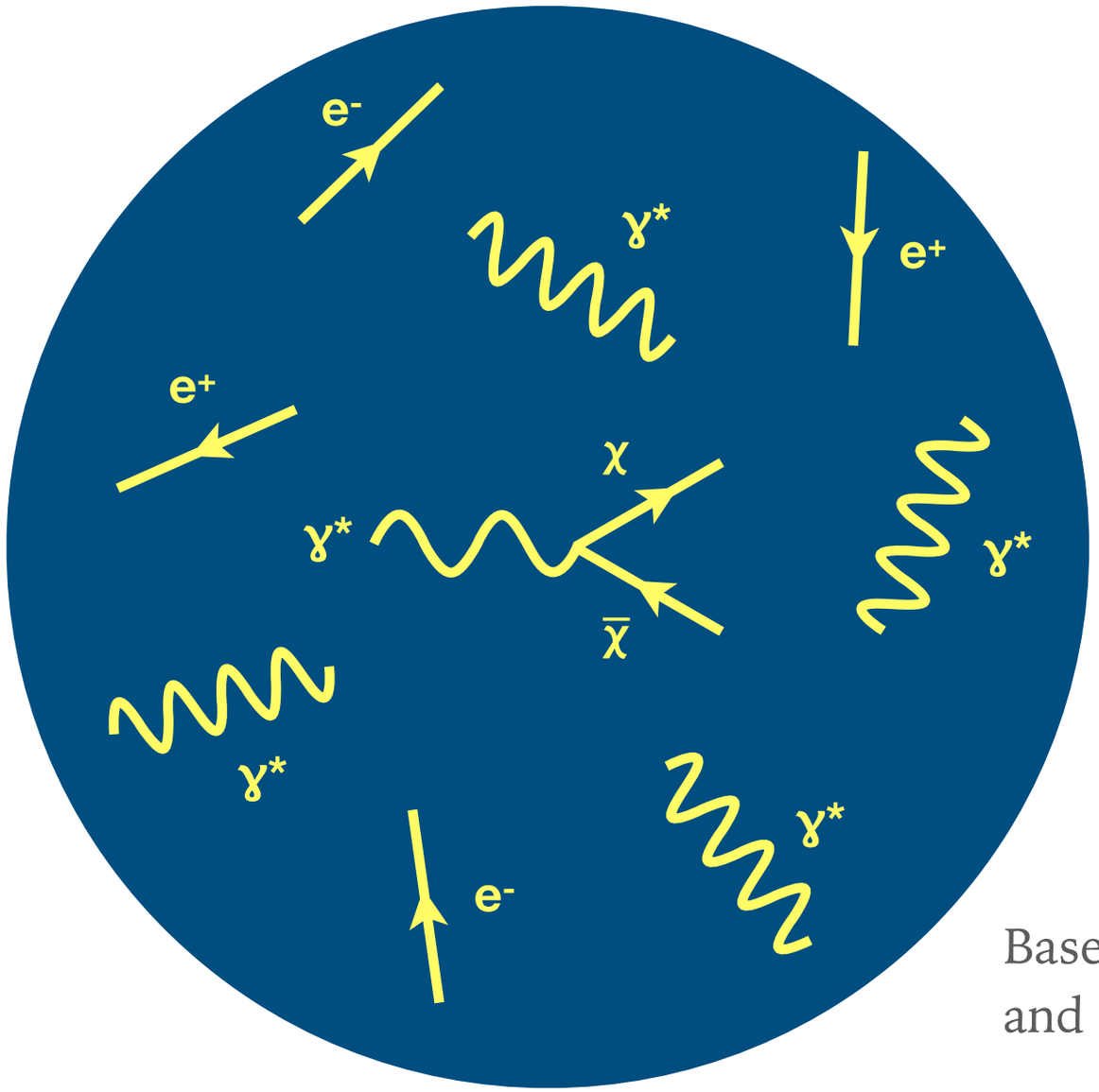


CONSOLIDATED PROBES OF SUB-MEV FREEZE-IN & LOWERING BARRIERS FOR INTERDISCIPLINARITY

Based on Dvorkin, Lin, **KS** (2011.08186)
and Dvorkin, Lin, **KS** PRD (Editors' Suggestion, 2019)

Katelin Schutz, MIT→McGill

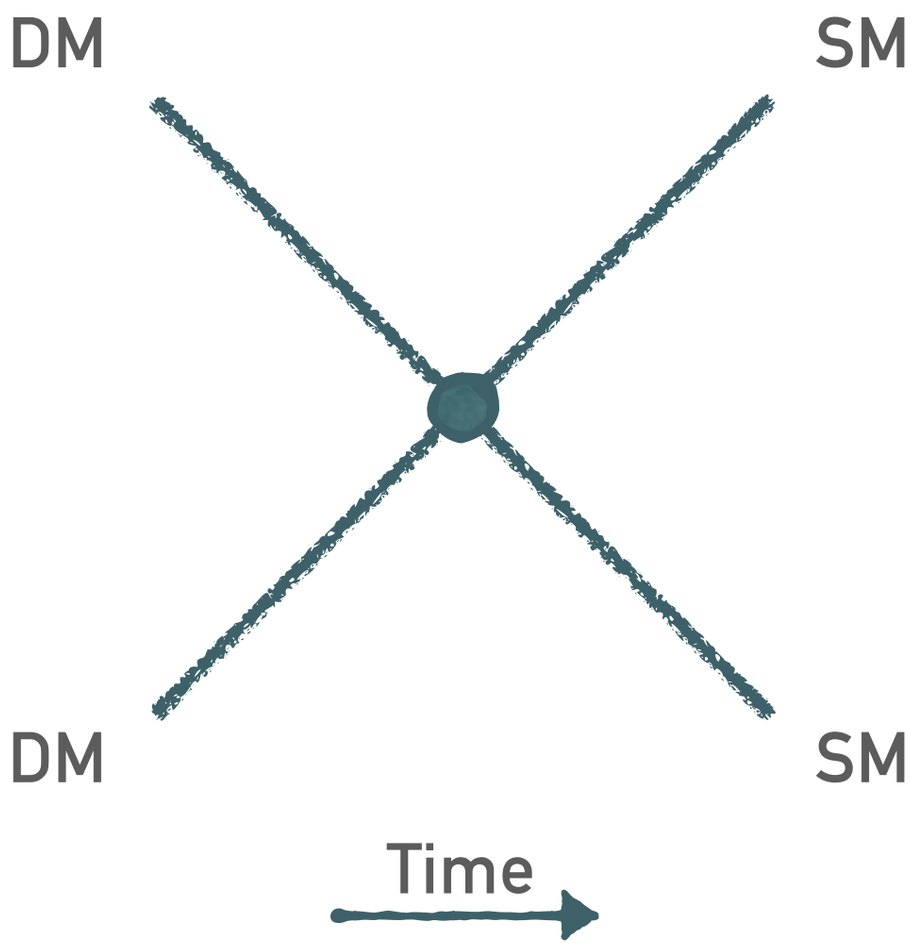
A Rainbow of Dark Sectors
Aspen, 3/22/2020

THROWING DOWN THE GAUNTLET

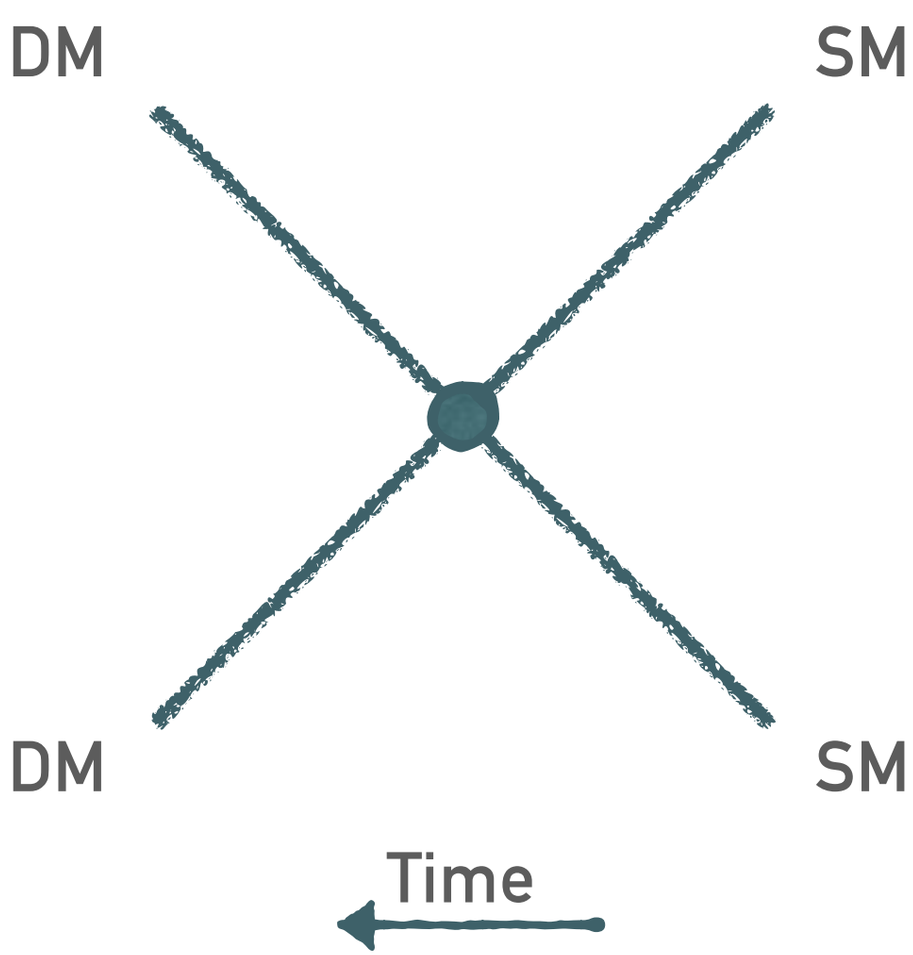
- I will treat sub-MeV freeze-in as a "case study" for a more general goal: let's try to move towards being more fully self-consistent & inclusive in matching early Universe theories of DM to cosmo/astro/lab constraints
- Can we work to lower the barrier of doing "end-to-end" limit-setting (considering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

MAKING DARK MATTER OUT OF LIGHT (AN EXAMPLE OF "THERMAL-ISH" IR-DOMINATED FREEZE-IN)

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



Thermal freeze-out



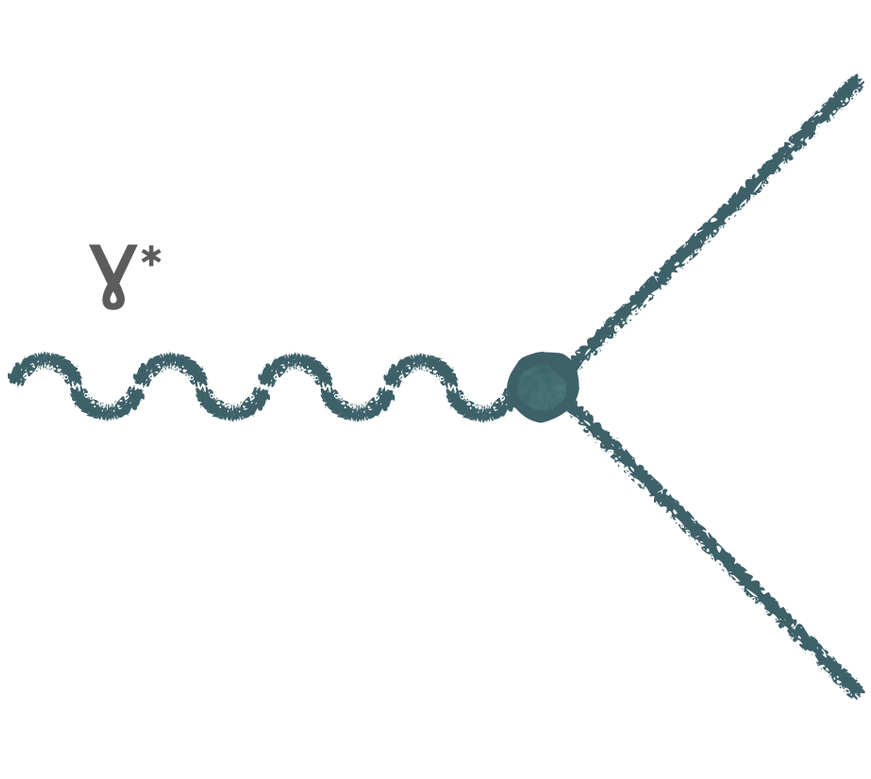
Thermal freeze-in
(Hall et al. 2009)

FOCUS ON EFFECTIVELY "MILLICHARGED" DARK MATTER AS SIMPLE PROXY FOR OTHER MODELS

- IR-dominated freeze-in implies light mediator
- Most light mediators with requisite coupling are excluded, except SM photon ("true millicharge") and kinetically mixed dark photon
- Charged DM often phenomenologically studied in astro without considering consistent early Universe origins*
- Freeze-in is the simplest way of making charged DM (simple freeze-out is excluded)
- Freeze-in through a light vector mediator is oft-quoted benchmark for direct detection (v^{-4} enhancement)

*highlights need for particle theorists

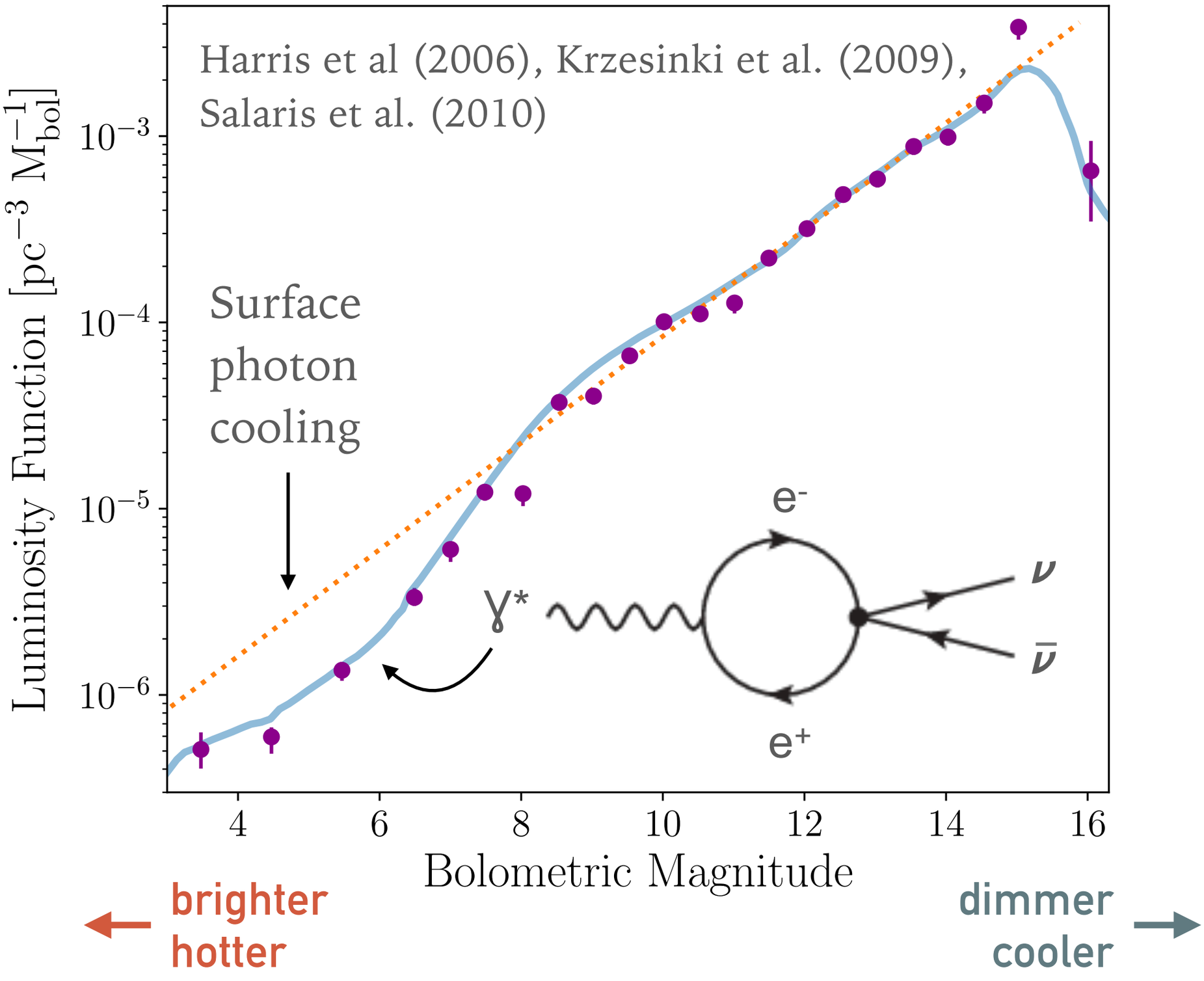
PHOTONS CAN DECAY IN A MEDIUM TO WEAKLY COUPLED PARTICLES



Photon has an in-medium mass inside plasma (“plasmon”), phase space available for decays

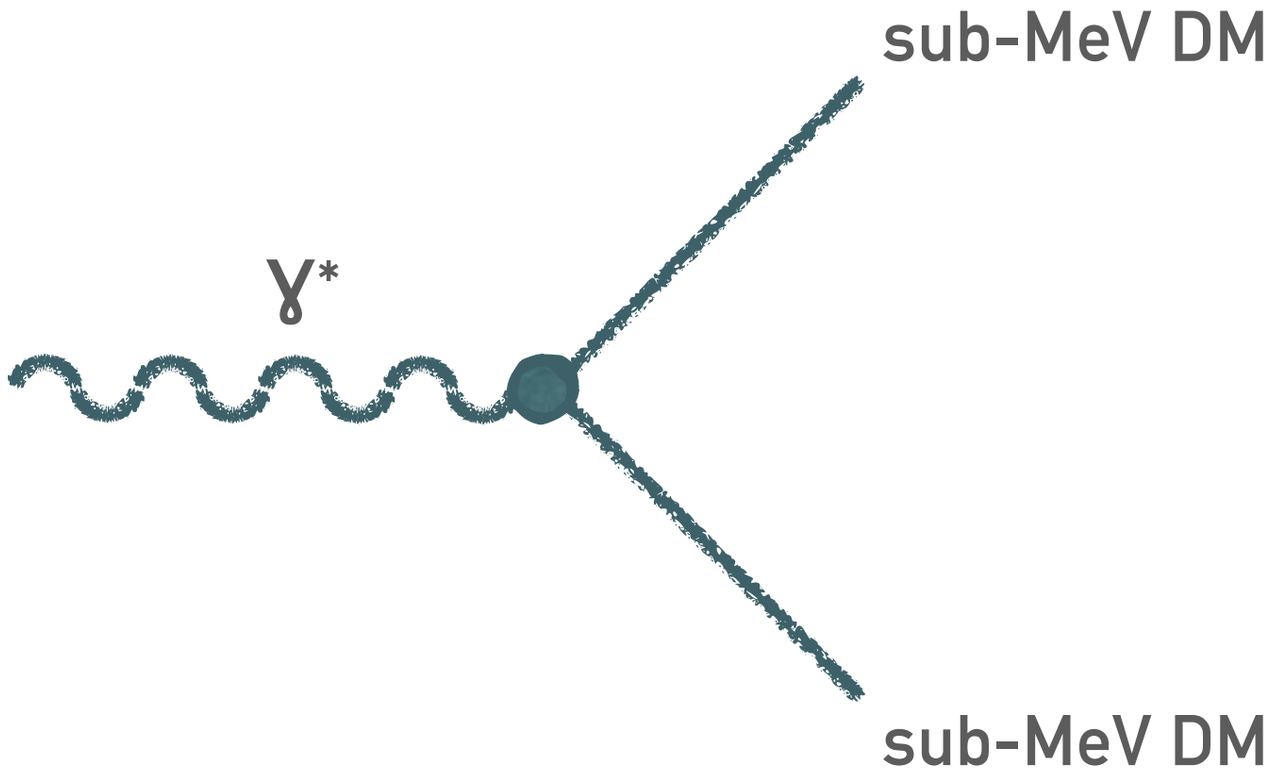
This process can extinguish stars quickly if the final state is unhindered by the plasma (this is a stellar energy loss mechanism in the Standard Model through decay to neutrinos)

WHITE DWARF COOLING AND POPULATION



*highlights need for stellar astrophysicists

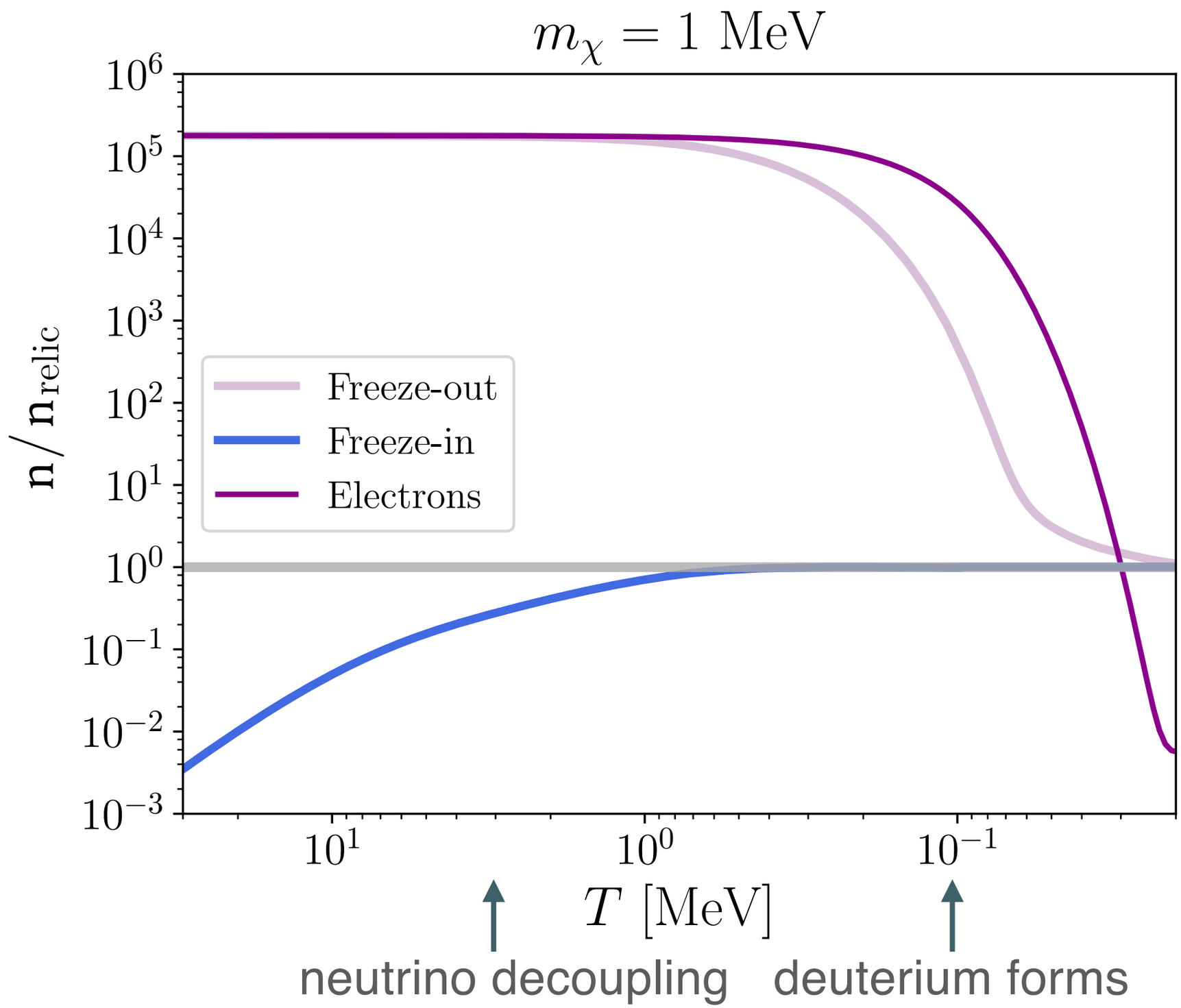
PLASMON DARK MATTER FREEZE-IN



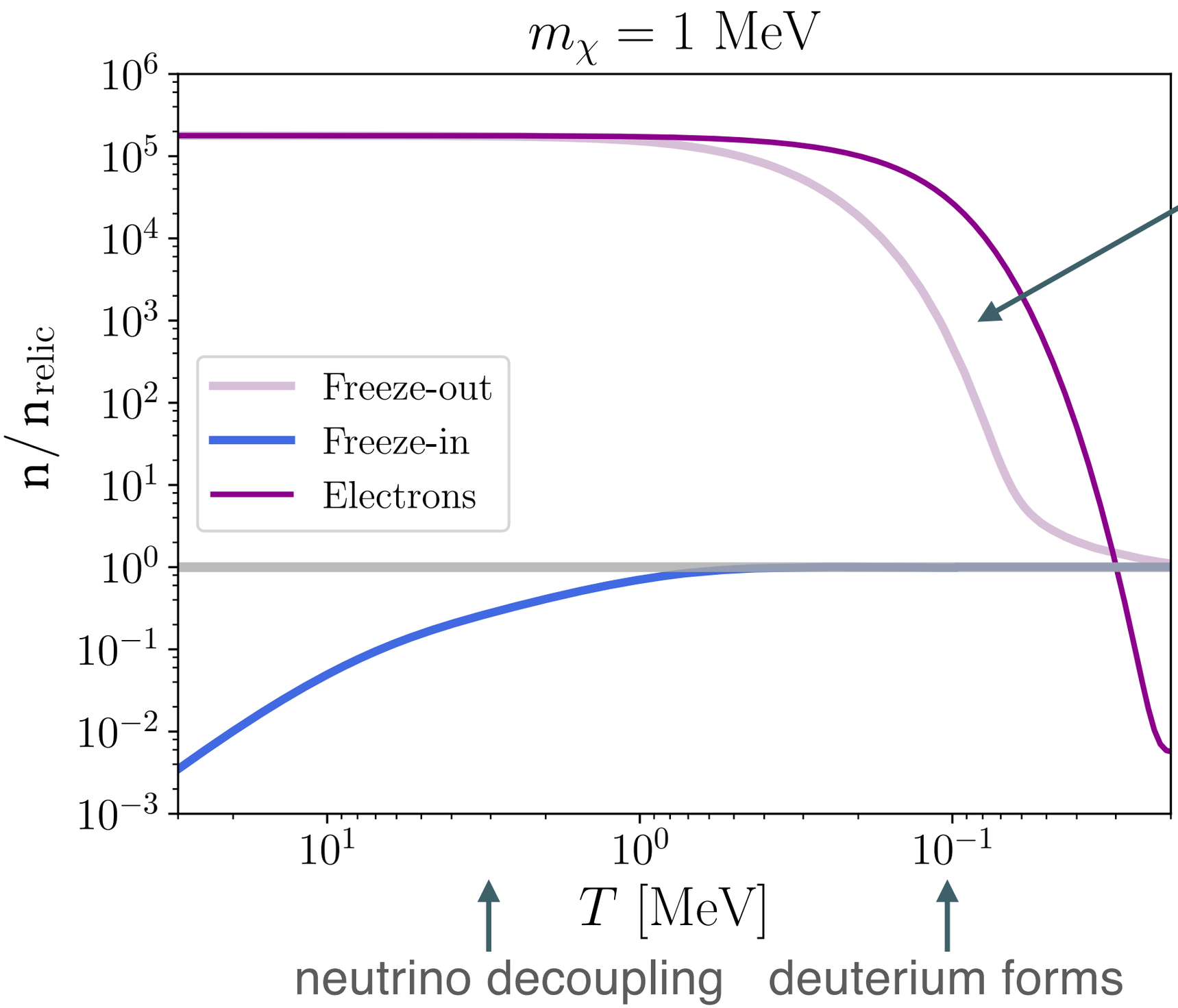
This process makes dark matter efficiently in the early Universe, which is a hot, relativistic plasma!

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

MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS

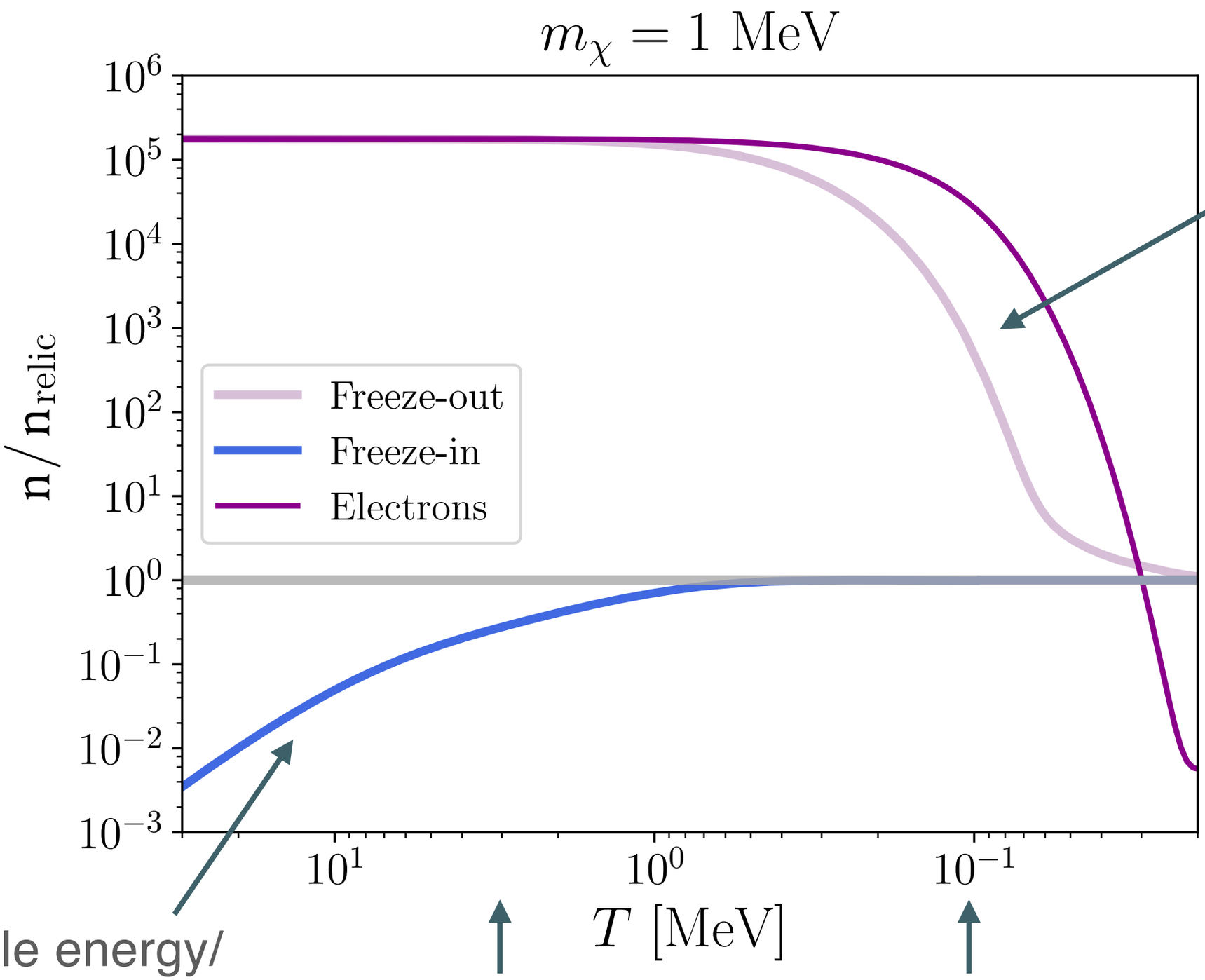


MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS



Energy/ entropy transfer means sub-MeV freeze-out is excluded by Big Bang Nucleo-synthesis (BBN)

MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS

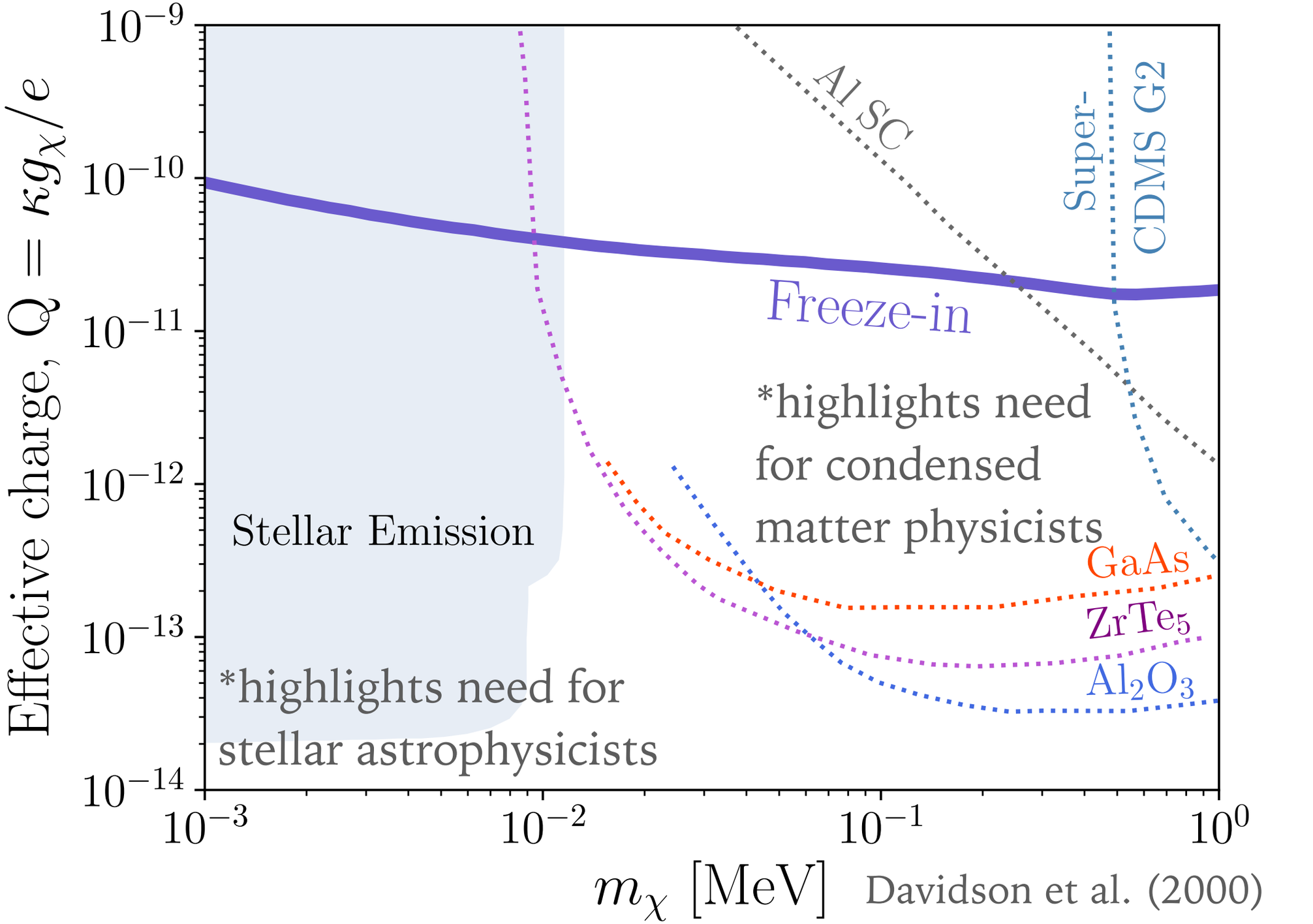


Energy/ entropy transfer means sub-MeV freeze-out is excluded by Big Bang Nucleo-synthesis (BBN)

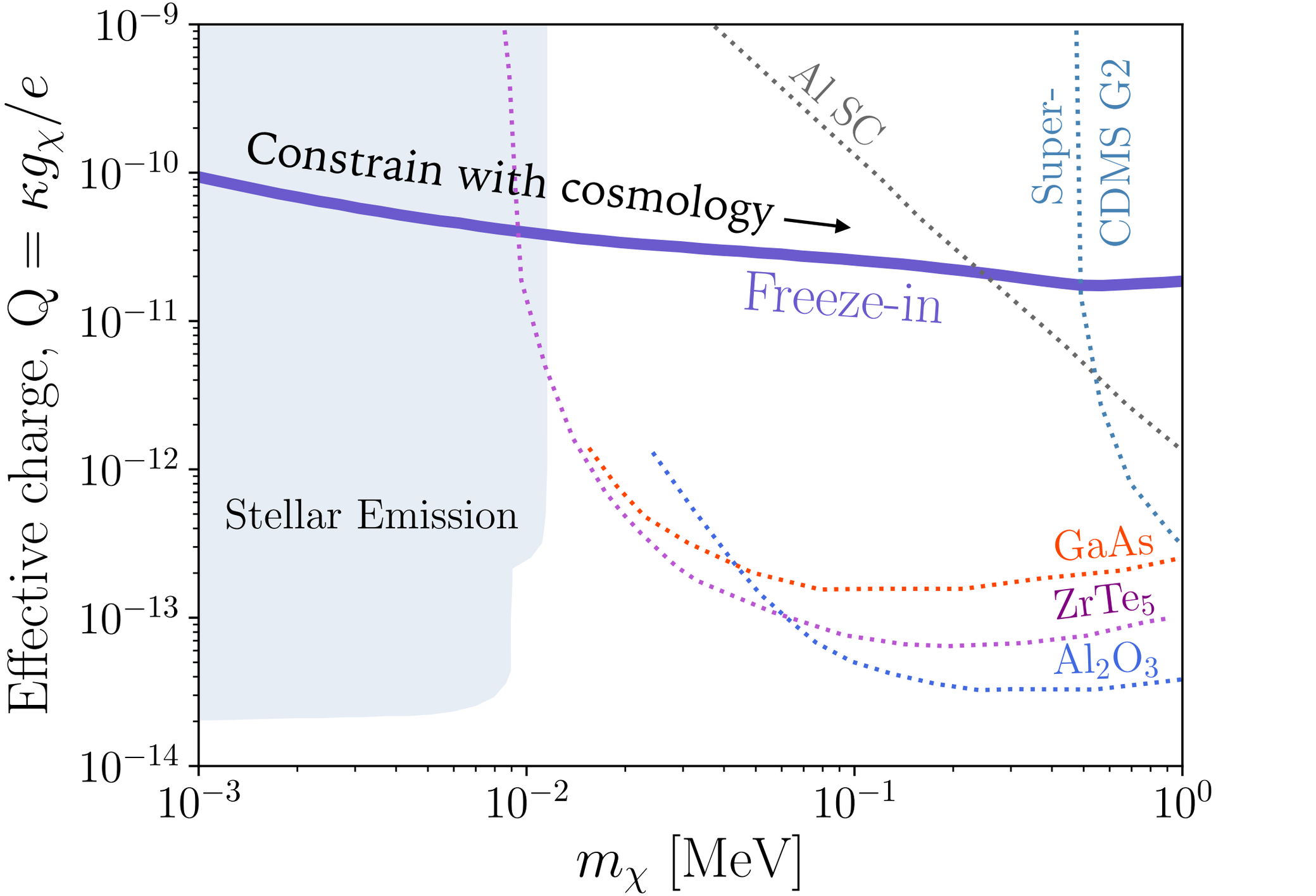
Very little energy/ entropy means no BBN issue

neutrino decoupling

deuterium forms



Davidson et al. (2000)
Vogel & Redondo (2013)
Griffin et al. (2018)



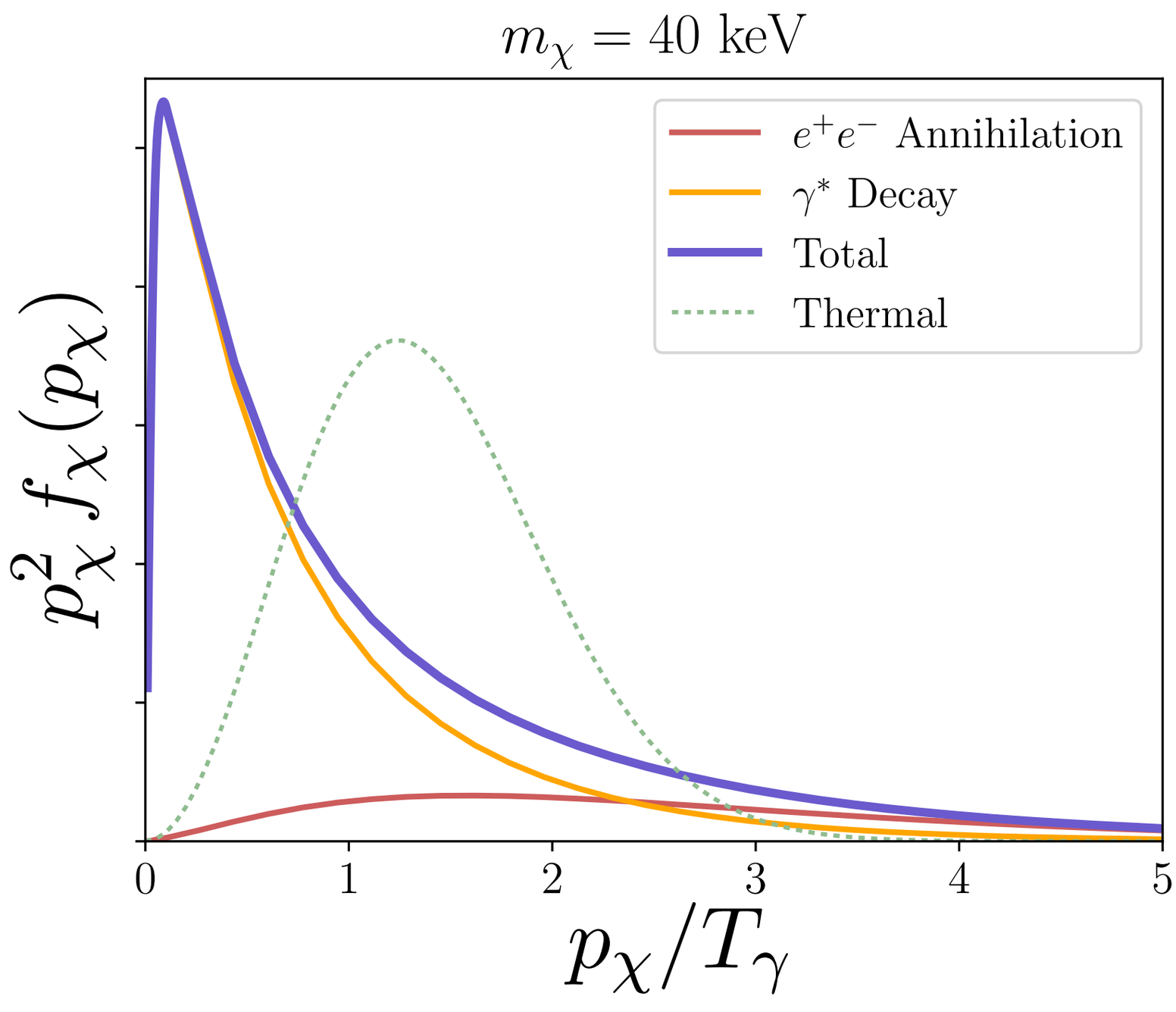
Dvorkin, Lin, **KS** 2011.08186

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

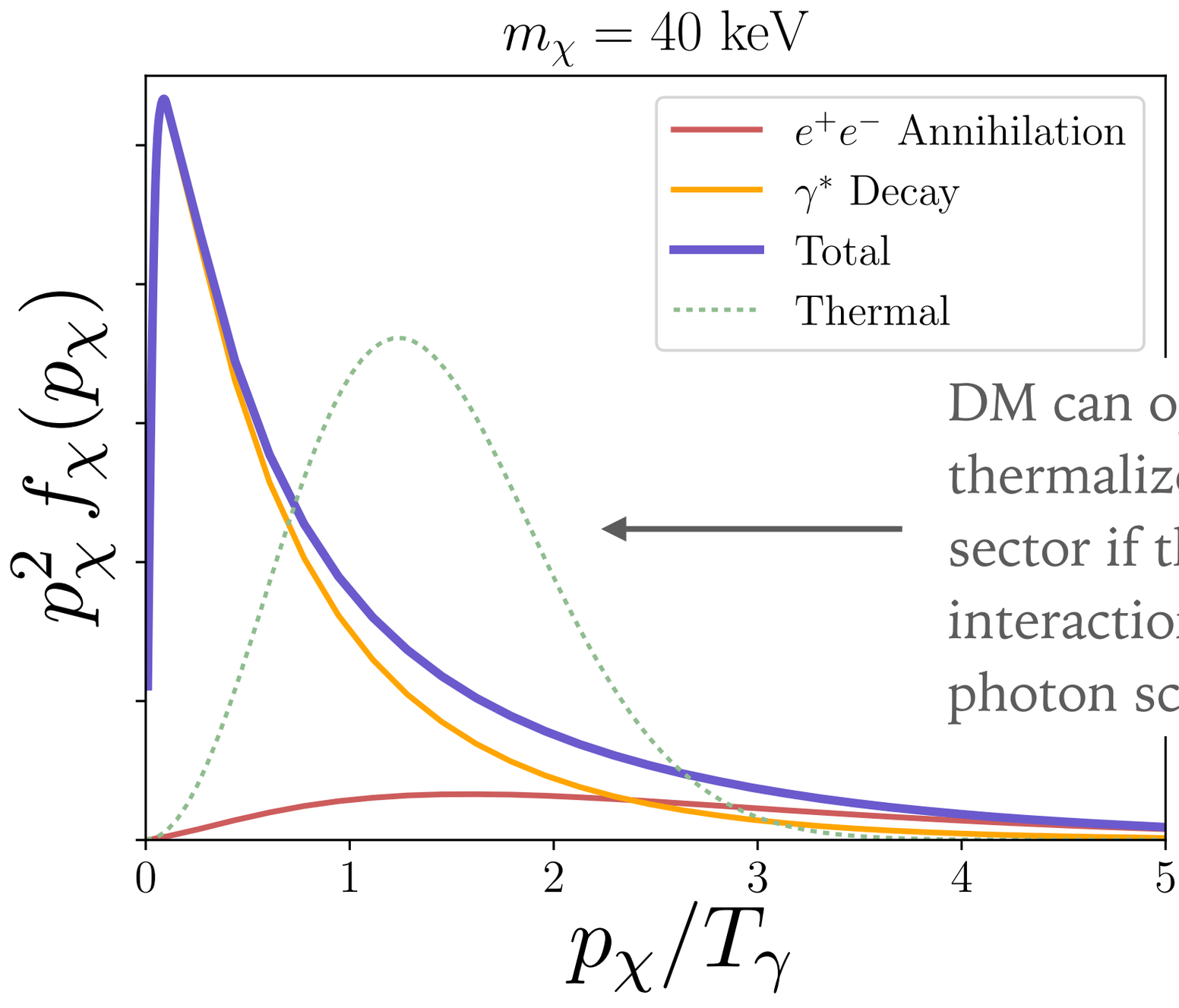
Dvorkin, Lin, **KS** (PRD 2019)

DEALING WITH NON-THERMAL PHASE SPACE



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

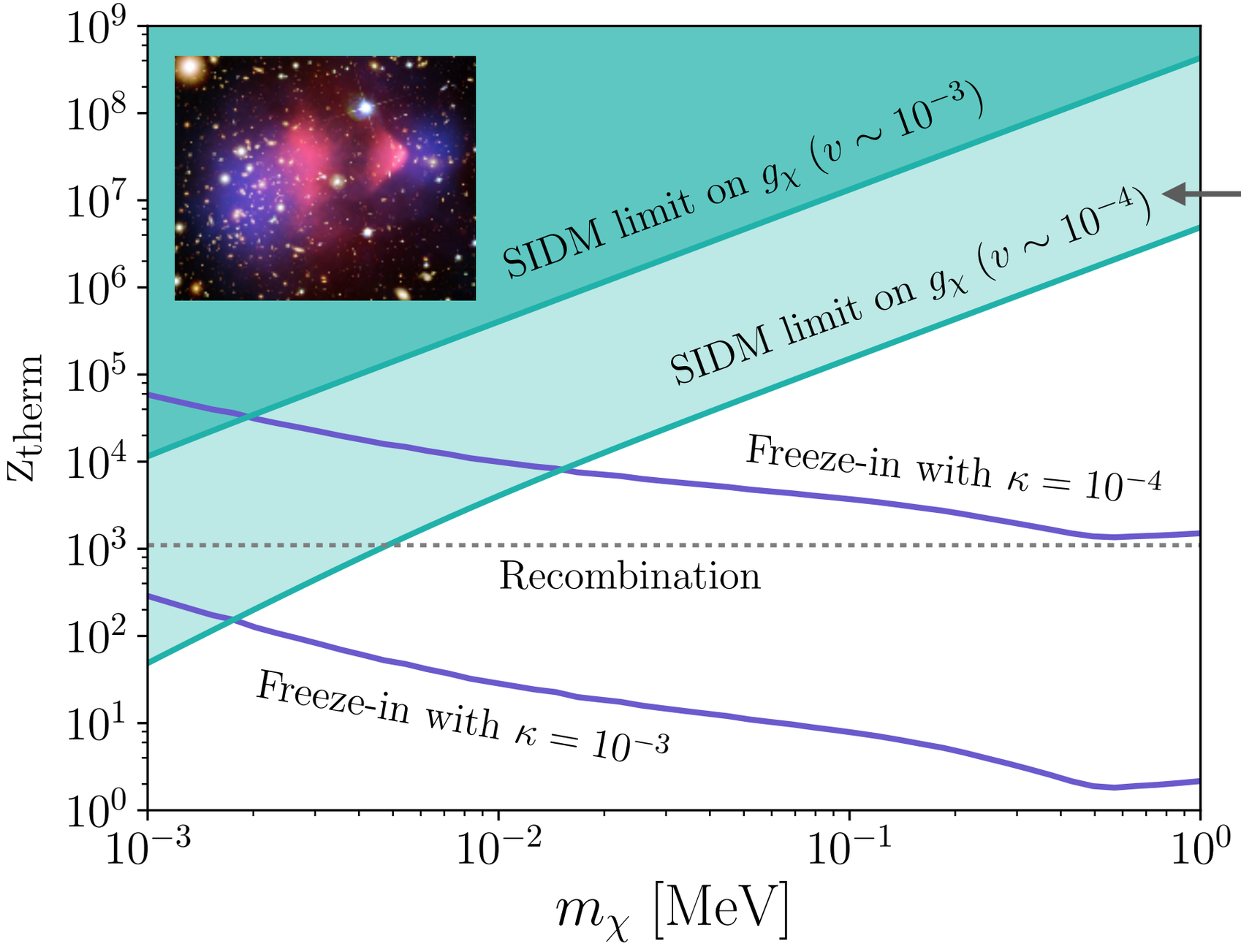
DEALING WITH NON-THERMAL PHASE SPACE



DM can optionally thermalize in its own sector if there are self-interactions (dark photon scattering)

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

DARK MATTER SELF-THERMALIZATION



*highlights need for simulators, observers to better understand internal dynamics of dwarf galaxies

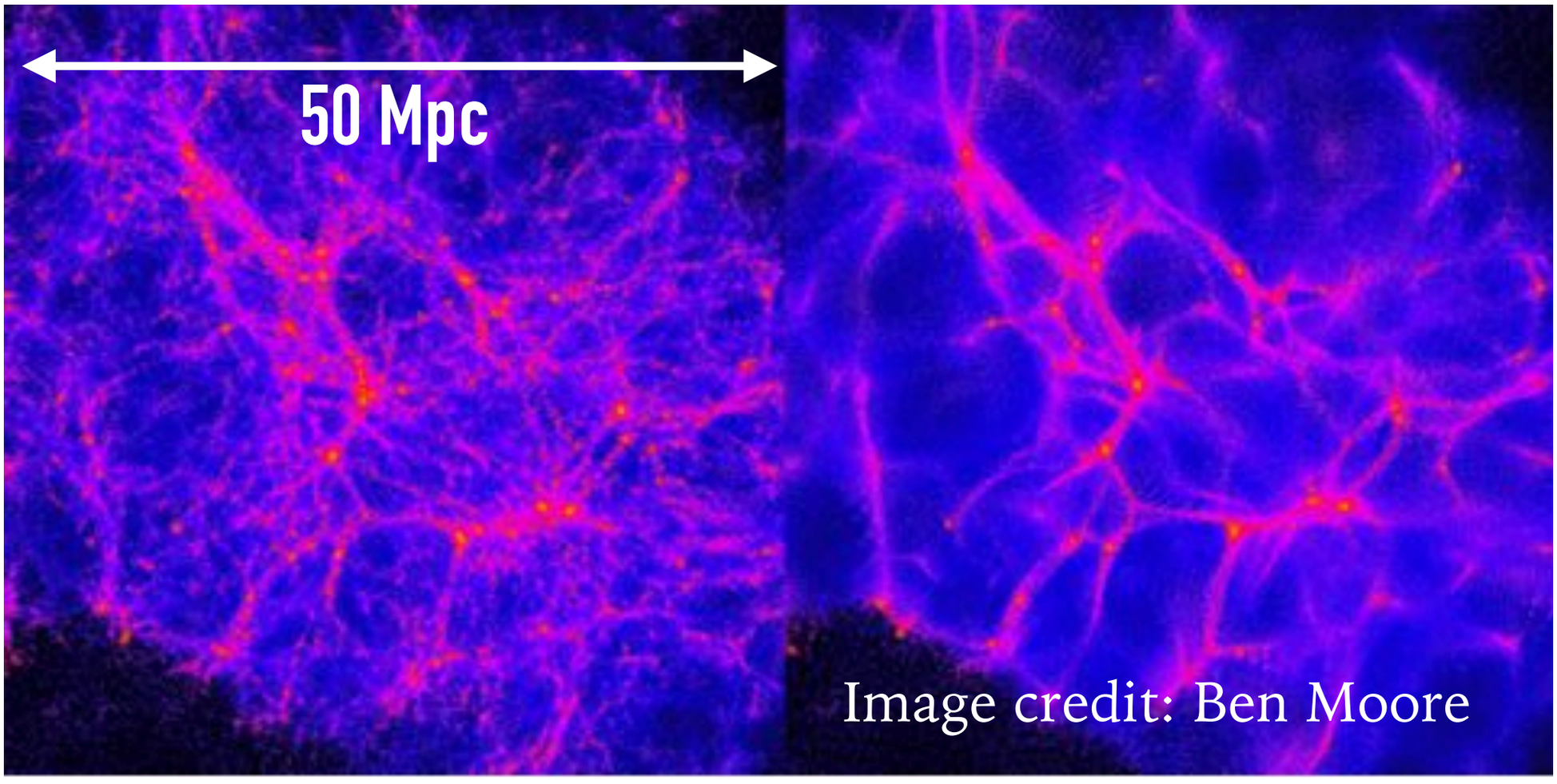
Dvorkin, Lin, **KS** (PRD 2019)

PHASE SPACE IMPLICATIONS FOR COSMOLOGY

Dvorkin, Lin, **KS** 2011.08186

VELOCITY EFFECTS ON CLUSTERING (WARM DARK MATTER EXAMPLE)

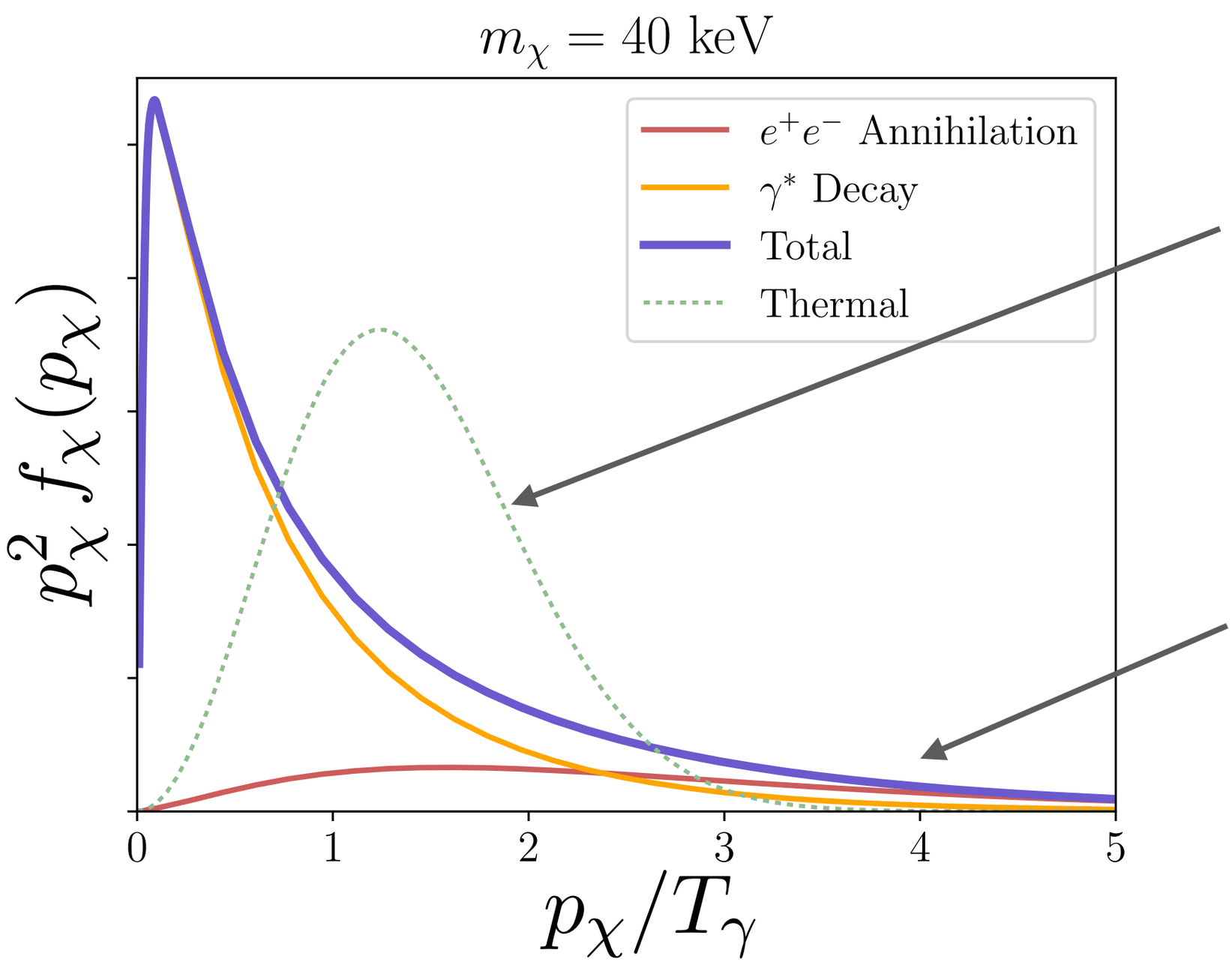
Warm dark matter initial conditions: $\Omega_\chi = \frac{m_\chi}{94\ \mathrm{eV}} \frac{11}{4} \left(\frac{T_\chi}{T_\gamma}\right)^3$



← Heavier

Lighter →

GRAVITATIONAL CLUSTERING AND PHASE SPACE

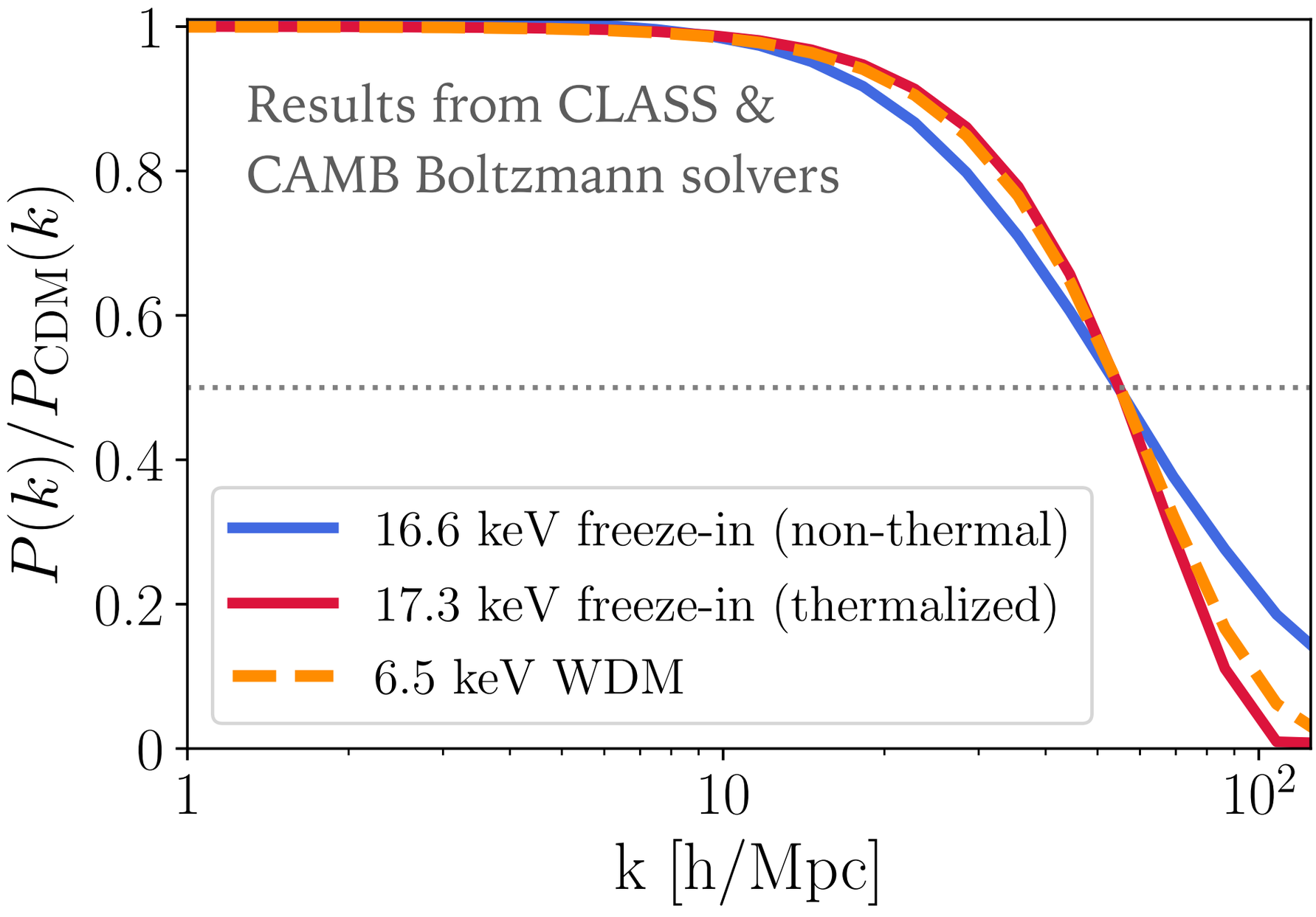


If DM can self-thermalize then it must have a nontrivial sound speed and can't stream freely

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

Dvorkin, Lin, **KS** 2011.08186

MAPPING WDM CONSTRAINTS TO FREEZE-IN CONSTRAINTS



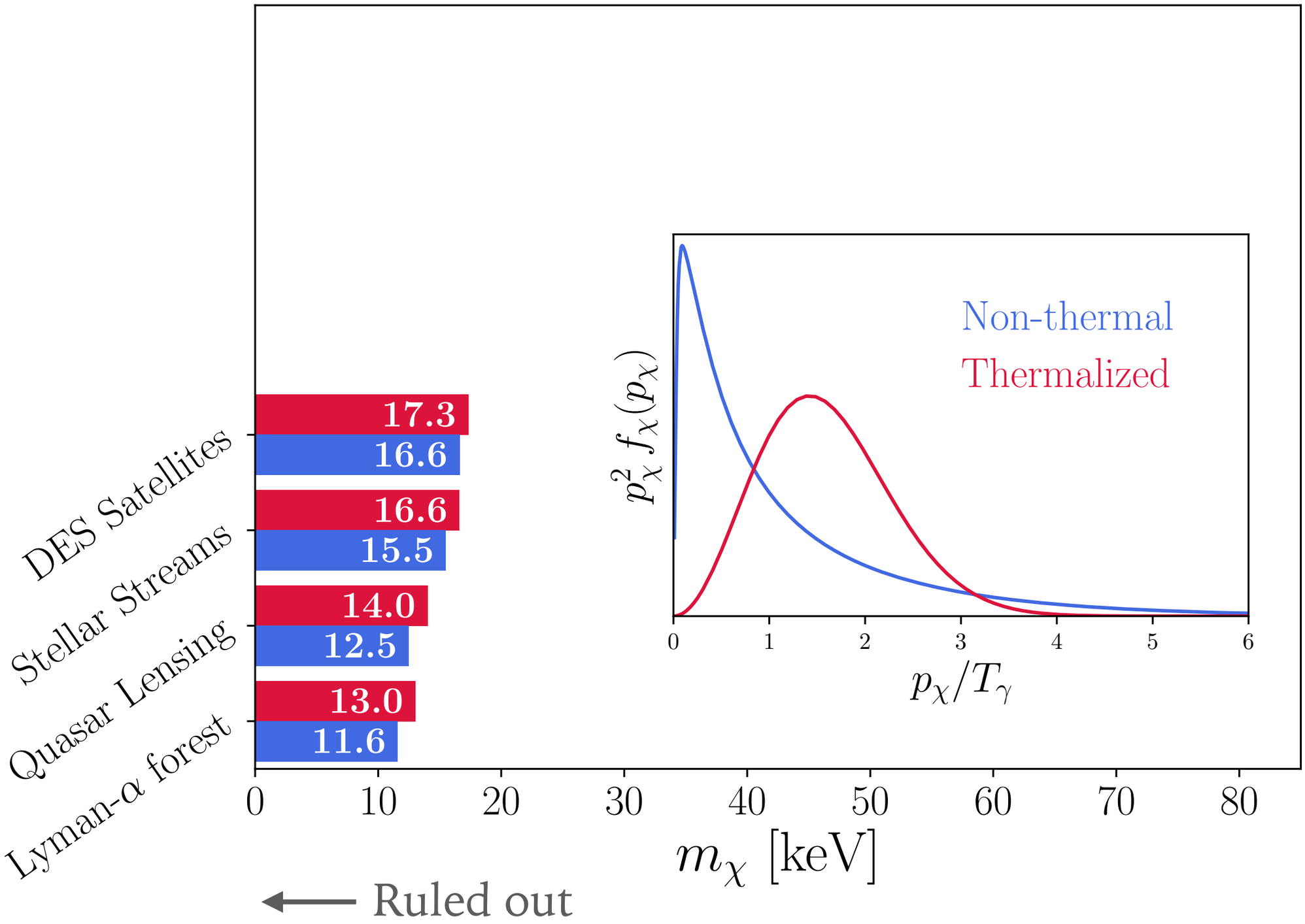
Dvorkin, Lin, **KS** 2011.08186

MATCHING PROBES OF WDM TO FREEZE-IN

- Procedure of matching at half-mode scale:
  - Has been tested for Lyman-alpha constraints, is conservative for shallow suppression
  - Is only an estimate for subhalo-based constraints, simulations needed!*
- Lots of recent & upcoming advances in observational probes of small scale structure formation**
  - More satellite galaxies (e.g. DES collaboration, see Nadler et al.)
  - Lensing (e.g. Gilman et al., Hsueh et al.)
  - Stellar streams (e.g. Banik et al.)
  - Combinations of the above with e.g. Rubin Observatory
  - Stronger Lyman-alpha limits (e.g. Rogers & Peiris)
  - 21 cm (e.g. Muñoz et al.)

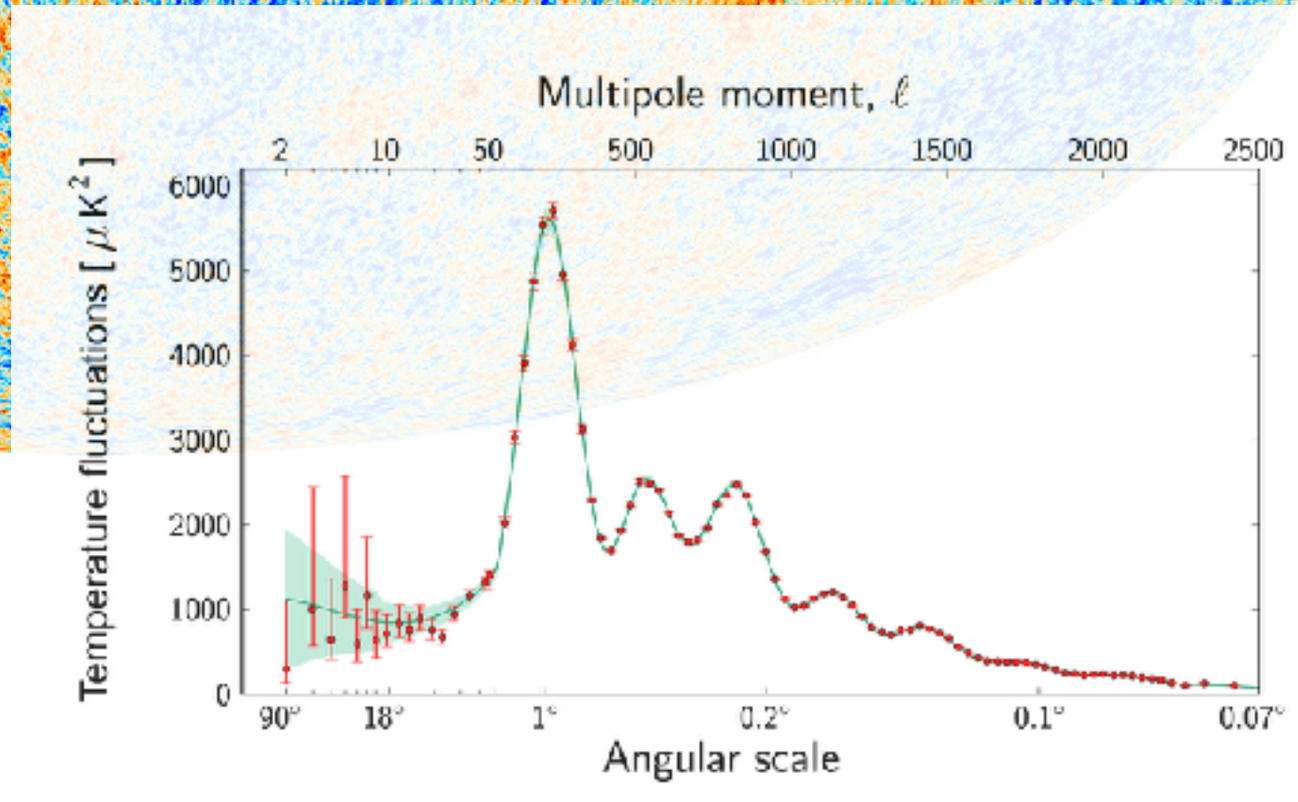
*highlights need for simulators
**highlights need for broad range of observers, simulators, data analysts

COSMOLOGICAL CONSTRAINTS ON FREEZE-IN

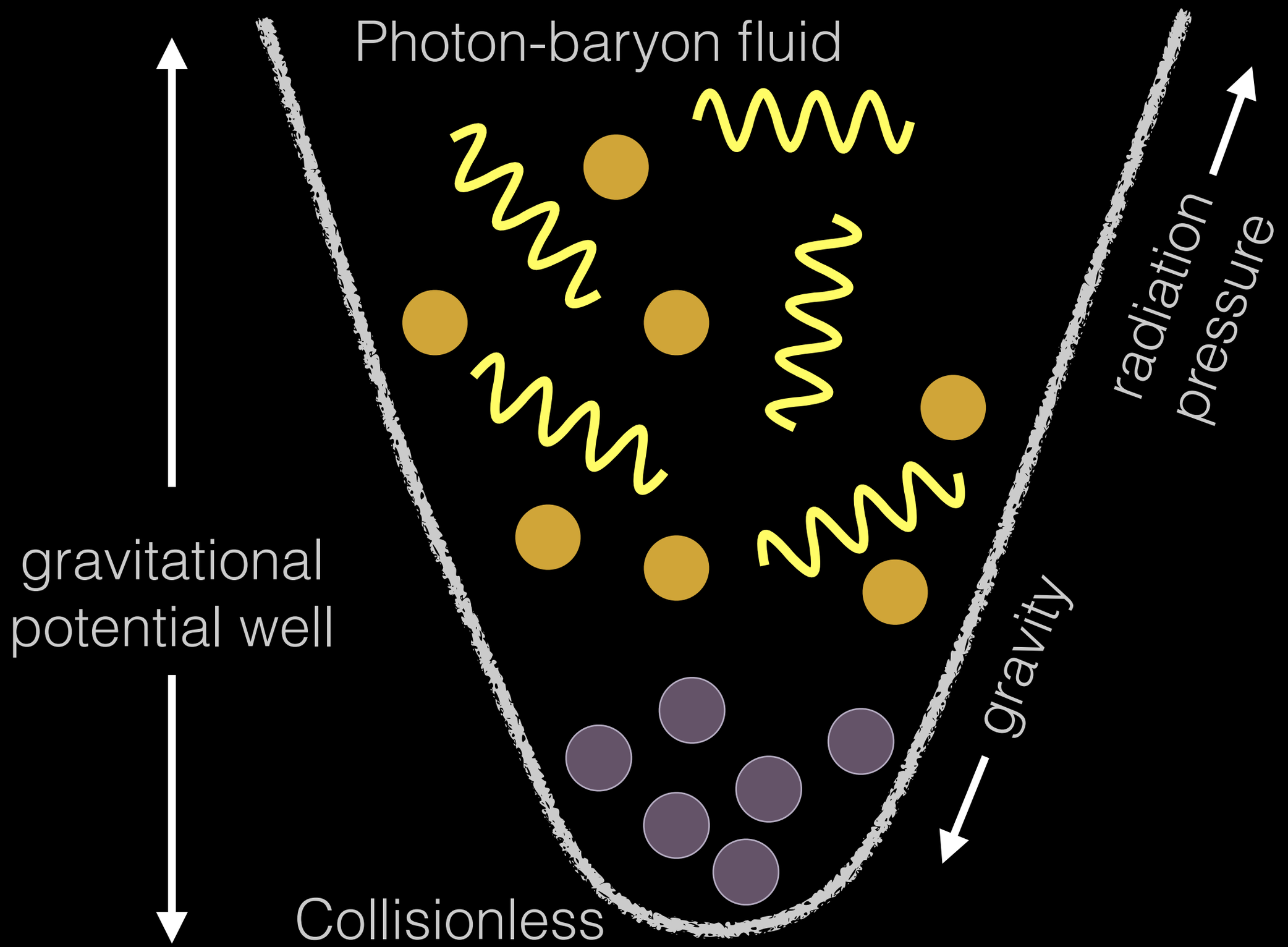


Dvorkin, Lin, **KS** 2011.08186

DARK MATTER–BARYON DRAG APPARENT IN THE CMB



Planck Collaboration


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

Dvorkin et al. 2014

Photon-baryon fluid

gravitational
potential well

radiation
pressure

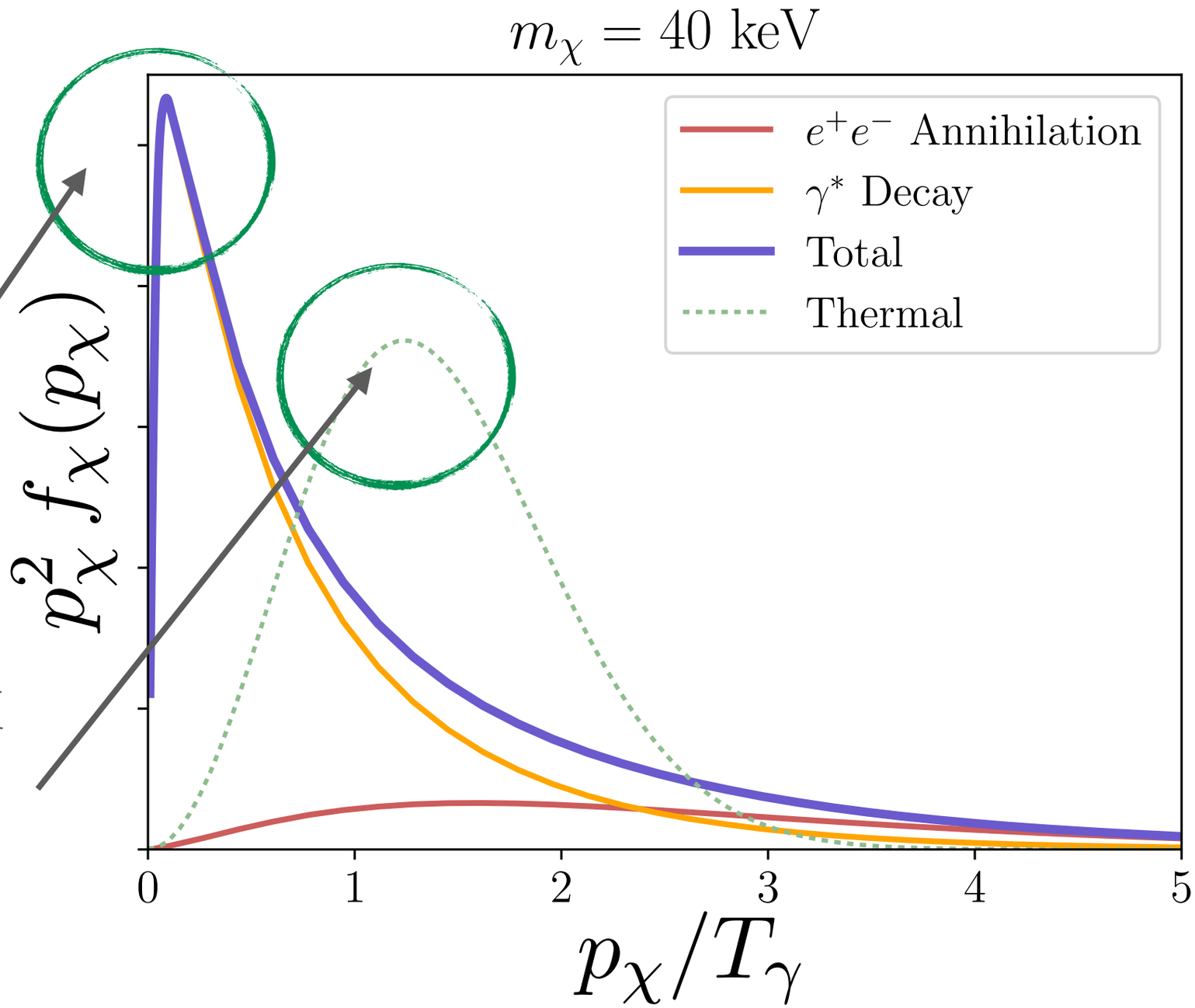
gravity

Partly collisional
dark matter

Scattering ~v^{-4}
for freeze-in

DM-BARYON SCATTERING AND PHASE SPACE

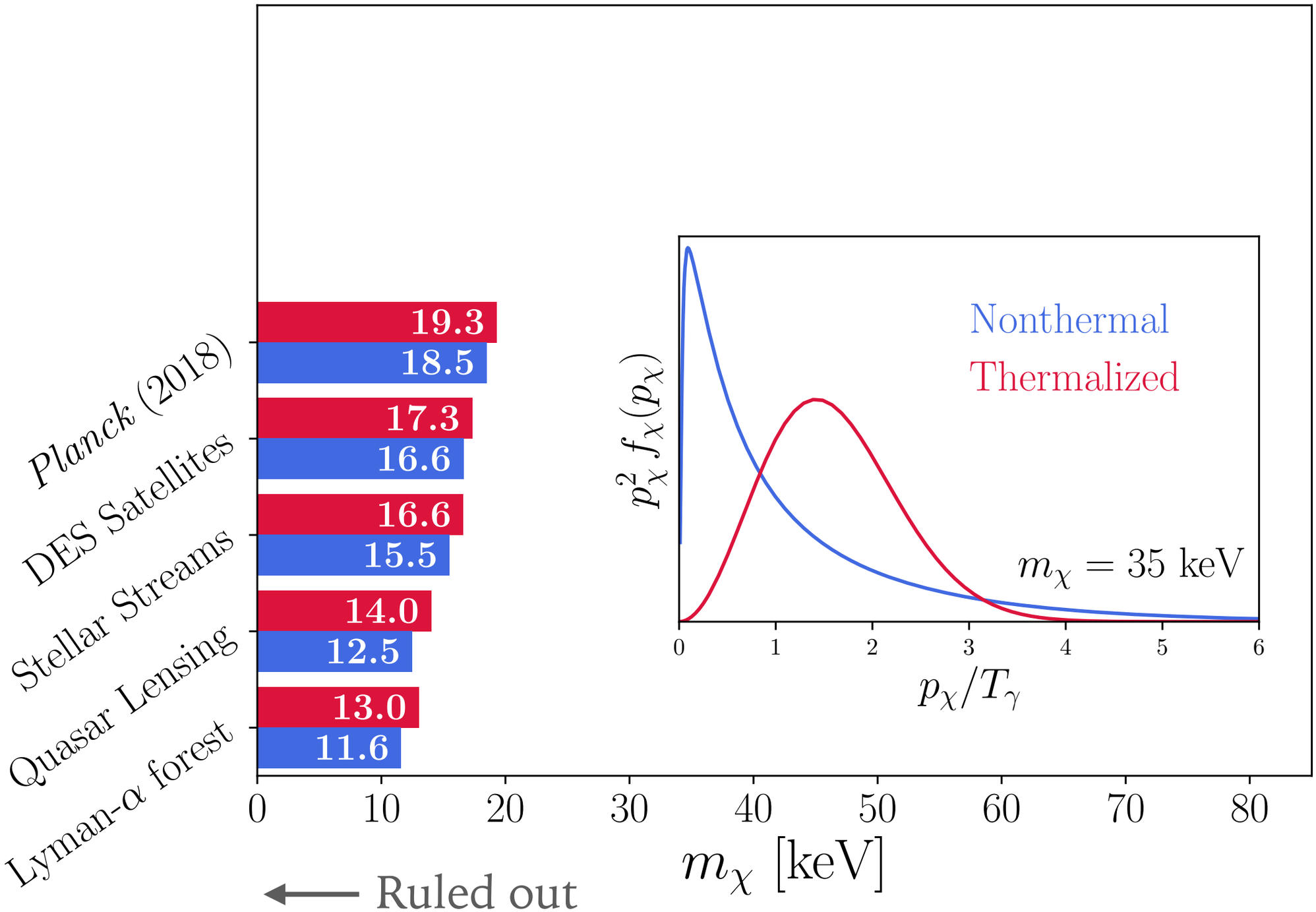
*highlights need for physical cosmologists



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

Dvorkin, Lin, **KS** 2011.08186

COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



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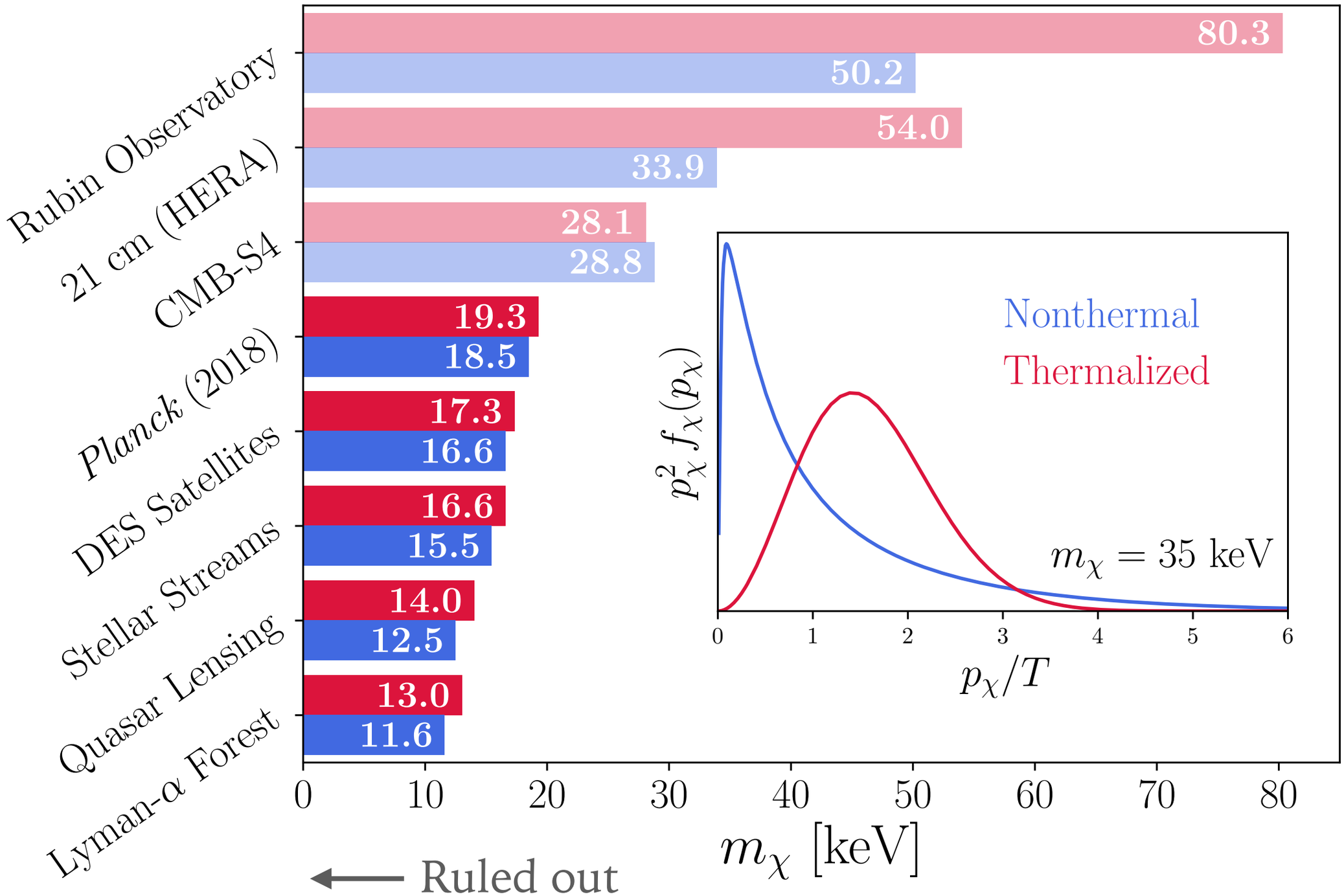
COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



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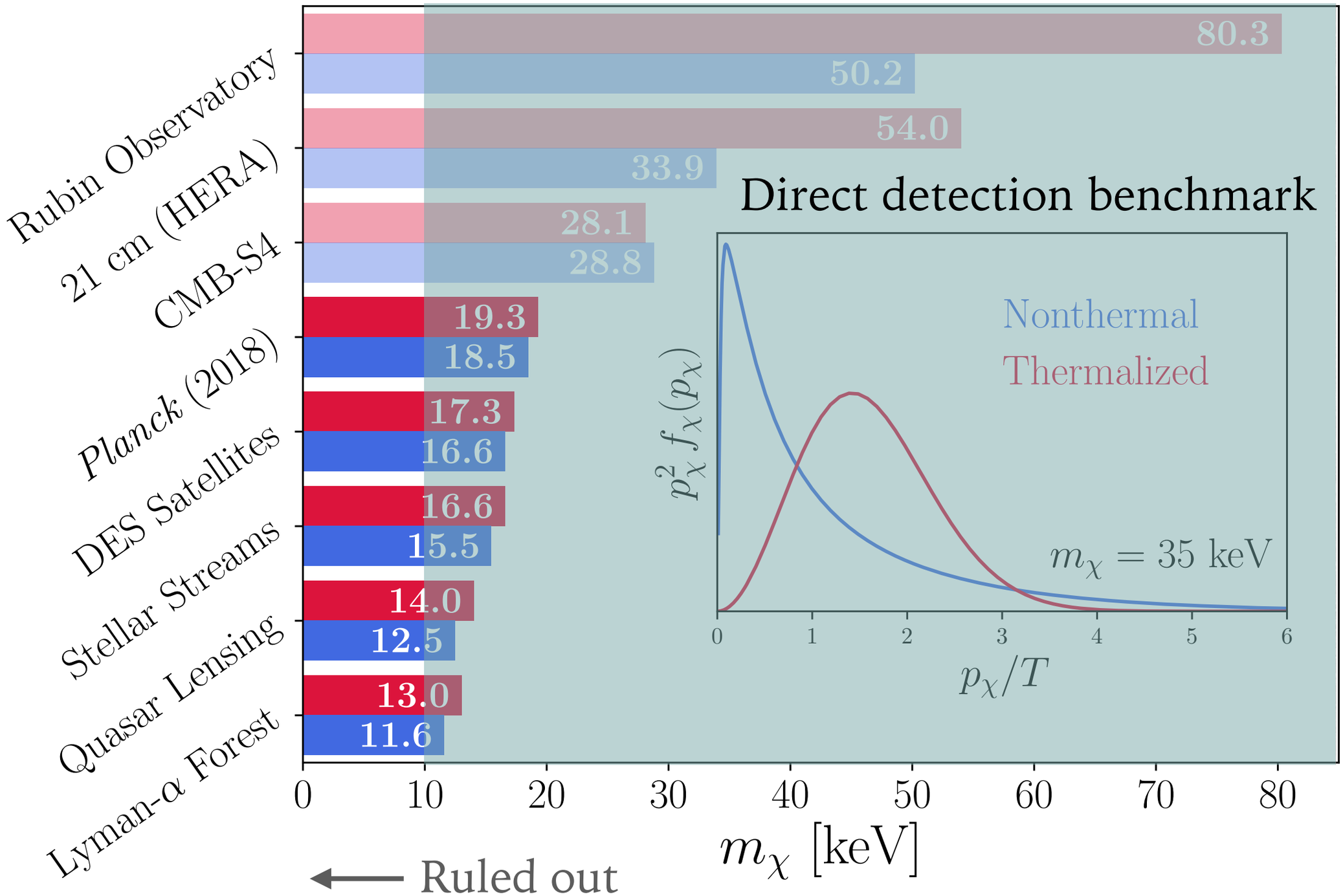
COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



Dvorkin, Lin, **KS** 2011.08186

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 in interdisciplinary way?