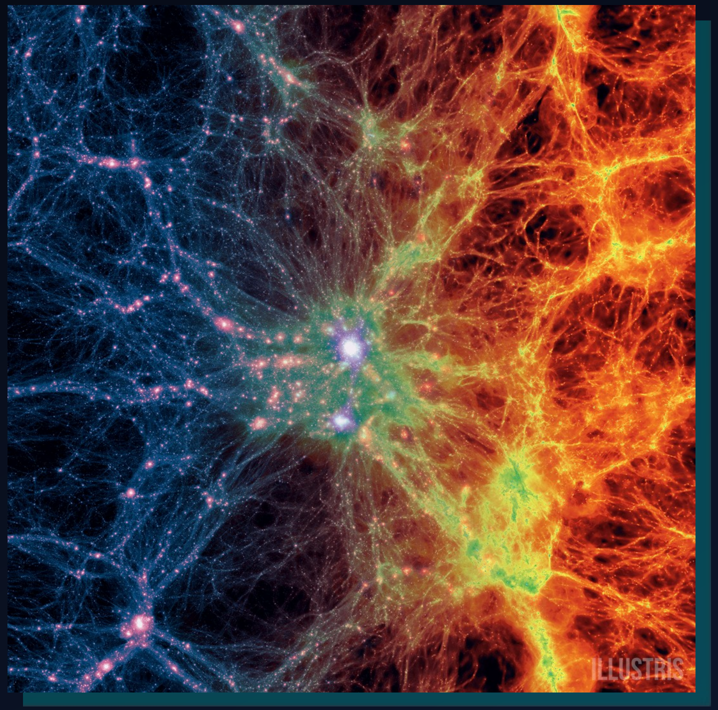
DARK MATTER THEORY II

REBECCA LEANE
SLAC NATIONAL ACCELERATOR LABORATORY

SLAC SSI LECTURES
AUG 15-16th 2022

Today's Outline

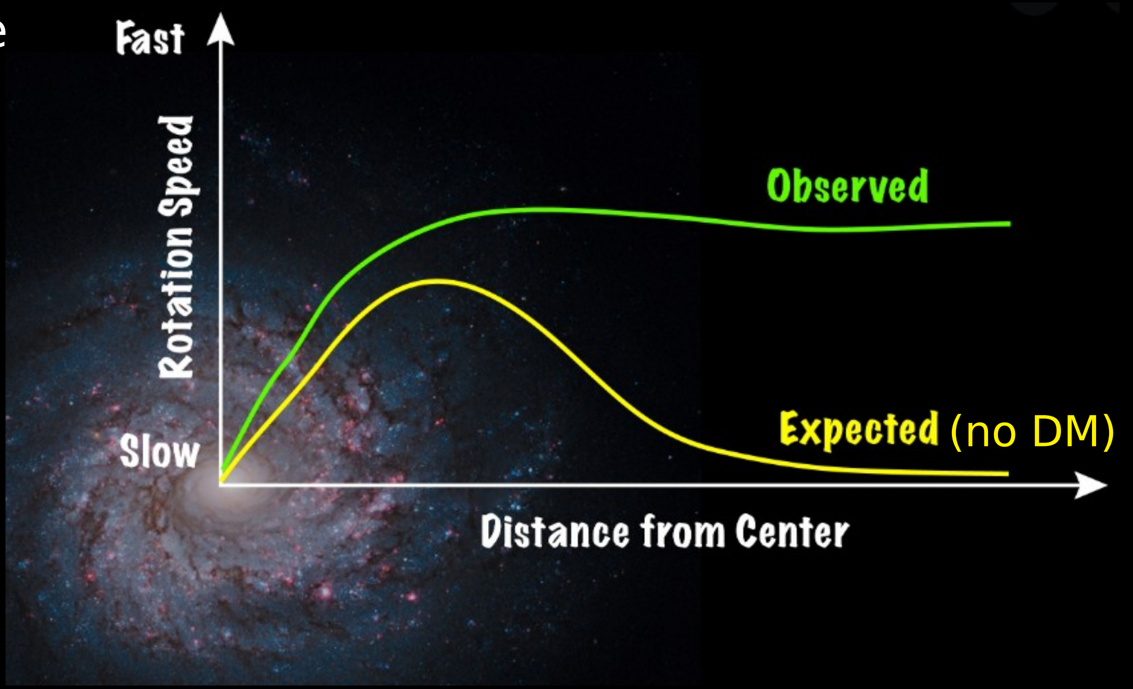
- WIMP recap and status
  - Searches and Constraints
- Newer Production Mechanisms
  - SIMPs, co-SIMPs
  - Freeze-in
- Axions
- MACHOs
  - Primordial Black Holes
- Outlook



Illustris Simulation

Recap: what we know about Dark Matter

- Makes up about 85% of matter in the Universe (~5x more mass than SM)
- Doesn't interact too much with light (or itself)
- Provides large scale structure of the Universe
- Structure tells us non-relativistic
- Forms halos around Galaxies
- Stable on cosmological timescales



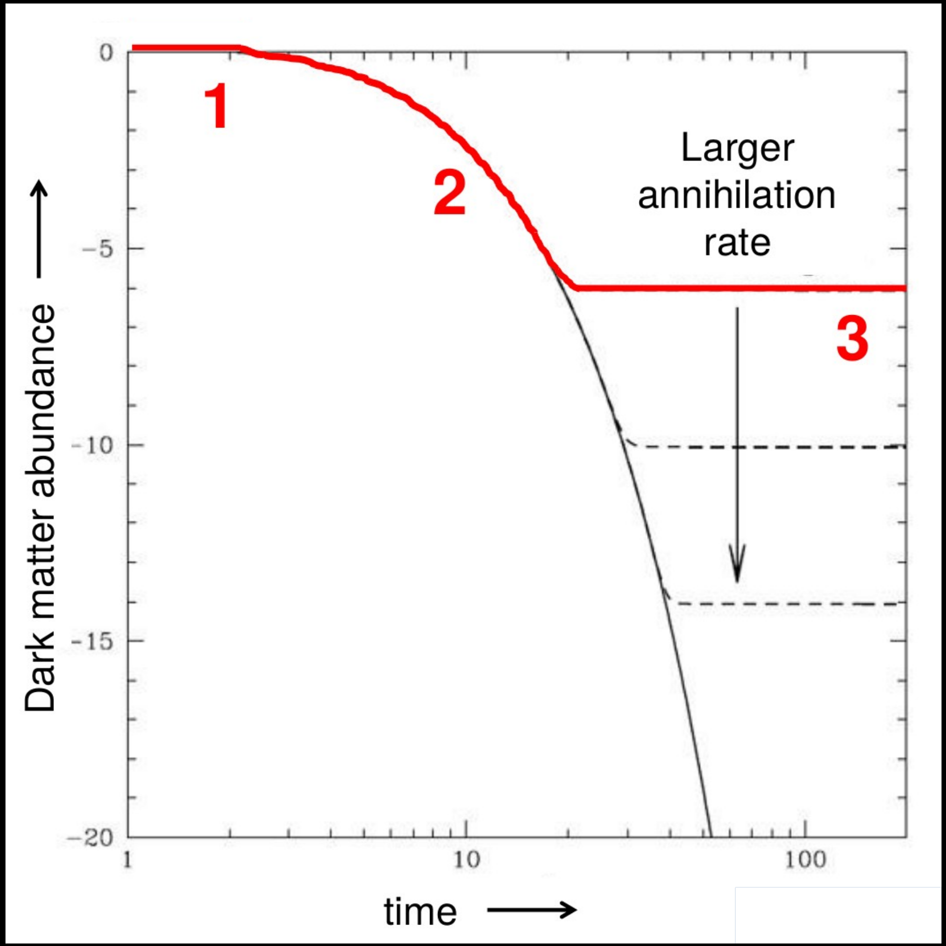
Cannot be explained by any known particles!

Recap: Dark Matter Abundance: WIMPs

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

2) Universe cools, only
DM + DM ⇒ visible particles

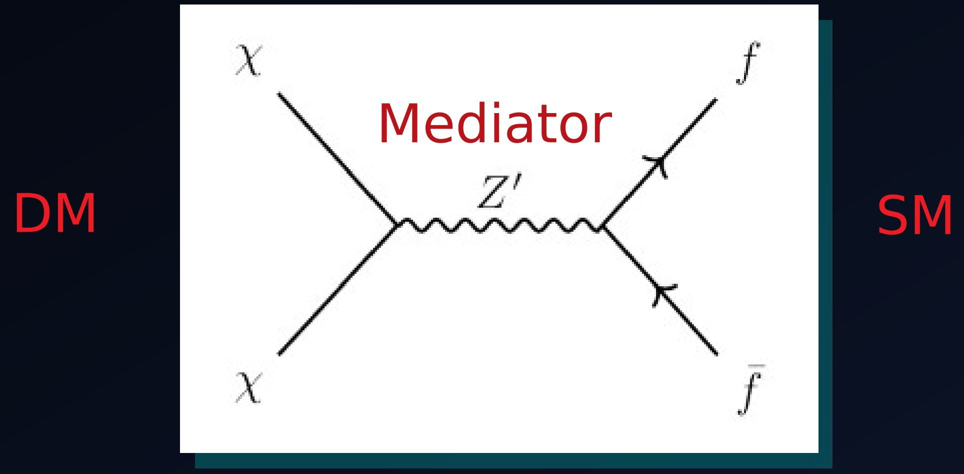
3) Universe expands too fast.
No more annihilations.
DM abundance is set.



Predicts a particular annihilation rate for dark matter.

Recap: Dark Sectors

- Standard Model (SM) mediated WIMP processes, e.g. with Z bosons, extremely constrained
- Need new fields beyond the SM!
- These can mediate interactions between the dark sector, and the SM



Dark Sectors

- Need new fields beyond the SM, consider extensions:
  - New scalar, pseudoscalar, fermion, or vector
- Symmetries of SM restrict how these fields interact with the SM

$$-\lambda_{HS}(S^\dagger S)(H^\dagger H)$$ Higgs Portal

$$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$ Axion Portal

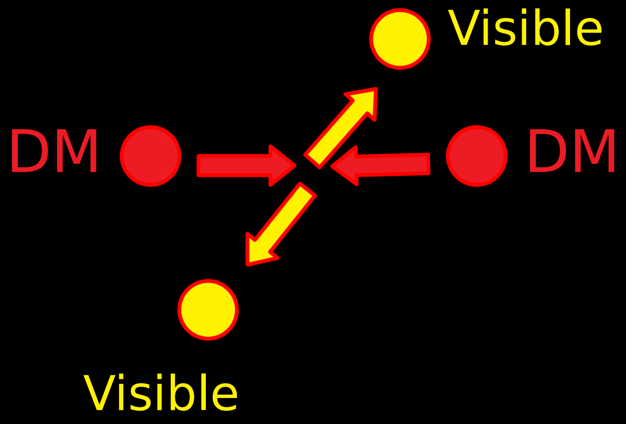
$$-\frac{\epsilon}{2}B_{\mu\nu}Z'^{\mu\nu}$$ Hypercharge Portal

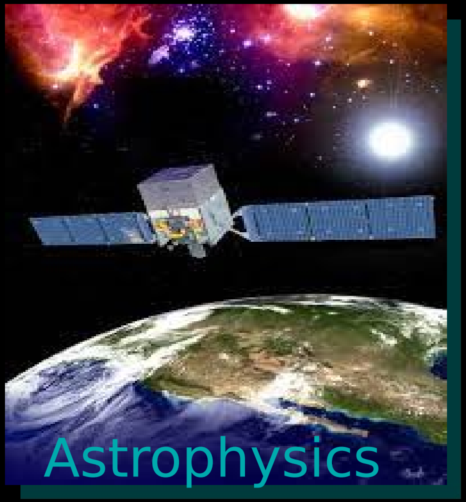
$$y_n LHN$$ Fermion Portal

Generally easiest to parameterize searches by generic masses and couplings

WIMP Dark Matter Search Program

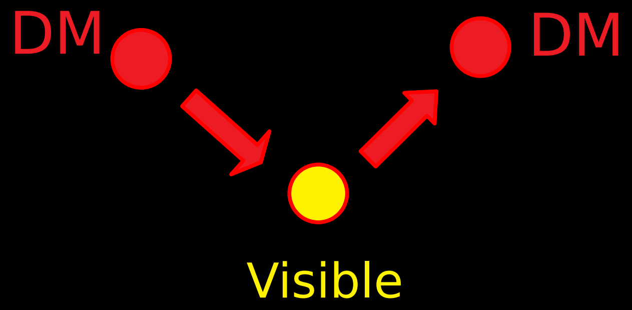
Annihilation





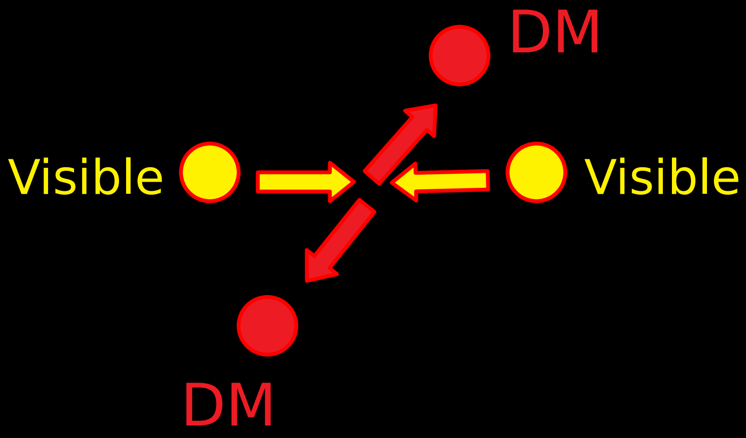
Astrophysics

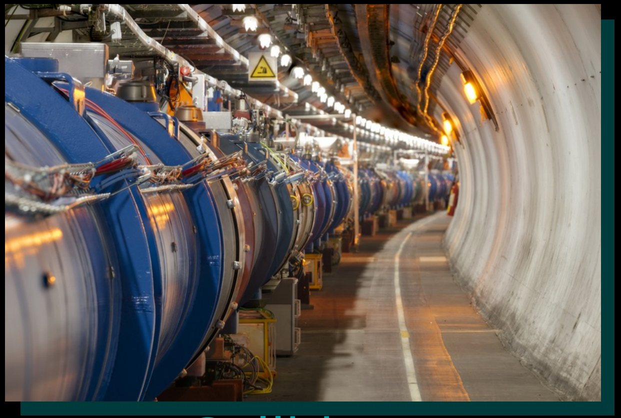
Scattering



Direct detection
+ Astrophysics

Production



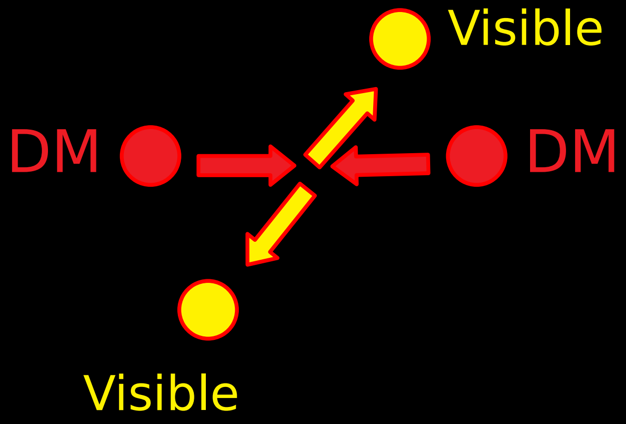


Colliders
+ Astrophysics

WIMP Dark Matter Search Program

M.E. Mozani’s lecture yesterday

Annihilation



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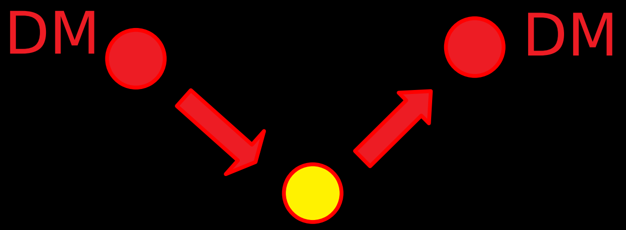

Direct detection
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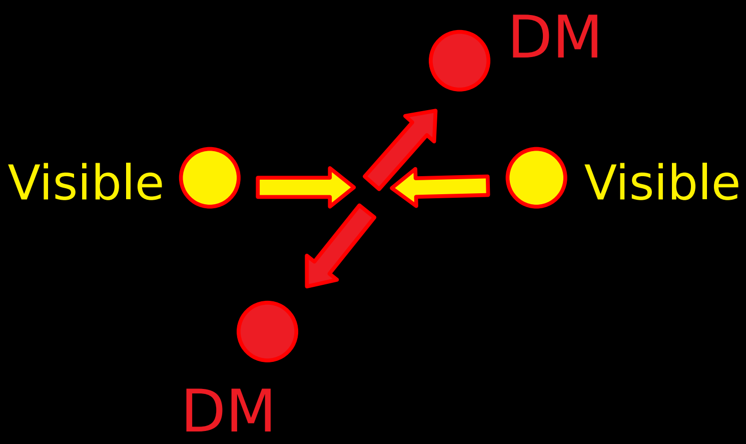
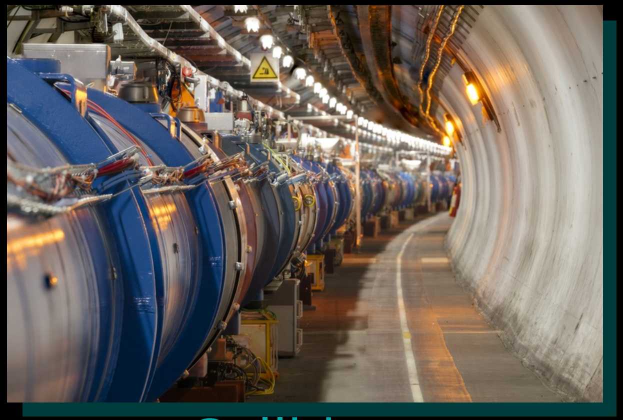
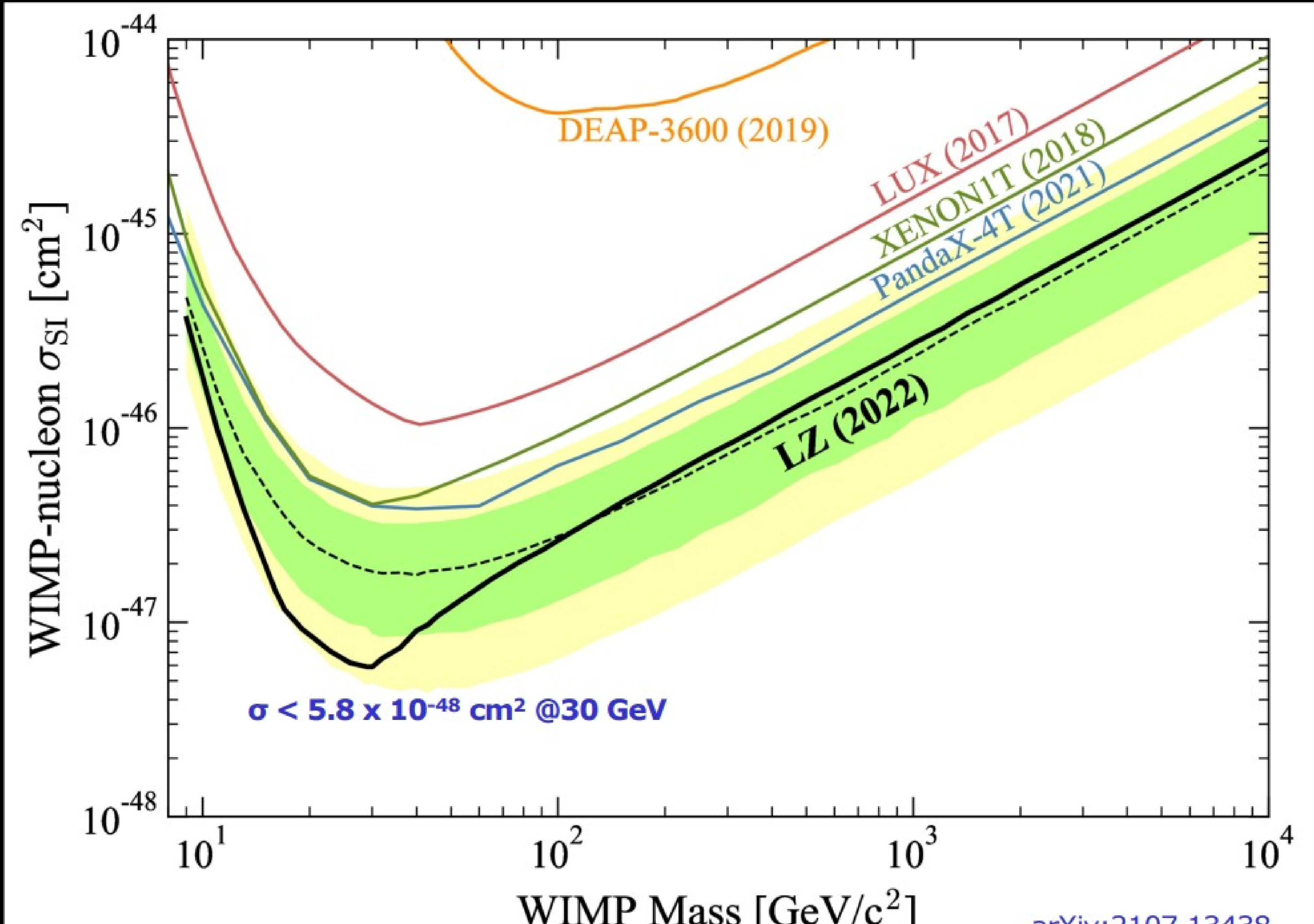




Colliders
+ Astrophysics

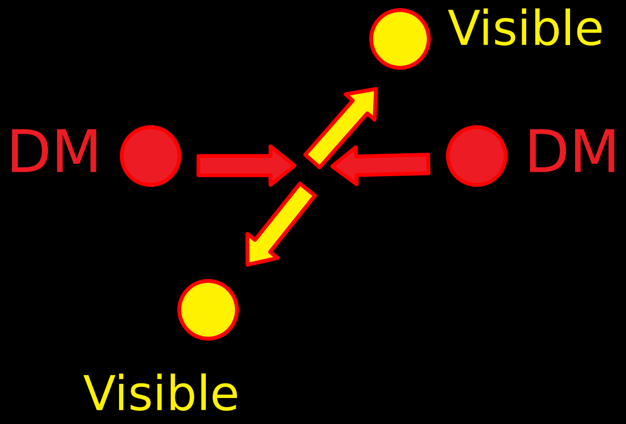
World-leading constraint on WIMPs



arXiv:2107.13438

WIMP Dark Matter Search Program

Annihilation



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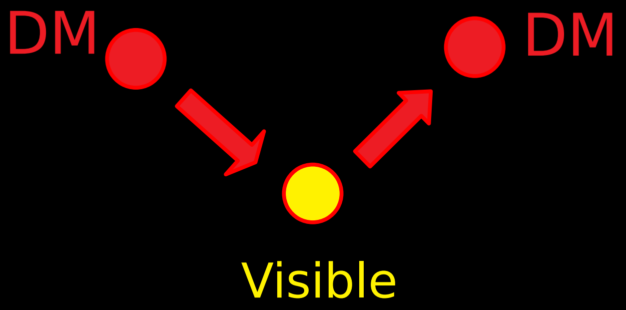

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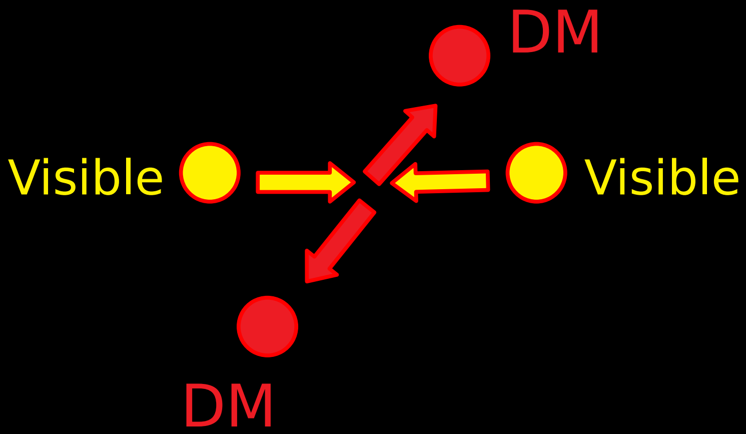
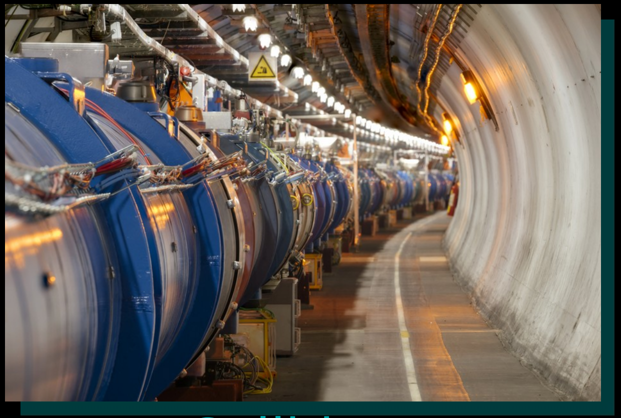
+ Astrophysics

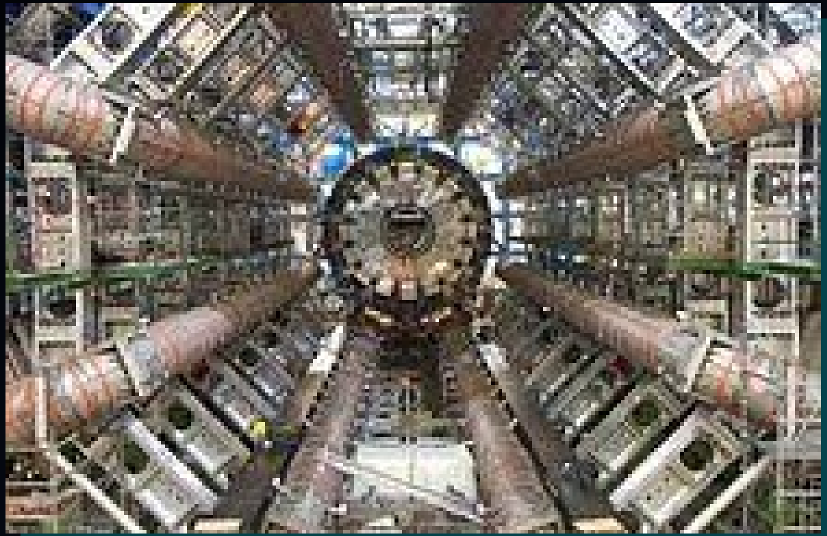
Production





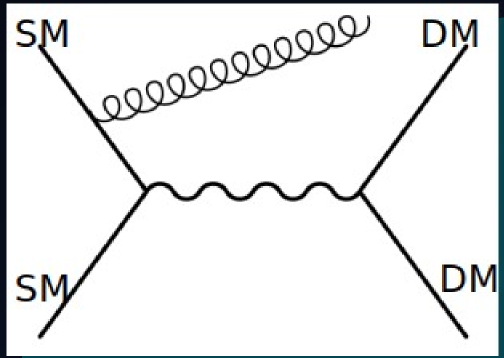
Colliders
+ Astrophysics

Dark matter at colliders



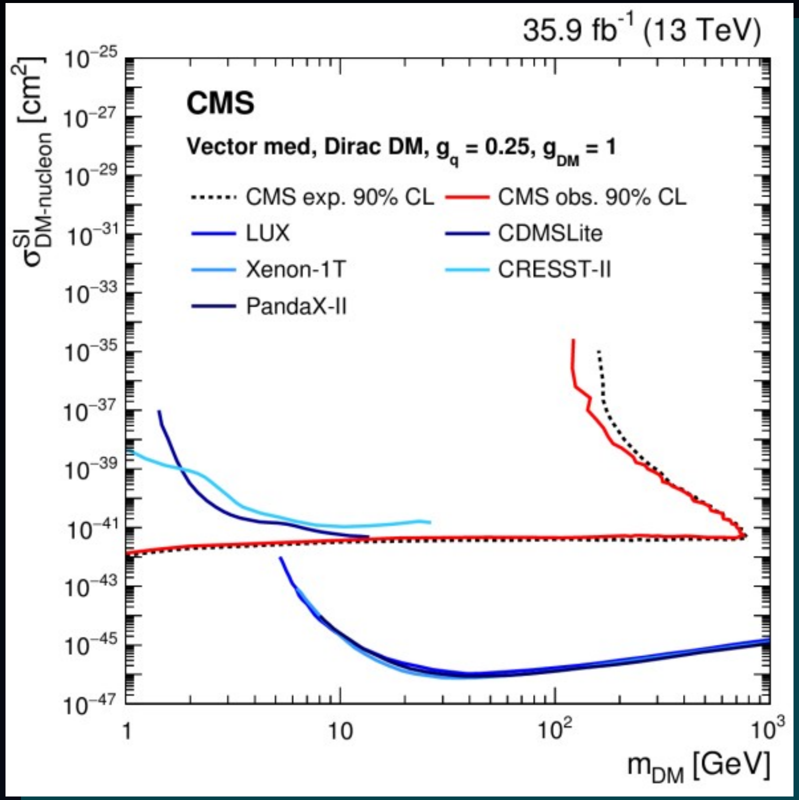
ATLAS

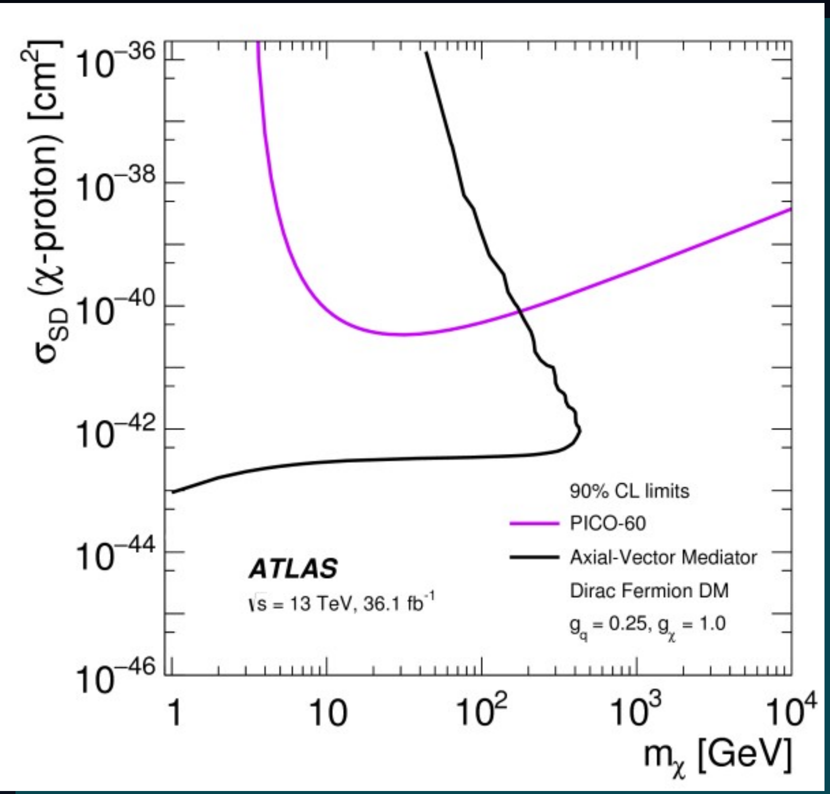
- Missing momentum searches test weak-scale dark matter

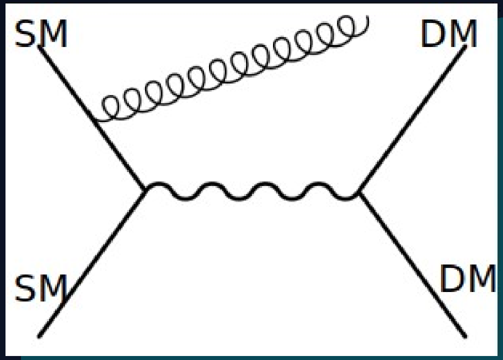


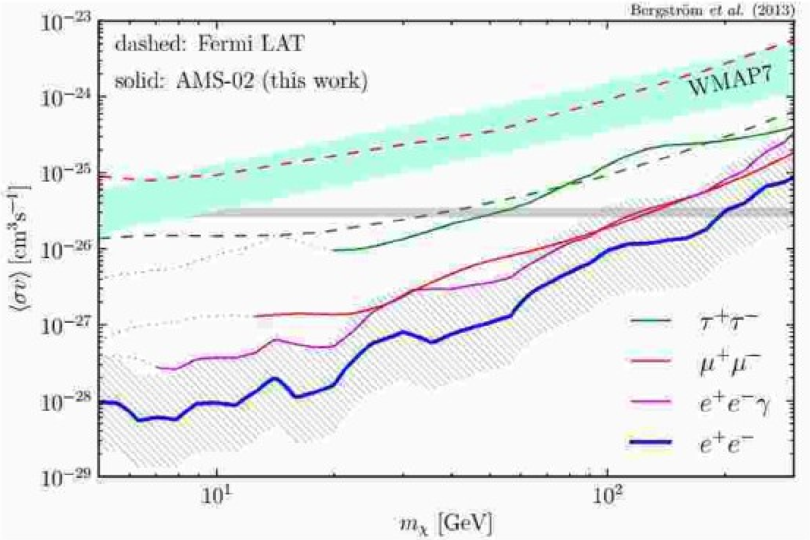
- Strong limits for mediator searches directly as well

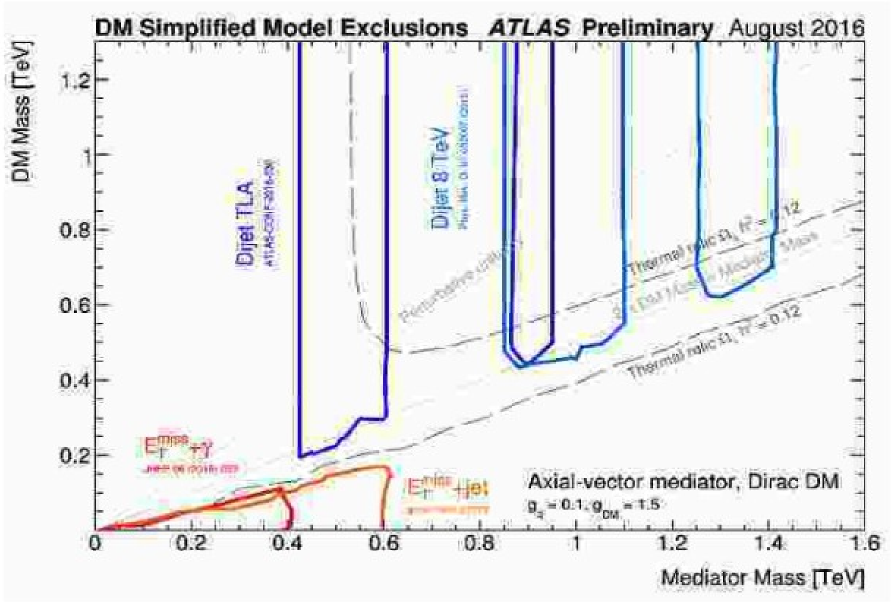
Mono-jet searches

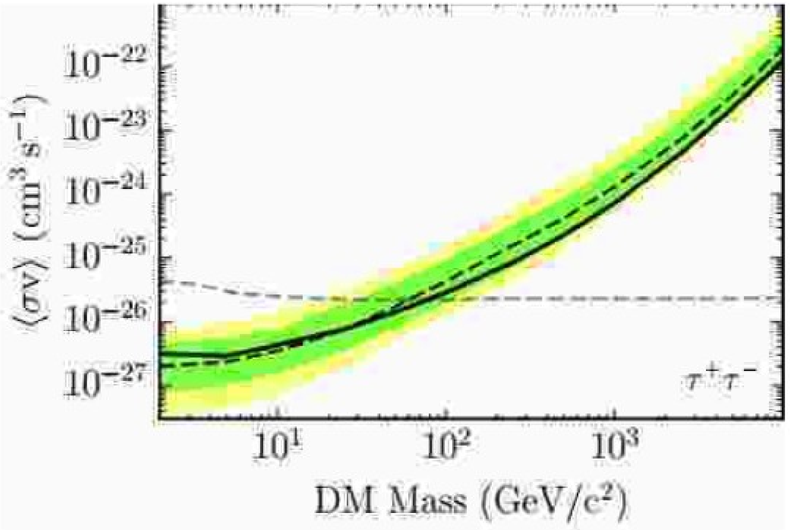


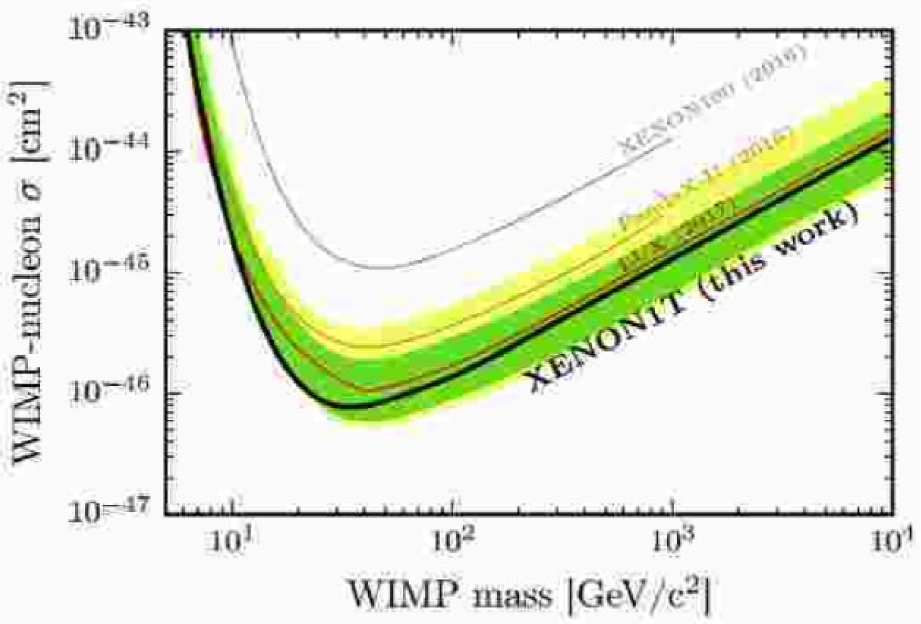


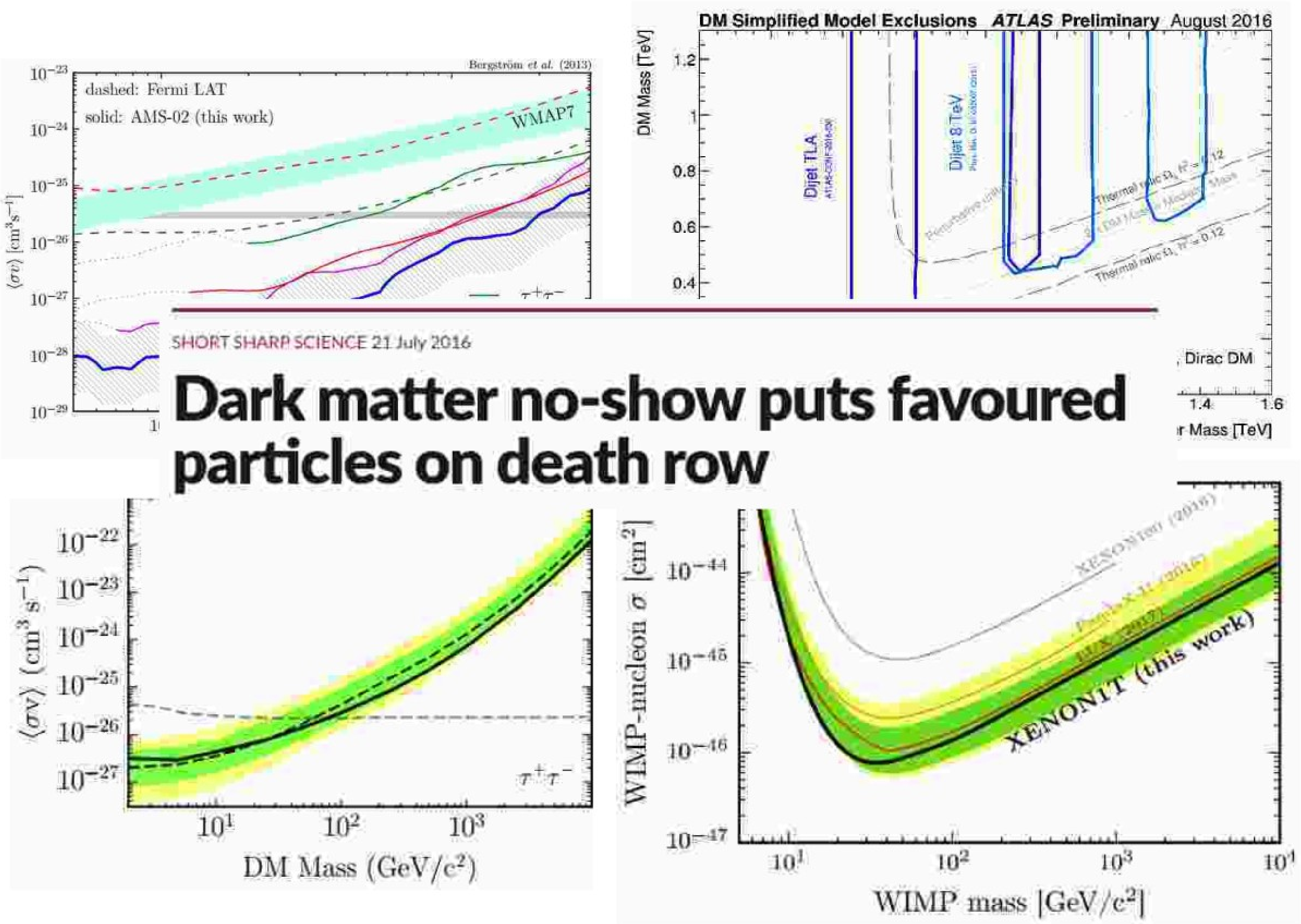



Bergström et al. (2013)
dashed: Fermi LAT
solid: AMS-02 (this work)
WMAP7
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
m_χ [GeV]
$\tau^+\tau^-$
$\mu^+\mu^-$
$e^+e^-\gamma$
e^+e^-


DM Simplified Model Exclusions ATLAS Preliminary August 2016
DM Mass [TeV]
Mediator Mass [TeV]
Dijet TLA
Dijet 8 TeV
Axial-vector mediator, Dirac DM
$g_q = 0.1, g_{DM} = 1.5$


$\langle \sigma v \rangle$ (cm^3 s^{-1})
$\tau^+\tau^-$
DM Mass (GeV/c^2)


WIMP-nucleon σ [cm^2]
XENON1T (this work)
WIMP mass [GeV/c^2]



Bergström et al. (2013)
dashed: Fermi LAT
solid: AMS-02 (this work)
WMAP7
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
DM Simplified Model Exclusions ATLAS Preliminary August 2016
DM Mass [TeV]
Dijet TLA
Dijet 8 TeV
Thermal relic $\Omega_c h^2$ = 0.12
Dirac DM
Mass [TeV]
SHORT SHARP SCIENCE 21 July 2016
Dark matter no-show puts favoured particles on death row
$\langle \sigma v \rangle$ (cm^3 s^{-1})
$\tau^+\tau^-$
DM Mass (GeV/c^2)
WIMP-nucleon σ [cm^2]
XENON100 (2016)
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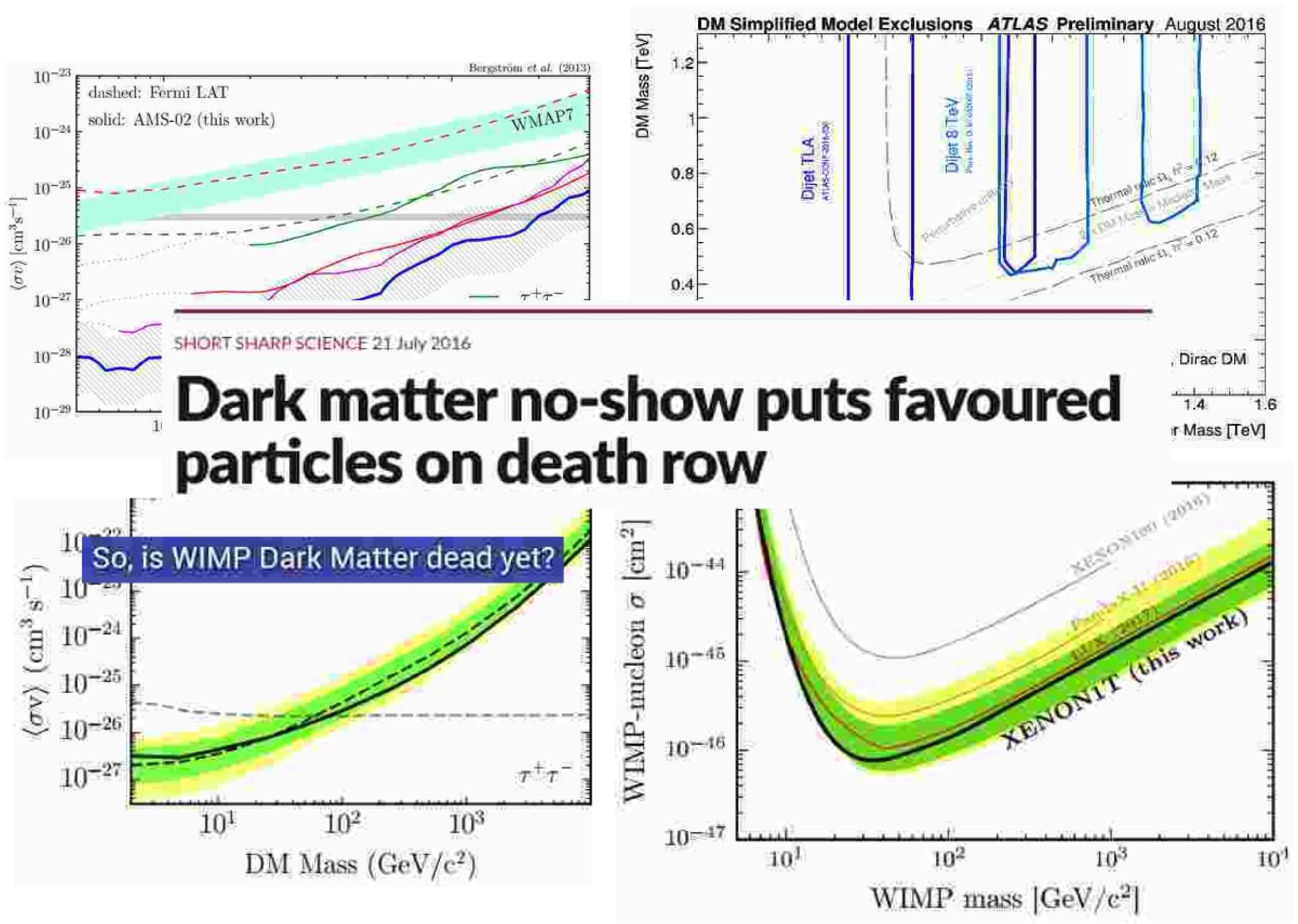
WIMP mass [GeV/c^2]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DM Simplified Model Exclusions ATLAS Preliminary August 2016
DM Mass [TeV]
Dijet TLA
Dijet 8 TeV
Dirac DM
Mass [TeV]
SHORT SHARP SCIENCE 21 July 2016
Dark matter no-show puts favoured particles on death row
So, is WIMP Dark Matter dead yet?
$\langle \sigma v \rangle$ (cm^3 s^{-1})
$\tau^+\tau^-$
DM Mass (GeV/c^2)
WIMP-nucleon σ [cm^2]
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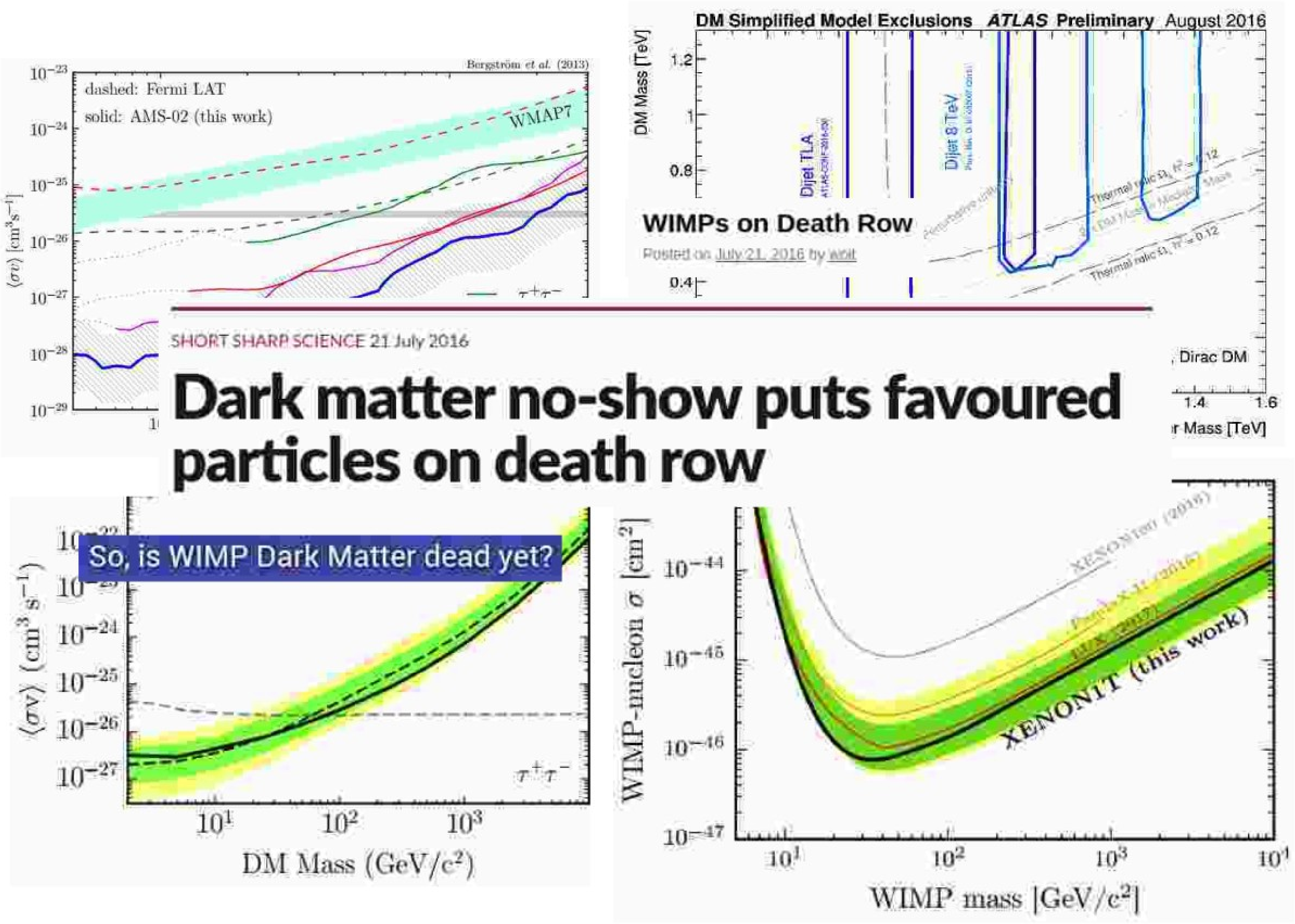
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WIMPs on Death Row
Posted on July 21, 2016 by woit
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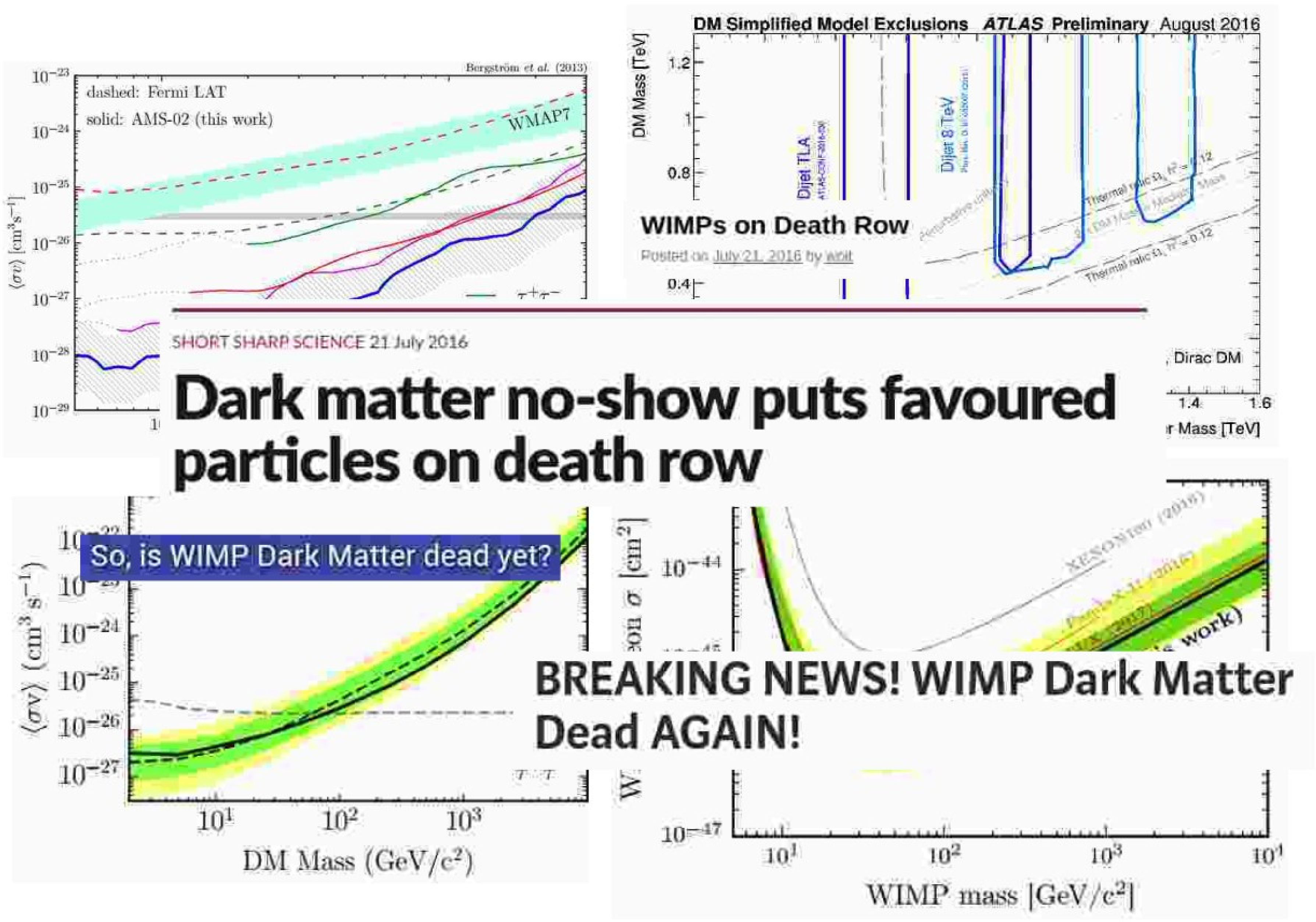
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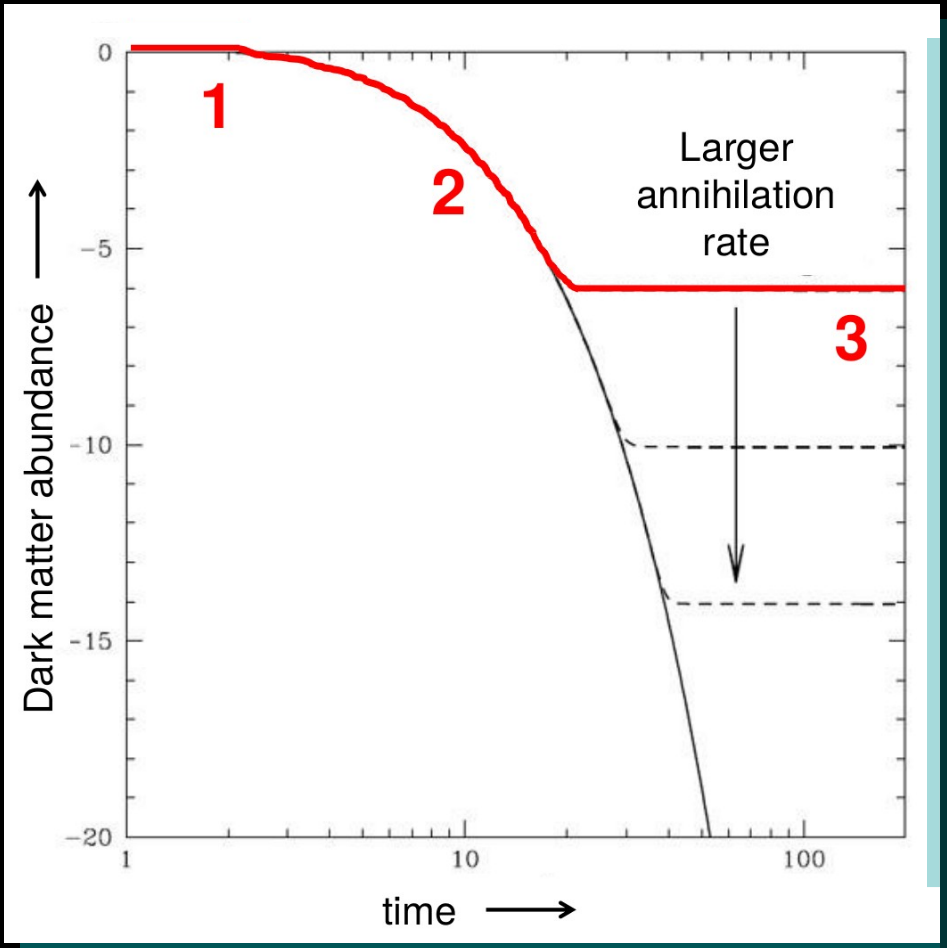
Dijet 8 TeV
WIMPs on Death Row
Posted on July 21, 2016 by woit
SHORT SHARP SCIENCE 21 July 2016
Dark matter no-show puts favoured particles on death row
So, is WIMP Dark Matter dead yet?
DM Mass (GeV/c²)
BREAKING NEWS! WIMP Dark Matter Dead AGAIN!
WIMP mass [GeV/c²]

Only annihilation provides the target rate

Scattering (direct detection) and production (colliders):
No well-defined scale because only some aspects of the interaction are being considered.

Those constraints tell you which WIMP models are excluded, but nothing about the remaining possibilities.



Only annihilation provides the target rate

Scattering (direct detection) and production (colliders):
No well-defined scale because only some aspects of the interaction are being considered.

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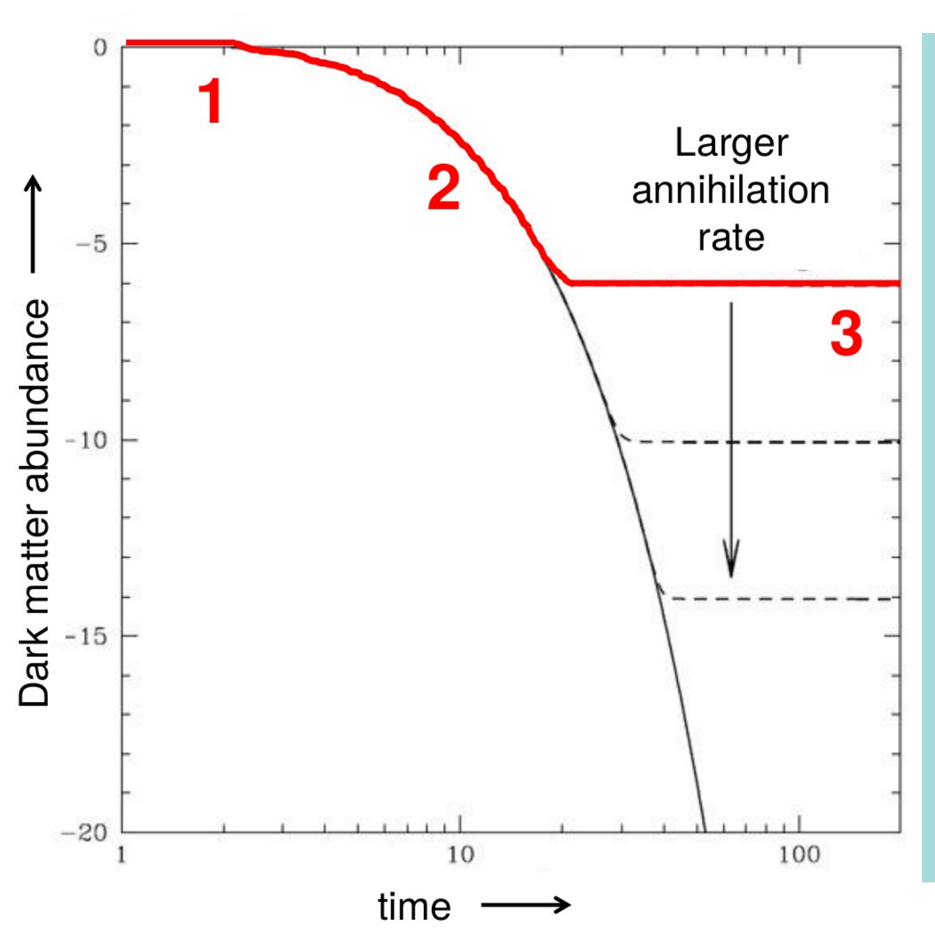
The most decisive way to test thermal WIMPs is through their annihilation products, as this exactly goes to their most fundamental feature: being annihilation relics, which sets a well-defined scale for the total cross section.



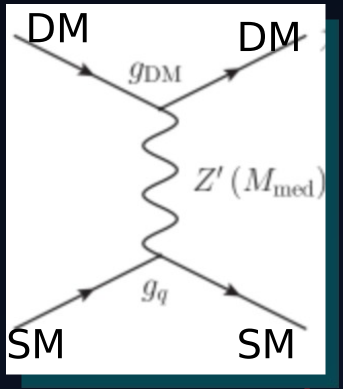
Hidden dark sectors:

- New fields that have small couplings to the SM
- Naturally occurs in many model scenarios; symmetries, or Higgs may have mass coupling dependence, etc
- If zero coupling to the SM, can't detect the DM!
- Need to interact at least very weakly with the SM to probe at particle experiments

Searching for hidden dark sectors

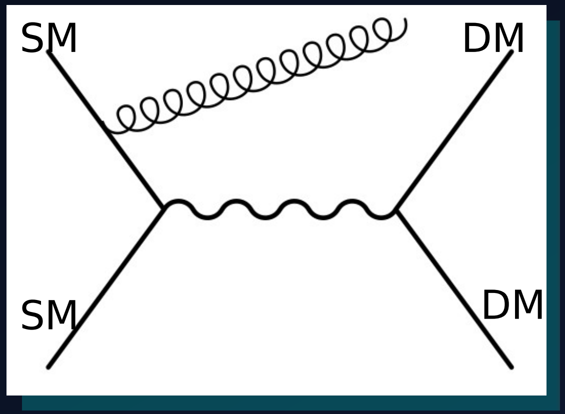
- Small coupling to SM minimizes constraints from scattering or production
  - Difficult but not impossible to probe!

Scattering



Suppressed :(

Production

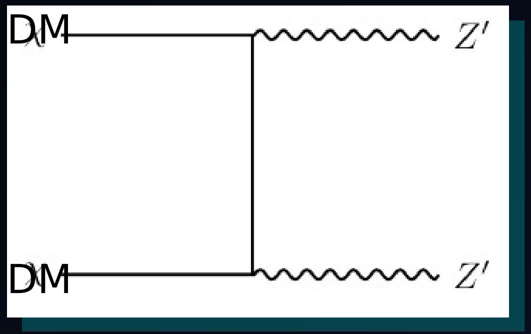


Suppressed :(

Searching for hidden dark sectors

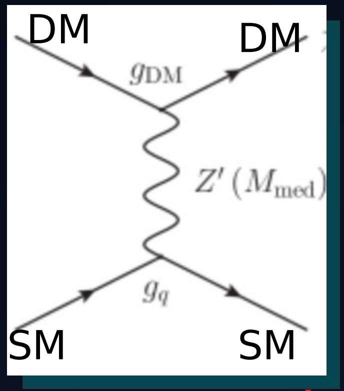
- Small coupling to SM minimizes constraints from scattering or production
  - Difficult but not impossible to probe!
- Large signals still possible for annihilation!
  - Cross section independent of SM coupling if particles produced on shell
  - Only then multiplied by branching fraction

Annihilation



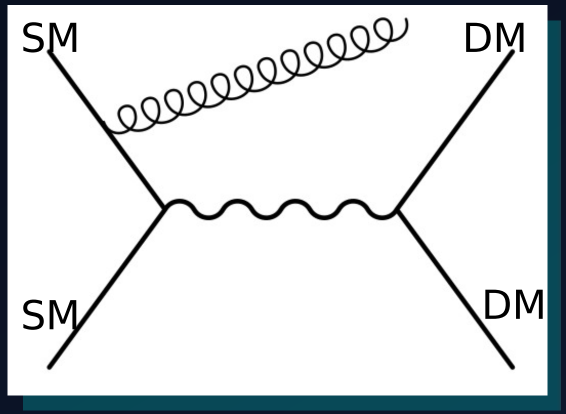
Not suppressed :)

Scattering



Suppressed :(

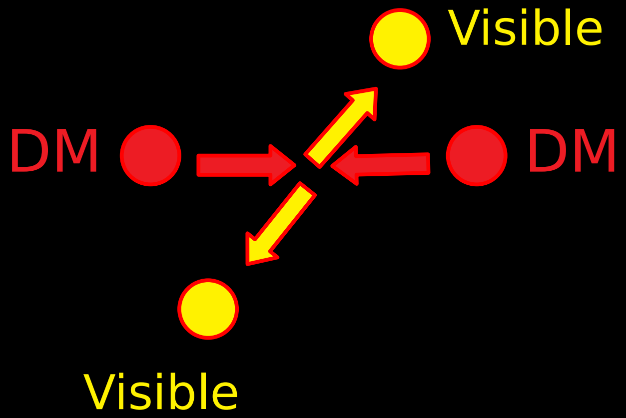
Production



Suppressed :(

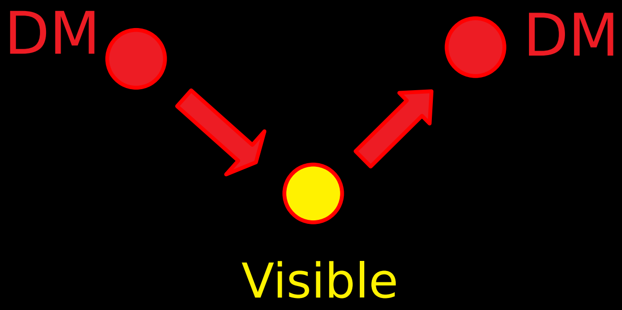
WIMP Dark Matter Search Program

Annihilation



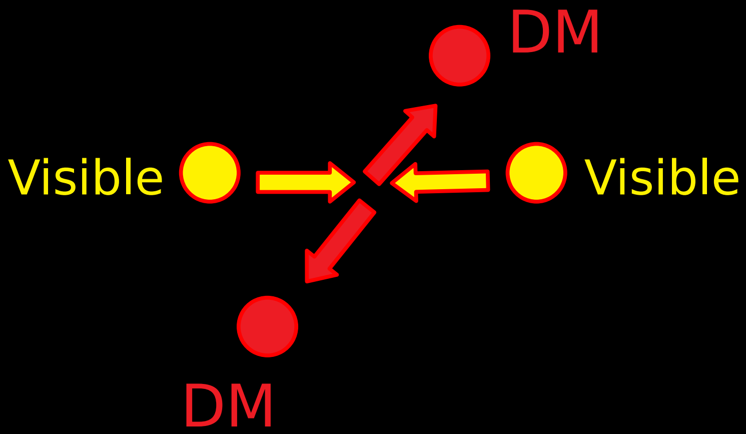
Astrophysics

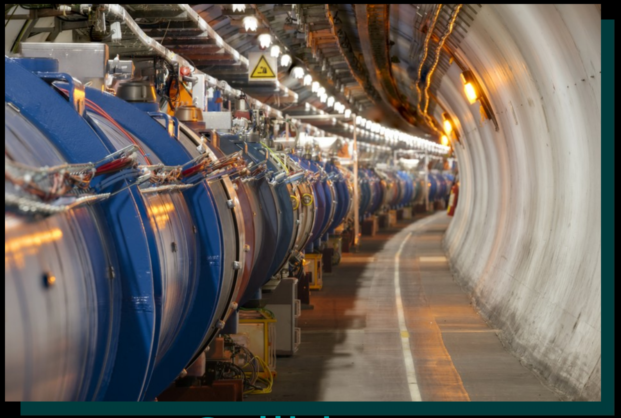
Scattering



Direct detection
+ Astrophysics

Production





Colliders
+ Astrophysics

INDIRECT DETECTION

Ingredient #1: DM Interaction Rate

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

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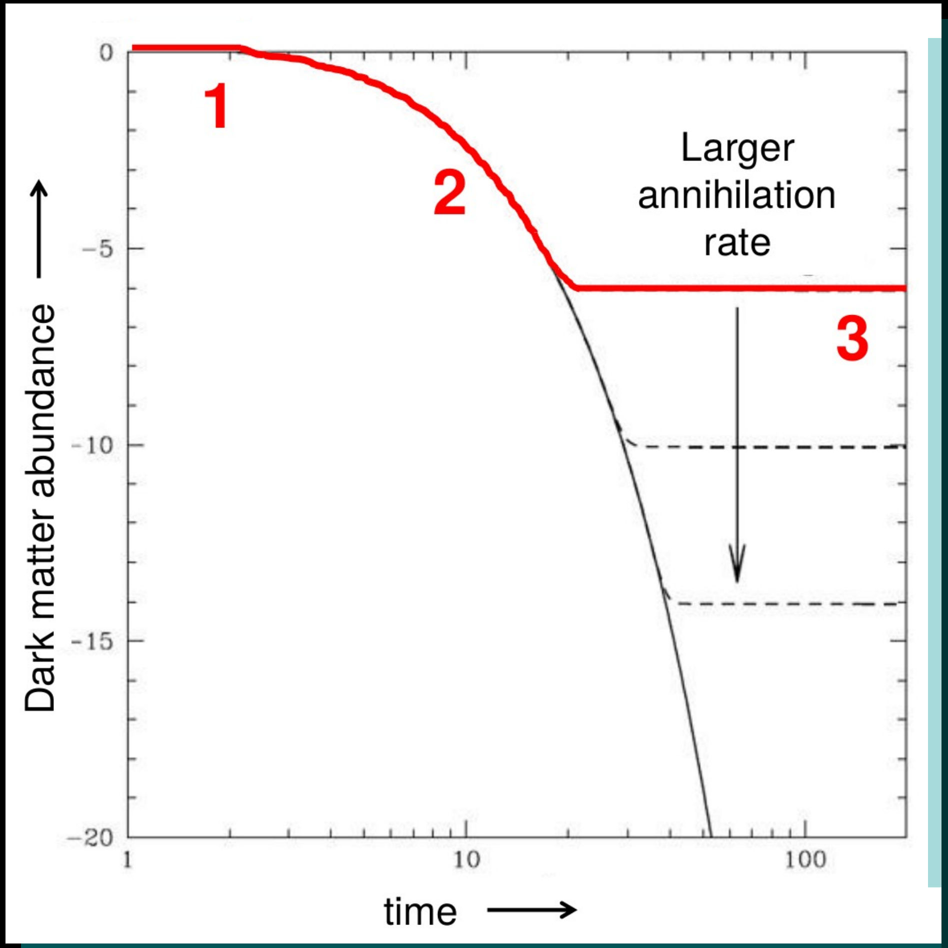
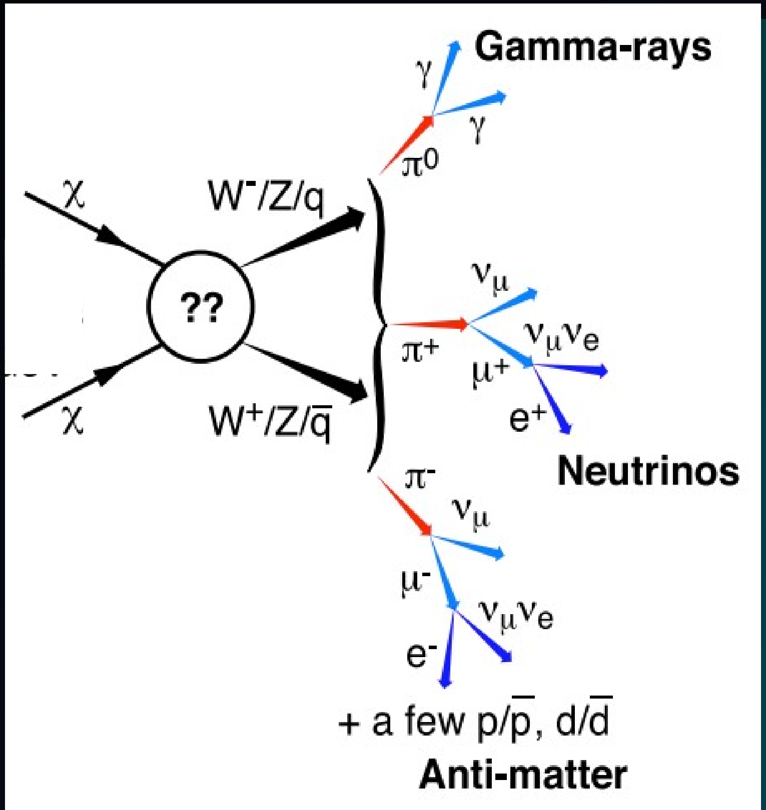
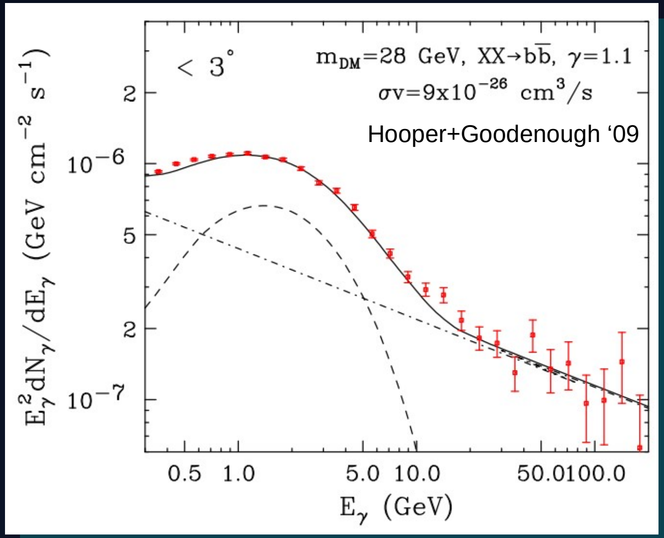


Ingredient #2: Energy Spectrum



Baltz et al 0806.2911

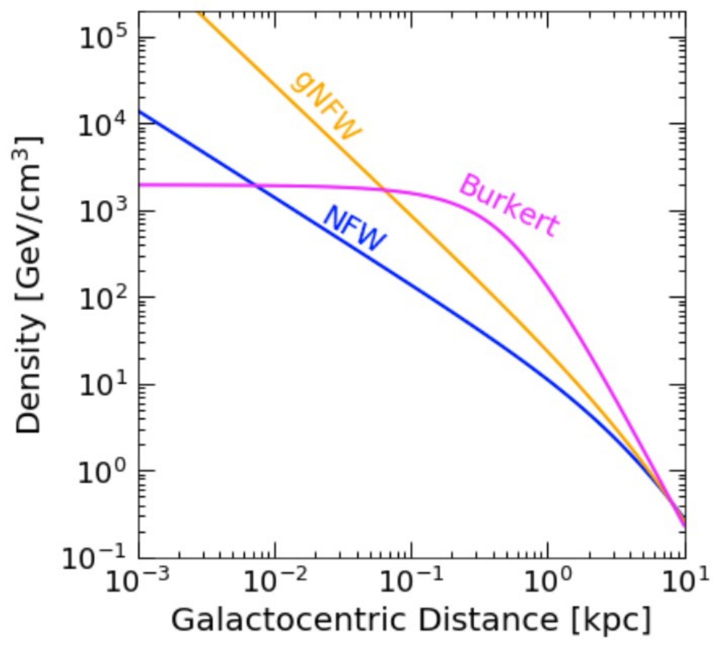
- Also driven by particle physics model
- Shape depends on:
  - branching ratios to final SM states
  - boosts of particles



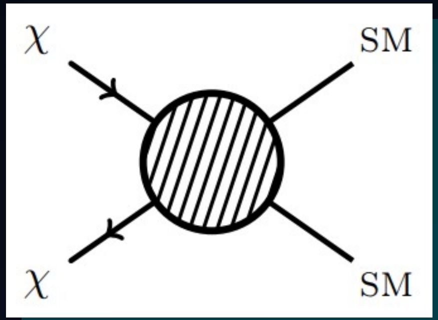
Ingredient #3: DM Density+Distribution

- Line of sight integral over DM density
  - J-factor (annihilation)
  - D-factor (decay)

- DM density profiles not well-known
  - large uncertainties



Indirect Detection Ingredients

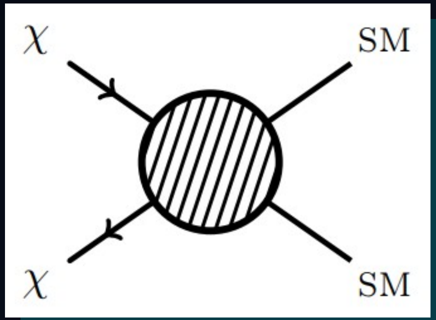


Particle Physics | Astrophysics

(Neutral particles)

$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a\, d\ell.$$

Indirect Detection Ingredients



Particle Physics

Astrophysics

(Neutral particles)

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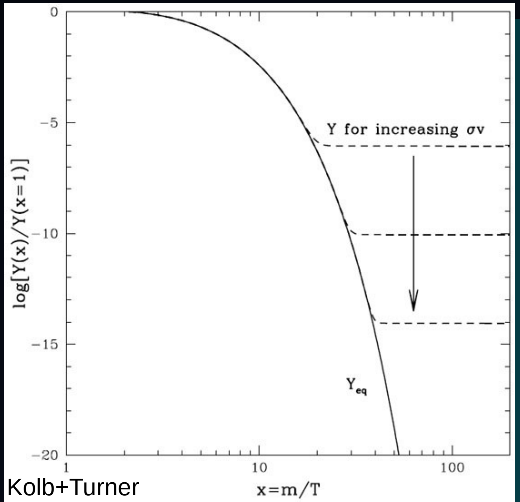
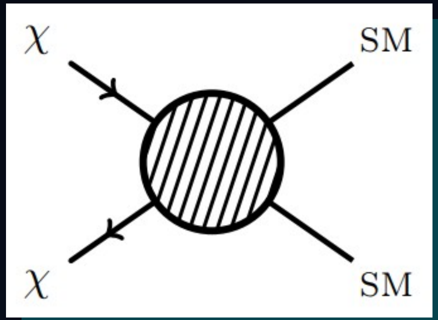
Annihilation cross section



Kolb+Turner

Indirect Detection Ingredients



Particle Physics Astrophysics

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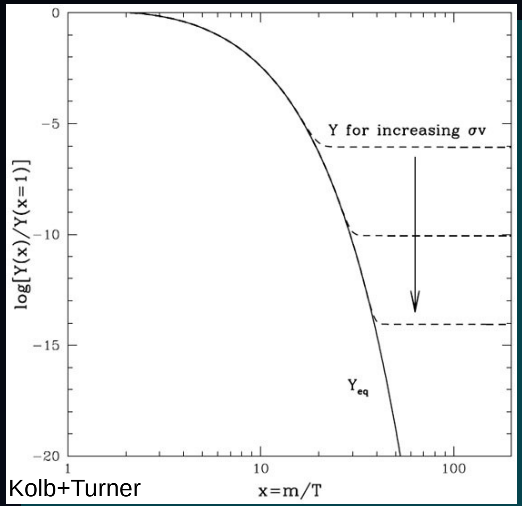
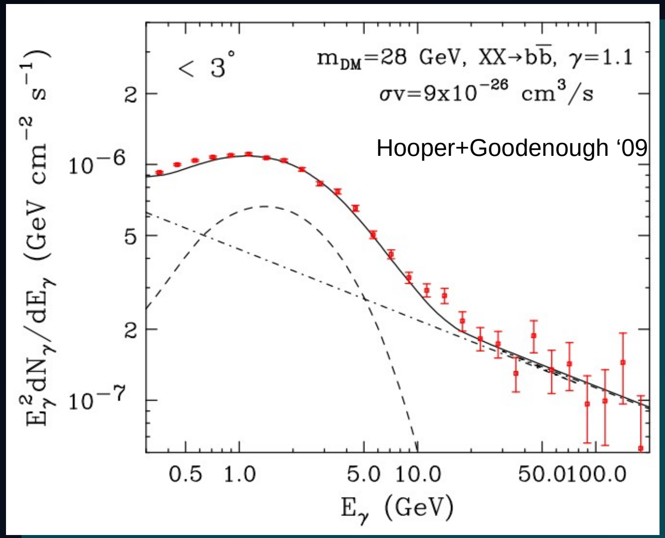
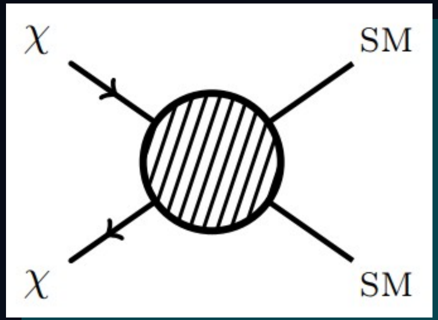
Annihilation cross section

Energy spectrum





Indirect Detection Ingredients



Particle Physics

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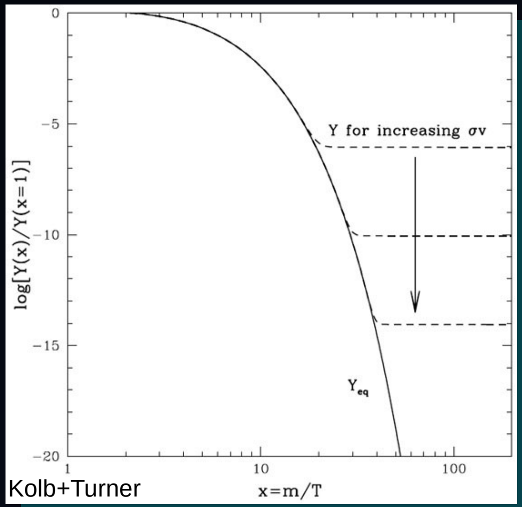
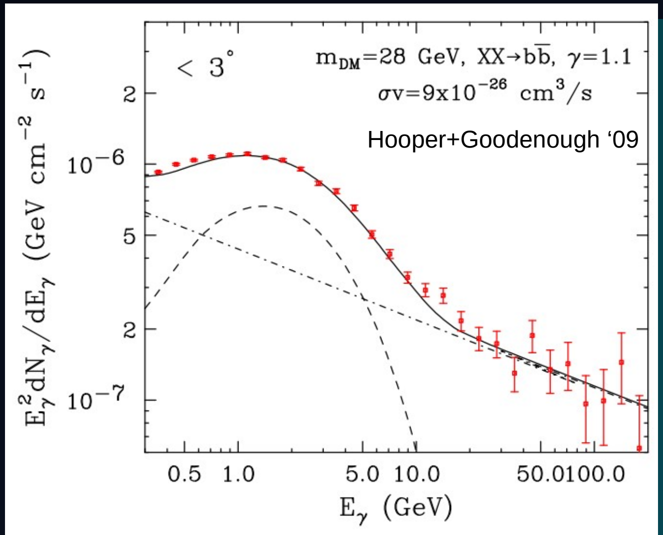
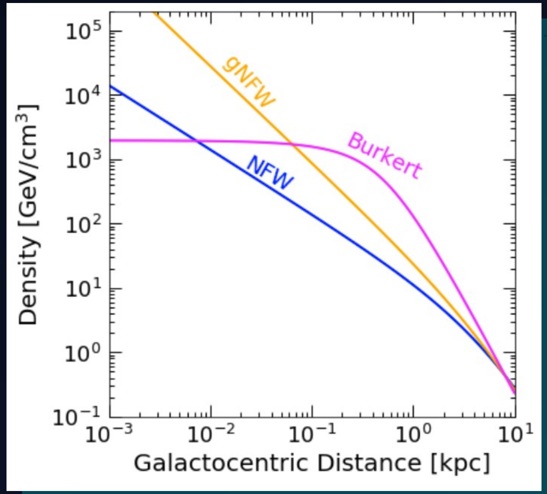
Annihilation cross section

Energy spectrum

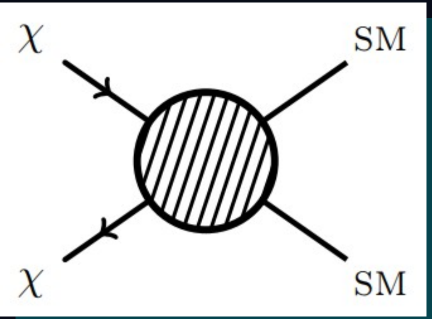
"J factor", DM density







Indirect Detection Ingredients



Particle Physics

Astrophysics

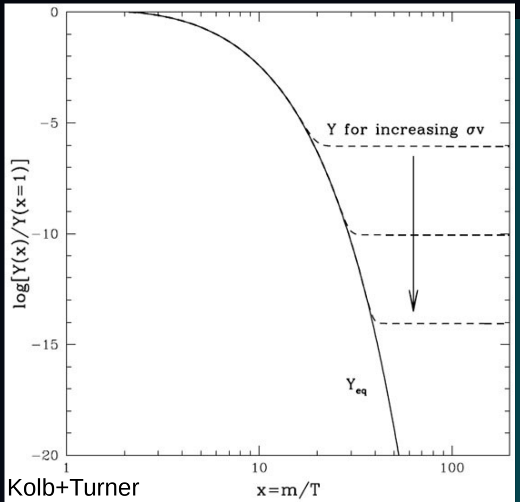
(Neutral particles)

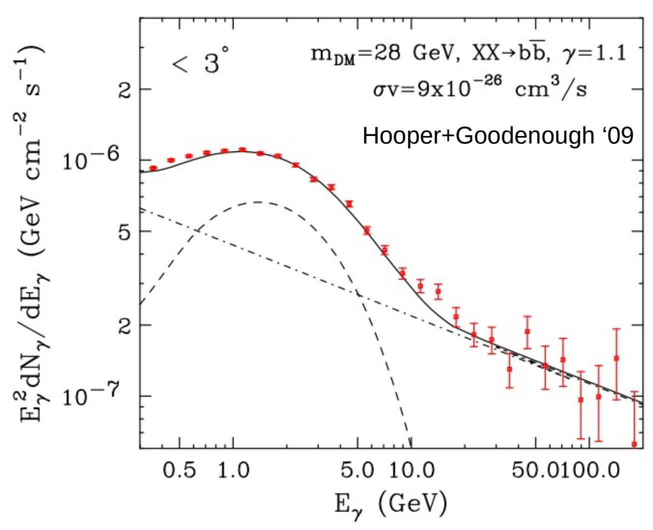
$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a \, d\ell.$$

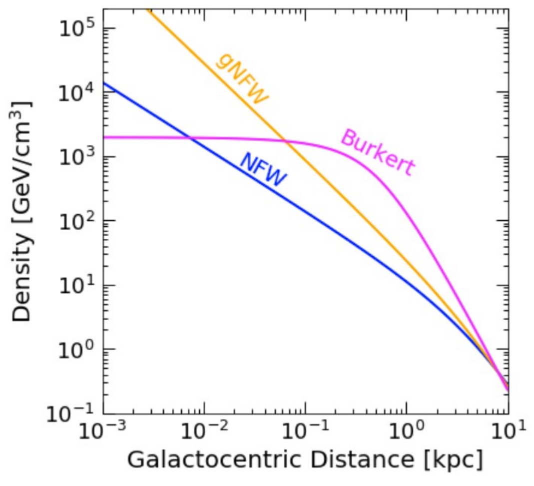
"J factor", DM density

Annihilation cross section

Energy spectrum

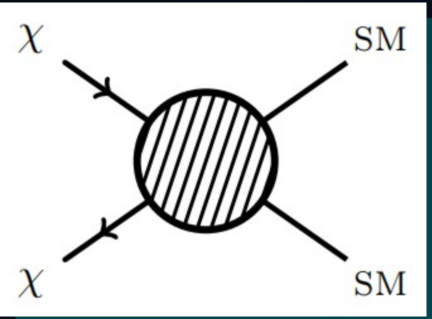






Look where this is large!

Indirect Detection Ingredients



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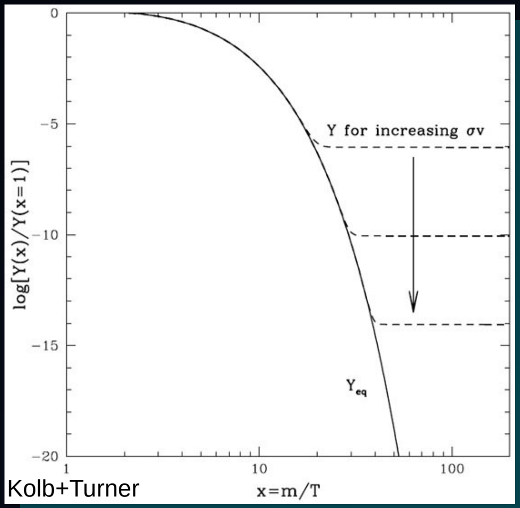
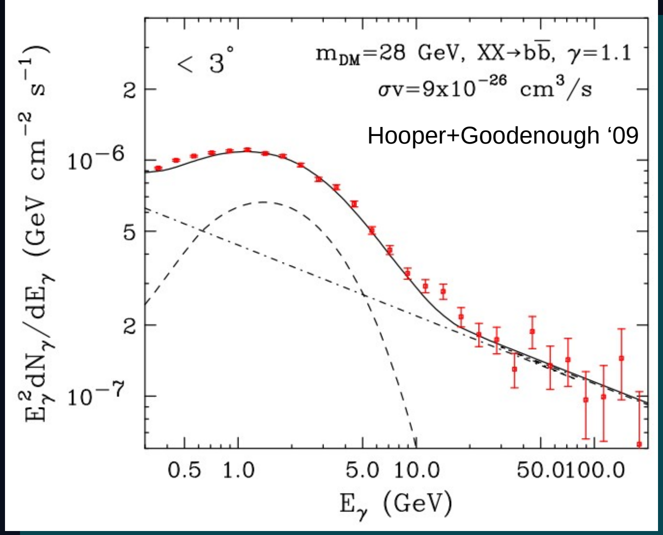
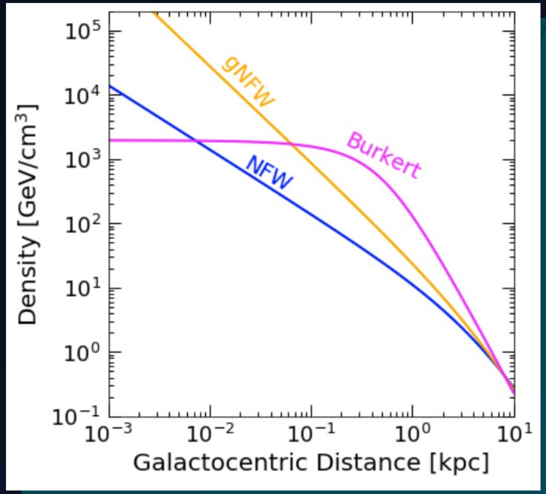




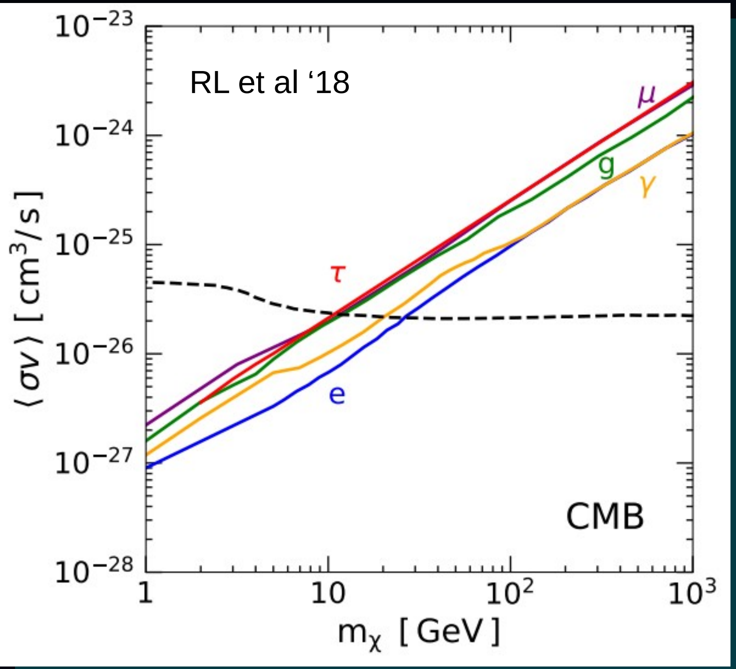


Look where this is large!

...or places with low background!

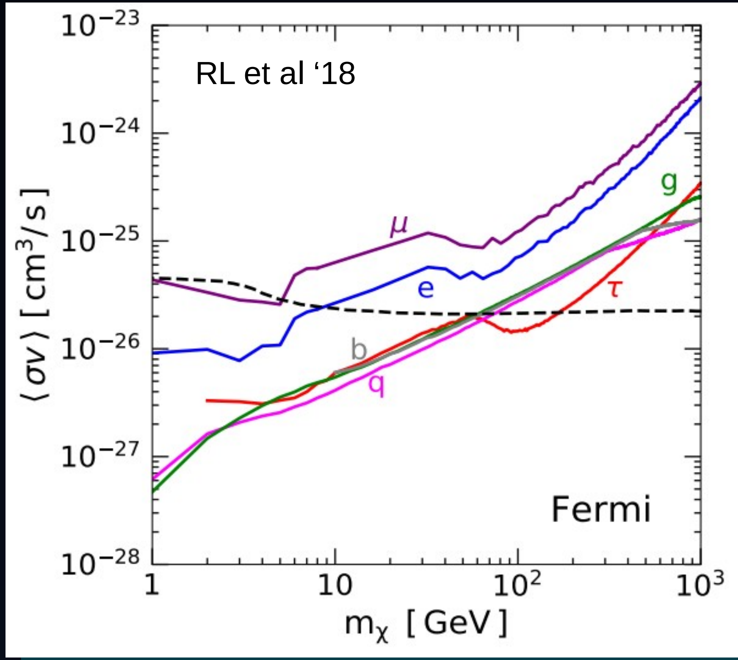
Complementarity: cornering WIMPs

Strongest low mass



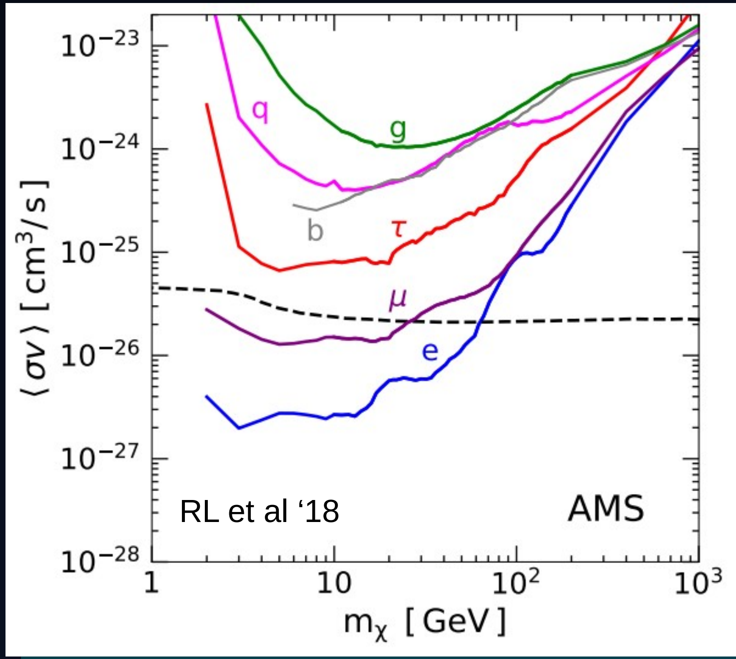
Also see Slatyer '15

Strongest for hadrons



Also see Fermi Collab '16

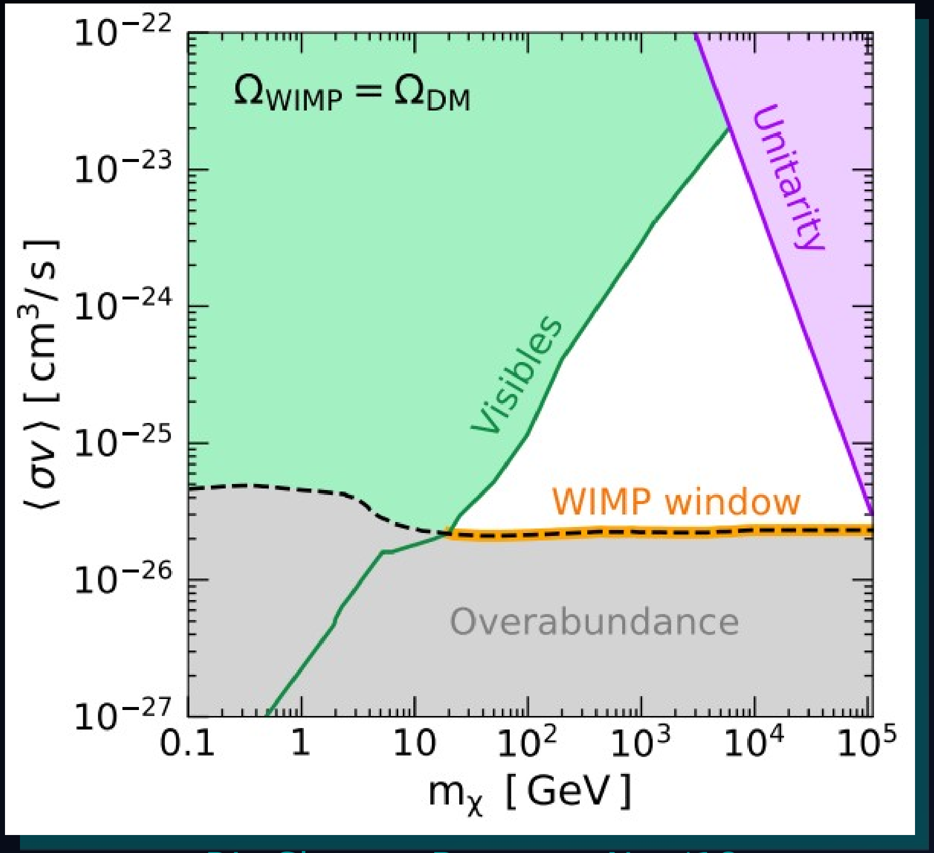
Strongest for leptons



Also see AMS collab '14

(strongest *and most robust* bounds)

Complementarity: cornering WIMPs



RL, Slatyer, Beacom, Ng, '18

WIMP is not dead!

Use all possible final states, combine strongest limits

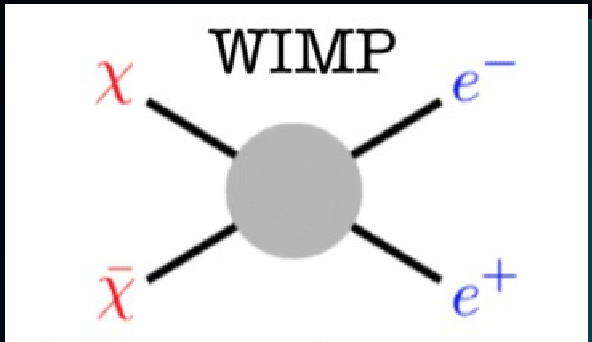
S-wave 2→2 thermal DM to visible states: mass greater than ~20 GeV

Still need to push through this window

OTHER TYPES OF FREEZEOUT

Range of freezeout options!

Zeldovich, Lee, Weinberg, Steigman, Turner,…+

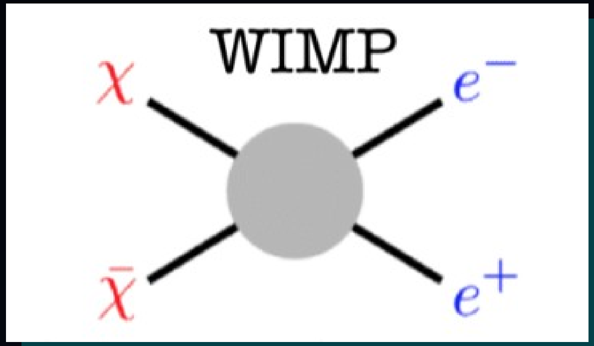


$$\Gamma_{\rm DM} = \langle \sigma v_{\rm rel.} \rangle \, n_{\rm DM} > H(T)$$

$$\Omega_{\rm DM} \, h^2 \approx \frac{0.12}{\langle \sigma v_{\rm rel.} \rangle \, [25 \mathrm{TeV}]^2}$$

Range of freezeout options!

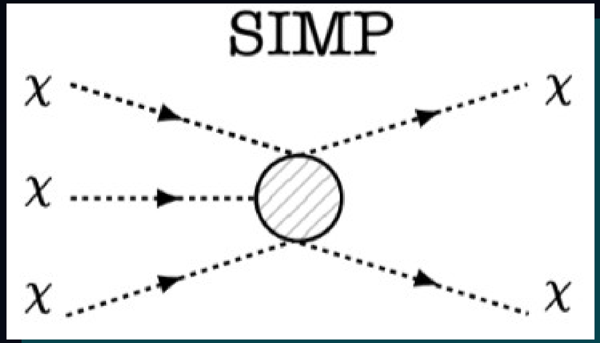
Zeldovich, Lee, Weinberg, Steigman, Turner,…+



$$\Gamma_{\mathrm{DM}} = \langle \sigma v_{\mathrm{rel.}} \rangle \, n_{\mathrm{DM}} > H(T)$$

$$\Omega_{\mathrm{DM}} \, h^2 \approx \frac{0.12}{\langle \sigma v_{\mathrm{rel.}} \rangle \, [25\mathrm{TeV}]^2}$$

Hochberg, Kuflik, Volanksy, Wacker, 2014



$$\Gamma_{\mathrm{DM}} = \langle \sigma_{3\to2} v_{\mathrm{rel.}}^2 \rangle \, n_{\mathrm{DM}}^2 > H(T)$$

$$\Omega_{\mathrm{DM}} \, h^2 \approx \left(\frac{\mathrm{MeV}}{m_{\mathrm{DM}}} \right) \frac{0.12}{\sqrt{\langle \sigma_{3\to2} v_{\mathrm{rel.}}^2 \rangle \, [3\mathrm{MeV}]^5}}$$

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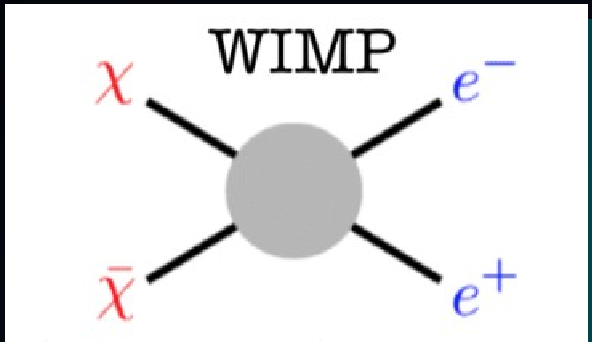

$$\Gamma_{\rm DM} = \langle \sigma v_{\rm rel.} \rangle \, n_{\rm DM} > H(T)$$

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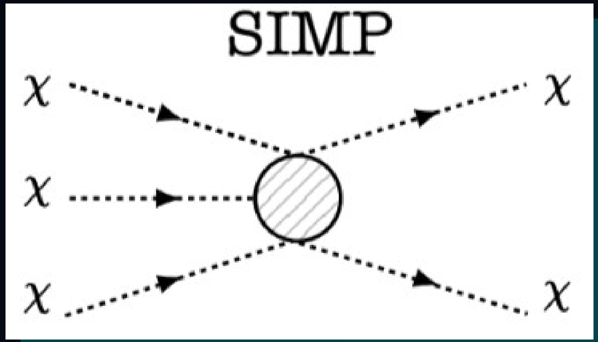
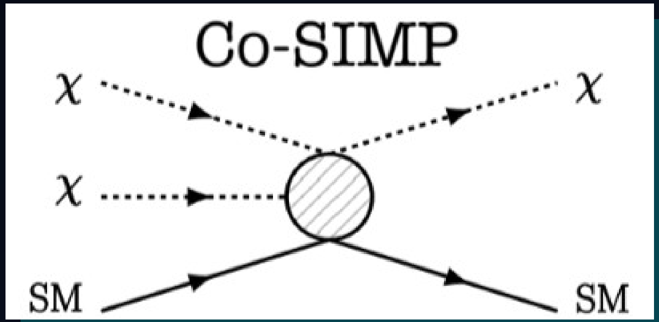
Hochberg, Kuflik, Volanksy, Wacker, 2014



$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v^2_{\rm rel.} \rangle \, n^2_{\rm DM} > H(T)$$

$$\Omega_{\rm DM}\, h^2 \approx \left(\frac{\rm MeV}{m_{\rm DM}}\right) \frac{0.12}{\sqrt{\langle \sigma_{3\to 2} v^2_{\rm rel.} \rangle \, [3{\rm MeV}]^5}}$$

Beacom, Smirnov, 2020



$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v^2_{\rm rel.} \rangle \, n_{\rm DM} n_{\rm SM} > H(T)$$

$$\Omega_{\rm DM} h^2 \approx \left(\frac{\rm MeV}{m_{DM}}\right)^3 \frac{0.12}{\langle \sigma_{3\to 2} v^2_{\rm rel.} \rangle [100\,{\rm MeV}]^5}$$

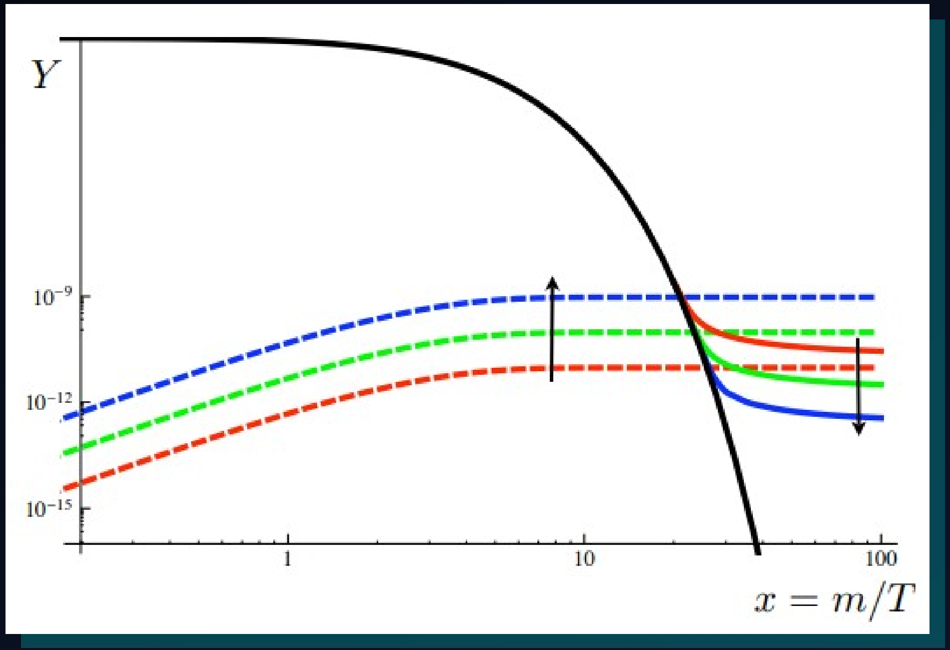
FREEZEOUT? FREEZE IN!

Dark matter freeze-in

- For freeze-out, the universe has a large population of DM that was in thermal equilibrium with the bath, that is depleted as the Universe cools

- For freeze-in, the universe starts with little DM and it never reaches thermal equilibrium with the bath

- At temperatures lower than the DM mass, the bath no longer has enough energy to produce it. Then, the DM is “frozen-in”

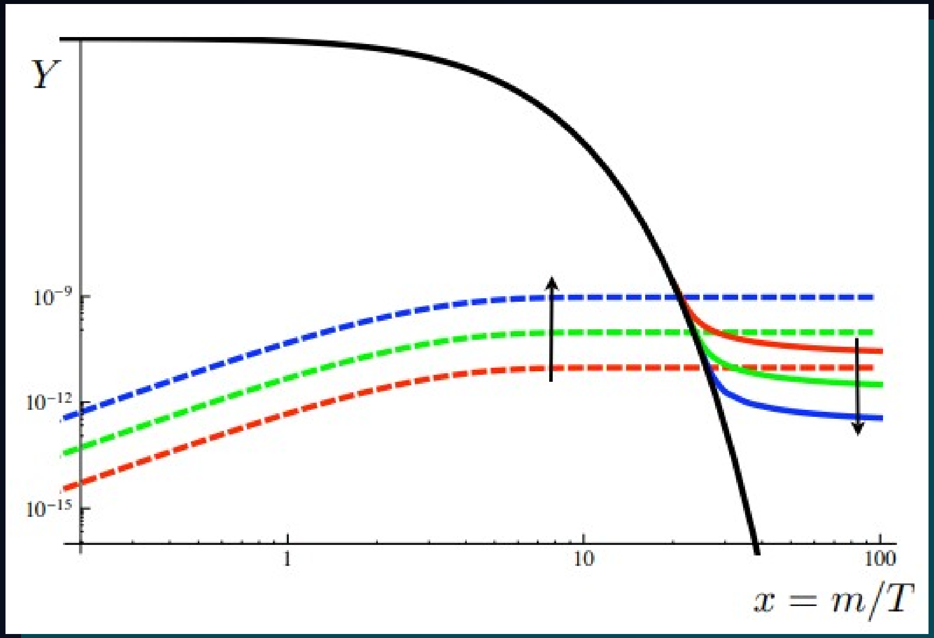


Arrows point in direction of increased DM-bath coupling

Hall, Jedamzik, March-Russell, West 2009

Dark matter freeze-in

- For freeze-out, the universe has a large population of DM that was in thermal equilibrium with the bath, that is depleted as the Universe cools
- For freeze-in, the universe starts with little DM and it never reaches thermal equilibrium with the bath
- At temperatures lower than the DM mass, the bath no longer has enough energy to produce it. Then, the DM is “frozen-in”
- Still gets us right abundance, but applies to models with much smaller couplings -- “Feebly Interacting Massive Particles”, or FIMPs

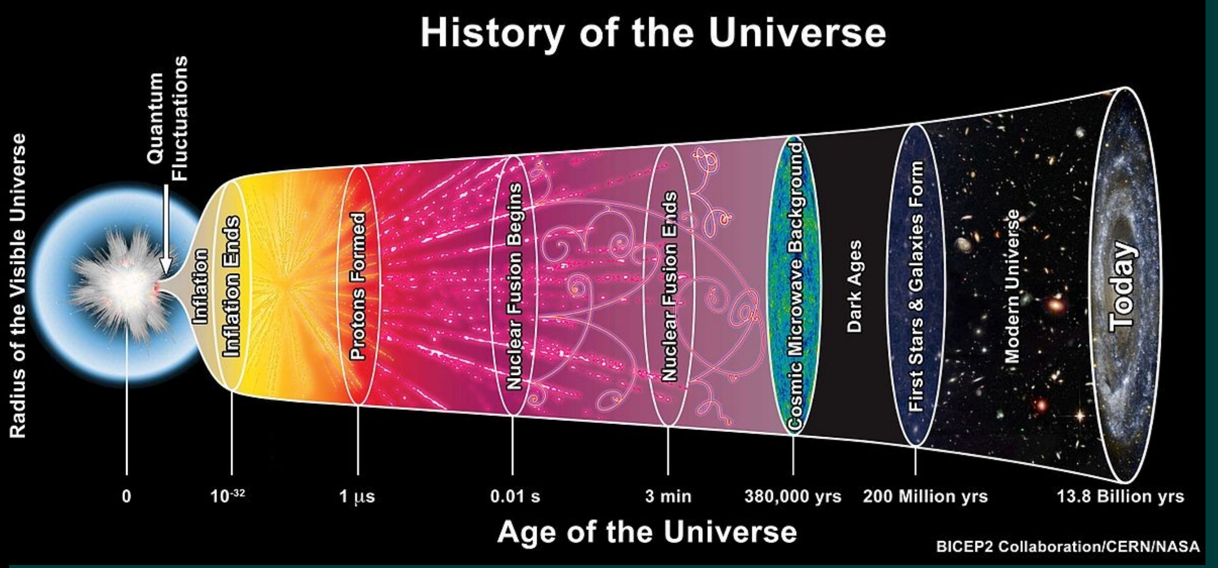


Arrows point in direction of increased DM-bath coupling

Hall, Jedamzik, March-Russell, West 2009

Uncertainties for the early Universe?

- WIMP freezes out before BBN and CMB
  - A lot could happen between these times!
- Some particle could decay into DM
- Some particle could decay into visible matter, diluting the original amount of DM



- Maybe physics was just different to what we expect! Hard to know.
  - Finding DM may give us a new window further back into the Universe

AXIONS

(see also Jure Zupan's earlier lecture)

Strong CP problem

- If interactions are allowed by all symmetries, they generally are present
- One term is suspiciously silent

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} G_{\mu\nu}\tilde{G}_{\mu\nu}$$

- Strange also because symmetry between matter and antimatter is broken in the weak interactions (CP violated), but not in strong interactions

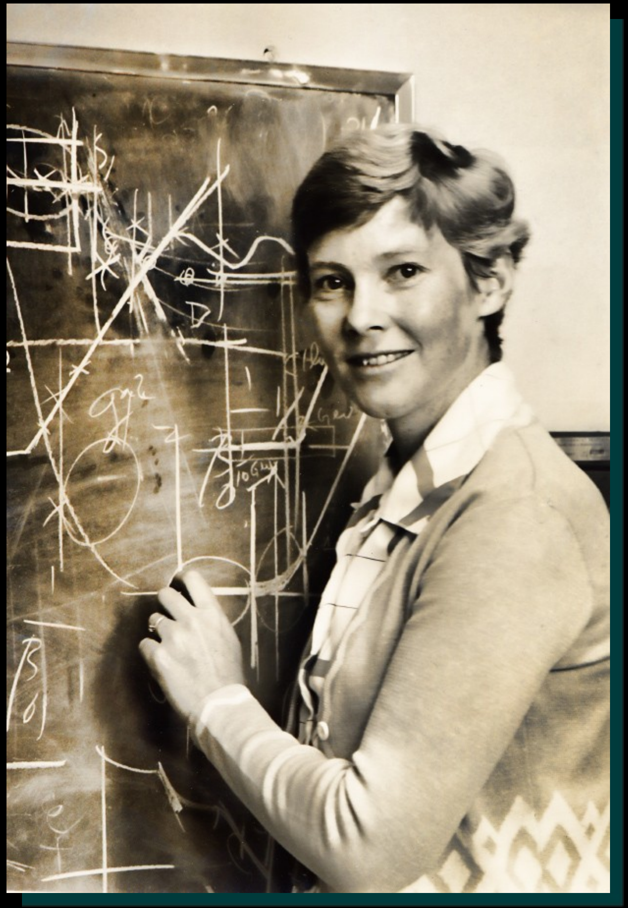
- Term should induce neutron electric dipole moment, but experimentally it is measured to be at least ~10 ORDERS OF MAGNITUDE below naive expectations ????

ENTER PECCEI + QUINN

Image: Quanta Magazine

Peccei-Quinn Symmetry

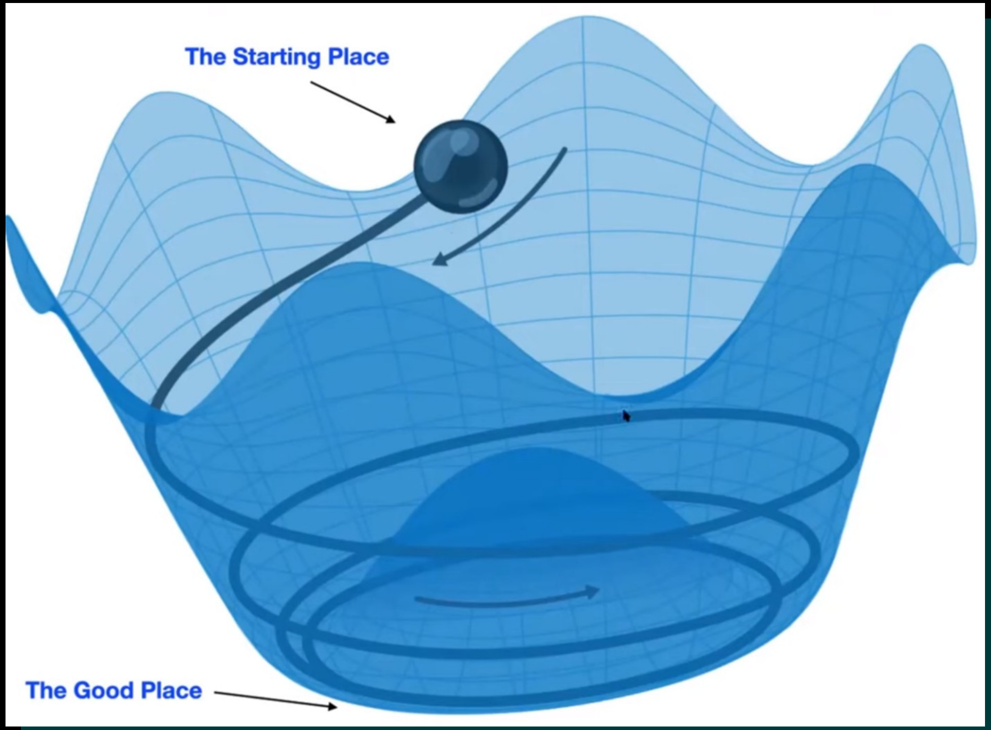
- If interactions are allowed by all symmetries, they generally are present
- So: Invoke new symmetry, Peccei-Quinn (PQ) symmetry, which is a minimal extension of the SM, which is is spontaneously broken



Helen Quinn in her SLAC office, ~1977
Source: Helen Quinn

Dynamical field

- Promote the unwanted coupling (theta) to a dynamical field that relaxes to zero: not fixed for all time, but instead changes over time
- Value of the field is the co-efficient of the "unwanted" interaction
- Energetically preferred coupling is small/zero (so over time of the Universe it evolves to zero)
- Quanta of this field is the QCD axion



Wilczek

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

Peccei, Quinn 1977
Wilczek 1978, Weinberg 1978
Vafa, Witten 1984

Dynamic

- Promote the unwa
dynamical field th
for all time, but in

- Value of the field
"unwanted" intera

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(so over time of t

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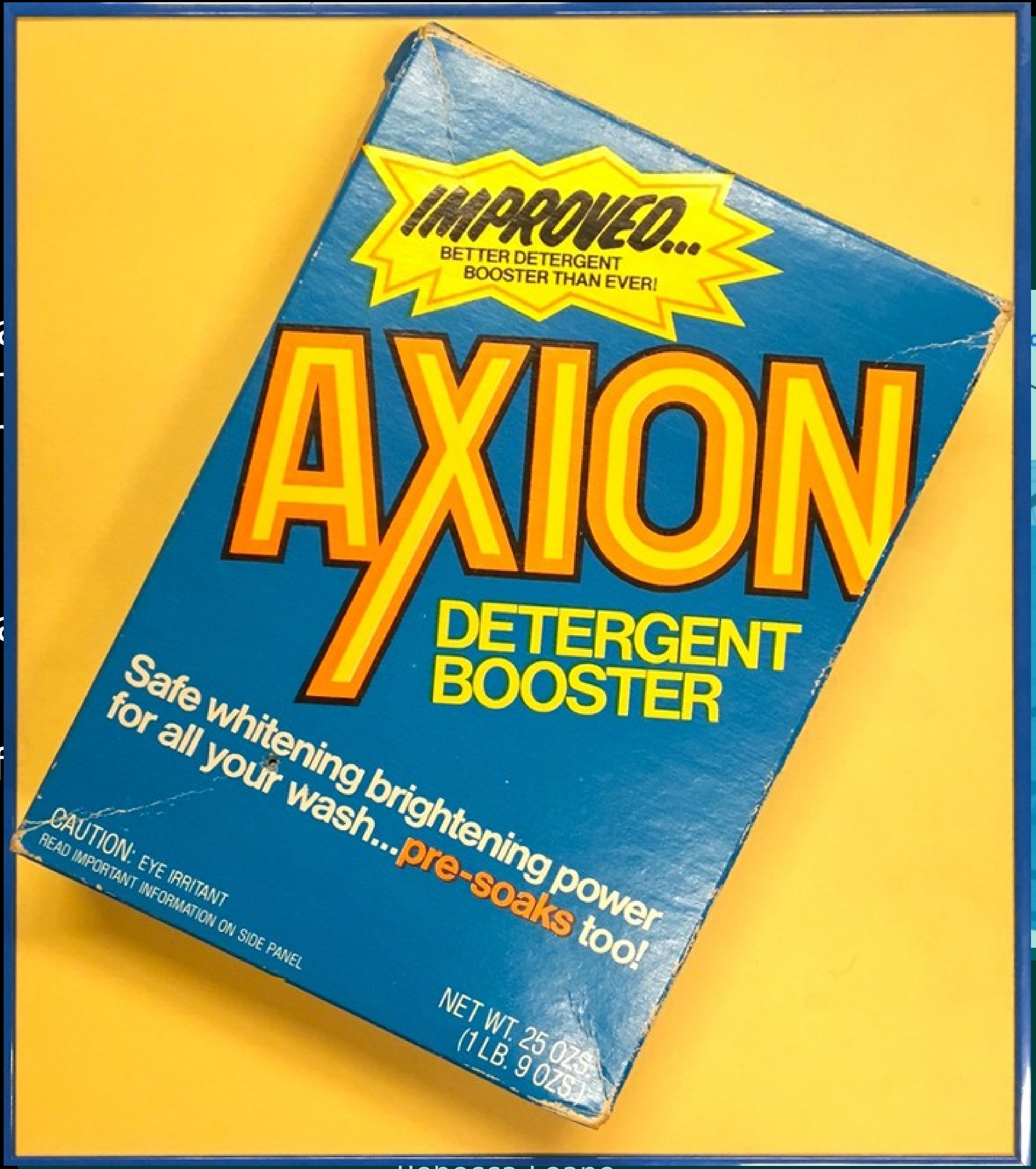
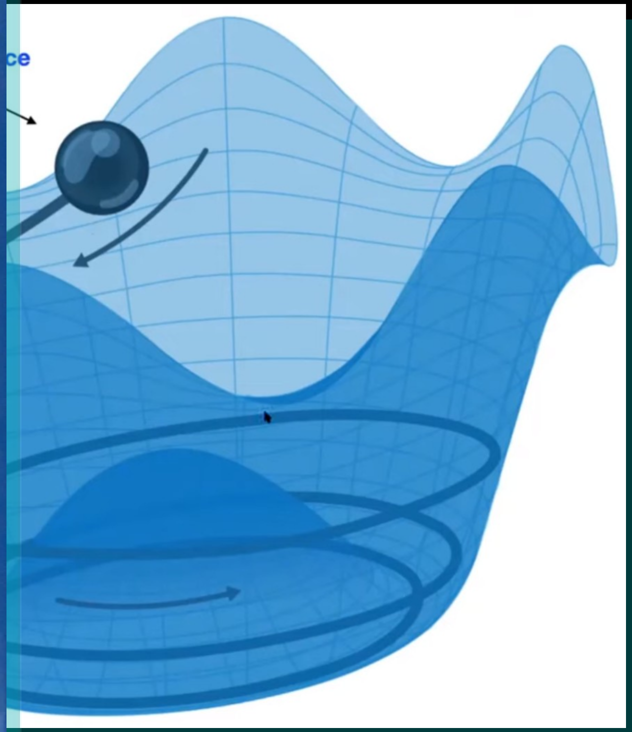


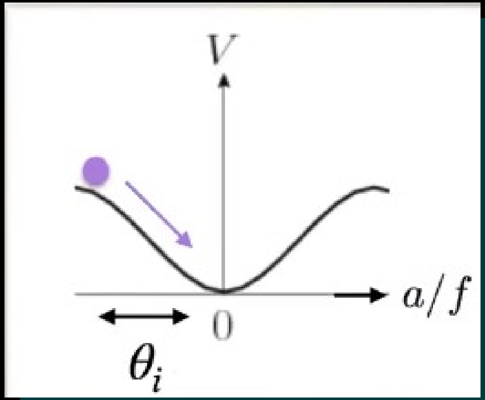


Wilczek

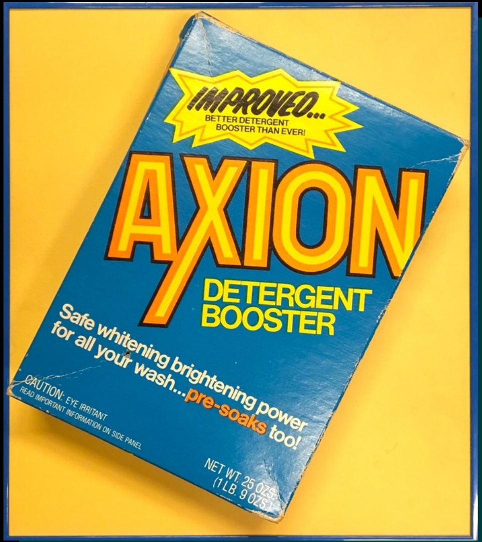
Rebecca Leane

Can be dark matter

- Production occurs in the early universe, misalignment mechanism
  - Relic abundance ok for small masses, ~10^-8 – 10^-3 eV
- Generally want mass less than about 20 eV for stability
- Can act as cold dark matter!



Zupan's slide



Increasingly popular, and can be DM!

A New Light Boson?

Steven Weinberg (Harvard U.)

Dec, 1977

12 pages

Published in: *Phys.Rev.Lett.* 40 (1978) 223-226

DOI: 10.1103/PhysRevLett.40.223

Report number: HUTP-77/A074

View in: OSTI Information Bridge Server, ADS Abstract Service, KEK scanned document

pdf cite claim 4,670 citations

Citations per year

Frank Wilczek (Columbia U. and Princeton, Inst. Advanced Study)

Nov, 1977

12 pages

Published in: *Phys.Rev.Lett.* 40 (1978) 279-282

DOI: 10.1103/PhysRevLett.40.279

Report number: Print-77-0939 (COLUMBIA)

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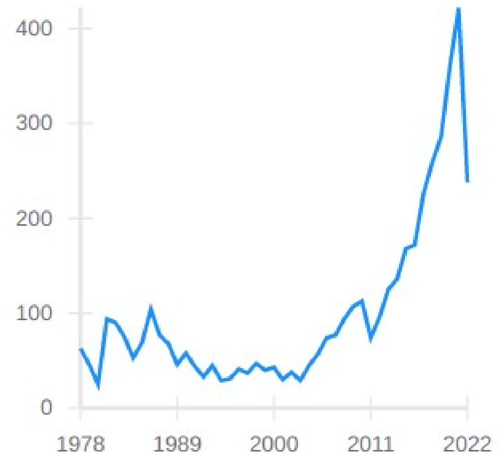


Testable interactions

- Can couple to gluons, EM, leptons, quarks

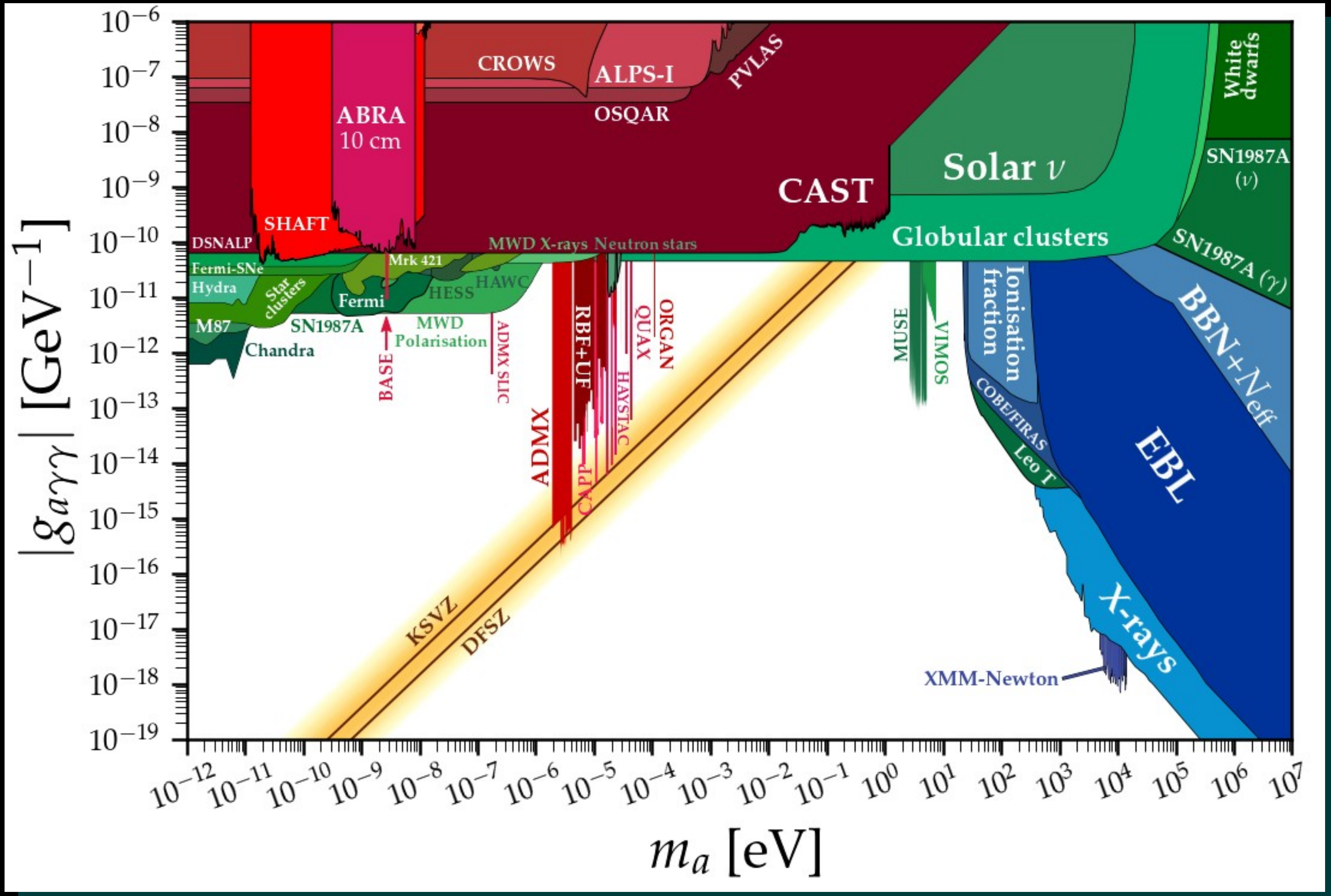
$$\mathcal{L}_{\text{int}} \sim -\frac{a}{F}\left(c_G\,\alpha_s G_{\mu\nu}\tilde{G}^{\mu\nu} + c_\gamma\,\alpha F_{\mu\nu}\tilde{F}^{\mu\nu} + d_q \sum_q m_q\,\bar{q}\gamma_5 q + d_l \sum_l m_l\,\bar{l}\gamma_5 l + \ldots\right)$$

- Modifies Maxwell's equations:

$$\begin{aligned}
\nabla \cdot E &= -\kappa \nabla a \cdot B \\
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\nabla \cdot B &= 0 \\
\nabla \times B &= \frac{\partial E}{\partial t} + \kappa\left(\dot{a}B + \nabla a \times E\right)
\end{aligned}$$

Some interactions can also apply to axion-like particles (ALPs)

Axion limits



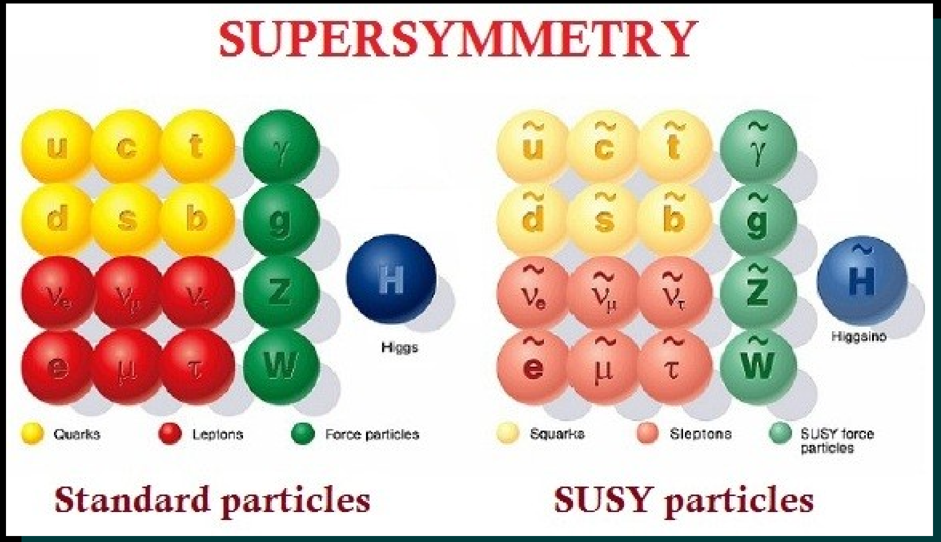
https://cajohare.github.io/AxionLimits/

COMPLETE DM MODELS

Complete DM models

- Axions:
  naturally appear in string theory, GUTs

- Supersymmetry:
  Prevailing new physics model for a long time, naturally gave us:
  - Dark matter candidate (avoid proton decay enforcing R-parity, so superpartners only couple in pairs to the SM → LSP)
  - Hierarchy problem solution, unification…



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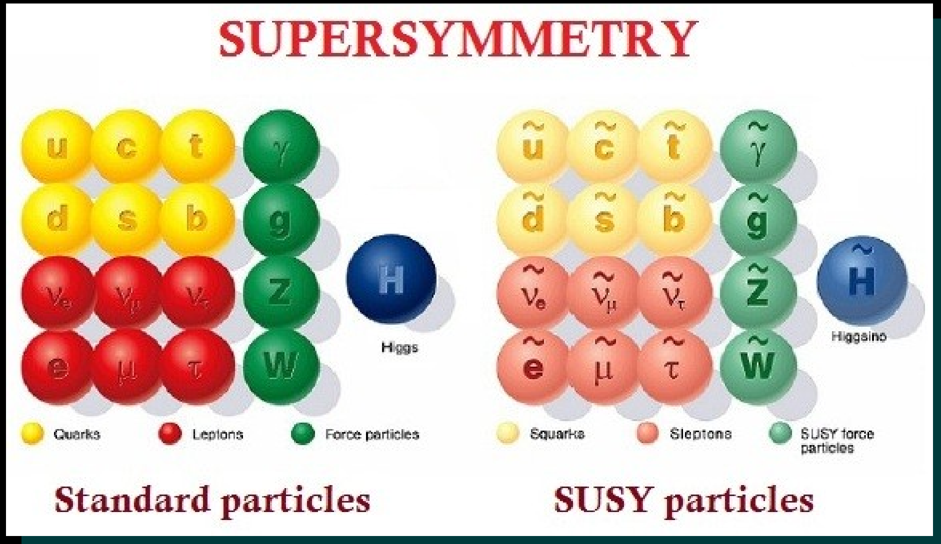
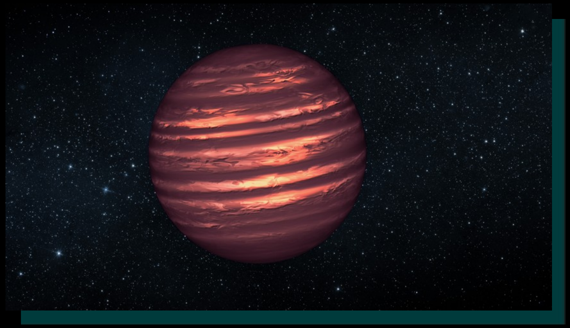


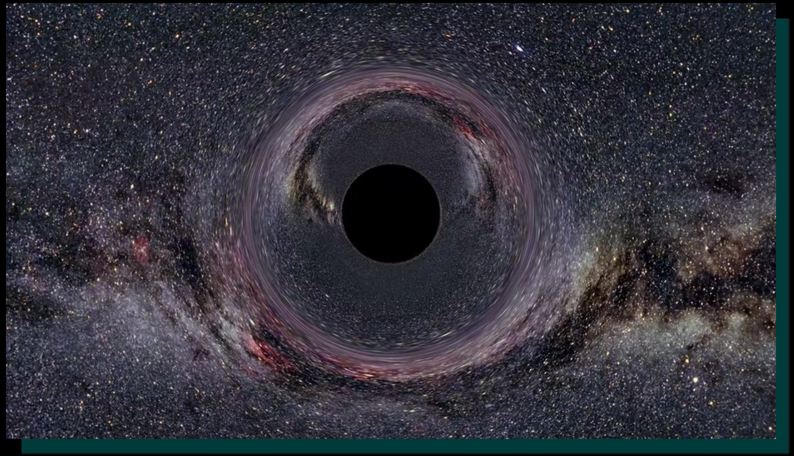
Complete models can guide us where us to look for other new physics
(see unification talks later this week)

MACHOS:
COMPOSITE DARK MATTER

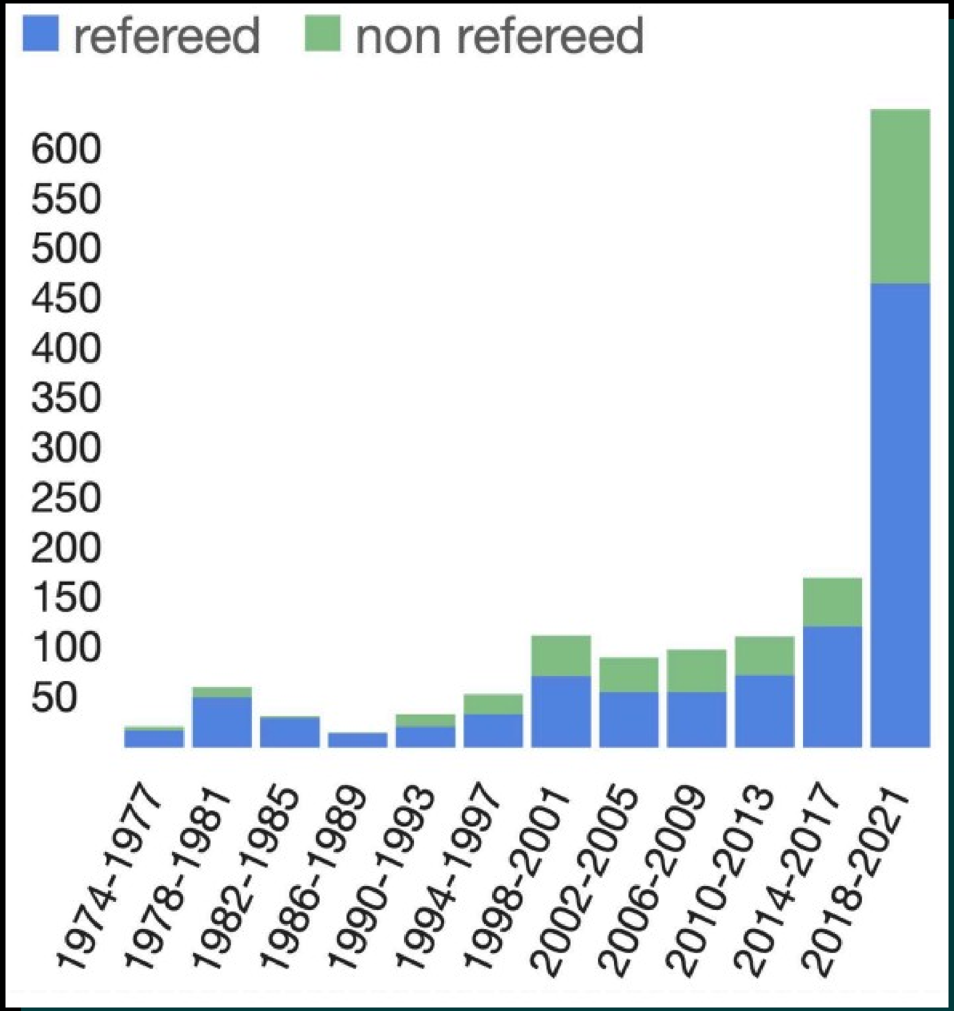
MACHOs

- Compact objects like black holes, neutron stars, brown dwarfs…
- Originally, was just thought could be baryonic objects
  - Hard to reconcile with observations:
    - CMB / BBN
    - Microlensing surveys
- Increasingly popular candidate: primordial black holes





Primordial Black Hole Popularity



Carr + Kuhnel, 2022

Primordial Black Holes

- First considered in 1966 by Zel'dovich and Novikov, in more detail by Hawking and Carr in the early 1970s

- What if DM is just black holes that formed before the epoch of BBN, AND with masses below the sensitivity range of microlensing surveys?

- Viable option, though we need (1) some production mechanism, and (2) some explanation of the current constraints from again CMB and lensing, among other things

Primordial Black Holes: Production

- Cosmological density time t after the Big Bang is

$$\rho \sim 1/(G t^2)$$

- Density needed for volume with mass M to fall within Schwarzschild radius is

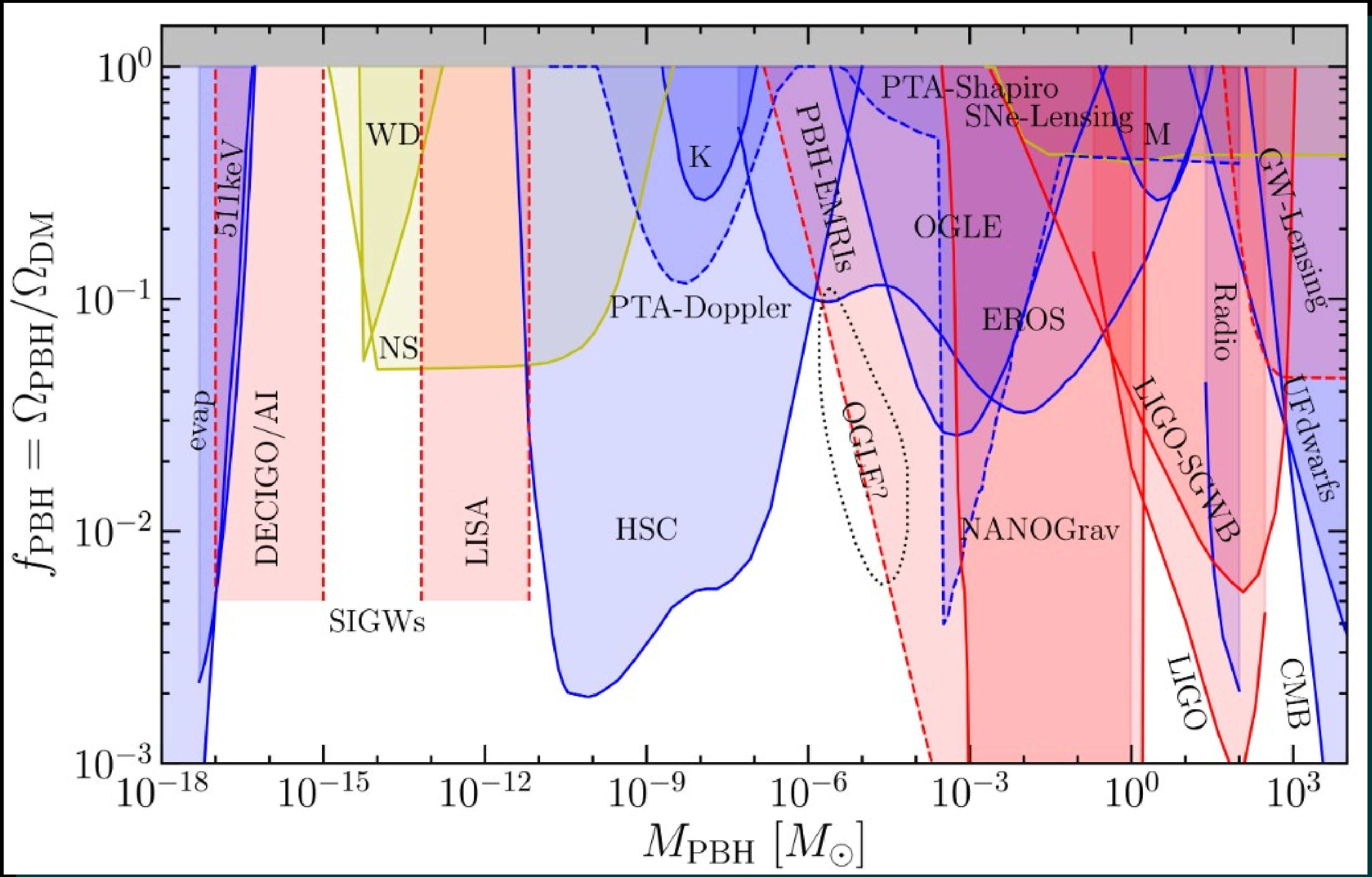
$$\rho \sim c^6/(G^3 M^2)$$

- Tells us that around the cosmological horizon, mass of PBHs would be

$$M \sim \frac{c^3 t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\,\mathrm{s}}\right) \mathrm{g}$$

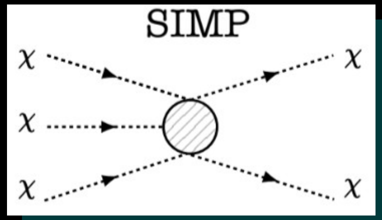
- Therefore, depending on formation time, could span huge mass range!

Primordial Black Holes: Constraints

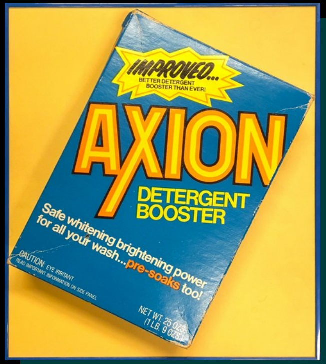


Green + Kavanaugh, 2007.10722

Outlook for dark matter

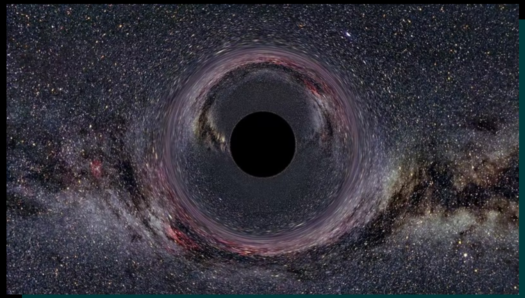


- Dark matter exists! Diverse range of evidence across many length scales
  - Finding its nature is a key goal of our community



- Hard to know the right dark matter theory direction. No clear excesses to explain, no clear "correct" model.

- Experiment and theory have historically informed each other, and will continue to do so. Extensive new technological advances and new instruments on the horizon.



- Dark matter could be around the corner!