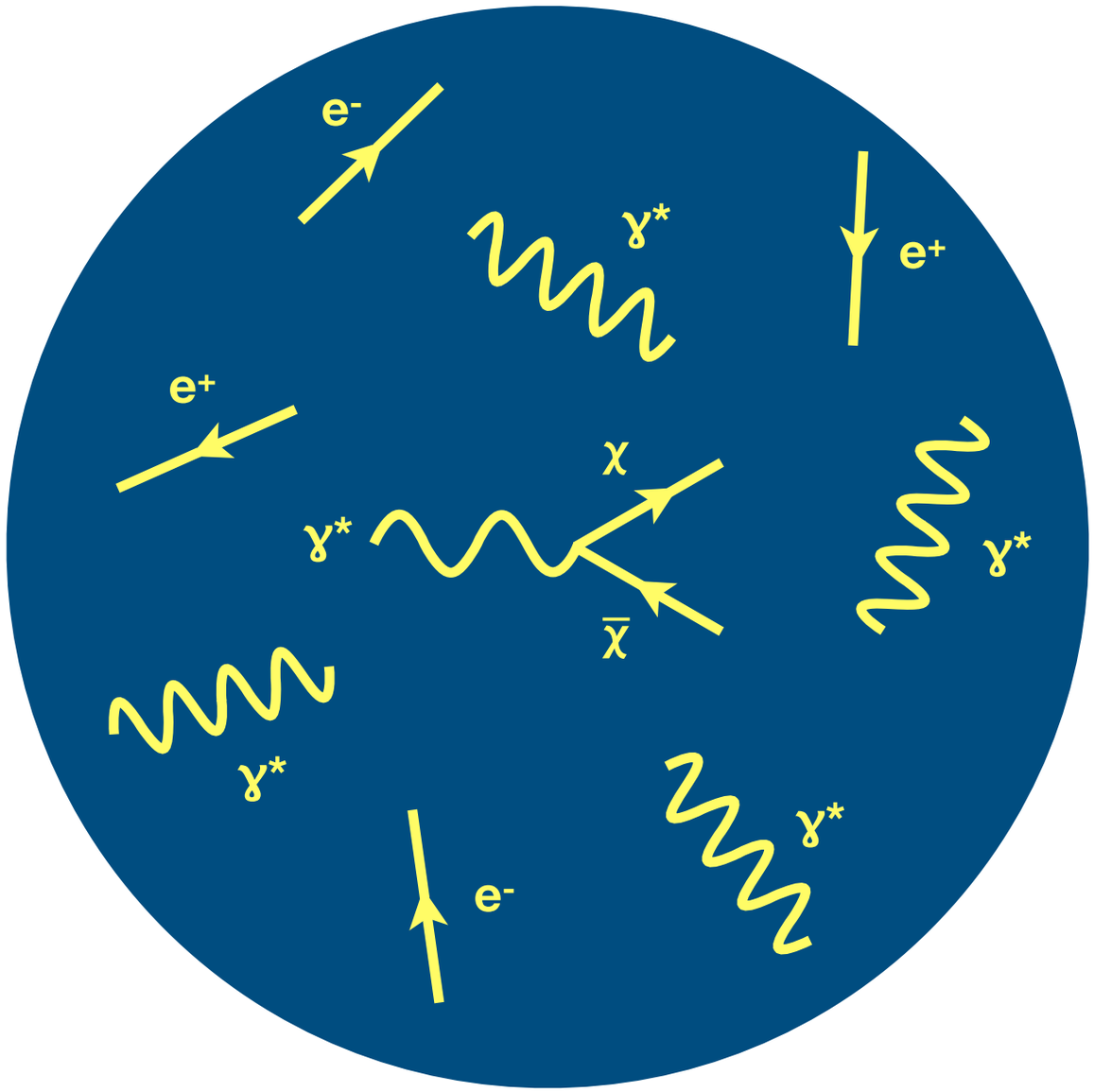



# MAKING DARK MATTER OUT OF LIGHT: THE COSMOLOGY OF SUB-MEV FREEZE-IN

*Katelin Schutz*

*Snowmass CF3 Meeting 8/17/2020*

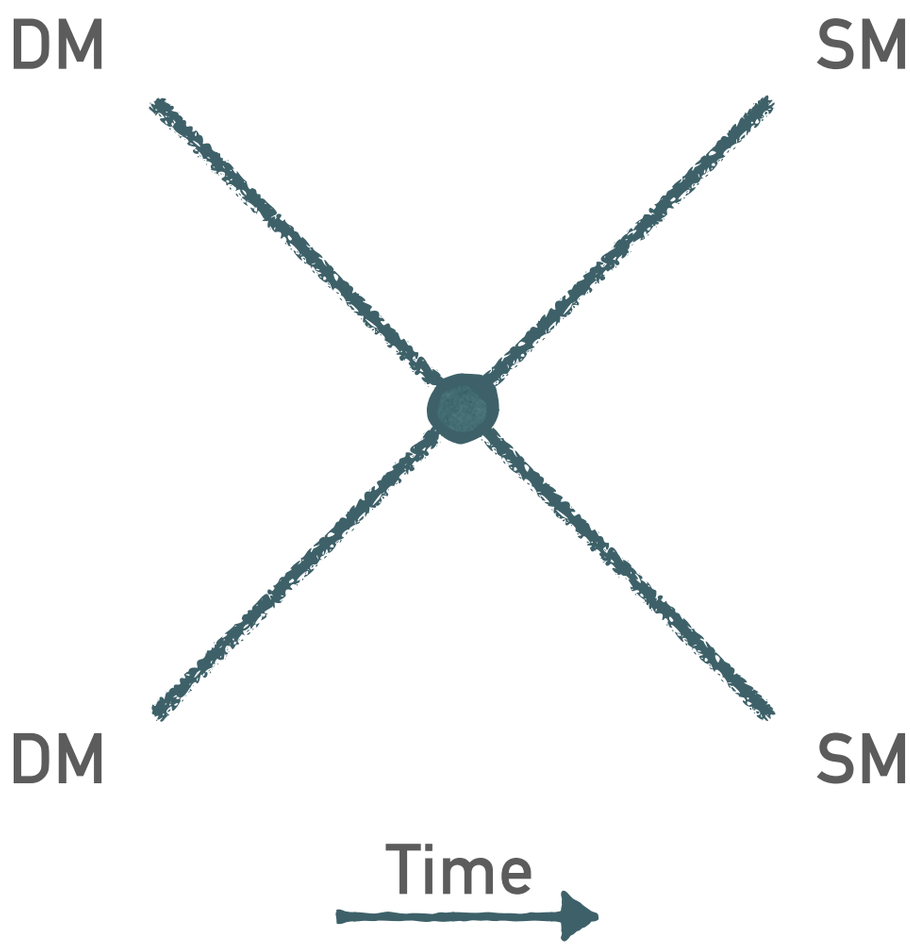
*Based on Dvorkin, Lin, **KS** in prep. (2009.xxxxx) and Dvorkin, Lin, **KS** PRD (2019)*

# POINT TO KEEP IN MIND FOR SNOWMASS PURPOSES

- I will treat sub-MeV freeze-in as a "case study" for a more general goal: let's try to move towards being more fully self-consistent in matching early Universe theories of DM to cosmo/astro constraints
- Can we work to lower the barrier of doing "end-to-end" limit-setting (considering full history of DM candidate) and make it so that we don't have to tailor analyses to specific theories? Should we be thinking about community recommendations on this front?

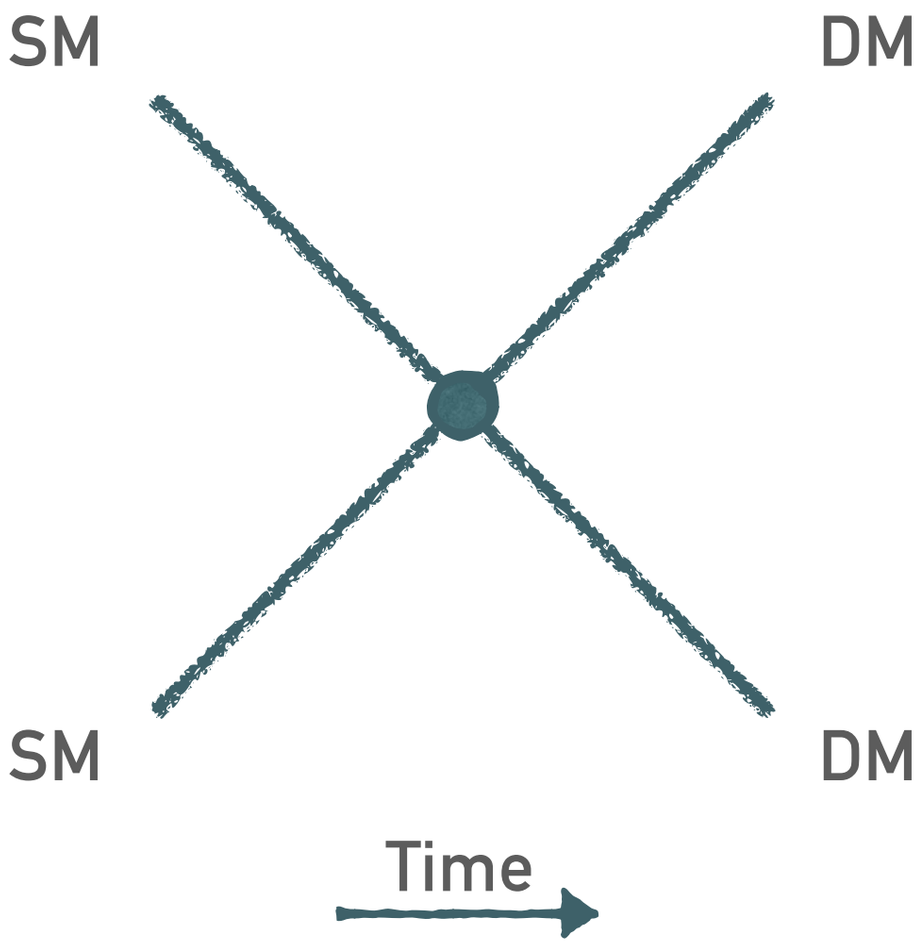
# MAKING DARK MATTER OUT OF LIGHT ("THERMAL-ISH" FREEZE-IN)

Dvorkin, Lin, **KS** (PRD 2019)



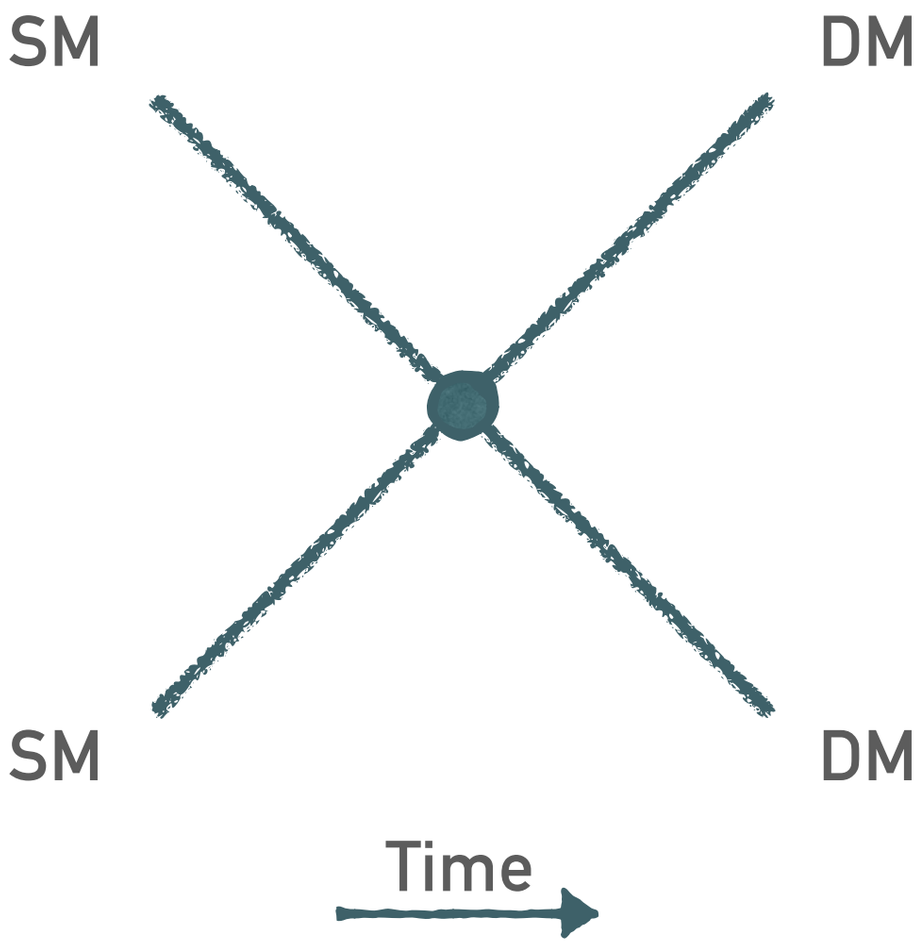

## Thermal freeze-out

- ☑ Relic abundance is independent of initial conditions of reheating after inflation (as long as DM is in the bath)
- ☑ Fine with BBN and $N_{eff}$ (above masses of a few MeV)
- ☑ Relevant couplings can be experimentally probed




Thermal freeze-in

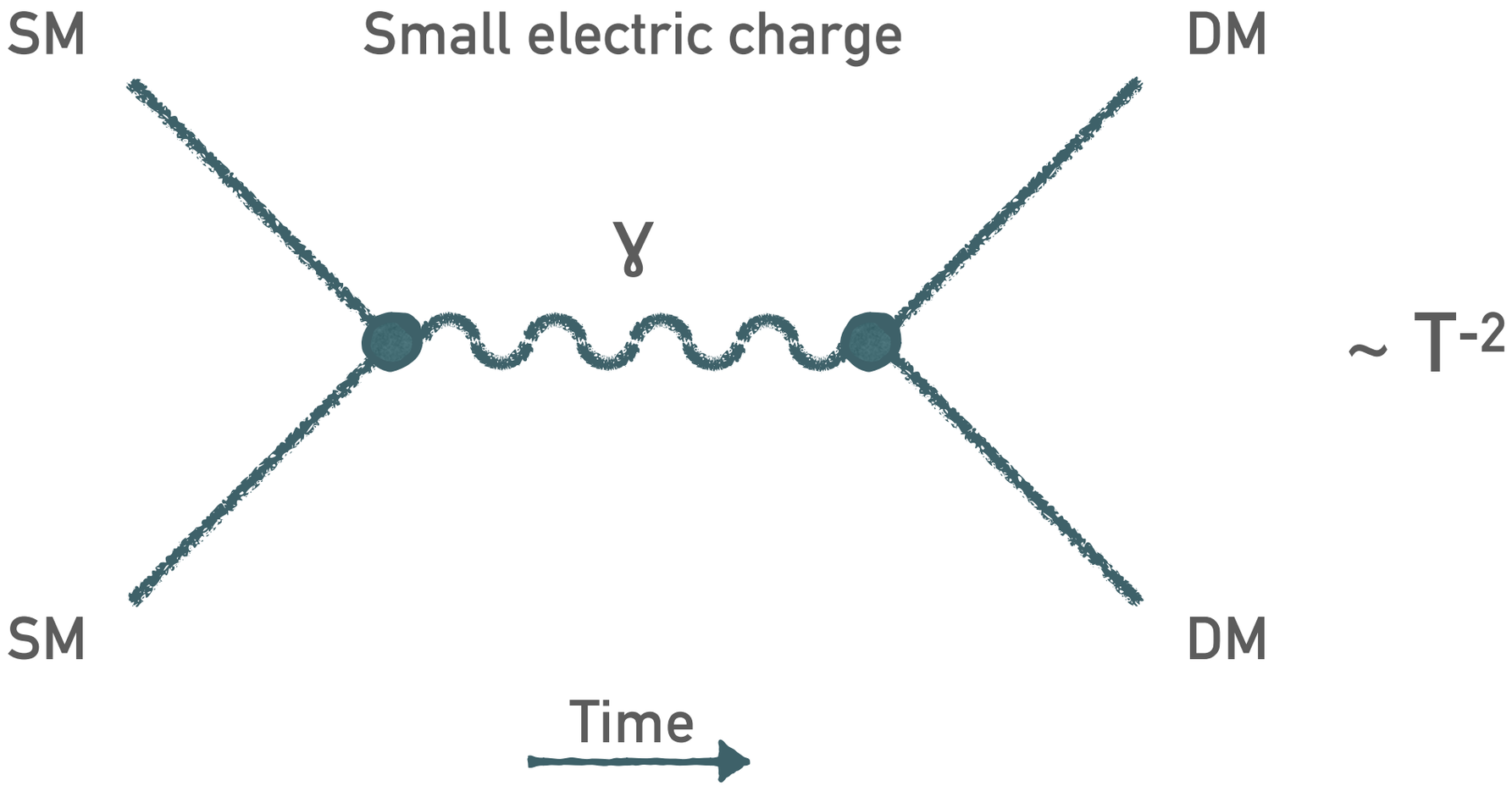
(Hall et al. 2009)



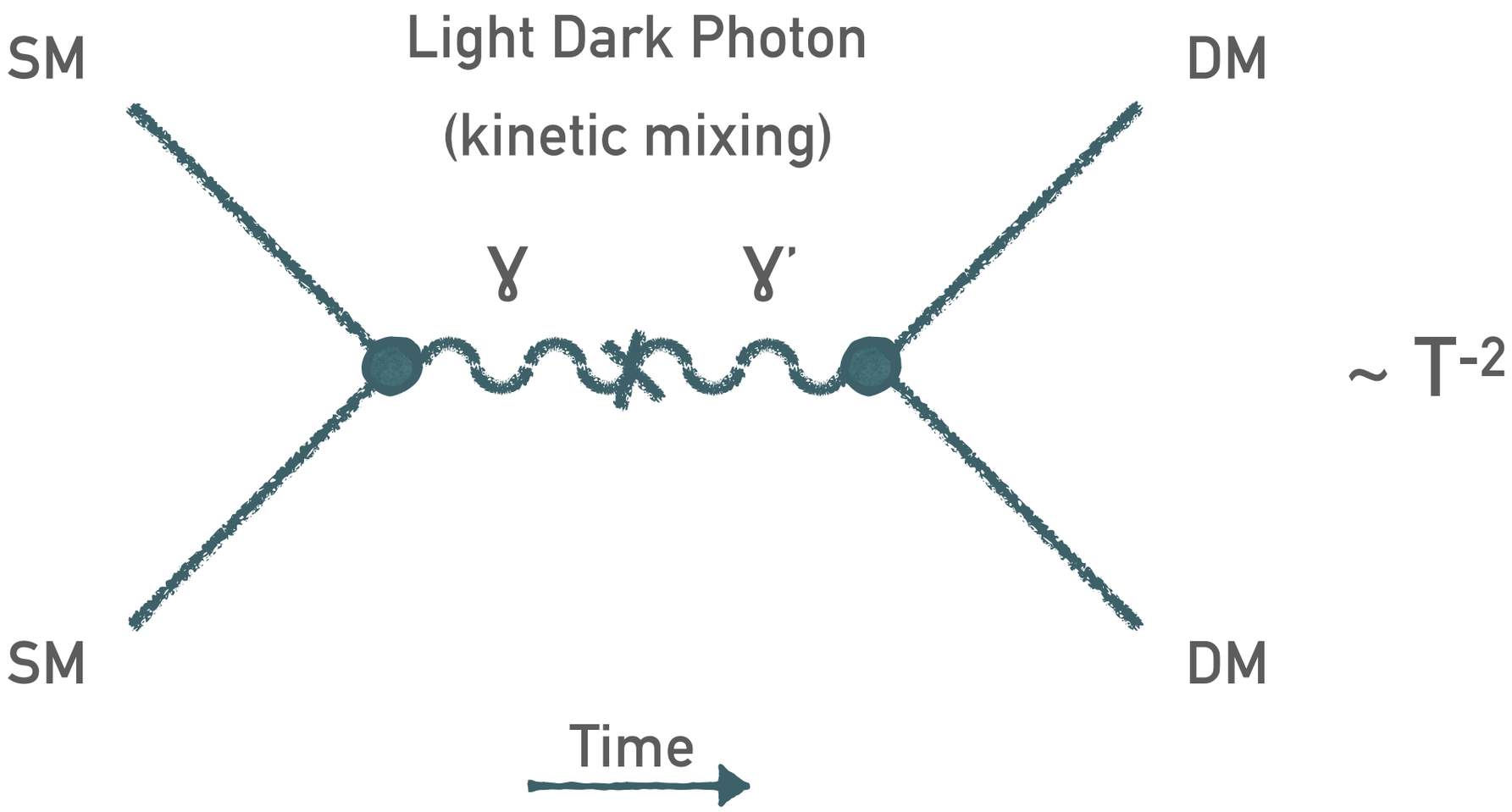

Thermal freeze-in

(Hall et al. 2009)

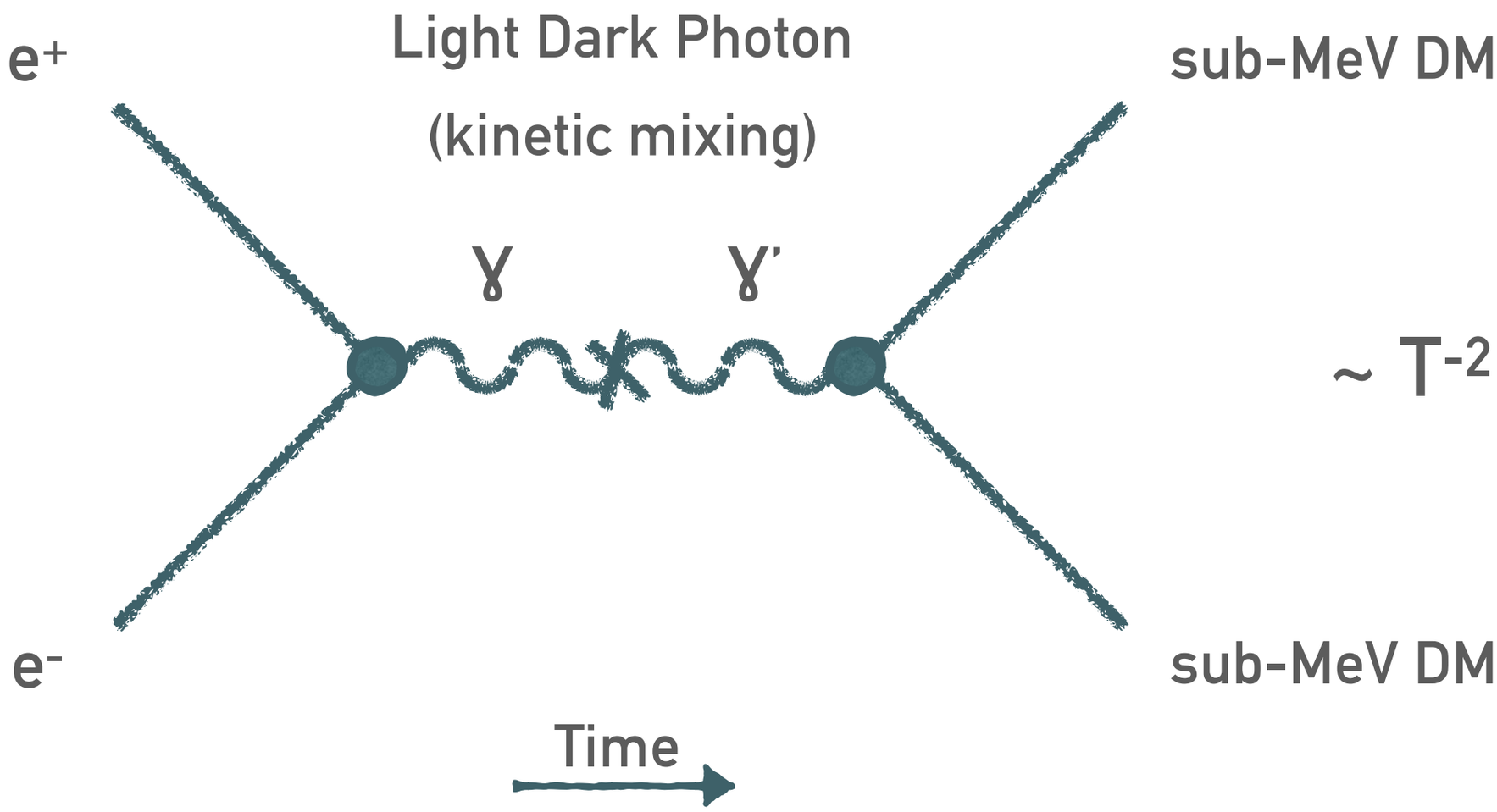
- Relic abundance is independent of initial conditions of reheating after inflation?



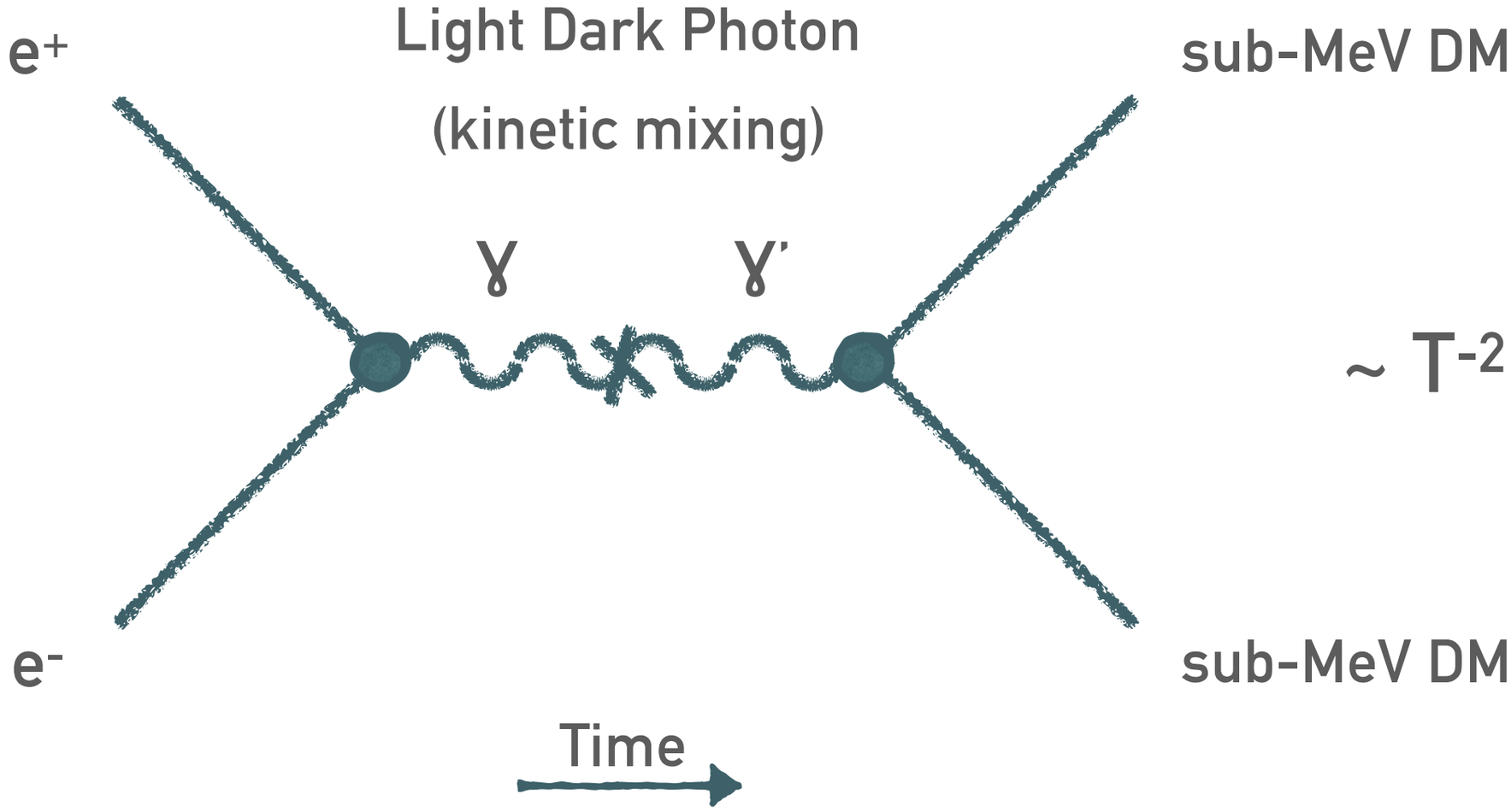

Freeze-in via a light mediator will happen at the lowest temperature that is kinematically available!




Freeze-in via a light mediator will happen at the lowest temperature that is kinematically available!

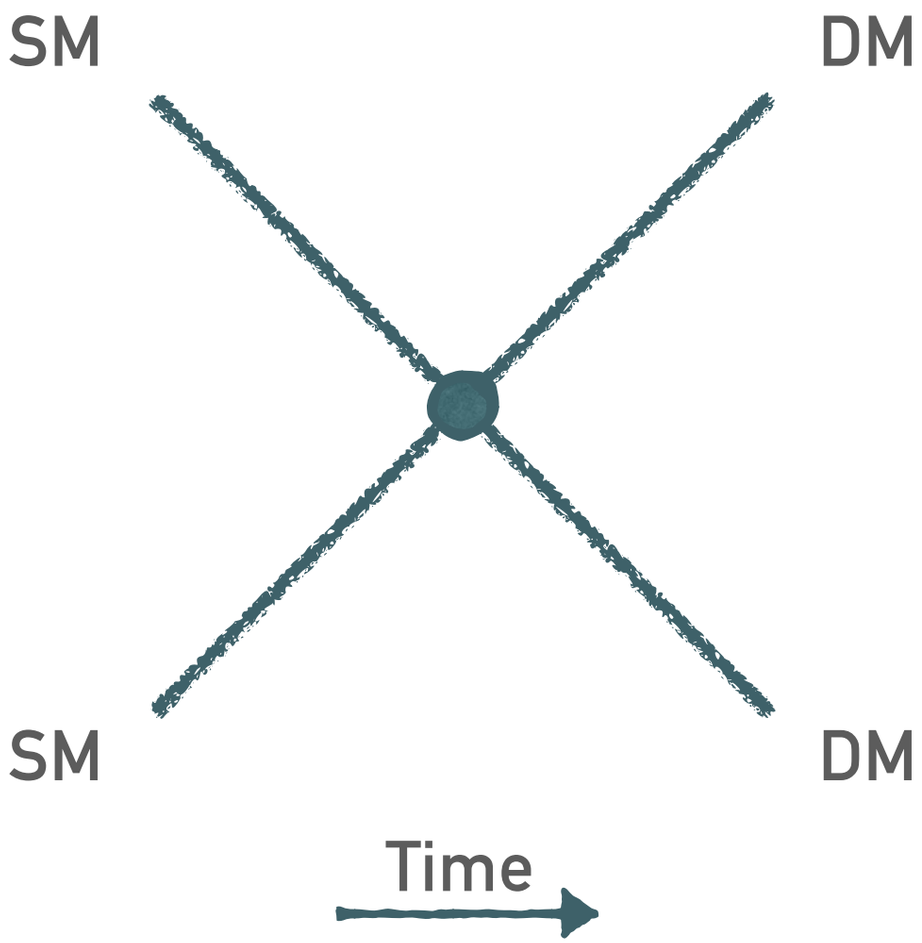



Freeze-in via a light mediator will happen at the lowest temperature that is kinematically available!



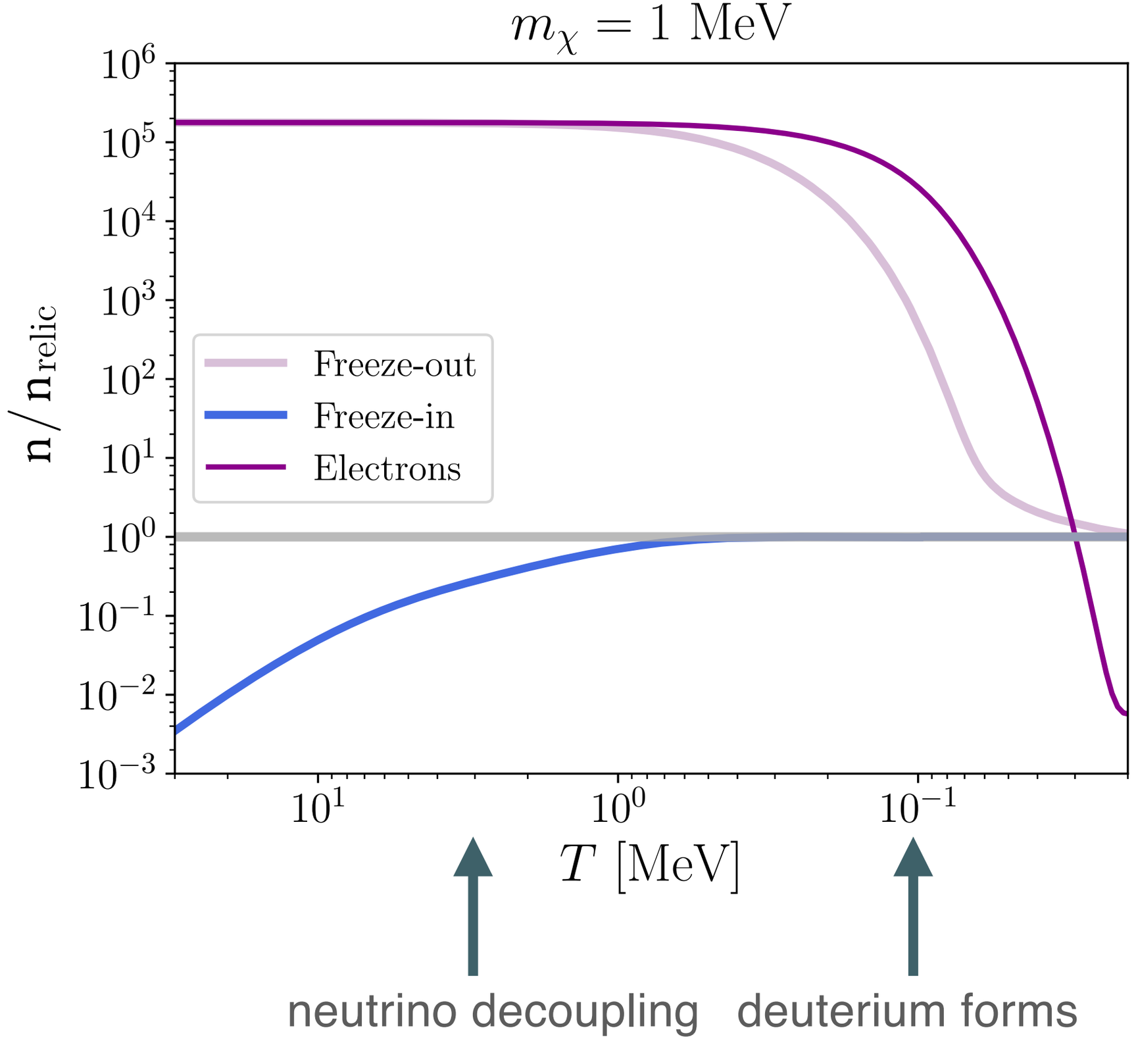

Freeze-in via a light mediator will happen at the lowest temperature that is kinematically available!

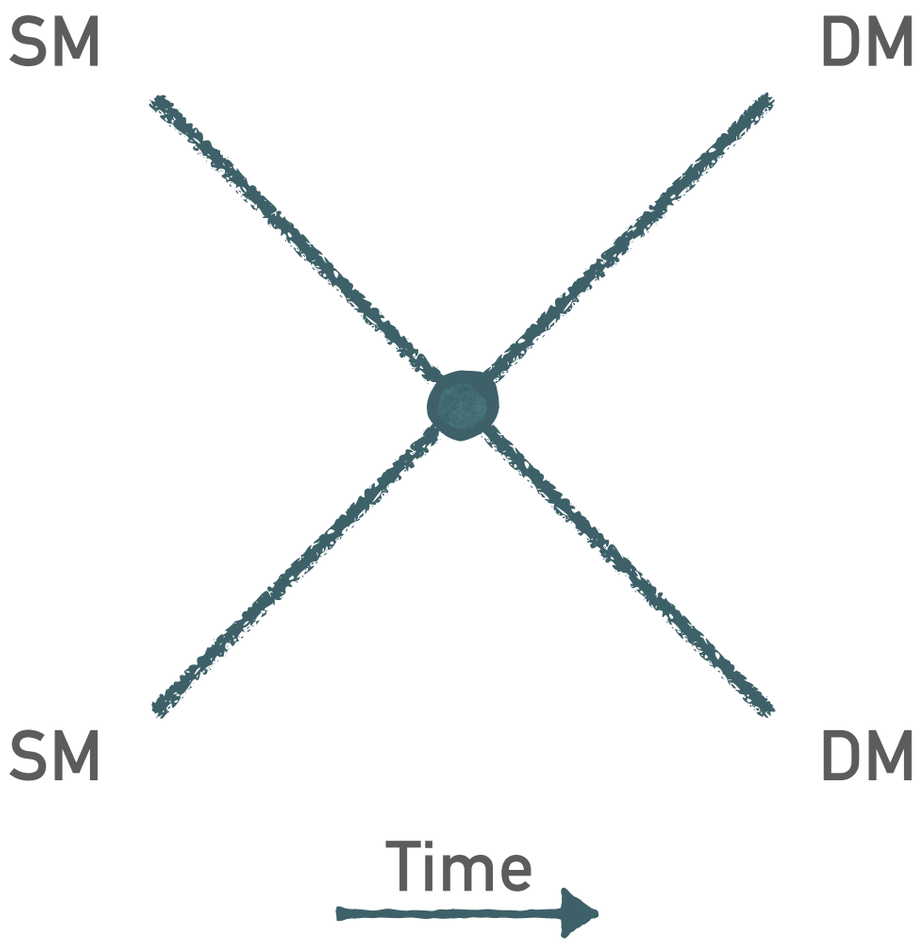
→ This is the simplest allowed way to make charged DM




# Thermal freeze-in

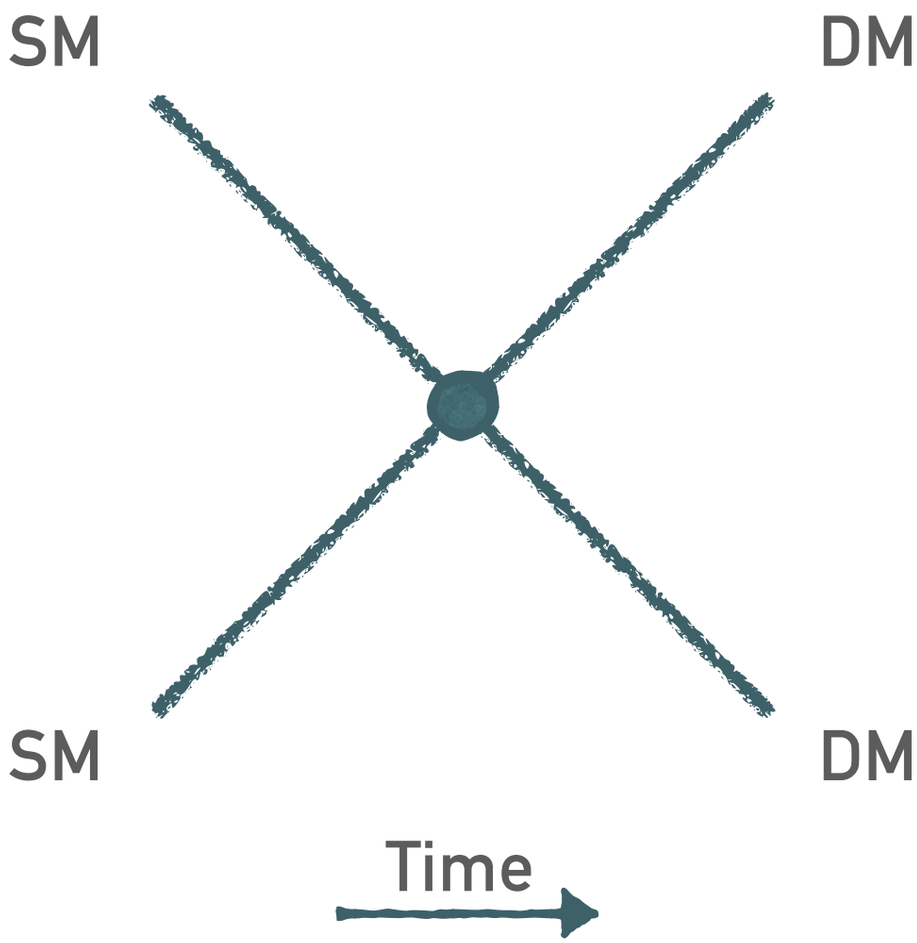
- [x] Relic abundance is independent of initial conditions of reheating after inflation, sensitive to low temperatures
- [ ] Fine with BBN and $N_{eff}$ ?


$m_\chi = 1$ MeV
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$\mathbf{n}/\mathbf{n}_{\rm relic}$
Freeze-out
Freeze-in
Electrons
$10^1$
$10^0$
$10^{-1}$
$T$ [MeV]
neutrino decoupling
deuterium forms




# Thermal freeze-in

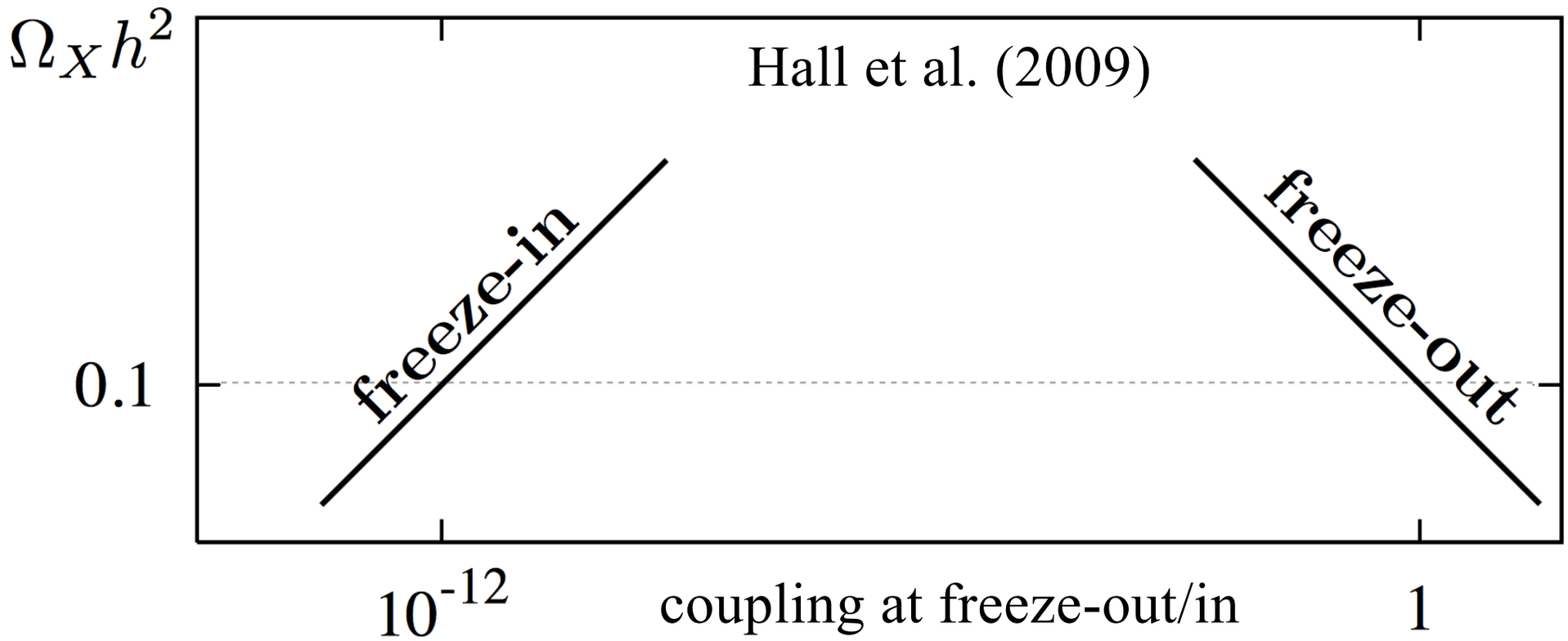
- ☑ Relic abundance is independent of initial conditions of reheating after inflation, sensitive to low temperatures
- ☑ Fine with BBN and $N_{eff}$ (above keV mass scale)



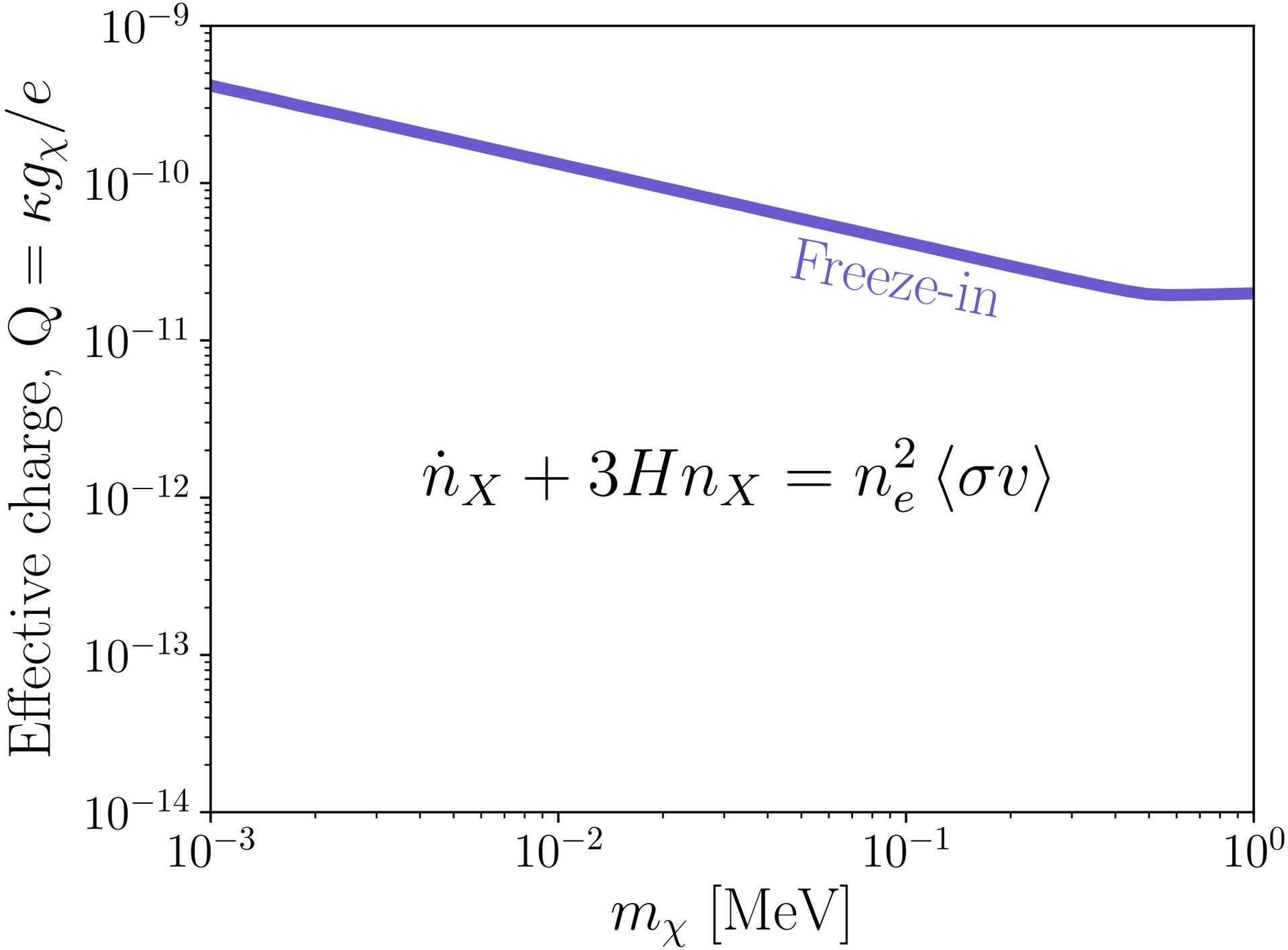

## Thermal freeze-in

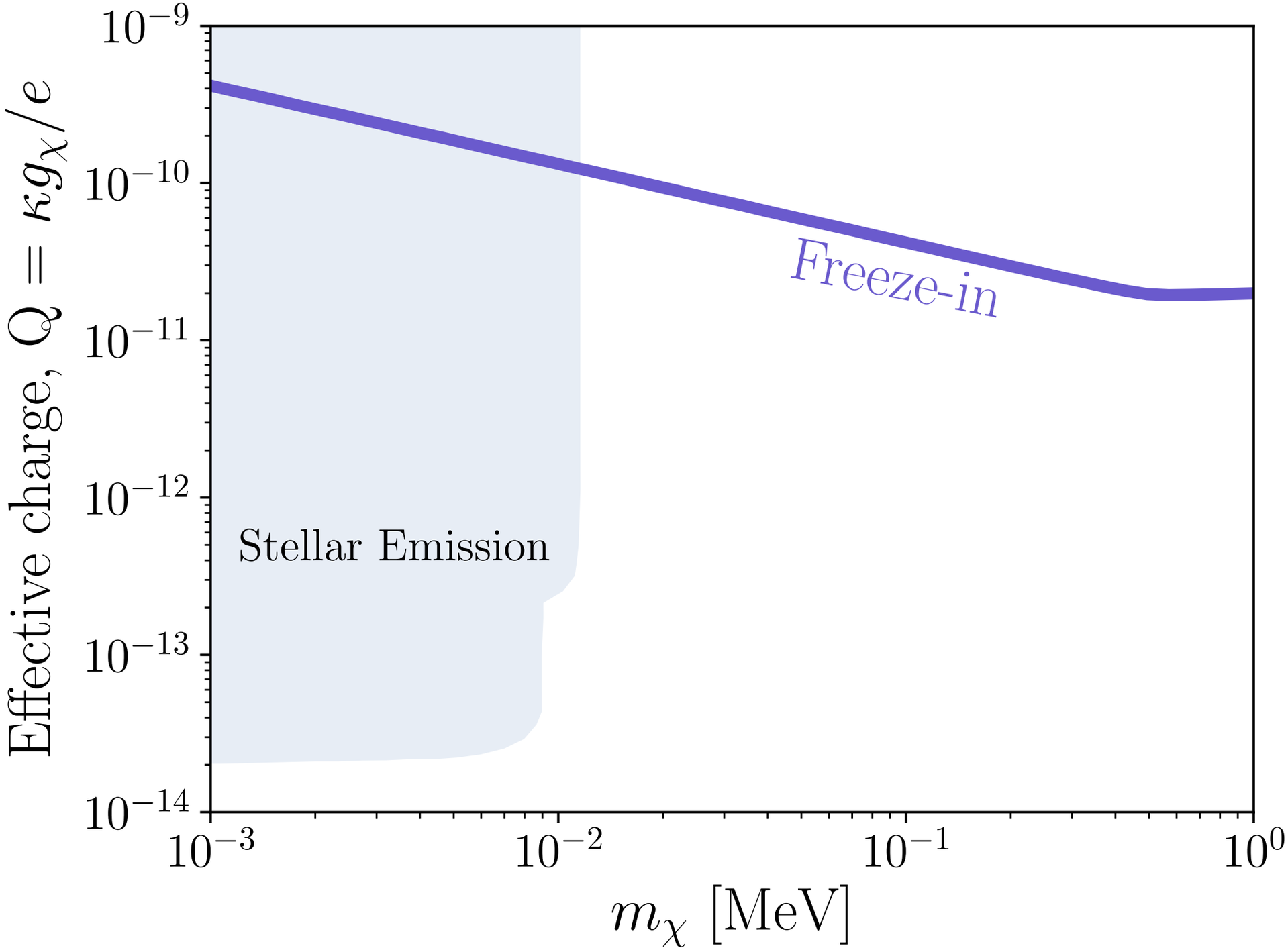
- ☑ Relic abundance is independent of initial conditions of reheating after inflation, sensitive to low temperatures
- ☑ Fine with BBN and $N_{eff}$ (above keV mass scale)
- ☐ Relevant couplings can be experimentally probed?

# FREEZE-IN VS. FREEZE-OUT COUPLINGS TO THE SM



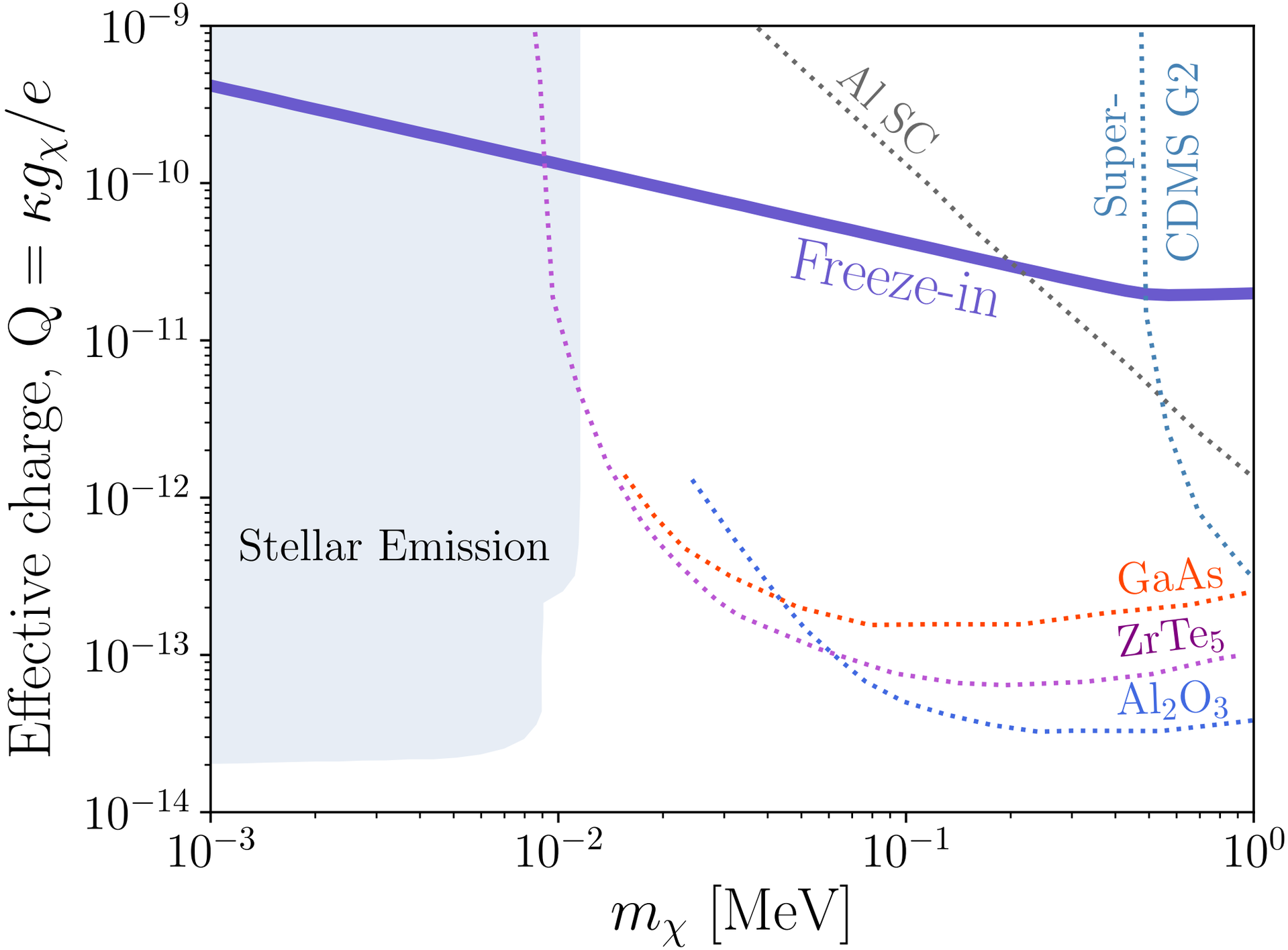

Much more observable if there is a low-velocity enhancement, for instance $v^{-4}$


Freeze-in
$\dot{n}_X + 3Hn_X = n_e^2 \langle \sigma v \rangle$
Effective charge, $Q = \kappa g_\chi / e$
$m_\chi$ [MeV]
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$

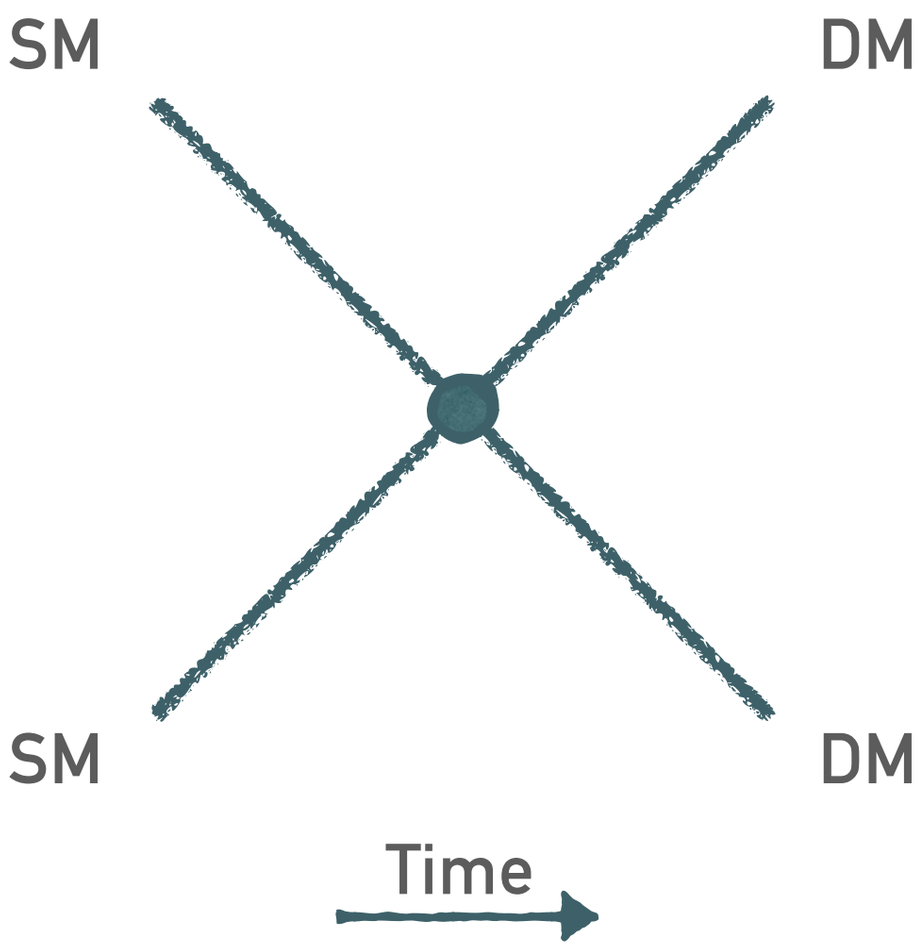



Davidson, Hannestad, Raffelt (2000)
see also Vogel & Redondo (2013)

# FREEZE-IN IS THE MAIN BENCHMARK FOR PROPOSED DIRECT DETECTION EXPERIMENTS




Griffin et al. (2018)




# Thermal freeze-in

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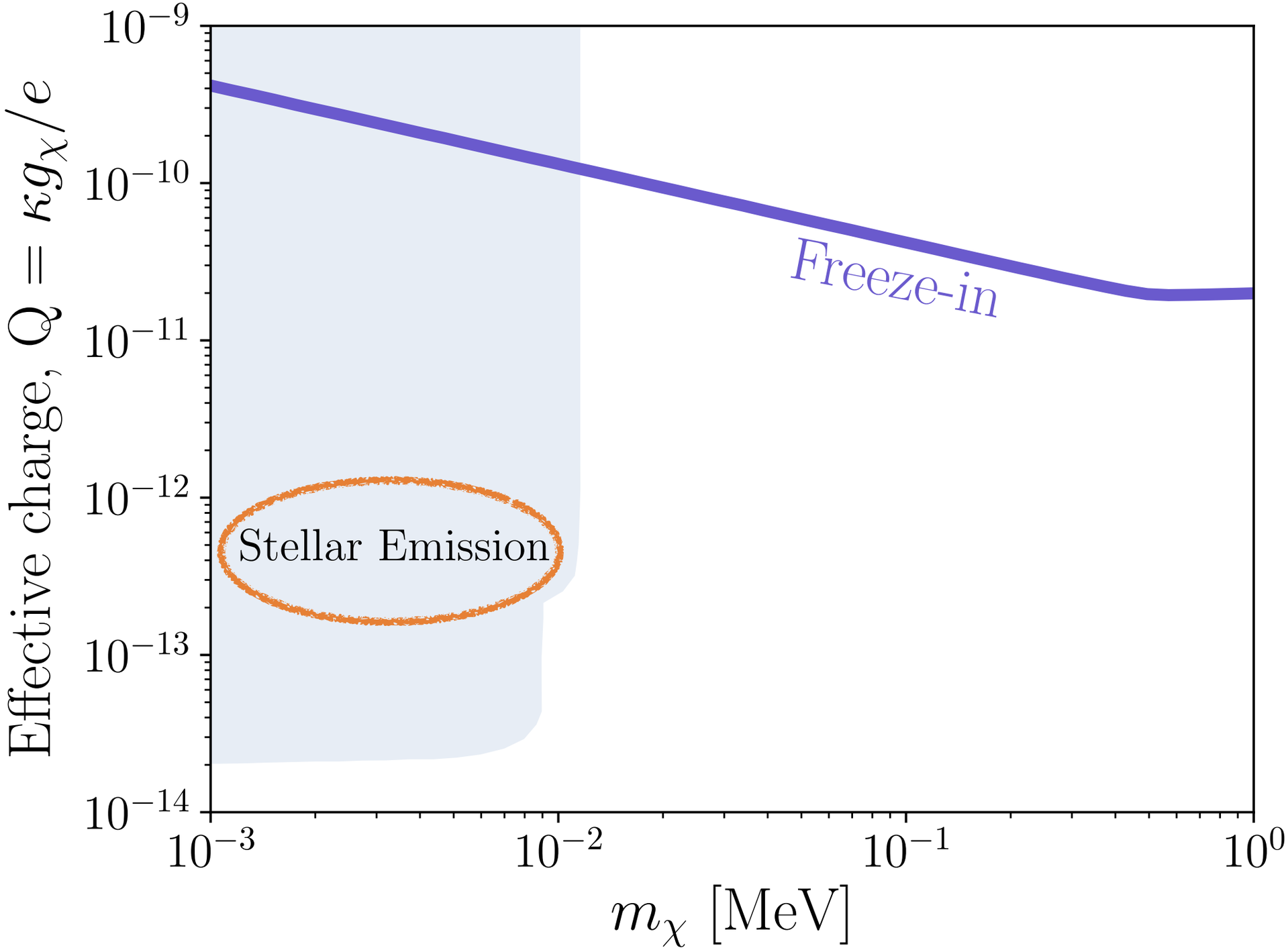
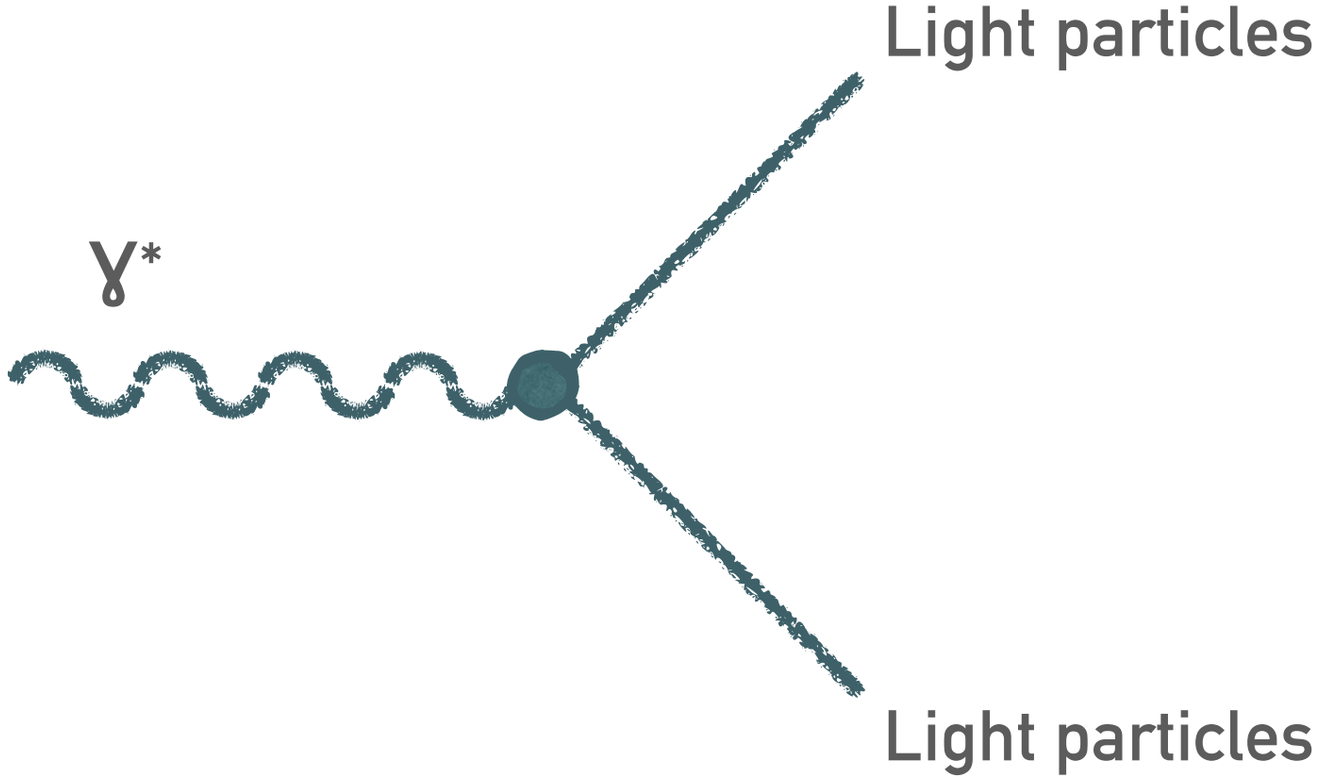
- ☑ Fine with BBN and $N_{eff}$ (above keV mass scale)
- ☑ Relevant couplings can be experimentally probed


Freeze-in
Stellar Emission
Effective charge, $Q = \kappa g_\chi / e$
$m_\chi$ [MeV]
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$

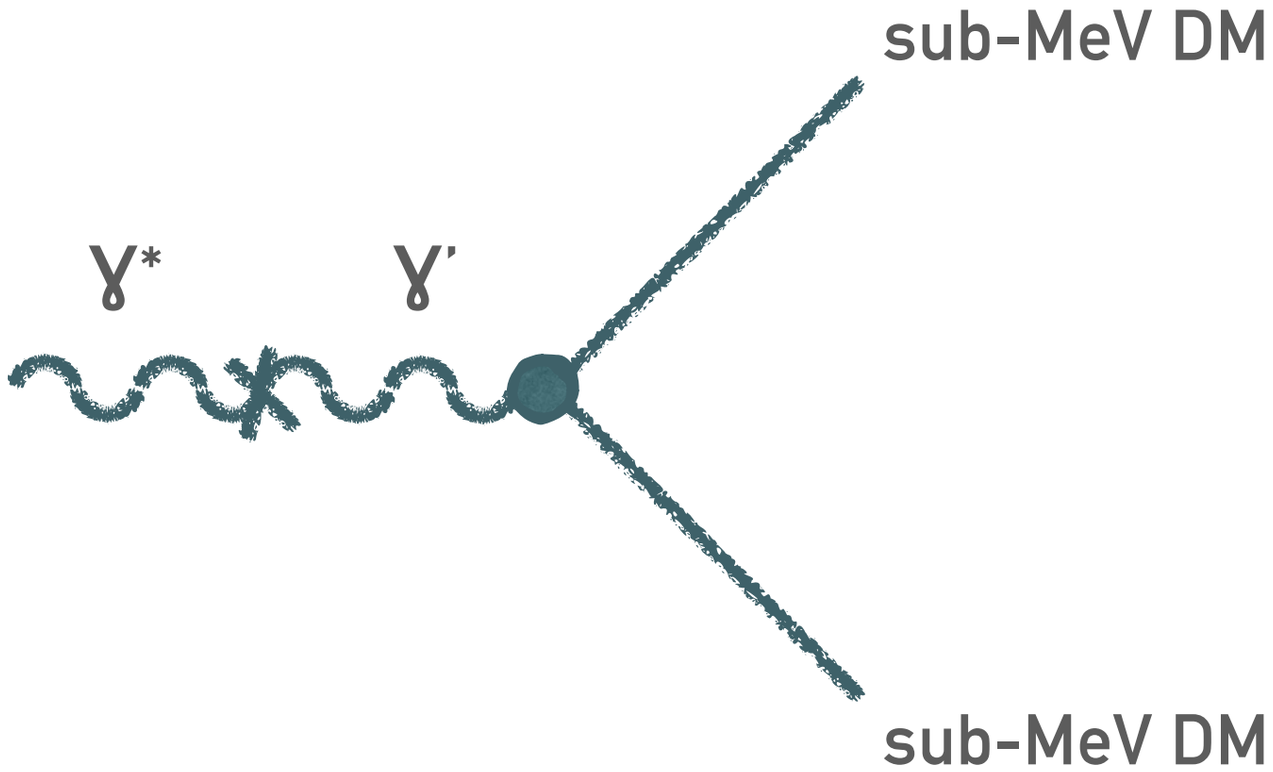
# STELLAR EMISSION CONSTRAINTS




Photon has an in-medium mass inside plasma, phase space available for decays

This process can extinguish stars quickly if the final state is unhindered by the plasma

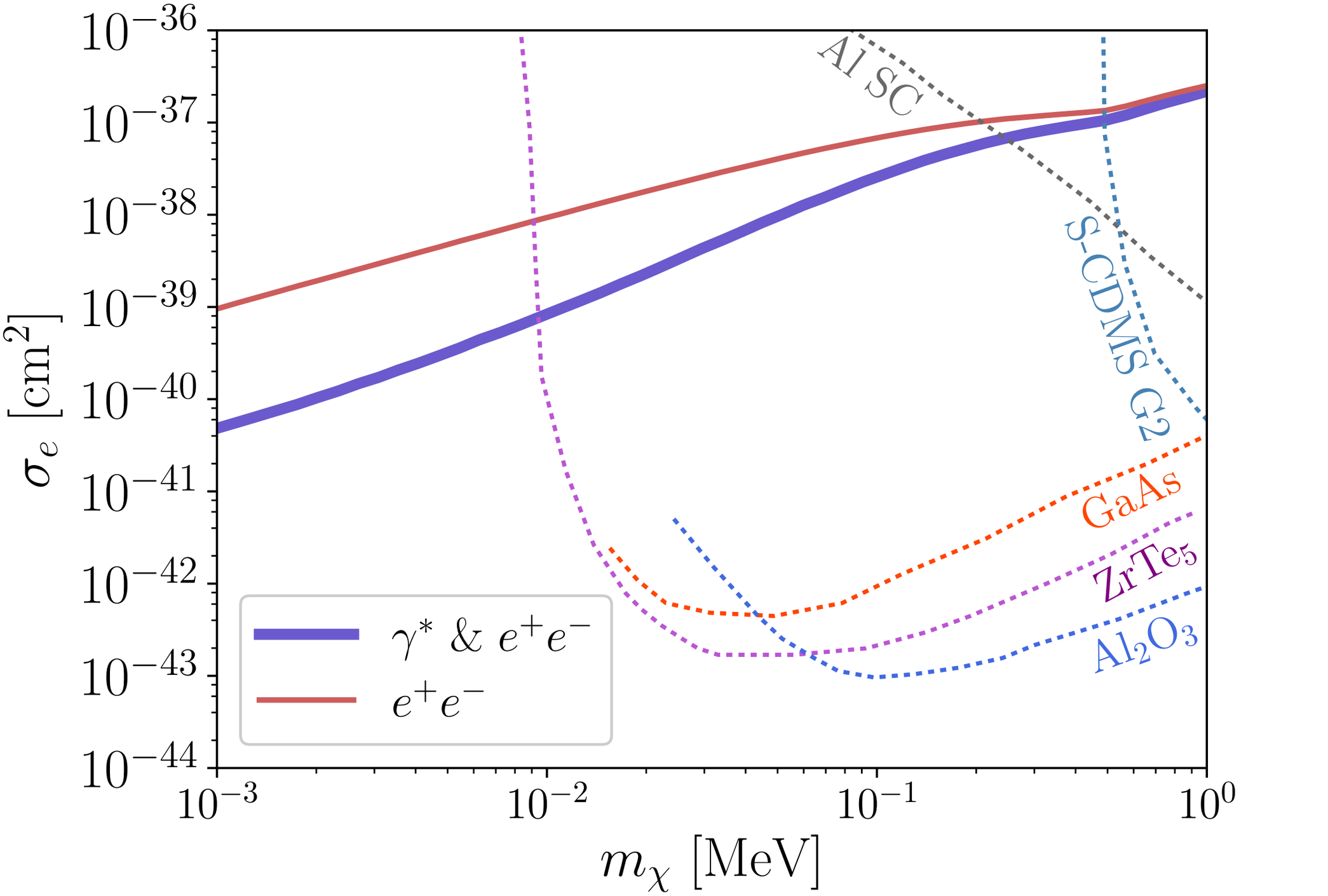
# PLASMON DARK MATTER




This process makes dark matter efficiently in the early Universe!

Dvorkin, Lin, **KS** (PRD 2019)

# DIRECT DETECTION IMPLICATIONS OF PLASMON CHANNEL



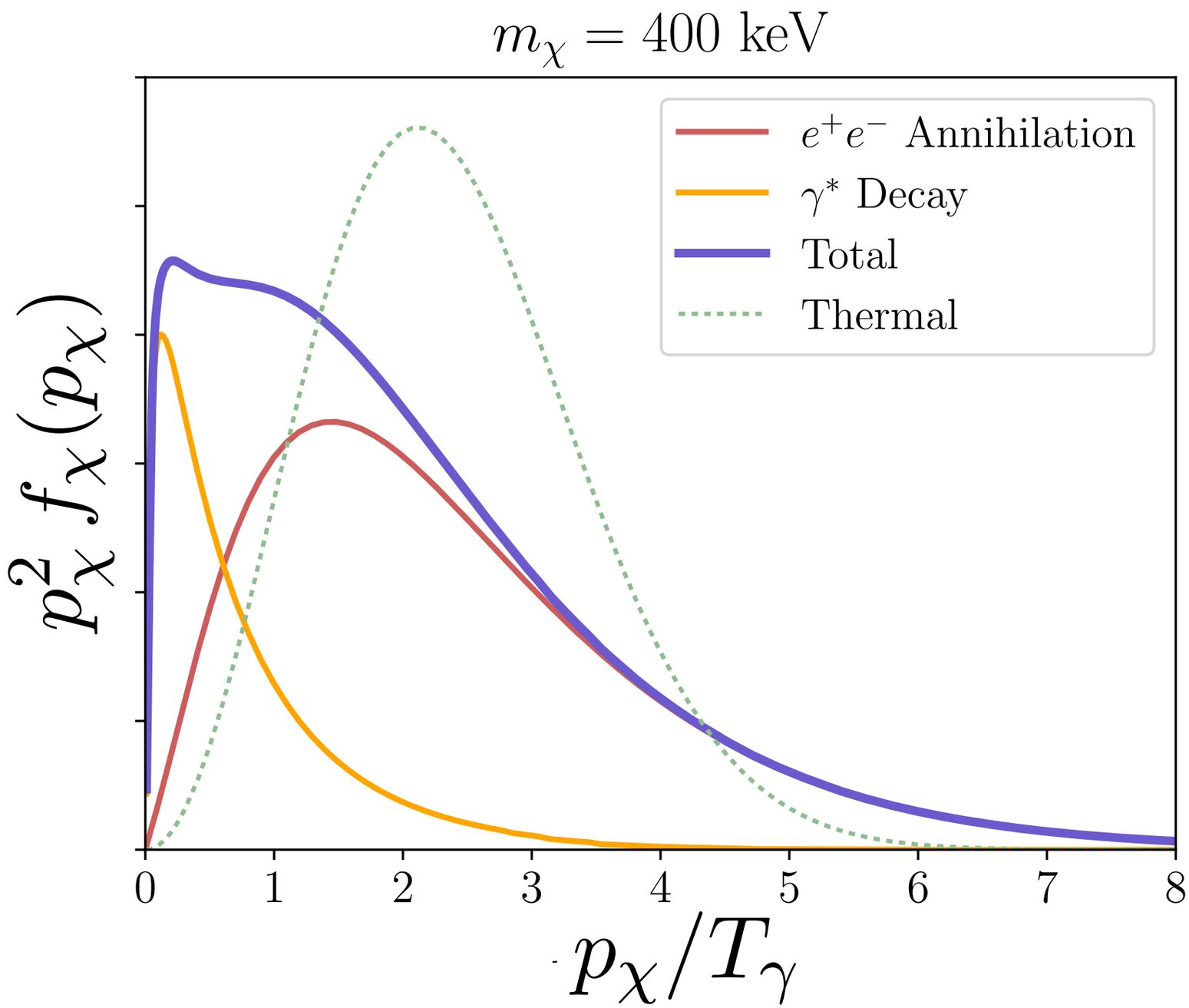

Dvorkin, Lin, **KS** (PRD 2019)

# DARK MATTER IS BORN "HOT" FROM FREEZE-IN

*Quotation marks because DM does not thermalize with the SM and doesn't necessarily possess a temperature

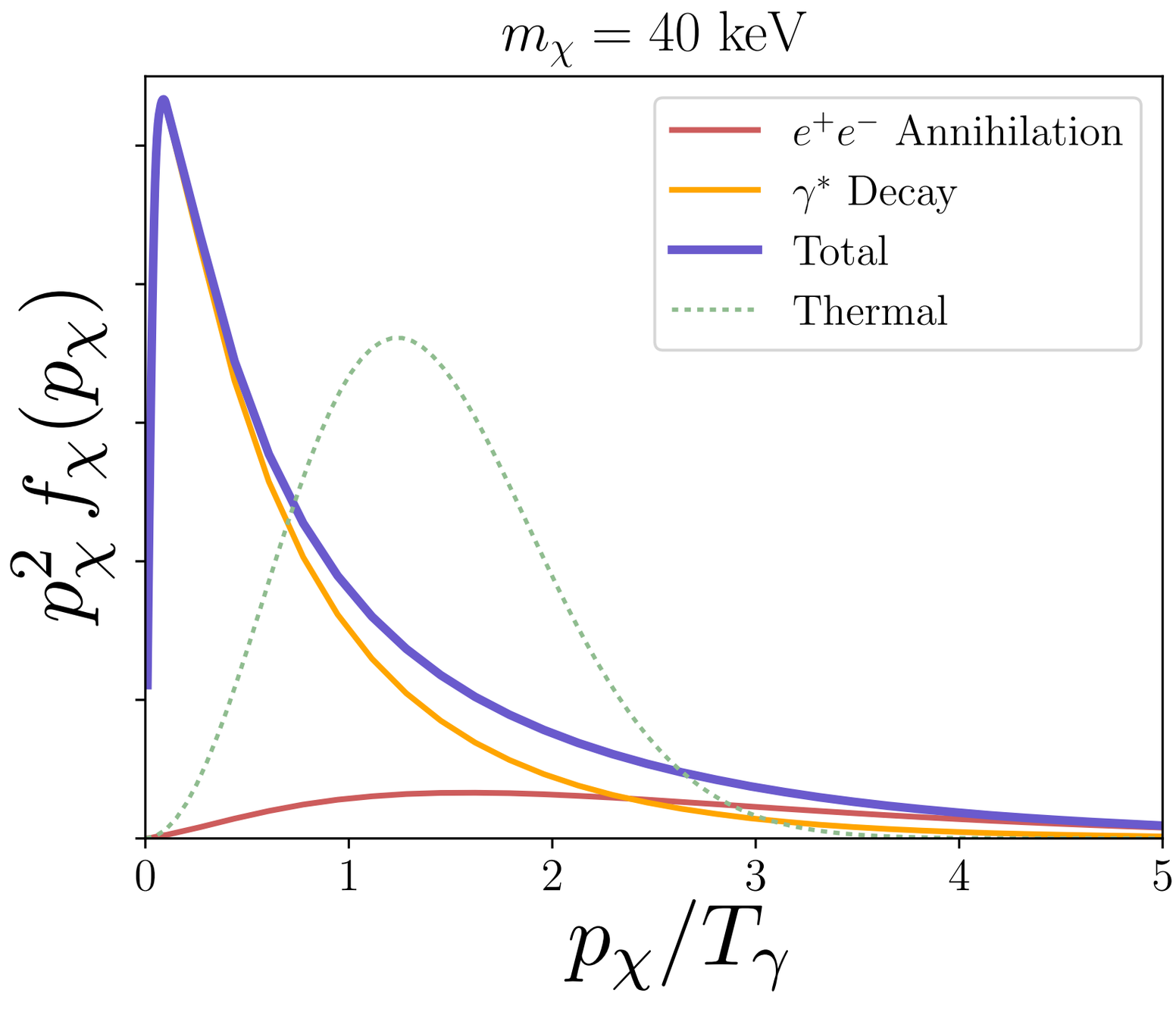
Dvorkin, Lin, **KS** (PRD 2019)

# DEALING WITH NON-THERMAL PHASE SPACE



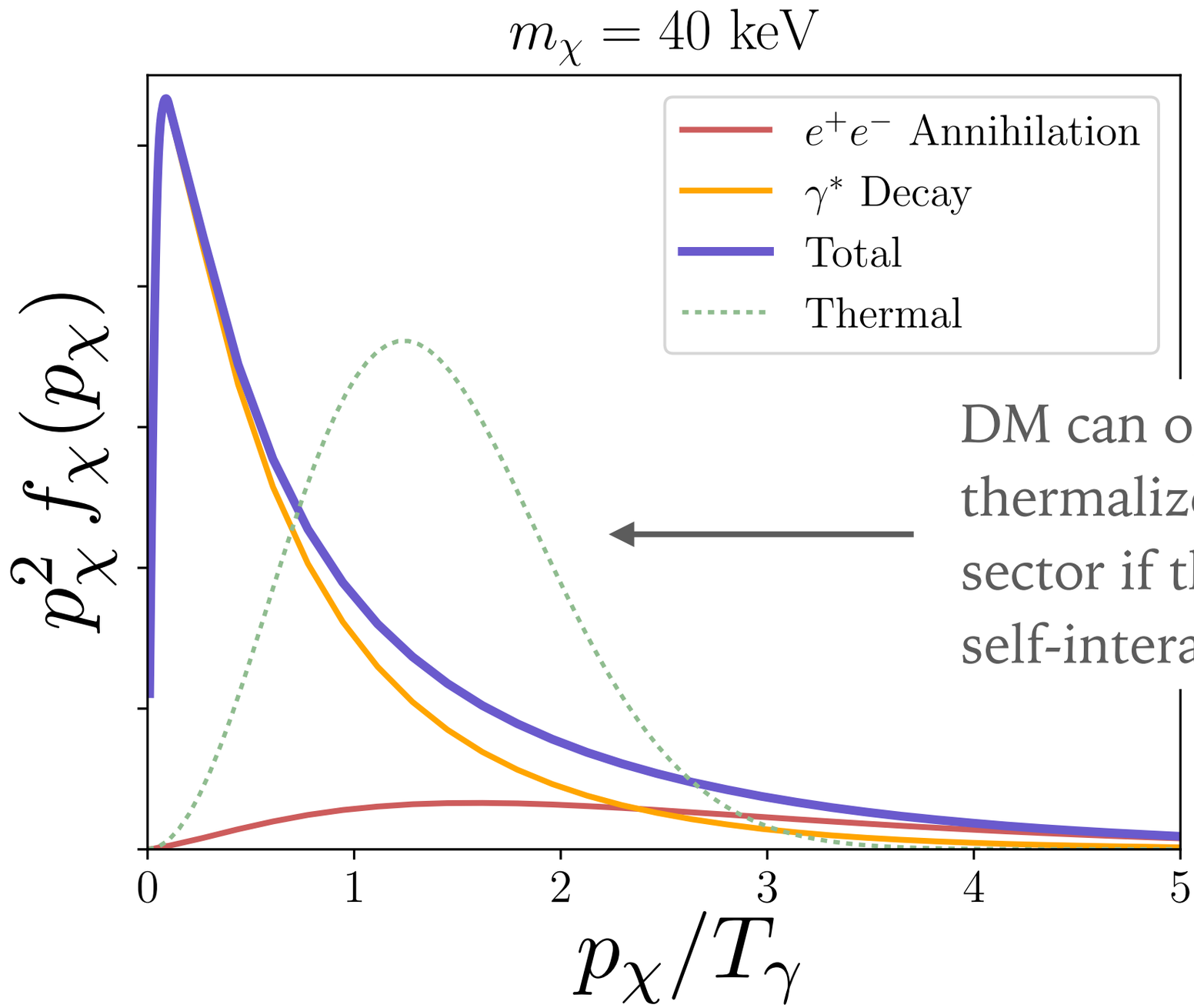

Dvorkin, Lin, **KS** (PRD 2019)

# DEALING WITH NON-THERMAL PHASE SPACE




Dvorkin, Lin, **KS** (PRD 2019)

# DEALING WITH NON-THERMAL PHASE SPACE




DM can optionally thermalize in its own sector if there are self-interactions

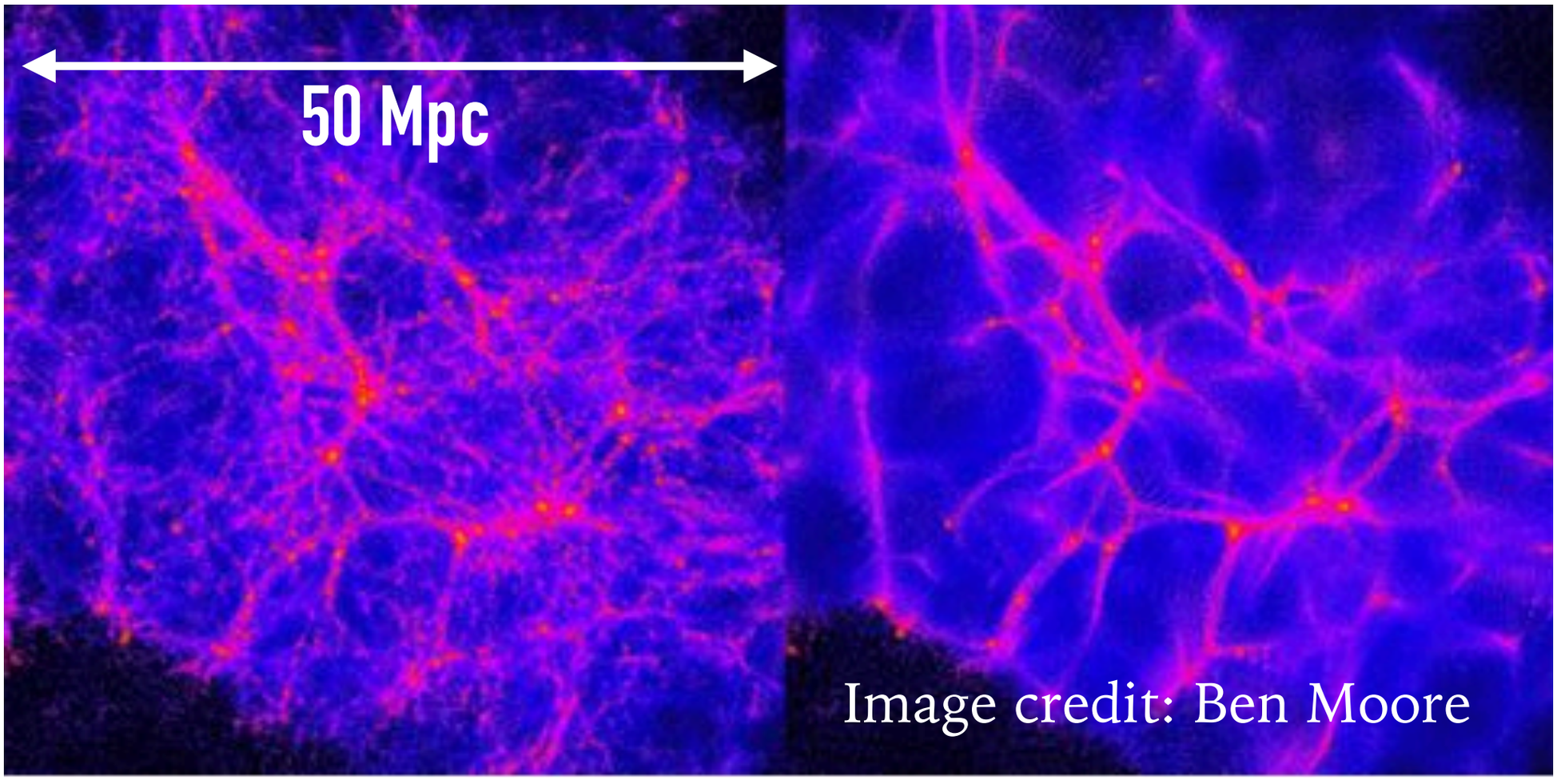
Dvorkin, Lin, **KS** (PRD 2019)

# PHASE SPACE IMPLICATIONS FOR COSMOLOGY

Dvorkin, Lin, **KS** in prep.

# VELOCITY EFFECTS ON CLUSTERING (WARM DARK MATTER EXAMPLE)

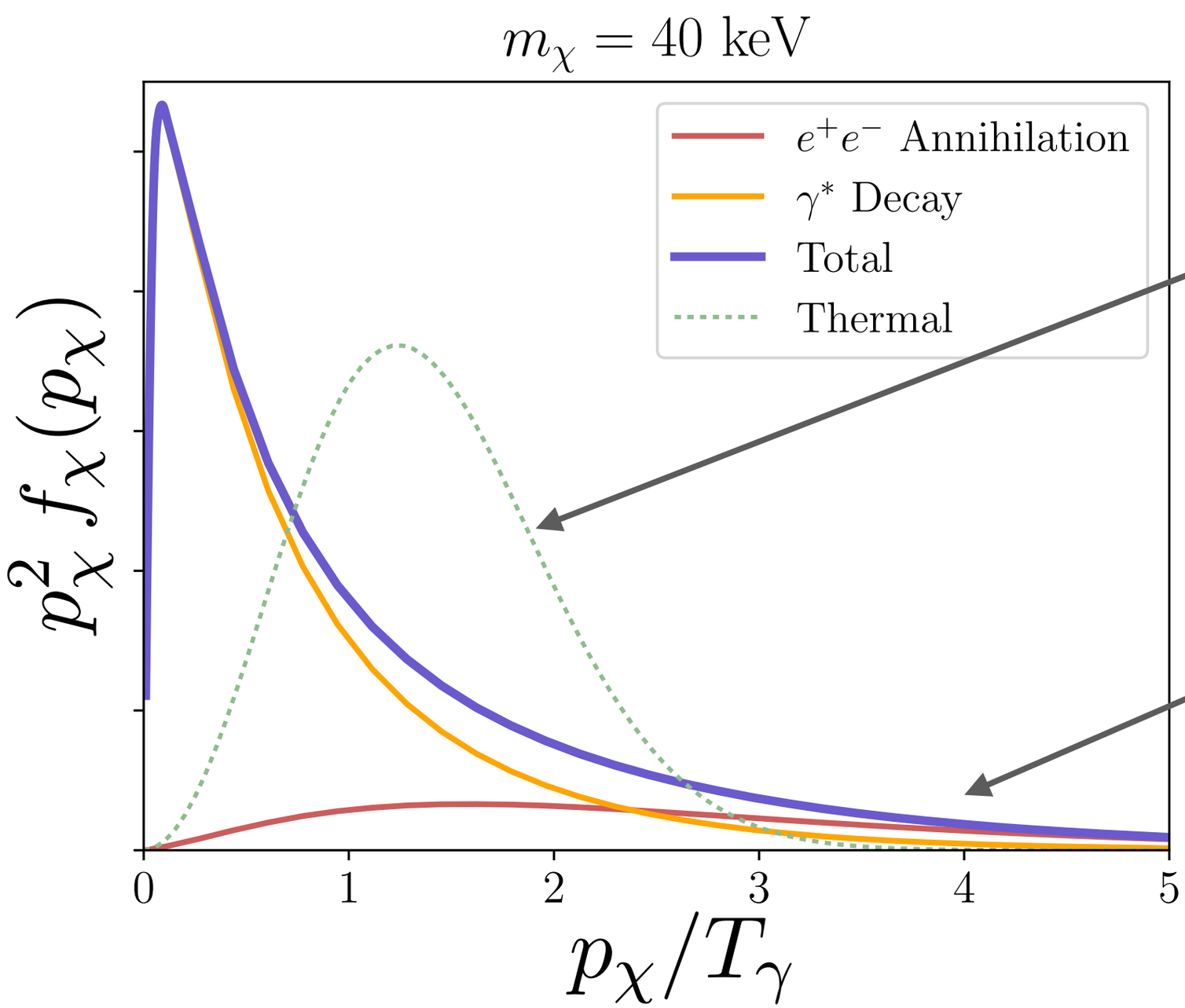
Warm dark matter initial conditions: $\Omega_\chi = \frac{m_\chi}{94\ \mathrm{eV}} \frac{11}{4} \left(\frac{T_\chi}{T_\gamma}\right)^3$




← Heavier

Lighter →

# GRAVITATIONAL CLUSTERING AND PHASE SPACE

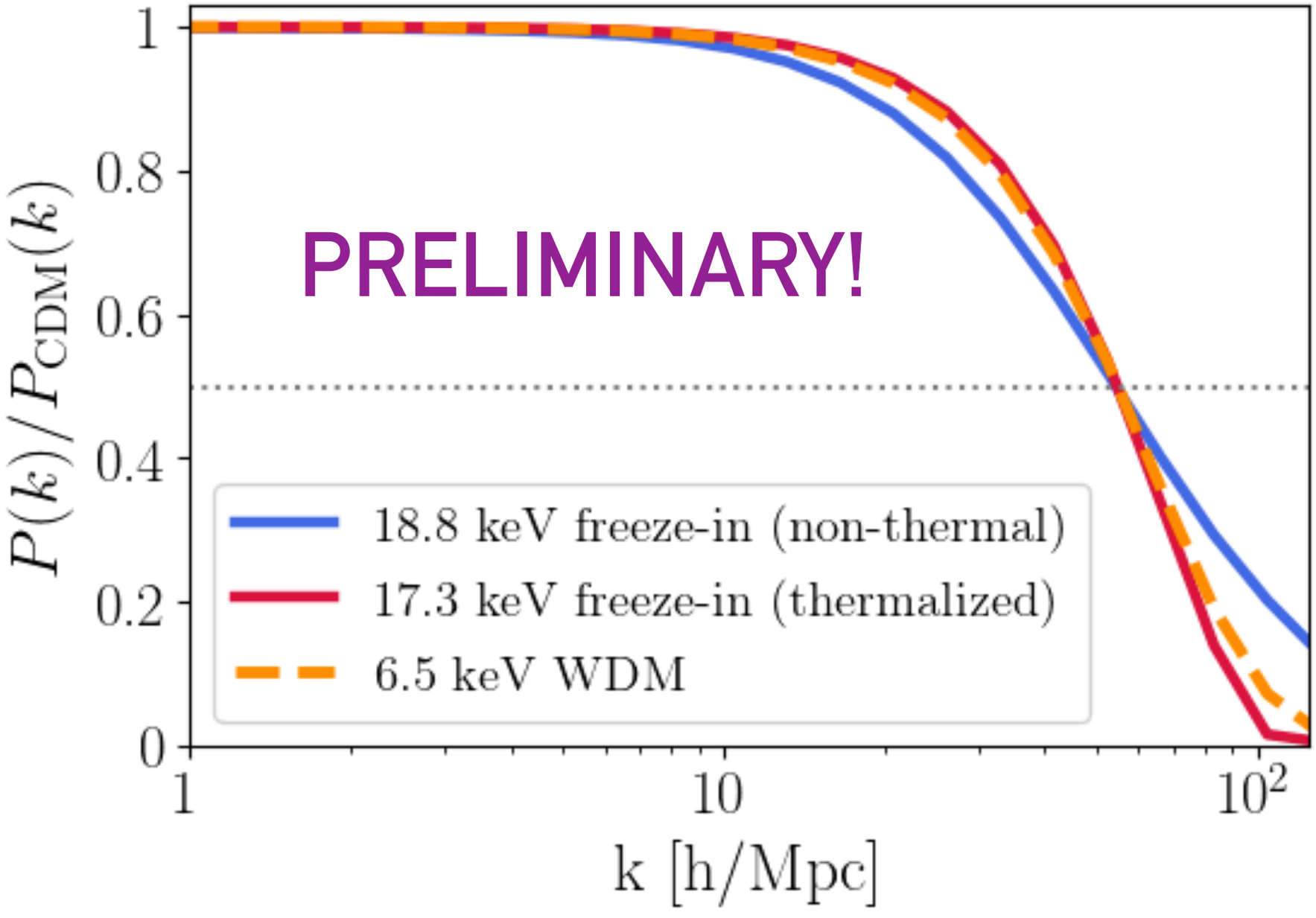



If DM can self-thermalize then it must have a nontrivial sound speed and can't stream freely

Non-thermal distribution has more low-low velocity particles but fatter high-velocity tail, can stream freely

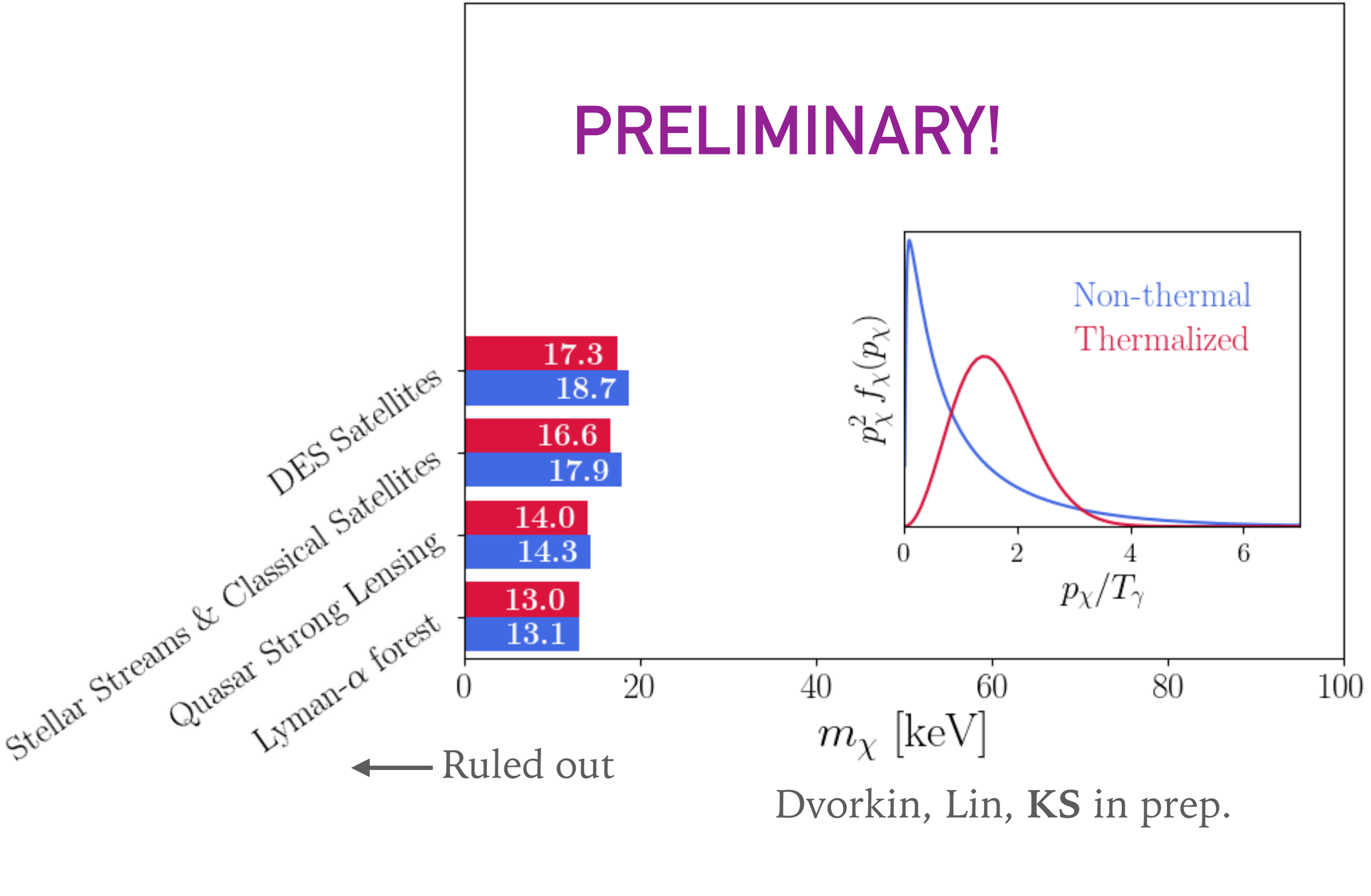
Dvorkin, Lin, **KS** in prep.

# MAPPING WDM CONSTRAINTS TO FREEZE-IN CONSTRAINTS



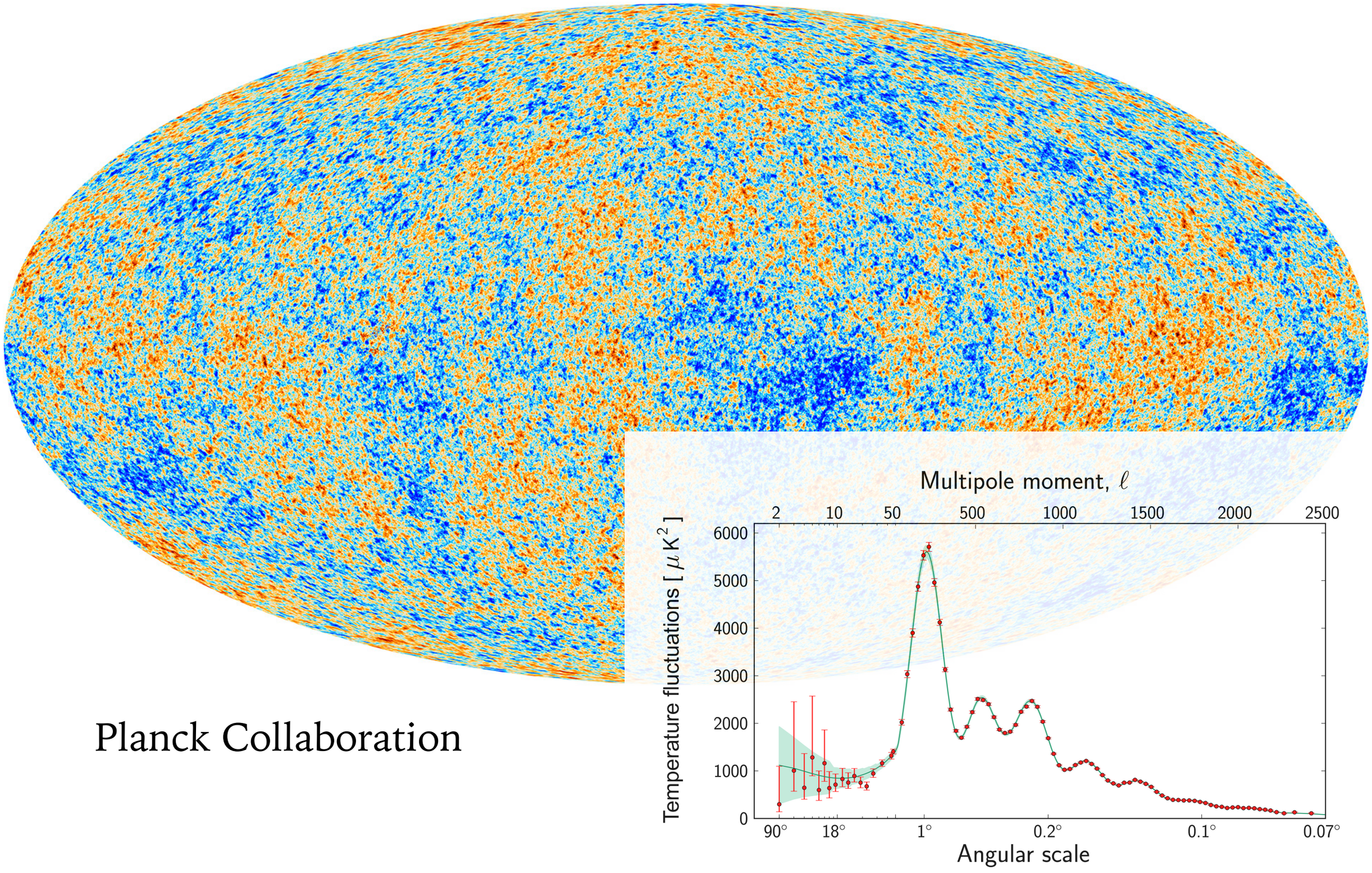

Dvorkin, Lin, **KS** in prep.

# COSMOLOGICAL CONSTRAINTS ON FREEZE-IN

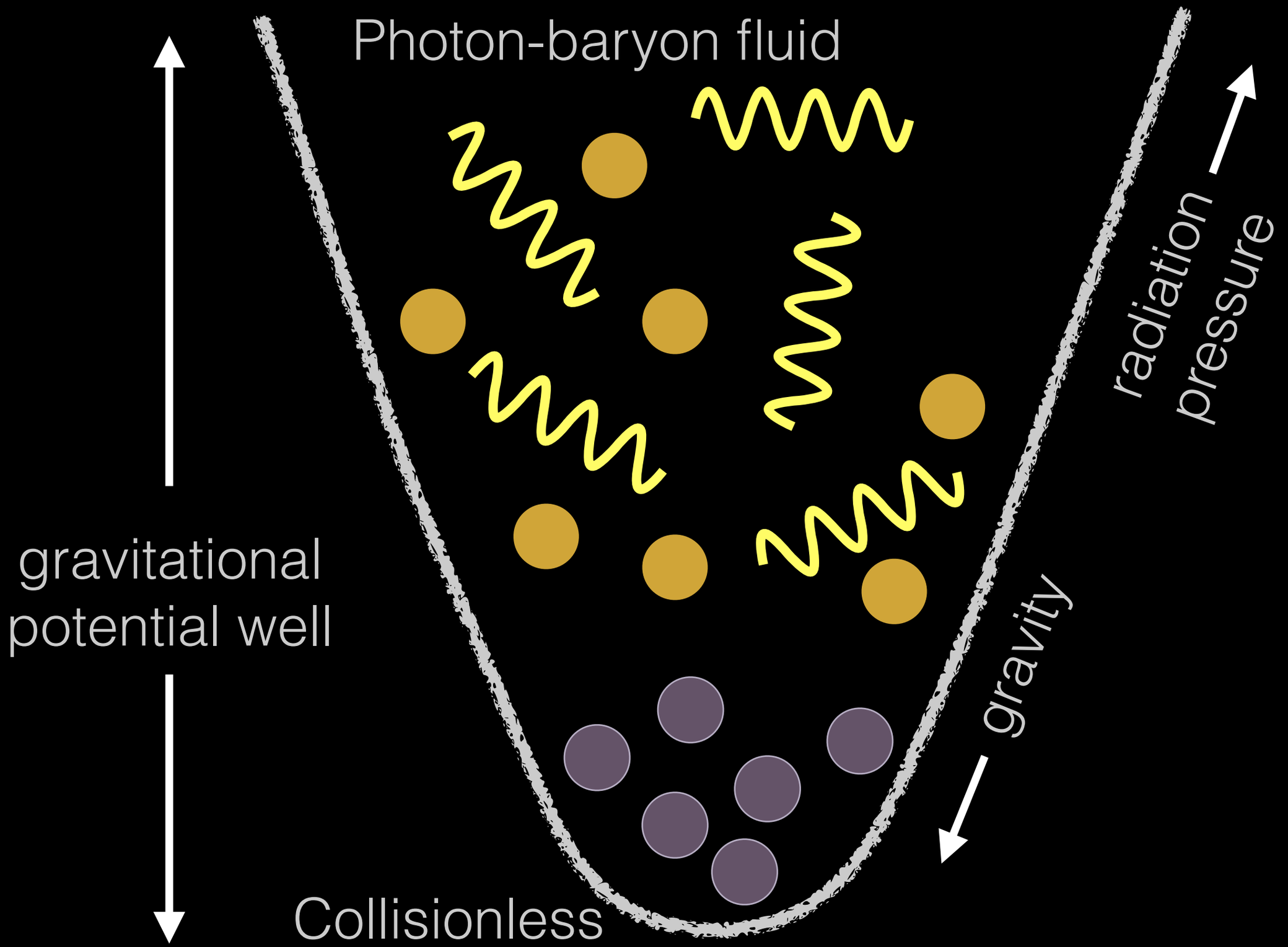


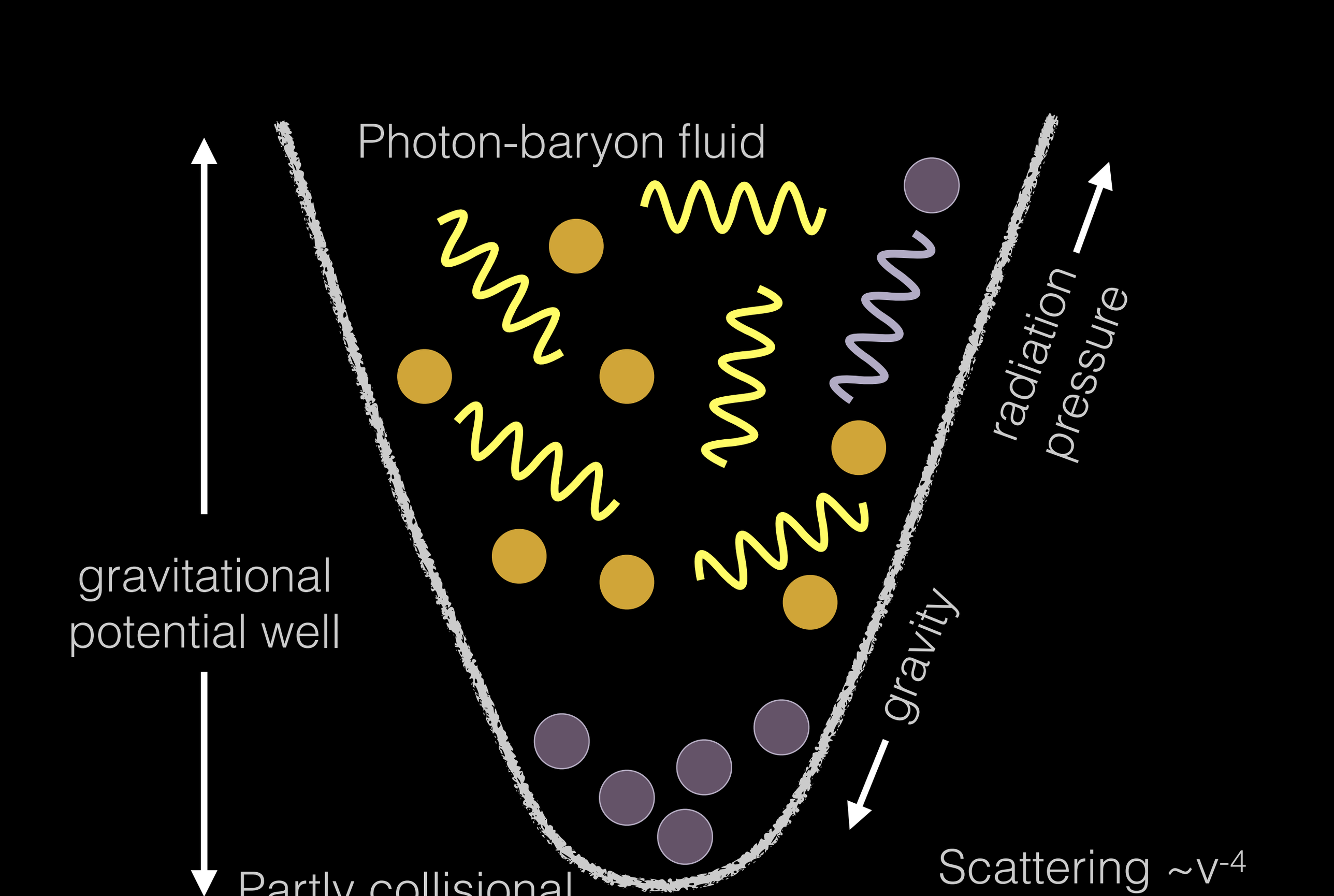

Dvorkin, Lin, **KS** in prep.

# DARK MATTER–BARYON DRAG APPARENT IN THE CMB

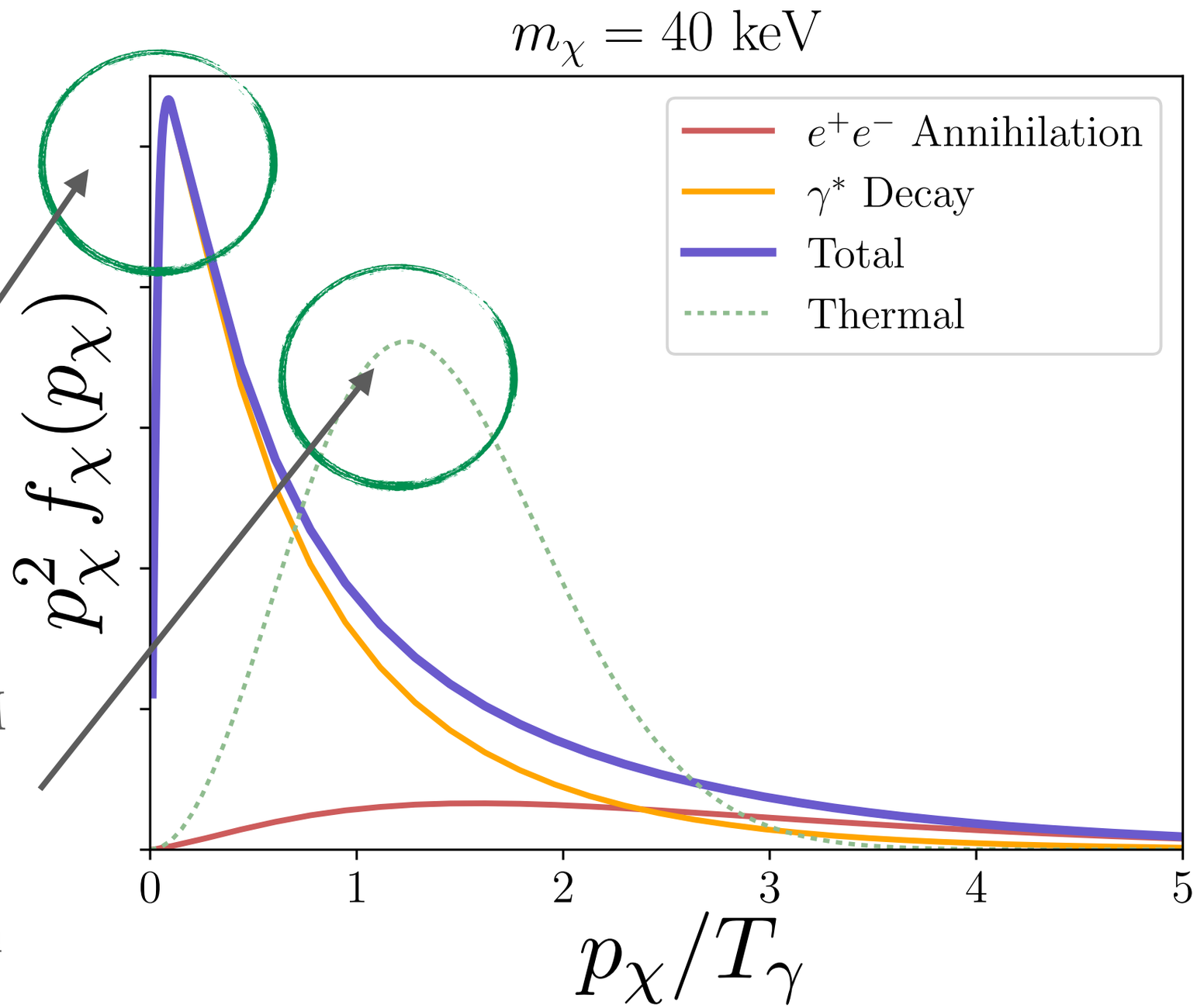



Planck Collaboration


Photon-baryon fluid
gravitational
potential well
radiation
pressure
gravity
Collisionless
dark matter


Photon-baryon fluid
radiation pressure
gravitational potential well
gravity
Partly collisional dark matter
Scattering ~v-4 for freeze-in

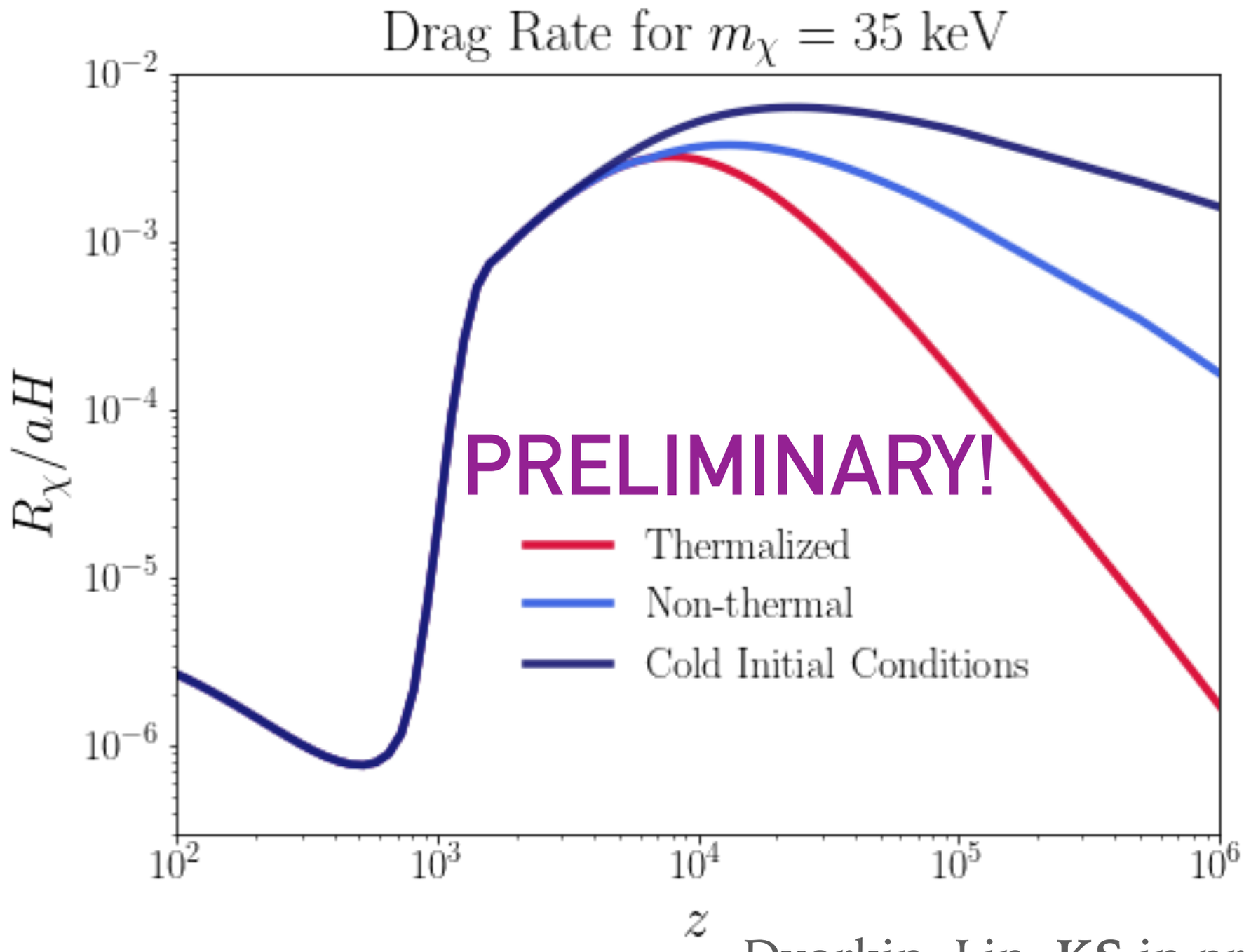
# DM-BARYON SCATTERING AND PHASE SPACE




More DM particles moving slower if DM does not thermalize, stronger $v^{-4}$ scattering effect seen in the CMB!

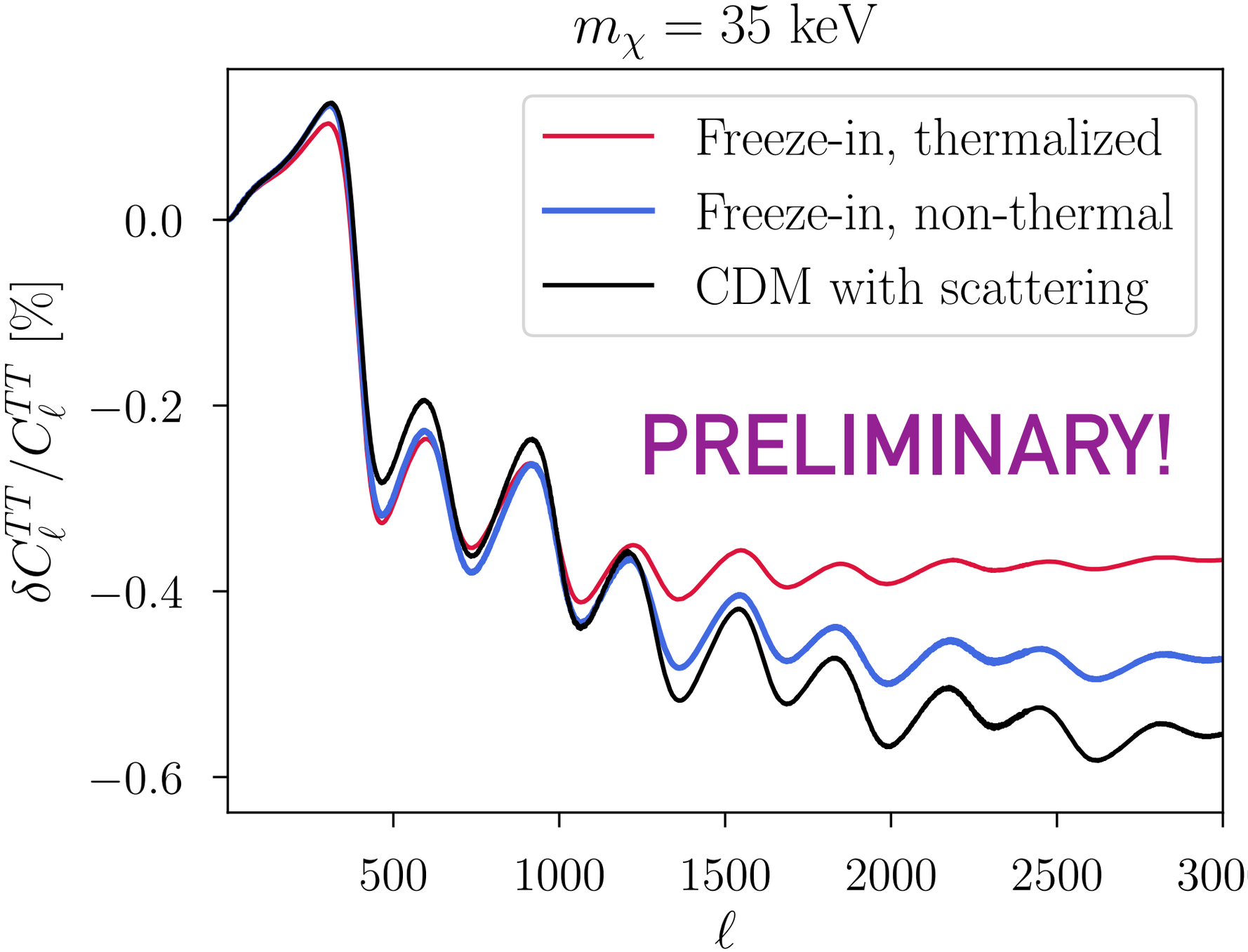
Dvorkin, Lin, **KS** in prep.

# DARK MATTER–BARYON DRAG RATE



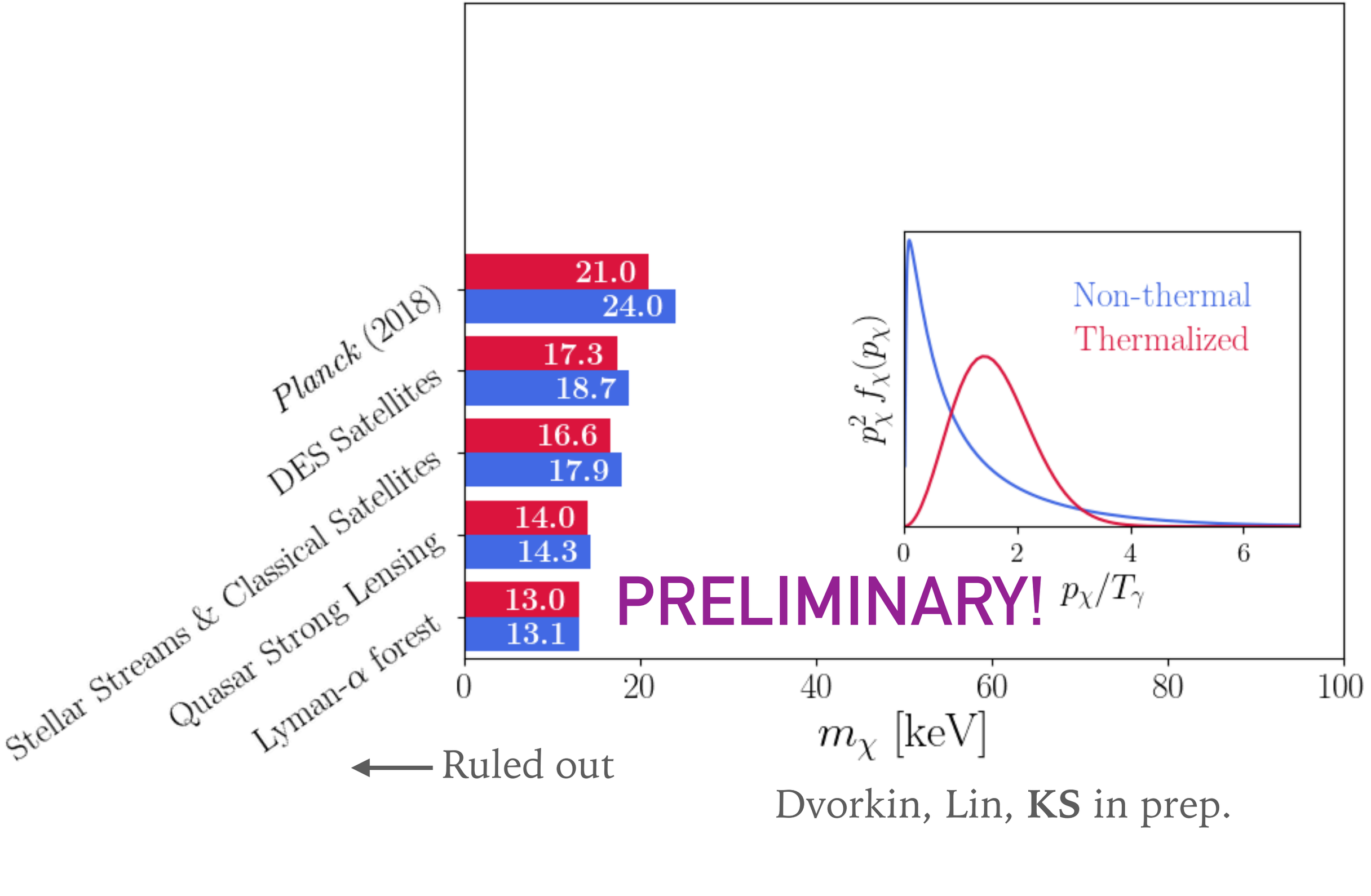

Dvorkin, Lin, **KS** in prep.

# DARK MATTER–BARYON DRAG EFFECT ON THE CMB



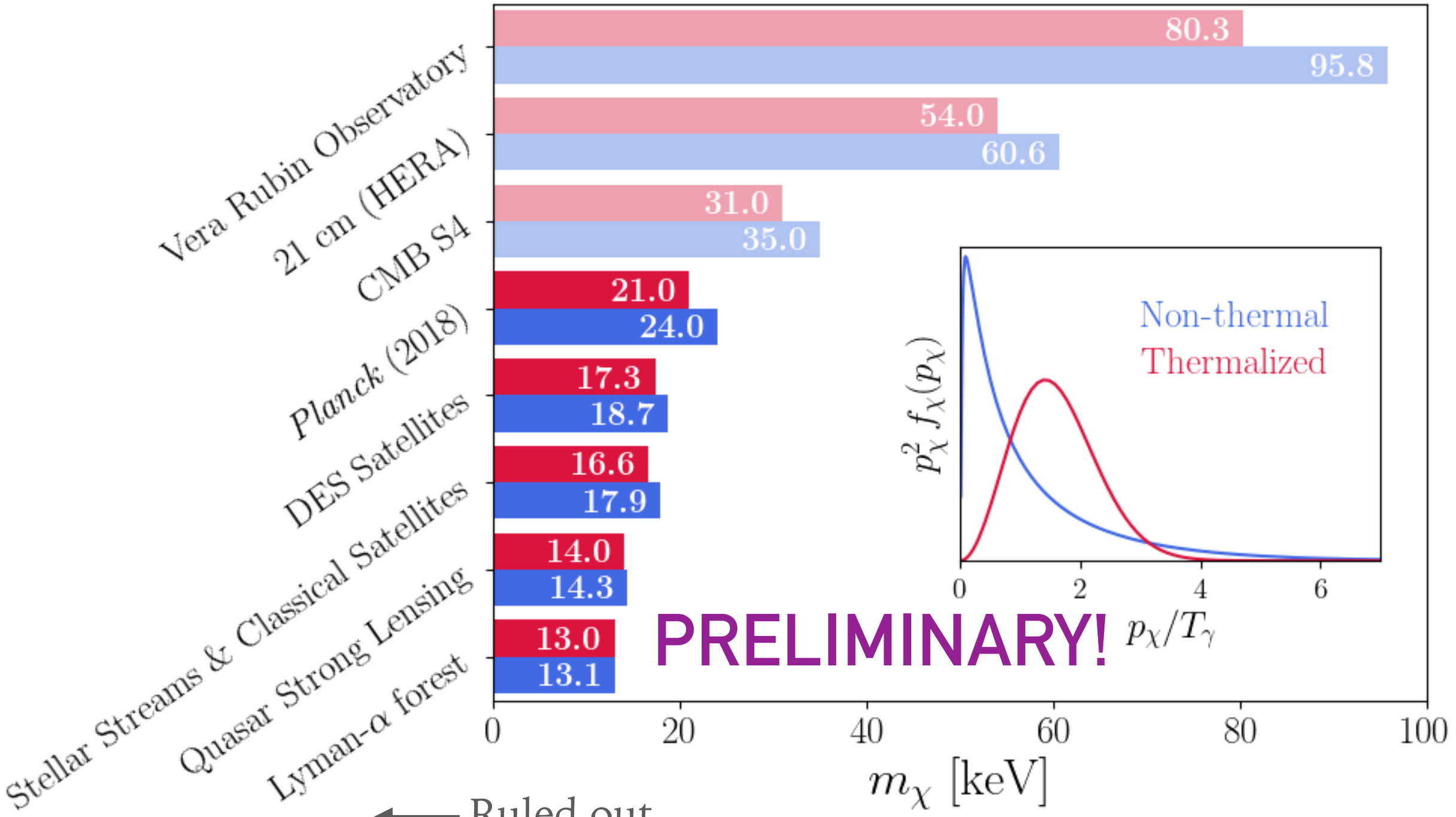

Dvorkin, Lin, **KS** in prep.

# COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



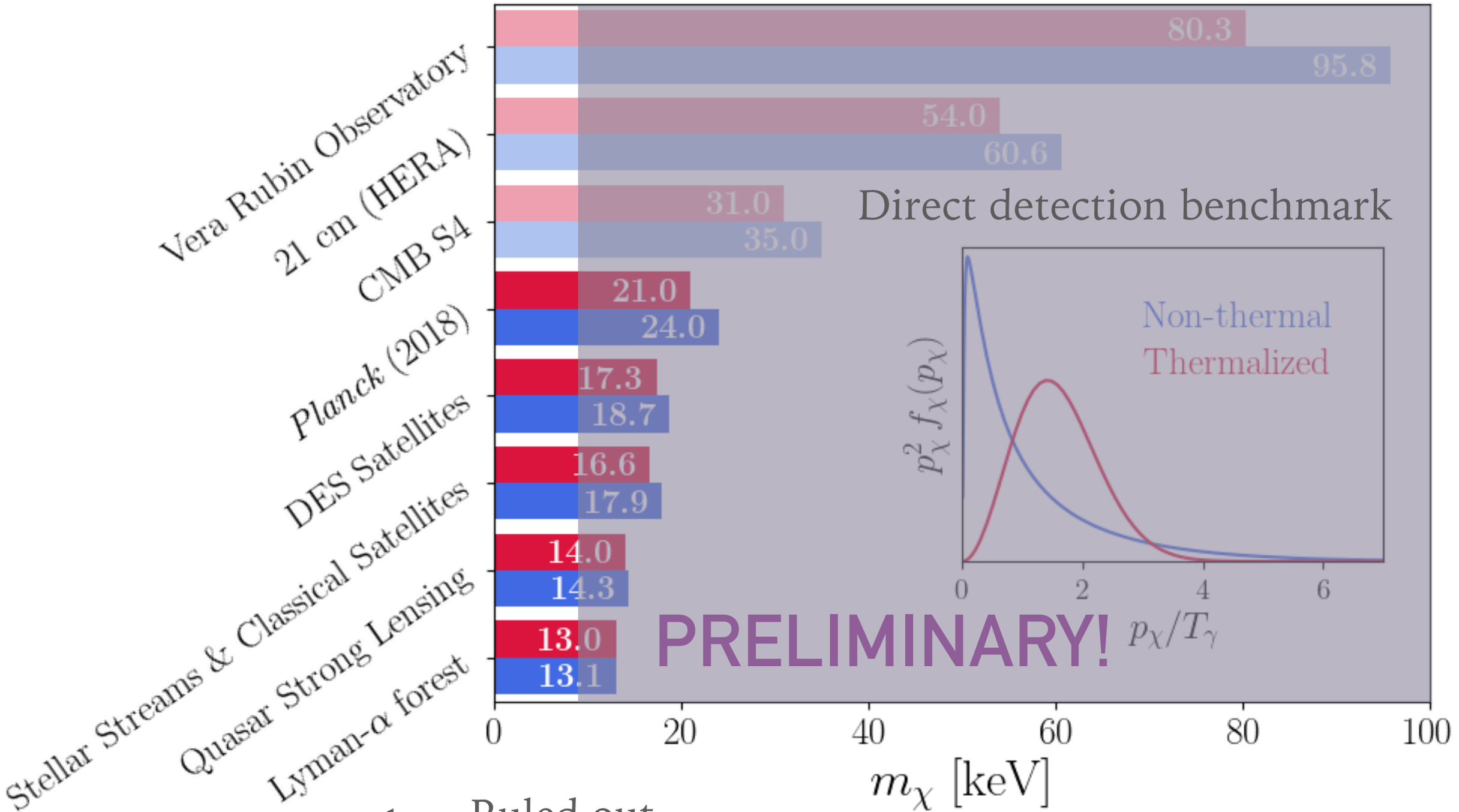

Dvorkin, Lin, **KS** in prep.

# FUTURE COSMOLOGICAL CONSTRAINTS ON FREEZE-IN




Dvorkin, Lin, **KS** in prep.

# FUTURE COSMOLOGICAL CONSTRAINTS ON FREEZE-IN




Dvorkin, Lin, **KS** in prep.

# SUMMARY

- DM could be made by freeze-in off of decaying light, simplest way to make charged DM
- Key benchmark for sub-MeV direct detection experiments
- Non-thermal phase space structure leads to interesting cosmology: warm DM behavior + baryon dragging
- Entire thermal history and phase space were crucial in setting self-consistent limit— what would it take to ensure that this can also be done for other DM theories?

# POINTS TO KEEP IN MIND FOR SNOWMASS PURPOSES

- Some questions relevant to freeze-in and beyond:
  - How can we map WDM ~keV mass limit to theories with thermal histories that are very different from WDM?
    - Can we set more consistent limits on theories with velocity-dependent DM scattering by considering full history of how such DM is produced?
- Are there other DM theories with constraints that are ripe for careful reconsideration accounting for their full thermal histories?