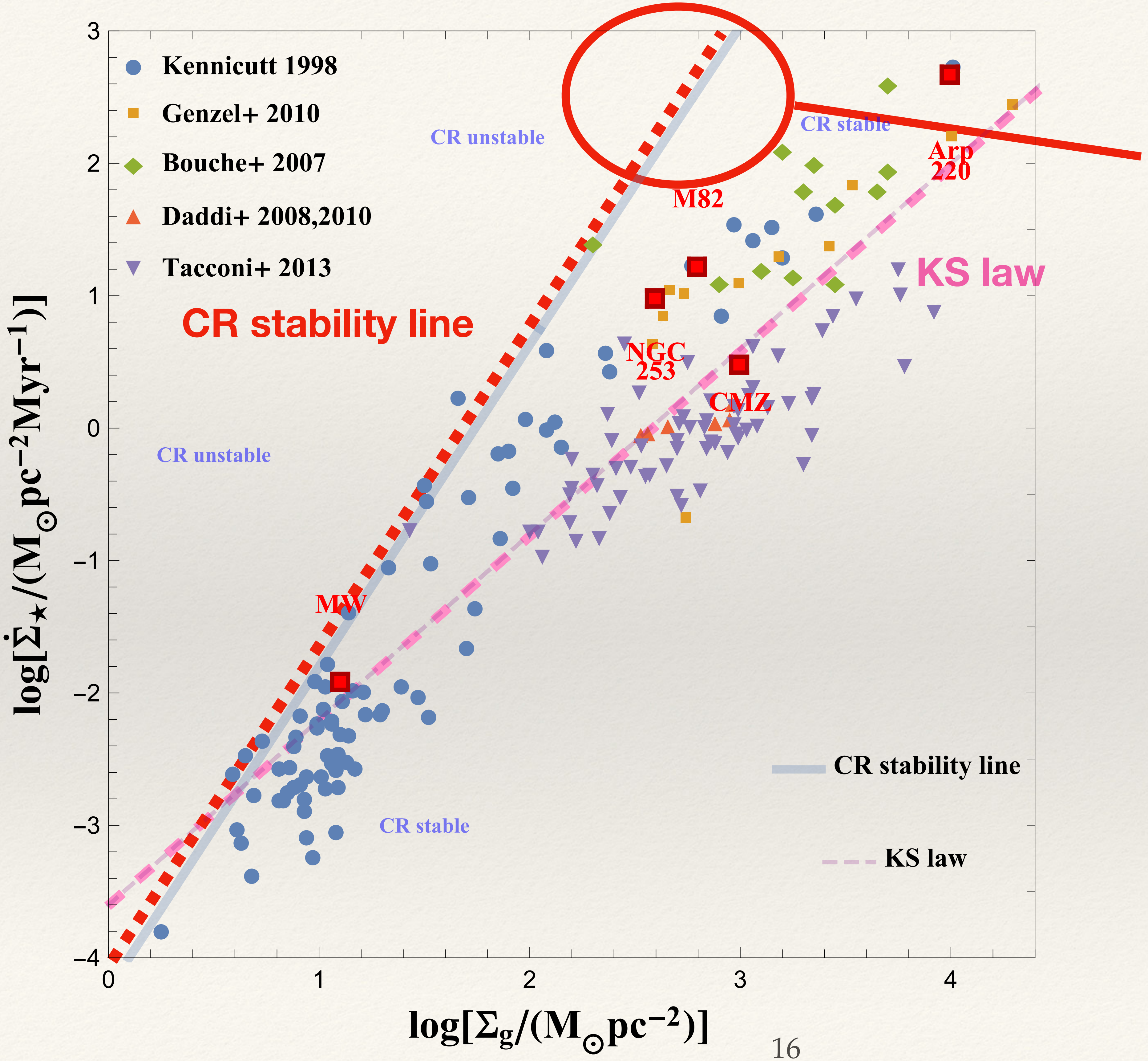

CRs NOT dynamically important in starbursts

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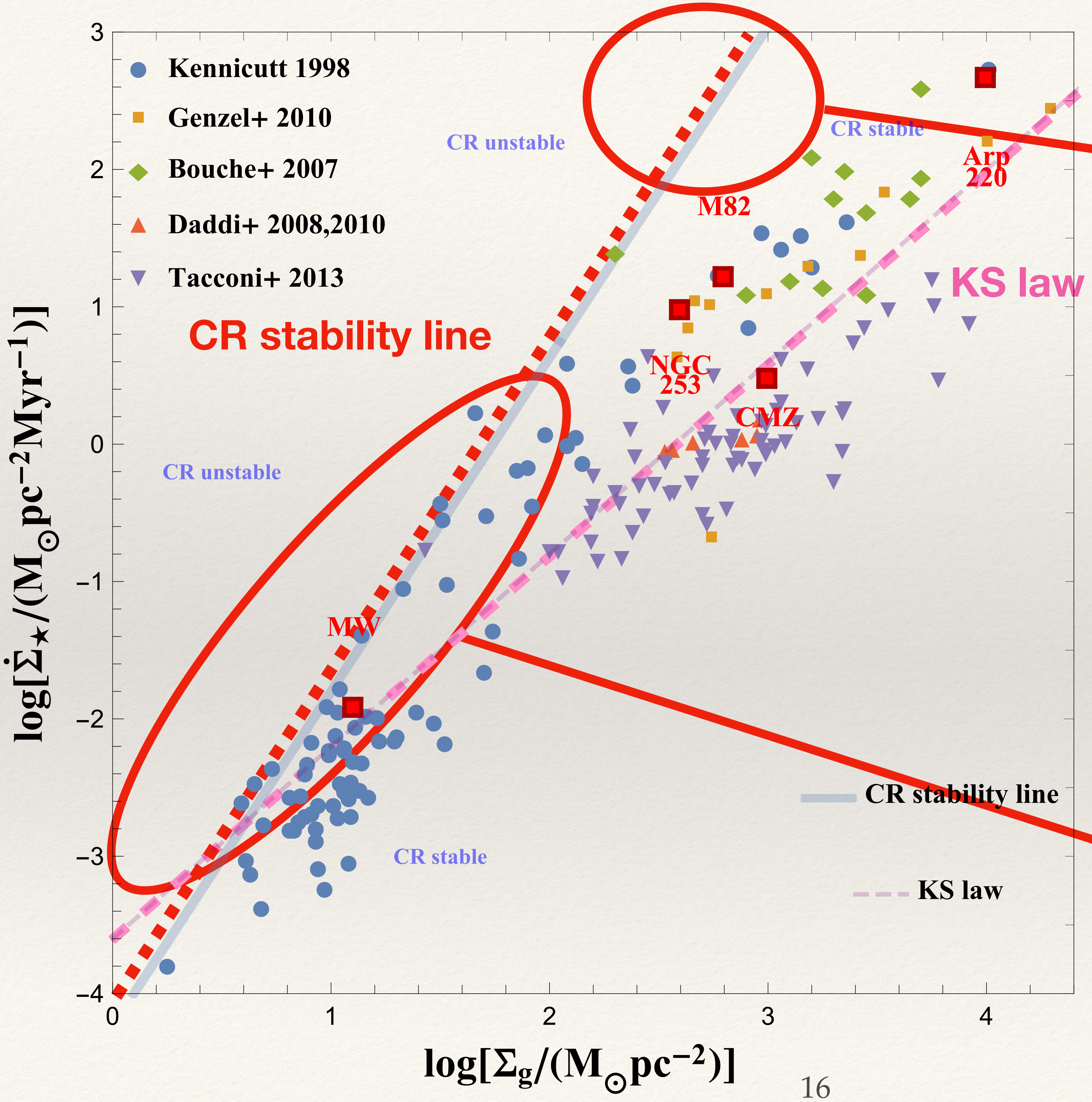

CRs NOT dynamically important in starbursts

CRs dynamically important in ‘ordinary’ galaxies

Summary

- In the dense, star-forming ISM phase, ~GeV CR transport is described by field line random walk at the **ion** Alfven speed v_{Ai}
- For most modern galaxies, star-forming galaxies ($\Sigma_{gas} < 10^{2.5}$ $M_\odot/pc^2$), CR feedback sets an ultimate limit to the star formation rate surface density