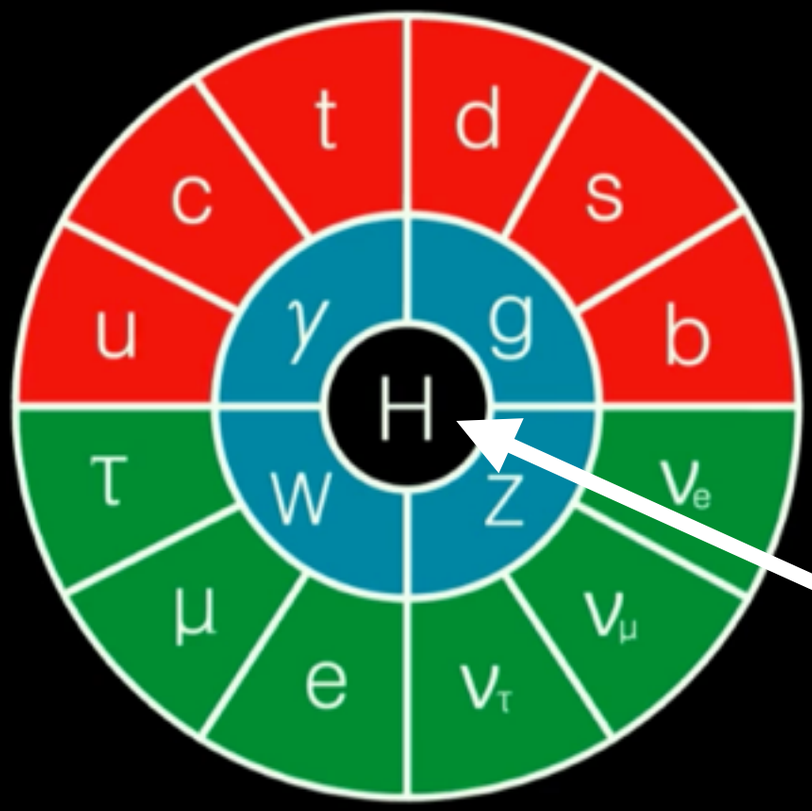
Light DM and Hidden Sectors
Extremely Biased Theory/Techniques Survey

Gordan Krnjaic

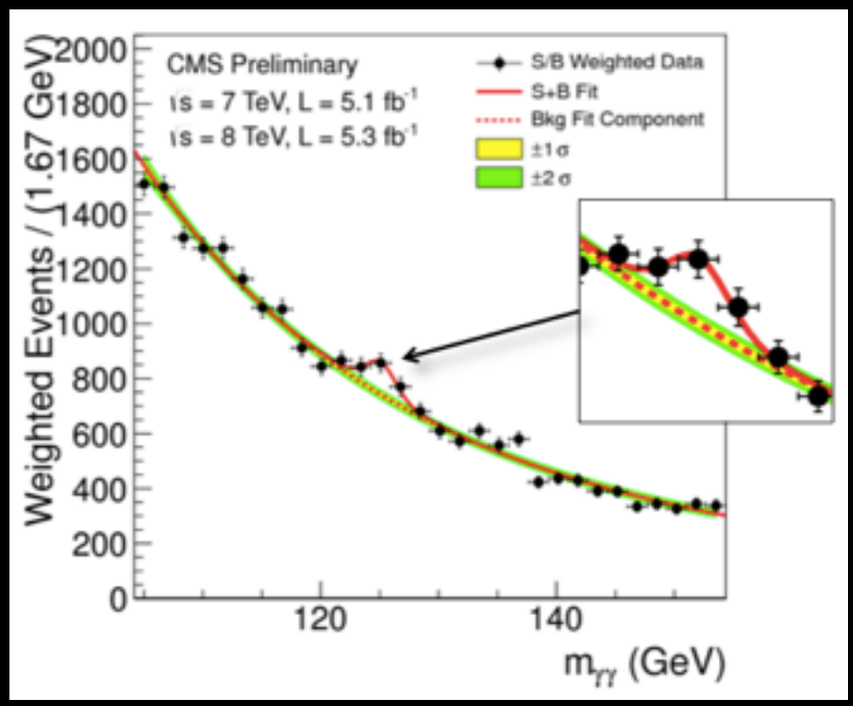
Hidden Sector Fixed Target Symposium 9/4/2019

The *Complete* Standard Model?

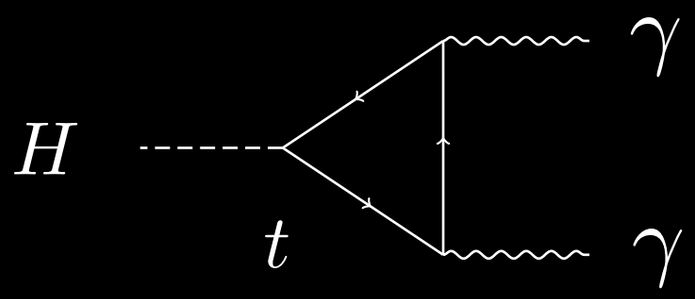


FERMIONS
MATTER
QUARKS
LEPTONS

BOSONS
FORCE CARRIERS
GAUGE BOSONS
HIGGS BOSON



Higgs looks very SM-like so far



No clear BSM discovery @LHC yet

NEWS IN BRIEF

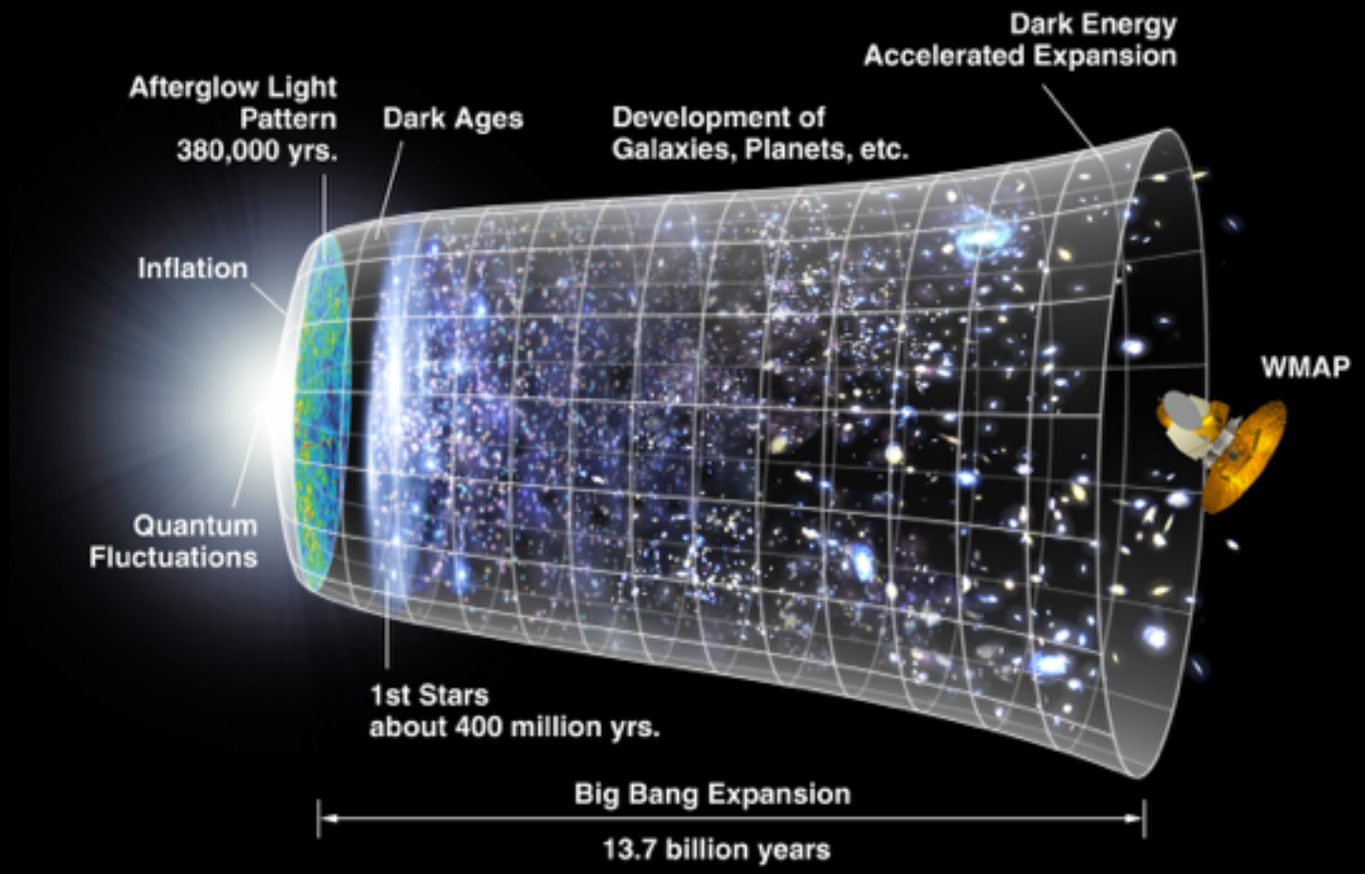
World's Physicists Complete Study Of Physics

1/14/10 9:00am • SEE MORE: SCIENCE & TECHNOLOGY

HARIMA, JAPAN—Saying that there was no more knowledge to acquire about the physical nature of the universe, the International Union of Pure and Applied Physics announced Monday that it had concluded the scientific study of matter, energy, force, and motion. "Yeah, that about does it for physics," said IUPAP member Sukekatsu Ushioda, powering down Japan's Super Photon ring particle accelerator. "All done. Math can pretty much take it from here." The world's top physicists also announced that they would celebrate the conclusion of physics by meeting at PJ's Pub later tonight for drinks.

the ONION®

Until We Consider Cosmology



Assumptions

General Relativity

Isotropy

Homogeneity

Inputs

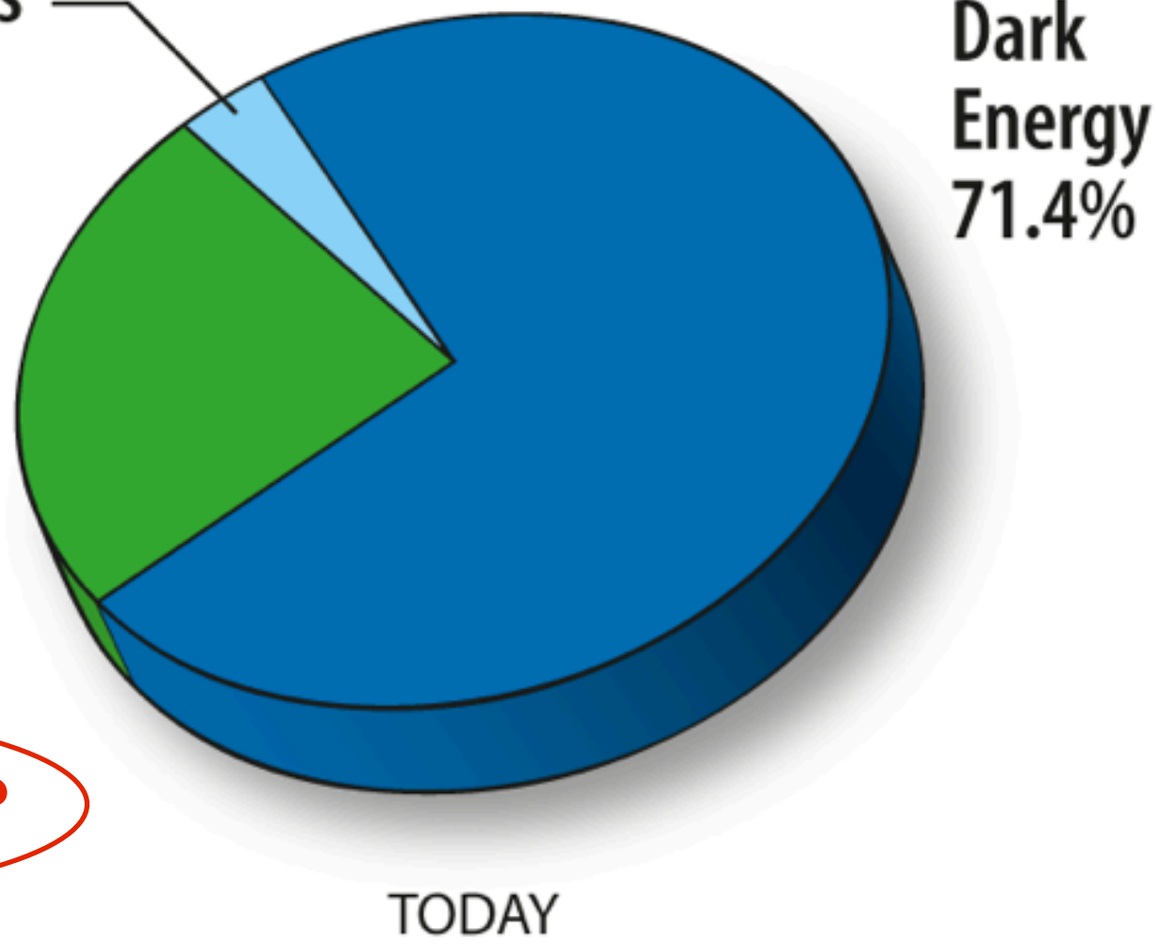
Energy Densities { Gravitating Matter, Interacting Matter
Radiation, Vacuum Energy, Curvature

Image: WMAP

Open Questions in Fundamental Physics

Neutrino Masses
Matter Asymmetry
Inflation

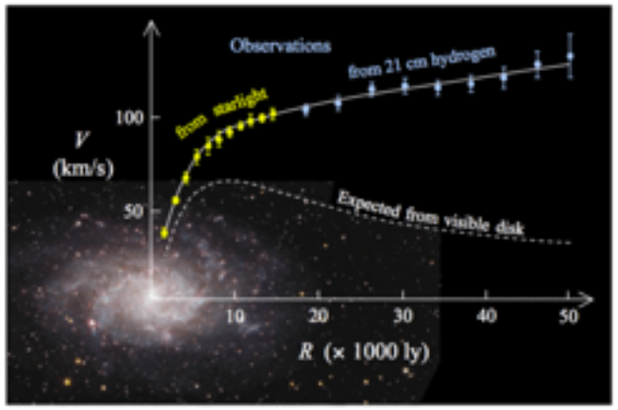
Accelerated Cosmic Expansion



What is this stuff?

Also Quantum Gravity

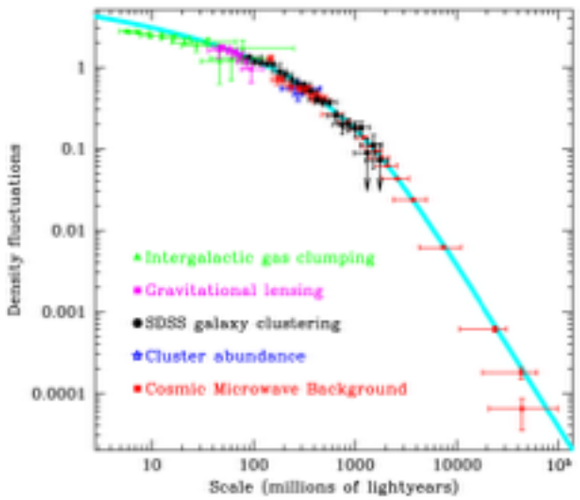
Remarkable Evidence for Dark Matter



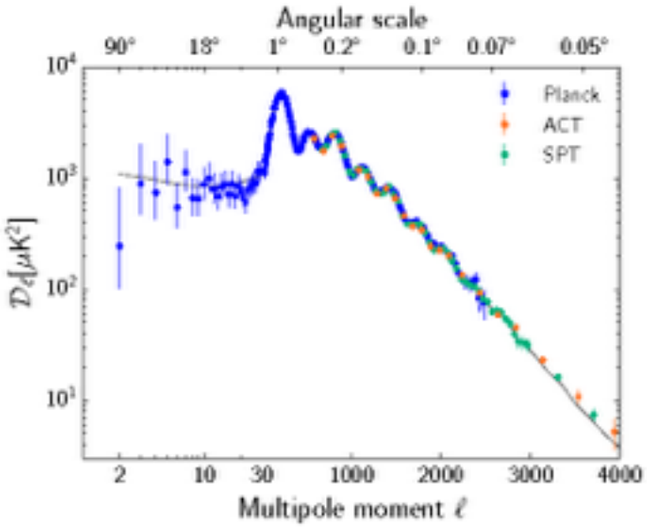
Rotation Curves

Gravitational Lensing

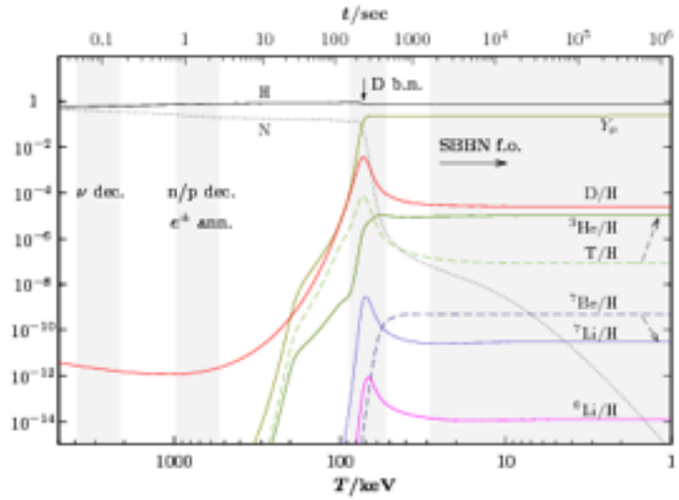
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum

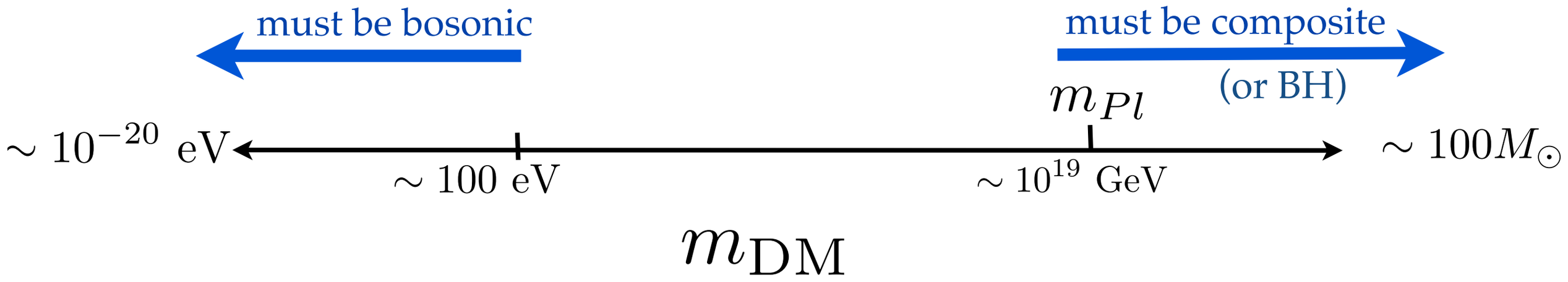


BBN Light Element Yields

Multiple independent, consistent observations
over **nearly** all of spacetime: kpc-Gpc, 13.7 Gyr ago-today

Holy Grail: extend our knowledge to terrestrial scales << kpc

What Clues Do We Have?



Huge space of allowed microscopic theories

Evidence only extends down to ~kpc (dwarf galaxy) scales

Theoretical guidance is essential

Need organizing principle for systematic progress

Overview

1) Why thermal DM?

2) Direct annihilation: **thermal targets**

3) “Hidden” annihilation: **visible decay searches**

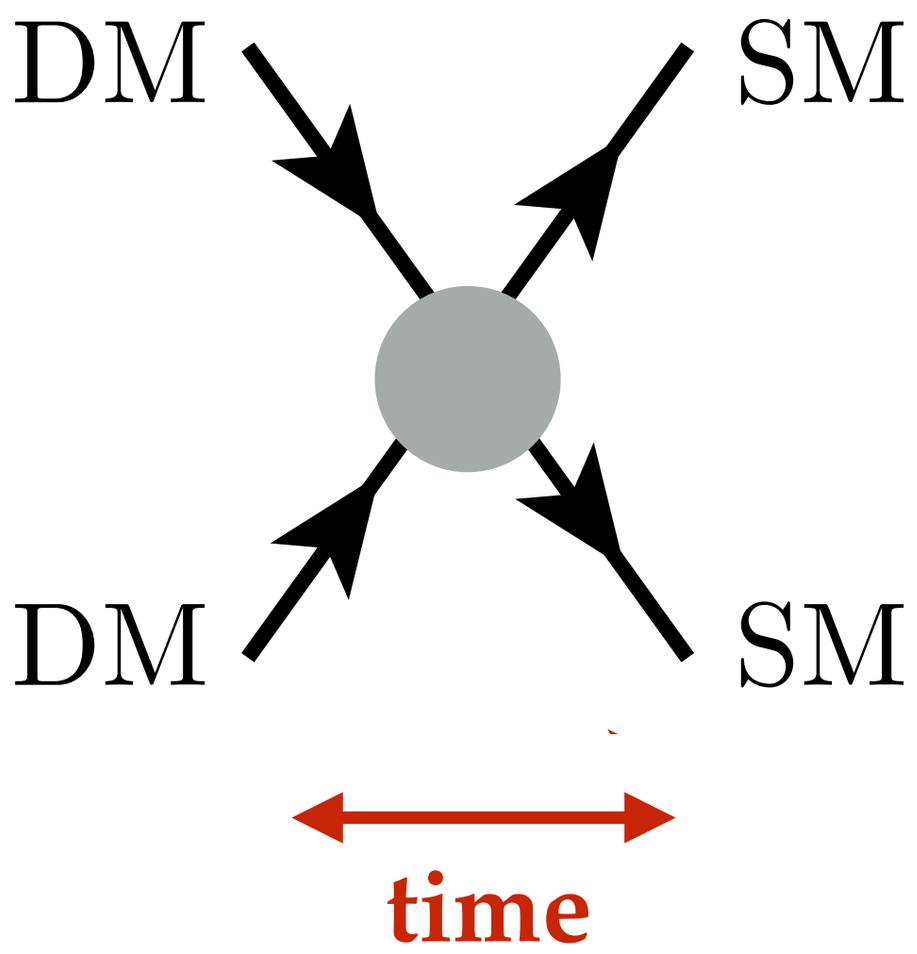
Overview

1) Why thermal DM?

2) Direct annihilation: **thermal targets**

3) “Hidden” annihilation: **visible decay searches**

Was DM ever in equilibrium with SM?



Chemical equilibrium: equal production/annihilation rates

Was DM ever in equilibrium with SM?

NO

How was it populated?

Initial conditions

Axion / ALP

WIMPzilla

Primordial BH

⋮

Rarely predictive

Was DM ever in equilibrium with SM?

NO

How was it populated?

Feeble coupling to us

Sterile Neutrino

Freeze In

SuperWIMP

⋮

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

too much stuff

$\sum \Omega_{\rm dark} > \Omega_{\rm DM}$

Light

$N_{\rm eff} > 3$ 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

If SM-DM equilibrium was **ever** achieved in early universe

$\Longrightarrow$ initial DM entropy must* be converted to SM particles

This simple fact has many remarkable consequences…

Q: What's so great about equilibrium?

A: Generic and easily achieved

Compare interaction rate to Hubble expansion

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

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

Equilibrium is reached in the early universe if

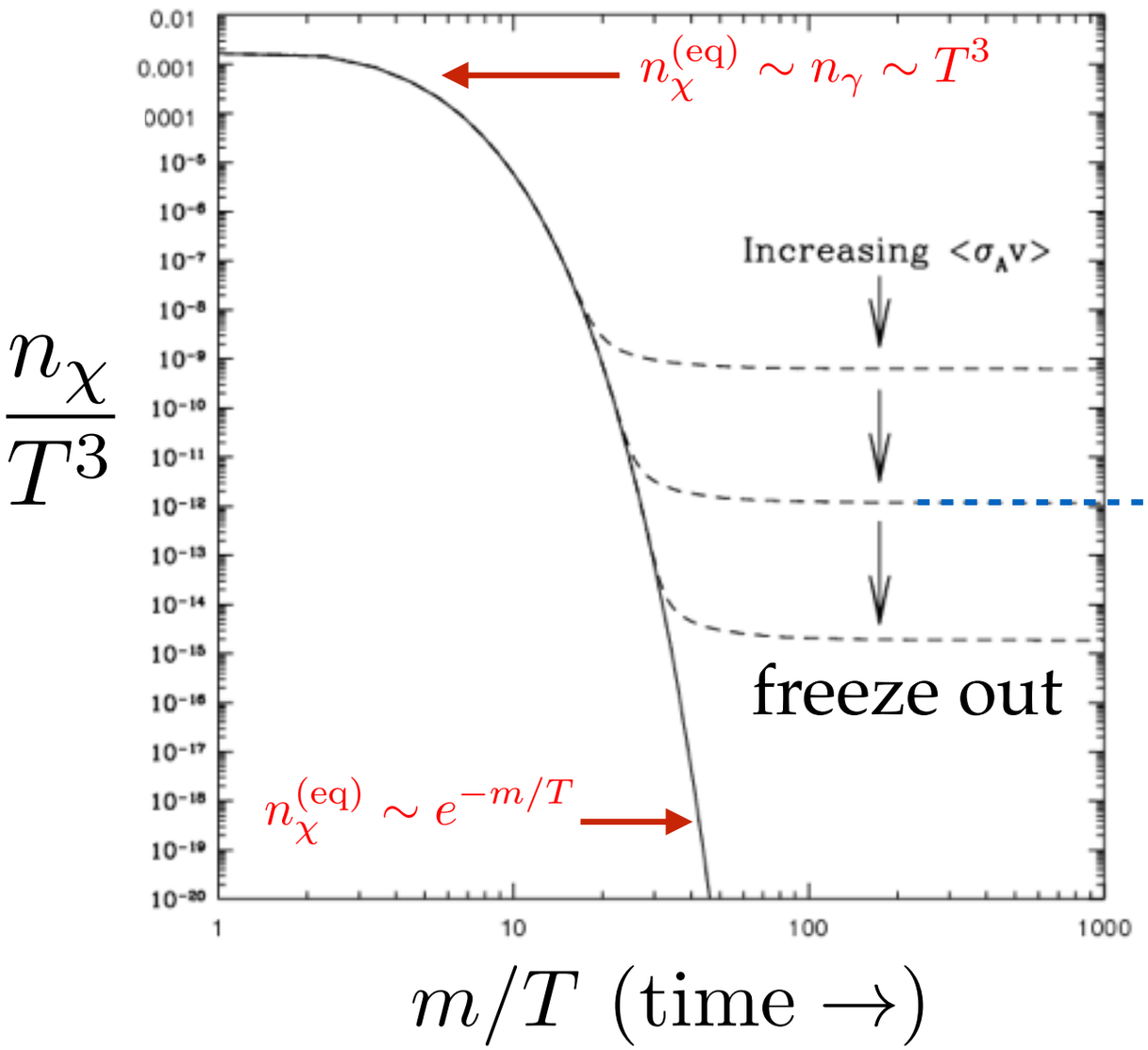
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Nearly all* models testable at accelerators were in equilibrium

Q: What's so great about equilibrium?

A: Minimum annihilation rate

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



$\frac{n_\chi}{T^3}$

m/T (time $\rightarrow$)

Griest et. al. 1992

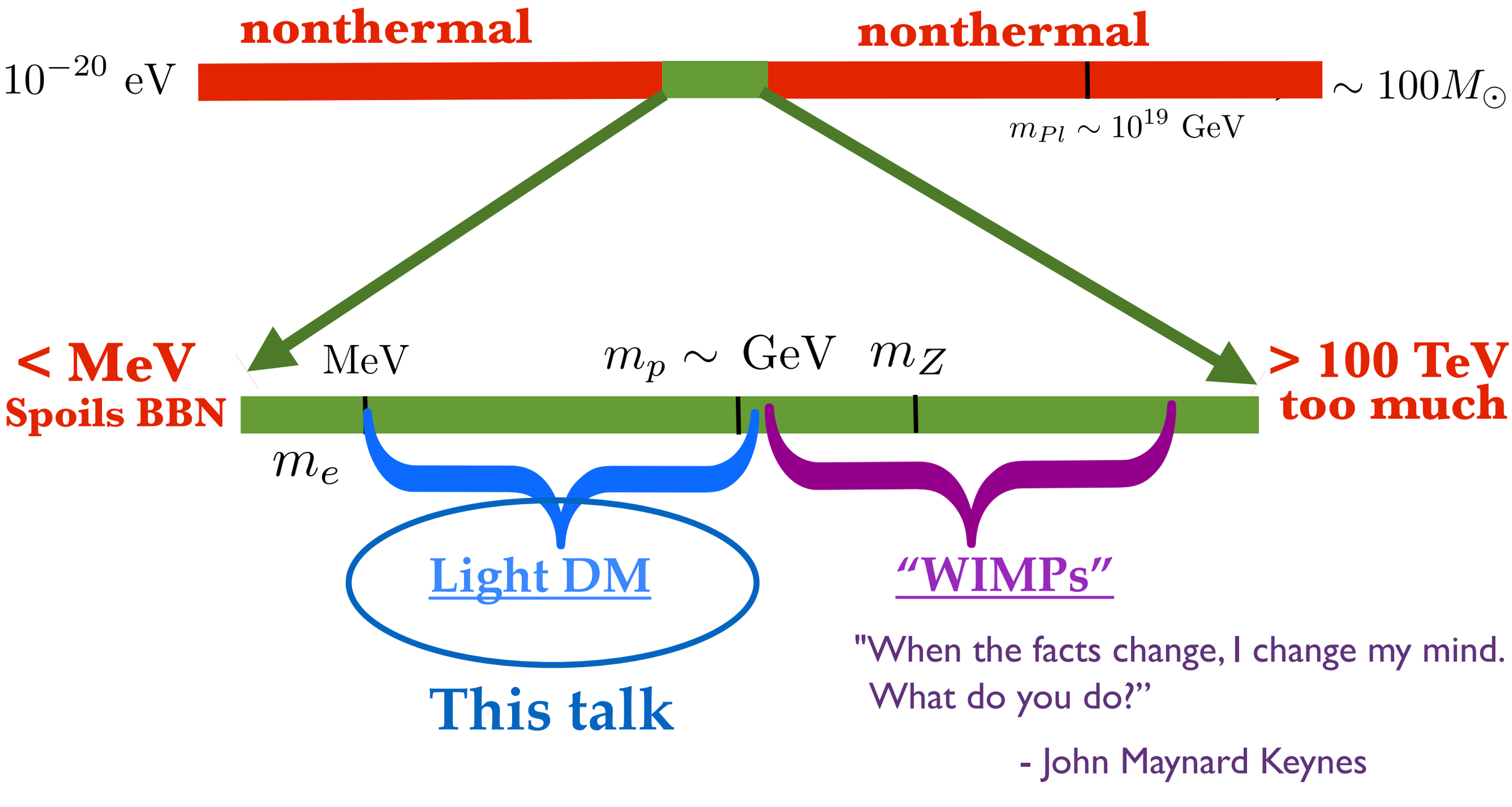
Initial condition calculable &
Insensitive* to unknown BSM

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

Much larger than the rate
to reach equilibrium initially!

Q: What's so great about equilibrium?

A: Narrows Viable Mass Range (!)



"When the facts change, I change my mind. What do you do?"

- John Maynard Keynes

Light DM vs. WIMPs

LDM must be neutral under SM

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

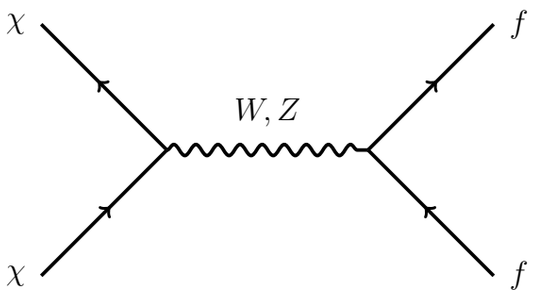
Light DM vs. WIMPs

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"



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

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

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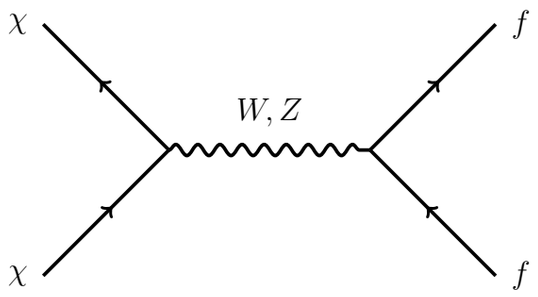

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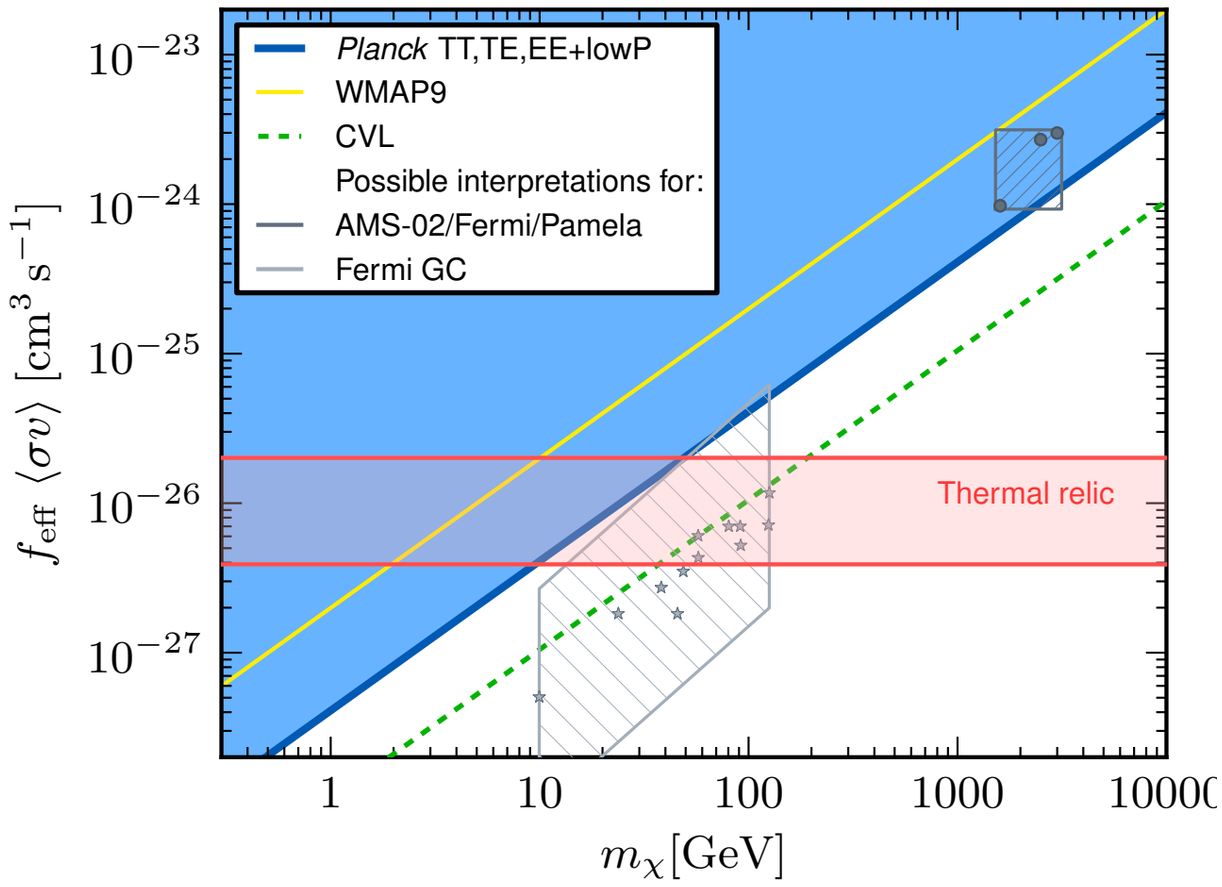
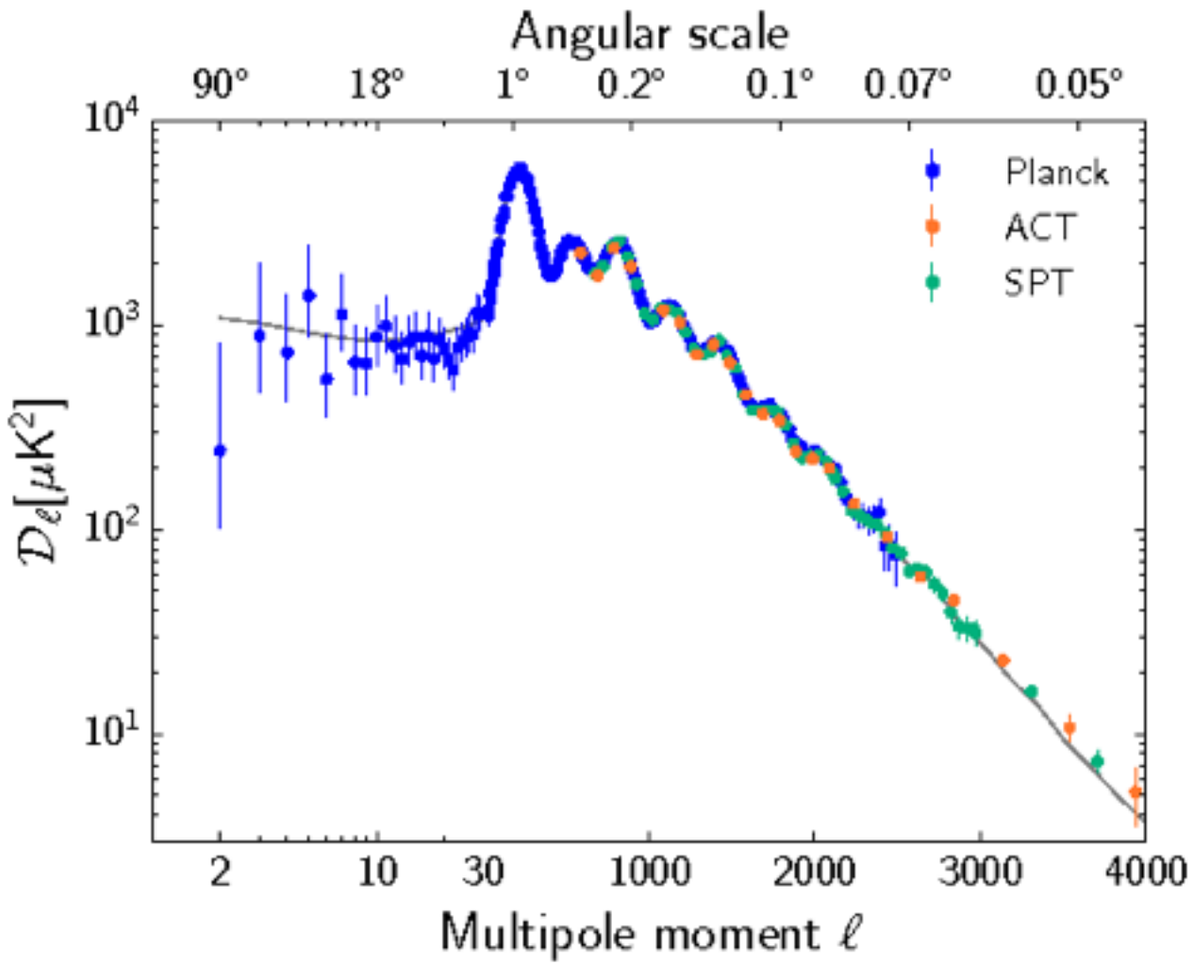
Lee/Weinberg '79

LDM interactions renormalizable at accelerator energies

Else rate too small — greatly simplifies space of possible theories

Light DM vs. WIMPs





Planck Collaboration 1502.01589

Rare out-of-equilibrium annihilation ionizes hydrogen @ CMB

CMB photons pass through extra plasma = bad

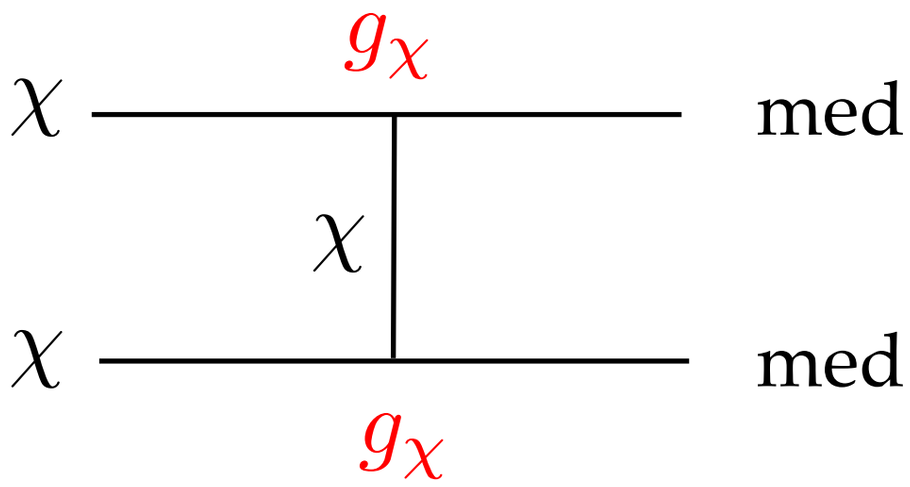
Rules out **s-wave** relic cross section for DM < 10 GeV

No indirect detection for viable models!

Who's Heavier: DM or Mediator?

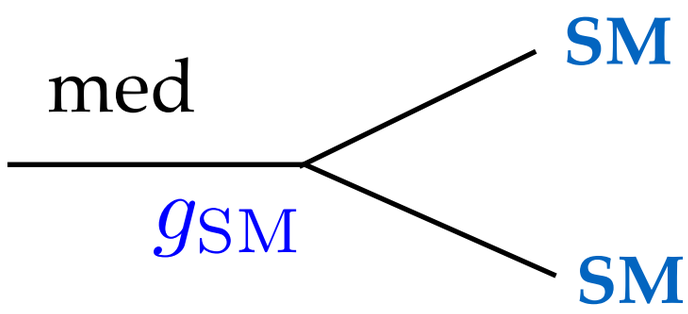
Hidden Annihilation

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



No clear experimental target

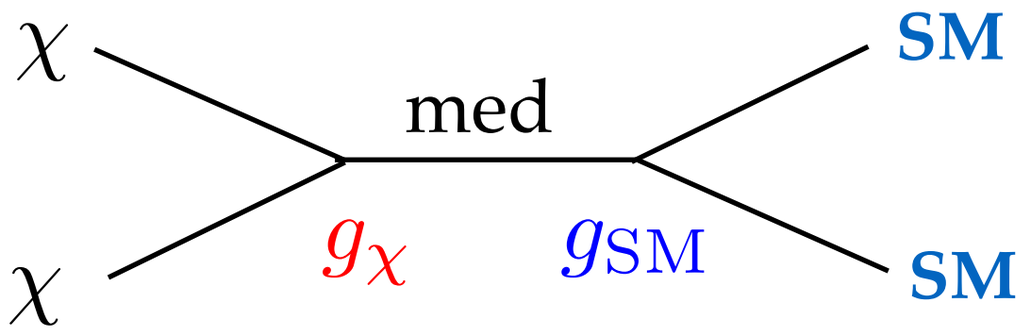
Abundance set by g_χ



Mediator decays to **SM**

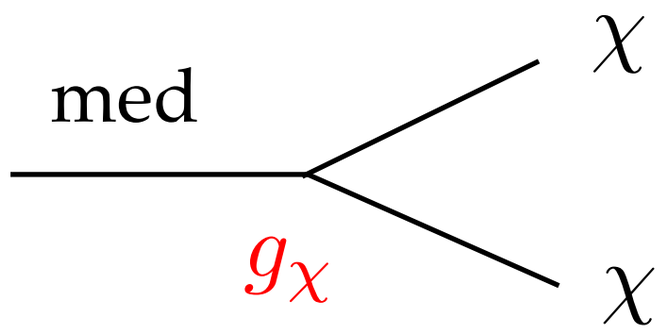
Direct Annihilation

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



Predictive thermal targets

Abundance depends on $g_{\rm SM}$



Mediator decays to **DM**

Was DM ever in equilibrium with SM?

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

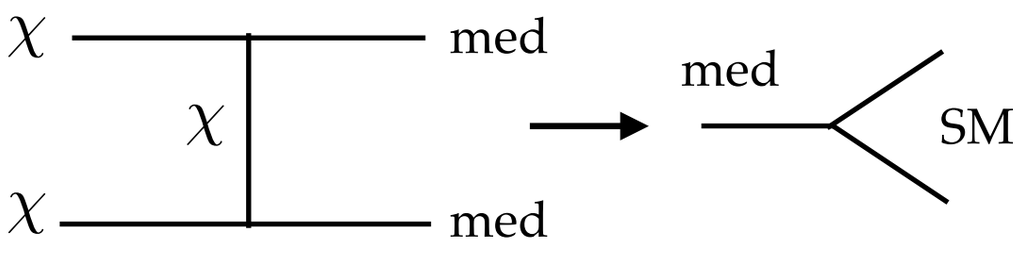
Where did its density go?

Visible matter

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

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

Hidden Annihilation

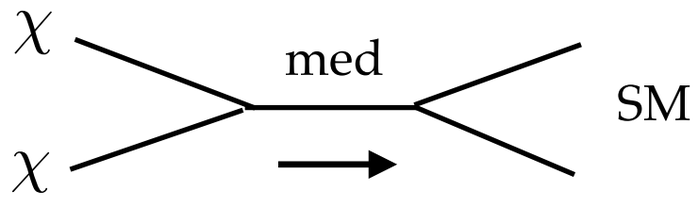


Two step process

Hard to test DM origin

Can discover mediator if lucky

Direct Annihilation



One step process

Density set by SM coupling

Clear experimental targets

Was DM ever in equilibrium with SM?

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

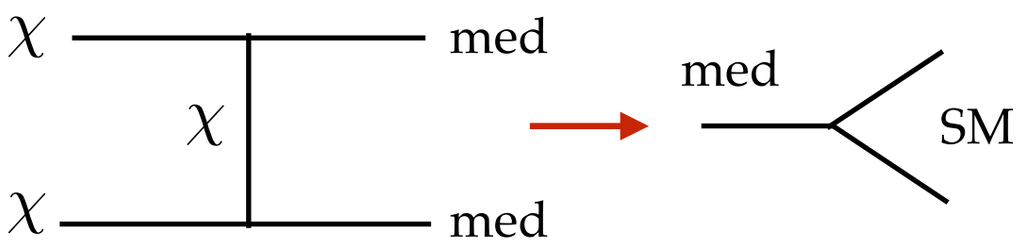
Where did its density go?

Visible matter

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

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

Hidden Annihilation



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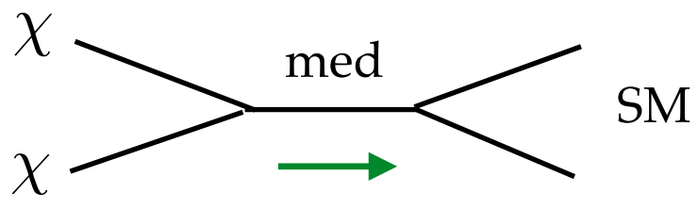


One step process

Density set by SM coupling

Clear experimental targets

Overview

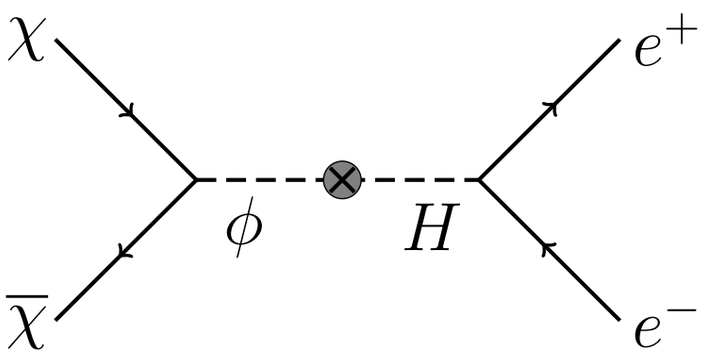
1) Why thermal DM?

2) Direct annihilation: thermal targets → **Theory**, Searches

3) "Hidden" annihilation: **visible decay searches**

4) Fixed targets **beyond DM** (millicharges,LLPs…)

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

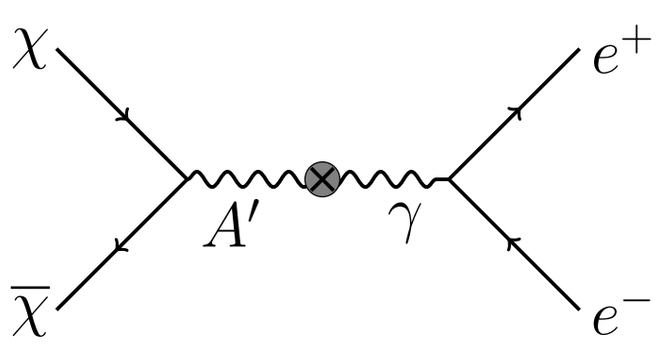


$\epsilon\, \phi H^\dagger H$

Neutral scalar
Mass mix w Higgs

$\rightarrow \epsilon \phi \dfrac{m_f}{v} \bar{f} f$

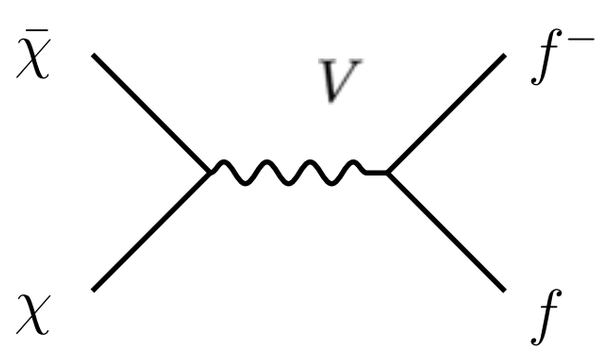
after EWSB



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

Dark photon A'
Kinetic mixing w/ γ

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



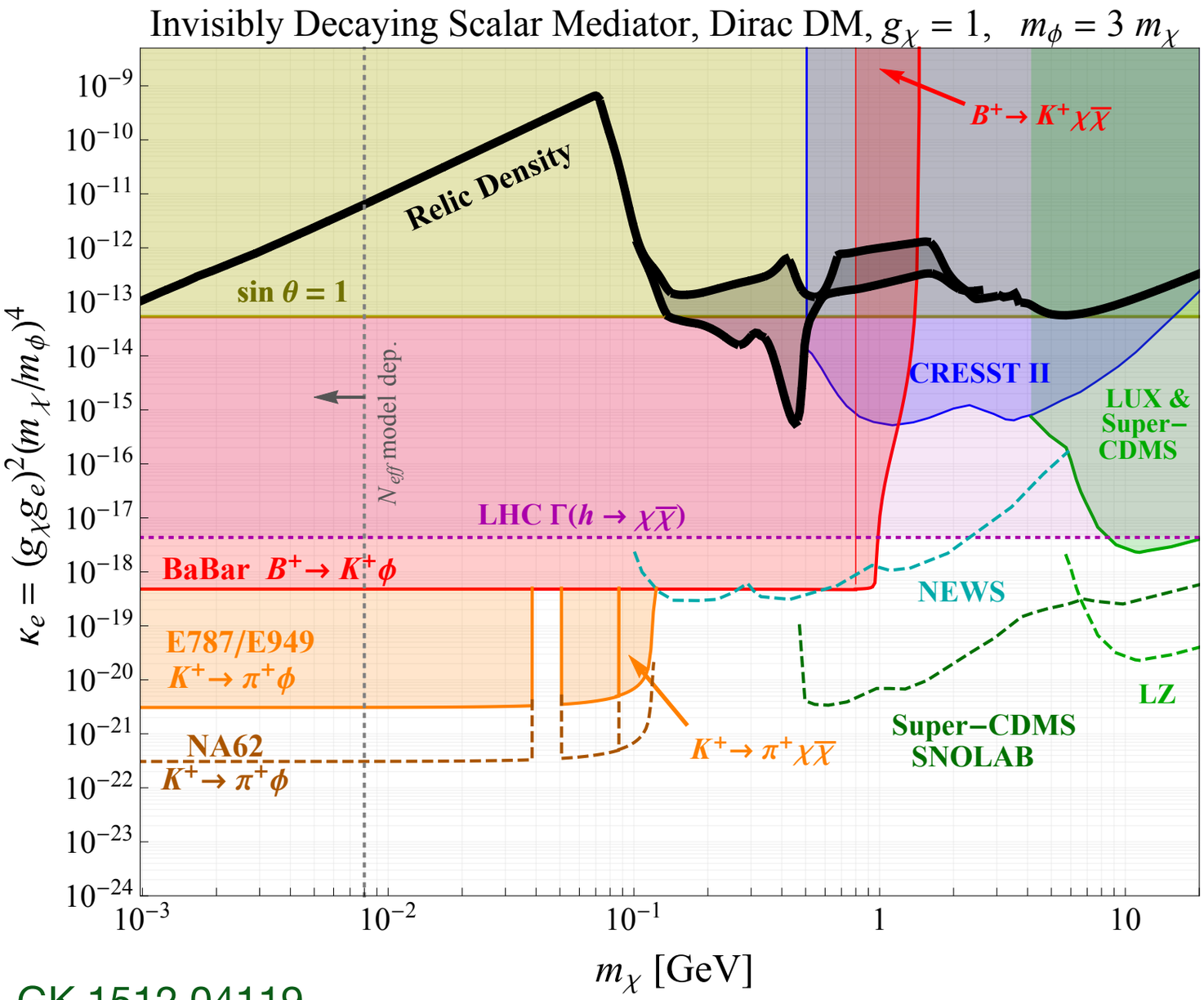
$V_\mu J^\mu_{\rm SM}$

Gauge known global quantum number

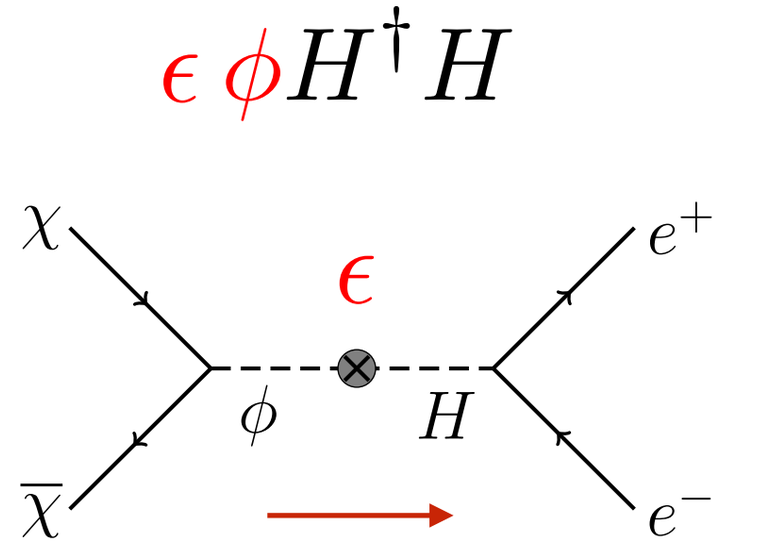
$U(1)_{B-3L_i}$
$U(1)_{B-L}$
$U(1)_{L_i-L_j}$

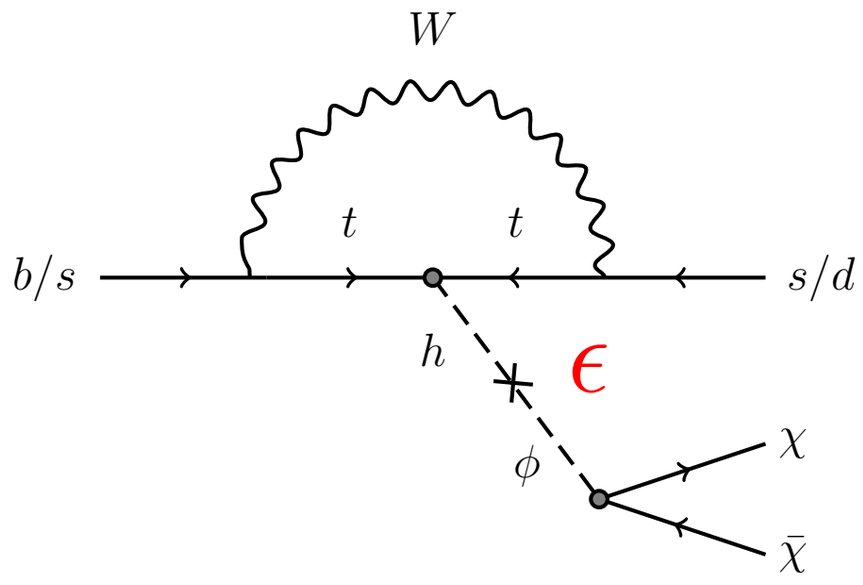
Complete list of renormalizable, anomaly-free options

Scalar-mediated direct-annihilation ruled out!



GK 1512.04119

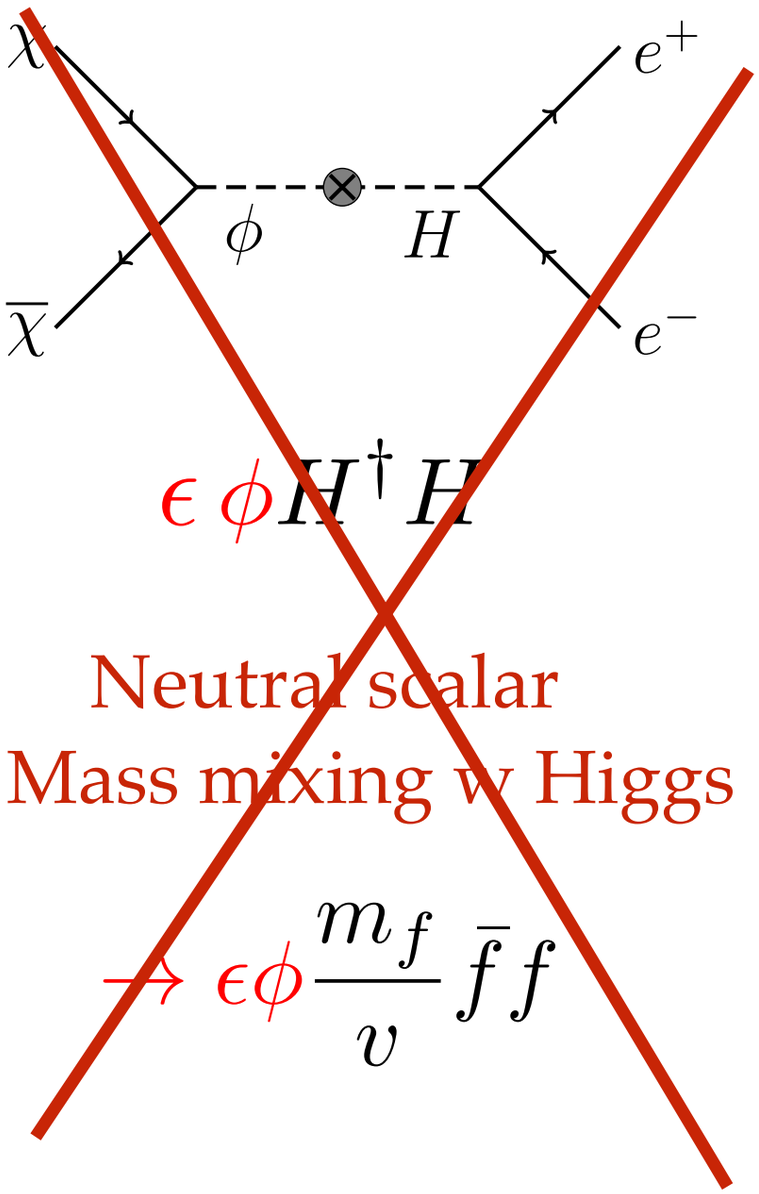




Conclusion independent of DM candidate

See Kelly, Zhang 1901.01259 for exceptions where scalar mediator interacts mainly with neutrinos

What kind of mediator for direct annihilation?

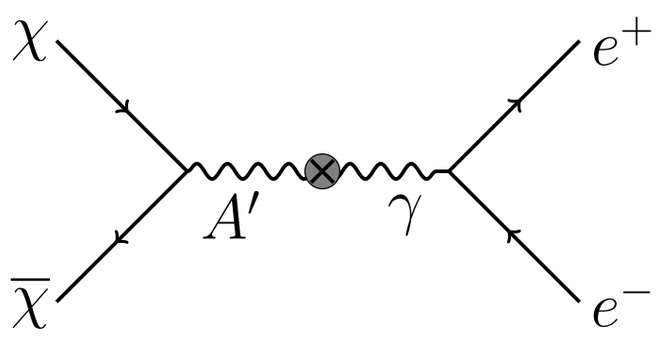


$\epsilon\, \phi H^\dagger H$

Neutral scalar
Mass mixing w Higgs

$\rightarrow \epsilon\phi \dfrac{m_f}{v} \bar{f} f$

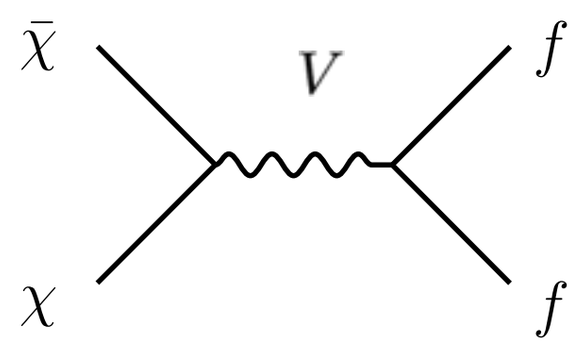
Direct annihilation
Ruled out



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

Dark photon A'
Kinetic mixing w / γ

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



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

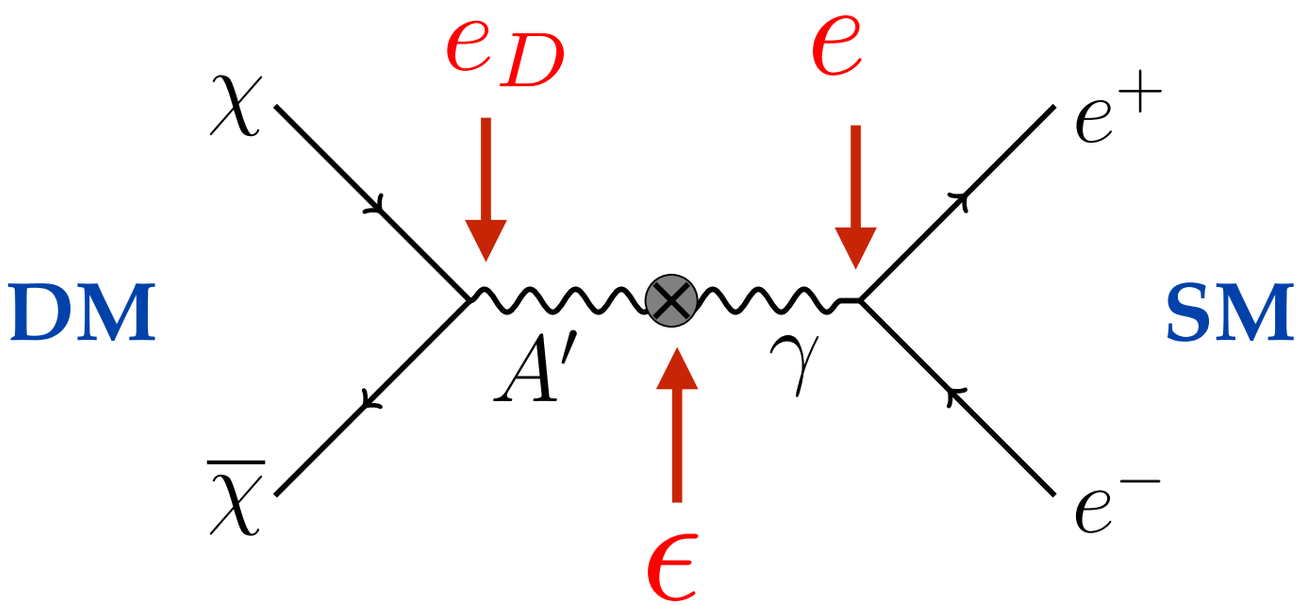
Gauge known global quantum number

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

Similar pheno, some minor differences

Representative Model: Dark Photon Mediator A'

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

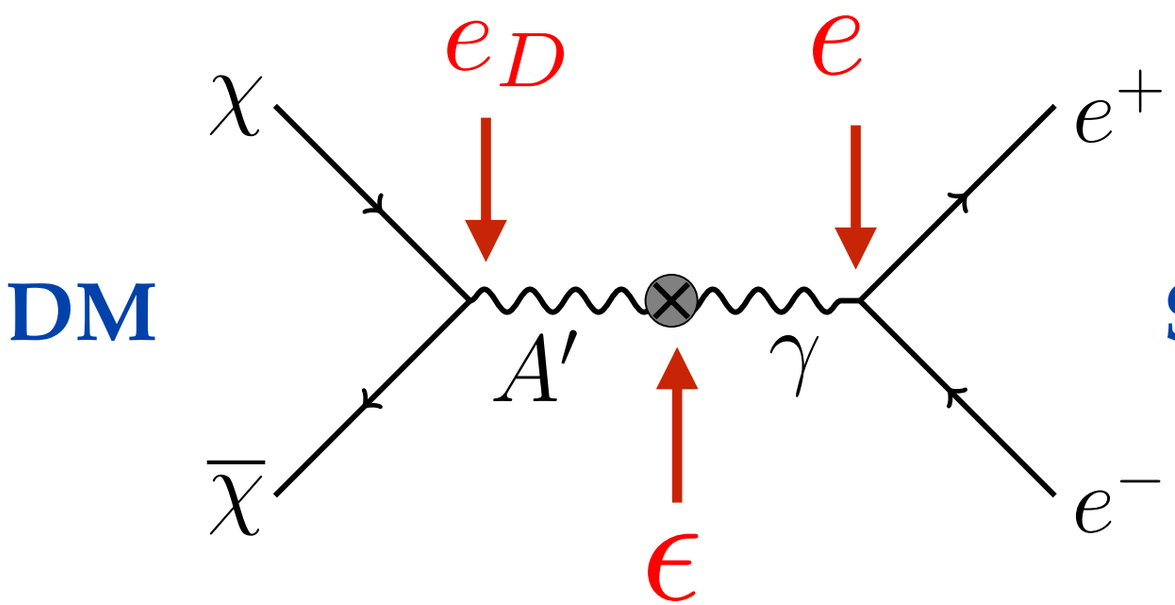
$$\mathcal{L} = -\frac{1}{4} F'_{\mu\nu} F'_{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu J^\mu_\chi + \epsilon A'_\mu J^\mu_{\rm EM}$$

Not the only model, but qualitatively similar to other 5th forces

Main difference : $J^\mu_{\rm EM} \to J^\mu_{B-L}$, $J^\mu_{L_i - L_i} \cdots$

Representative Model: Dark Photon Mediator A'

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

Critical freeze out value of y for each DM candidate

$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Direct annihilation $m_{A'} > m_\chi$ Unitarity $\alpha_D \lesssim 1$

$\Longrightarrow$ Minimum SM coupling ϵ required for thermal freeze out

Finite list of CMB-safe DM candidates

$$\mathcal{L} \supset g_D A'_\mu J^\mu_\chi$$

$$J^\mu_\chi = \begin{cases} \overline{\chi}\gamma^\mu\chi & \text{Asym. Dirac} \\ \overline{\chi}_1\gamma^\mu\chi_2 & \text{Pseudo}-\text{Dirac} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana} \\ i\chi^*\partial_\mu\chi & \text{Scalar} \end{cases}$$

$\overline{\chi}$ all annihilate away pre-CMB

no more **annihilation** partners

Heavier χ_2 decays pre-CMB

no more **coannihilation** partners

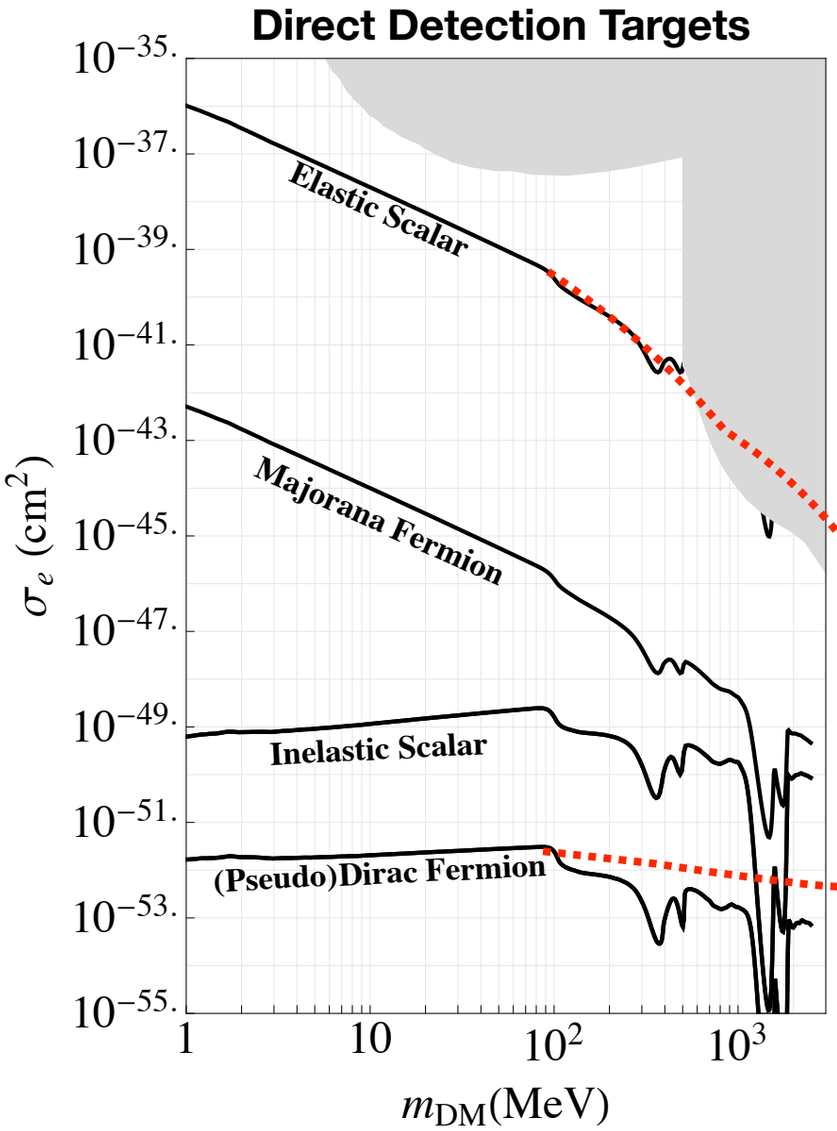
$\sigma v \propto v^2$ velocity redshifts

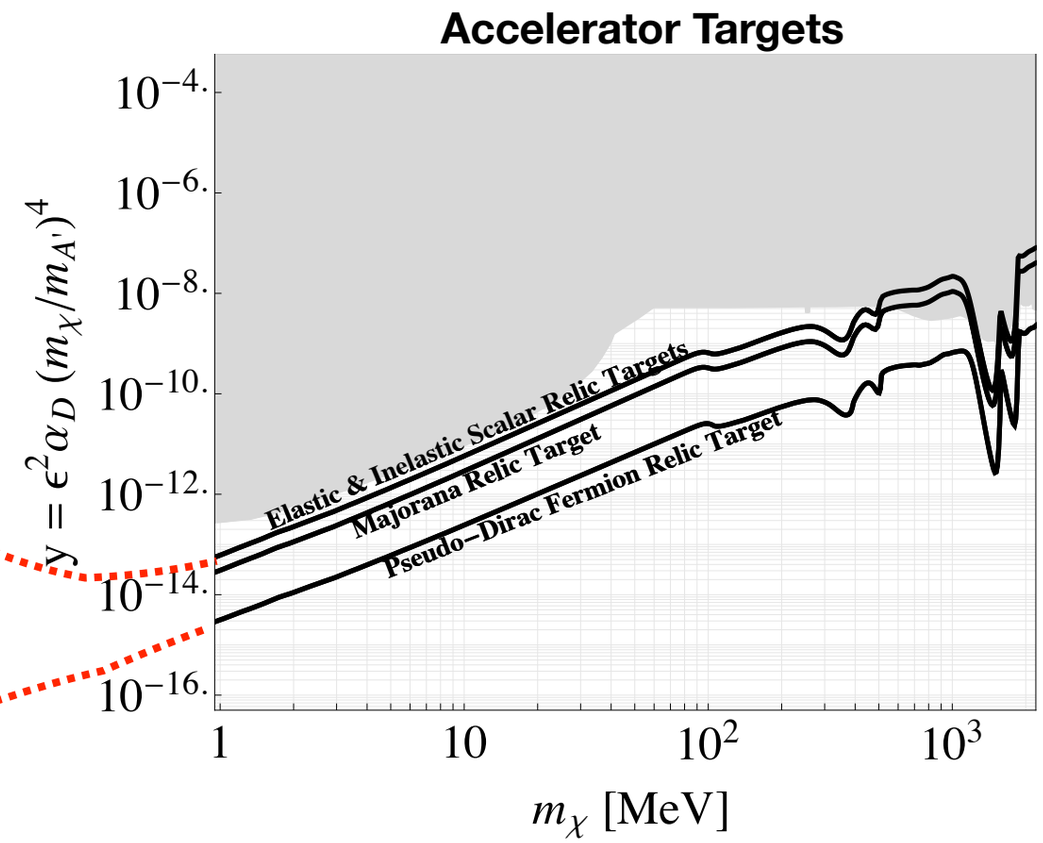
tiny annihilation rate at CMB

Safe models require either:

P-wave annihilation	**Different DM population @ CMB**
Scalar or Majorana	Asymmetric Dirac or Pseudo-Dirac

Why Accelerators? Accessible Thermal Targets





non-relativistic cross sections can be loop- or velocity- suppressed

Relativistic freeze-out kinematics

Calculable dark matter rate

No astrophysical uncertainties

Thermal targets within reach

Cosmic Visions Report https://arxiv.org/abs/1707.04591

Overview

1) Why thermal DM?

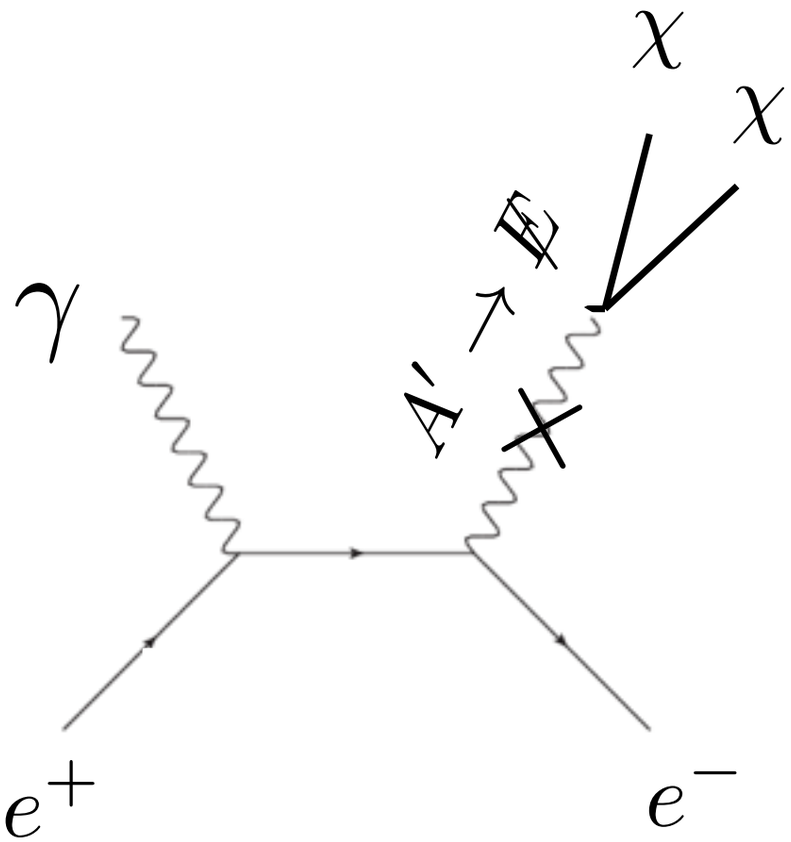
2) Direct annihilation: thermal targets → Theory / **Searches**

3) "Hidden" annihilation: **visible decay searches**

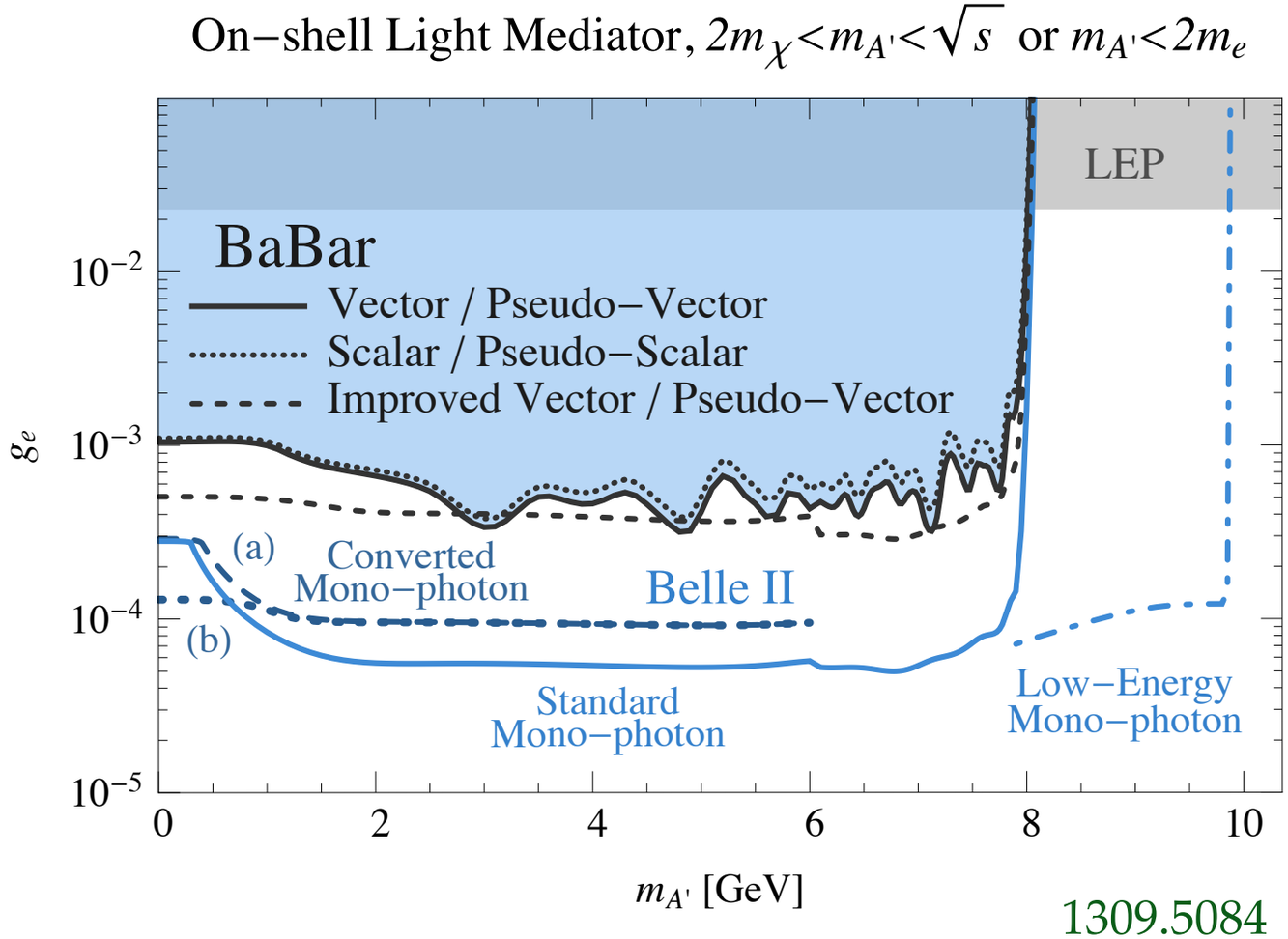
4) Fixed targets **beyond DM** (millicharges,LLPs…)

B-Factory Strategy

Mono photon missing energy bump search: BABAR, Belle II



$$m^2_{A'} = (p_\gamma - p_{e+} - p_{e-})^2$$



1309.5084

CM energy known ~ 10 GeV

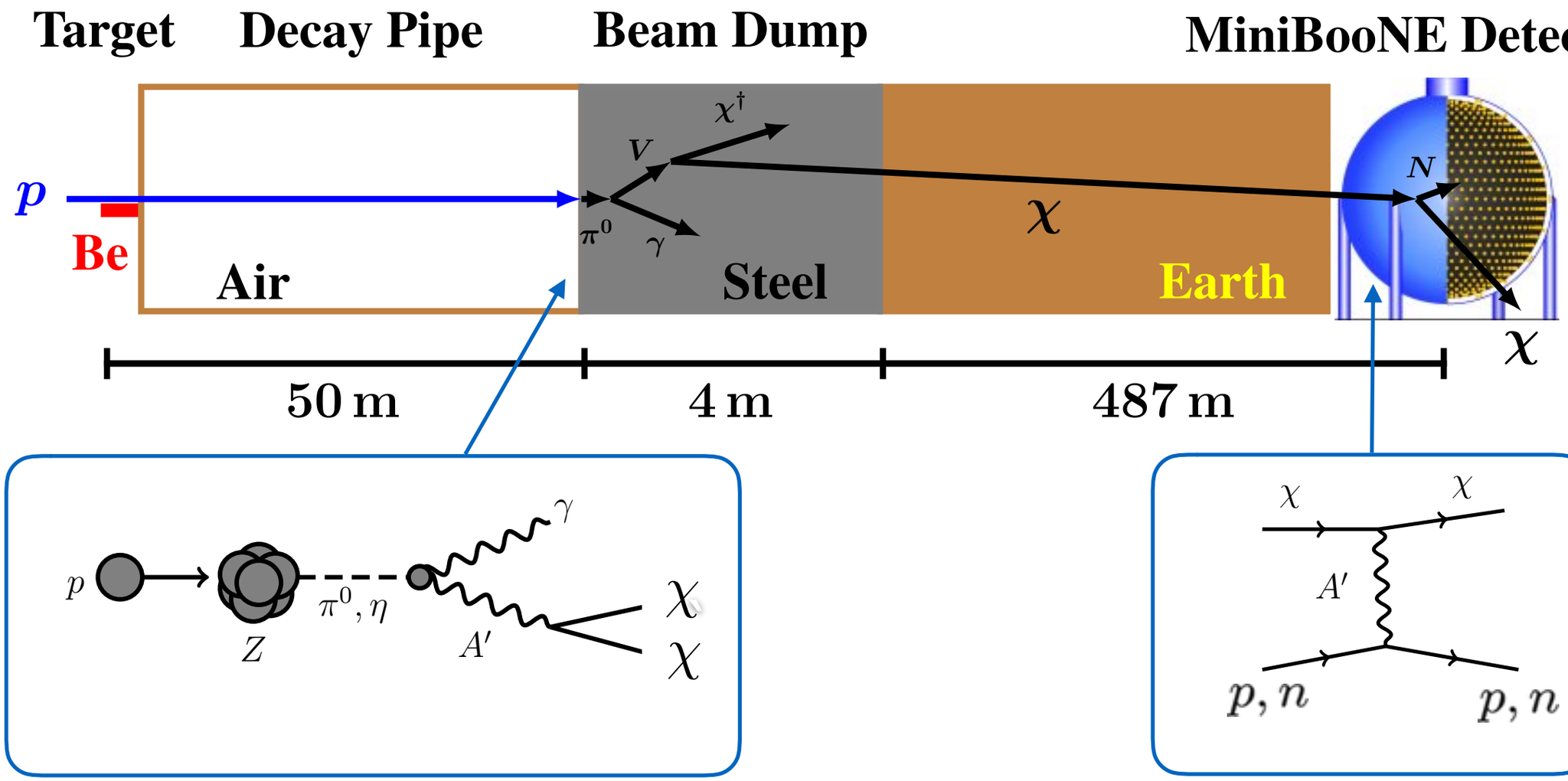
Izaguirre, GK, Schuster, Toro 1307.6554

Essig, Mardon, Papucci, Volansky Zhong 1309.5084

BABAR Collaboration arXiv:1702.03327

Beam Dump Strategy

"Relativistic direct detection" Existing bounds from LSND, E137, MiniBooNE



Step 1: Make relativistic DM in target

Step 2: DM scatters in detector

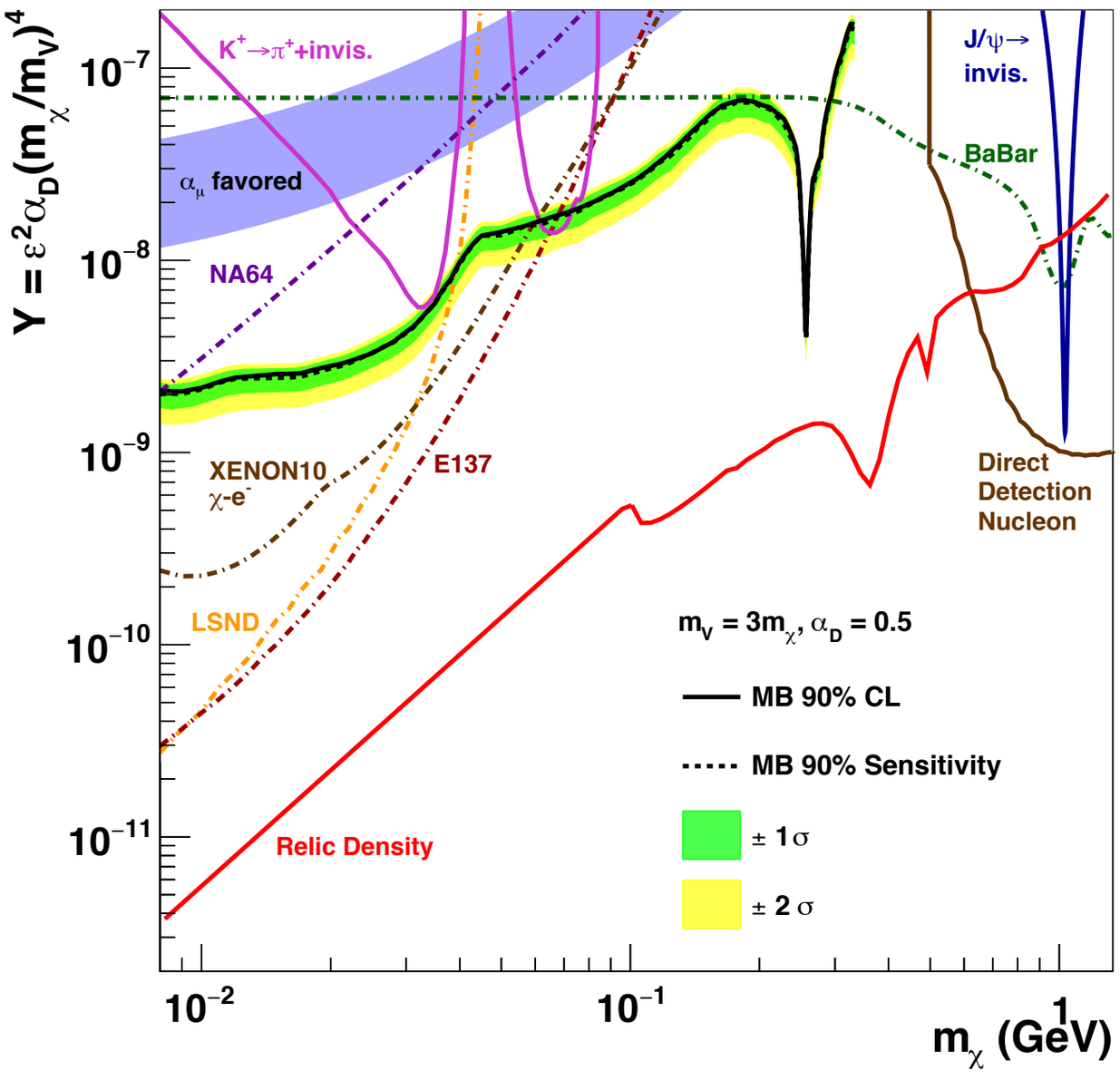
Batell, Pospelov, Ritz 0903.0363
deNiverville, Pospelov, Ritz 1107.4580
Izaguirre, GK, Schuster, Toro 1307.6554

Use proton or electron beam

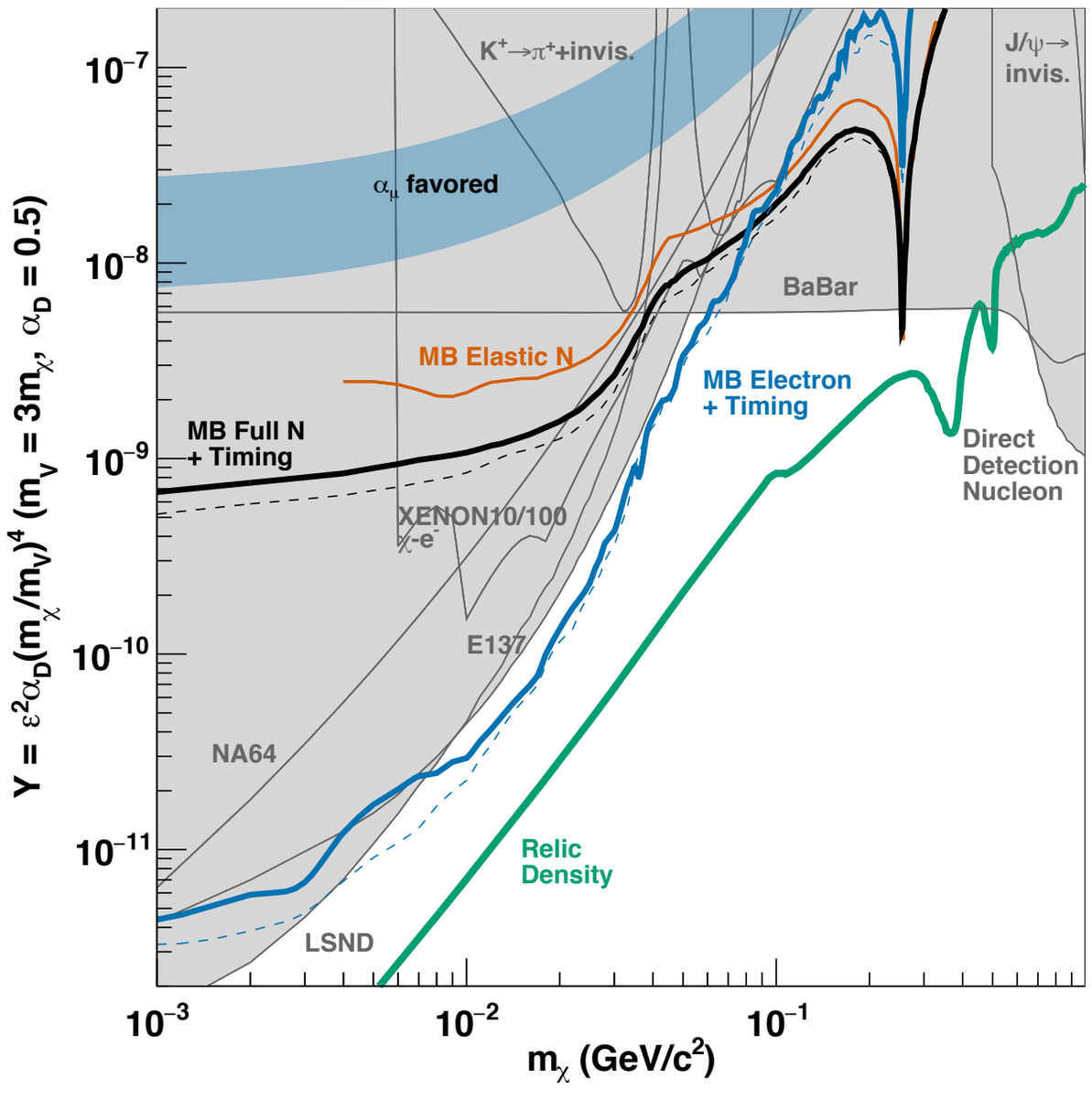
$$[\text{production}] \times [\text{detection}] \propto \epsilon^4$$

Beam Dump Strategy

Latest results from MinBooNE 2018. First **ever** dedicated search for LDM



MiniBooNE Collaboration Phys. Rev. Lett. 118 (2017)

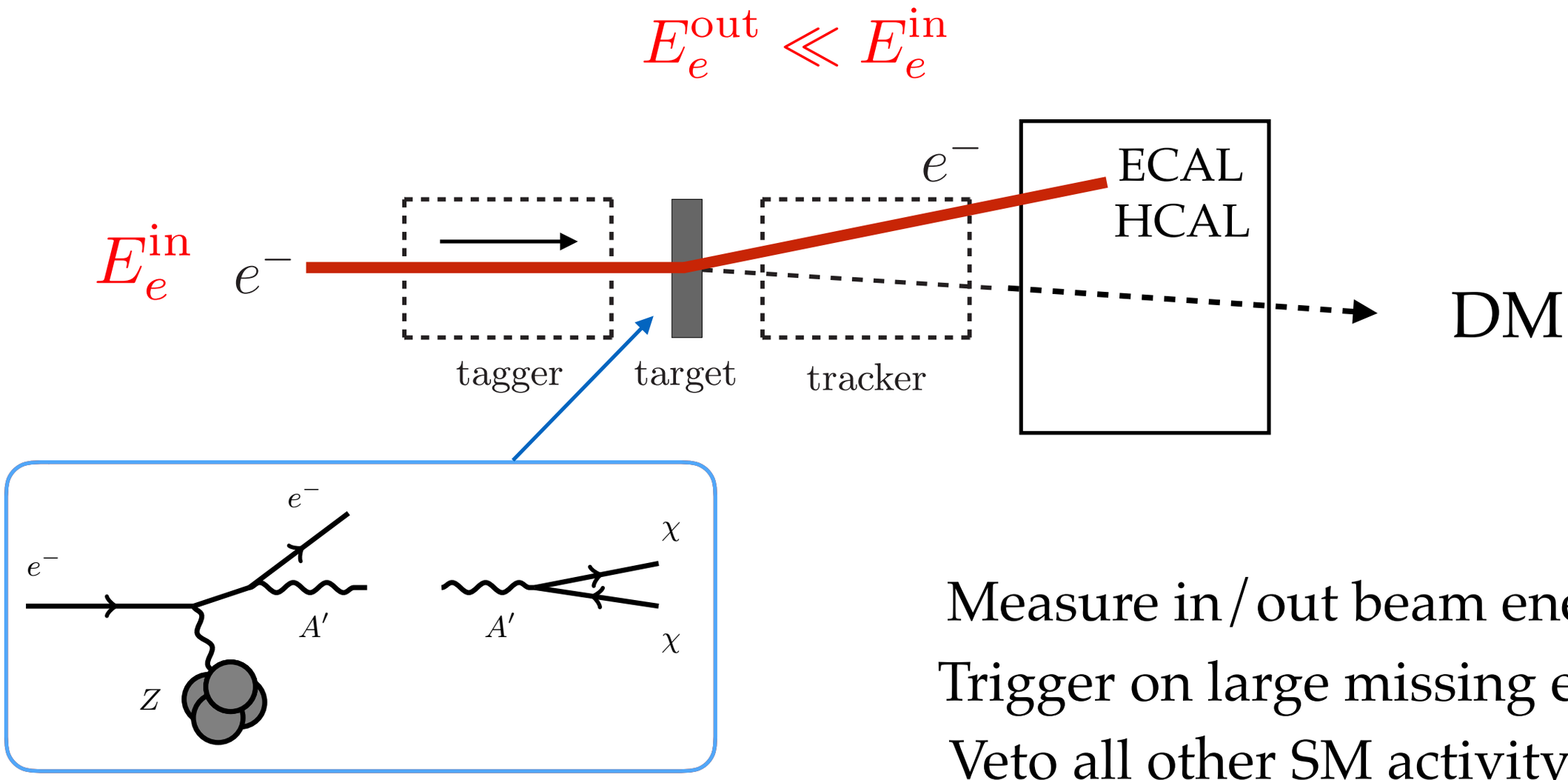


MiniBooNE Collaboration 1807.06137

Missing Momentum Strategy

Signal is the **electron or muon beam** itself: LDMX, NA64, M^3

If DM is produced, beam loses large energy fraction



NA64 Collaboration 1610.02988

LDMX Collaboration 1808.05219

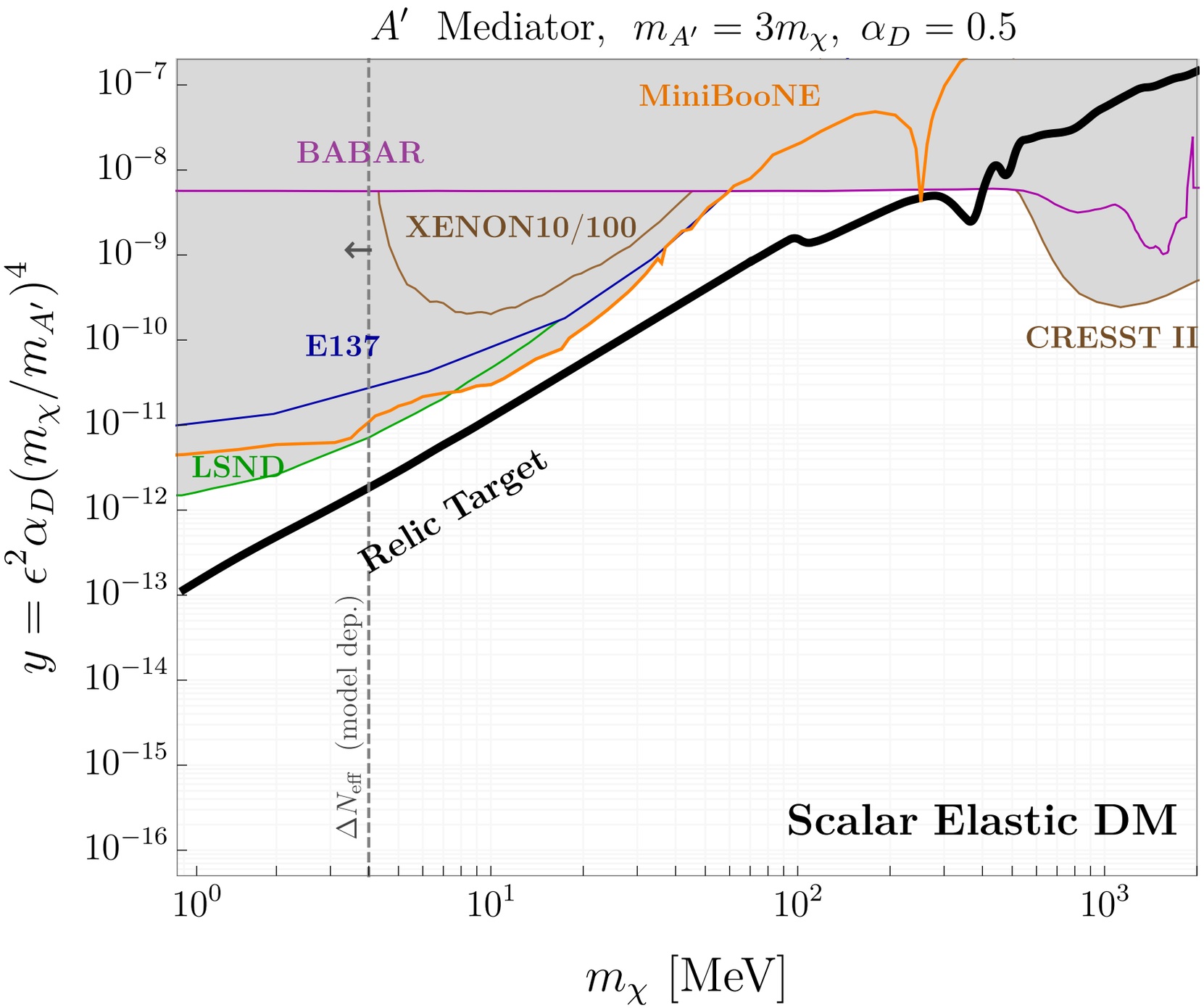
Measure in/out beam energy

Trigger on large missing energy

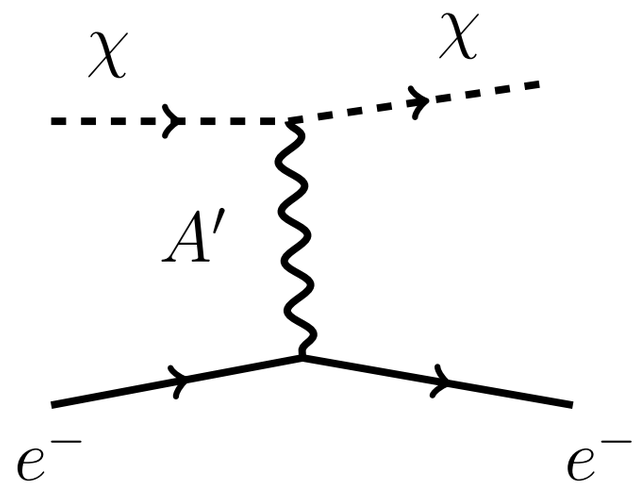
Veto all other SM activity

(see Nhan & Yoni's talks)

Comprehensive Coverage: Dark Photon Mediator A'



Spin-0 Scalar DM



$$A'_\mu \chi^* \partial_\mu \chi$$

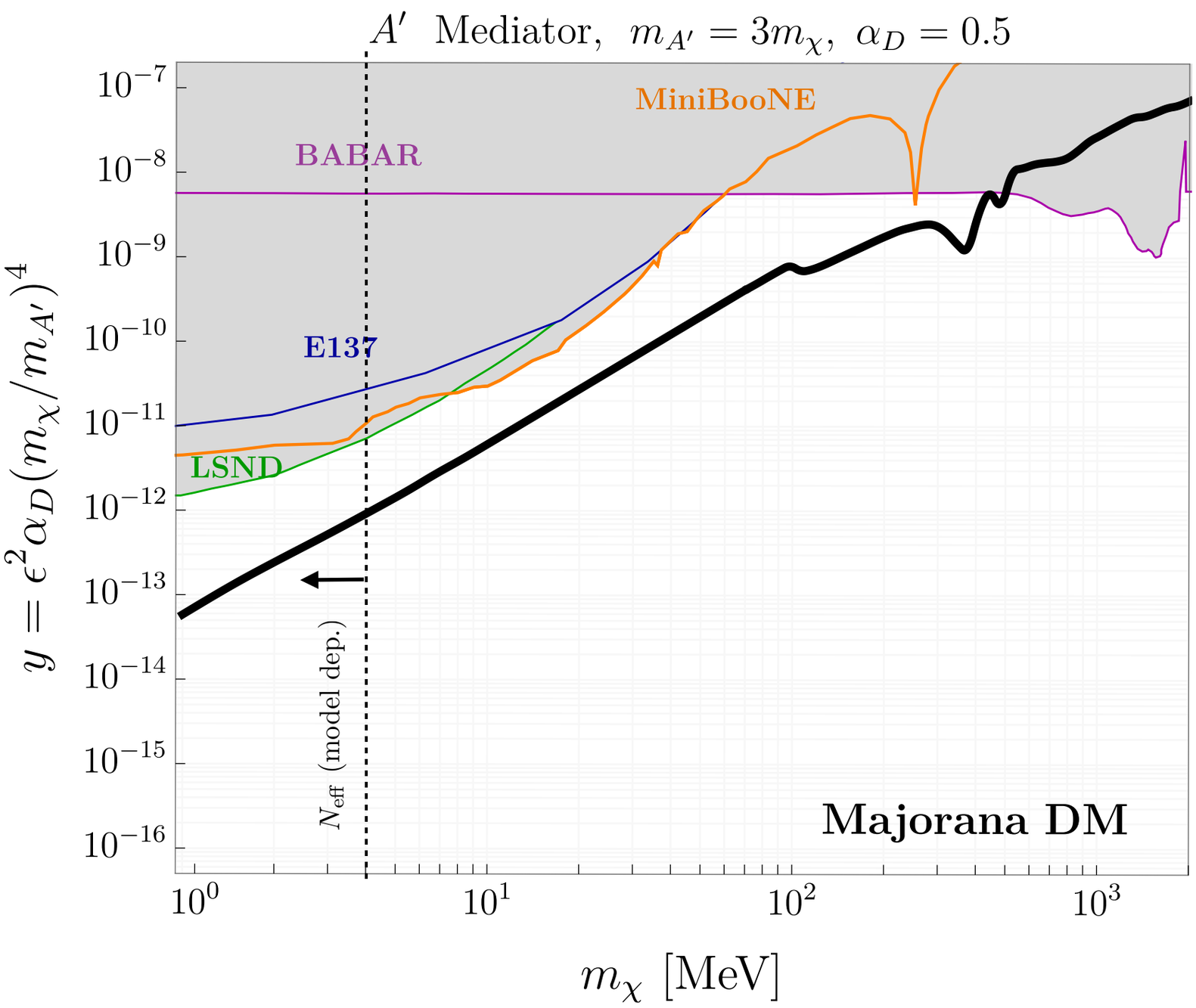
CMB safe

Direct annihilation

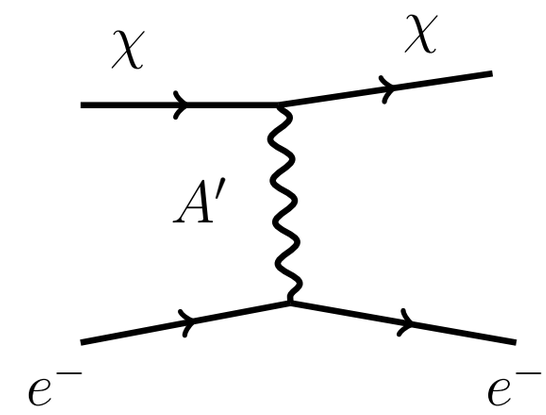
p-wave suppressed at recombination

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

Comprehensive Coverage: Dark Photon Mediator A'



Spin-1/2 Majorana DM



$$A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

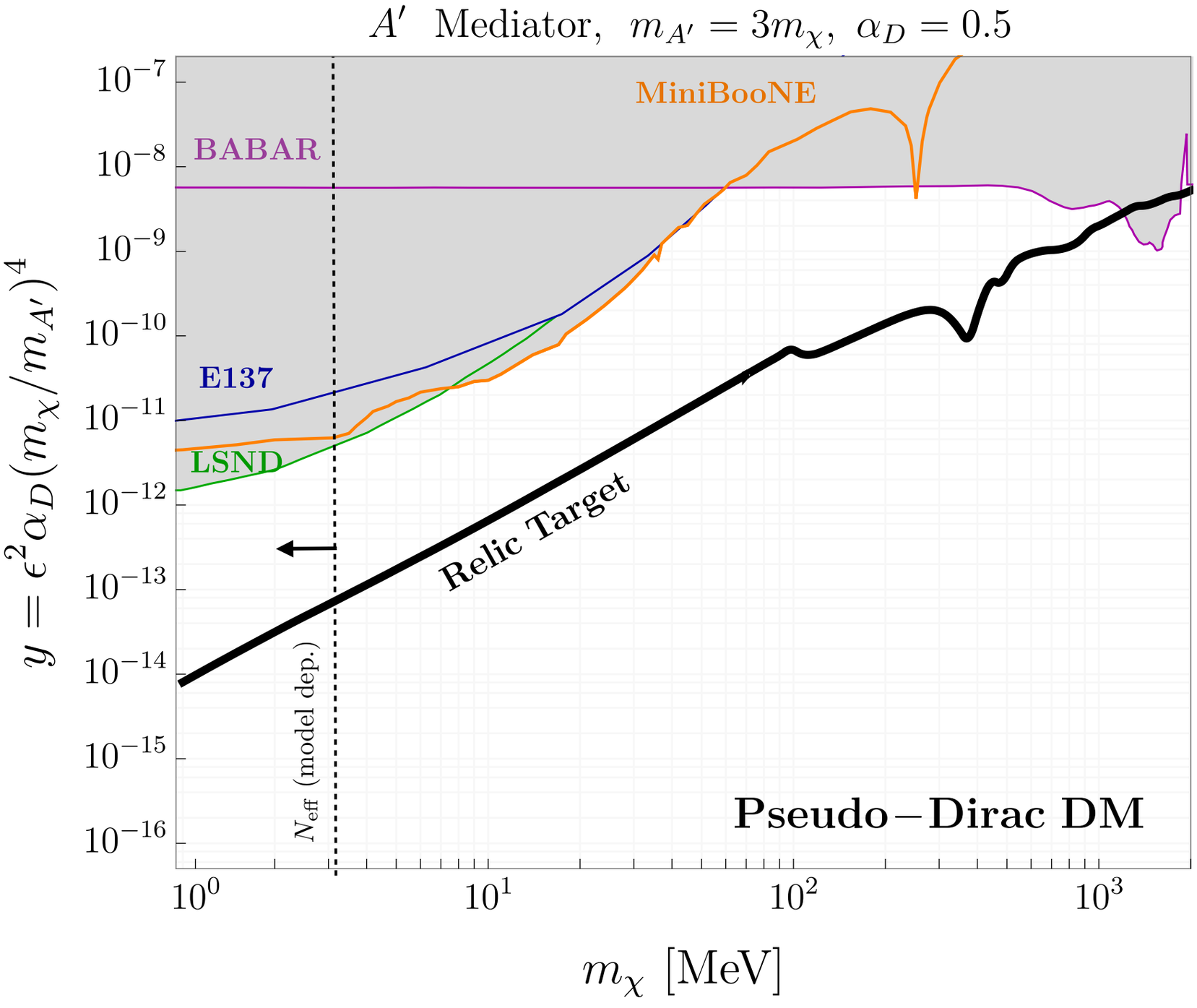
CMB safe

Direct annihilation

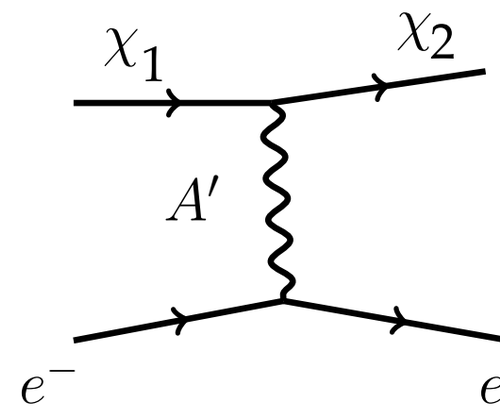
p-wave suppressed at recombination

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

Comprehensive Coverage: Dark Photon Mediator A'



Spin-1/2 "Dirac" DM

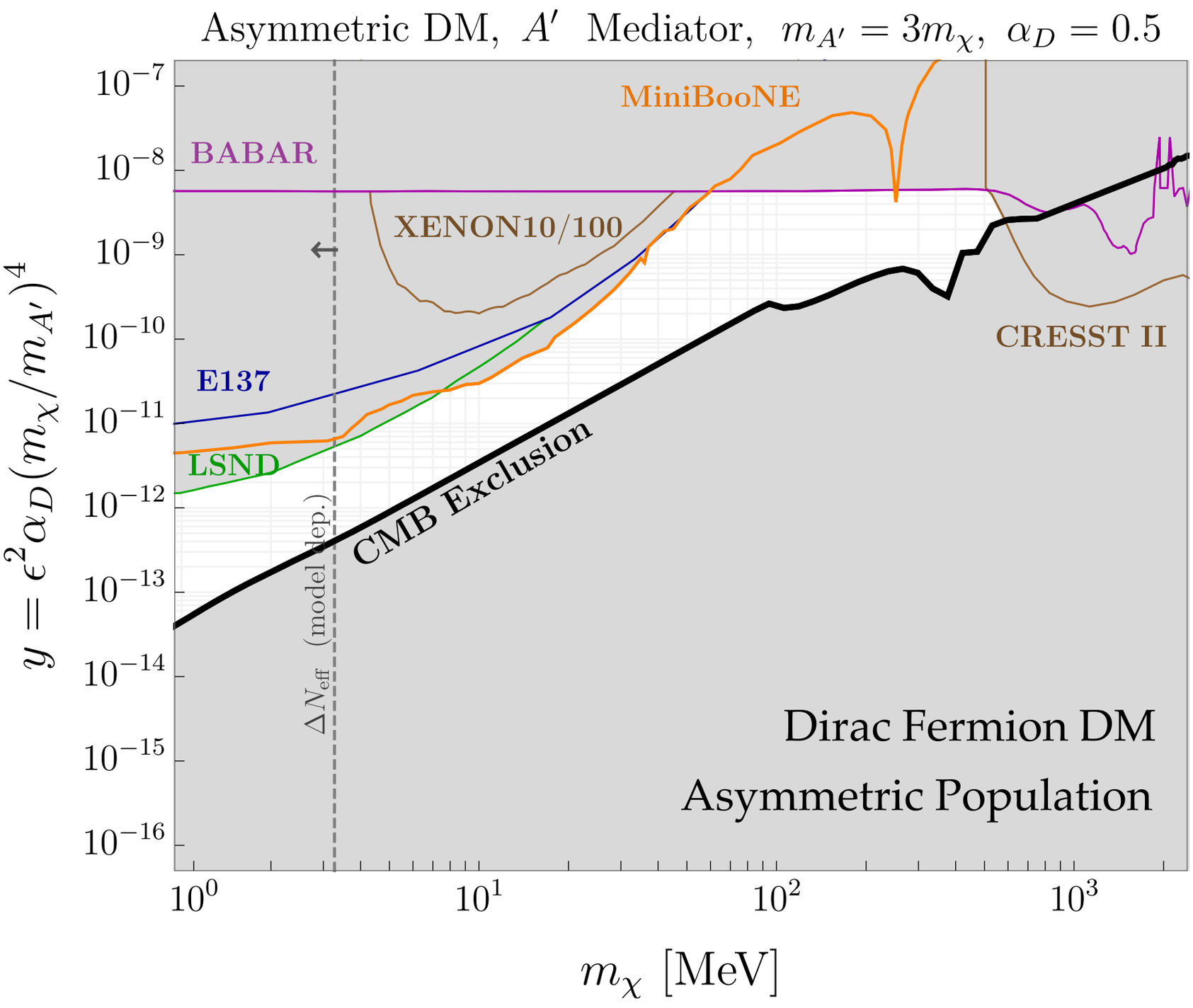


$$A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$

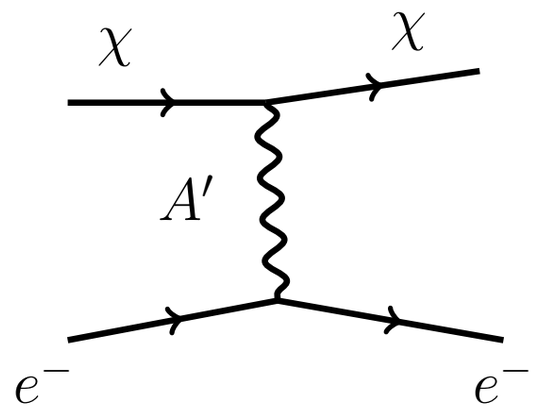
CMB safe
heavier partner $\chi 2$
decays before
recombination

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

Comprehensive Coverage: Dark Photon Mediator A'



Spin-1/2 Dirac DM



$$A'_\mu \bar{\chi} \gamma^\mu \chi$$

CMB safe
antiparticles
gone before
recombination

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

Overview

1) Why thermal DM?

2) Direct annihilation: **thermal targets**

3) "Hidden" annihilation: visible decays → **Theory**, Searches

4) Fixed targets **beyond DM** (LLPs)

Was DM ever in equilibrium with SM?

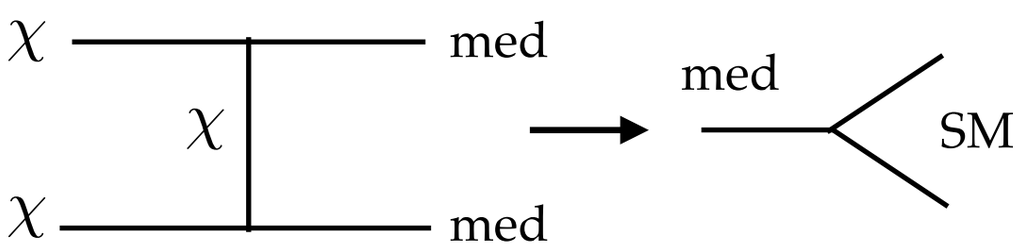
YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Visible matter

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

Hidden Annihilation



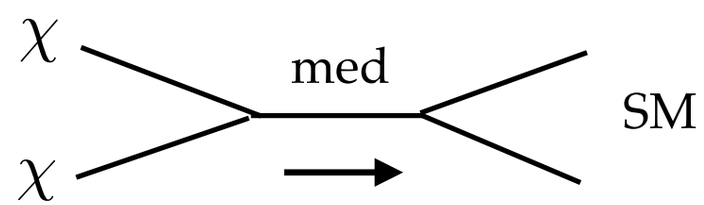
Two step process

Hard to test DM origin

Can discover mediator if lucky

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

Direct Annihilation

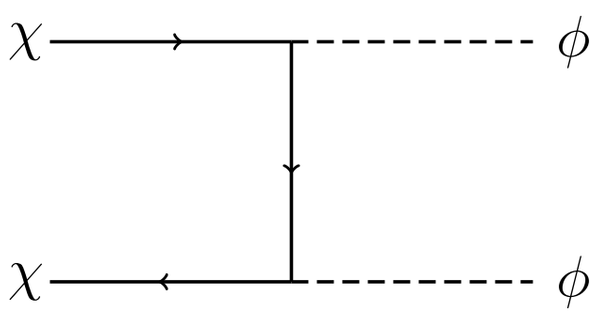


One step process

Density set by SM coupling

Clear experimental targets

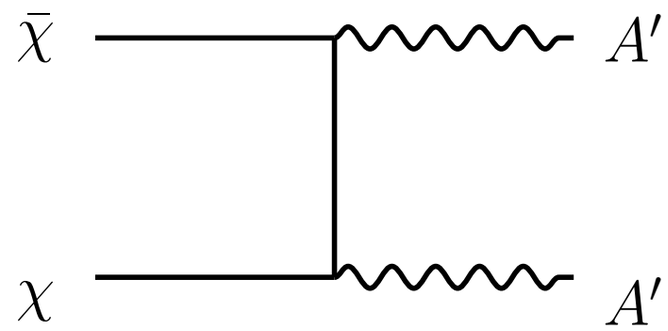
What kind of mediator for hidden annihilation? $m_\chi > m_{\rm med}$



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

Neutral scalar
Mass mixing w Higgs

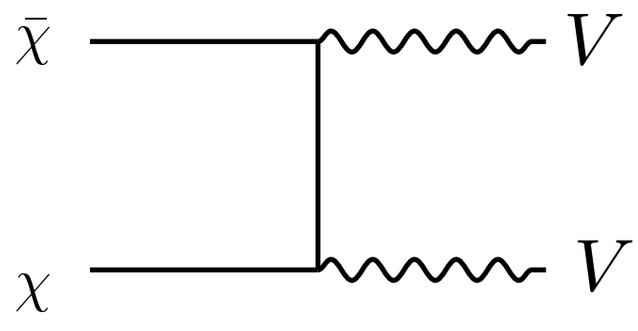
$\rightarrow \epsilon\phi \dfrac{m_f}{v}\bar{f}f$



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

Dark photon A'
Kinetic mixing w / γ

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



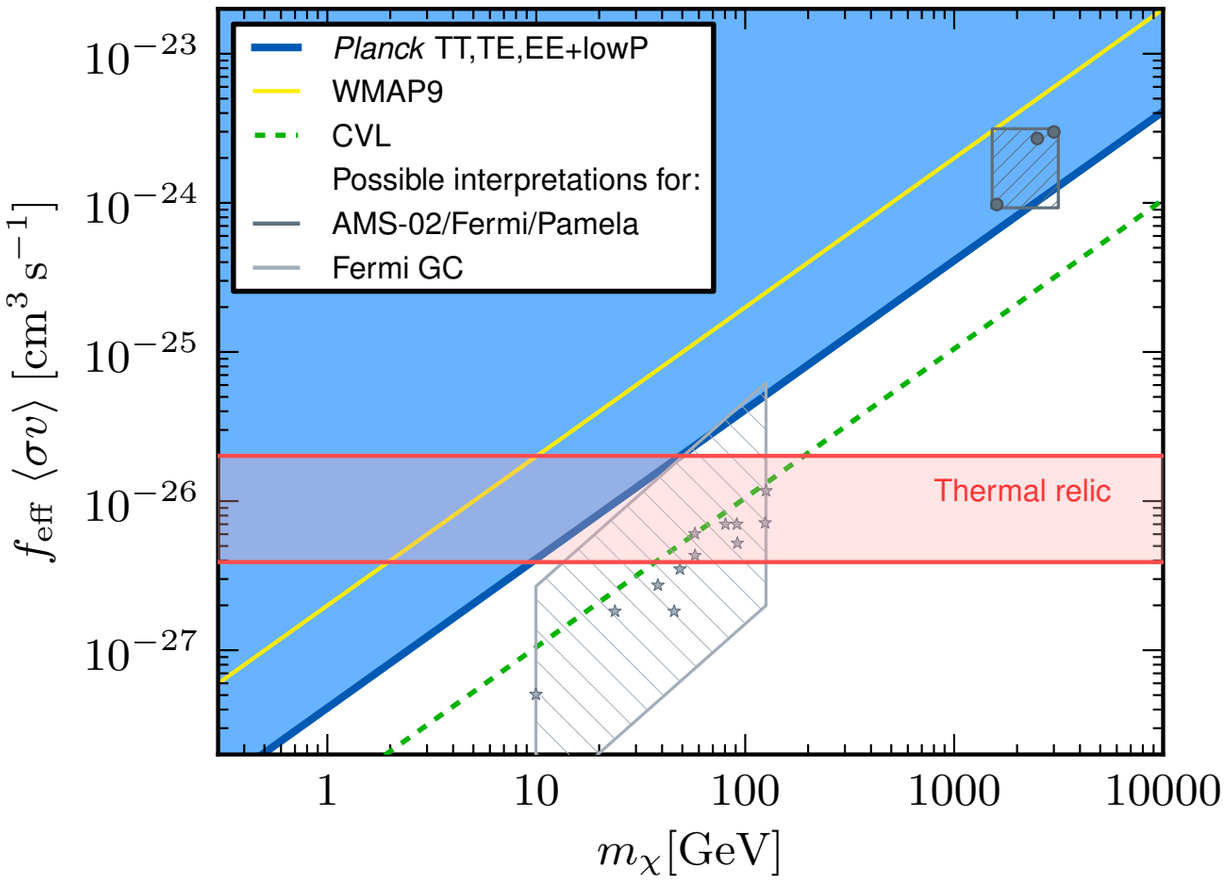
$V_\mu J^\mu_{\rm SM}$

Gauge known global
quantum number

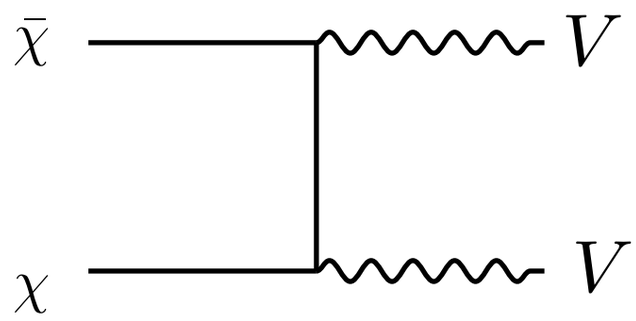
$U(1)_{B-3L_i}$
$U(1)_{B-L}$
$U(1)_{L_i-L_j}$

Complete* list of renormalizable, anomaly-free options

CMB kills hidden annihilation to vectors



Planck Collaboration 1502.01589

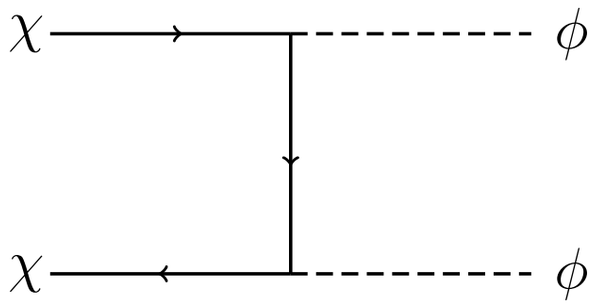


Annihilation to 2 vectors always s-wave process for all DM candidates

Danger!

Early universe equilibrium still possible if DM has particle/antiparticle asymmetry

What kind of mediator for hidden annihilation? $m_\chi > m_{\rm med}$



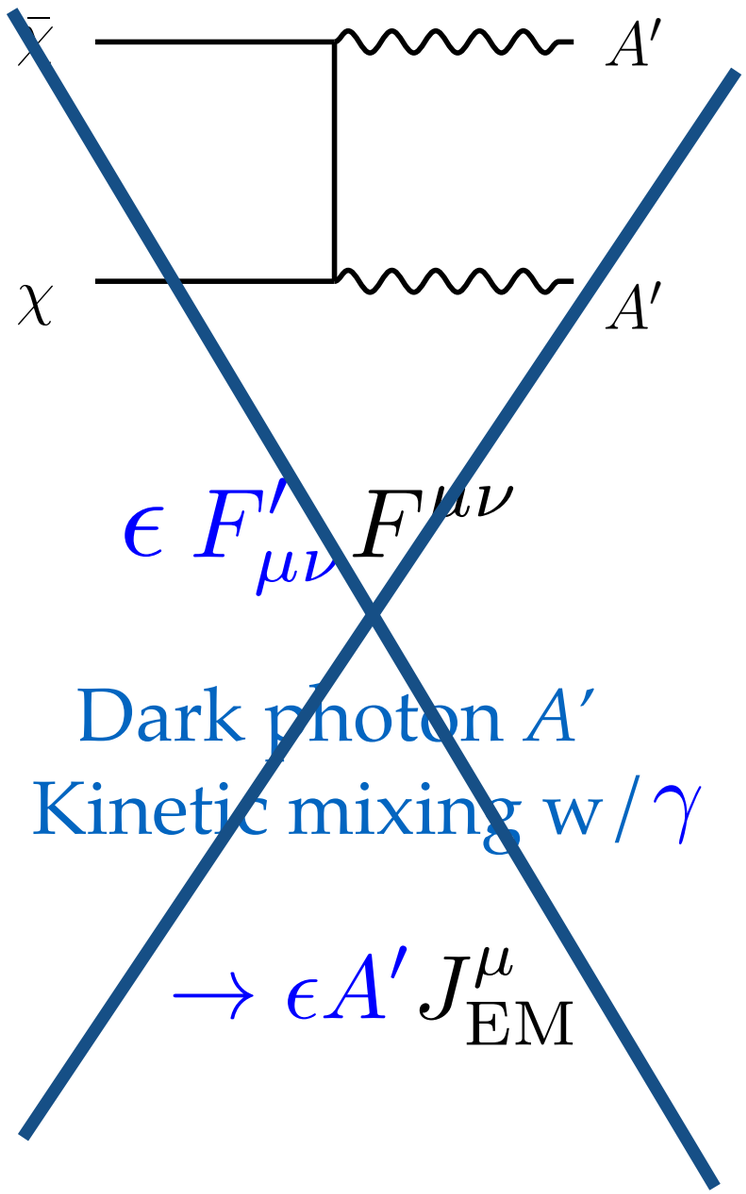
$\epsilon\,\phi H^\dagger H$

Neutral scalar
Mass mixing w Higgs

$\rightarrow \epsilon\phi \dfrac{m_f}{v}\bar{f}f$

CMB safe

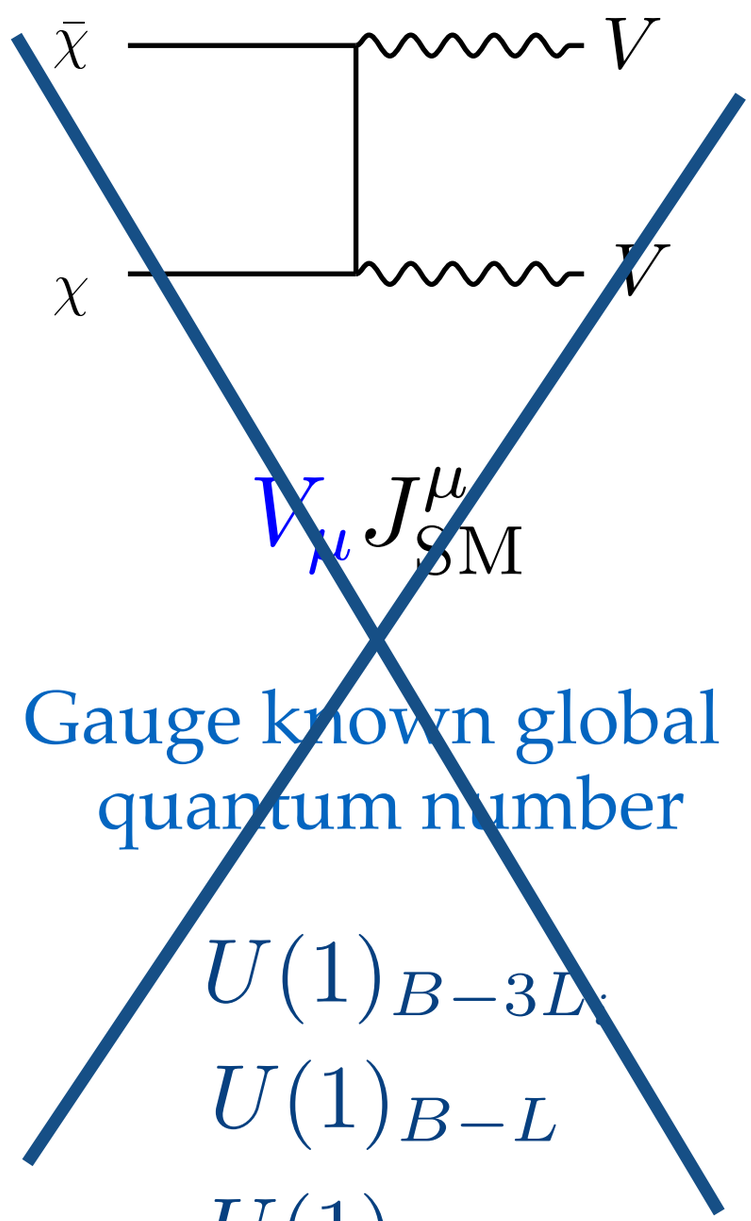
p-wave
(still no DM target)



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

Dark photon A'
Kinetic mixing w / γ

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



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

Gauge known global
quantum number

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

Ruled out except for V that decay to neutrinos

Overview

1) Why thermal DM?

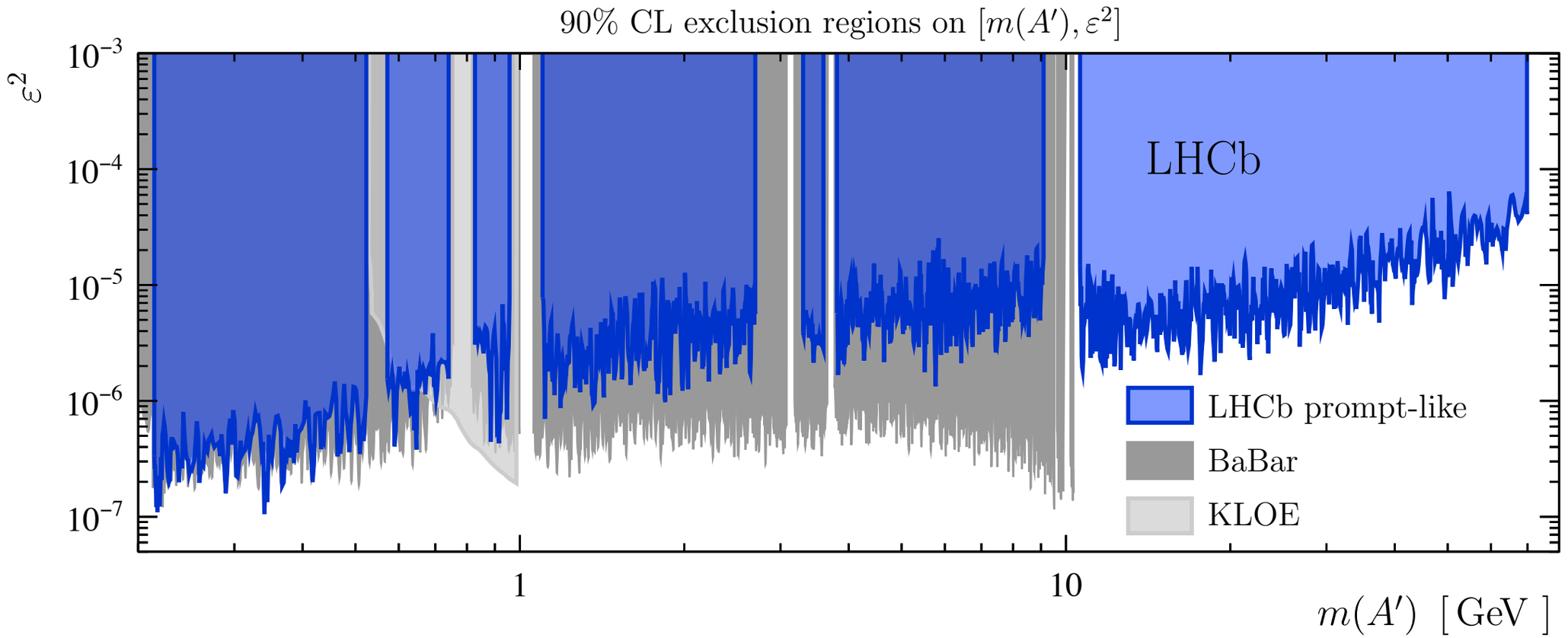
2) Direct annihilation: **thermal targets**

3) "Hidden" annihilation: visible decays → Theory, **Searches**

Many of the following are motivated by DM annihilation, but **same mediator decay signature** even if totally unrelated to DM

Collider strategy: prompt decays

Resonance searches for visible daughters: BABAR, Belle II, LHCb…



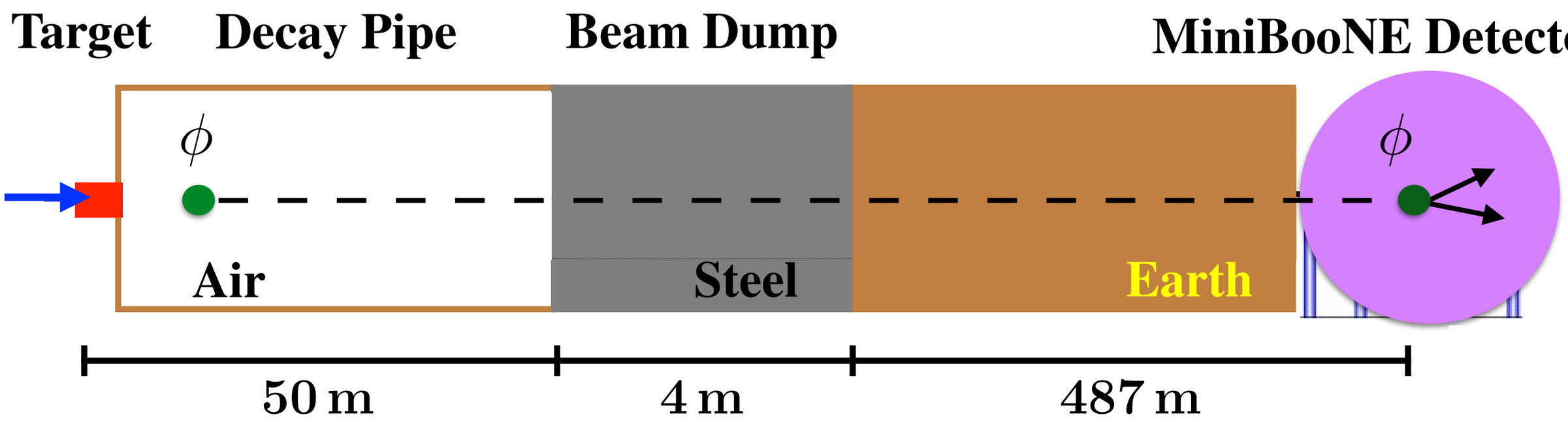
B-factories: continuum production $e^+e^- \to \gamma A' \to \gamma(e^+e^-)$

Colliders (also short-er baseline fixed targets) $K^+ \to \pi^+ A' \to \pi^+(e^+e^-)$

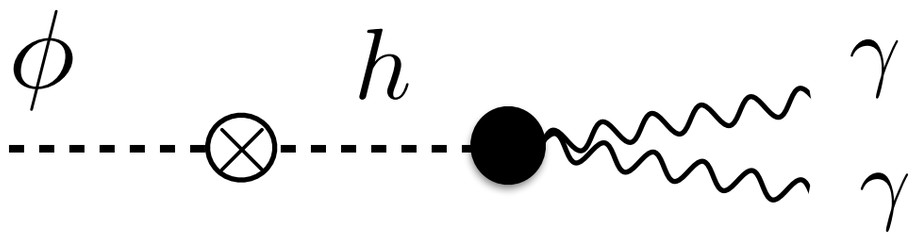
LHCb Collaboration 1710.02867

and many other channels / mesons etc.

Beam Dumps: LLP searches



1) LLP produced in target
2) Passes through shielding
3) Decays in detector



Even though this is motivated by hidden DM annihilation

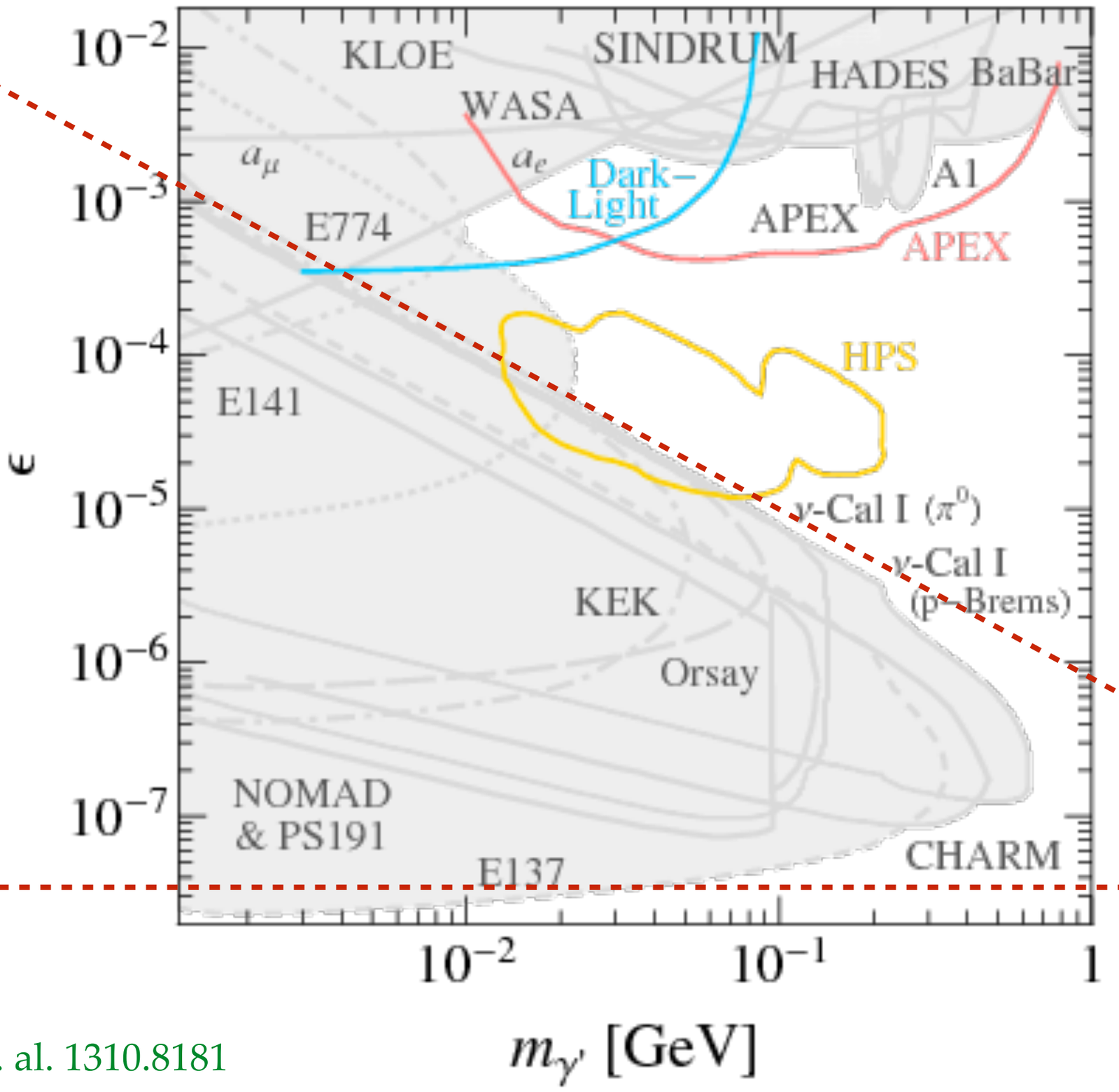
same signature even if LLP is unrelated to DM

Visibly Decaying Vectors

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

prompt decay searches

Beam dump LLP

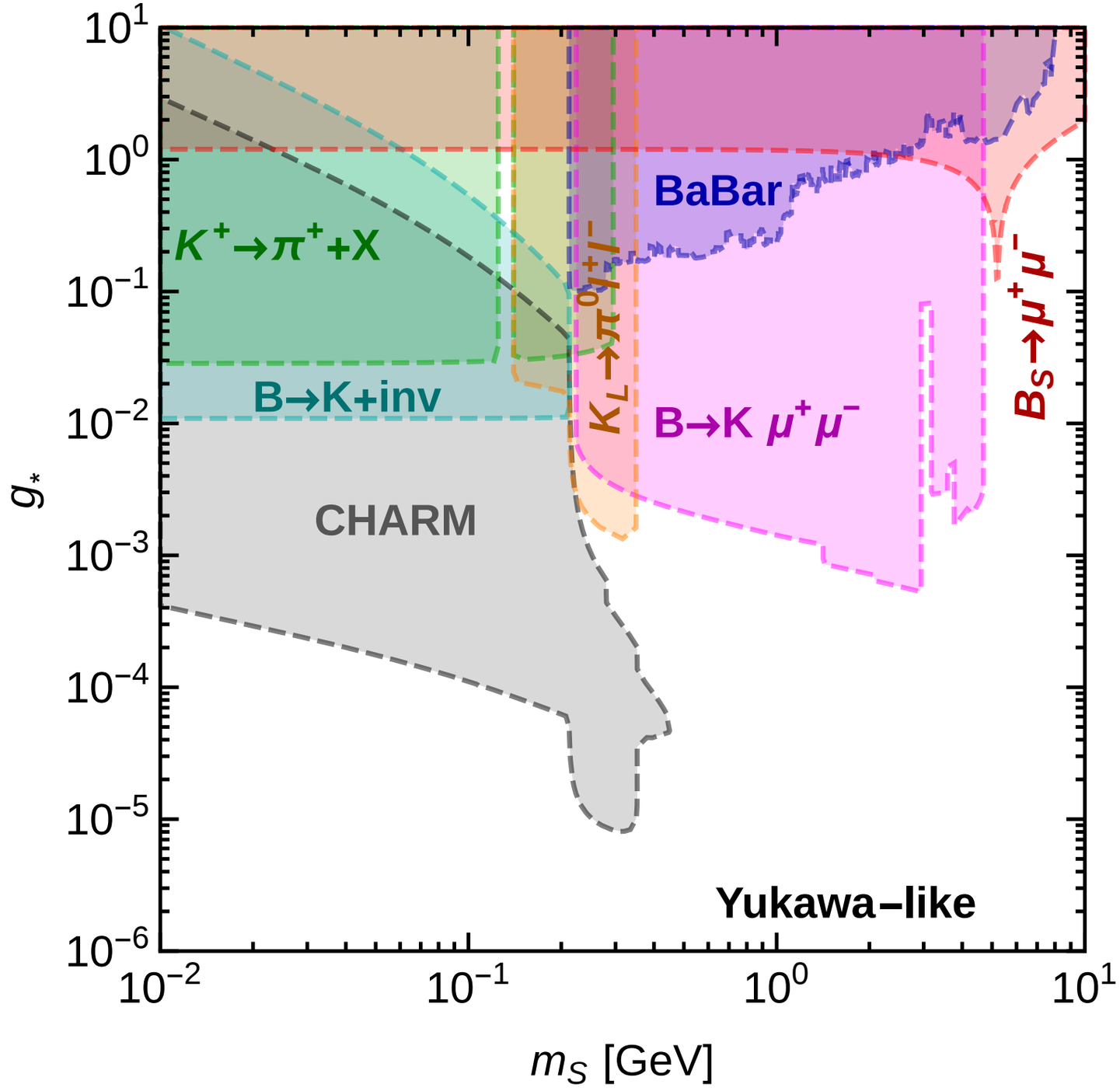


decay too fast

no events

Bossi et. al. 1310.8181

Beam Dumps: Scalar LLP Searches



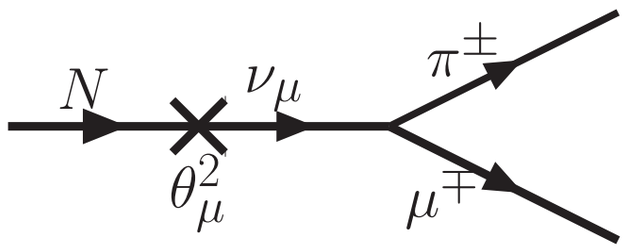
$\epsilon \, \phi H^\dagger H$

Alekhin et. al. 1504.04855

same signature even if LLP is unrelated to DM

Heavy Neutral Leptons

$$LHN$$

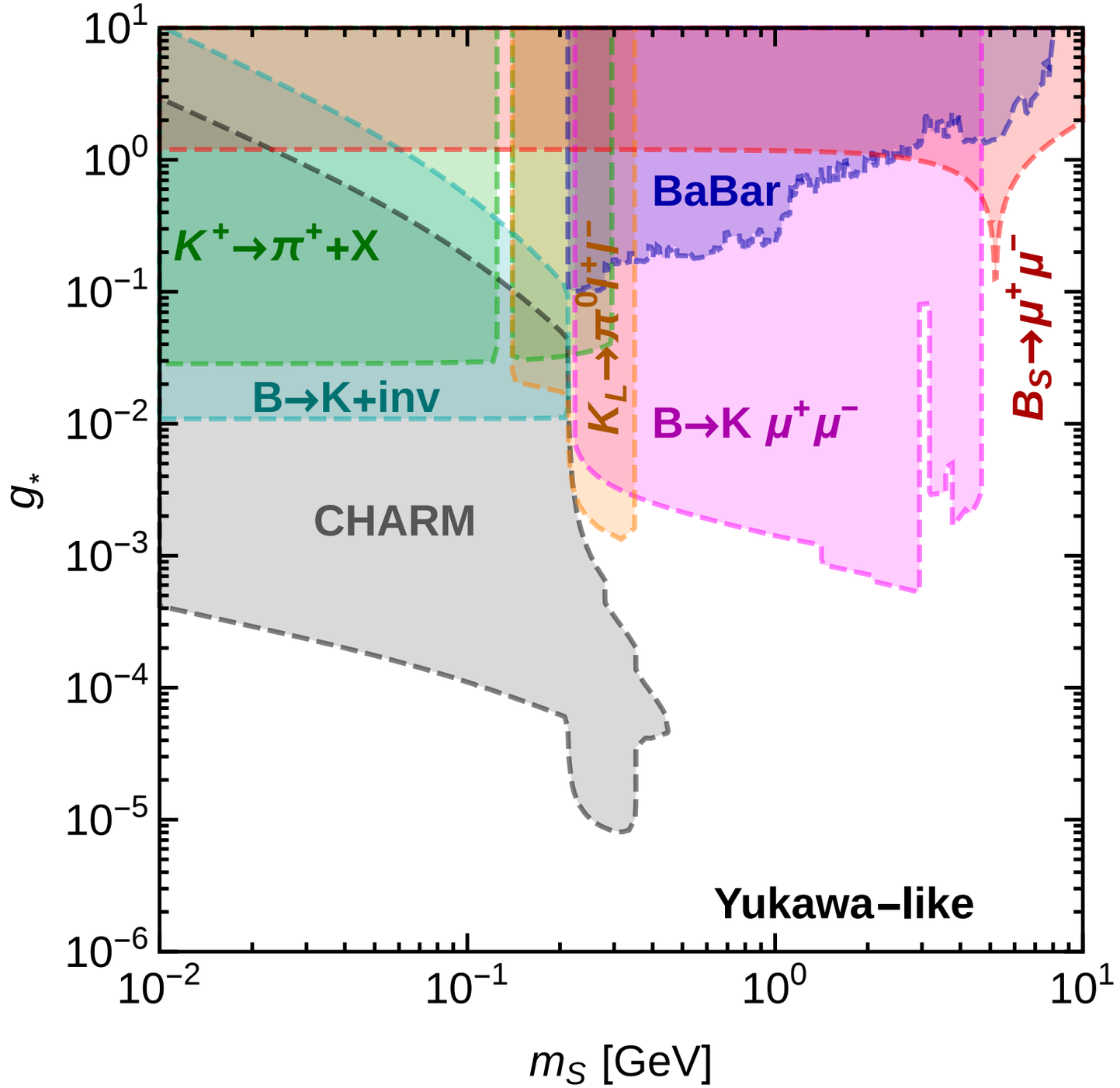


Unrelated to thermal DM

may be related to BAU

or neutrino masses

Alekhin et. al. 1504.04855



Summary

A Modest Proposal $\Gamma(\mathrm{DM} \leftrightarrow \mathrm{SM}) > H$

Rate beats Hubble expansion at *some* point [easy to realize]

Thermodynamics Set Initial Condition $n_{\mathrm{DM}} \sim T^3$

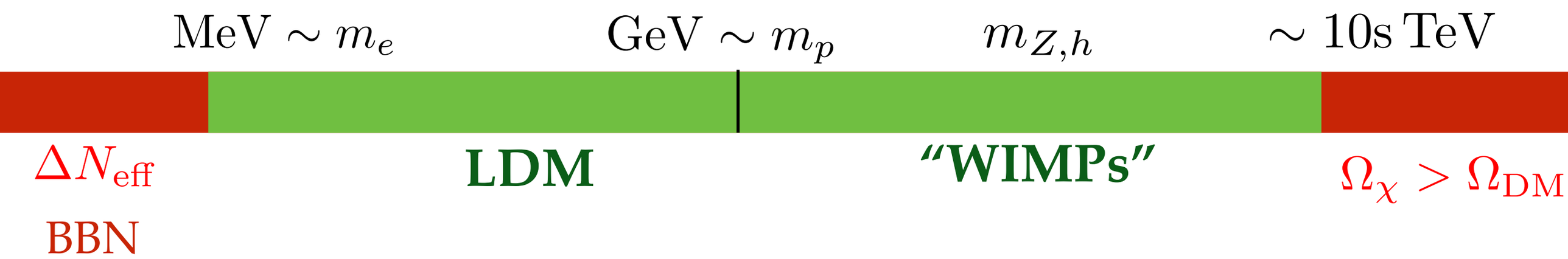
Insensitive to unknown high scales [inflation, baryogenesis…]

Predicts Min. Annihilation Rate $\sigma v \gtrsim 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

Equilibrium overproduces DM, must deplete with non-gravitational force

Viable Window In Our Neighborhood

Coincidentally in broad vicinity of the electroweak scale



New Frontier of Hidden Sector Searches

$\mathrm{MeV} \sim m_e$ $\mathrm{GeV} \sim m_p$ $m_{Z,h}$ $\sim 10\mathrm{s}\,\mathrm{TeV}$

LDM | **"WIMPs"**

Missing Momentum
LDMX, NA64, M^3

Beam Dumps:
MiniBooNE, MicroBooNE, BDX
ICARUS, SBND, DUNE, JSNS2
REDTOP, Dark/SpinQuest, NOvA
SHiP, FerMINI, Stopped Pions…

Direct Detection

Indirect Detection

Collider Production

New accelerator searches cover direct annihilation targets

+ improve coverage for mediators in hidden annihilation forces

I didn't have time to discuss…

The new revolution in < GeV in direct detection

Lot's of complementary new ideas here (pros/cons compared to accel.)

SENSEI Crisler, Estrada, Tiffenberg et. al. 1804.00088 (among others)

Strongly coupled < GeV dark sectors

3->2 "hidden" annihilation (SIMPs), Hochberg et al 1402.5143

Elastically decoupling DM (ELDER), Tsai et al 1512.04545

Fixed target searches, Blinov et al. 1801.05805

Other Beam Dump Signatures

Dark tridents: de Gouvea, Fox, Harnik, Kelly, Zhang 1809.06388

Millicharged particles FerMINI Kelly, Tsai 1812.03998

Millicharged particles LAr-TPC Harnik, Liu, Palamara 1902.03246

Inelastic DM decays Kahn et. al. 1806.05185

… also your favorite model/experiment (sorry)

Thanks!