Do we care about MeV-GeV scale DM?

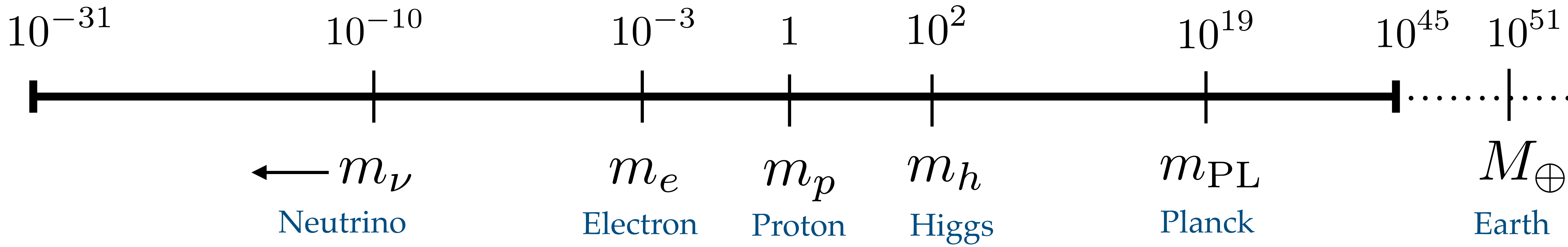
¯_(ツ)_/¯

Gordan Krnjaic

Fermilab THE UNIVERSITY OF CHICAGO

iDMEu Kickoff Meeting May 12, 2021

Huge Range of Possible DM Masses



$m_p \approx \text{GeV}/c^2 \approx 10^{-24}\,\text{gram}$

$m_{\rm PL} = G_N^{-1/2}$

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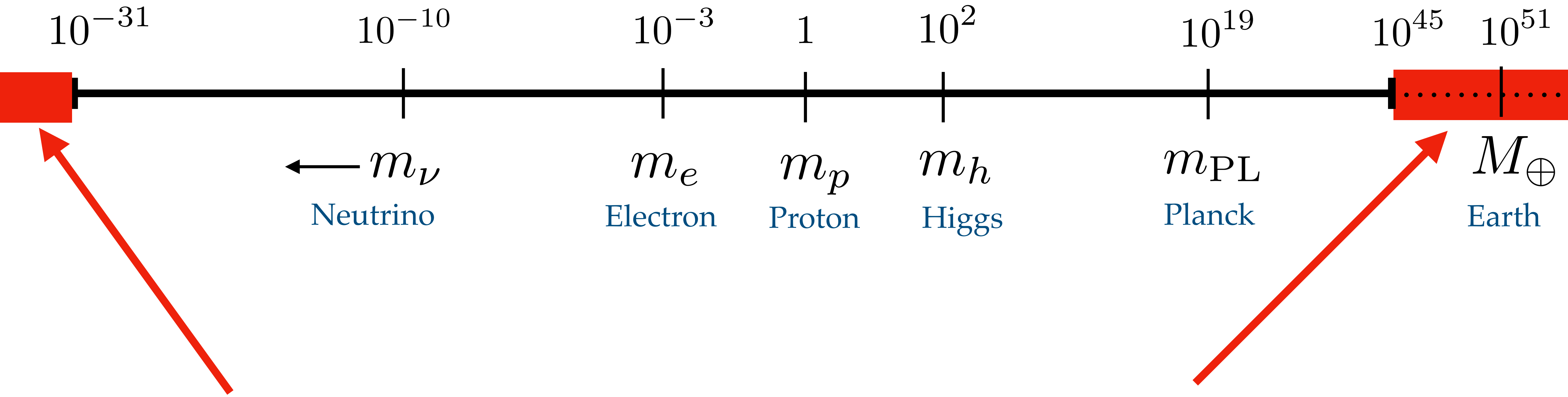


de Broglie wavelength can't exceed dwarf galaxy scales

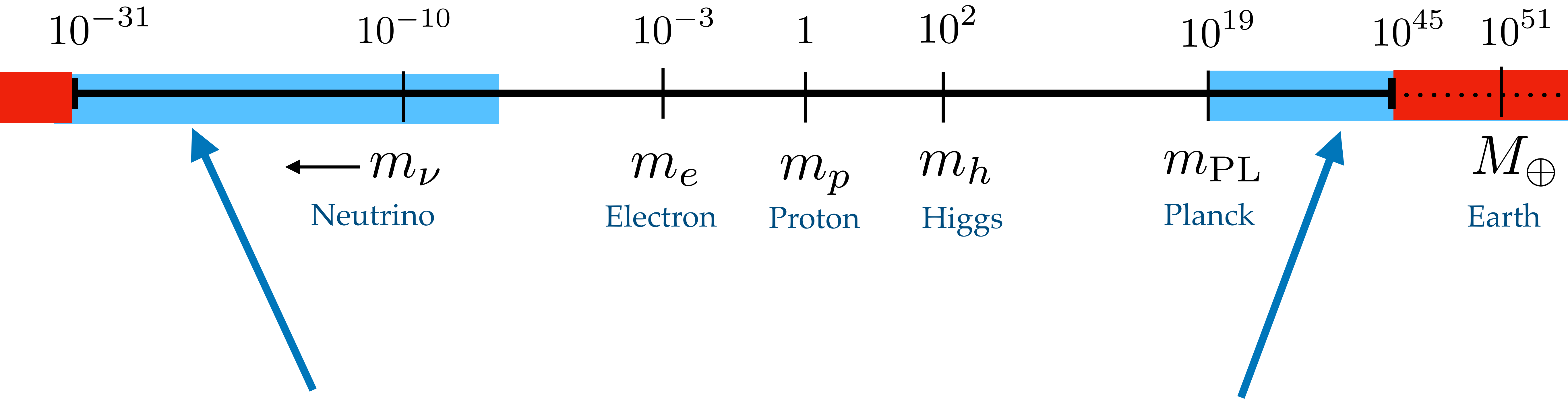
$$\lambda_{\rm dB} = \frac{2\pi}{mv} = 0.4\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m_{\rm DM}}\right)\left(\frac{10^{-3}c}{v}\right)$$

Would have been observed indirectly via microlensing

Greene, Kavanagh 2007.10722

Can't be all (or even most) of the dark matter

Huge Range of Possible DM Masses



Must be bosonic (integer spin)

Fermions require $m_{\rm DM} > 50\,{\rm eV}/c^2$
to populate halo $M_{\rm gal} \sim 10^{12} M_\odot$

Must be primordial black hole
or extended object

Example: dark nuclei
GK, Sigurdson 1406.1171

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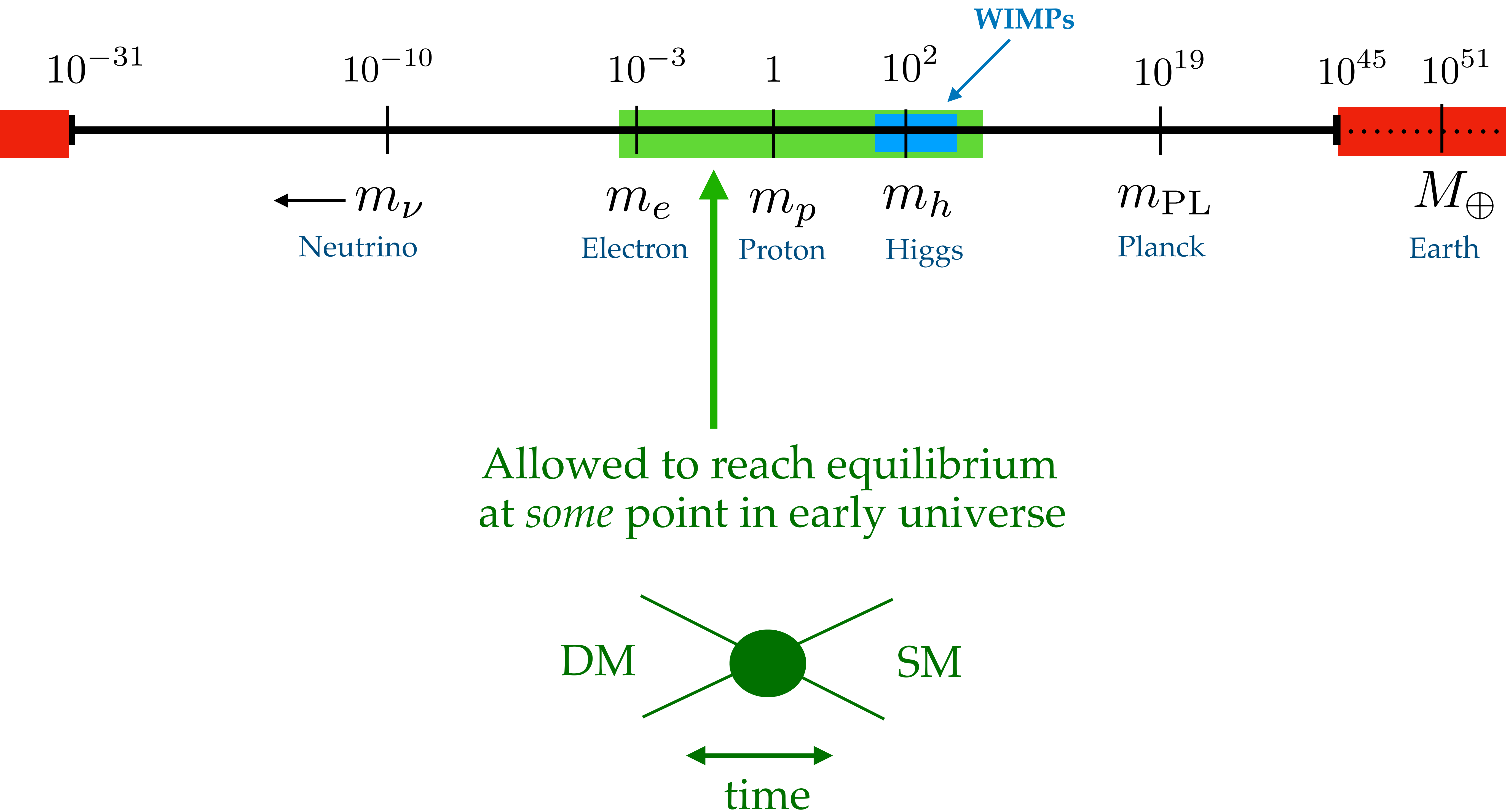

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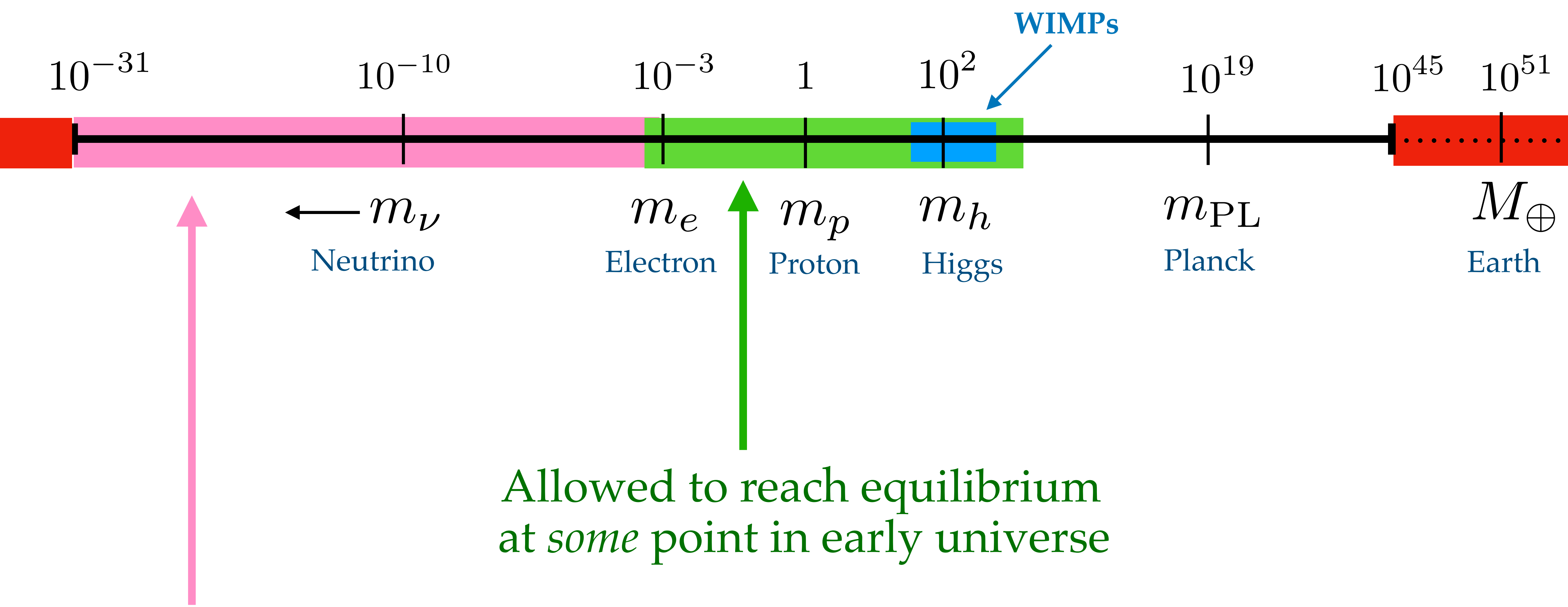


Allowed to reach equilibrium
at *some* point in early universe

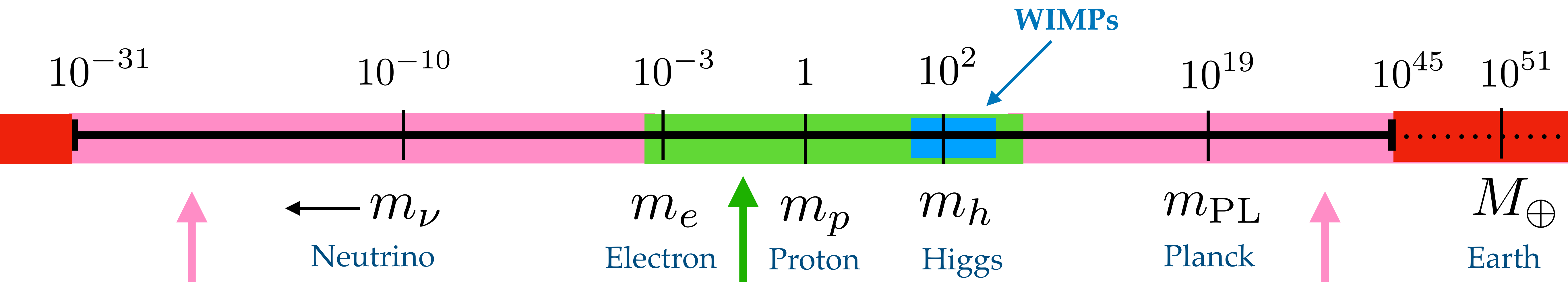
No equilibrium for $m <$ MeV

DM relativistic at BBN
spoils* light element yields

$N_{\rm eff} > 3$

*unless thermalization after BBN [Berlin, Blinov 1706.07046]

Huge Range of Possible DM Masses



Allowed to reach equilibrium
at *some* point in early universe

No equilibrium for $m <$ MeV

DM relativistic at BBN
spoils* light element yields

$N_{\rm eff} > 3$

No equilibrium for $m >$ 100 TeV

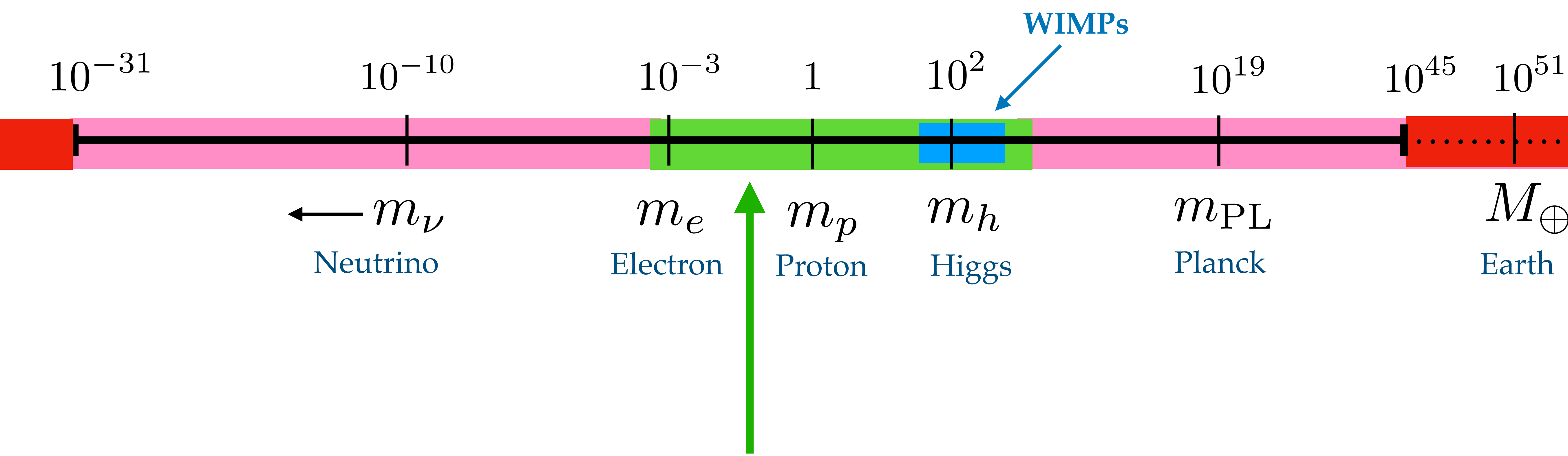
DM overproduced unless
unitarity is violated**

Griest, Kamionkowski PRL **1990**

*unless thermalization after BBN [Berlin, Blinov 1706.07046]

** nonstandard cosmology can evade this

Huge Range of Possible DM Masses

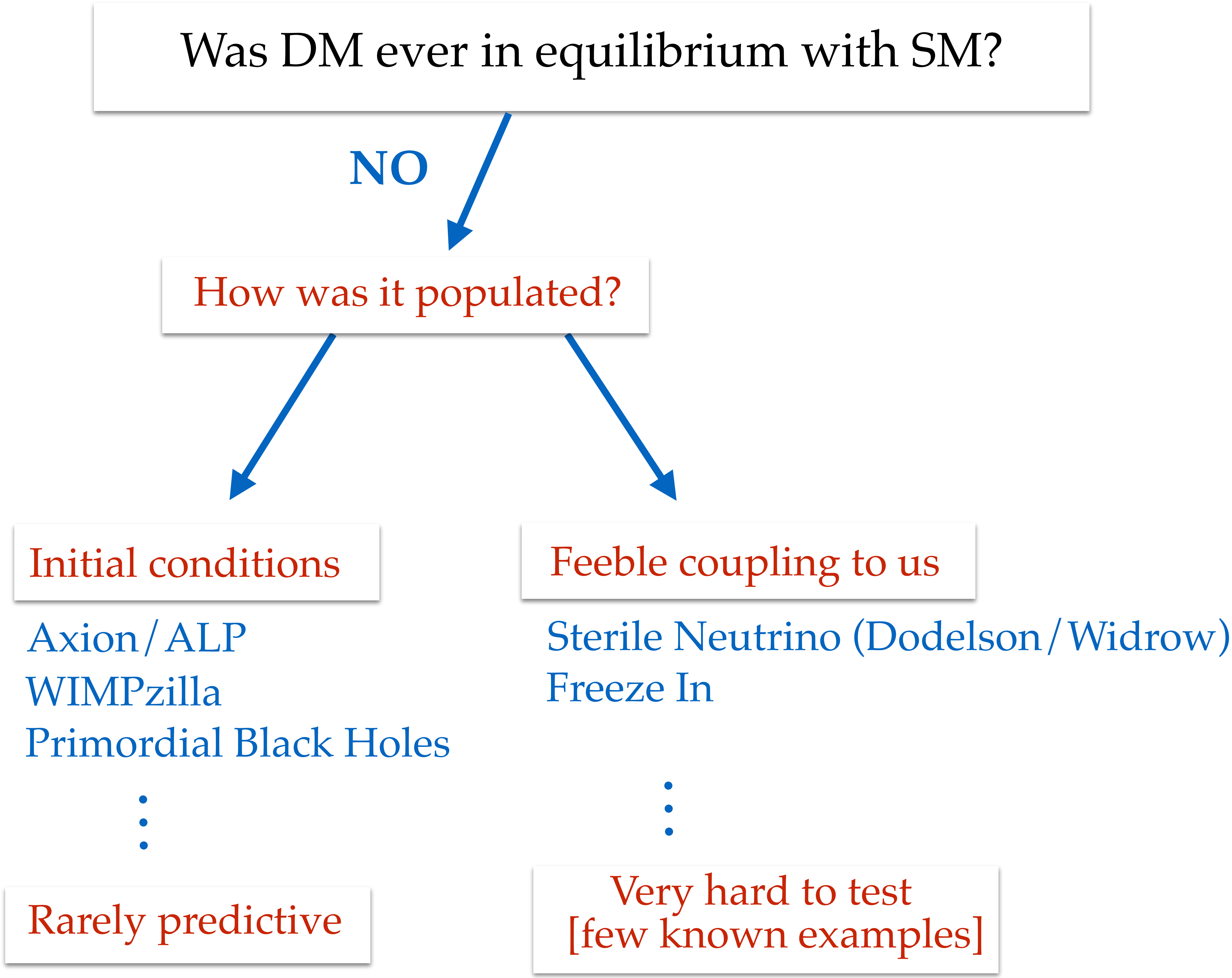


Allowed to reach equilibrium
at *some* point in early universe

Narrows viable DM mass range
… and scales are under our noses!

Ok, but why should we care? ¯_(ツ)_/¯

Was DM ever in equilibrium with SM?


Was DM ever in equilibrium with SM?
NO
How was it populated?
Initial conditions
Axion / ALP
WIMPzilla
Primordial Black Holes
⋮
Rarely predictive
Feeble coupling to us
Sterile Neutrino (Dodelson / Widrow)
Freeze In
⋮
Very hard to test
[few known examples]

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Nowhere

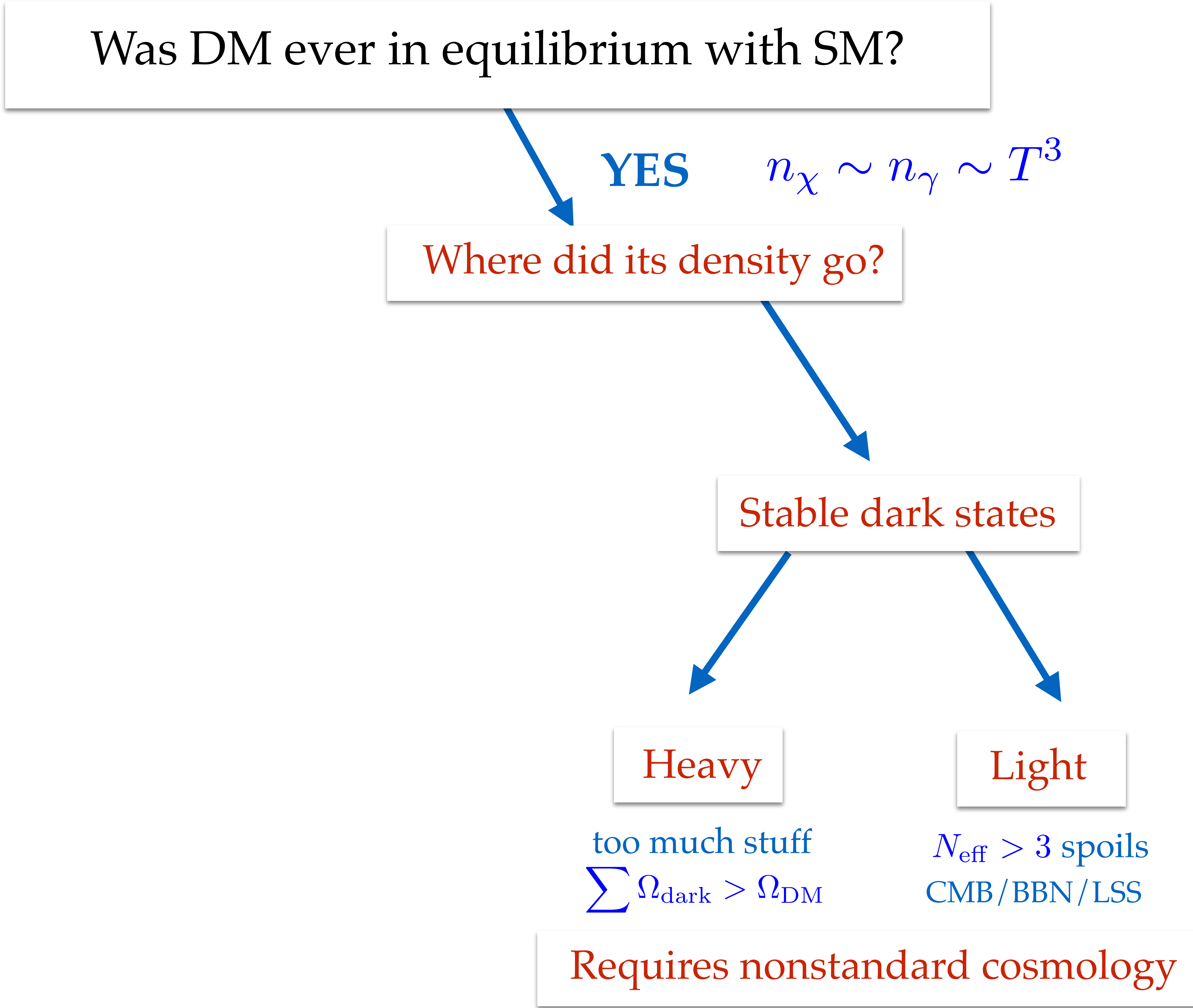
Today we have measured that

$$\rho_\chi \sim 10^3\,\mathrm{eV\,cm^{-3}}$$
$$n_\gamma \sim 10^2\,\mathrm{cm^{-3}}$$

Equilibrium predicts DM mass

$$m_\chi \sim 10\,\mathrm{eV}$$

Too hot for large scale structure


Was DM ever in equilibrium with SM?
YES
$n_\chi \sim n_\gamma \sim T^3$
Where did its density go?
Stable dark states
Heavy
Light
too much stuff
$\sum \Omega_{\rm dark} > \Omega_{\rm DM}$
$N_{\rm eff} > 3$ spoils
CMB / BBN / LSS
Requires nonstandard cosmology

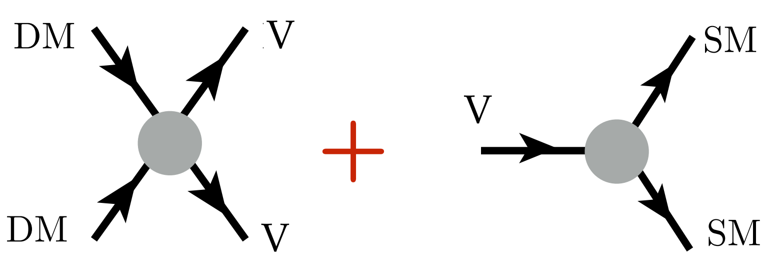
Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Visible matter

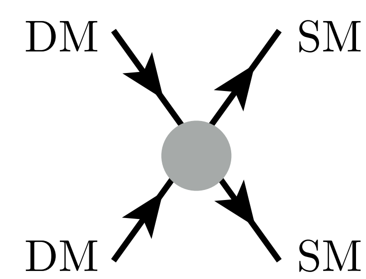
"Hidden" Annihilation



Visibly decaying dark state (V)

Motivates new force searches

Direct Annihilation



1-to-1 relation between lab / cosmology

Nearly all models robustly testable

Q: What's so great about equilibrium?

A: Generic and easy to achieve

Compare interaction rate to Hubble expansion

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

$$H \sim n\sigma v \quad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4}\bigg|_{T=m_\chi}$$

Equilibrium is reached in the early universe if

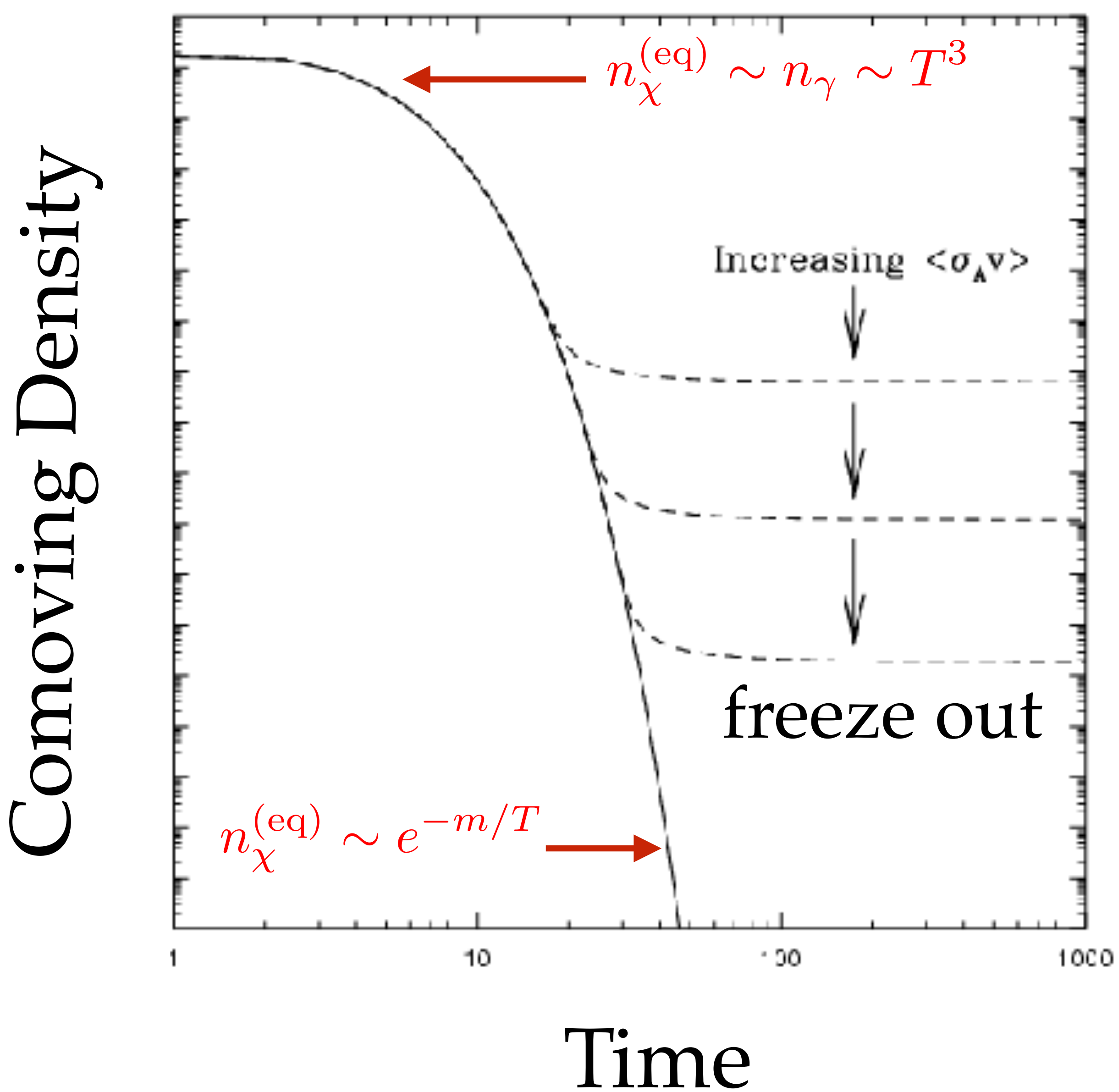
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\text{GeV}}\right)^2\left(\frac{\text{GeV}}{m_\chi}\right)^{3/2}$$

Nearly all testable models feature equilibrium at early times

Q: What's so great about equilibrium?

A: Minimum annihilation rate

$$n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$



It's easy to reach equilibrium

Even a tiny coupling does it

But must decouple at right time

Need a much larger coupling

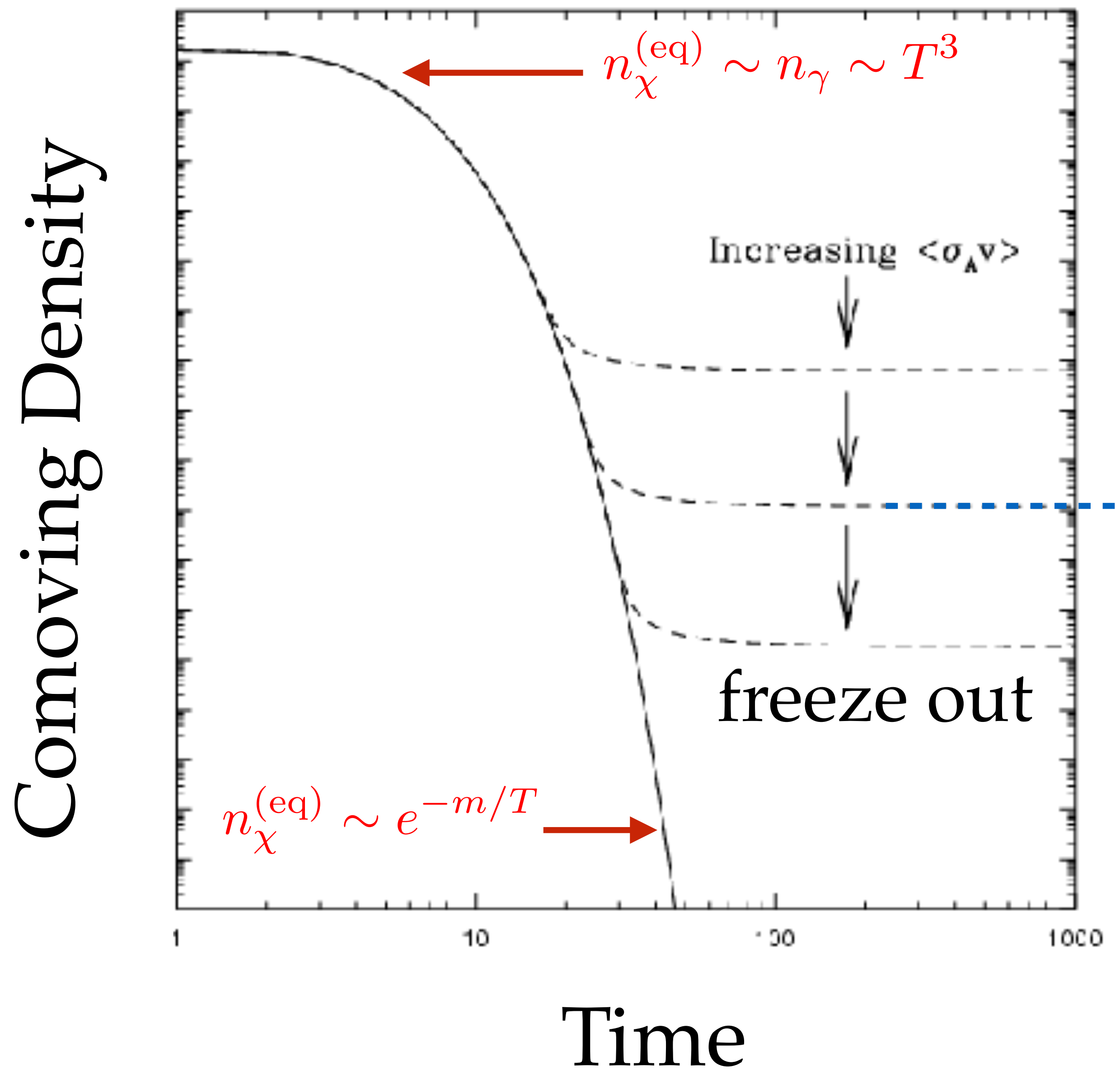
Decouple early = too much DM

Decouple late = too little DM

Q: What's so great about equilibrium?

A: Minimum annihilation rate

$$n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$

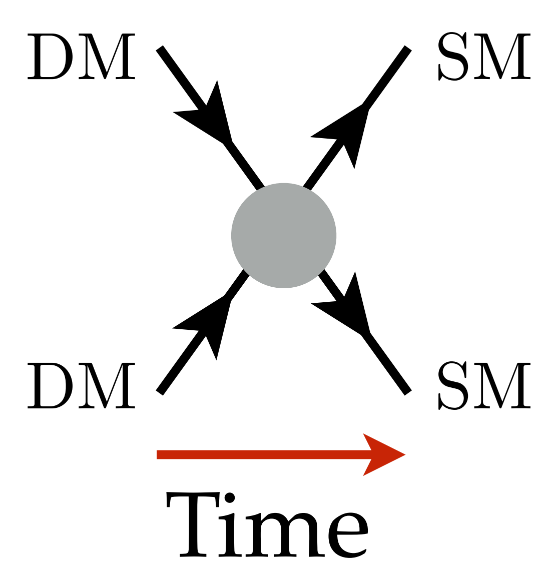


Symmetric DM population

$$n_\chi = n_{\overline{\chi}}$$

Observed density requires

$$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$



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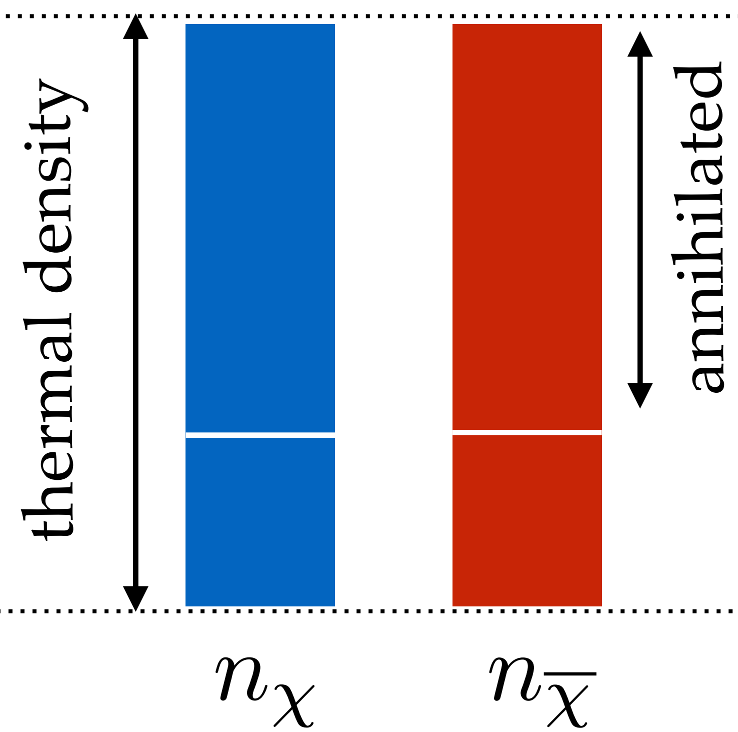
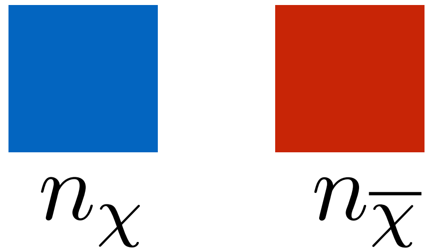
Symmetric DM



Early Universe

$T \gg m_\chi$

$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

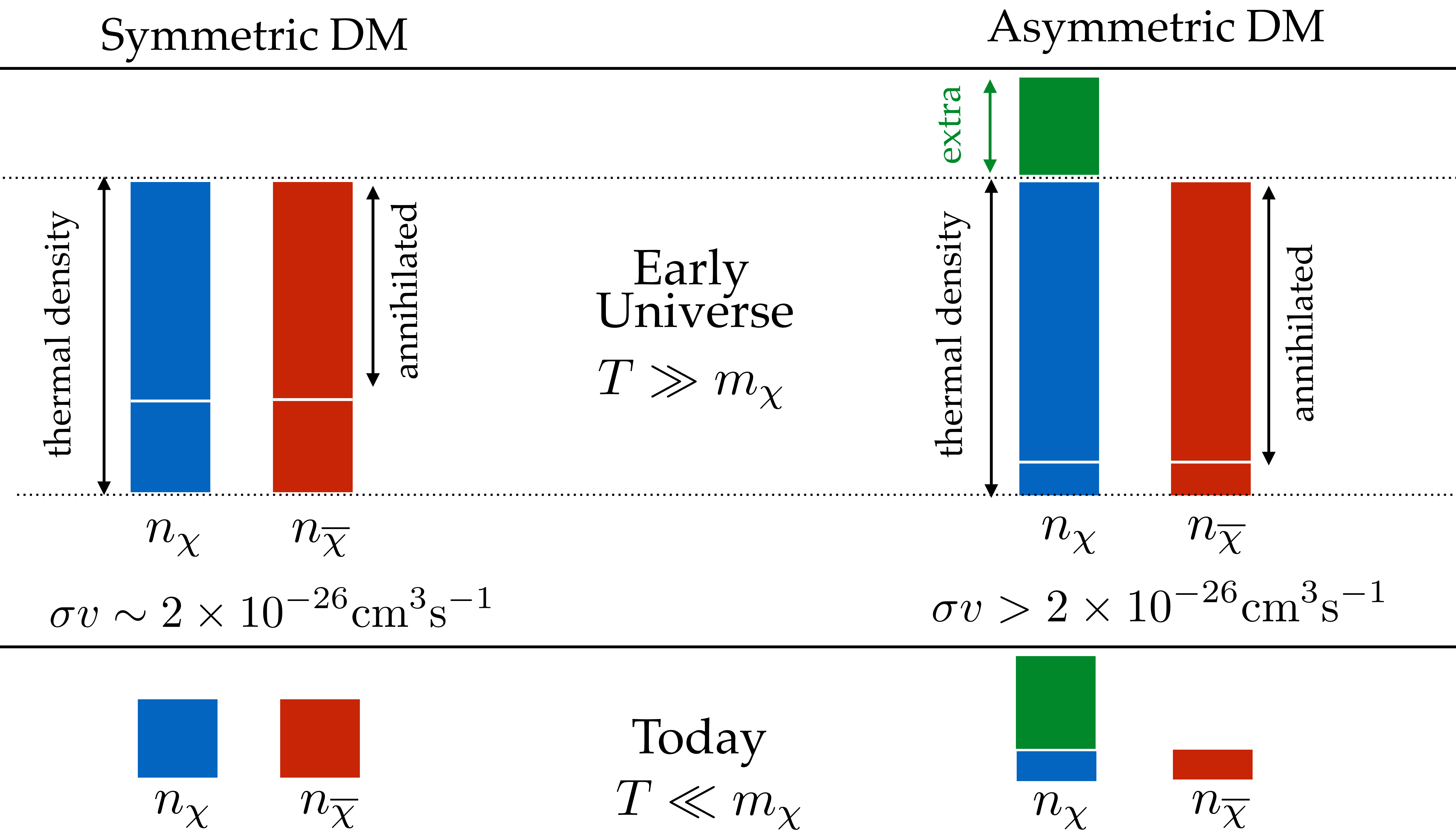


Today

$T \ll m_\chi$

Q: What's so great about equilibrium?

A: Minimum annihilation rate



Q: What's so great about equilibrium?

A: Insensitive to unknown high energy scales

Initial condition known

Independent of unknown physics (e.g. inflation)

Mass & couplings set abundance

Calculable, can learn a lot about hidden sector if lucky

Only *other* UV insensitive mechanism is "freeze-in"

- Ad hoc initial condition $n_\chi(0) = 0$
- DM produced through tiny couplings, **very hard to test**

Light DM vs. WIMPs

LDM must be neutral under SM

Else would have been discovered @ LEP/Tevatron/LHC…

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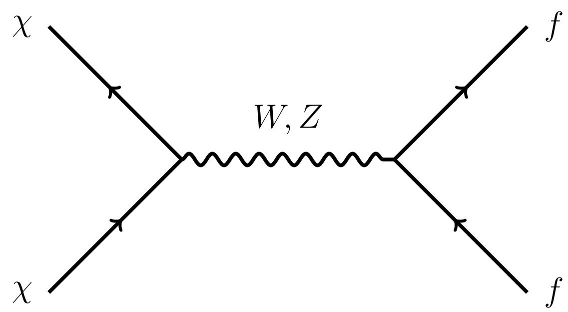
Else would have been discovered @ LEP/Tevatron/LHC…

LDM requires light new mediators

Overproduced without additional light, neutral "mediators"



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Lee/Weinberg '79

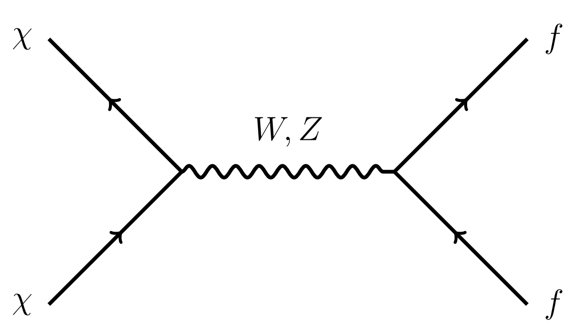
Light DM vs. WIMPs

LDM must be neutral under SM

Else would have been discovered @ LEP / Tevatron / LHC…

LDM requires light new mediators

Overproduced without additional light, neutral “mediators”



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Lee/Weinberg ‘79

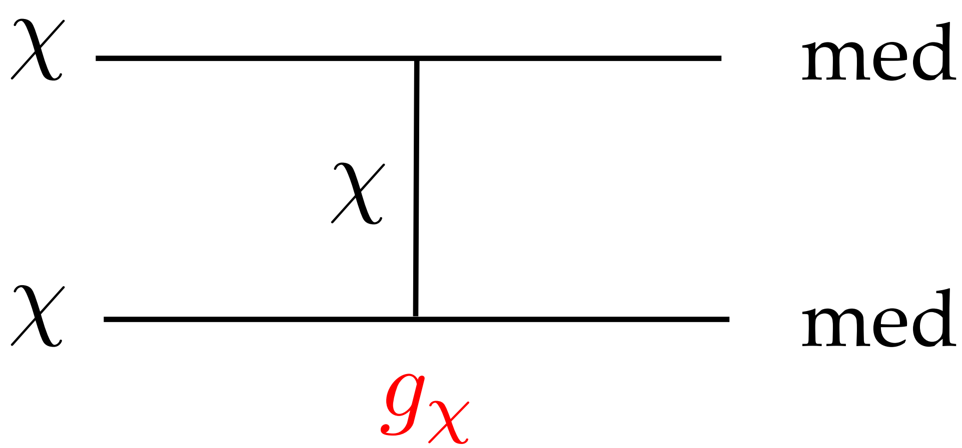
LDM interactions renormalizable at accelerator energies

Else rate too small — greatly simplifies space of possible theories

Who’s Heavier: DM or Mediator?

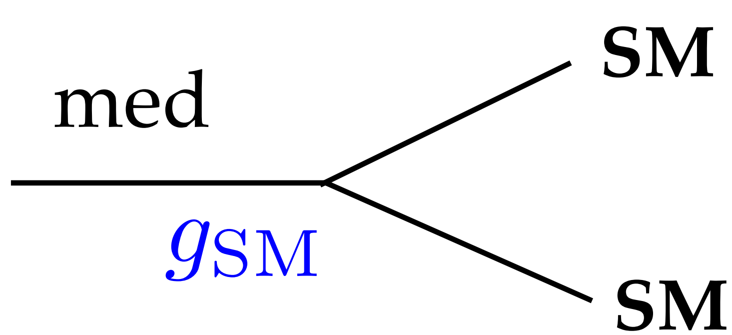
Hidden Annihilation

$m_\chi > m_{\mathrm{med}}$



No clear experimental target

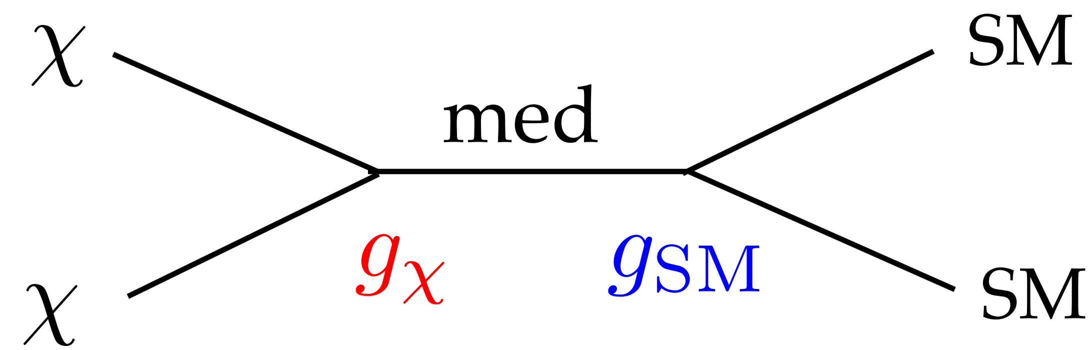
Abundance set by g_χ



Mediator decays **visibly**

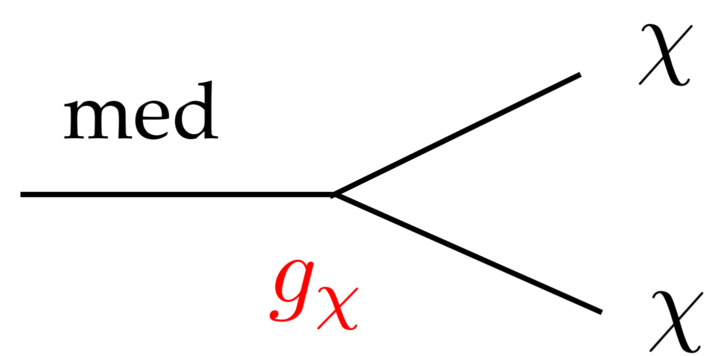
Direct Annihilation

$m_\chi < m_{\mathrm{med}}$



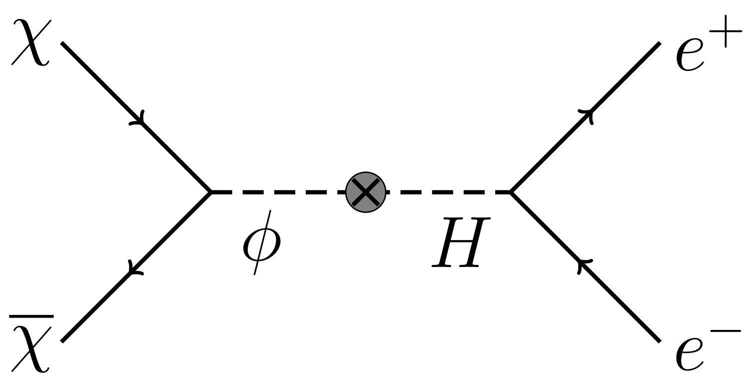
Predictive thermal targets

Abundance depends on g_{SM}



Mediator decays **invisibly***

What kind of mediator for direct annihilation? $m_\chi < m_{\rm med}$

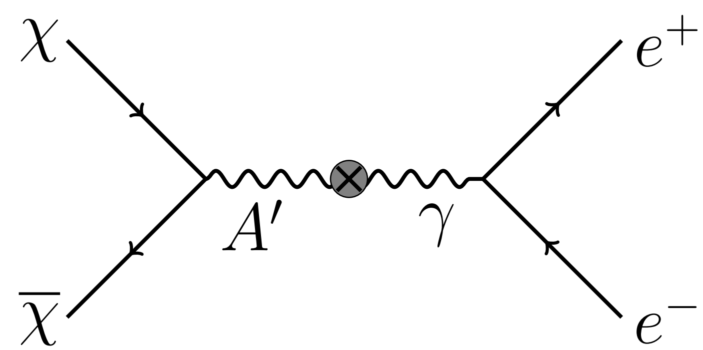


$$\epsilon\, \phi H^\dagger H$$

Neutral scalar
Mass mix w Higgs

$$\to \epsilon \phi \frac{m_f}{v} \bar{f} f$$

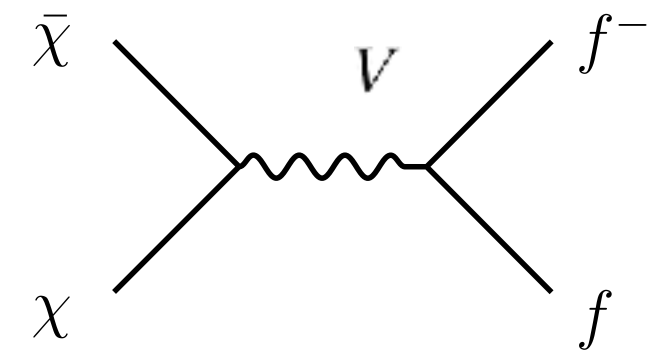
after EWSB



$$\epsilon\, F'_{\mu\nu} F^{\mu\nu}$$

Dark photon A'
Kinetic mixing w/ γ

$$\to \epsilon A' J^\mu_{\rm EM}$$



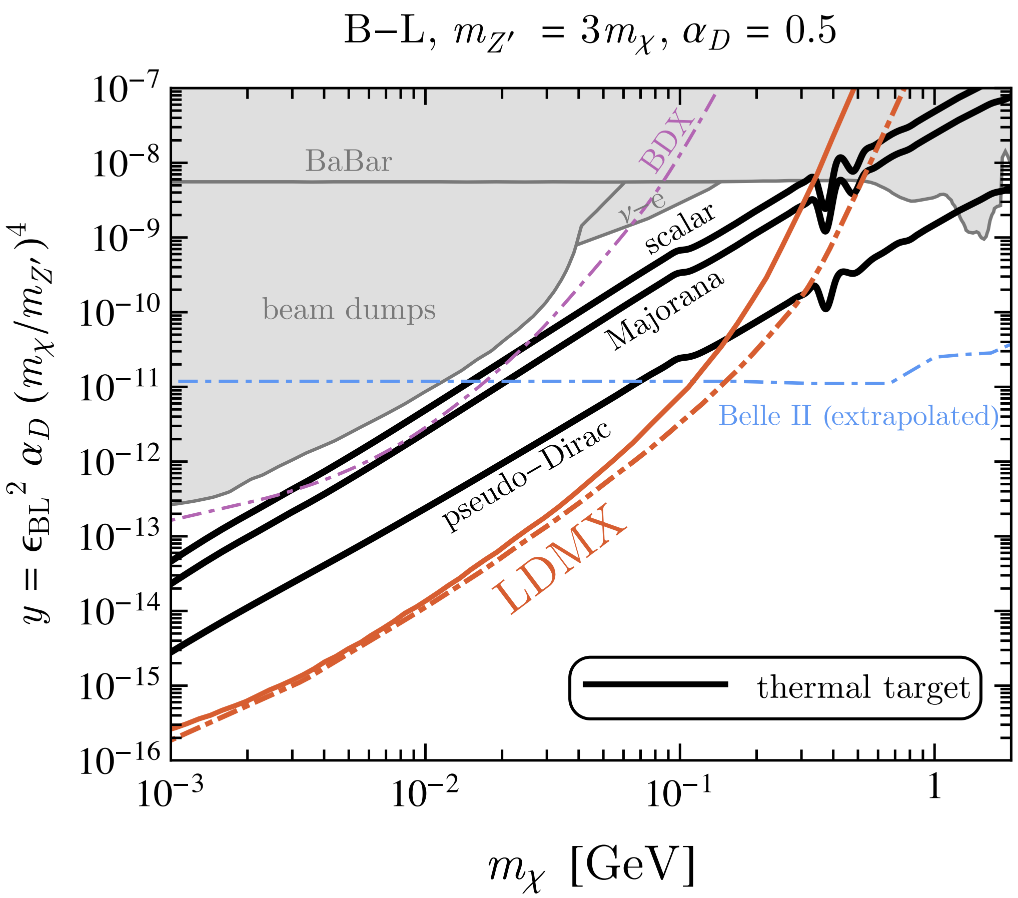
$$V_\mu J^\mu_{\rm SM}$$

Gauge known global quantum number

$$U(1)_{B-3L_i}$$
$$U(1)_{B-L}$$
$$U(1)_{L_i-L_j}$$

Complete list of theoretically consistent options

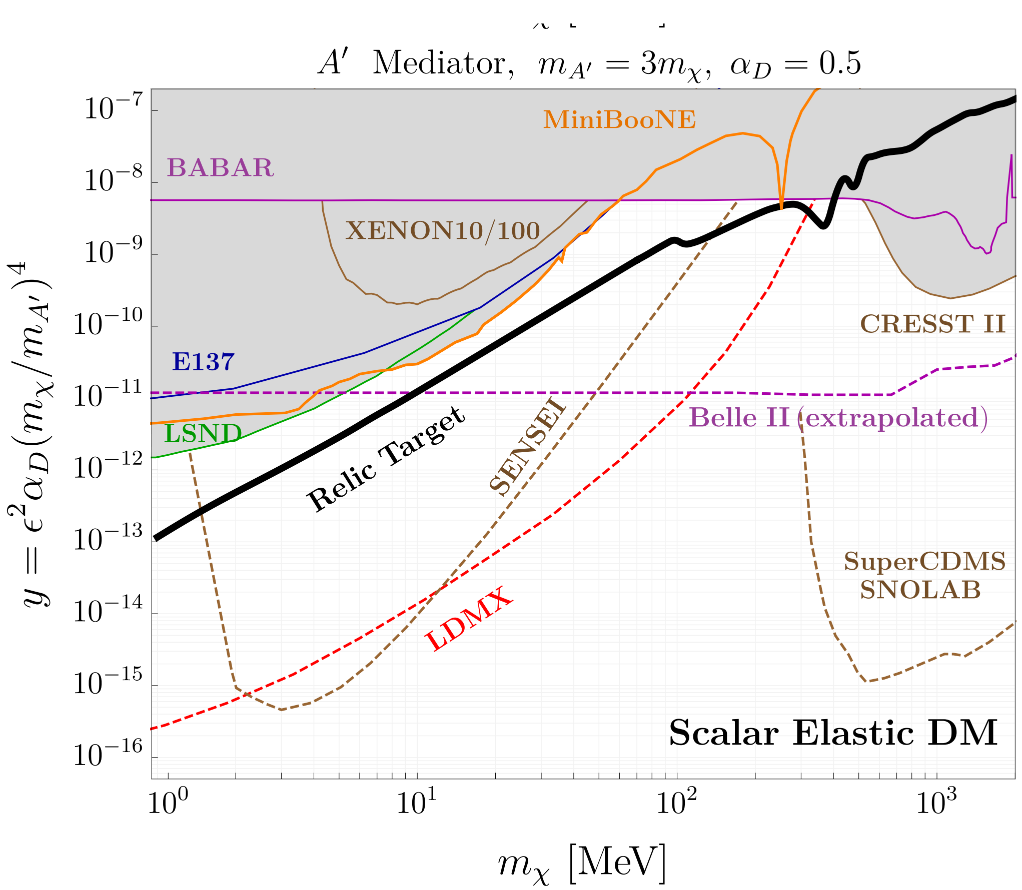
Direct Annihilation Targets



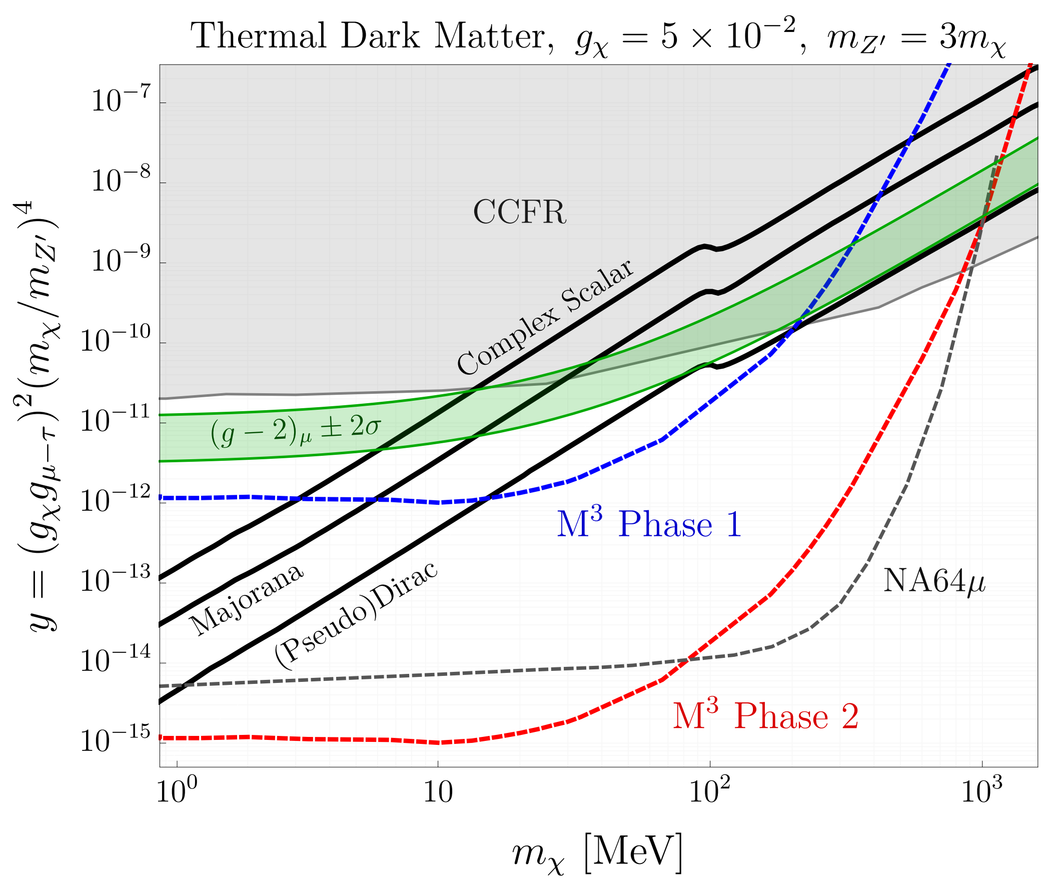
Highly predictive for light DM

Most models testable with similar searches

Rare opportunity to discover/falsify



Bonus connection to muon g-2



Blinov, Berlin, GK, Schuster, Toro arXiv:1807.01730

Kahn, GK, Tran, Whitbeck 1804.03144

Who's Heavier: DM or Mediator?

Hidden Annihilation

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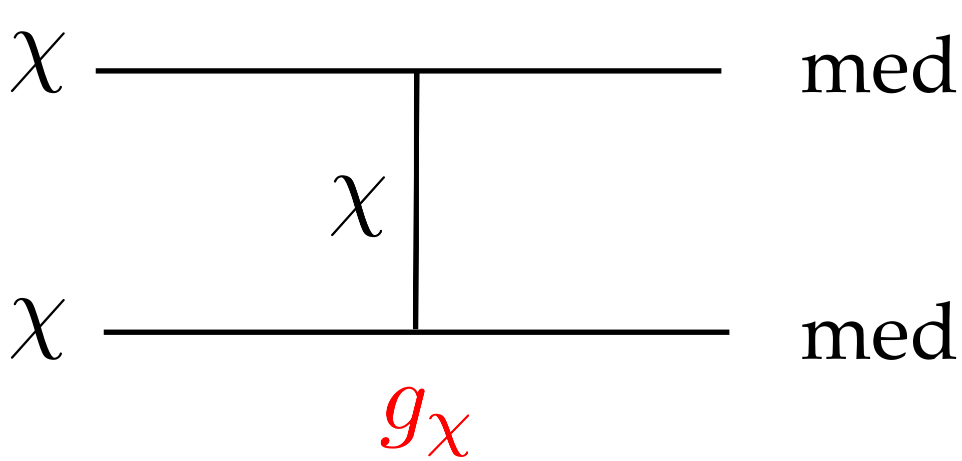

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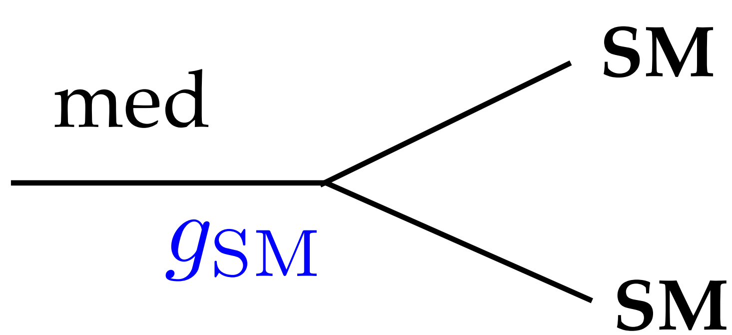

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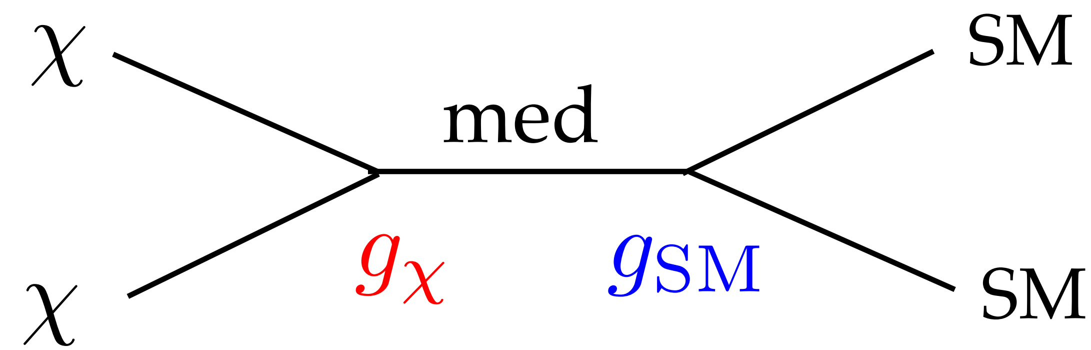
Direct Annihilation

$m_\chi < m_{\text{med}}$



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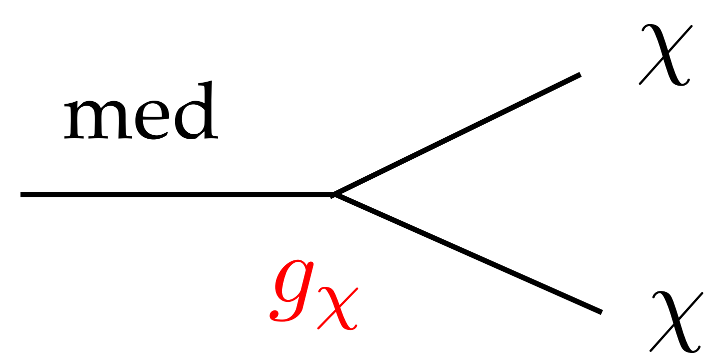
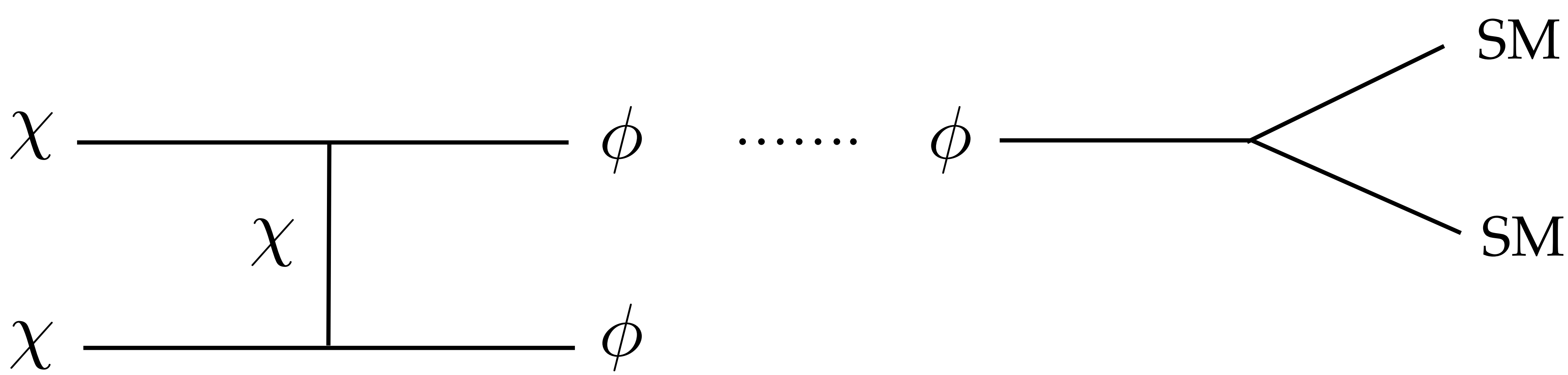


Mediator decays **invisibly***

Hidden Annihilation to Mediator

"Secluded" DM $(m_\chi > m_\phi)$

Pospelov, Ritz, Voloshin 0711.4866



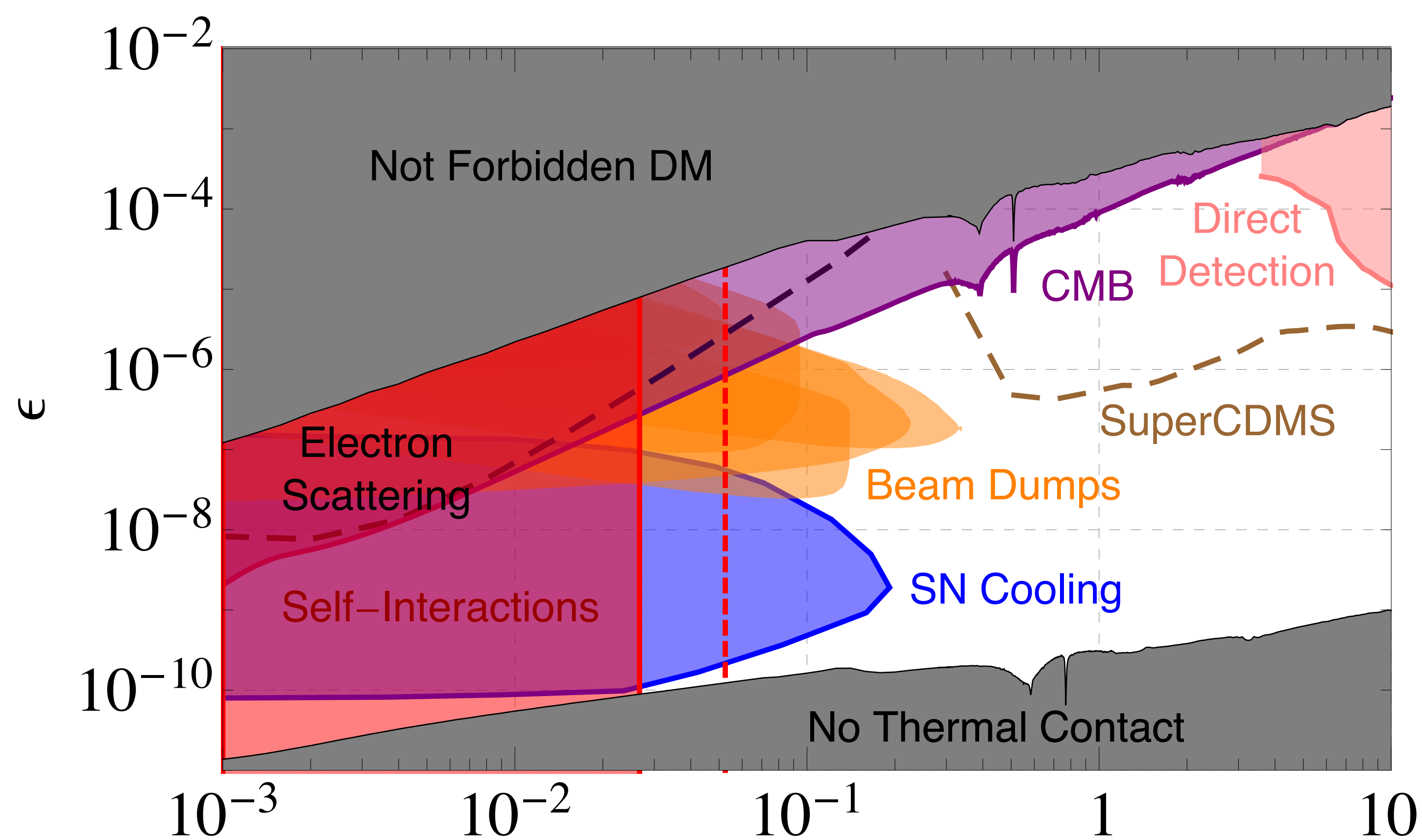
Motivates mediator searches

"Forbidden" DM

$(m_\chi < m_\phi)$

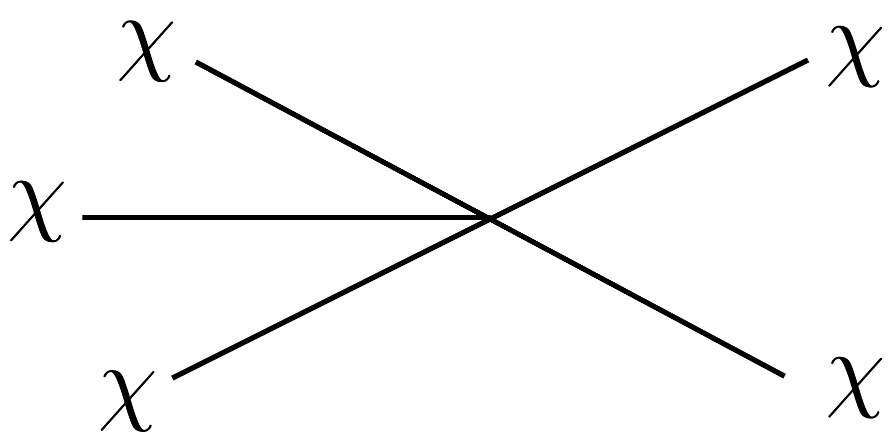
Annihilate to *heavier* mediators

Carlson, Machacek, Hall '92
D'Agnolo, Ruderman 1505.07107

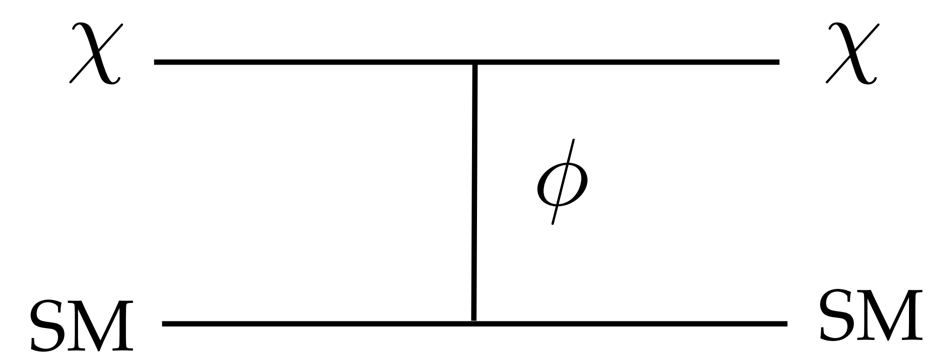


Hidden Annihilation to DM (3+ to 2)

Annihilation



Cooling w/ mediator



Cannibalization: 3-2 annihilation only (DM hot, ruled out)

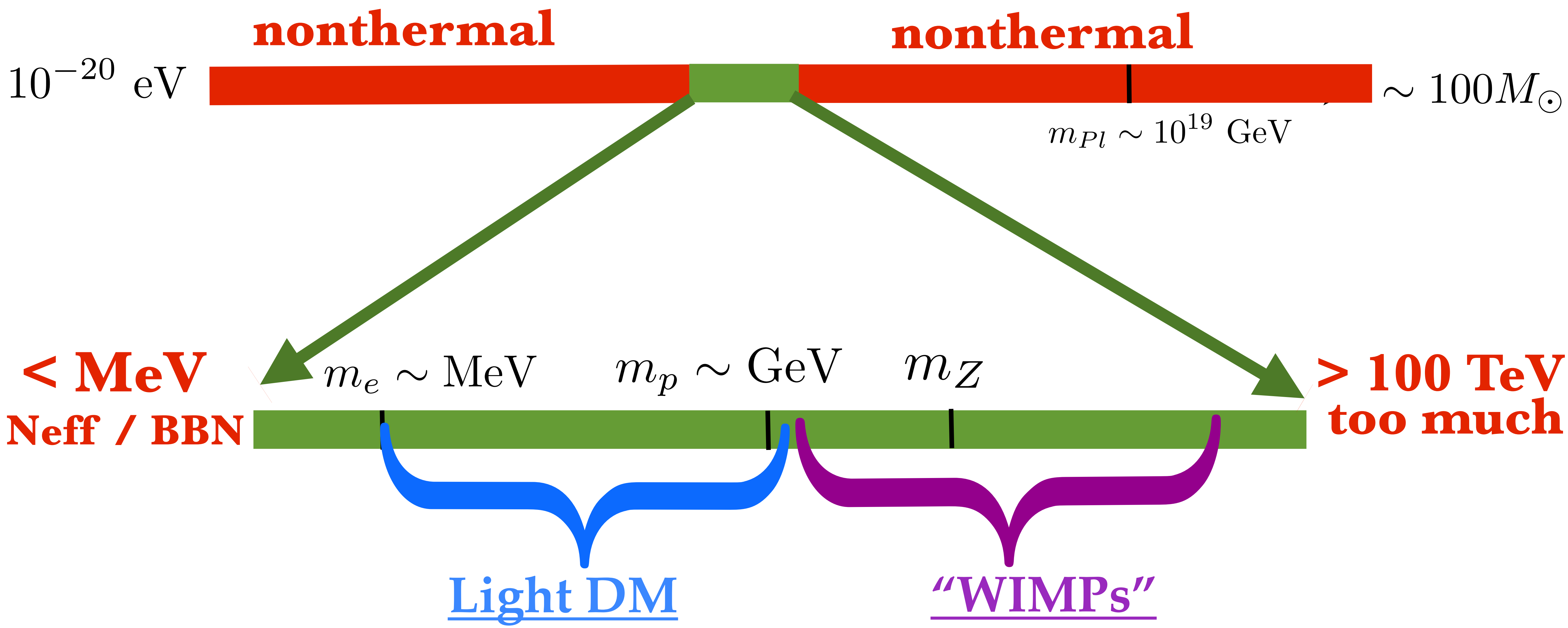
Carlson, Machacek, Hall '92

SIMP: 3-2 freeze out, then SM scattering cools DM

Hochberg Kuflik Volansky Wacker 1402.5143

ELDER: SM-DM scattering decouples first, 3-2 freeze out later

Kuflik Prelstein Rey-Le Lorier, Tsai 1512.04545



Thermal DM is grounded in a simple physical requirement

MeV-GeV range currently under explored

Finite list of new mediators that enable thermal origin

Direct annihilation = predictive & testable experimental milestones

Biased view: it's a no brainer

If we can test some predictive thermal DM model, we must

Thanks!