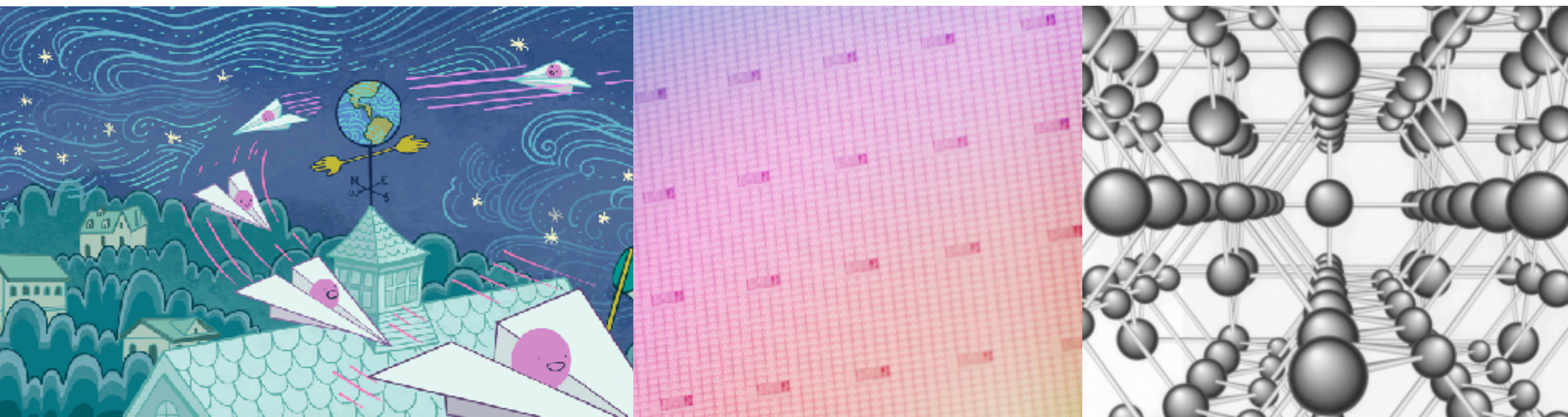


Low mass particle-like dark matter

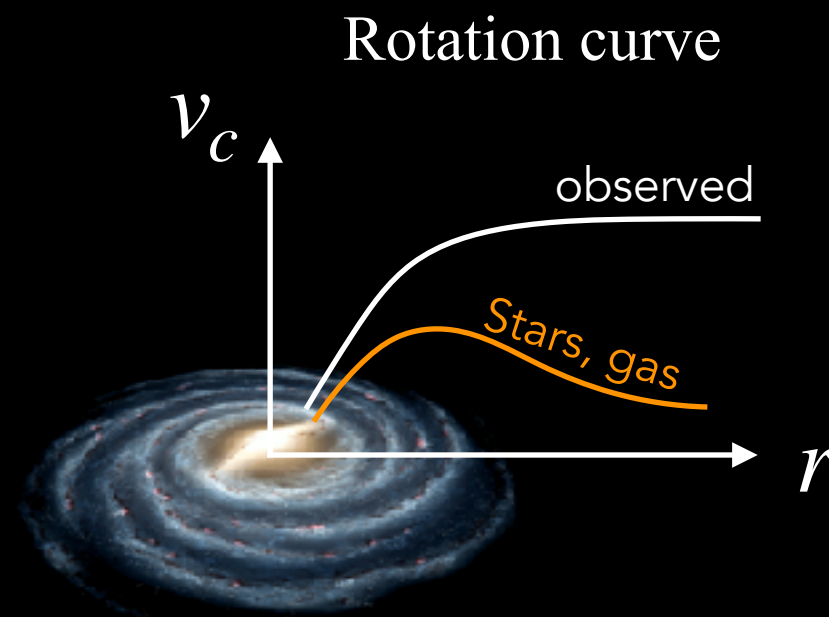
Tongyan Lin

UC San Diego

SLAC Summer Institute 2026

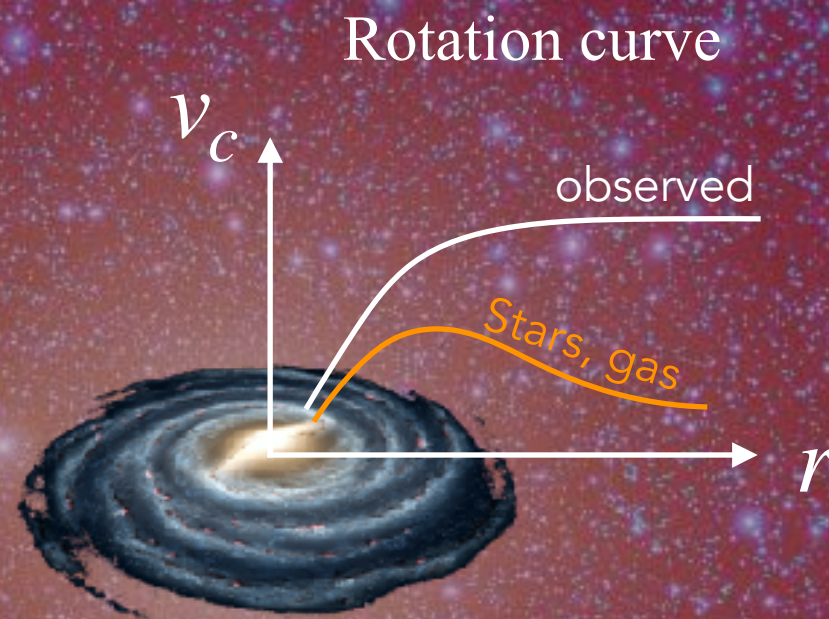


We live inside a dark matter halo.



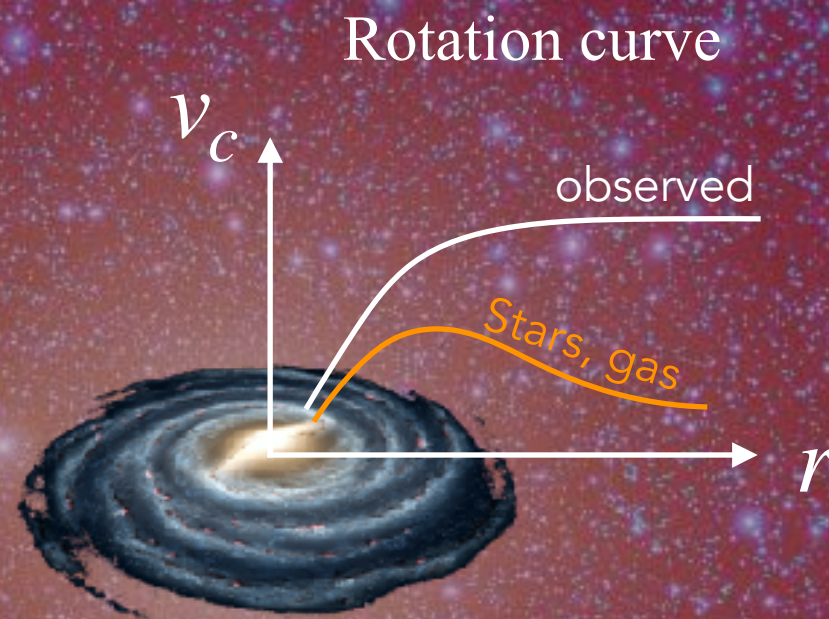
Aquarius simulation

We live inside a dark matter halo.



Aquarius simulation

We live inside a dark matter halo.



How do we detect it?

Aquarius simulation

Detecting dark matter

Detecting dark matter

Weak interactions

Low density

Large SM backgrounds

Detecting dark matter

Weak interactions

Low density

Large SM backgrounds

Unknown properties

Detecting dark matter

Weak interactions

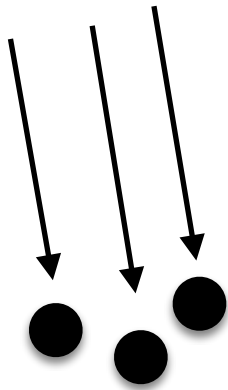
Low density

Large SM backgrounds

Unknown properties

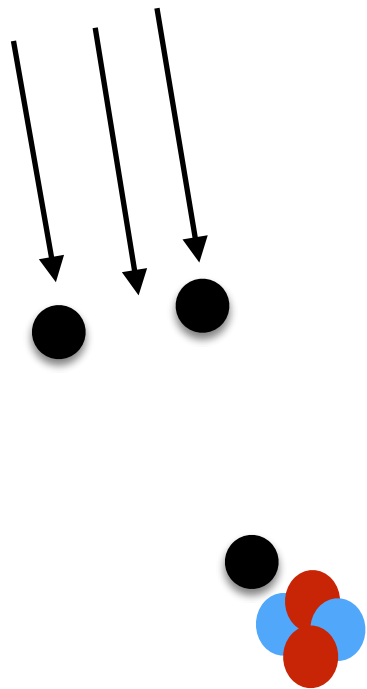
We need sensitive probes for a range of DM theories

DM “wind”



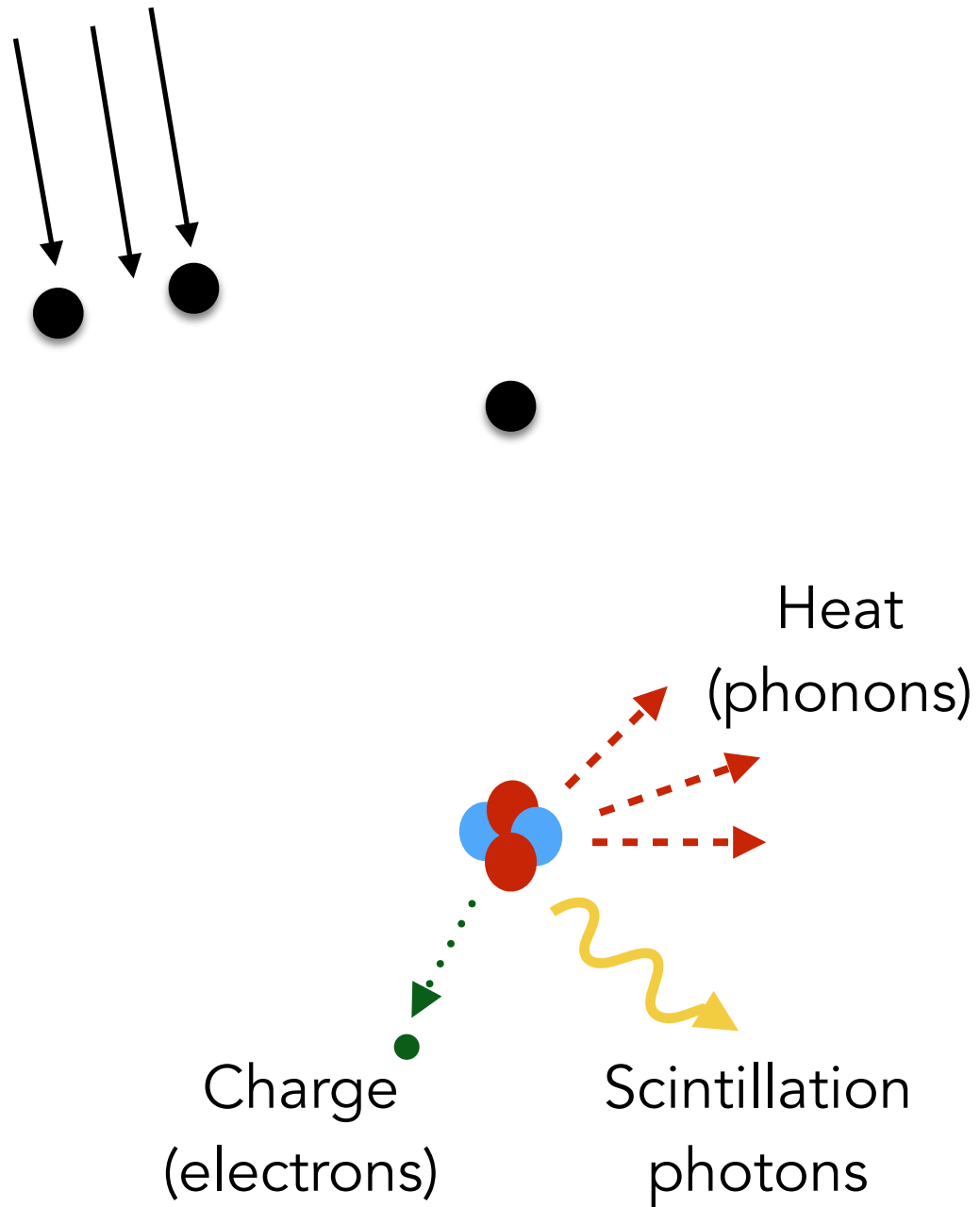
Direct detection of nuclear recoils

DM “wind”



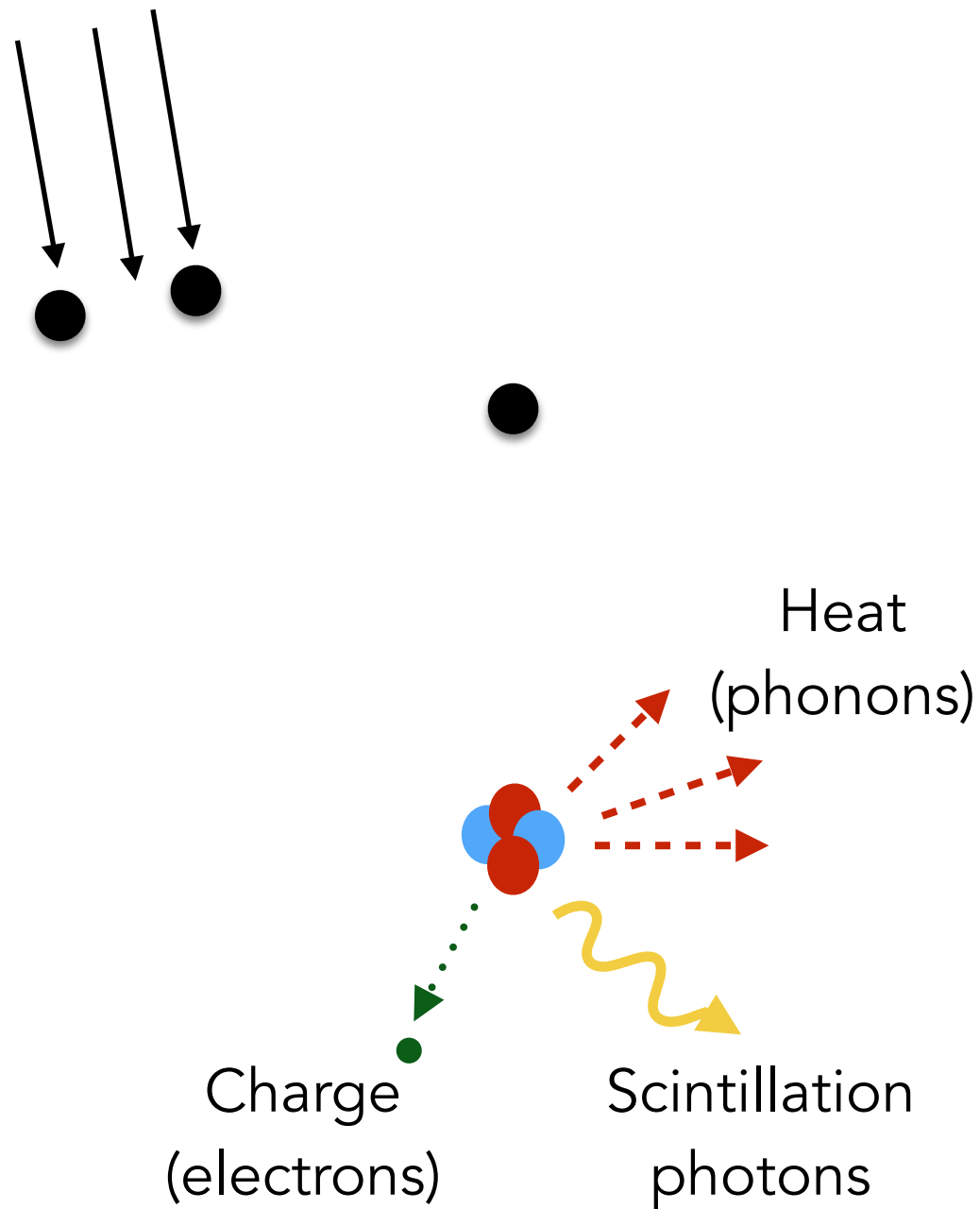
Direct detection of nuclear recoils

DM "wind"

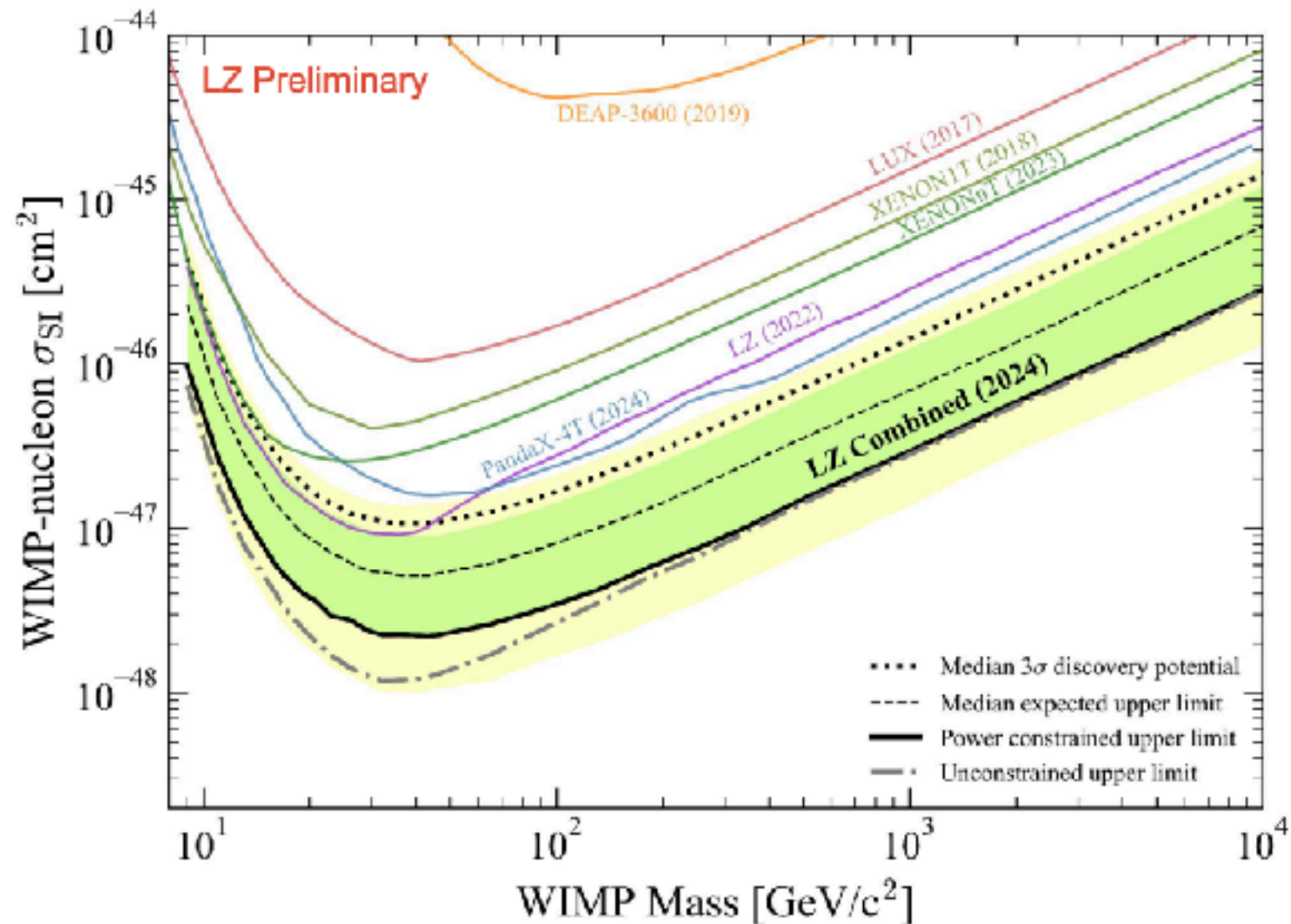


Direct detection of nuclear recoils

DM “wind”

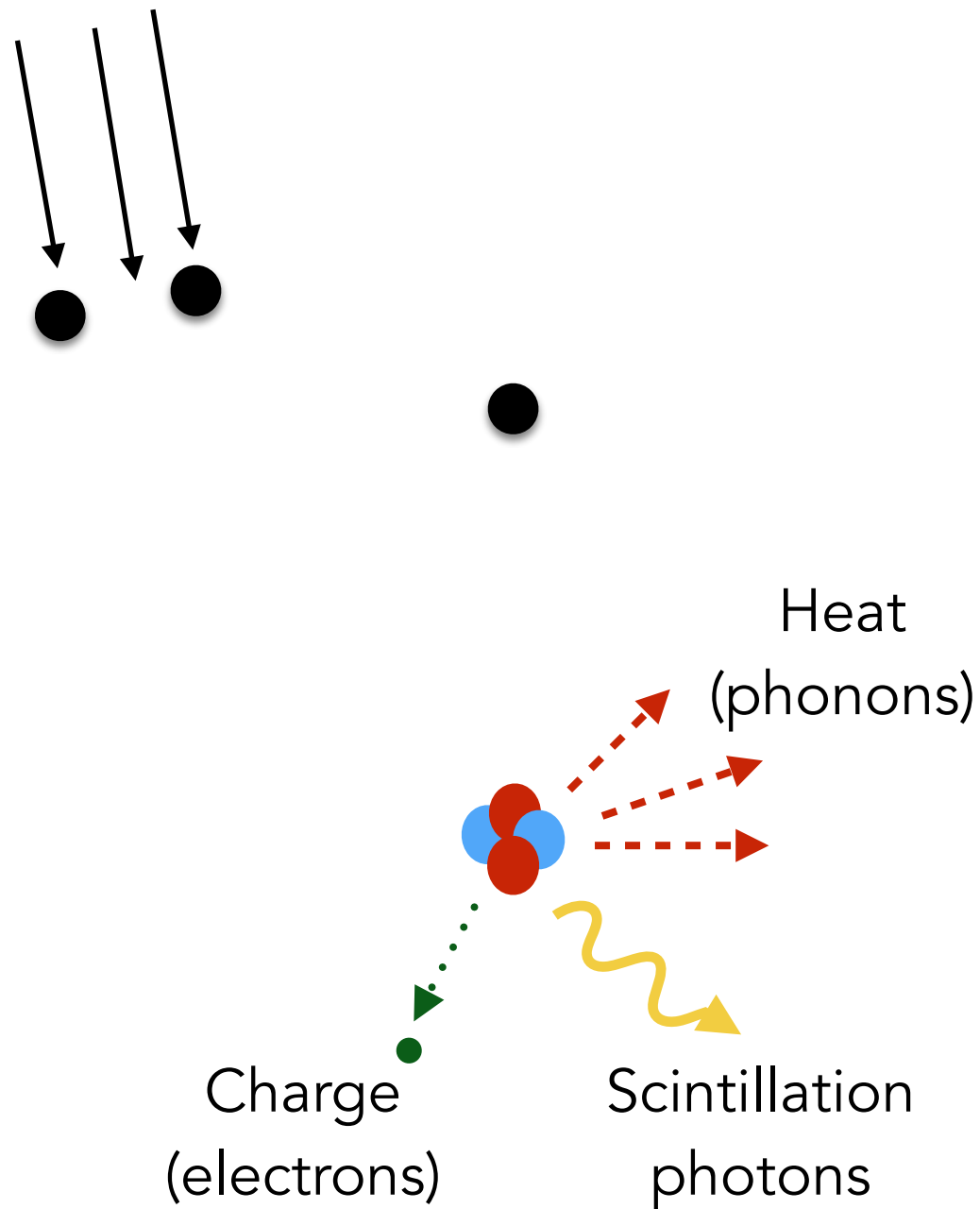


Strong constraints on **interaction cross section** when **DM mass** comparable to nucleus mass

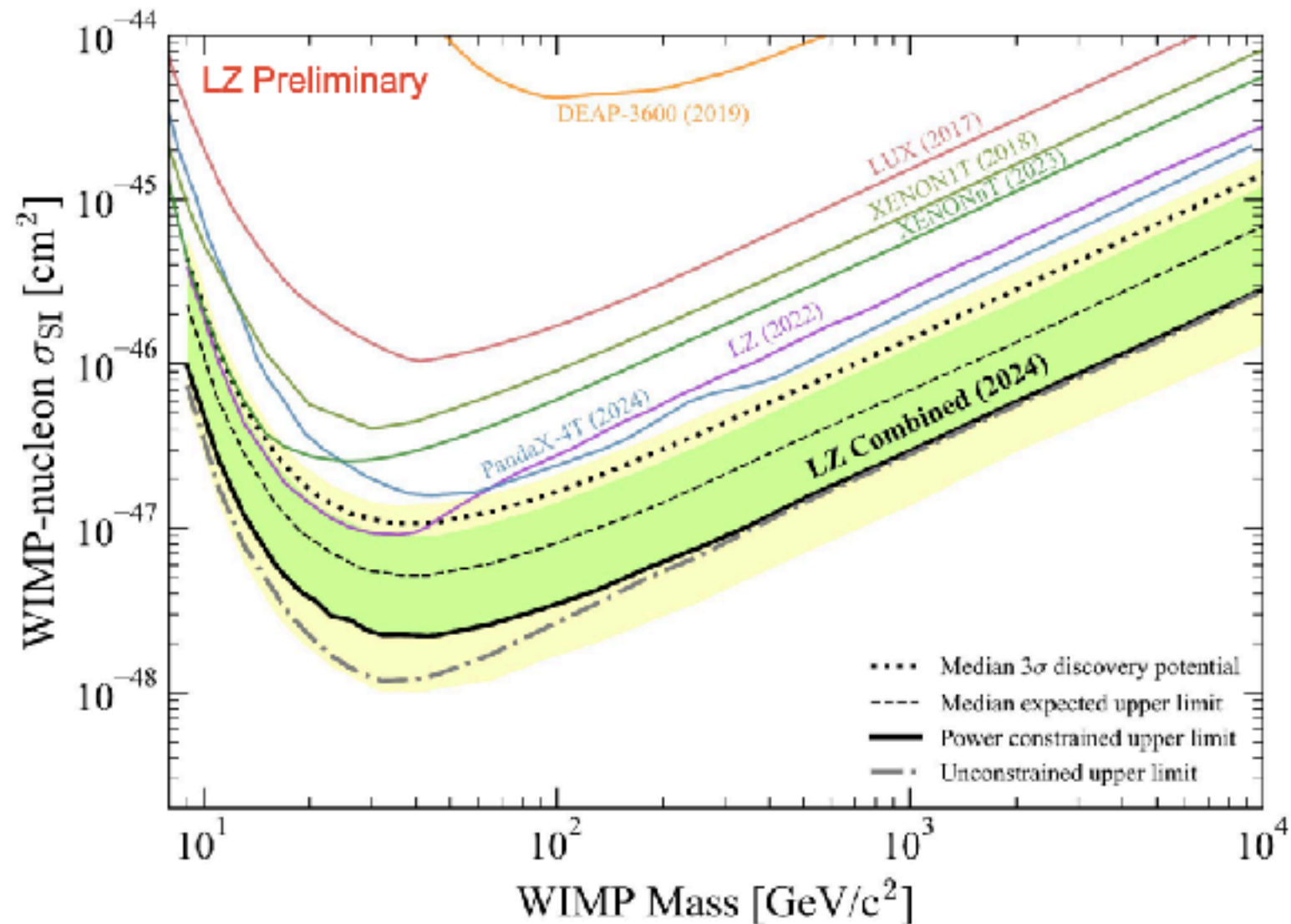


Direct detection of nuclear recoils

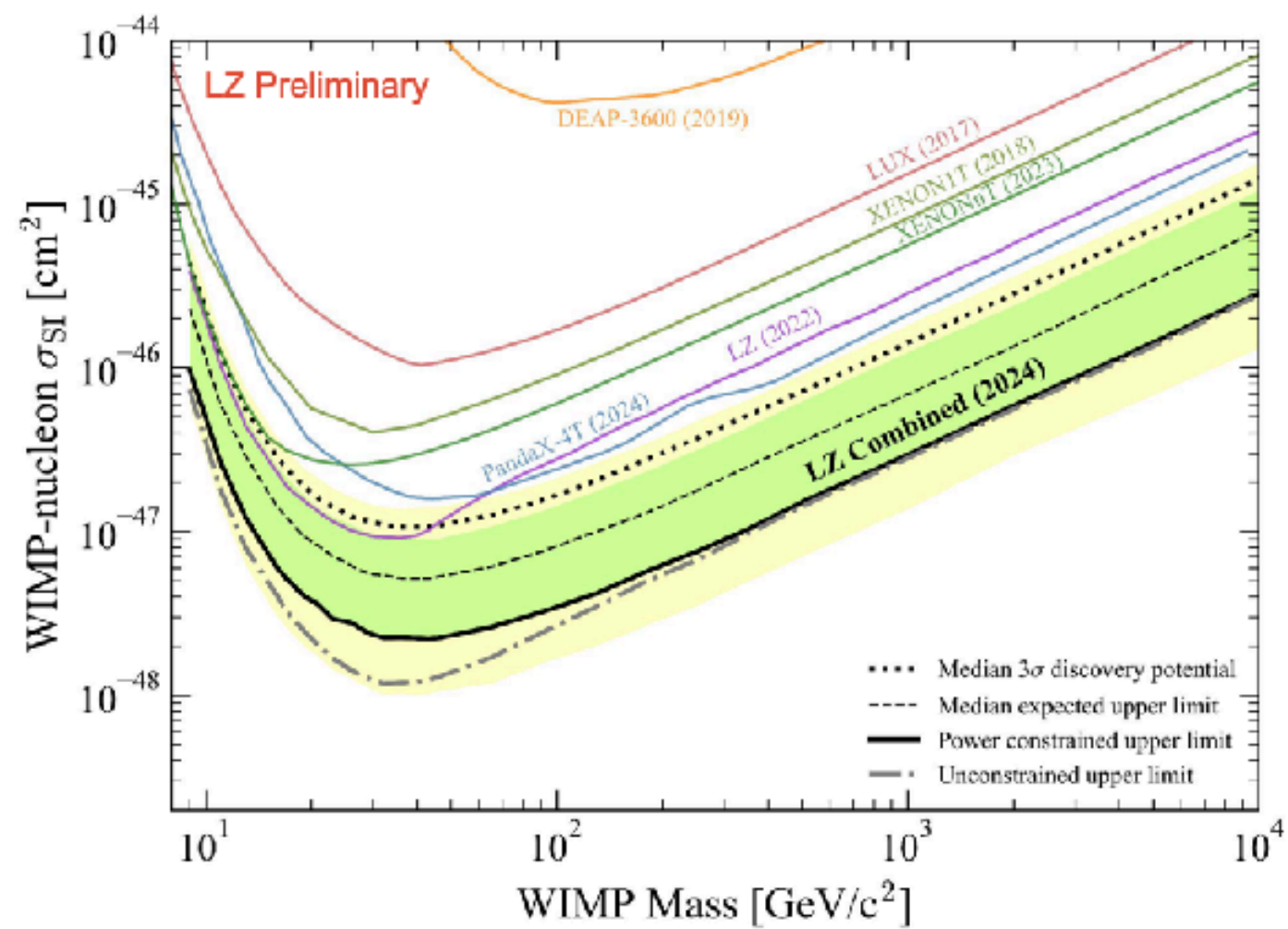
DM “wind”

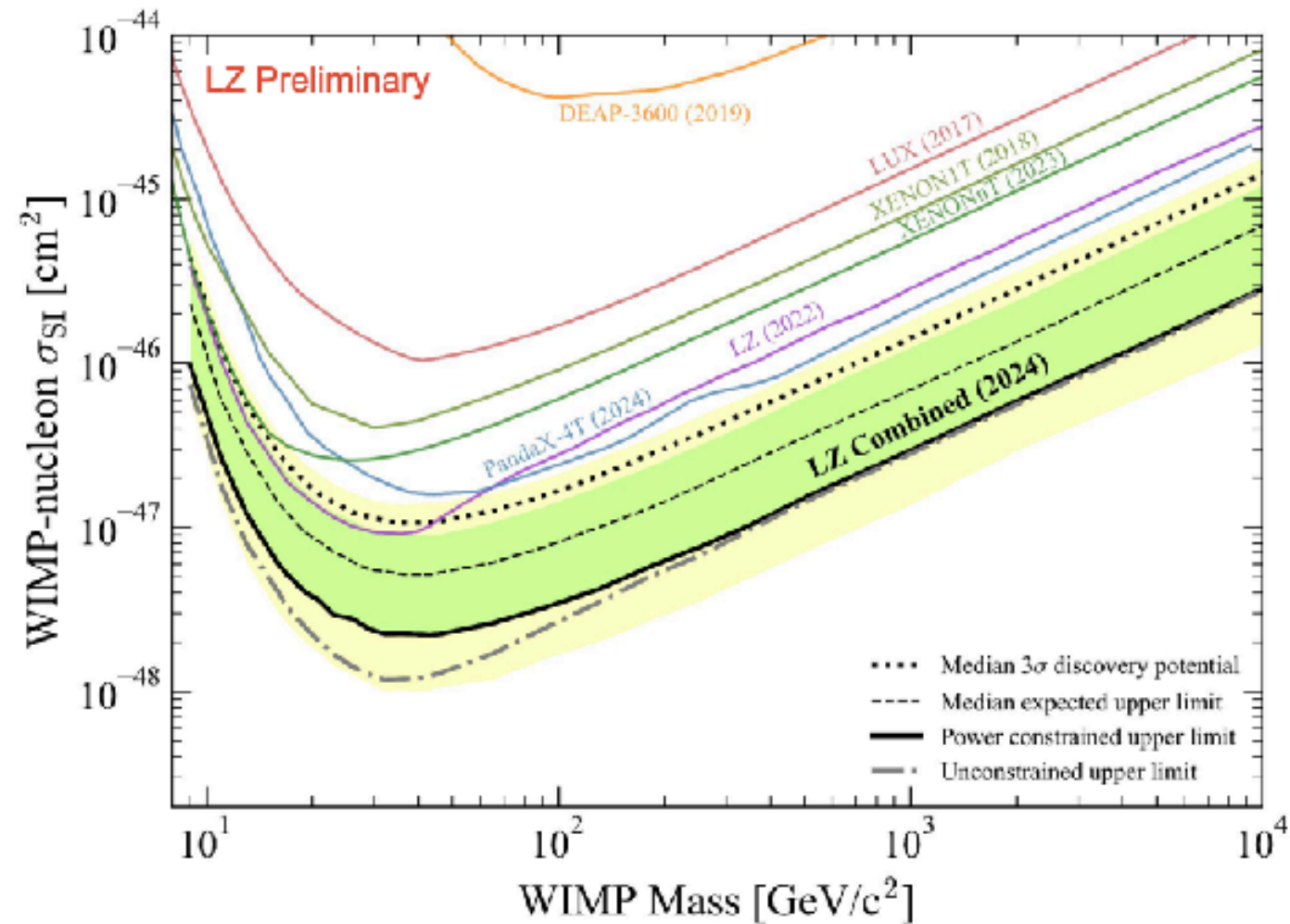


Strong constraints on **interaction cross section** when **DM mass** comparable to nucleus mass

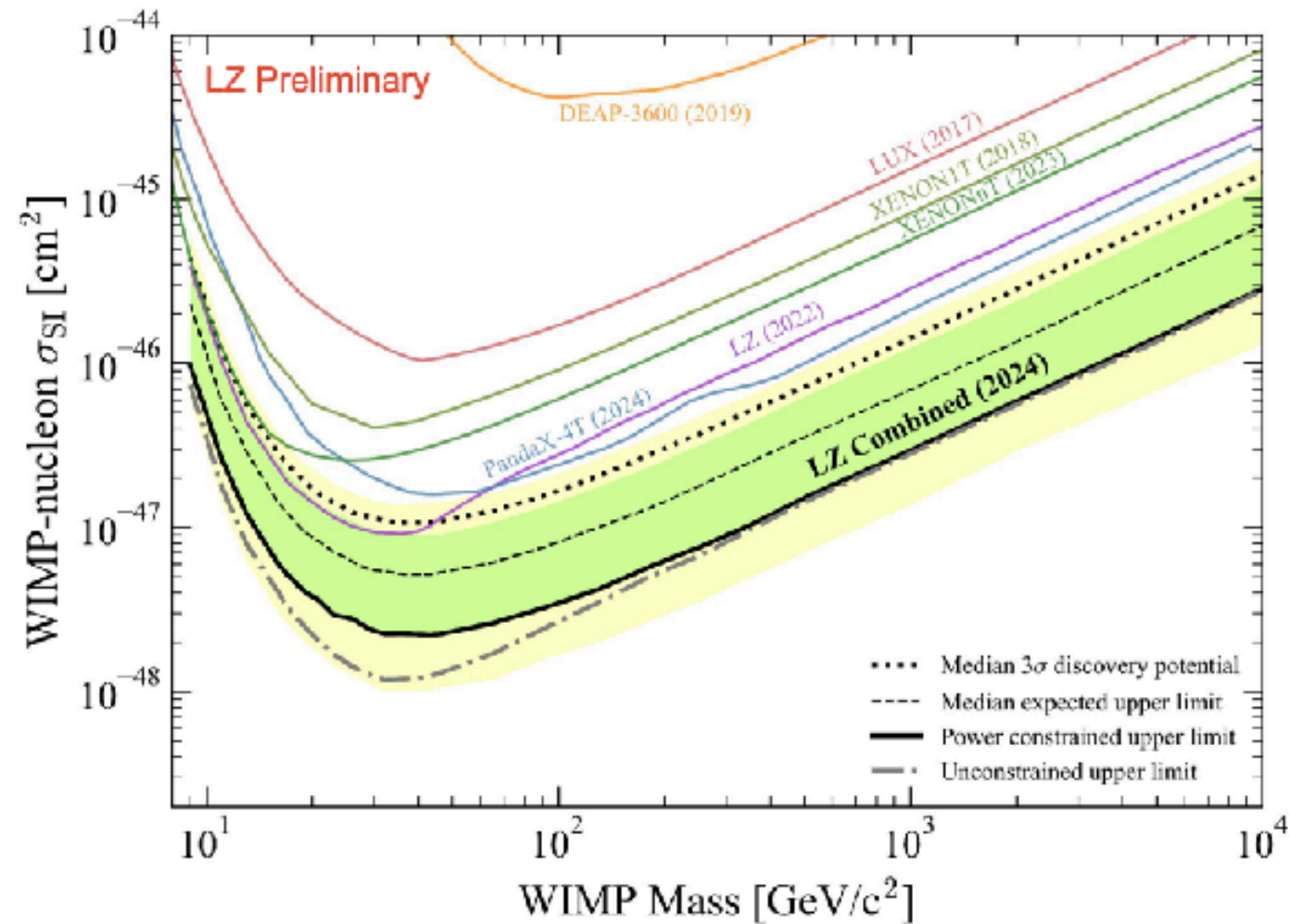


15 orders of magnitude weaker than electroweak interactions
 Similar to the effect of Pluto's gravity relative to Earth's





This is a motivated, but specific range in possible particle mass.

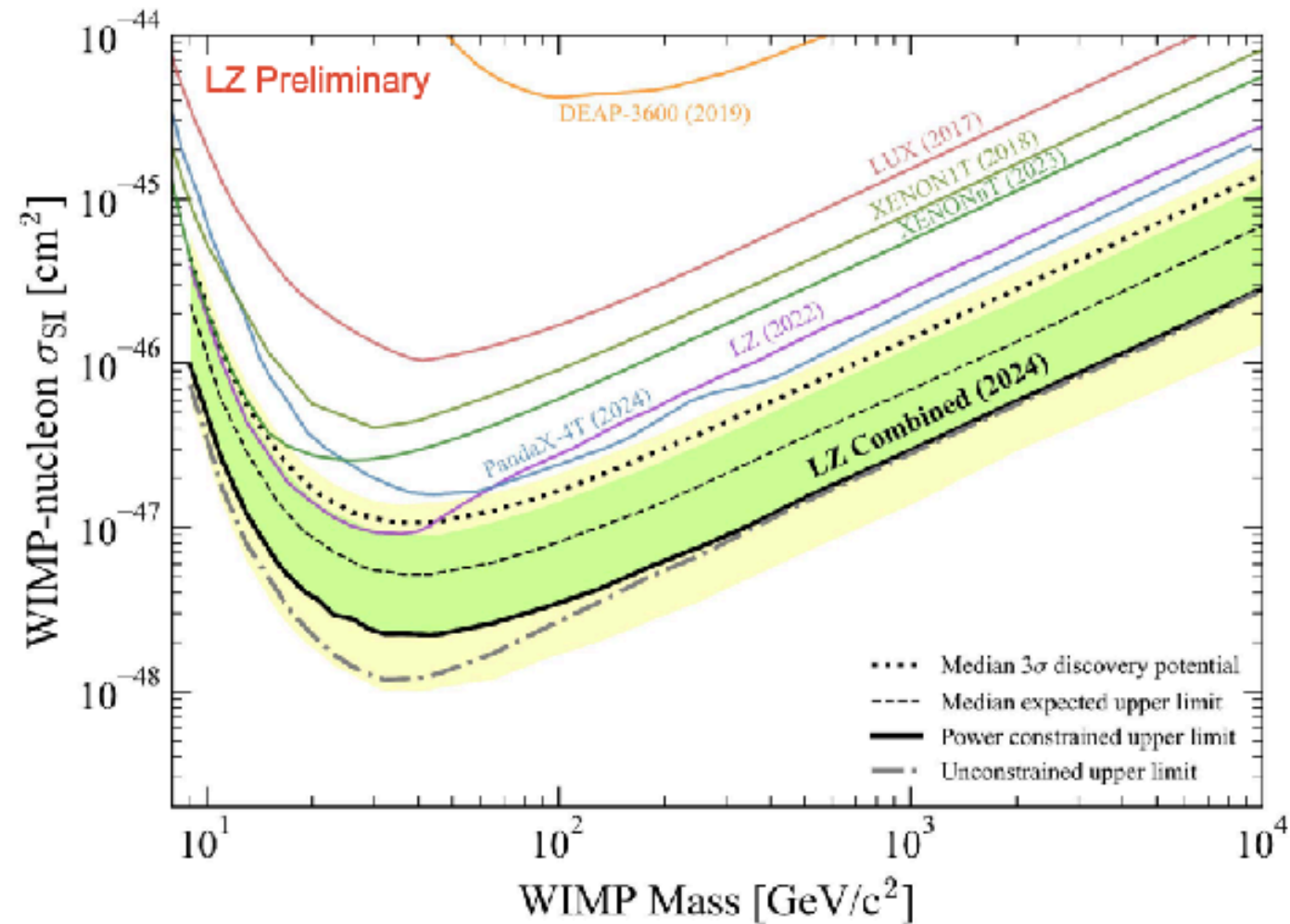


“Ultra-heavy” DM



This is a motivated, but specific range in possible particle mass.

“Light” dark matter

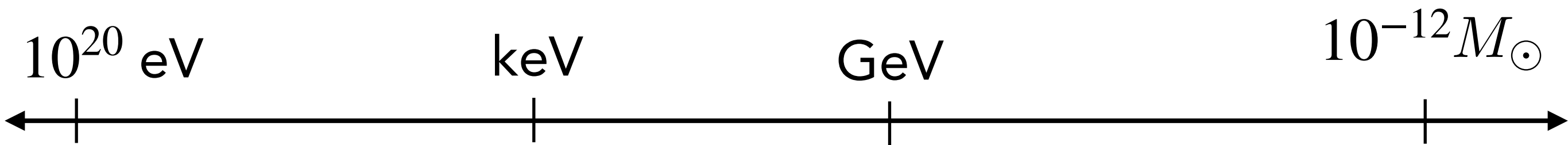


“Ultra-heavy” DM



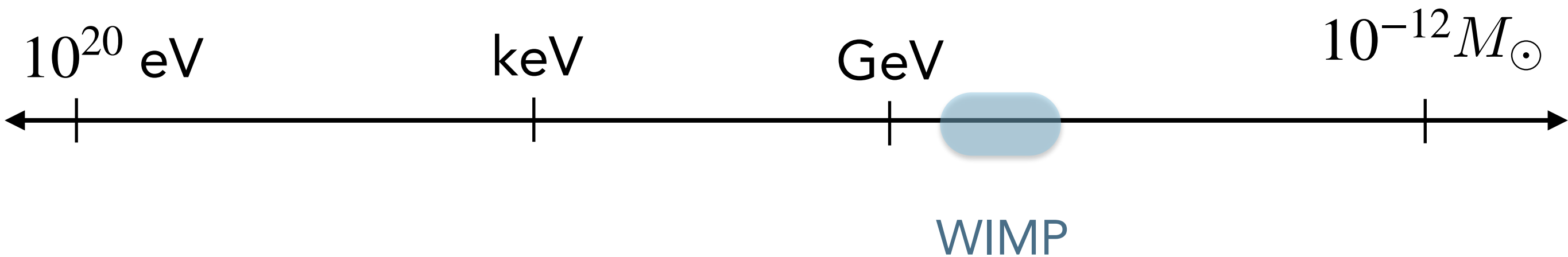
This is a motivated, but specific range in possible particle mass.

Mass scale of dark matter



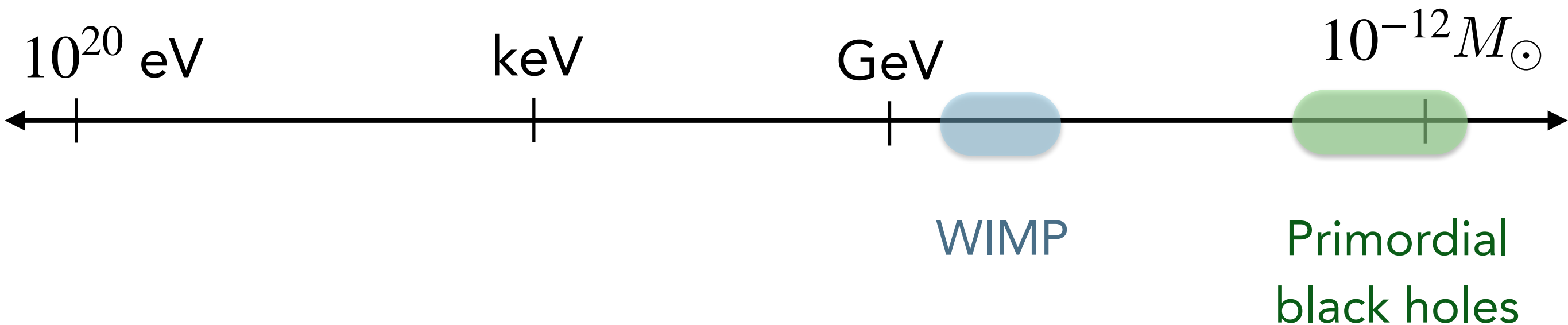
Going after 20 orders of magnitude in mass
for light+ultralight dark matter

Mass scale of dark matter



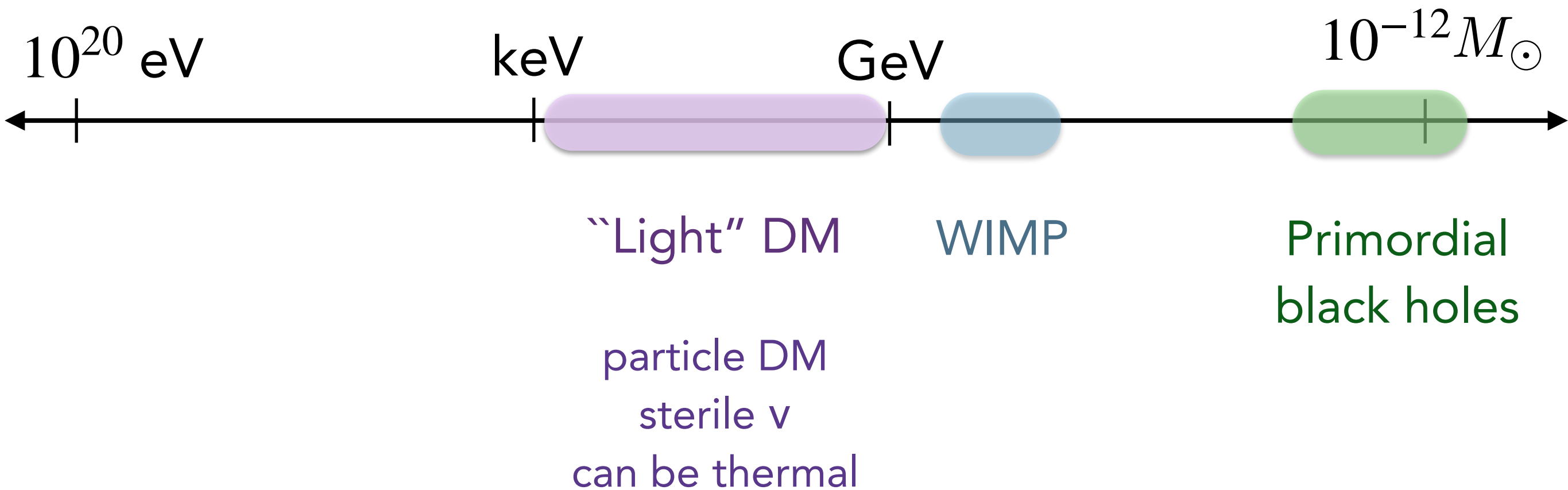
Going after 20 orders of magnitude in mass
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Mass scale of dark matter



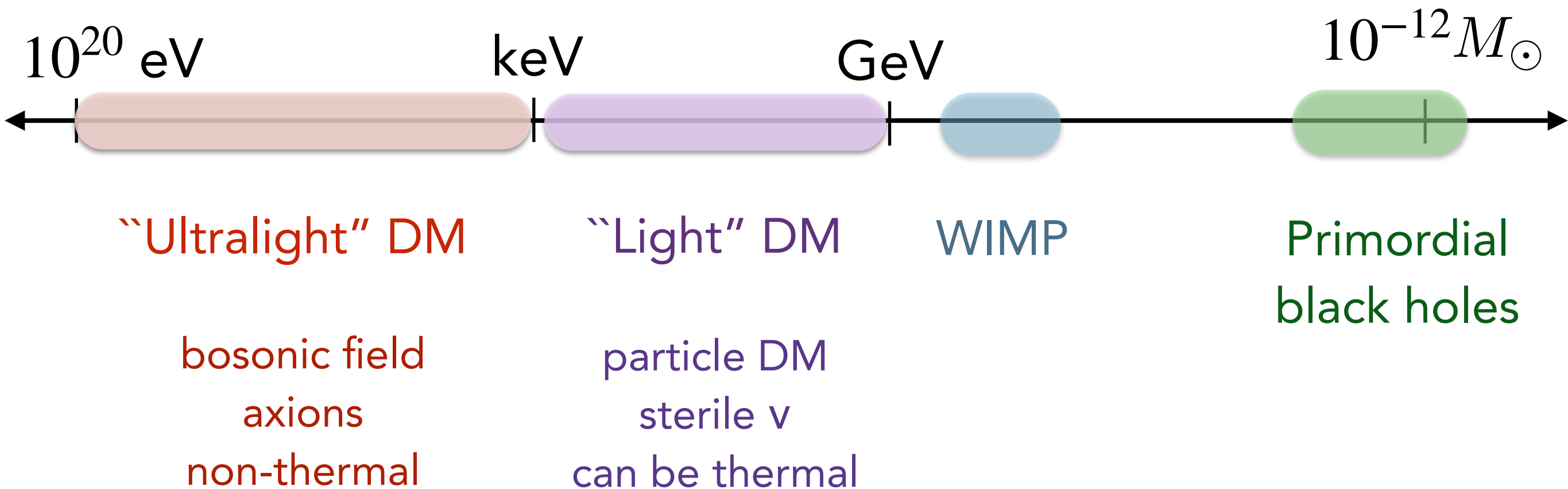
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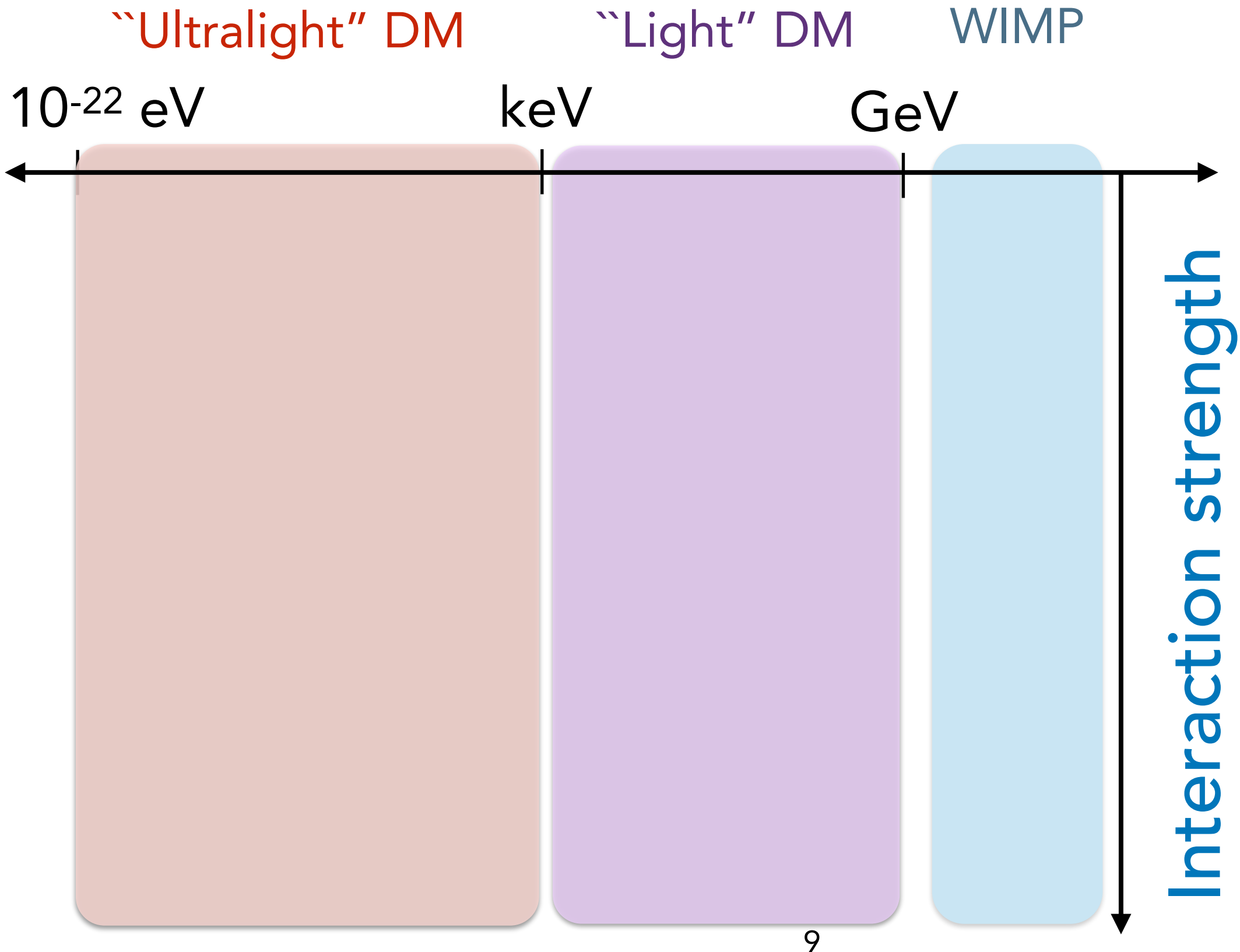
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Mass scale of dark matter

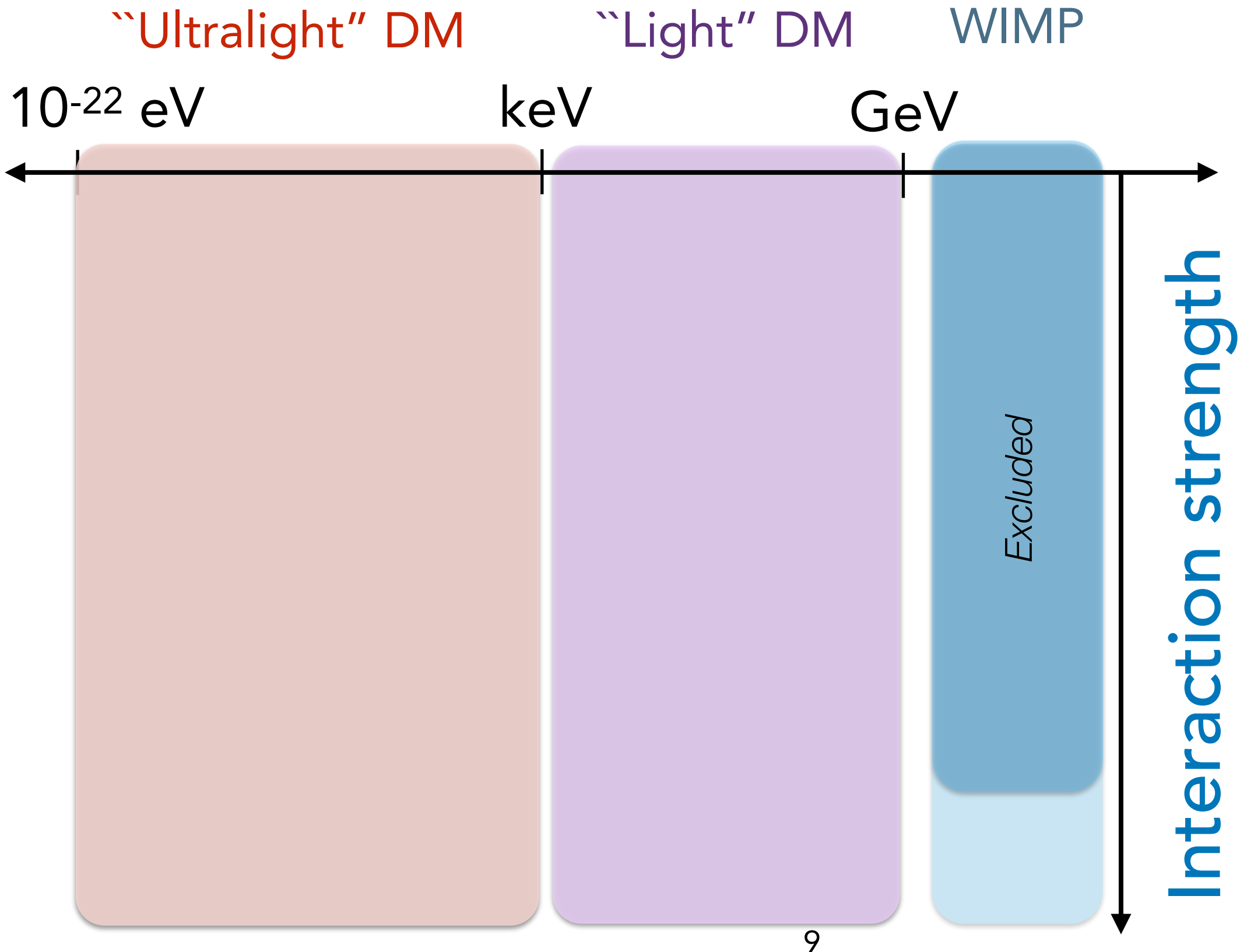


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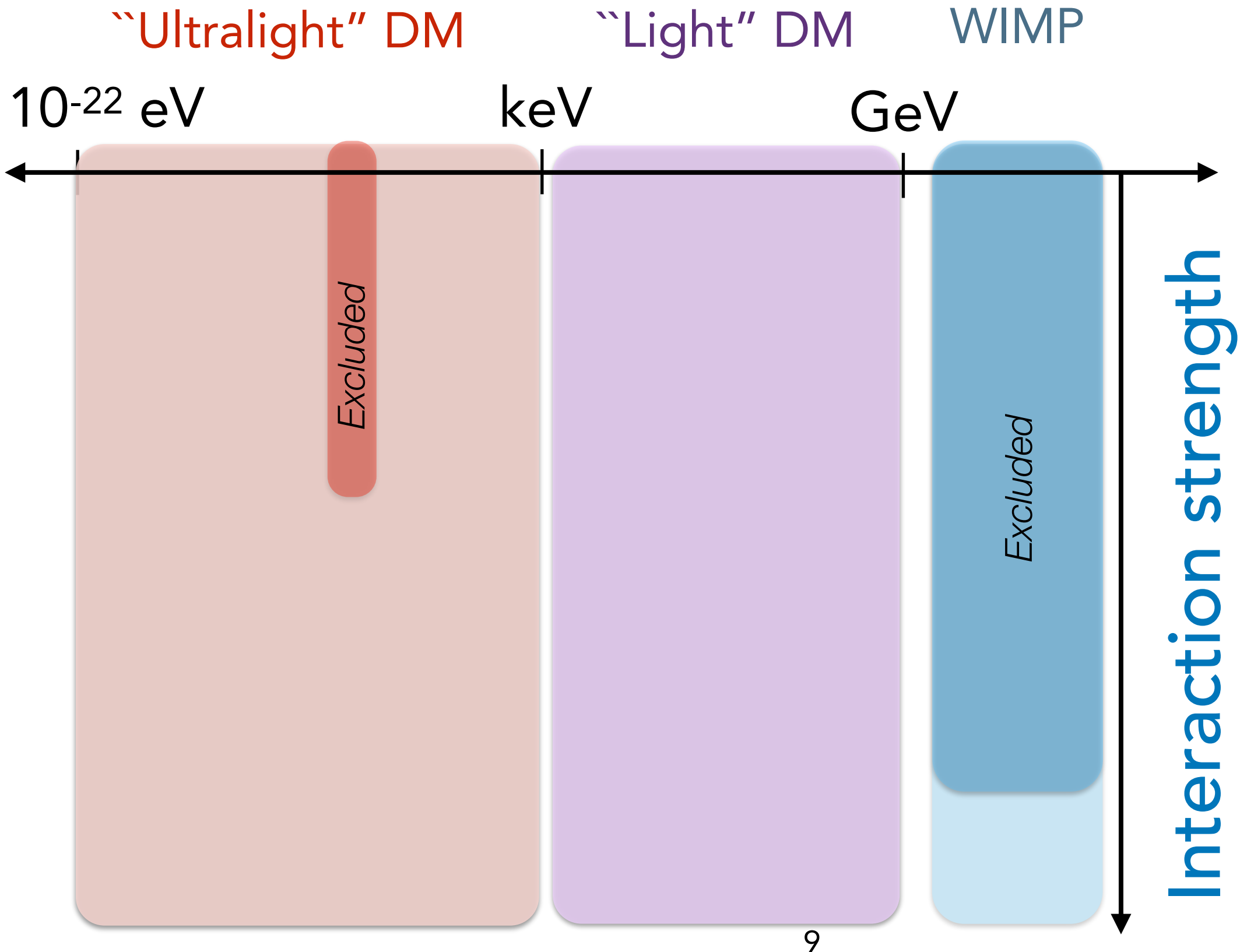
Mass scale of dark matter



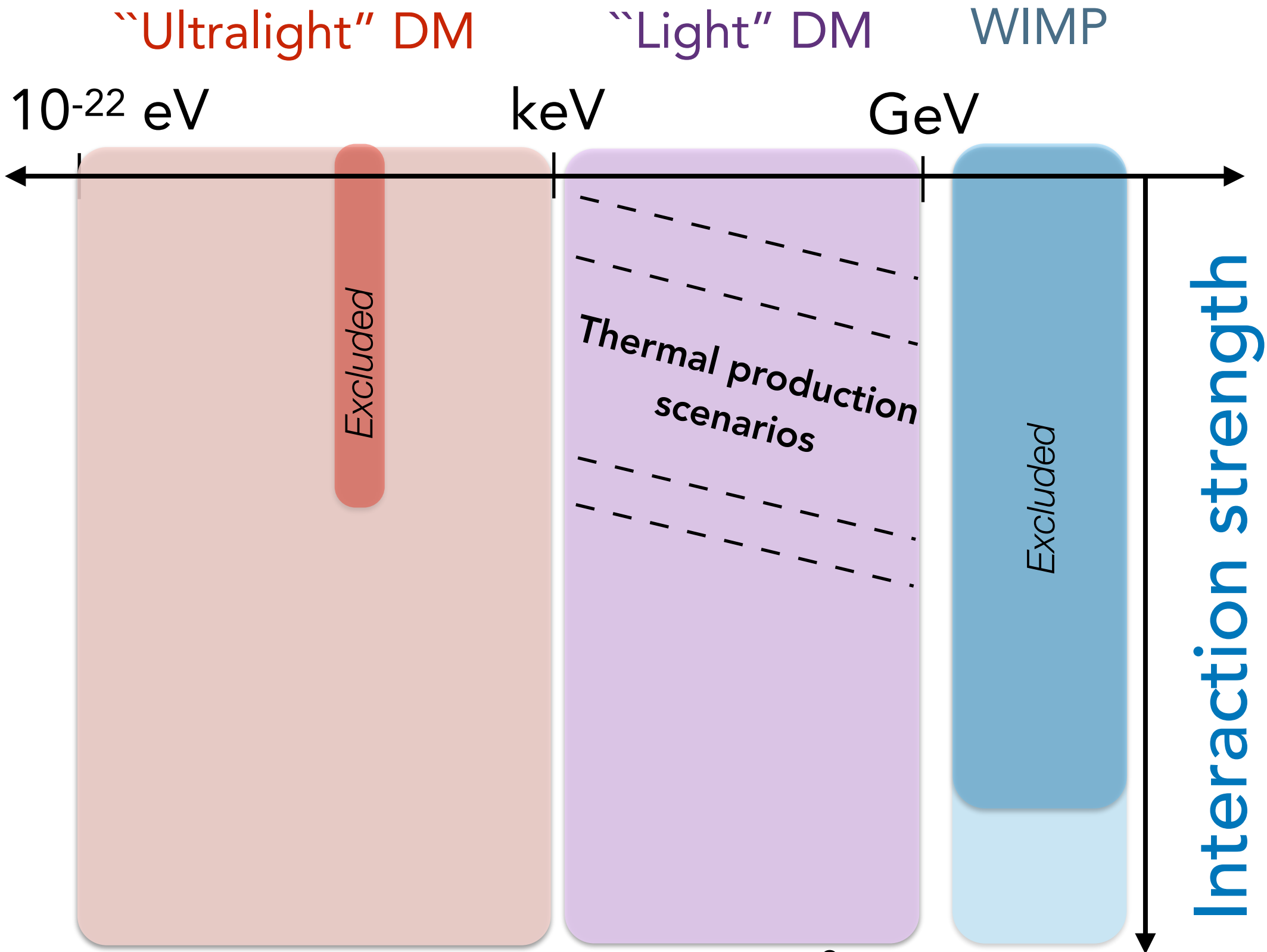
Mass scale of dark matter



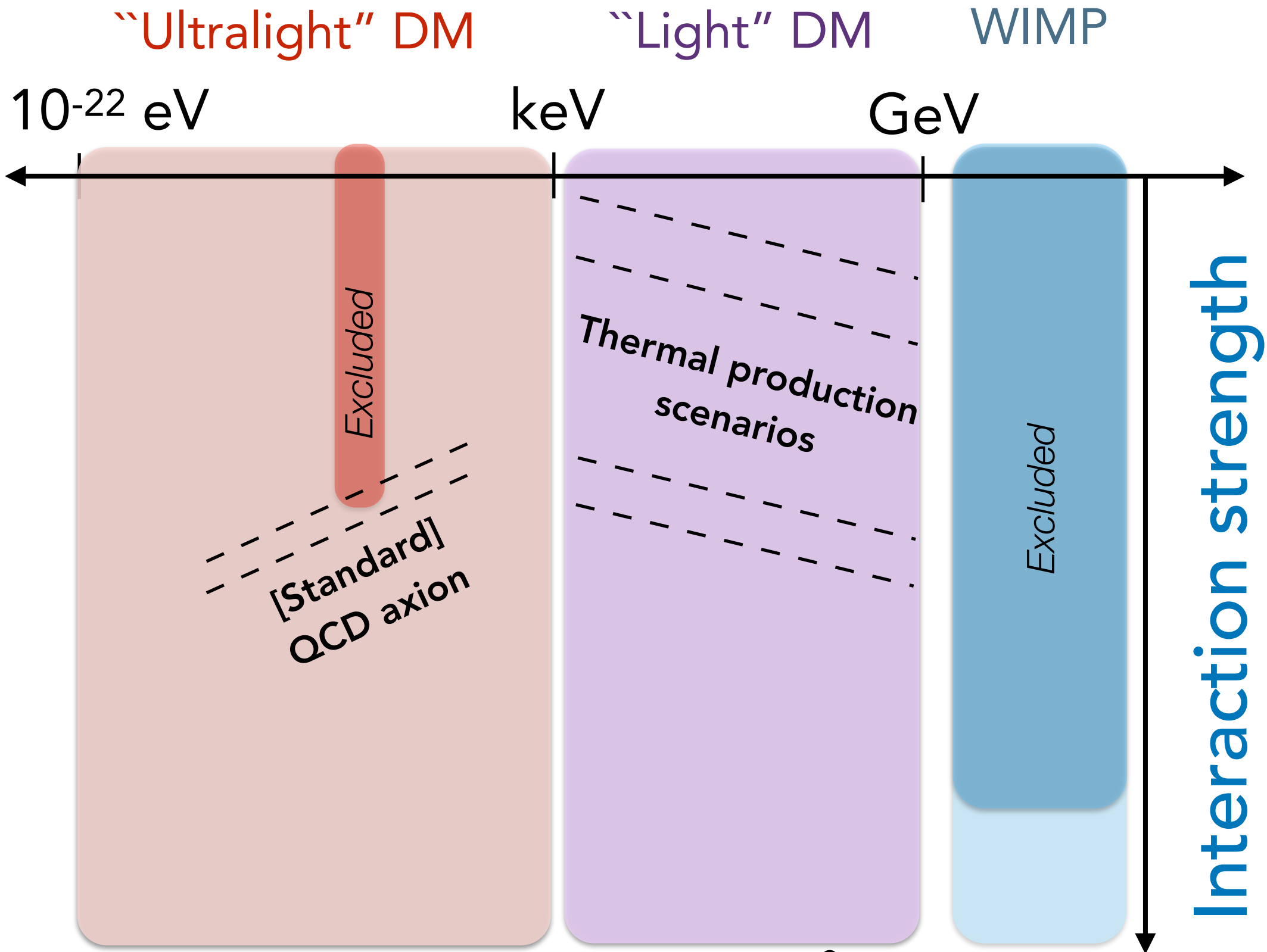
Mass scale of dark matter



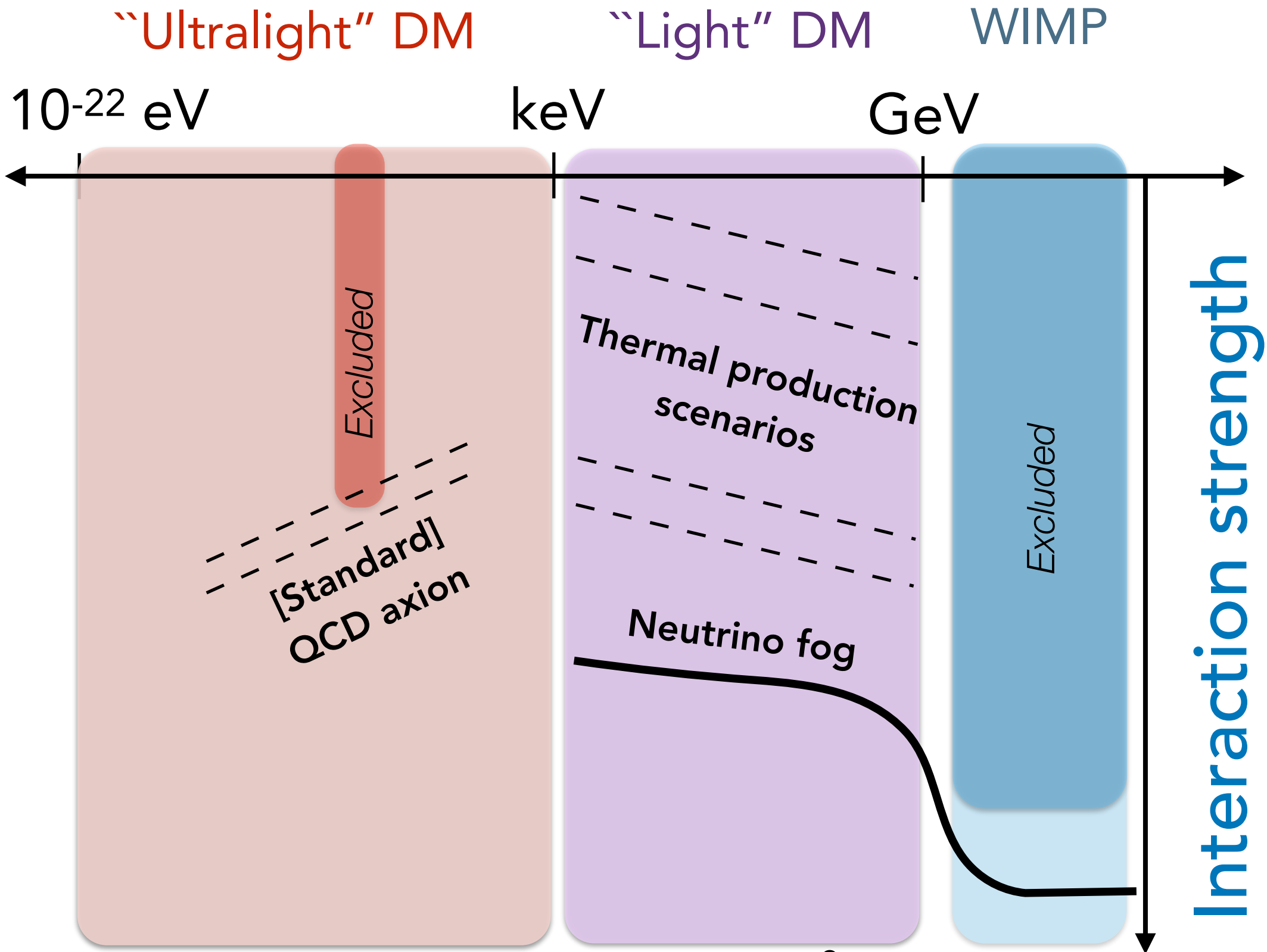
Mass scale of dark matter



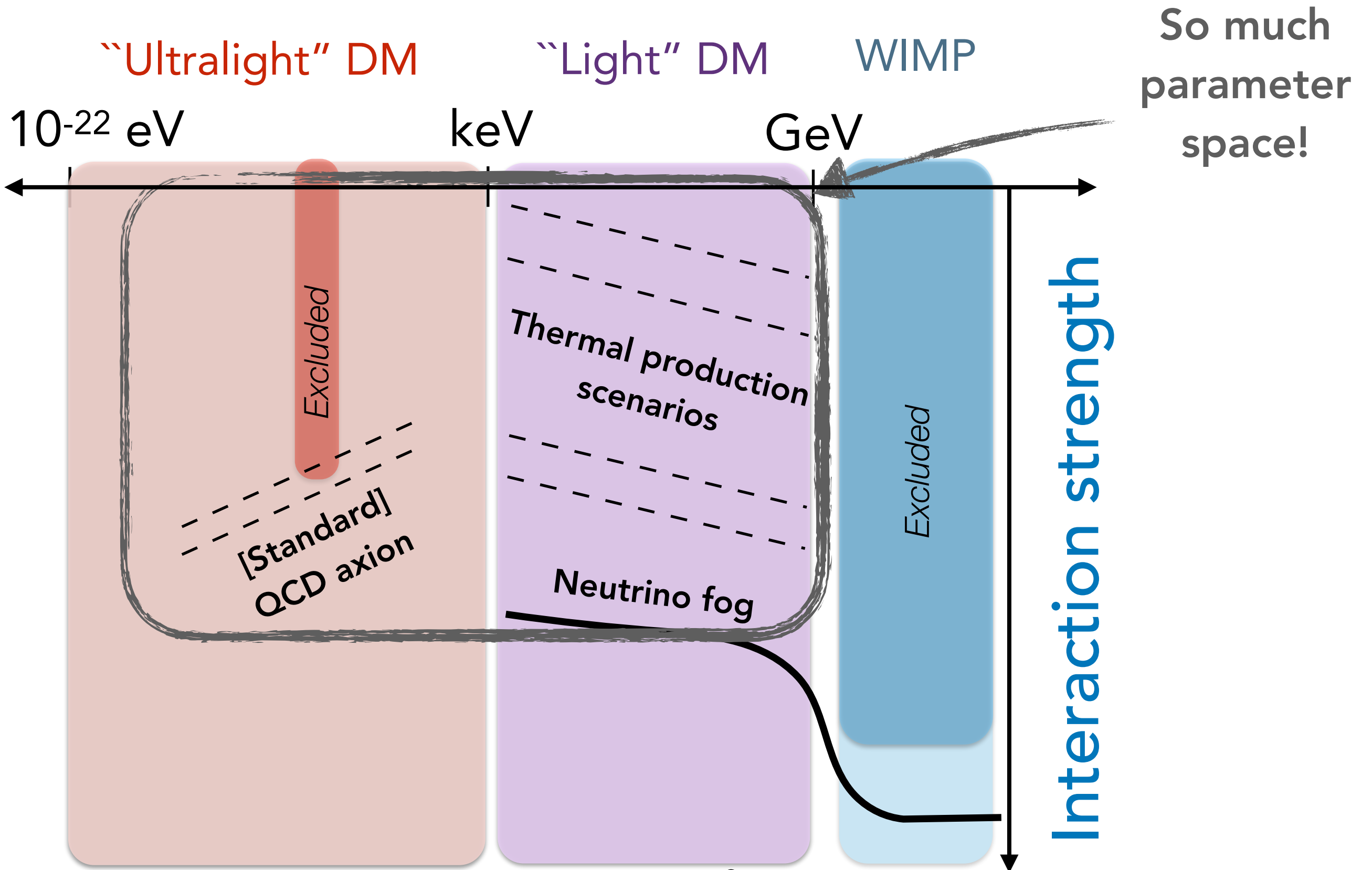
Mass scale of dark matter



Mass scale of dark matter

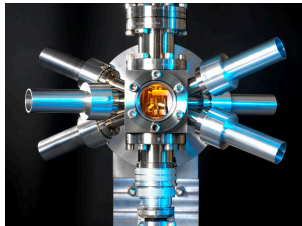


Mass scale of dark matter



New concepts

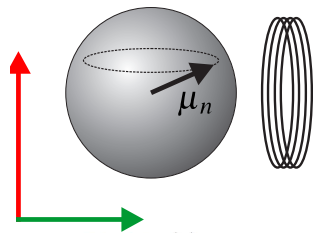
Atomic clocks



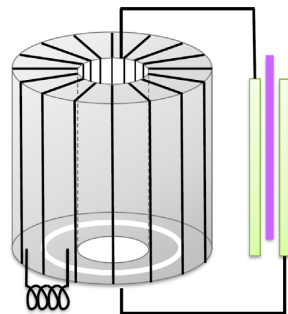
SRF Cavity



NMR



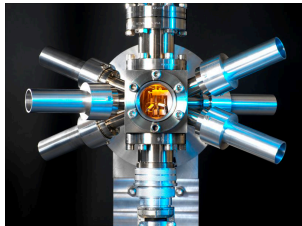
LC Resonators



New concepts

technologies

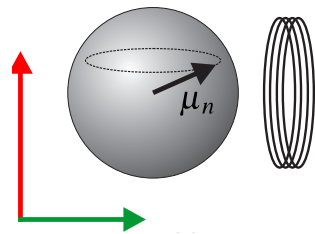
Atomic clocks



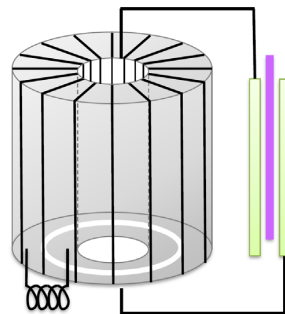
SRF Cavity



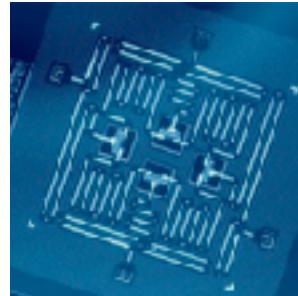
NMR



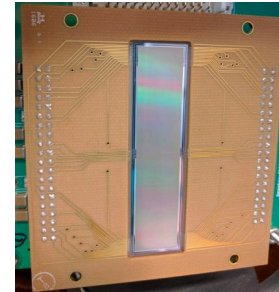
LC Resonators



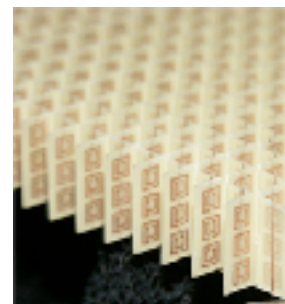
Qubits



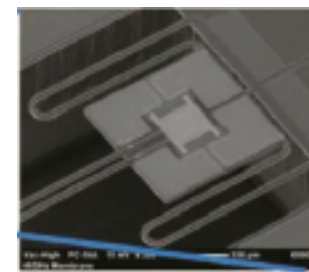
Skipper CCD



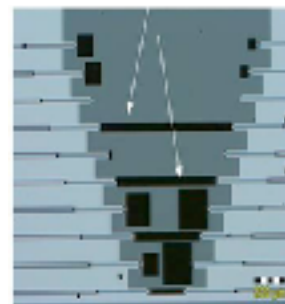
Metamaterials



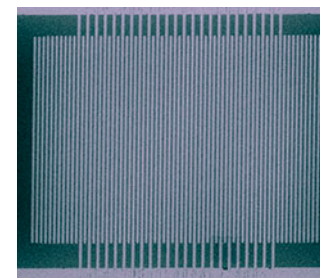
TES



KIDs

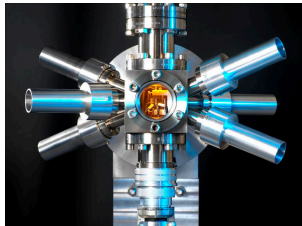


SNSPDs



New concepts

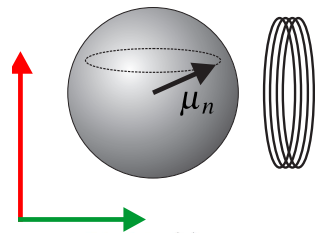
Atomic clocks



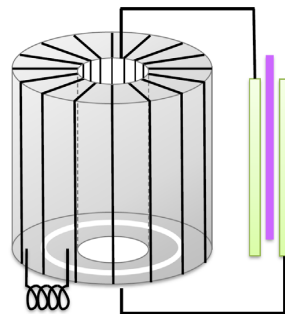
SRF Cavity



NMR

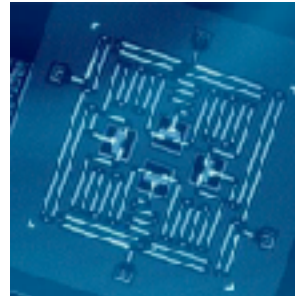


LC Resonators

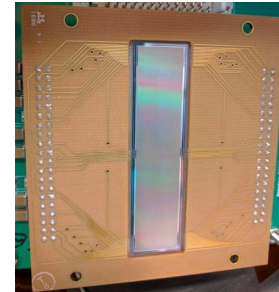


technologies

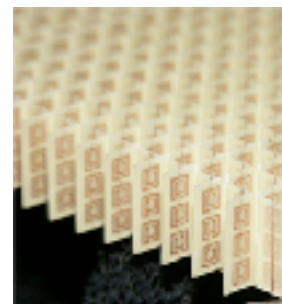
Qubits



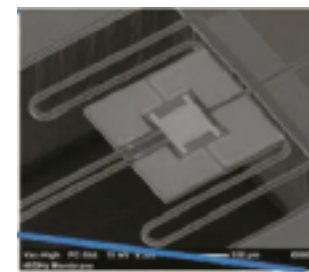
Skipper CCD



Metamaterials



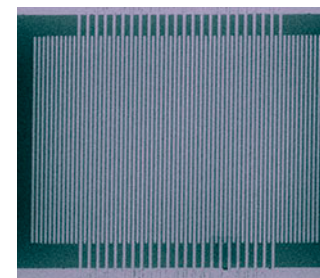
TES



KIDs

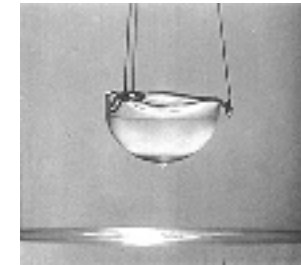


SNSPDs



materials

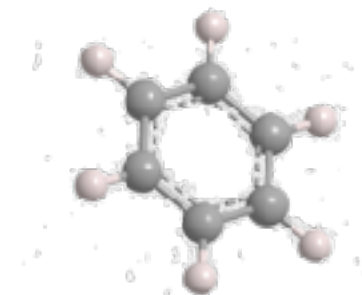
Superfluid He



Polar crystals



Organic molecules



Dirac material

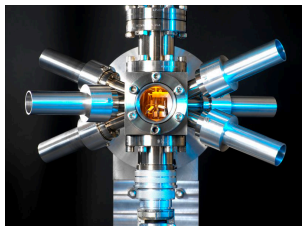


New concepts

technologies

materials

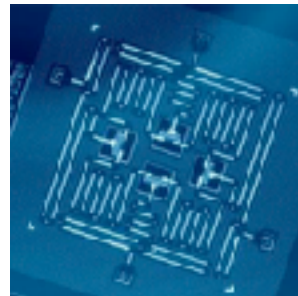
Atomic clocks



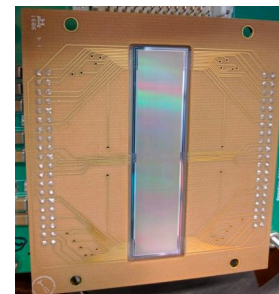
SRF Cavity



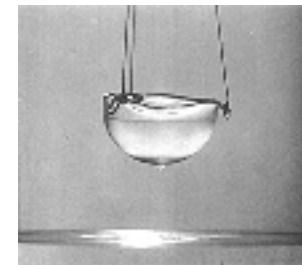
Qubits



Skipper CCD



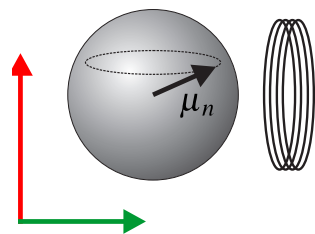
Superfluid He



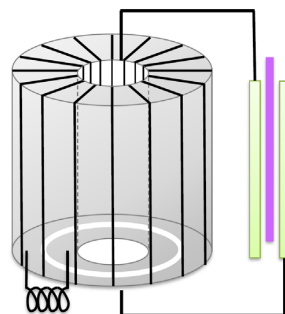
Polar crystals



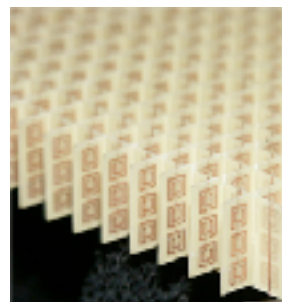
NMR



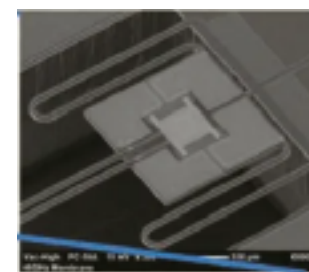
LC Resonators



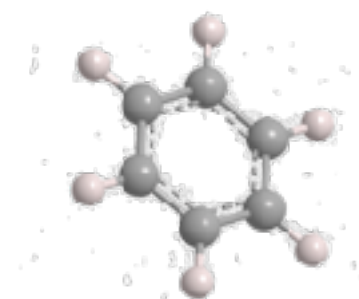
Metamaterials



TES



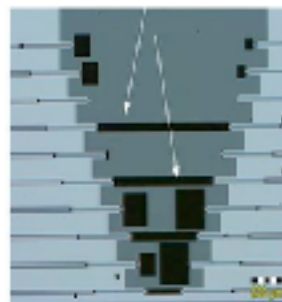
Organic molecules



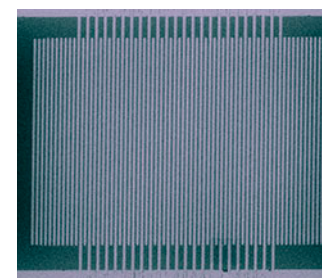
Dirac material



KIDs



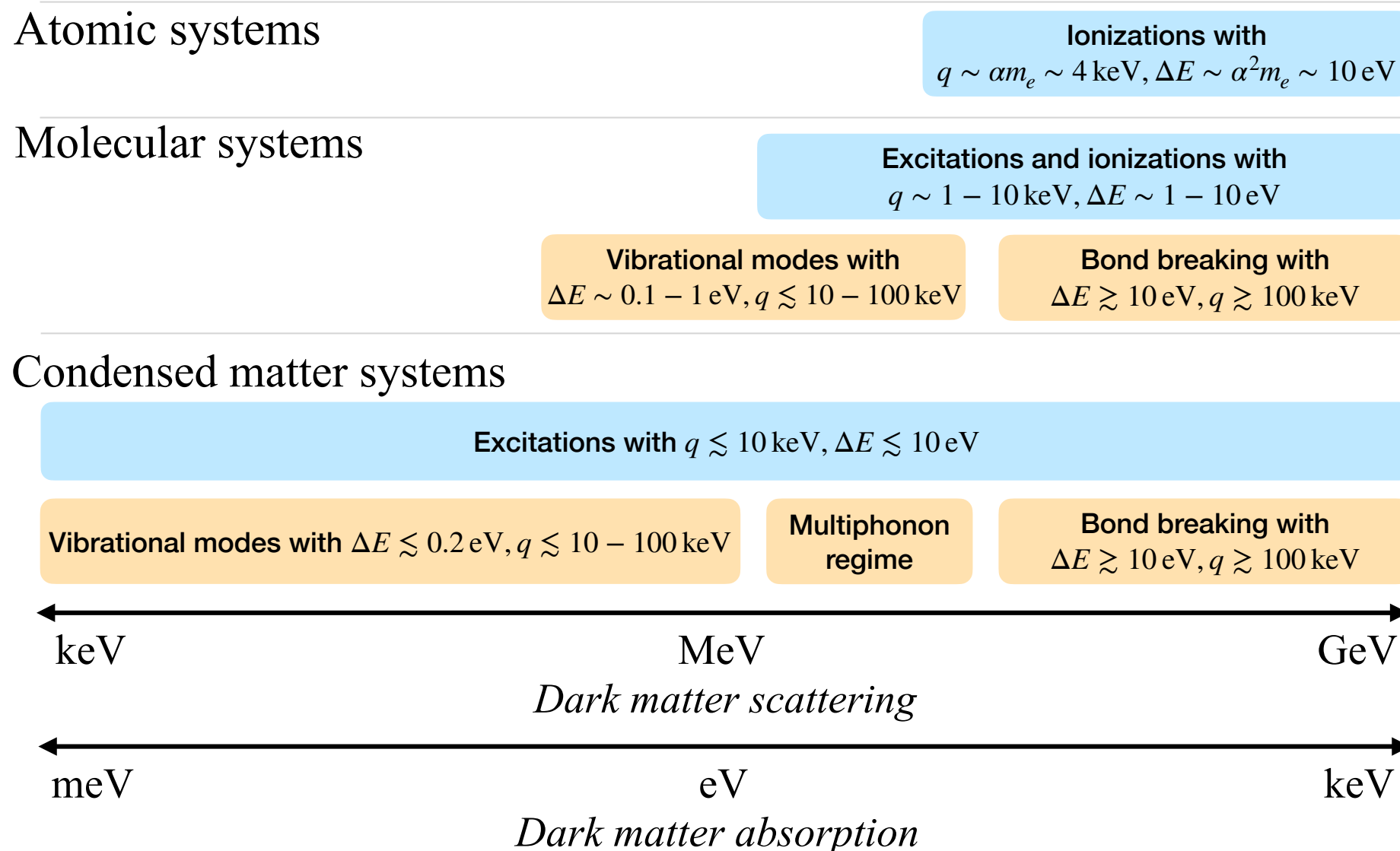
SNSPDs



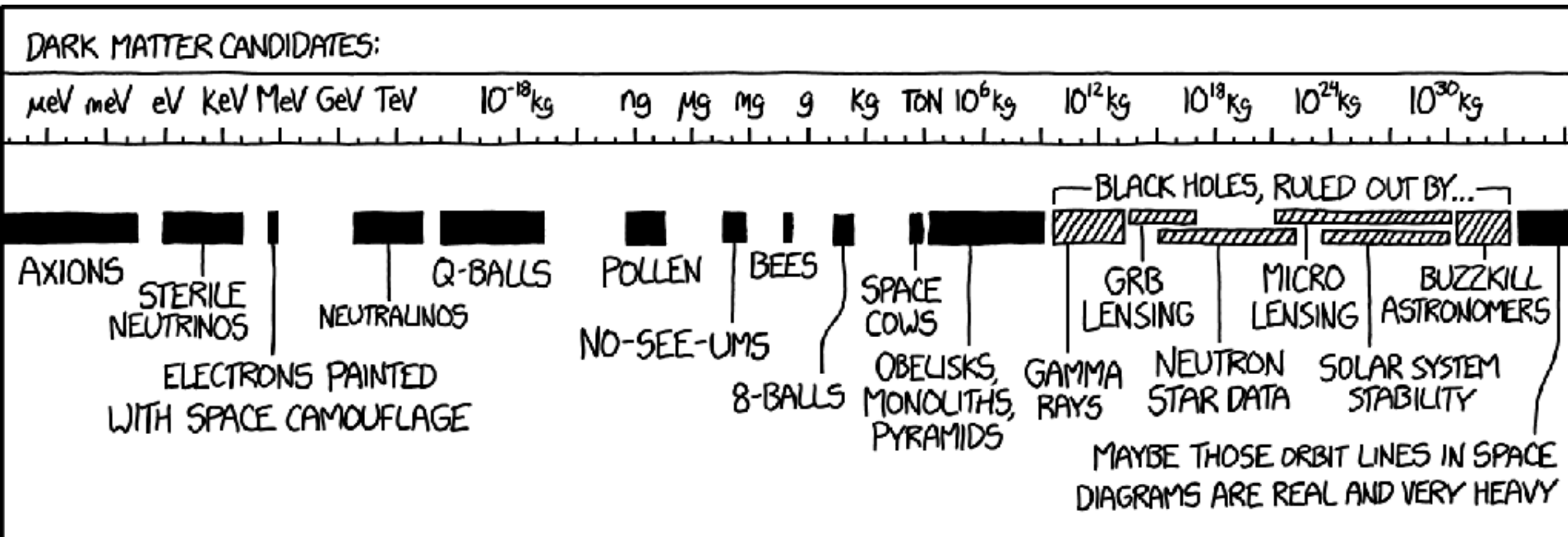
New windows into light dark matter!

Detection concepts for particle-like DM

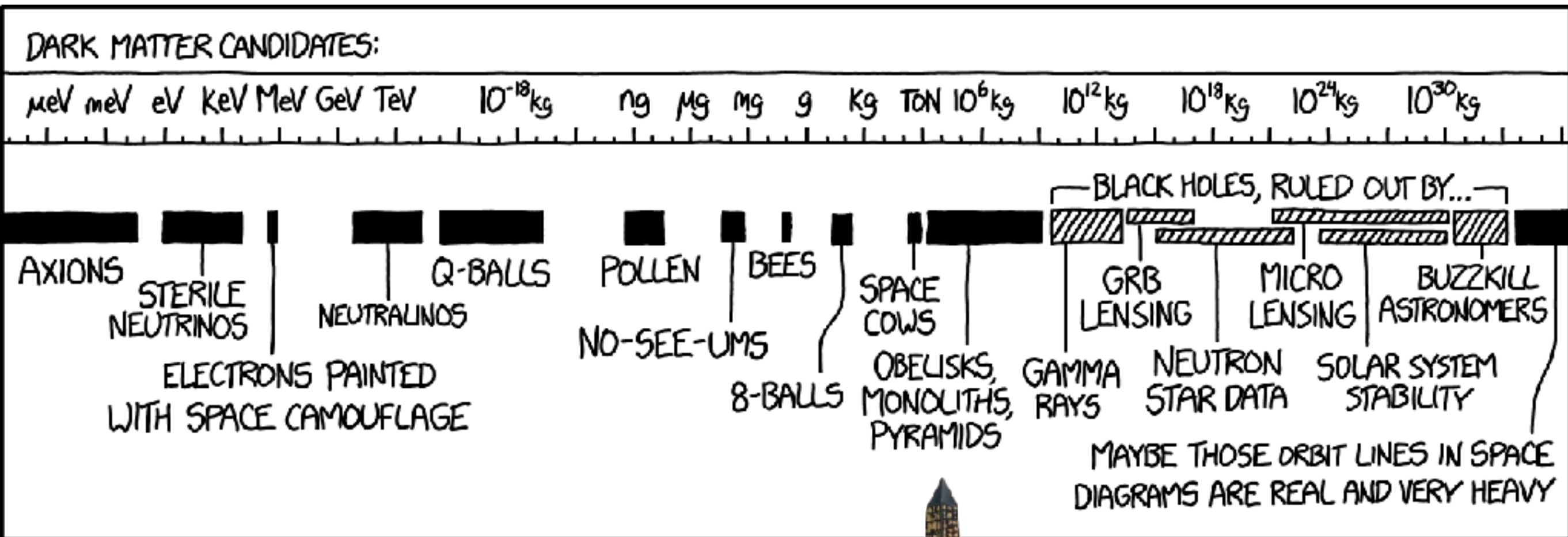
Utilize diversity of excitation modes in nature and advances in neighboring fields including materials science, quantum sensing.



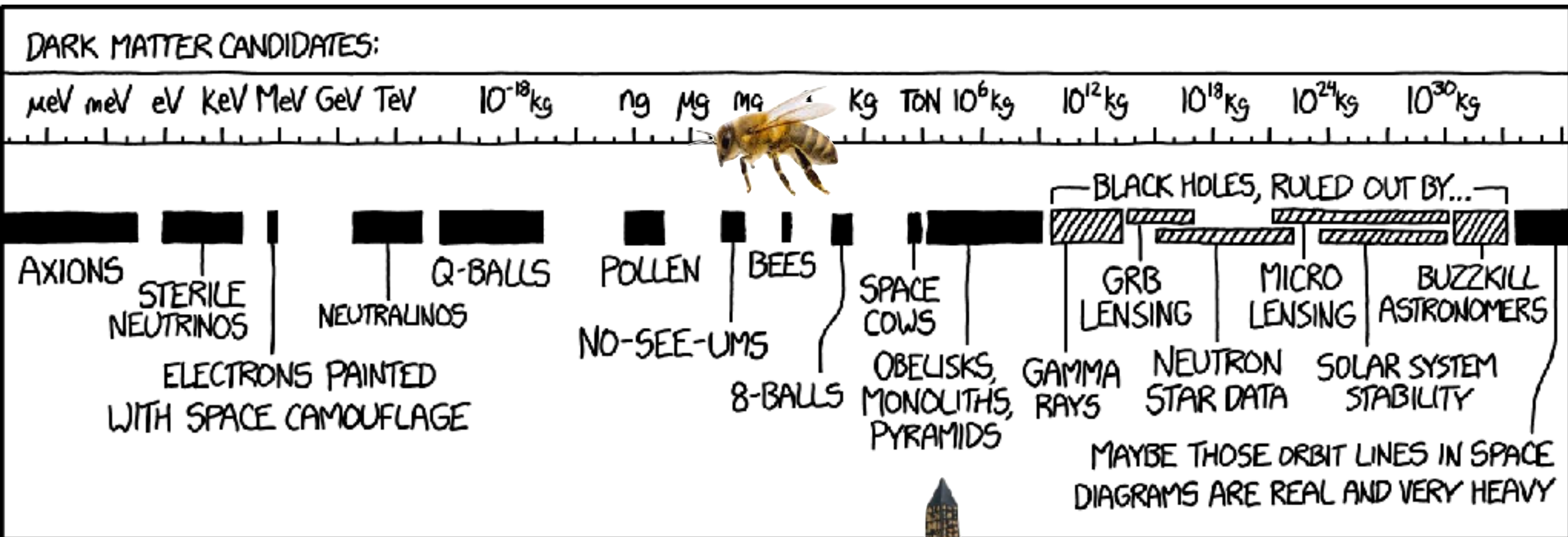
Dark matter: is anything possible?



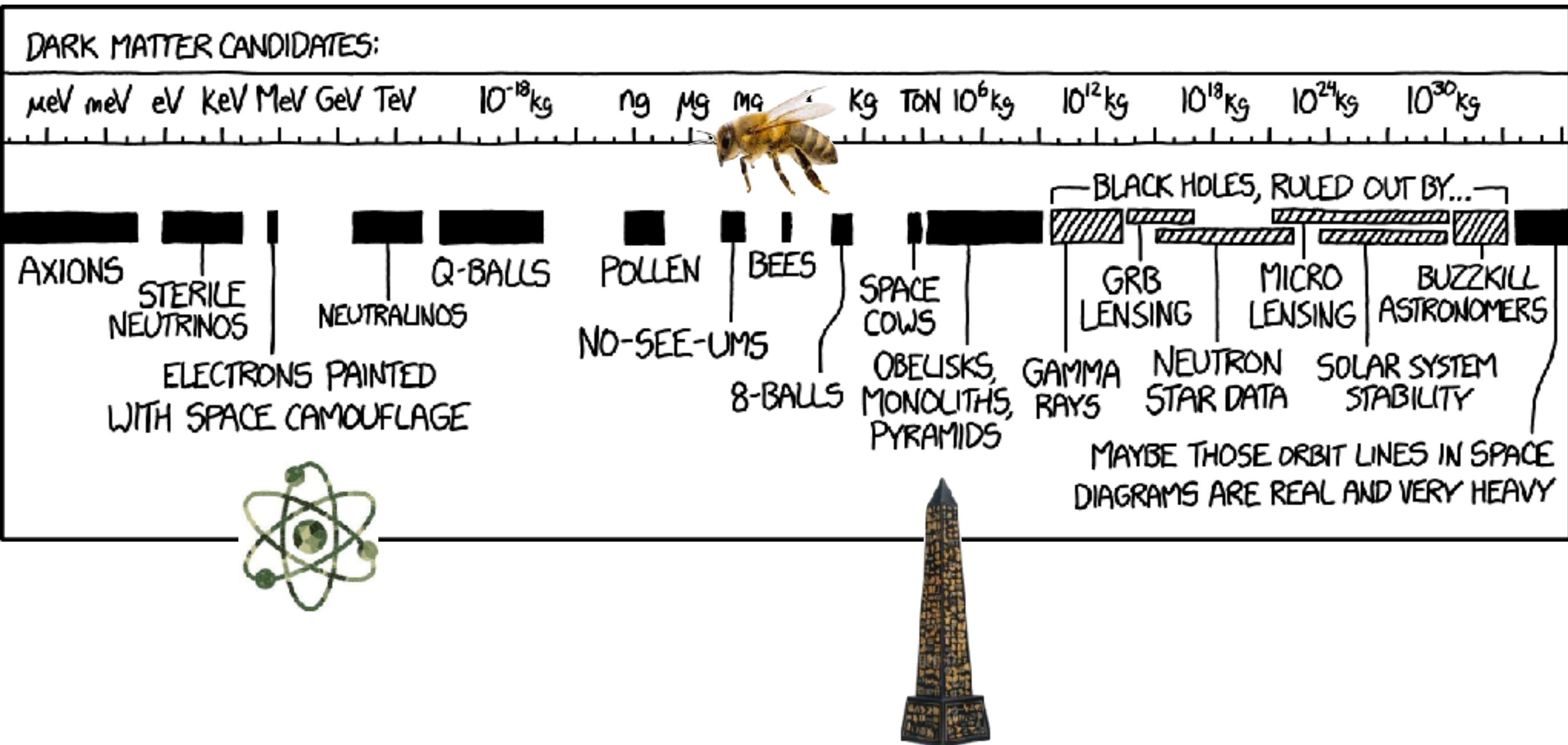
Dark matter: is anything possible?



Dark matter: is anything possible?



Dark matter: is anything possible?



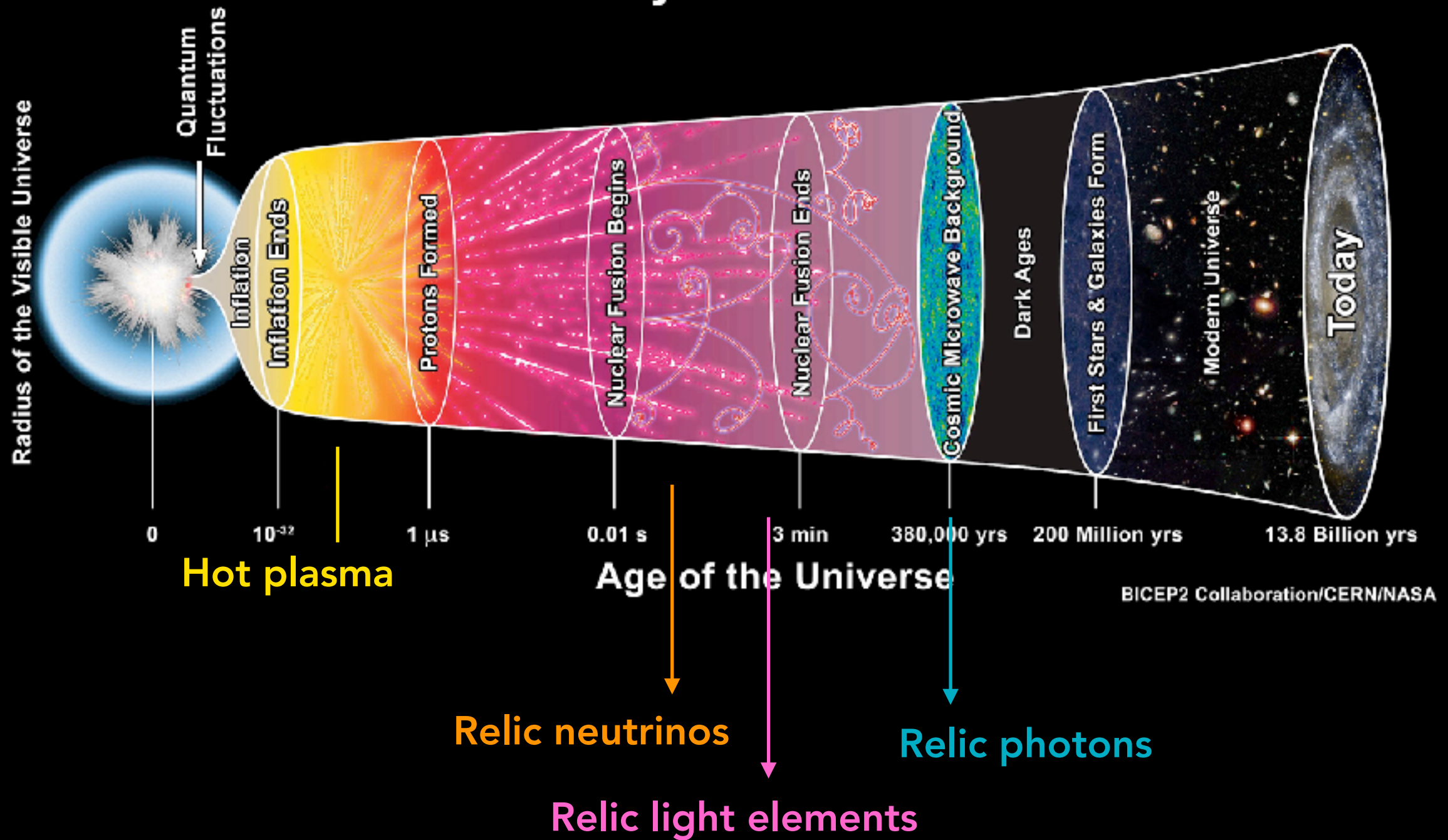
Light particle dark matter

$$(\text{keV} \lesssim M_{\text{DM}} \lesssim \text{GeV})$$

Defining contours of what's possible and motivated
(in the context of direct detection)

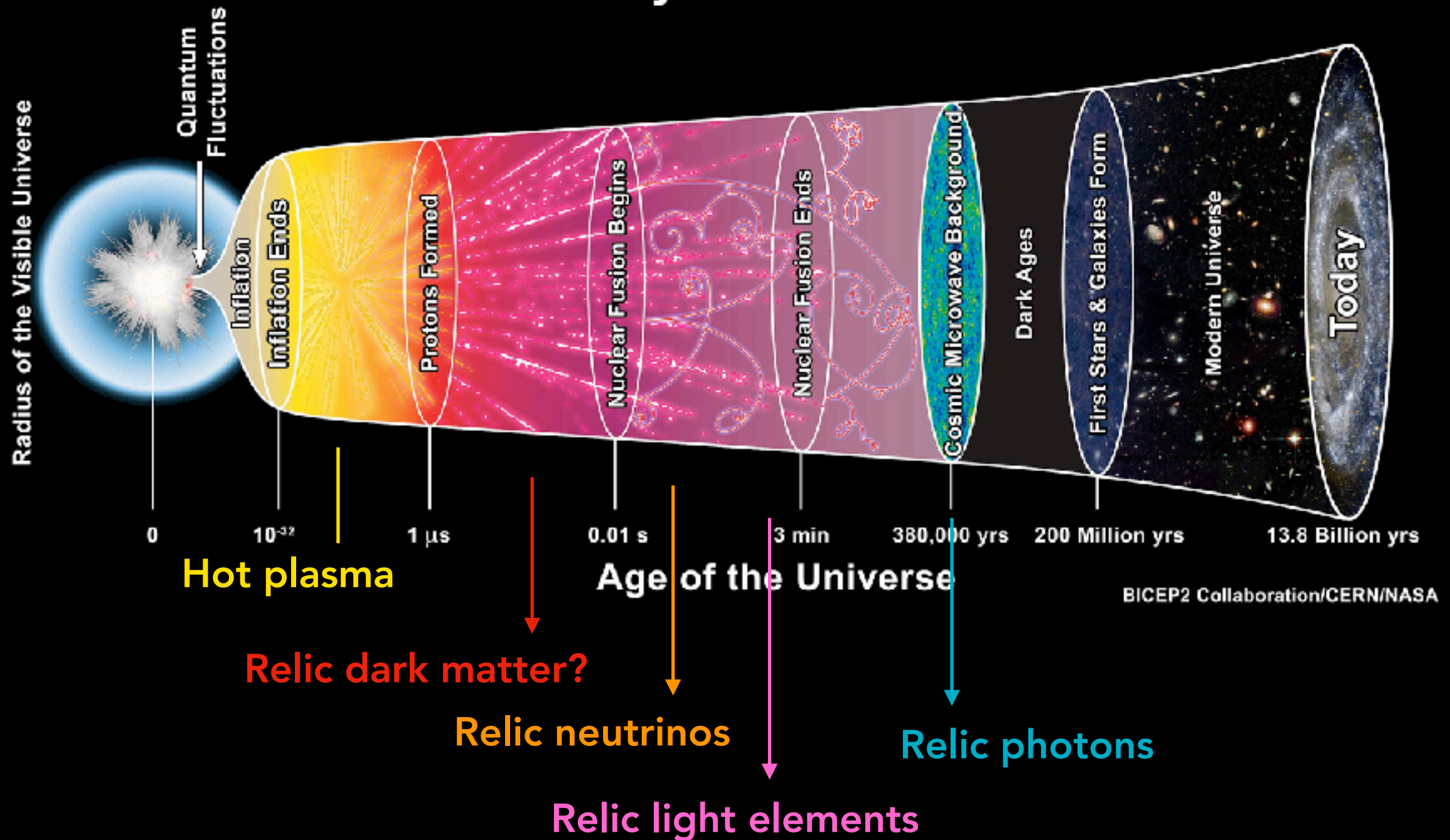
I. Relic abundance and cosmology

History of the Universe



Was dark matter produced out of the hot plasma early on?

History of the Universe



Was dark matter produced out of the hot plasma early on?

If dark matter was ever in thermal equilibrium with the SM or produced from the SM plasma, it inherits $p_{\text{DM}} \sim T_{\text{SM}}$.

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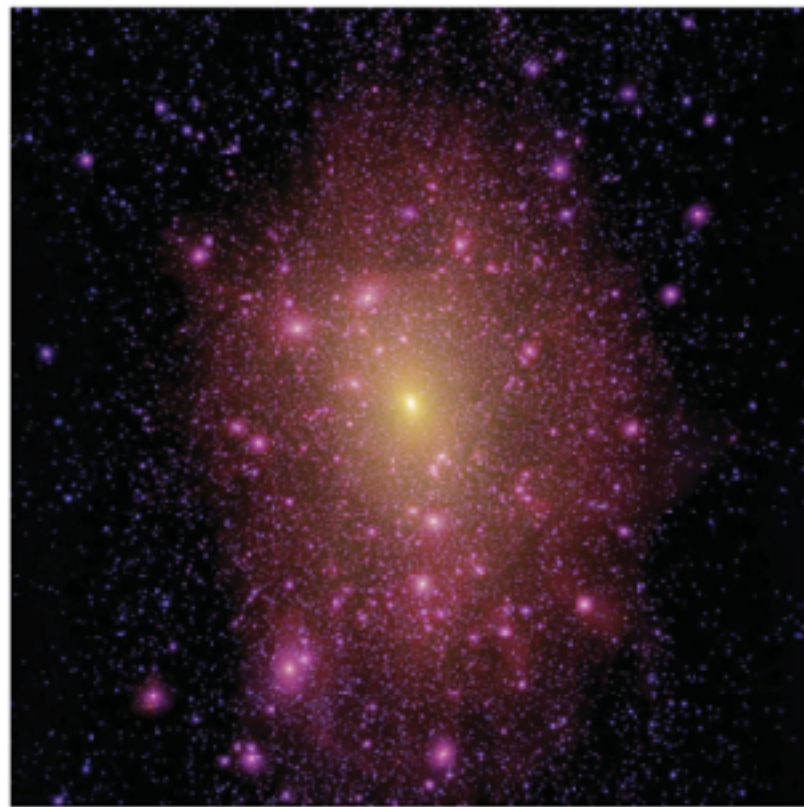
For keV-scale DM, at the time of matter-radiation equality

$$v_{\text{DM}} \sim T_{\text{SM}}/m_{\text{DM}} \sim 0.01$$

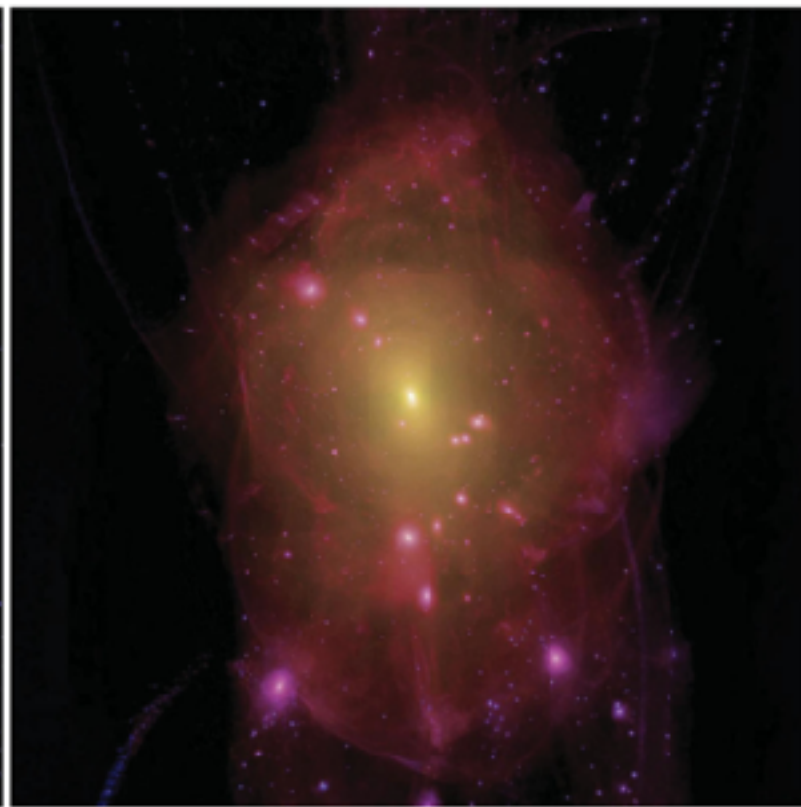
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For keV-scale DM, at the time of matter-radiation equality

$$v_{\text{DM}} \sim T_{\text{SM}}/m_{\text{DM}} \sim 0.01$$



Cold dark matter

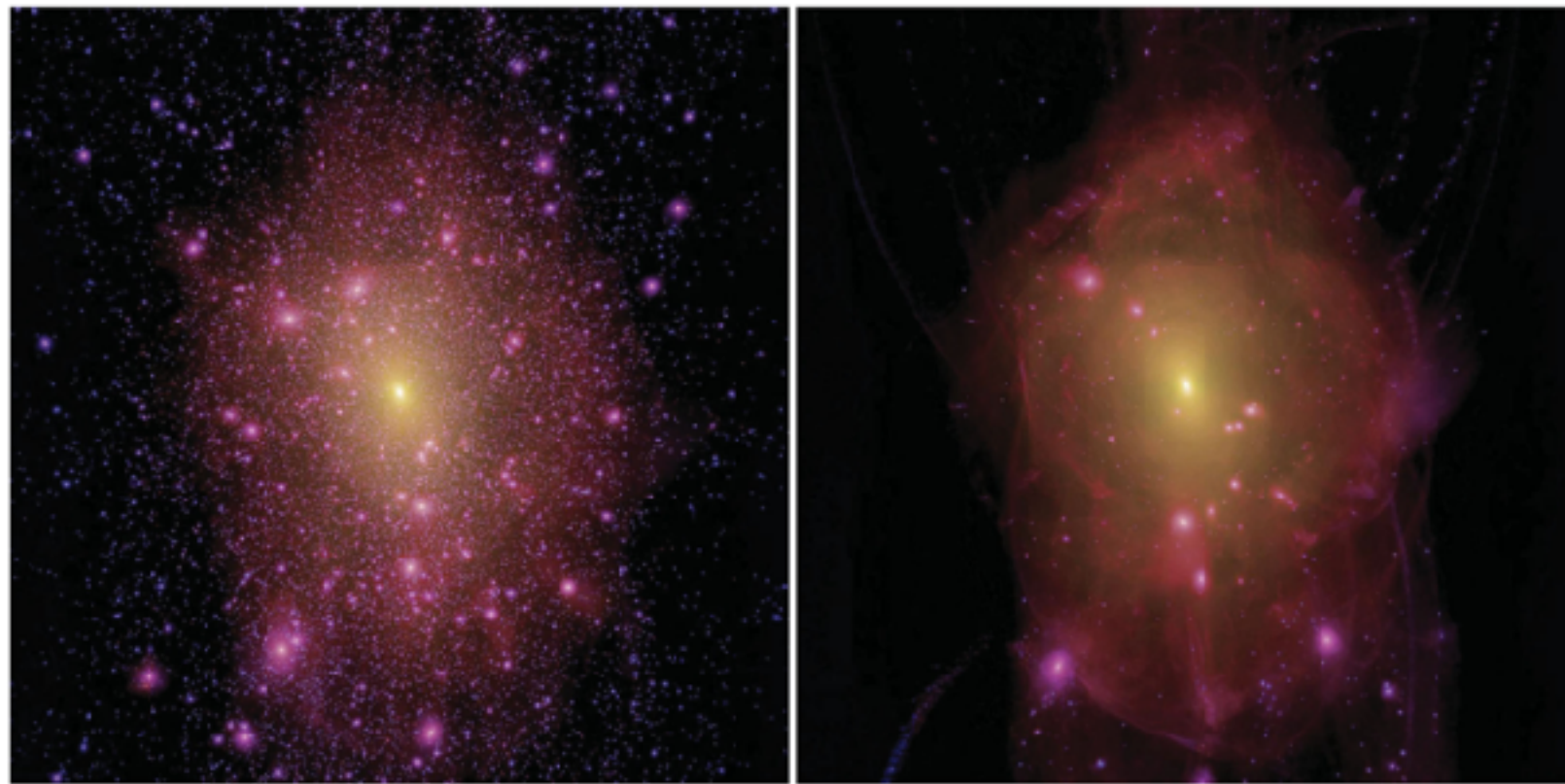


Warm dark matter (2 keV)

If dark matter was ever in thermal equilibrium with the SM or produced from the SM plasma, it inherits $p_{\text{DM}} \sim T_{\text{SM}}$.

For keV-scale DM, at the time of matter-radiation equality

$$v_{\text{DM}} \sim T_{\text{SM}}/m_{\text{DM}} \sim 0.01$$



Cold dark matter

Warm dark matter (2 keV)

Challenging for thermal(ish) candidates to have mass below ~ 10 keV

Required relic abundance

Track everything relative to photon entropy: s_γ

Required relic abundance

Track everything relative to photon entropy: s_γ

abundance $Y_{\text{fo}} \equiv \frac{n_\chi}{s_\gamma} \Big|_{\text{fo}} \quad \rho_\chi^{\text{today}} = m_\chi Y_{\text{fo}} s_{\gamma, \text{today}}$

Obtain the correct relic abundance if $Y_{\text{fo}} \approx \frac{\text{eV}}{m_\chi}$

Required relic abundance

Track everything relative to photon entropy: s_γ

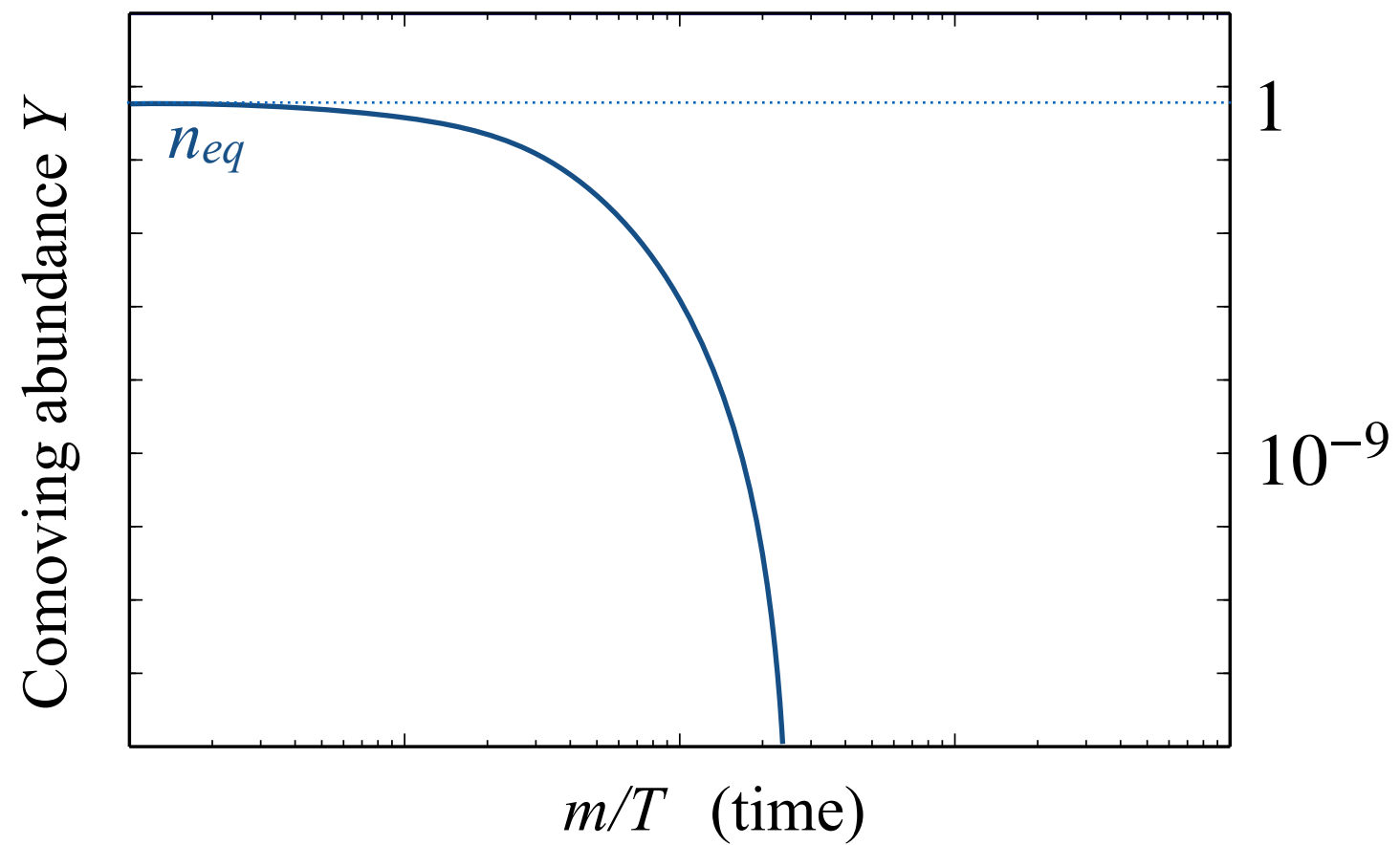
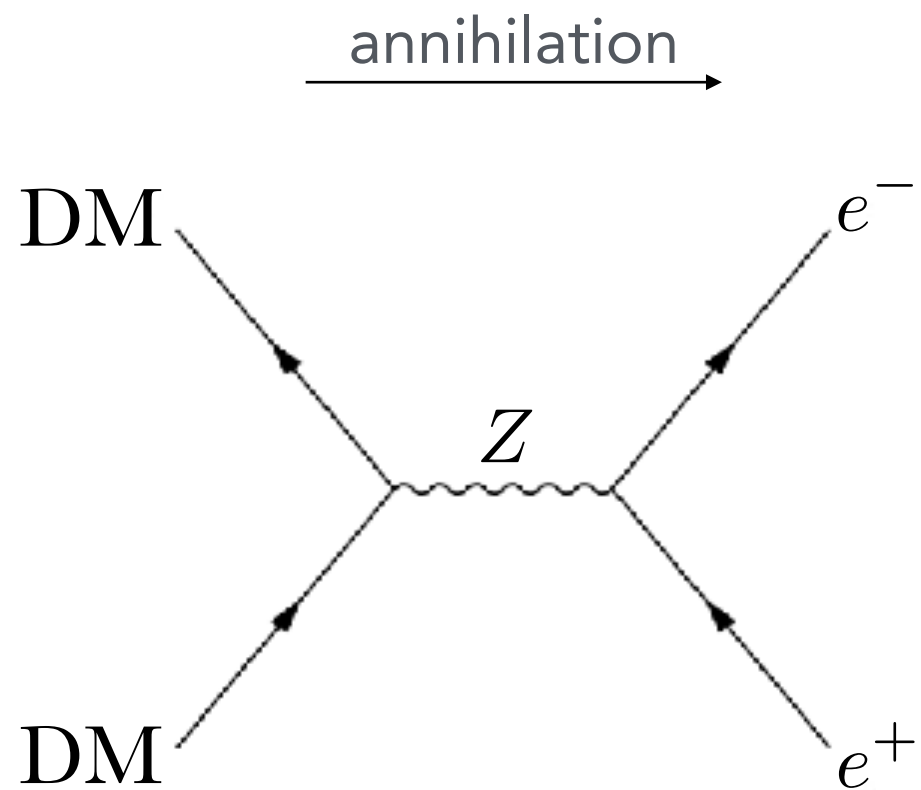
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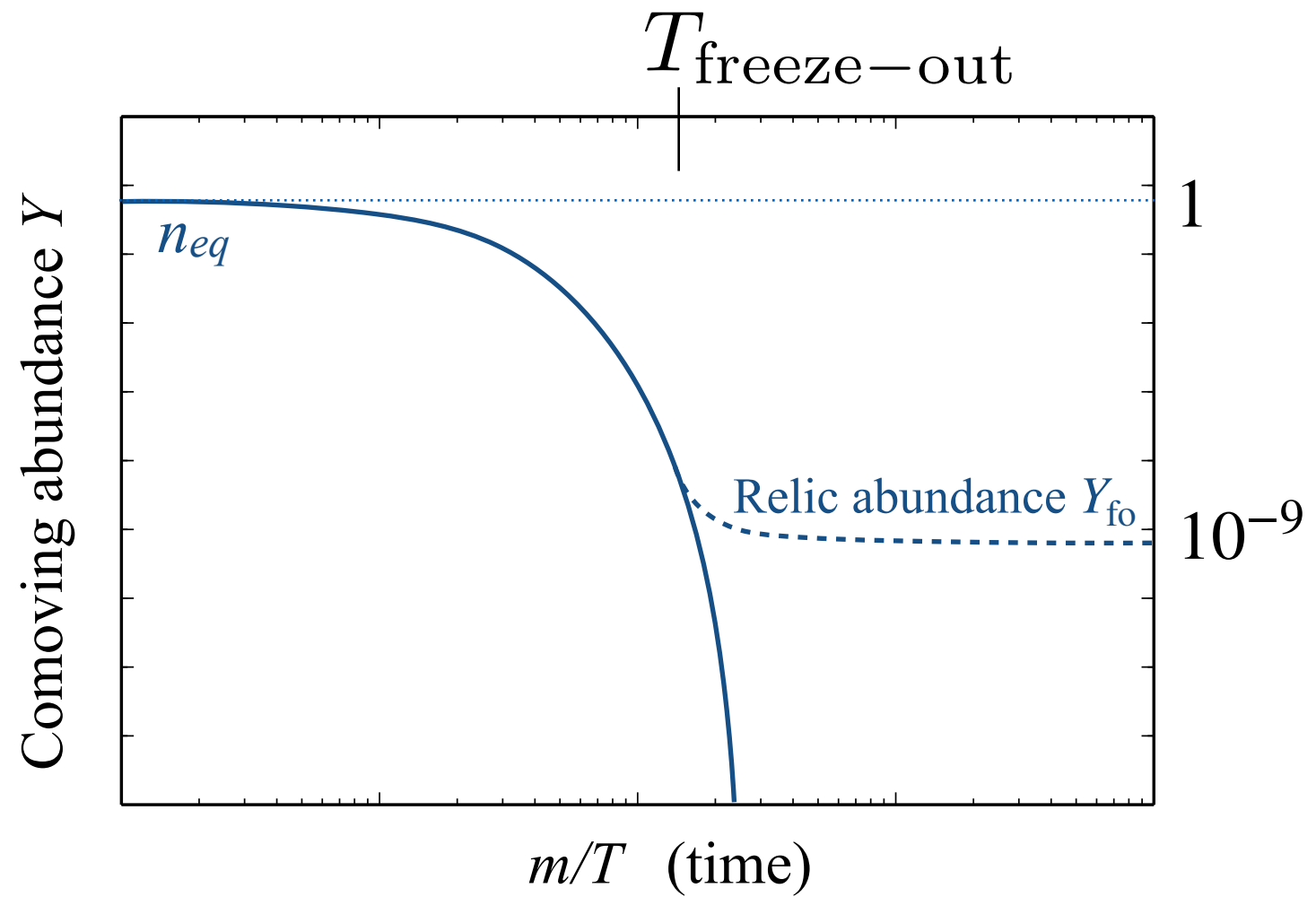
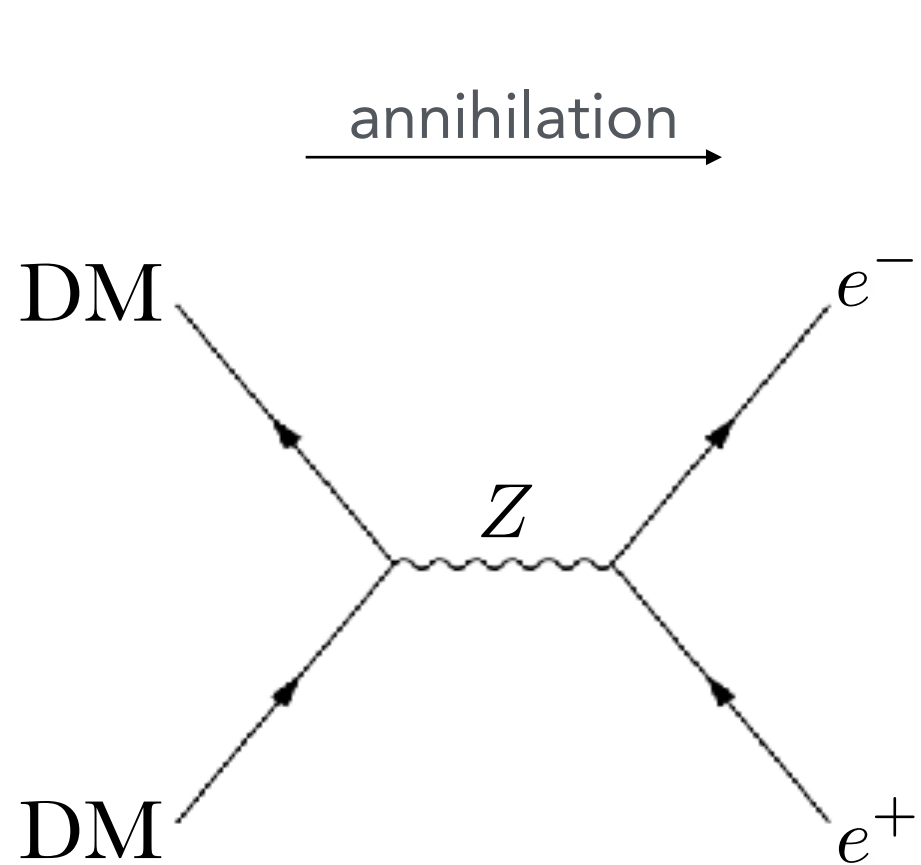
Warm dark matter bounds $m_\chi > \text{few keV}$

Need mechanisms that give abundance $Y \ll 10^{-3}$

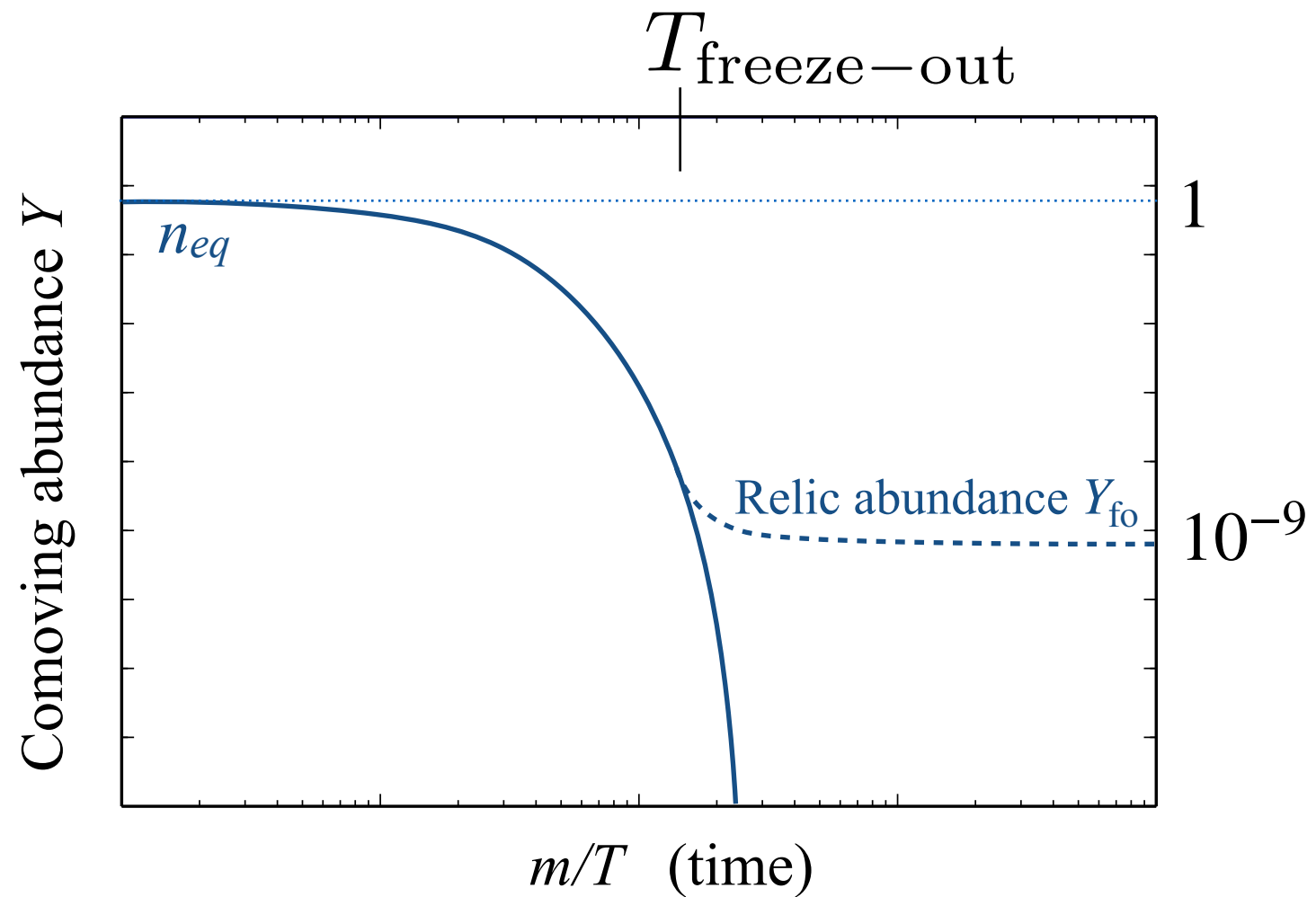
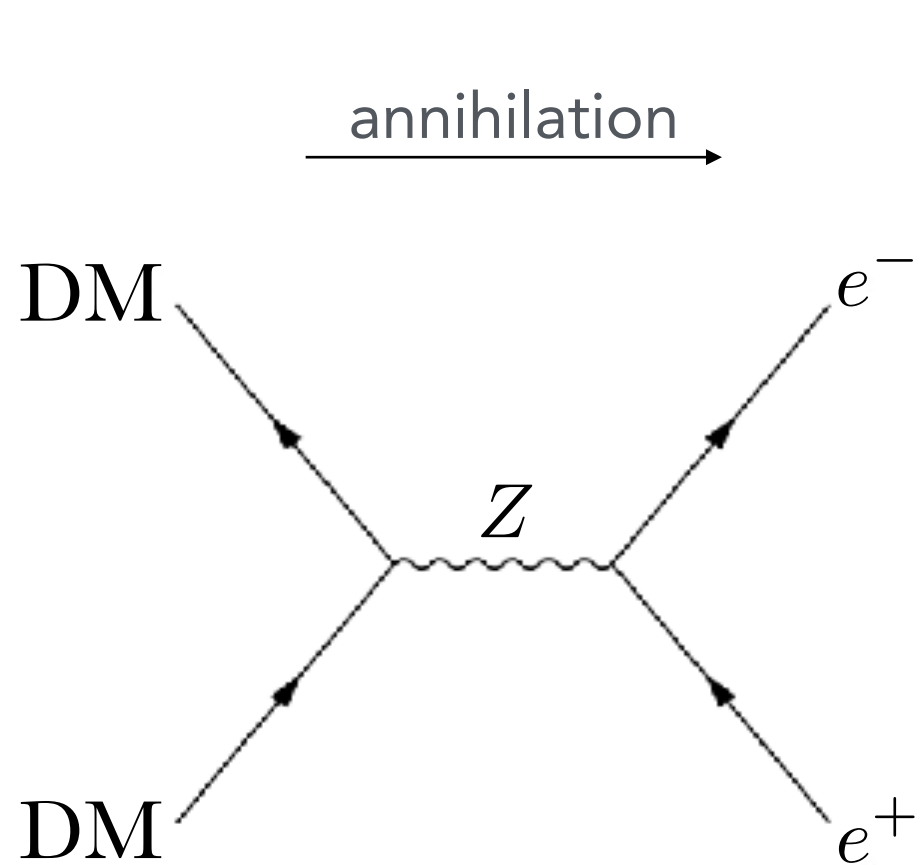
Freeze-out



Freeze-out

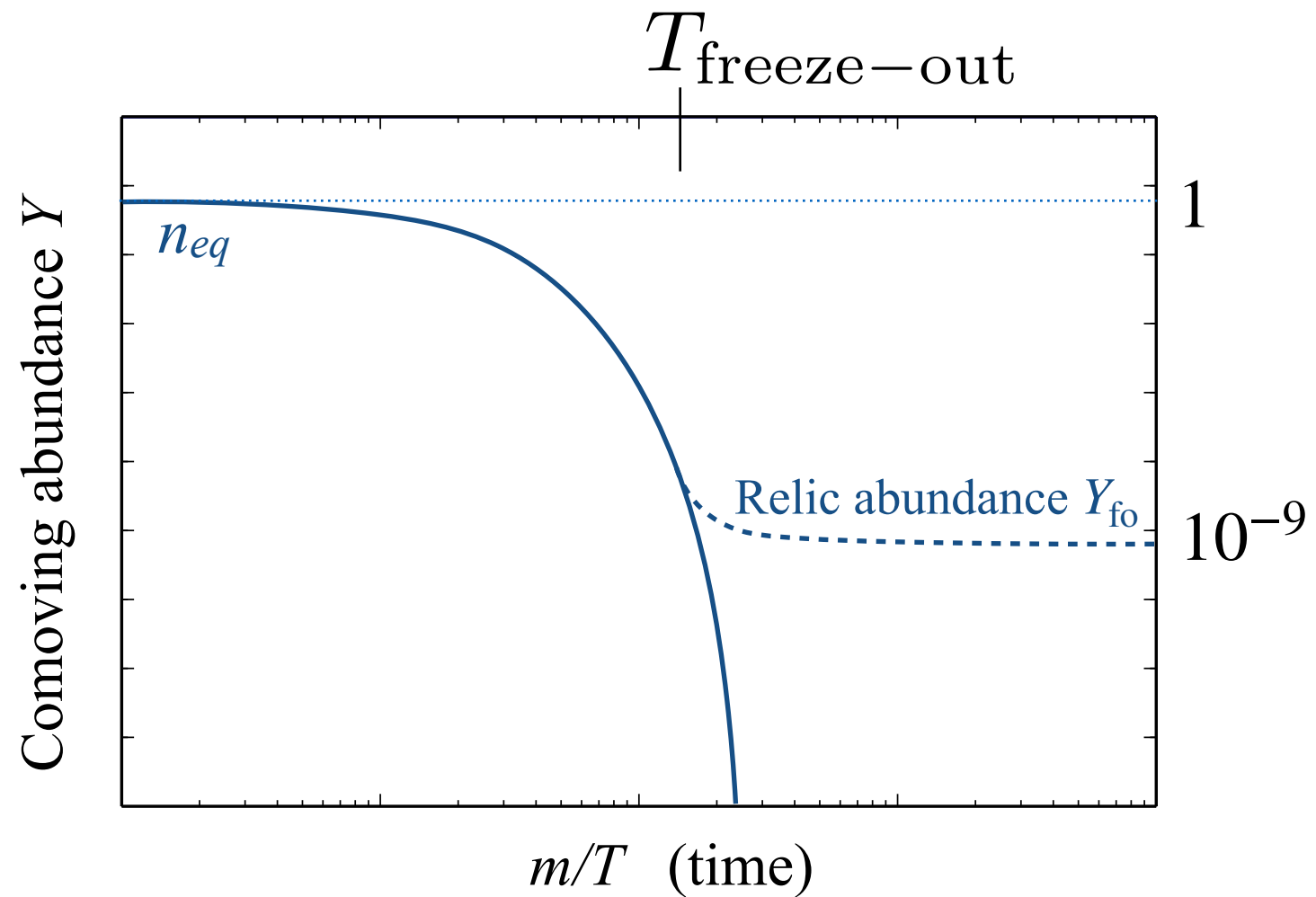
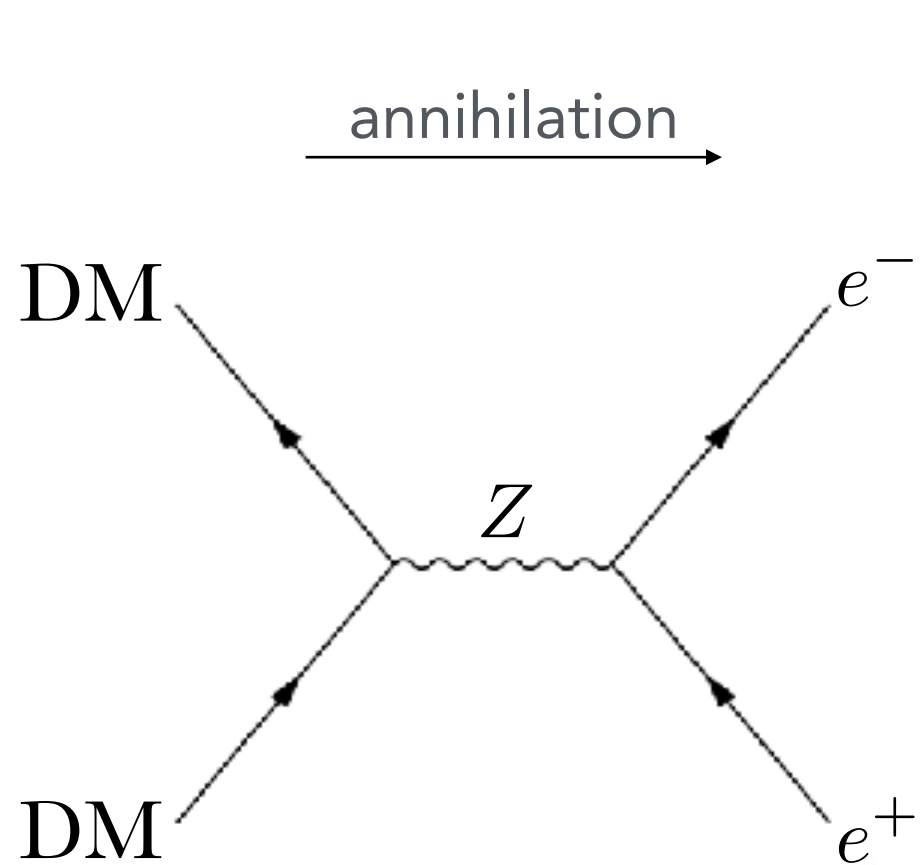


Freeze-out



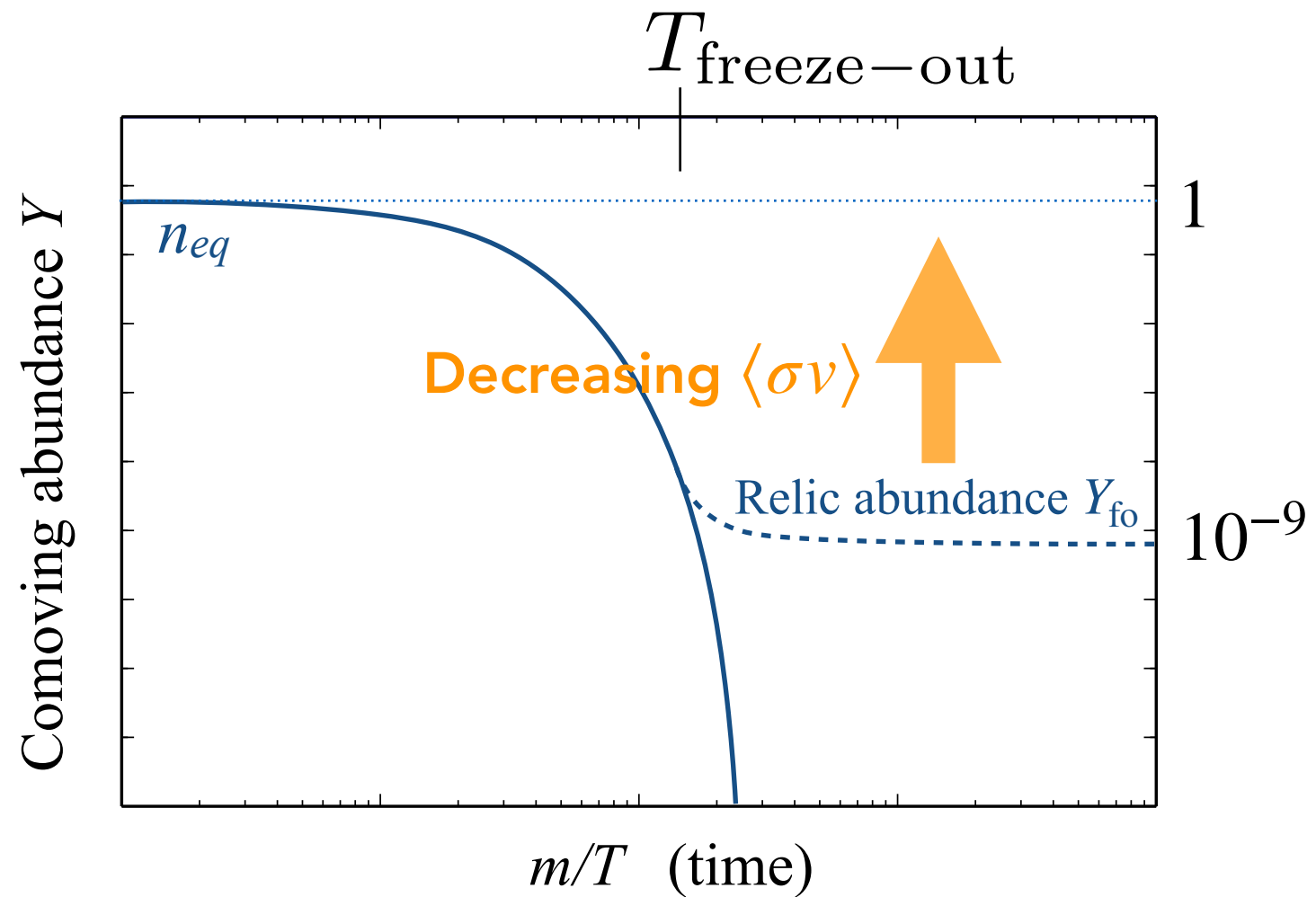
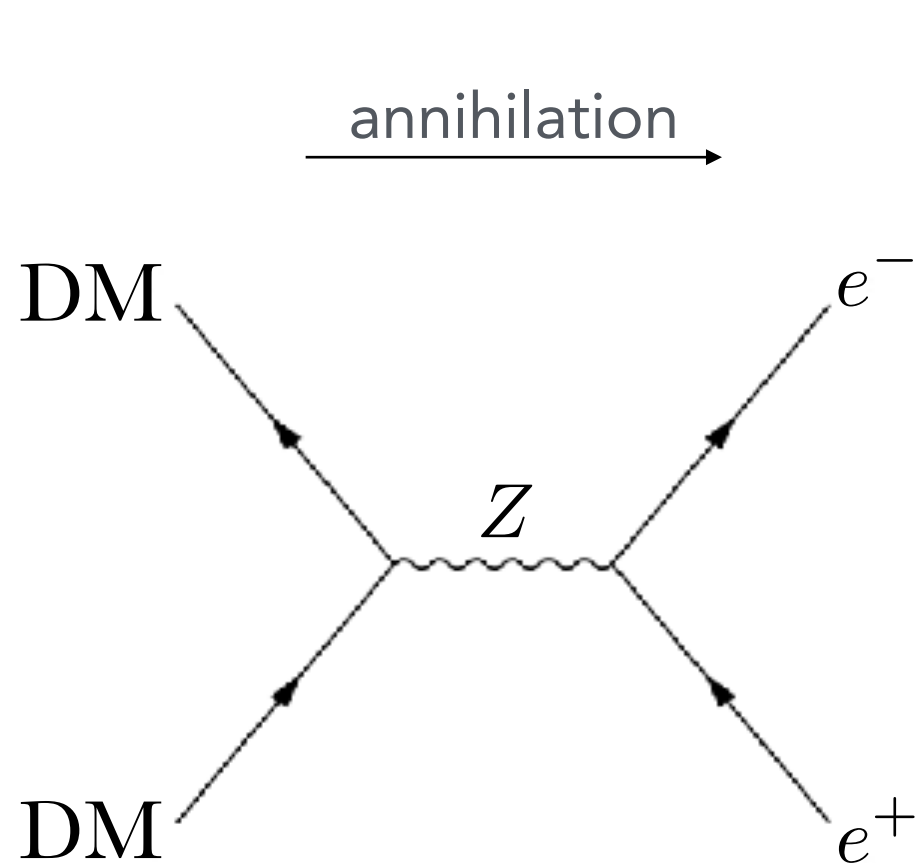
Freezeout when DM is nonrelativistic gives small abundance Y

Freeze-out



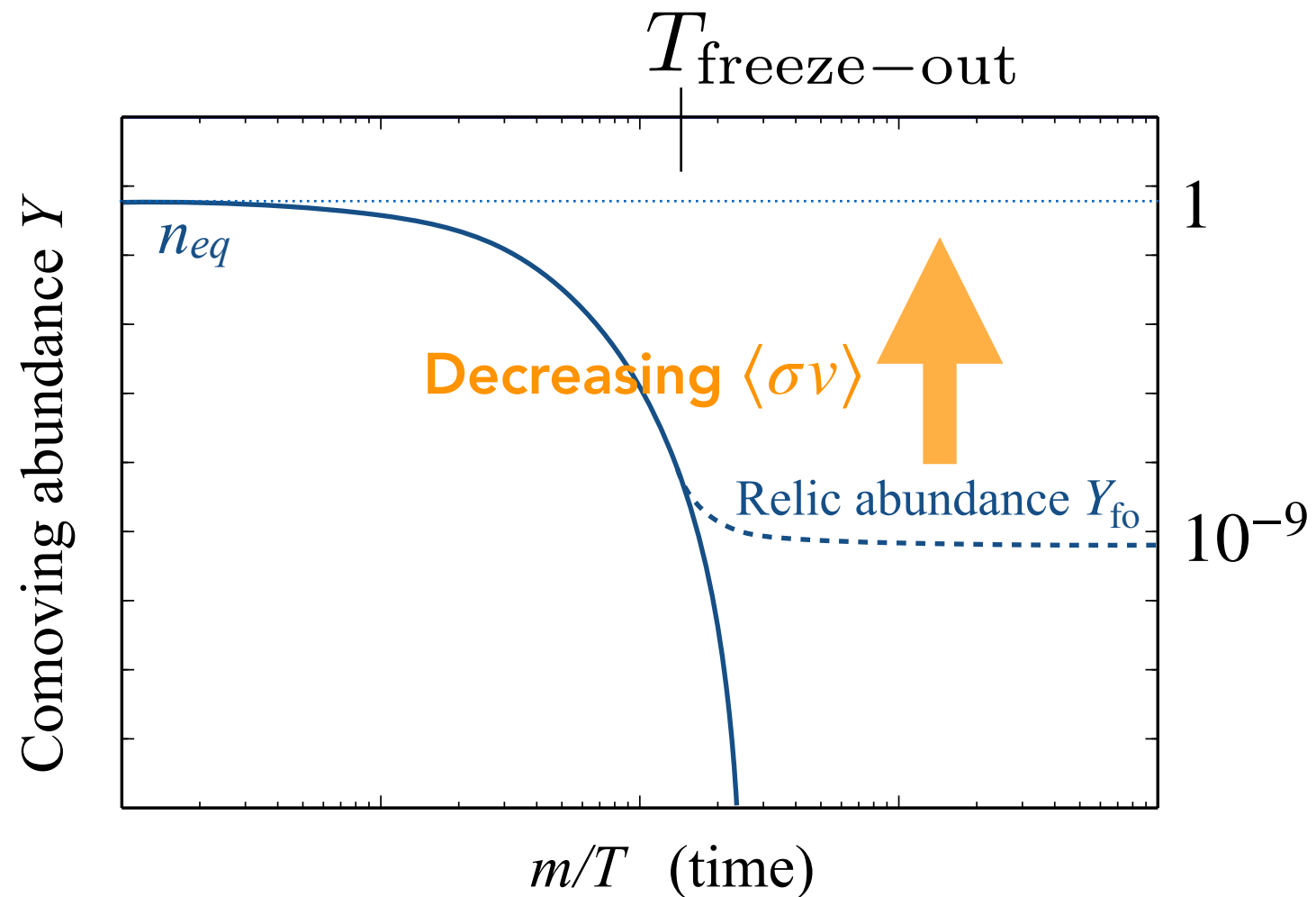
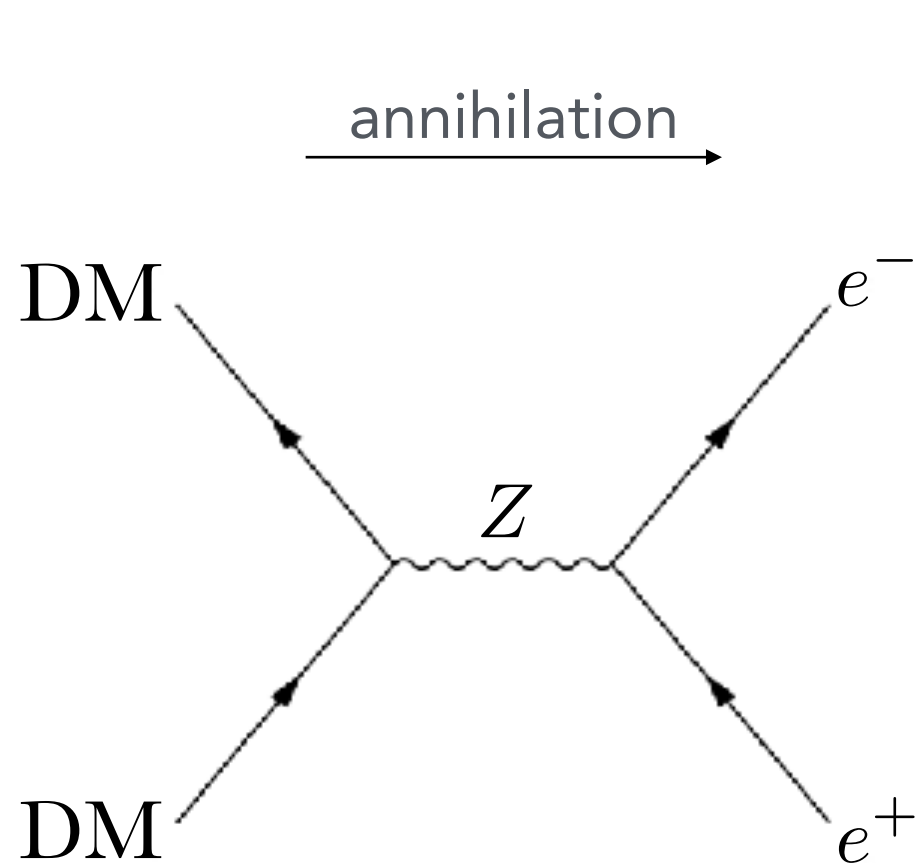
Freezeout set by annihilation cross section $\frac{\Gamma}{H} \sim \frac{n_\chi \langle \sigma v \rangle}{H} \sim 1$

Freeze-out



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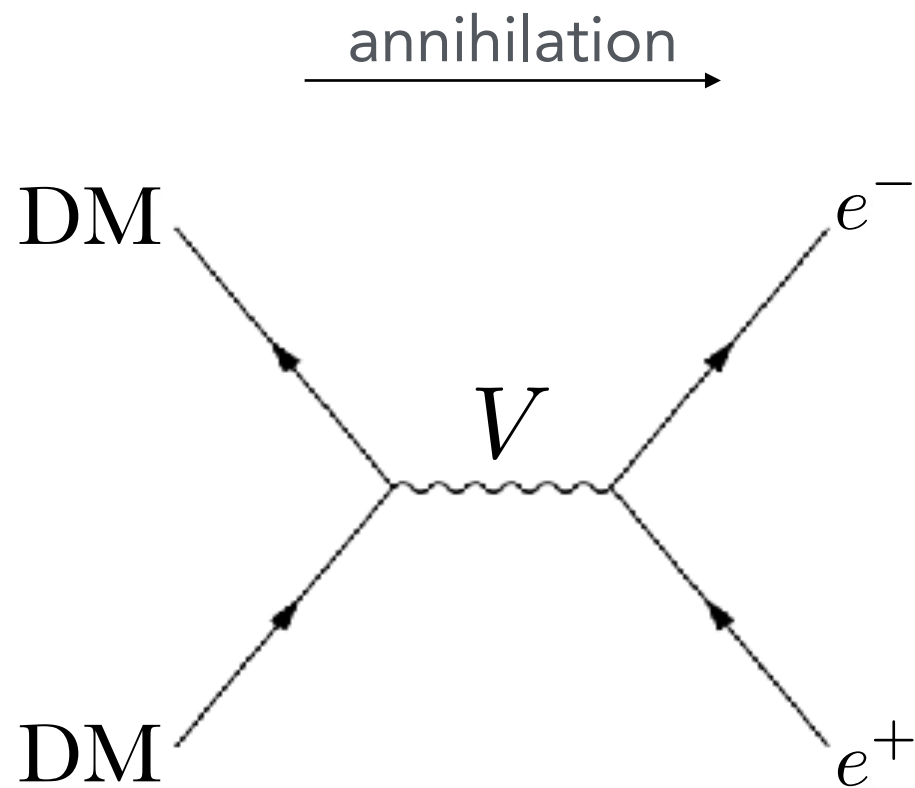
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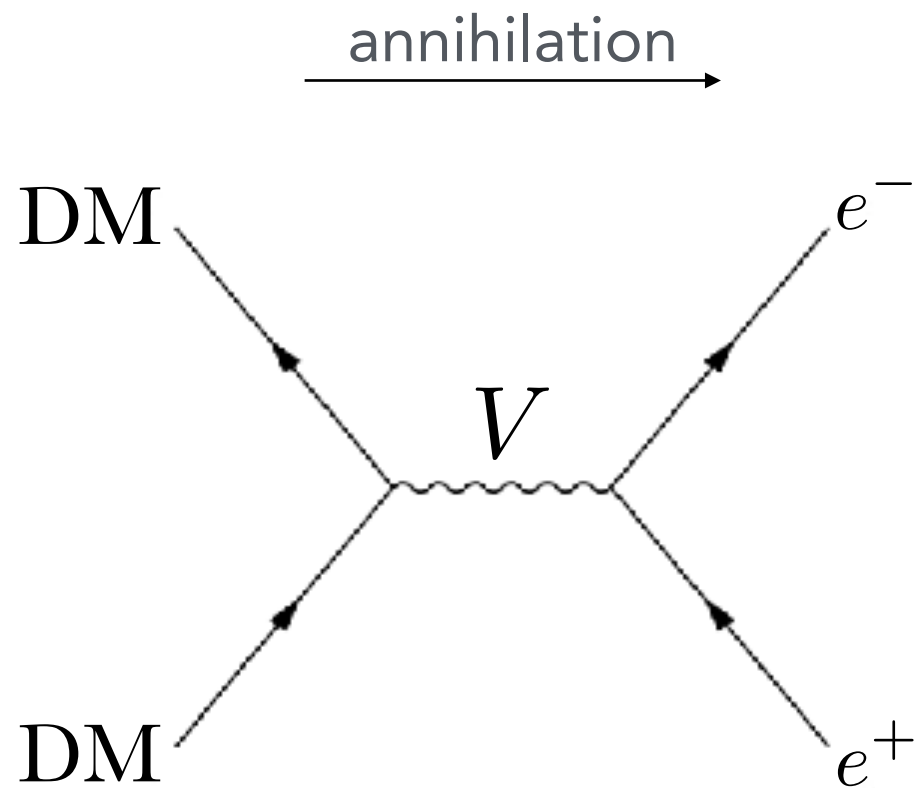
Thermal relic cross section $\langle\sigma v\rangle \simeq \frac{\alpha_W^2 m_\chi^2}{M^4} \underset{\text{WIMP Miracle}}{\sim} \frac{\alpha_W^2}{\text{TeV}^2}$

Sub-GeV thermal relics



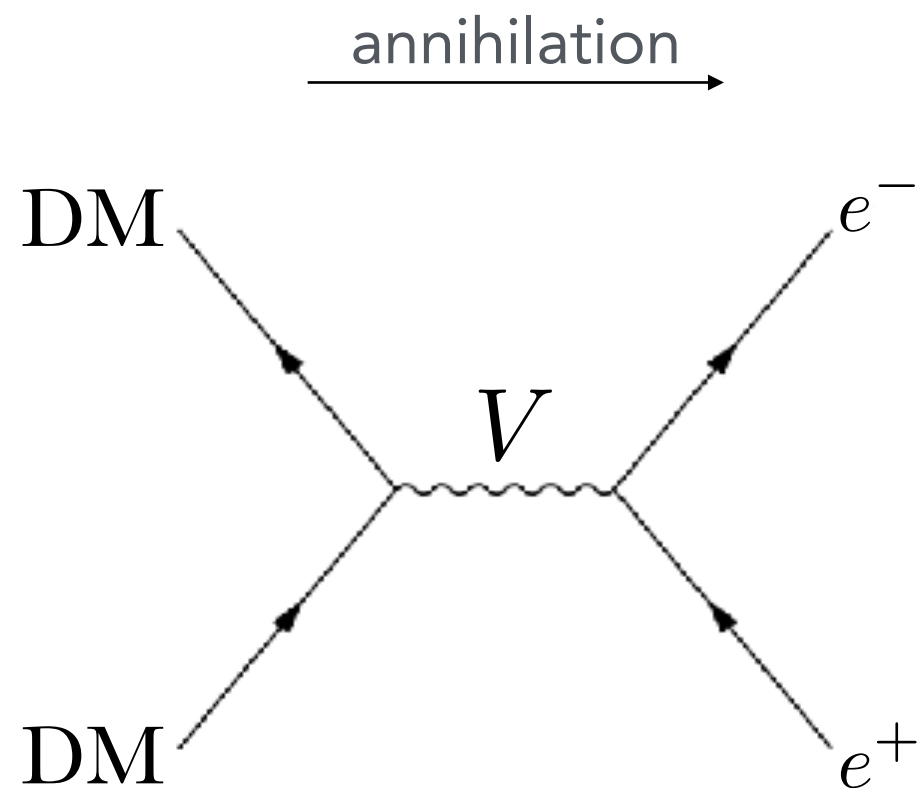
$$\langle \sigma v \rangle \simeq \frac{16\pi\alpha_\chi^2 m_\chi^2}{m_V^4}$$

Sub-GeV thermal relics



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Sub-GeV thermal relics



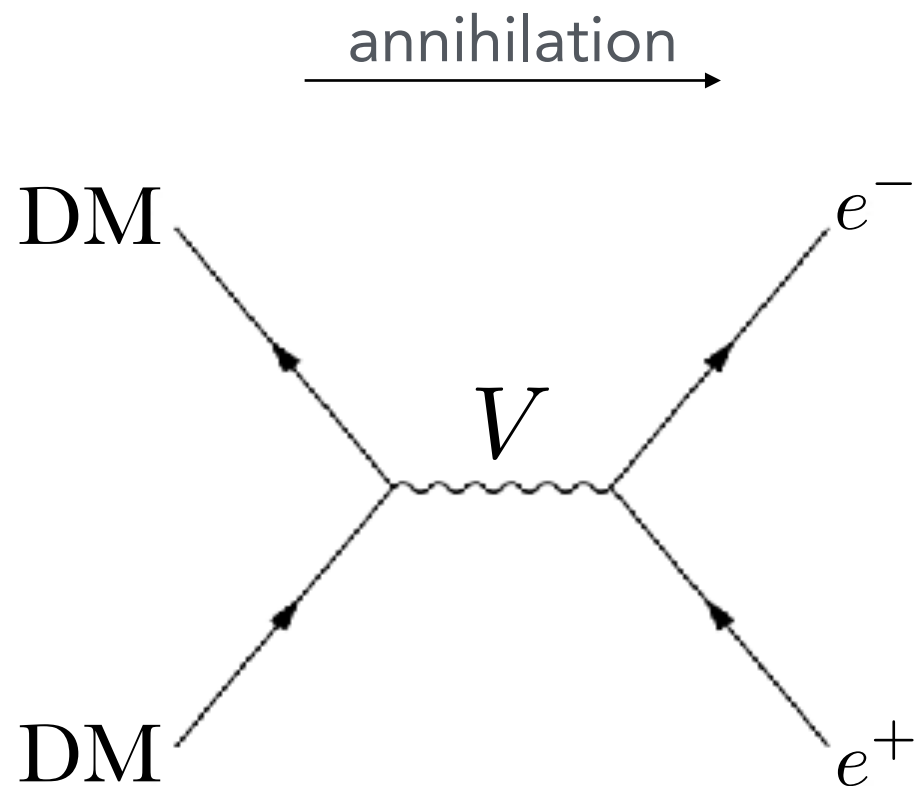
For weak interactions

$$m_V = m_W, \alpha_\chi = \alpha_w$$

$\langle\sigma v\rangle$ is too small and
sub-GeV dark matter is overproduced
[Lee-Weinberg bound]

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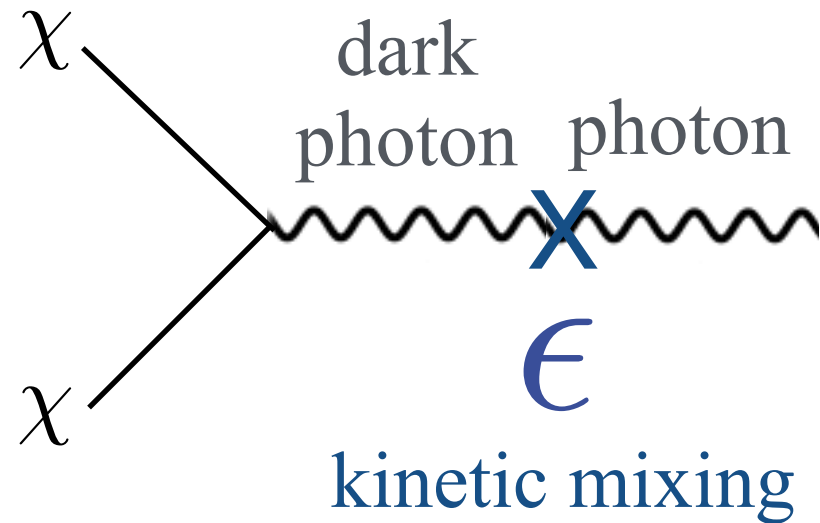
$$\langle \sigma v \rangle \simeq \frac{16\pi\alpha_\chi^2 m_\chi^2}{m_V^4}$$

Even without this argument, direct
detection would be suppressed for
sub-GeV DM by m_χ^2/m_V^2 and from
collider bounds (e.g. $Z \rightarrow \chi\chi$)

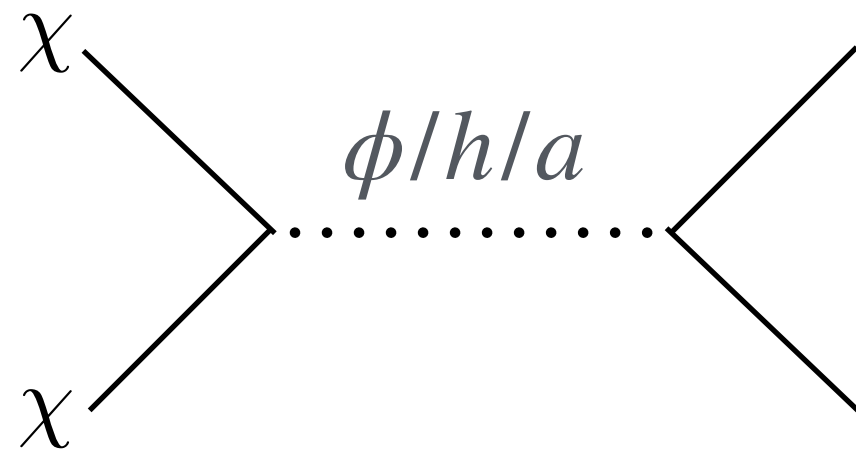
Light mediators wanted

Portals to the Standard Model

vector portal

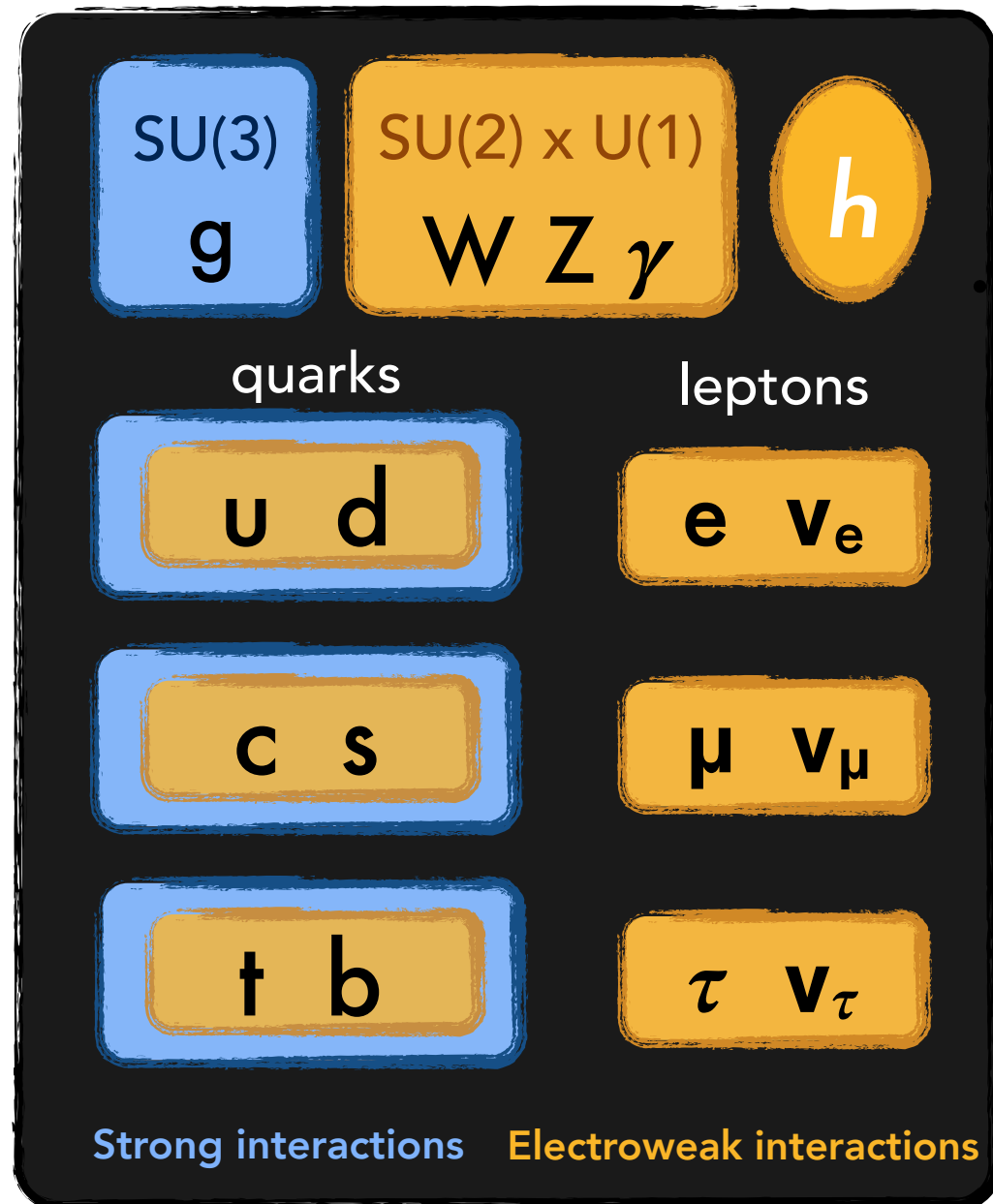


Scalar, Higgs or axion portal

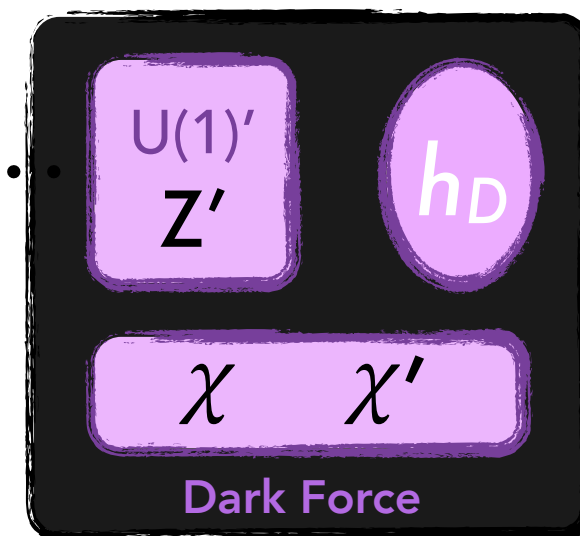


Dark sectors

Standard Model



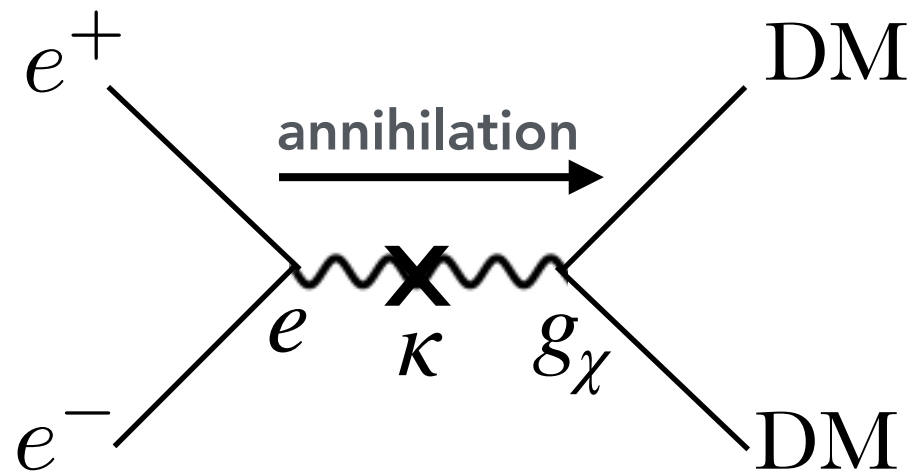
Possible
dark sector



May include:
dark gauge forces, dark higgs,
inelastic splittings, composite
sector, very light particles, ...

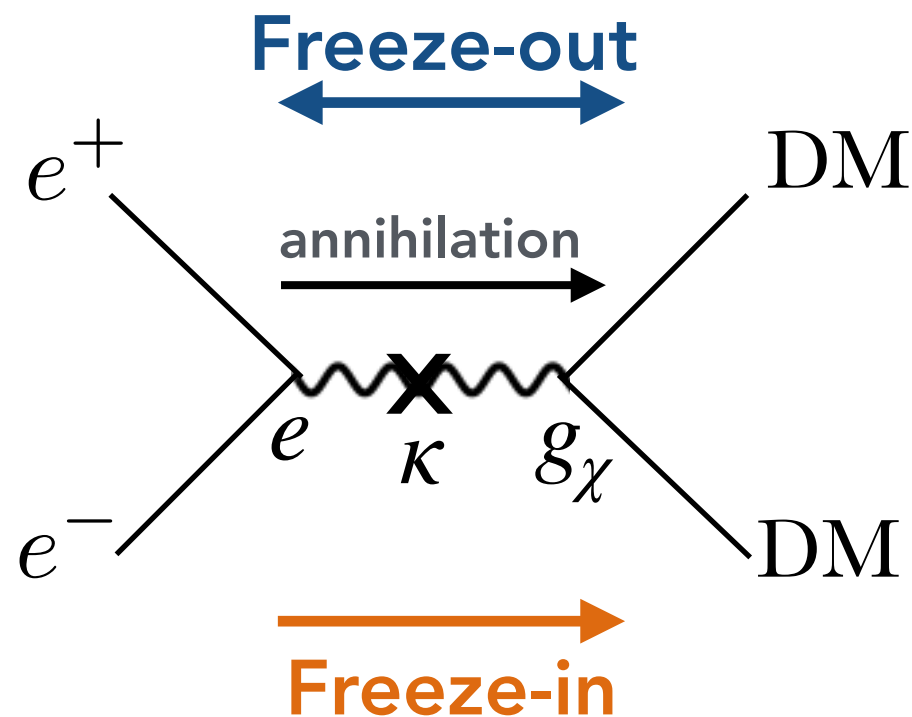
Sub-GeV thermal relics

The existence of light mediators (and other light, very weakly-coupled particles) opens up new possibilities for achieving relic abundance.



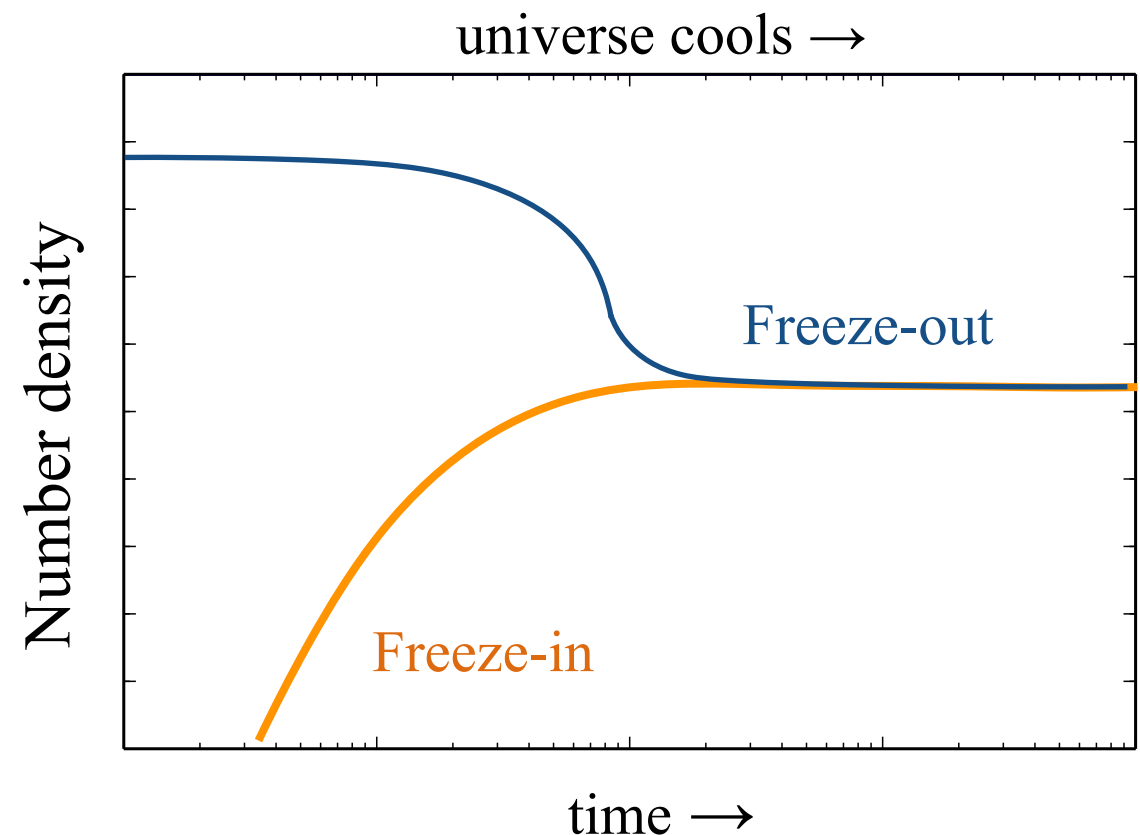
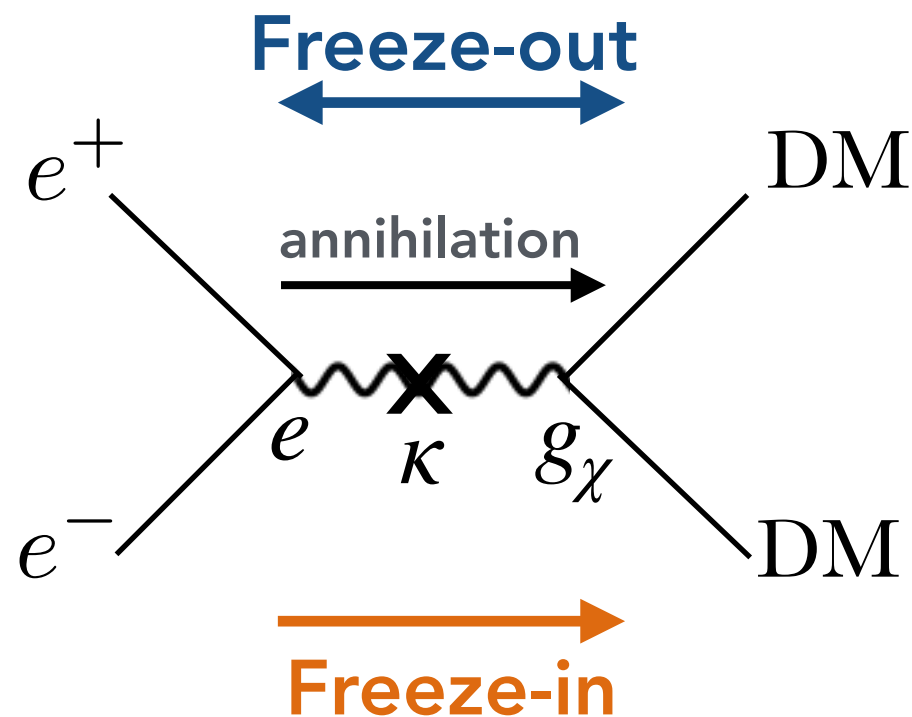
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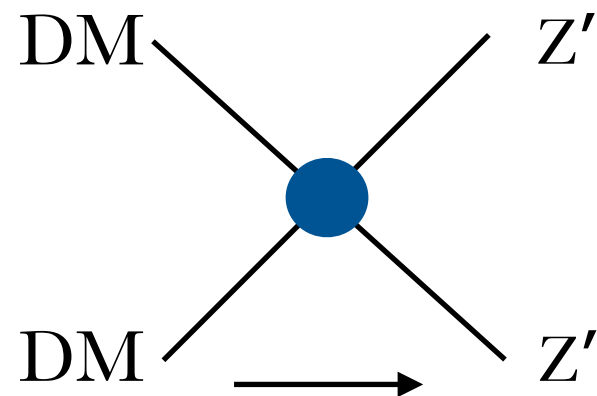
Sub-GeV thermal relics

More processes depleting the dark matter number density:

Sub-GeV thermal relics

More processes depleting the dark matter number density:

annihilation to
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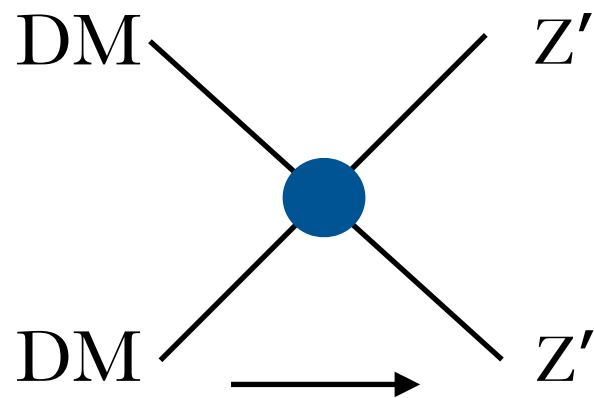


e.g. Boehm and Fayet 2003,
Pospelov et al. 2007,
Feng and Kumar 2008

Sub-GeV thermal relics

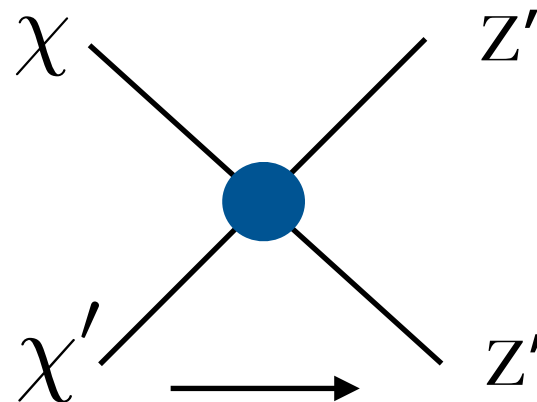
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co-annihilation
and co-scattering

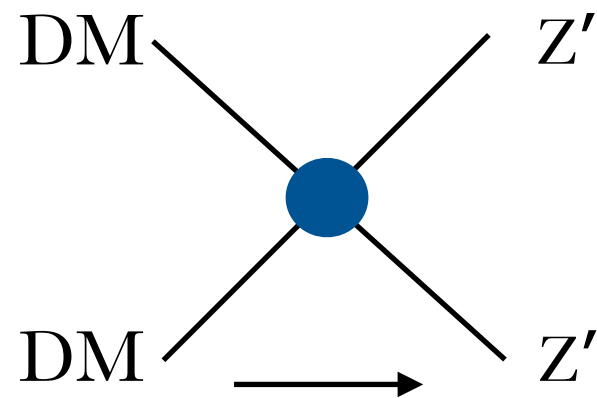


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D'Agnolo et al. 2017
Izaguirre et al. 2017

Sub-GeV thermal relics

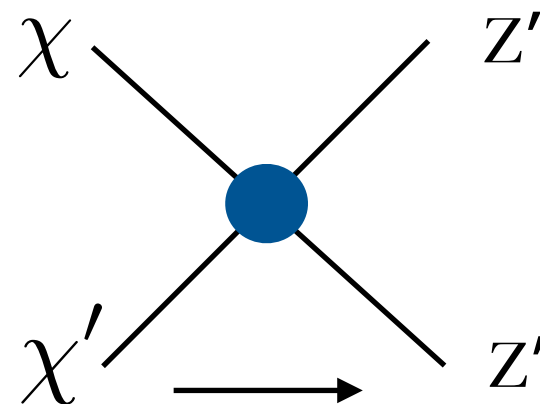
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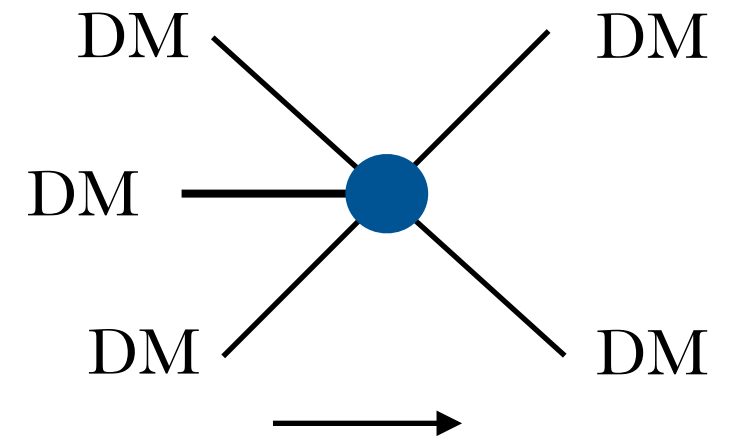
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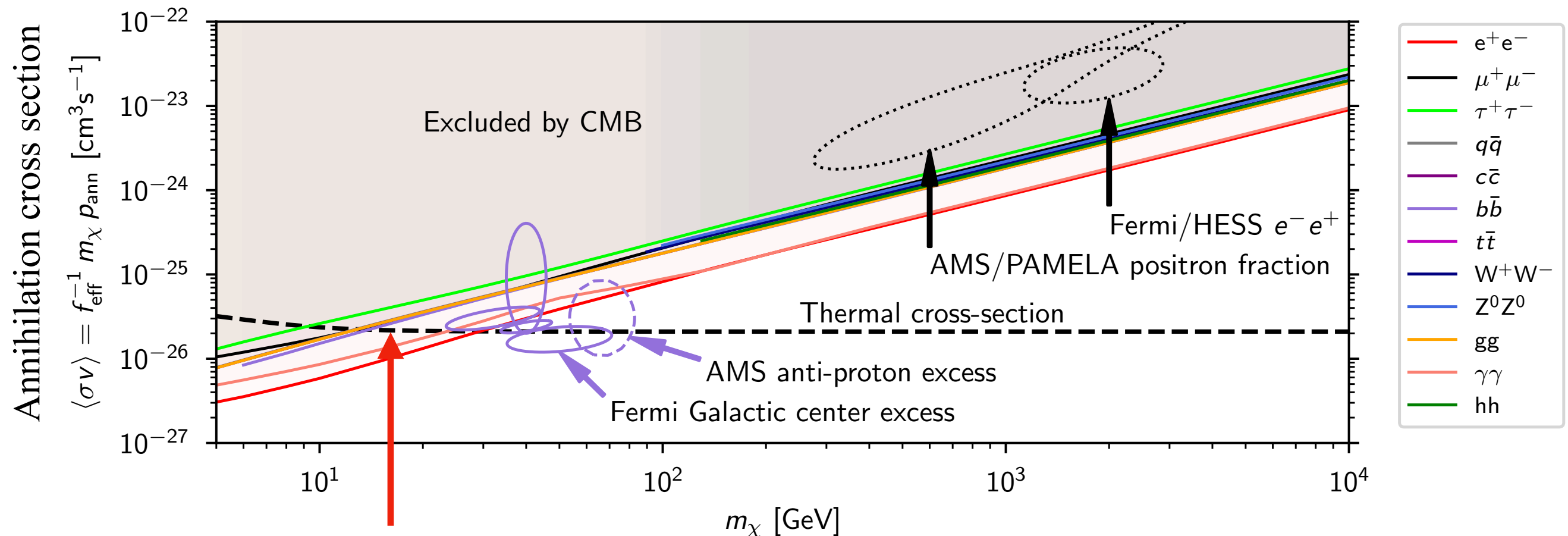
e.g. Griest and Seckel 1991
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Izaguirre et al. 2017

3 to 2 annihilation



e.g. Carlson et al. 1992
Hochberg et al. 2014, 2015
Kuflik et al. 2015
Farina et al. 2016

Indirect detection constraints



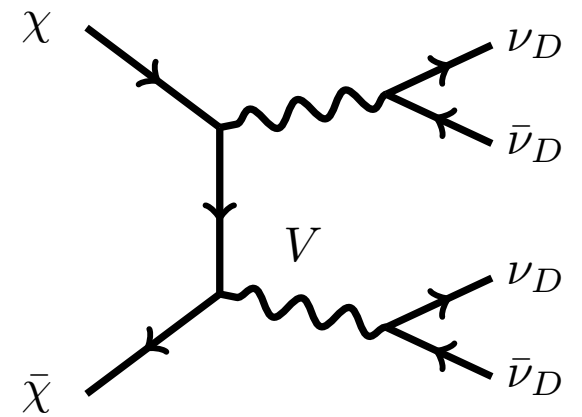
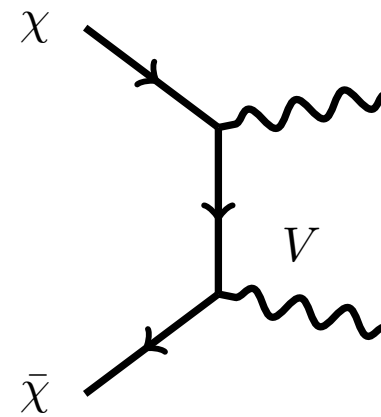
Target annihilation cross section for thermal freezeout

Thermal relic DM with s-wave annihilation to SM states (except $\nu\nu$) is strongly constrained by CMB + indirect bounds for $m_\chi < 10$ GeV

Indirect detection constraints

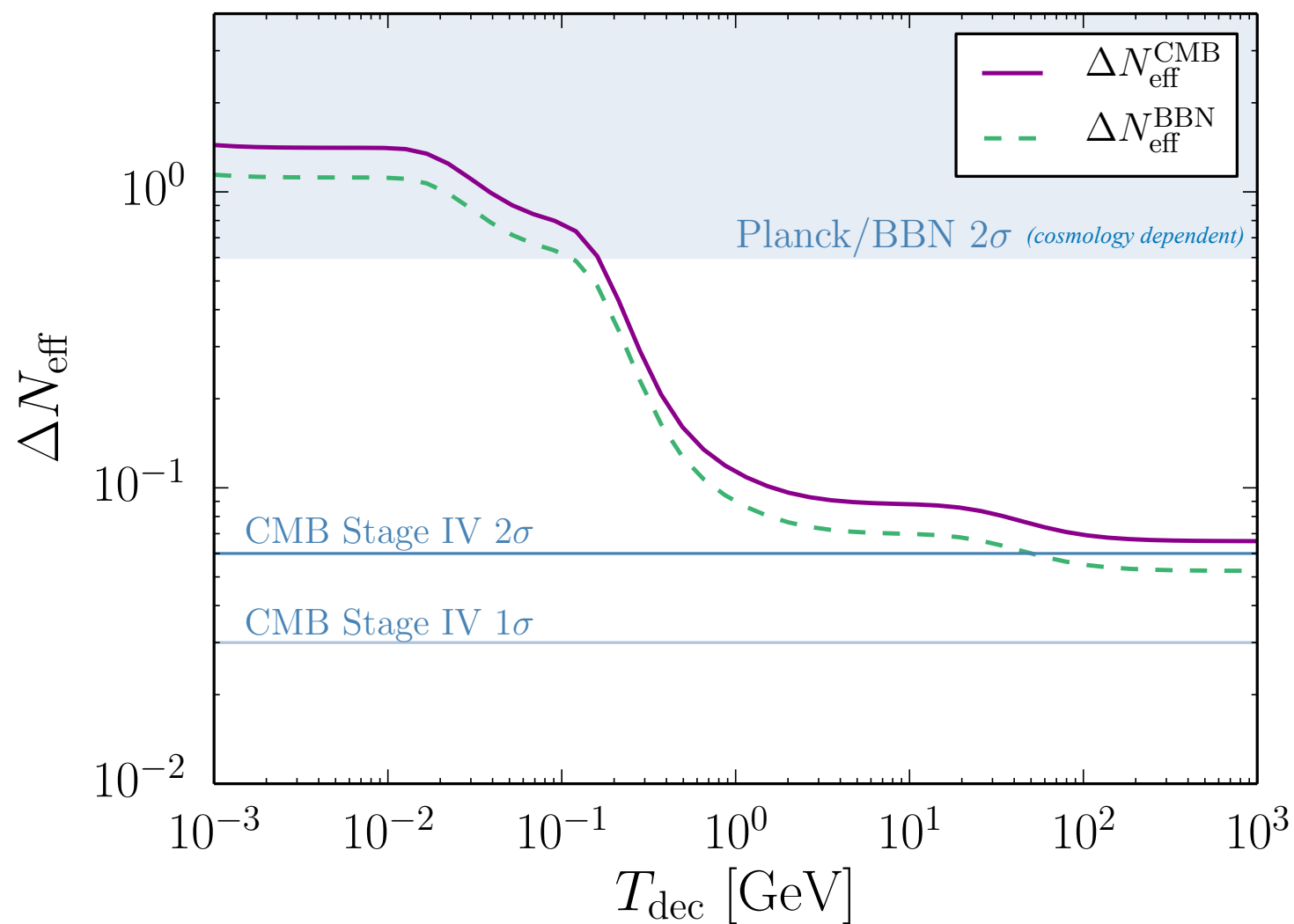
Not hard to evade these constraints

- Secluded sectors: annihilate within dark sector
- Asymmetric DM
- Velocity-suppressed annihilation
- Small inelastic splittings (but this can hurt direct detection)



N_{eff}

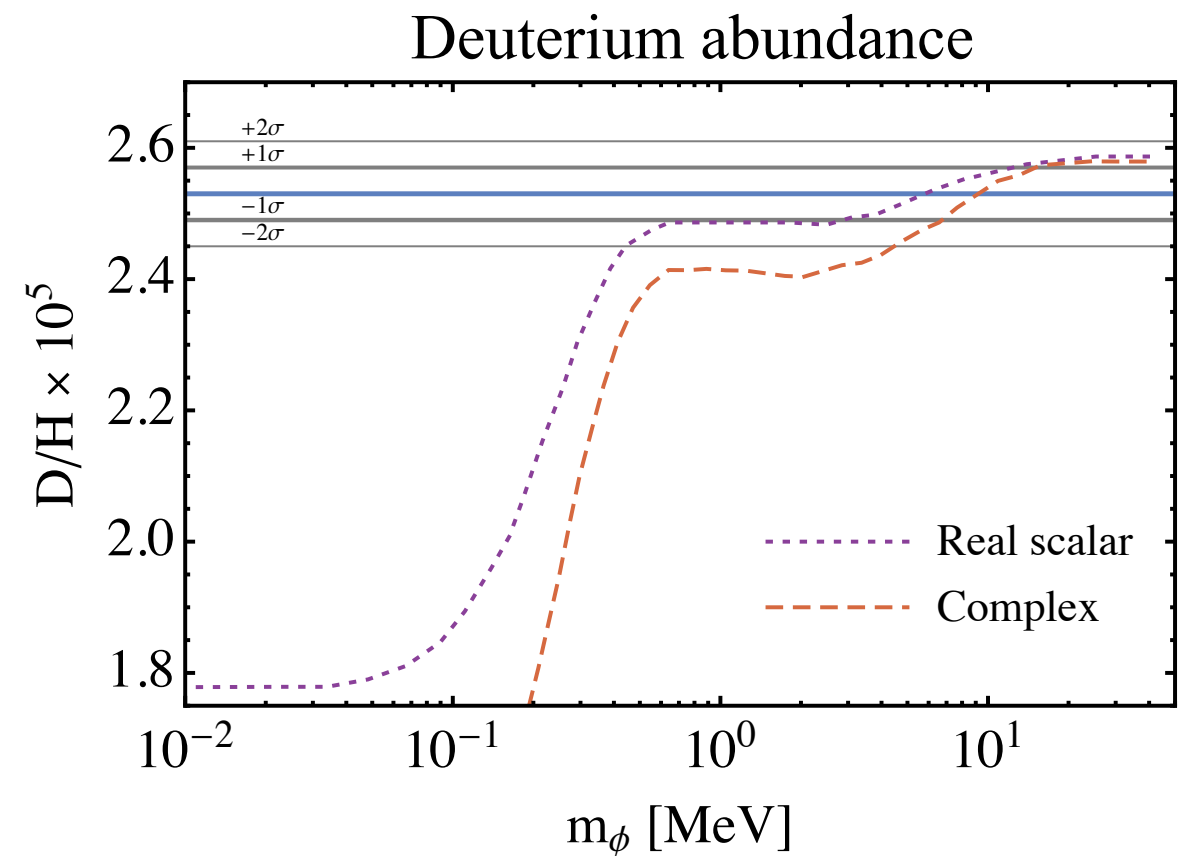
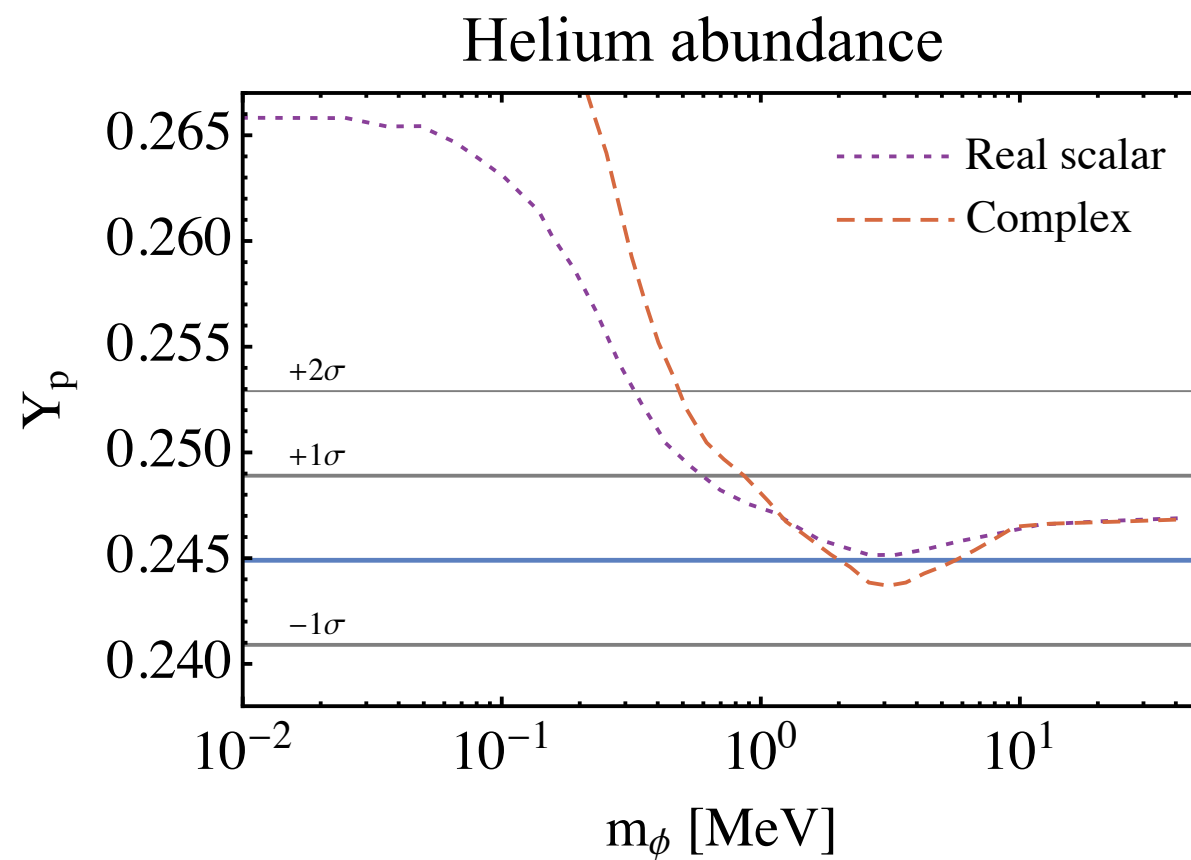
Anything that was in equilibrium below QCD phase transition could contribute to relativistic degrees of freedom



Decoupling temperature of dark sector [GeV]

BBN

If DM or mediator is in equilibrium with the SM photons/electrons *during* BBN, this can further modify abundances

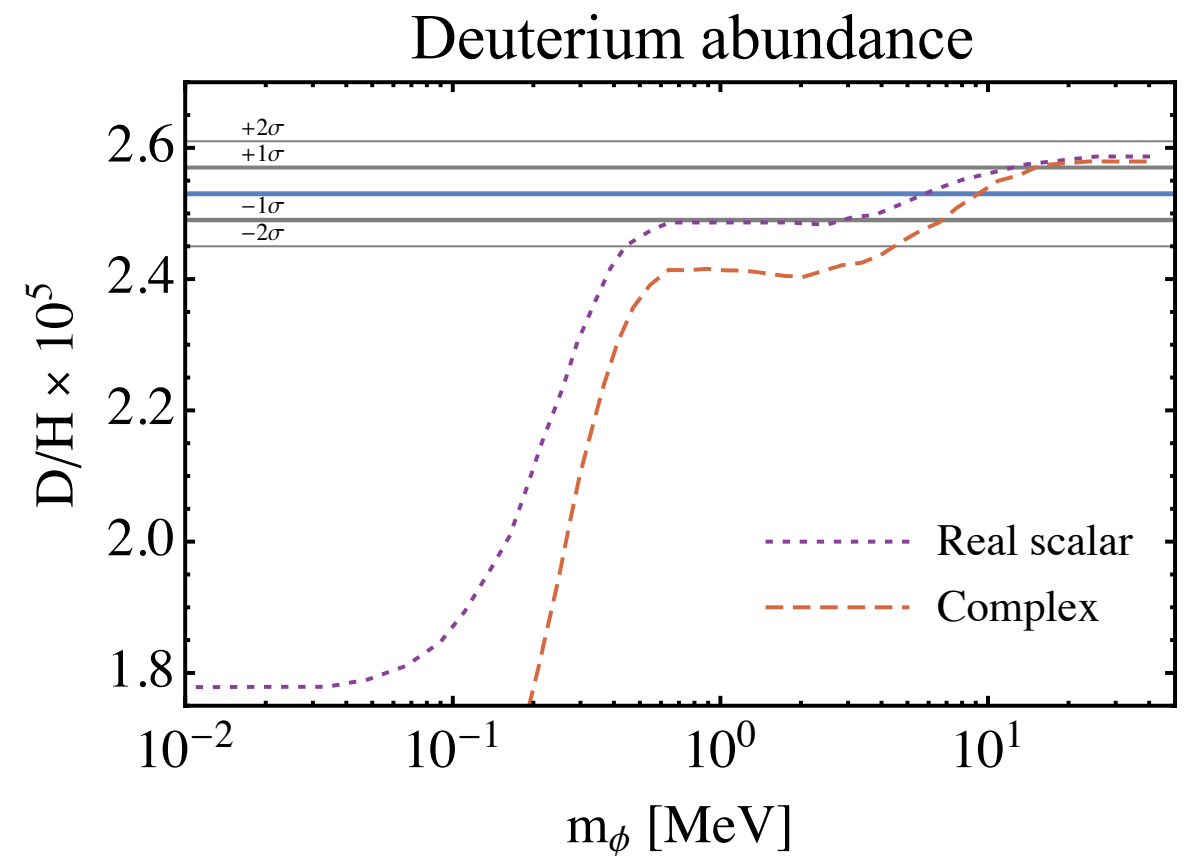
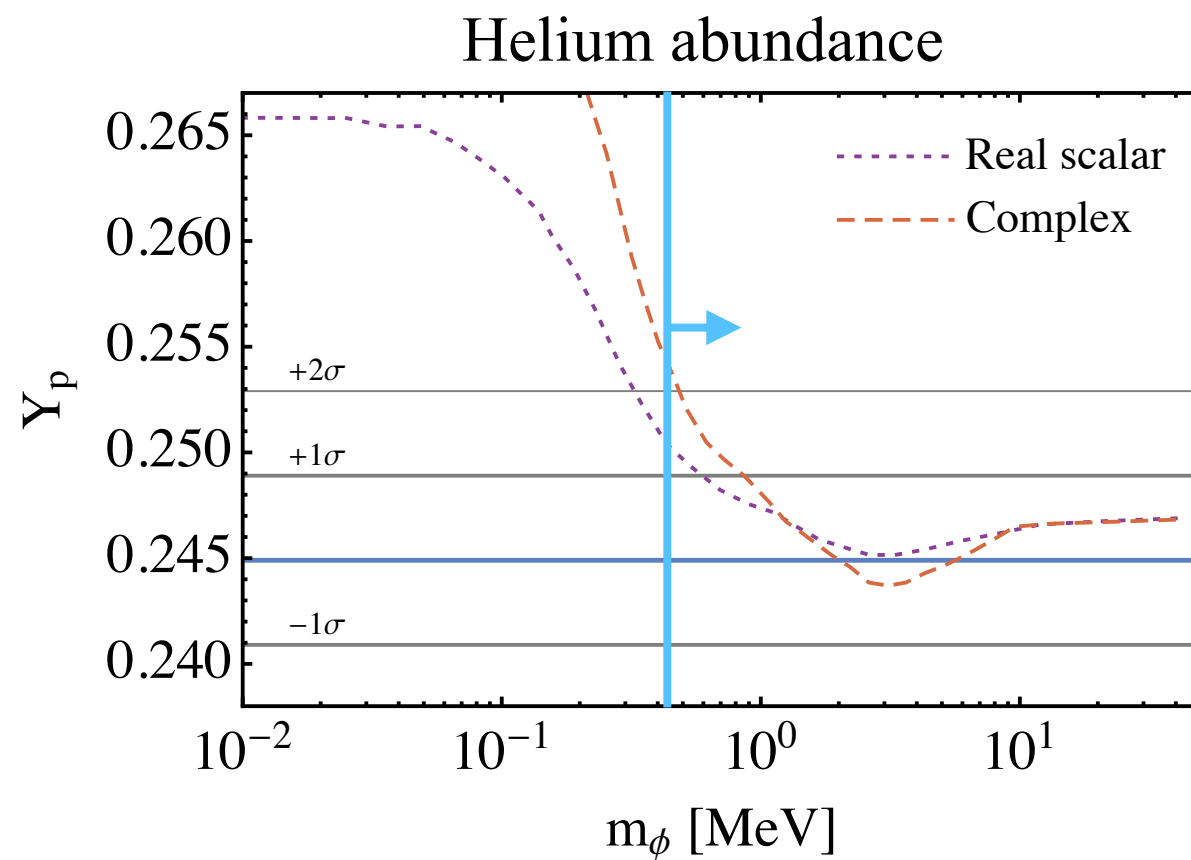


Generally requires $m_\chi \gtrsim \text{MeV}$

Boehm et al. 1303.6270
Nollett & Steigman 2014
Sabti et al. 2021

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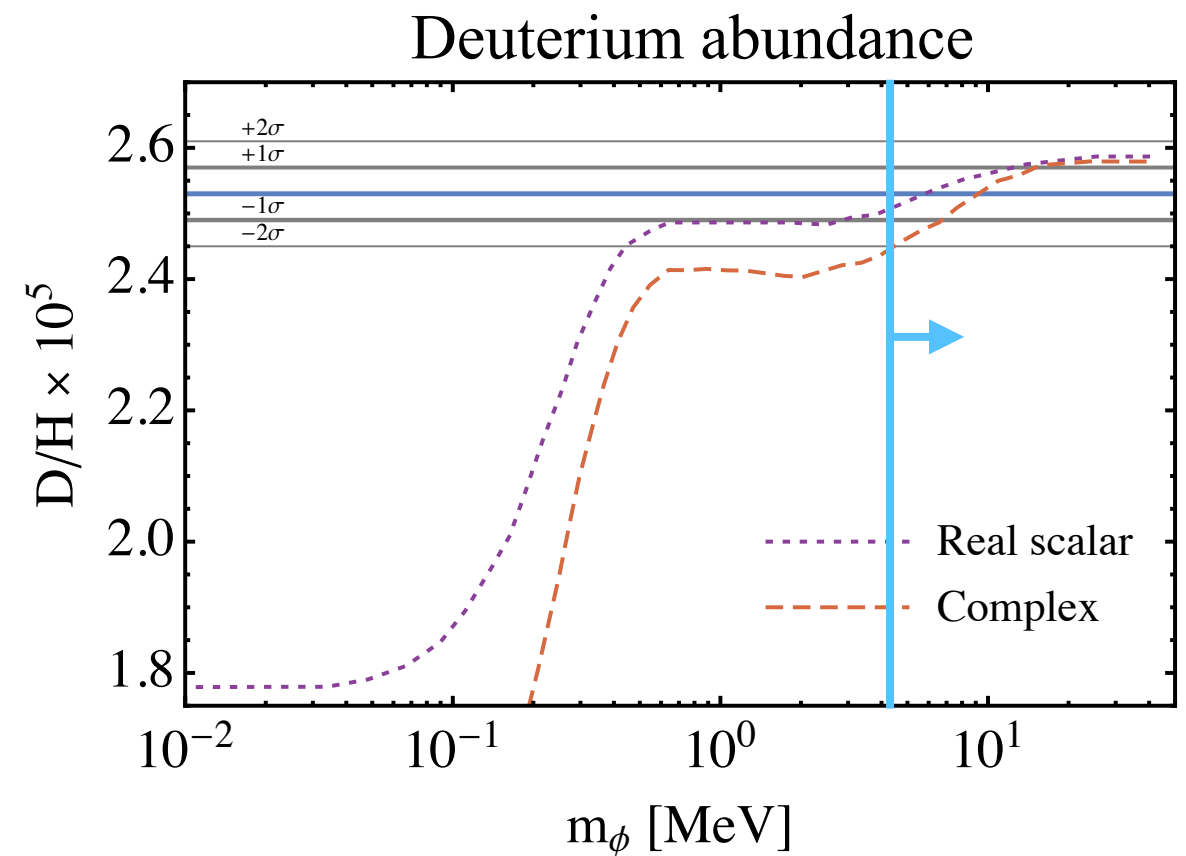
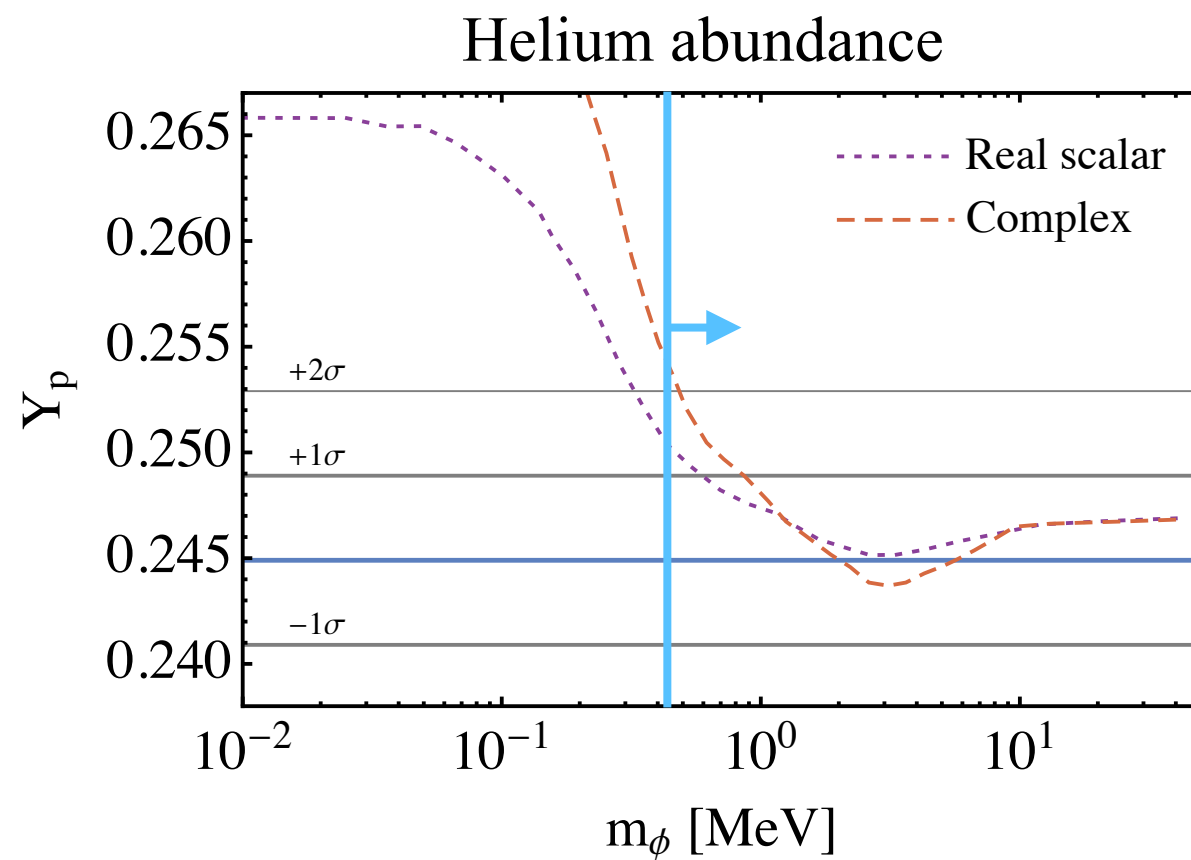


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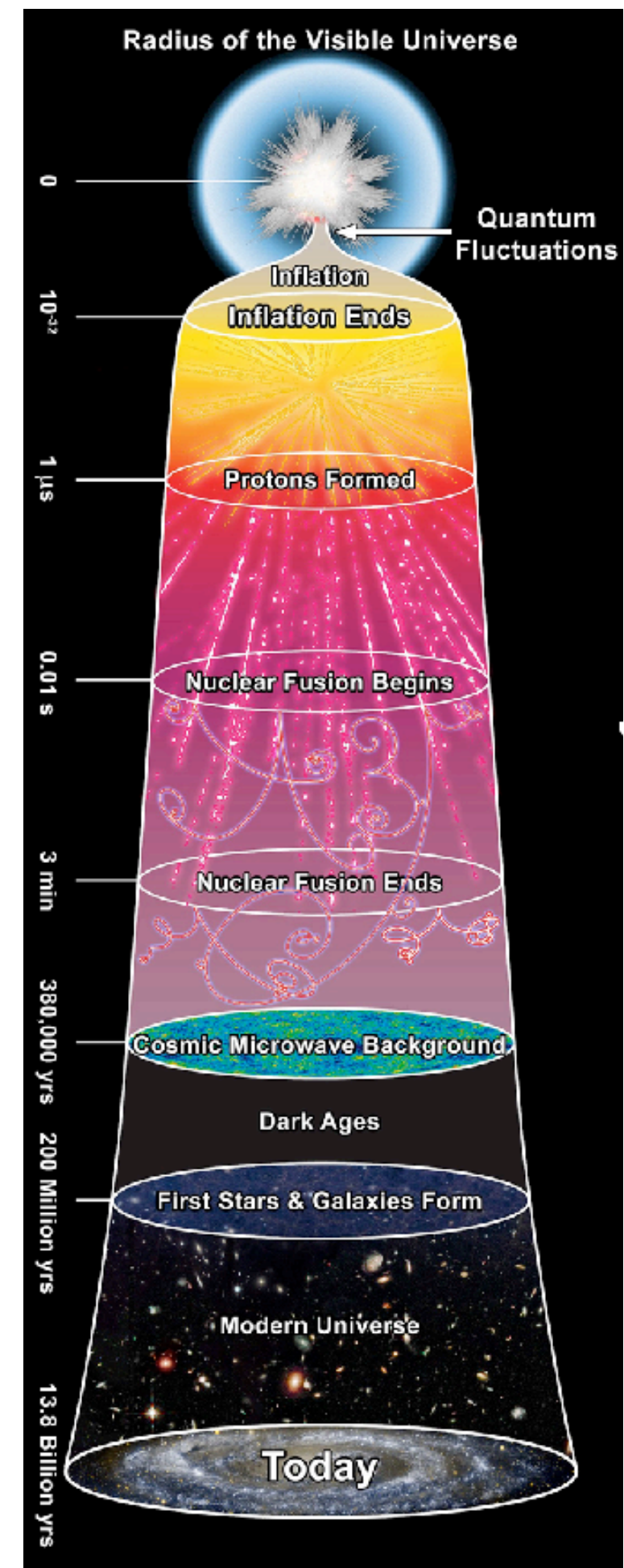


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Recap

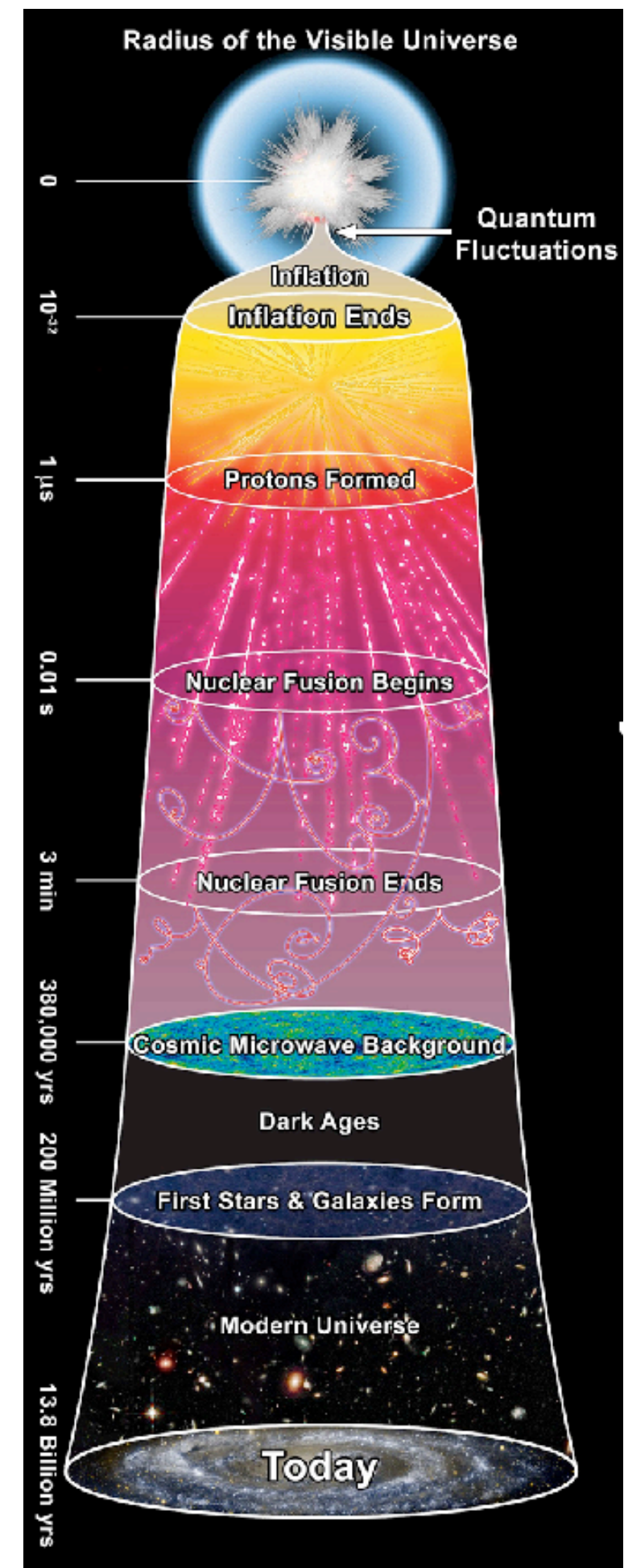
Relic dark
matter?



Recap

- Sub-GeV dark sectors are a compelling framework for DM as a thermal relic and other thermal-ish scenarios

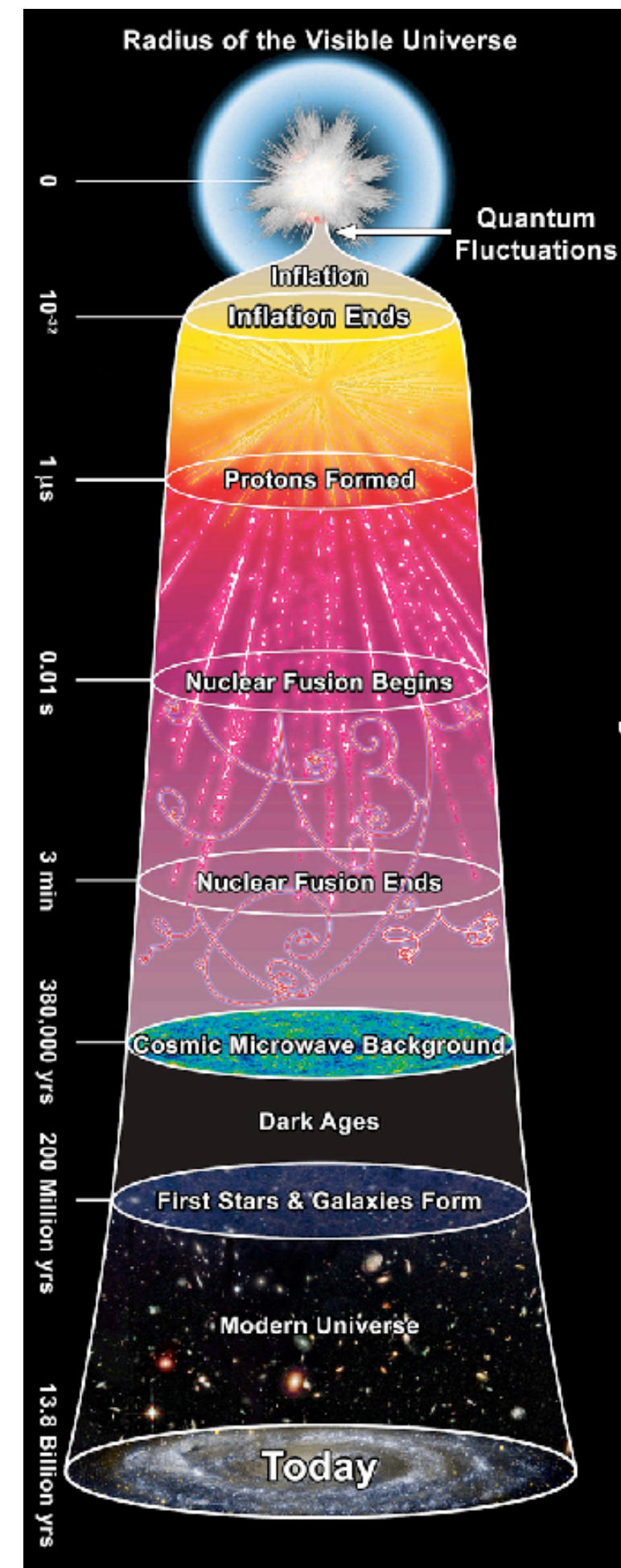
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- Sub-GeV dark sectors are a compelling framework for DM as a thermal relic and other thermal-ish scenarios
- $m_\chi \gtrsim 10$ keV from structure formation

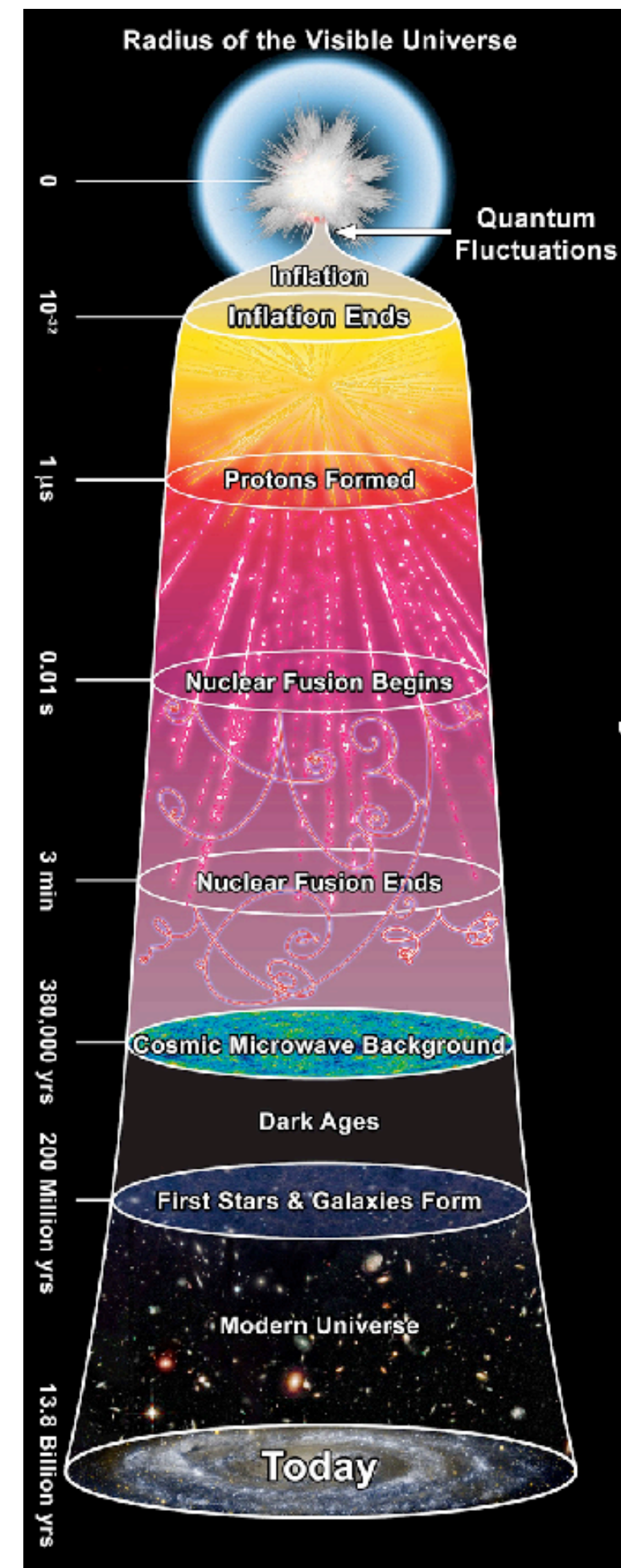
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Recap

- Sub-GeV dark sectors are a compelling framework for DM as a thermal relic and other thermal-ish scenarios
- $m_\chi \gtrsim 10$ keV from structure formation
- $m_\chi \gtrsim 10$ MeV from BBN (unless secluded from SM bath)

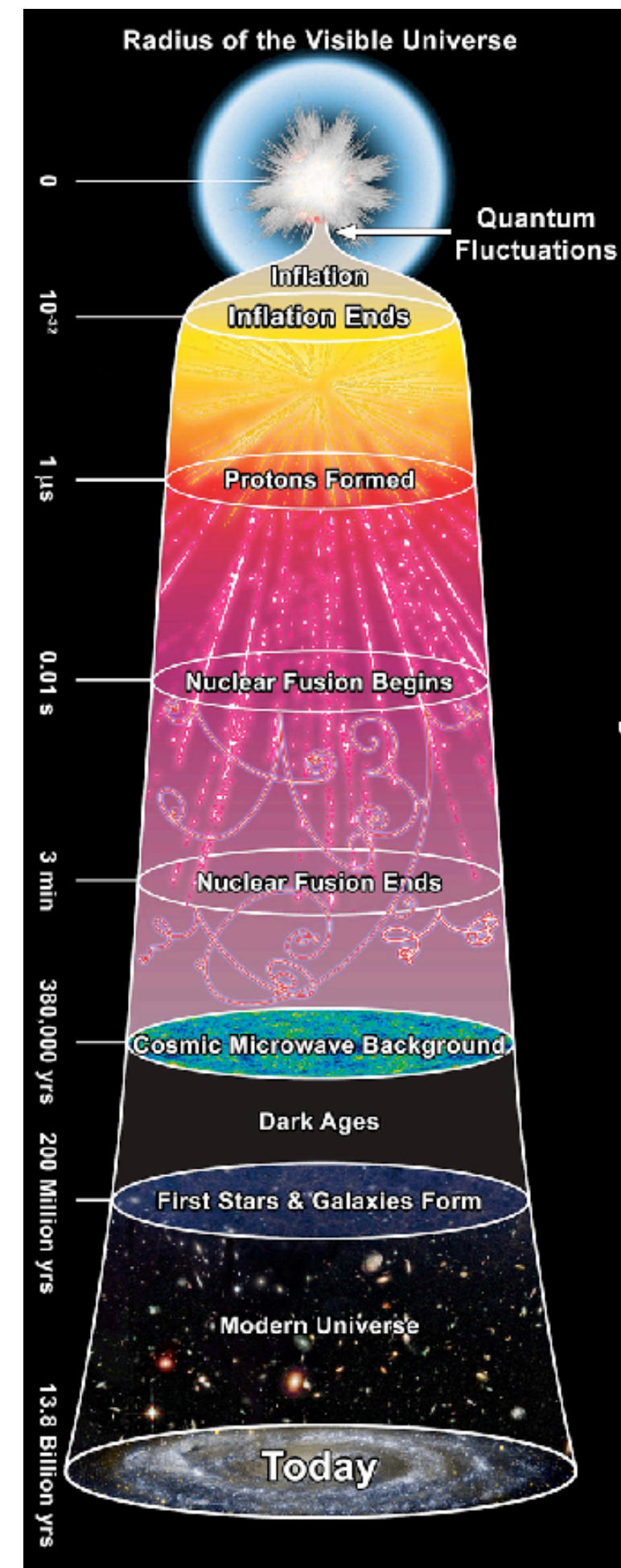
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Recap

- Sub-GeV dark sectors are a compelling framework for DM as a thermal relic and other thermal-ish scenarios
- $m_\chi \gtrsim 10$ keV from structure formation
- $m_\chi \gtrsim 10$ MeV from BBN (unless secluded from SM bath)
- Conversely: detection can indirectly probe period just before BBN

Relic dark
matter?



II. Direct detection

Constraints on allowed direct detection signals

Set aside the question of relic abundance for the moment.

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- BBN (He, D abundances) and N_{eff} measurements

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Constraints on allowed direct detection signals

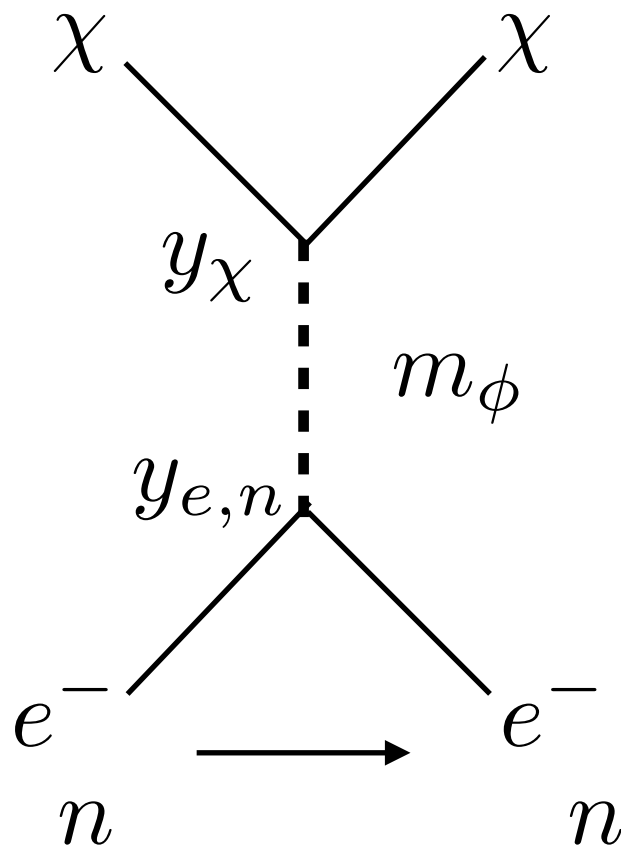
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- BBN (He, D abundances) and Neff measurements
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- Stellar cooling constraints on new light mediator
- DM self-interactions

Simplified portal setup

For simplicity, consider all scalars

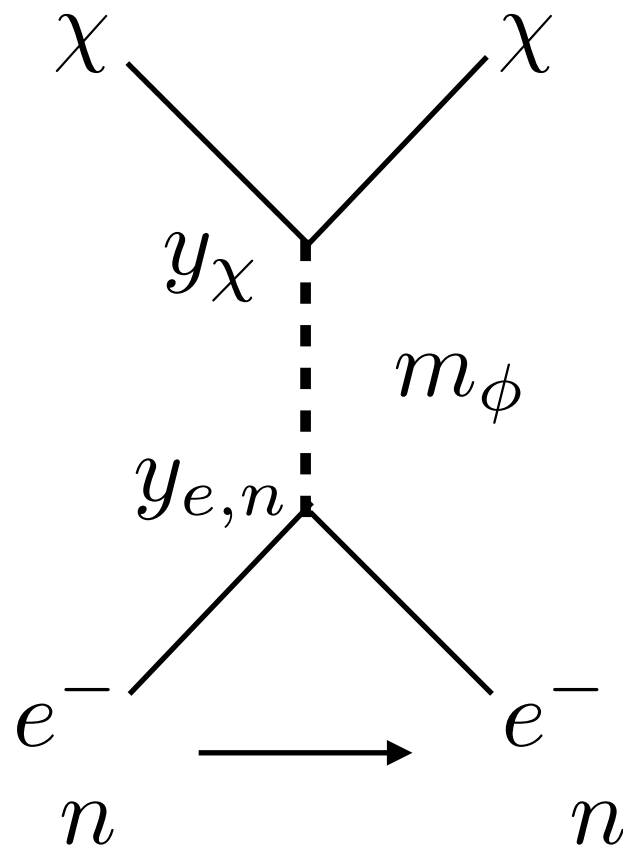
$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi\phi\chi^2$$



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Scattering in direct detection:

$$\bar{\sigma}_e \equiv \frac{y_\chi^2 y_e^2}{4\pi} \frac{\mu_{\chi e}^2}{(m_\phi^2 + \alpha^2 m_e^2)^2}$$

Reference scale for
momentum transfer

$$q_{\text{typical}} \simeq \alpha m_e$$

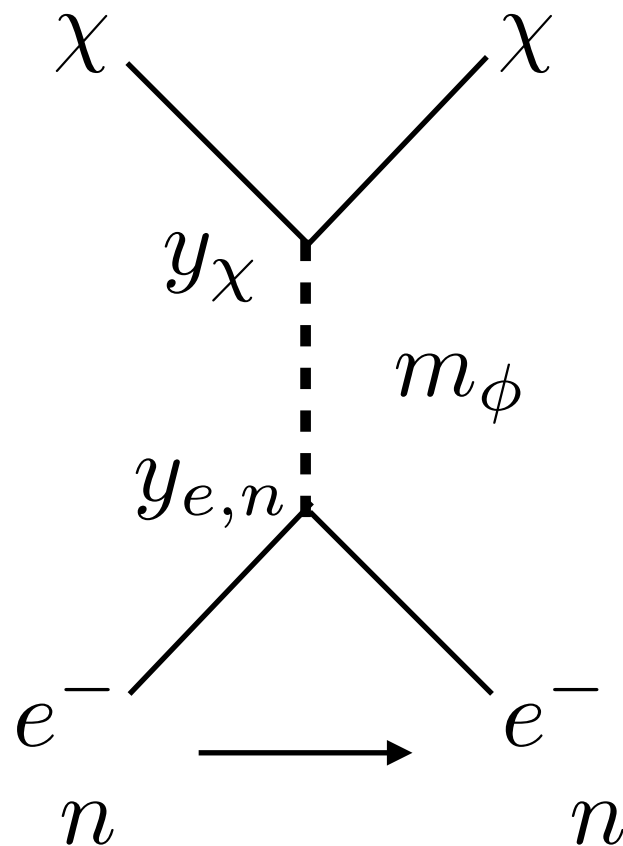
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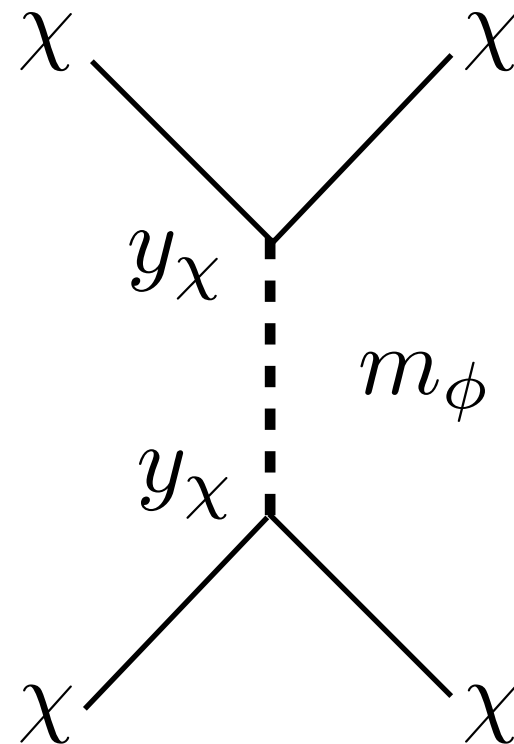
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$$q_{\text{typical}} \simeq m_\chi v_{DM}$$

Larger cross section benefits from larger $y_\chi, y_{e,n}$ and smaller m_ϕ

DM self-interactions

Constraint on y_χ from
DM-DM scattering



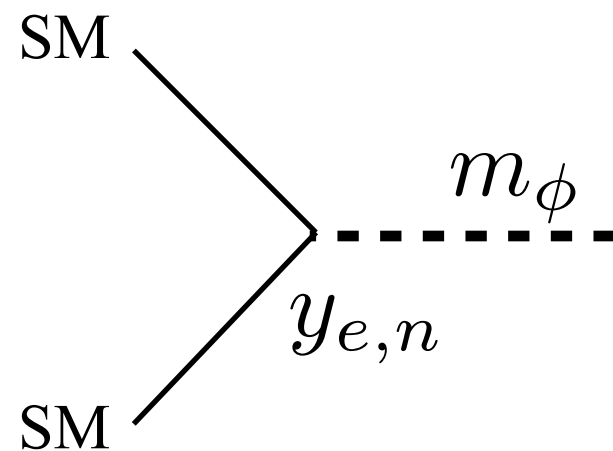
Upper bounds vary by system (clusters, dwarfs,...) and depend on m_ϕ .

Roughly: $\sigma/m \lesssim 1 - 10^3 \text{ cm}^2/\text{g}$

Constraints on mediator

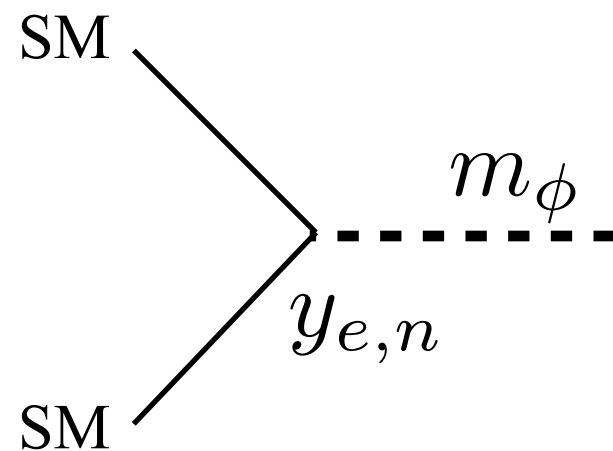
Constraints on mediator

Emission of mediator in stars,
early universe (BBN)

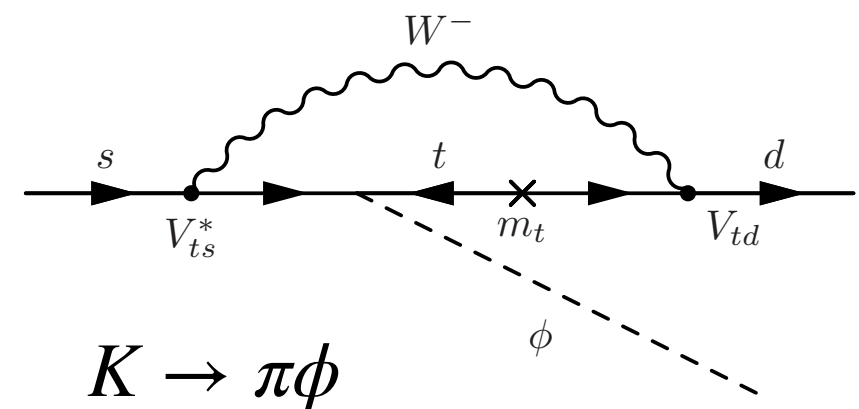


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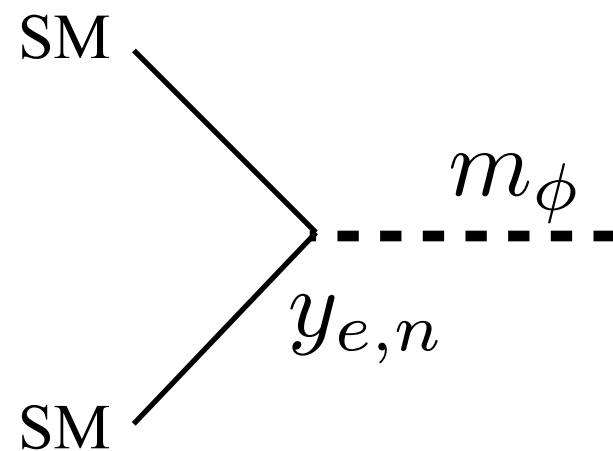


Rare meson decays,
collider probes

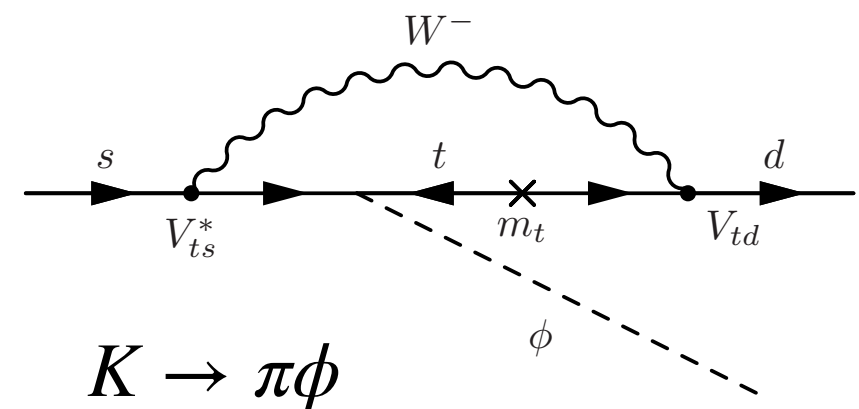


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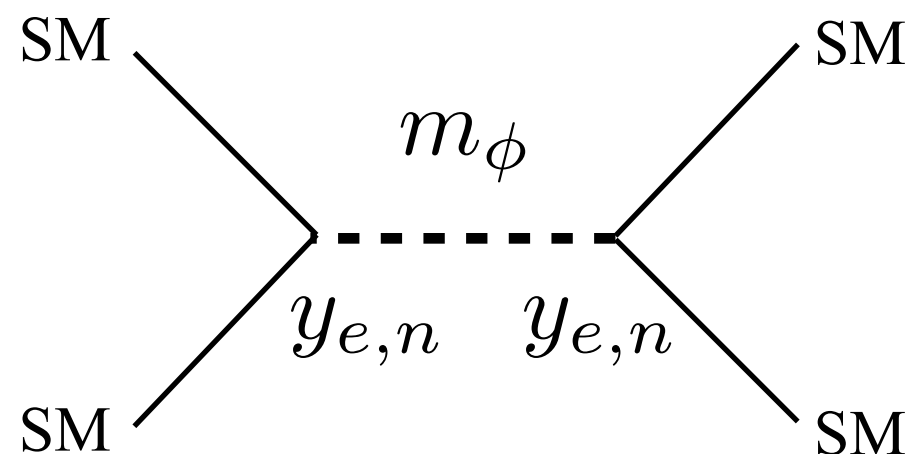
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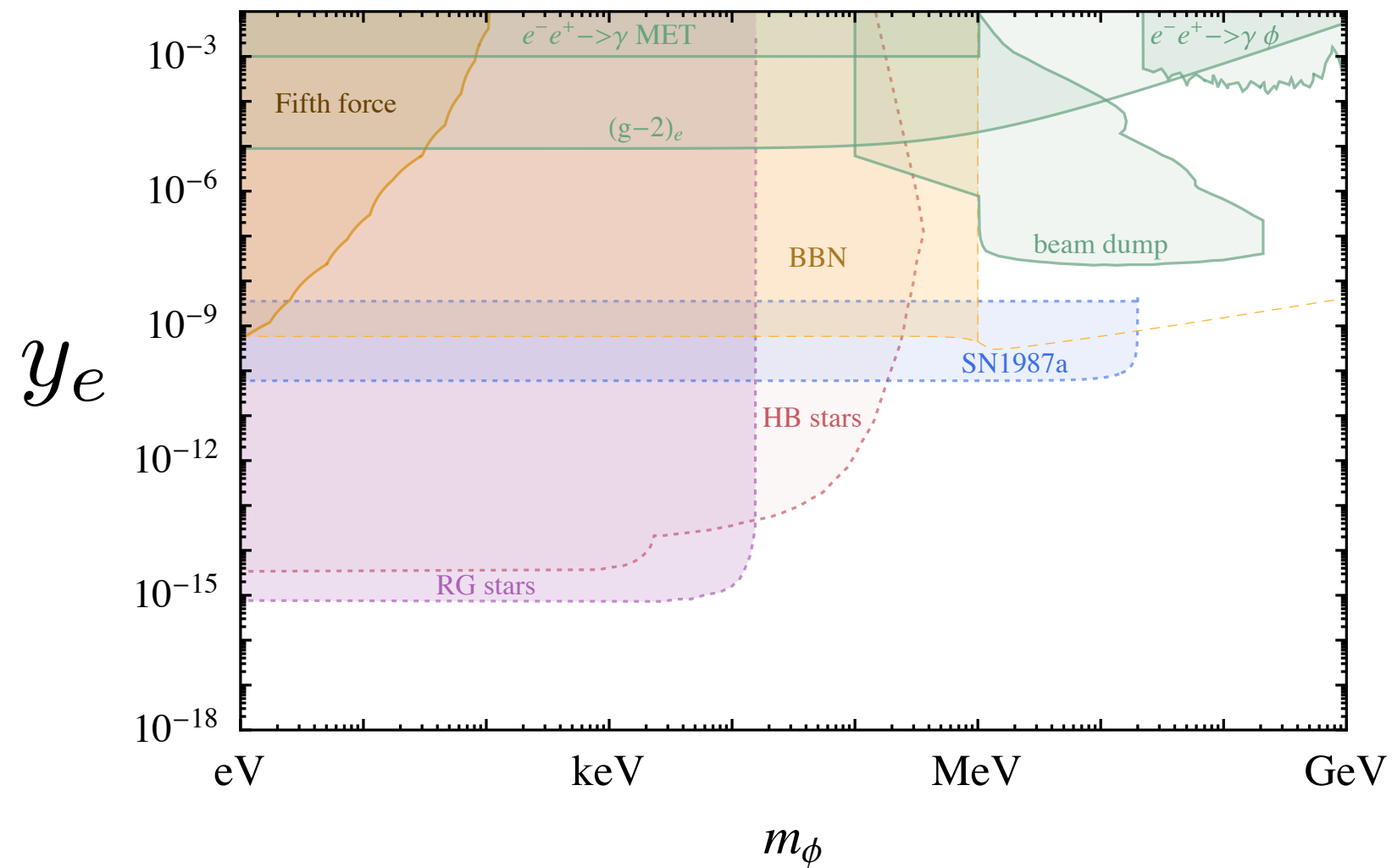
Rare meson decays,
collider probes



Fifth-force searches



Leptophilic scalar



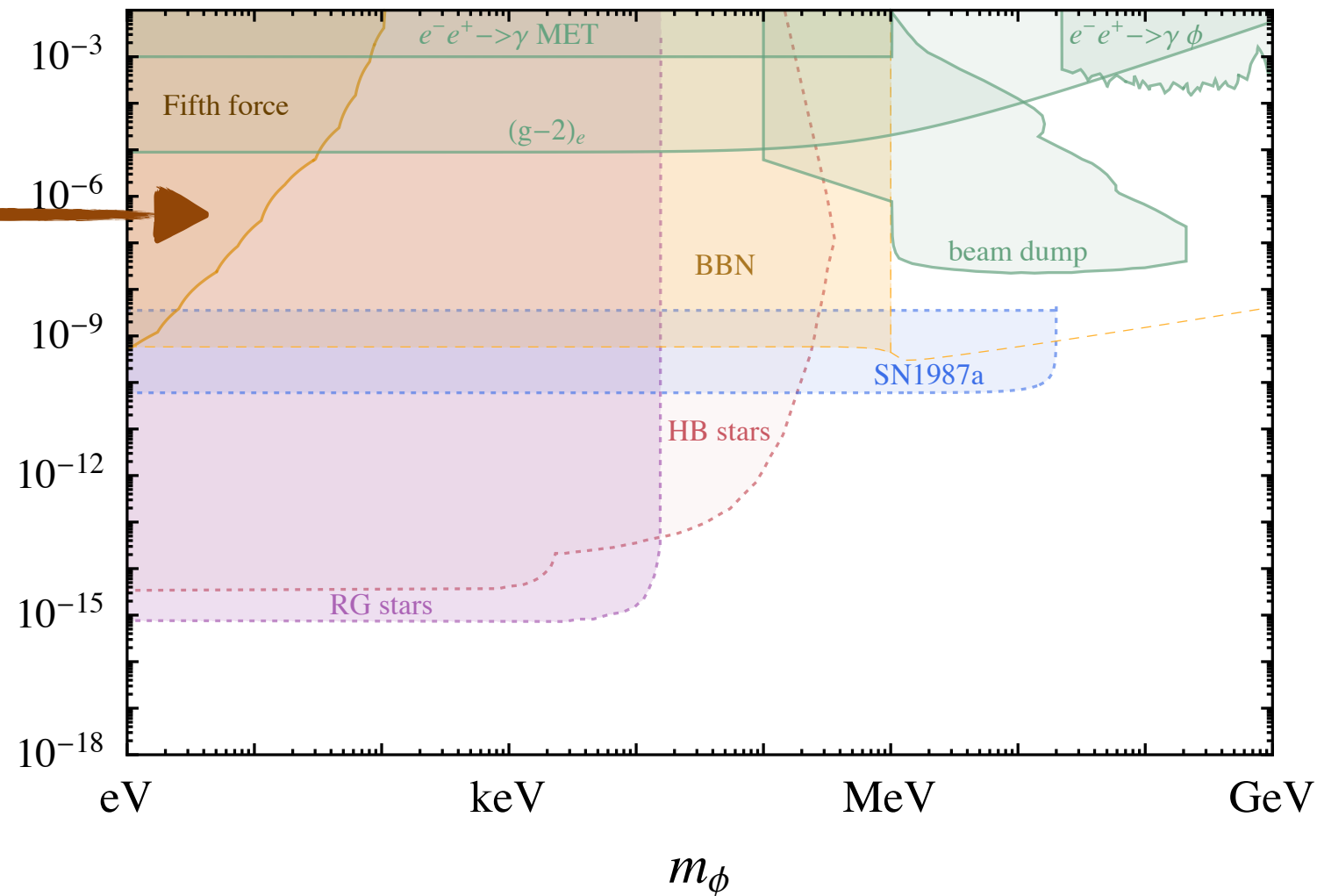
Scalar coupled to electron

Leptophilic scalar

Fifth force

[Murata & Tanaka 2015]

y_e



Scalar coupled to electron

Leptophilic scalar

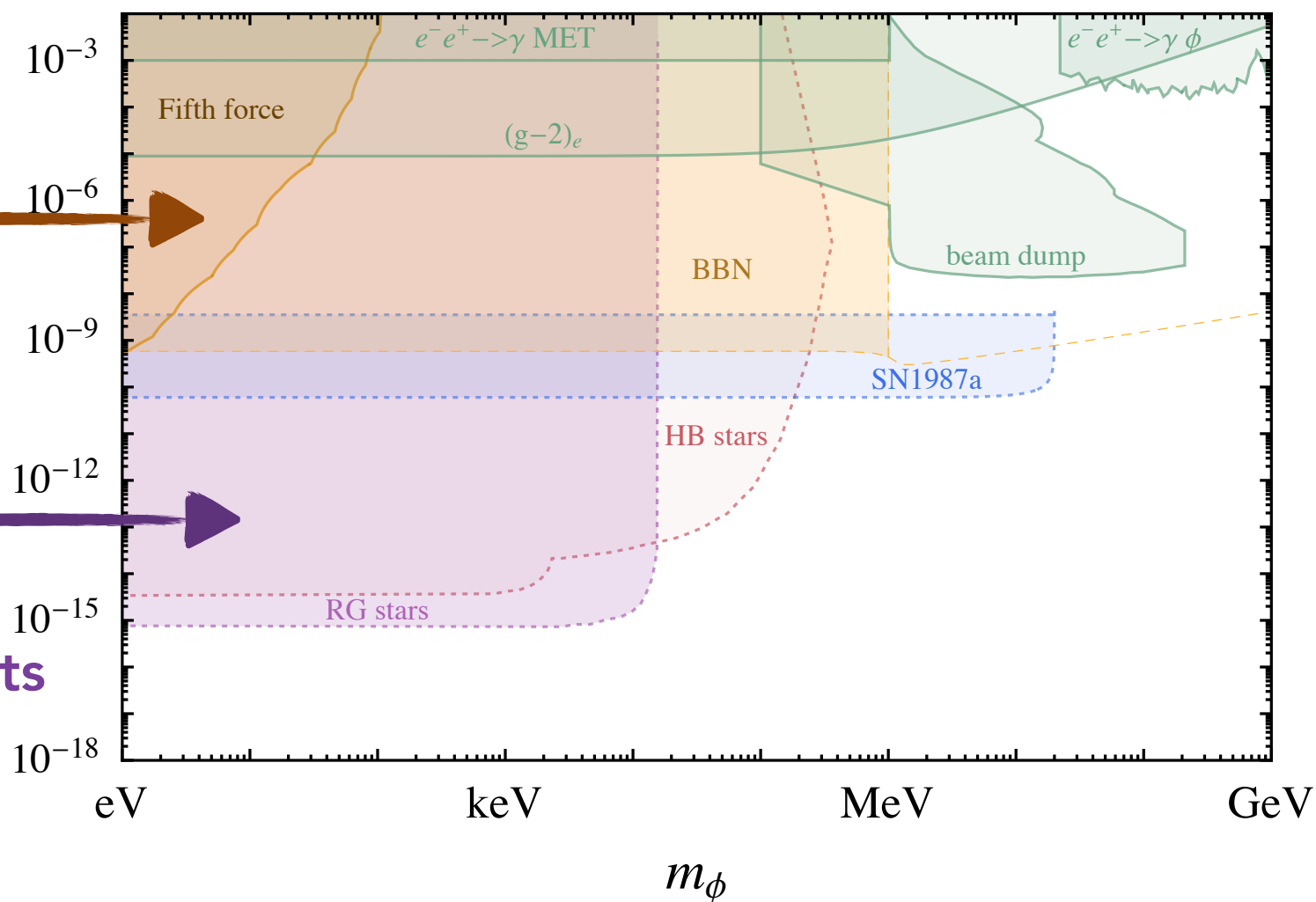
Fifth force

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**Anomalous
energy loss in
stellar environments**

[Hardy & Lasenby 2017]



Scalar coupled to electron

Leptophilic scalar

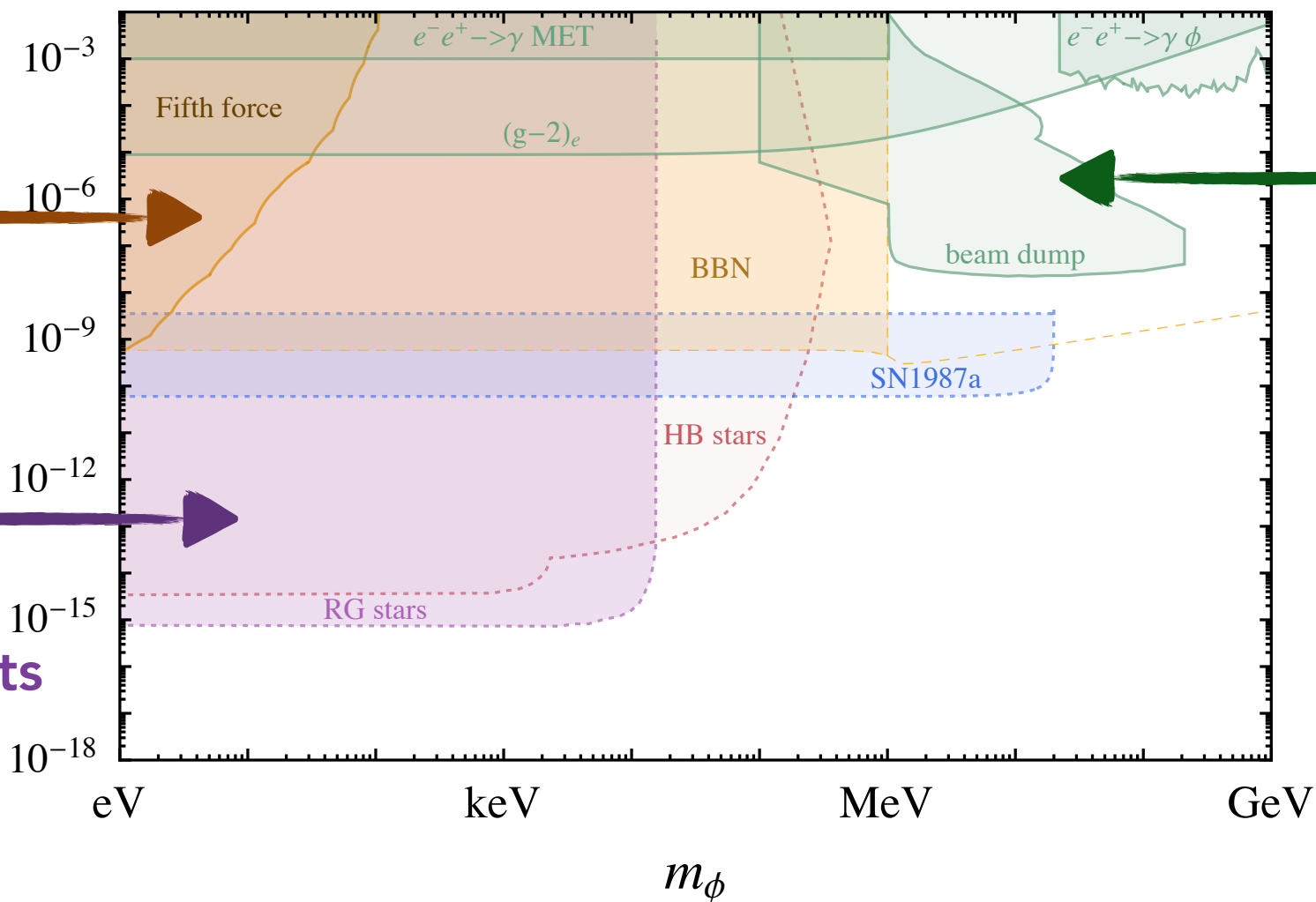
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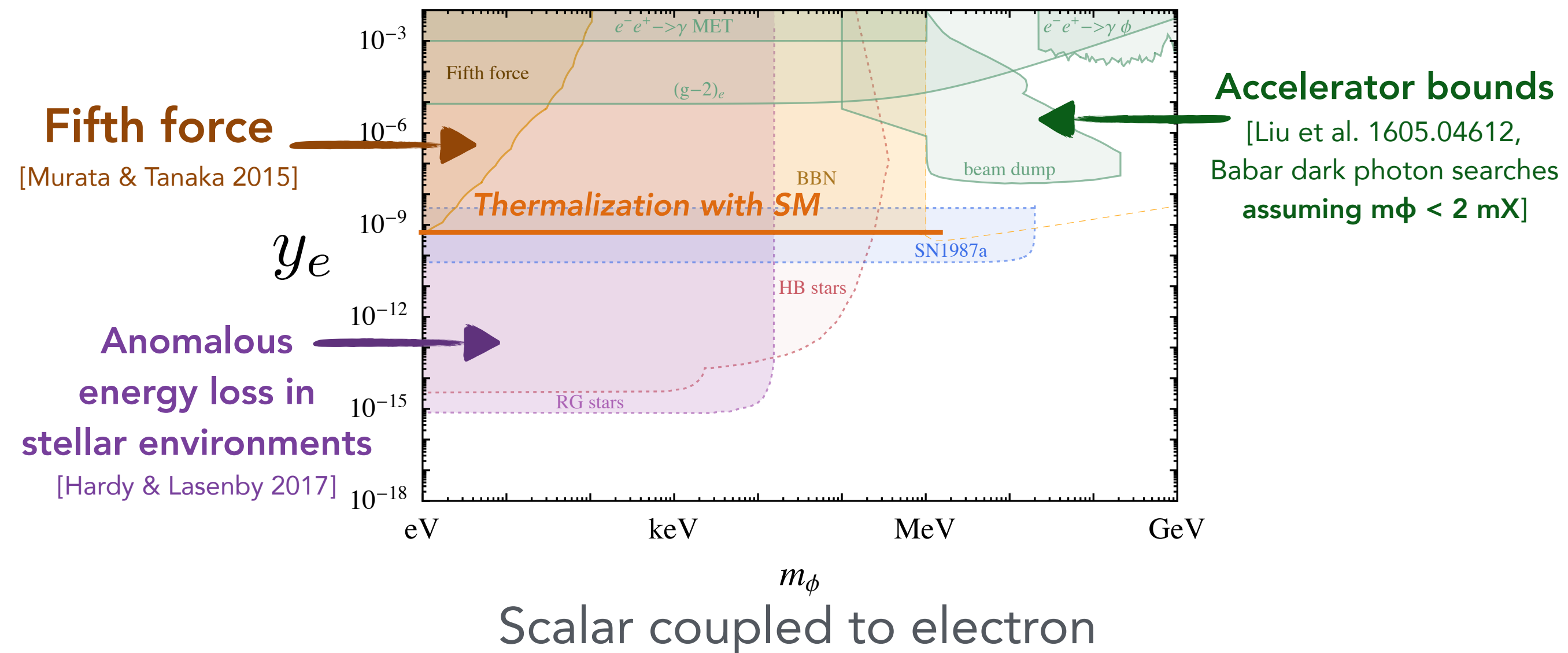


Accelerator bounds

[Liu et al. 1605.04612,
Babar dark photon searches
assuming $m\phi < 2 \text{ mX}$]

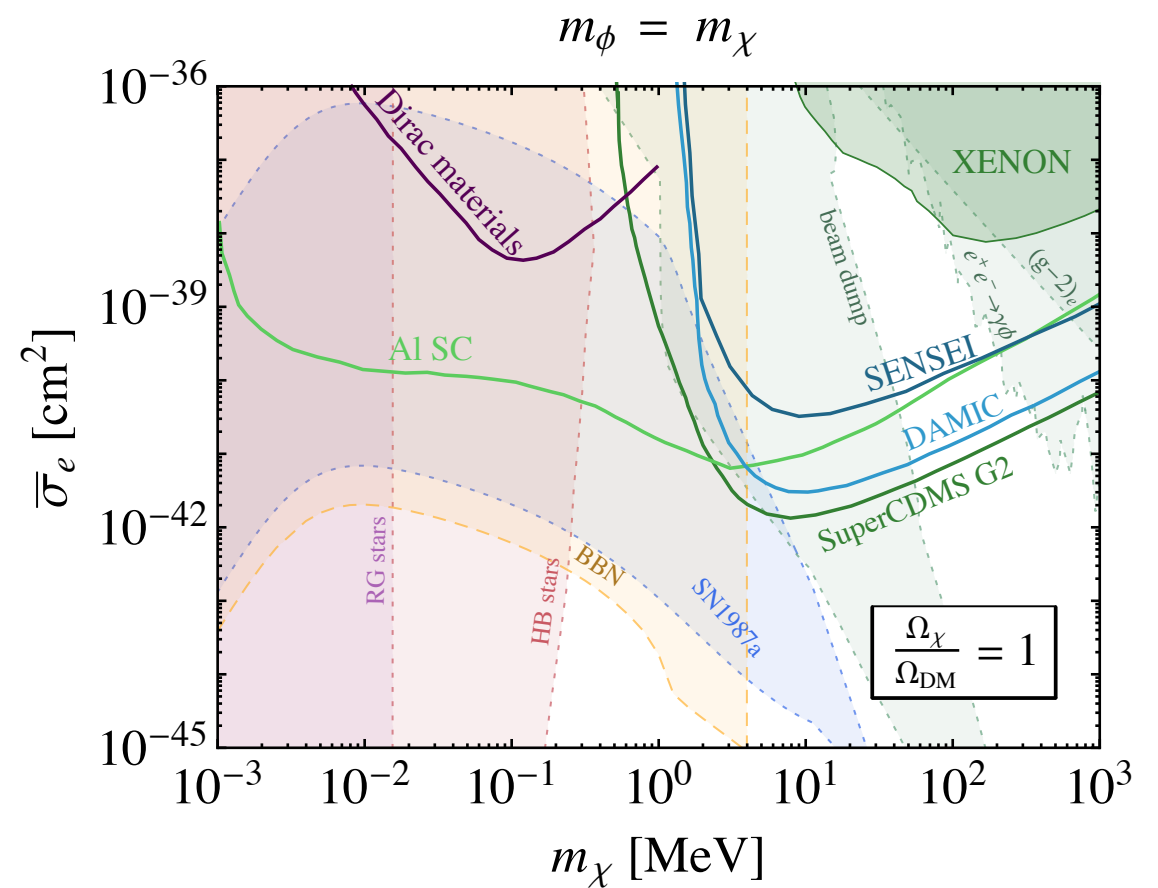
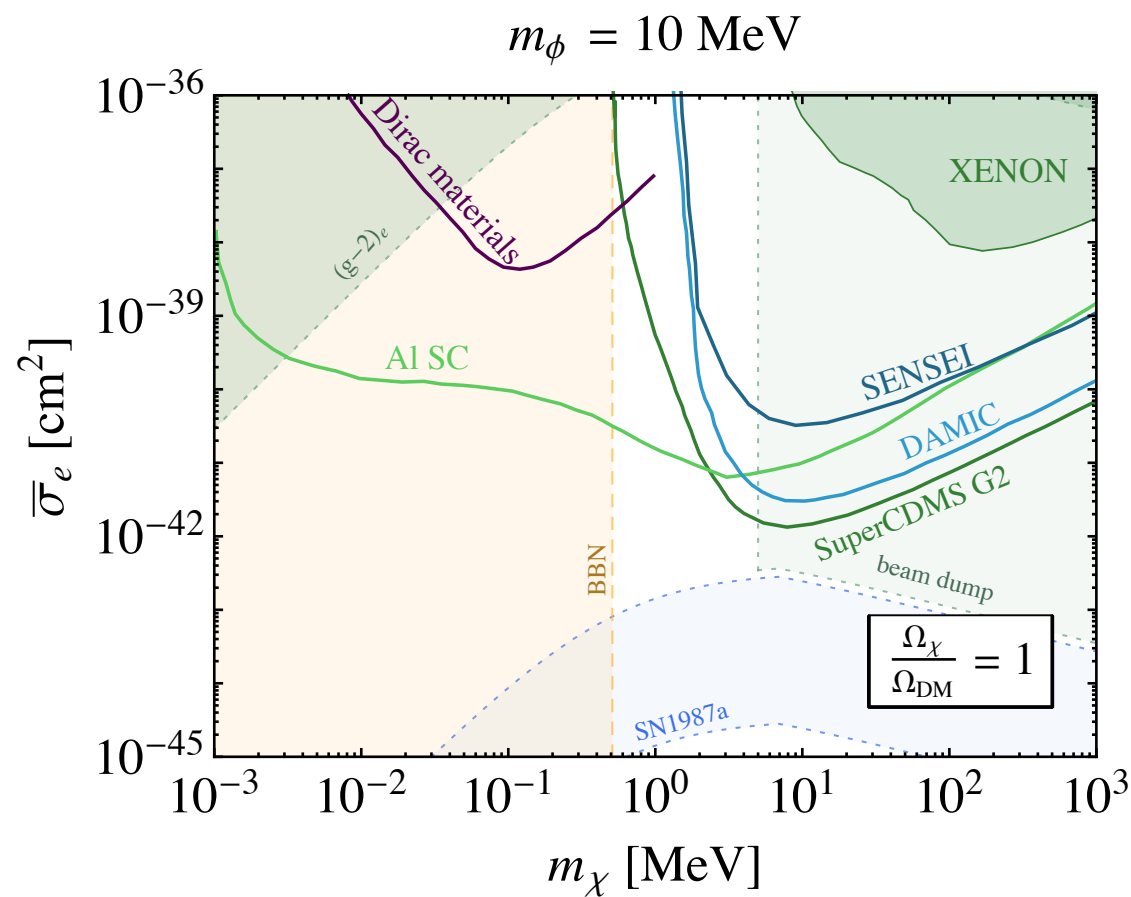
Scalar coupled to electron

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Electron scattering

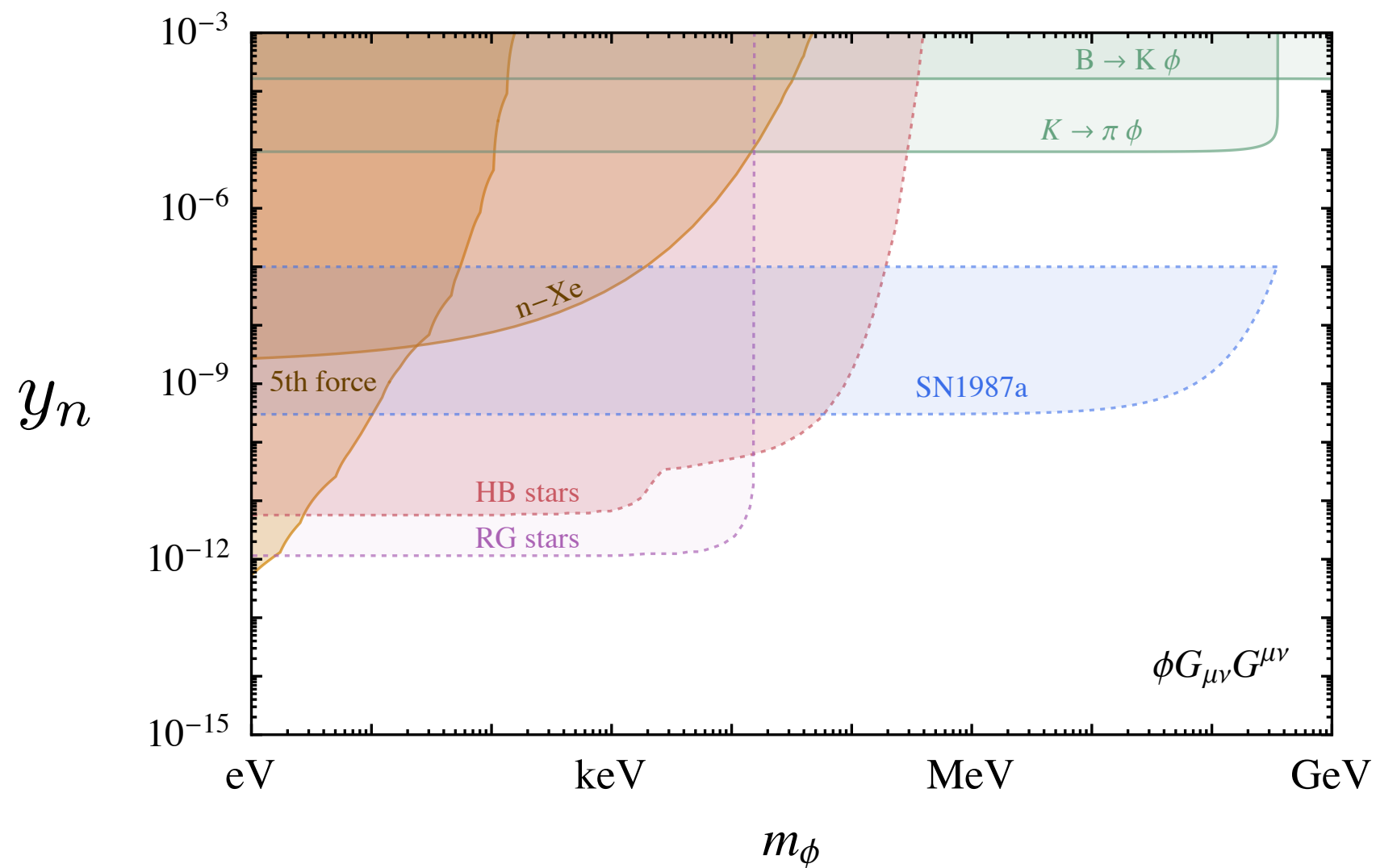
Assuming “heavy” mediator $m_\phi \gtrsim m_\chi v$



DM masses below MeV are strongly constrained by
BBN measurements of ΔN_{eff} .

Nucleo-philic scalar

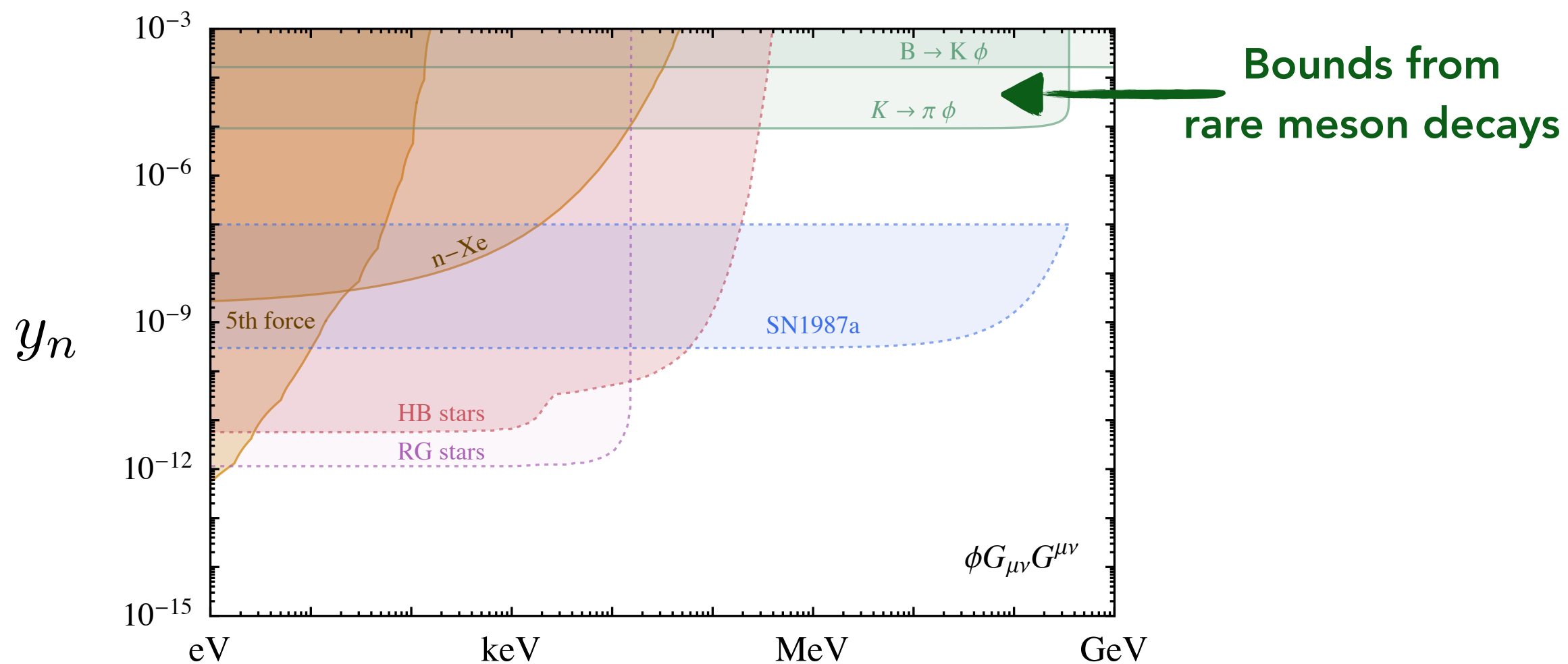
Thermalization of mediator is dangerous
below QCD phase transition



Scalar coupled to gluons

Nucleo-philic scalar

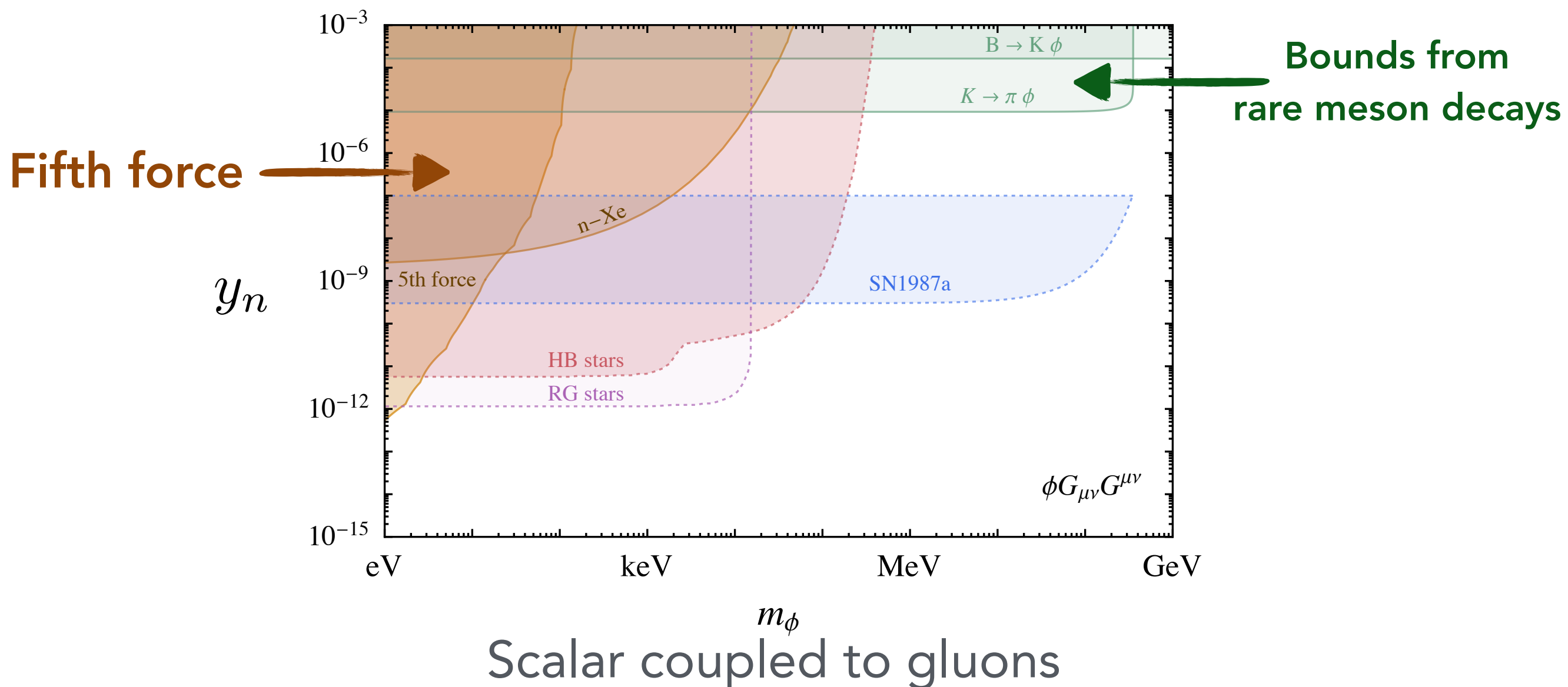
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Scalar coupled to gluons

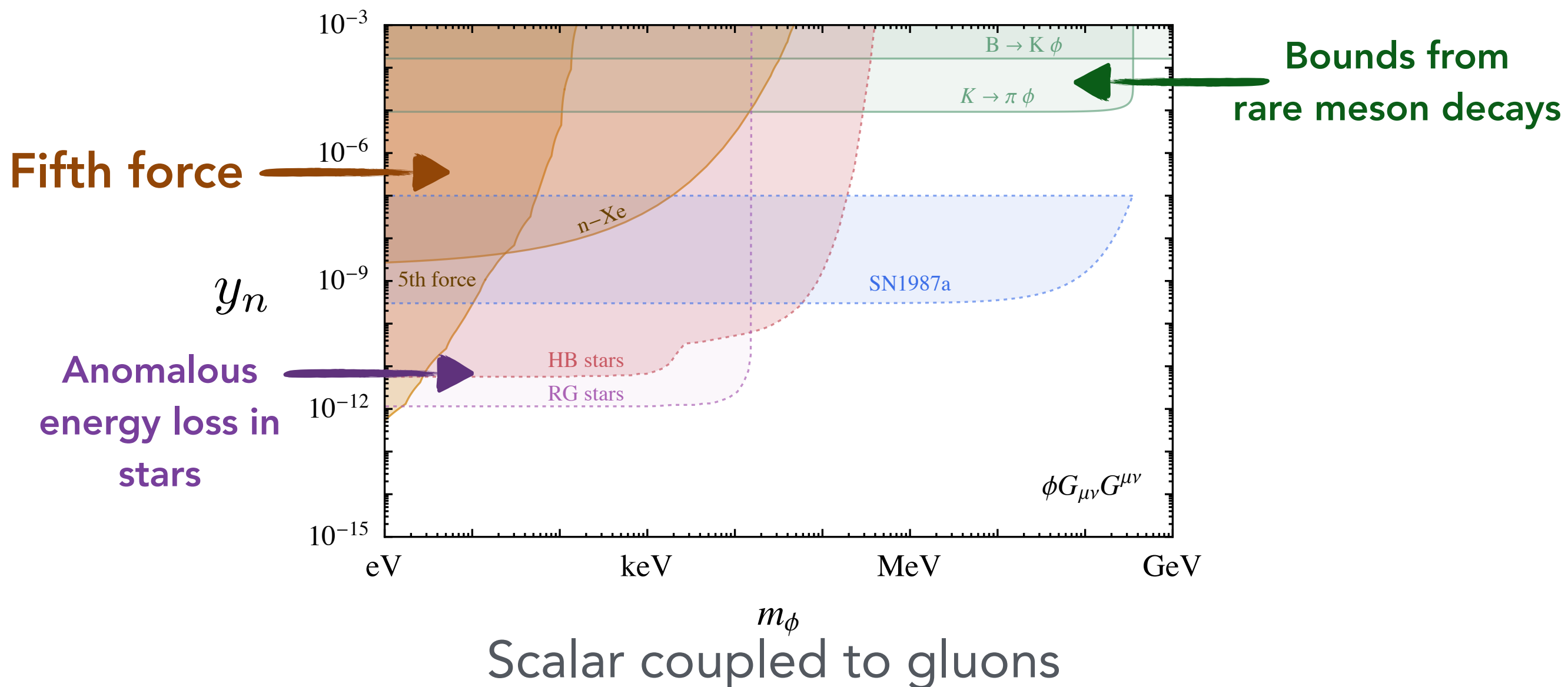
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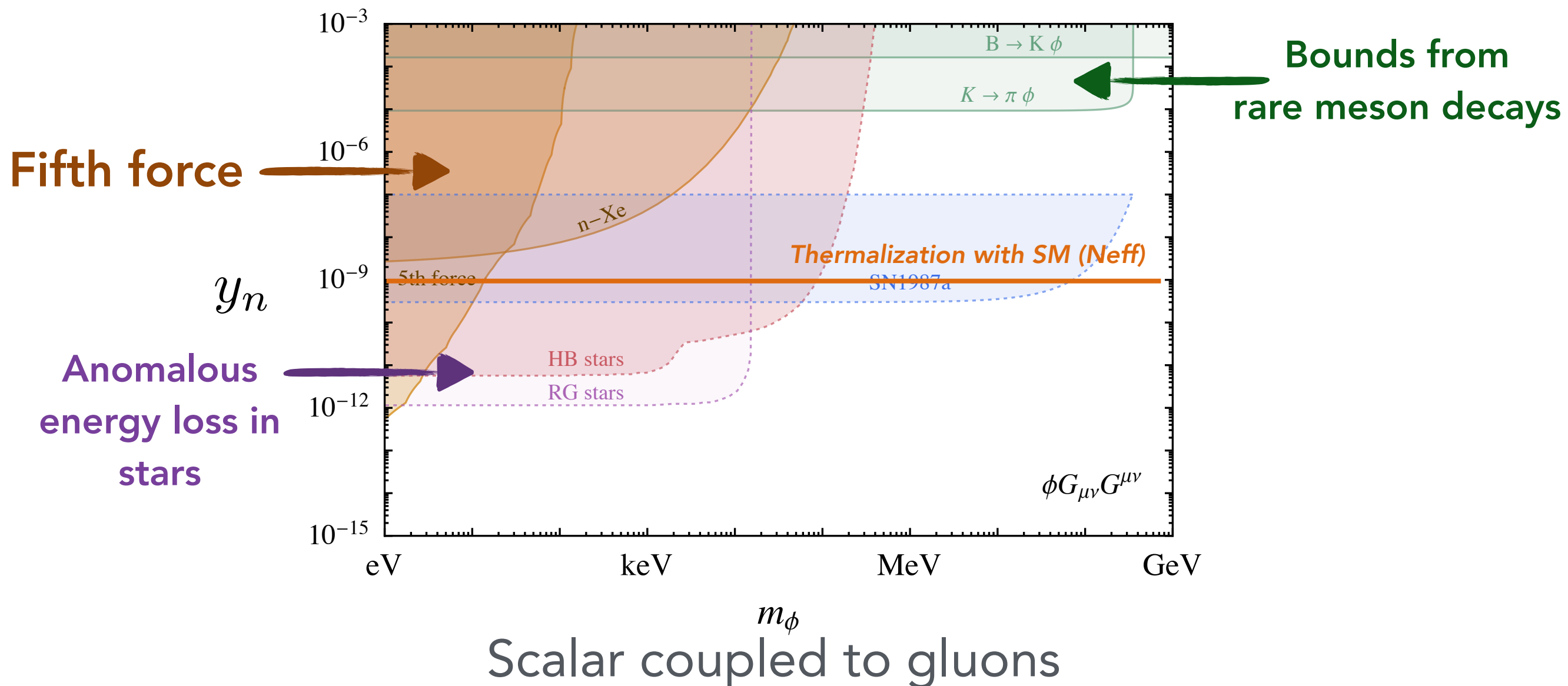
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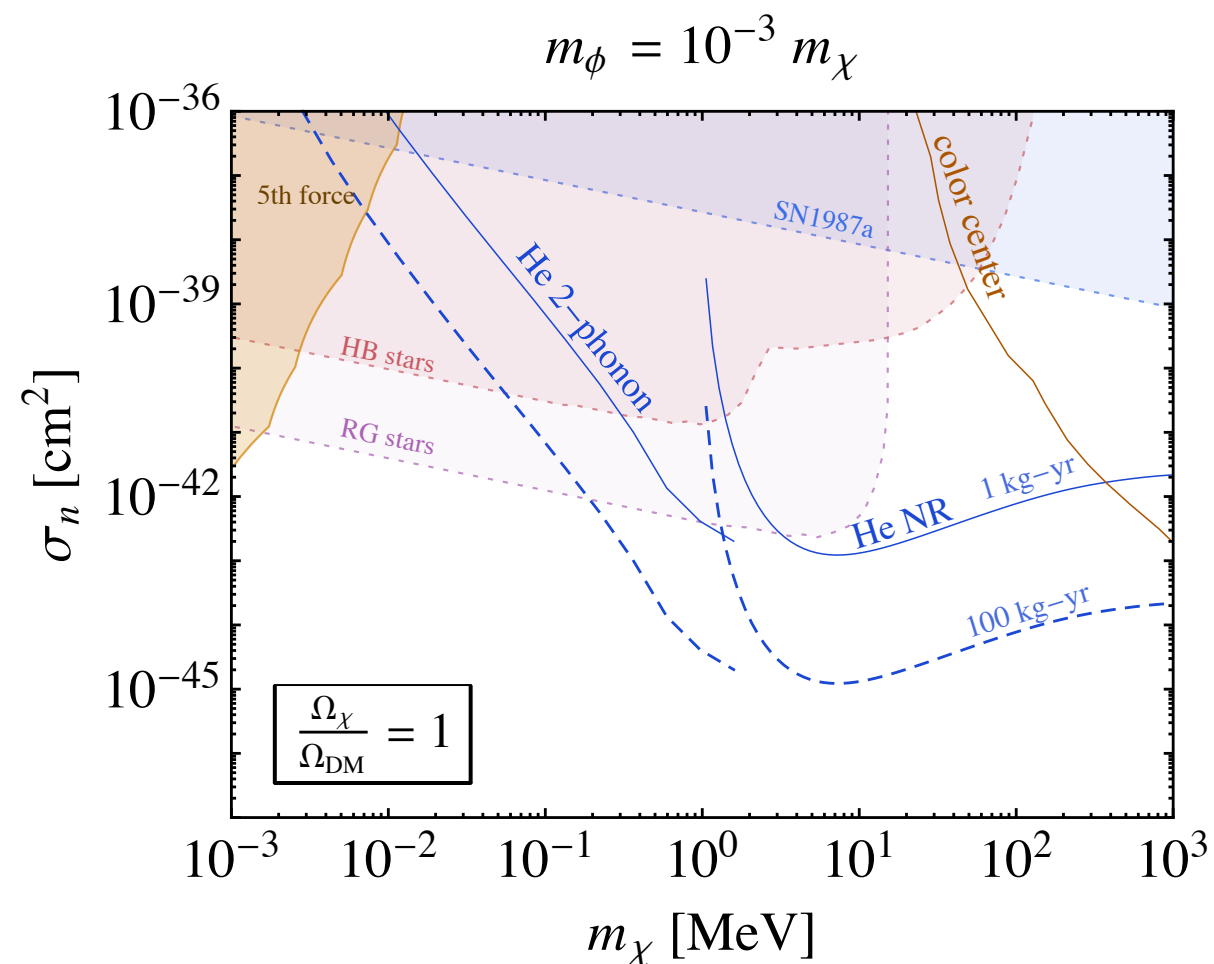
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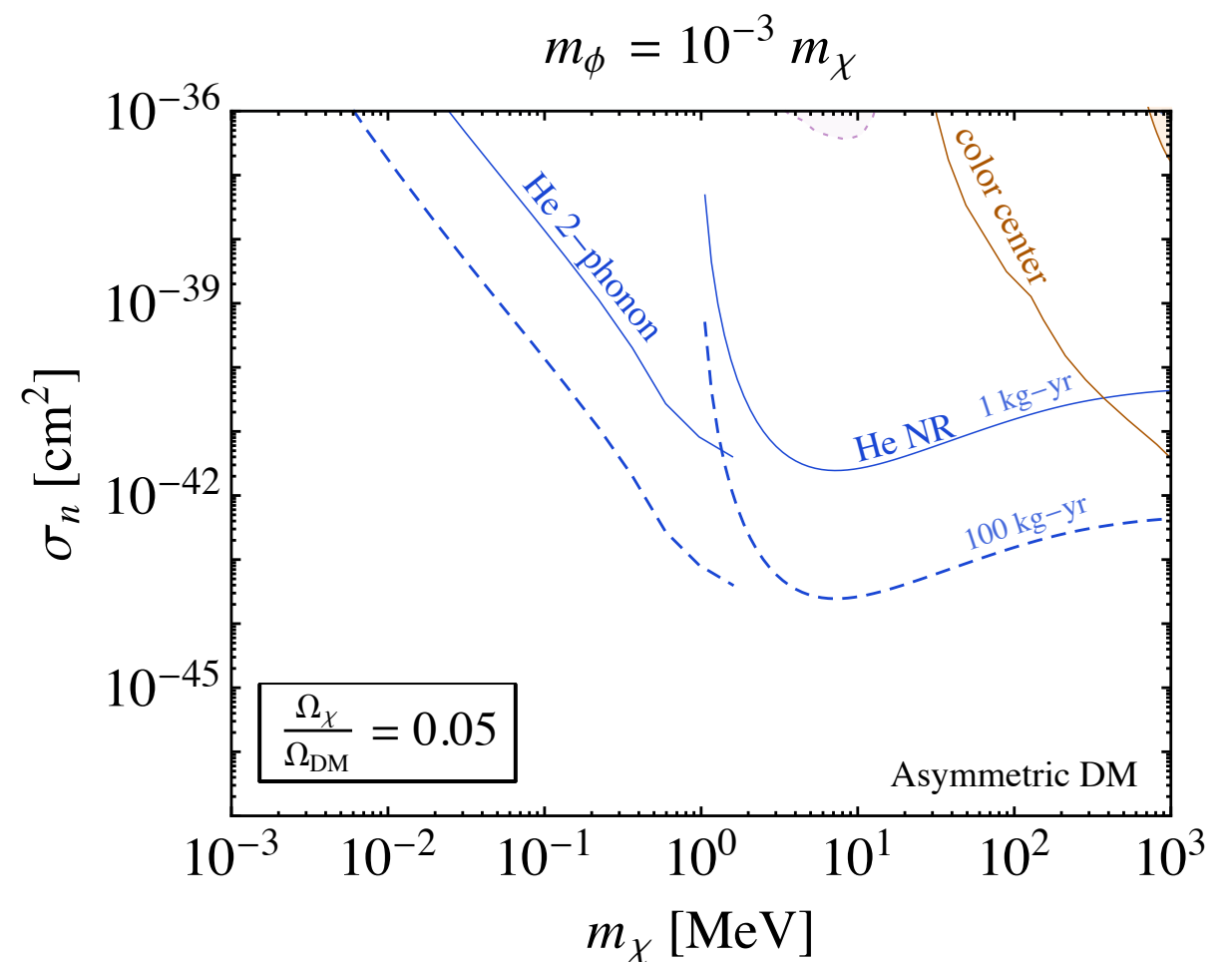


Nuclear recoils

“Light” mediator case $m_\phi \lesssim 10^{-3} m_\chi$



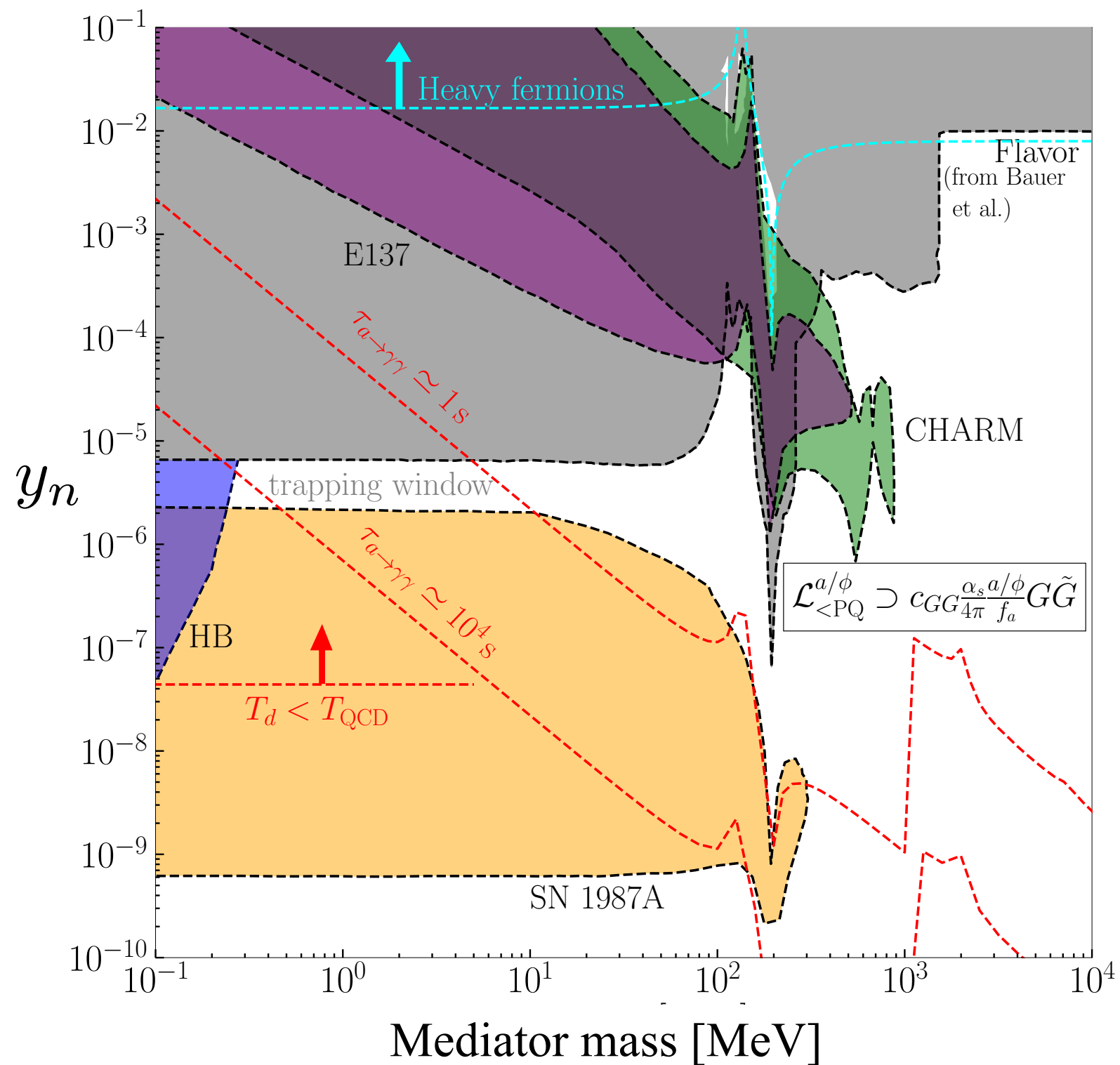
with SIDM bounds



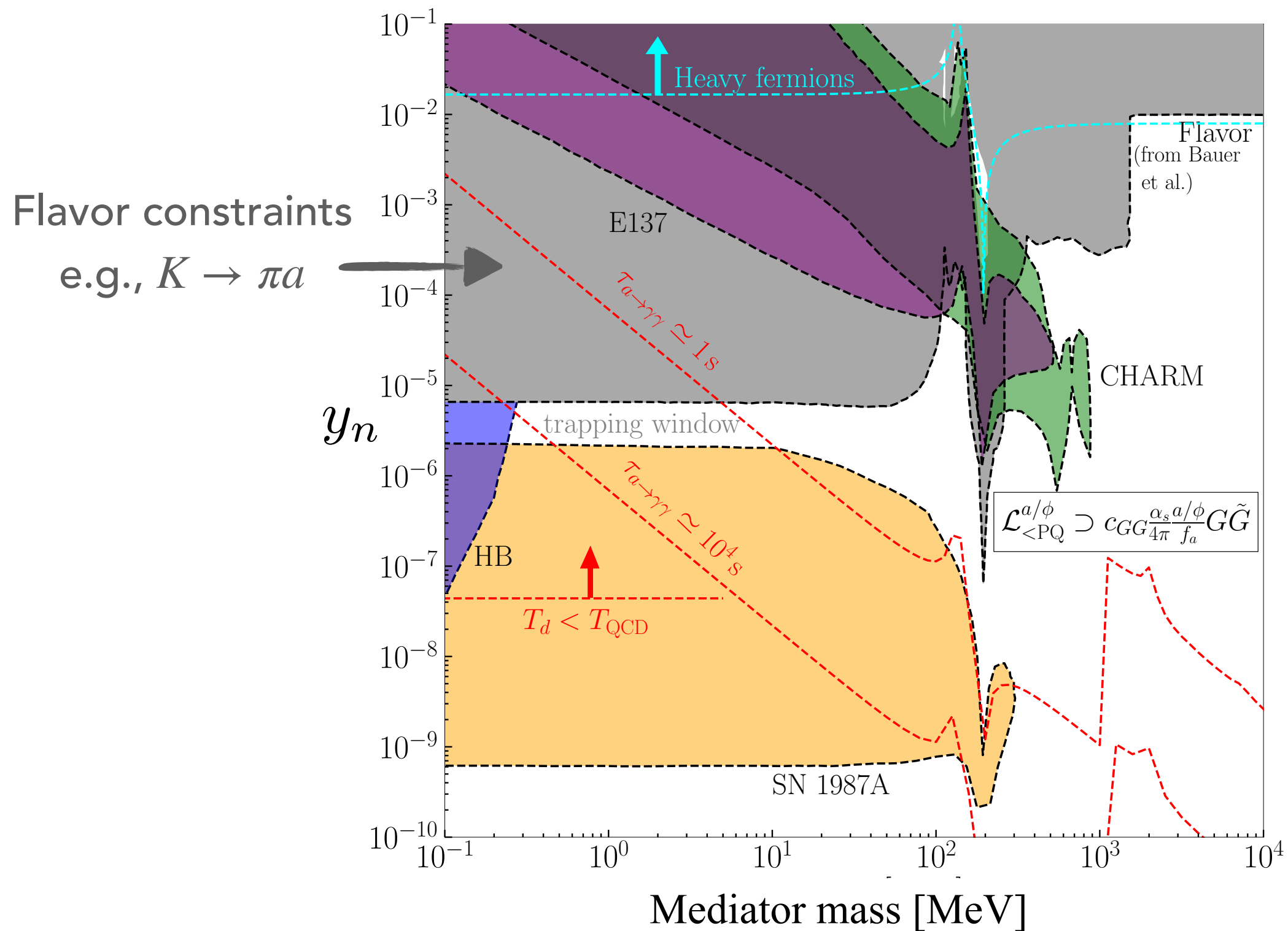
without SIDM bounds

From Knapen, TL, Zurek 2017
 See also: Green and Rajendran 2017
 Cox, Dolan, Wood 2024
 Cox, Dolan, Ghosh 2025

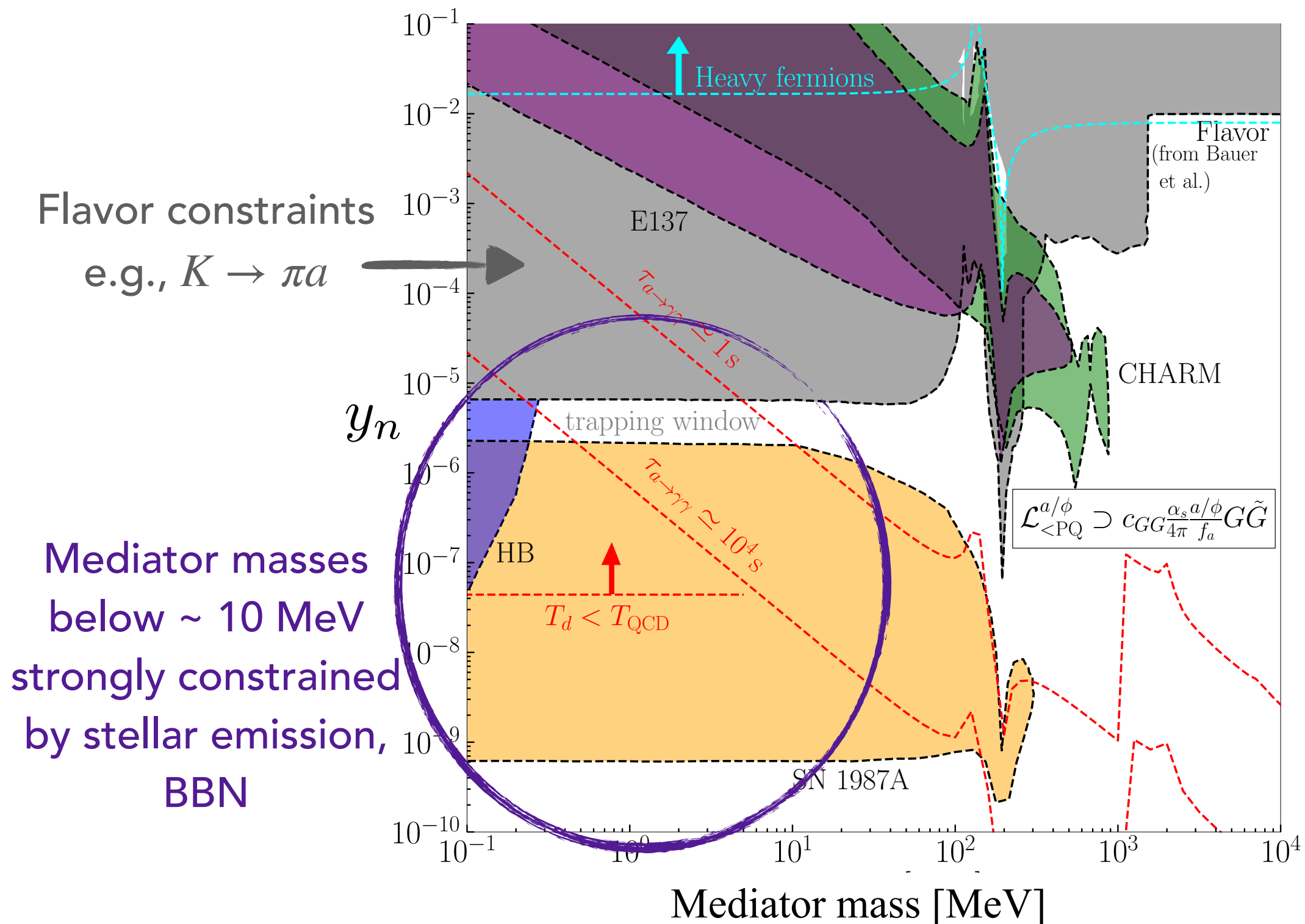
Pseudoscalar mediator



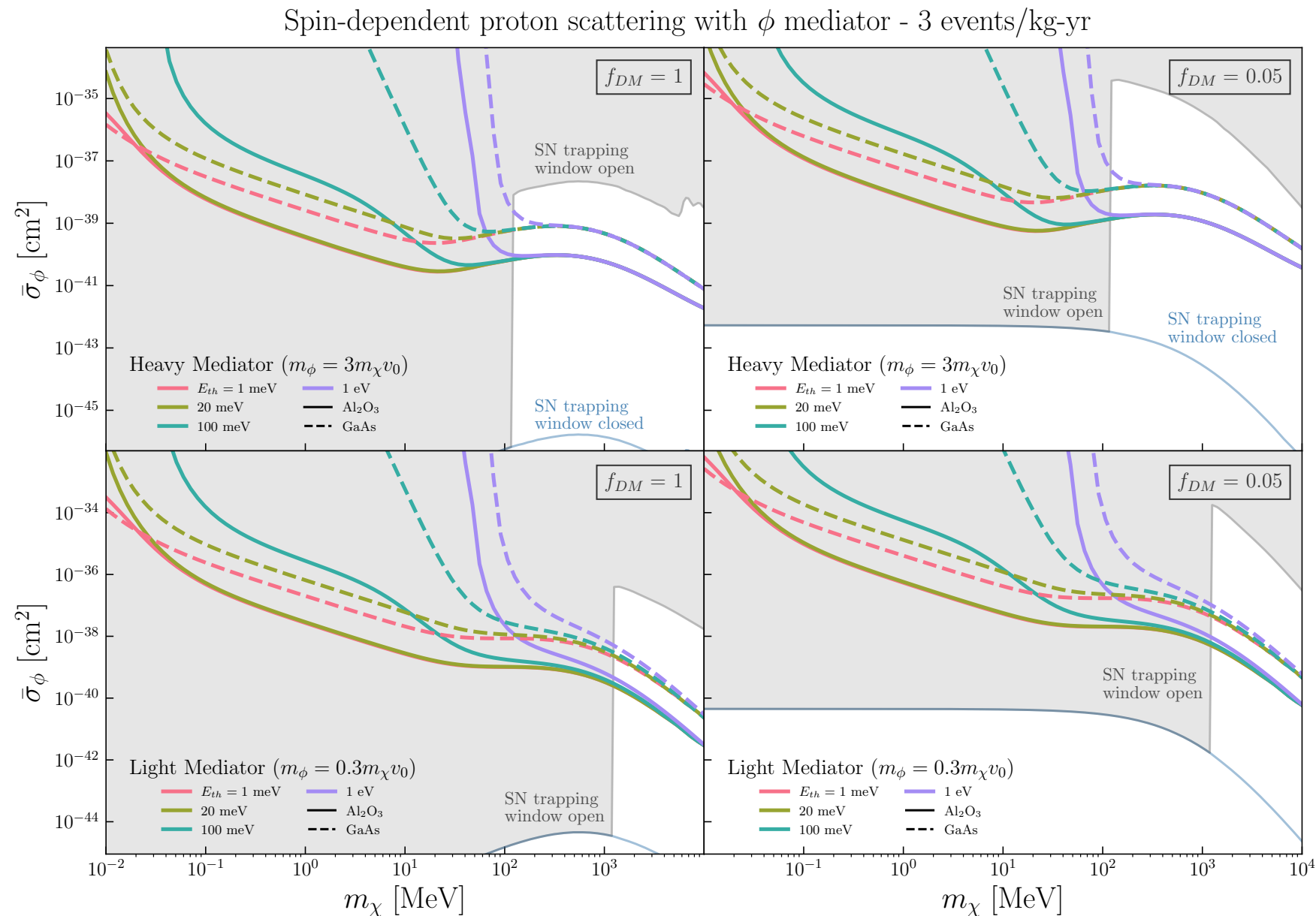
Pseudoscalar mediator



Pseudoscalar mediator



Spin-dependent scattering



Upshot: for scalar/pseudoscalar mediators, strong upper bounds on σ for $m_\chi \lesssim 10 - 100$ MeV

All products



↔ 180

Nearby, 9 mi

Motorola Moto G 2025 Prepaid Smartphone

\$39.99

Best Buy & more

3.8 ★★★★★ (110)



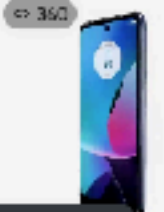
Nearby, 9 mi

Apple iPhone 17

\$829.00

Apple & more

4.5 ★★★★★ (8.9K)



↔ 360

Nearby, 9 mi

Verizon Moto G Play 2024 Prepaid Smartphone

\$29.88

Walmart

3.5 ★★★★★ (256)



18% OFF

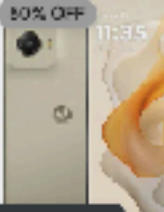
Nearby, 9 mi

Google Pixel 10a

\$424.00 ~~\$499~~

Google Store & more

4.6 ★★★★★ (1.3K)



50% OFF

Nearby, 8 mi

Motorola Moto G Stylus 5G 2024

\$199.99 ~~\$400~~

Best Buy & more

4.2 ★★★★★ (1.6K)



Nearby, 2 mi

Apple iPhone 17e

\$599.00

Apple & more

4.6 ★★★★★ (3.1K)



Nearby, 9 mi

Samsung Galaxy A17 5G Prepaid Smartphone

\$99.88

Walmart & more

3.4 ★★★★★ (8)



Also nearby

Google Pixel 10

\$799.00

Google Store & more

4.6 ★★★★★ (1.9K)



↔ 360

Also nearby

Samsung Galaxy S26 Ultra

\$41.66/mo x 36

Best Buy & more

4.8 ★★★★★ (54K)



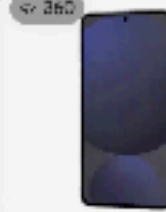
Nearby, 14 mi

Apple iPhone 16e Black

\$349.00

Walmart & more

3.9 ★★★★★ (1.2K)



↔ 360

Samsung Galaxy S24 FE

\$36.00

Scrignalia e... & more

4.7 ★★★★★ (15K)



13% OFF

Nearby, 9 mi

Samsung Galaxy S26

\$774.99 ~~\$898~~

Best Buy & more

4.7 ★★★★★ (16K)



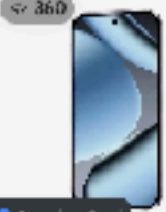
Nearby, 2 mi

Apple iPhone 17e 256GB White

\$599.00

Apple & more

4.1 ★★★★★ (221)



↔ 360

Nearby, 9 mi

Google Pixel 10 Pro

\$999.00

Google Store & more

4.4 ★★★★★ (2.3K)



↔ 360

Nearby, 9 mi

Apple iPhone 15

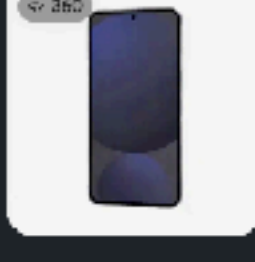
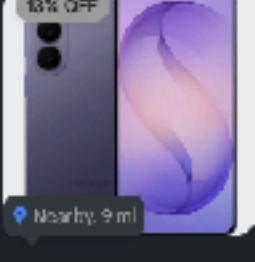
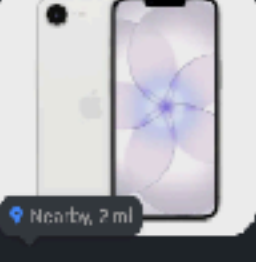
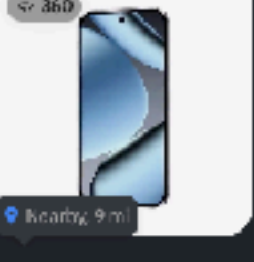
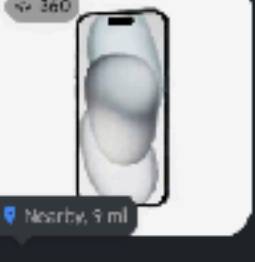
\$499.00

Walmart & more

4.6 ★★★★★ (36K)

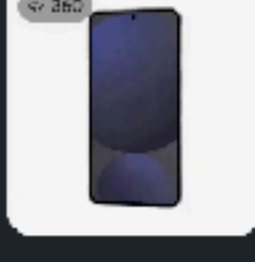
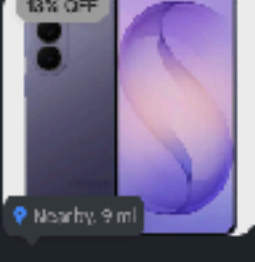
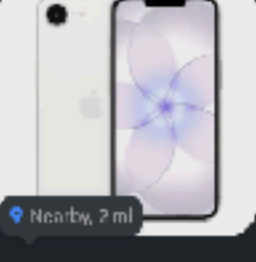
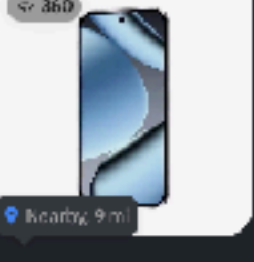
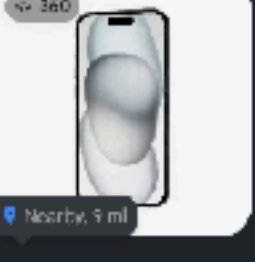
It's good to have options

All products

 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 8 mi
Motorola Moto G 2025 Prepaid Smartphone \$39.99 Best Buy & more 3.8 ★★★★★ (110)	Apple iPhone 17 \$829.00 Apple & more 4.5 ★★★★★ (8.9K)	Verizon Moto G Play 2024 Prepaid Smartphone \$29.88 Walmart 3.5 ★★★★★ (256)	Google Pixel 10a \$424.00 \$499 Google Store & more 4.6 ★★★★★ (1.3K)	Motorola Moto G Stylus 5G 2024 \$199.99 \$400 Best Buy & more 4.2 ★★★★★ (1.6K)
 Nearby, 2 mi	 Nearby, 9 mi	 Also nearby	 Also nearby	 Nearby, 14 mi
Apple iPhone 17e \$599.00 Apple & more 4.6 ★★★★★ (3.1K)	Samsung Galaxy A17 5G Prepaid Smartphone \$99.88 Walmart & more 3.4 ★★★★★ (8)	Google Pixel 10 \$799.00 Google Store & more 4.6 ★★★★★ (1.9K)	Samsung Galaxy S26 Ultra \$41.66/mo x 36 Best Buy & more 4.8 ★★★★★ (54K)	Apple iPhone 16e Black \$349.00 Walmart & more 3.9 ★★★★★ (1.2K)
 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 2 mi	 Nearby, 9 mi	 Nearby, 9 mi
Samsung Galaxy S24 FE \$36.00 Serigrafia e... & more 4.7 ★★★★★ (15K)	Samsung Galaxy S26 \$774.99 \$998 Best Buy & more 4.7 ★★★★★ (16K)	Apple iPhone 17e 256GB White \$599.00 Apple & more 4.1 ★★★★★ (221)	Google Pixel 10 Pro \$999.00 Google Store & more 4.4 ★★★★★ (2.3K)	Apple iPhone 15 \$499.00 Walmart & more 4.6 ★★★★★ (36K)

It's good to have options

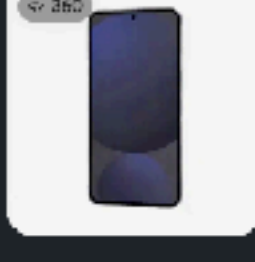
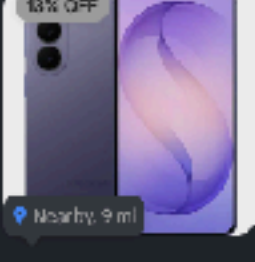
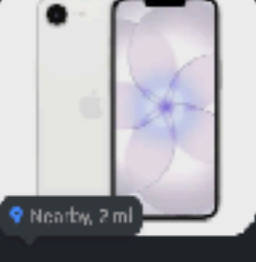
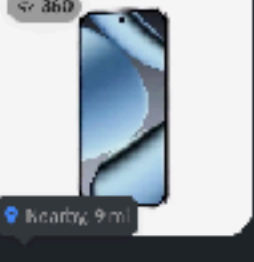
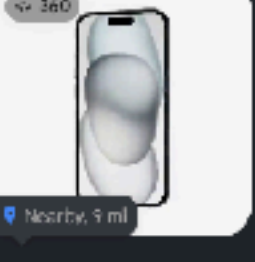
All products

 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 8 mi
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 Nearby, 2 mi	 Nearby, 9 mi	 Also nearby	 Also nearby	 Nearby, 14 mi
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 Nearby, 9 mi	 Nearby, 9 mi	 Nearby, 2 mi	 Nearby, 9 mi	 Nearby, 9 mi
Samsung Galaxy S24 FE \$36.00 Serigrafia e... & more 4.7 ★★★★★ (15K)	Samsung Galaxy S26 \$774.99 \$999 Best Buy & more 4.7 ★★★★★ (16K)	Apple iPhone 17e 256GB White \$599.00 Apple & more 4.1 ★★★★★ (221)	Google Pixel 10 Pro \$999.00 Google Store & more 4.4 ★★★★★ (2.3K)	Apple iPhone 15 \$499.00 Walmart & more 4.6 ★★★★★ (36K)

It's good to have options

Not all of them give you large
direct detection cross sections

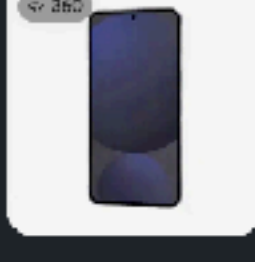
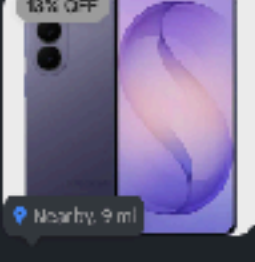
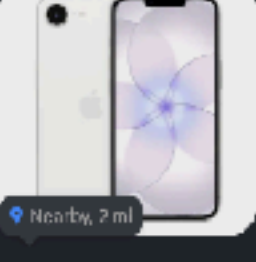
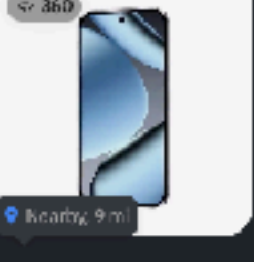
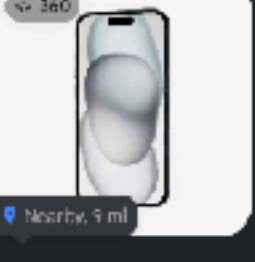
All products

 Nearby, 9 mi Motorola Moto G 2025 Prepaid Smartphone \$39.99 Best Buy & more 3.8 ★★★★★ (110)	 Nearby, 9 mi Apple iPhone 17 \$829.00 Apple & more 4.5 ★★★★★ (8.9K)	 Nearby, 9 mi Verizon Moto G Play 2024 Prepaid Smartphone \$29.88 Walmart 3.5 ★★★★★ (256)	 Nearby, 9 mi 18% OFF Google Pixel 10a \$424.00 \$499 Google Store & more 4.6 ★★★★★ (1.3K)	 Nearby, 8 mi 50% OFF Motorola Moto G Stylus 5G 2024 \$199.99 \$400 Best Buy & more 4.2 ★★★★★ (1.6K)
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It's good to have options

Not all of them give you large
direct detection cross sections

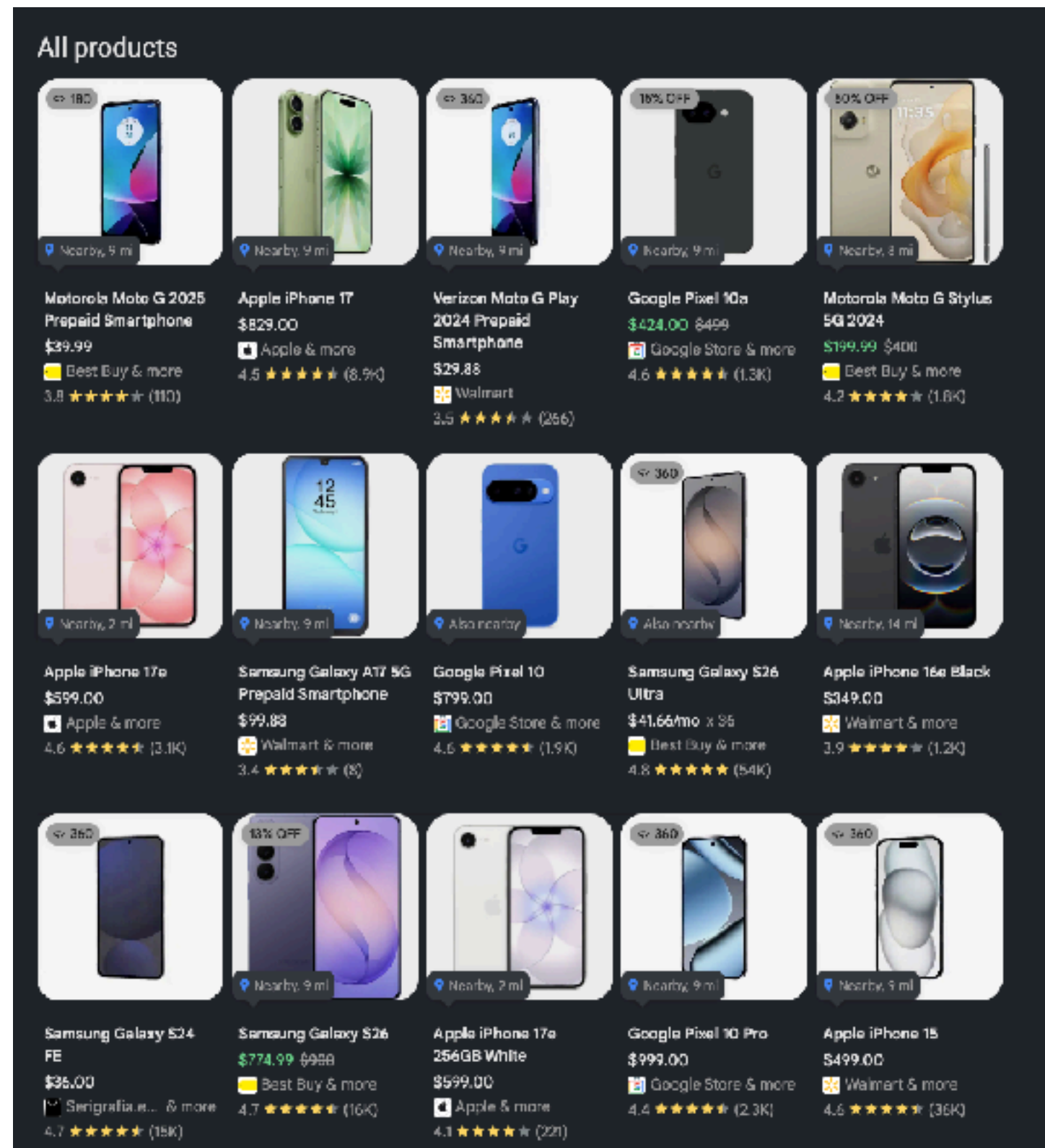
All products

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It's good to have options

Not all of them give you large
direct detection cross sections

To talk to the dark sector, you
only need one



It's good to have options

Not all of them give you large
direct detection cross sections

To talk to the dark sector, you
only need one

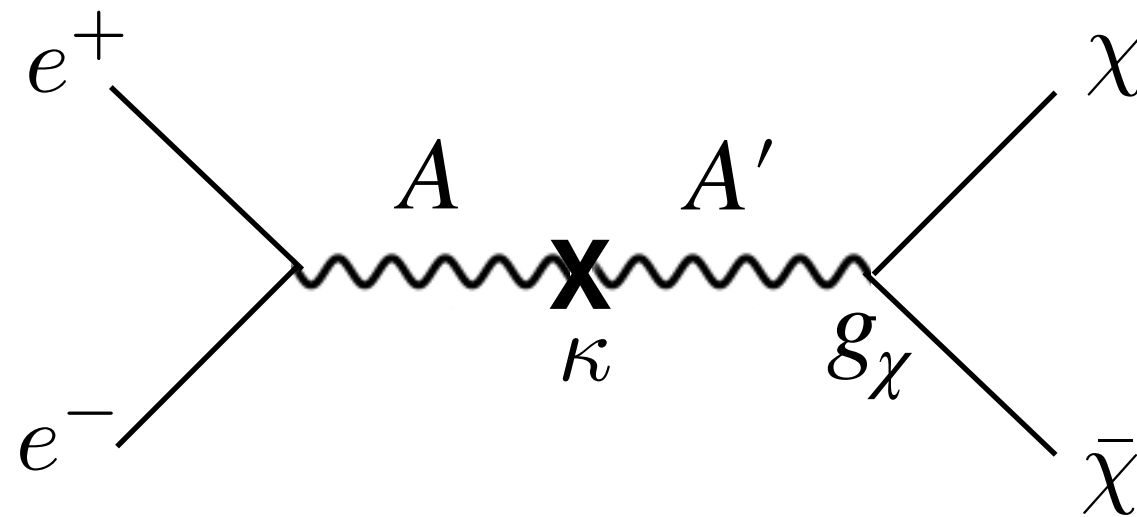


All products

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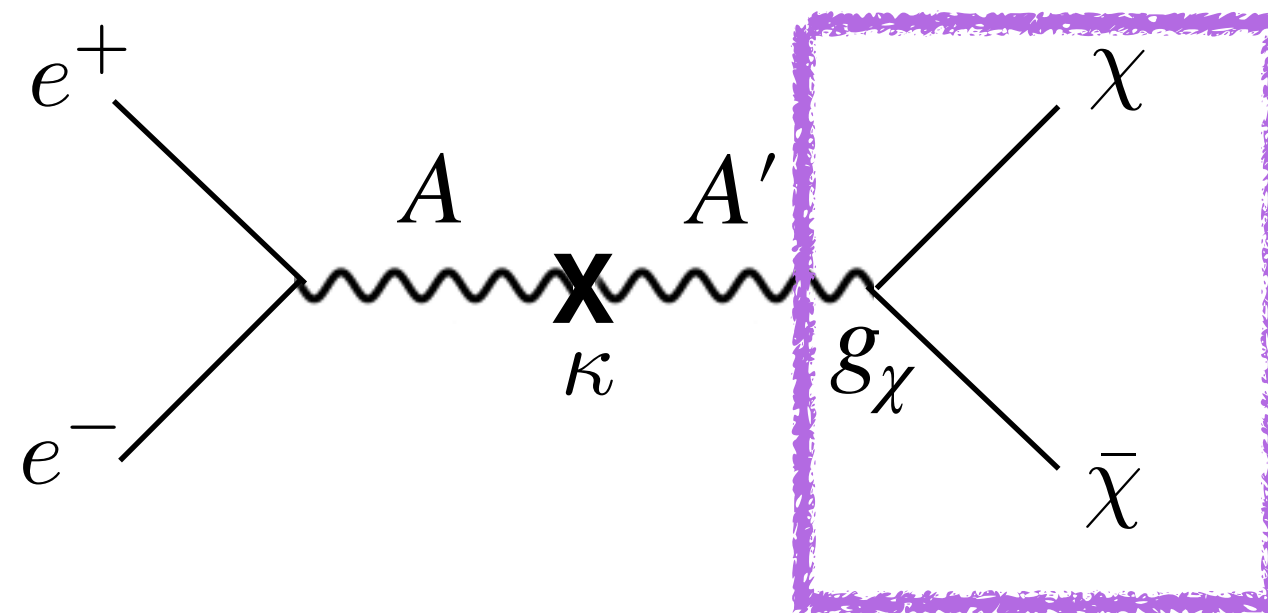
Dark photon portal

Simplest realization with fermion DM and dark photon A'



Dark photon portal

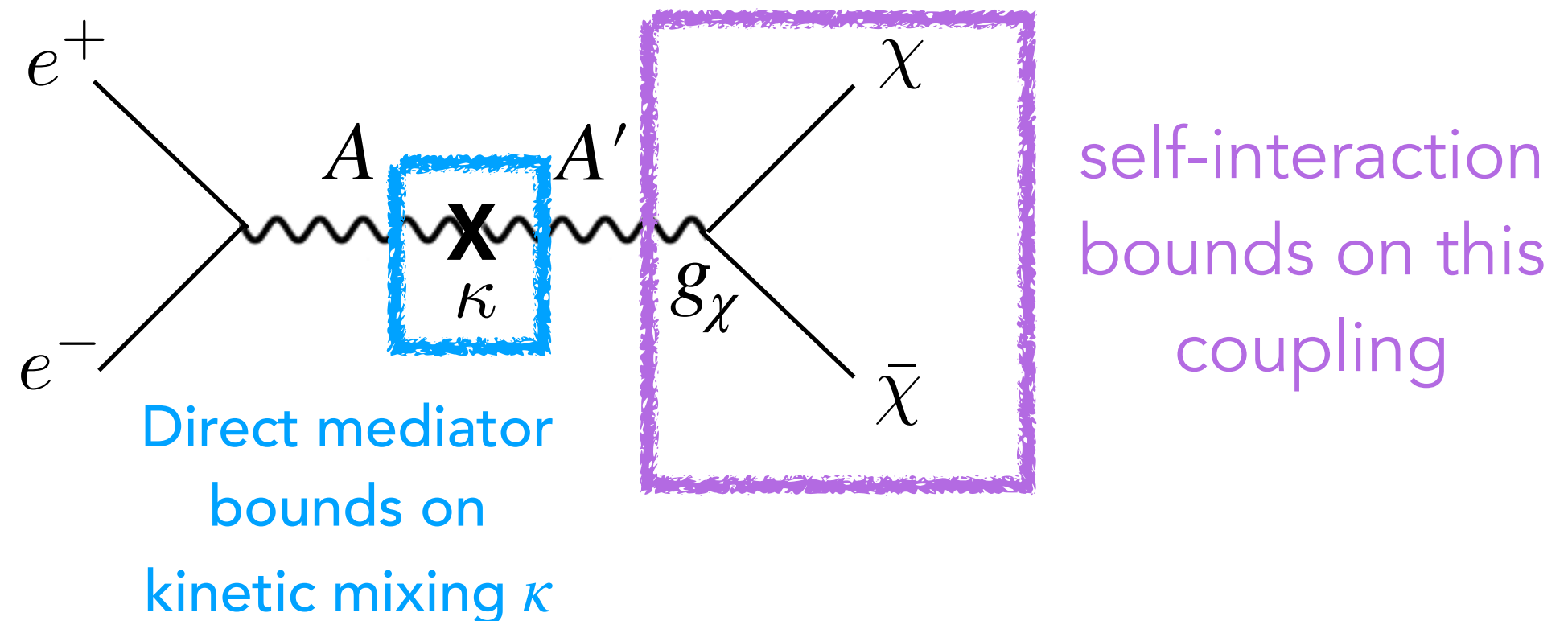
Simplest realization with fermion DM and dark photon A'



self-interaction
bounds on this
coupling

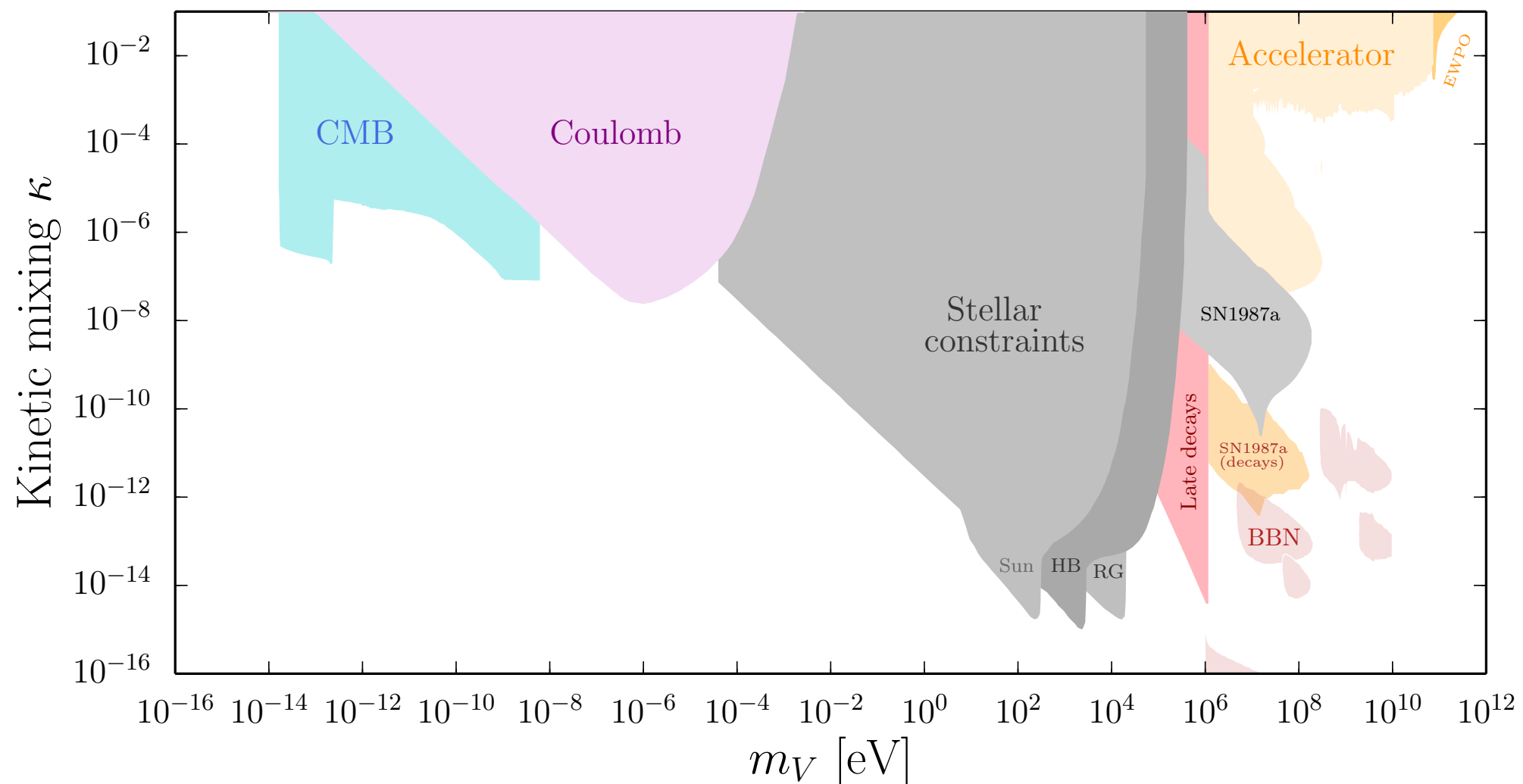
Dark photon portal

Simplest realization with fermion DM and dark photon A'



Dark photon portal

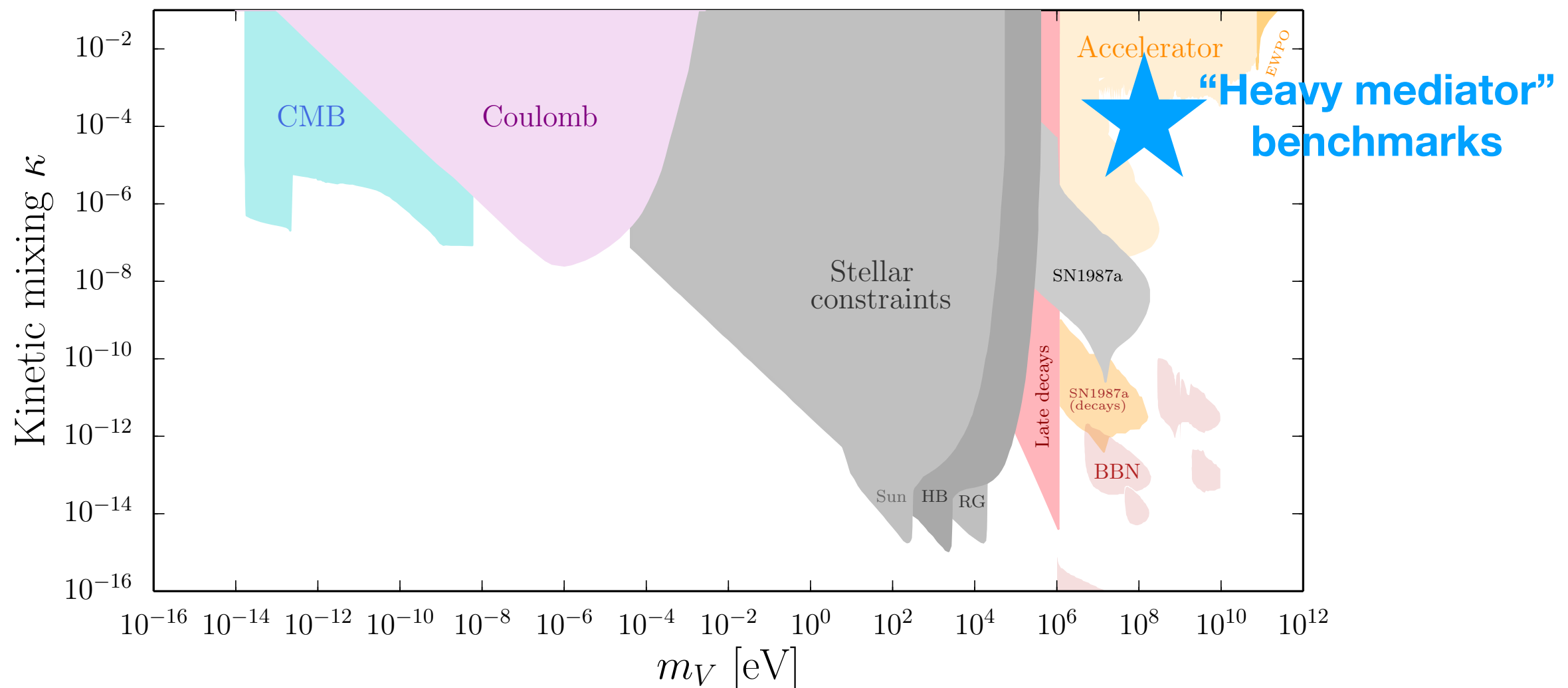
Stellar and fifth force constraints are much weaker for dark photon mediators due to *screening*



Kinetically-mixed dark photon

Dark photon portal

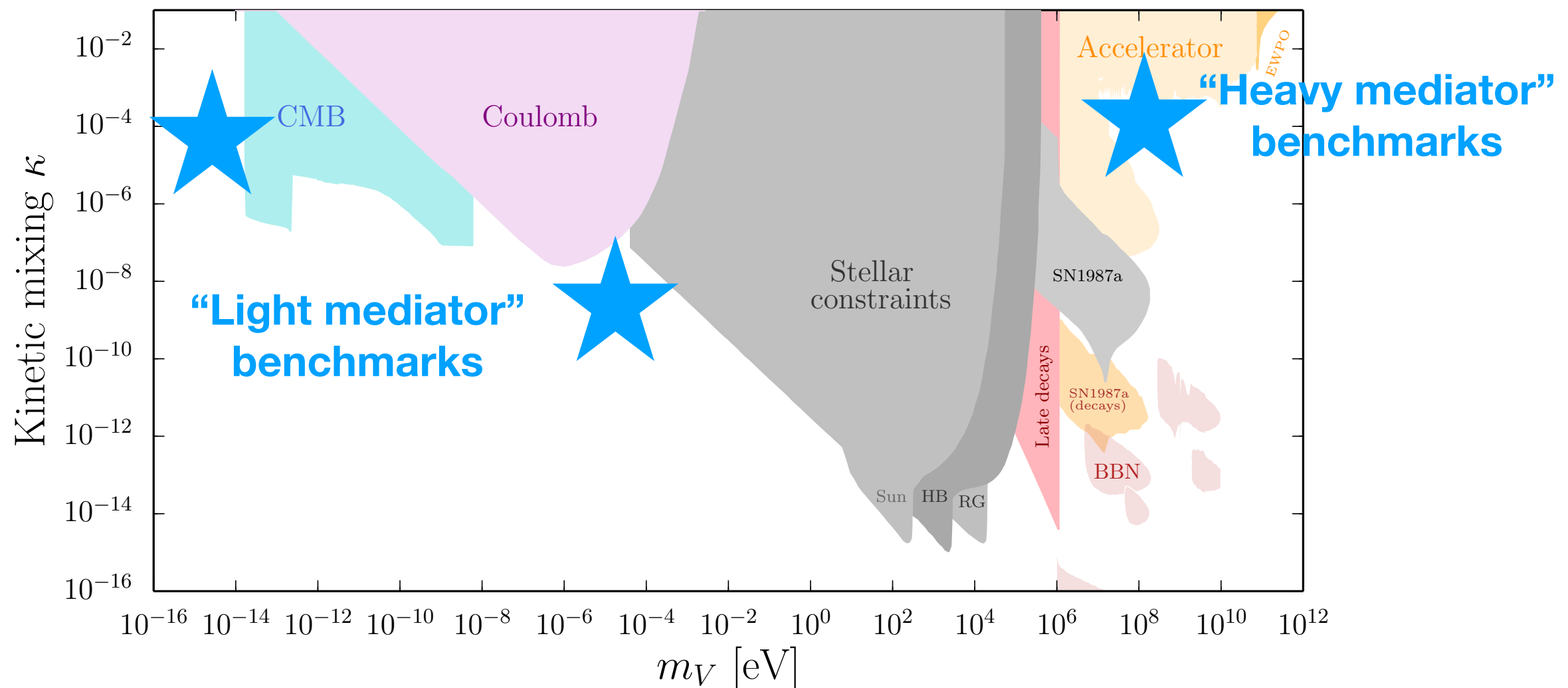
Stellar and fifth force constraints are much weaker for dark photon mediators due to *screening*



Kinetically-mixed dark photon

Dark photon portal

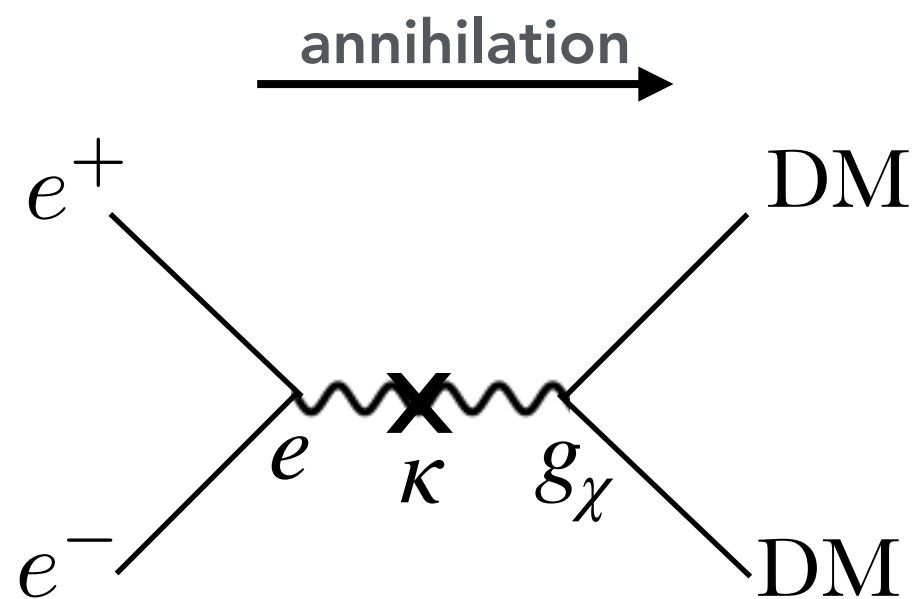
Stellar and fifth force constraints are much weaker for dark photon mediators due to *screening*



Kinetically-mixed dark photon

Heavy mediators: freeze-out

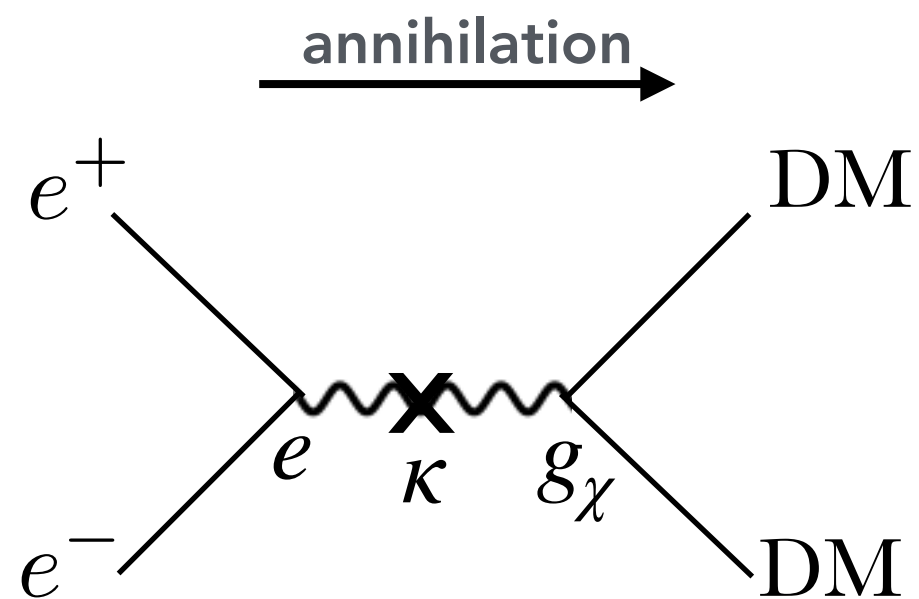
Dark photon portal:



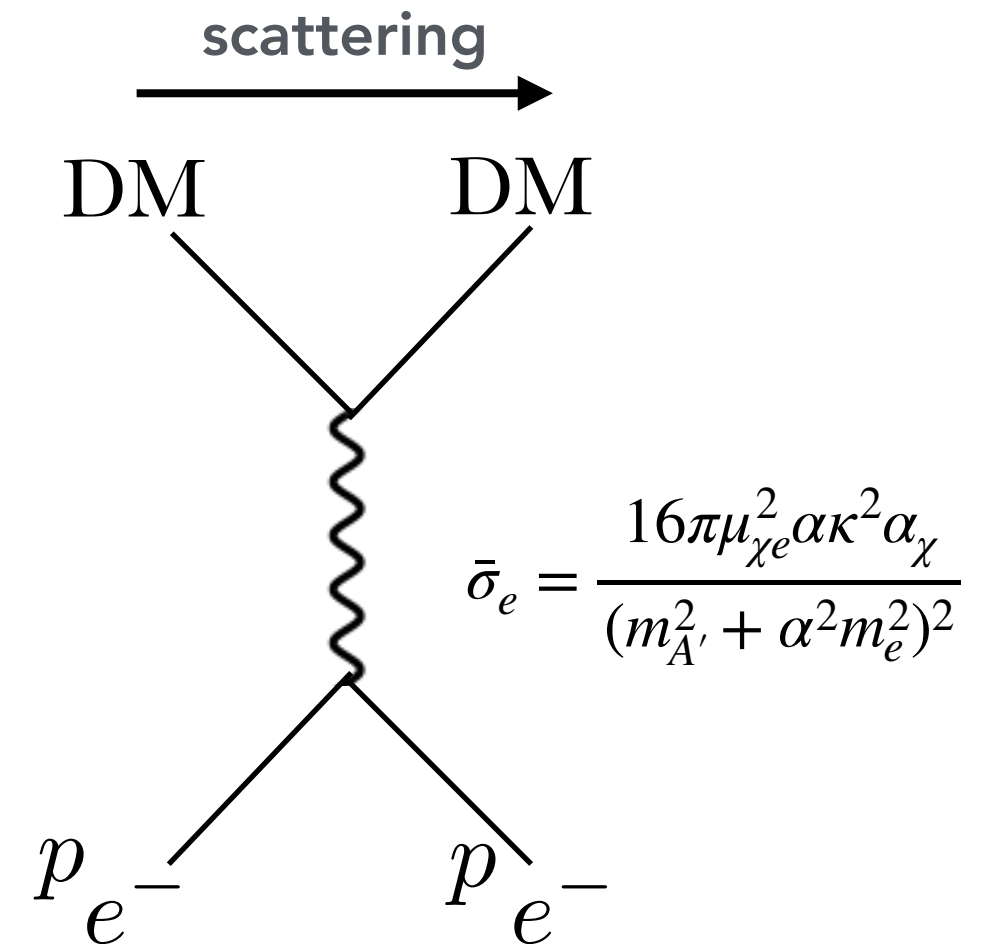
Viable for $m_\chi \gtrsim 10 \text{ MeV}$
(due to N_{eff} , BBN bounds)
with $m_{A'} \gtrsim 10 \text{ MeV}$

Heavy mediators: freeze-out

Dark photon portal:



Viable for $m_\chi \gtrsim 10 \text{ MeV}$
(due to N_{eff} , BBN bounds)
with $m_{A'} \gtrsim 10 \text{ MeV}$

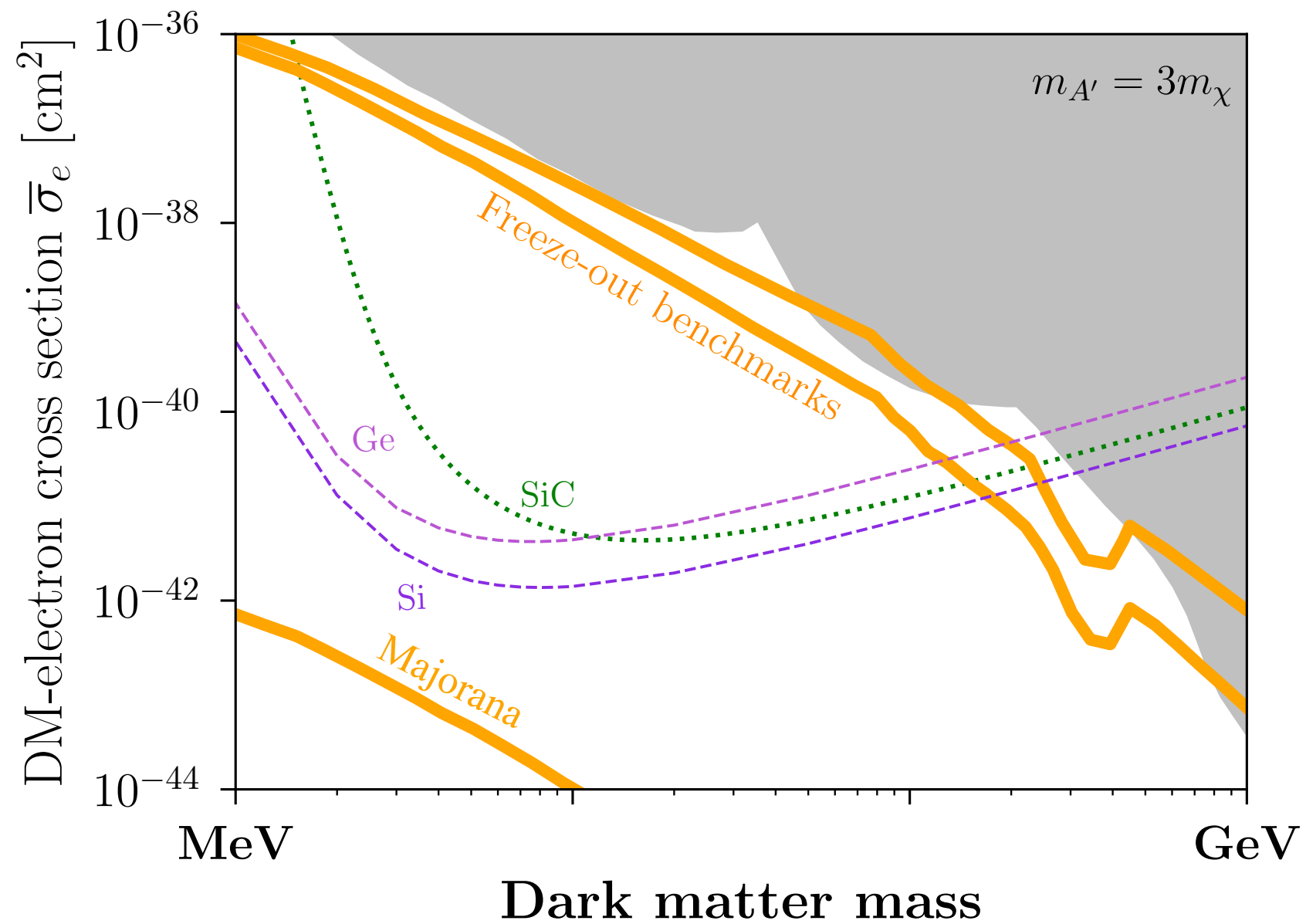


Predictive and detectable in
the **heavy mediator limit**

$$m_{A'} > m_{\text{DM}}$$

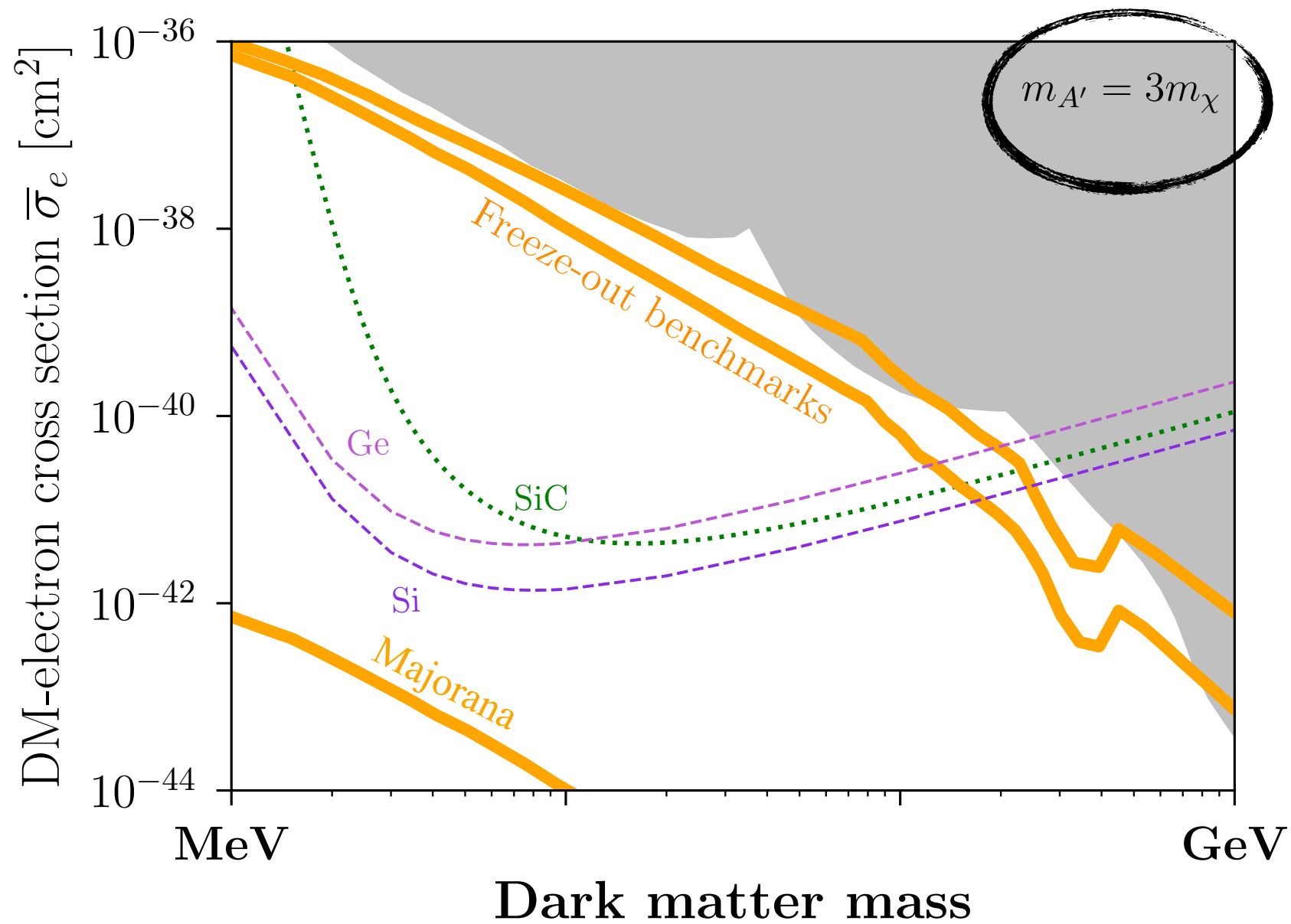
Freeze-out benchmarks

Example freeze-out scenarios

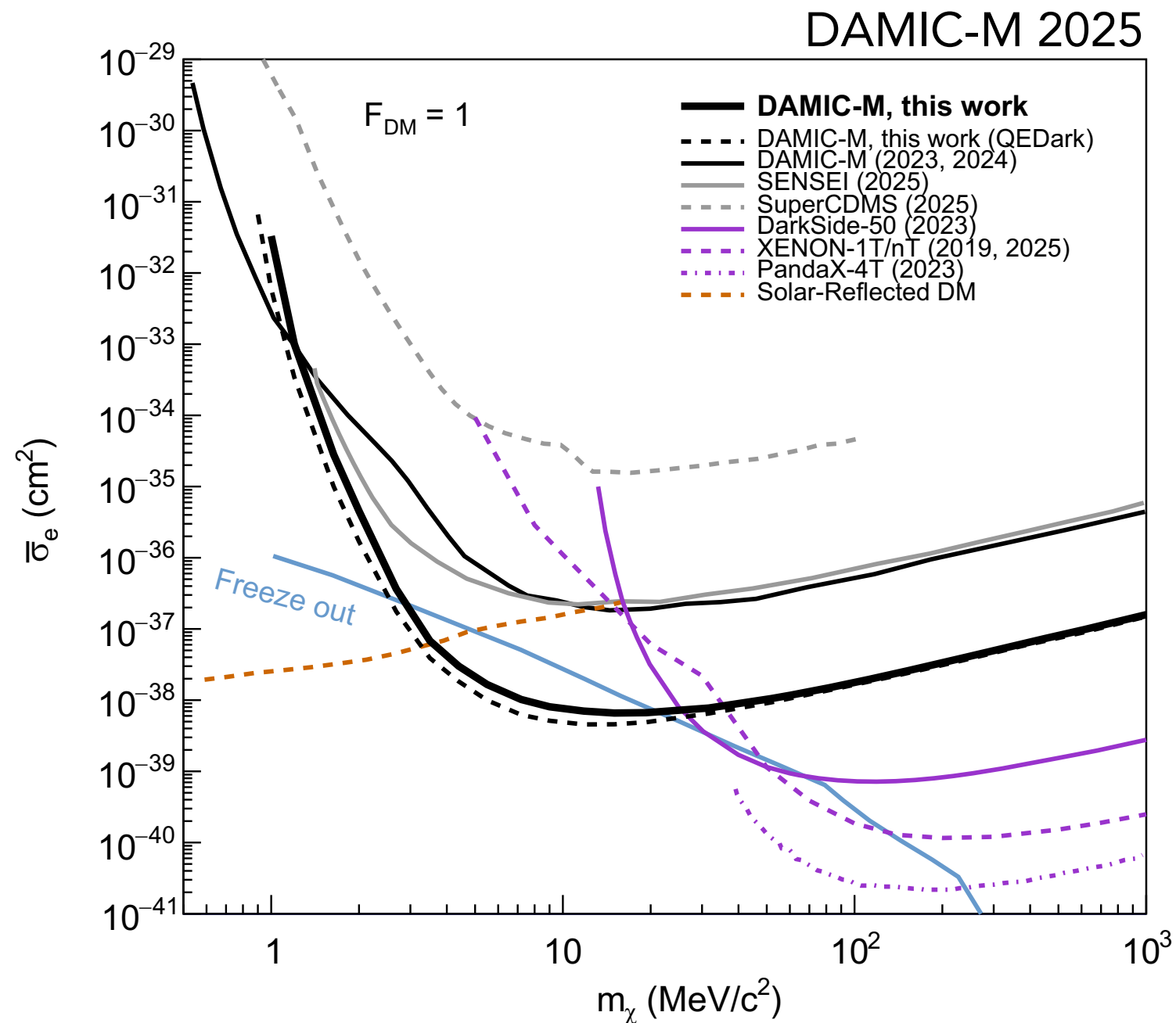


Freeze-out benchmarks

Example freeze-out scenarios



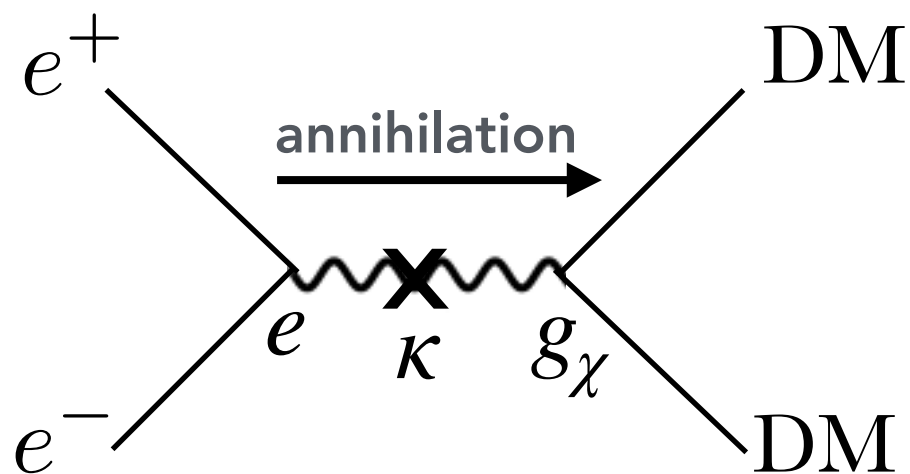
Freeze-out benchmarks



Remarkable progress excluding the simplest freeze-out benchmark

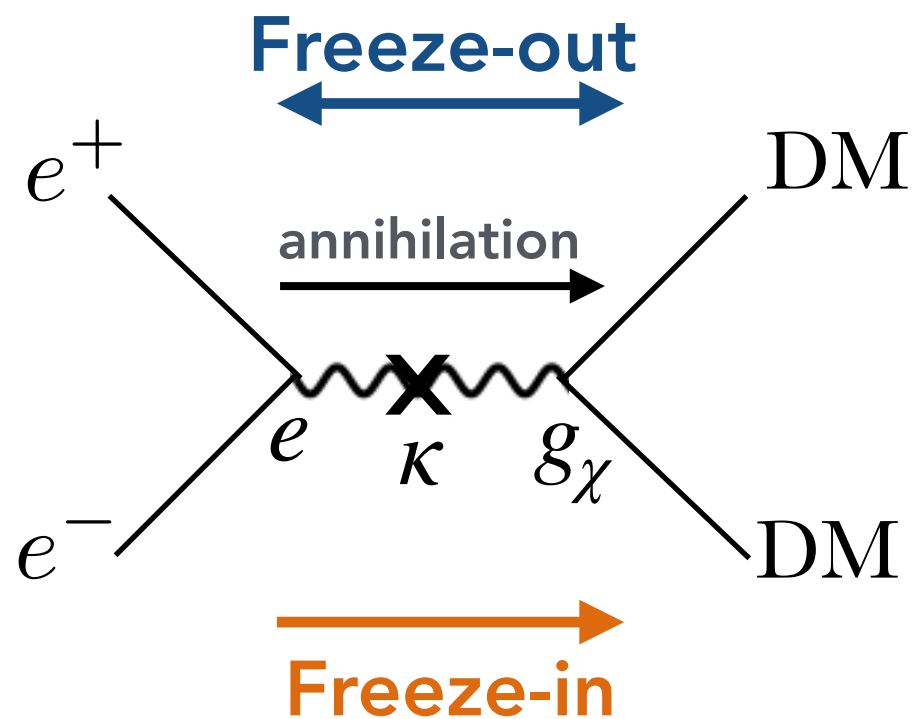
Vector portal

Dark photon (A') portal:



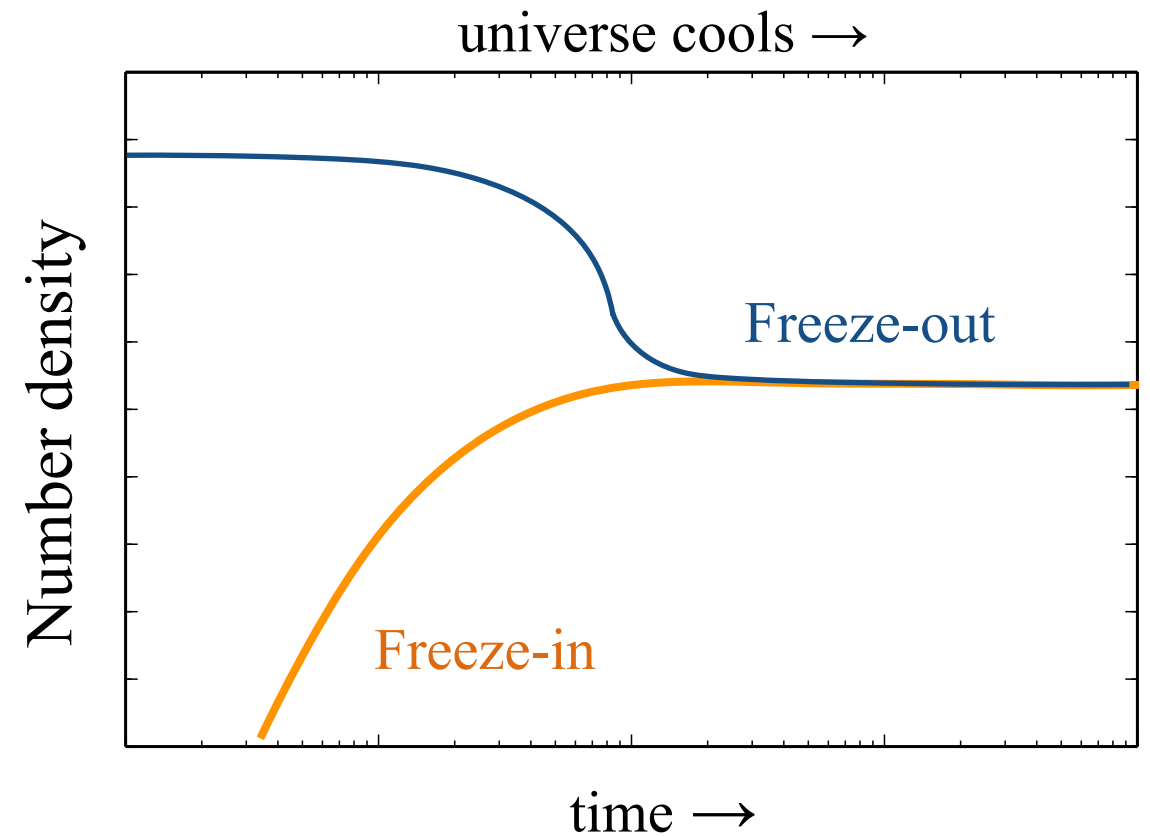
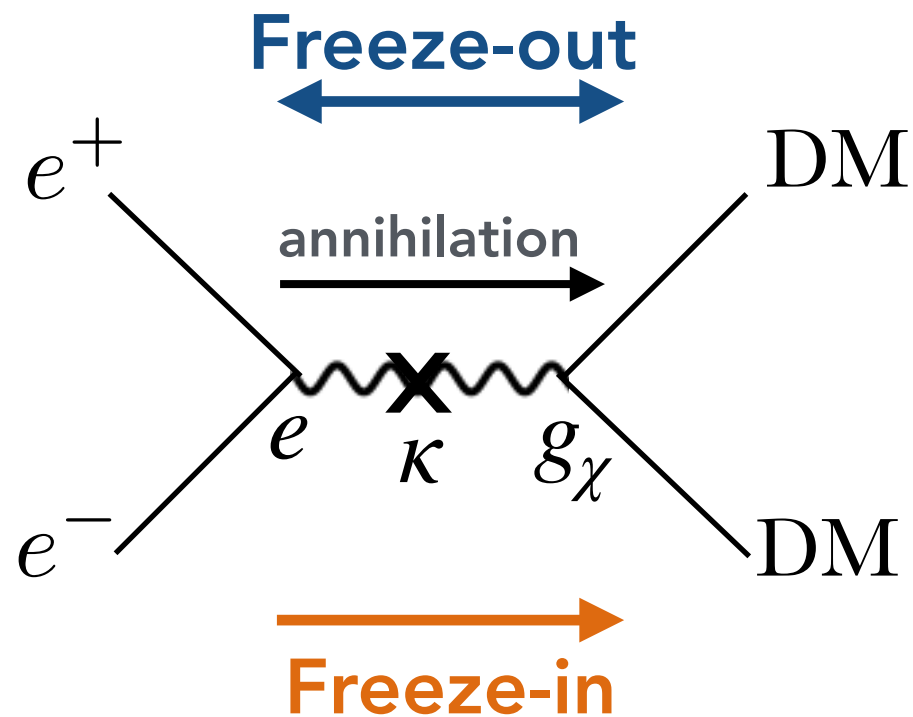
Vector portal

Dark photon (A') portal:



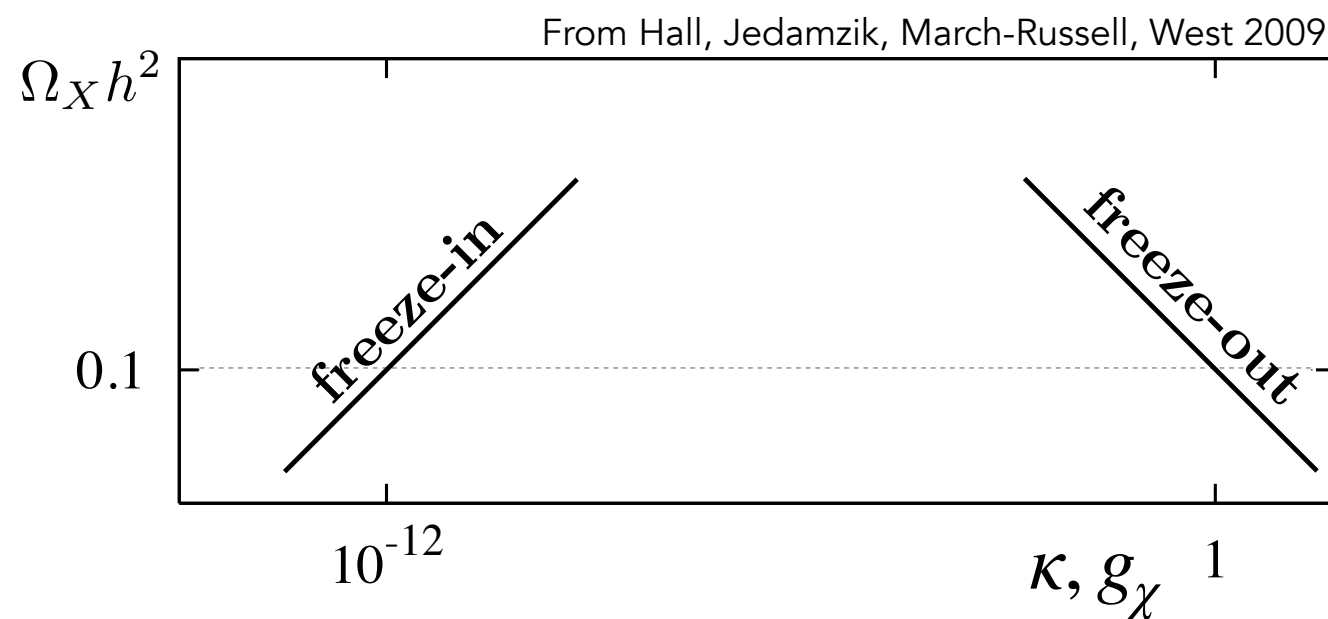
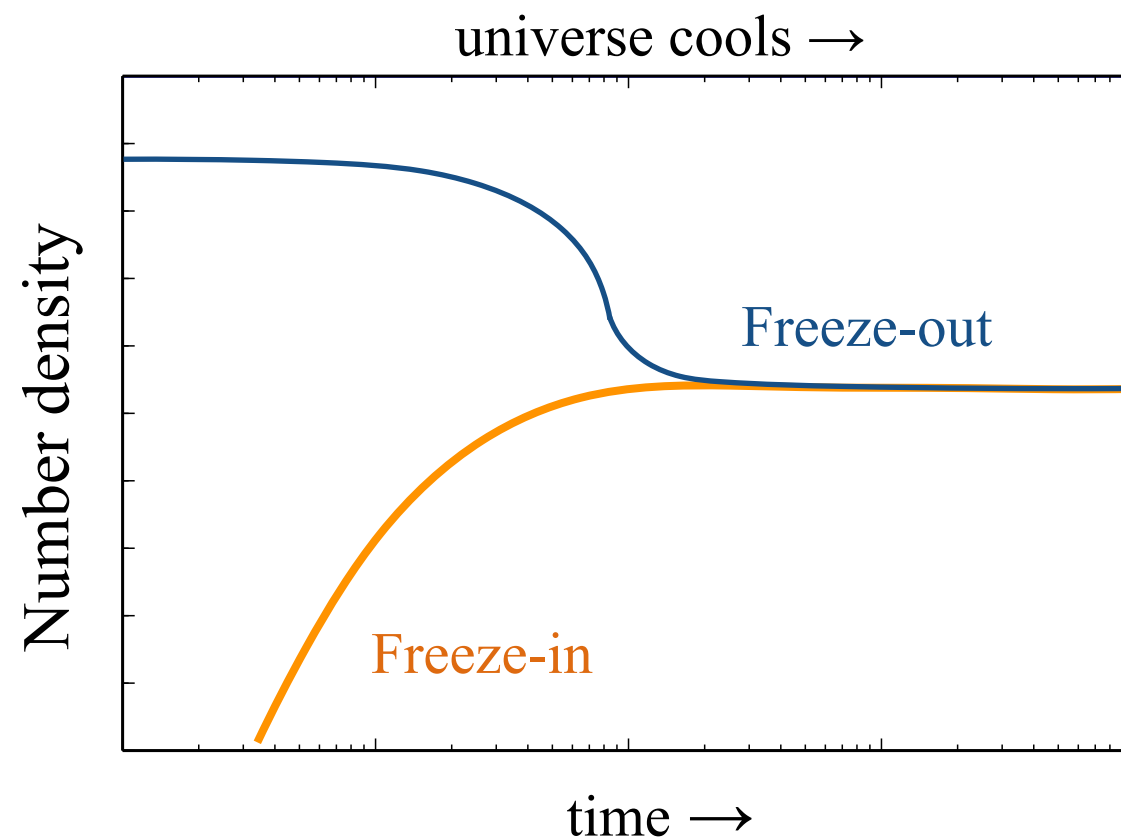
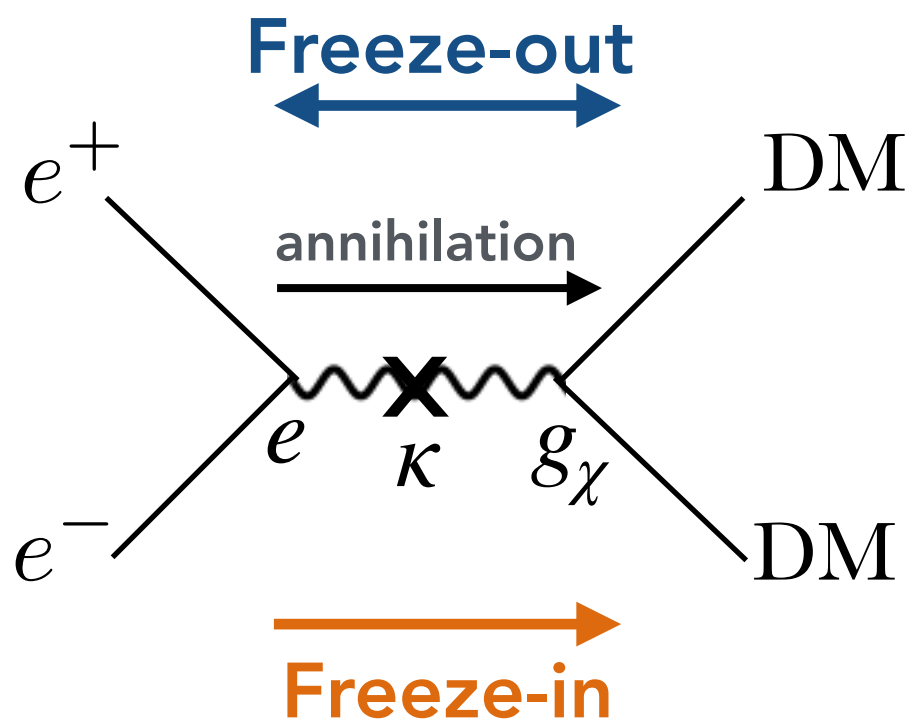
Vector portal

Dark photon (A') portal:



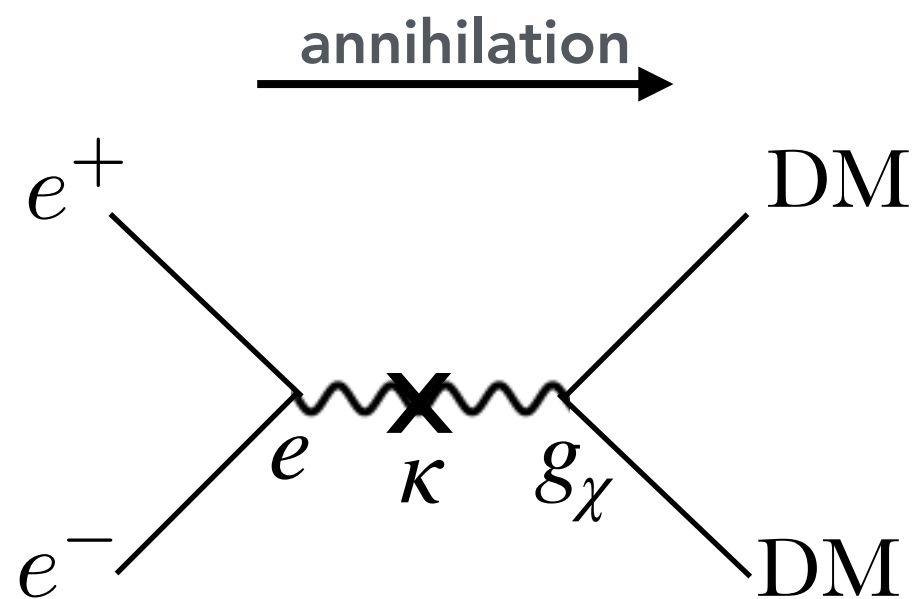
Vector portal

Dark photon (A') portal:



Freeze-in: light mediators

Dark photon portal:



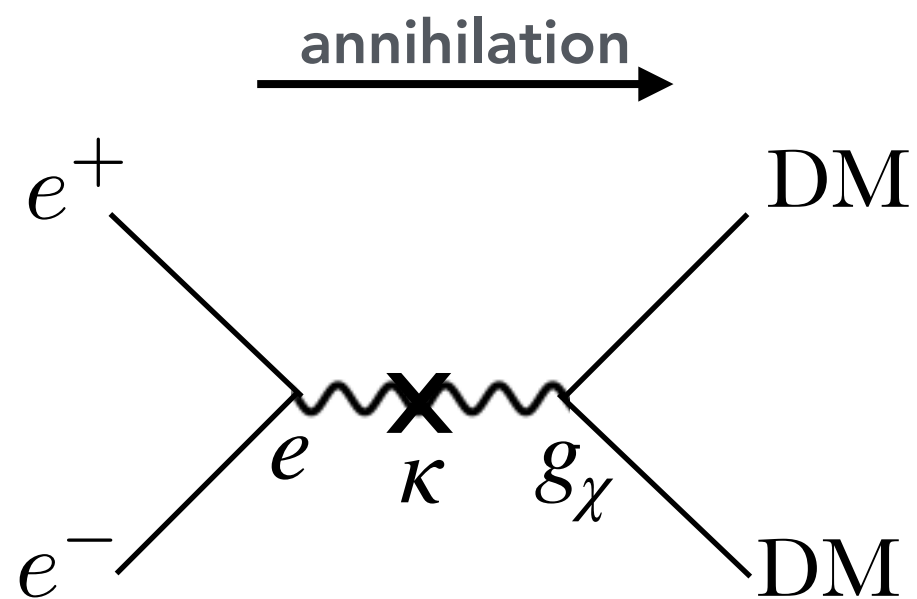
Not in equilibrium with SM

thermal bath: $\kappa g_\chi \simeq 10^{-12}$

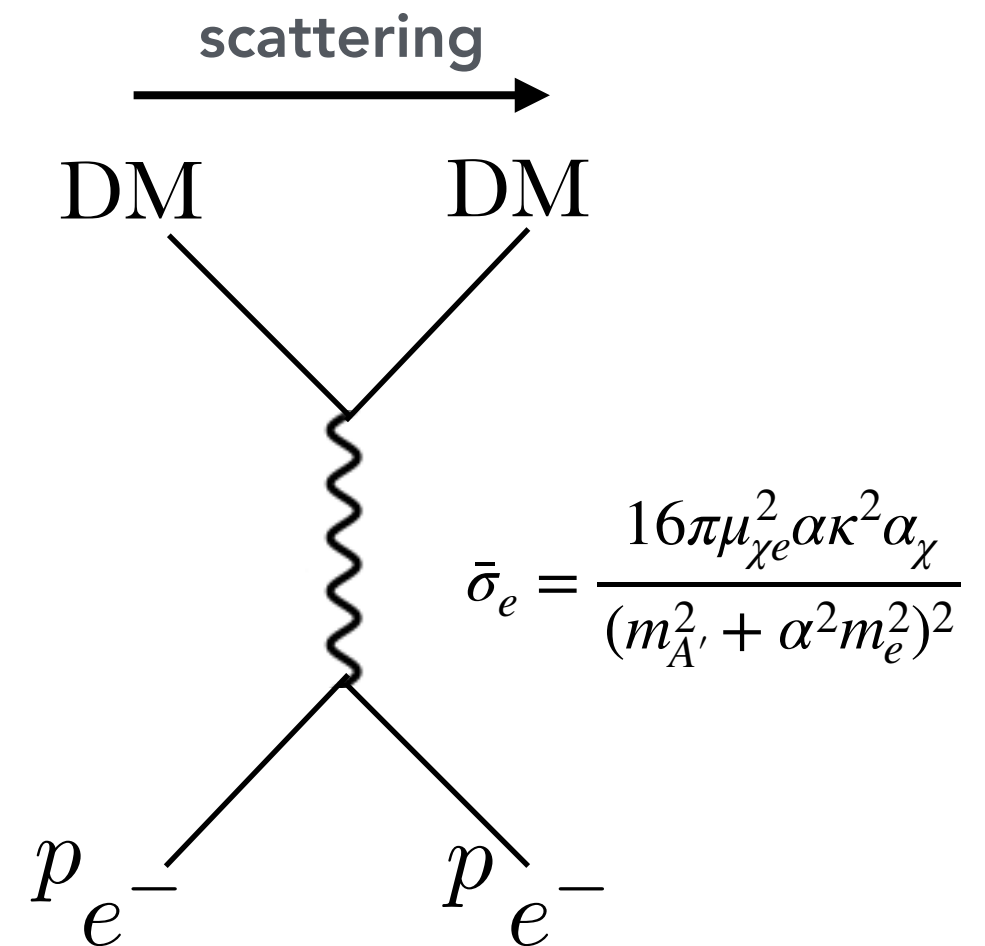
Viable down to $m_\chi \sim 10 \text{ keV}$

Freeze-in: light mediators

Dark photon portal:



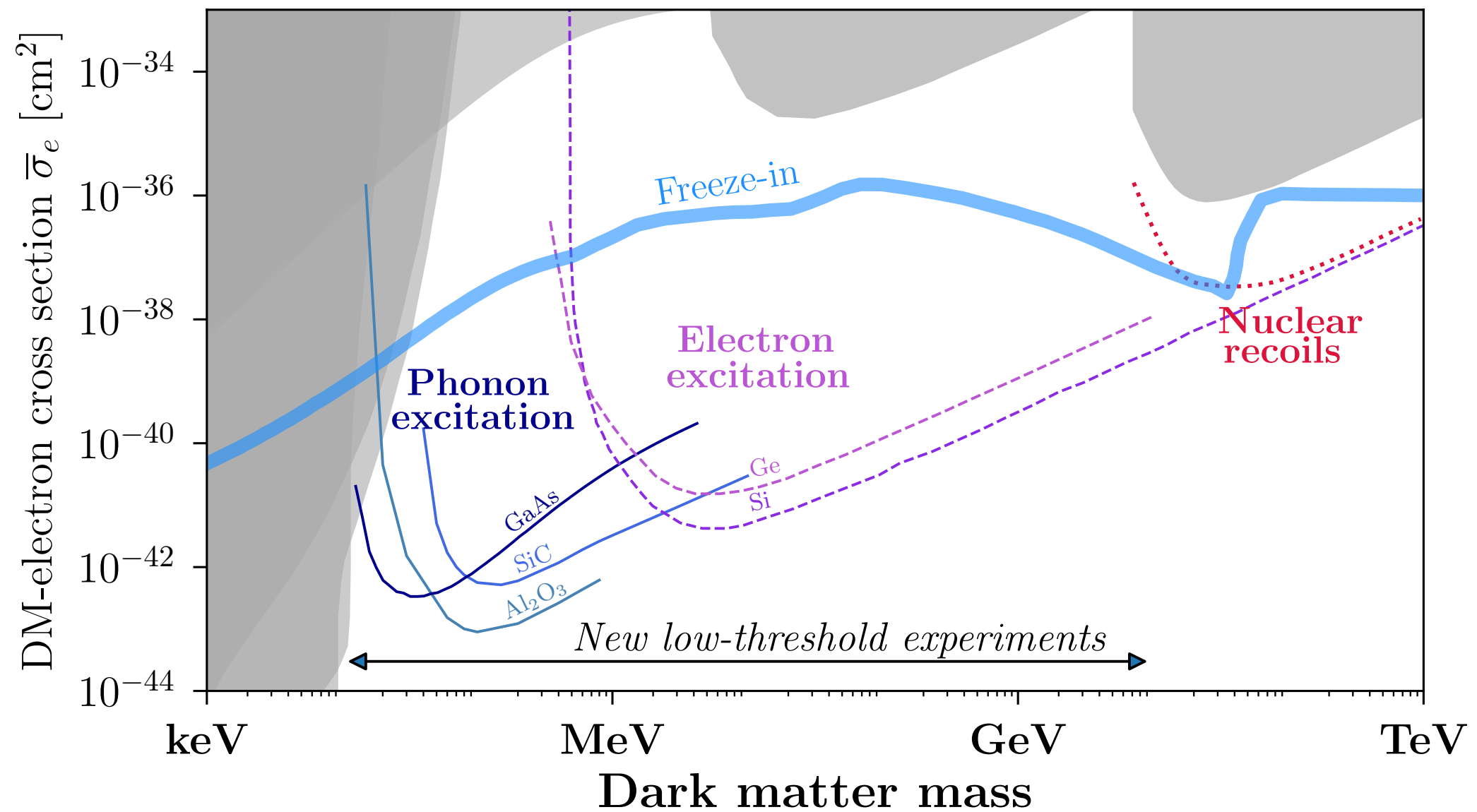
Not in equilibrium with SM
thermal bath: $\kappa g_\chi \simeq 10^{-12}$
Viable down to $m_\chi \sim 10 \text{ keV}$



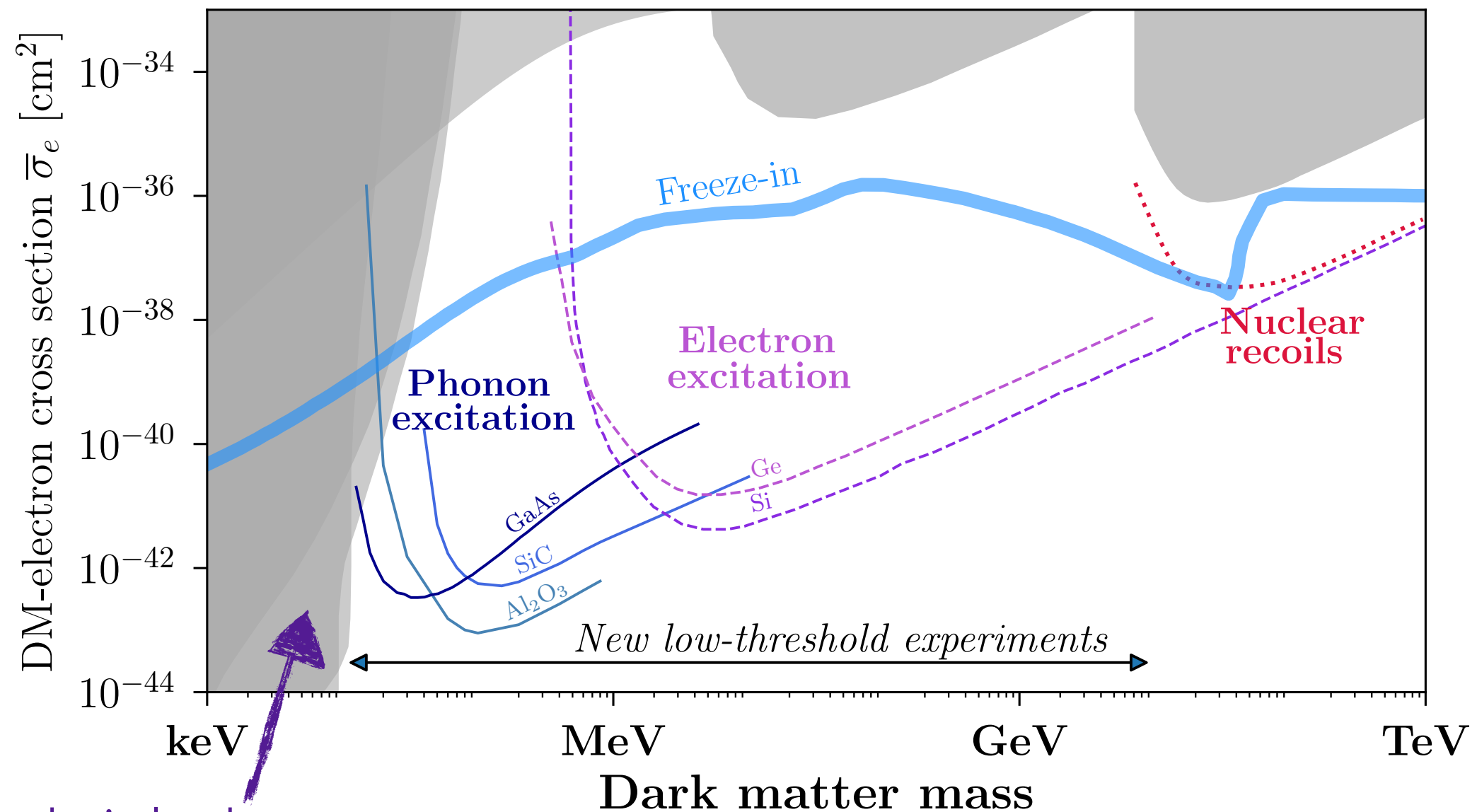
Predictive and detectable in
the **light mediator limit**

$$m_{A'} \ll m_{\text{DM}}$$

Direct detection of freeze-in

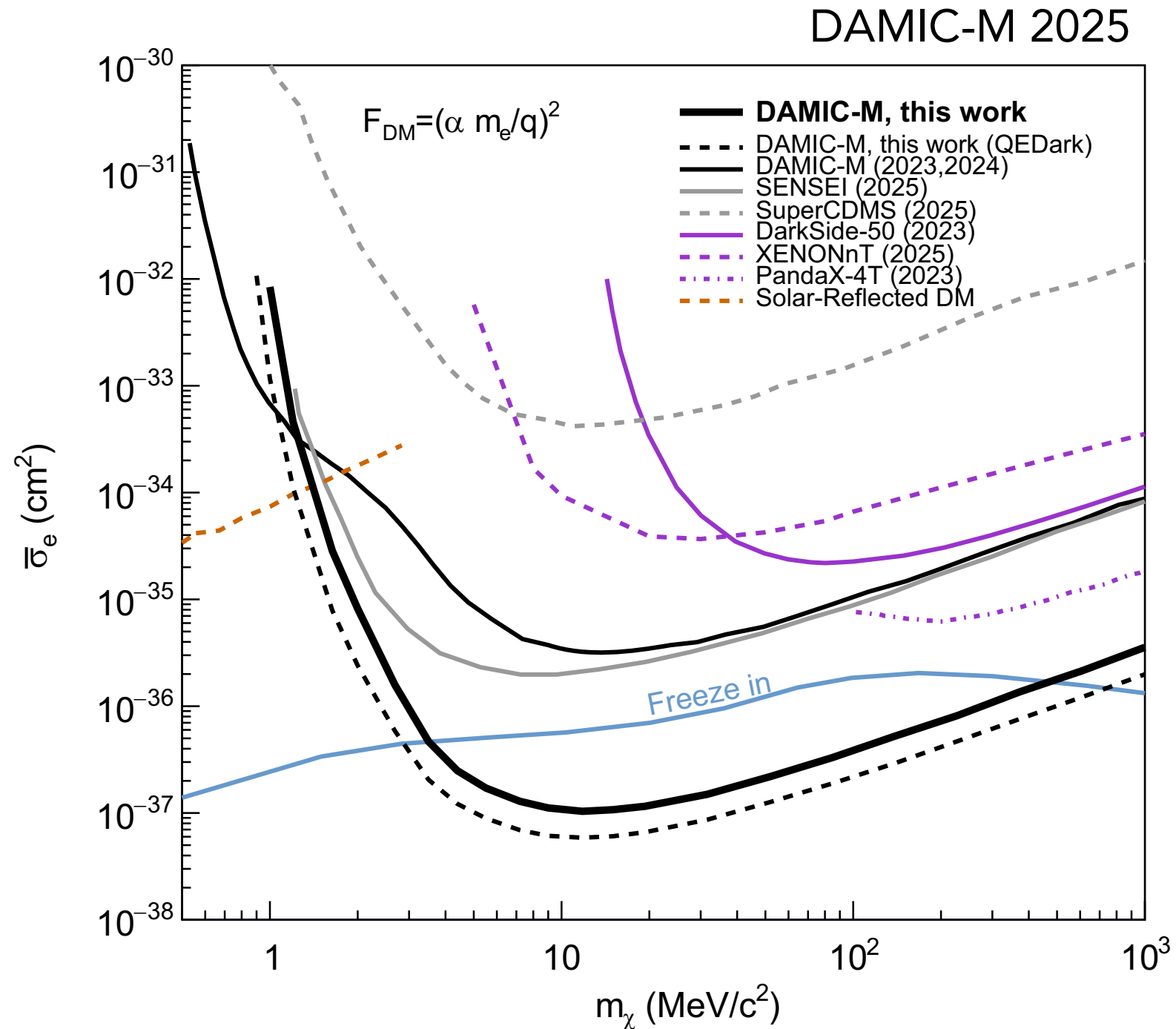


Direct detection of freeze-in



Astrophysical and
cosmological bounds at
low DM mass from $\bar{\chi}\chi$
production

Direct detection: light mediator

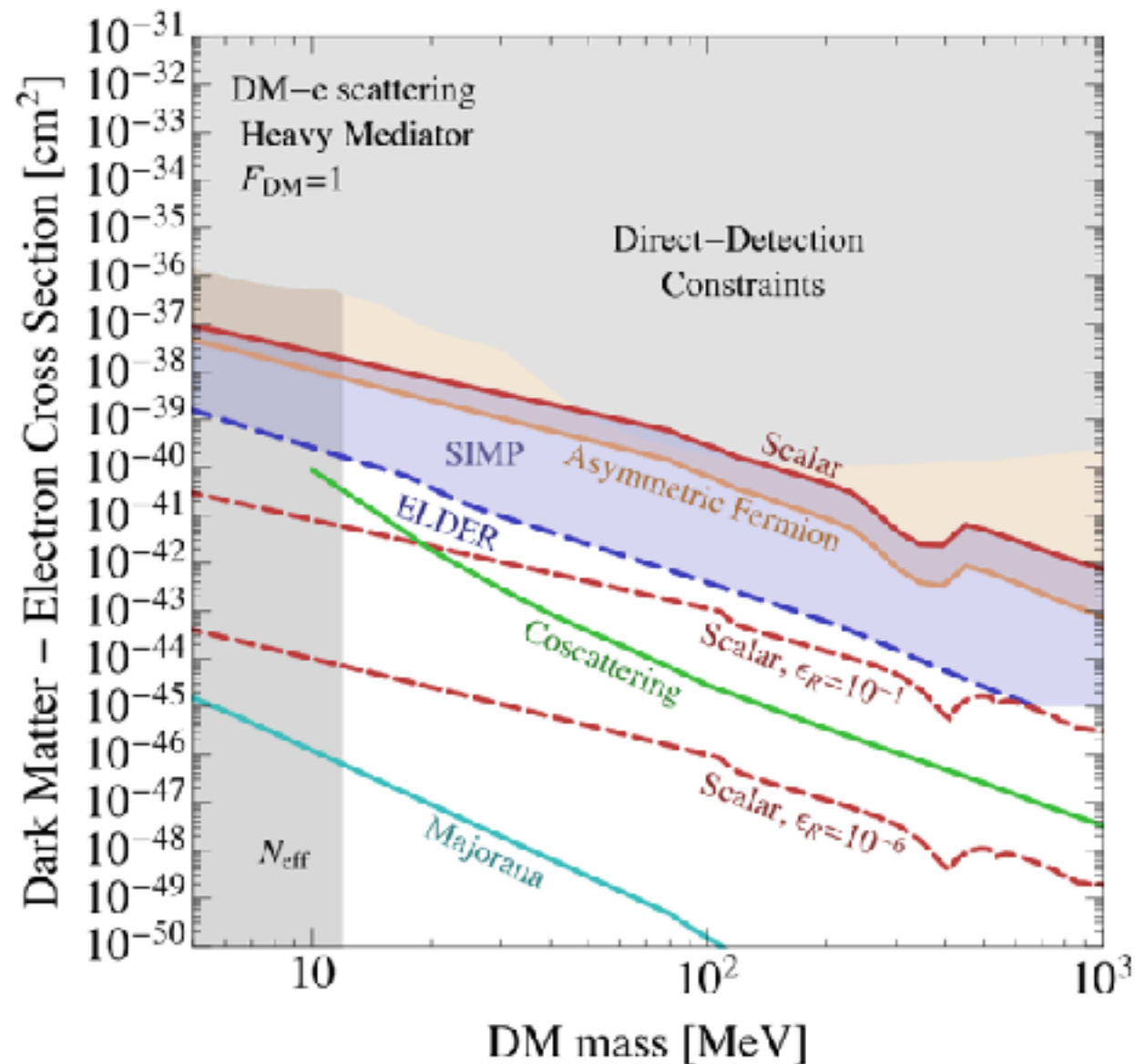


Remarkable progress testing freeze-in above ~few MeV

Beyond benchmarks

Benchmarks assume a particular relic density scenario, but there are many.

These lines assume $m_{A'} = 3m_\chi$

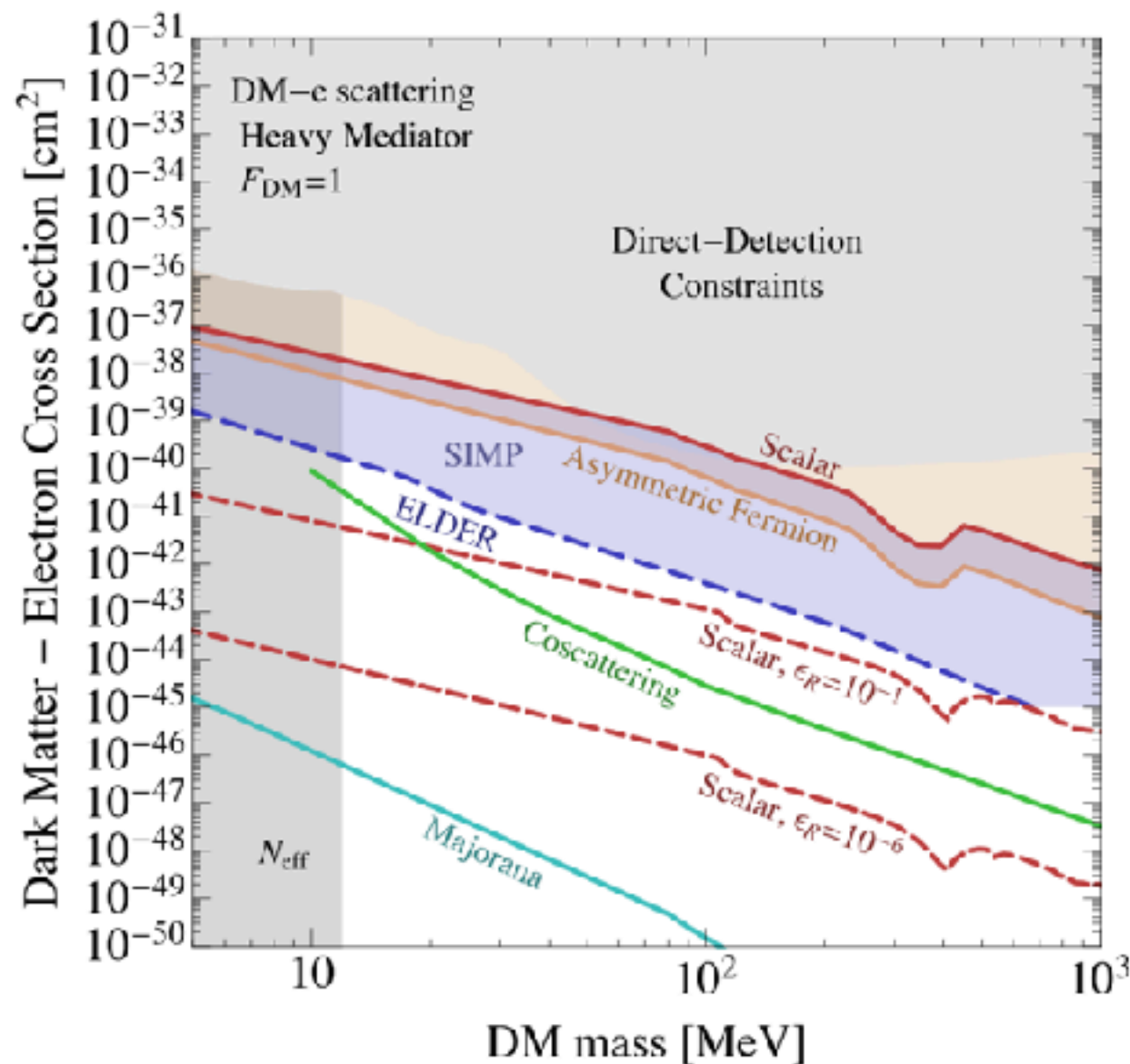


Snowmass report 2022

Beyond benchmarks

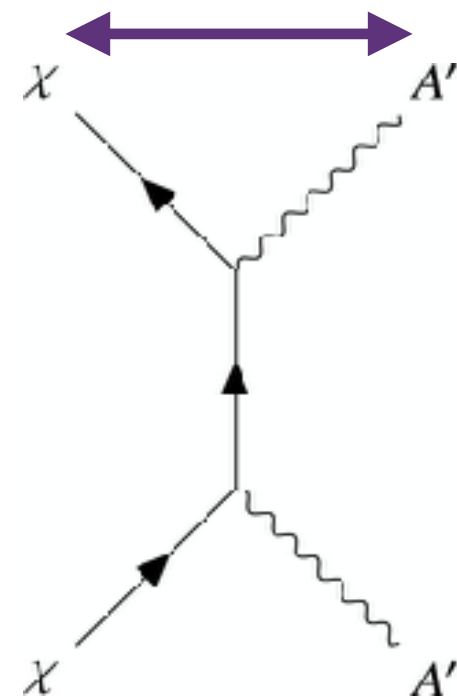
Benchmarks assume a particular relic density scenario, but there are many.

These lines assume $m_{A'} = 3m_\chi$



Snowmass report 2022

Secluded annihilation
when $m_\chi > m_{A'}$

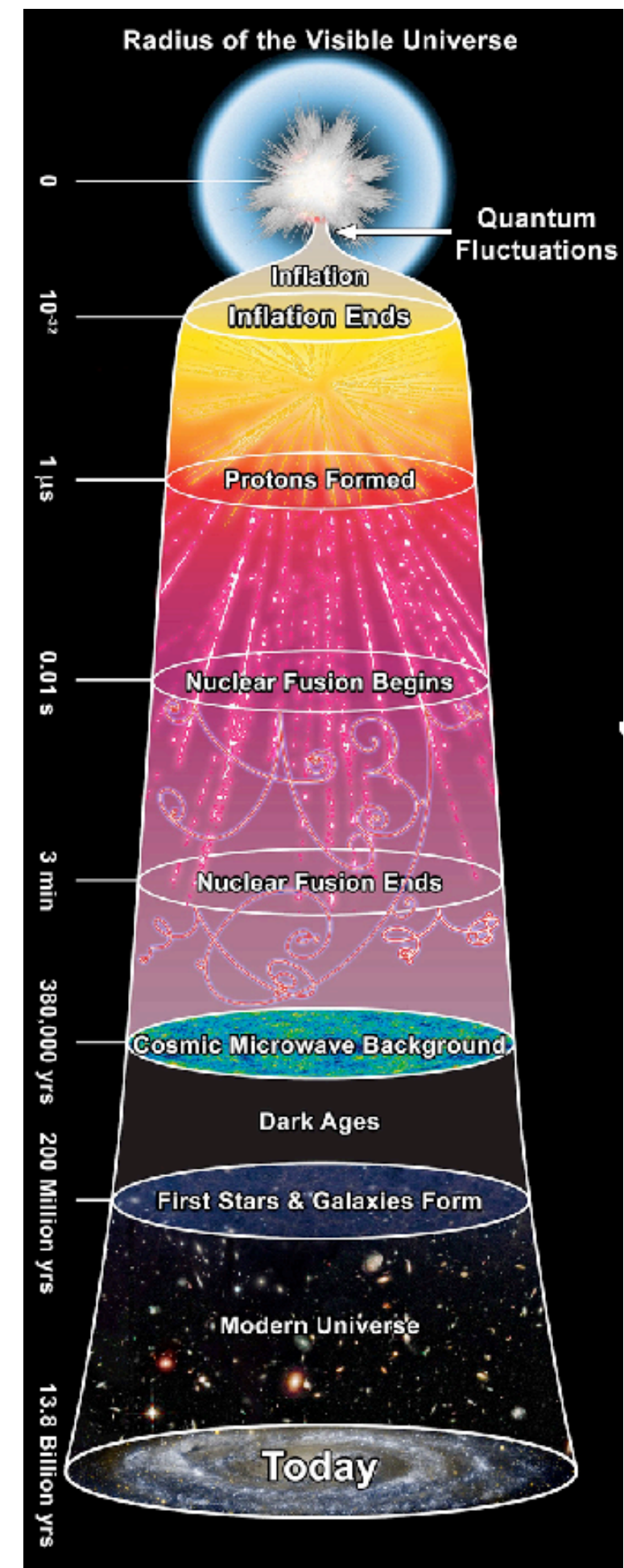


A' : Dark photon mediator

No single prediction for scattering rate in this case: can live down to neutrino fog easily for $m_\chi \gtrsim 10 \text{ MeV}$

Cosmology

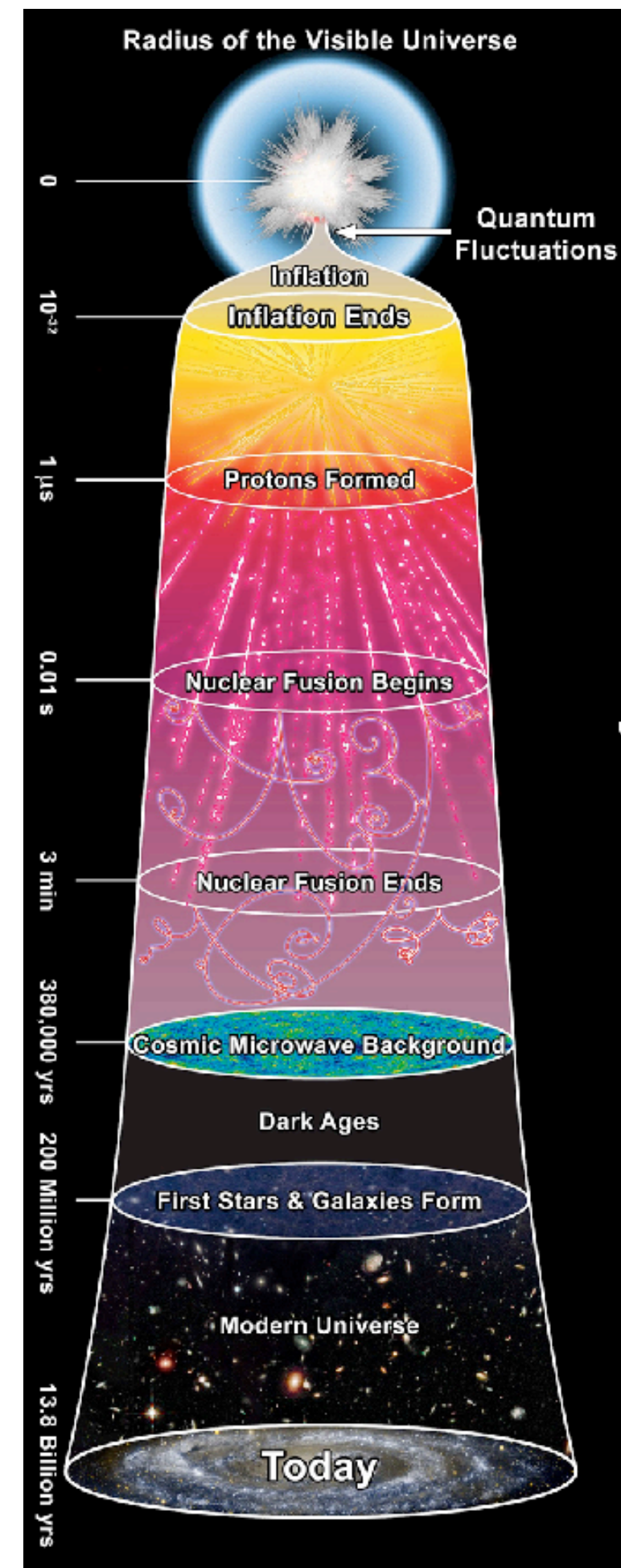
Relic dark
matter?



Cosmology

- For sub-GeV DM, relic density motivates the existence of light mediators and the existence of *dark sector*

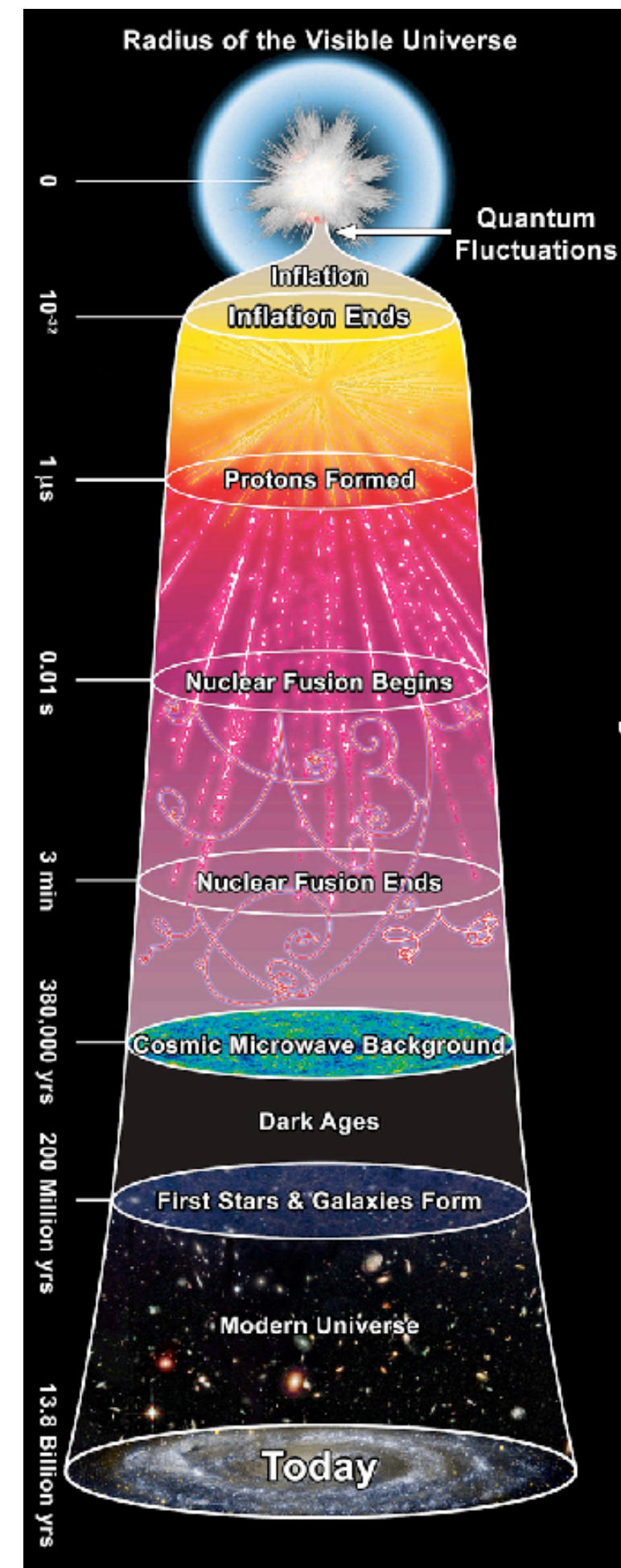
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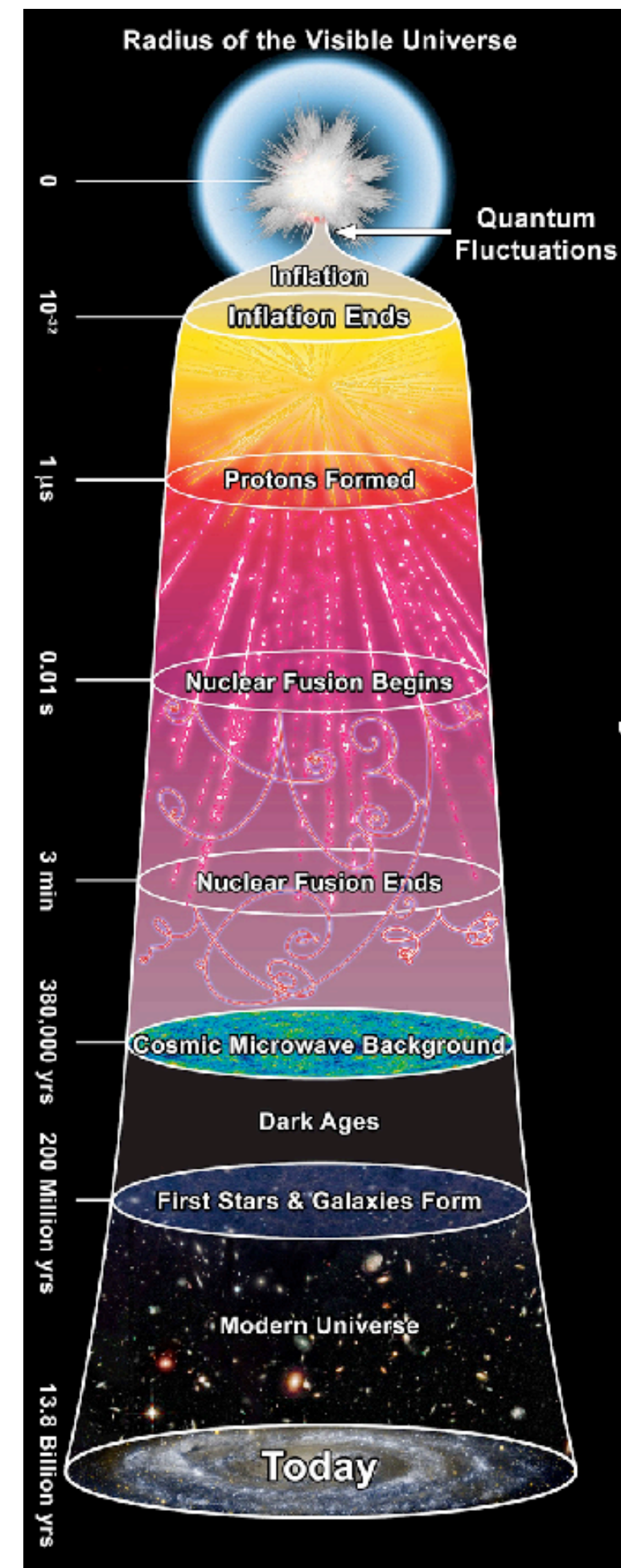
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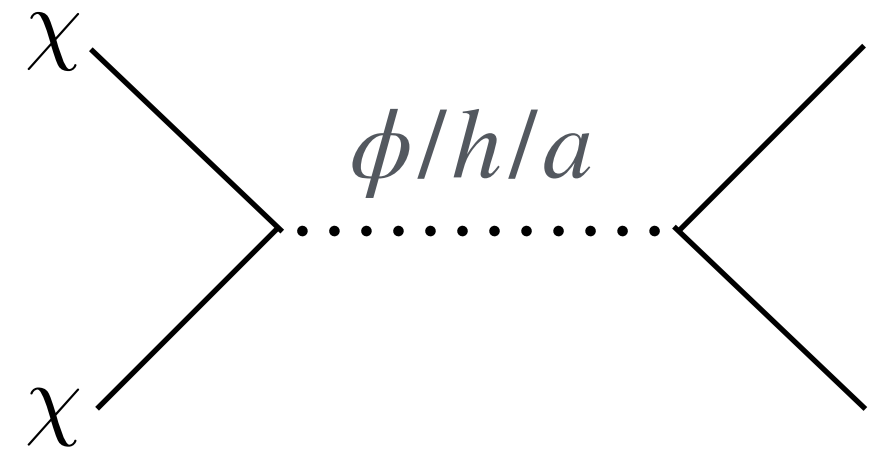
- For sub-GeV DM, relic density motivates the existence of light mediators and the existence of *dark sector*
- BBN and CMB Neff limits the influence of sub-GeV sectors on the SM bath
- Sub-GeV DM searches probe our thermal history from $\sim$ MeV to GeV

Relic dark
matter?

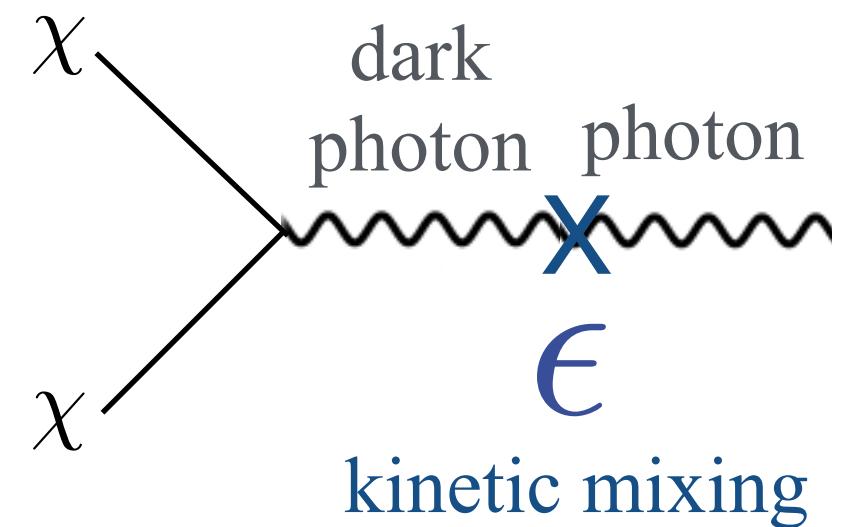


Dark sectors

Scalar, Higgs or axion portal



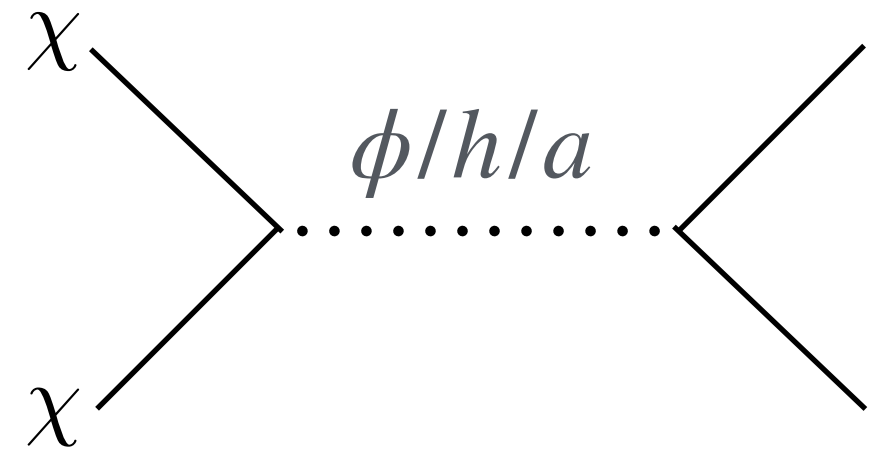
vector portal



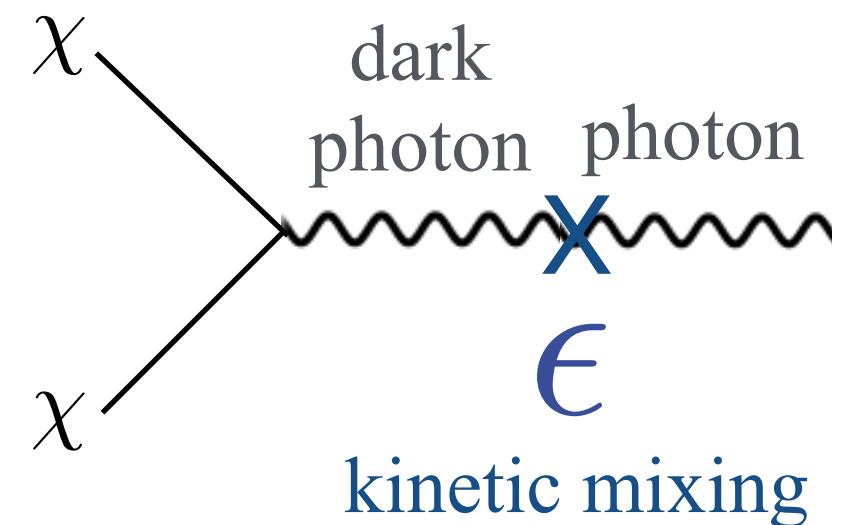
Dark sectors

- Constraints on light (sub-GeV) mediators lead to upper bounds on σ , which are particularly strong for sub-MeV DM and pseudo/scalar mediators.

Scalar, Higgs or axion portal



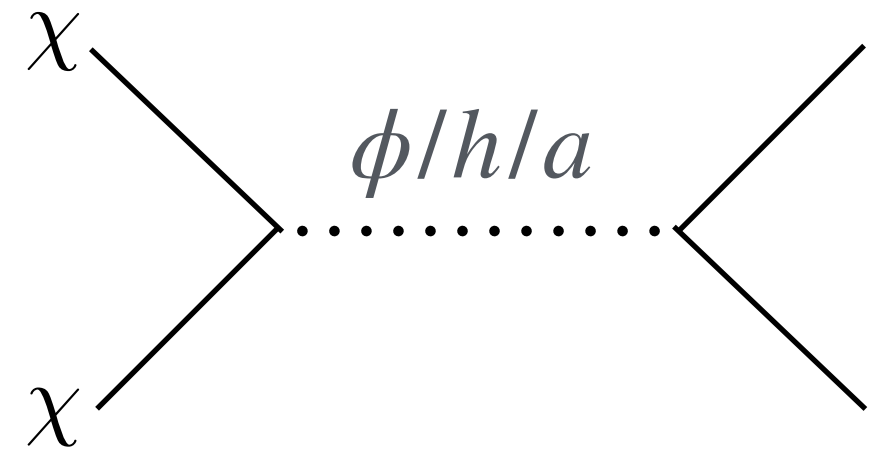
vector portal



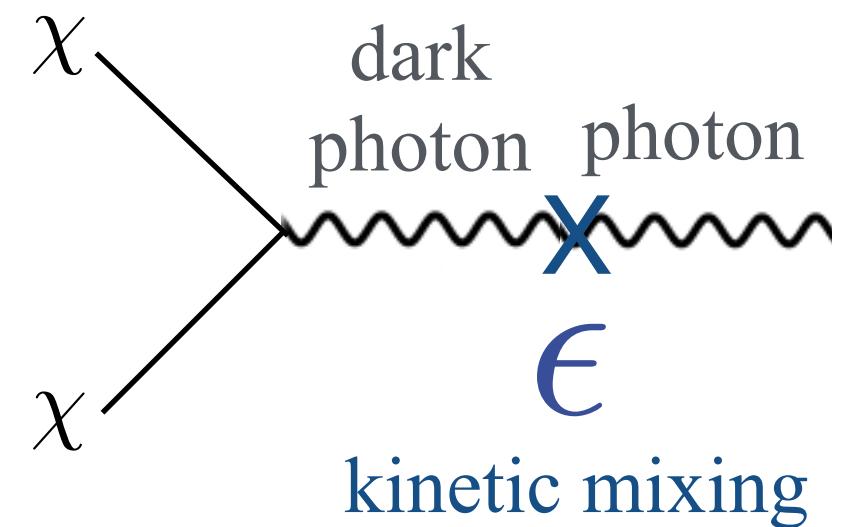
Dark sectors

- Constraints on light (sub-GeV) mediators lead to upper bounds on σ , which are particularly strong for sub-MeV DM and pseudo/scalar mediators.
- Dark photons are special - they evade some bounds for low (sub-keV) dark photon mass

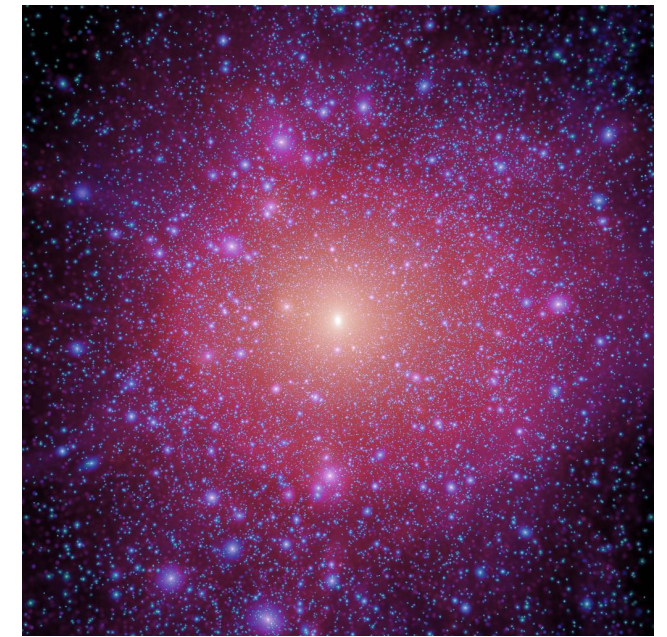
Scalar, Higgs or axion portal



vector portal

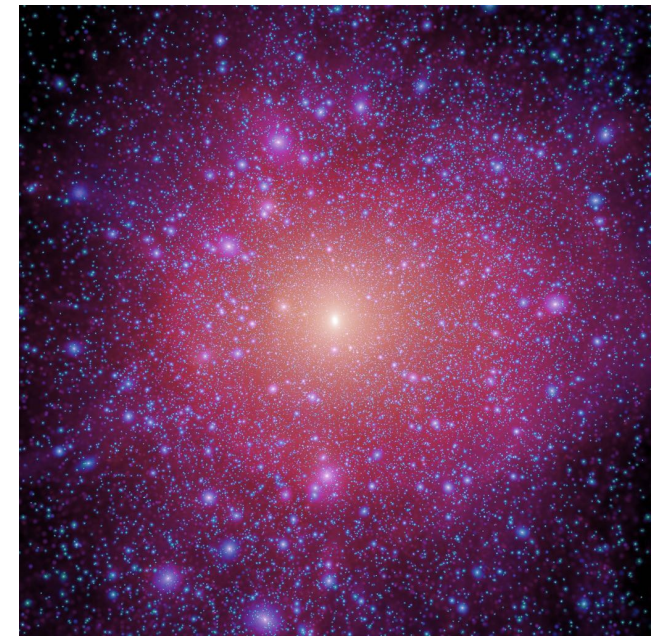


Detecting dark matter



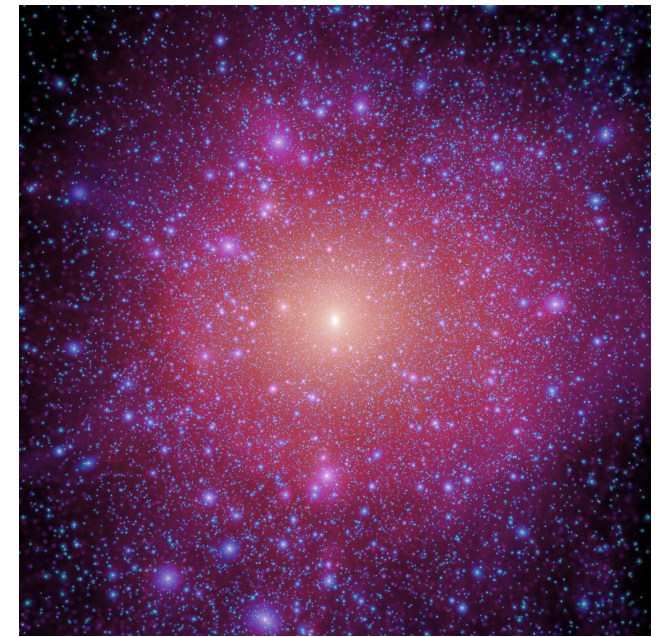
Detecting dark matter

- New technologies have already made substantial progress in testing benchmarks.



Detecting dark matter

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- We shouldn't tie ourselves too much to simple explanations of relic density. Dark matter exists and we are surrounded by it!



Detecting dark matter

- New technologies have already made substantial progress in testing benchmarks.
- We shouldn't tie ourselves too much to simple explanations of relic density. Dark matter exists and we are surrounded by it!
- We have a unique opportunity to continue probing new regimes for DM in the keV-GeV scale.

