

Probing exotic energy injection in the 21-cm power spectrum

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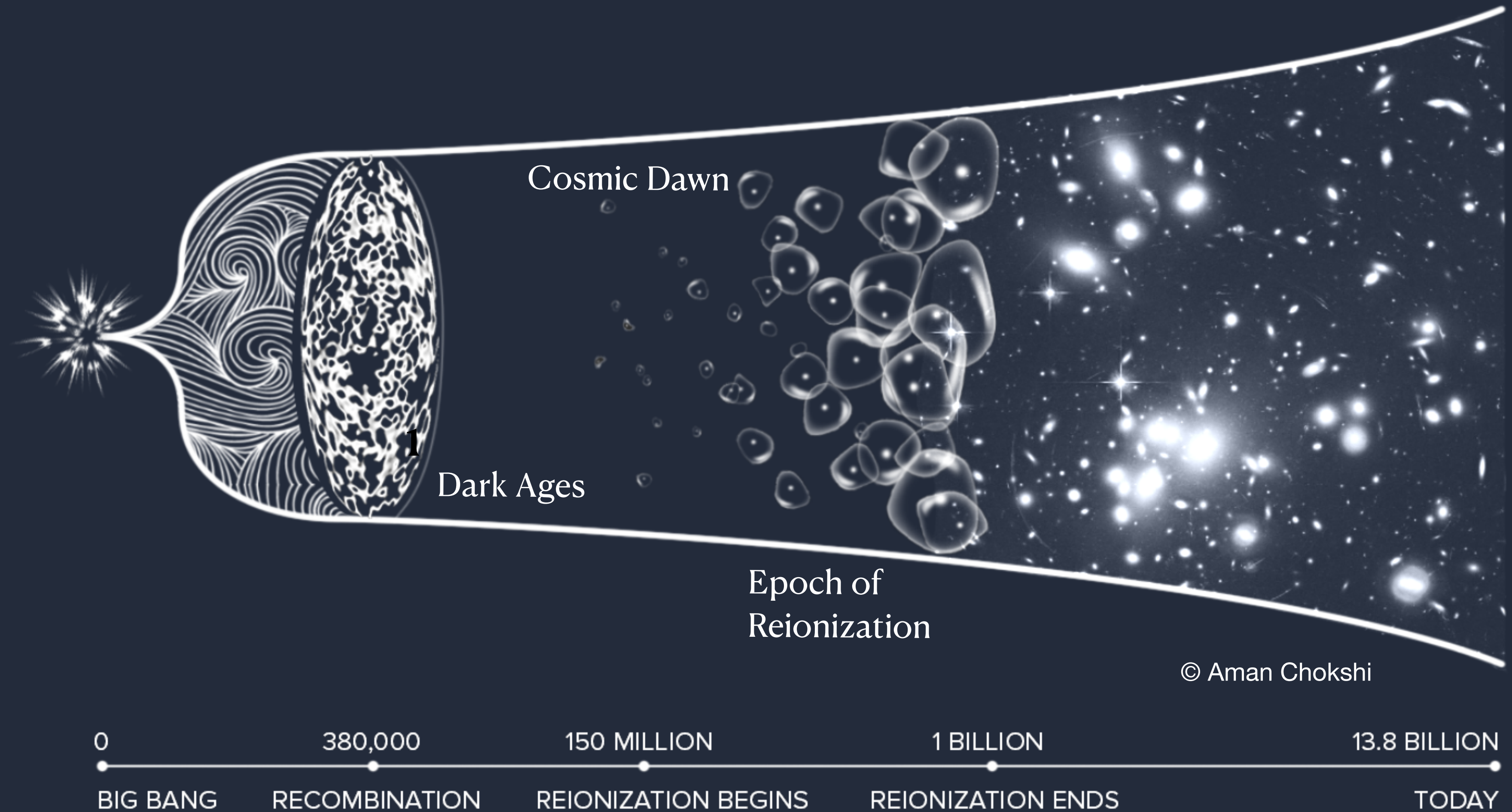


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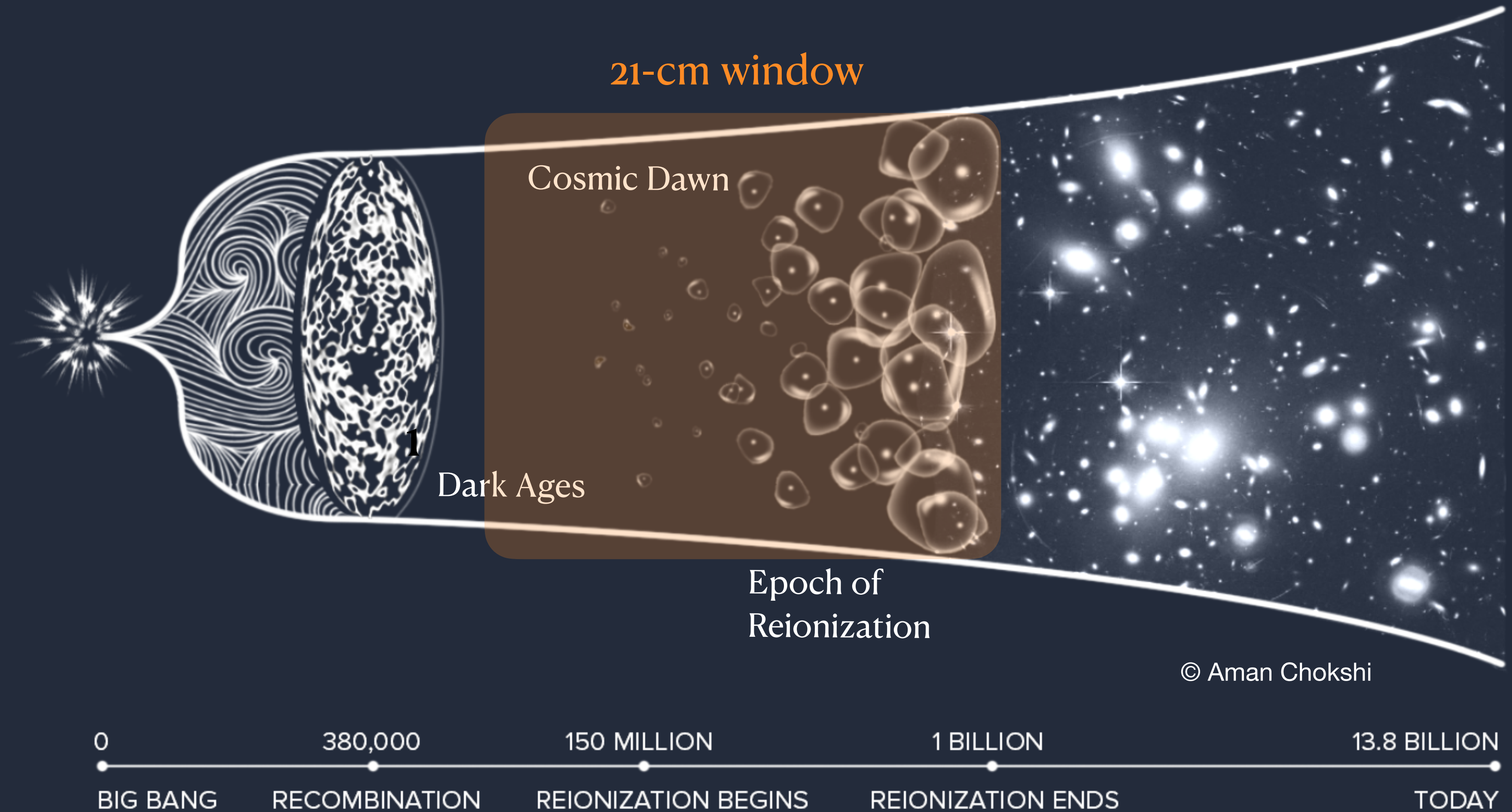
Λ CDM Cosmological Model

The first stars produce X-ray and UV, heating and ionizing the universe



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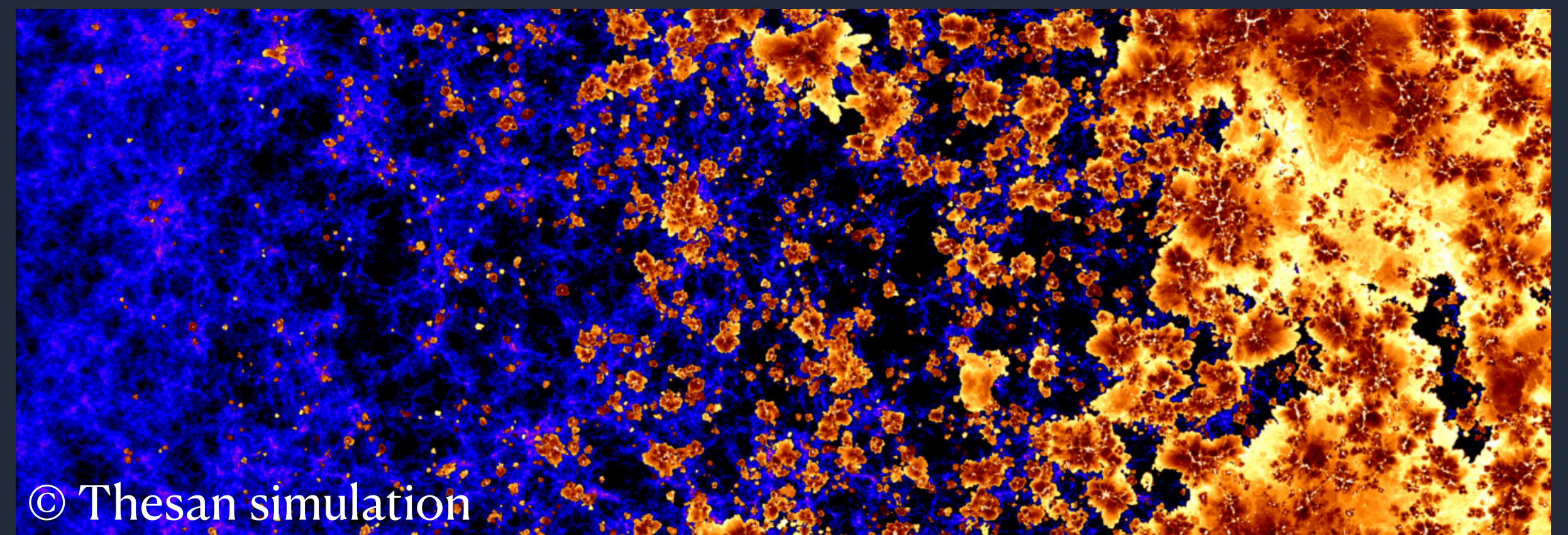
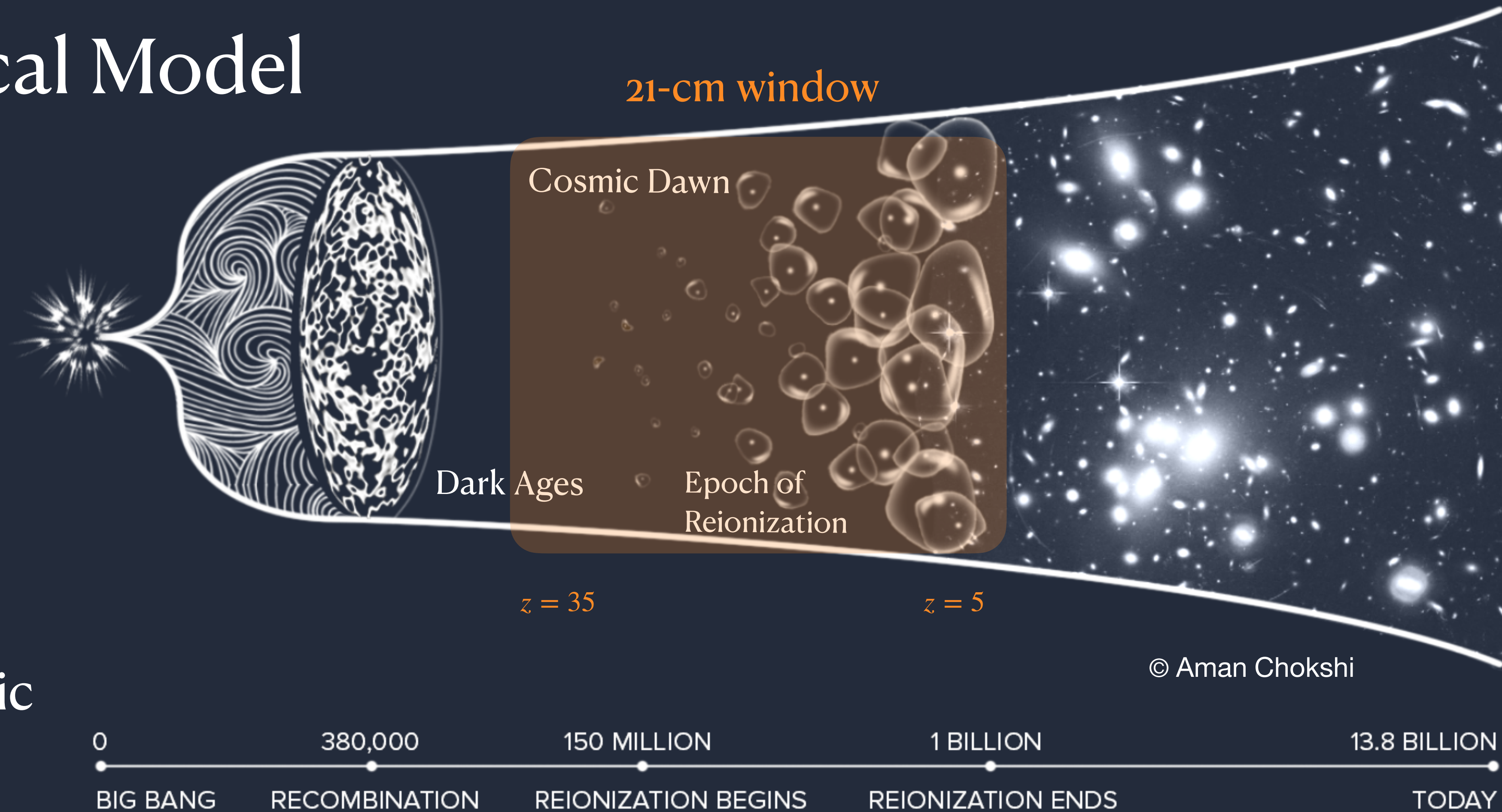


Λ CDM Cosmological Model

The first stars produce X-ray and UV, heating and ionizing the universe

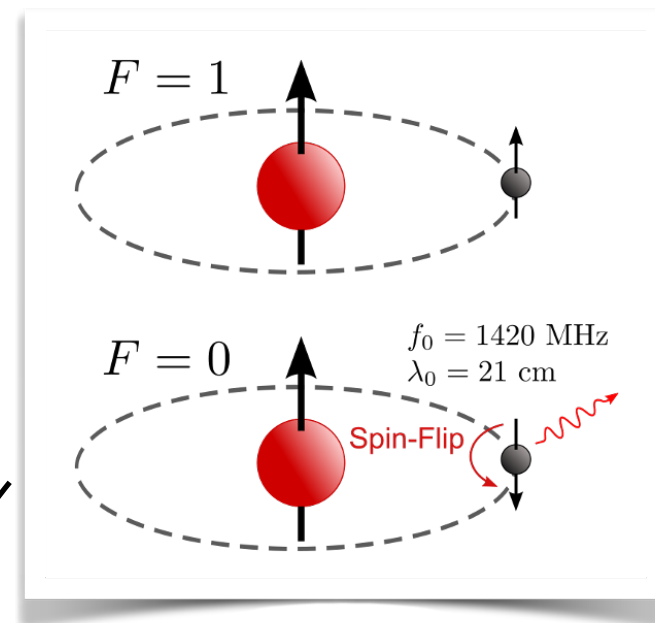
Dark Matter and other exotic energy injection can also affect the universe

Energy injection changes IGM thermal and ionization states



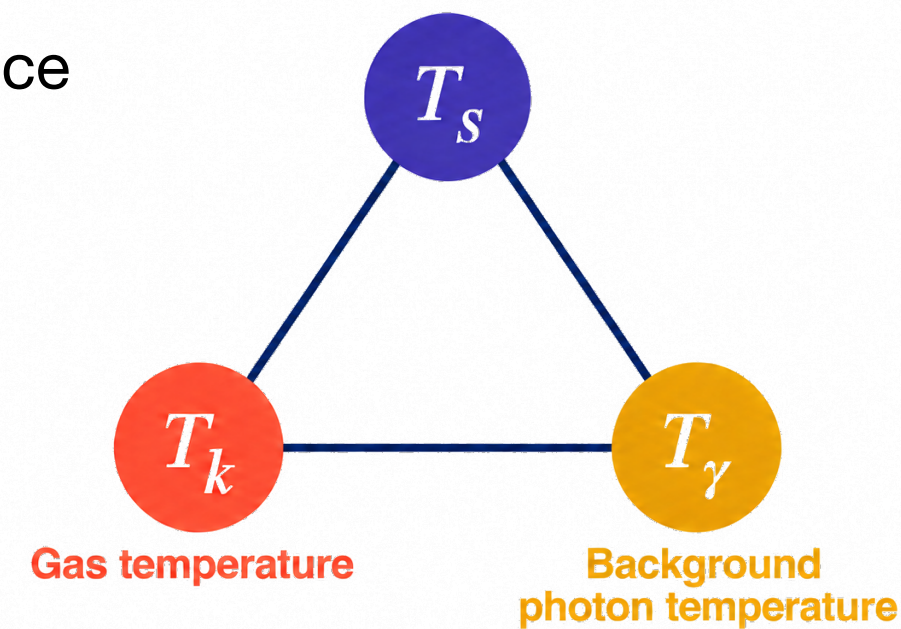
21-cm line

Spin-flip transition in neutral H



Relative abundance

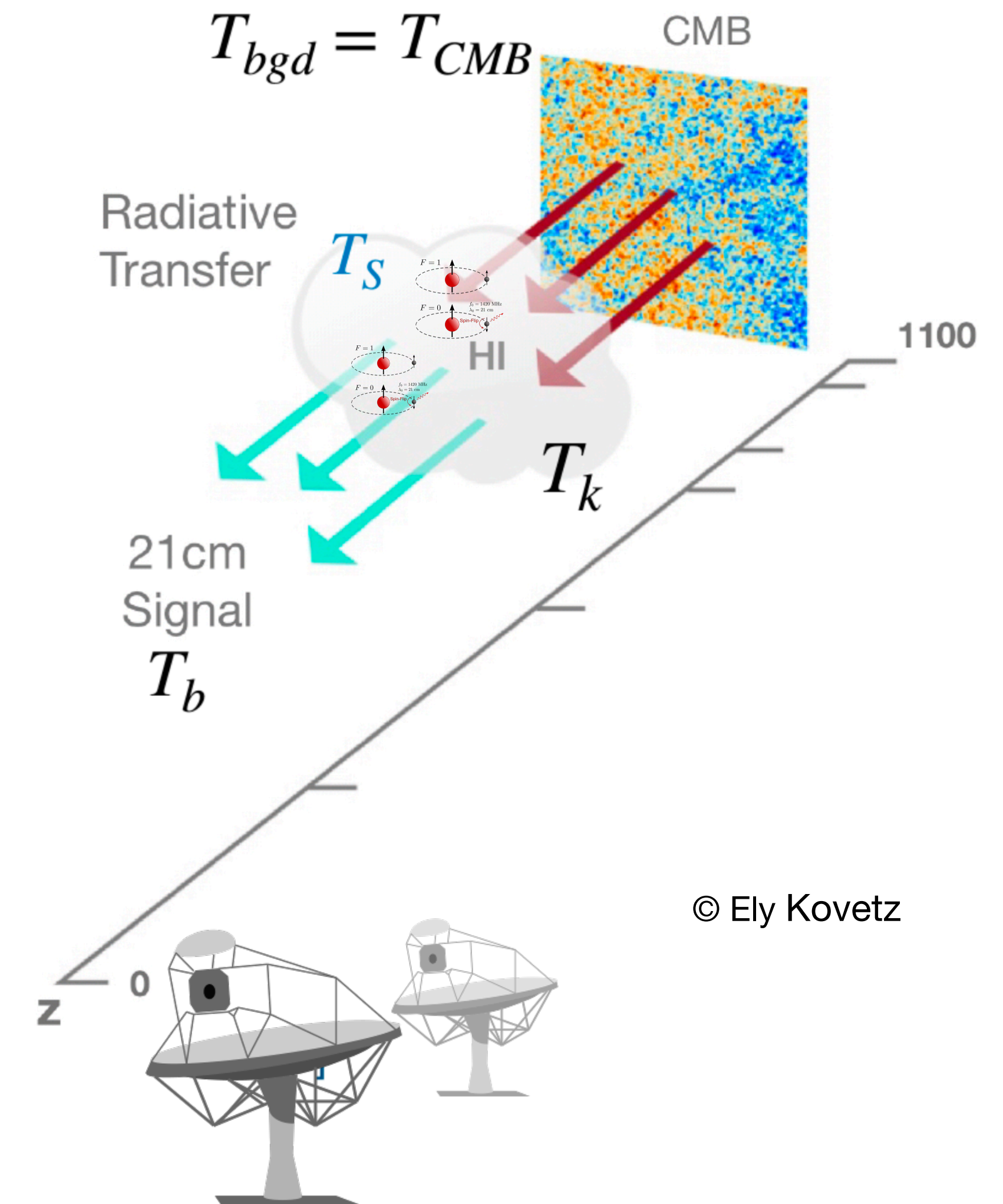
Spin temperature



δT_b encodes the **thermal** and **ionization** state of the IGM

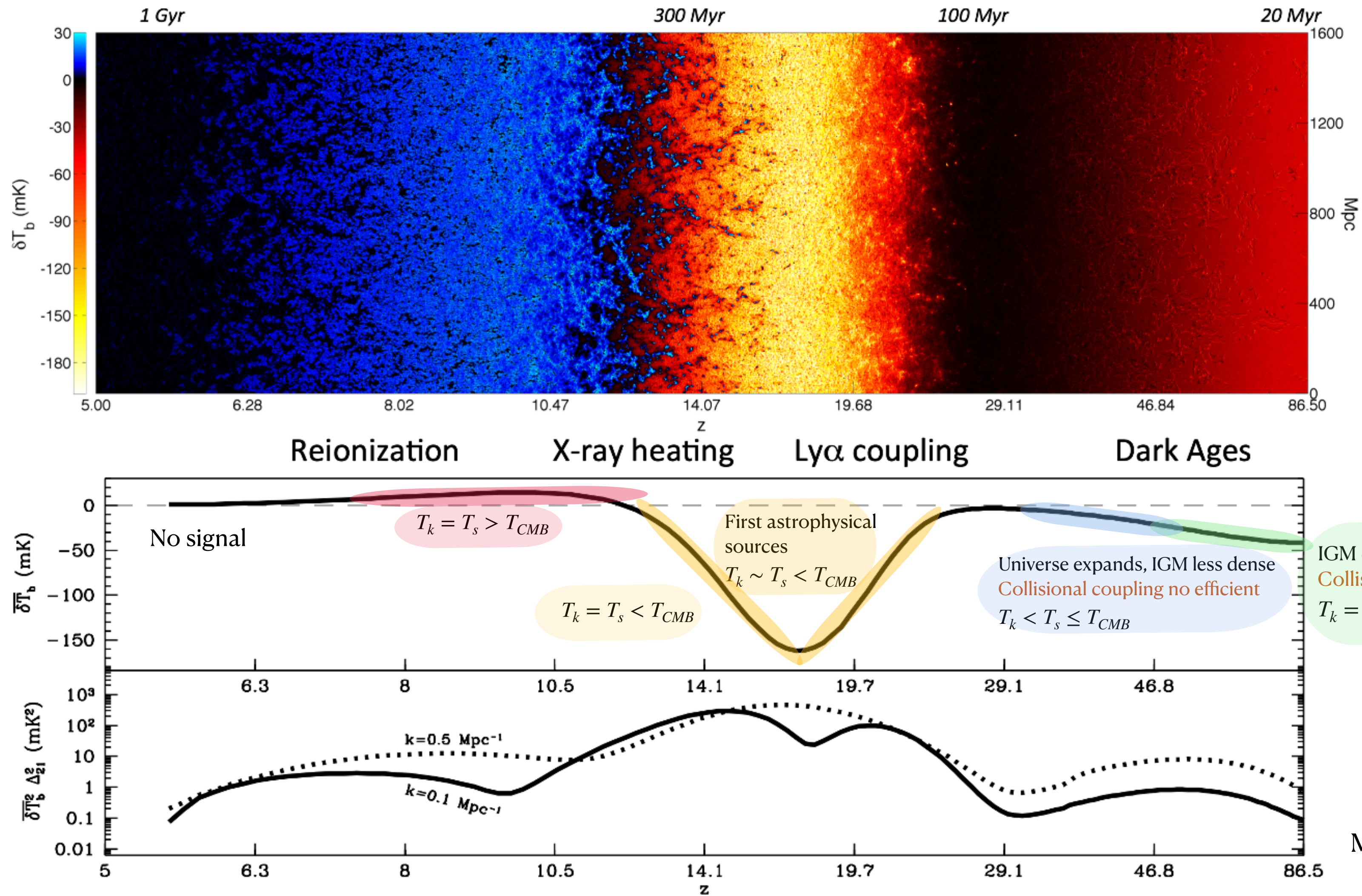
We measure the brightness temperature δT_b

$$\delta T_b \propto x_H (T_s - T_\gamma) / T_s$$



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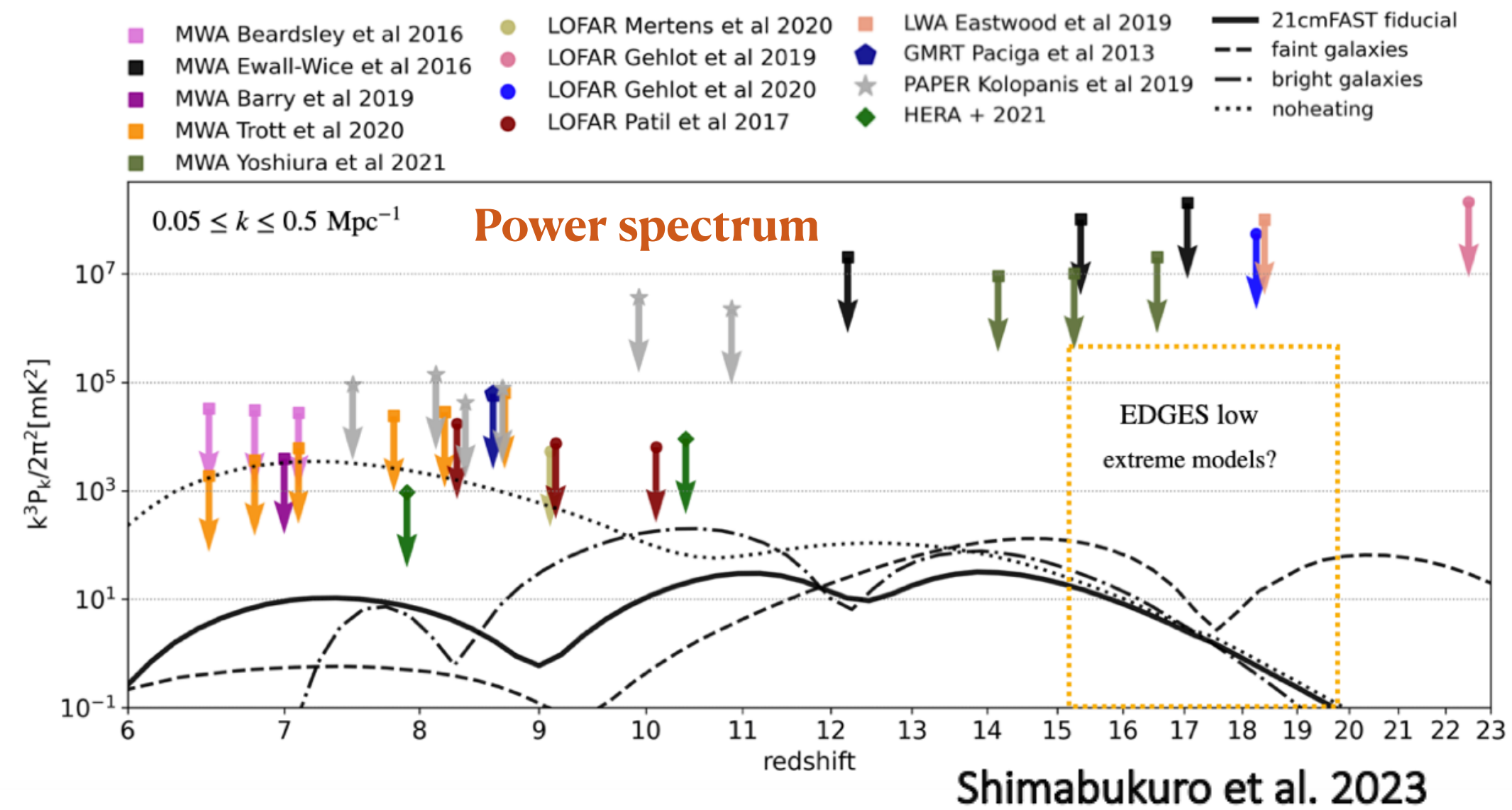
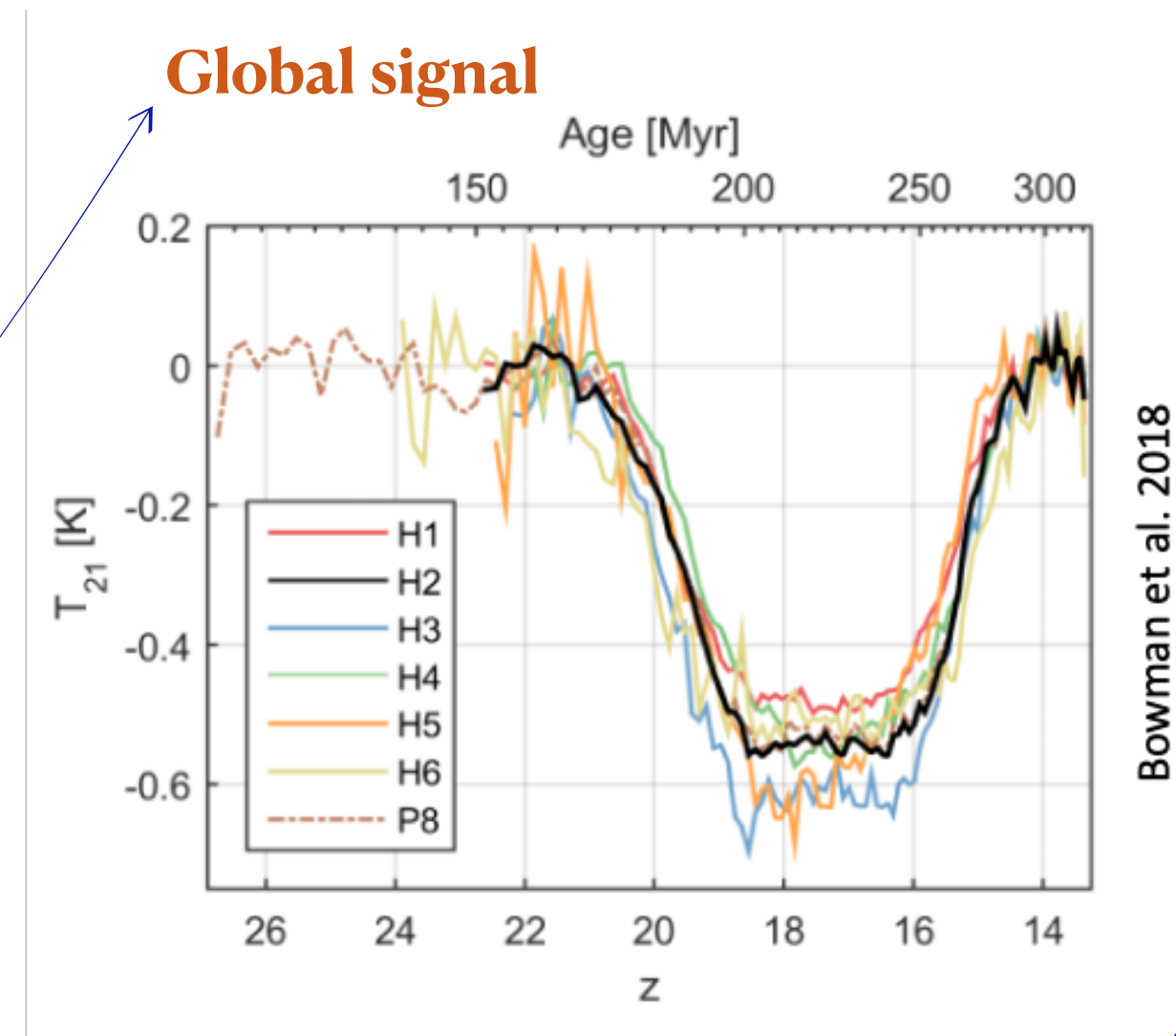
21-cm signal is a powerful probe of Cosmic Dawn and Dark Ages



Sensitive to Astrophysics (X-rays, UV), Cosmology (structure formation), Exotic physics (DM)



Observational searches



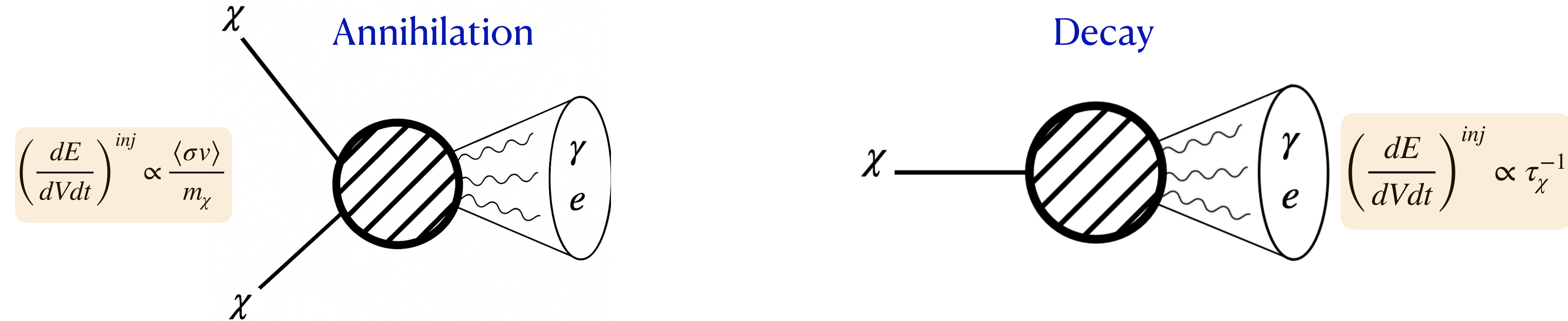
In a few years...

SKAO



DM energy injection/deposition

Some DM scenarios impact the thermal and ionization history of the IGM



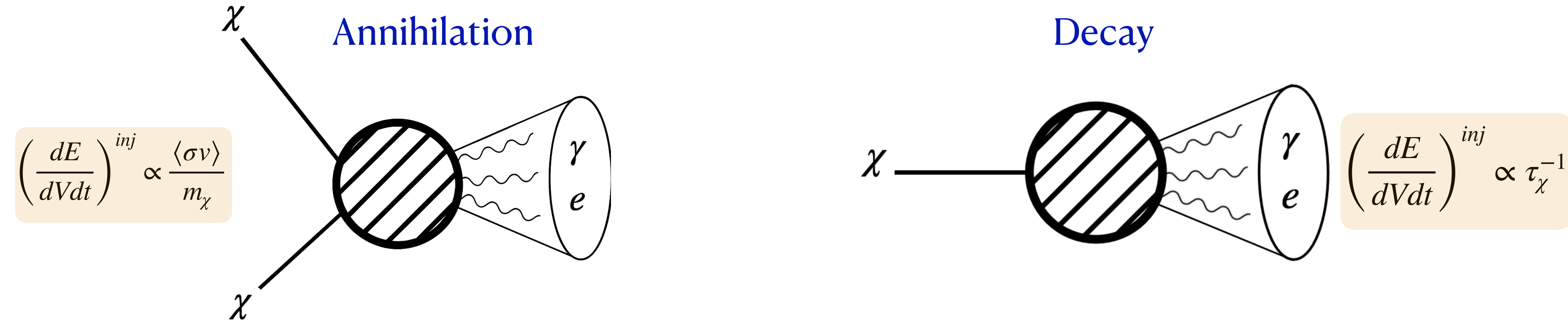
Rate of energy injection/deposition into c = **heat, ionization, excitation**

$$\left(\frac{dE}{dVdt}\right)_c^{dep} \equiv f_c \left(\frac{dE}{dVdt}\right)^{inj}$$

See previous work e.g. Furlanetto 2006, Slatyer 2016, Lopez-Honorez 2016

DM energy injection/deposition

Some DM scenarios impact the thermal and ionization history of the IGM



Rate of energy injection/deposition into c = **heat, ionization, excitation**

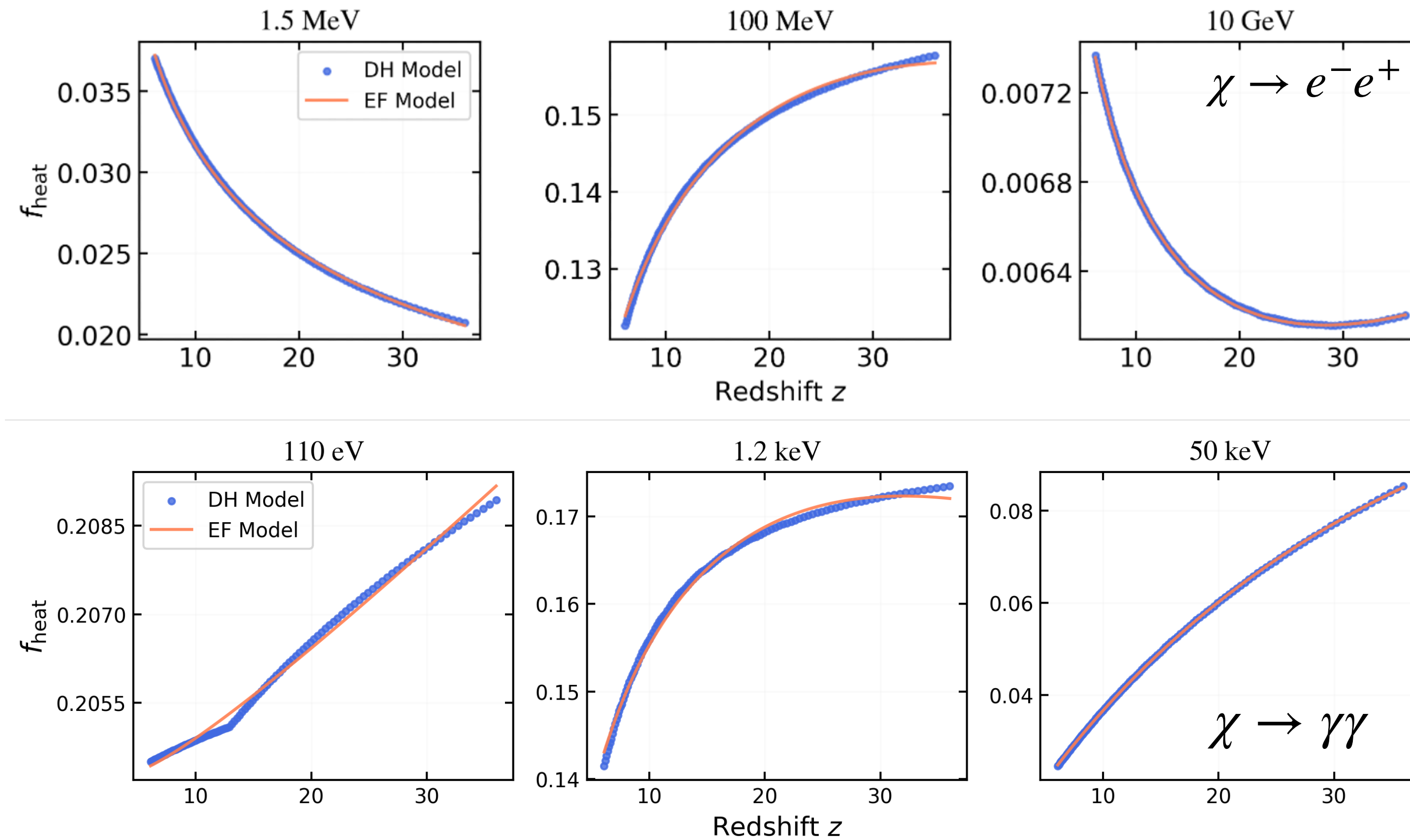
$$\left(\frac{dE}{dVdt}\right)_c^{dep} \equiv f_c \left(\frac{dE}{dVdt}\right)^{inj}$$

Energy deposition efficiency per channel

Can be obtained using
DarkHistory

How do we study this exotic energy injection ?

Develop an **effective model (EF)** for the DM heating deposition f_{heat} to efficiently include DM decay effects in the 21-cm signal.

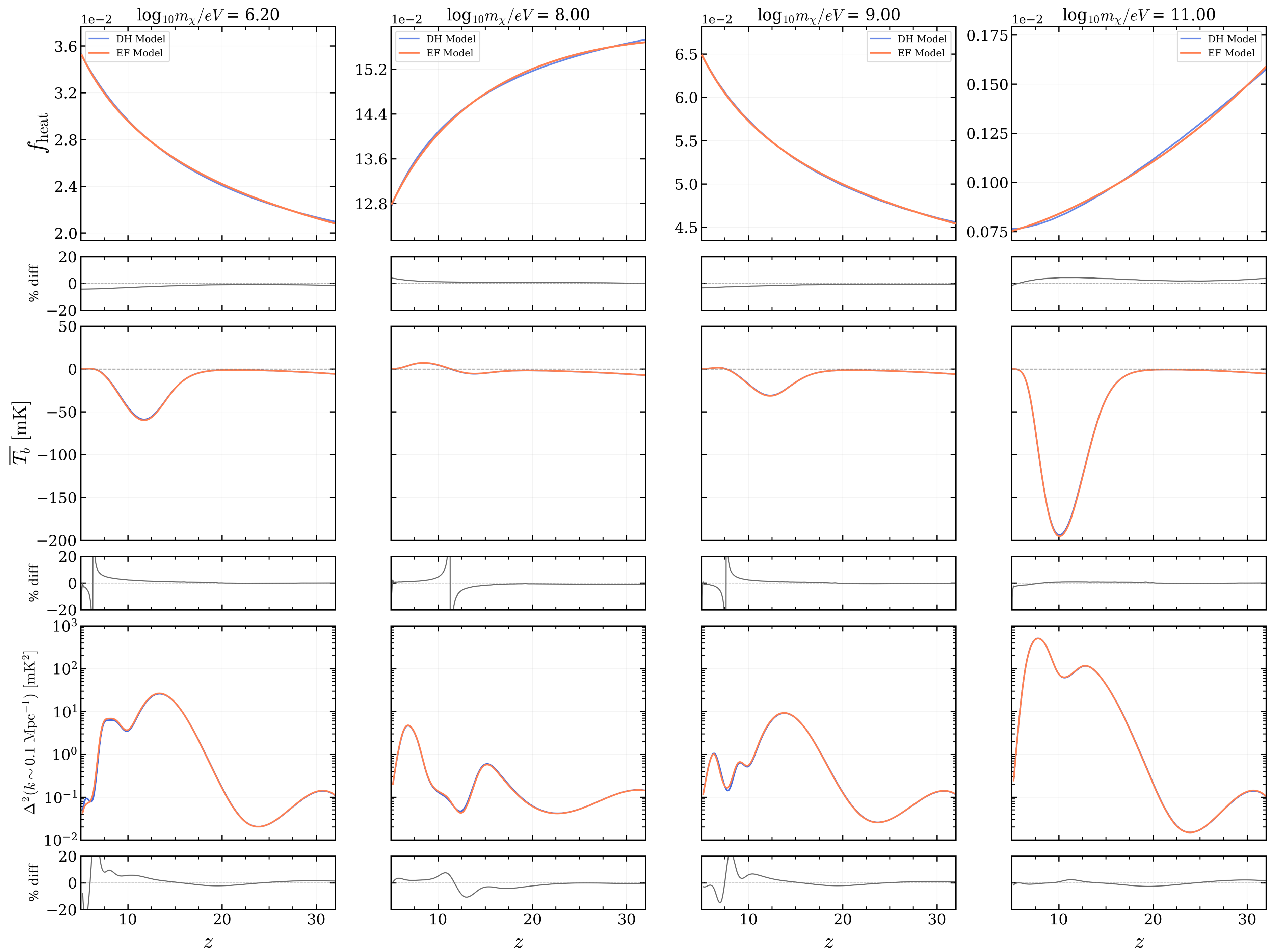


Comparison of DH results and our EF predictions

$$f_{heat}(z) = f_0 e^{a(z-z_0)} \left(\frac{z+1}{z_0+1} \right)^b$$

Other channels can be included as

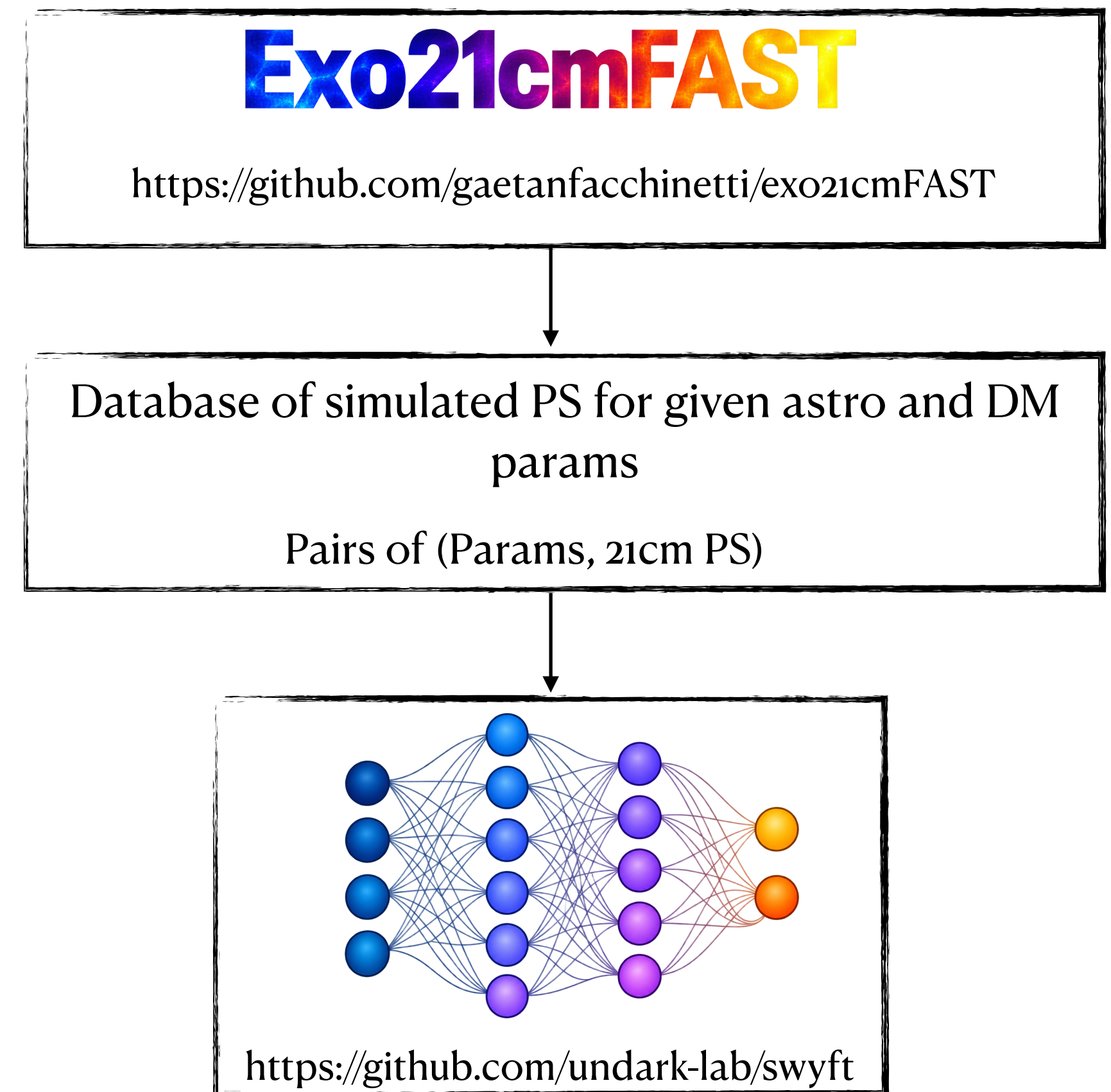
$$\frac{f_{ion,HII}}{f_{heat}}, \frac{f_{ion,HeII}}{f_{heat}}, \frac{f_{exc}}{f_{heat}}$$



How do we use the EF model to learn about DM properties

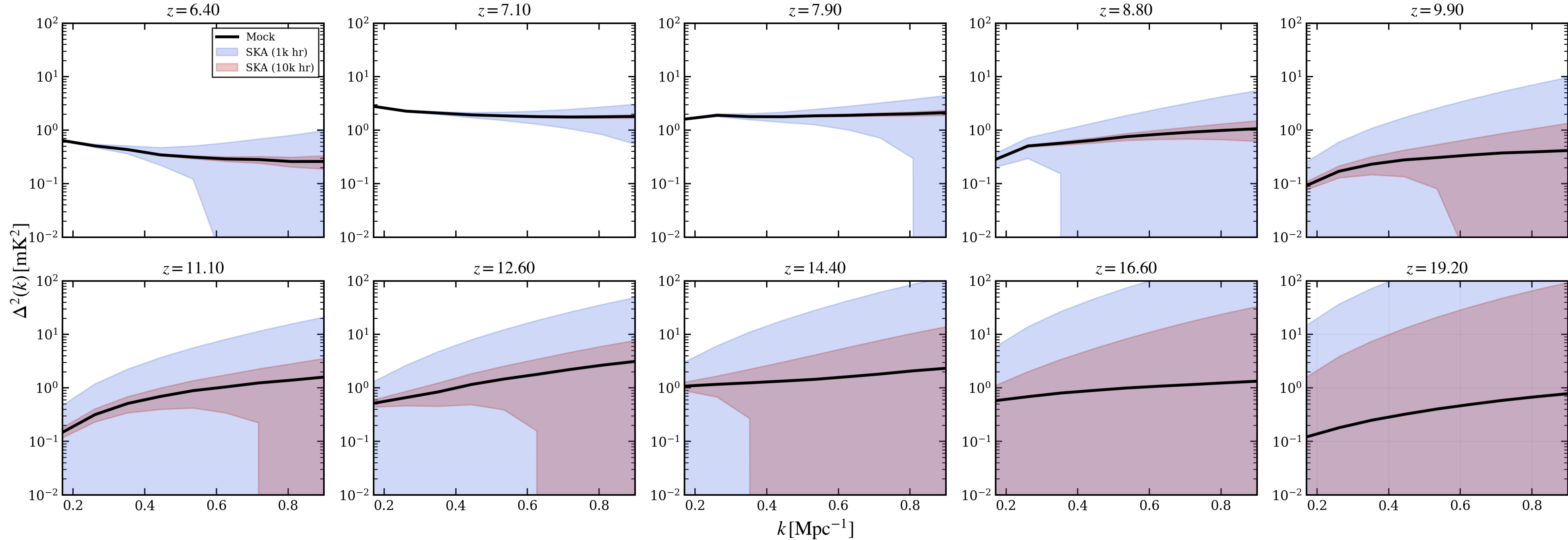
We use **Simulation-Based Inference (SBI)** to constrain the posterior distribution of the model parameters

- Simulator
- Generate parameter-simulation pairs from the simulator
- Train a neural network to **approximate the likelihood-to-evidence ratio**
- Evaluate a mock observation
- Predictions



Mock Observation

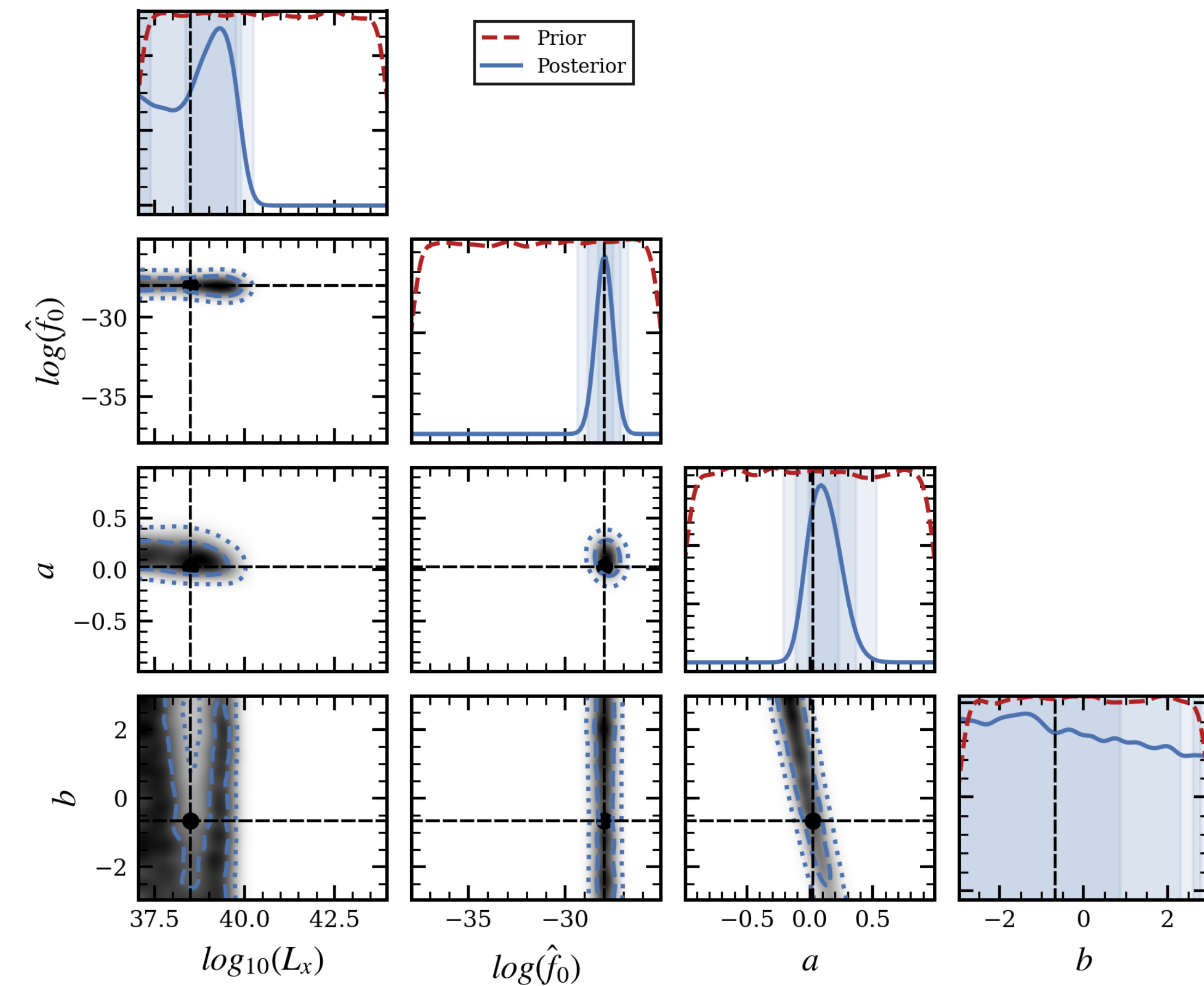
We generate 21-cm PS by varying the astrophysical and DM params
and adding different levels of SKA thermal noise



The shaded regions indicate the 1σ noise from a 1000 hr/10000 hr observation with SKA

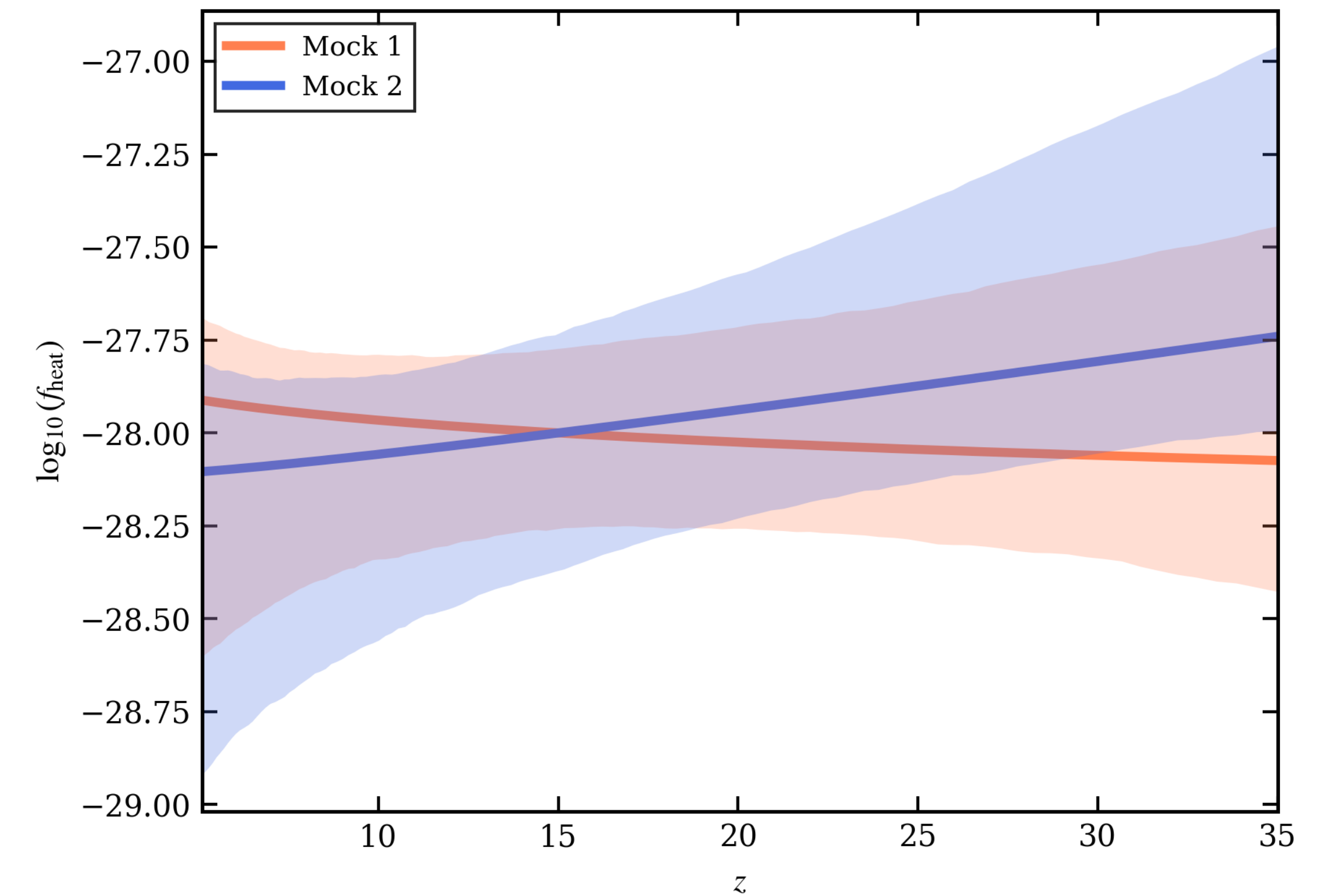
Simulated Mock Observation

Posterior distribution of the model params



Example with an uninformative prior for the EF model params

Recovered heating history using the EF and SBI



Recovering the heating history provides a bridge between the 21-cm PS and the underlying DM properties.

Recovering the heating history to learn about DM properties

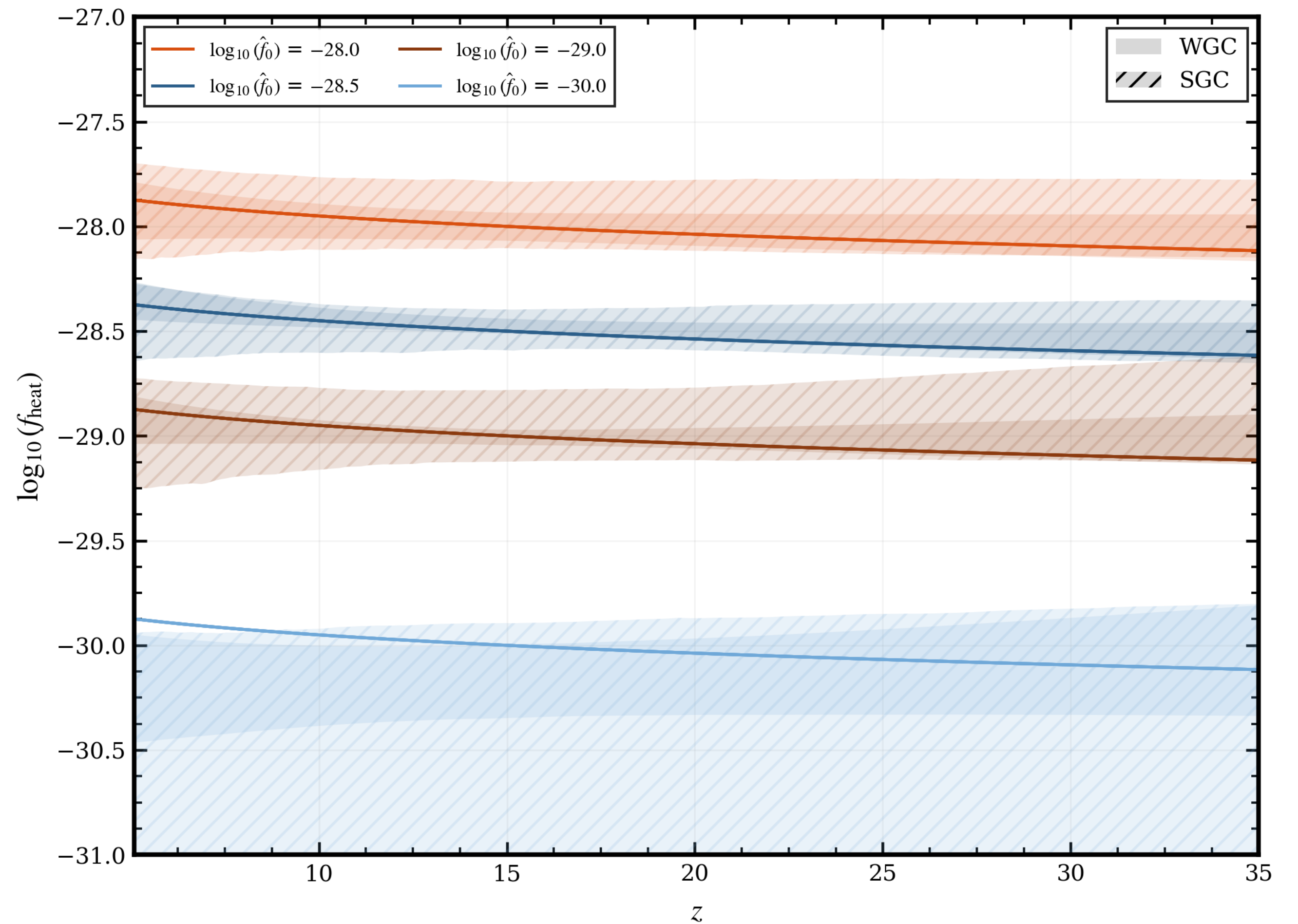
Create a motivated prior for the EF model params e.g. DM decaying into $\chi \rightarrow e^-e^+$ in the range of:

$$10^6 \leq m_\chi \leq 10^{12} \text{ eV} \quad 10^{26} \leq \tau_\chi \leq 10^{33} \text{ s}$$

Recovered heating for different scenarios:

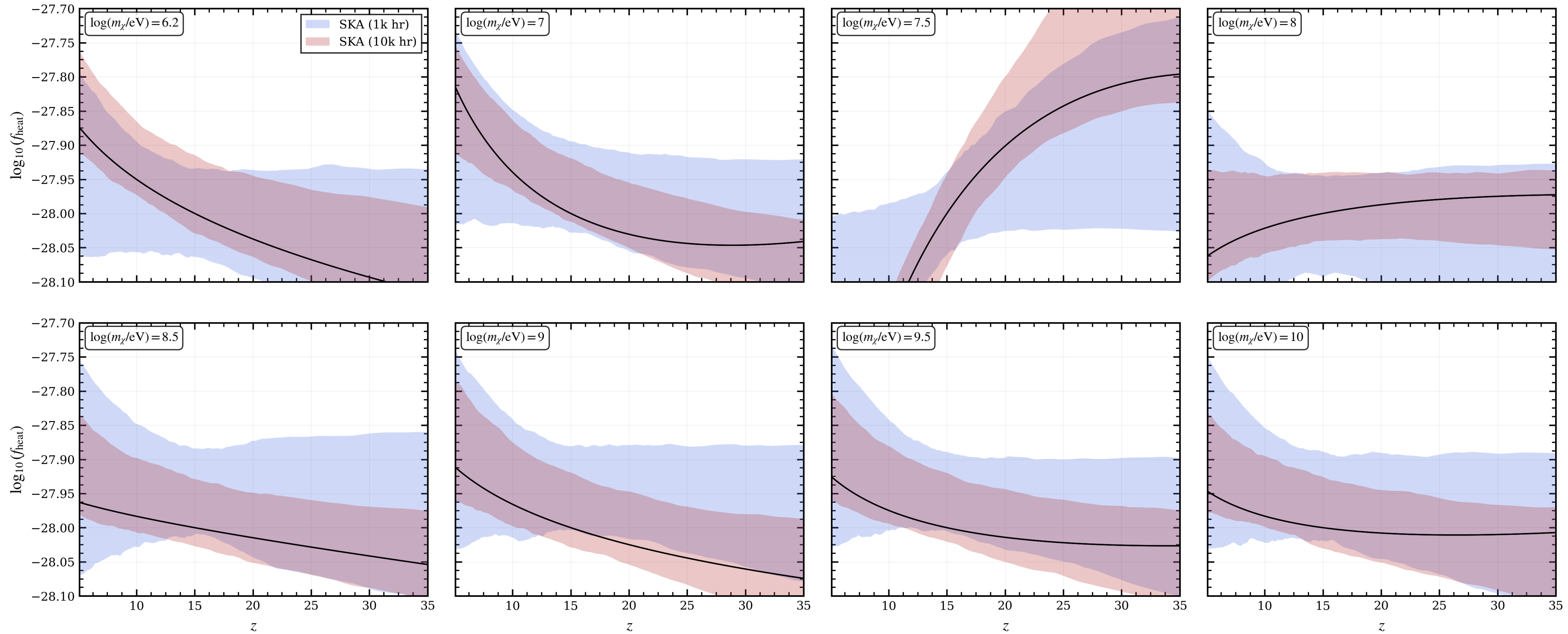
Weak galaxy scenario (WGC) - $L_X = 10^{38.5}$

Strong galaxy scenario (SGC) - $L_X = 10^{40.5}$



When recovering the heating history, the **amplitude** gives information about the lifetime (τ_χ)

Recovering the heating history to learn about DM properties



When recovering the heating history, the **shape** gives information about the mass (m_χ)

What can we learn about DM with our framework?

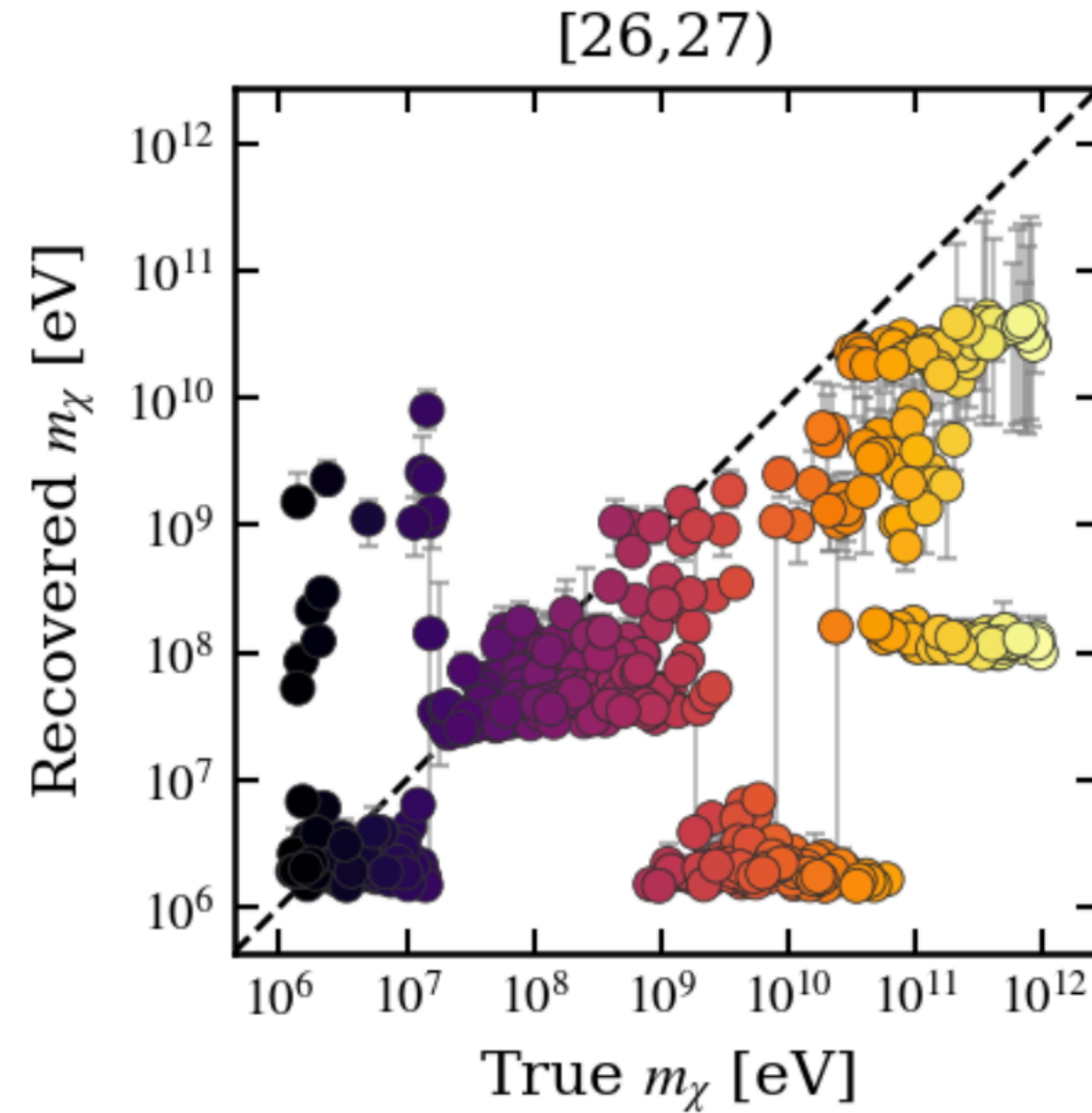
Assumptions:

- 1) Explore DM decay channel into e^-e^+ .
- 2) Mock observation includes DM contribution.
- 3) Recover posterior of (m_χ, τ_χ) .

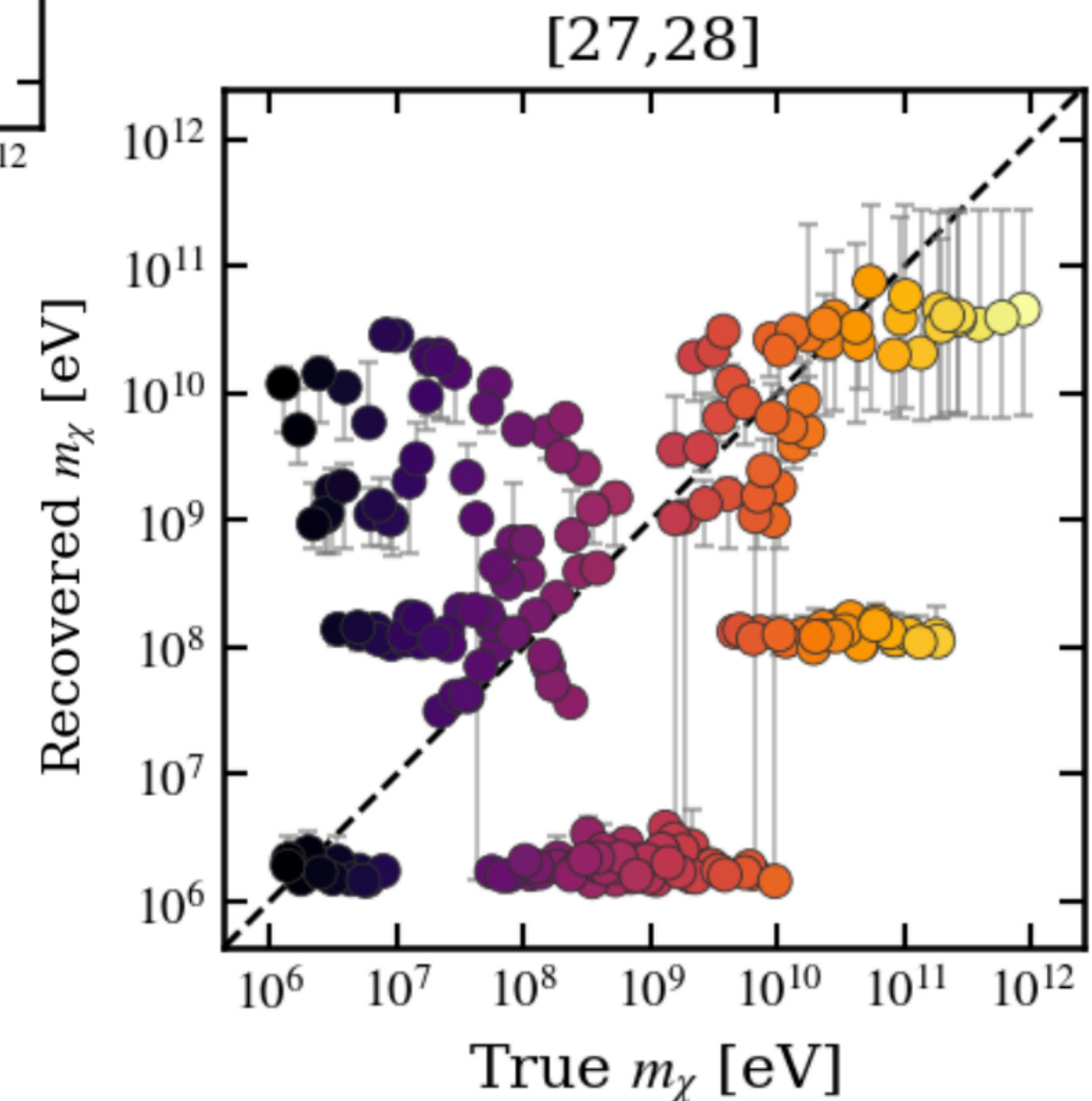
$$\chi \rightarrow e^-e^+$$

$$10^6 \leq m_\chi \leq 10^{12} \text{ eV}$$

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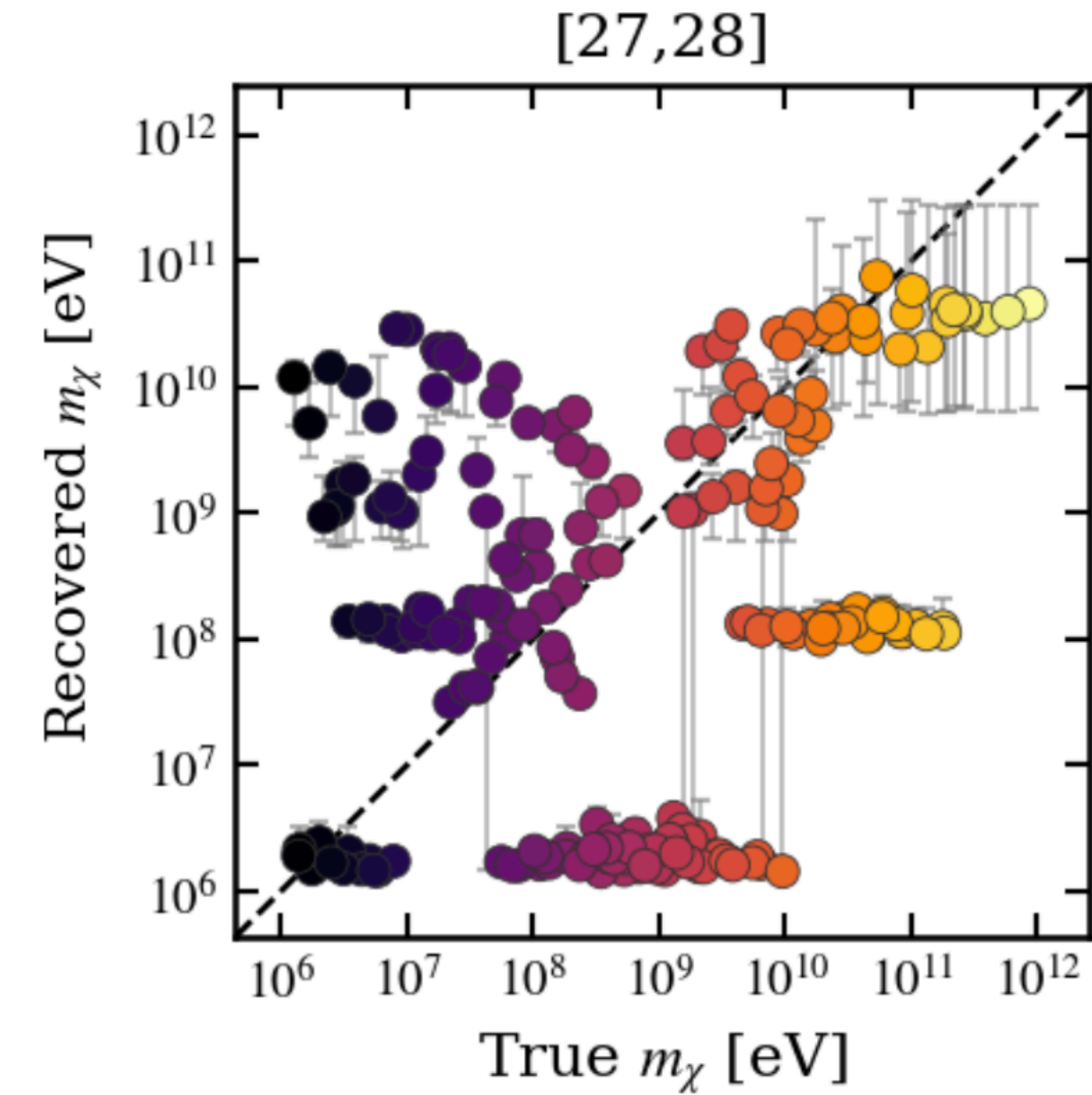
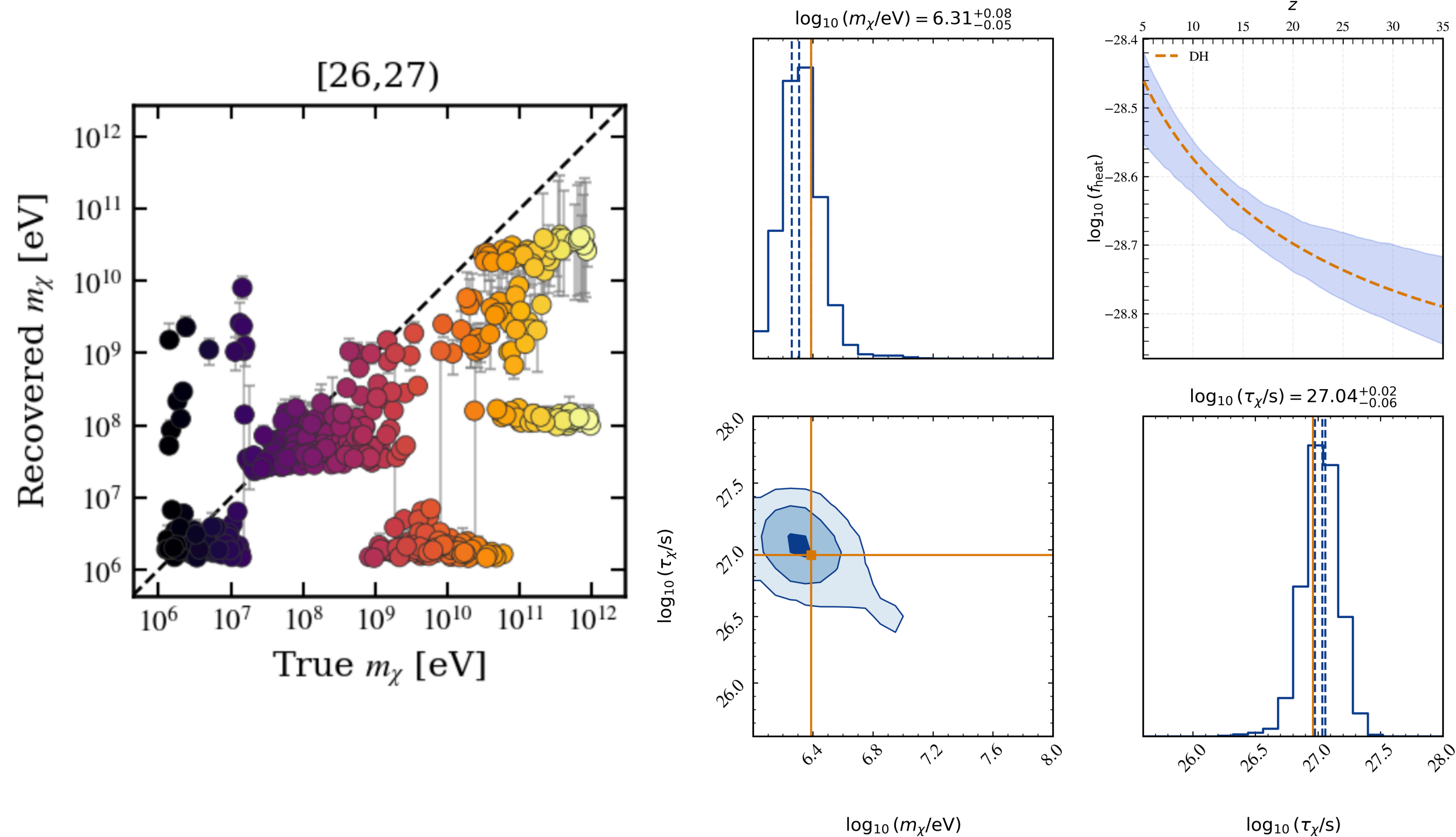


Preliminary results



What can we learn about DM with our framework?

Preliminary results

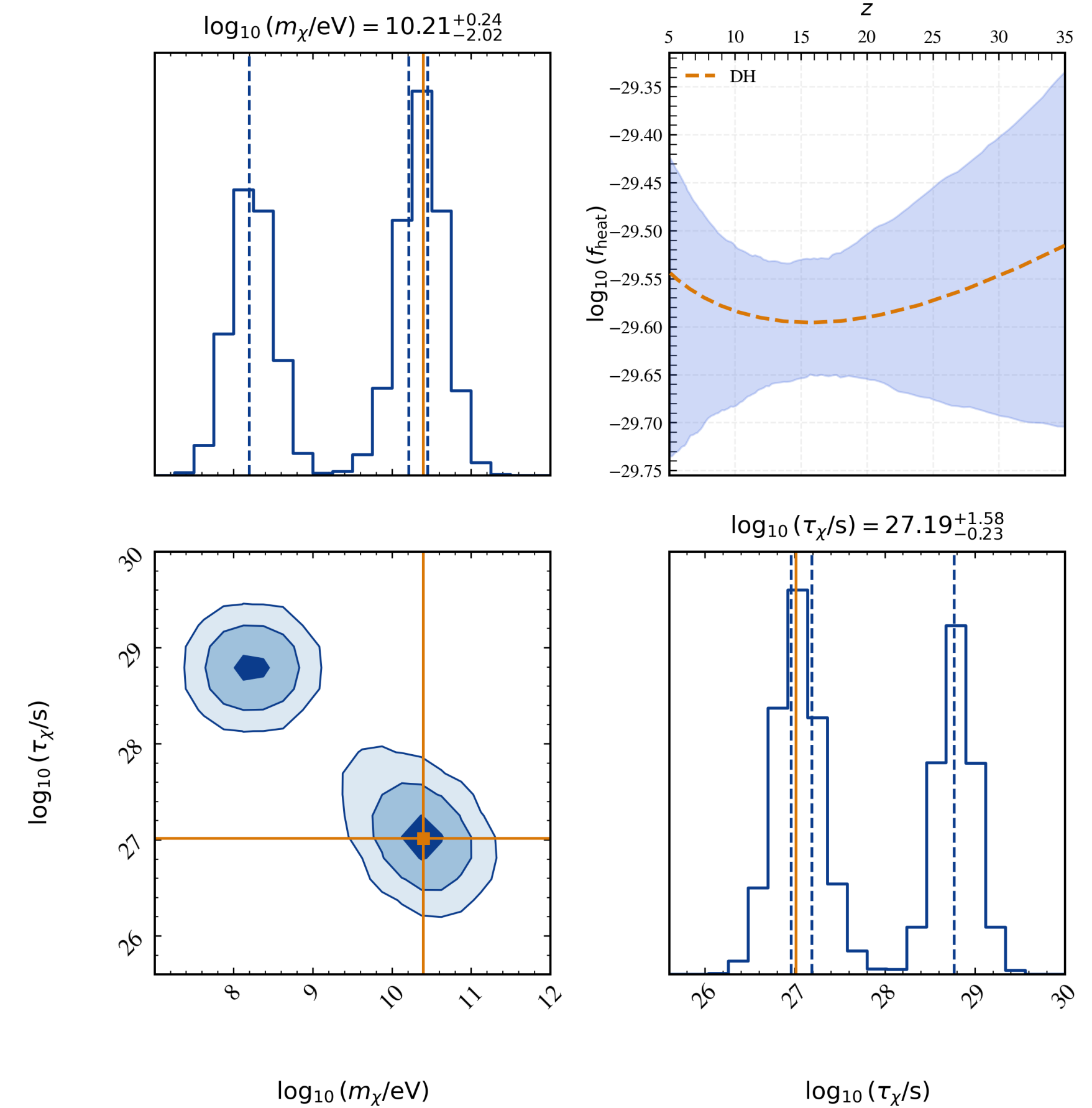
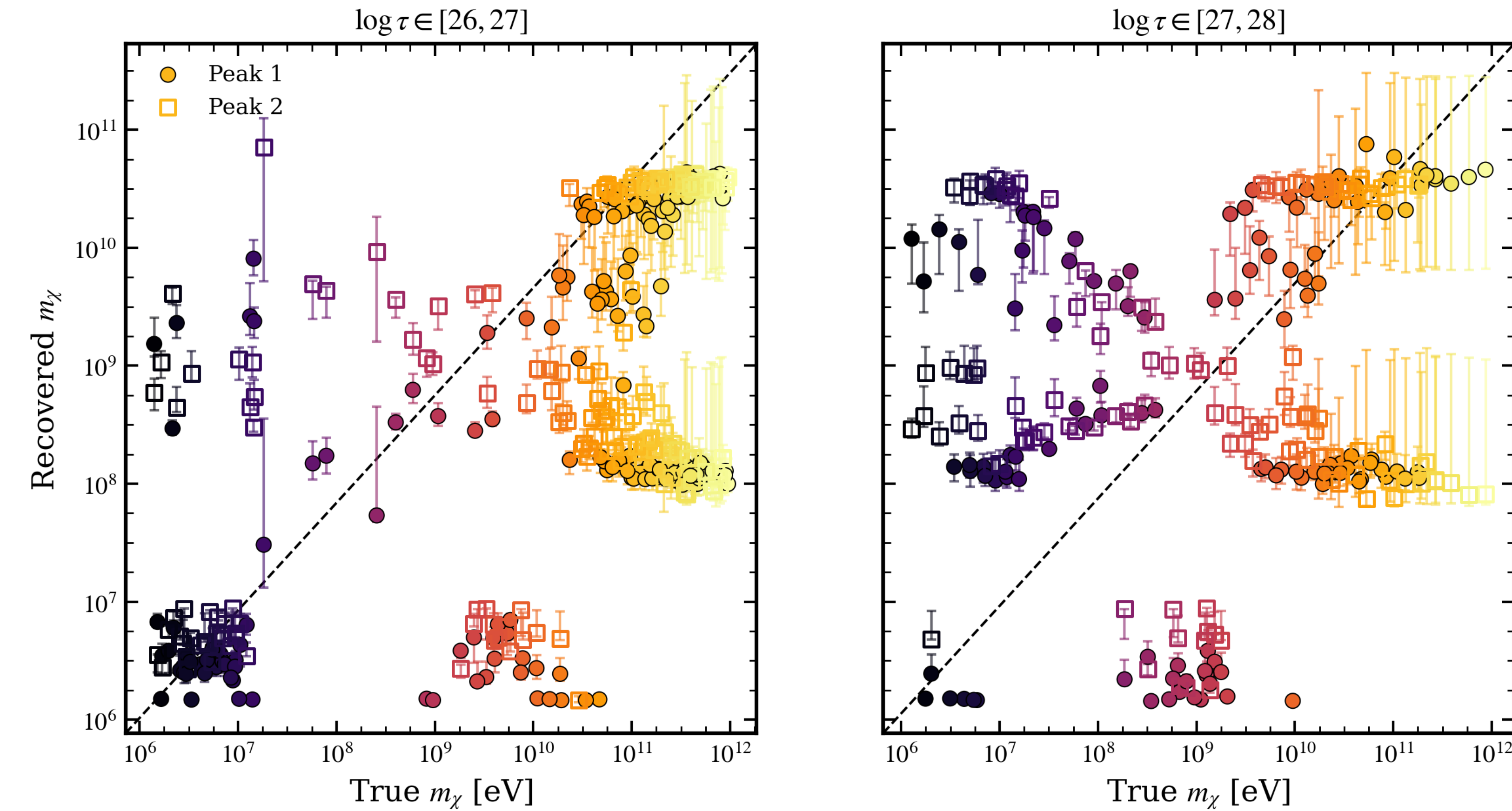


Posterior distribution of the mass and lifetime

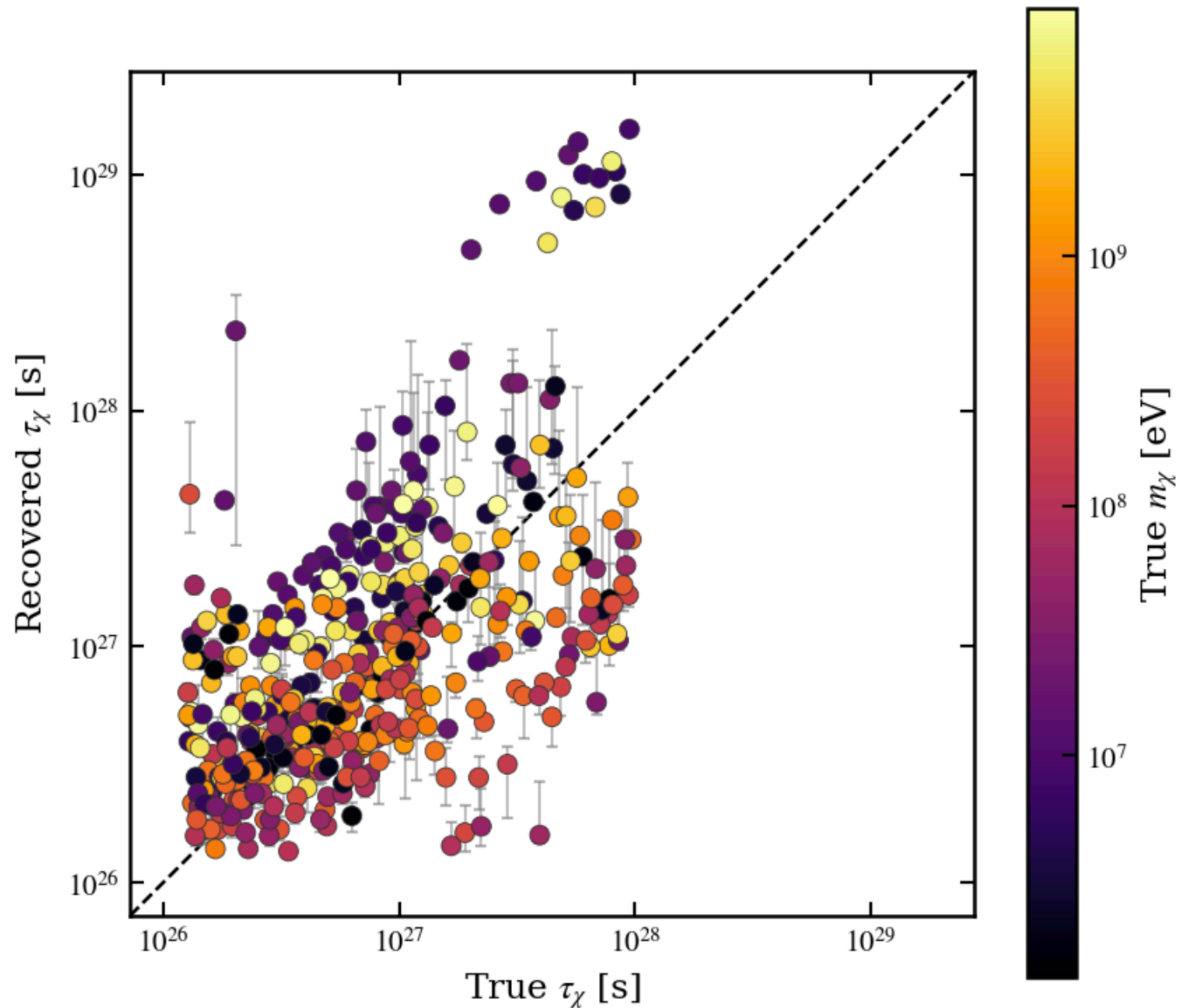
What can we learn about DM with our framework?

Similar heating histories can be produced by different combinations of mass and lifetime, resulting in multiple posterior peaks.

Preliminary results



What can we learn about DM with our framework?

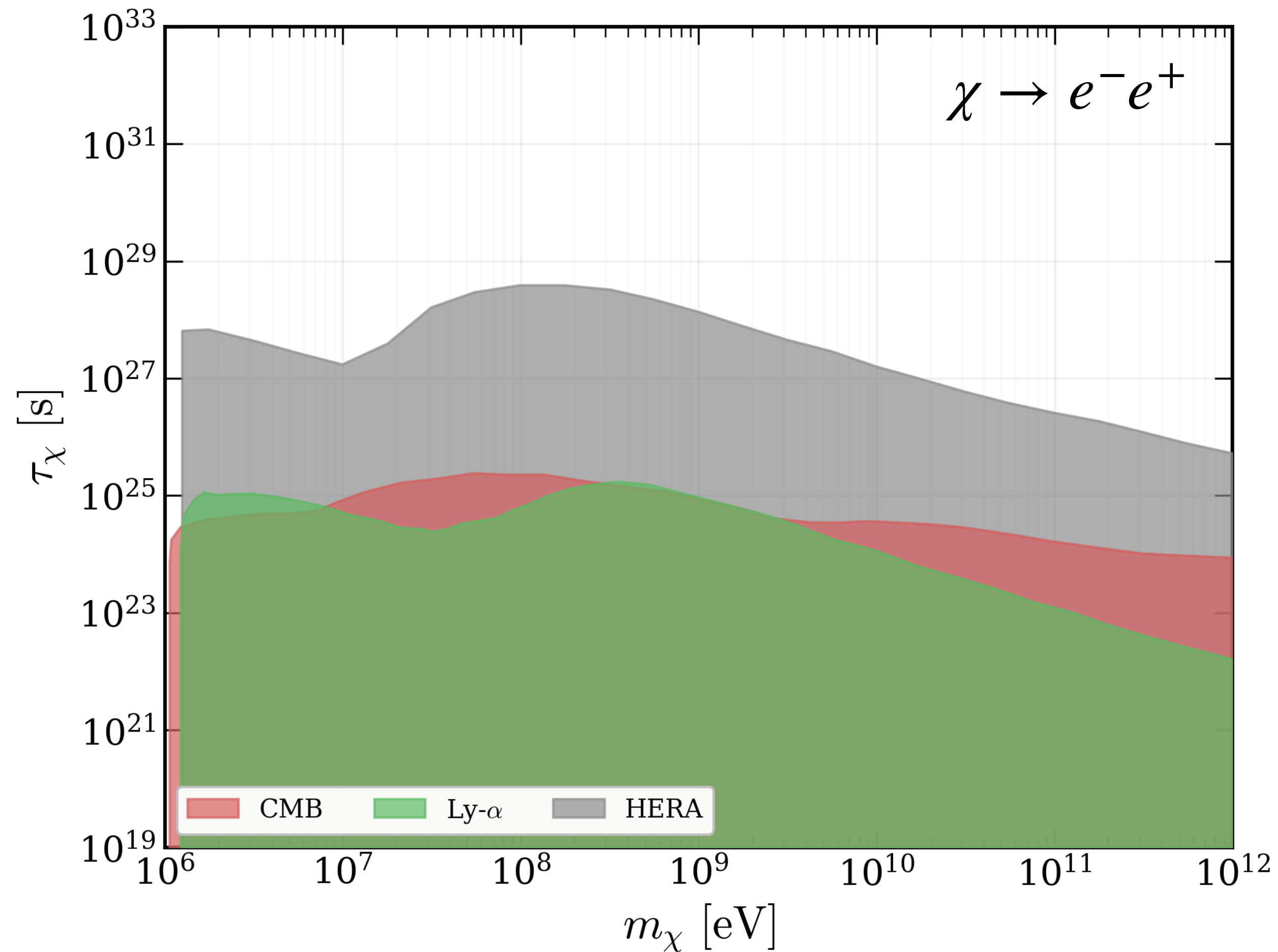


Key takeaways:

- Good recovery for intermediate masses and shorter lifetimes.
- Recovery becomes less precise as DM heating signal weakens.
- Secondary posterior peaks may arise from mass-lifetime degeneracies.

What can we learn about DM with our framework?

Forecasts on 21-cm bounds on DM decay



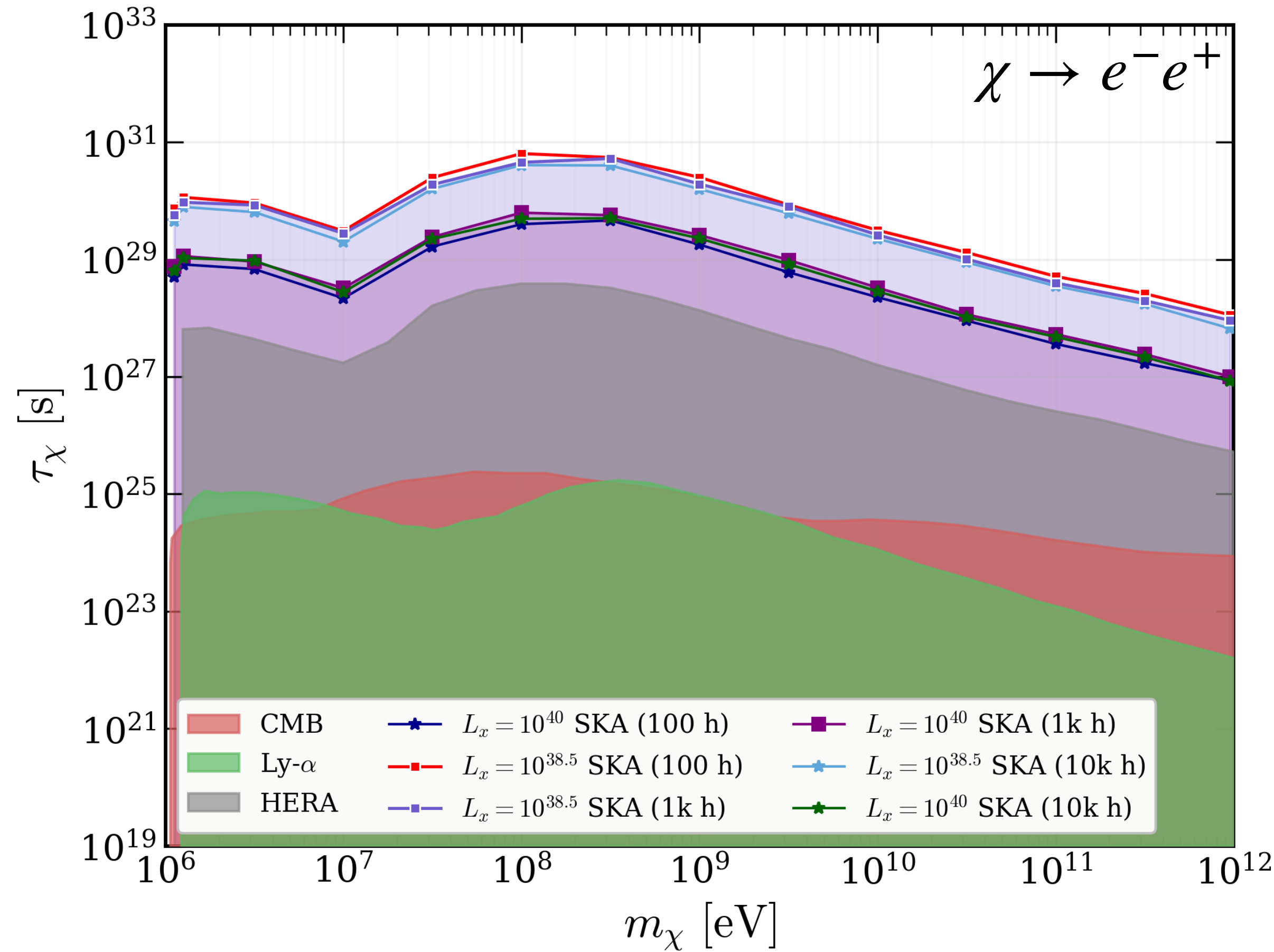
Assumptions:

- 1) Mock observation without DM contribution.
- 2) Standard astrophysical model + instrumental noise.

Constraints on the dark matter lifetime (at 95% level)

What can we learn about DM with our framework?

Forecasts on 21-cm bounds on DM decay



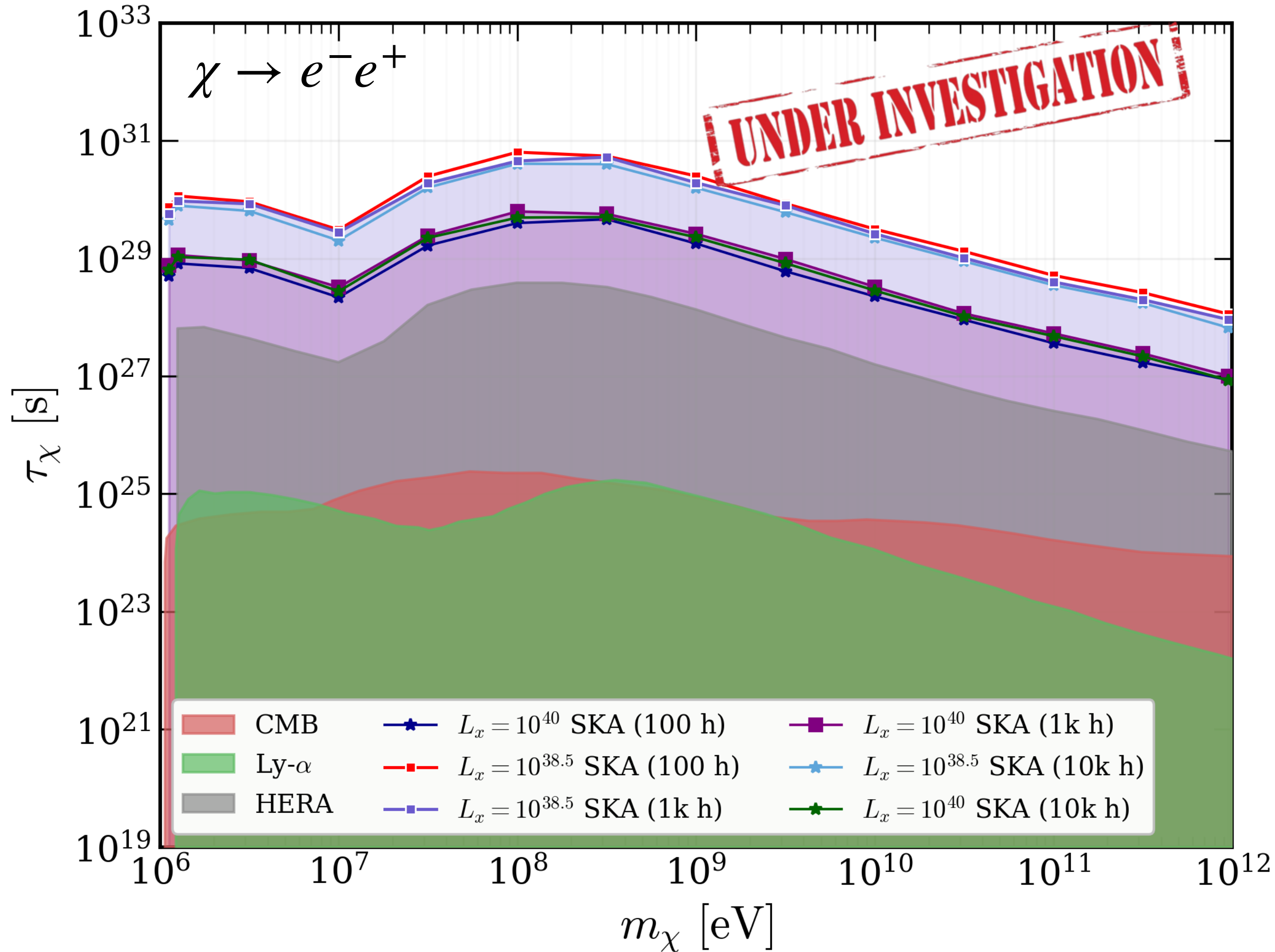
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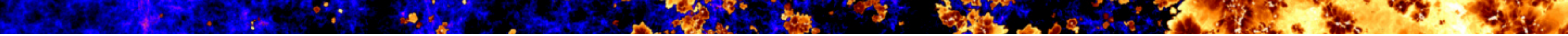
Conclusions

- * The 21-cm signal opens a new observational window on exotic physics during Cosmic Dawn, particularly on scenarios that modify the thermal and ionization evolution of the IGM.
- * We introduce a parameterisation of the heating history that captures its amplitude, shape and redshift evolution.
- * Combining this parameterisation with SBI demonstrates the potential to reconstruct the heating history from the 21-cm PS.
- * Recovering the heating history provides a bridge between 21-cm observations and the underlying DM properties.

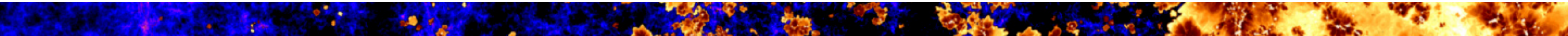
Thank you!



© Tom Gauld
New Scientist



BACKUP SLIDES

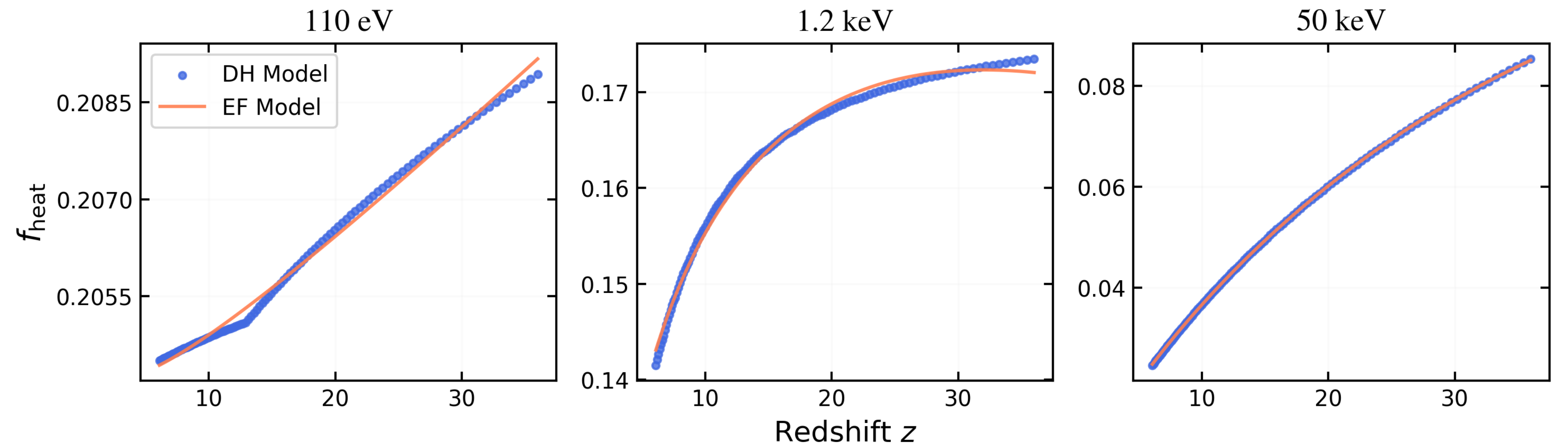


Effective Model

DM decaying into photon pair

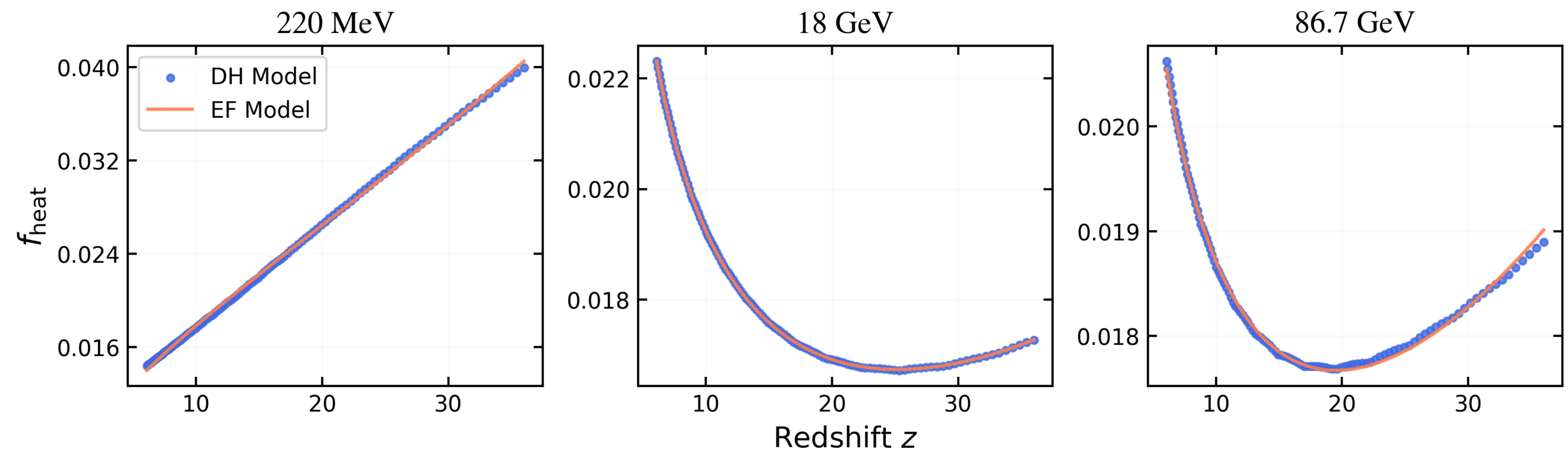
$$\chi \rightarrow \gamma\gamma$$

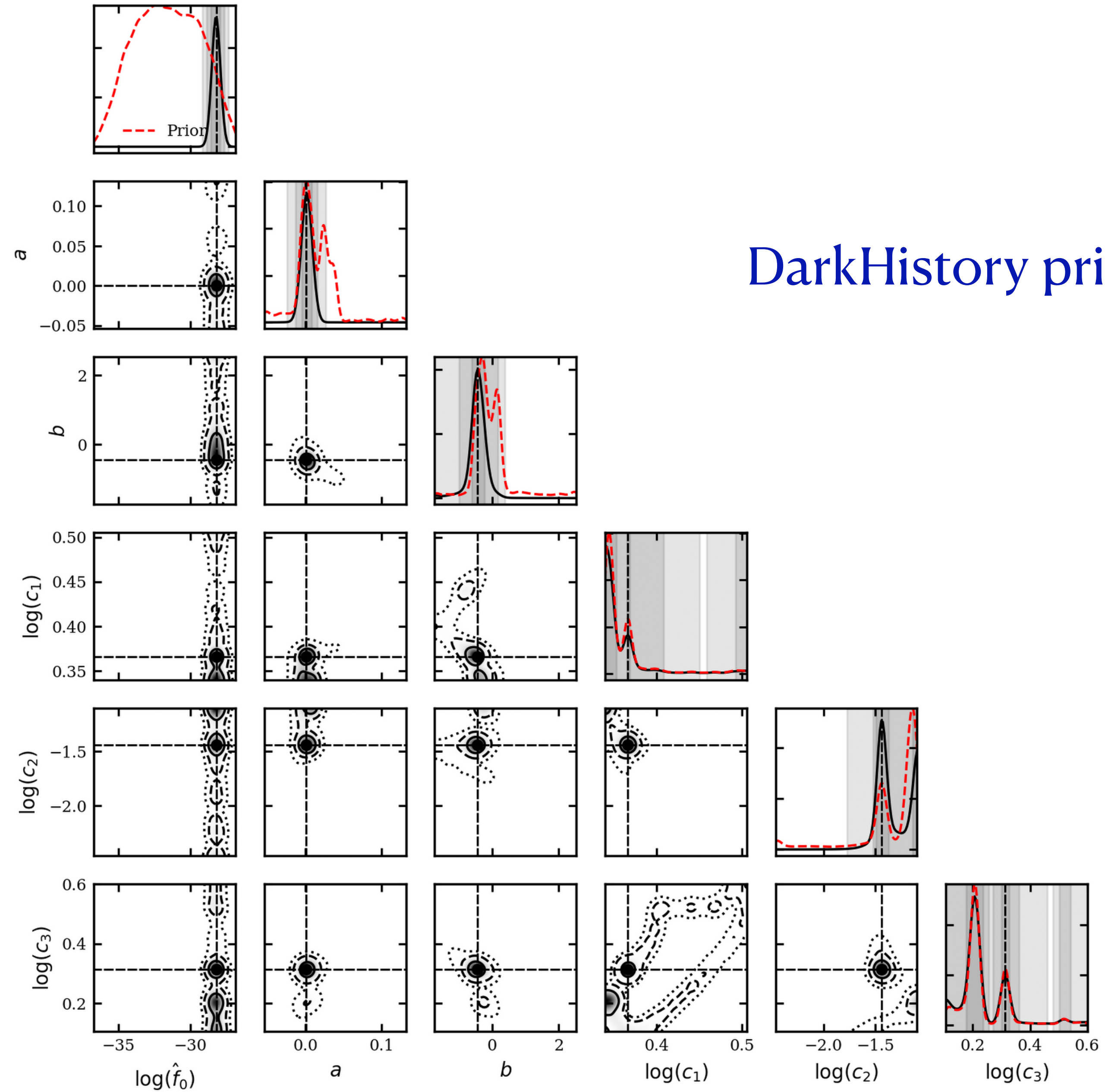
More decay/annihilation channels can be explored with the EF



DM annihilating into photon pair

$$\chi\chi \rightarrow \gamma\gamma$$





DarkHistory prior for decay into electron/positron pair

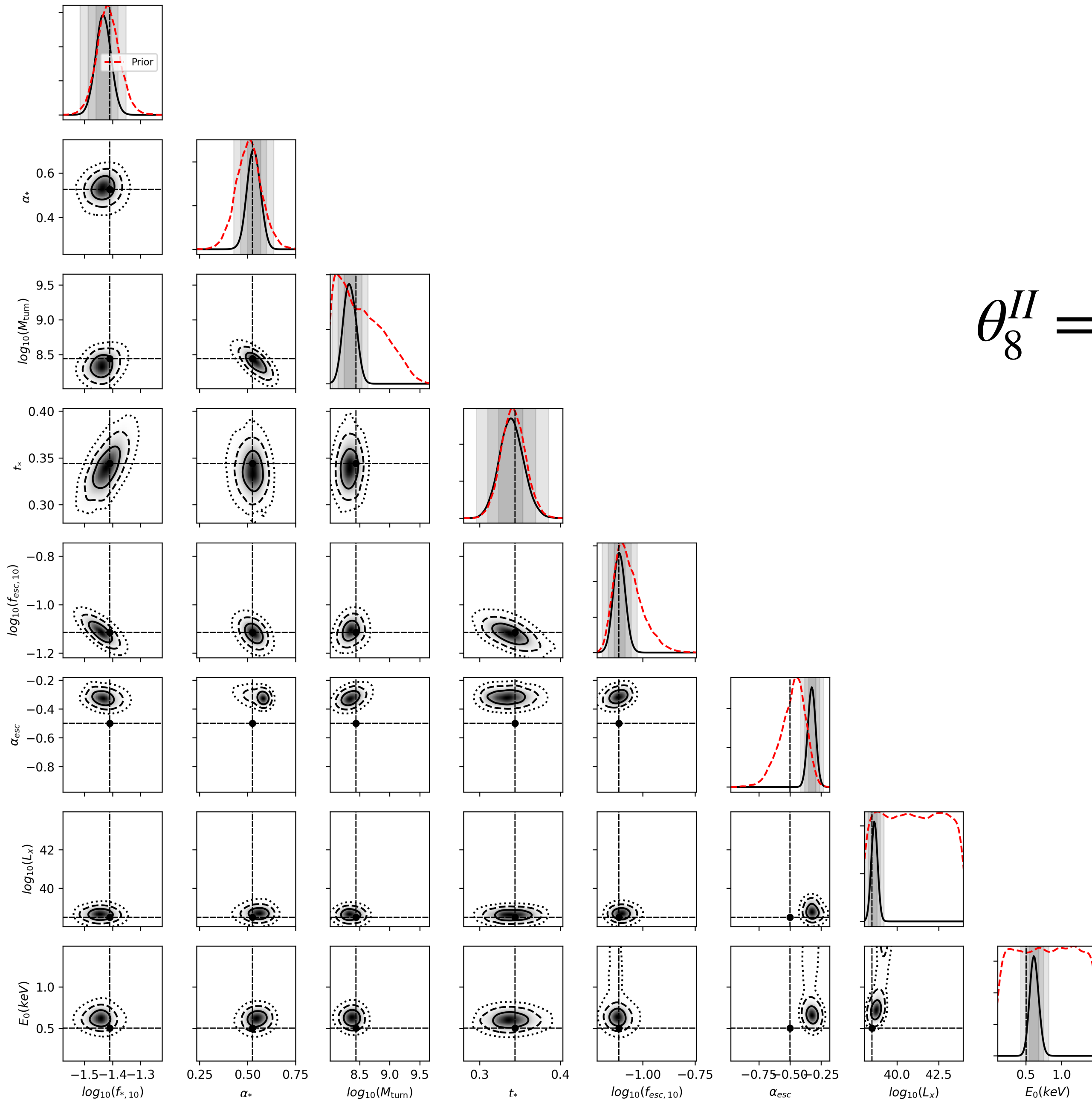
Astrophysical parameters and prior

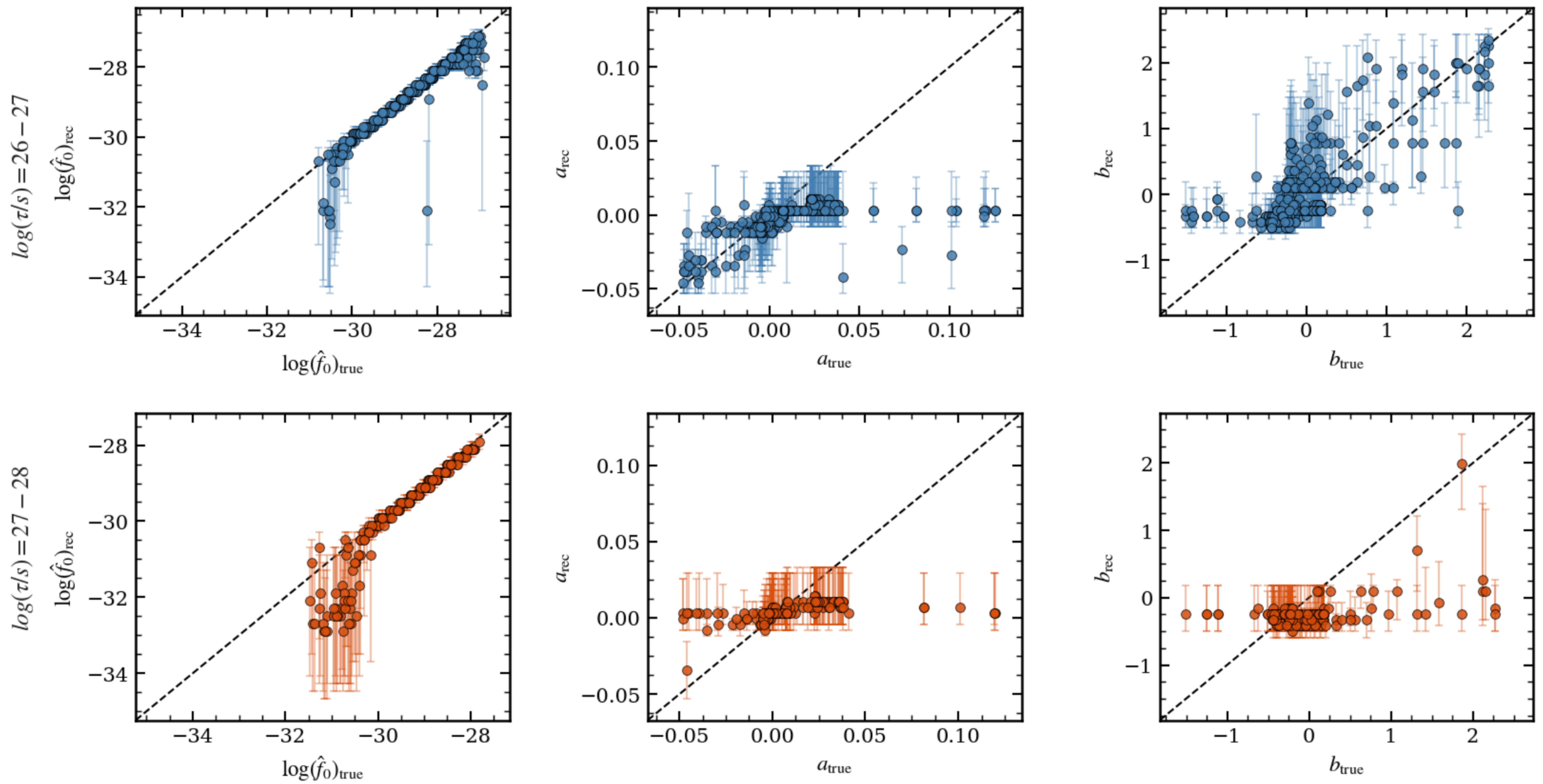
Single stellar population (Pop II-only) - ACG

$$\theta_8^{II} = (f_{*,10}, \alpha_*, f_{esc,10}, \alpha_{esc}, M_{turn}, t_*, L_X/SFR, E_0)$$

The params describe galaxy properties such as:

- * Stellar-to-halo mass ratios
- * UV ionizing escape fraction
- * Characteristic mass below which star formation becomes inefficient
- * Timescale of star formation
- * Soft-band X-ray luminosity to star formation rate ratio
- * Minimum energy for X-ray to heat the IGM.





Good recovery of the EF model params is linked to strong DM heating

