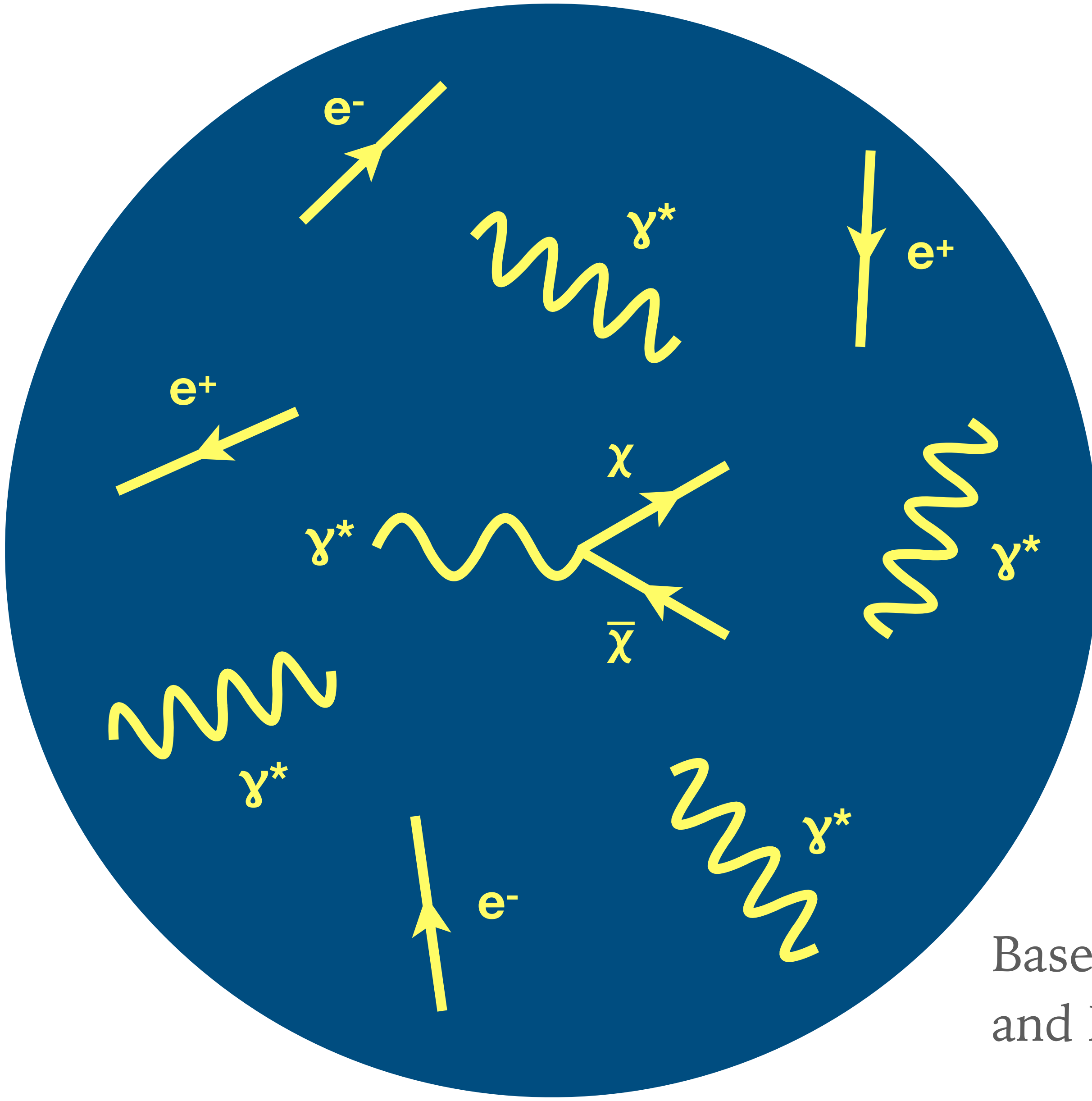


MAKING DARK MATTER OUT OF LIGHT: THE COSMOLOGY OF SUB-MEV FREEZE-IN

Based on Dvorkin, Lin, **KS** in prep. (2011.xxxxx)
and Dvorkin, Lin, **KS** PRD (Editors' Suggestion, 2019)

Katelin Schutz, MIT→McGill

IPMU APEC Seminar

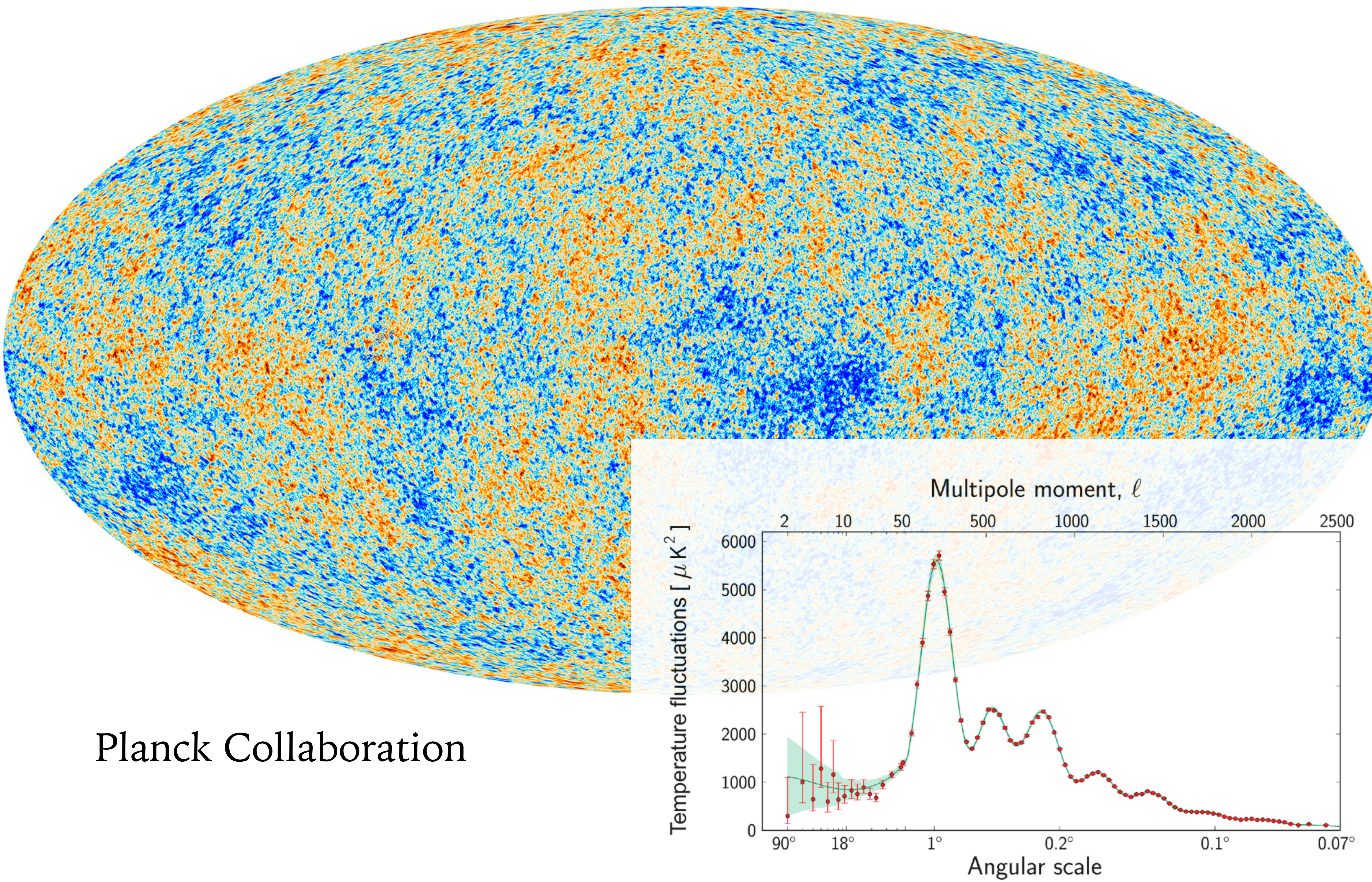
11/4/2020

DARK MATTER EXISTS AND IS DARK*


MERGING GALAXY CLUSTERS
NORMAL MATTER GETS HOT
SEEN IN X-RAYS
MASS SEEN WITH GRAVITATIONAL LENSING


LARGE SCALE STRUCTURE
THINGS DON'T CLUSTER AS WELL WHEN THEY ARE MADE OF ONLY BARYONS

CMB & CMB LENSING

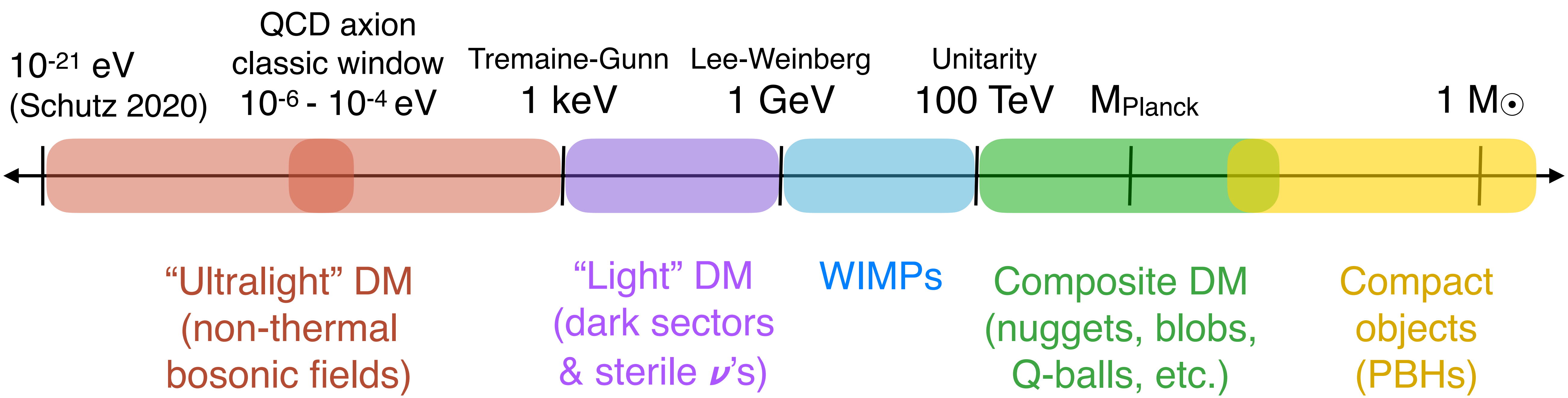


Planck Collaboration

WHAT IS THE DARK MATTER?

DARK MATTER MASS

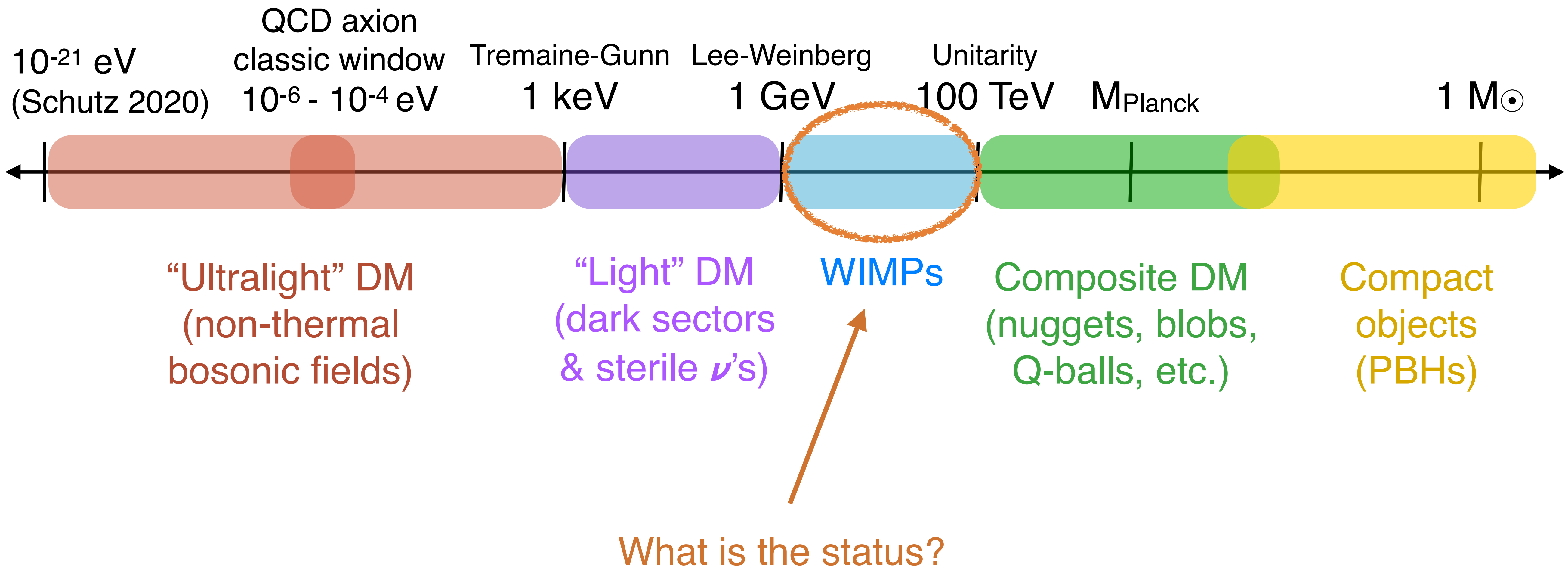
(not to scale)



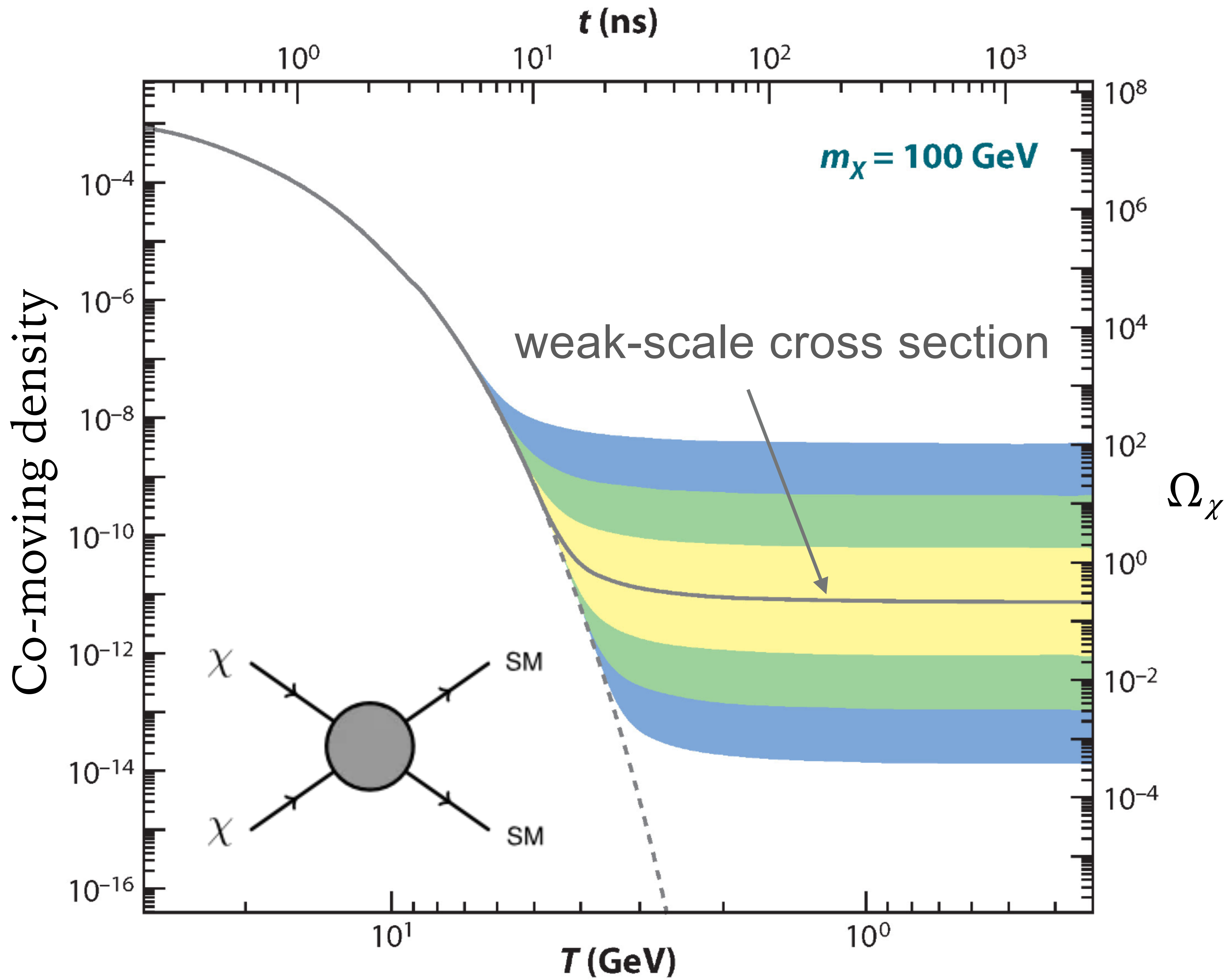
➤ Many possibilities spanning 90+ orders of magnitude!

DARK MATTER MASS

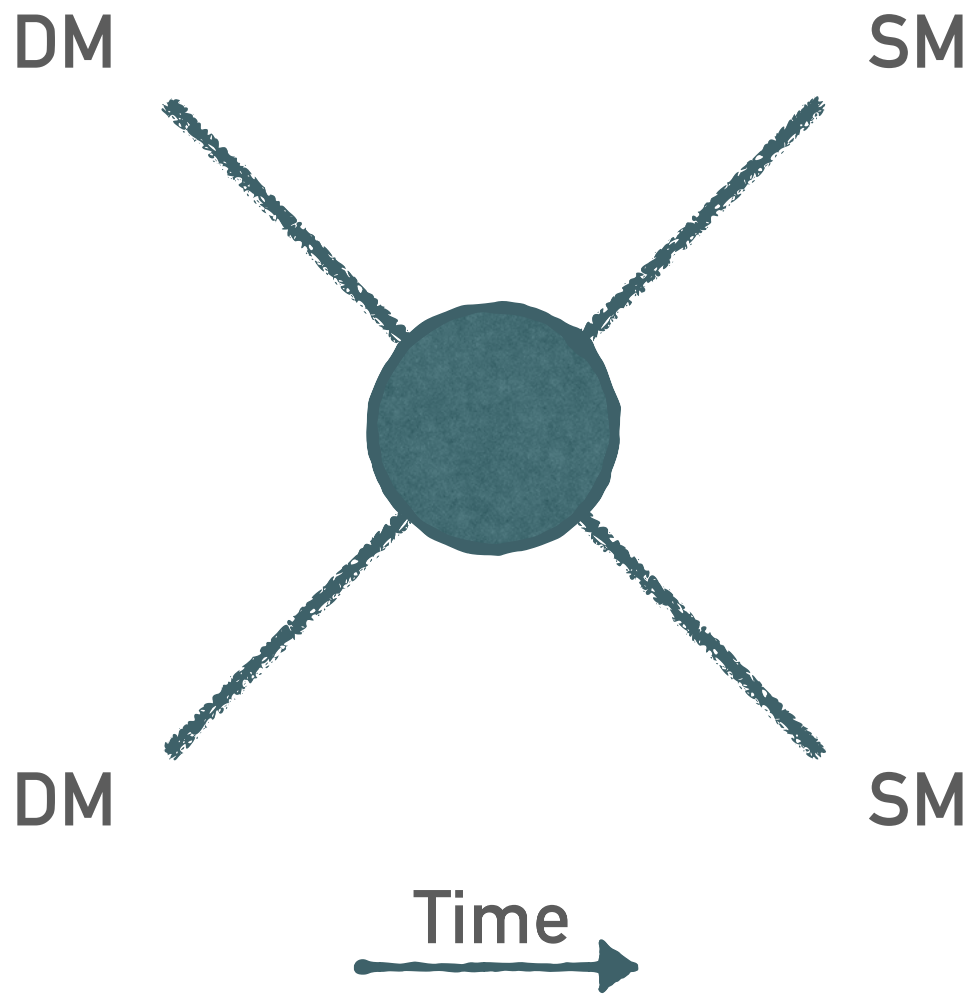
(not to scale)



THERMAL DARK MATTER CANDIDATE: WIMPS (FREEZE-OUT)



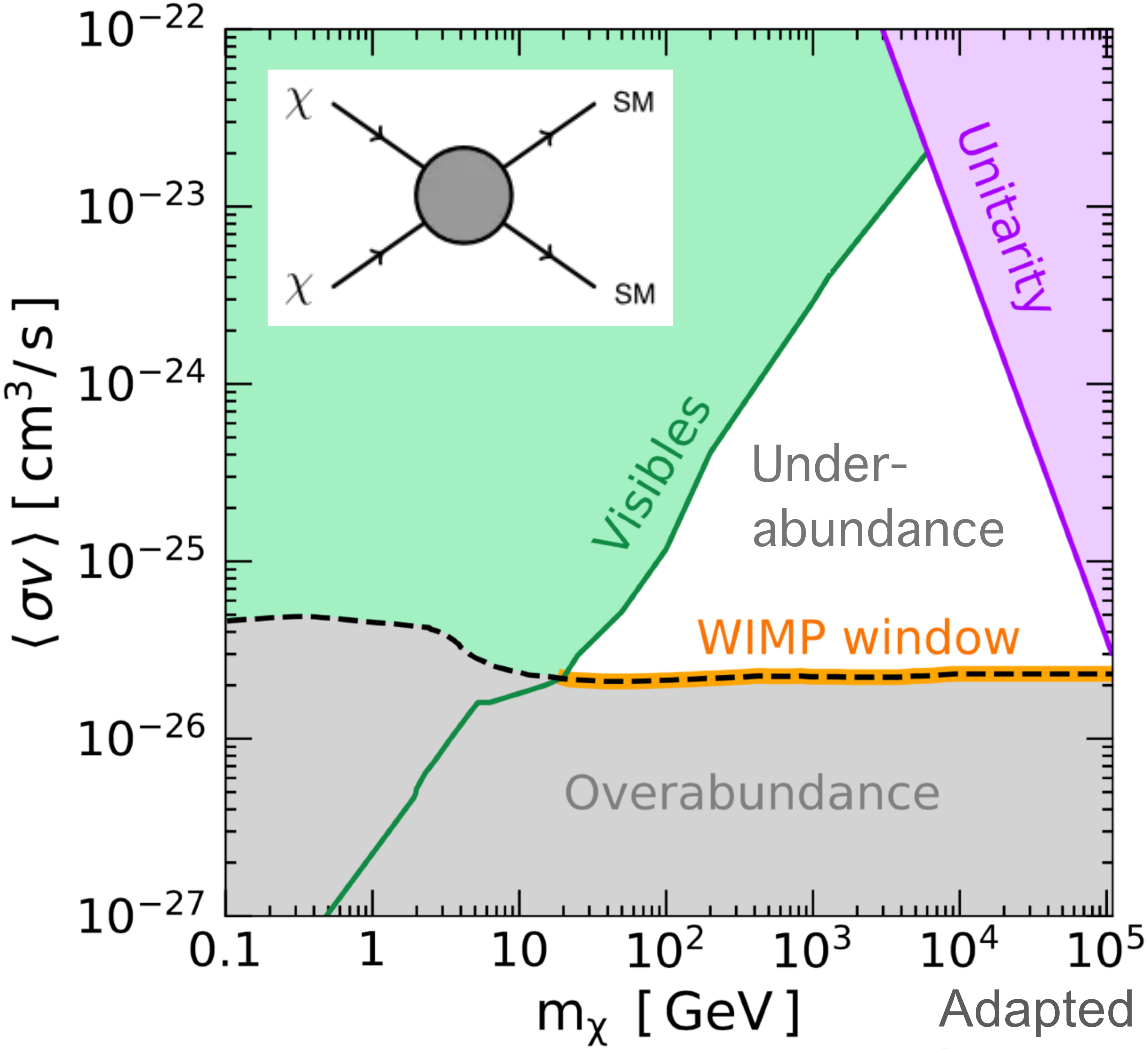
Adapted from Jonathan Feng



Thermal freeze-out

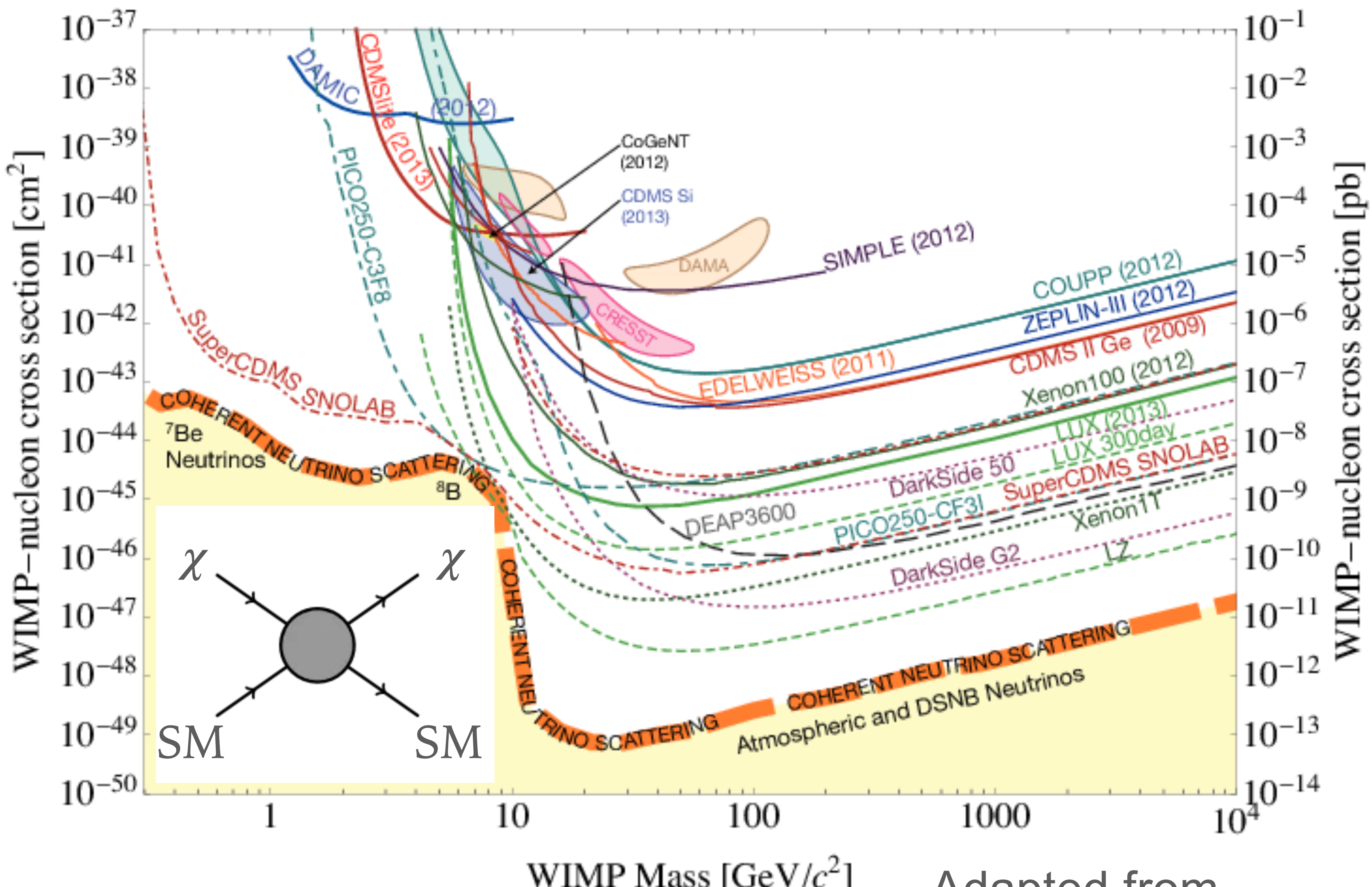
- ☑ Relic abundance is independent of initial conditions of reheating after inflation (as long as DM is in the bath)
- ☑ Fine with BBN and N_{eff} (above masses of a few MeV)
- ☑ Relevant couplings can be experimentally probed

WIMP (THERMAL FREEZE-OUT) INDIRECT DETECTION WINDOW



Adapted from
Leane et al. (2018)

WIMP DIRECT DETECTION (MODEL DEPENDENT)



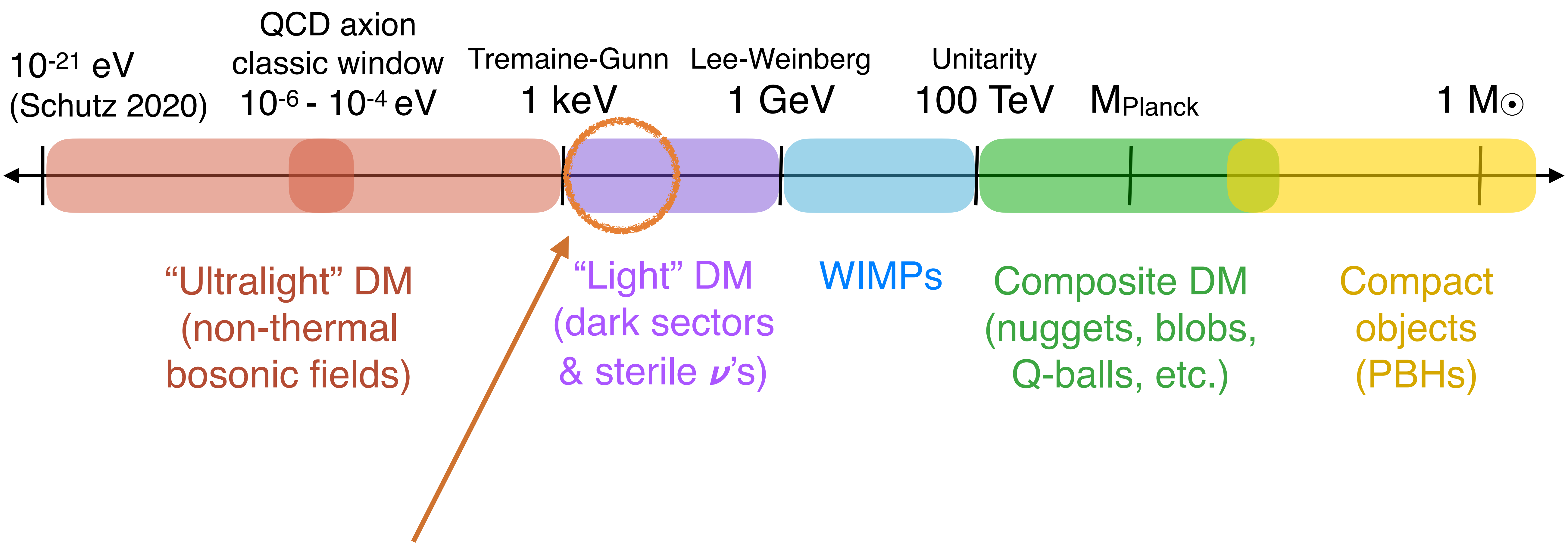
Adapted from Snowmass 2013 report

GOING BEYOND THE WIMP PARADIGM

- The WIMP was only one thermal scenario, emergence of the weak scale (WIMP miracle) could well be a coincidence of nature (e.g. "who ordered the muon?")
- The SM isn't minimal so why should the DM be minimal?
- Lots of new technologies and observations will allow us to probe different kinds of models

DARK MATTER MASS

(not to scale)

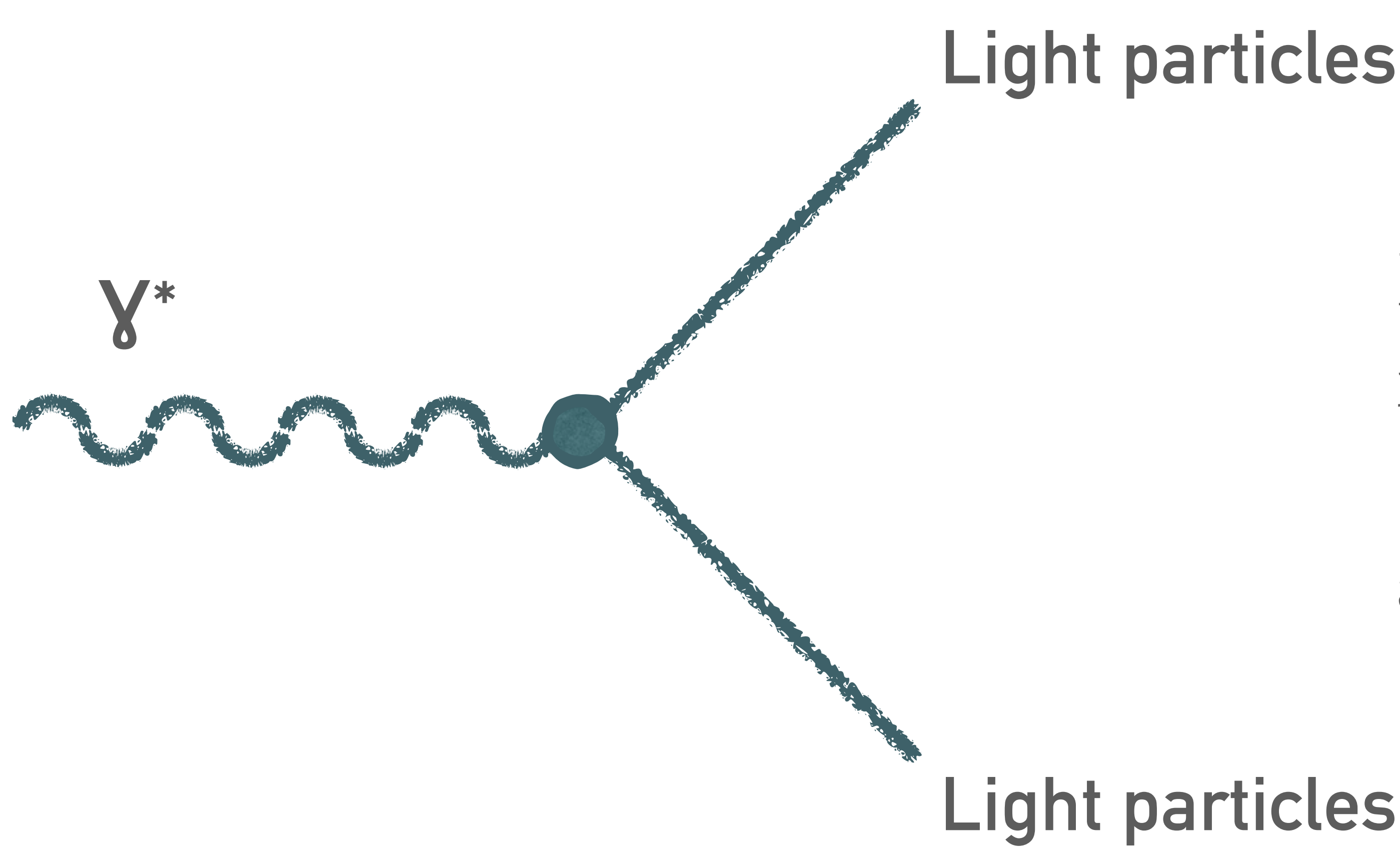


Deep dive on this mass range
today, emphasize power of
diverse astrophysical systems

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

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

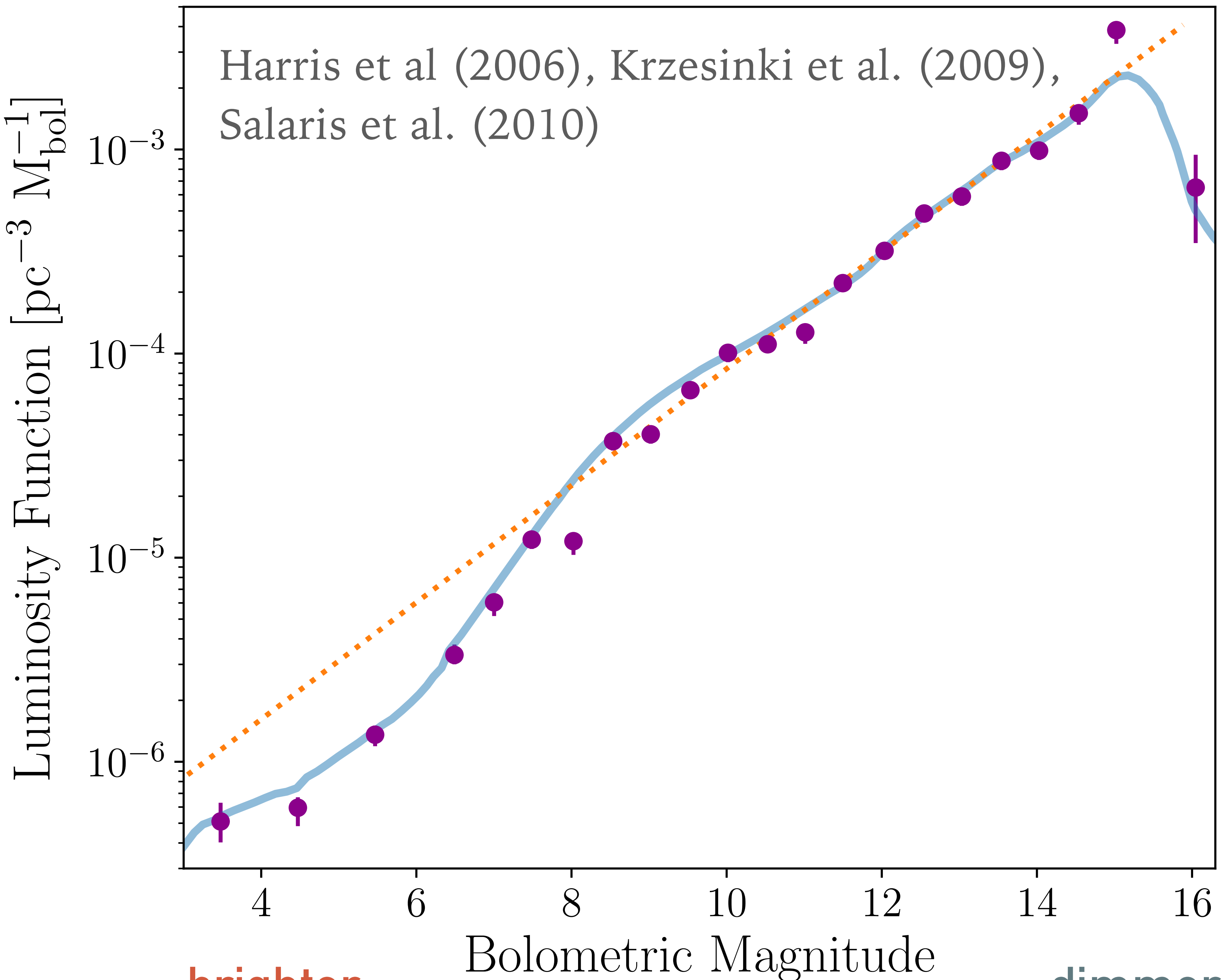
PHOTONS CAN DECAY IN A MEDIUM TO WEAKLY COUPLED PARTICLES



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)

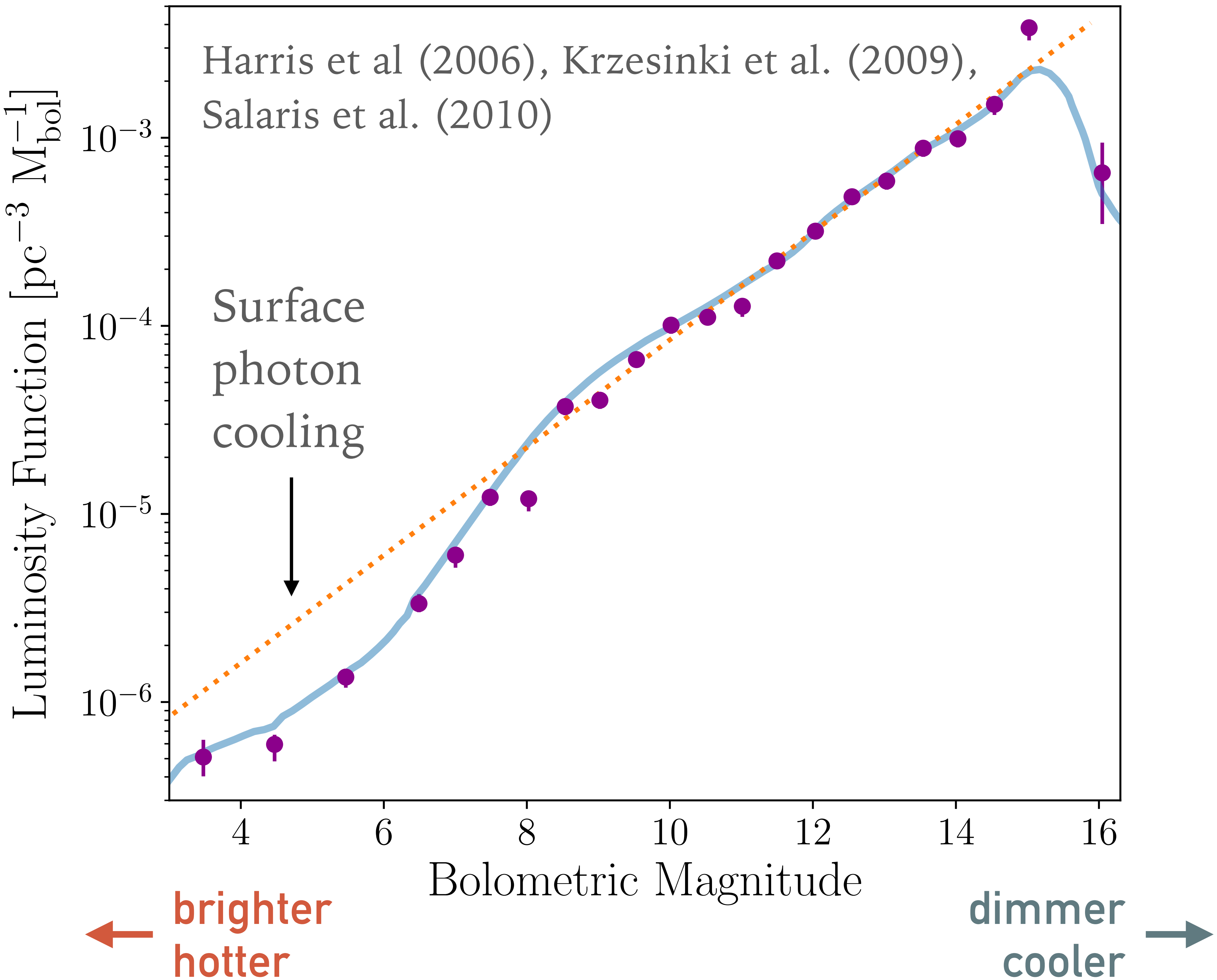
WHITE DWARF COOLING AND POPULATION



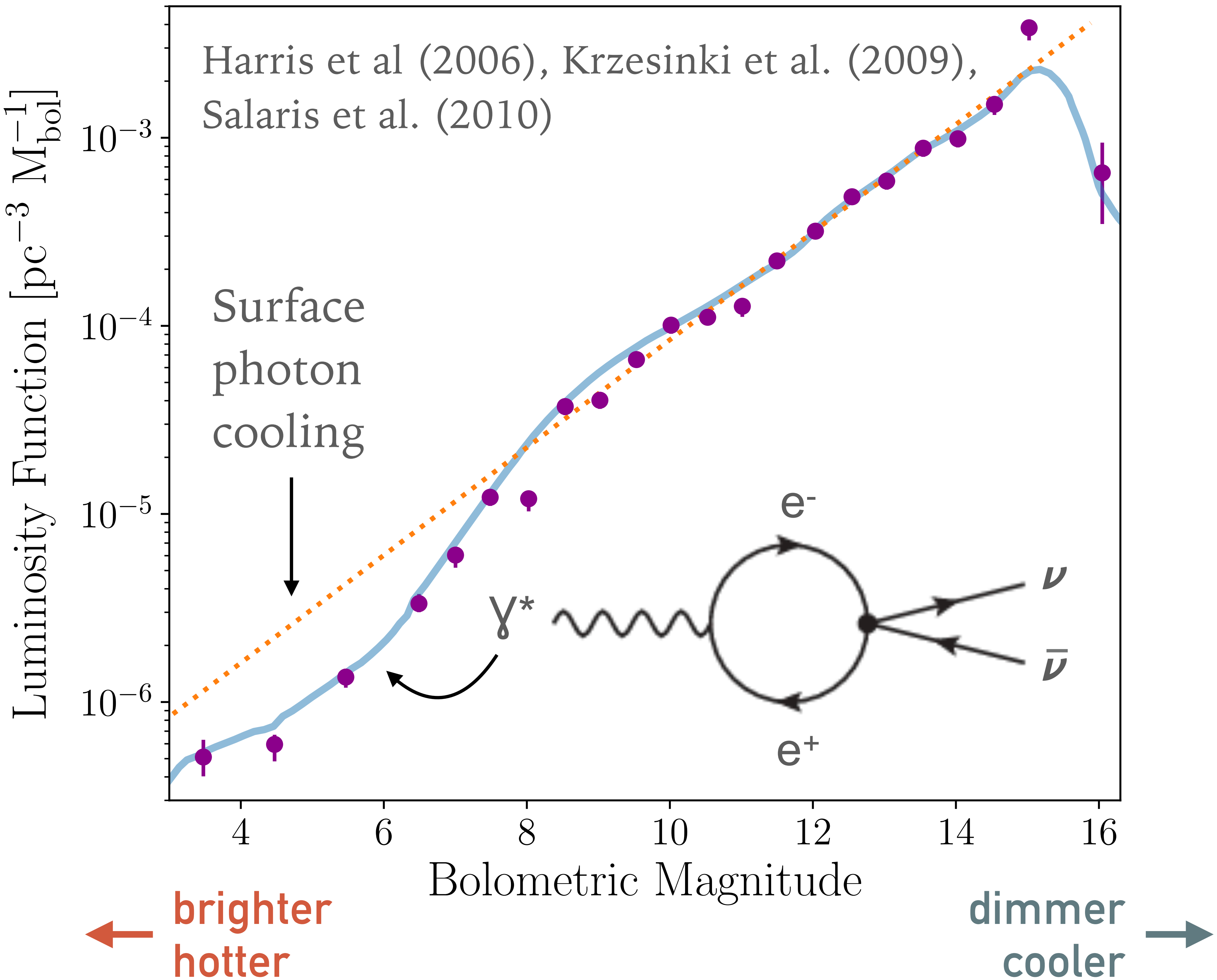
brighter
hotter

dimmer
cooler

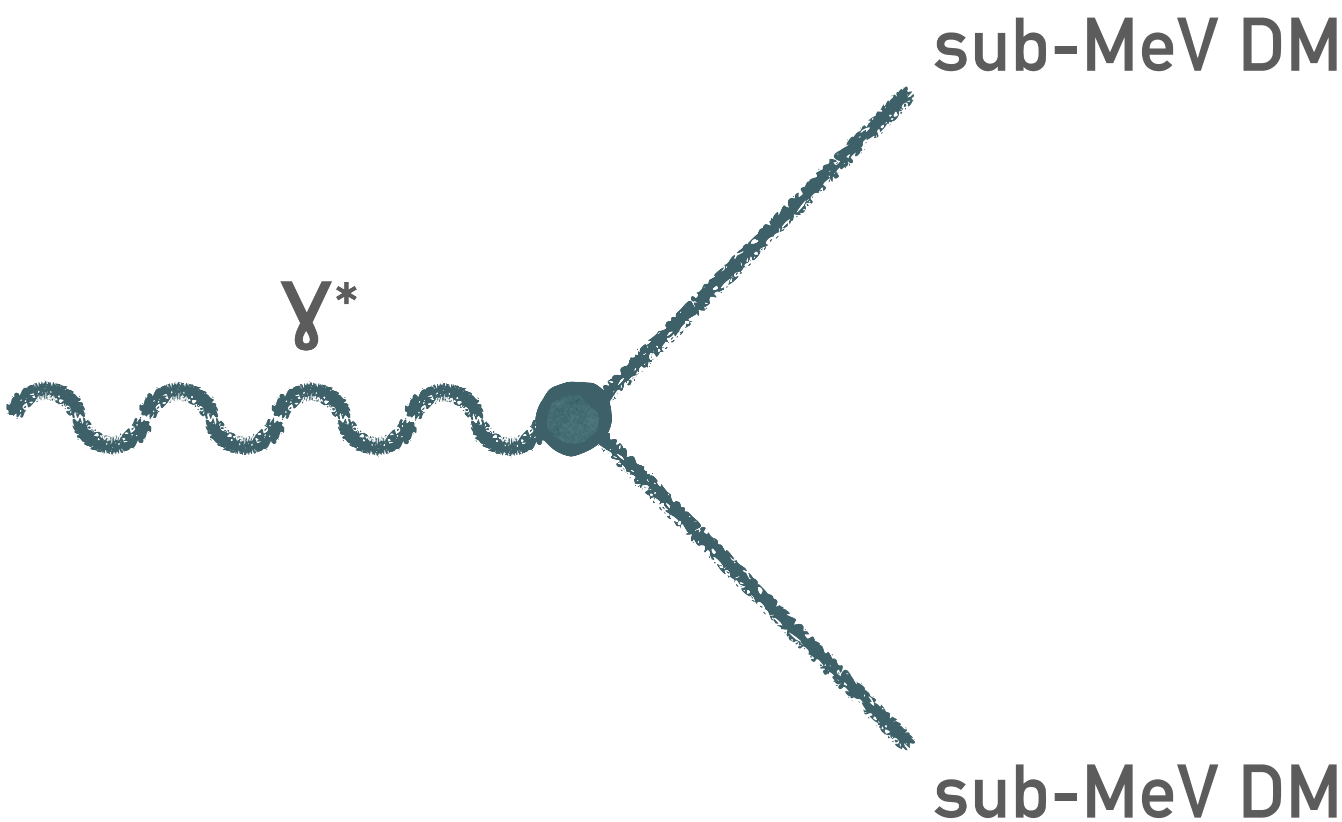
WHITE DWARF COOLING AND POPULATION



WHITE DWARF COOLING AND POPULATION

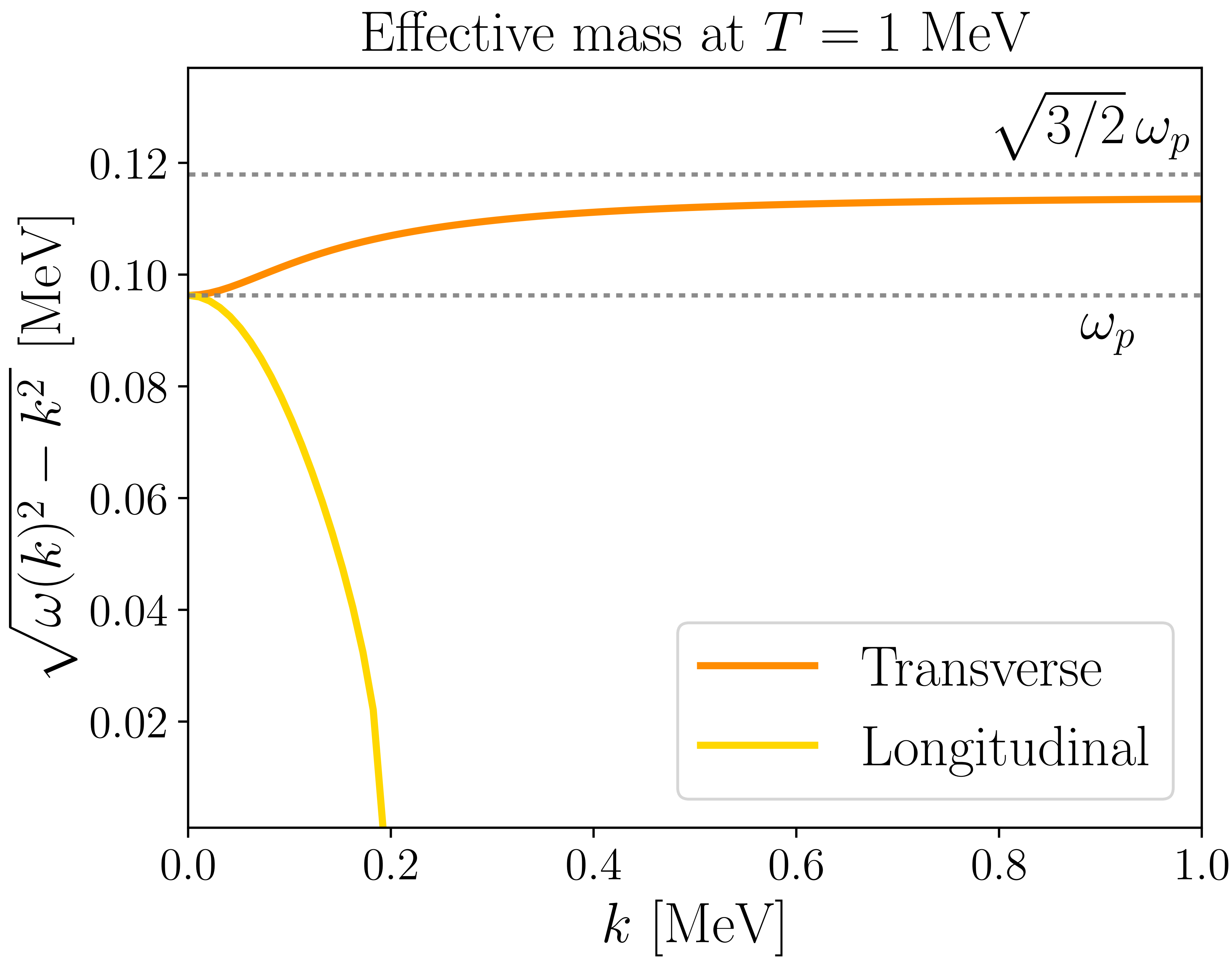


PLASMON DARK MATTER FREEZE-IN



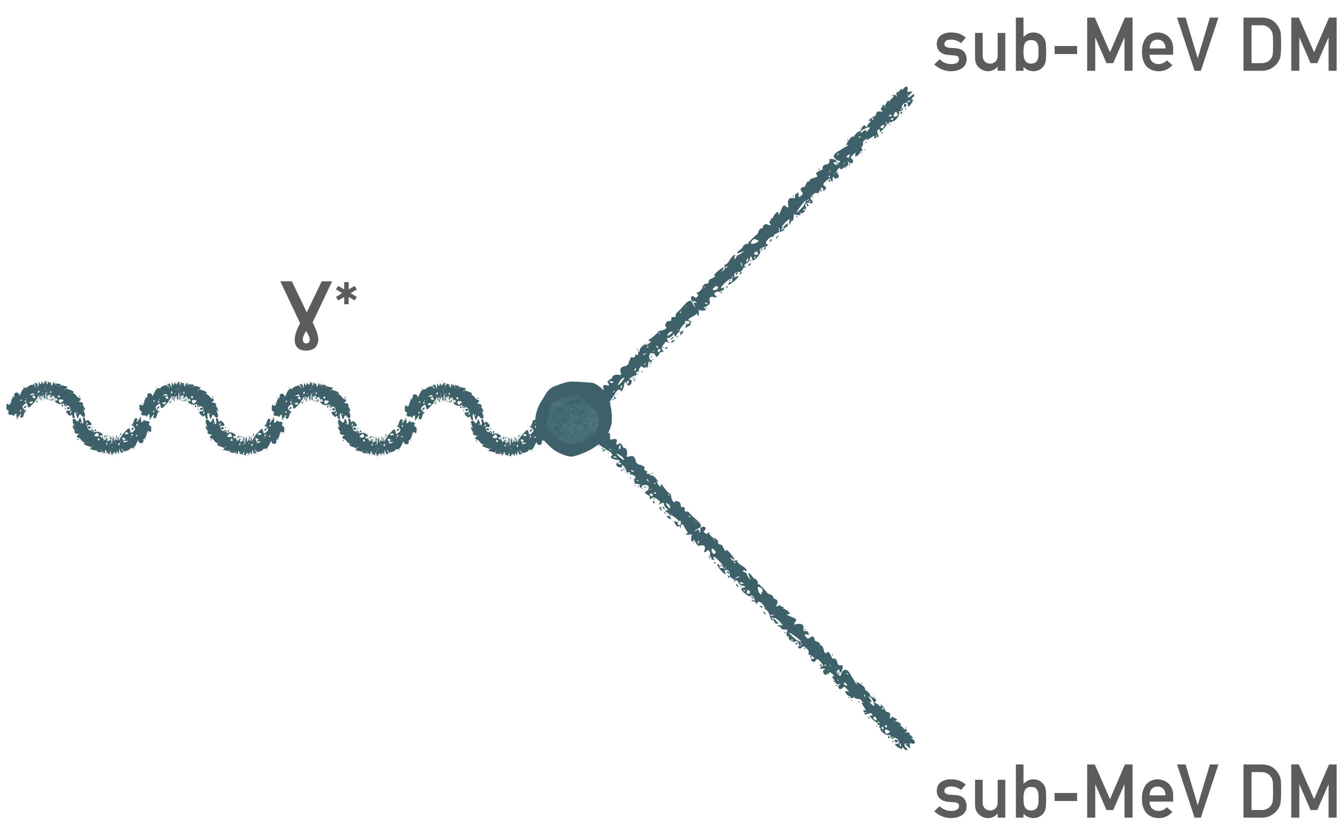
This process makes dark matter efficiently in the early Universe, which is a hot, relativistic plasma!

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



Dvorkin, Lin, KS 1902.08623

PLASMON DARK MATTER FREEZE-IN



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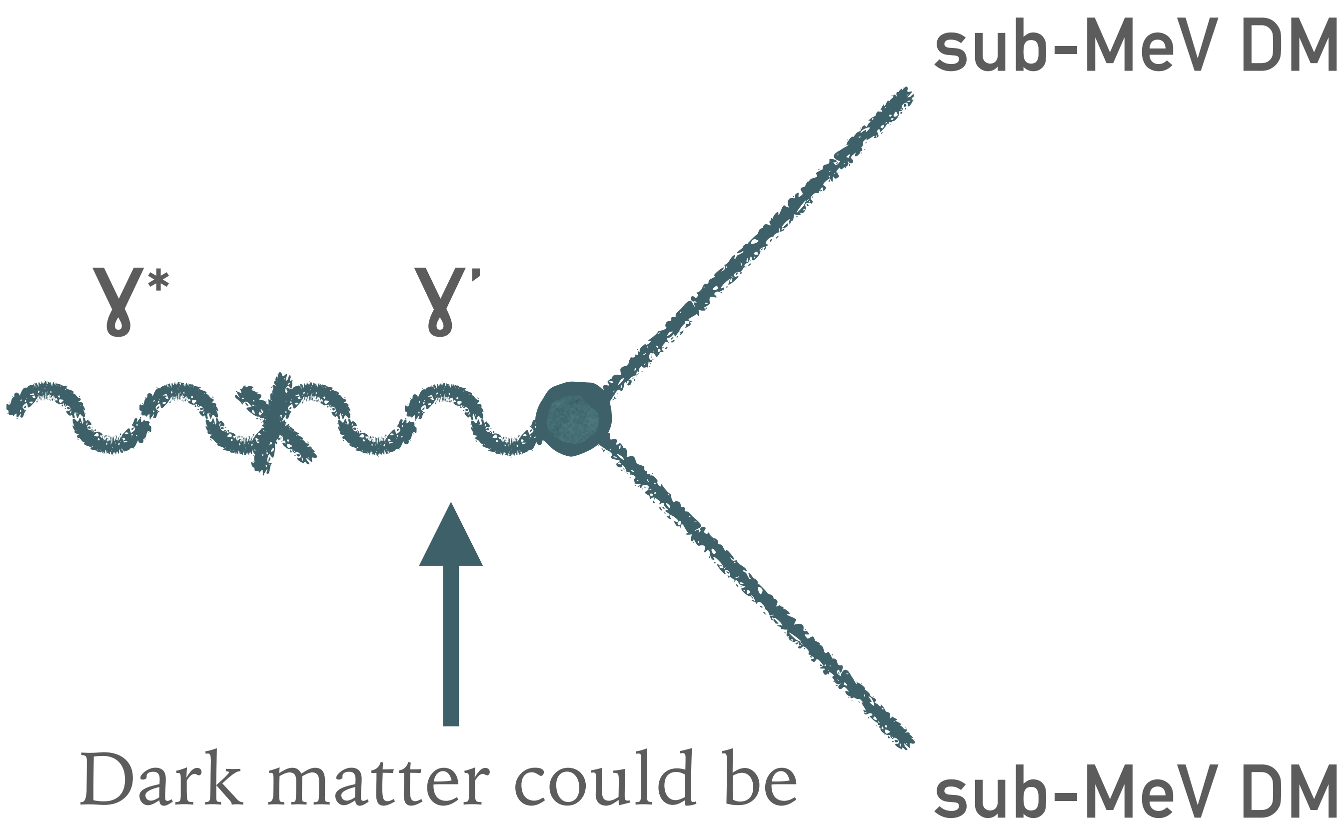
PLASMON DARK MATTER FREEZE-IN

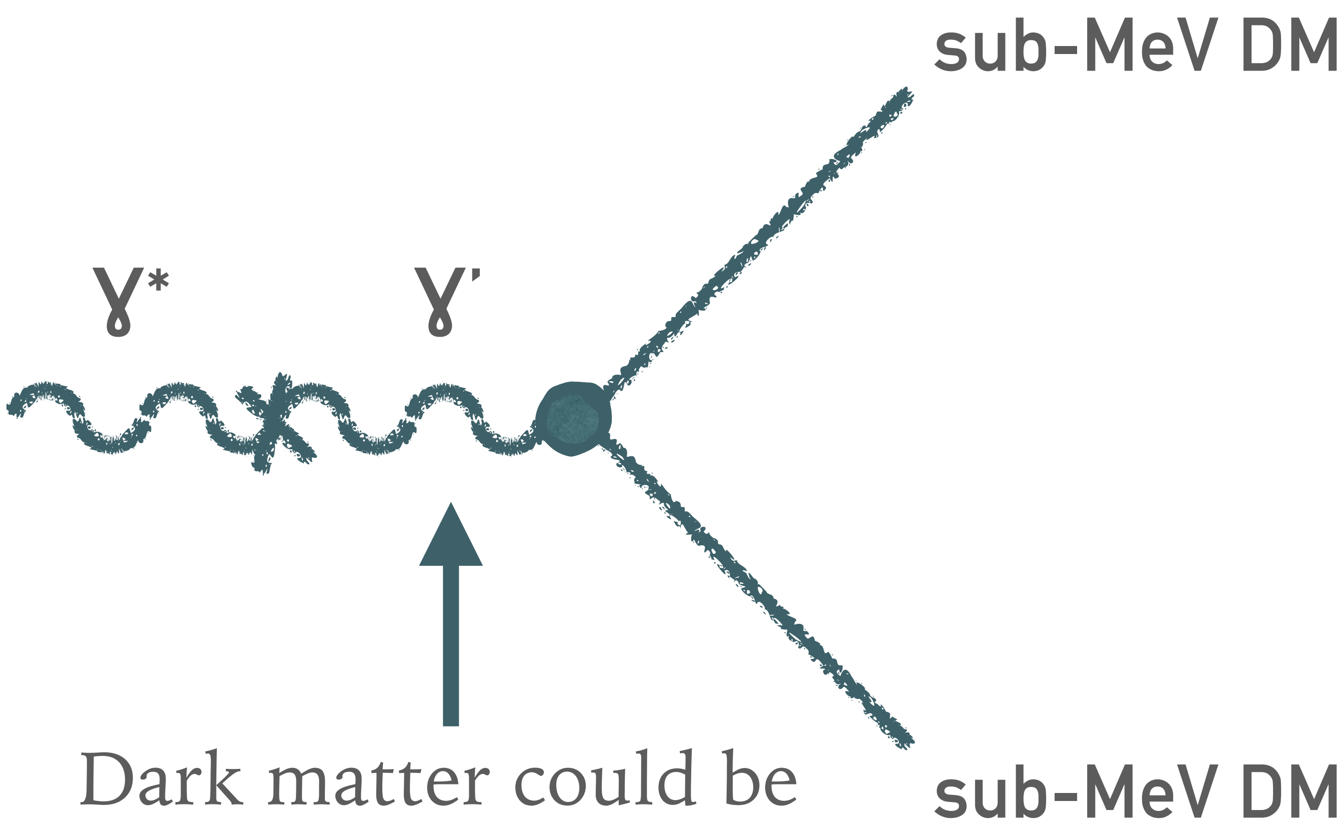


Dark matter could be charged under dark version of E&M with a "dark photon"

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

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

PLASMON DARK MATTER FREEZE-IN



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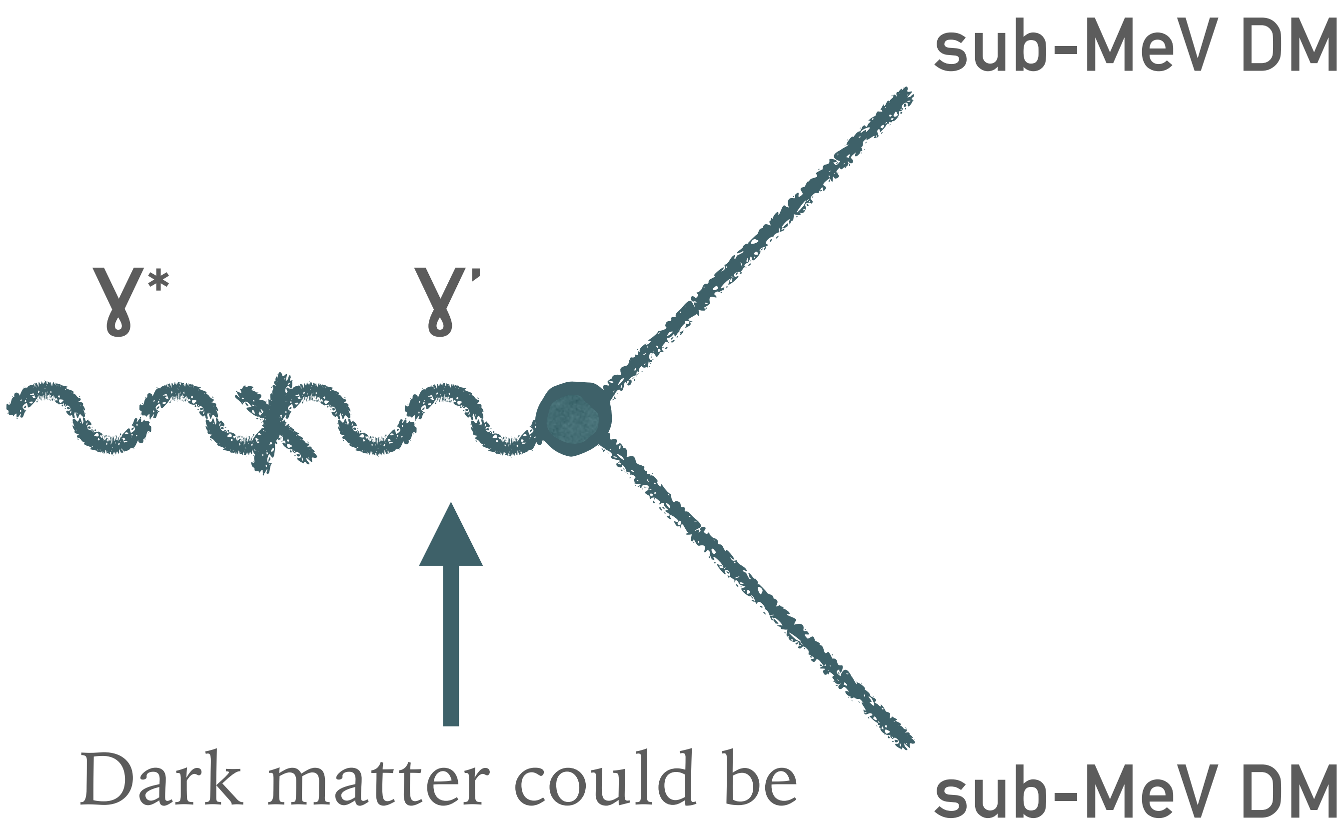


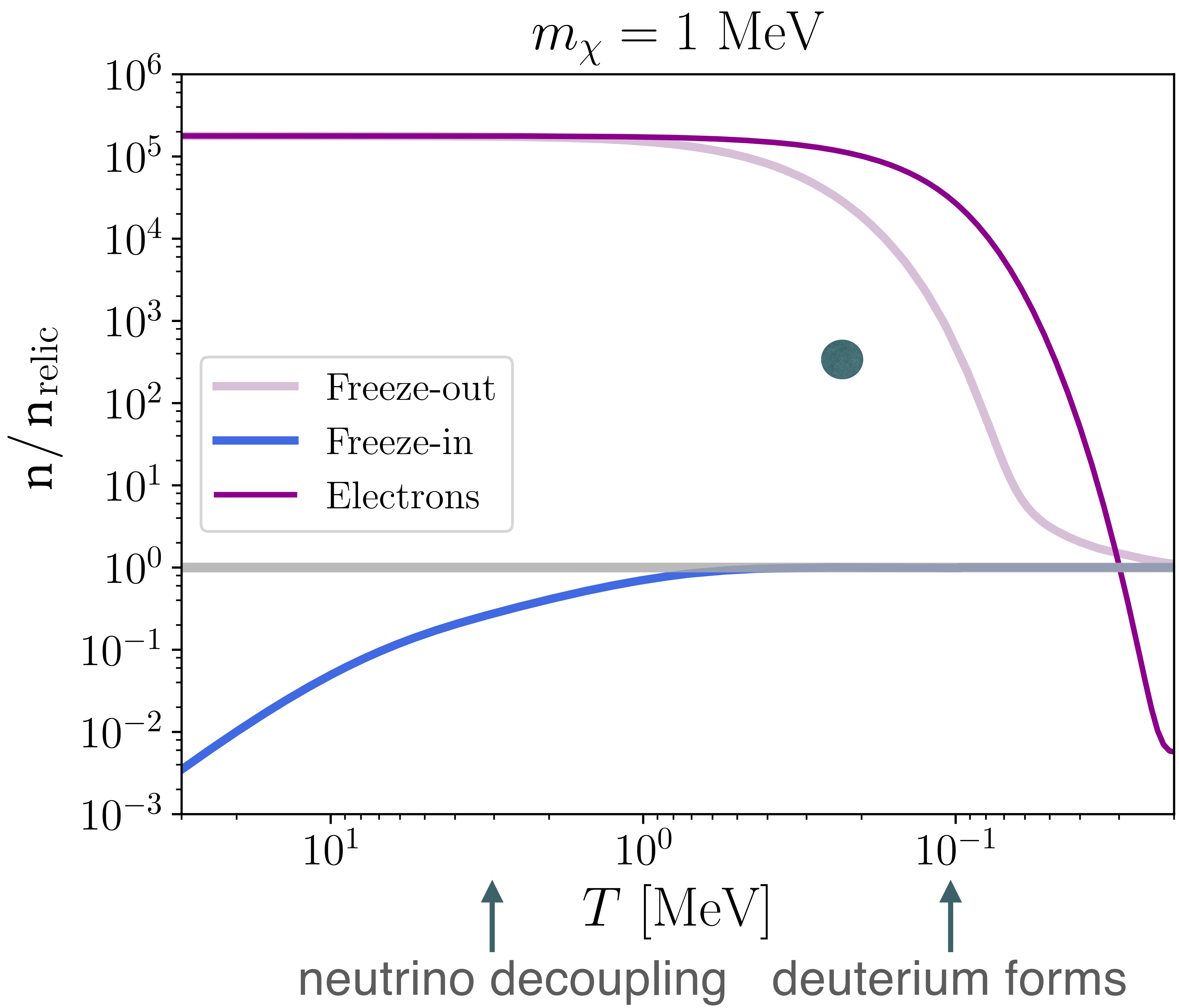
Dark matter could be charged under dark version of E&M with a "dark photon"

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

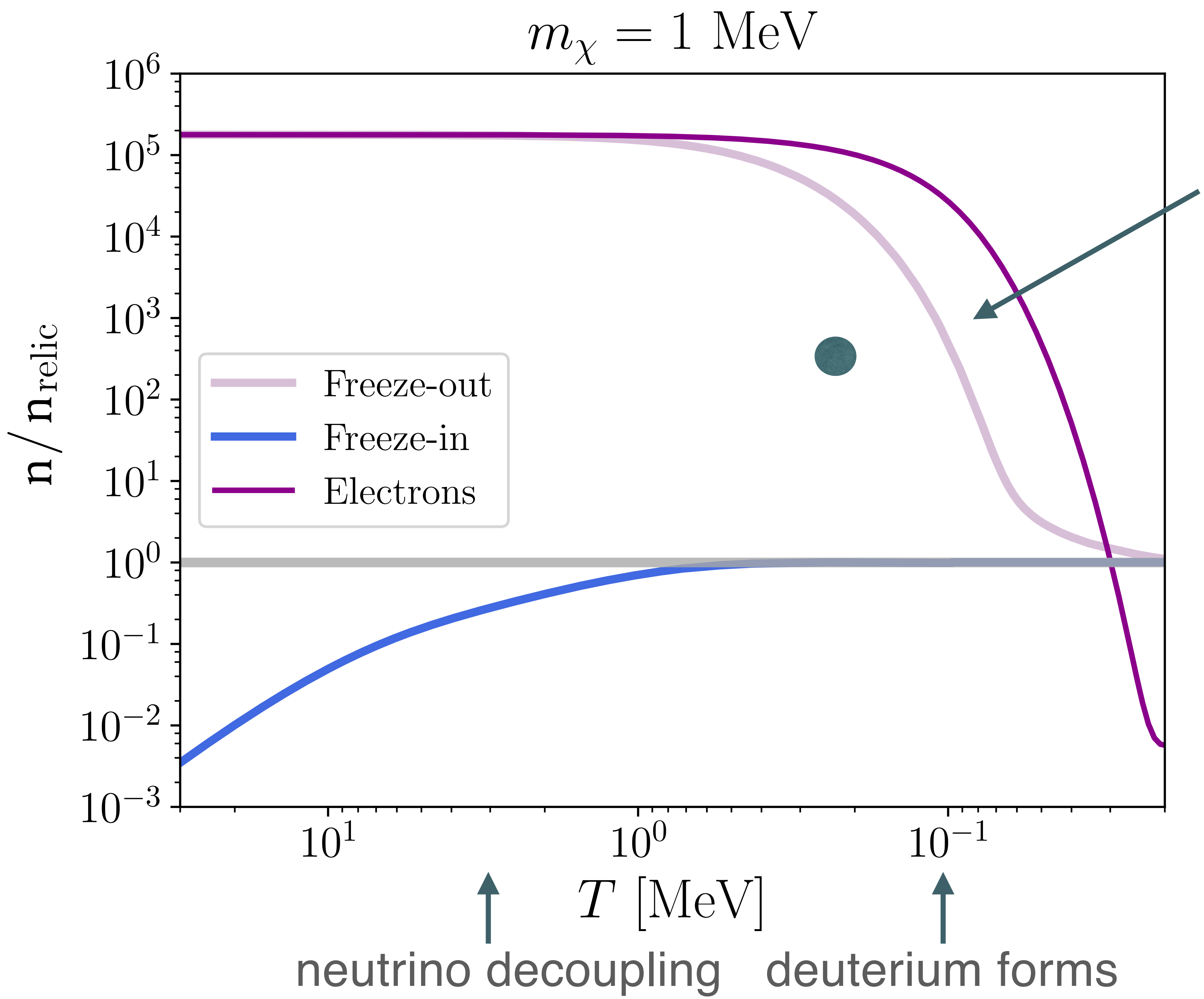
This is the simplest way of making effectively charged DM (freeze-out is excluded)

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

MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS

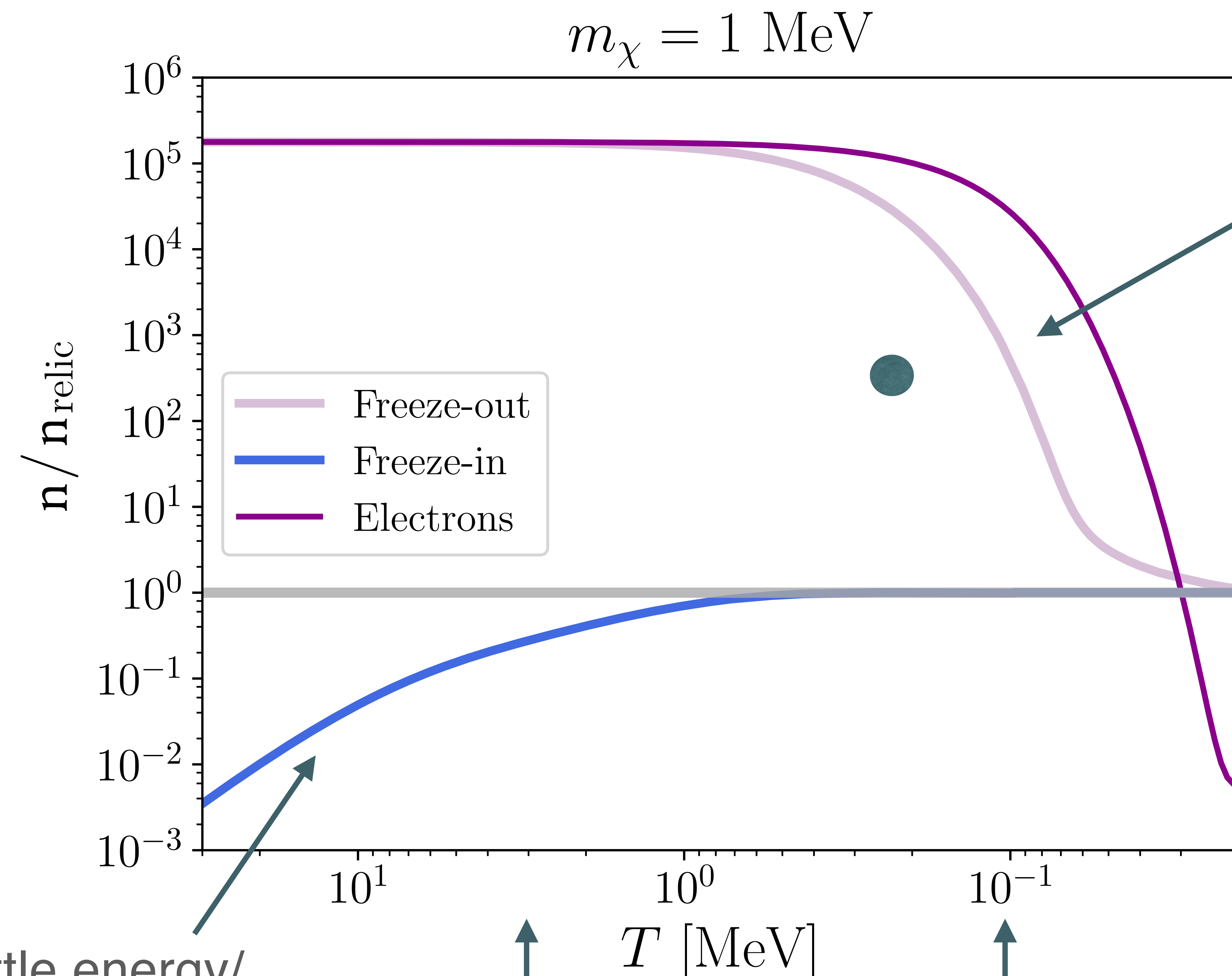


MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS



Energy/entropy transfer means sub-MeV freeze-out is excluded by BBN

MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS



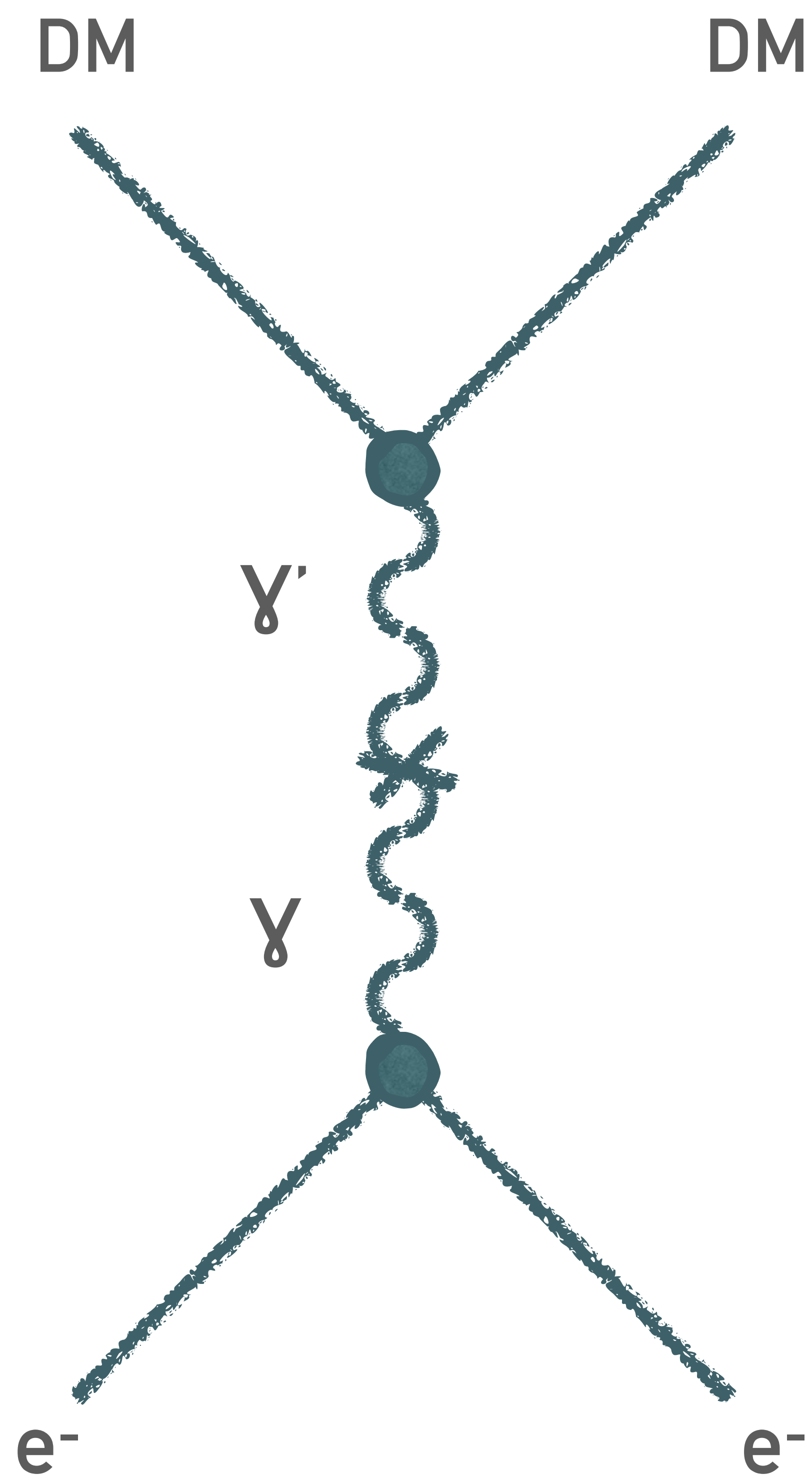
Energy/ entropy transfer means sub-MeV freeze-out is excluded by BBN

Very little energy/ entropy means no BBN issue

neutrino decoupling

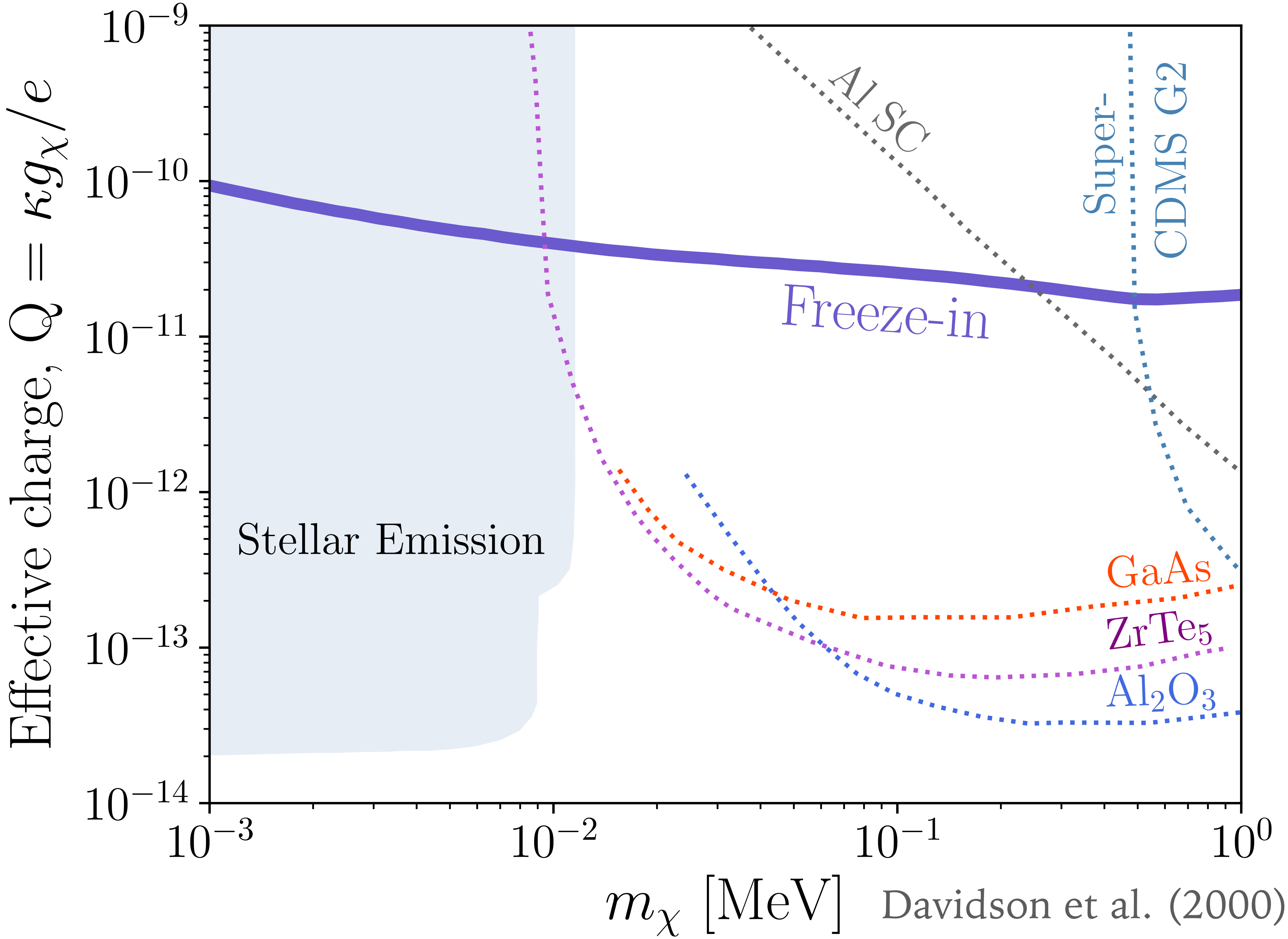
deuterium forms

PLASMON DARK MATTER IS TESTABLE IN THE LAB



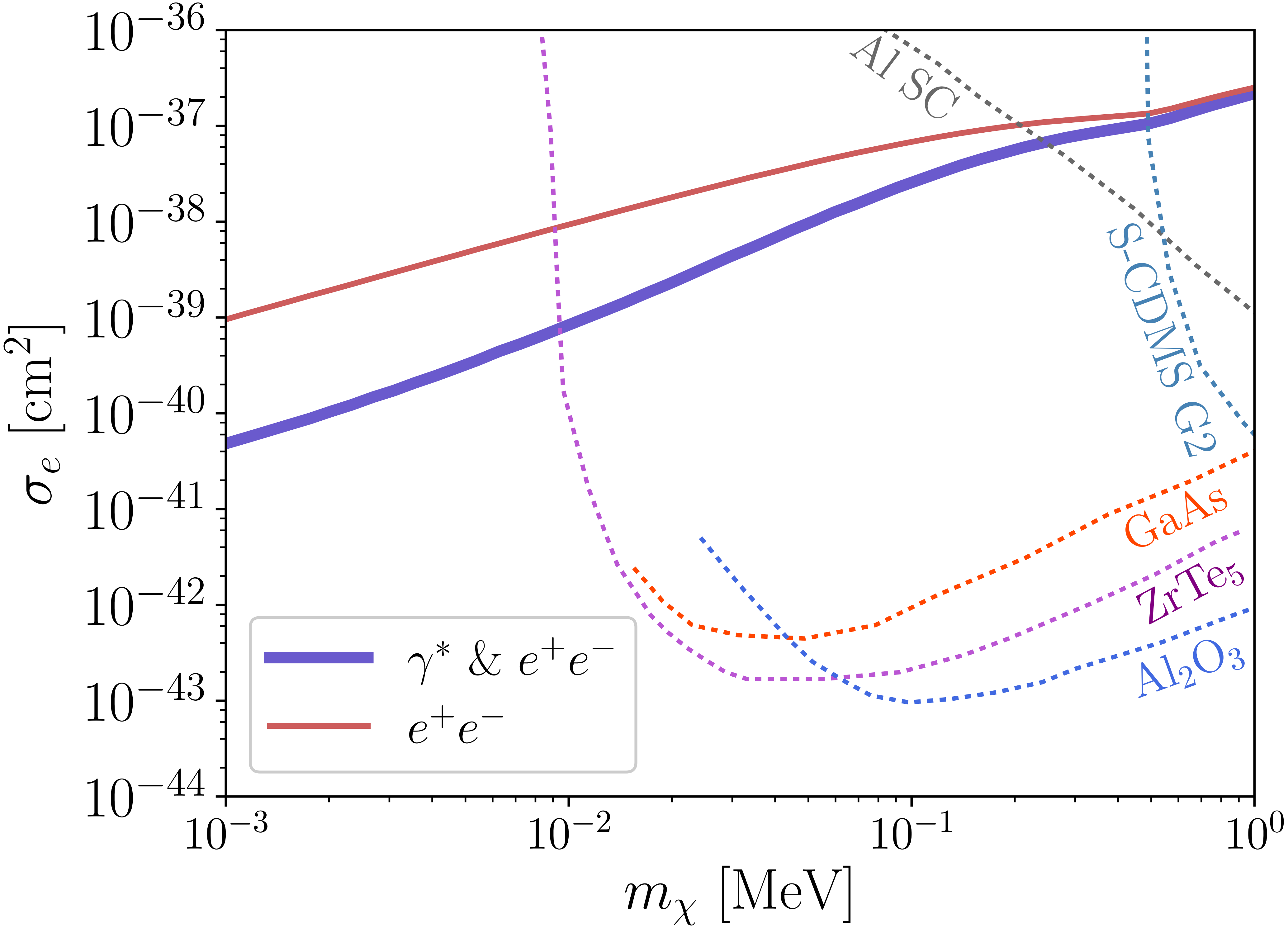
- DM never in thermal equilibrium means that the coupling must be <u>*tiny*</u>
- DM scattering via a very light mediator like a dark photon has a v^{-4} enhancement to the cross section (like Rutherford scattering)
- The typical speed of DM in our Galaxy is 10^{-3} c so that's 12 orders of magnitude of enhancement for a direct detection experiment!

PROPOSED DIRECT DETECTION EXPERIMENTS TARGETING FREEZE-IN

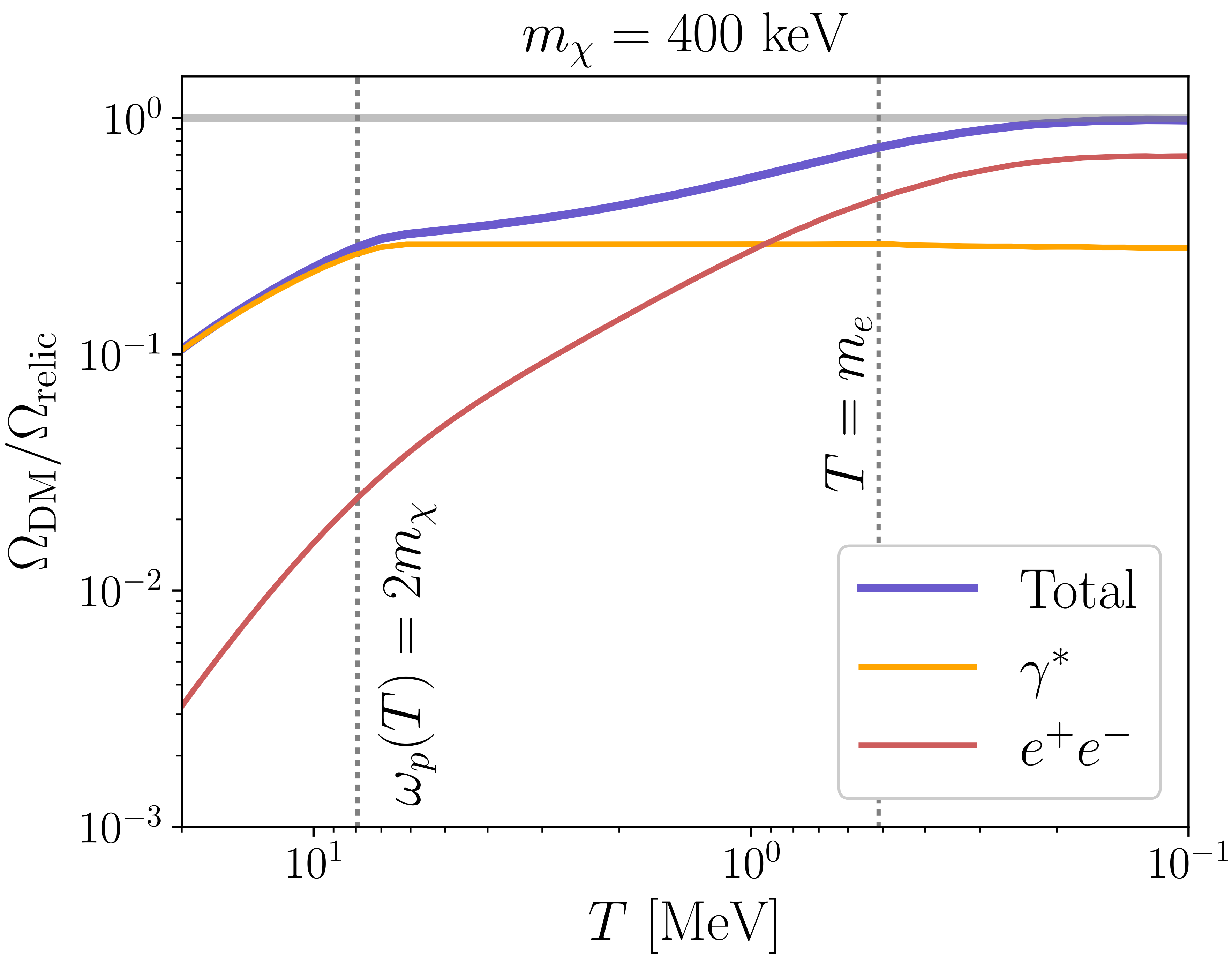


Davidson et al. (2000)
Vogel & Redondo (2013)
Griffin et al. (2018)

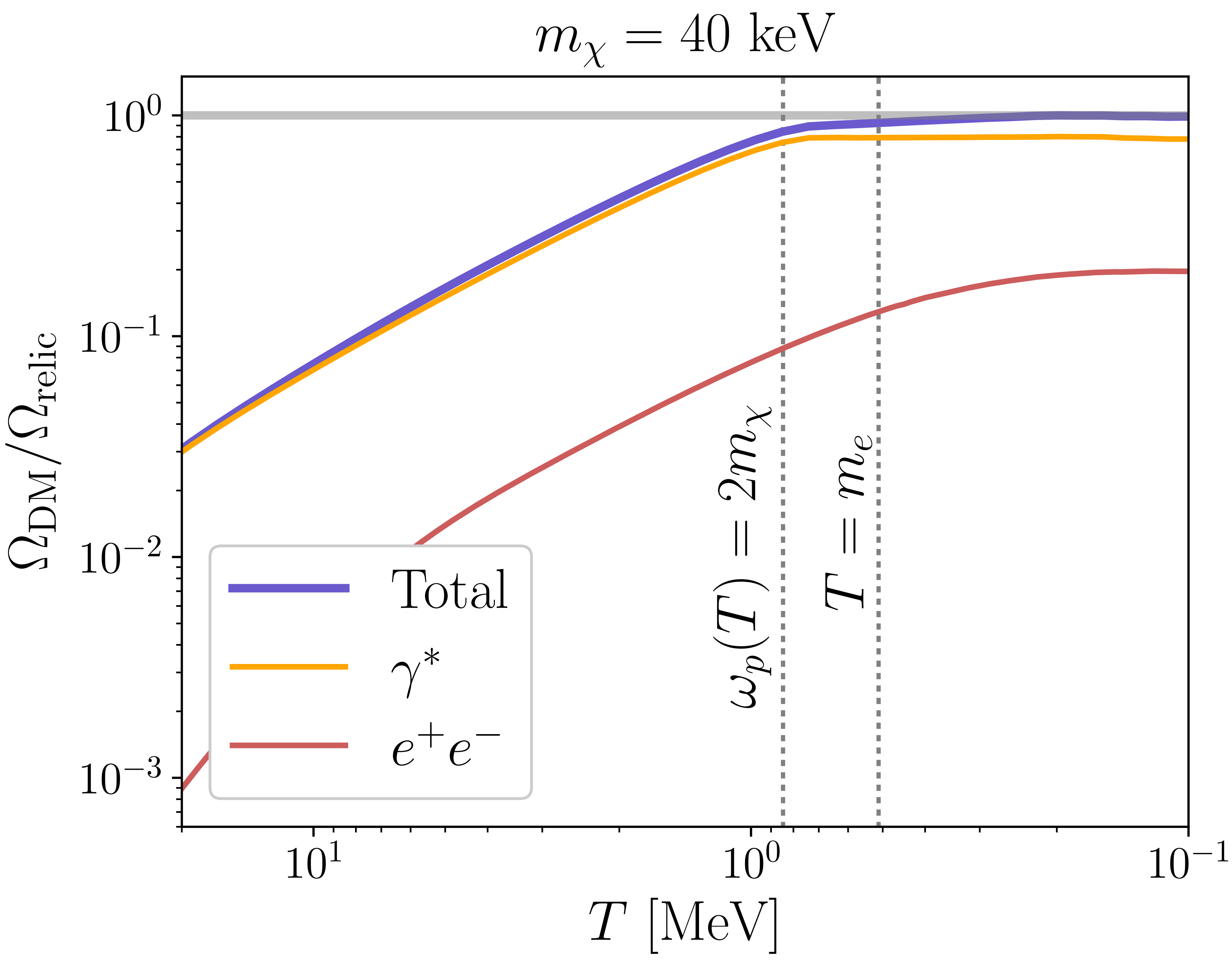
INCLUDING PLASMONS IS ESSENTIAL



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

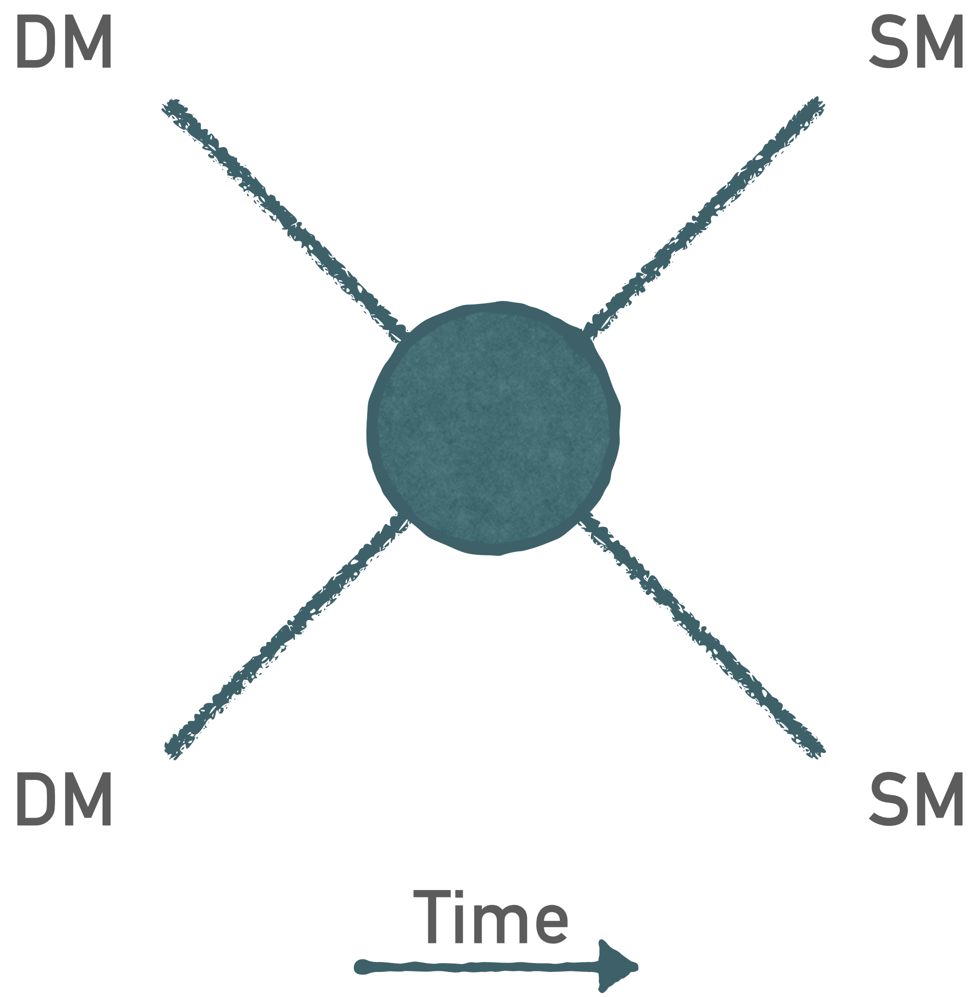


Dvorkin, Lin, KS 1902.08623



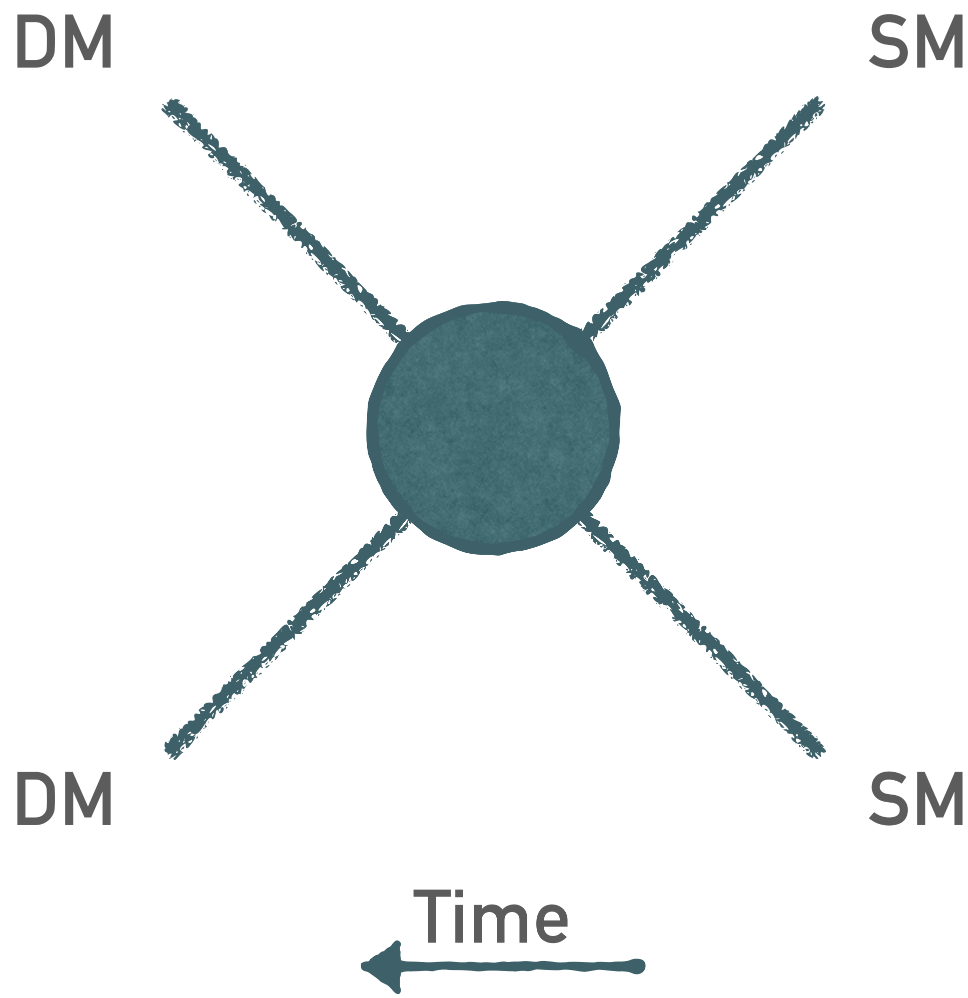
Dvorkin, Lin, KS 1902.08623

A QUICK RECAP:



Thermal freeze-out

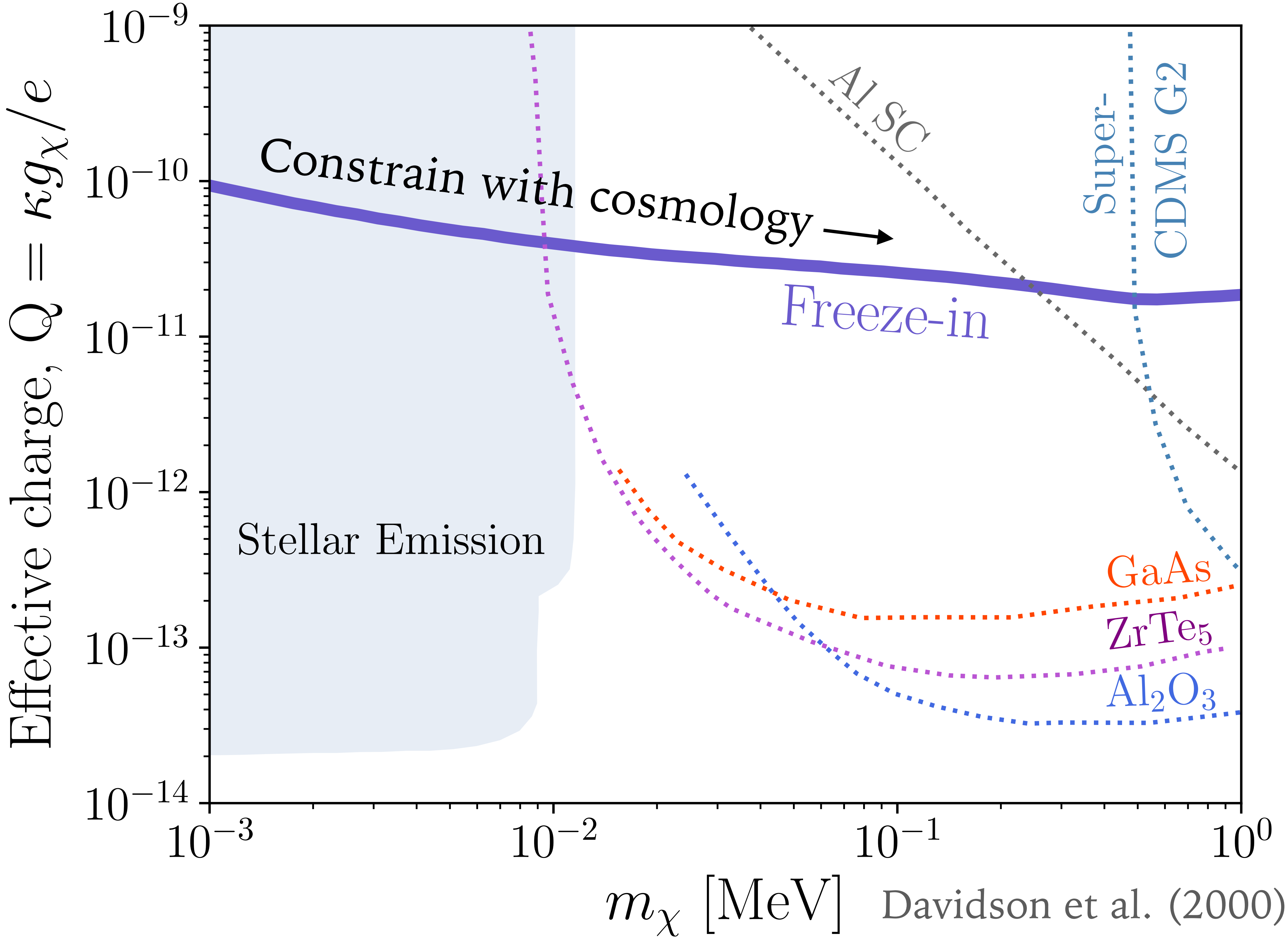
- ☑ Relic abundance is independent of initial conditions of reheating after inflation (as long as DM is in the bath)
- ☑ Fine with BBN and N_{eff} (above masses of a few MeV)
- ☑ Relevant couplings can be experimentally probed



Thermal freeze-in
(specifically via a light vector including plasmon decay)

- ☑ Relic abundance is independent of initial conditions (most dark matter is made at low temperatures)
- ☑ Fine with BBN and $N_{\rm eff}$ (above masses of a few keV)
- ☑ Relevant couplings can be experimentally probed, are a key benchmark in proposed experiments

PROPOSED DIRECT DETECTION EXPERIMENTS TARGETING FREEZE-IN



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

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

un-truncated Boltzmann hierarchy: $$\frac{\partial f}{\partial t} - H\frac{p^2}{E}\frac{\partial f}{\partial E} = \frac{C[f]}{E}$$

DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy:

$$\frac{\partial f}{\partial t} - H\frac{p^2}{E}\frac{\partial f}{\partial E} = \frac{C[f]}{E}$$

how phase space changes
over cosmic time

DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy:

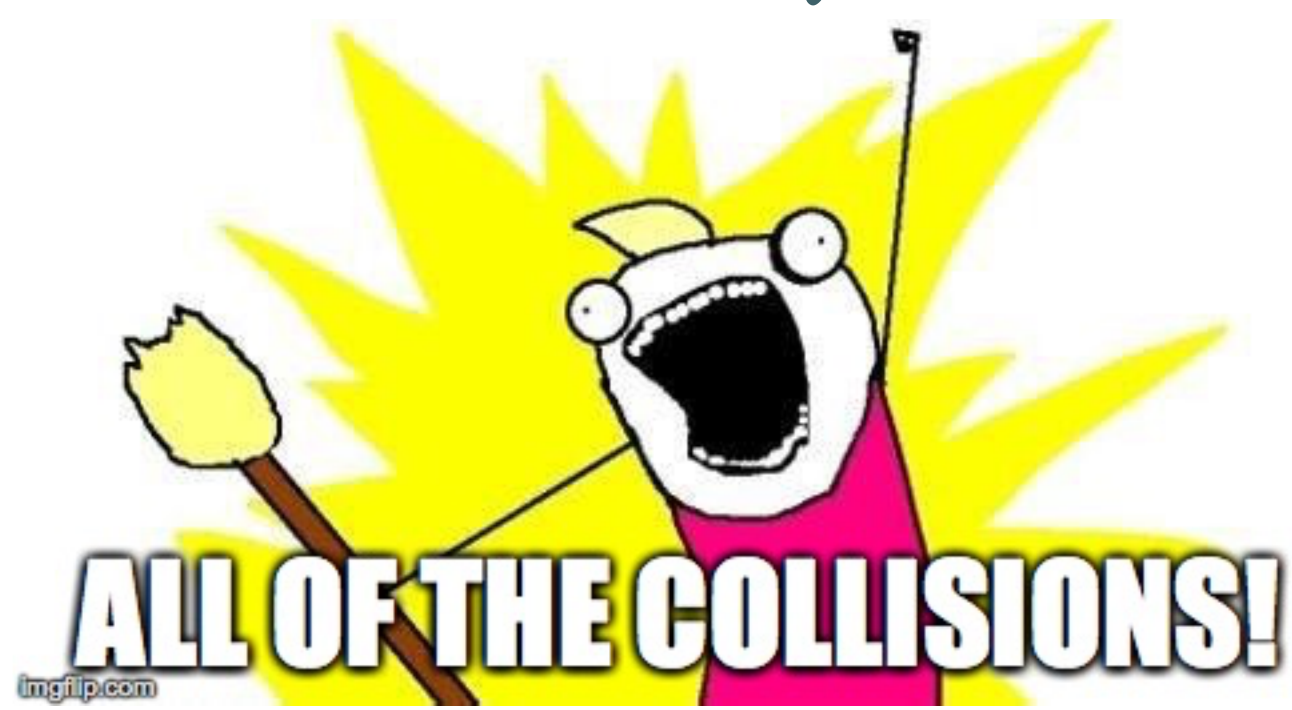
$$\frac{\partial f}{\partial t} - H\frac{p^2}{E}\frac{\partial f}{\partial E} = \frac{C[f]}{E}$$

accounting for ordinary
redshifting from expansion

DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy:

$$\frac{\partial f}{\partial t} - H\frac{p^2}{E}\frac{\partial f}{\partial E} = \frac{C[f]}{E}$$



DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy:

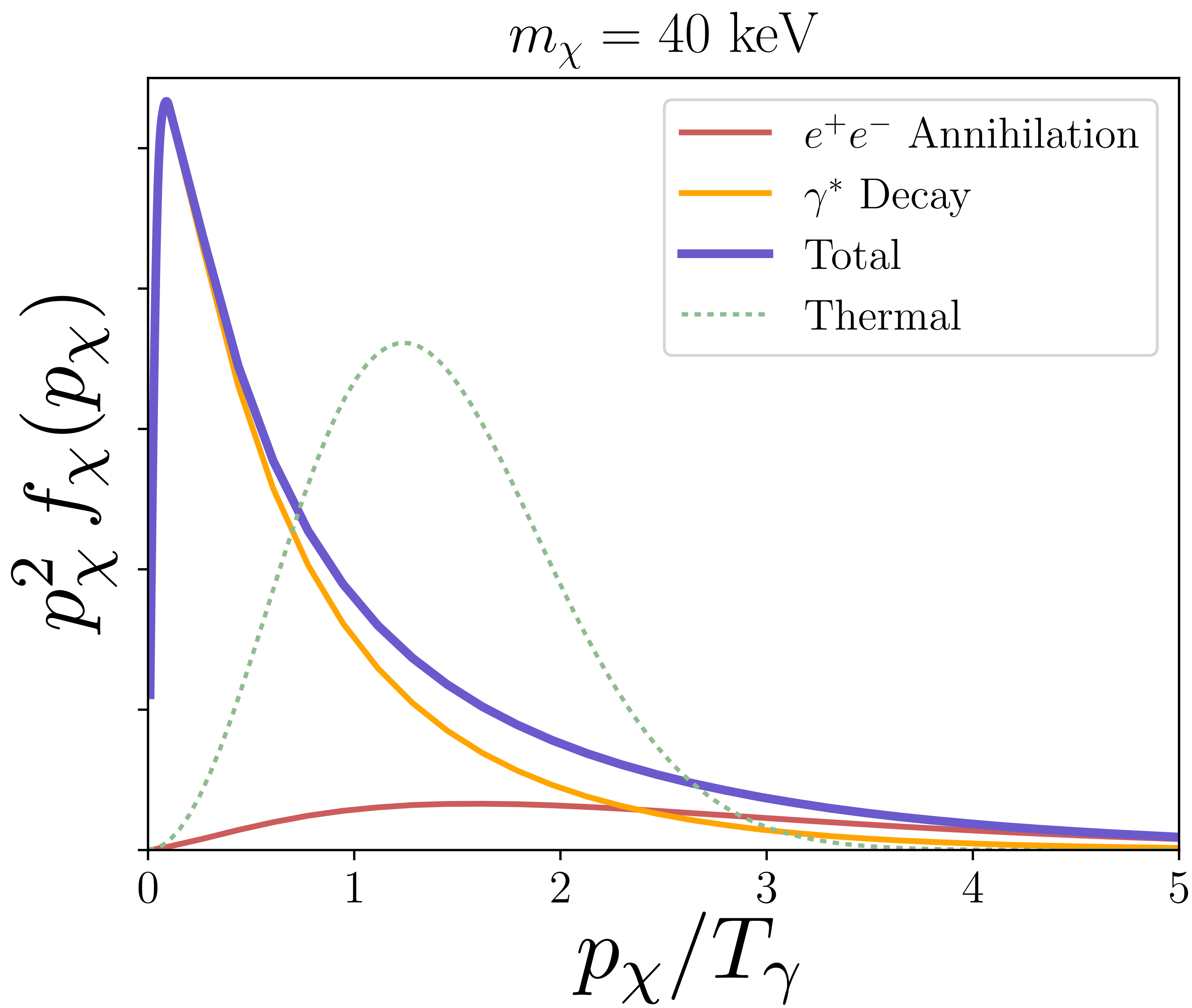
$$\frac{\partial f}{\partial t} - H \frac{p^2}{E} \frac{\partial f}{\partial E} = \frac{C[f]}{E}$$

$$\frac{C[f_{X_1}]}{E_{X_1}} = \int \frac{đ^3 p_{e_1}}{2E_{e_1}} \frac{đ^3 p_{e_2}}{2E_{e_2}} \frac{đ^3 p_{X_2}}{2E_{X_2}} f_{e_1} f_{e_2}\, \delta^{(4)}(\Sigma\, p)\, |\mathcal{M}|^2_{e_1+e_2 \to X_1+X_2} + \int \frac{đ^3 p_{\gamma*}}{2E_{\gamma*}} \frac{đ^3 p_{X_2}}{2E_{X_2}} f_{\gamma*}\, \delta^{(4)}(\Sigma\, p)\, |\mathcal{M}|^2_{\gamma* \to X_1+X_2}$$

key fact: due to low DM occupation number, the collisions are actually independent of the DM phase space!

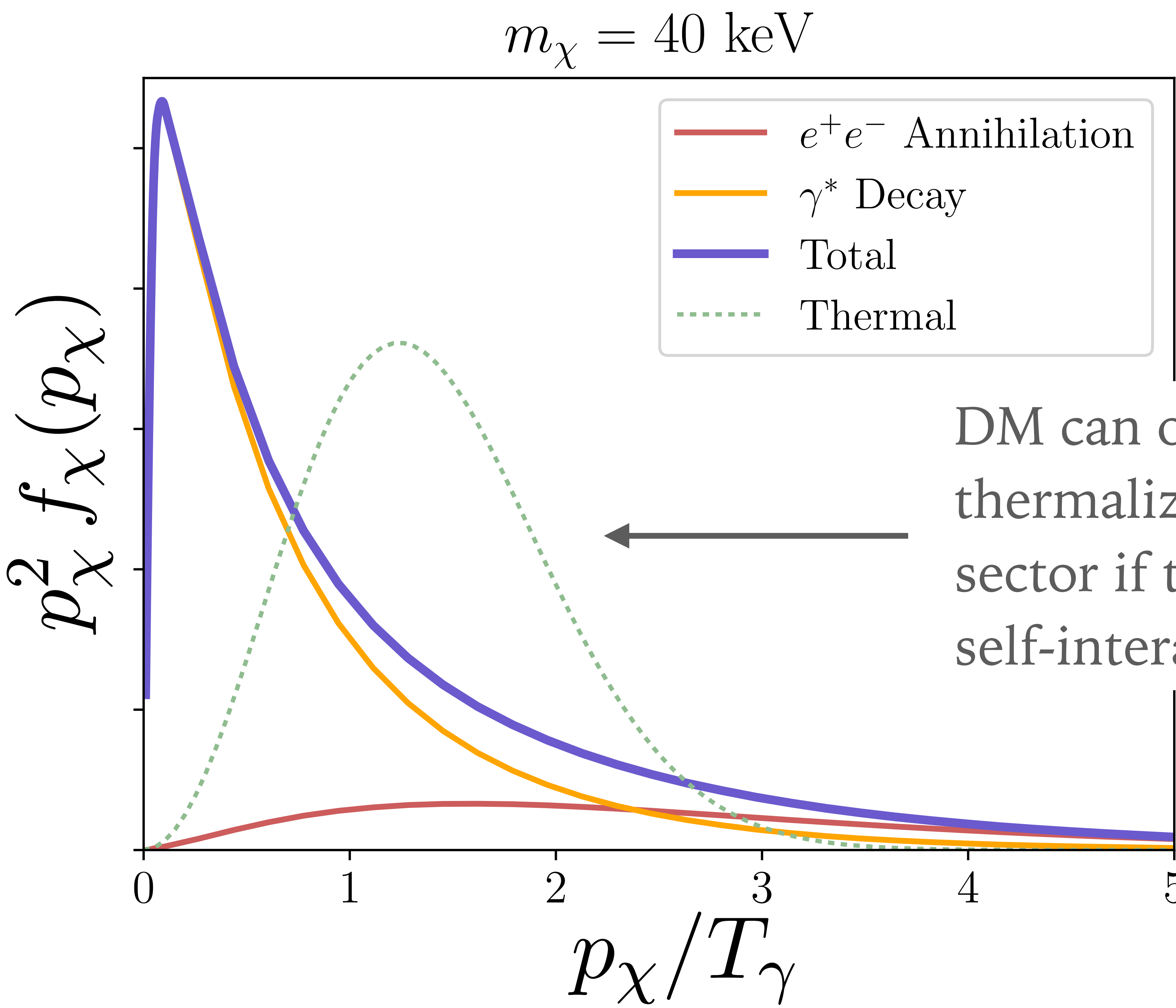
$$f_X(p,t) = \int_{t_i}^{t} dt' \, \frac{C\left(\frac{a(t)}{a(t')}\, p, t'\right)}{E}$$

DEALING WITH NON-THERMAL PHASE SPACE



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

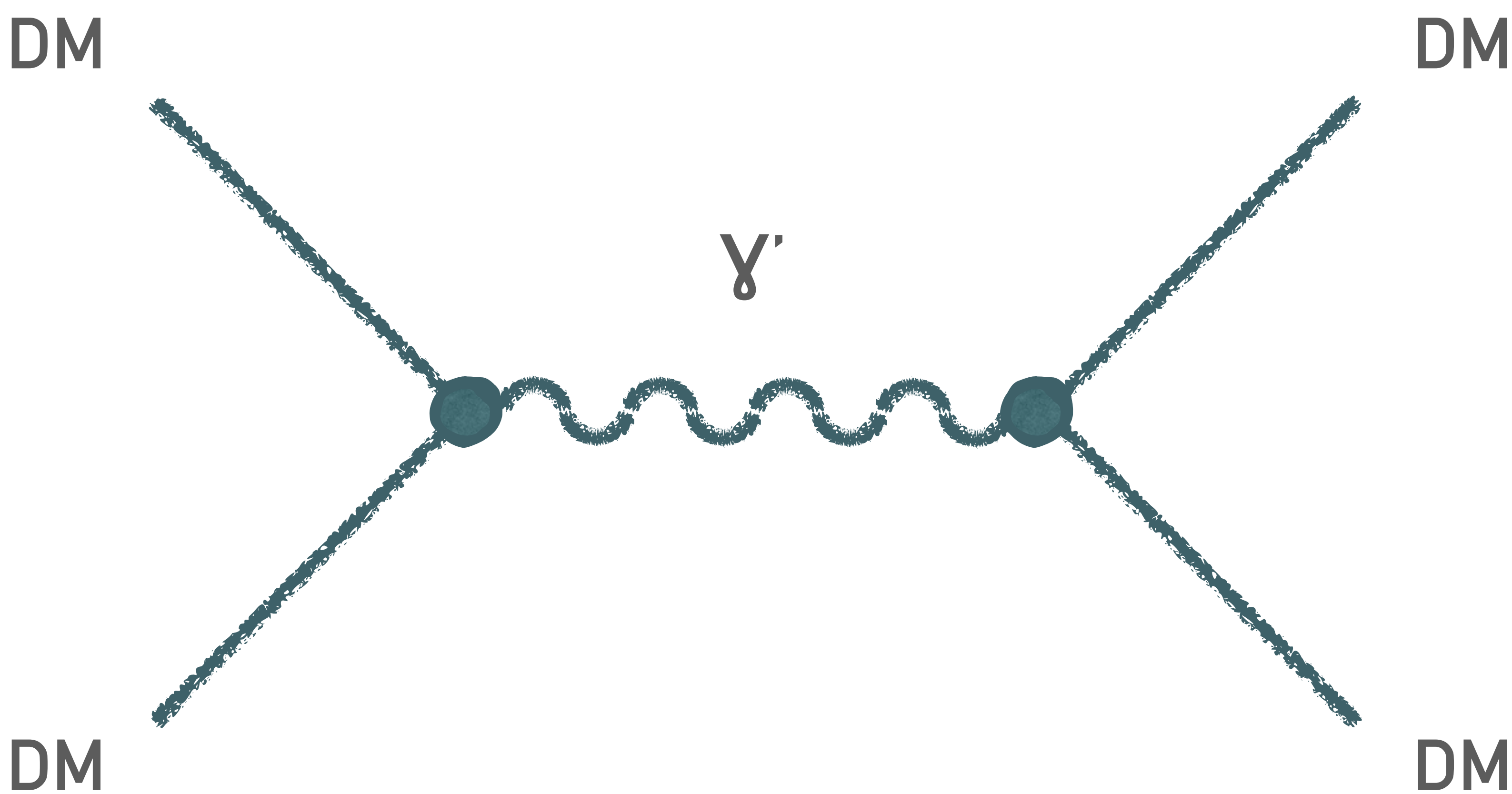
DEALING WITH NON-THERMAL PHASE SPACE



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

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

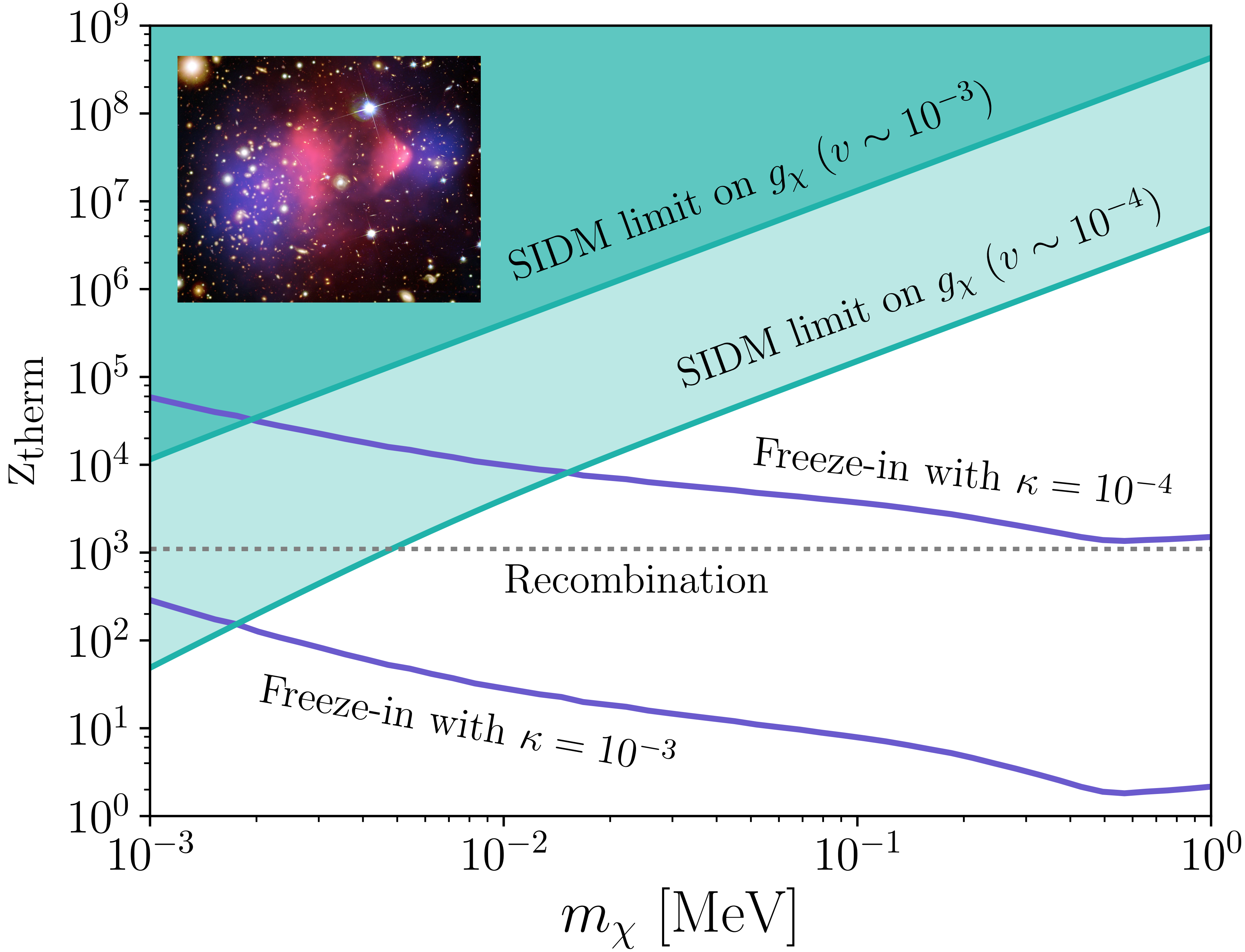
DARK MATTER SELF-THERMALIZATION



$\sim g_x^4$

DM self-scattering has v^{-4} scaling and is especially effective at late times

DARK MATTER SELF-THERMALIZATION



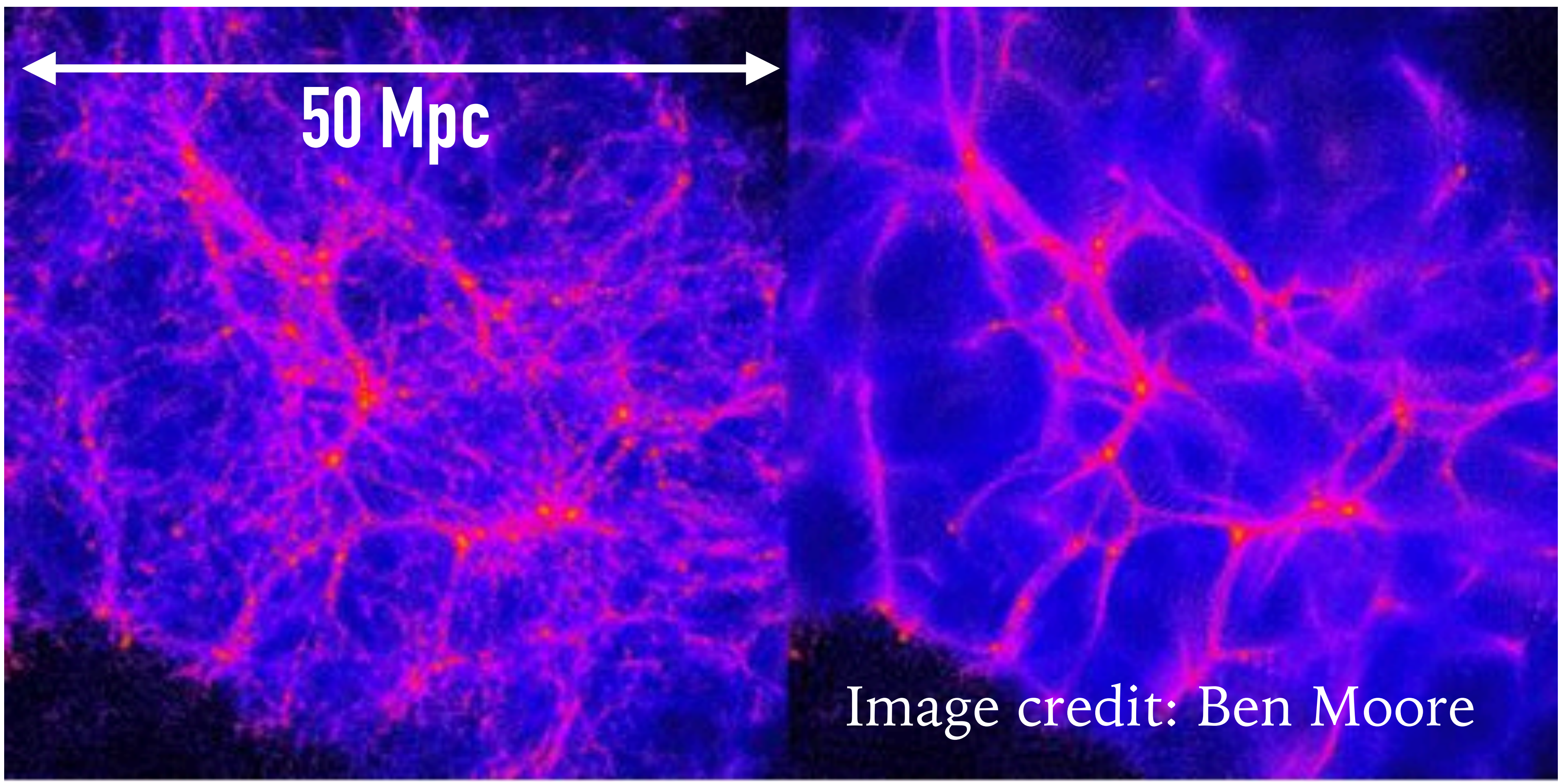
Dvorkin, Lin, **KS** (PRD 2019)

PHASE SPACE IMPLICATIONS FOR COSMOLOGY

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

VELOCITY EFFECTS ON CLUSTERING (WARM DARK MATTER EXAMPLE)

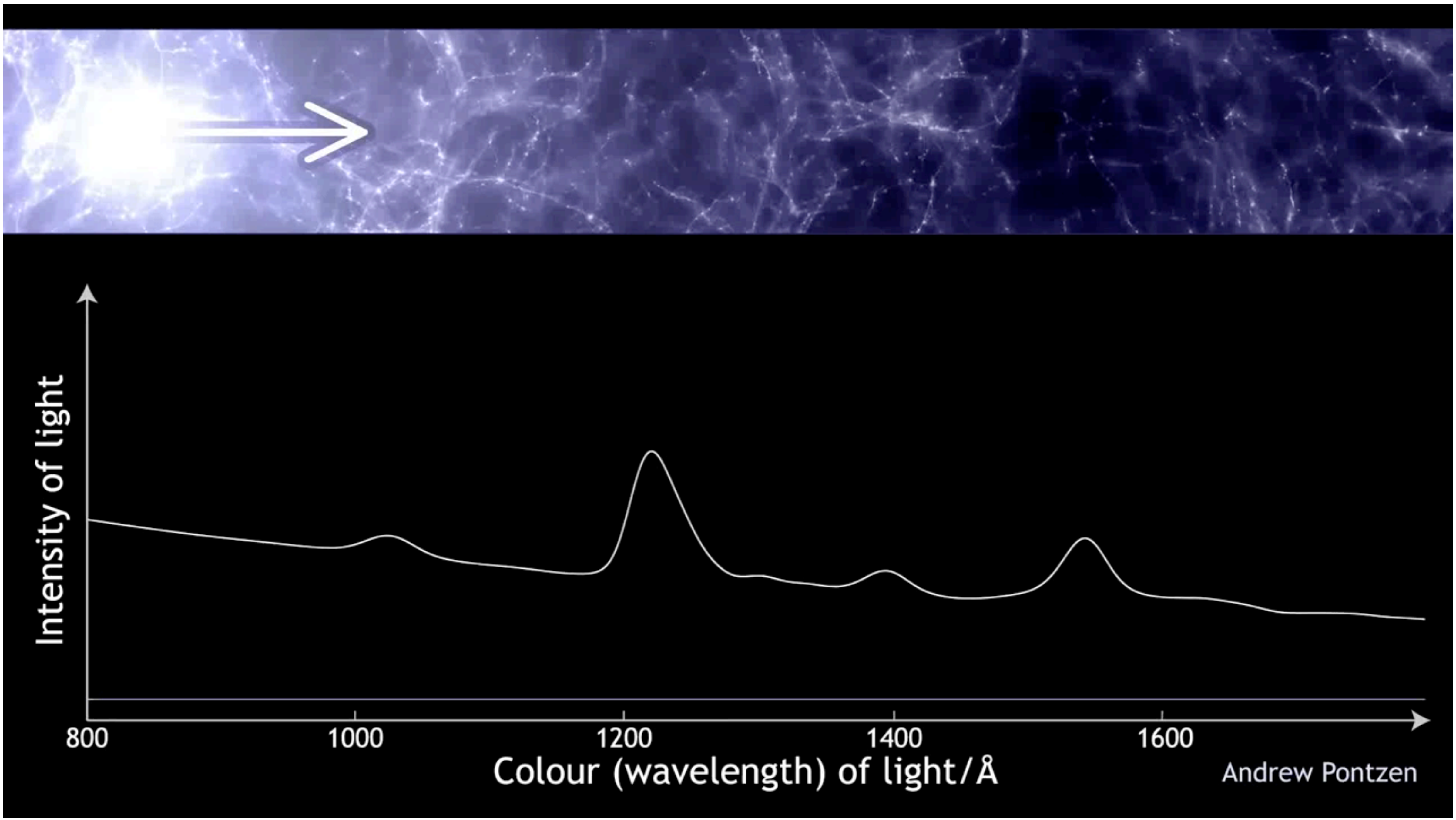
Warm dark matter initial conditions: $$\Omega_\chi = \frac{m_\chi}{94\ \mathrm{eV}} \frac{11}{4} \left(\frac{T_\chi}{T_\gamma}\right)^3$$



← Heavier, Cooler

Lighter, Hotter →

A PROBE OF POWER SPECTRUM SUPPRESSION: LY-A FOREST



EFFECT ON LOW-MASS HALOS AND SUB HALOS

- Suppressed clustering on small scales would mean fewer low-mass halos and subhalos, which we can look for using various methods:

Choose your own adventure! (time permitting)

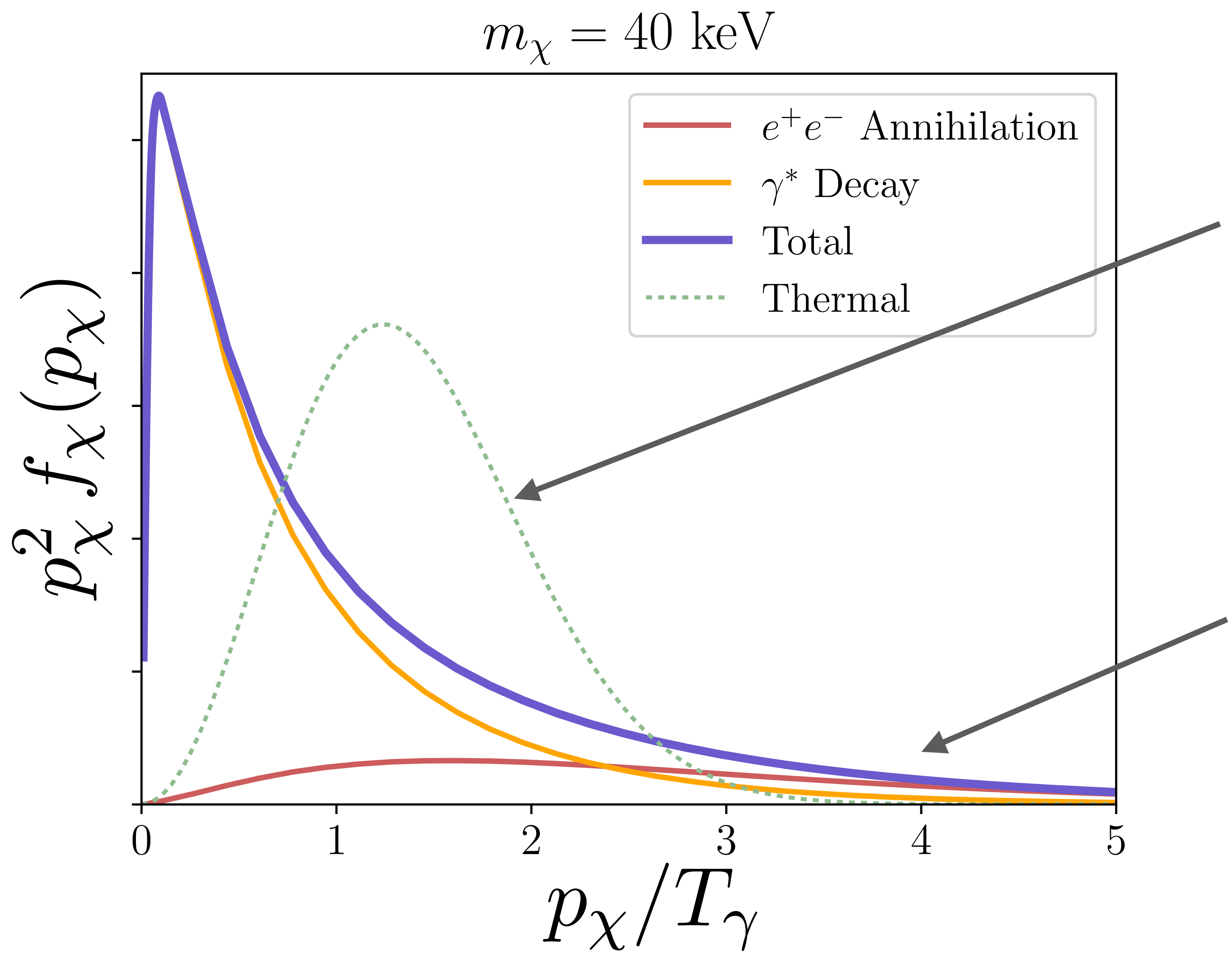
Stellar Streams

Quadruply imaged, strongly lensed quasars

Dwarf galaxy counts

21 cm cosmology

GRAVITATIONAL CLUSTERING AND PHASE SPACE

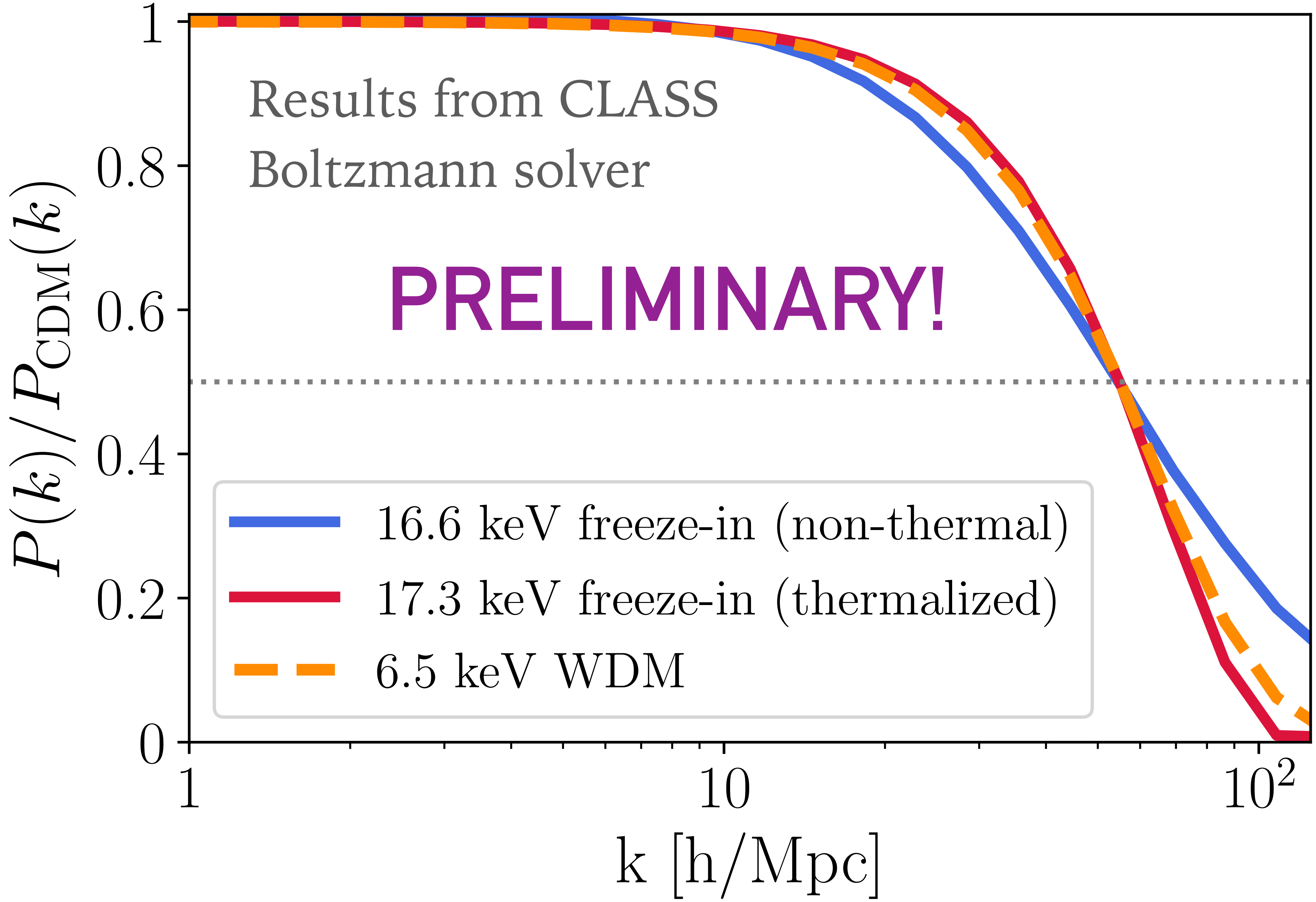


If DM can self-thermalize then it must have a nontrivial sound speed and can't stream freely

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

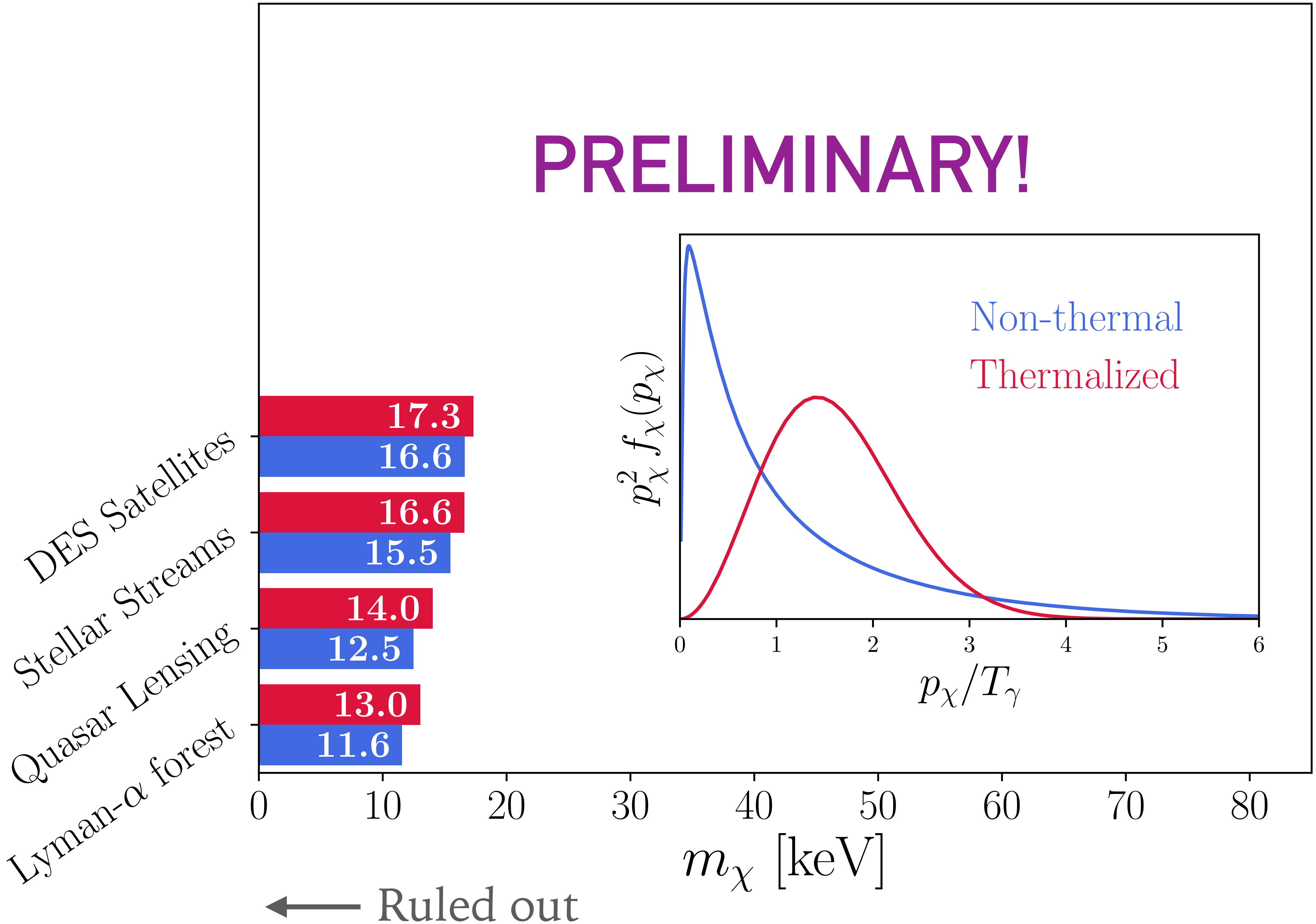
Dvorkin, Lin, **KS** in prep.

MAPPING WDM CONSTRAINTS TO FREEZE-IN CONSTRAINTS



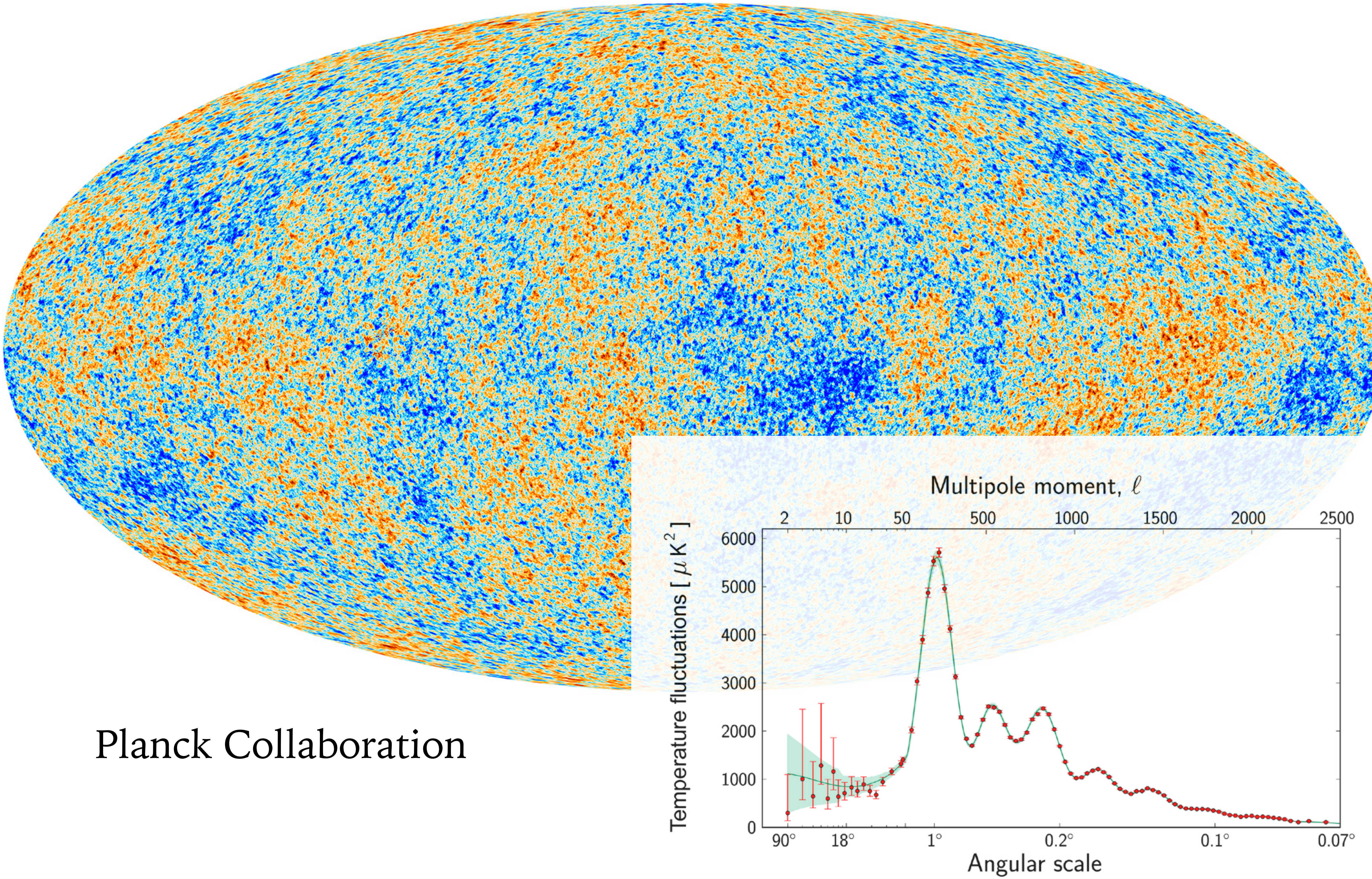
Dvorkin, Lin, **KS** in prep.

COSMOLOGICAL CONSTRAINTS ON FREEZE-IN

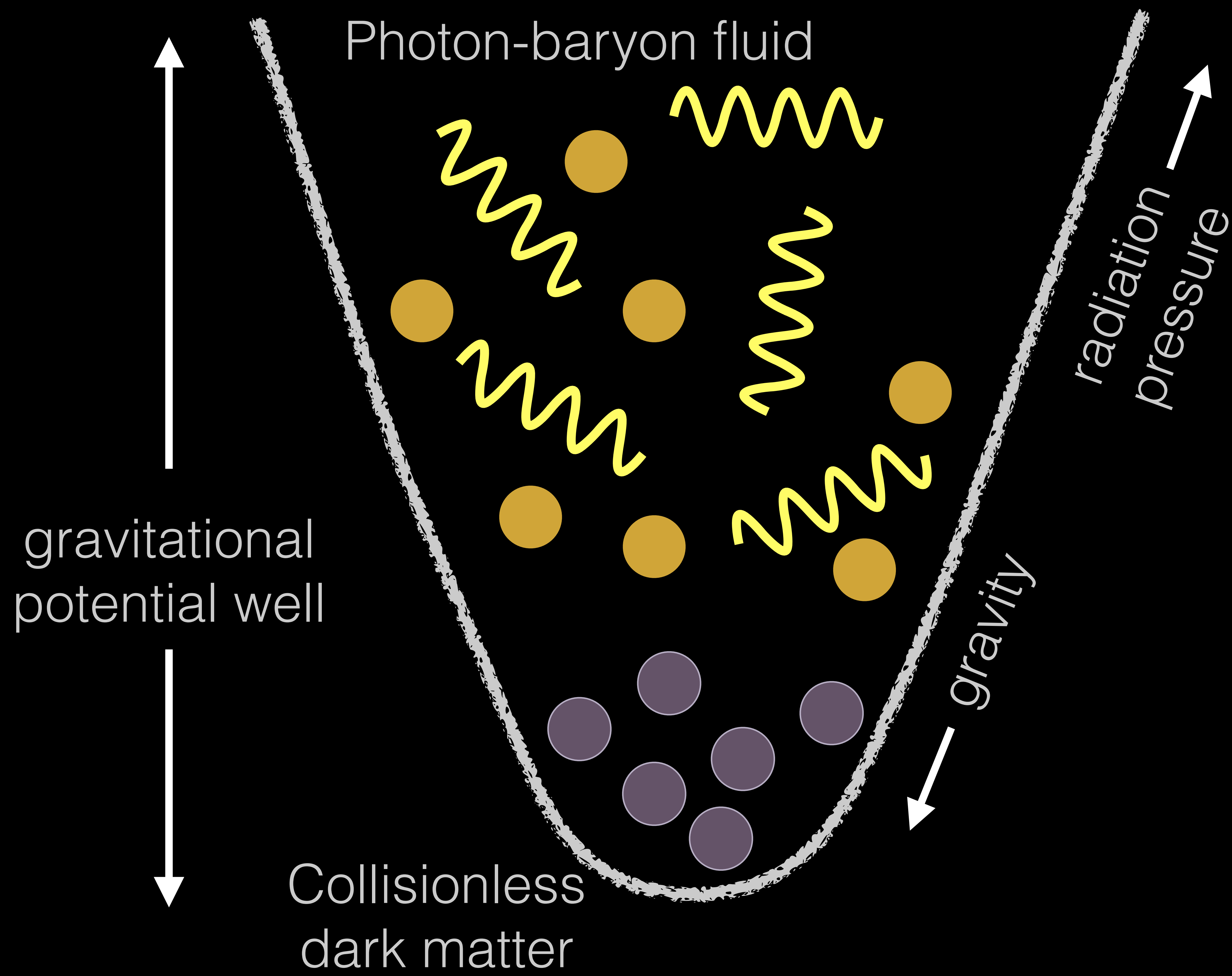


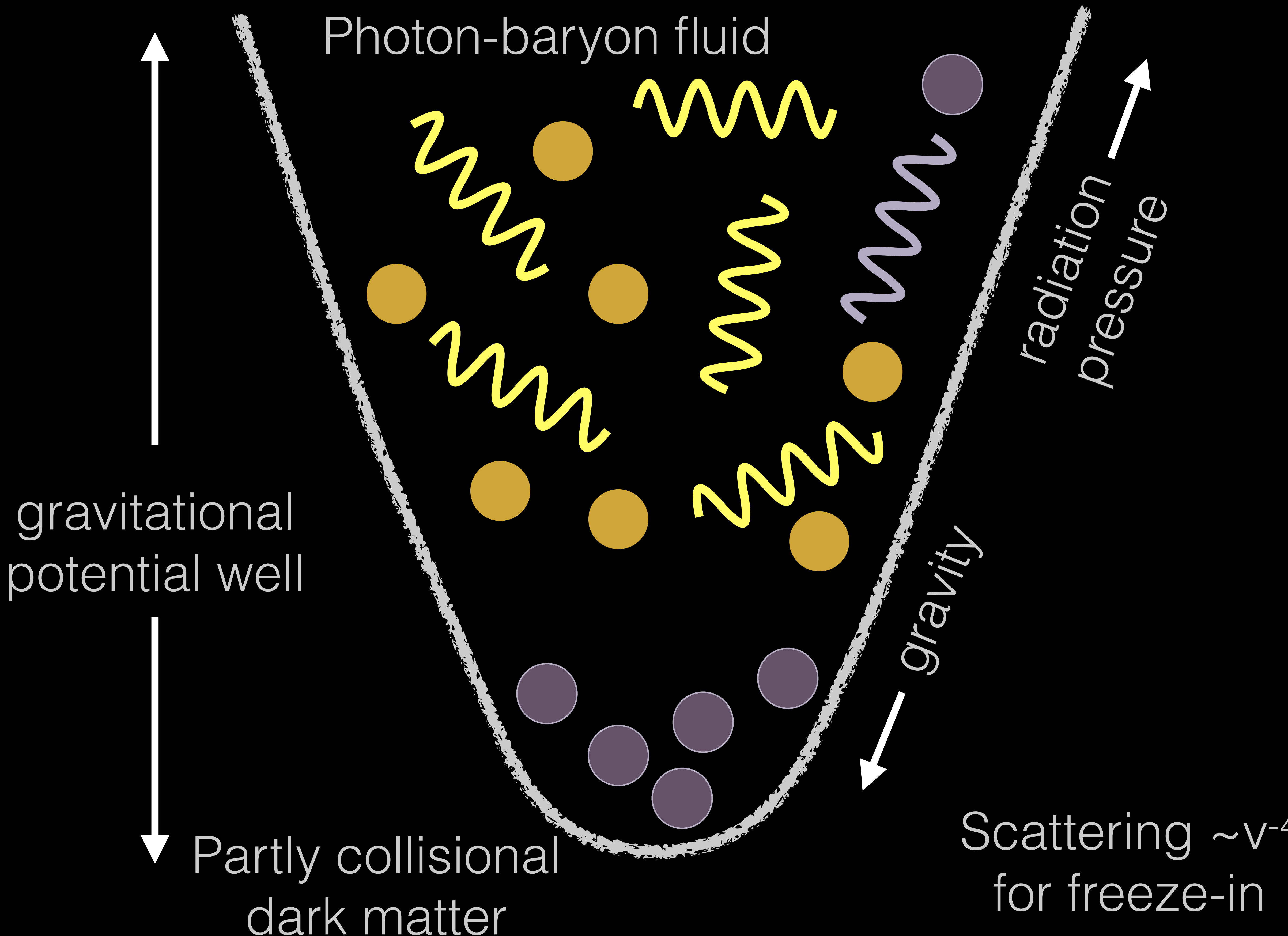
Dvorkin, Lin, **KS** in prep.

DARK MATTER–BARYON DRAG APPARENT IN THE CMB

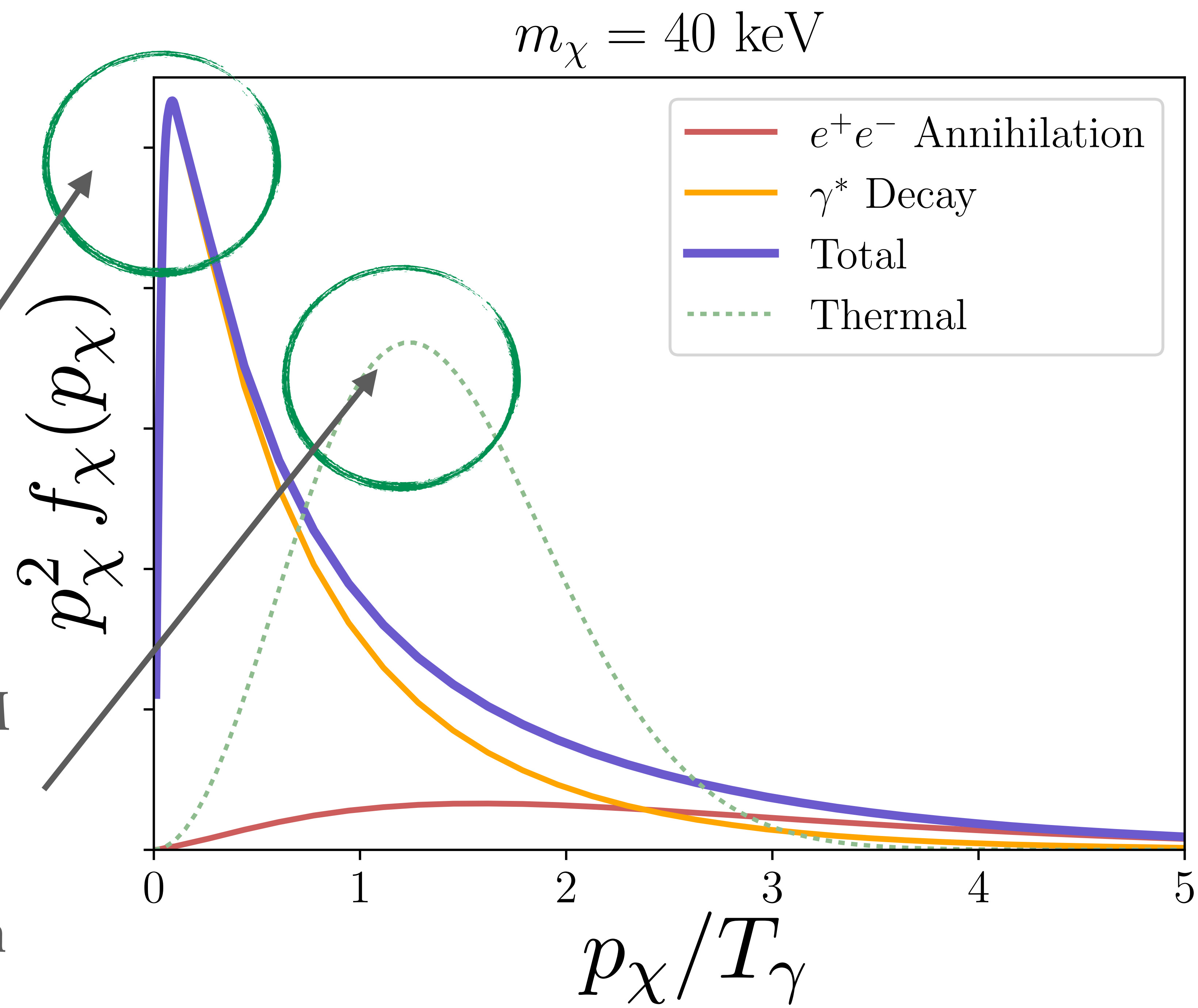


Planck Collaboration


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


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

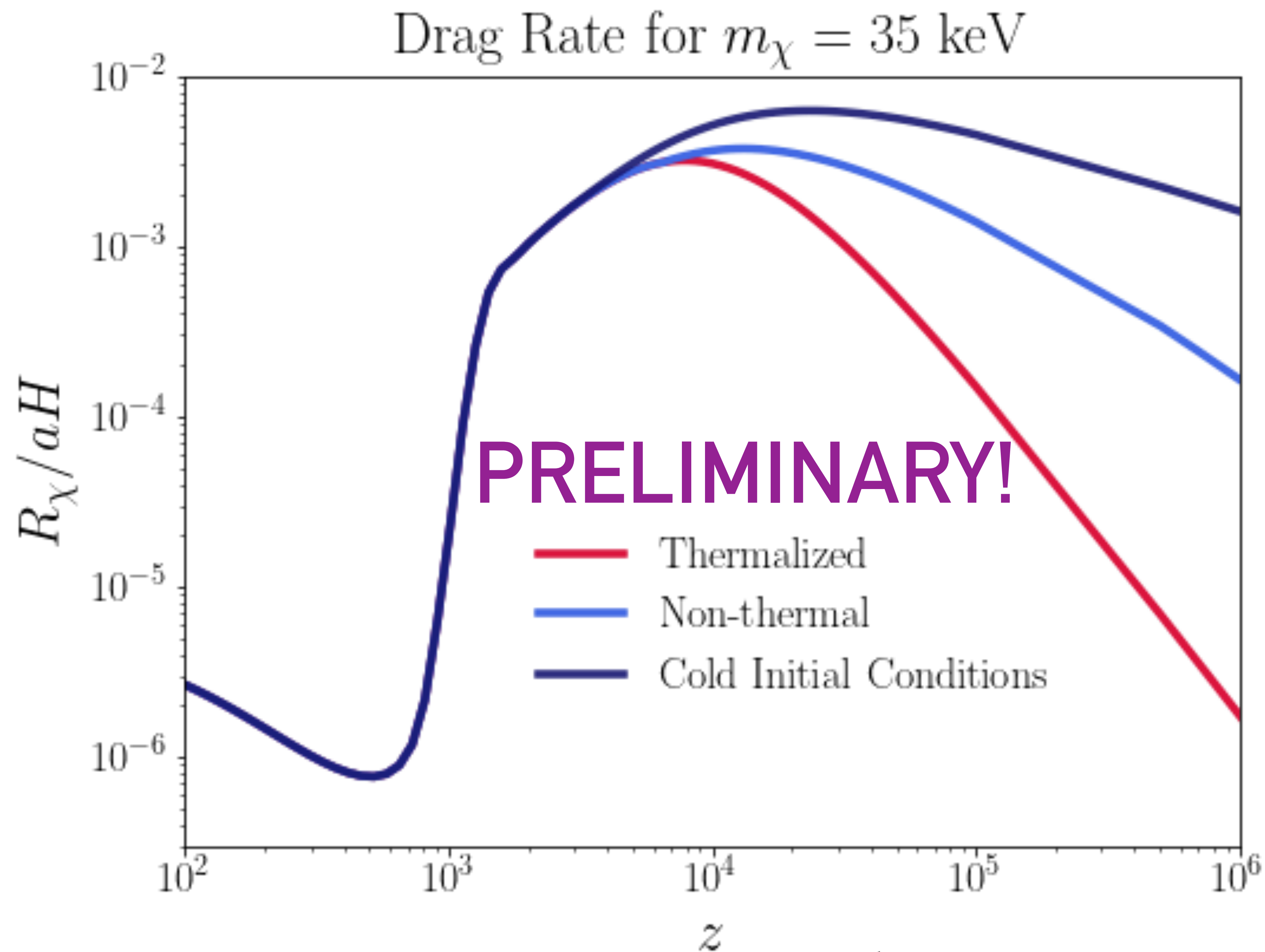
DM–BARYON SCATTERING AND PHASE SPACE



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

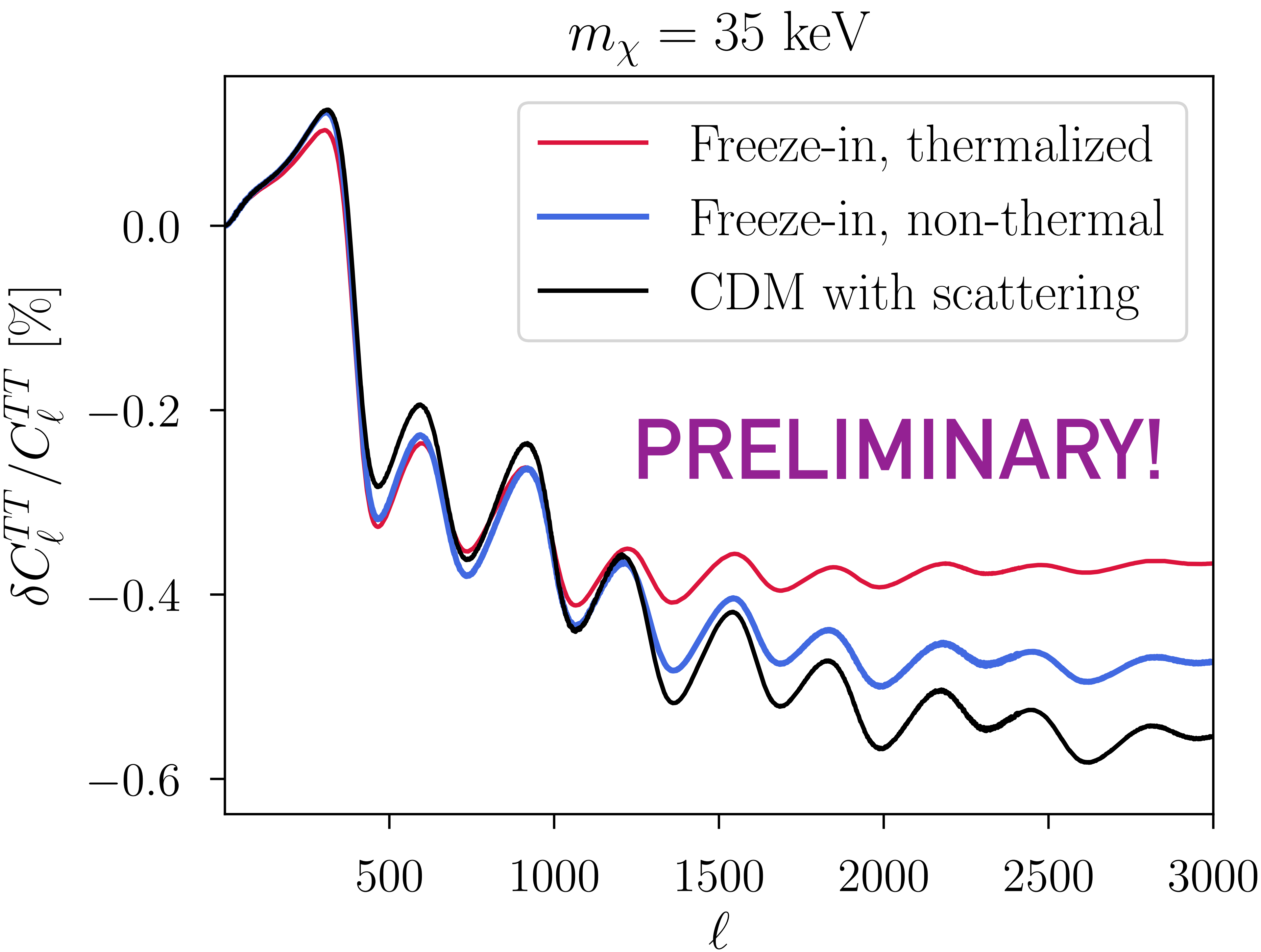
Dvorkin, Lin, **KS** in prep.

DM–BARYON DRAG RATE



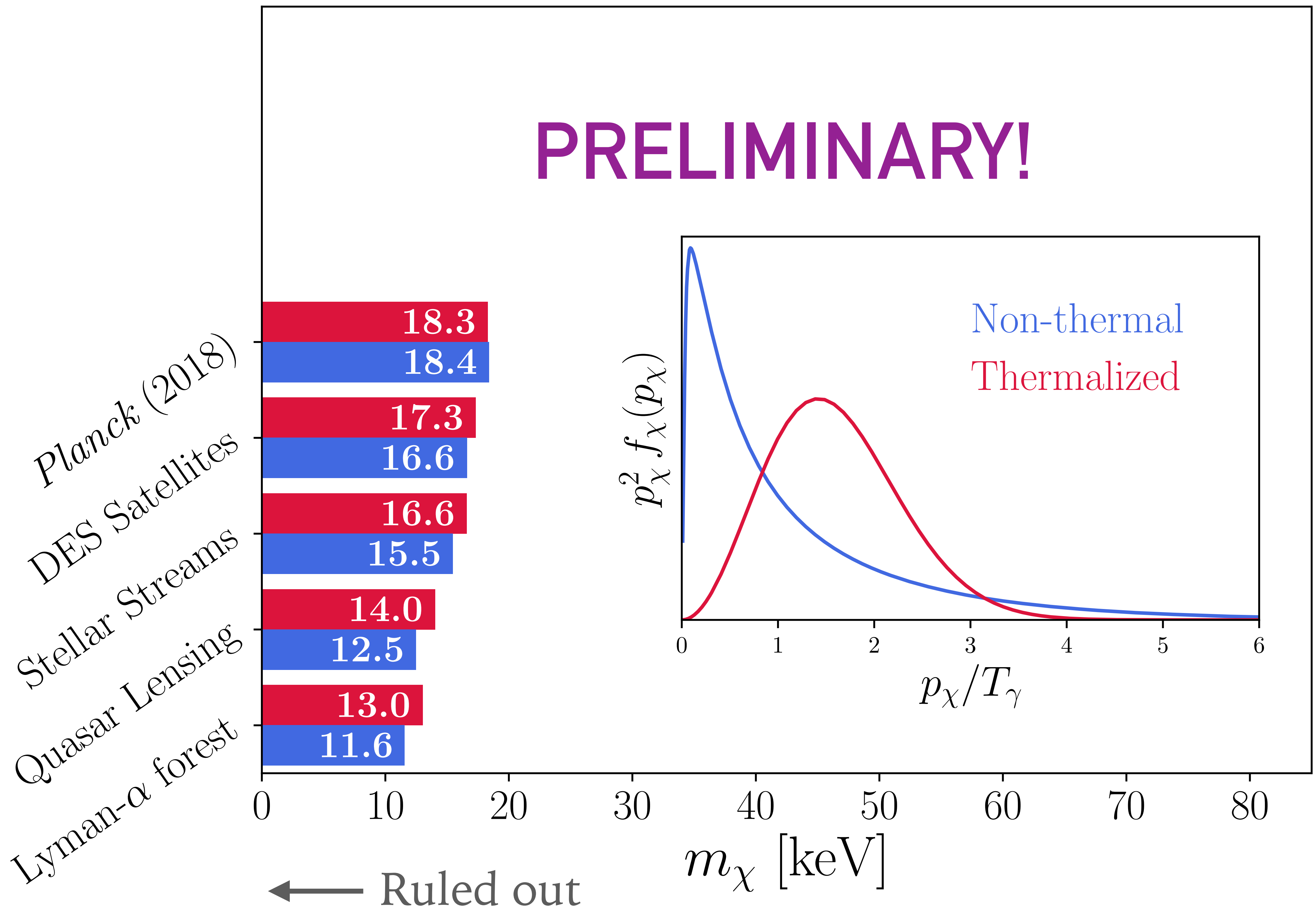
Dvorkin, Lin, **KS** in prep.

DARK MATTER–BARYON DRAG EFFECT ON THE CMB



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

COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



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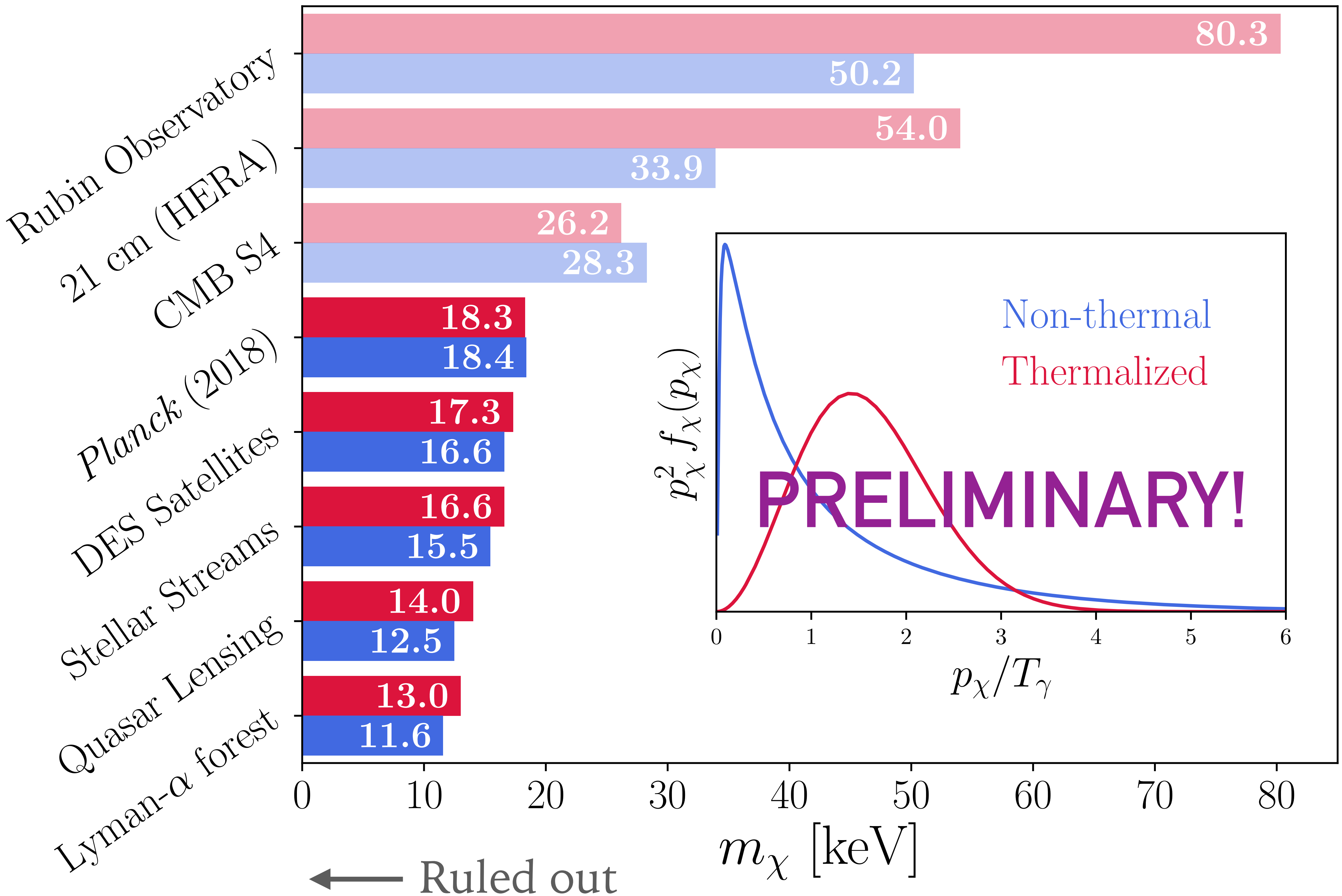
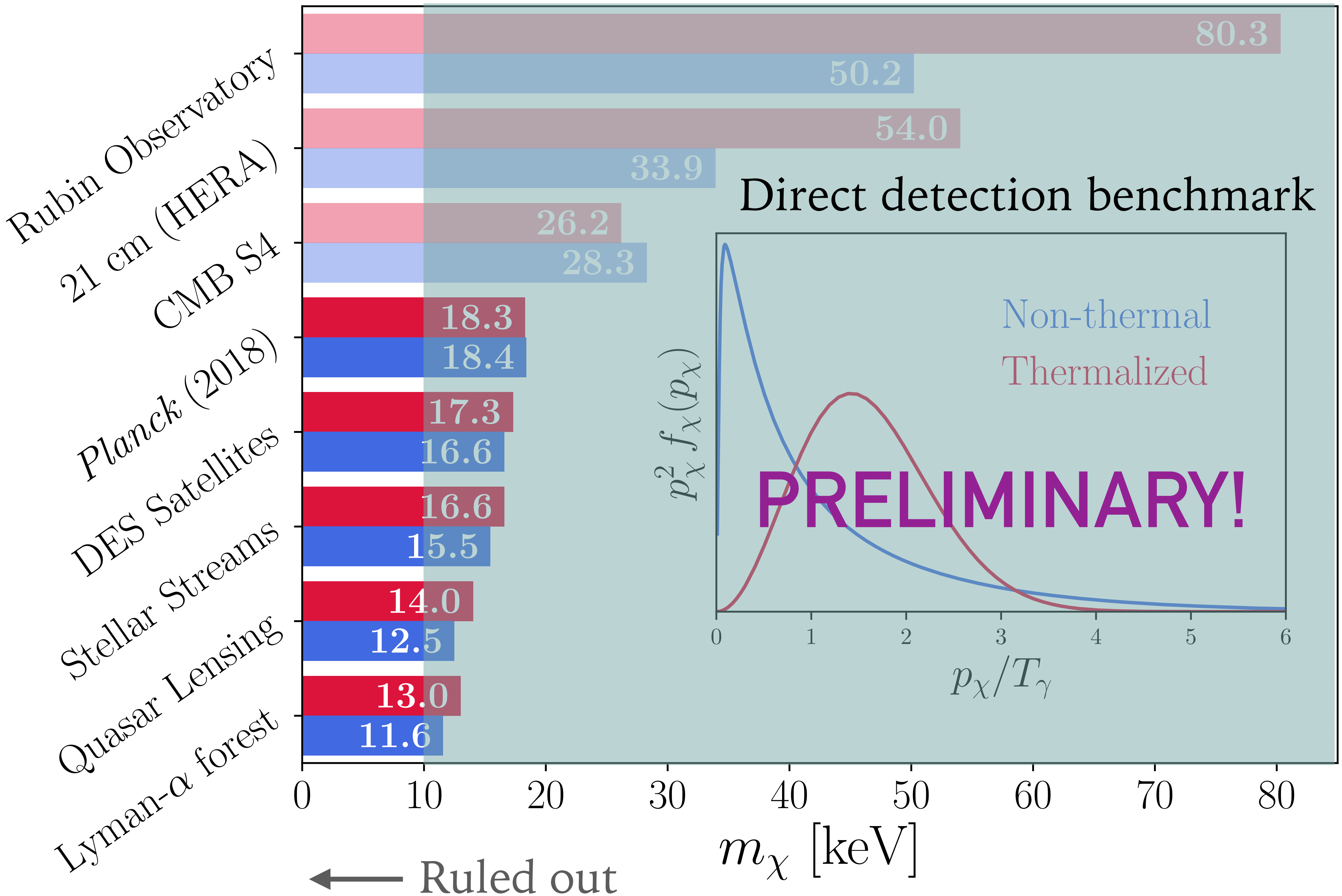
COSMOLOGICAL CONSTRAINTS ON FREEZE-IN



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

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 novel cosmology: warm DM behavior & baryon dragging
- It's a big Universe! Lots of complementarity between probes and room for creativity

COME JOIN ME AT MCGILL!

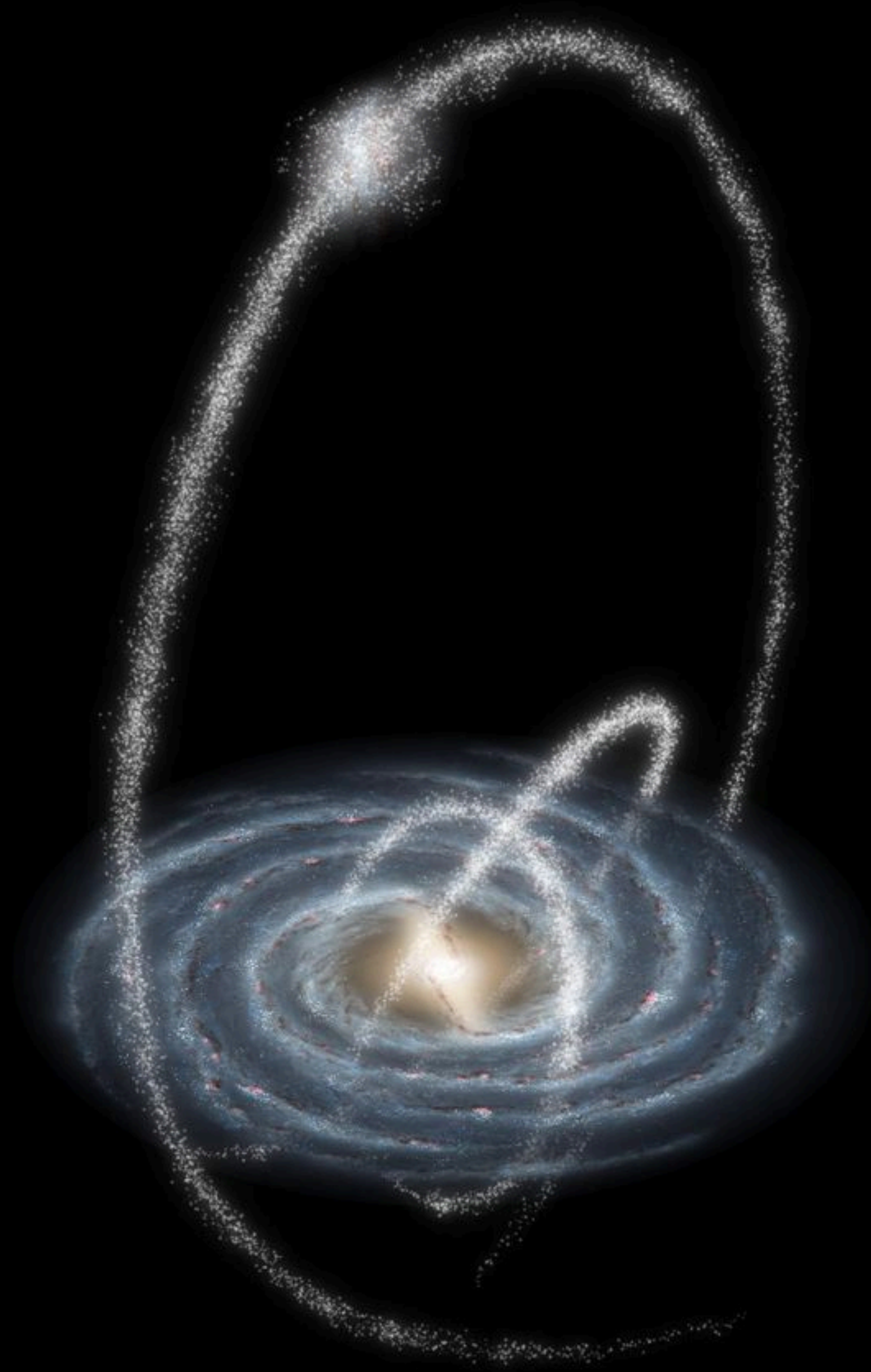
- Looking for grad students and postdocs with a willingness to mix it up, have fun thinking about different topics in the multi-pronged hunt for DM
- Montréal is a great place to live and work, French optional (both for living and professionally— McGill is an English-speaking institution)

ANY QUESTIONS?

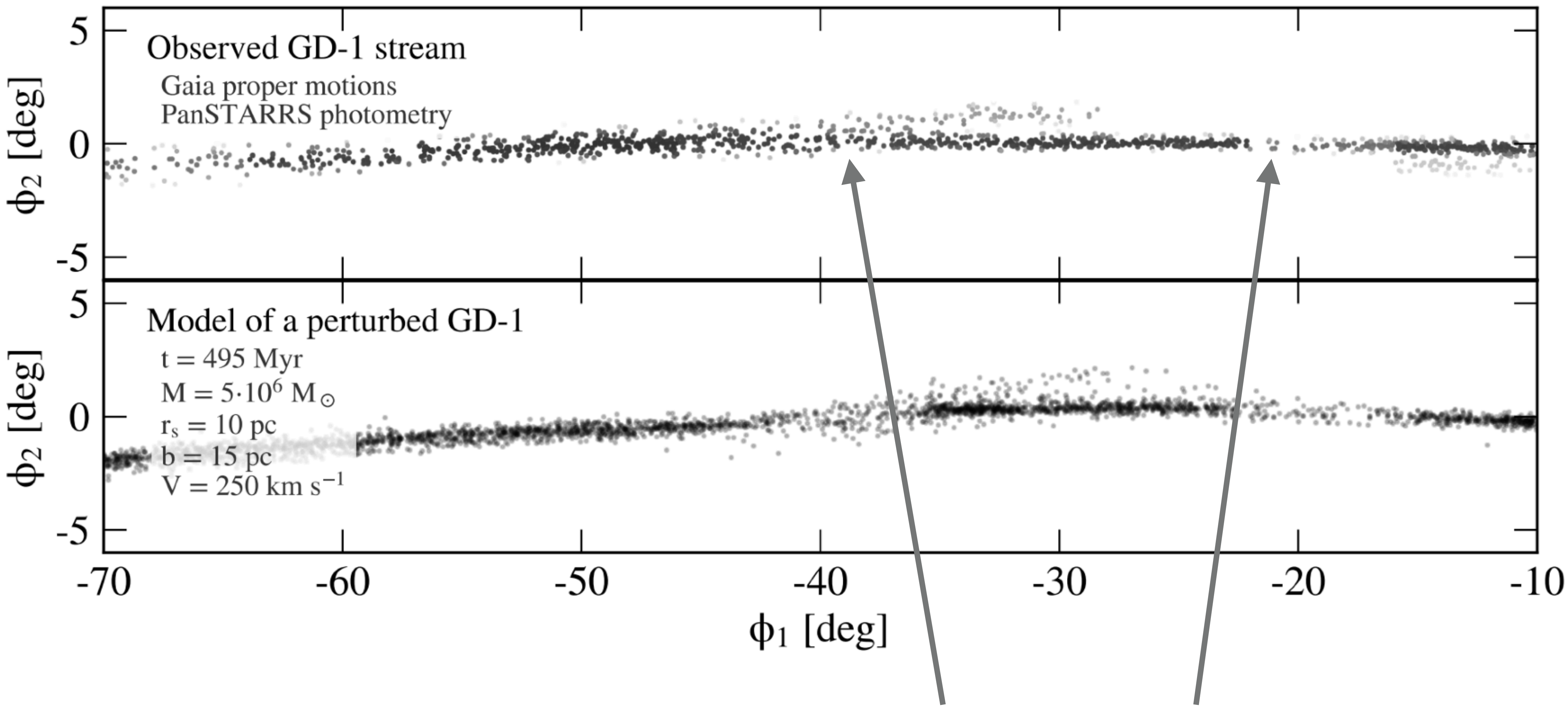
BACKUP SLIDES

STELLAR STREAMS

STELLAR STREAMS (~40 KNOWN IN MILKY WAY)



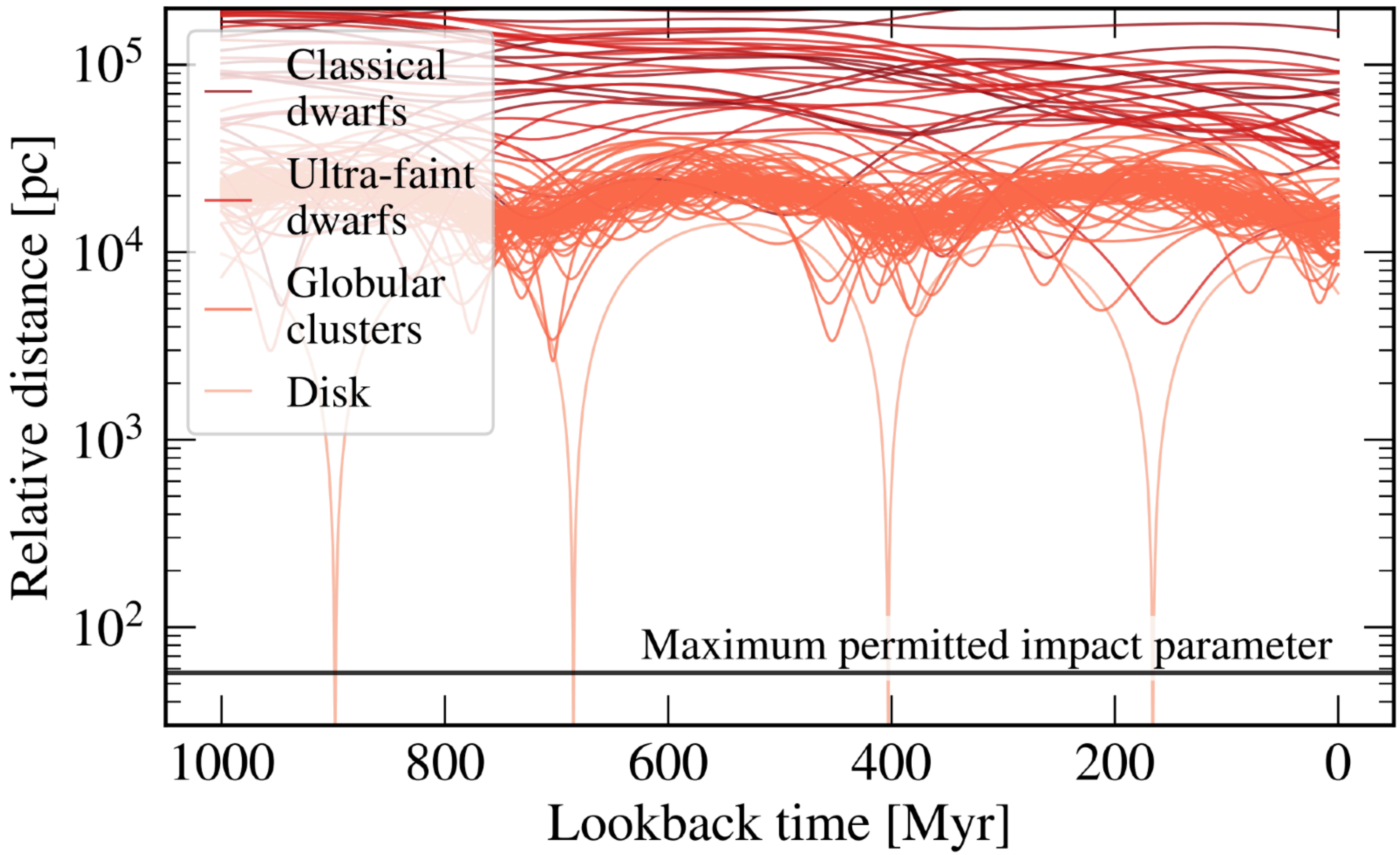
GAIA HAS HELPED US "CLEAN" STREAMS



Features in stream imply a perturber

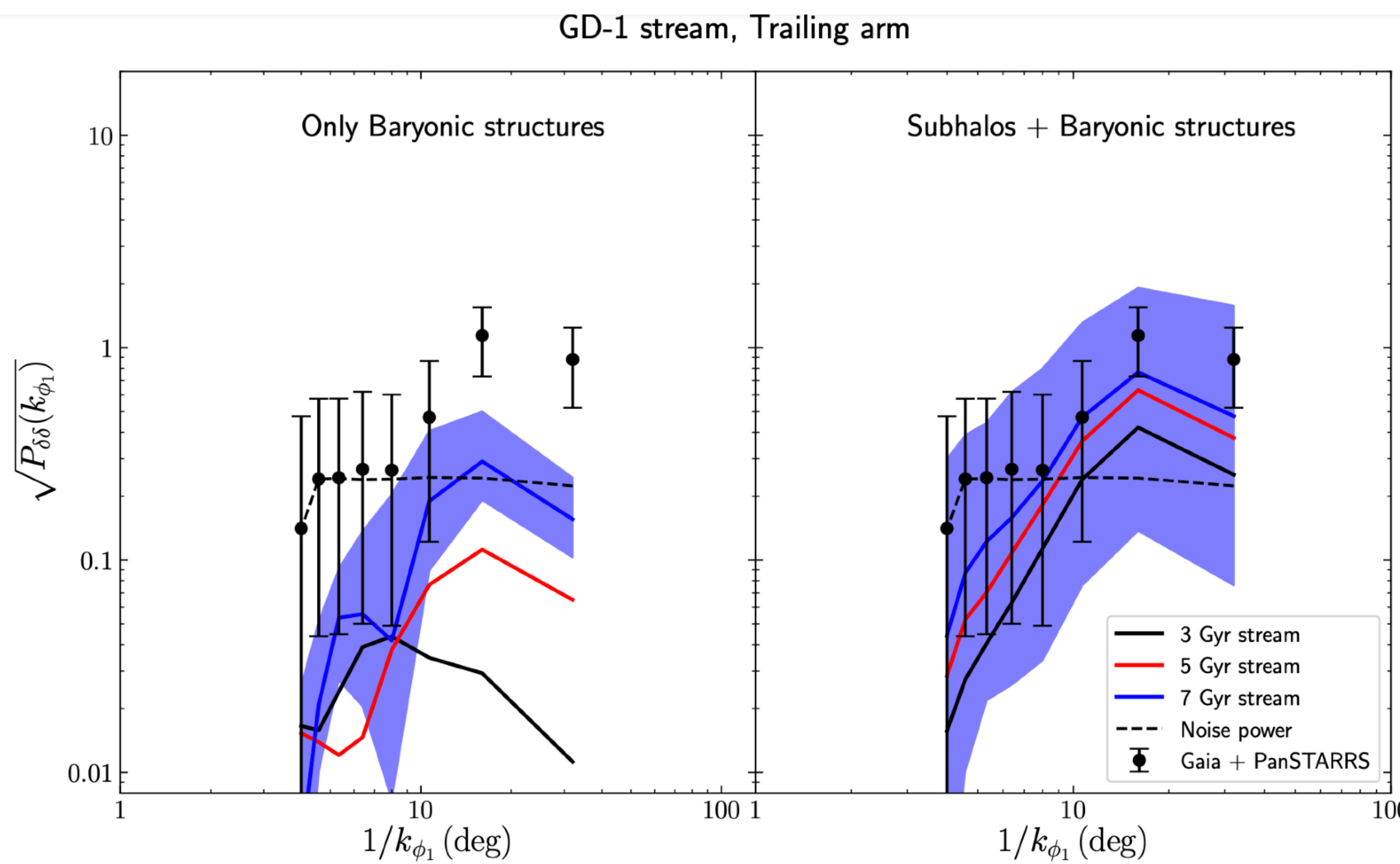
Bonaca, Hogg, Price-Whelan, Conroy (2018)

COULD THE PERTURBER OF GD-1 BE LUMINOUS?



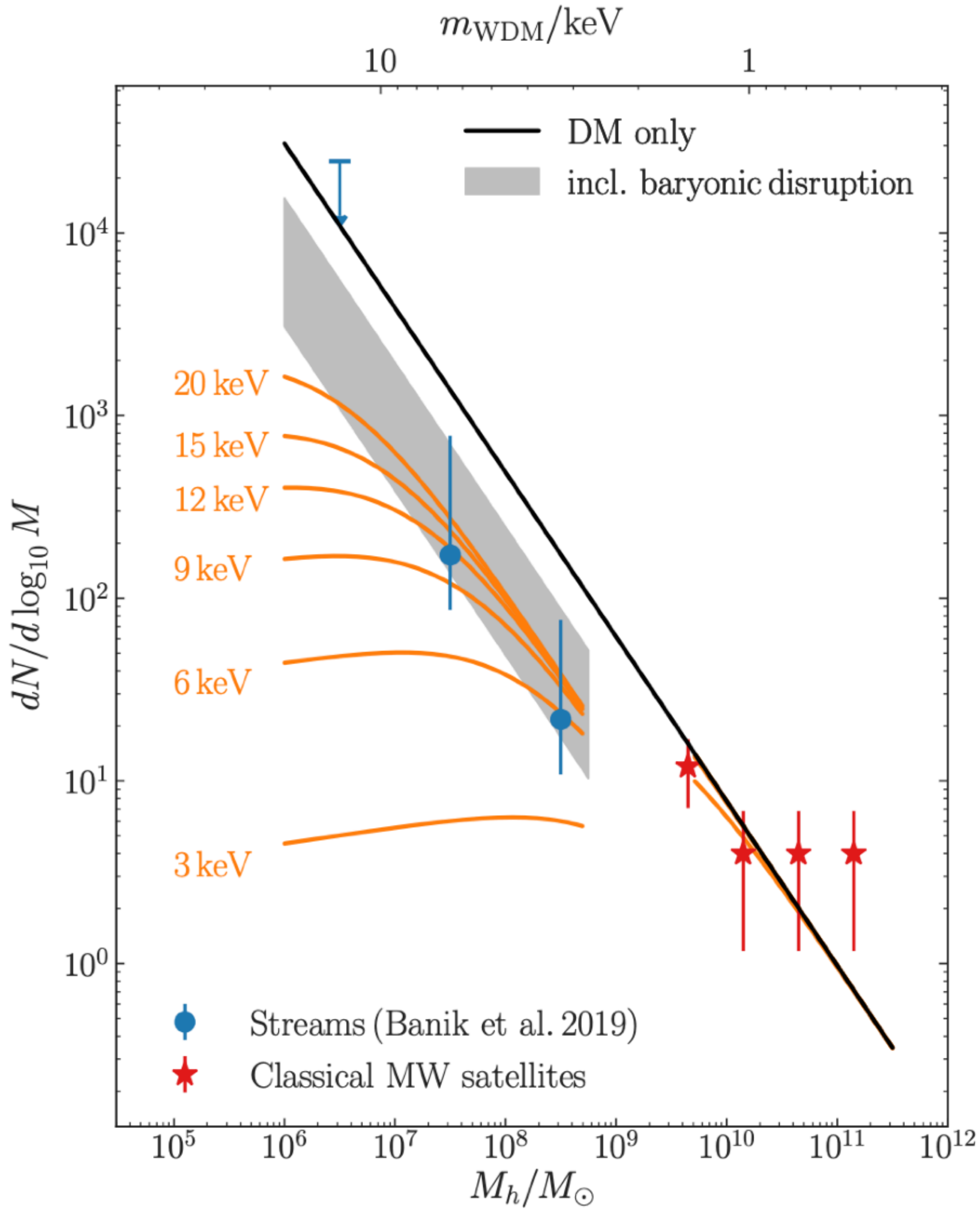
Bonaca, Hogg, Price-Whelan, Conroy (2018)

LOOKING AT POWER SPECTRUM RATHER THAN INDIVIDUAL FEATURES



Banik, Bovy, Bertone, Erkal, deBoer (2019)

CLAIMED MEASUREMENT OF THE HALO MASS FUNCTION

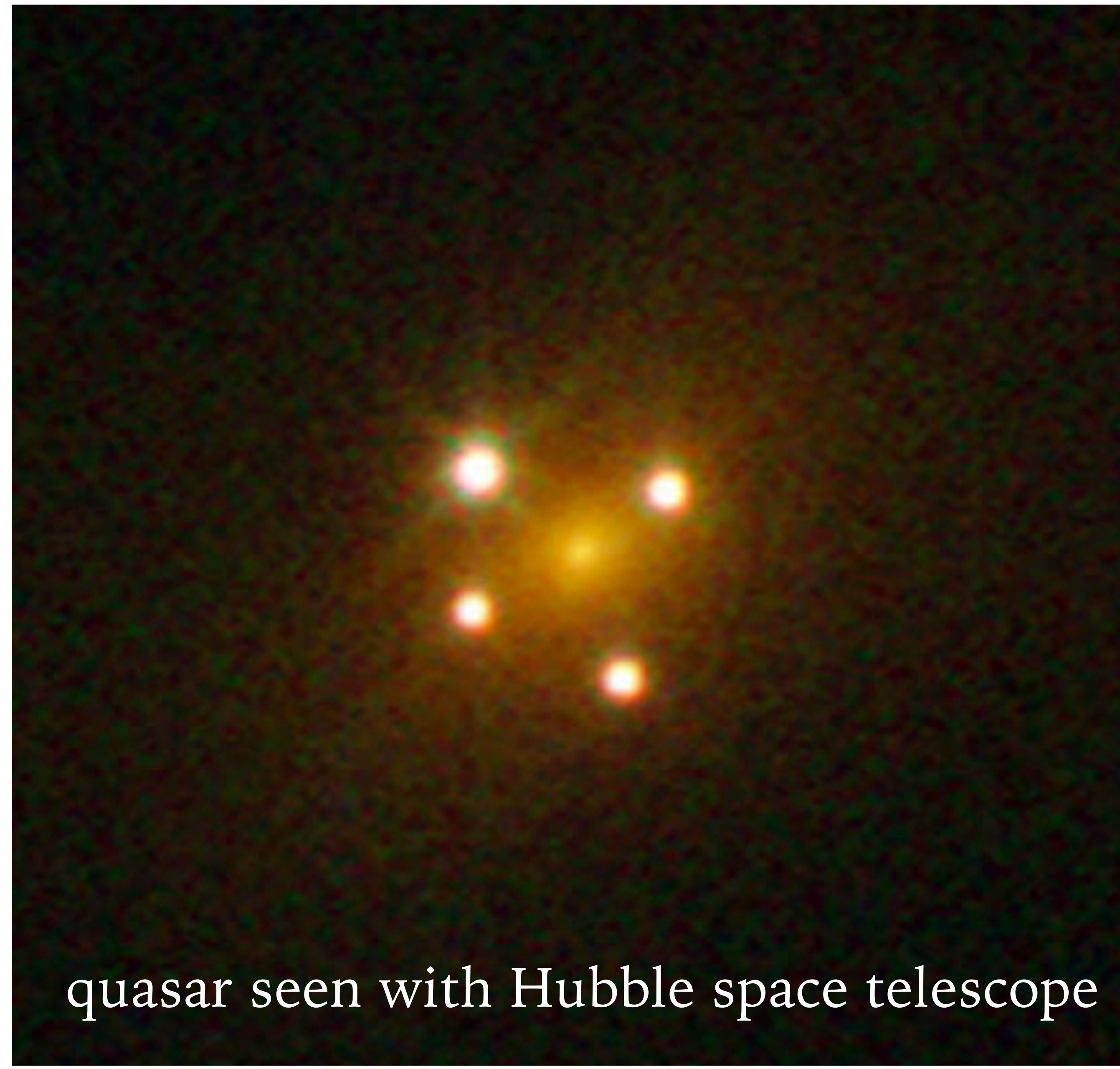


- Banik et al. (2019) claim WDM limit of 6.3 keV by combining power spectra of streams with classical satellites
- Constraint will also apply to freeze-in, limit of around 15 keV

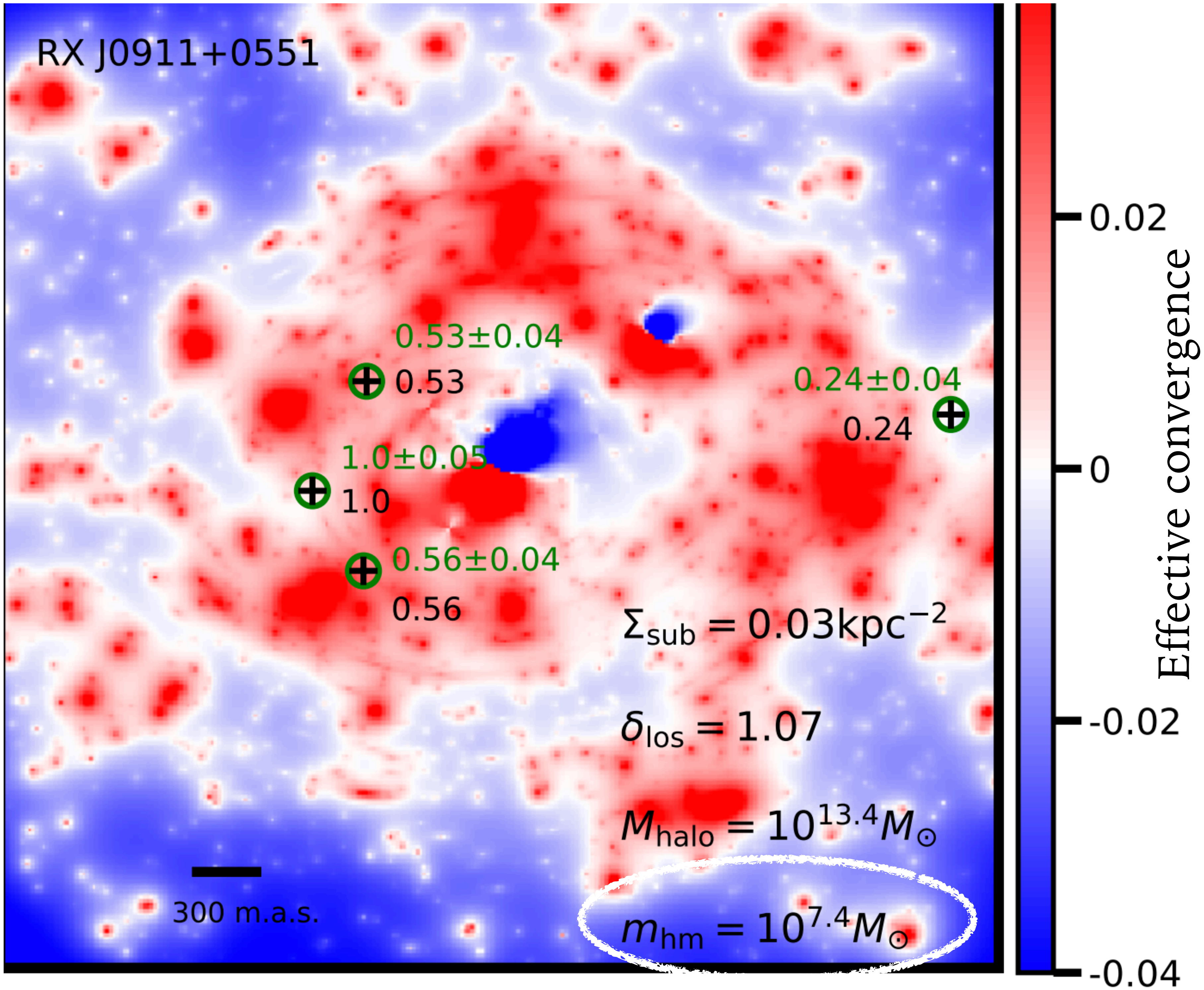
STRONG LENSING

SUBSTRUCTURE CAN BE PROBED WITH GRAVITATIONAL LENSING

- Gravitationally lensed quasars can appear as four images surrounding lens galaxy
- Locations and relative fluxes of images are sensitive to substructure of lens galaxy (second derivatives of lensing potential)


quasar seen with Hubble space telescope

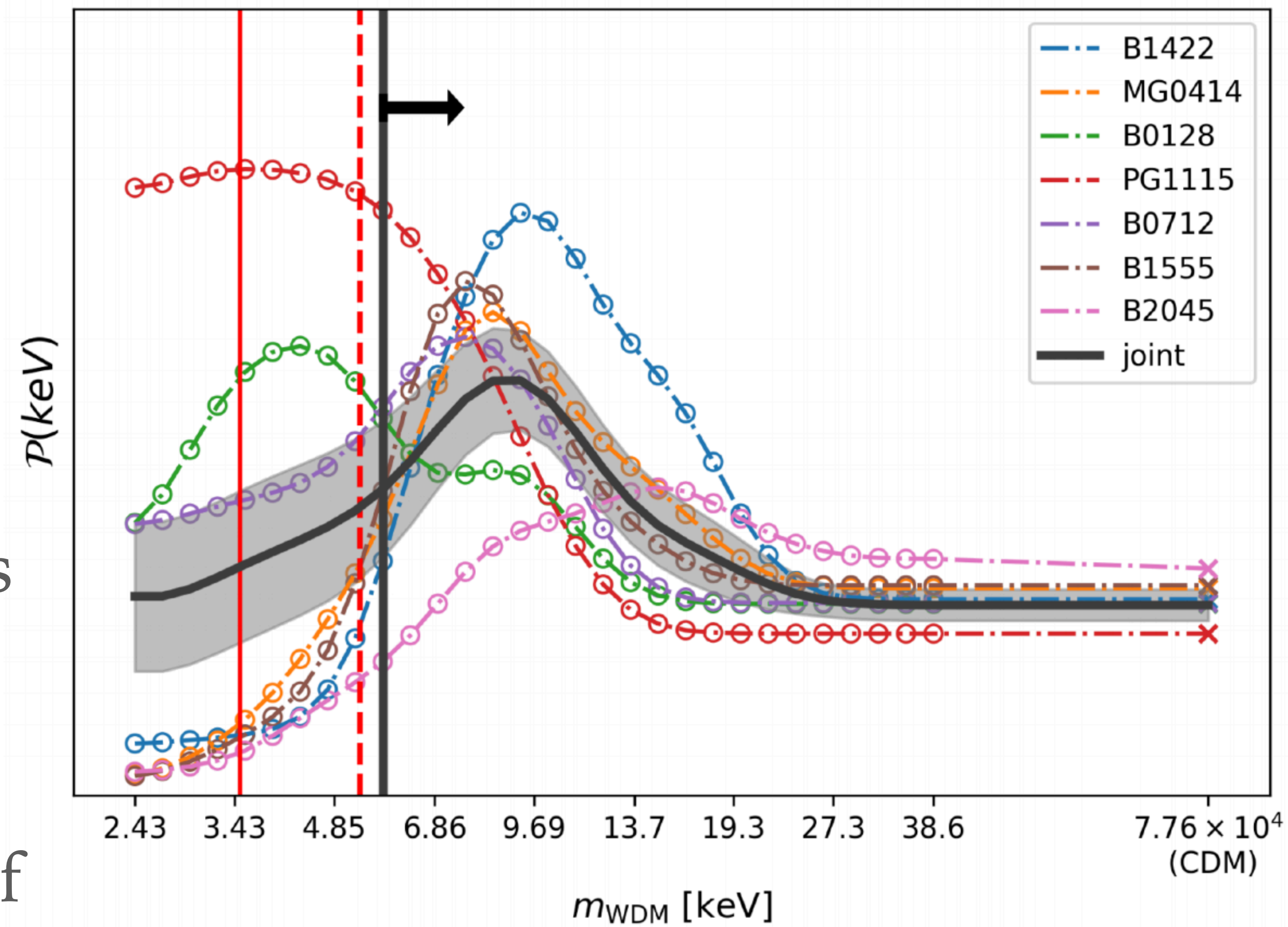
EFFECTIVE CONVERGENCE MAP (HIGH-RANKING REALIZATION)



Gilman et al. (2019)

LENSING CONSTRAINTS ON WDM

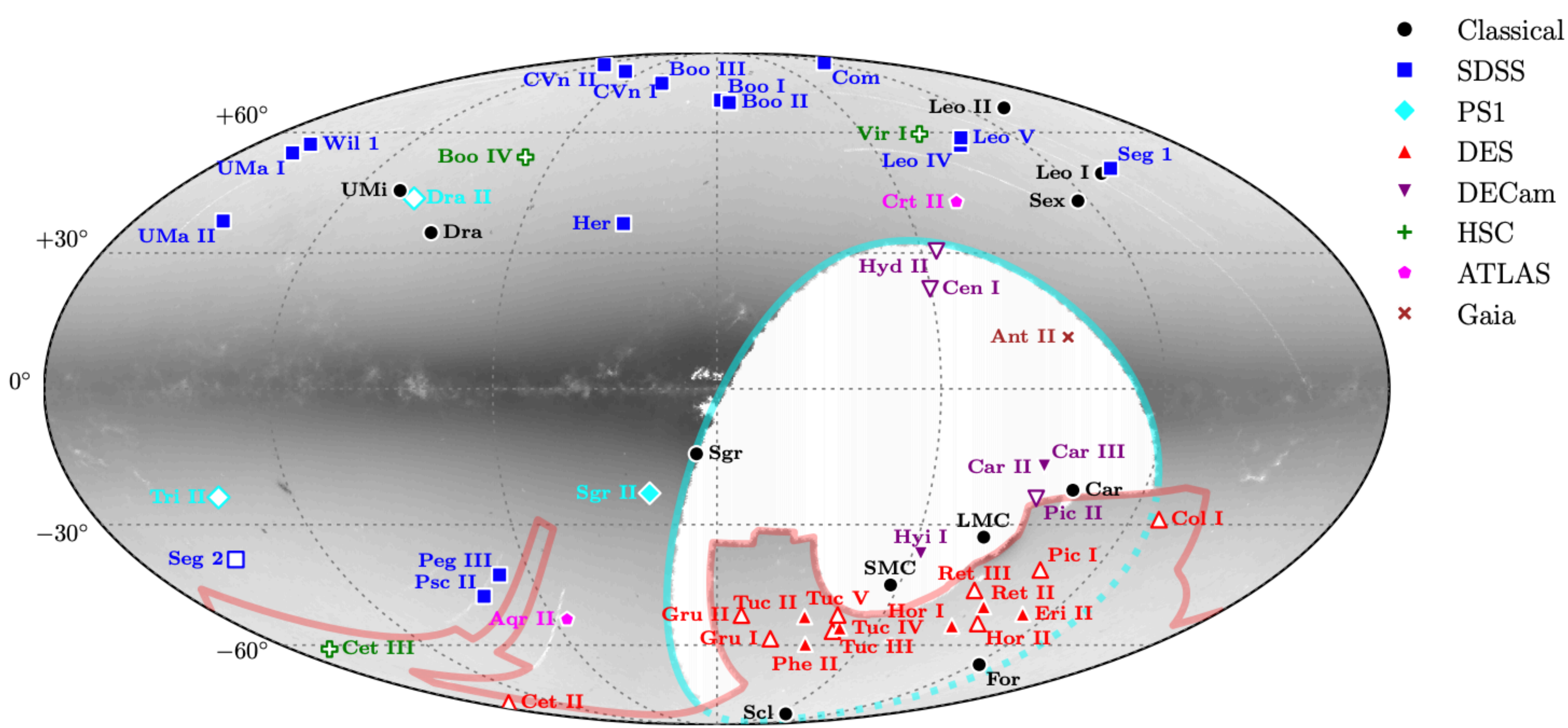
- Analysis of 8 quads by Gilman et al. 2019 excludes WDM lighter than 5.2 keV
- Slightly different analysis of 7 different quads by Hsueh et al. 2019 excludes WDM lighter than 5.6 keV
- This translates to a limit of ~13 keV on freeze-in (depending on thermalization)



Hsueh et al. (2019)

DWARF GALAXY COUNTS

FINDING NEW DWARF GALAXIES



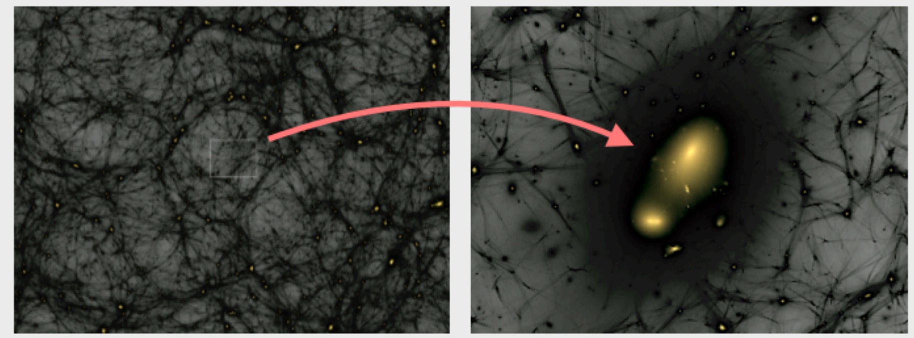
Drlica-Wagner et al. (DES collaboration, 2019)

UNDERSTANDING GALAXY–HALO CONNECTION EMPIRICALLY

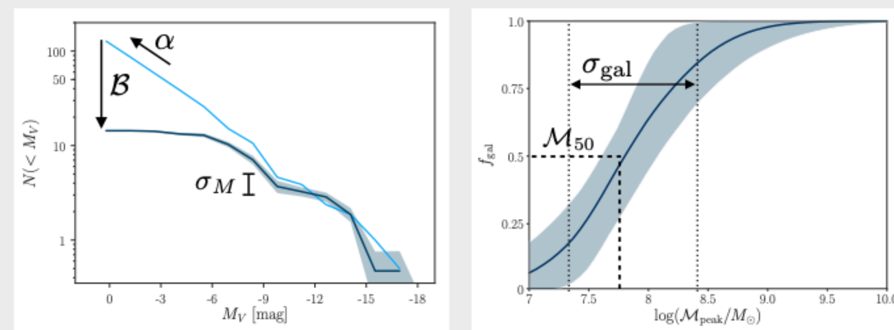
Nadler et al. (DES Collaboration 2019)

Markov Chain Monte Carlo

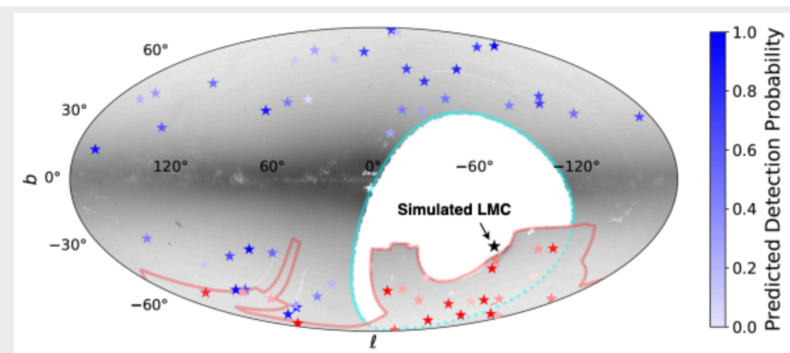
1. Resimulate Milky Way-like halos from large cosmological volume.



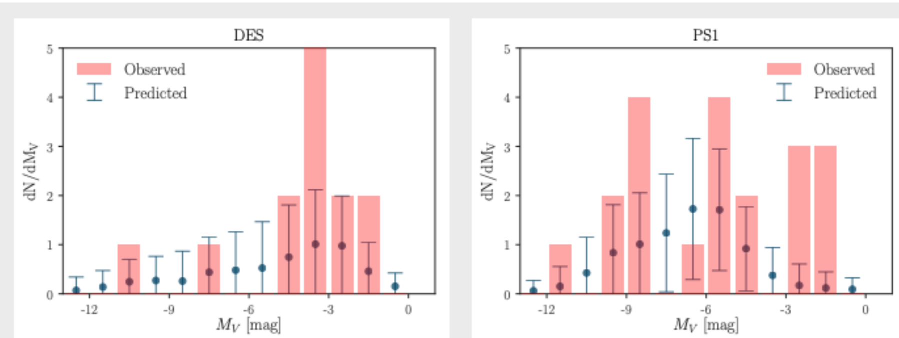
2. Paint satellite galaxies onto subhalos using galaxy—halo model.



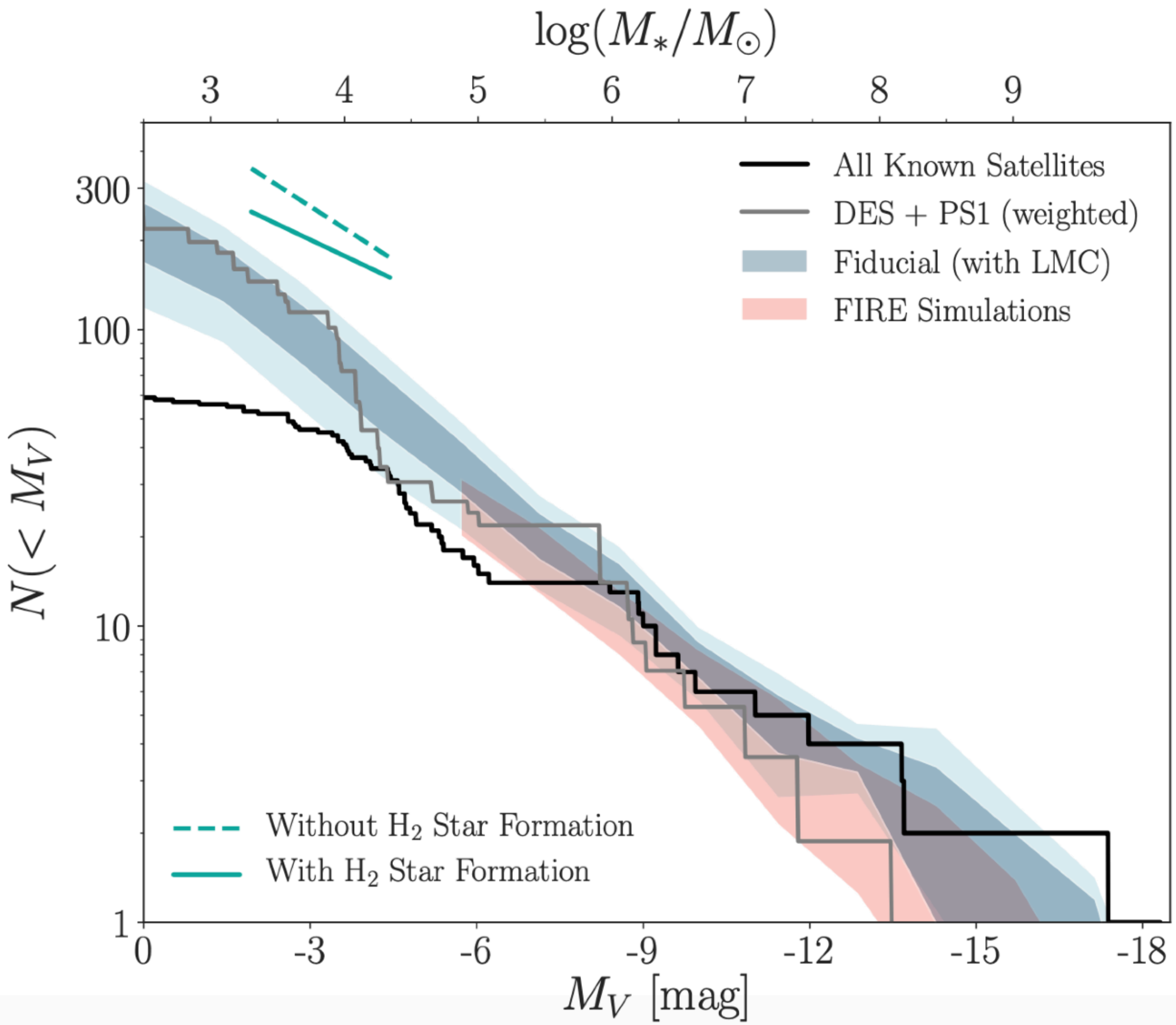
3. Apply observational selection functions based on imaging data.



4. Calculate likelihood of observed satellites given galaxy—halo connection parameters.



UNDERSTANDING GALAXY-HALO CONNECTION EMPIRICALLY

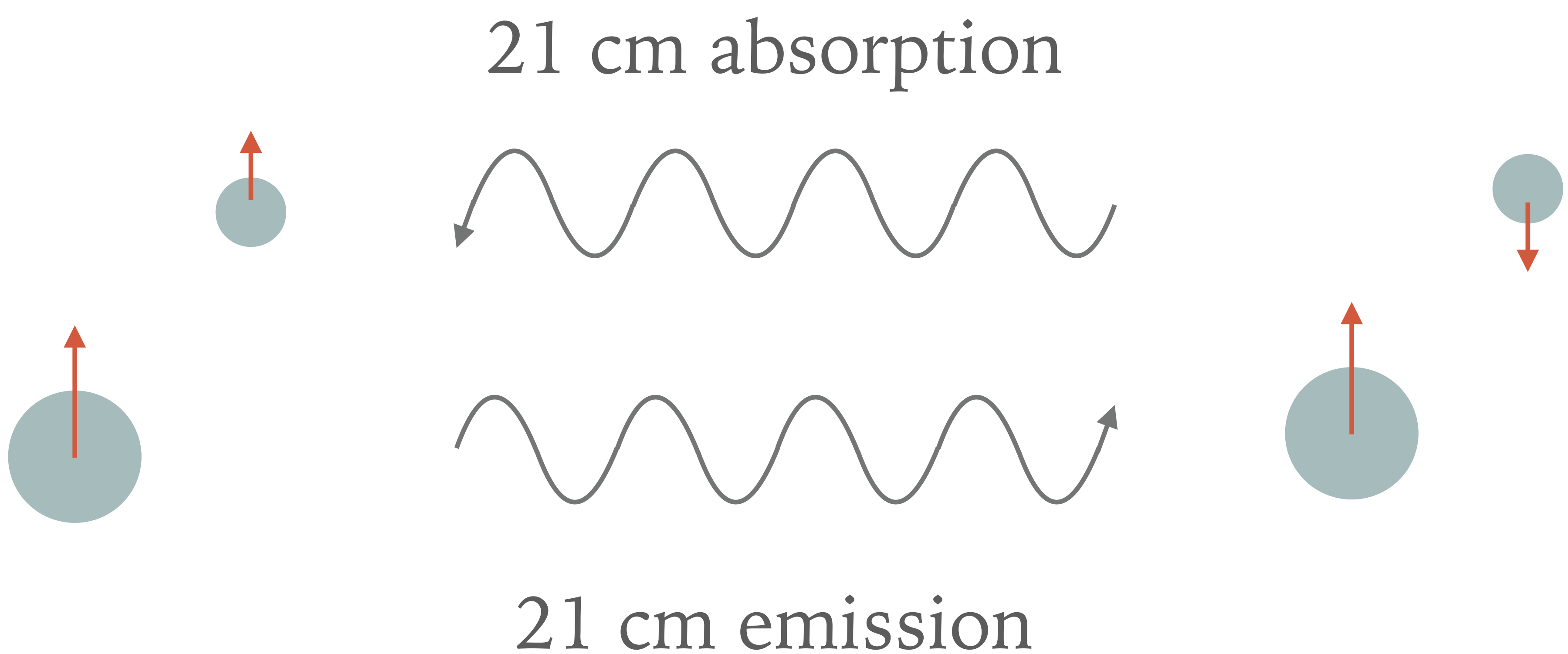


The presence of low-mass subhalos (after accounting for selection effects) is consistent with CDM and rules out WDM masses below 6.5 keV (and freeze-in below 17 keV)

Nadler et al. (DES Collaboration 2019,2020)

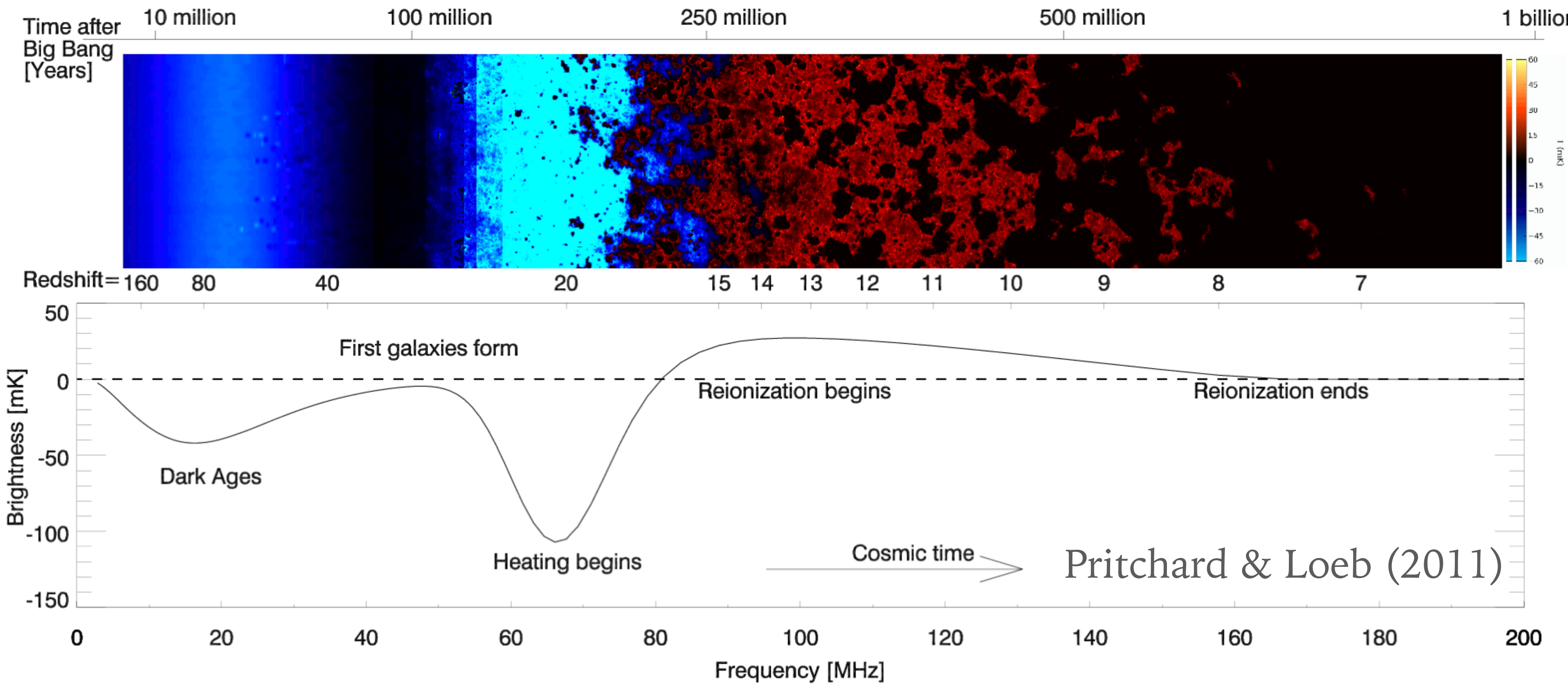
21 CM COSMOLOGY

21 CM COSMOLOGY



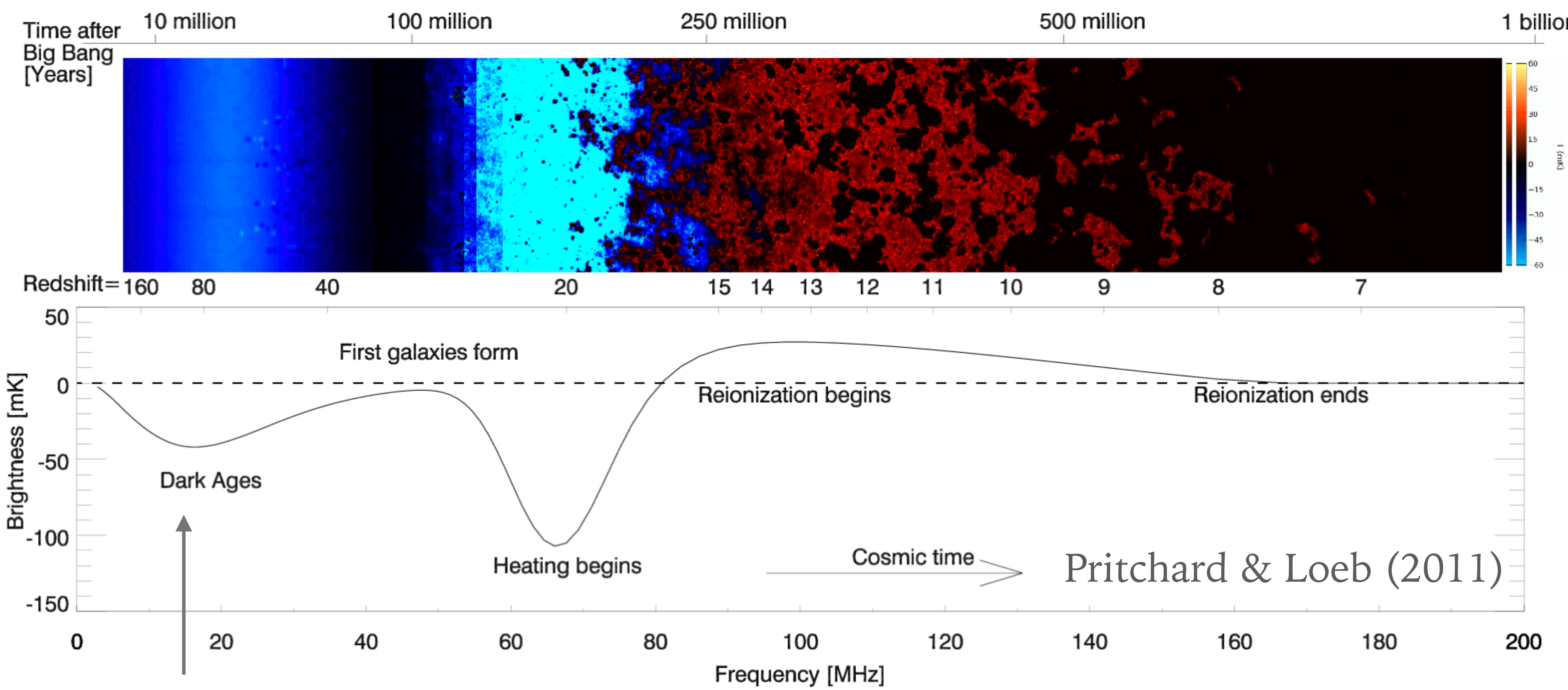
Whether we see this in emission or absorption depends on complicated physics of how the spin temperature, kinetic gas temperature (velocity) and CMB temperature are coupled…

THE 21 CM GLOBAL SIGNAL



Pritchard & Loeb (2011)

THE 21 CM GLOBAL SIGNAL

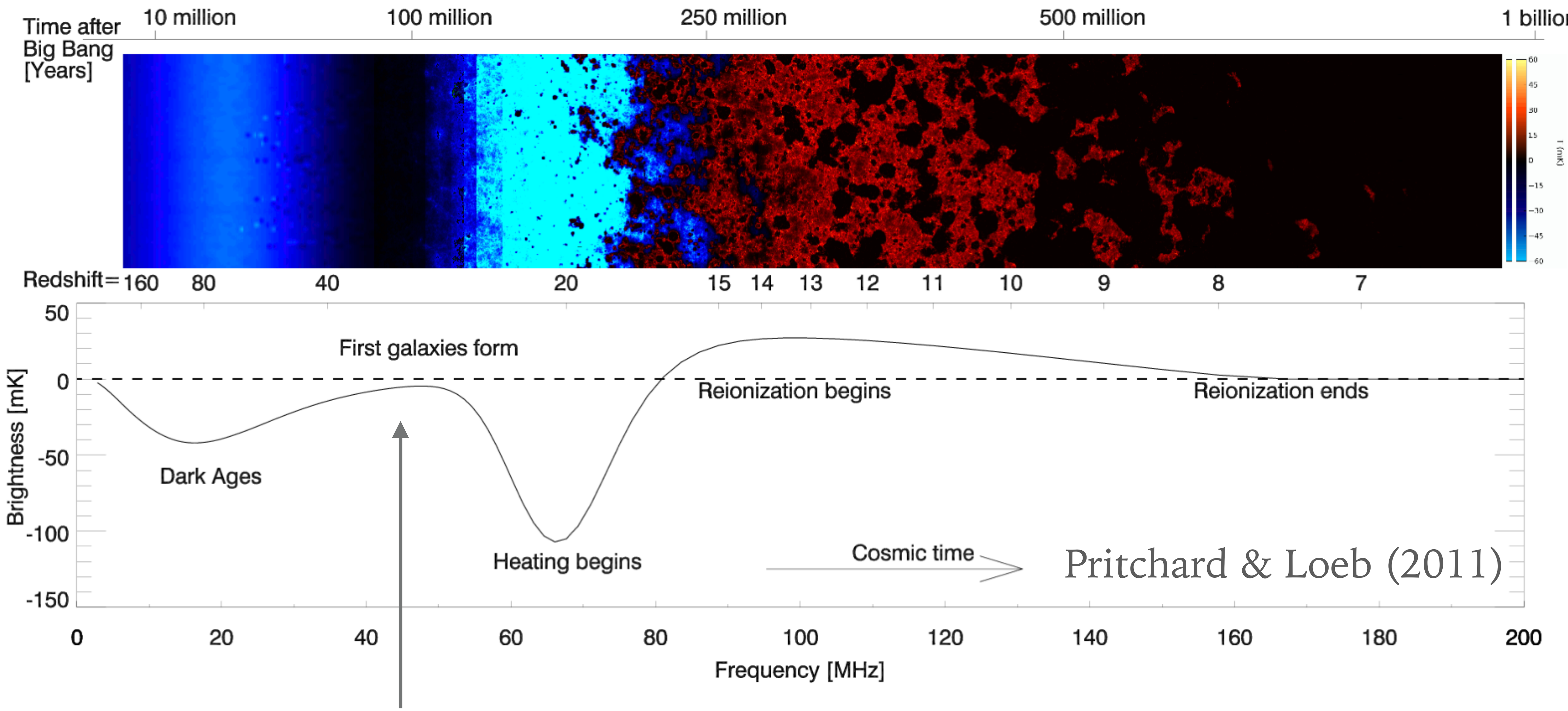


Pritchard & Loeb (2011)

$T_{spin} = T_{kin} < T_{CMB}$

high density, frequent collisions couple spin and kinetic temperatures, not many free electrons to couple CMB and kinetic temperatures

THE 21 CM GLOBAL SIGNAL

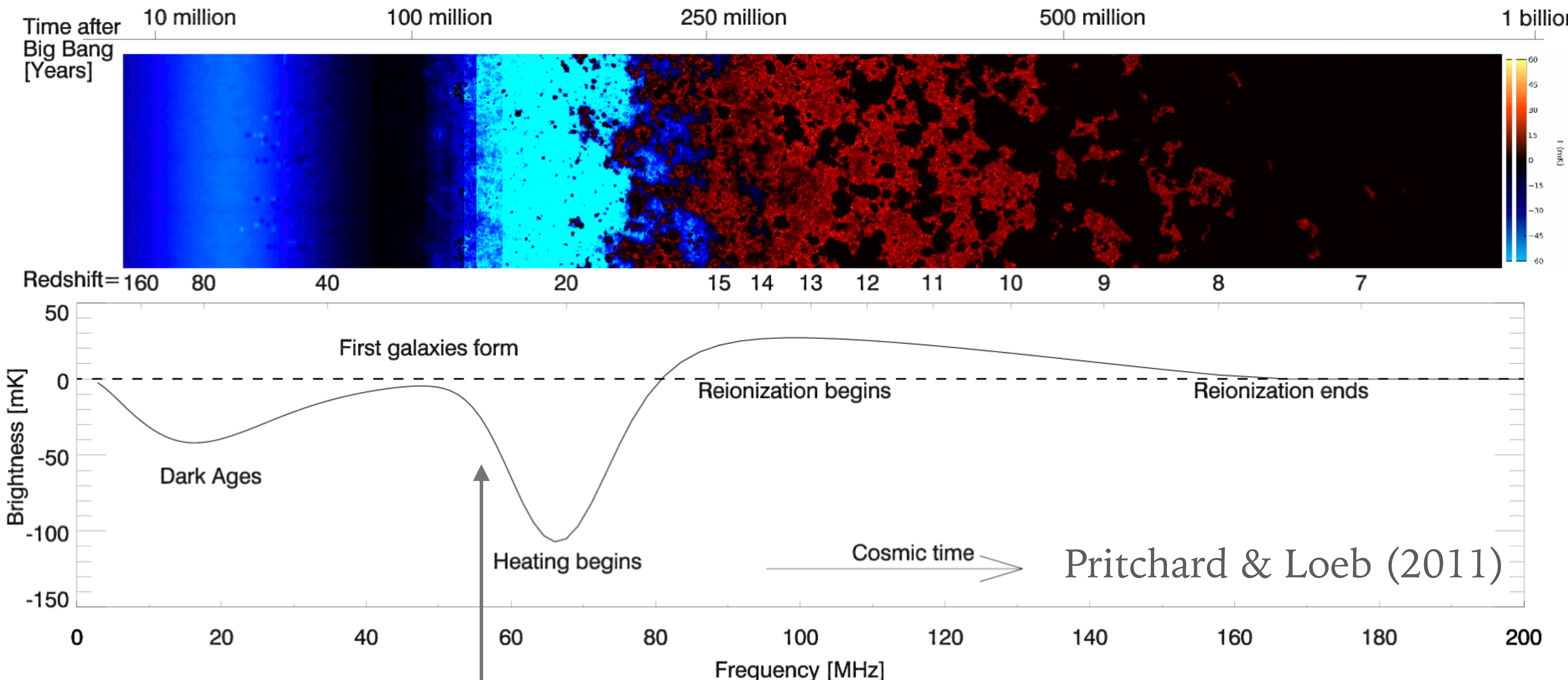


Pritchard & Loeb (2011)

$T_{spin} = T_{CMB} > T_{kin}$

fewer collisions, spin temperature more coupled to CMB

THE 21 CM GLOBAL SIGNAL

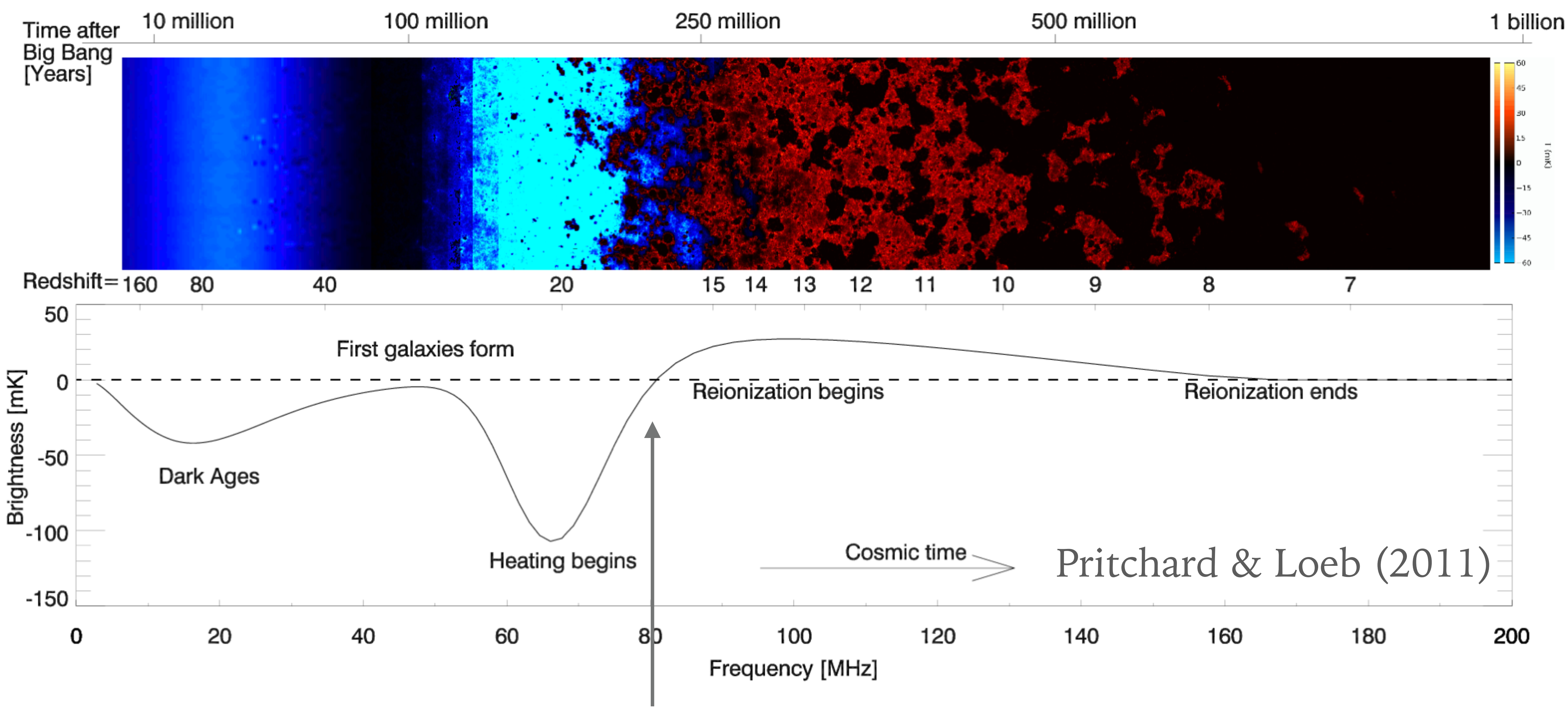


Pritchard & Loeb (2011)

$T_{spin} \rightarrow T_{kin} < T_{CMB}$

WF effect couples ly-α photons to spin temperature, drives spin temperature down to kinetic temperature

THE 21 CM GLOBAL SIGNAL

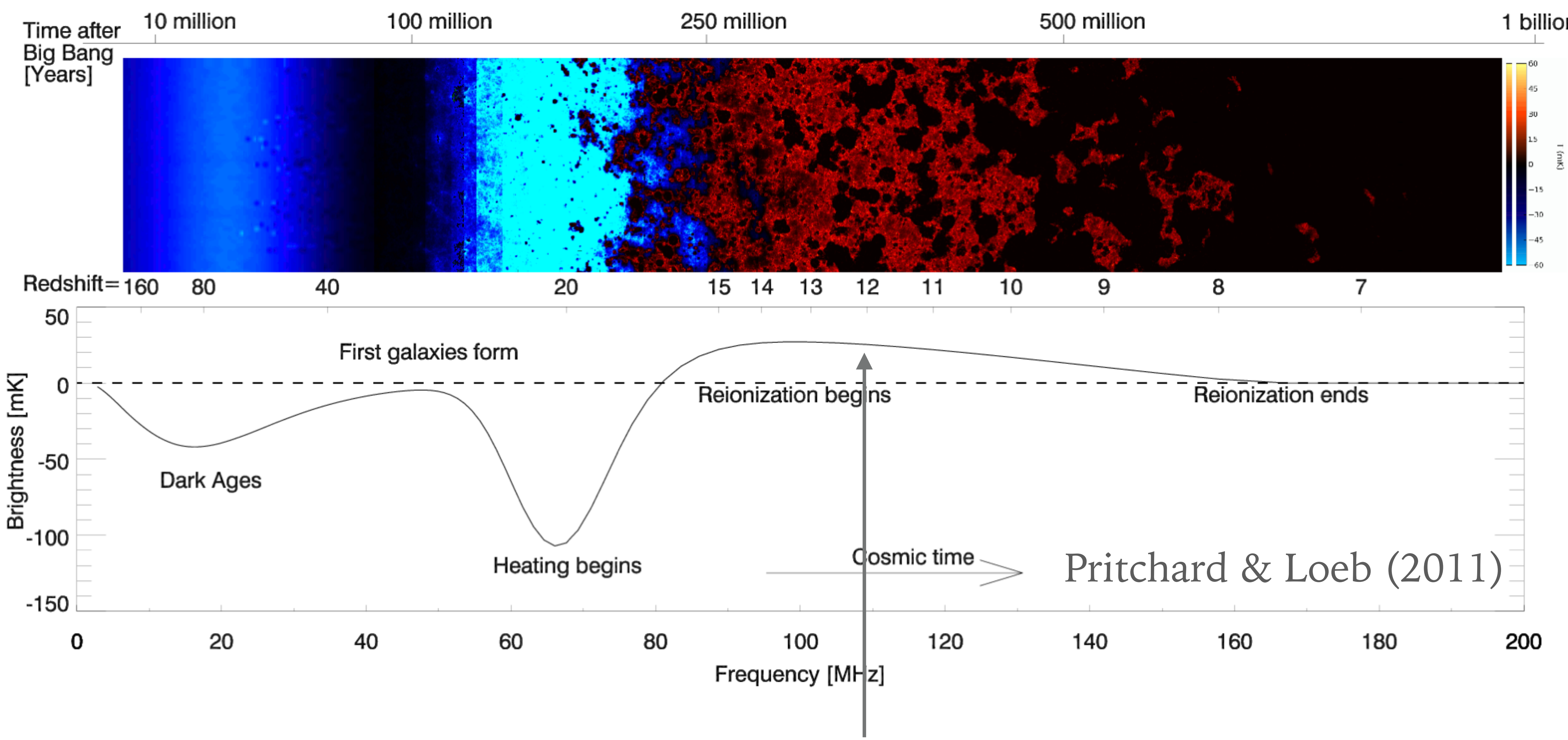


Pritchard & Loeb (2011)

$T_{spin} \rightarrow T_{kin} > T_{CMB}$

bright sources heat up the gas, which eventually gets hotter than the CMB

THE 21 CM GLOBAL SIGNAL

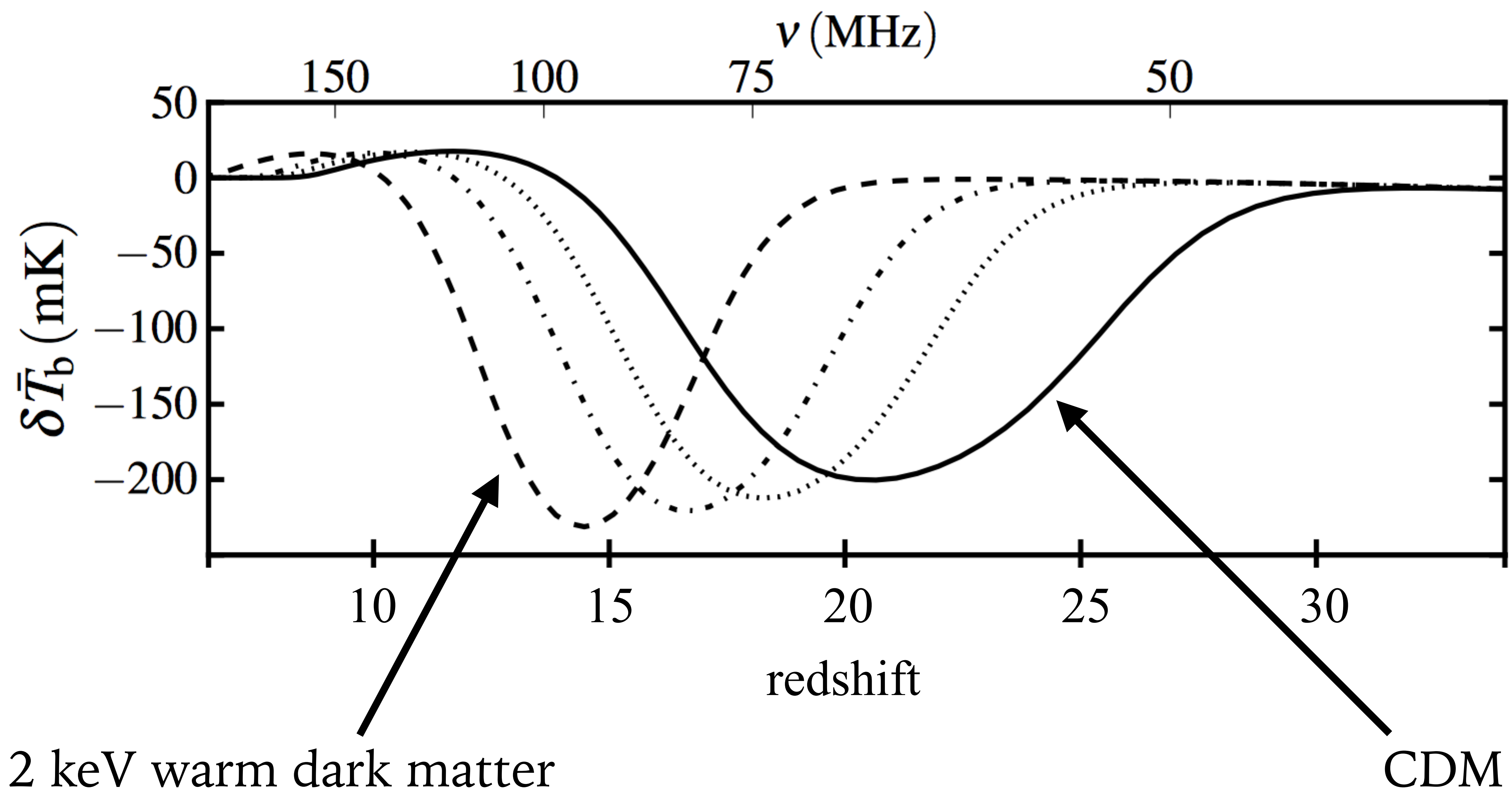


Pritchard & Loeb (2011)

$T_{spin} \rightarrow T_{kin} > T_{CMB}$

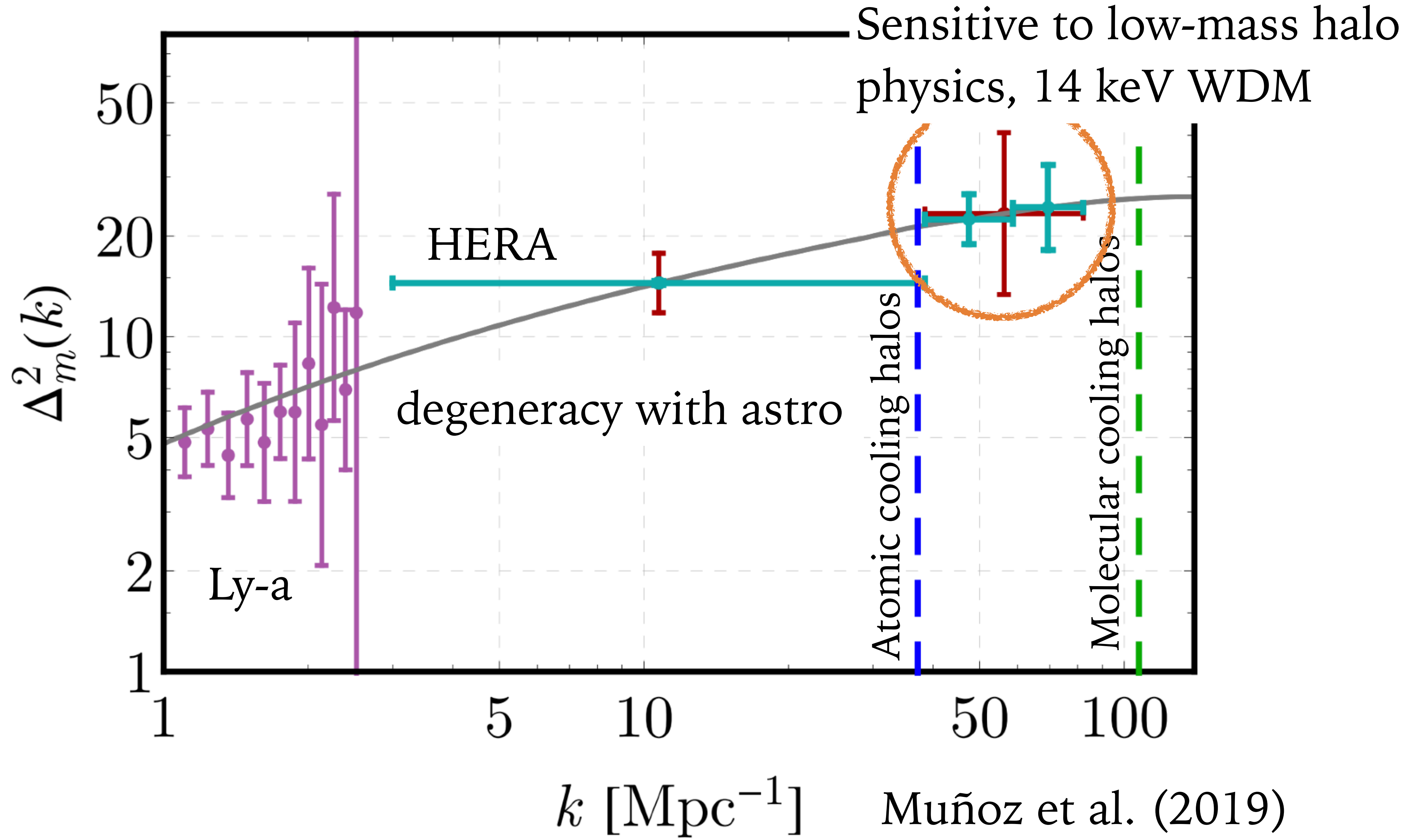
same bright sources emit ionizing radiation, decreasing signal strength (fewer neutral atoms)

FEWER LOW-MASS HALOS & 21 CM



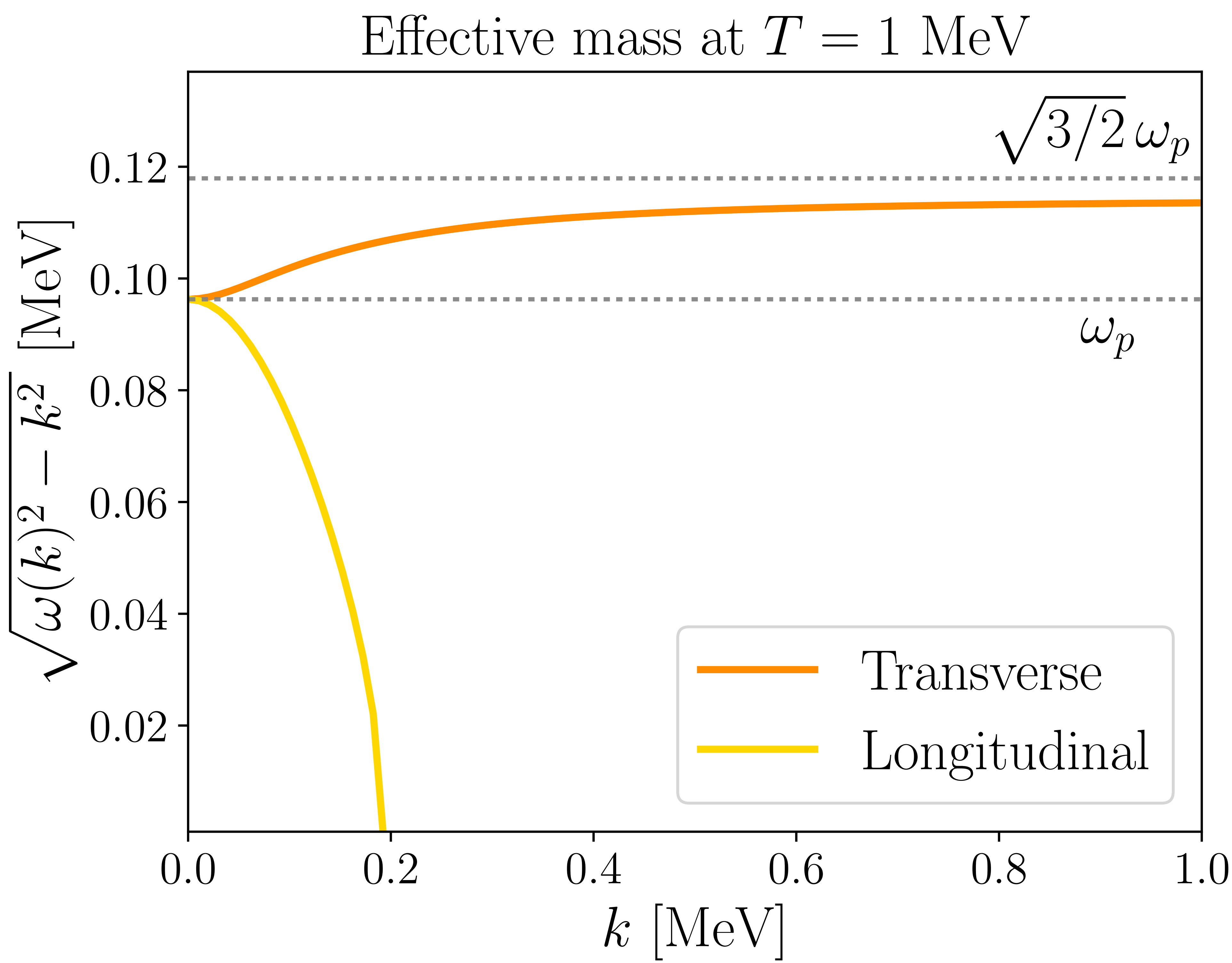
Sitwell et al. (2013)

FEWER LOW-MASS HALOS & 21 CM



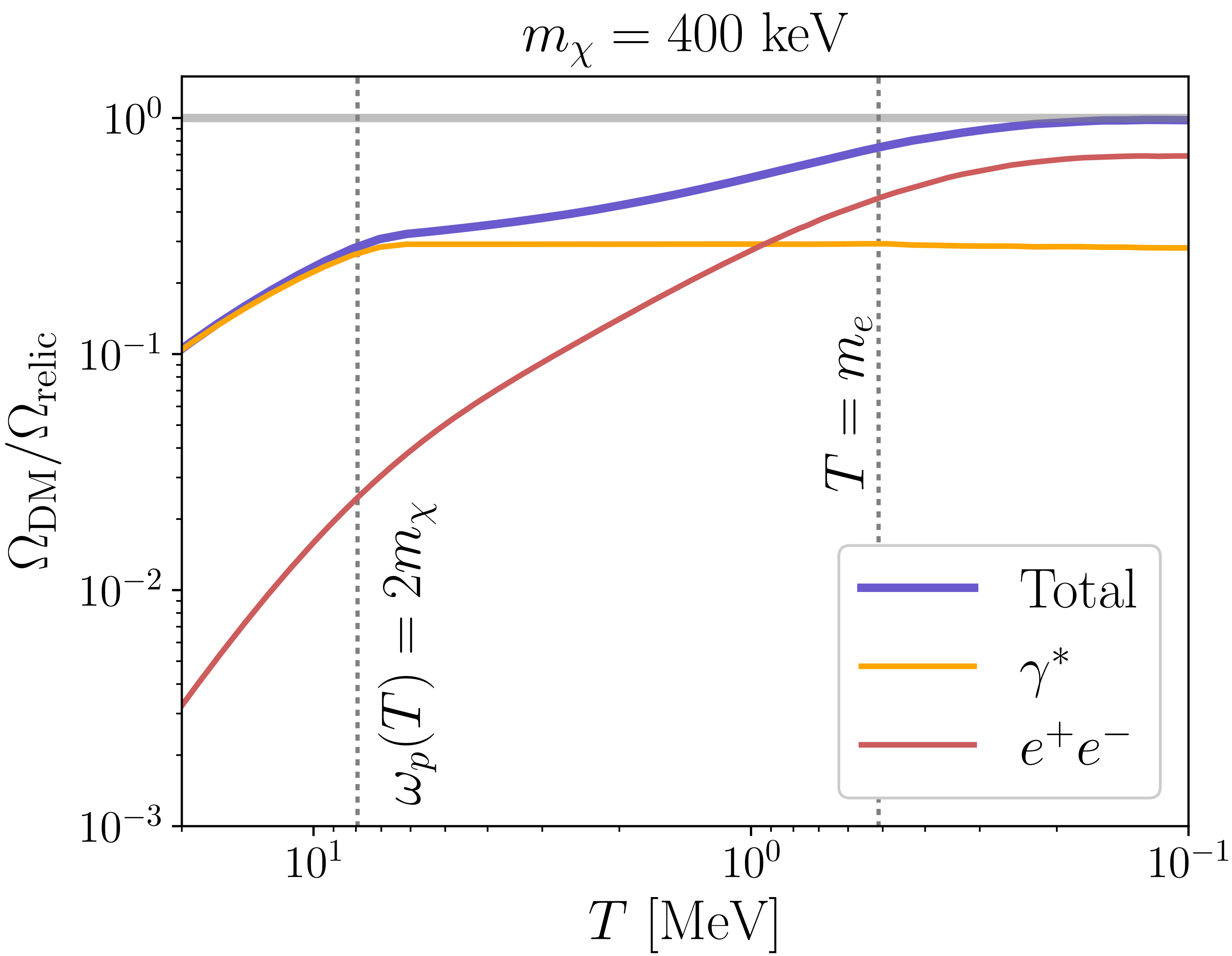
Muñoz et al. (2019)

MISCELLANEOUS



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

MASS DEPENDENCE OF PLASMON CHANNEL



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

DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy: $$\frac{\partial f}{\partial t} - H\frac{p^2}{E}\frac{\partial f}{\partial E} = \frac{C[f]}{E}$$

$$\frac{C[f_{X_1}]}{E_{X_1}} = \int \frac{đ^3 p_{e_1}}{2E_{e_1}}\frac{đ^3 p_{e_2}}{2E_{e_2}}\frac{đ^3 p_{X_2}}{2E_{X_2}} f_{e_1} f_{e_2}\, \delta^{(4)}(\Sigma\, p)\, |\mathcal{M}|^2_{e_1+e_2\to X_1+X_2} + \int \frac{đ^3 p_{\gamma *}}{2E_{\gamma *}}\frac{đ^3 p_{X_2}}{2E_{X_2}} f_{\gamma *}\, \delta^{(4)}(\Sigma\, p)\, |\mathcal{M}|^2_{\gamma * \to X_1+X_2}$$

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annihilations

DEALING WITH NON-THERMAL PHASE SPACE

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plasmon decays

DEALING WITH NON-THERMAL PHASE SPACE

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Note frame dependent thermal factors, must evaluate in rest frame of plasma

DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy:

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NB: ignore scattering at early times (close to freeze-in) both with DM and with baryons because momenta are relatively high and t-channel scattering is peaked at low momentum transfer

DEALING WITH NON-THERMAL PHASE SPACE

un-truncated Boltzmann hierarchy:

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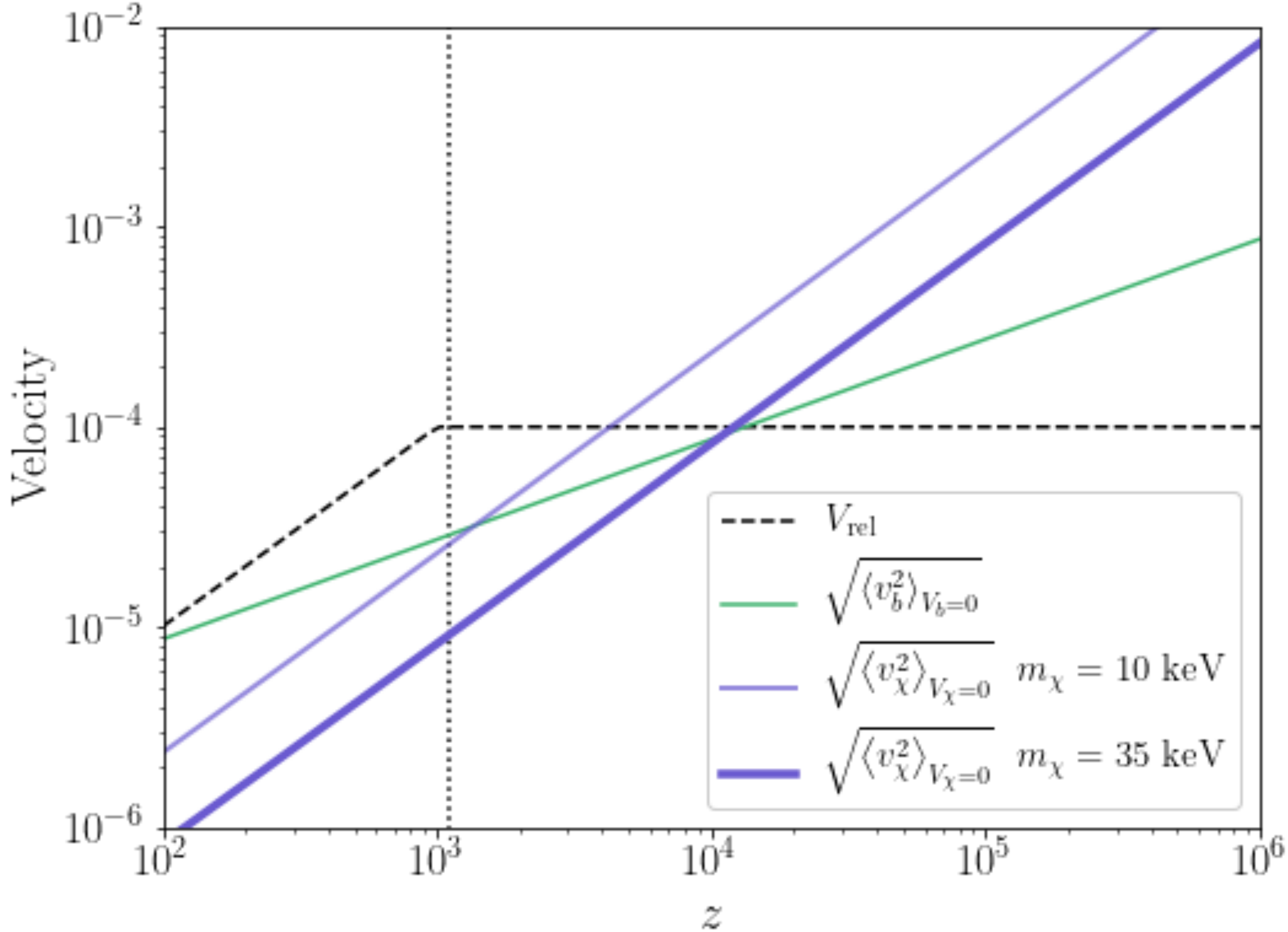
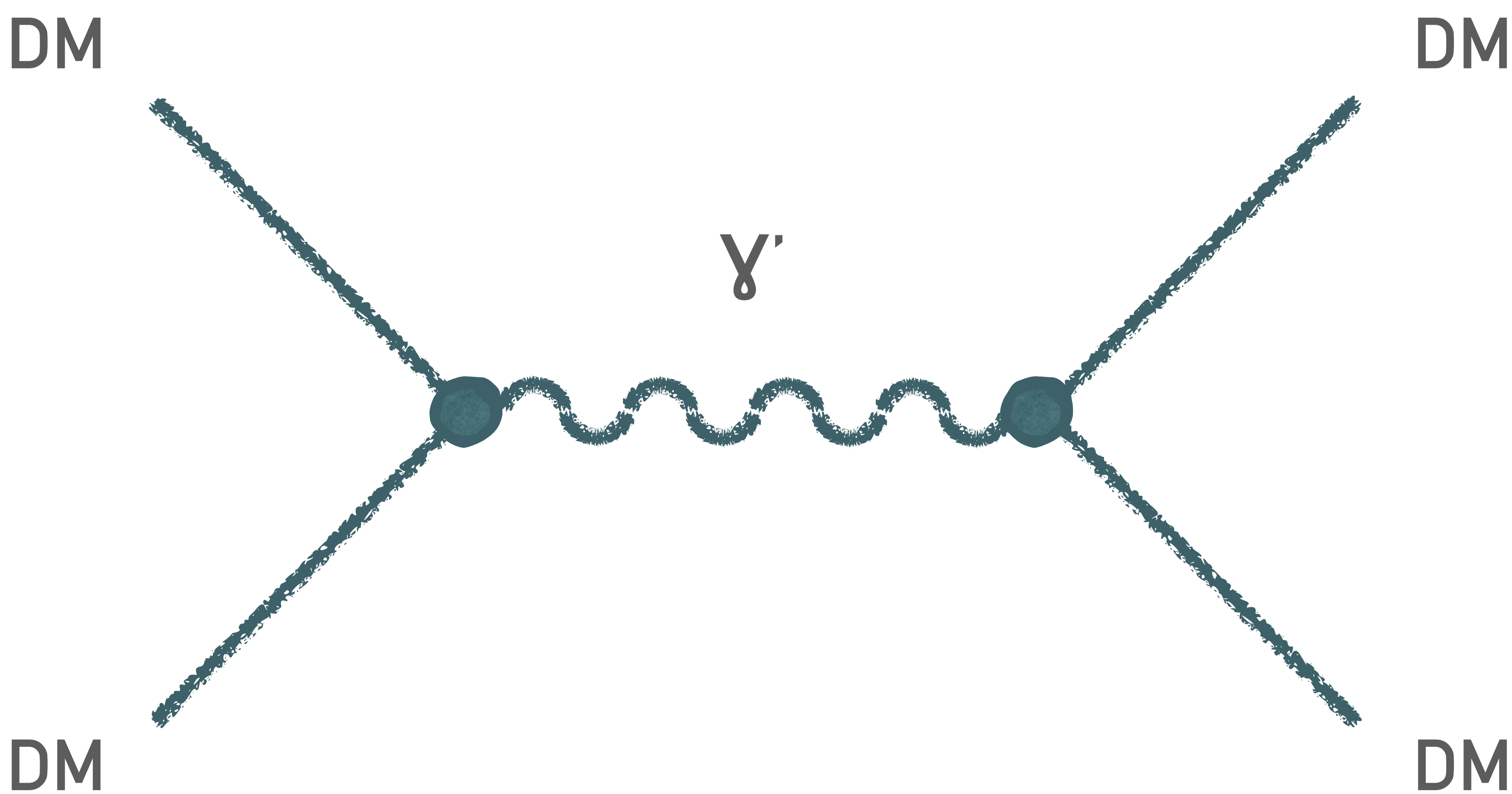
key fact: due to low DM occupation number, the collisions are actually independent of the DM phase space!

$$f_X(p,t) = \int_{t_i}^{t} dt' \, \frac{C\left(\frac{a(t)}{a(t')}\, p, t'\right)}{E}$$



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Velocity
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
z
$V_{\rm rel}$
$\sqrt{\langle v_b^2 \rangle_{V_b=0}}$
$\sqrt{\langle v_\chi^2 \rangle_{V_\chi=0}}$ $m_\chi = 10$ keV
$\sqrt{\langle v_\chi^2 \rangle_{V_\chi=0}}$ $m_\chi = 35$ keV

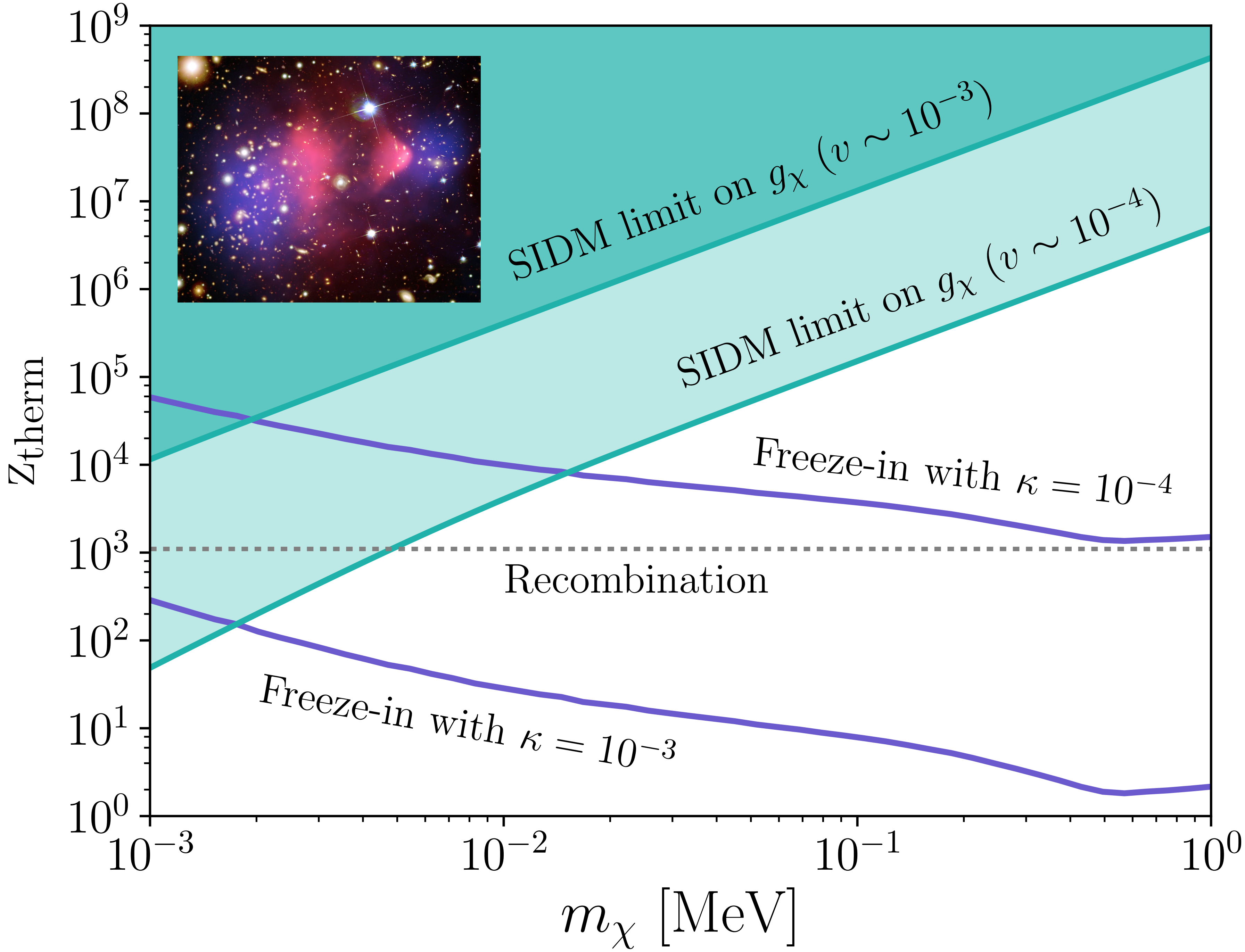
DARK MATTER SELF-THERMALIZATION



$\sim g_X^4$

DM self-scattering has v^{-4} scaling and is especially effective at late times

DARK MATTER SELF-THERMALIZATION



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