The Windows and Walls of the Labyrinth

Silvia Almada Monter
PhD Student
with Max Gronke
MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Escape of Lyman Radiation from Galactic Labyrinths, Crete,Greece,
April 9th, 2025

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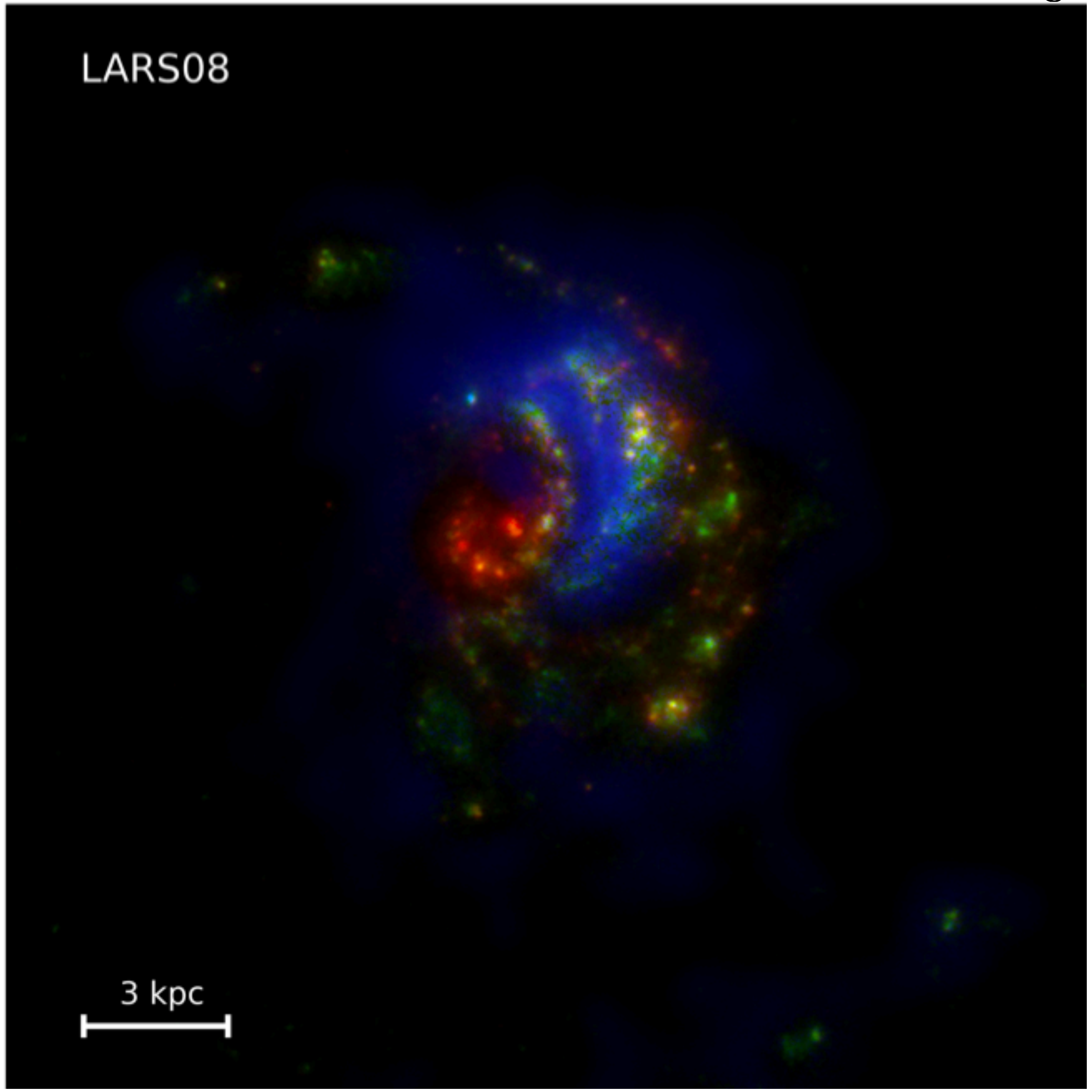
The Windows and Walls of the **Labyrinth (?)**


Melinder et al. (2023)



There's a lot of data out there!

But not a clear theoretical interpretation of Lyman α observables

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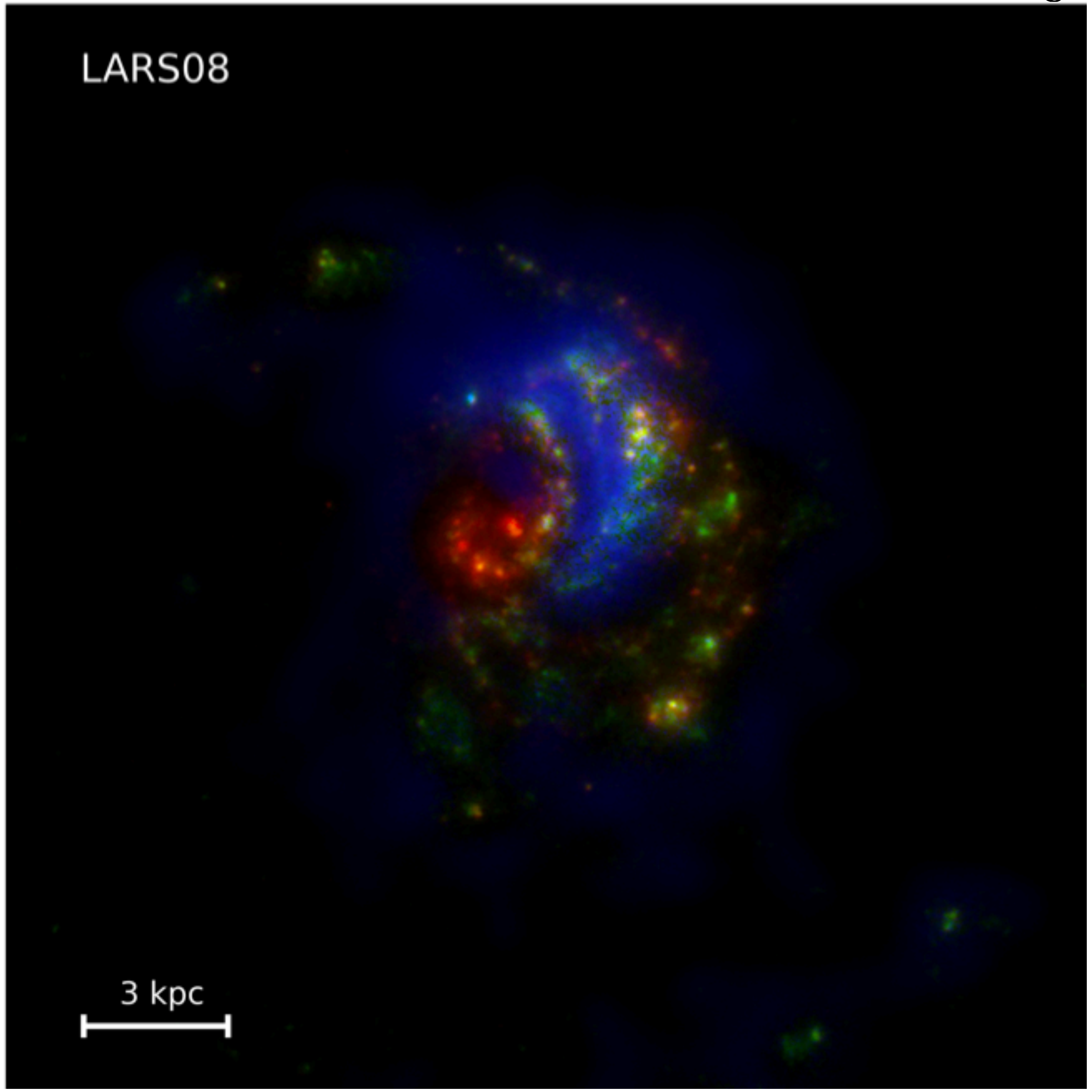

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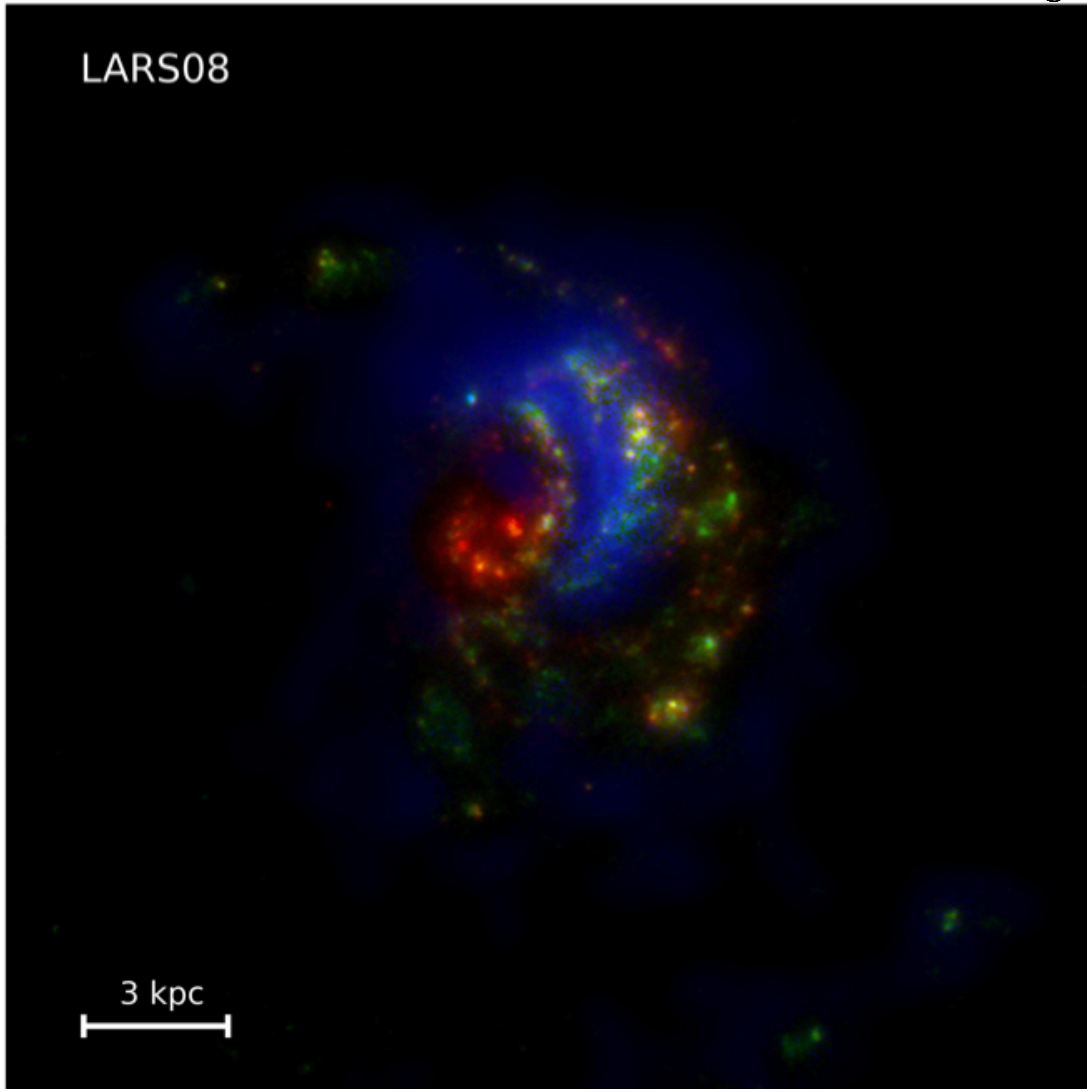

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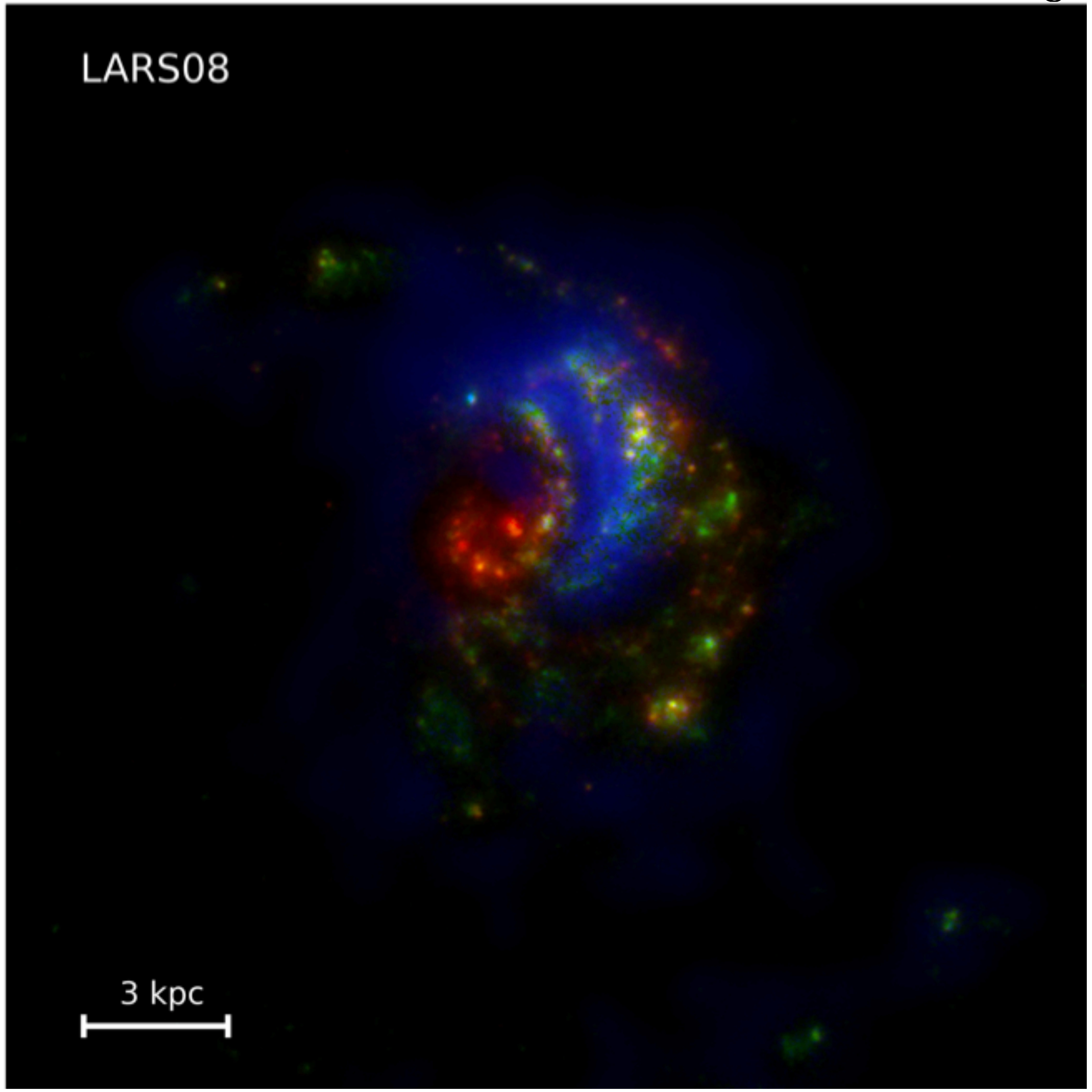

Astrophysical gas is anisotropic!

Which gas do Lyα photons really probe? Which density?

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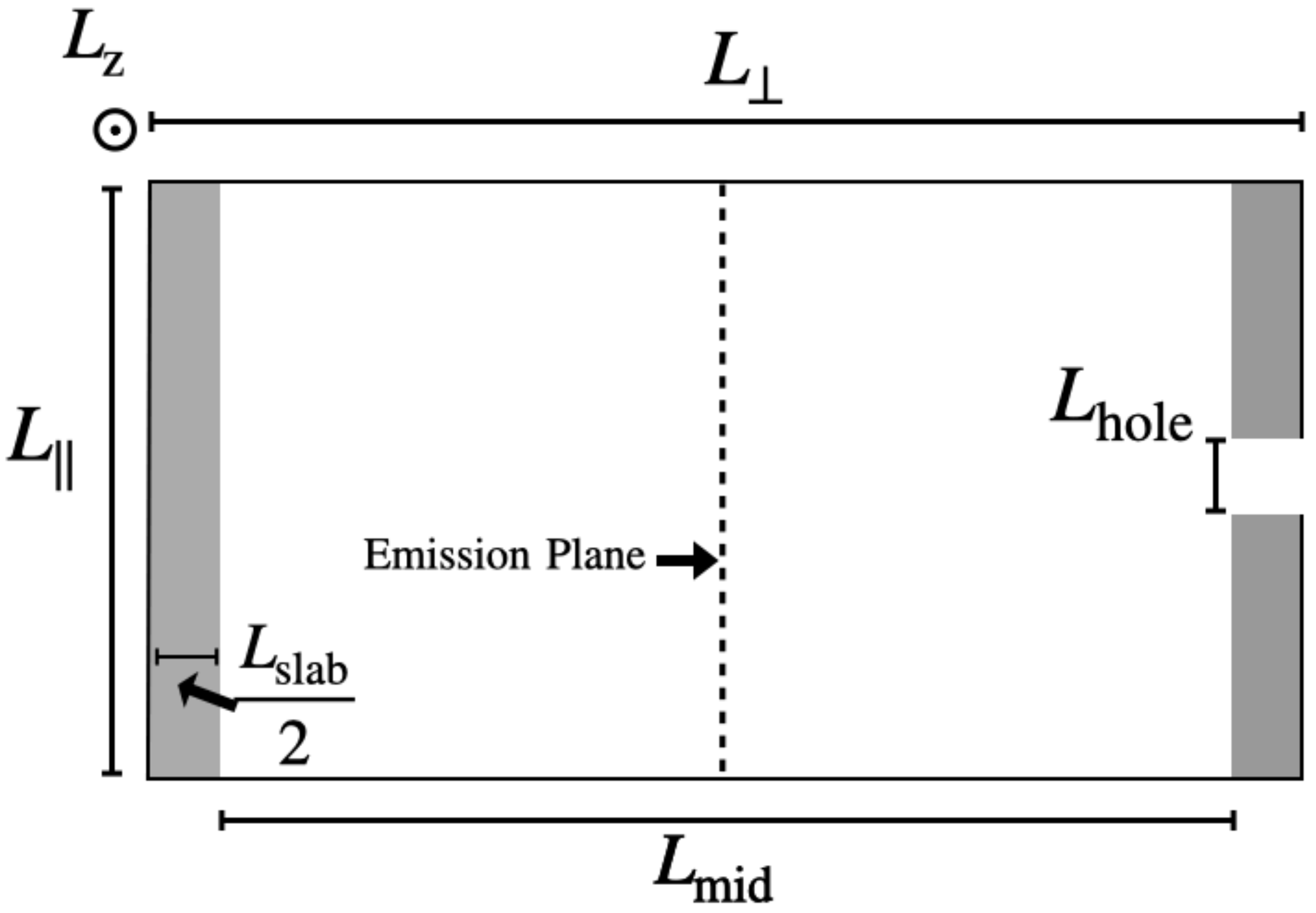
Which density?

Approach: simplified gas distribution with anisotropies



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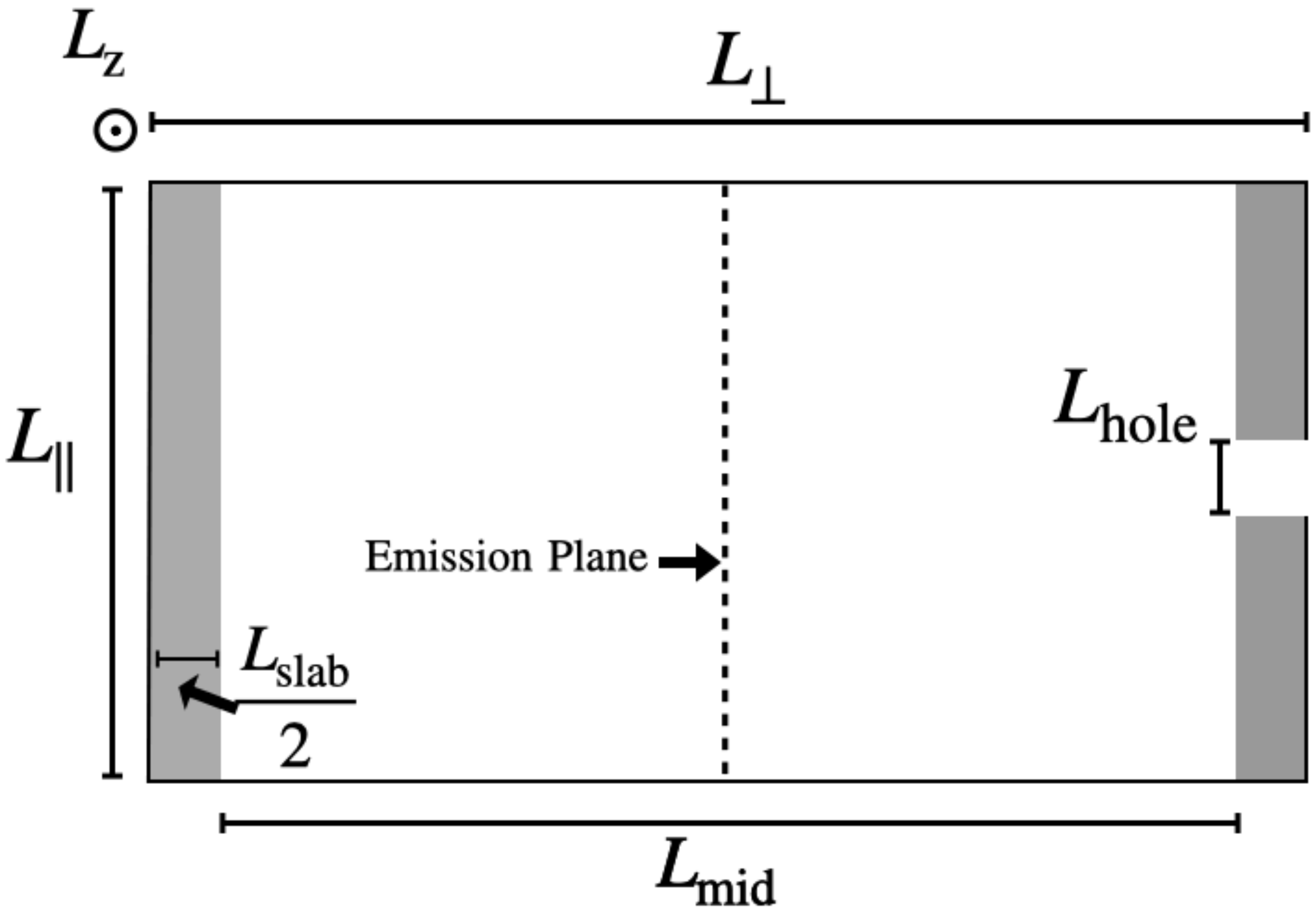
Approach: simplified gas distribution with anisotropies

Semi-infinite slab, Monte Carlo RT



Area Fraction

$$\tilde{s} = \frac{L_{hole}^2}{L_\parallel L_z}$$

$$\tilde{f} = \frac{F_{hole}}{F_{slab}}$$

To quantify the flux escaping from the slab and from the hole

What do we expect?...

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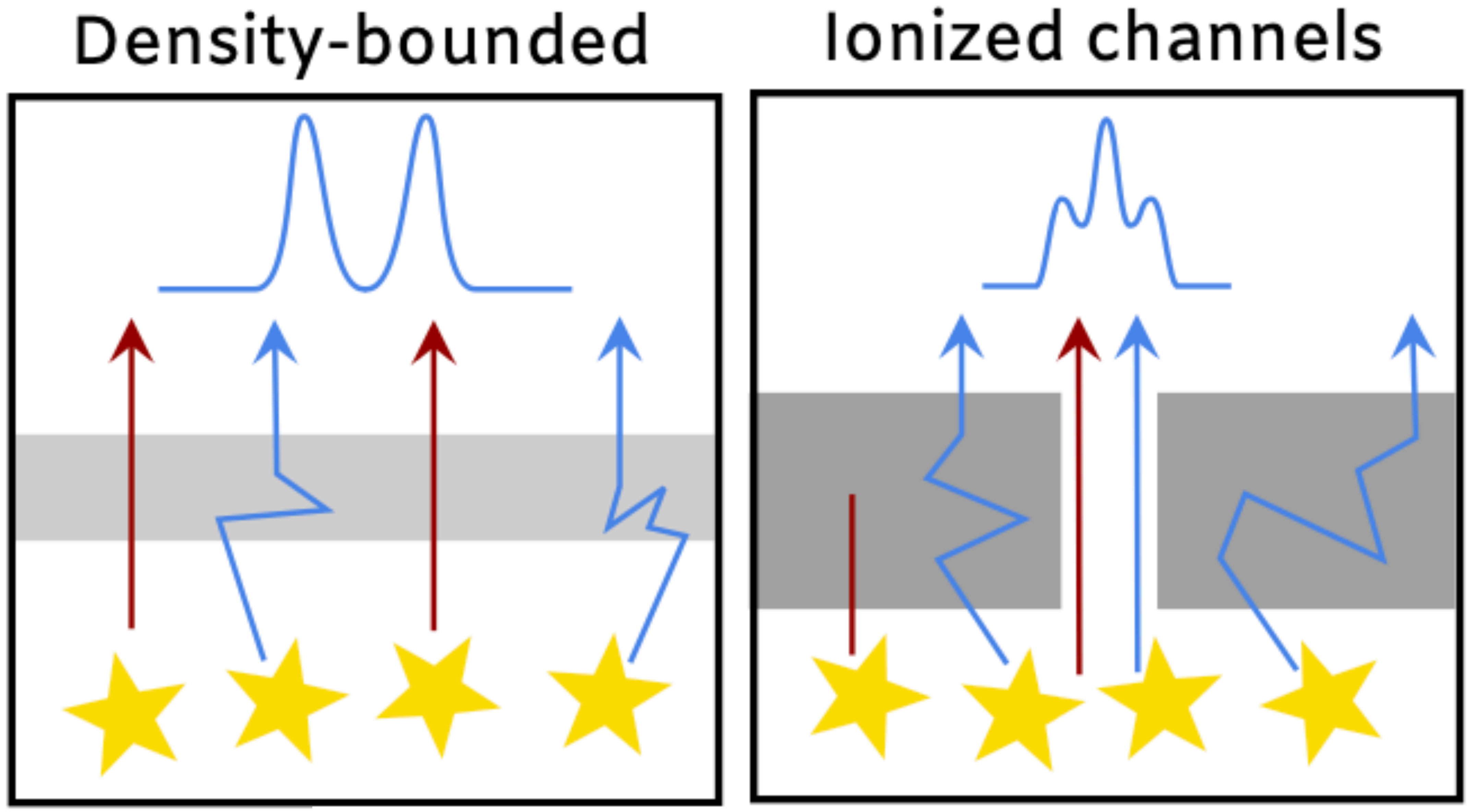

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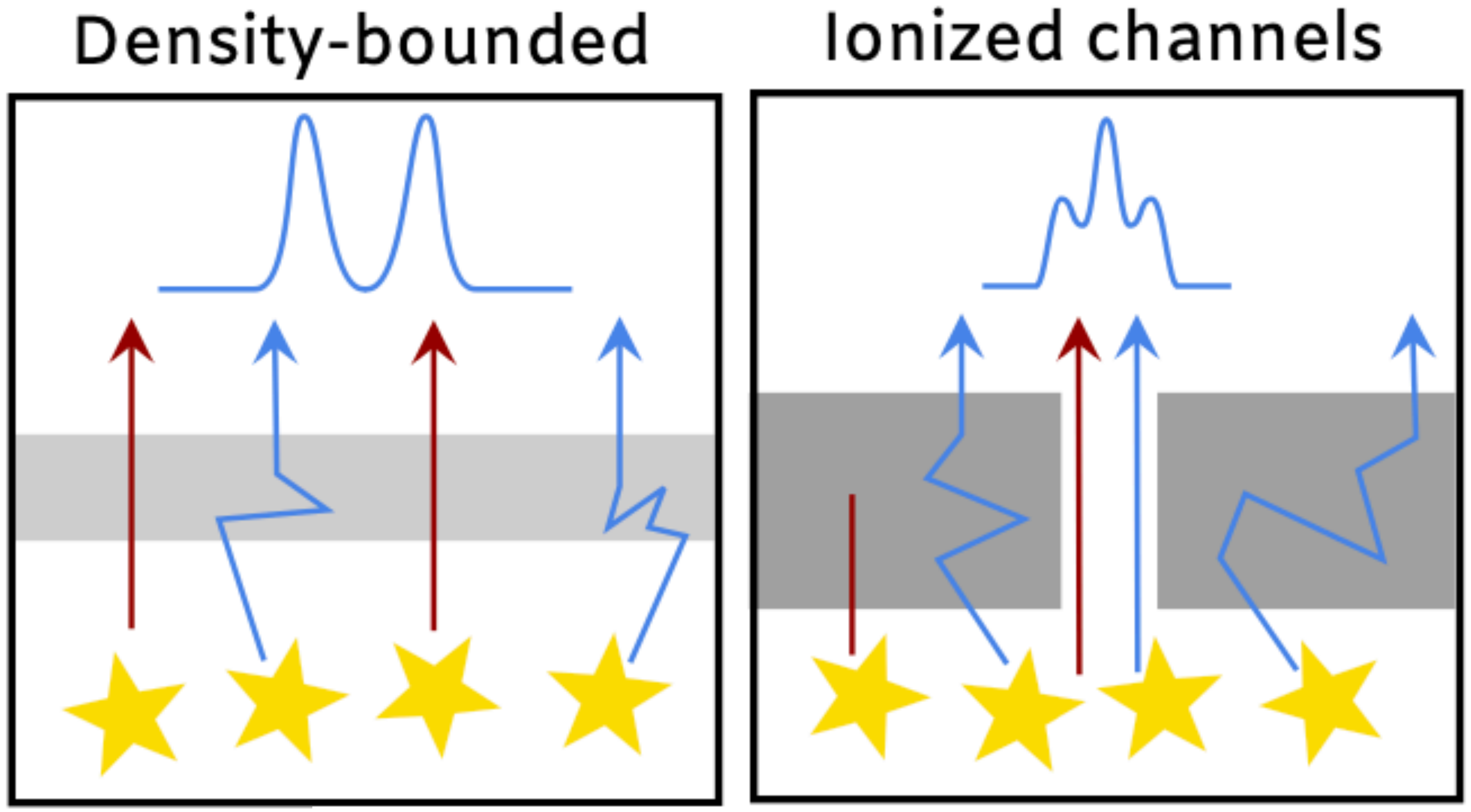

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$$F_{Slab} = \frac{4}{3\tau} \simeq \tau^{-1}$$

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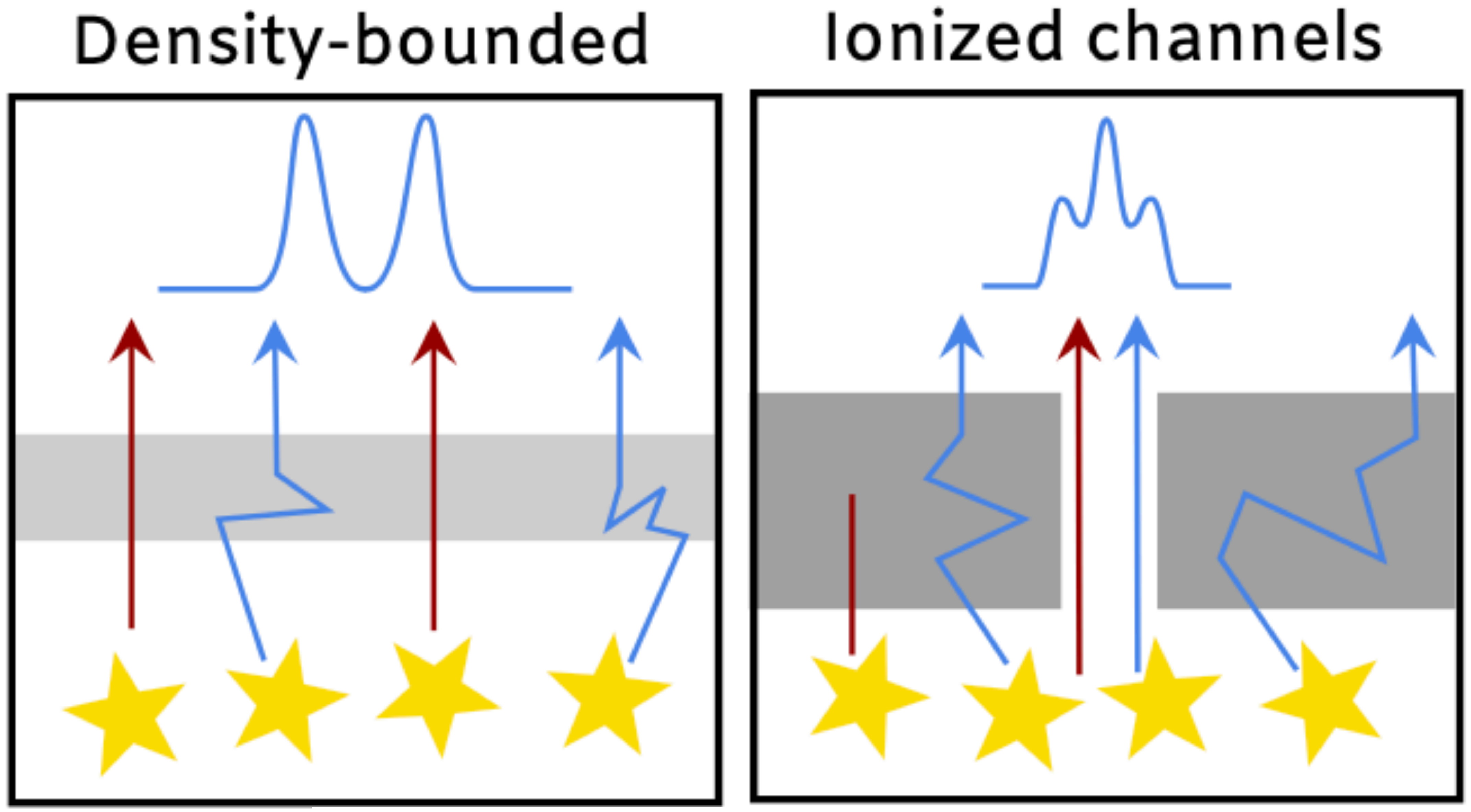

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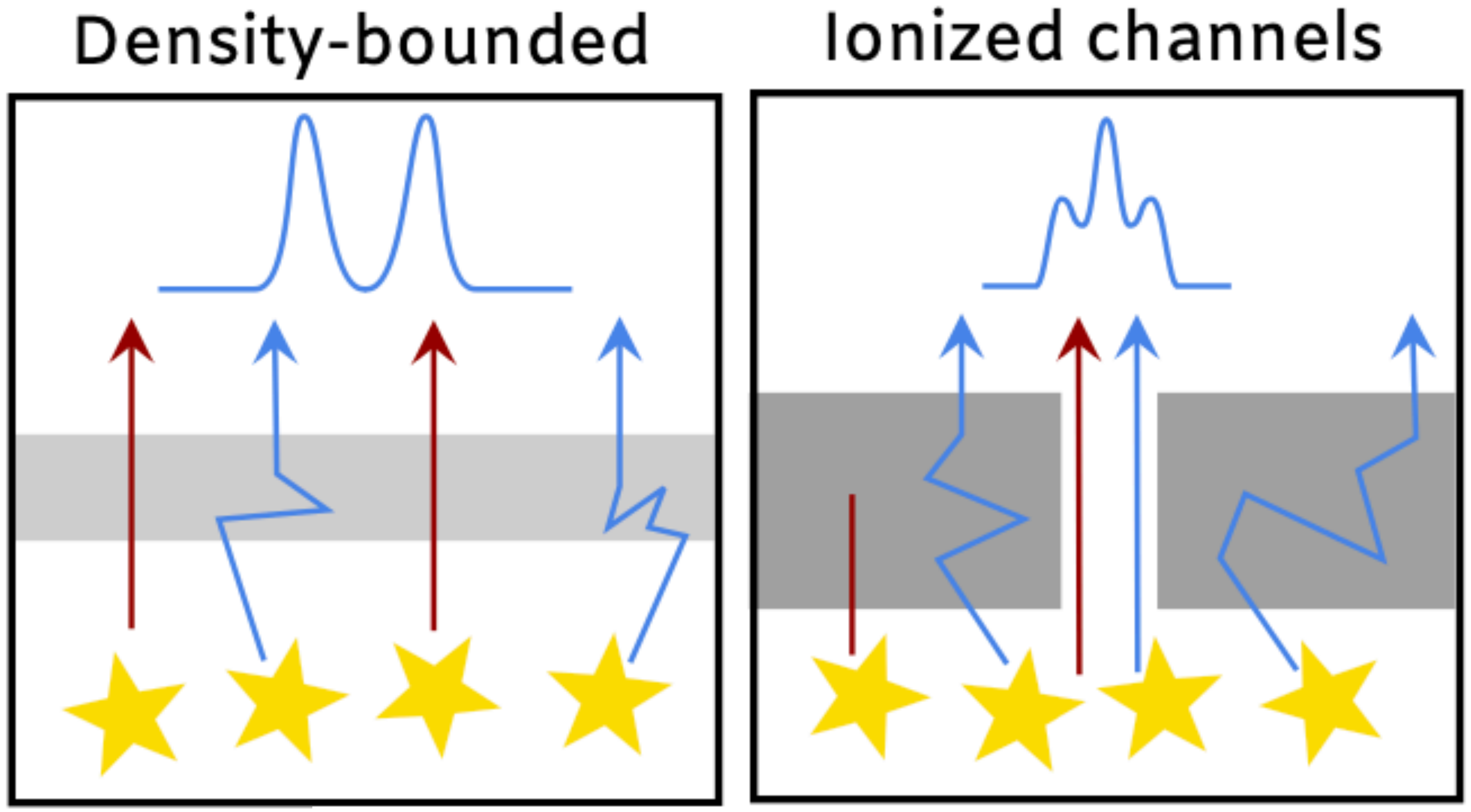

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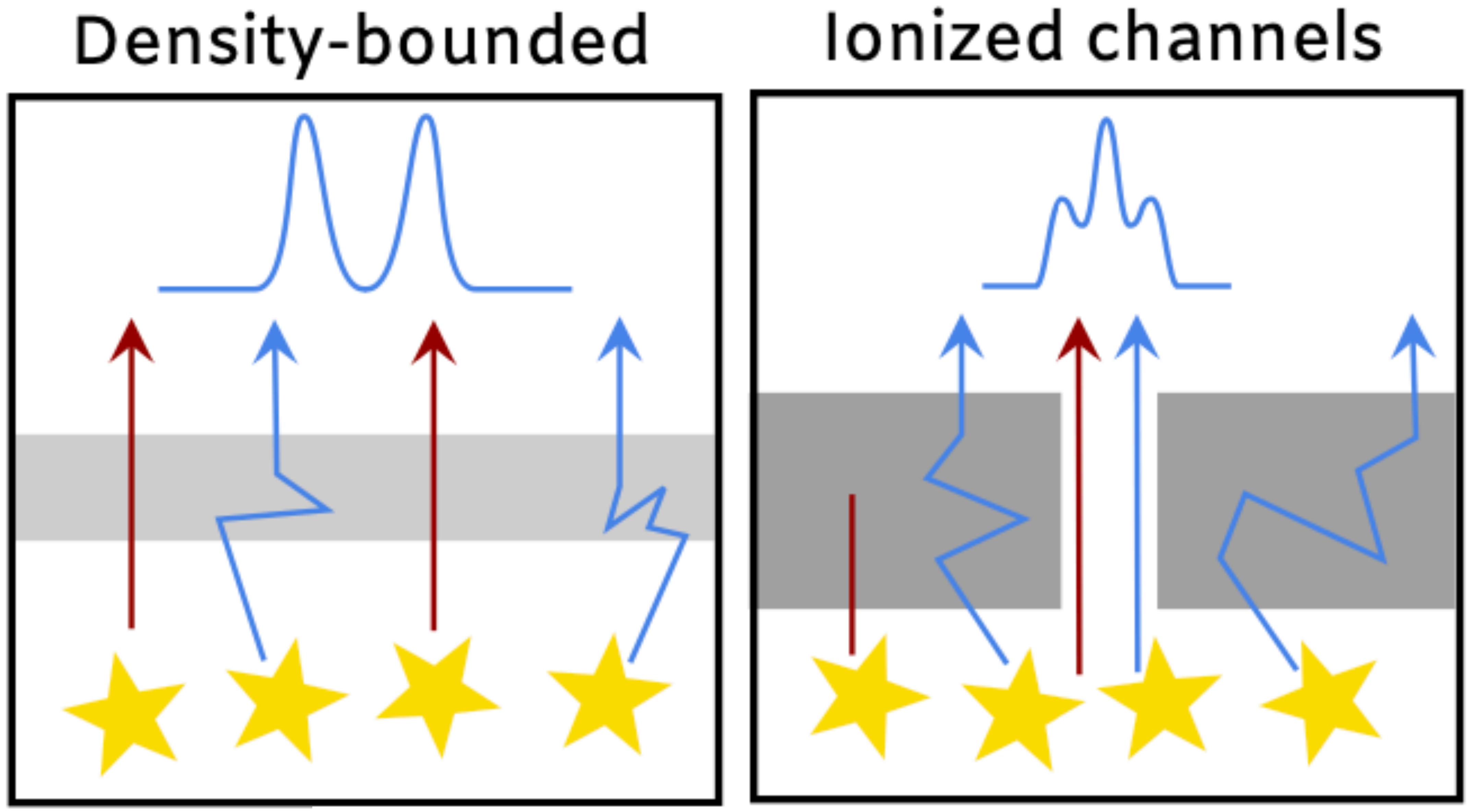

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$$\tilde{f} = \frac{F_{\text{hole}}}{F_{\text{slab}}} \simeq \tilde{s}\tau$$

$$\tau \simeq 10^5$$
$$\tilde{s} \simeq 0.1$$

$$\Rightarrow \tilde{f} \simeq 10^4$$

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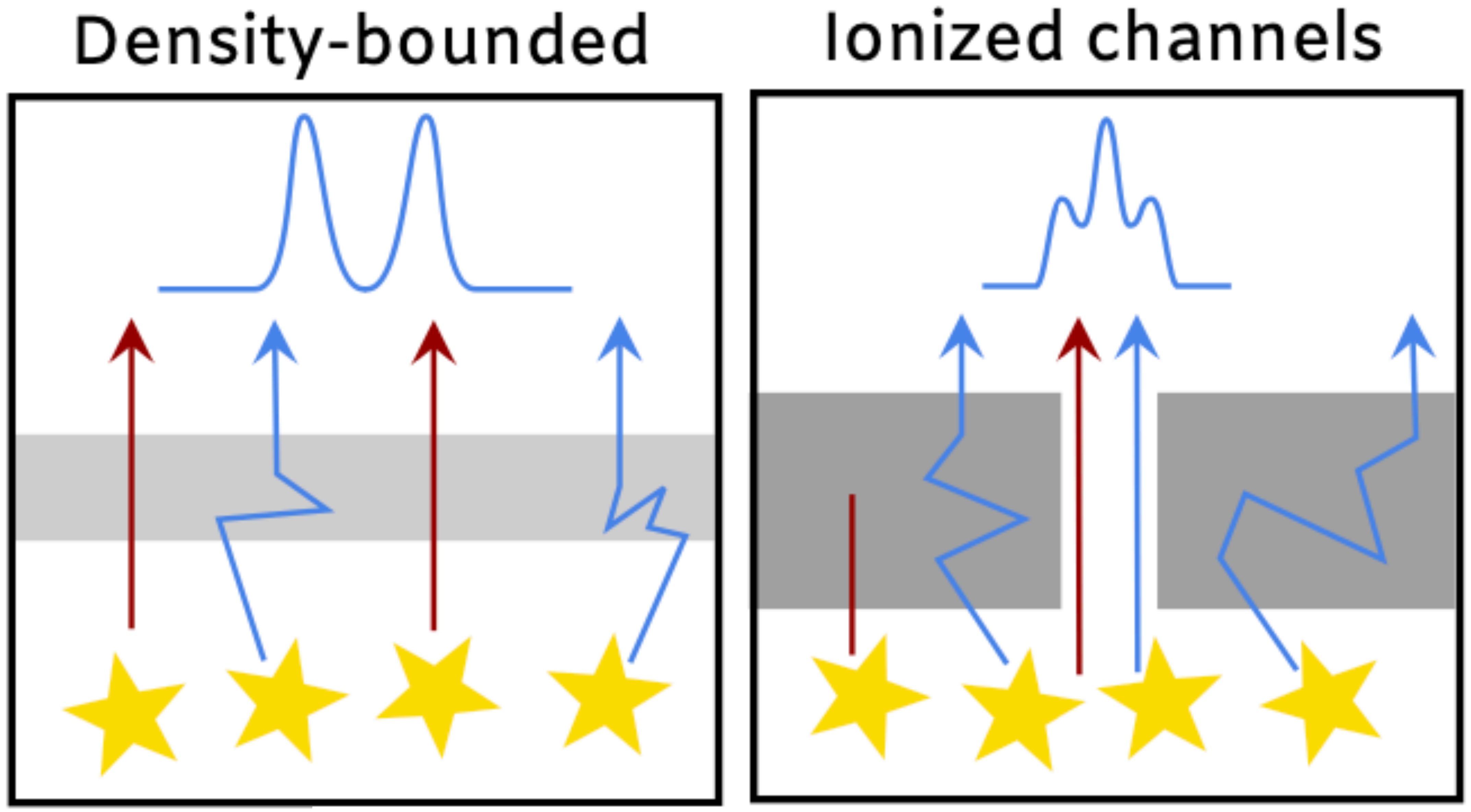

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$$F_{hole} \simeq \tilde{s}$$

Expectation: Large peaks close to the line center! Almost no red an blue peaks

The outcome…

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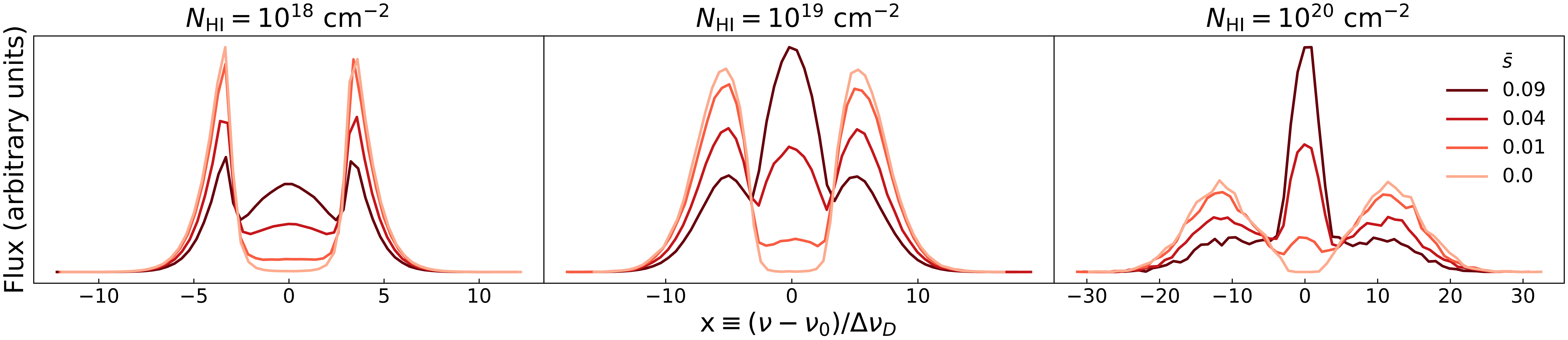
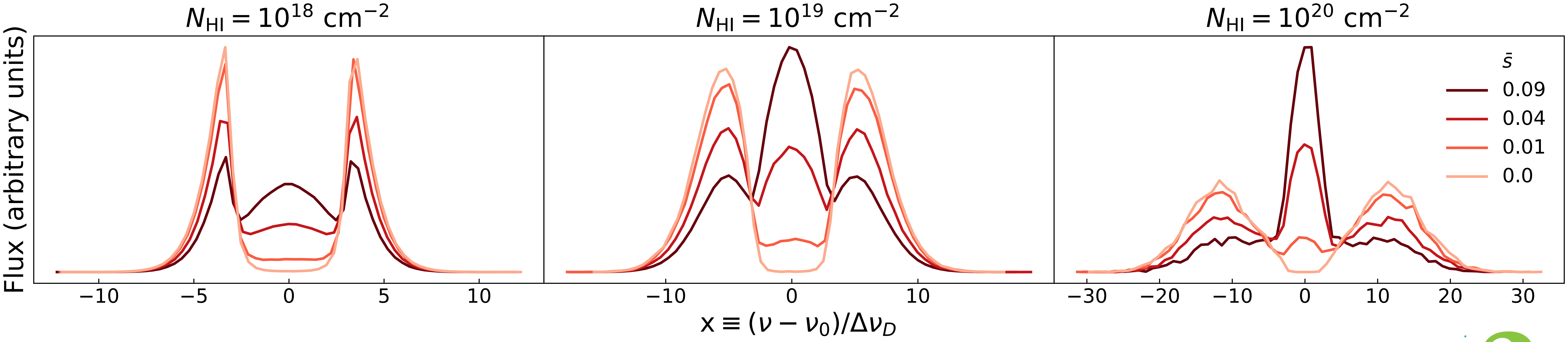


$N_{HI} = 10^{18}$ cm^{-2}
$N_{HI} = 10^{19}$ cm^{-2}
$N_{HI} = 10^{20}$ cm^{-2}
Flux (arbitrary units)
$\bar{s}$
0.09
0.04
0.01
0.0
−10
−5
0
5
10
−10
0
10
−30
−20
−10
0
10
20
30
$x \equiv (\nu - \nu_0)/\Delta\nu_D$

The outcome...



Huh? Triple peaks?

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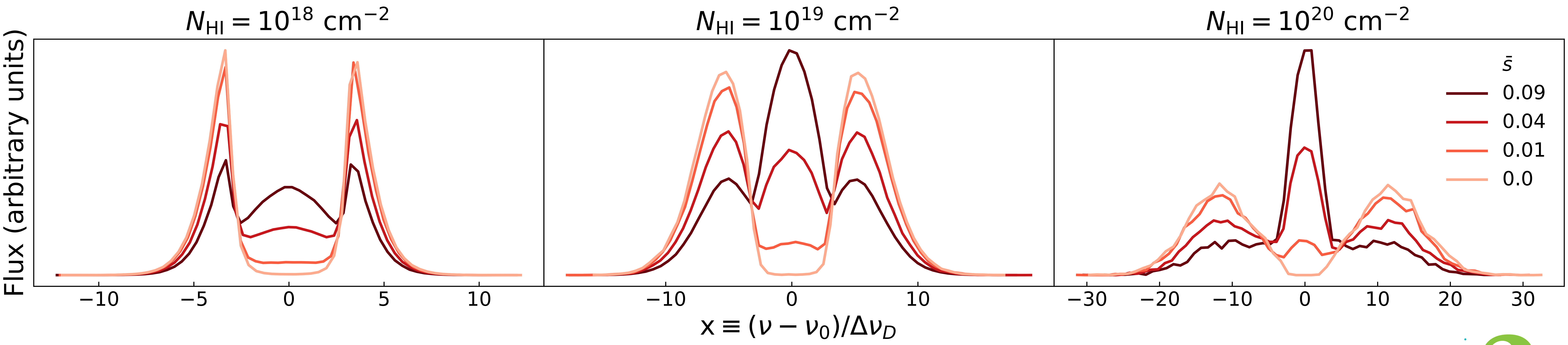

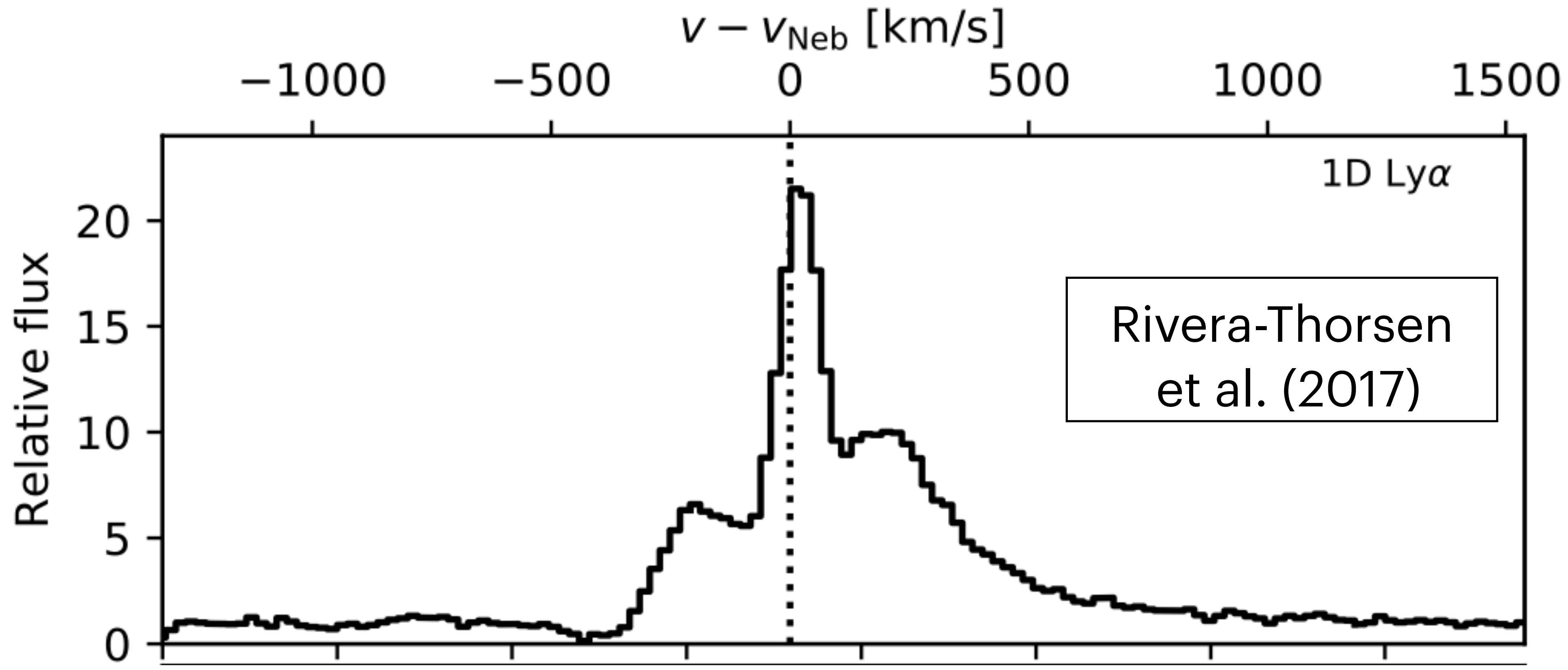

Huh? Triple peaks?

✓ Yes, there are some (rare) observed cases (Sunburst Arc)

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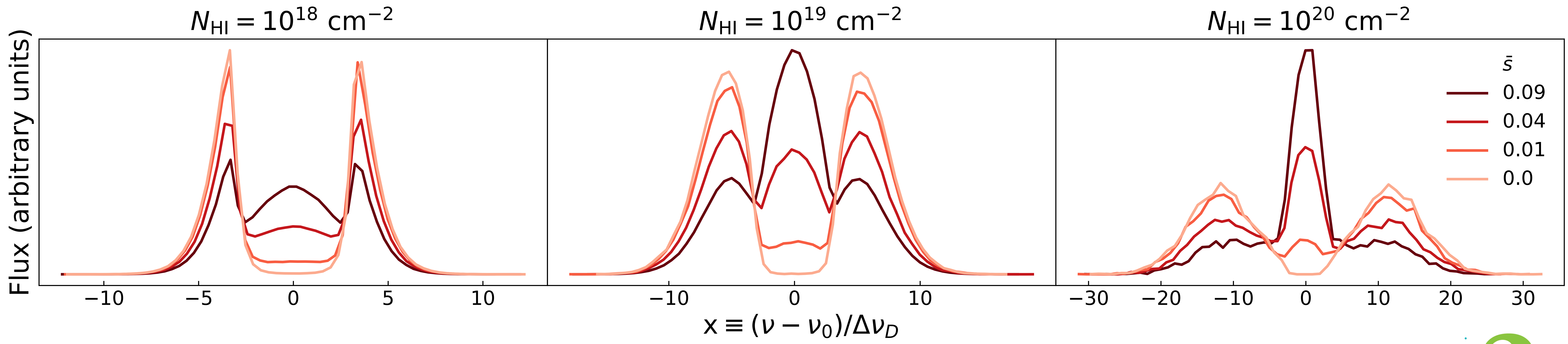

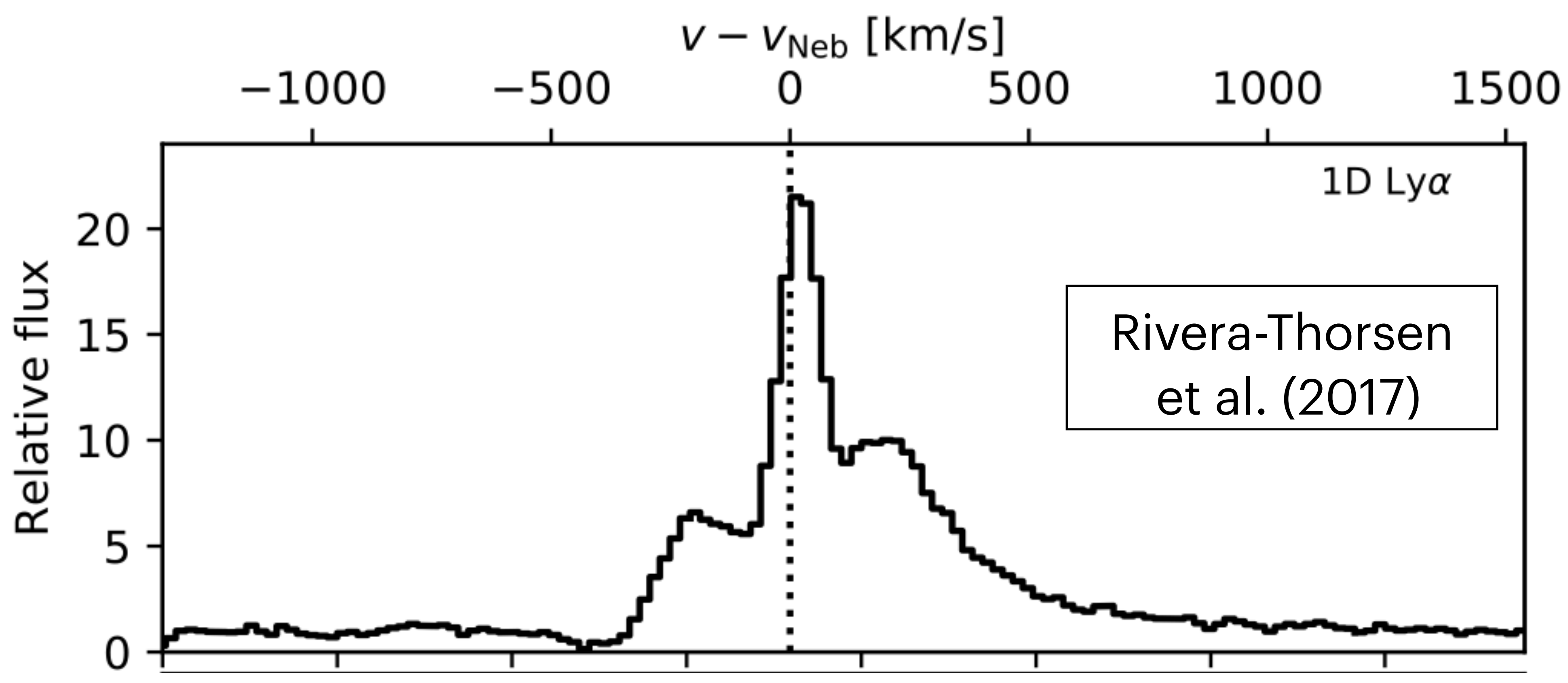

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- ✓ Yes, there are some (rare) observed cases (Sunburst Arc)
- ✓ Yes, flux near the line centre is expected

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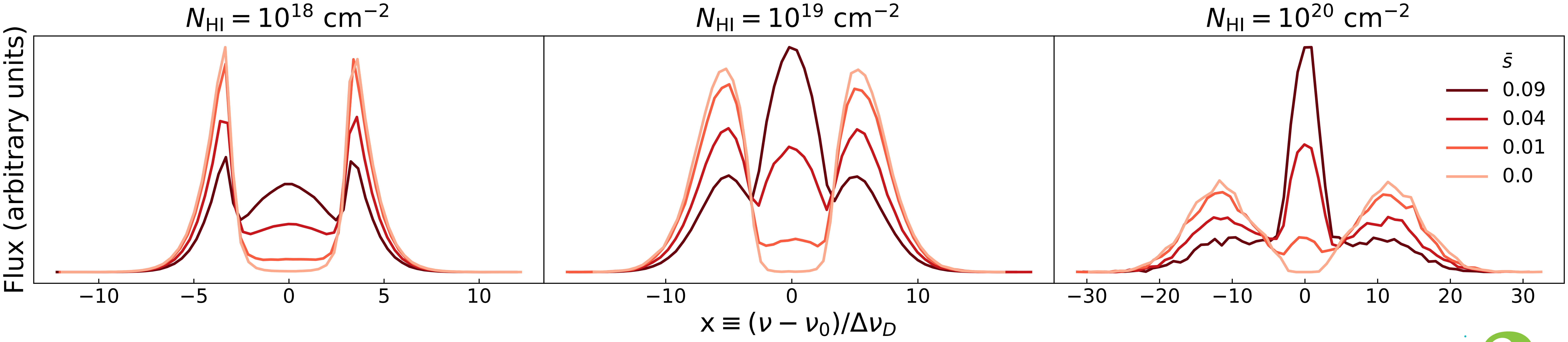

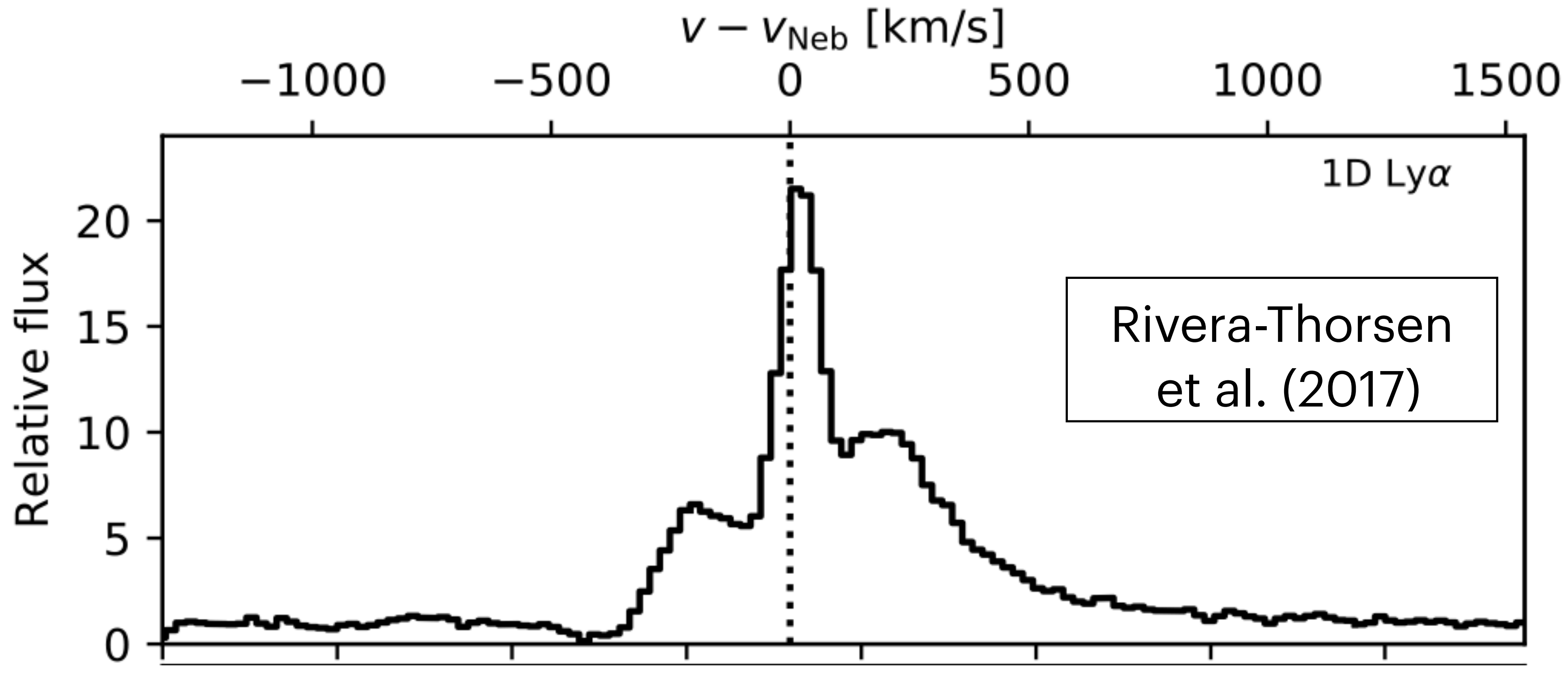

Huh? Triple peaks?

✓ Yes, there are some (rare) observed cases (Sunburst Arc)

✓ Yes, flux near the line centre is expected

✓ But… but… why is the central peak so small?

The puzzles…

The puzzles...

- **Puzzle no. 1**

$$\tilde{f} \simeq \frac{T_{\text{hole}}}{T_{\text{slab}}} \simeq \tilde{s}\tau$$

$$\tilde{f} \simeq 10^4$$

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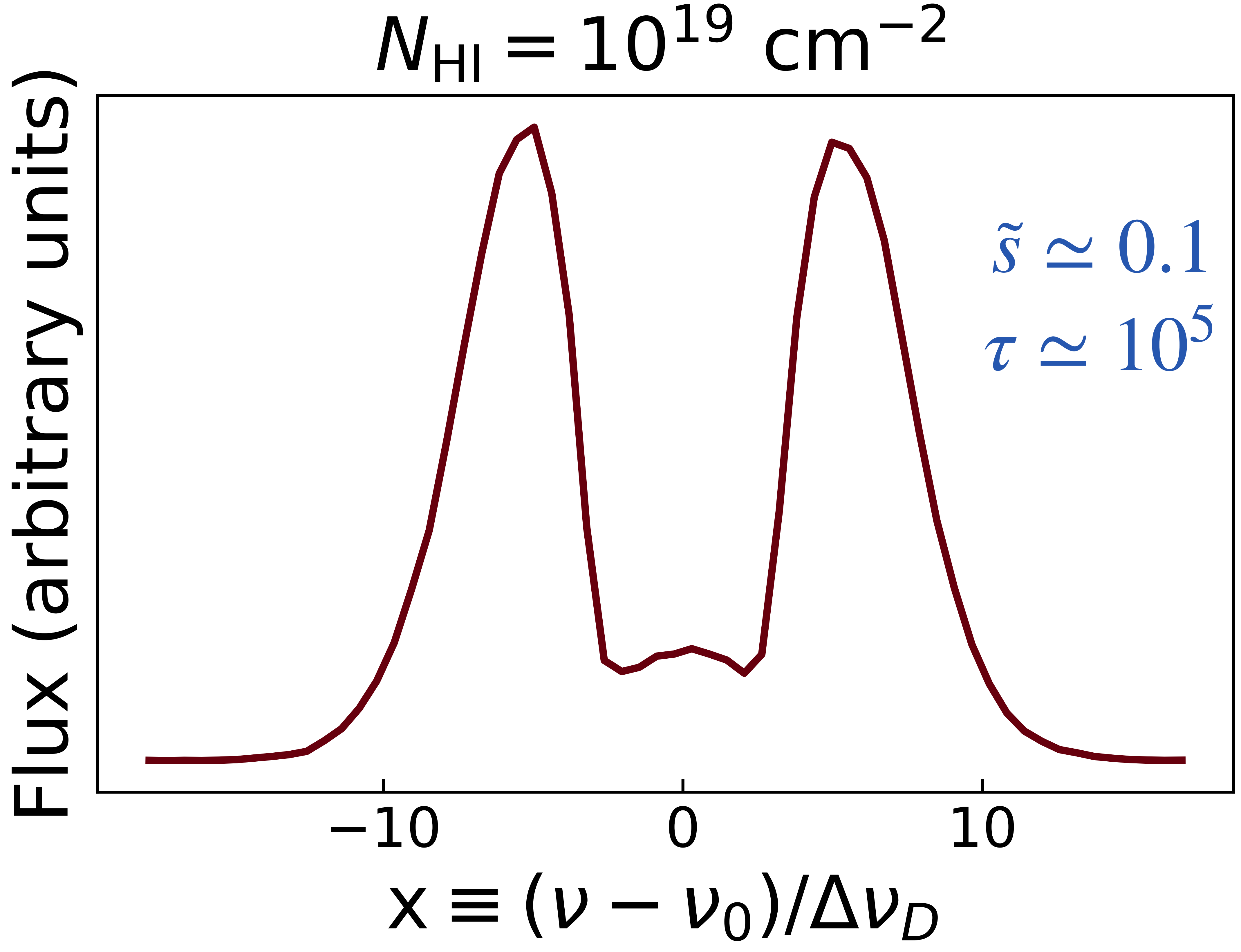

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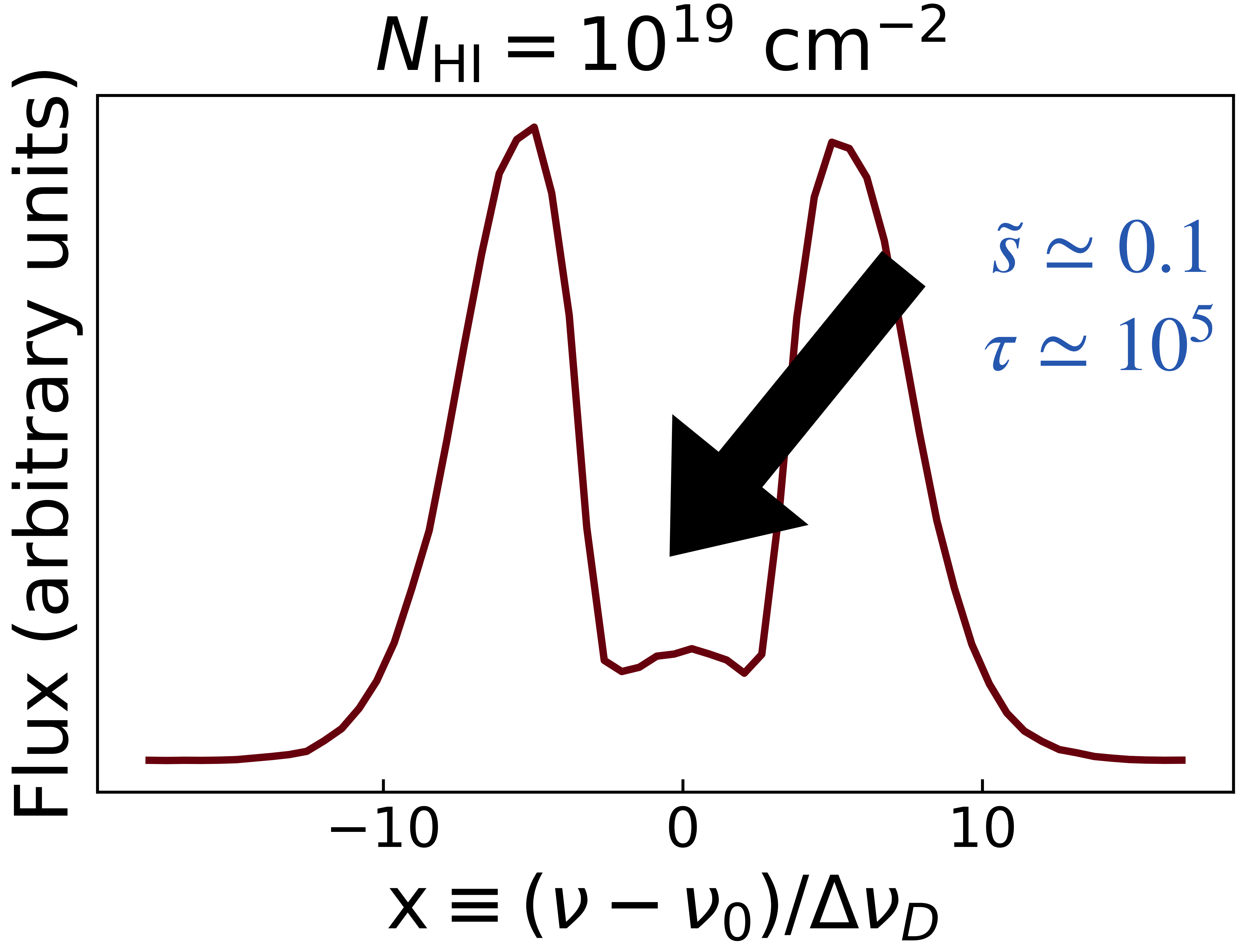

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- **Puzzle no. 1**

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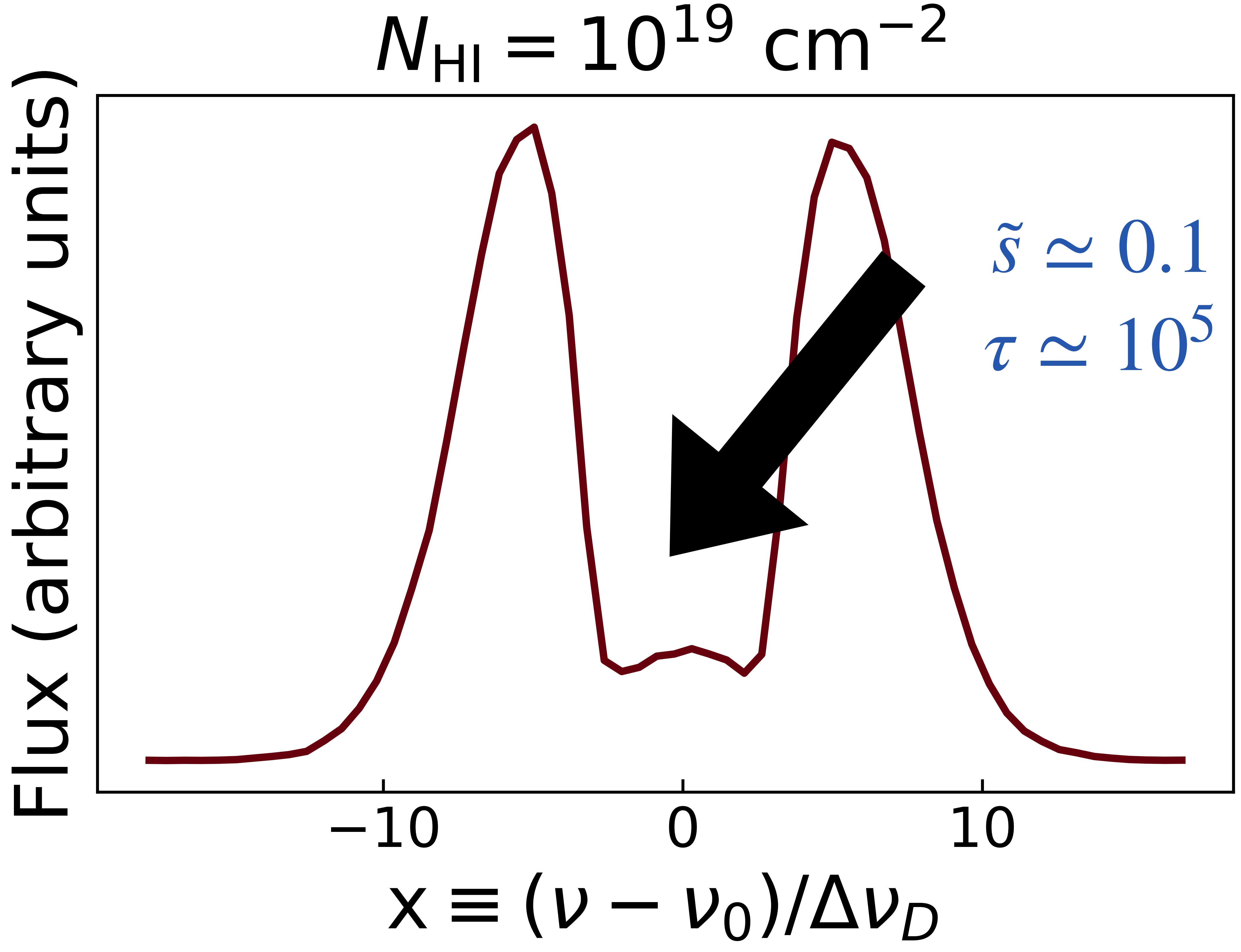
Central peak should be 4 orders of magnitude larger than the blue-red peaks

Nearly all the flux should pass through the hole forming a centrally peaked spectrum!



Against common sense…

Crossing walls and windows: the curious escape of Lyman-α photons through ionised channels

Almada Monter, Silvia; Gronke, Max

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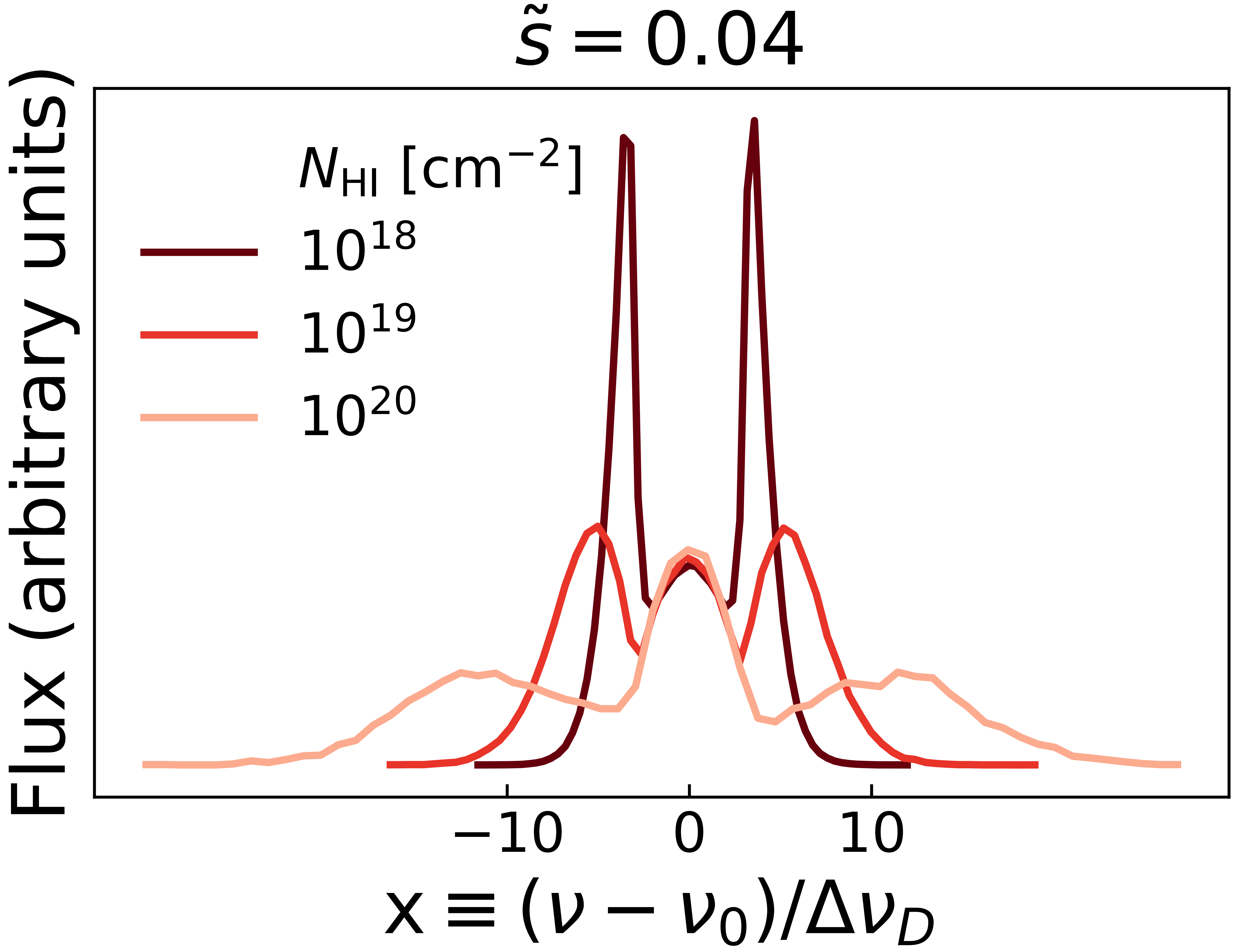
Almost no variation with optical depth



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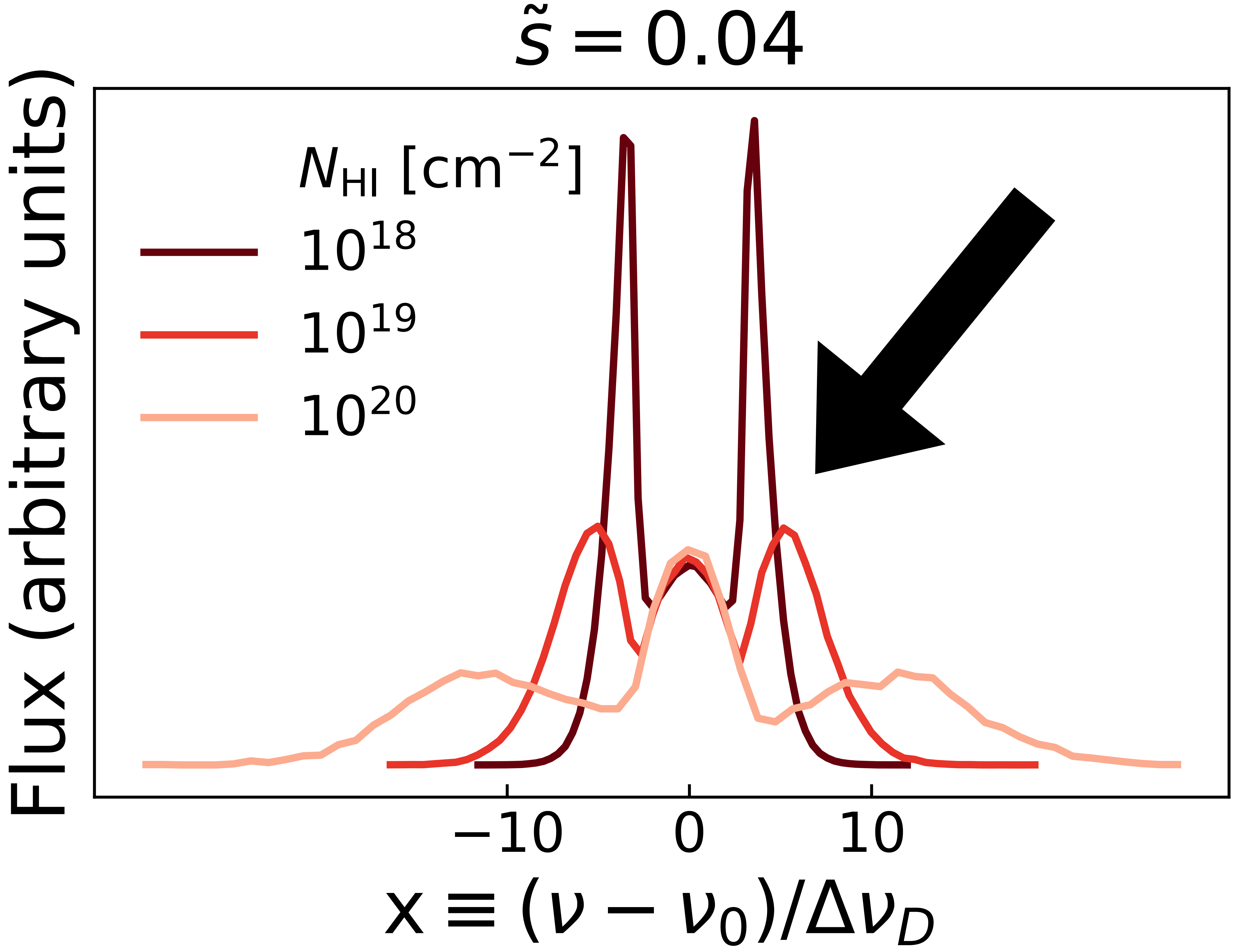

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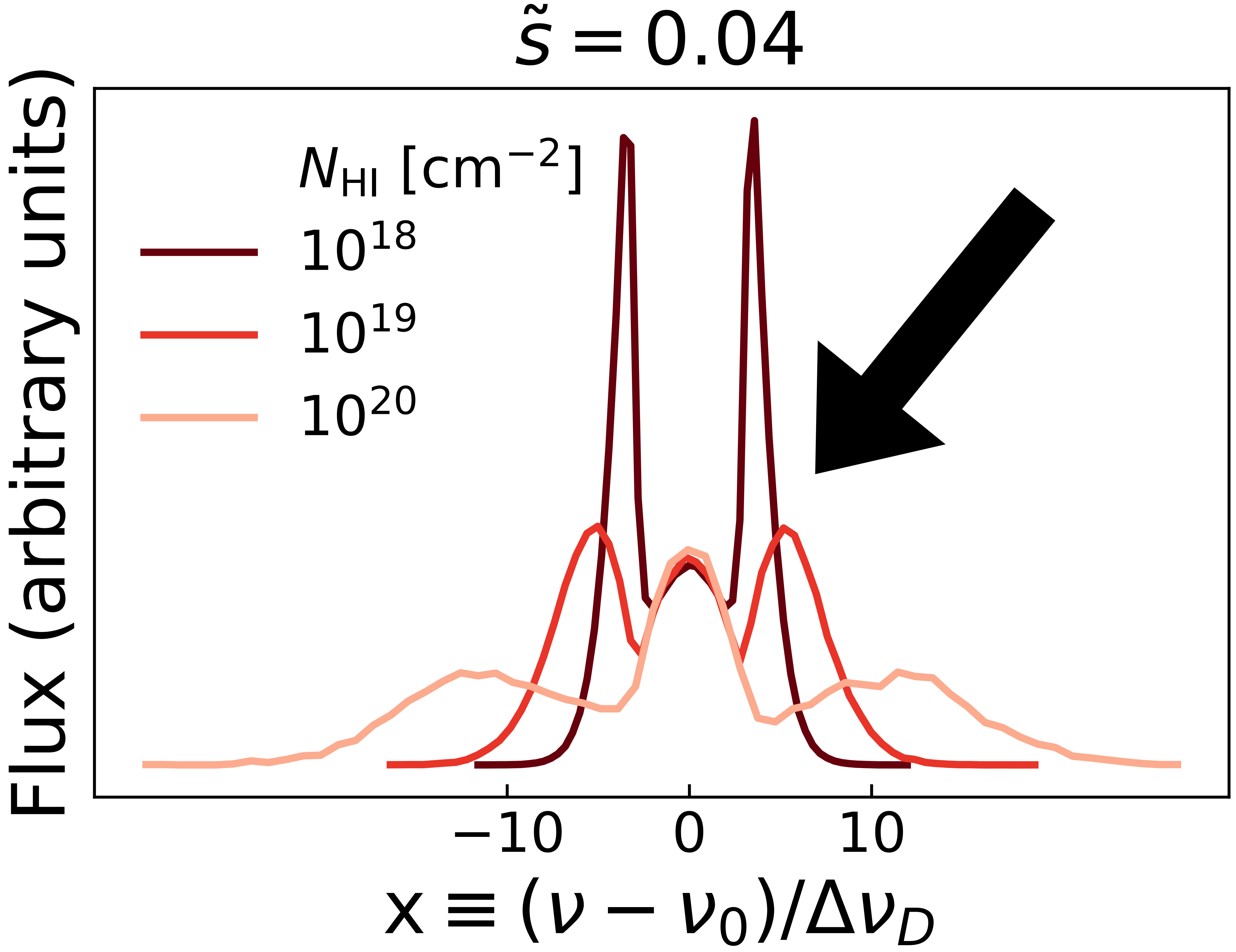

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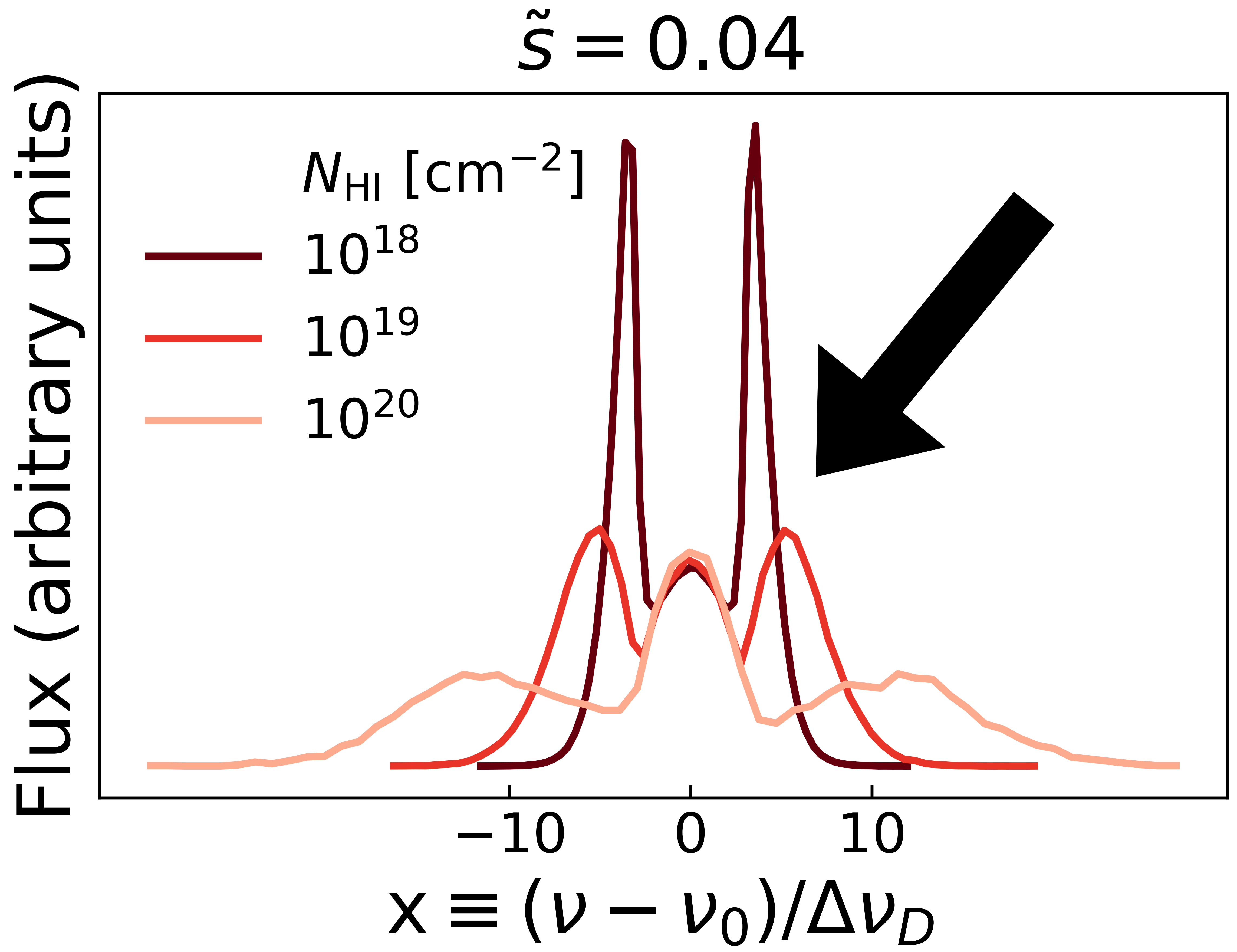
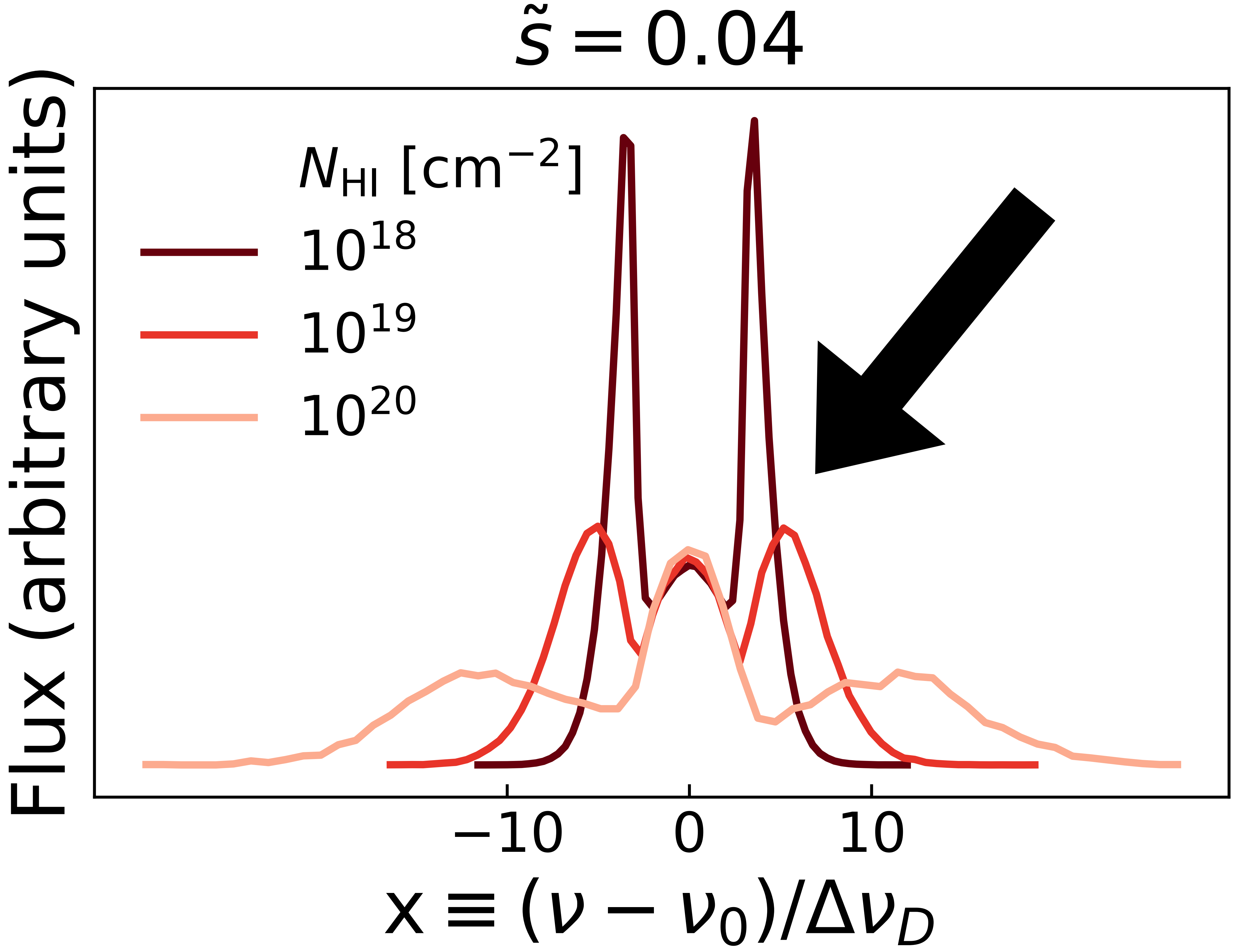


The puzzles...

- ✤ **Puzzle no. 2**

$$\tilde{f} \simeq \frac{F_{\mathrm{hole}}}{F_{\mathrm{slab}}} \simeq 2\,\tilde{s}\tau$$

Almost no variation with optical depth



The puzzles…

- **Puzzle no. 2**

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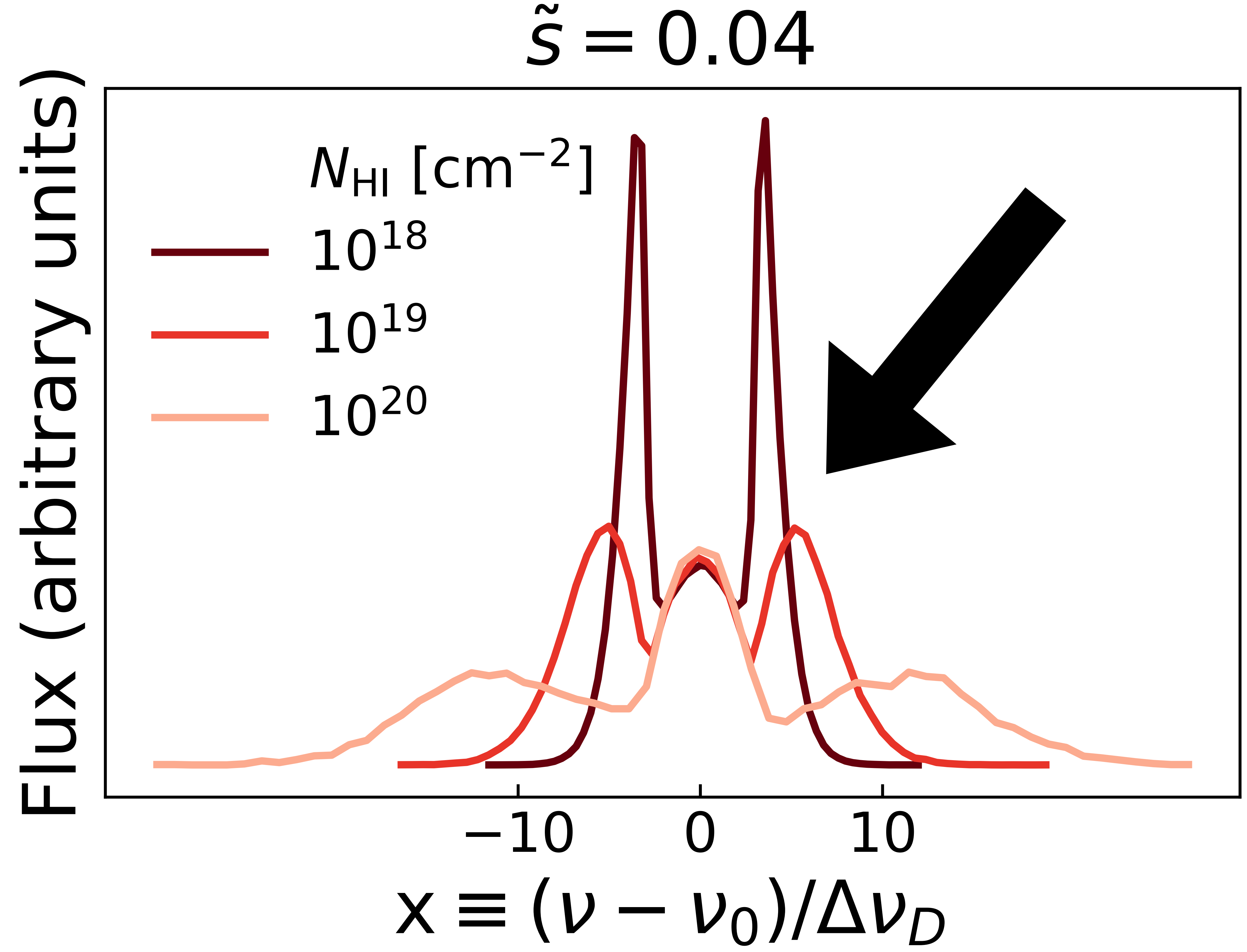
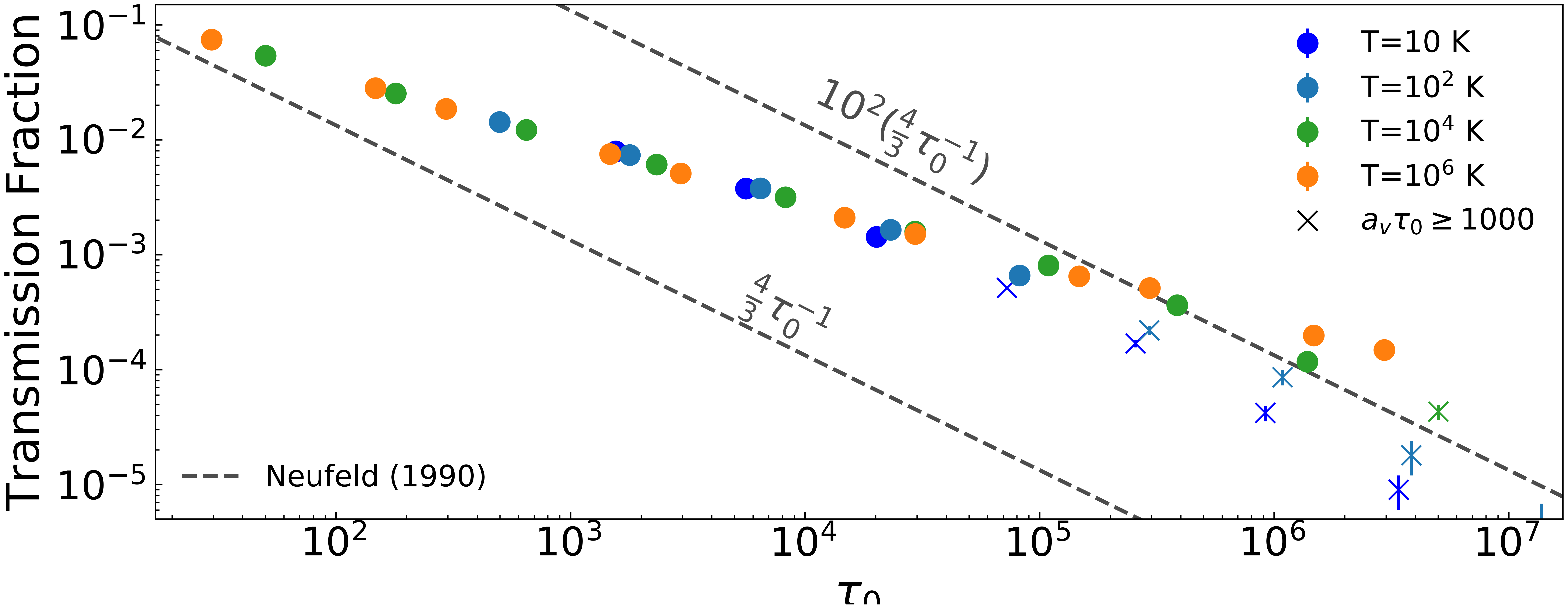
Maybe there's something with the transmission in the slab….

Almost no variation with optical depth



Let’s check the transmission through gas (no hole for now)...



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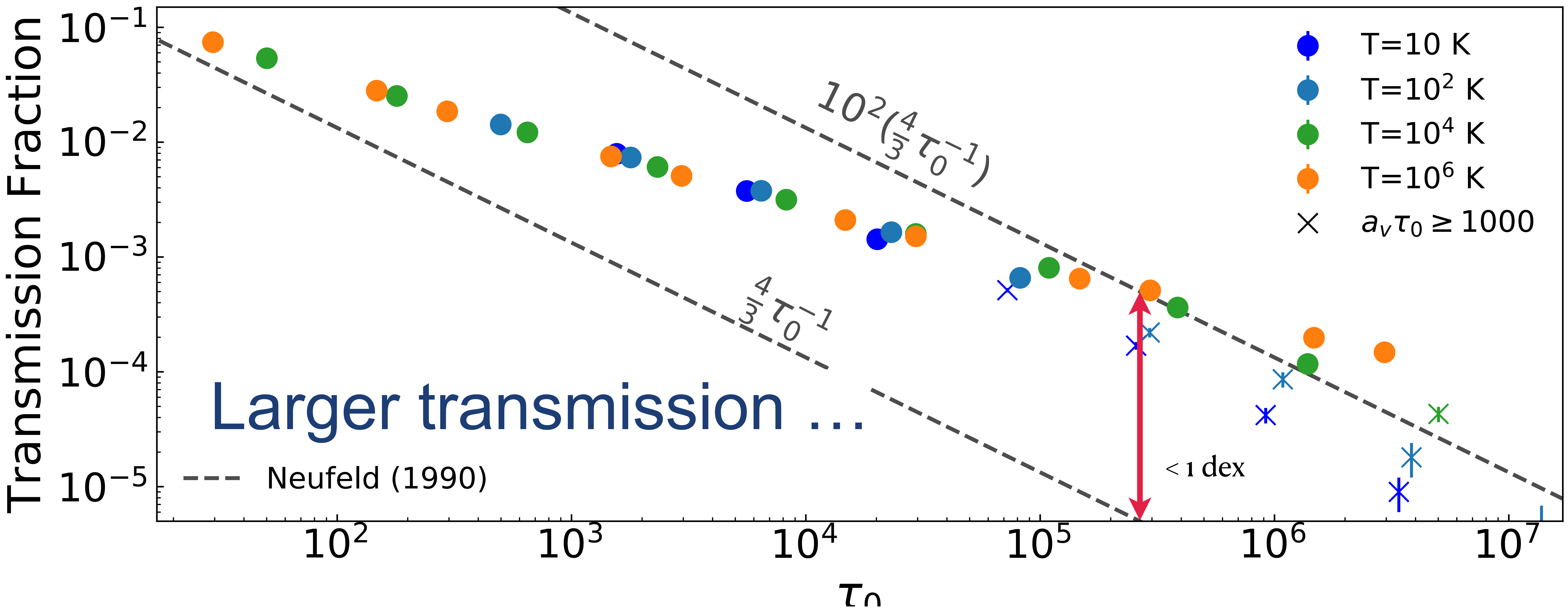

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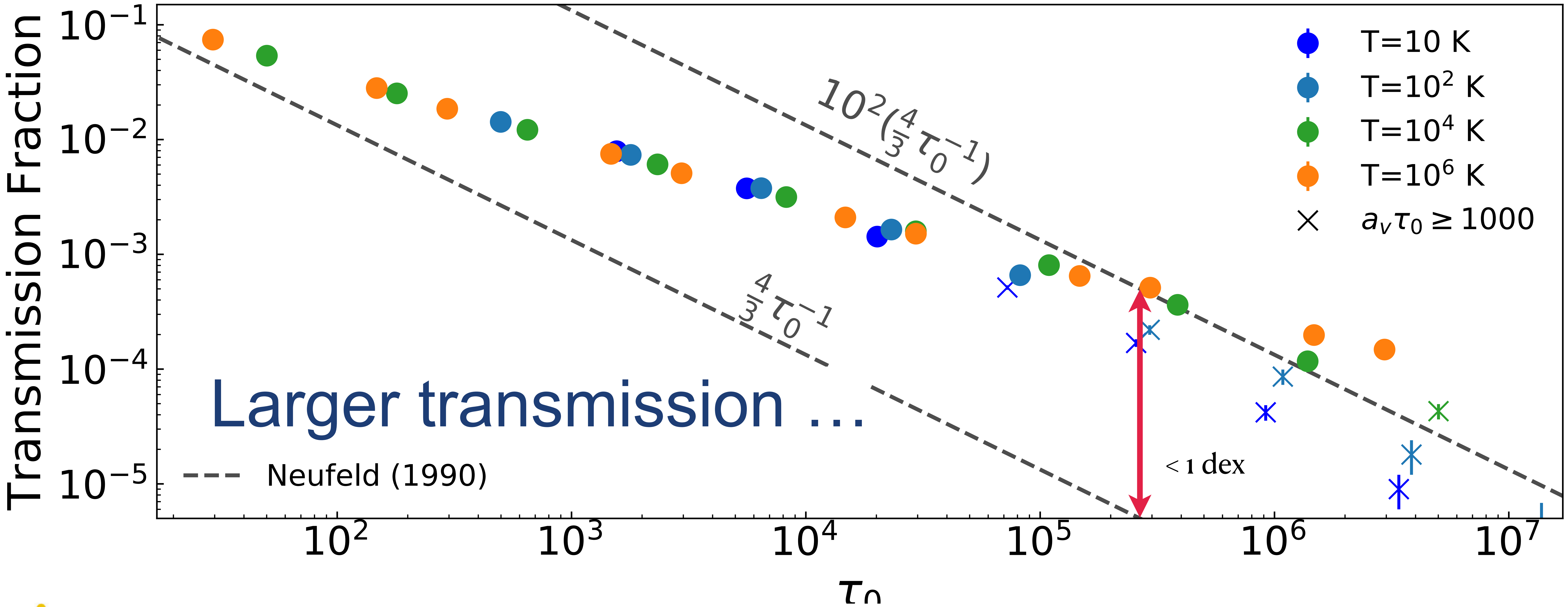

Let's count scatterings …

The solution...

(In a "few" equations)

Gambler's ruin… or a Goat's ruin

$$\frac{\partial p}{\partial t} = \frac{1}{2}\sigma^2 \frac{\partial^2 p}{\partial z^2}$$

Diffusion equation with an absorber barrier at $z_b = 0$
$\sigma = \lambda c^2$, and p is probability of wining/being transmitted

Obtain solution using method of images. → Two widening Gaussians with variance $\sigma^2 t$ and means $\pm z_0$

$$F_{\mathrm{reflected}}(t) = 1 - \int_0^\infty p(t, z)\mathrm{d}z$$

Cumulative fraction of reflected photons

$$f_{\mathrm{reflected}}(t) = \frac{\mathrm{d}F_{\mathrm{reflected}}}{\mathrm{d}t} = \frac{z_0}{\sqrt{2\pi t^3 \sigma^2}} \exp\left(-\frac{z_0^2}{2t\sigma^2}\right)$$

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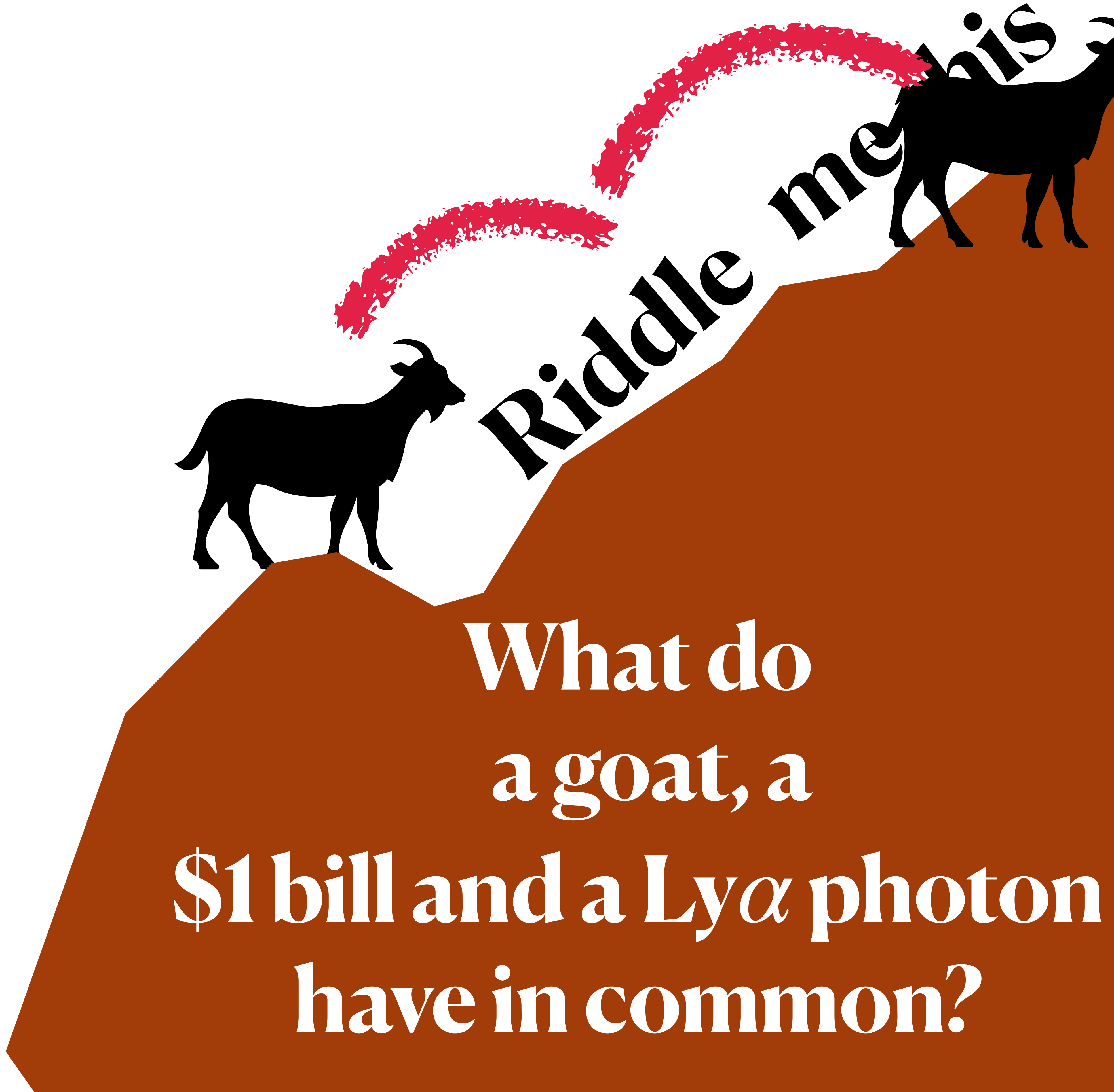
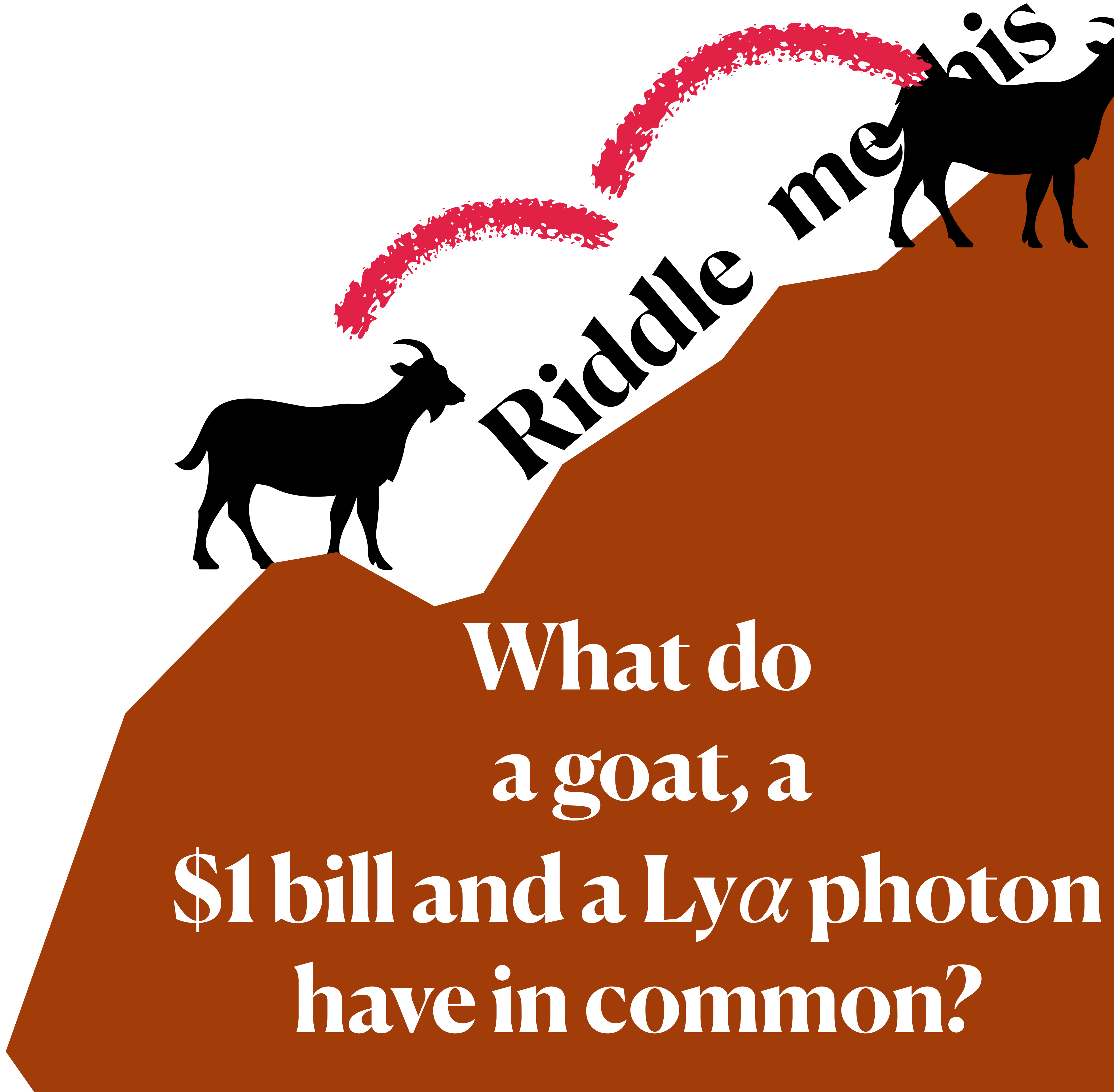


The solution… Gambler's ruin… or a Goat's ruin

Transmitted goat!

(Adams 1972)



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Reflected goat!

(Like most!)

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Reflected goat!

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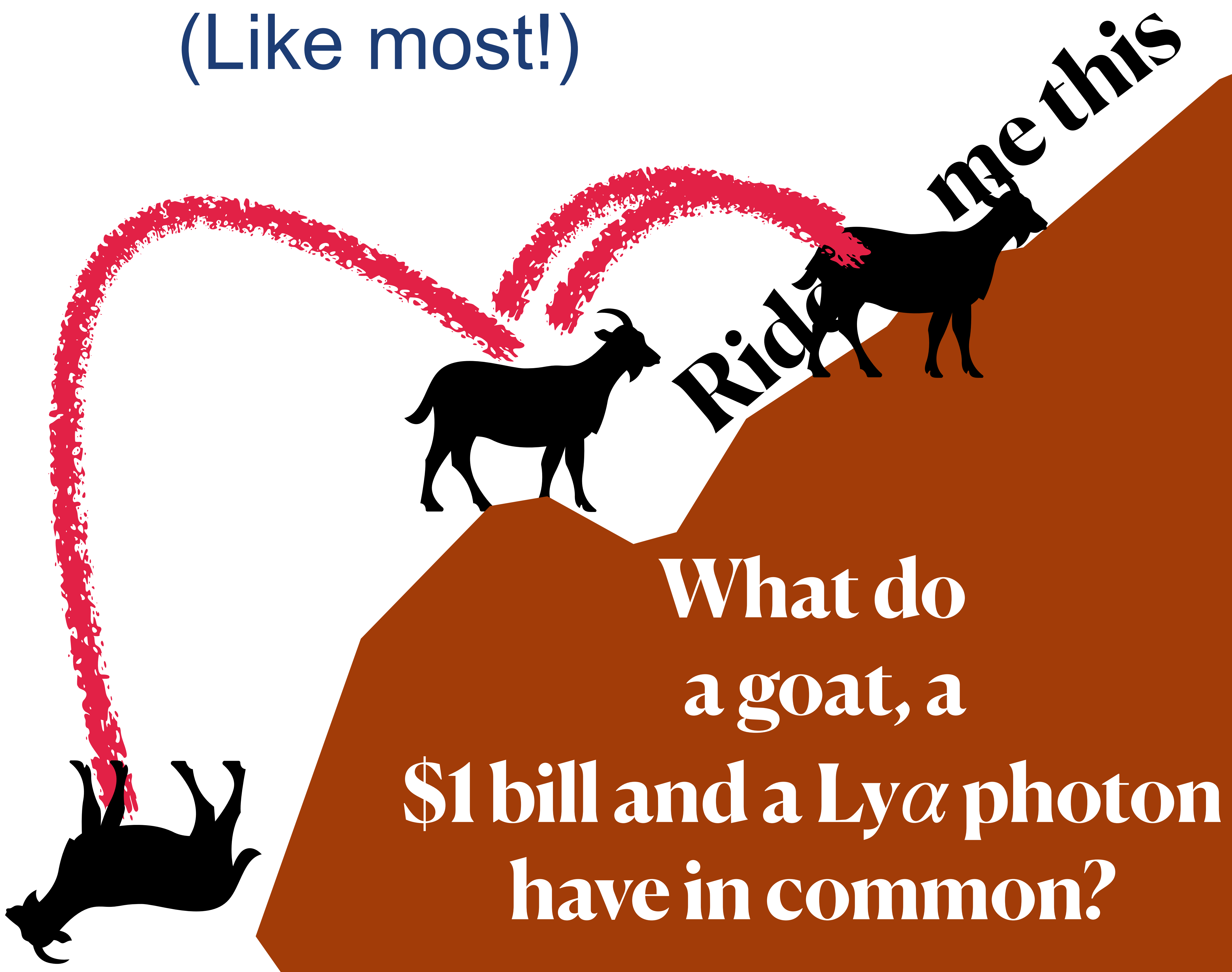
(Unlike goats) Lyman-α photons are likely to escape after

$$N_{scat} \sim \tau_0$$

Chance to scatter until escape frequency (long enough mean free path!)

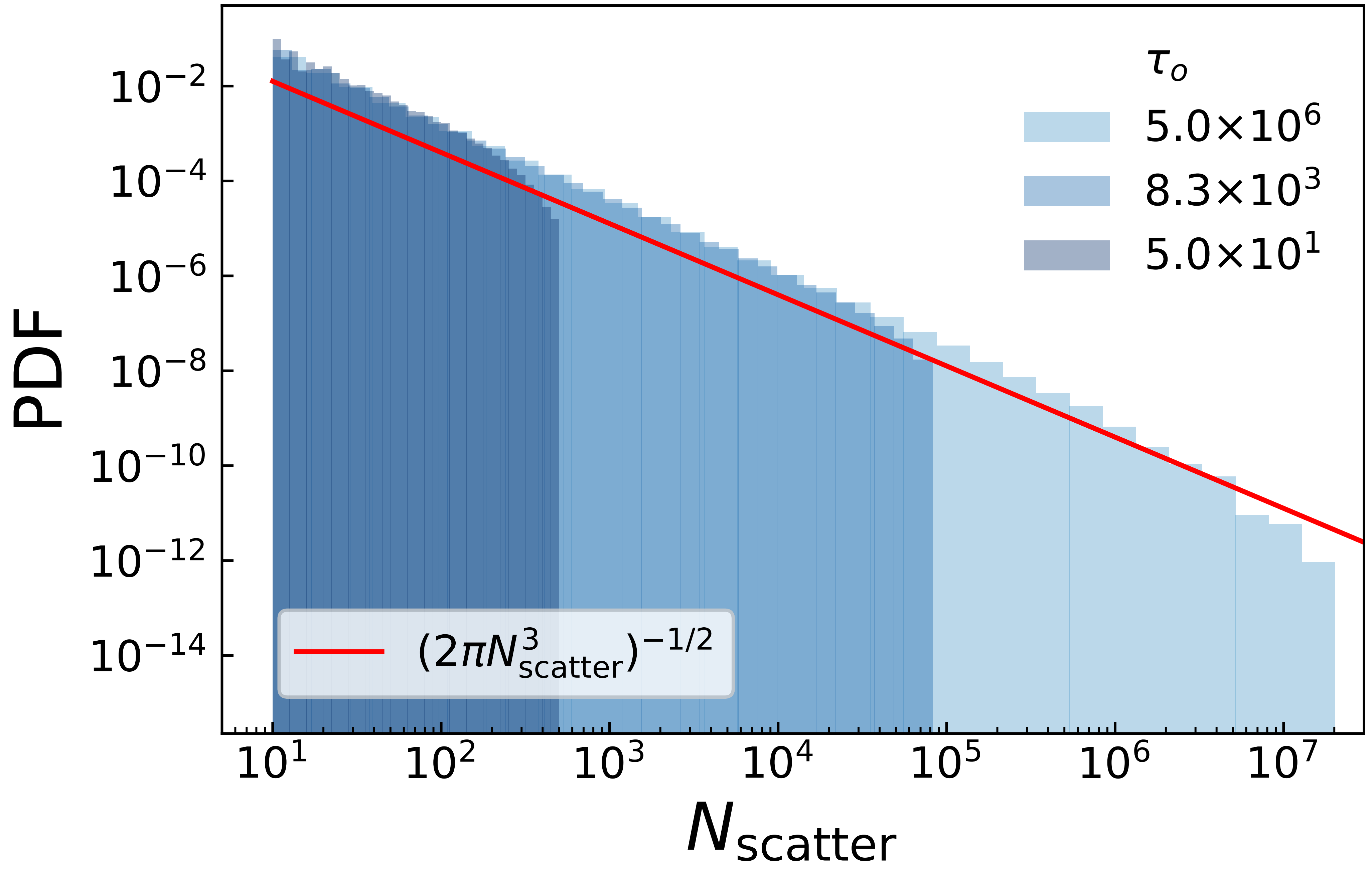


The solution...

(In a "few" plots)

Lévy distribution

$$f_{\text{reflected}}(N_{\text{scatter}}) = \frac{1}{\sqrt{2\pi N_{\text{scatter}}^3}} \exp\left(-\frac{1}{2N_{\text{scatter}}}\right)$$



Lyα photons are NOT Ping-pong balls!

Scatter many times before reflection

SlabTransmission Probability

$$T_{\text{slab}} = \frac{1}{2}\int_{\tau_0}^{\infty} f_{\text{reflected}}(n)\text{dn} \approx (2\pi\tau_0)^{-1/2}$$

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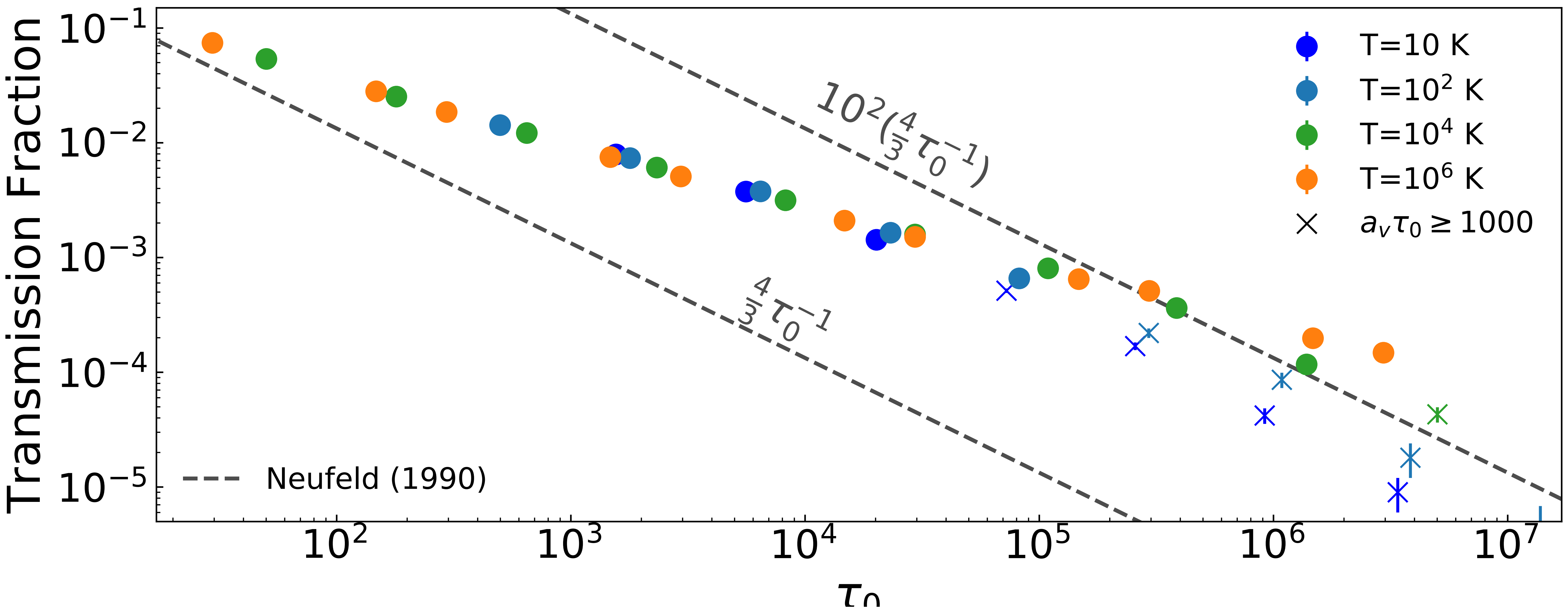

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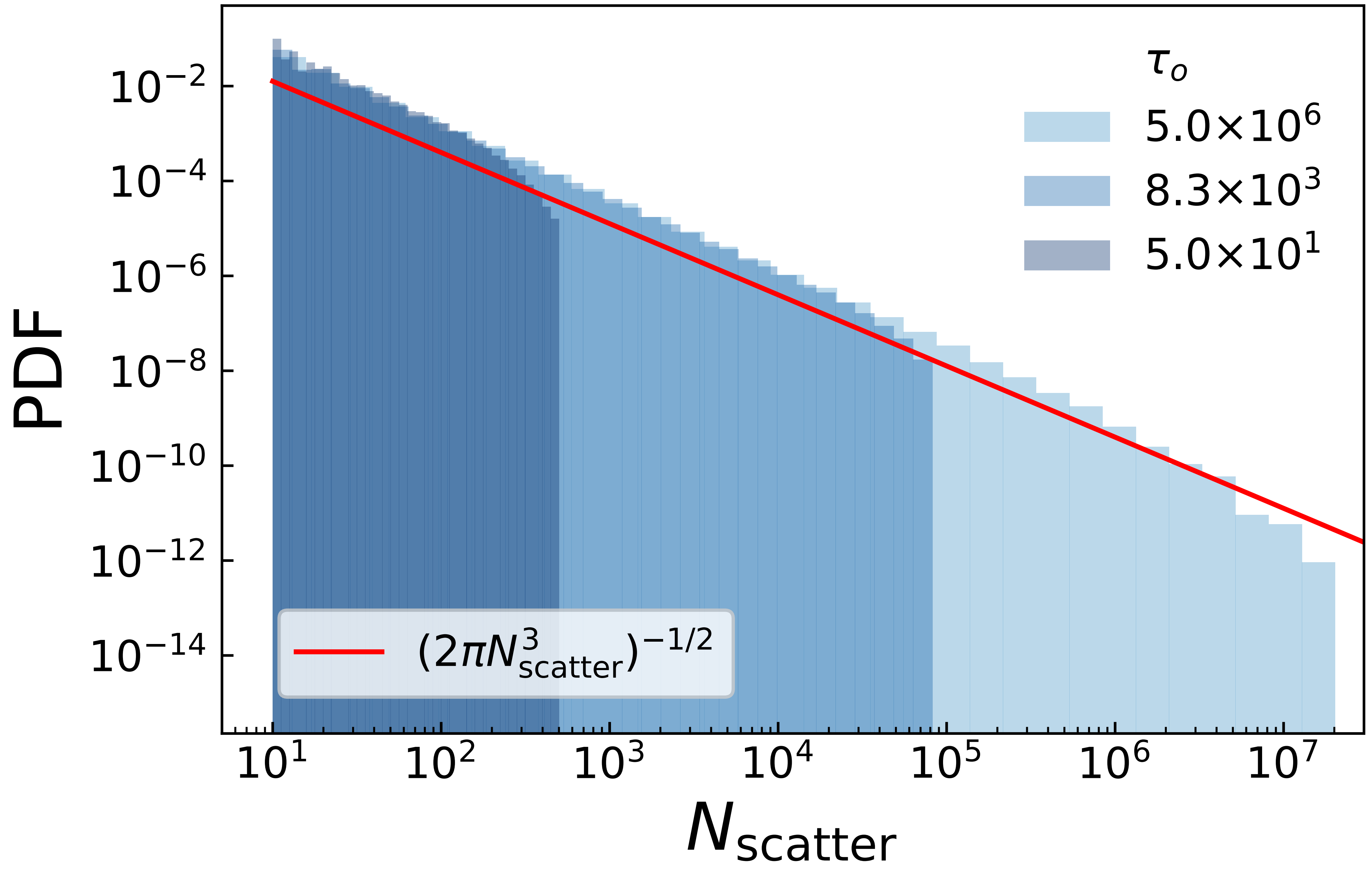

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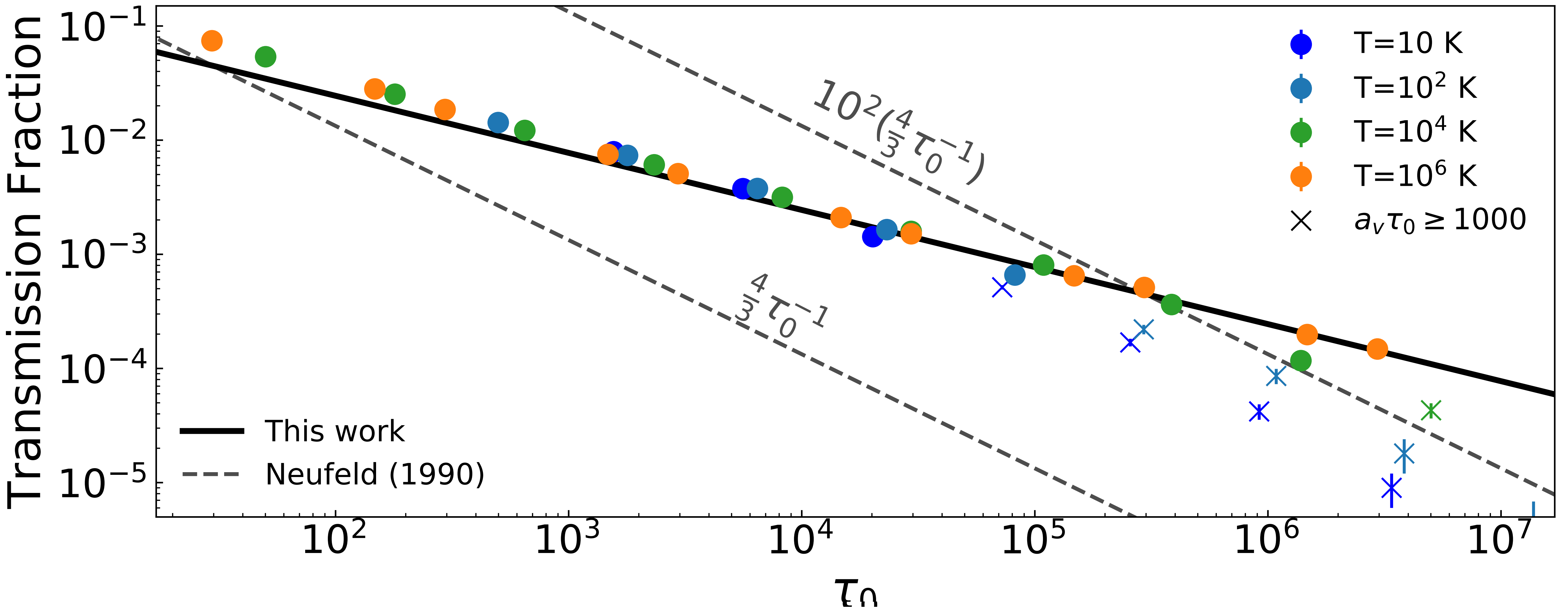


The solution...

(In a few words)

Lyα photons are reflected by the gas after many scatterings

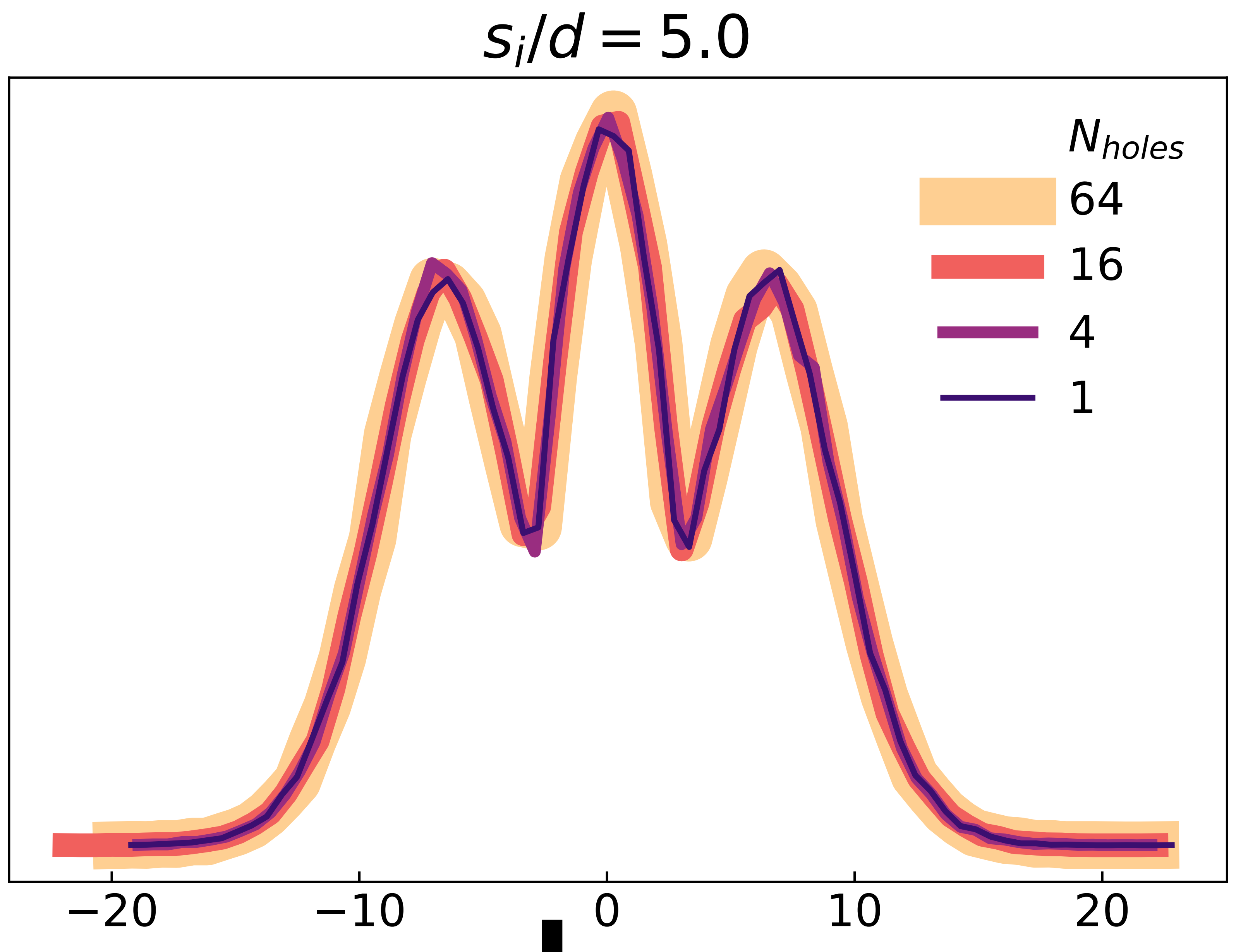
More scatters facilitate shift in frequency $x > x_{esc}$
increase mean free path

Much larger transmission probability through the slab

What about? ...

Ly α traces more general properties of the distribution!

More than one hole



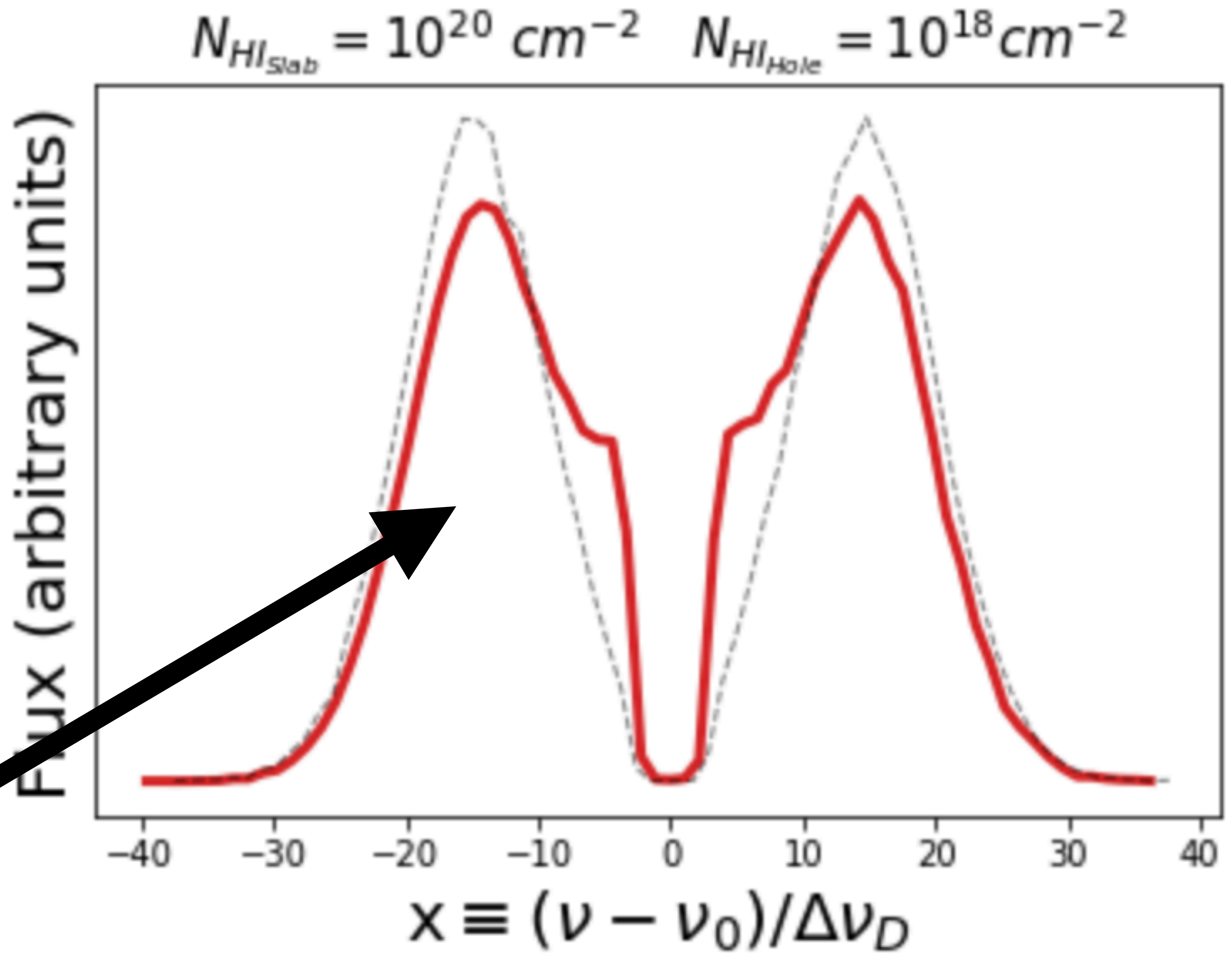
Constrain total hole size

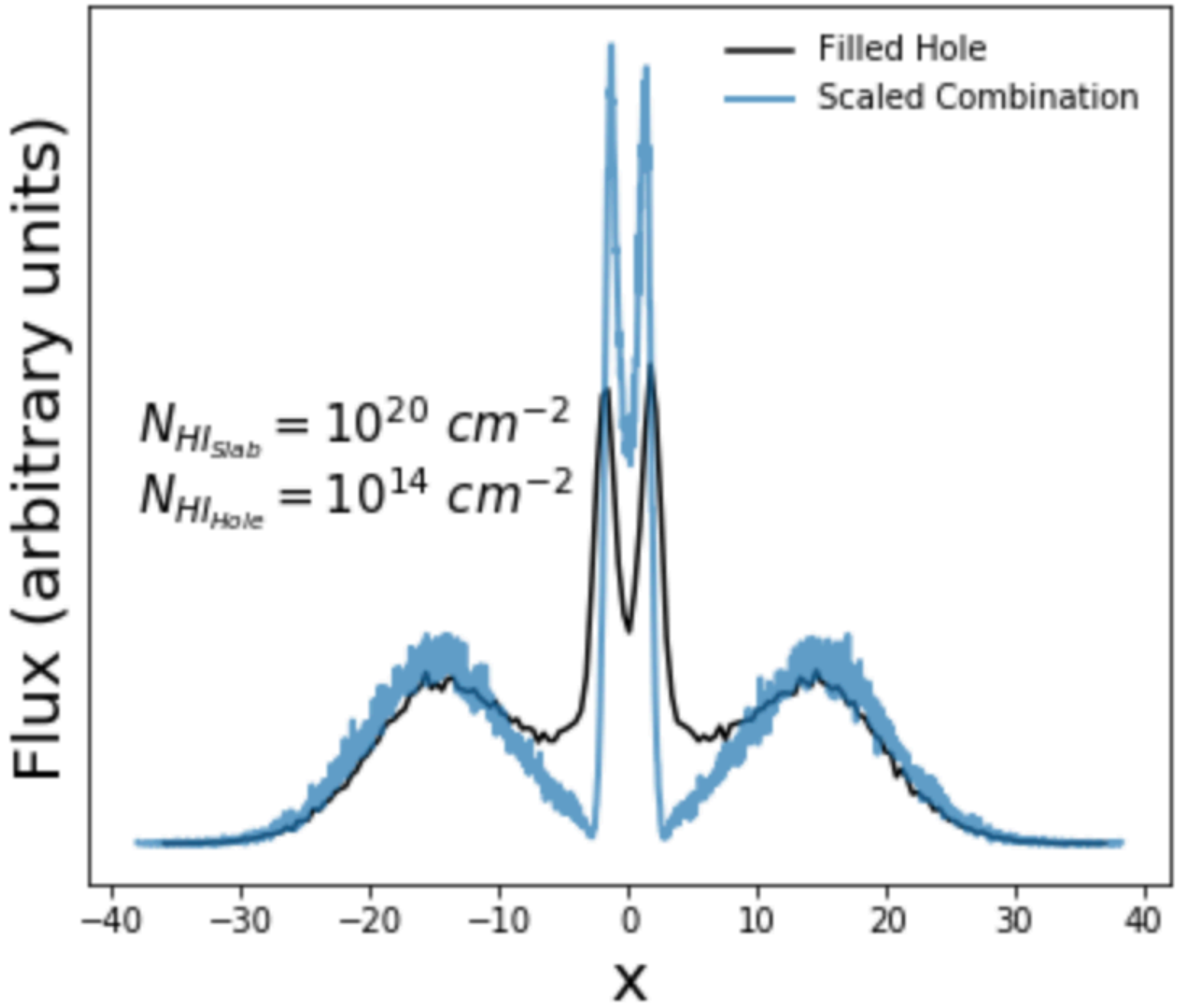
hole + high column density gas

Asymmetric blue-red peaks

Model low and high column densities using $\tilde{f}$

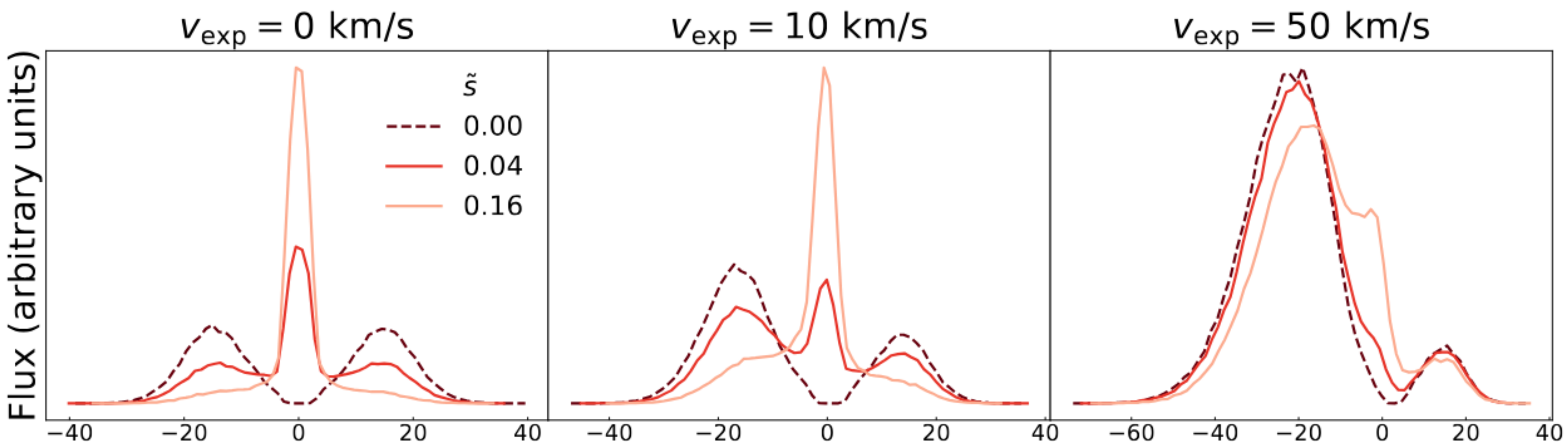
Filled hole

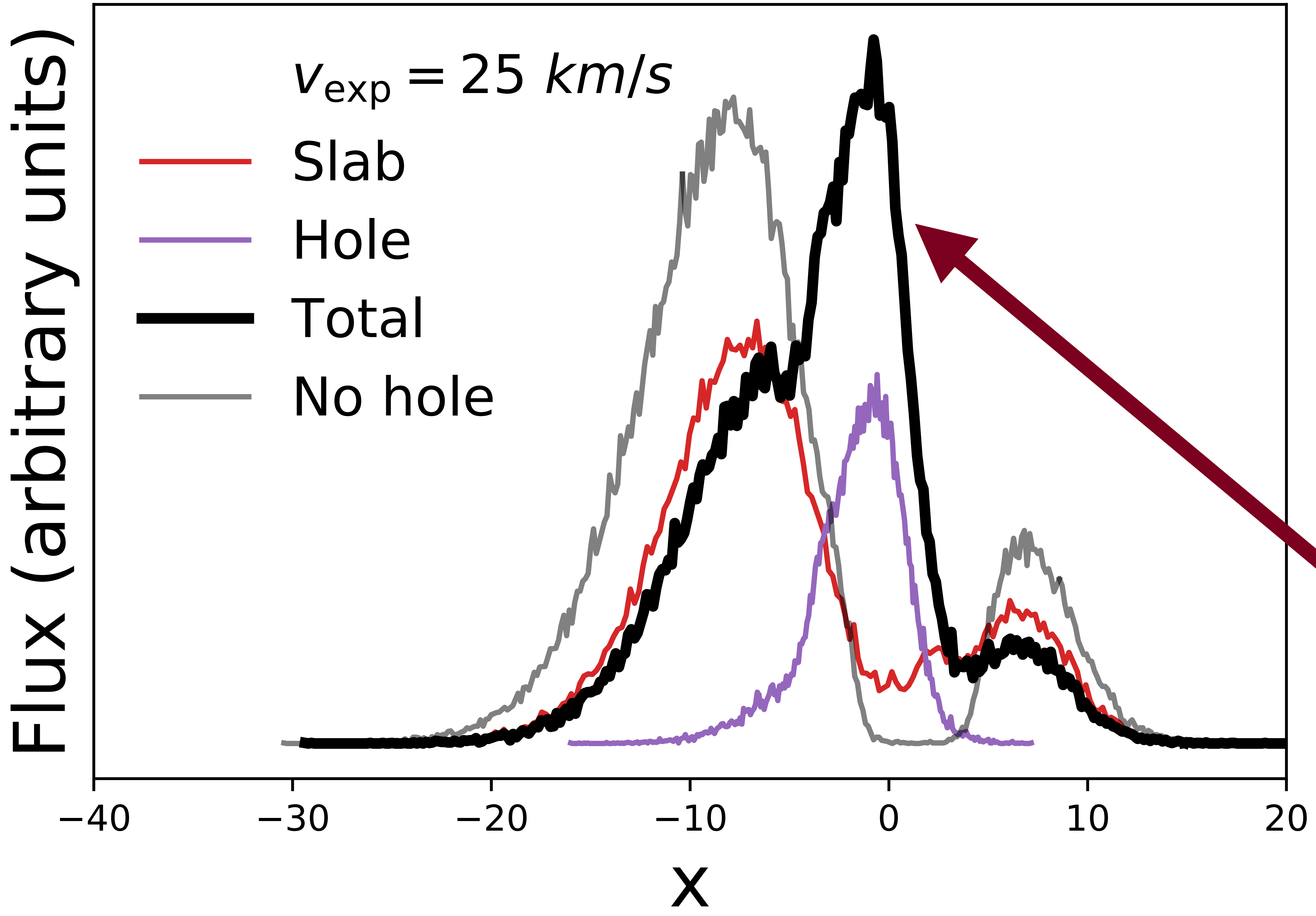




What about? ...

Outflows





Fusion of red and central peaks
asymmetric line profile

What about? ...

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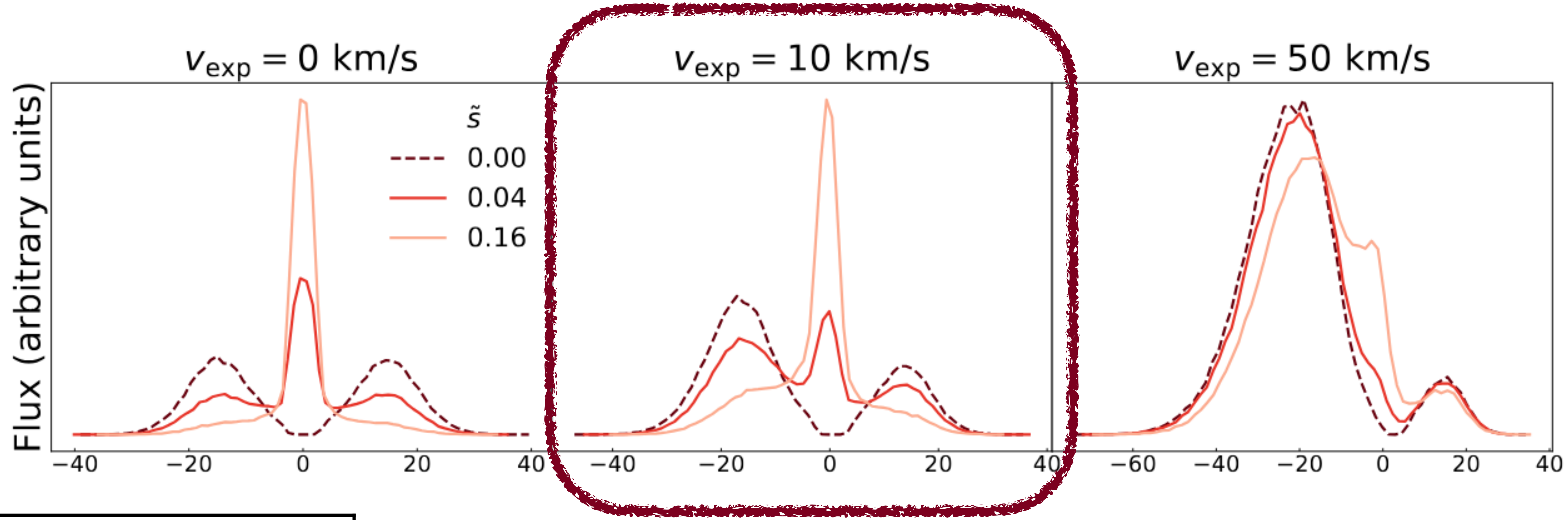

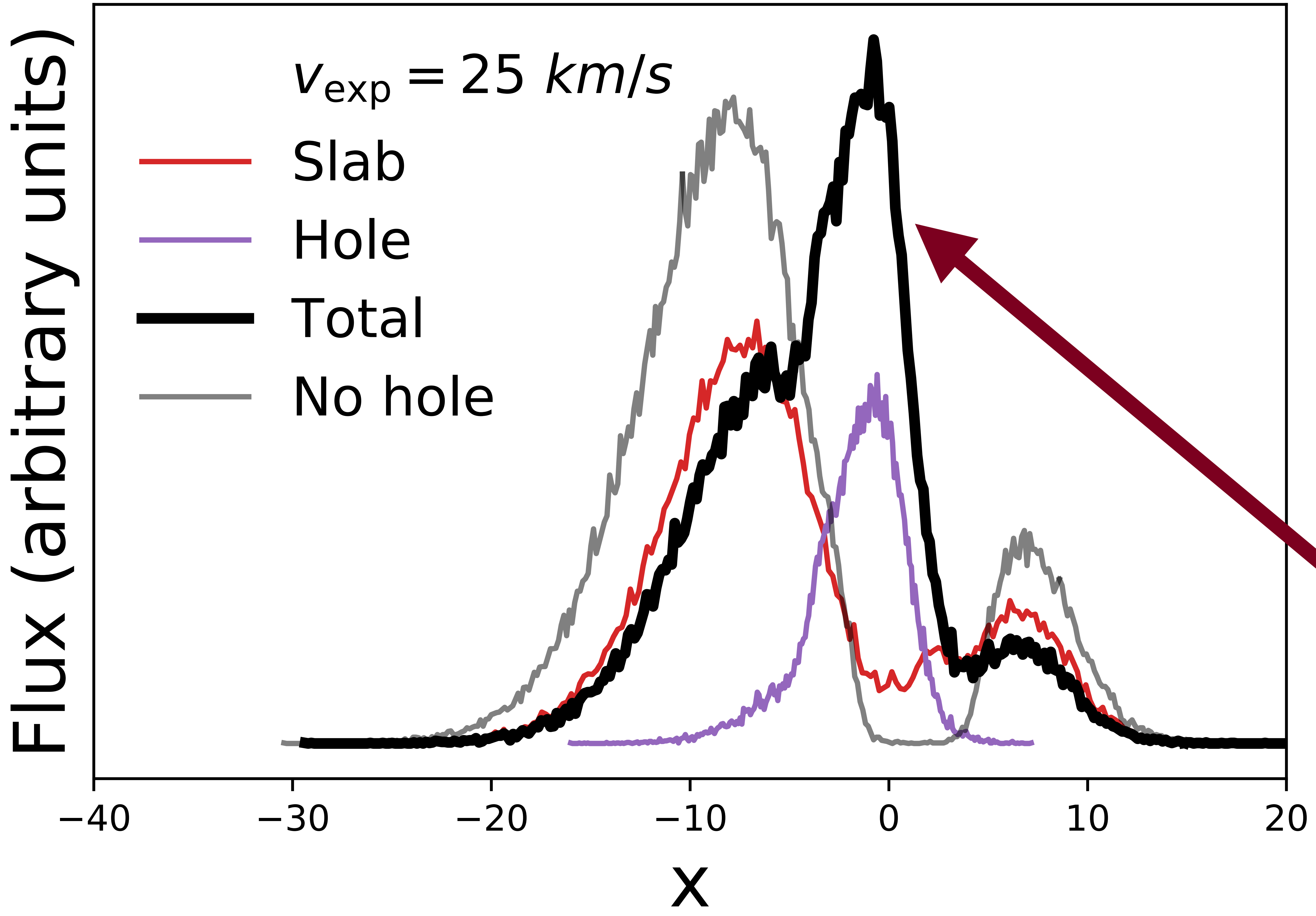

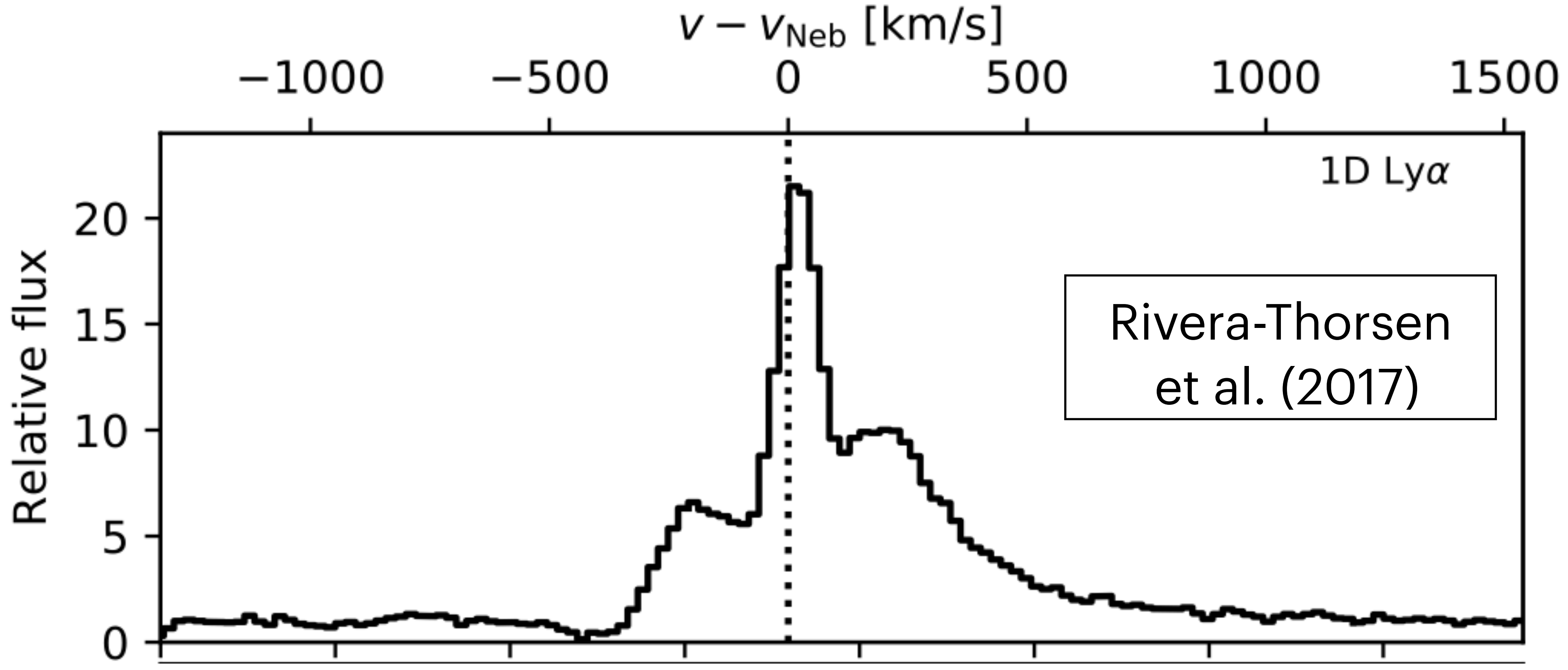

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Implications…

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- Holes, even if the Lyα line profile does not show them (as we thought)

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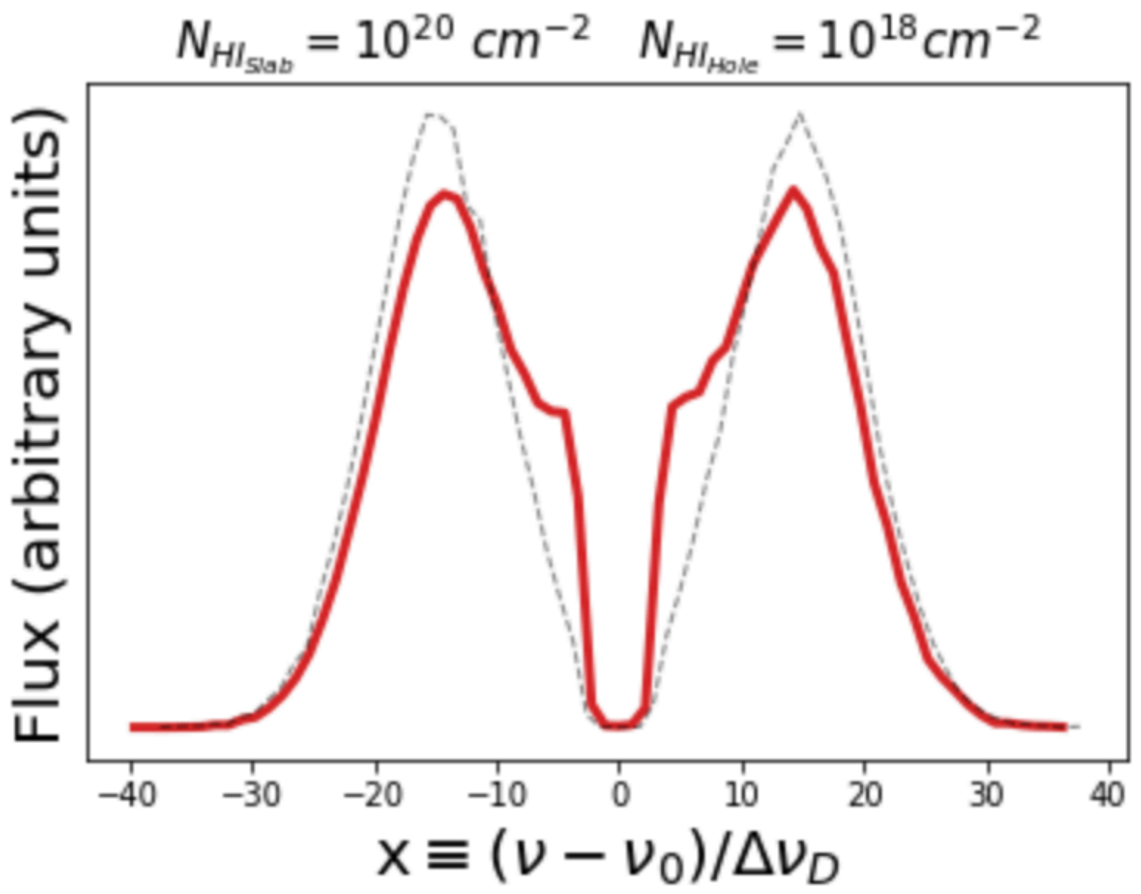

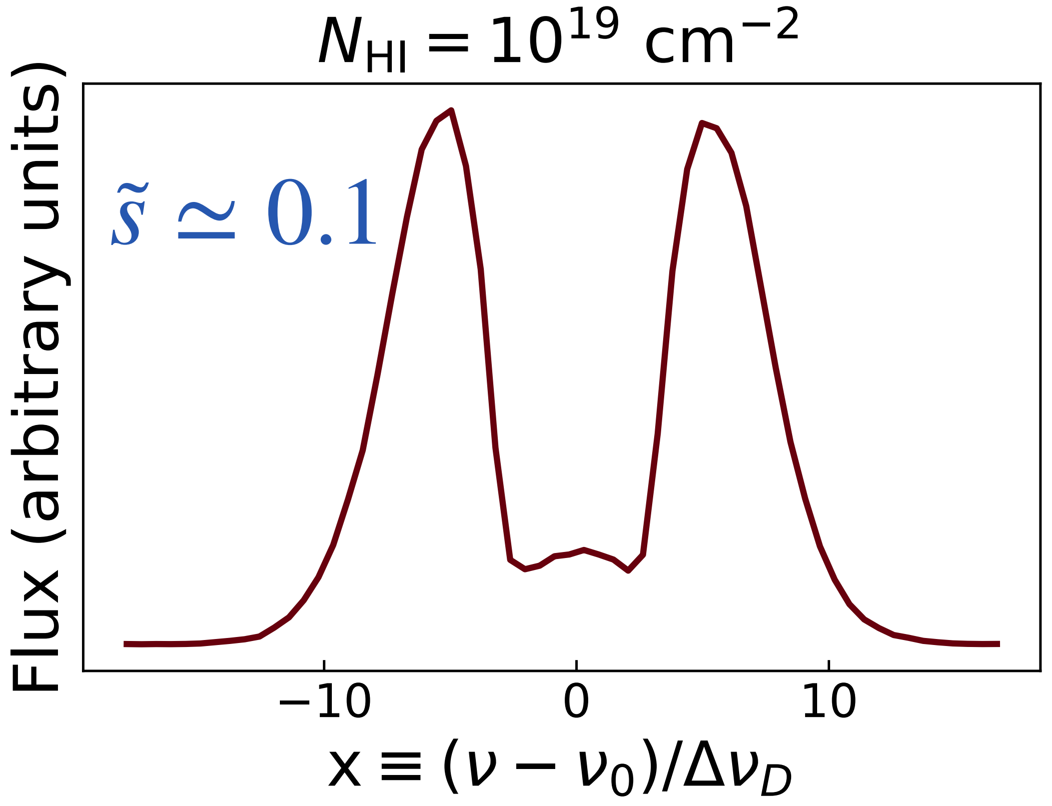

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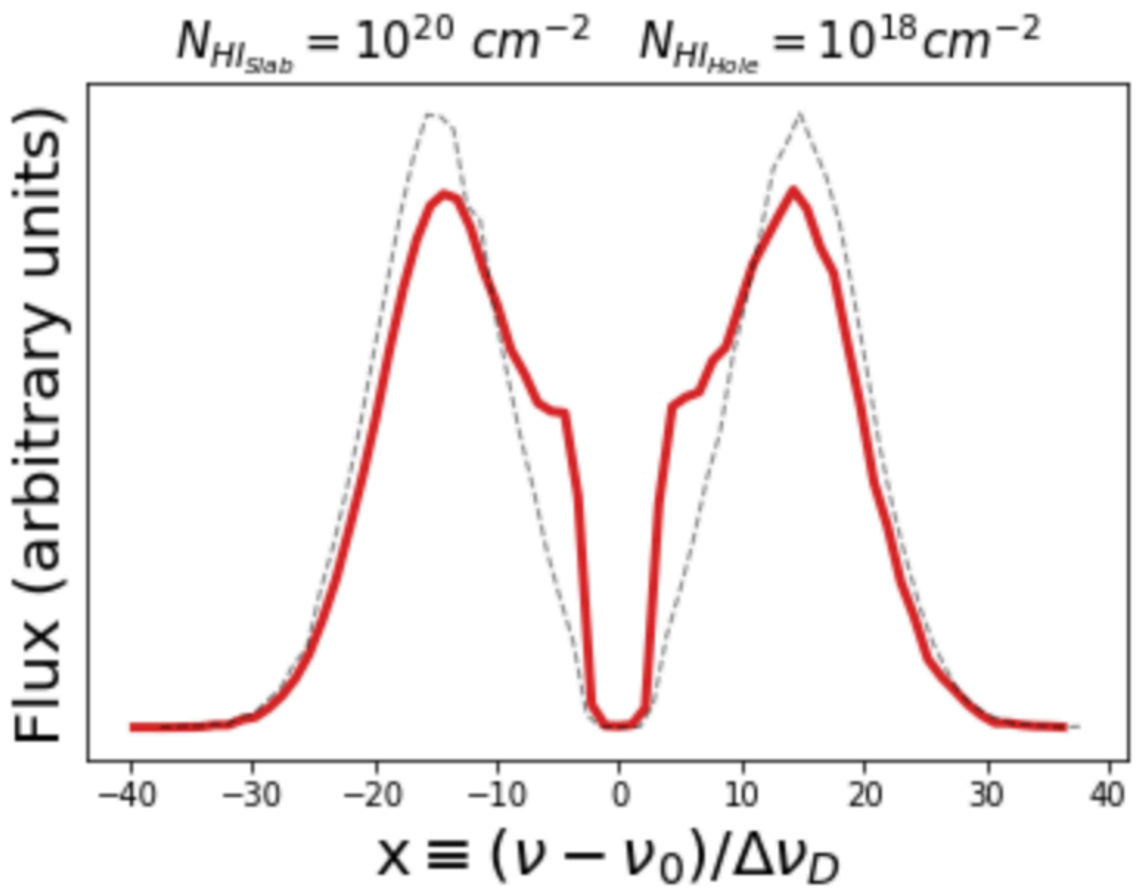

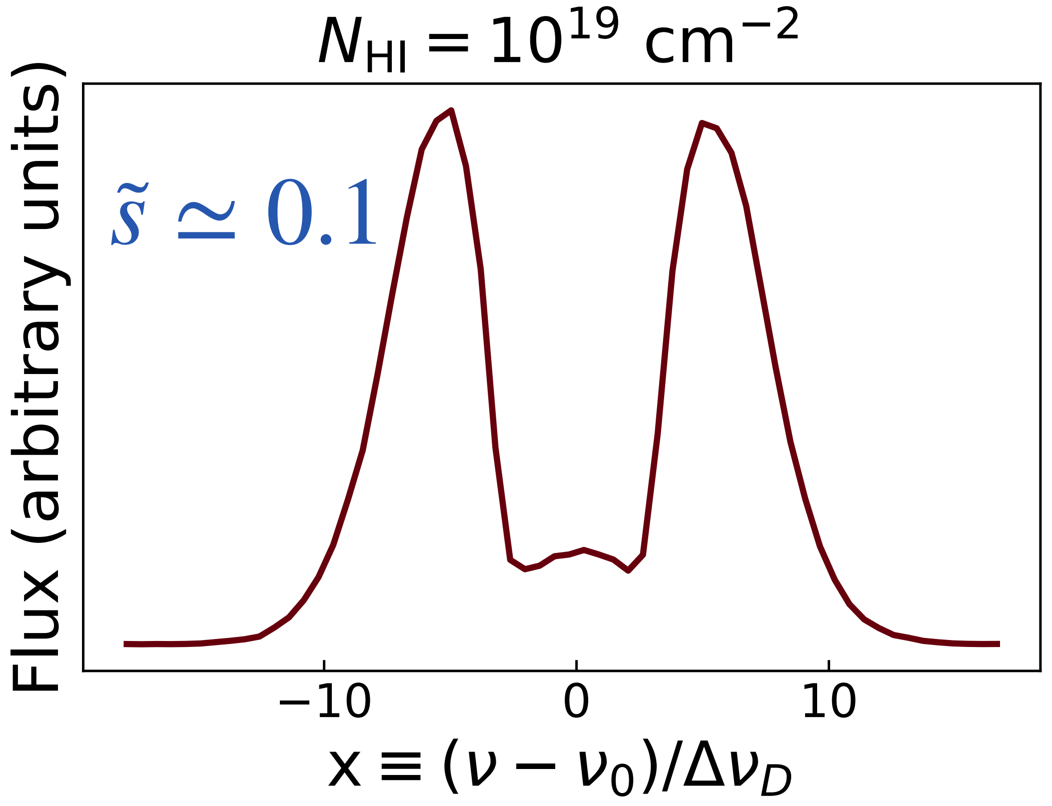

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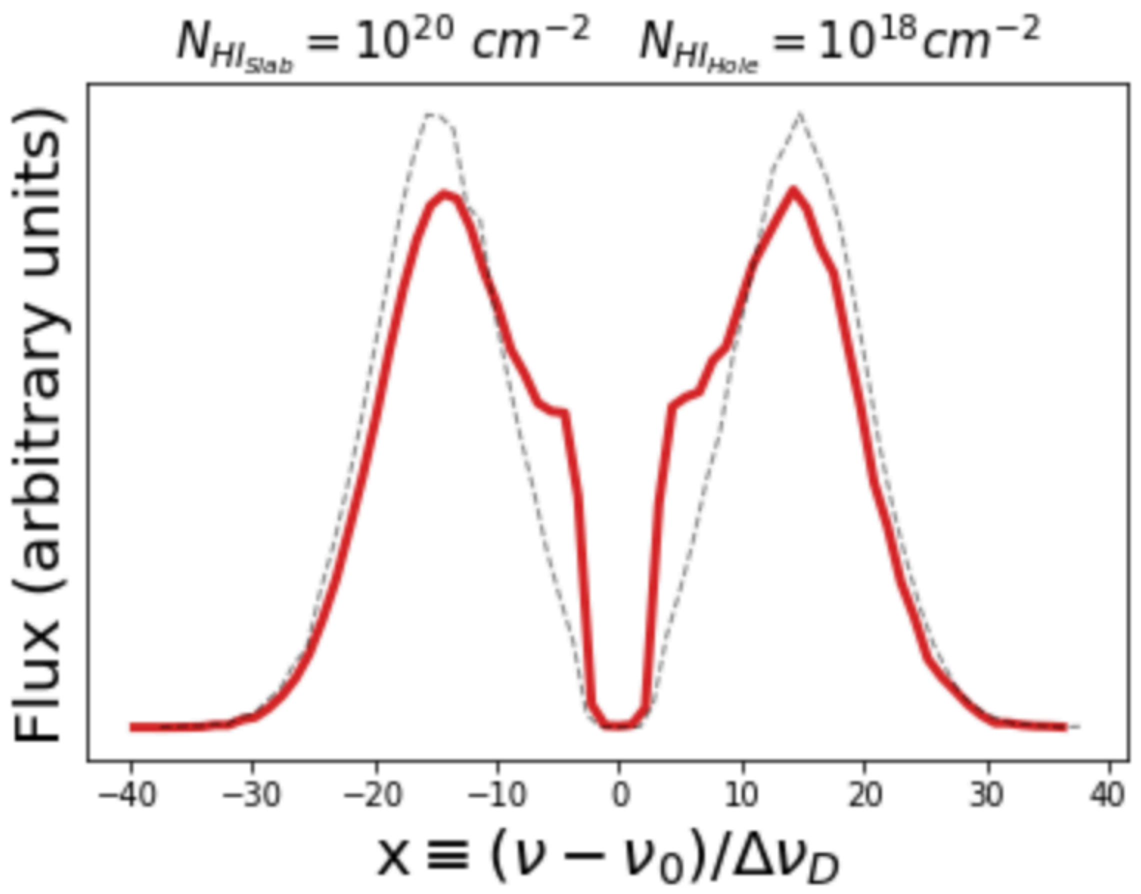

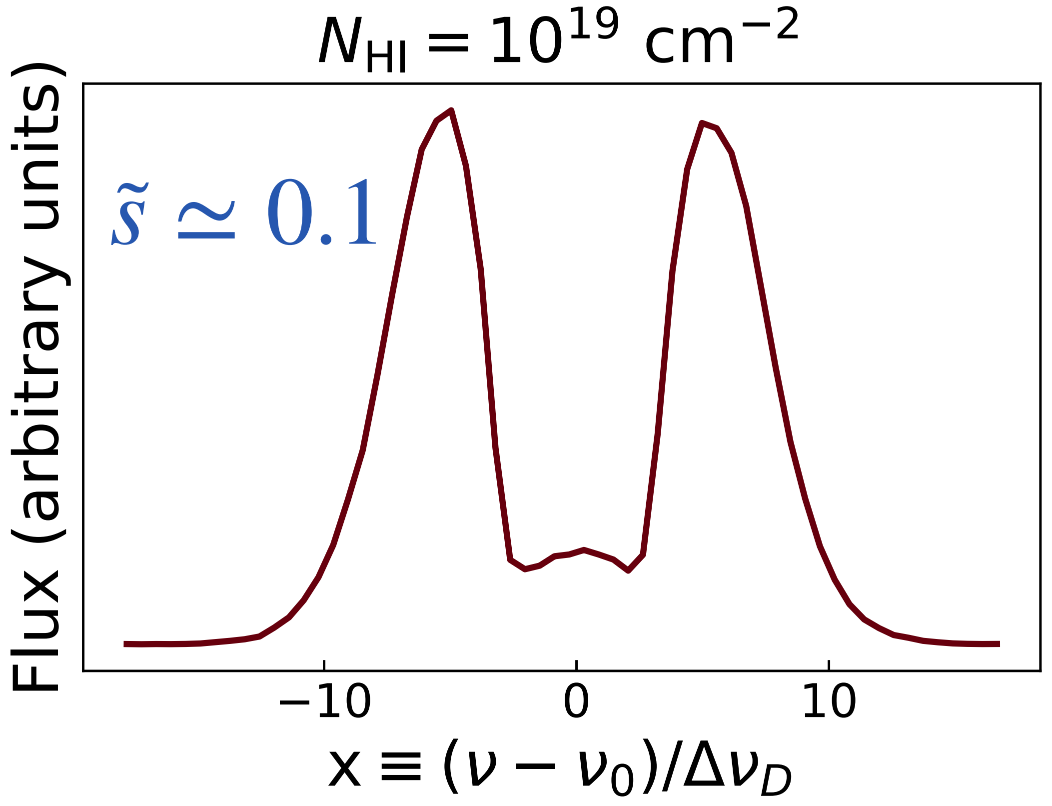

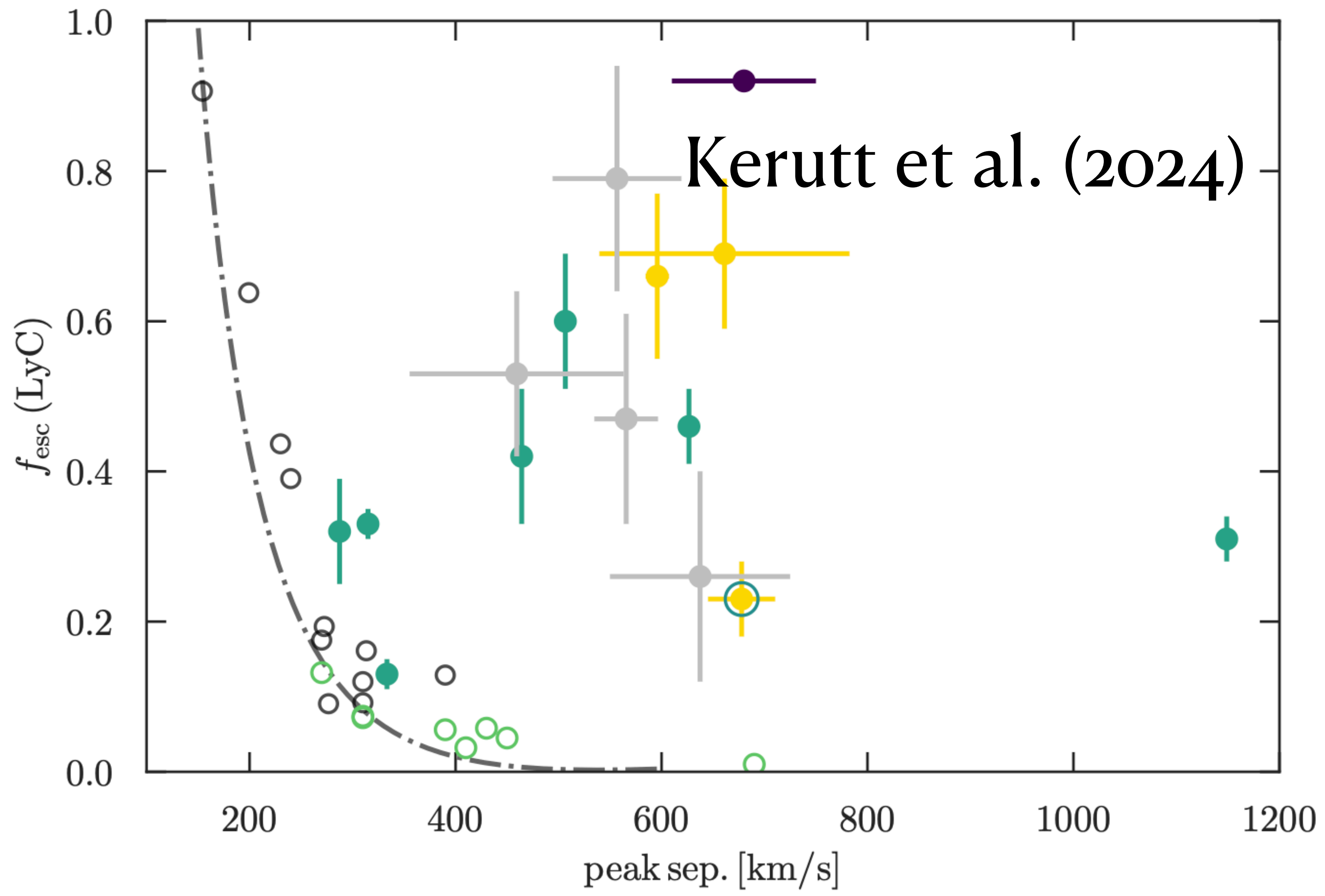

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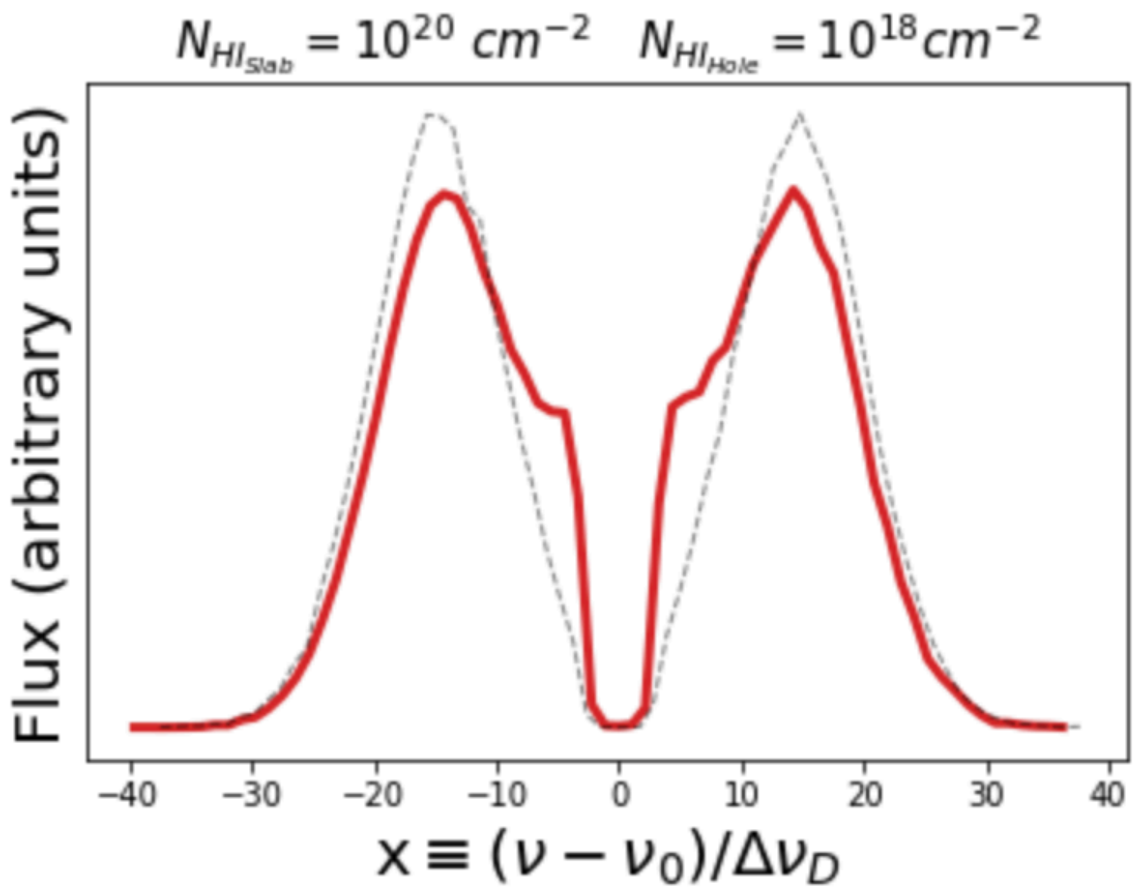

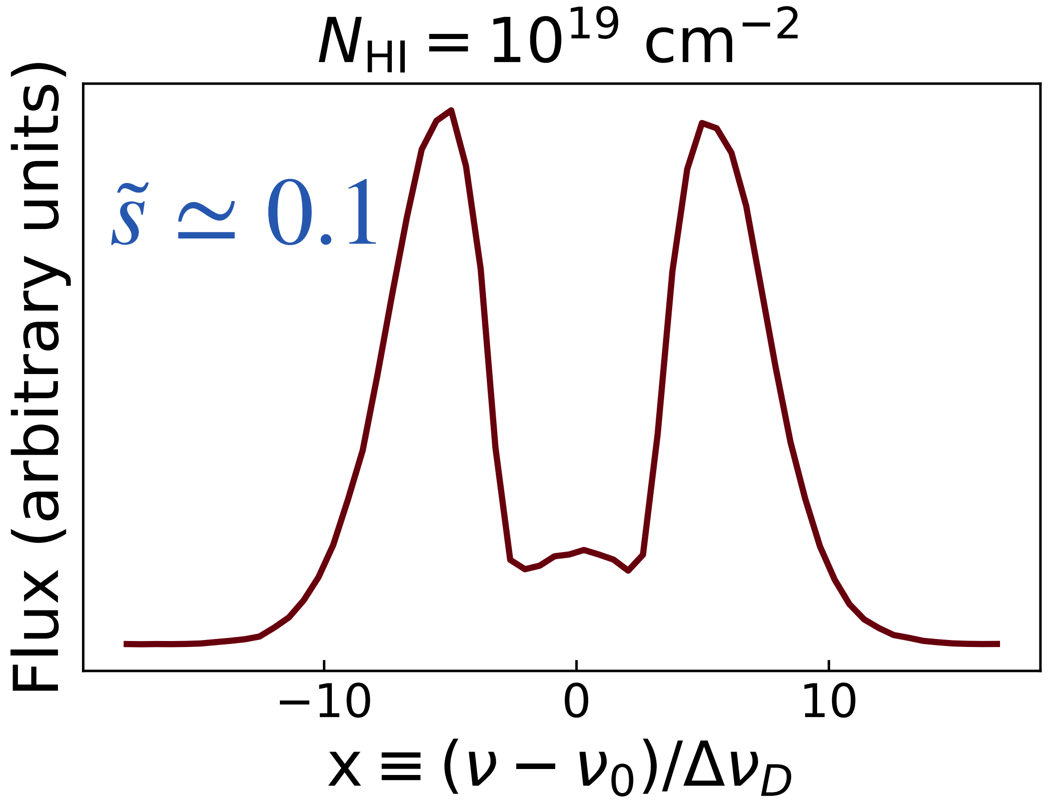

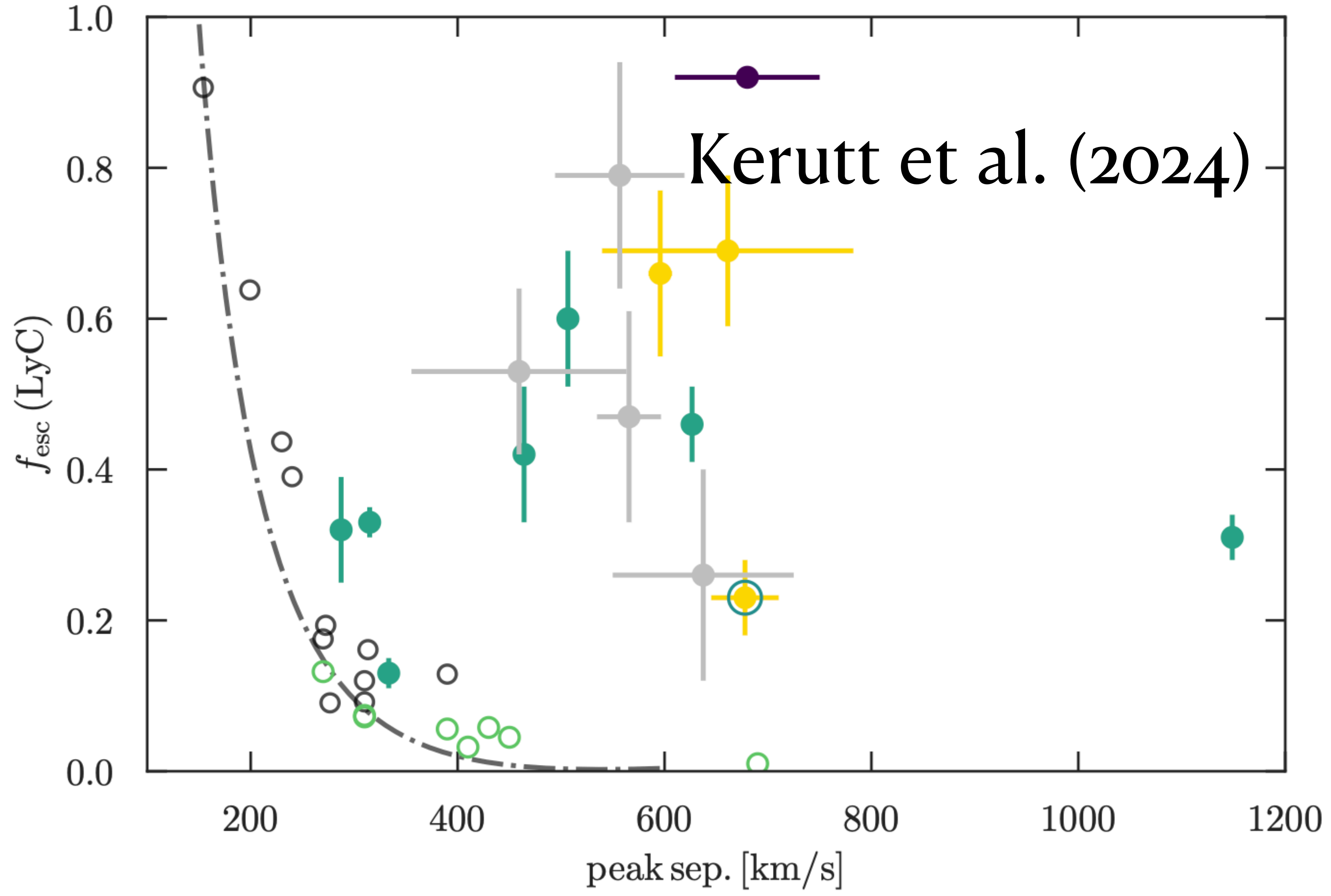

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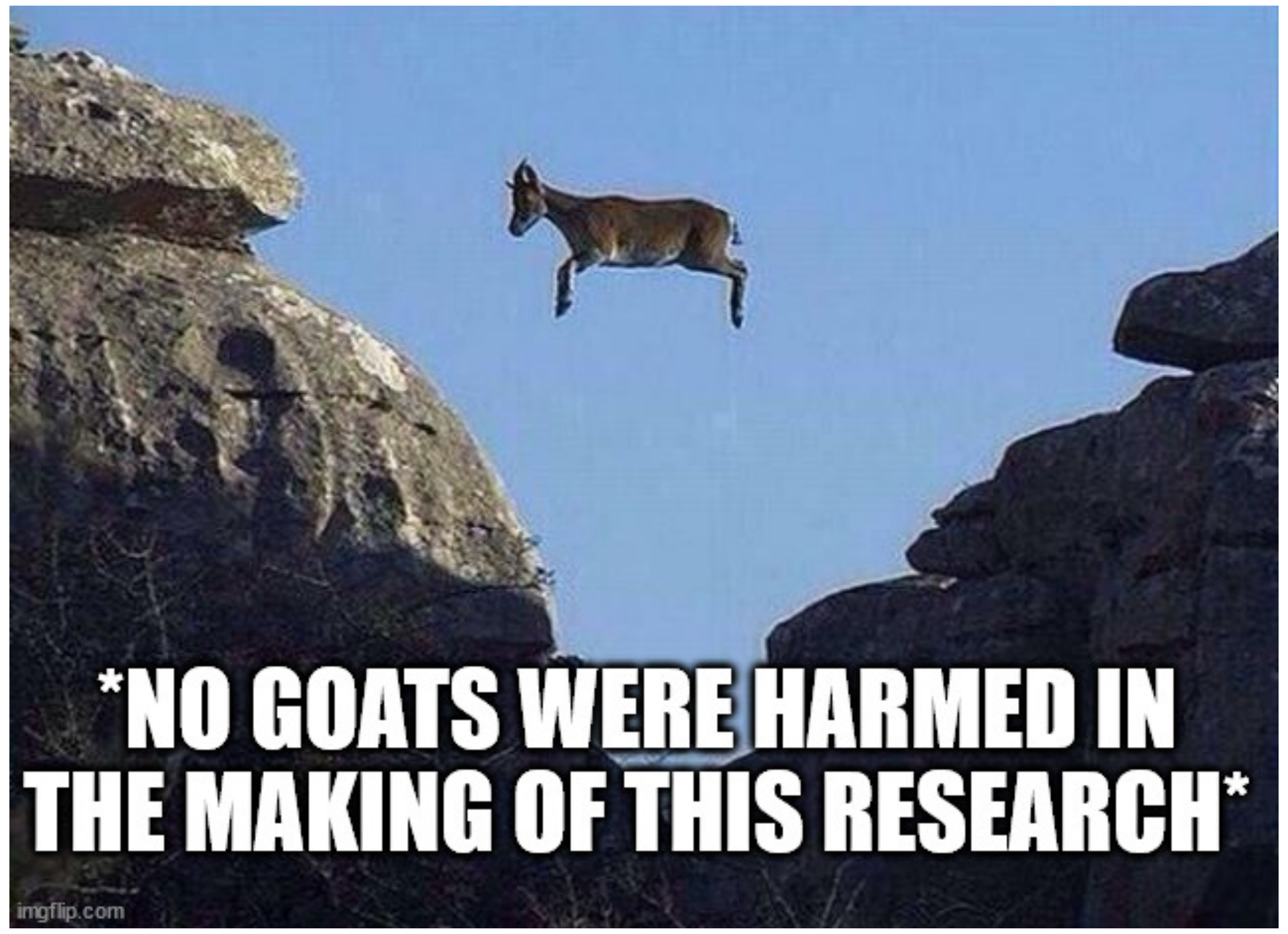
Understand Lyα escape to use it as LyC tracer!

Take home message

- Photons undergo multiple scatterings before escaping, increasing the transmission probability significantly.
- *Lyα* photons probe more general properties of the N_{HI} distribution, rather than just the path of least resistance.
- Channels with certain sizes could be 'hidden' even in high column density systems. No need to have very small channels.
- Asymmetries of line profiles might be an indication of empty/low density channels

$$T_{\mathrm{slab}} = (2\pi\tau_0)^{-1/2}$$



Thank you!

arXiv:2404.07169v1

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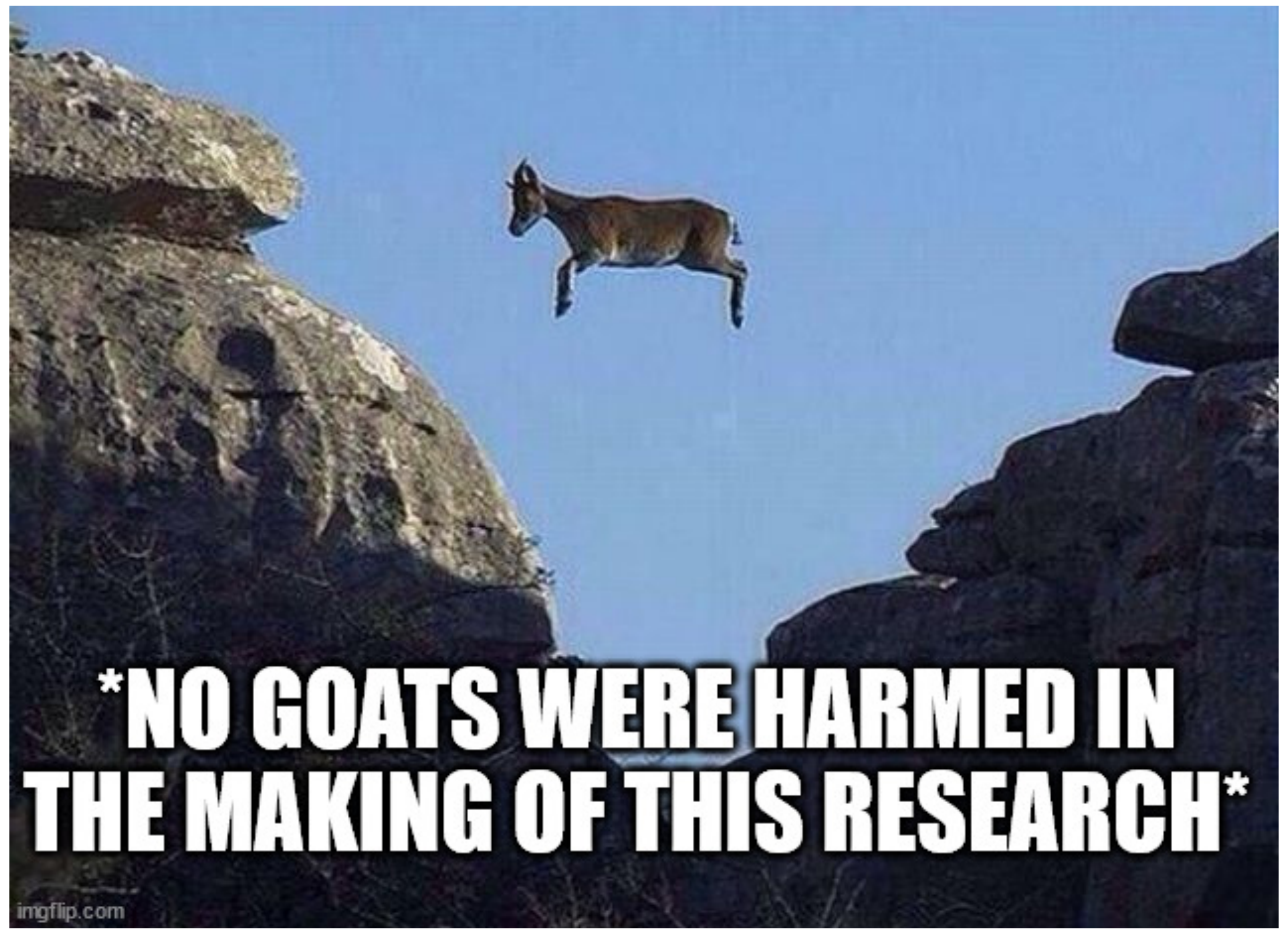

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