# Dark Matter Theory

## with a focus on hidden sector DM and new experimental opportunities

Natalia Toro

SLAC National Accelerator Laboratory

# Dark Matter Facts

- ✦ Stable (most of the DM has $\Gamma^{-1} \gtrsim 10^{17}$ to $10^{-27}$/s )
- ✦ Less interactive than stable SM matter
  - ⇒New constituent(s) beyond Standard Model
- ✦ Cosmological abundance: $\Omega_{DM}h^2$=0.12 (Planck)
  - – Most of it non-relativistic during structure formation

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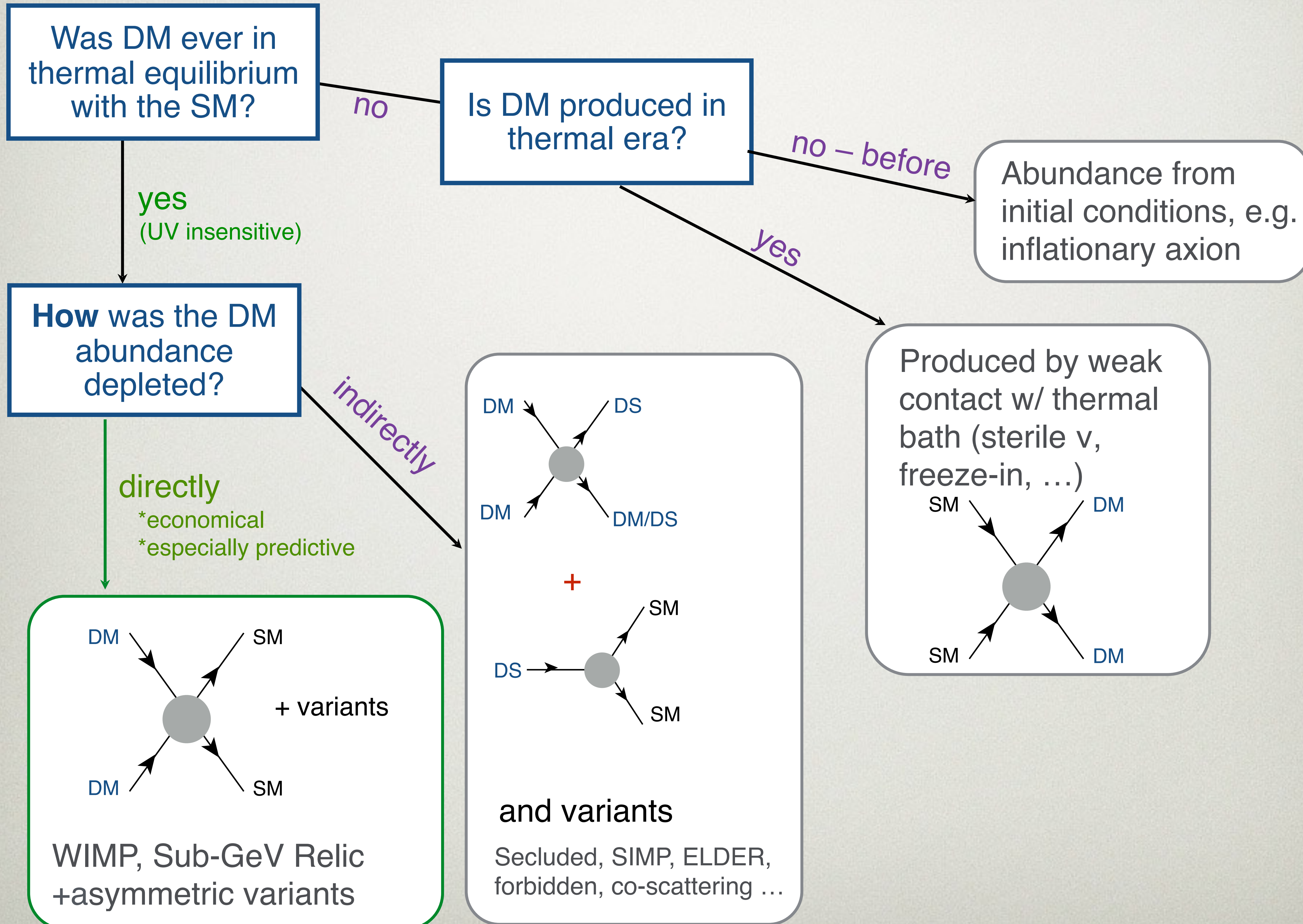
✦ Cosmological abundance: $\Omega_{DM}h^2$=0.12 (Planck)

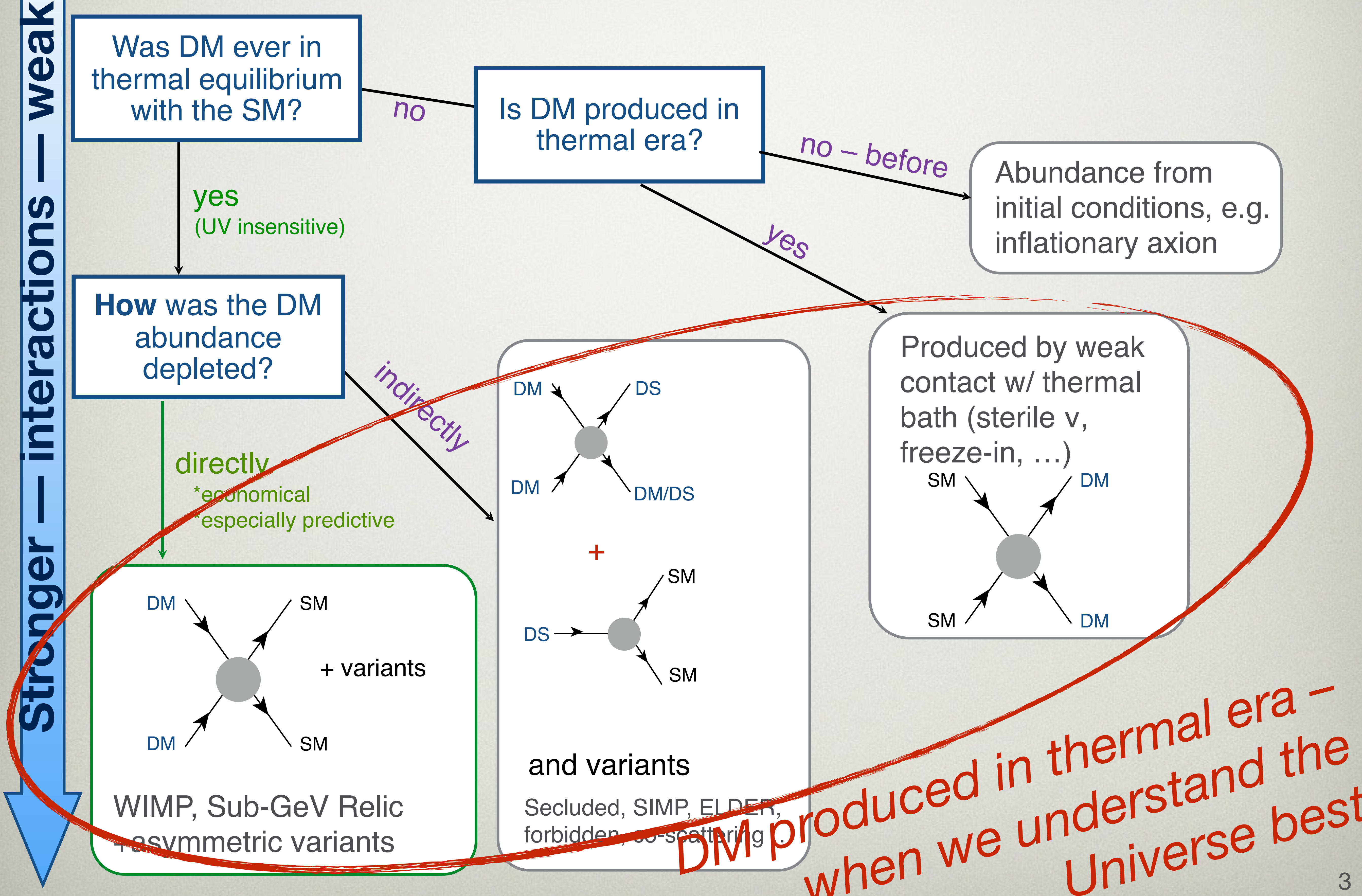
– Most of it non-relativistic during structure formation

*natural to organize thinking about DM around the* ***origin*** *of this cold abundance*

# Dark Matter Taxonomy

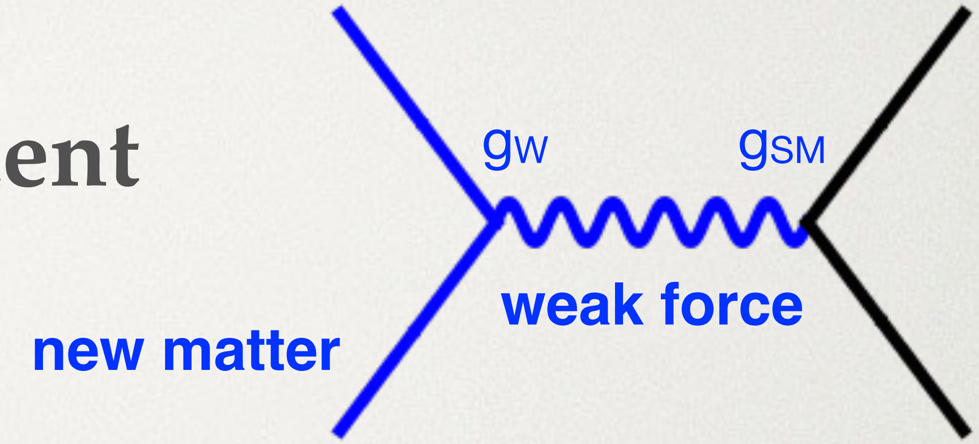


# Dark Matter Taxonomy



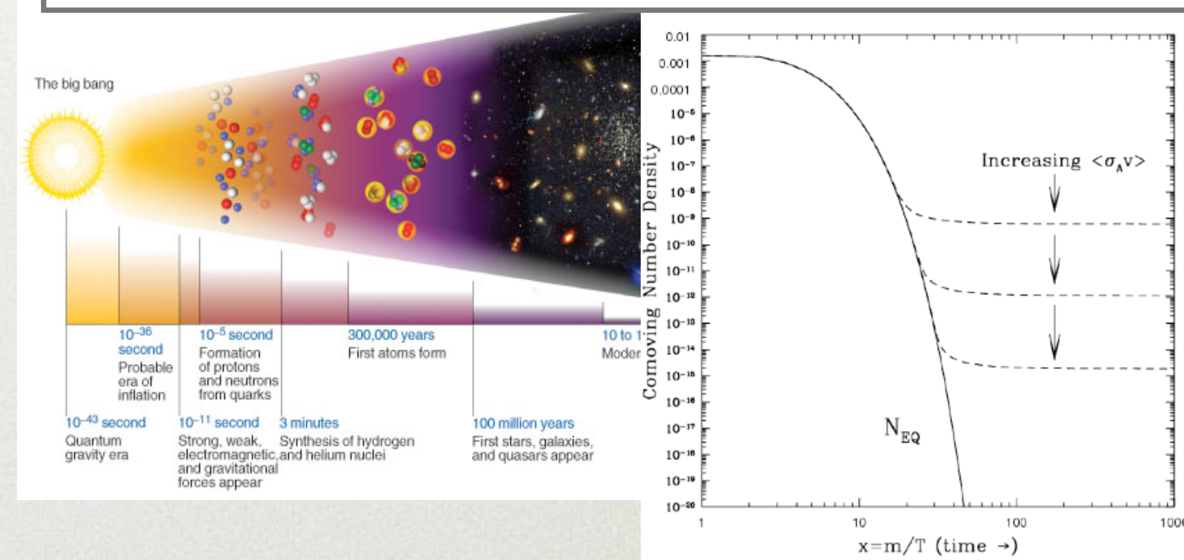
# A Strong Candidate: WIMP DM

## Simple, familiar particle content

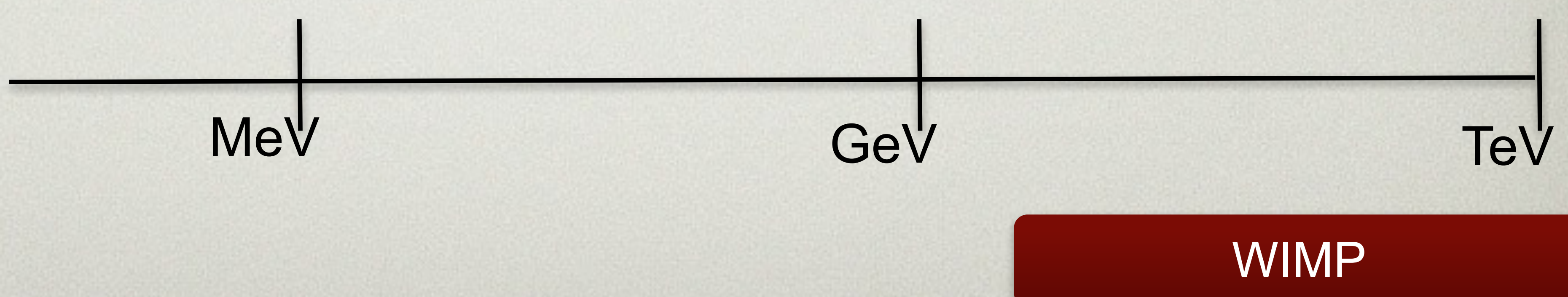



## Simple, predictive cosmology

DM with thermal freeze-out origin

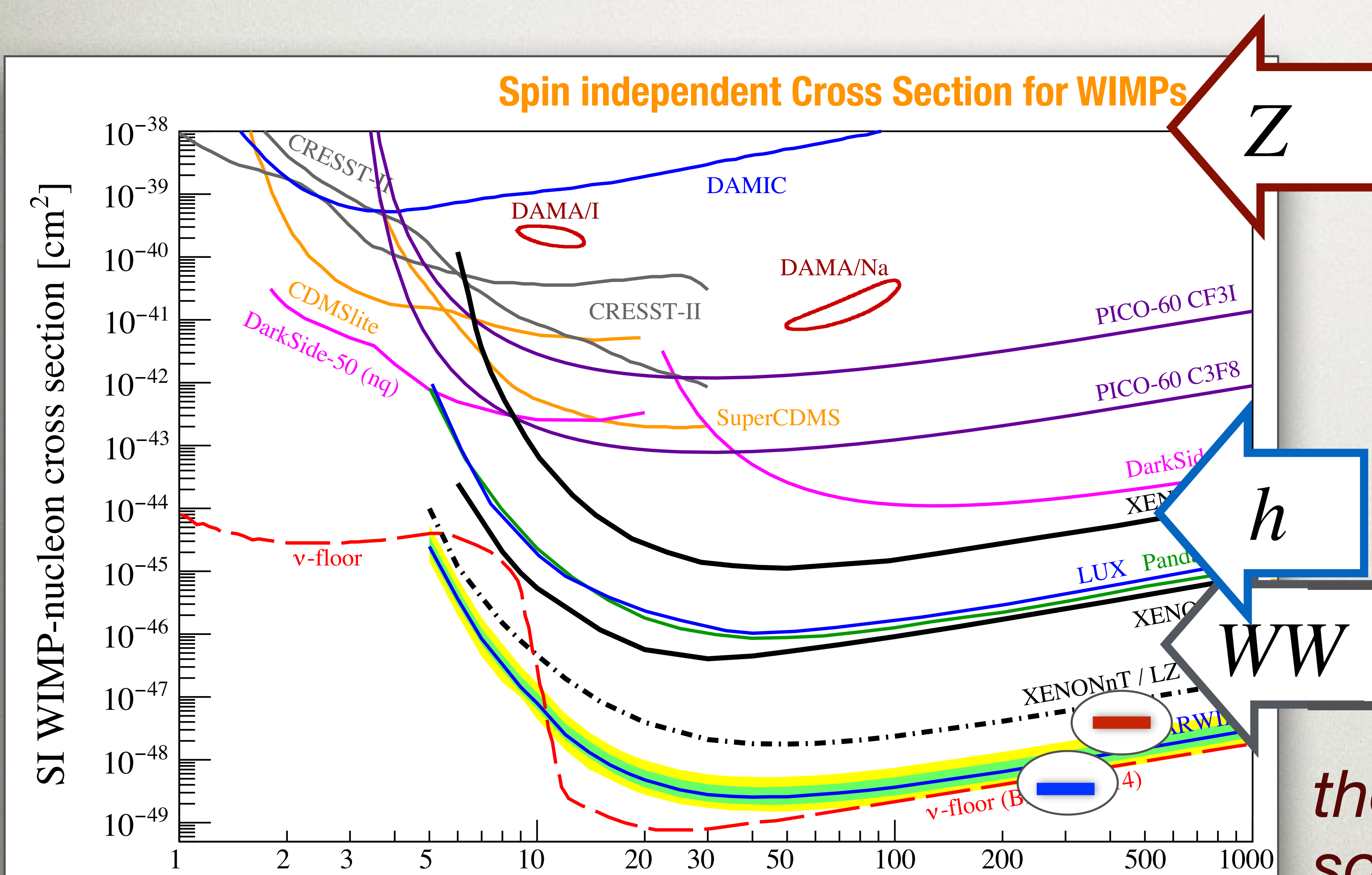



## Physics-rich mass range



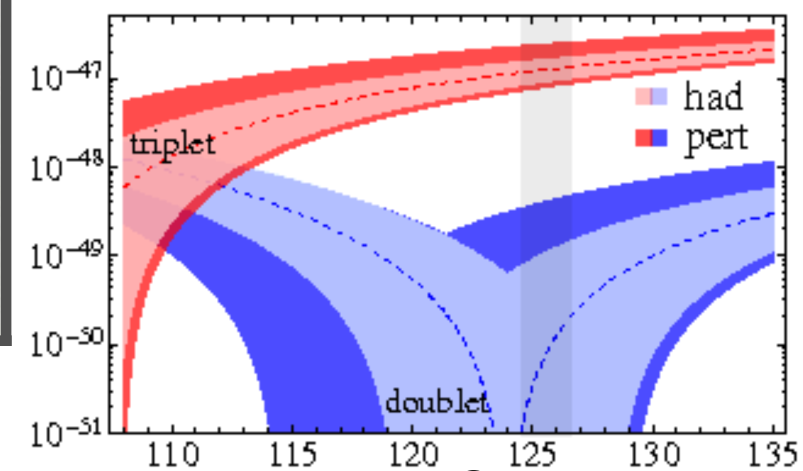
# WIMP Predictions: Direct Detection

Dimensional analysis → predicted strength of interactions for different weak-scale mediators




DARWIN, Biondi 2018

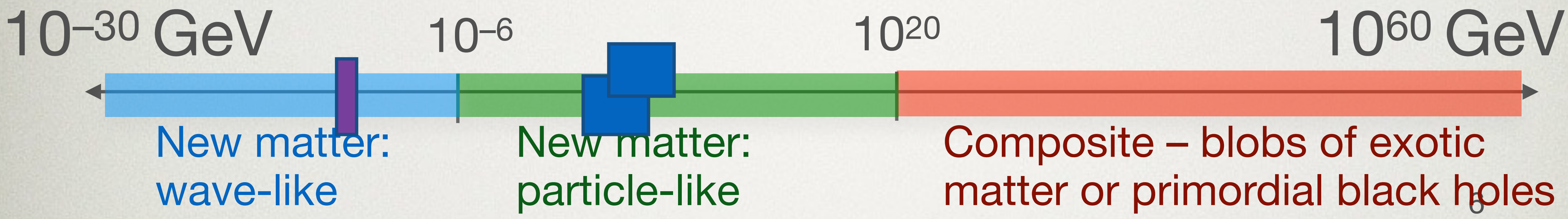
*Too quick!*
*cancellations→*
*≲$10^{-47}$ cm² for simple models*




Hill & Solon 2013

*though "mostly" explored, solid motivation to complete WIMP program*

# New Directions



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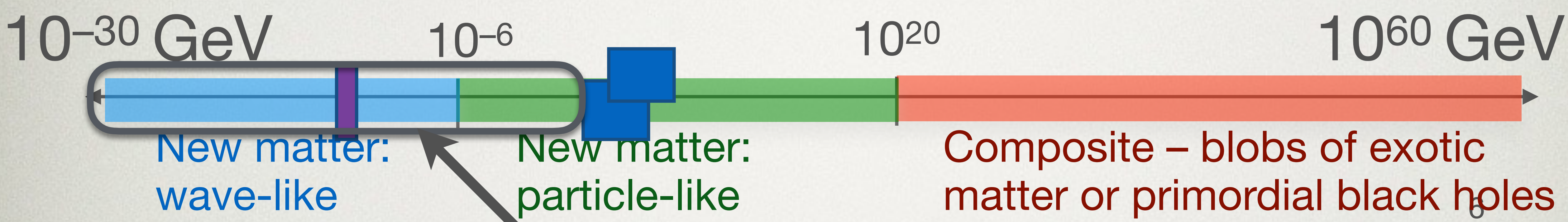


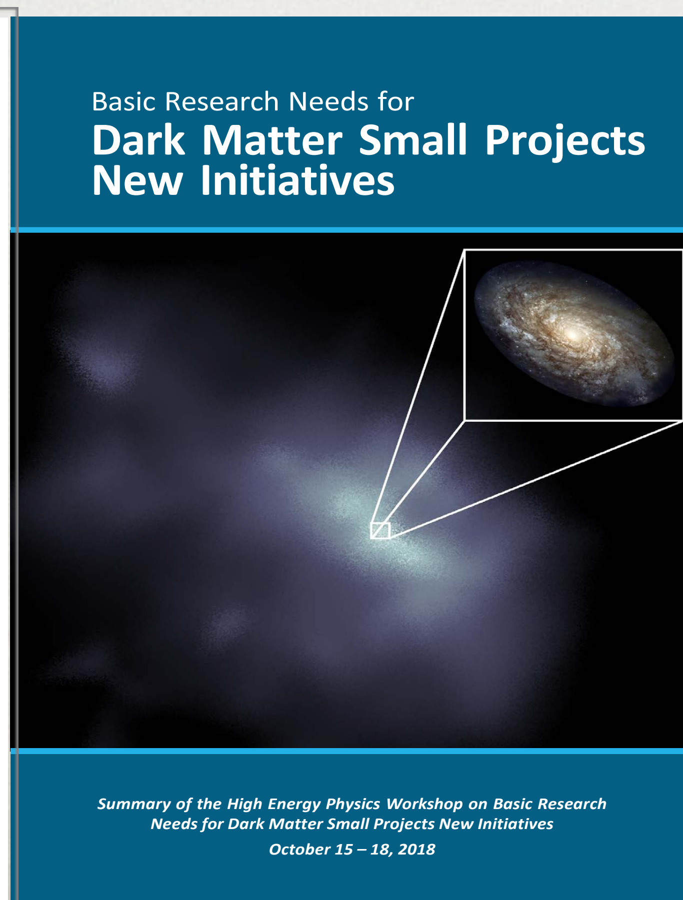



Confluence of (slightly) broader theoretical frameworks and new experimental ideas developed over the last few years

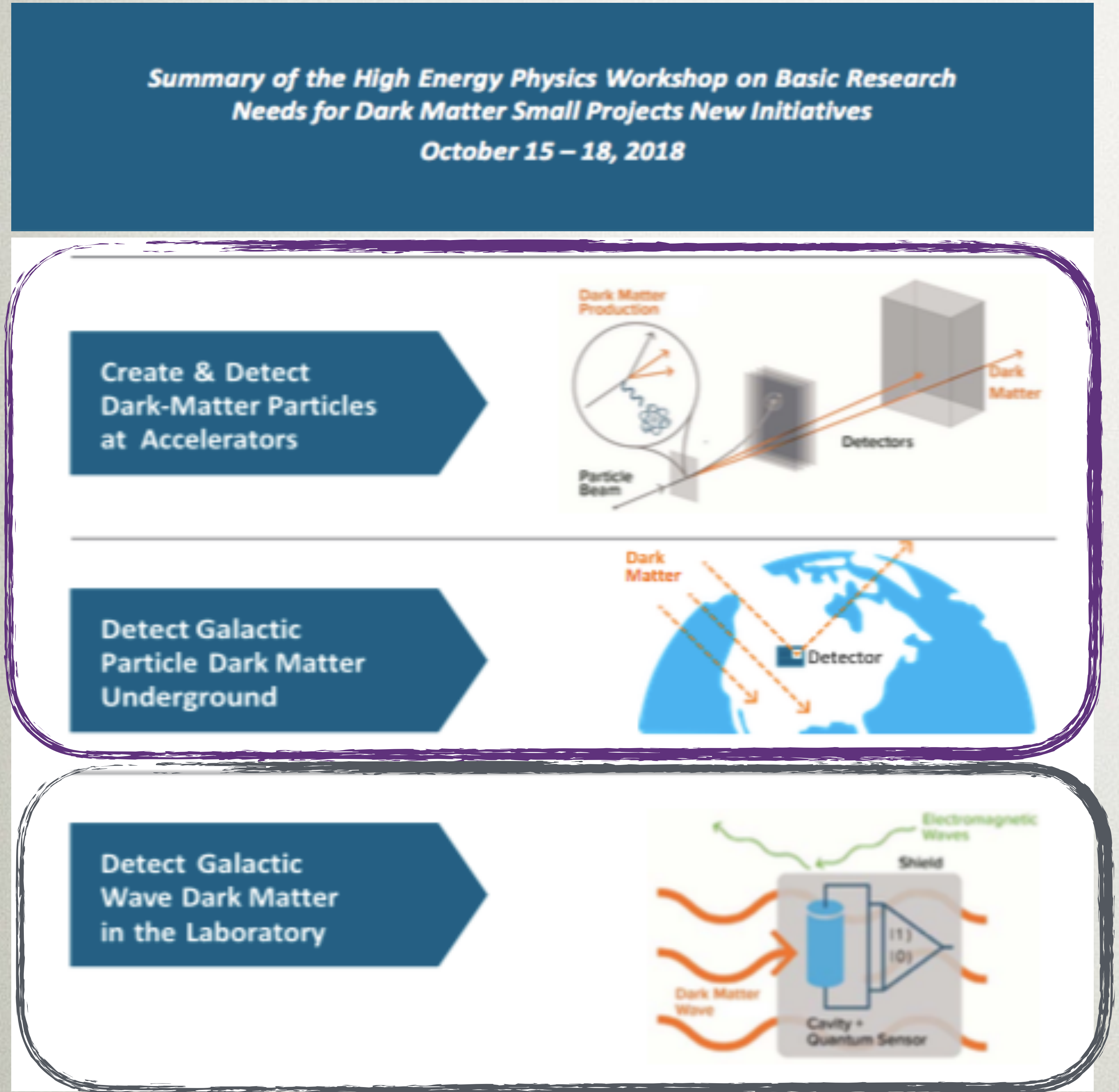
→ three new avenues to pursue

**US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report**

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC member),[12] Natalie Roe (Coordinator),[13] Gray Rybka (SAC member),[14] Pierre Sikivie (SAC member),[15] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,16] Richard Van De Water (SAC member),[17] Neal Weiner (SAC member),[18] Kathryn Zurek (SAC member),[13,12] Eric Adelberger,[14] Andrei Afanasev,[19] Derbin Alexander,[20] James Alexander,[21] Vasile Cristian Antochi,[22] David Mark Asner,[23] Howard Baer,[24] Dipanwita Banerjee,[25] Elisabetta Baracchini,[26] Phillip Barbeau,[27] Joshua Barrow,[28] Noemie Bastidon,[29] James Battat,[30] Stephen Benson,[31] Asher Berlin,[9] Mark Bird,[32] Nikita Blinov,[9] Kimberly K. Boddy,[33] Mariangela Bondì,[34] Walter M. Bonivento,[35] Mark Boulay,[36] James Boyce,[37,31] Maxime Brodeur,[38] Leah Broussard,[39] Ranny Budnik,[40] Philip Bunting,[12] Marc Caffee,[41] Sabato Stefano Caiazza,[42] Sheldon Campbell,[7] Tongtong Cao,[43] Gianpaolo Carosi,[44] Massimo Carpinelli,[45,46] Gianluca Cavoto,[22] Andrea Celentano,[1] Jae Hyeok Chang,[6] Swapan Chattopadhyay,[3,47] Alvaro Chavarria,[48] Chien-Yi Chen,[49,16] Kenneth Clark,[50] John Clarke,[12] Owen Colegrove,[10] Jonathon Coleman,[51] David Cooke,[25] Robert Cooper,[52] Michael Crisler,[23,3] Paolo Crivelli,[25] Francesco D'Eramo,[53,54] Domenico D'Urso,[45,46] Eric Dahl,[29] William Dawson,[44] Marzio De Napoli,[34] Raffaella De Vita,[1] Patrick DeNiverville,[55] Stephen Derenzo,[13] Antonia Di Crescenzo,[56,57] Emanuele Di



# New Directions

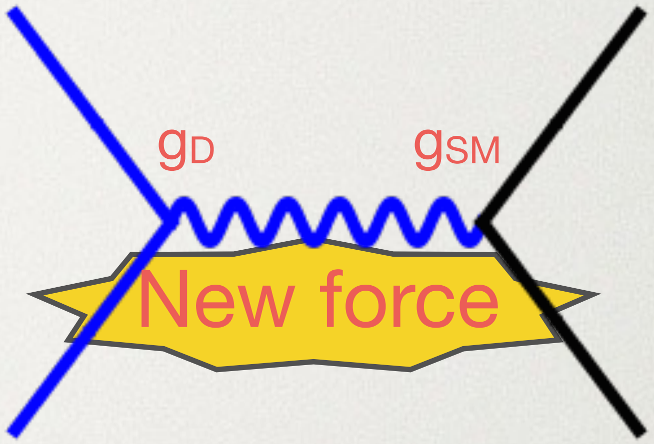



*Particle DM, with particular motivation from hidden sector DM*

*Axion & other wave-like DM,*
*see L. Winslow's talk*

# A Small Step Away from WIMPs: Hidden Sector DM

Simple, familiar particle content



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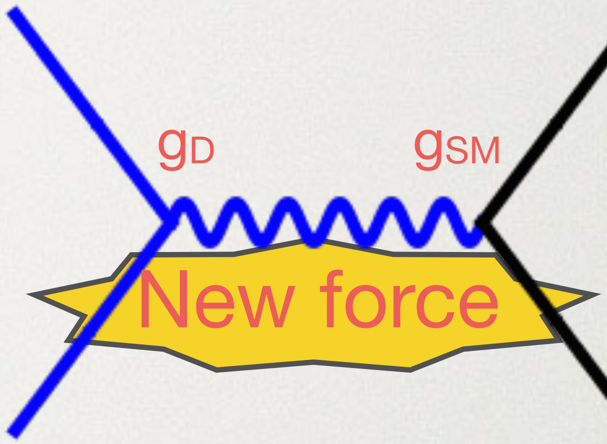


Immediate rewards for this assumption:
– dark matter can be stabilized by new charge
– preserve & extend much of the WIMP story

Immediate perils:
– why haven't we seen the force yet?
*maybe because it doesn't couple very strongly to us*

# A Small Step: Hidden Sector DM

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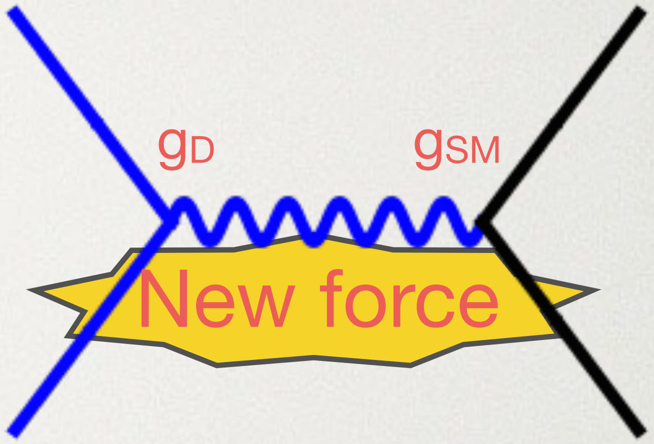
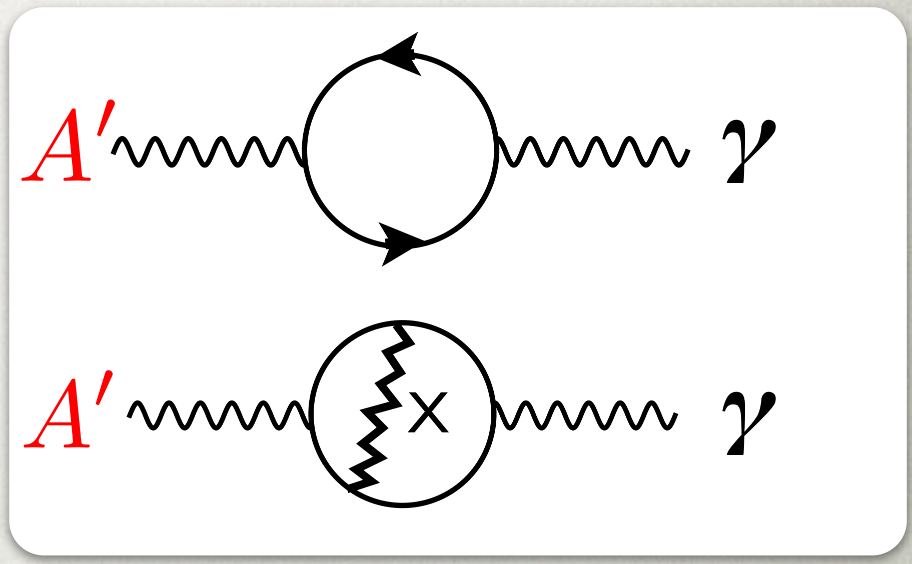


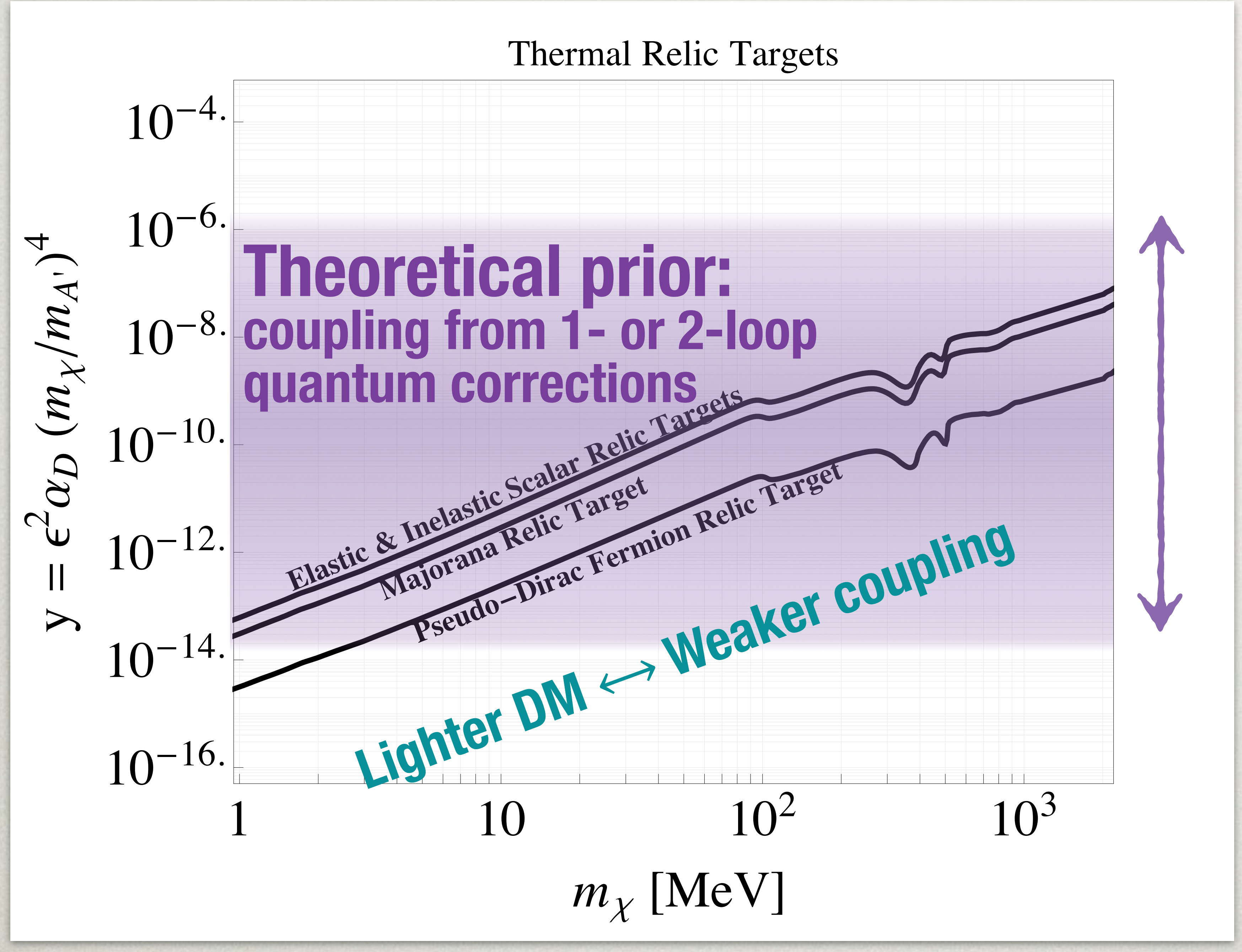

Vector Portal $\frac{1}{2}\epsilon_Y \, F^{Y}_{\mu\nu} F'^{\mu\nu}$




→ expect small couplings $g_{\rm SM} \sim (10^{-6} - 10^{-2})e$

Given small couplings, also generic to consider sub-weak-scale masses – comparable to electron and proton masses

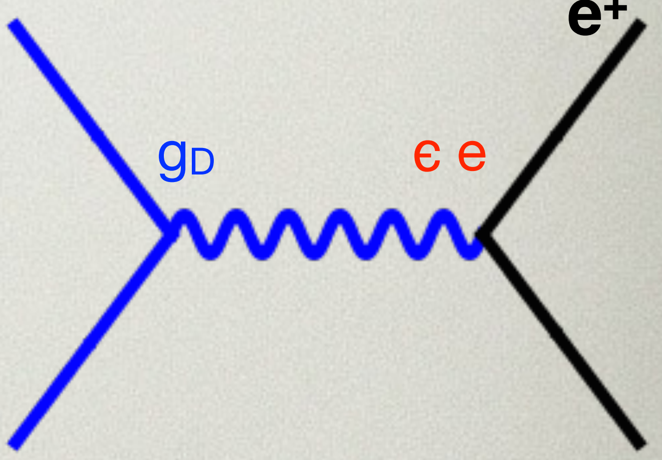
# Light Thermal Dark Matter




prediction from thermal dark matter:

$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm^3/s}$

$\sim \alpha_D\, \epsilon^2 \alpha\, \frac{m_{DM}^2}{m_{A'}^4}$



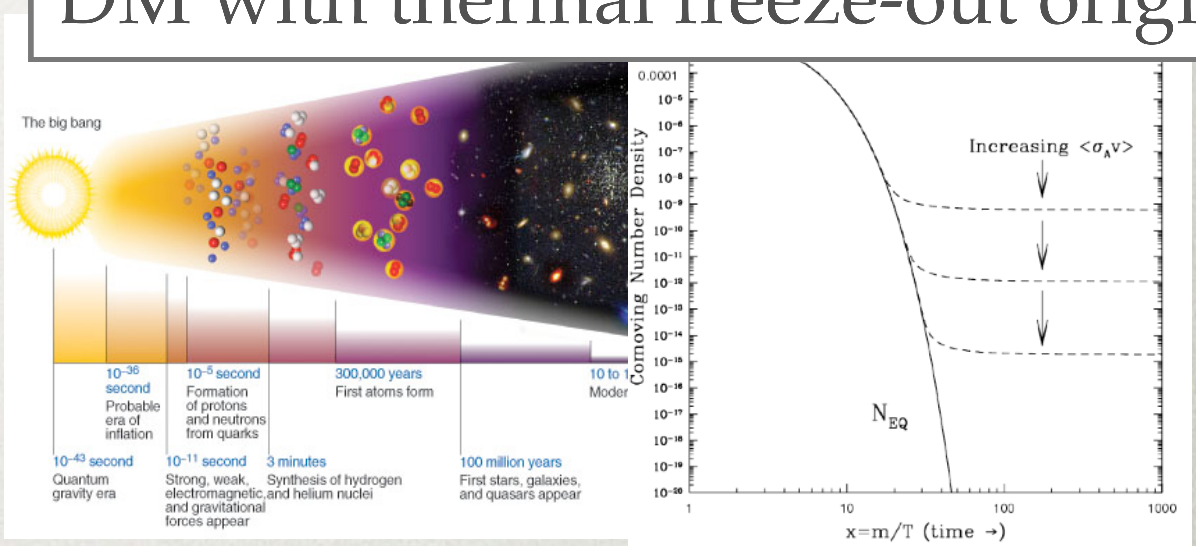

Natural generalization of thermal WIMP to lower masses

# Hidden Sector Dark Matter
## Direct Freeze-Out

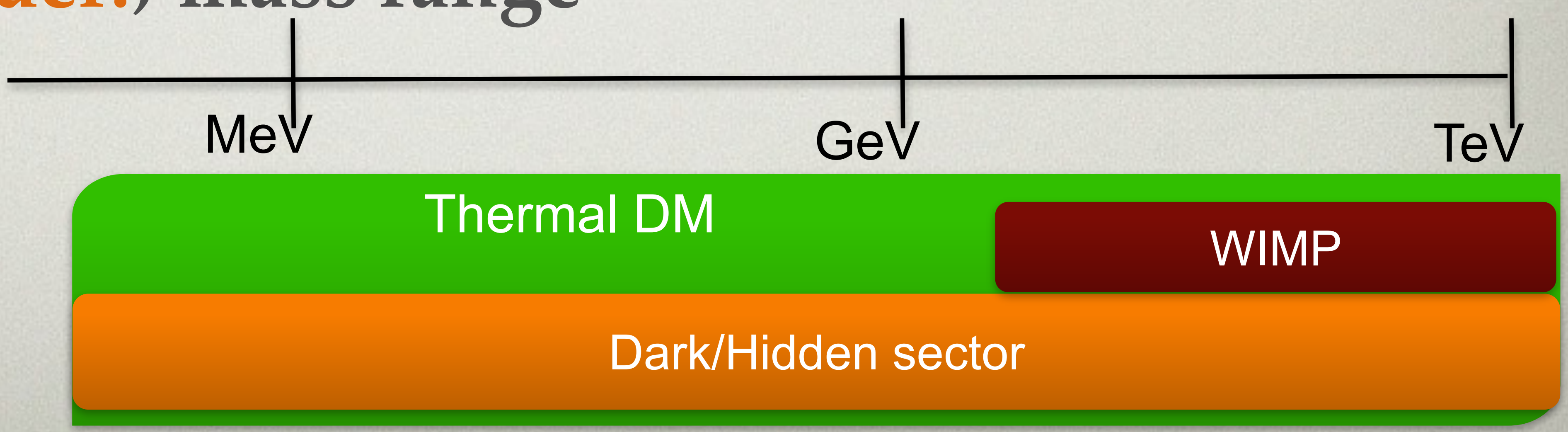
Simple, familiar particle content


Simple, predictive cosmology

DM with thermal freeze-out origin

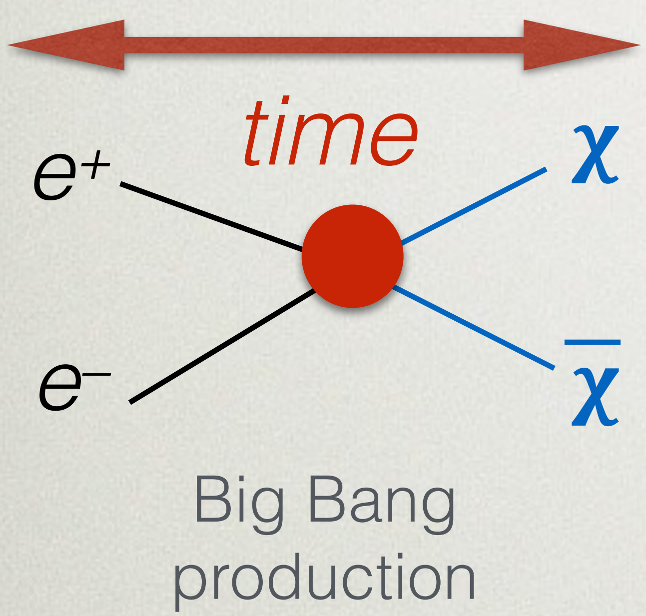


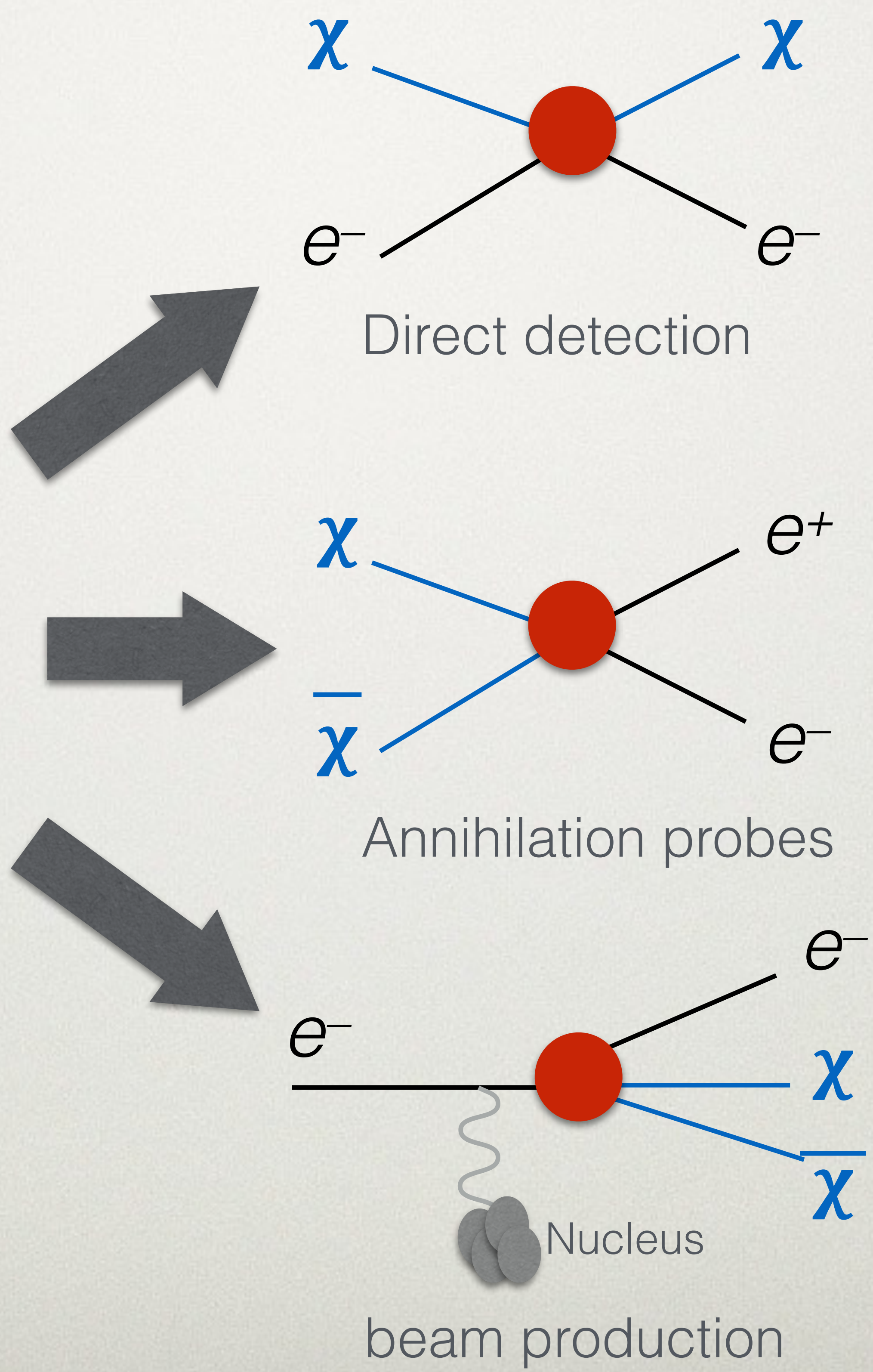

Motivated (**broader!**) mass range



# Testing Thermal Dark Matter

**Momentum scale in :**
***$q \sim m_\chi$***




***"Shake it"***

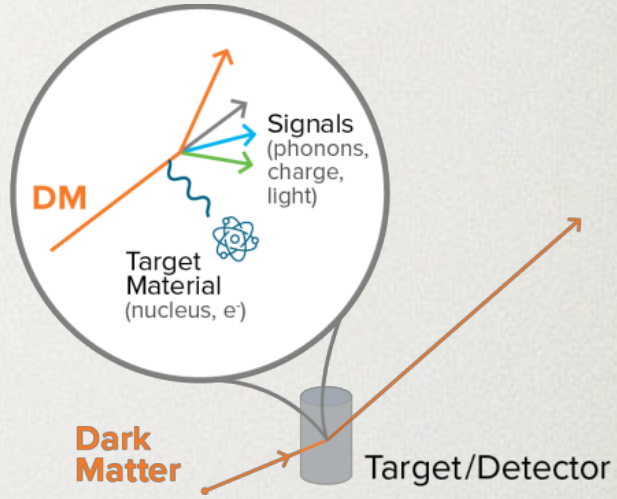
***"Break it"***

***"Make it"***

interaction as
-out →
predictions for
models!

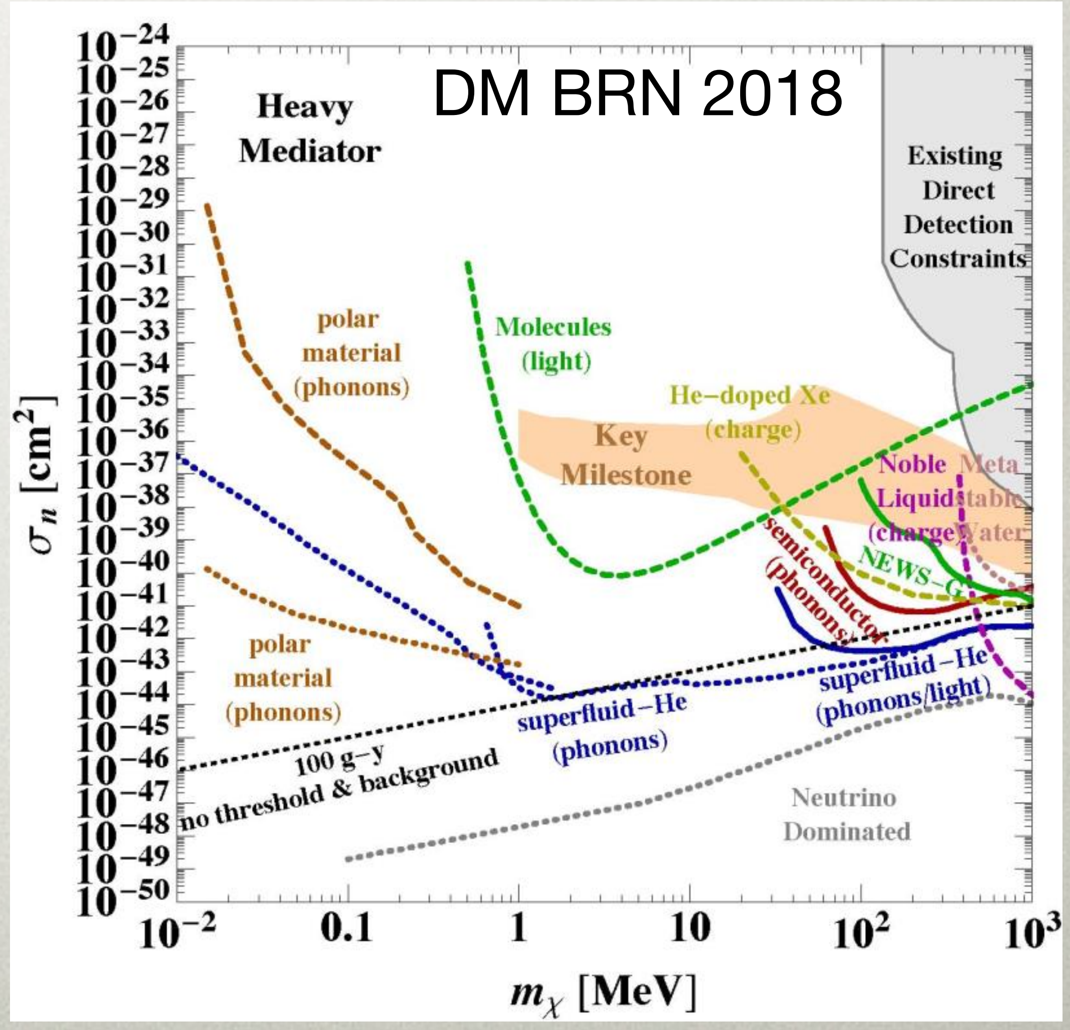
# Looking for Thermal Dark Matter: Scattering

Light DM → lower energy transfer in scattering, **below traditional energy thresholds.**

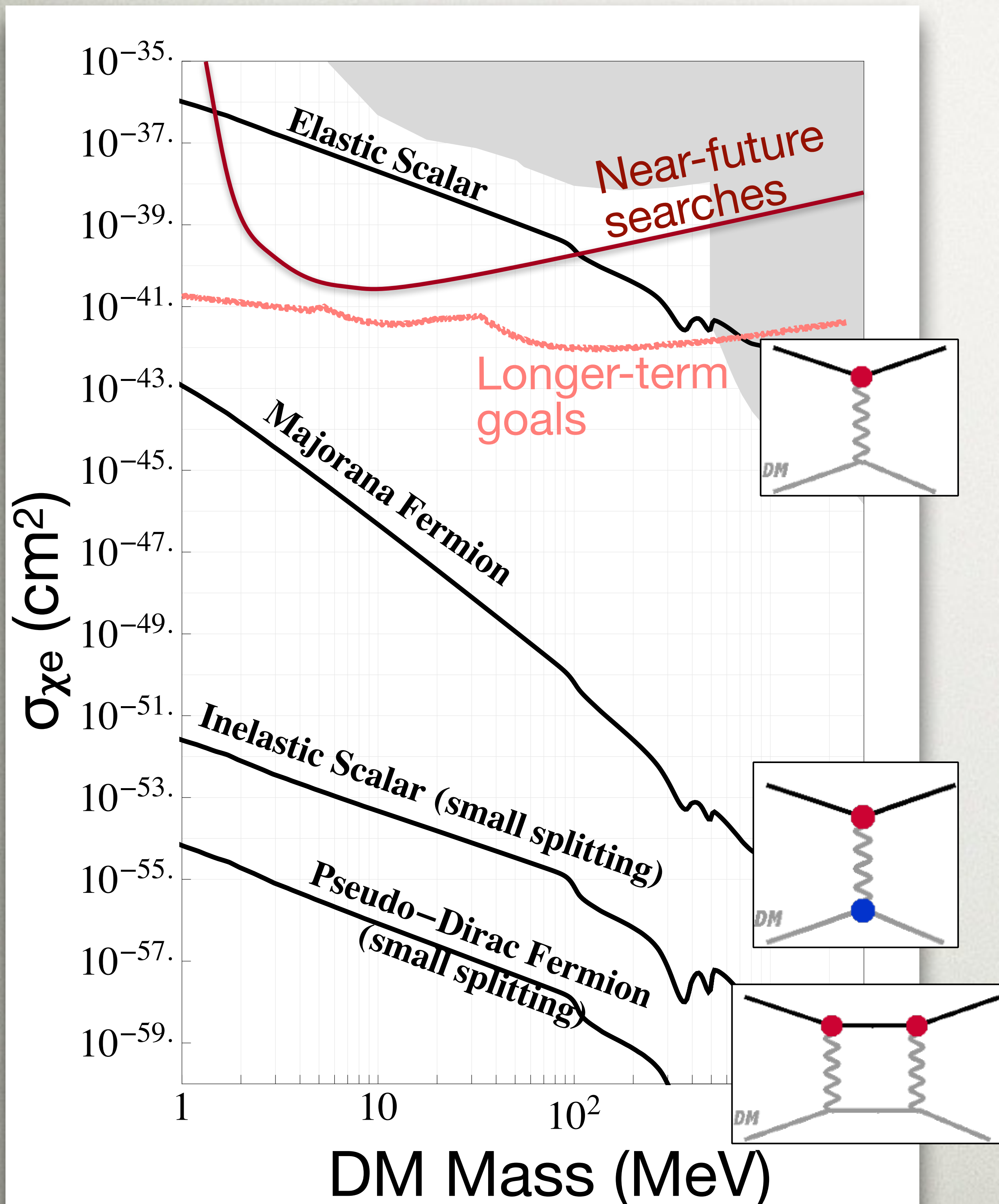



**New ideas:**
Detect light DM scattering off nuclei or electrons by developing detectors with **~eV threshold.**

Long-term goal: **meV-scale threshold** using low-gap excitations in advanced materials, novel sensors



# CAUTION: Kinematic Extrapolations!



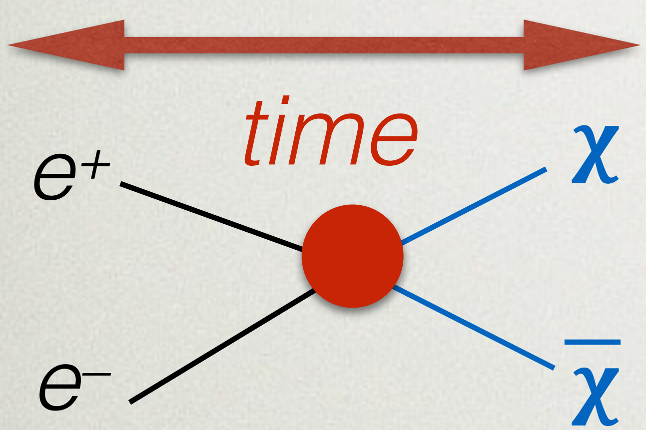

Spin & coupling structure of DM → substantial effect on scattering rate:

- Scattering rate controlled by small dark matter coupling to familiar matter
- Scattering suppressed by $(v/c)^2 \sim 10^{-6}$
- Low-velocitiy scattering reactions scale as ***square*** of small coupling)

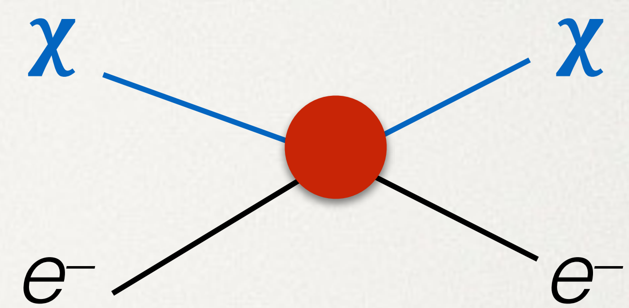
(Note: there are also models where $q \ll m_\chi$ **enhances** signals!)

# Testing Thermal Dark Matter

**Momentum scale in** ✕ **:**
***$q \sim m_\chi$***



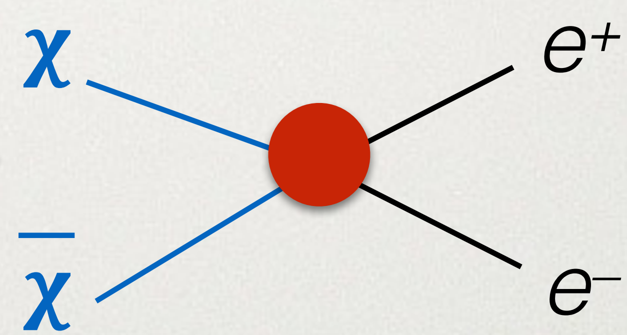

Big Bang production




Direct detection

***$q \ll m_\chi$***

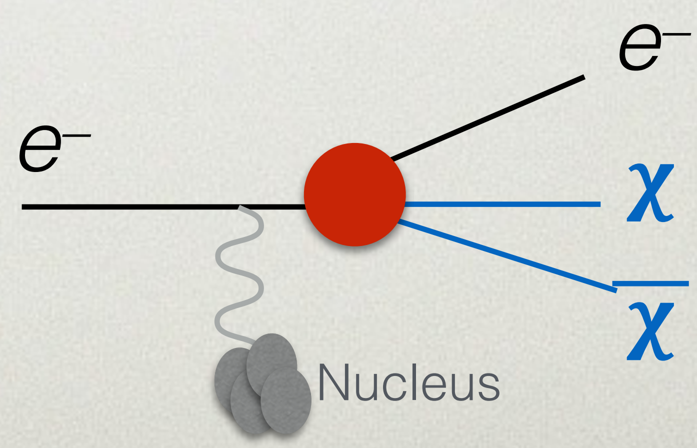
*far from Big Bang production*




Annihilation probes

***$q \ll m_\chi$***

*far from Big Bang production*




beam production

***$q \gtrsim m_\chi$***

***similar to Big Bang production***

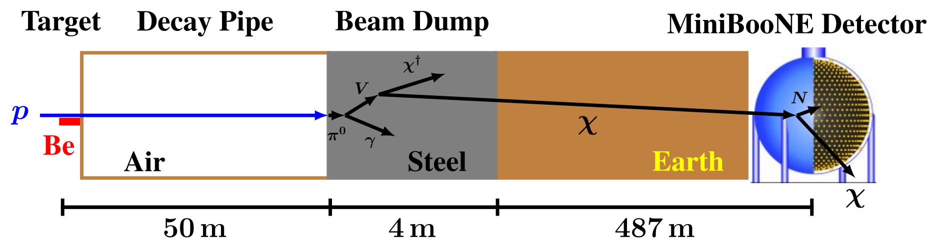
Similar energy scale →
**predicted rate more robust to interaction structure**

# Dark Matter Production

## Two powerful fixed-target approaches

### Beam Dump Re-Scattering

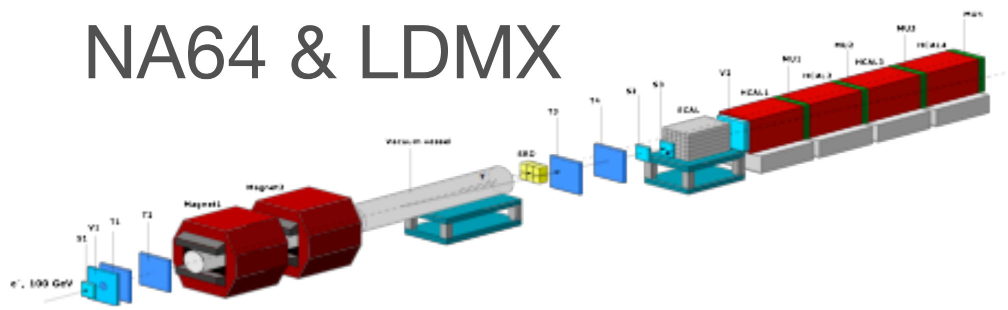
E137, LSND, MiniBooNE, BDX, SBND, COHERENT




Look for neutral-current scattering of DM in downstream detector

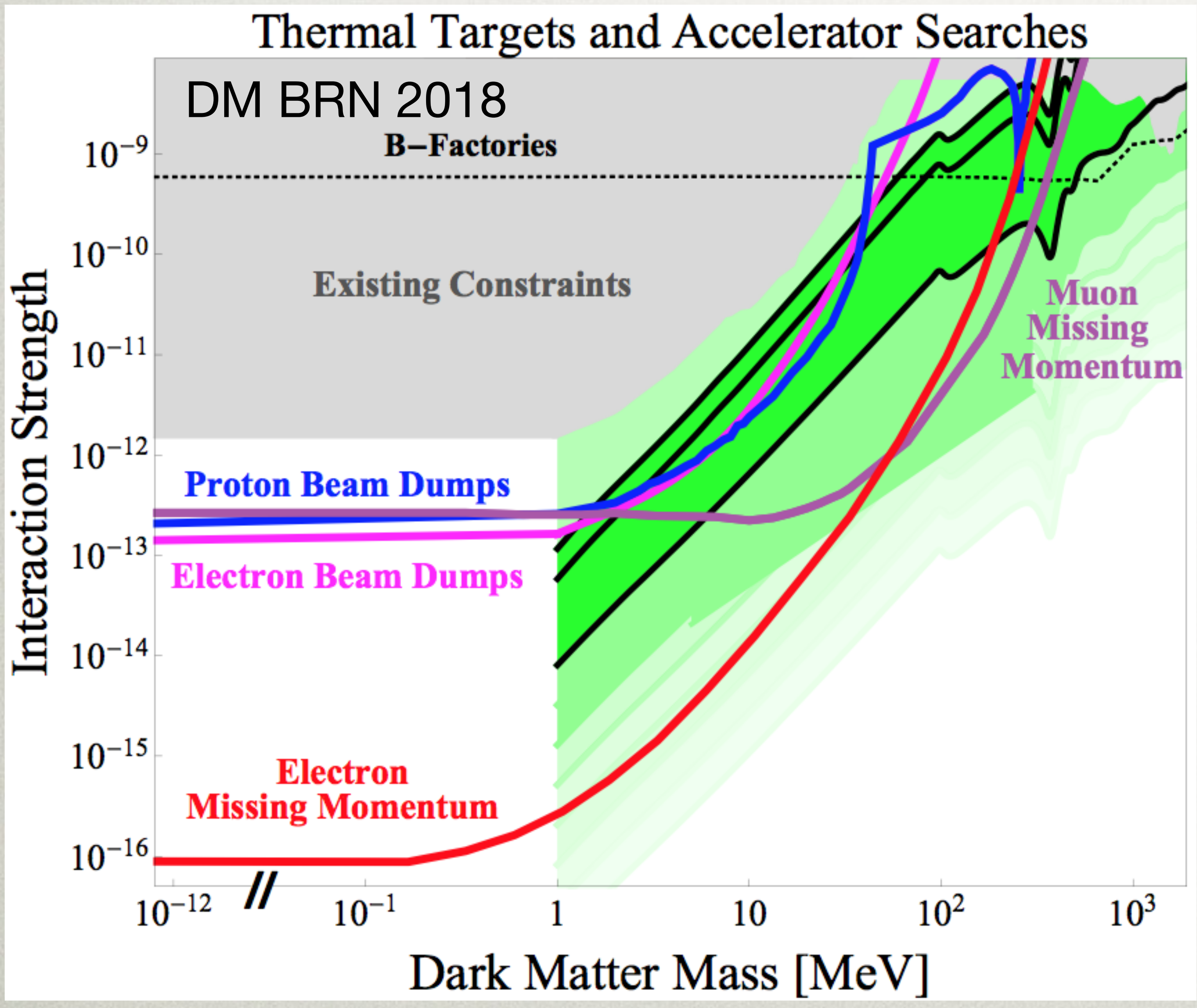
### Missing energy/ momentum

NA64 & LDMX



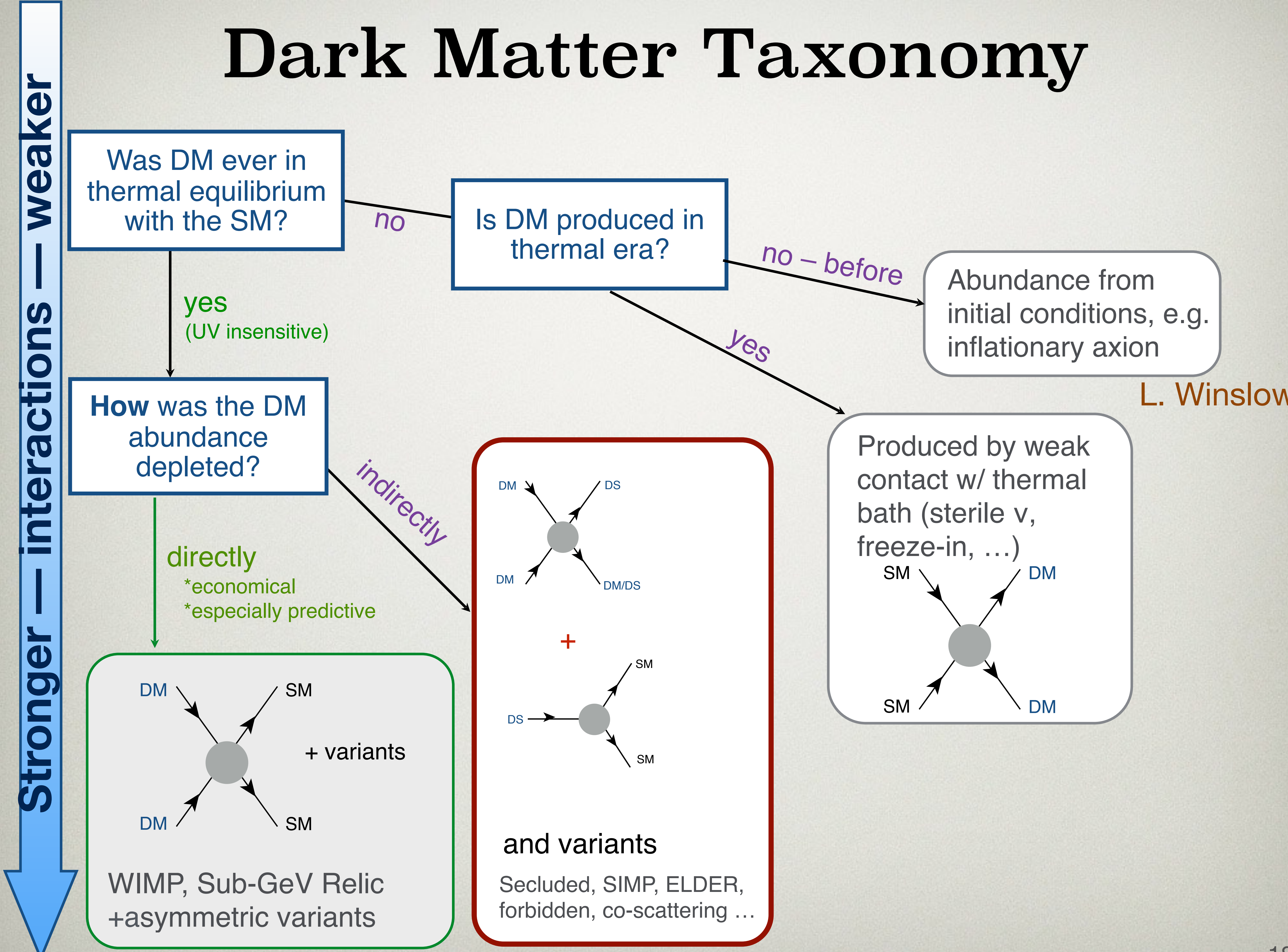
Infer DM production from recoil lepton kinematics & clean missing energy signal

# Accelerator Searches Confront Light Thermal DM



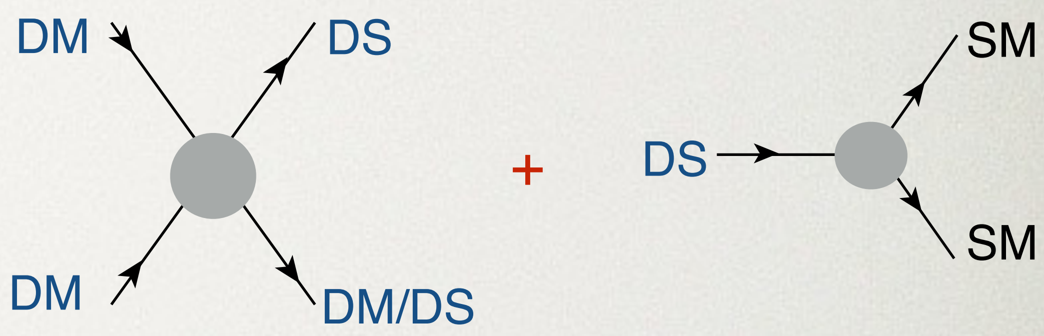

The predictive case of direct DM annihilation is accessible to next-generation experiments for **all** DM spins.

# Dark Matter Taxonomy



# Indirect Thermal Models

Models where at least one process controlling DM freeze-out is internal to the dark sector.




Thermal freeze-out constrains **couplings within the dark sector**, but may have little to do with the interactions relevant to DM production – typically less predictive

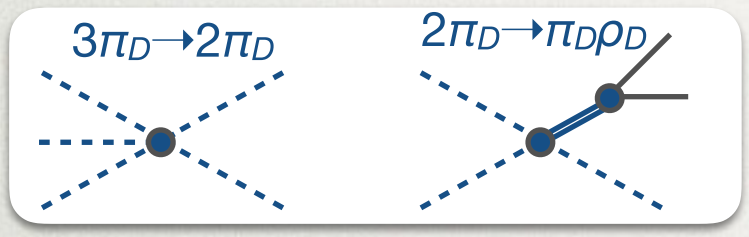
Some scenarios nonetheless lead to distinctive signals and/or new predictions.

There are many possibilities and special cases;
I will only consider 2 examples today.

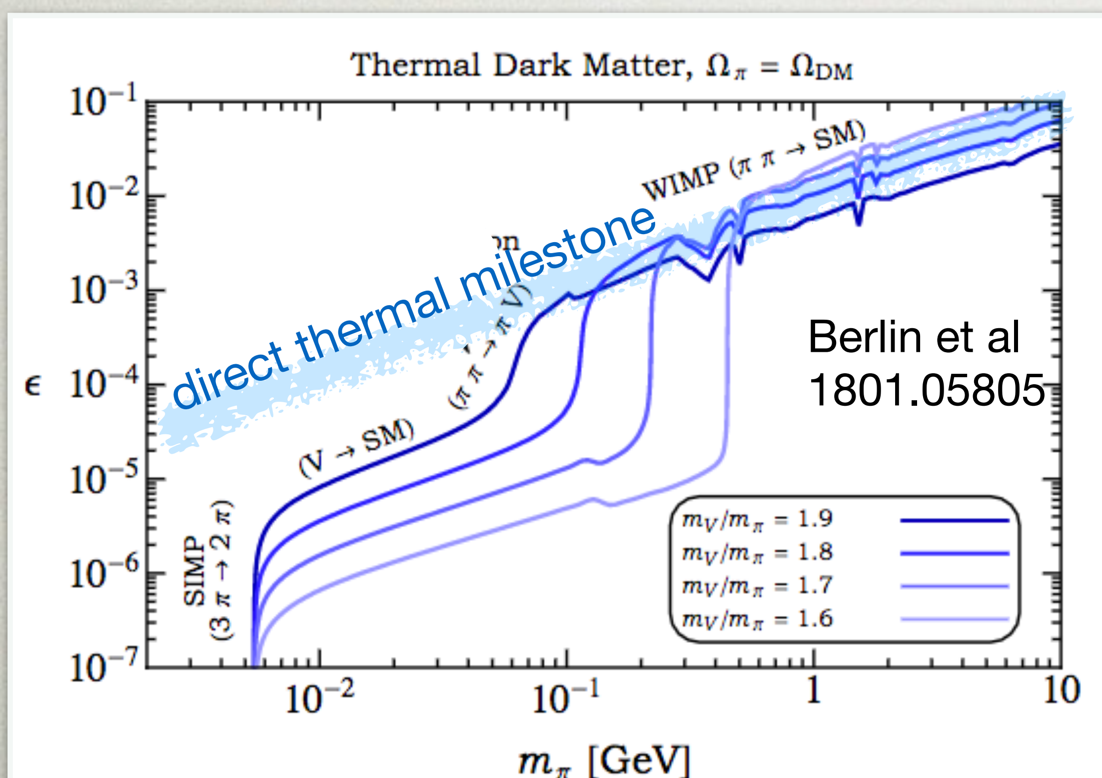
# Indirect Thermal Models

## motivate new signals and milestones

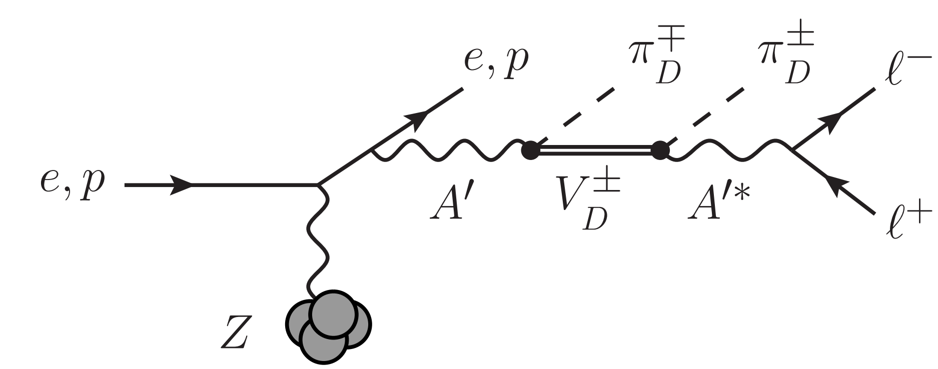
New freeze-out channels if DM is "pion" of a strongly coupled dark sector (SIMP –Hochberg et al 2014):

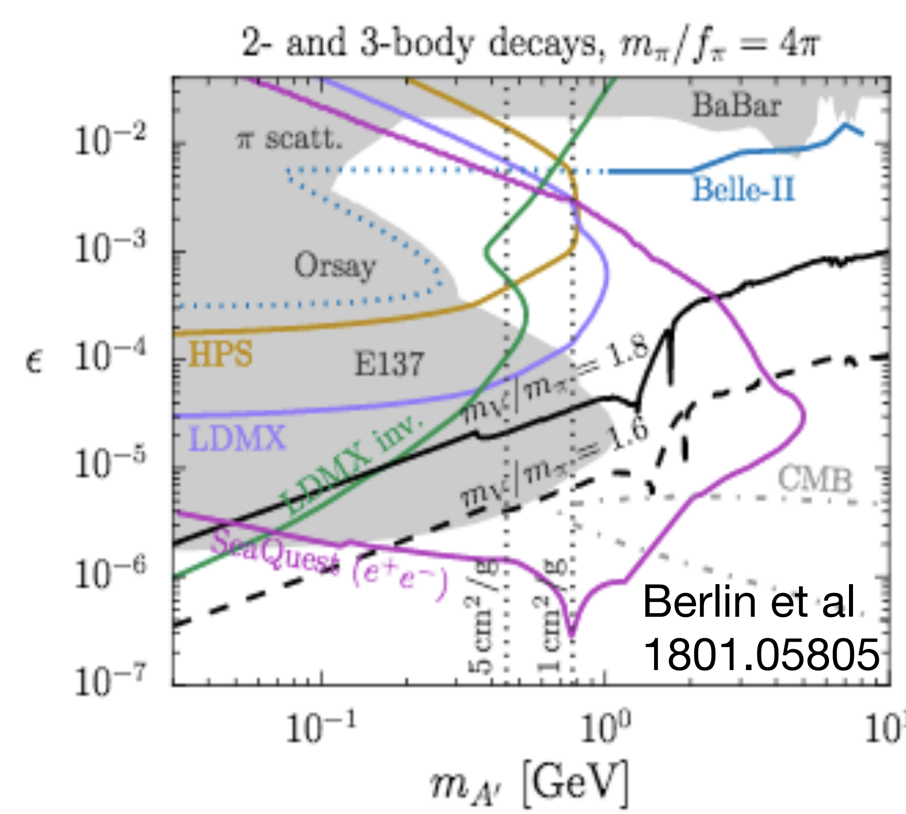



**change but don't eliminate milestone for expected coupling to SM**



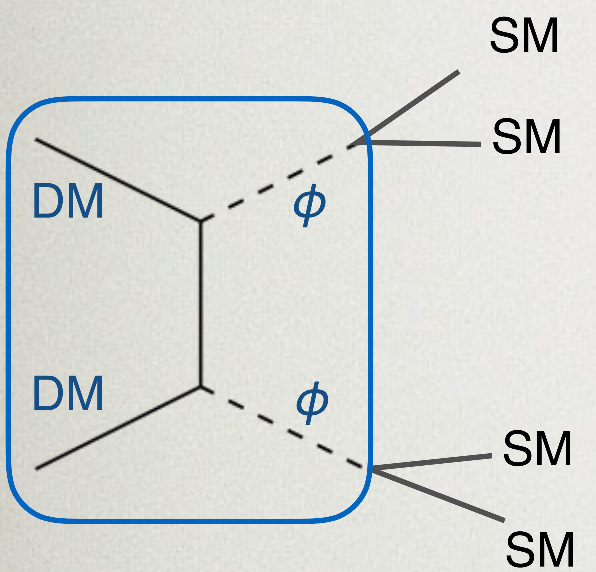

Also implies new signal: produce **unstable** dark hadrons at accelerators



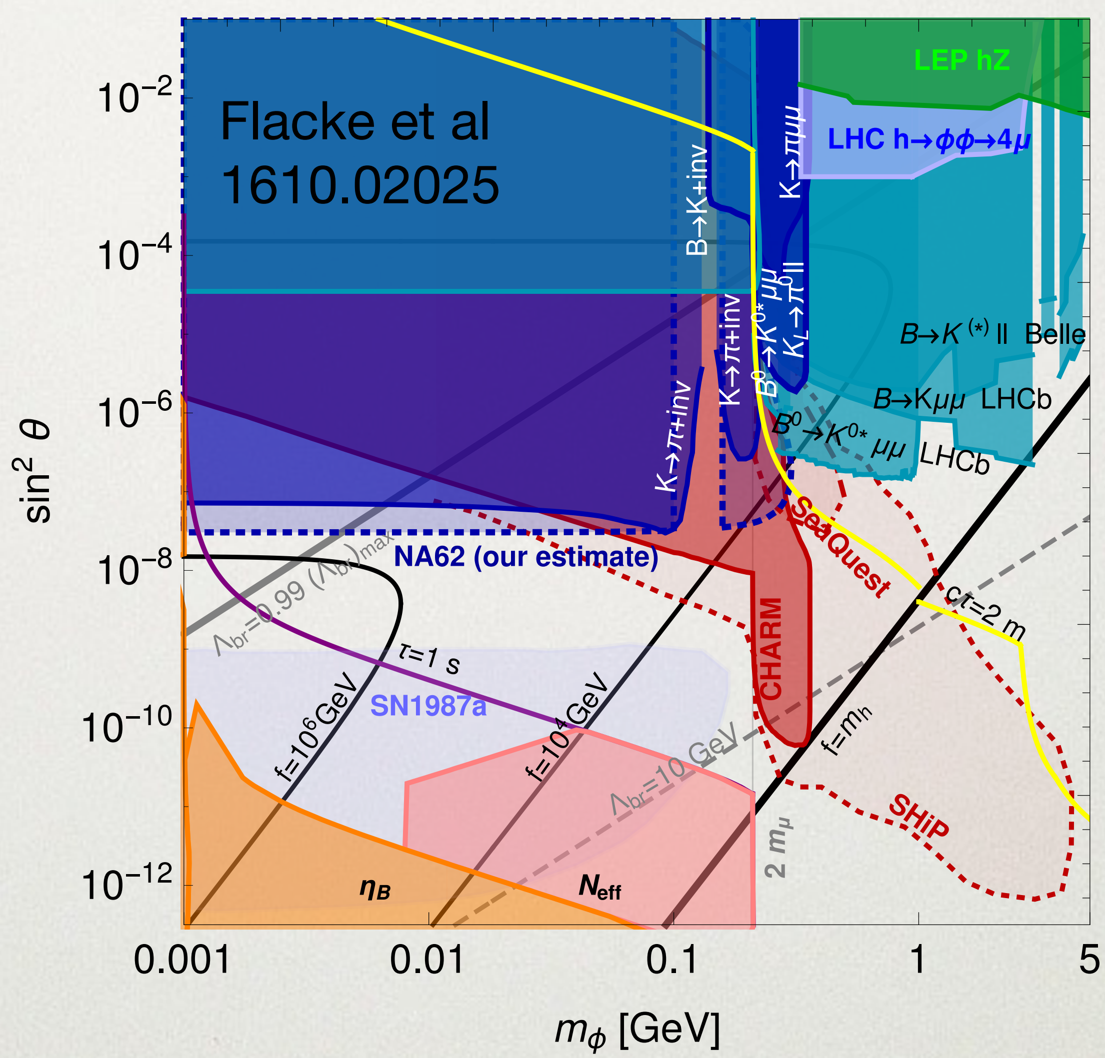
# Indirect Thermal Models

## allow very weak couplings




annihilate to new scalar $\phi$, $\phi \to ff$ via Higgs mixing but annihilation rate controlled by *DM-DM-$\phi$* Yukawa

**Direct Constraints on Higgs mixing**




ϕ-e coupling $\lesssim 10^{-10} \Rightarrow$ DM production beyond reach.
No sharp target, but DM-nuclear scattering and mediator production signals are detectable **and complementary**

# Dark Matter Taxonomy

Stronger — interactions — weaker

Was DM ever in thermal equilibrium with the SM?

no

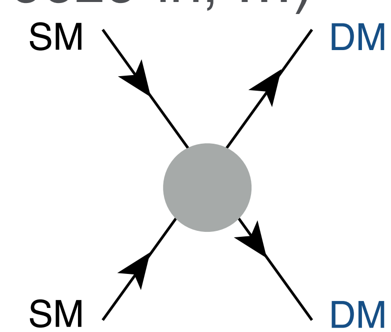
Is DM produced in thermal era?

no – before

Abundance from initial conditions, e.g. inflationary axion

yes

Produced by weak contact w/ thermal bath (sterile ν, freeze-in, …)

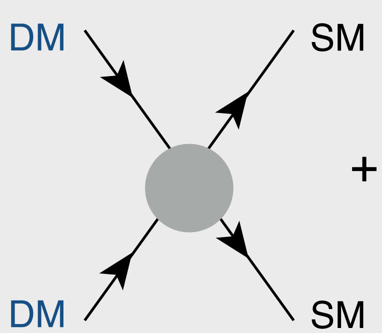



L. Winslow

yes
(UV insensitive)

How was the DM abundance depleted?

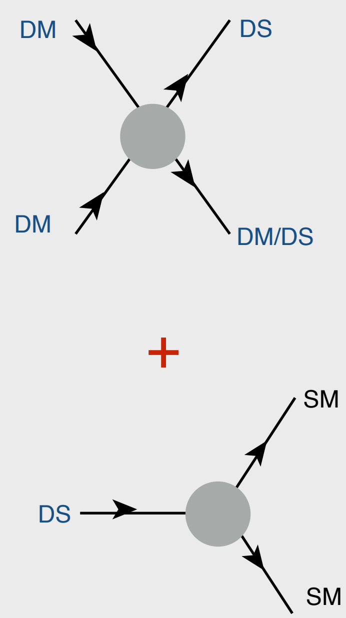
directly
*economical
*especially predictive




+ variants

WIMP, Sub-GeV Relic
+asymmetric variants

indirectly

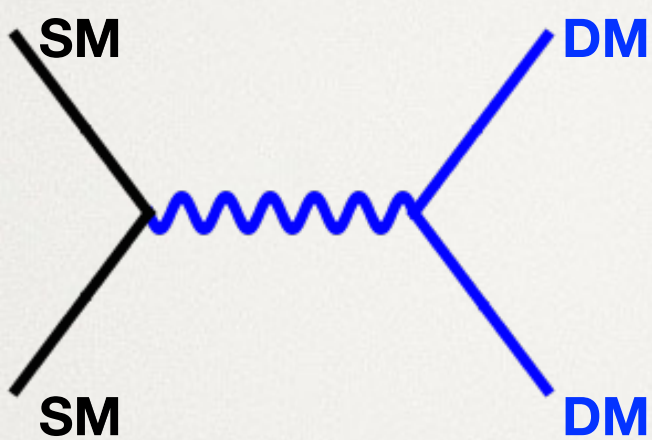



and variants

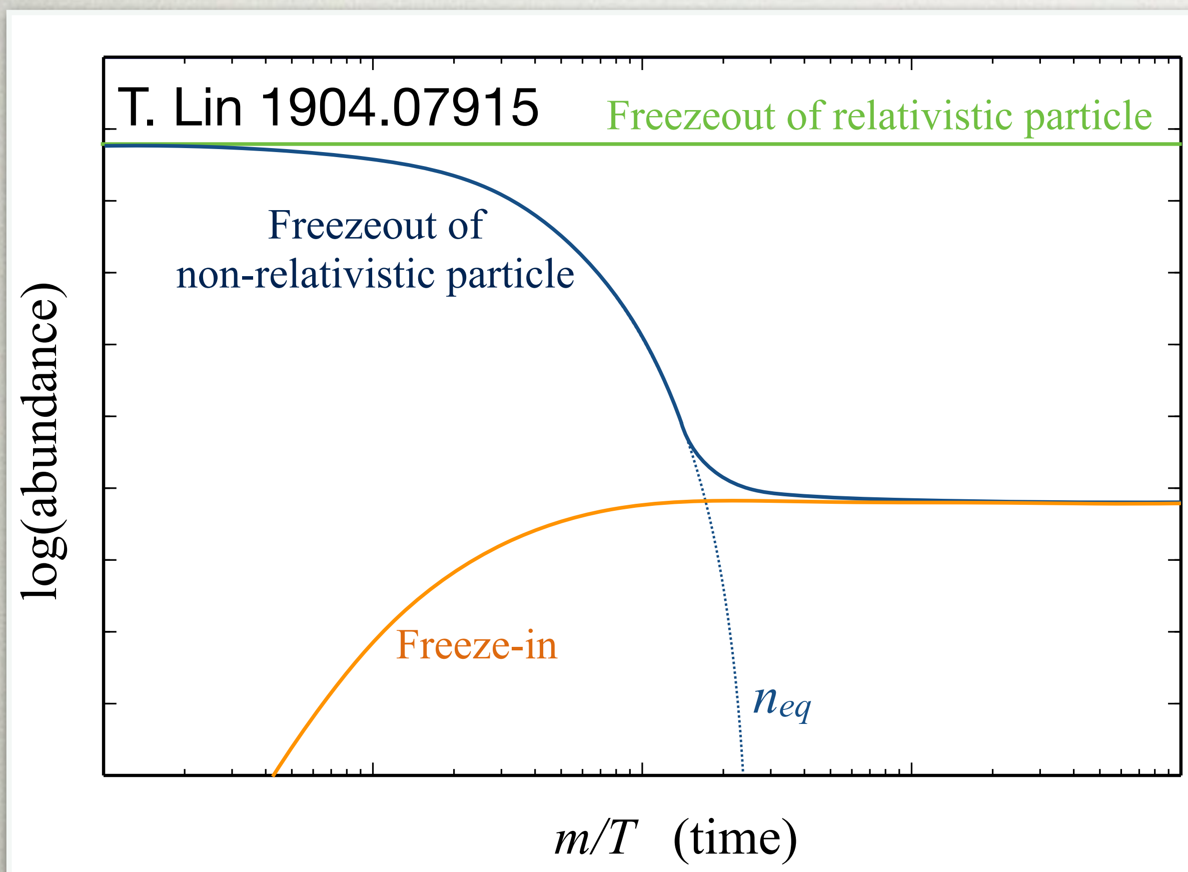
Secluded, SIMP, ELDER, forbidden, co-scattering …

# Dark Matter Freeze-In

Feeble DM-SM interactions produce DM in early Universe, but never enough to thermalize




*One of the few simple possibilities for sub-MeV DM produced in thermal era*




Light hidden-sector realization requires $\alpha_{DM} \times \alpha_{SM} \sim 10^{-26}$

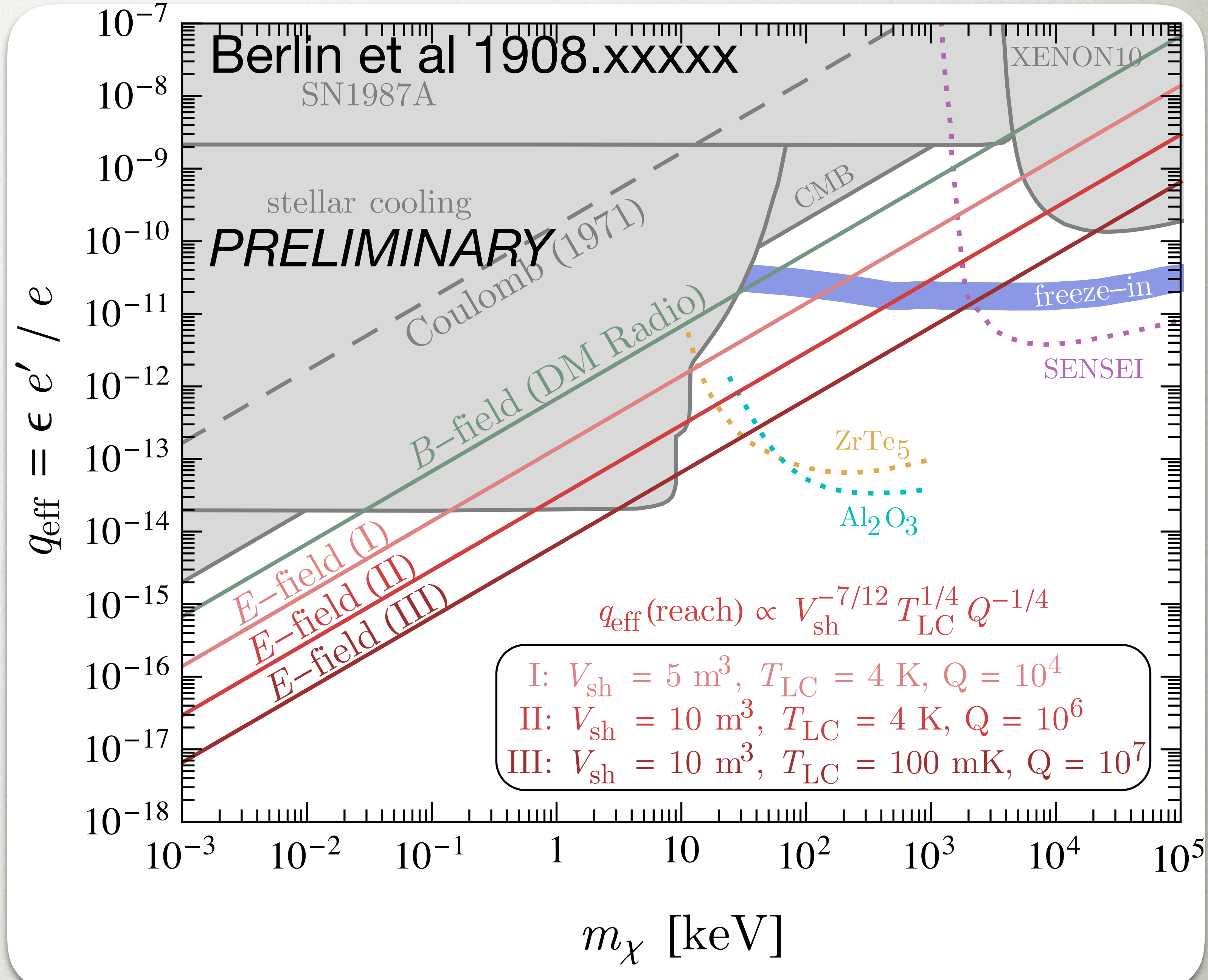
$\Rightarrow$ naively undetectable

…but for $m_{DM}$<MeV, independent bounds on $\alpha_{DM}$ and $\alpha_{SM}$ imply **very** light mediator, $\lesssim 10^{-10}$ eV

(this is also a possibility – though not required – for heavier DM)

# Dark Matter Freeze-In: Light Mediators

**If** mediator is very light **and** DM has elastic, v-independent coupling (e.g. elastic scalar or Dirac fermion), **then** scattering cross-section ~ $\alpha_{DM}\, \alpha_{SM}/q^4$ dramatically enhanced at low momentum transfer $q$!




→ freeze-in accessible in direct detection, and by macroscopic EM deflection of DM

# Summary

- ✦ The DM abundance may be the sharpest clue to the properties of its constituents – but of course, this abundance can be realized in a variety of ways.
- ✦ Three possibilities make close contact with the thermal history of ordinary matter, dominated by late times:
  - **Thermal freeze-out of direct DM-to-SM annihilation**
  - **Indirect thermal freeze-out scenarios**
  - **Freeze-in of very feebly coupled DM**
    - All of these can be realized in the context of hidden-sector DM.

# Summary

- Three possibilities make close contact with the thermal history of ordinary matter:
  - **Thermal freeze-out of direct DM-to-SM annihilation** provides a sharp coupling prediction.
    - Leads to narrow range of expected production rates at accelerators, with some cases also accessible to direct detection
  - **Indirect thermal freeze-out scenarios** offer almost-limitless possibilities – predictive or not, experimentally accessible or not
    - Underscore the complementary roles of searches for mediators and other dark sector particles.
  - **Freeze-in of very feebly coupled DM** involves very weak couplings, and opens up sub-MeV DM.
    - If freeze-in interaction is long-range, direct detection and electromagnetic deflection can explore substantial parameter space.

# Summary

- The variety of possible experimental signatures (even within hidden-sector particle DM!) underscores the need for a multi-pronged search program.
- The required experiments are small — and realizing them will thoroughly explore broad paradigms for DM

# BACKUP

# the Vicinity of the Weak Scale

TeV

GeV

MeV

## SM Matter

$M_W$

$M_{proton} \sim M_{large} e^{-\#}$

(accidentally close to weak scale)

$m_e \sim \text{small } \# \times M_W$

(derived from weak scale)

## Dark Matter?

Looked here for decades!
Generic mass scale for matter with O(1) coupling to origin of EWSB

Where do we expect hidden-sector matter?

$\sim M_W \times e^{-\#}$

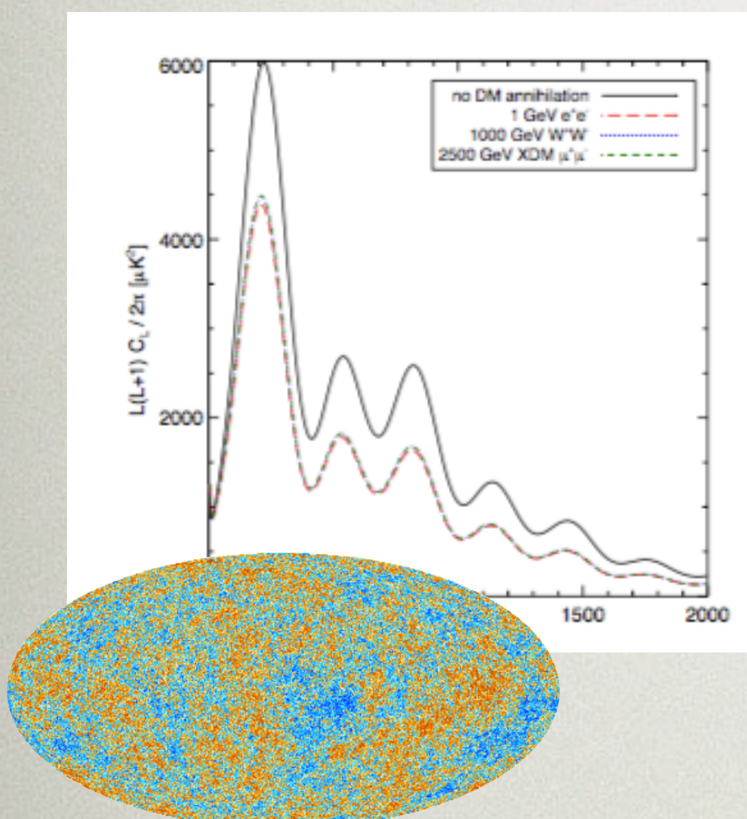
"hidden valley" → confined below weak scale

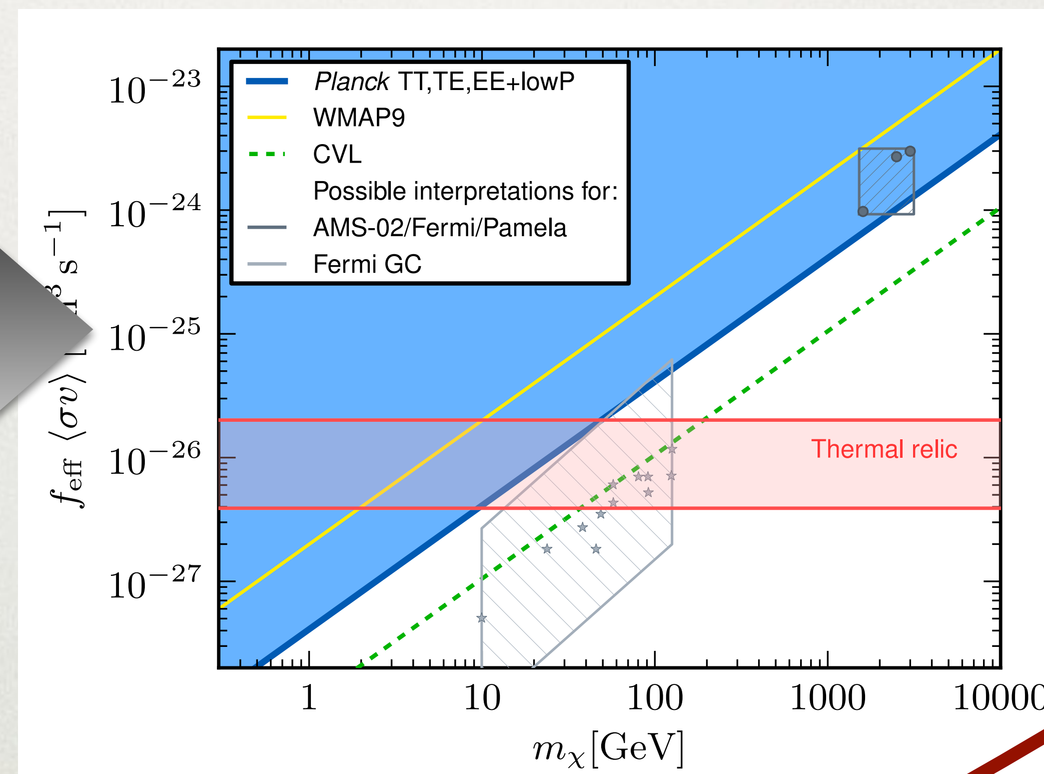
Radiatively generated Higgs-dark-scalar mixing

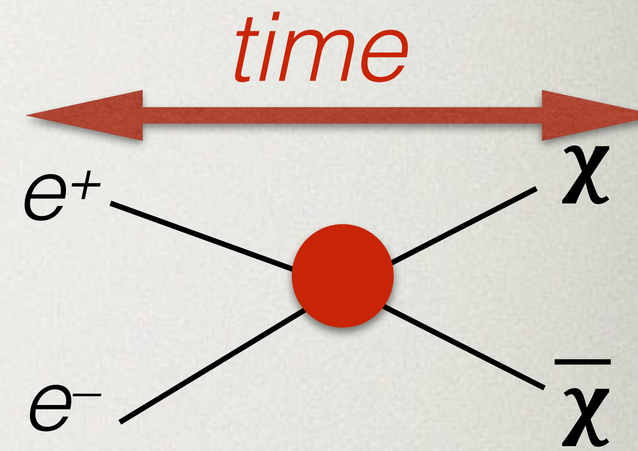
$\text{small } \# \times M_W$

# Looking for Thermal Dark Matter: Annihilation

Current best constraints from effect of DM annihilation on CMB power spectrum




Big Bang production

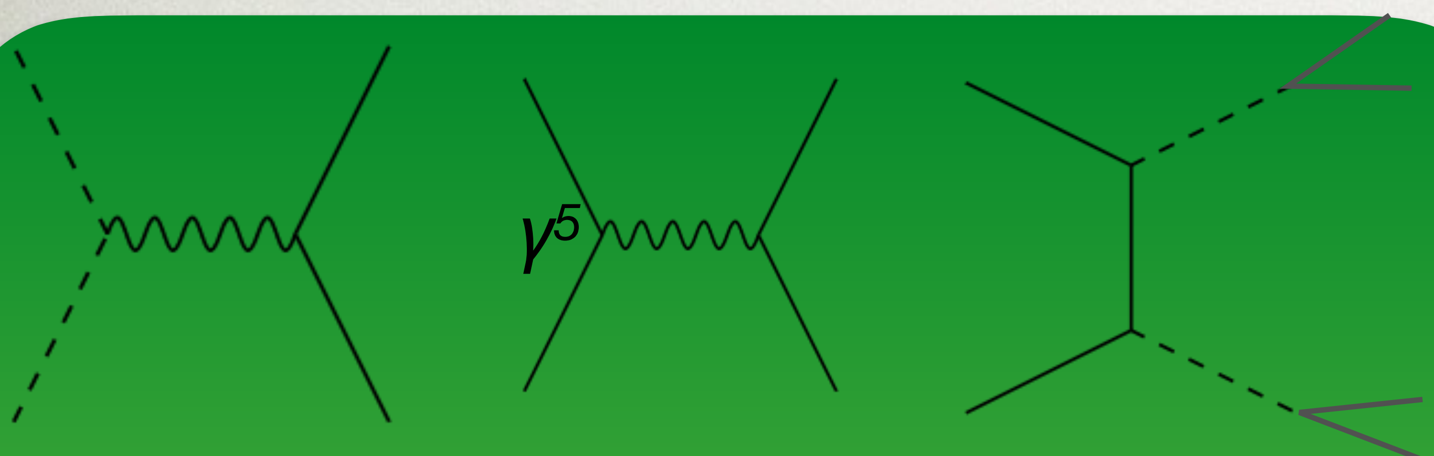
For ≲10 GeV DM, low-energy annihilation cross-section must be **substantially less** than thermal freeze-out cross-section $3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

# Dark Matter Annihilation

**Some DM spins and interactions have suppressed annihilation at low temperatures**

## $p$-wave annihilation

$\sigma_{\text{ann}} \sim v^2 \sim T/m_{\text{DM}}$



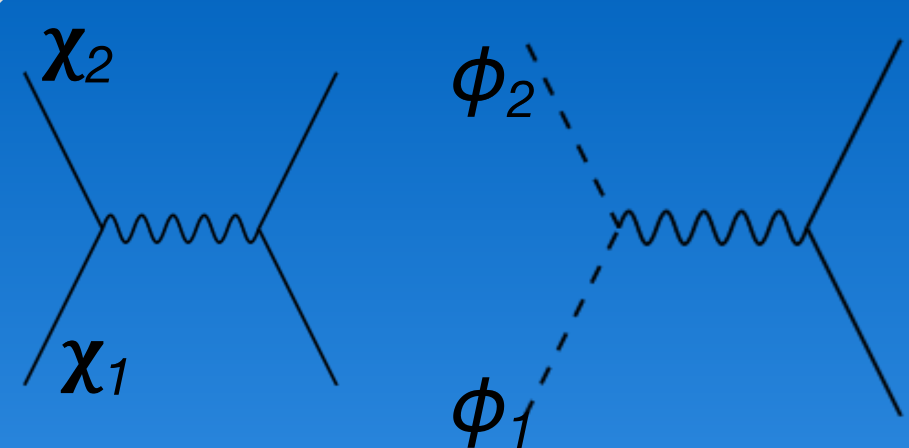

Scalar Majorana

Vector (or generalized) portal

Secluded annihilation to singlet scalars

## Inelastic (Co)annihilation

$\Gamma_{\text{ann}} \sim n_1 \boldsymbol{n_2} \sigma_{\text{ann}}$



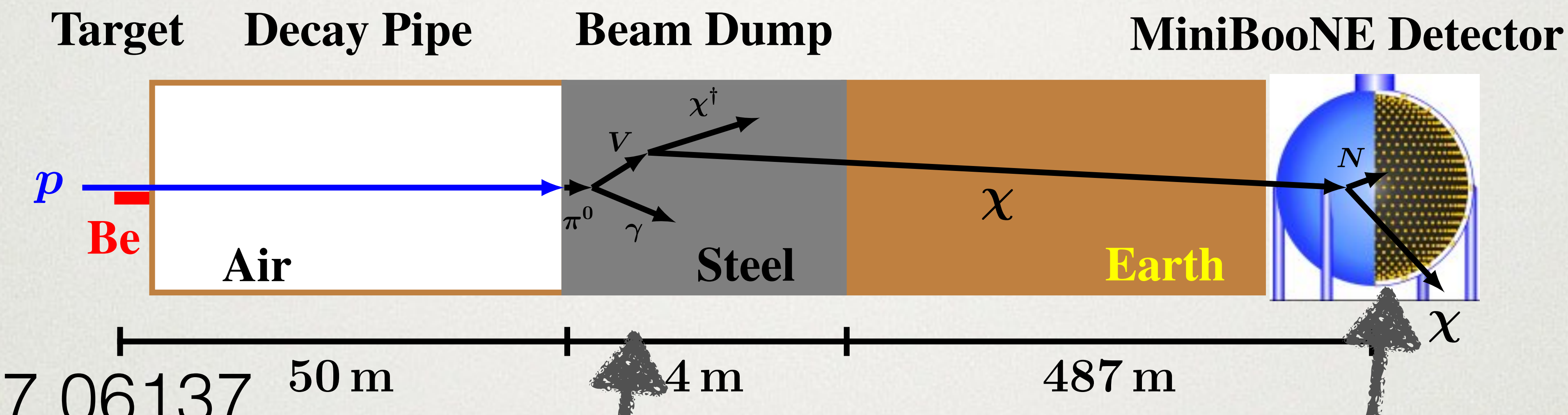

Pseudo-Dirac

Inelastic Scalar

*generic if DM has U(1)-breaking mass term*

# Dark Matter Beams

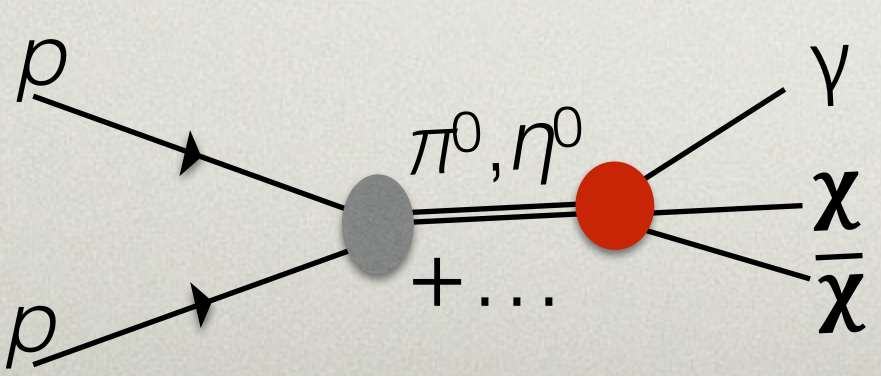
Already set powerful constraints - significant improvements possible with existing electron and proton beams, detectors

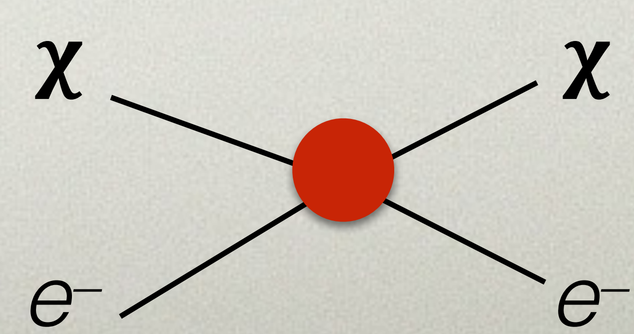



arXiv:1807.06137

Produce dark matter in dump

Look for (relativistic) scattering in detector

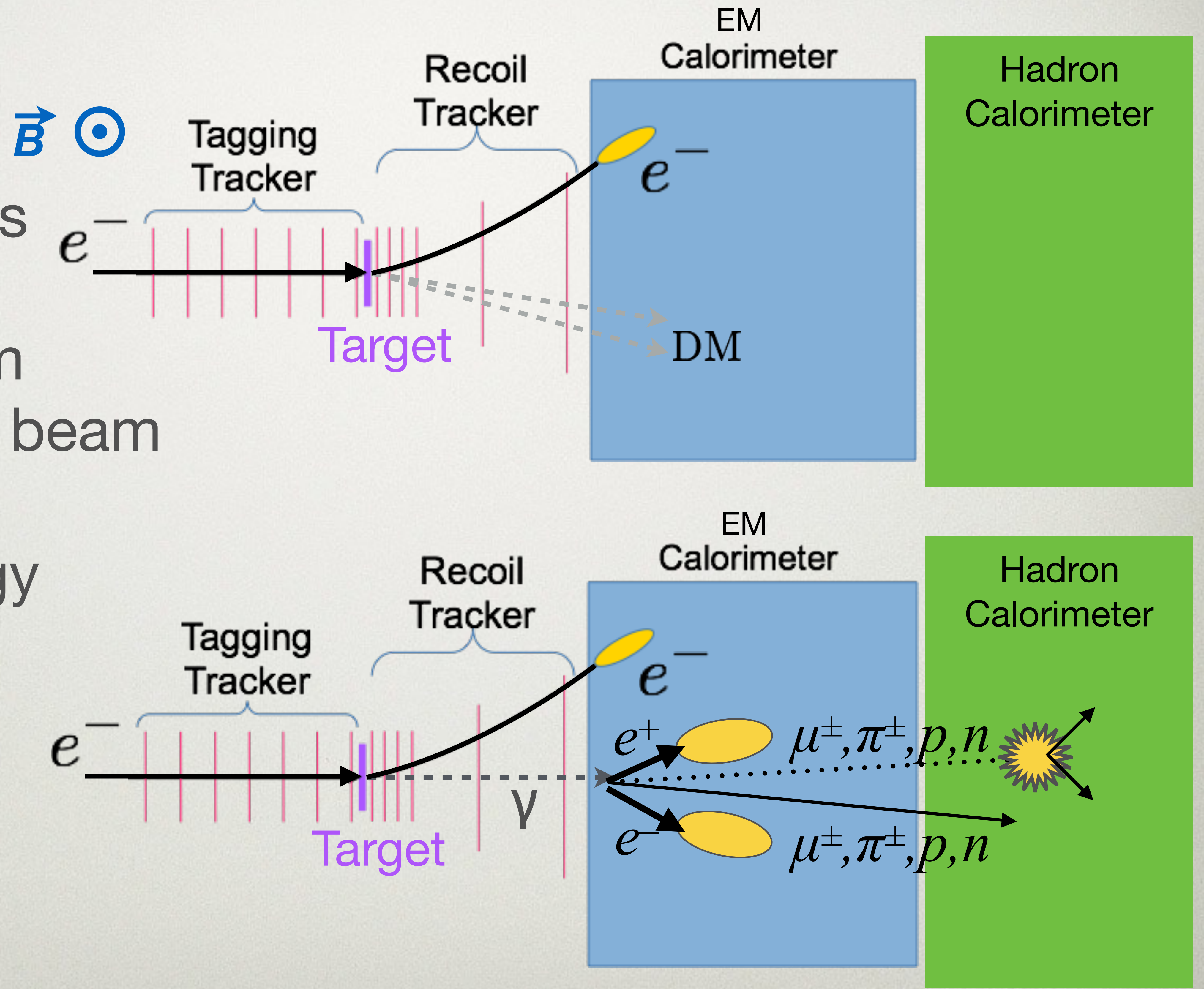


# Missing Energy/Momentum

**Signal:**

1) Energy loss and/or momentum transfer to beam electron,
2) **veto** energy deposits from other outgoing particles




See talk by J. Mans on LDMX

# Direct Deflection of DM