Dark Matter Candidates

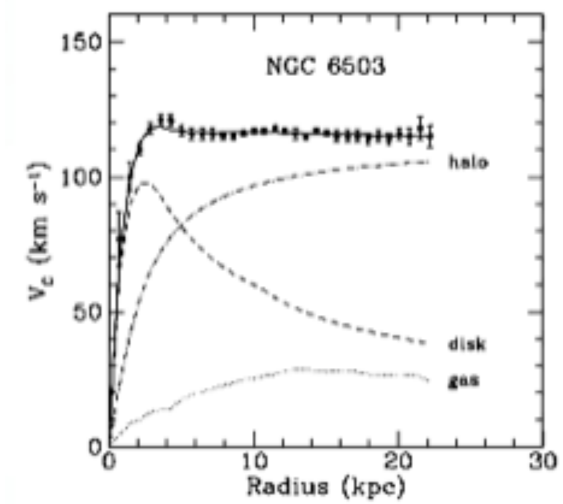
Pearl Sandick

THE UNIVERSITY OF UTAH®

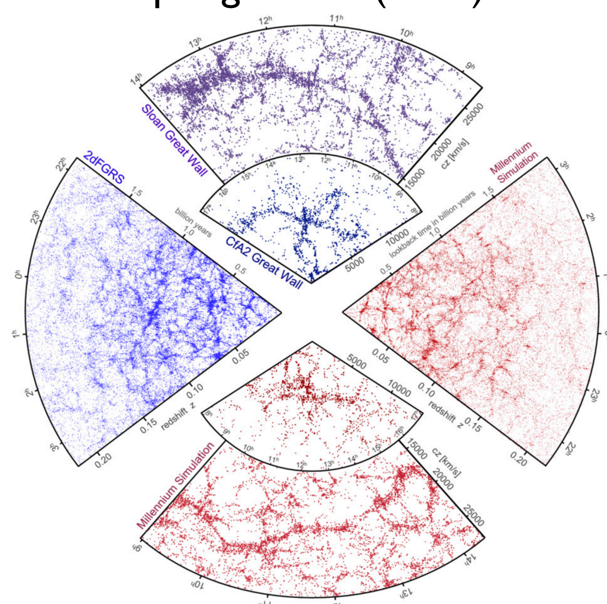
“Old News”

Observations

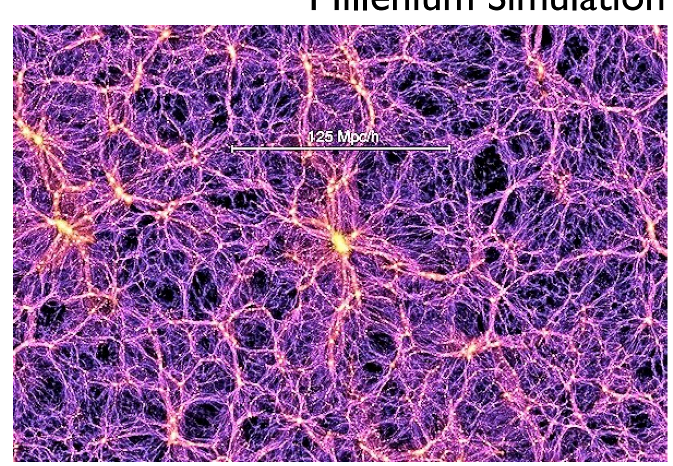
- Galactic Rotation Curves
- Cluster Dynamics, incl. collisions
- Velocity dispersions of galaxies (dark matter extends beyond the visible matter)
- Weak Gravitational Lensing (distribution of dark matter)
- Structure Formation
- “Concordance Model”

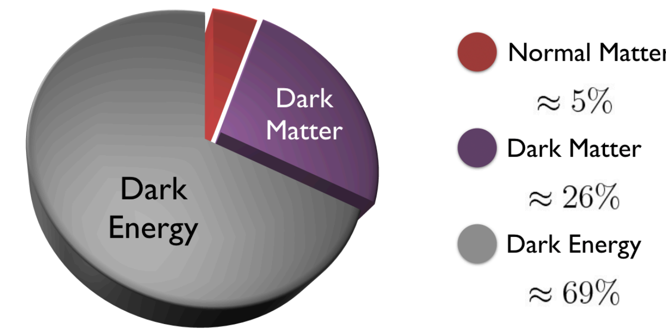


Springel et al. (2006)



Millenium Simulation

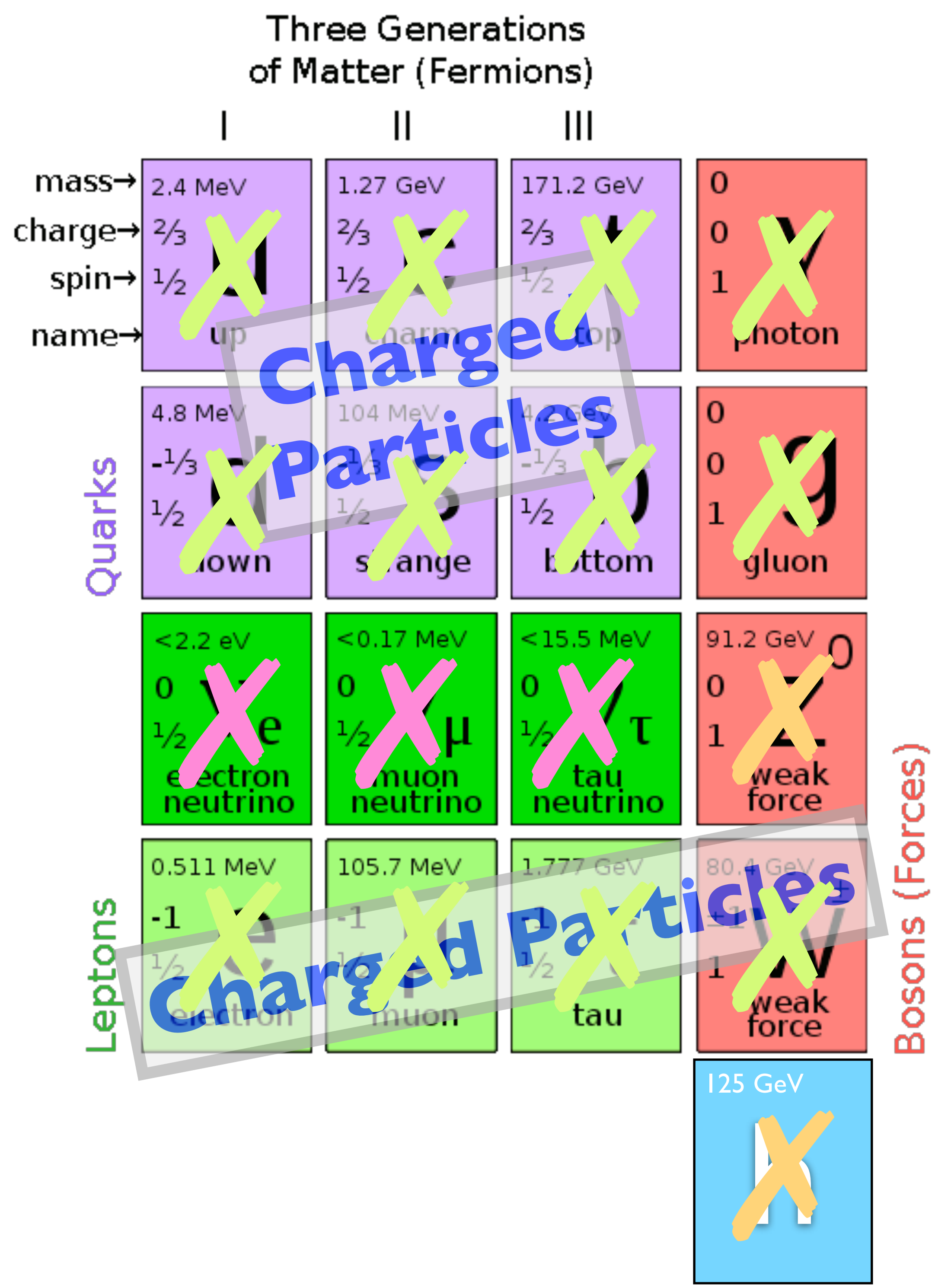




Summary

- Some explanation is necessary for observed gravitational phenomena.
- There’s a lot of it ($\Omega_{DM}h^2$=0.1200±0.0012 or Ω_{DM}≈0.265).
- It’s largely non-relativistic (cold).
- It’s stable or very long-lived.
- It’s dark ([largely] neutral).
- It’s not regular matter (element abundances, structure formation).

SM Particles? (No.)



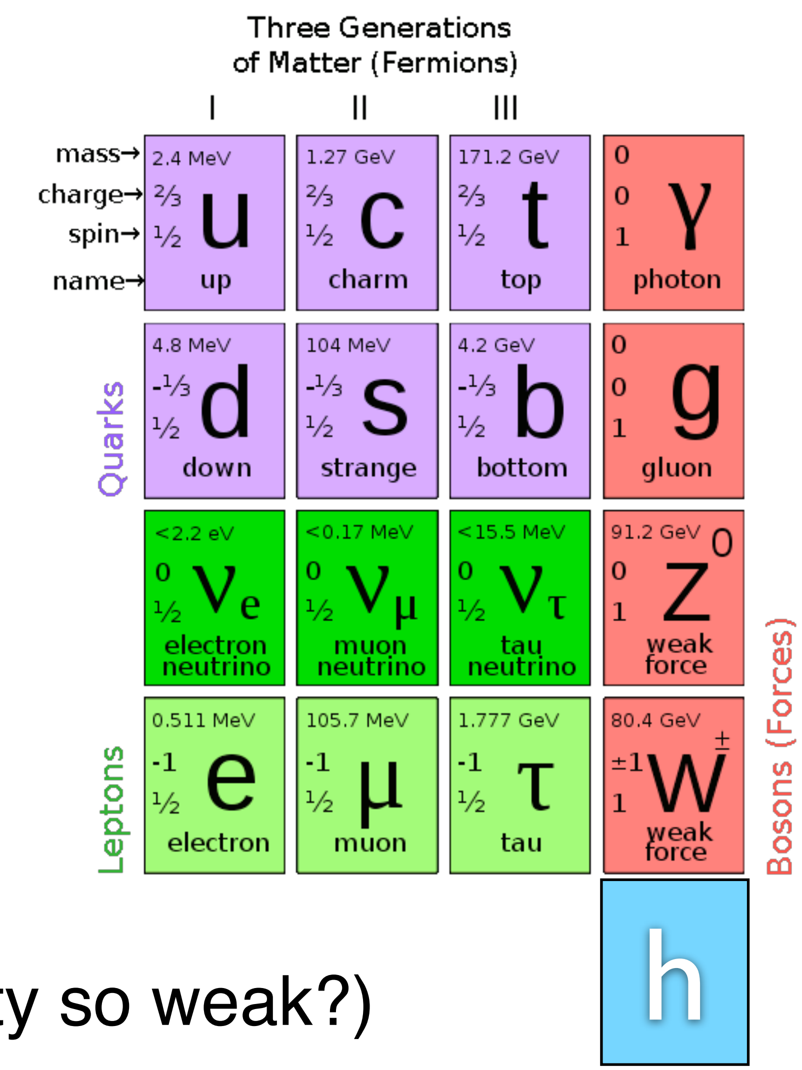
interact too strongly
(not dark)

disappear too quickly
(not stable)

"hot" dark matter
(too light)

Standard Model

- The Standard Model **works**.
  - verified by collider experiments
- The Standard Model is **not complete**.
  - does not include dark matter
  - does not include dark energy
  - does not include neutrino masses
  - does not include gravity
  - cannot explain the matter-antimatter asymmetry
  - *does* include a Hierarchy Problem (Why is gravity so weak?)
  - and more…



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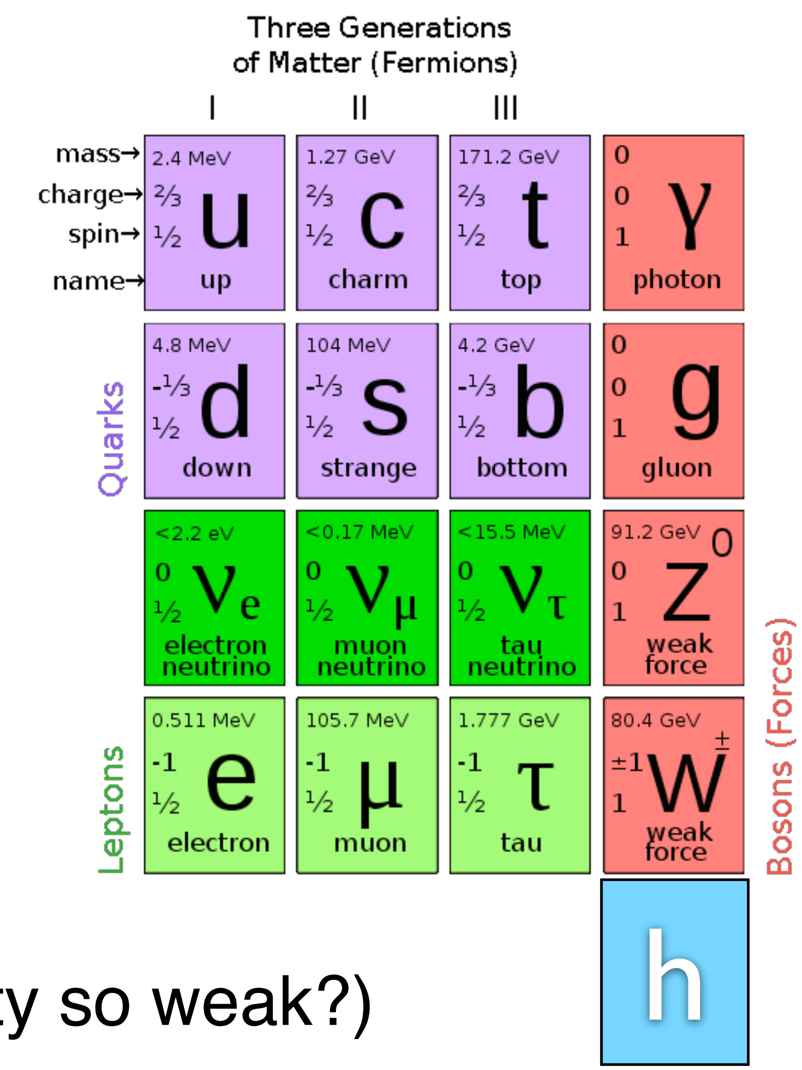
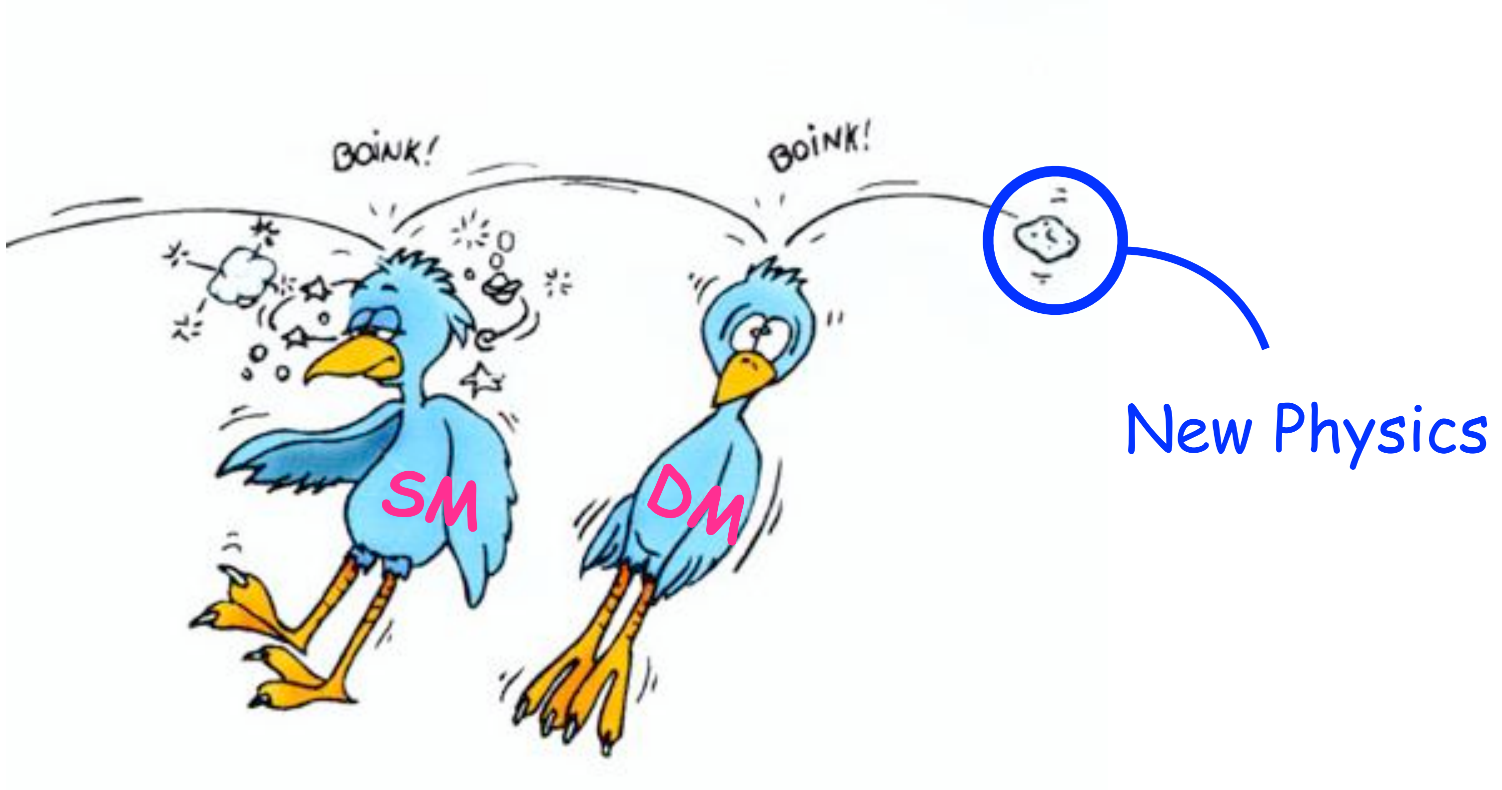
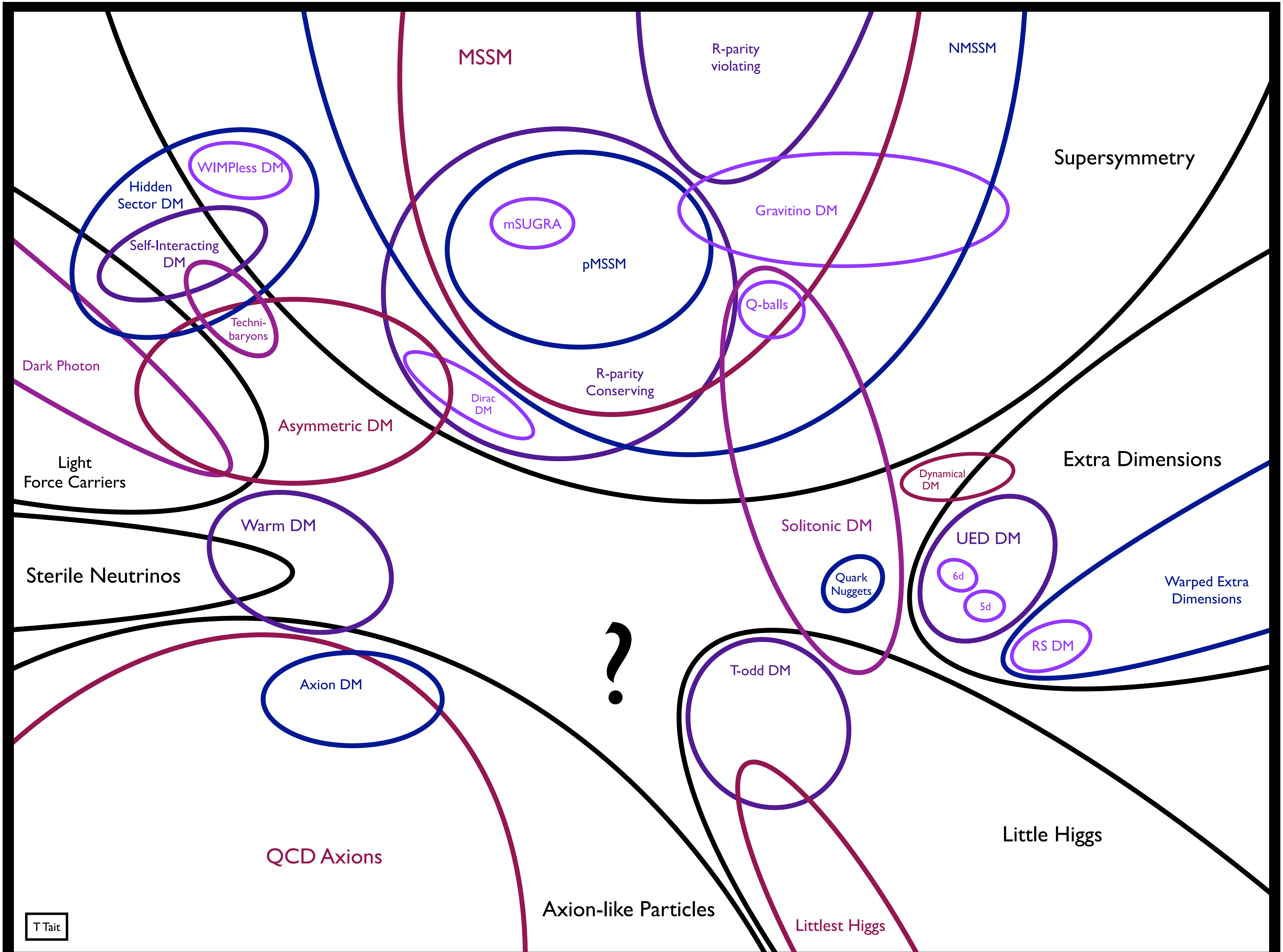


Many of these could or should be addressed within the context of a theory that includes new heavy particles.

Model-Building

- DM embedded in frameworks that address other open questions in particle physics
  - E.g. Hierarchy Problem, Strong-CP Problem, Neutrino Masses and Mixings
  - Guiding Principle: naturalness




MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity
Conserving
Dirac
DM
Dark Photon
Asymmetric DM
Light
Force Carriers
Dynamical
DM
Extra Dimensions
Warm DM
Solitonic DM
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Sterile Neutrinos
Quark
Nuggets
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5d
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RS DM
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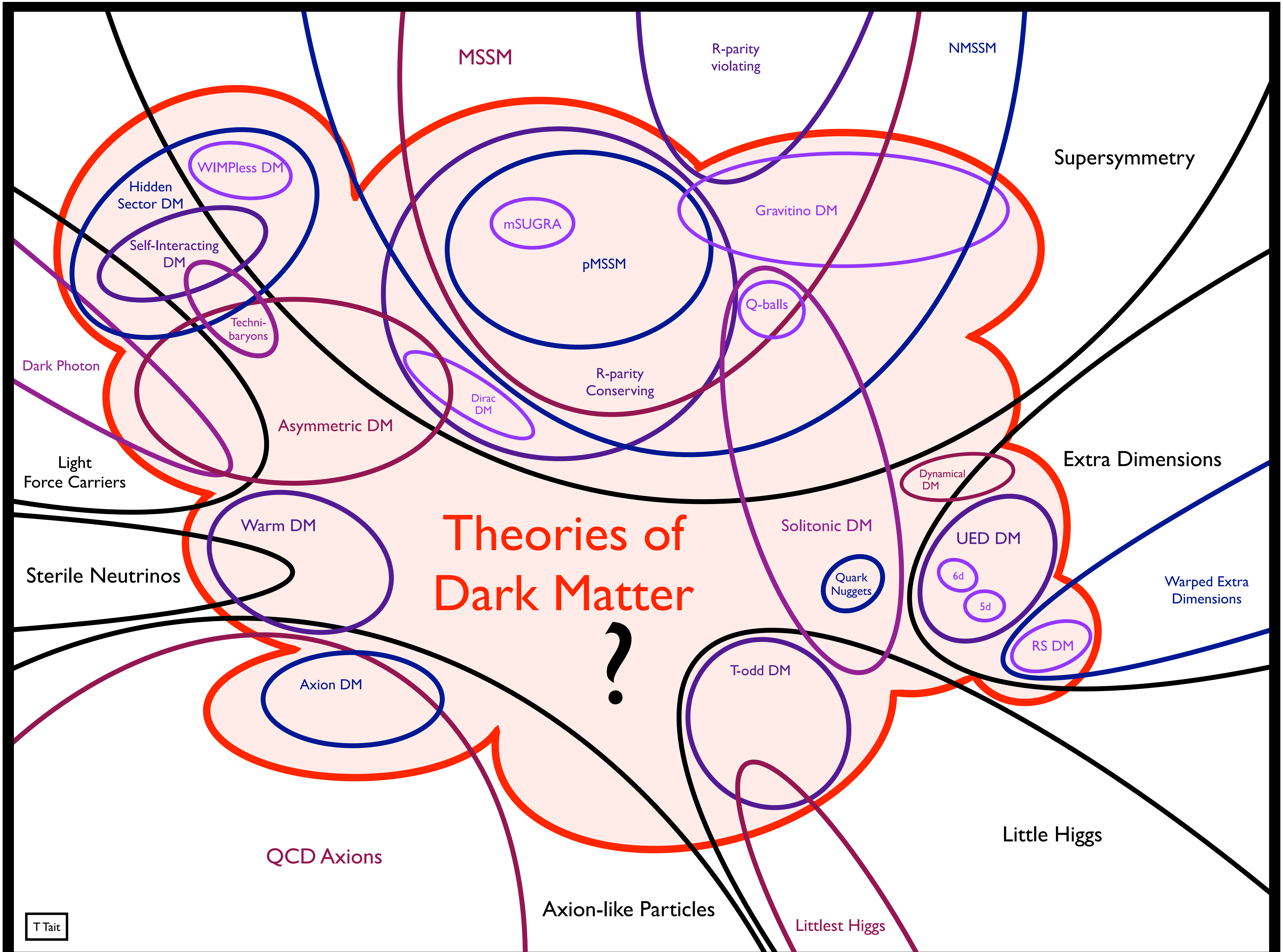
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait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  - Guiding Principle: naturalness
- Ad hoc or candidates to explain signals/anomalies in particle physics and astrophysics
  - Guiding Principles: minimalism, realism(?), “No Stone Unturned”

DM Properties

- Type: Fundamental particle, composite particle, condensate, PBH, multi-component…?
- Relic Temperature: Cold, warm, (hot)
- Interactions: gravitational, w/ self, w/ “portal”, w/ extended new physics sector
- Production: thermal, non-thermal, freeze-out, freeze-in, cannibalization, number-changing processes, asymmetry, decays, gravitational production, PBH evaporation …

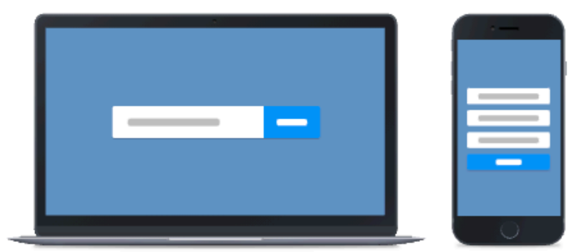
Dark Matter Production

- **Thermal**: produced through processes taking place in thermal equilibrium
  - Examples: freeze-out, production from scatterings or decays of other particles in the plasma
- **Non-Thermal**: produced through an out-of-thermal-equilibrium process
  - Examples: freeze-in, gravitational production, misalignment mechanism, out-of-equilibrium decays of heavier particles

Candidates

Word Cloud!

Join by Web

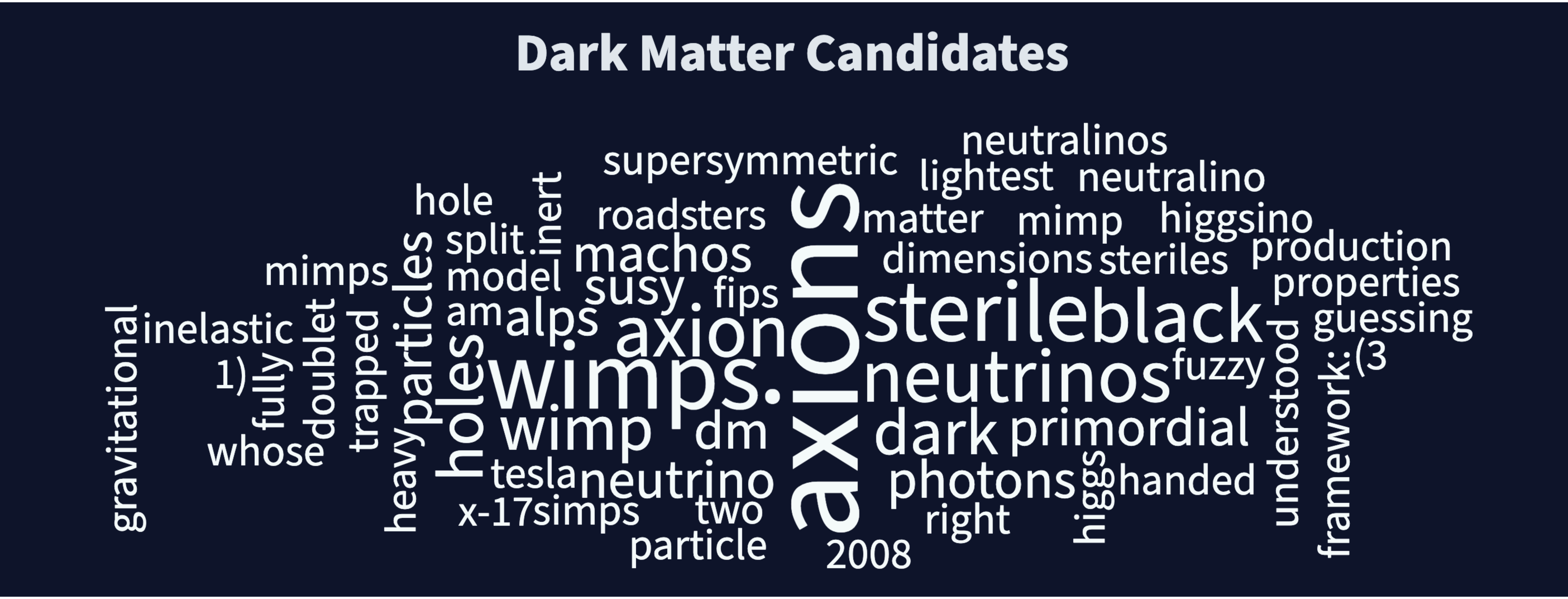


1. Go to **PollEv.com**
2. Enter **PEARLSANDICK359**
3. Respond to activity

Join by Text

1. Text **PEARLSANDICK359** to **37607**
2. Text in your message

Results


Dark Matter Candidates
axions
wimps.
sterile
black
neutrinos
axion
dark
primordial
wimp
holes
photons
neutrino
machos
susy
particles
supersymmetric
neutralinos
lightest
neutralino
matter
mimp
higgsino
roadsters
hole
split.
inert
model
mimps
am
alps
fips
dimensions
steriles
production
properties
guessing
fuzzy
(3
understood
framework:
inelastic
gravitational
1)
fully
doublet
trapped
heavy
whose
dm
tesla
x-17
simps
two
particle
2008
right
higgs
handed

Candidates

- Weakly Interacting Massive Particles (WIMPs): neutralinos, LKP, LTP…
- Light bosons: Axions, Axion-Like Particles (ALPs), Fuzzy Dark Matter (FDM)
- E-WIMPs/super-WIMPs/FIMPs: gravitino, axino, KK graviton
- Sterile neutrino
- Strongly Interacting Massive Particles (SIMPs)
- Asymmetric Dark Matter (ADM)
- WIMPzilla
- Primordial Black Hole (PBH)

Candidates

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WIMPs

- Naturally* account for the abundance of dark matter we observe
- Already exist in many extensions of the Standard Model
  - Supersymmetry, Kaluza-Klein, Little Higgs…
- Remain a compelling possibility despite null search results to date

Additional Ingredient

- It's not enough to have a theory with extra particles at the weak scale; also need a symmetry to make the lightest new particle stable.
- No problem! We need this anyway (proton stability, neutron-antineutron oscillations, large neutrino masses...)

Theory	Z_2 Parity	Dark Matter
SUSY	R-parity	LSP
UED	KK-parity	LKP
Little Higgs	T-parity	LTP

$$R = (-1)^{(3B+L+2S)}$$

$$= \begin{cases} +1 \text{ for SM prtcls} \\ -1 \text{ for SUSY prtcls} \end{cases}$$

Relic Abundance

1. New (heavy) particle χ in thermal equilibrium:

$$\chi\chi \rightleftarrows f\bar{f}$$

2. Universe expands and cools:

$$\chi\chi \not\rightleftarrows f\bar{f}$$

3. χ's "freeze out"

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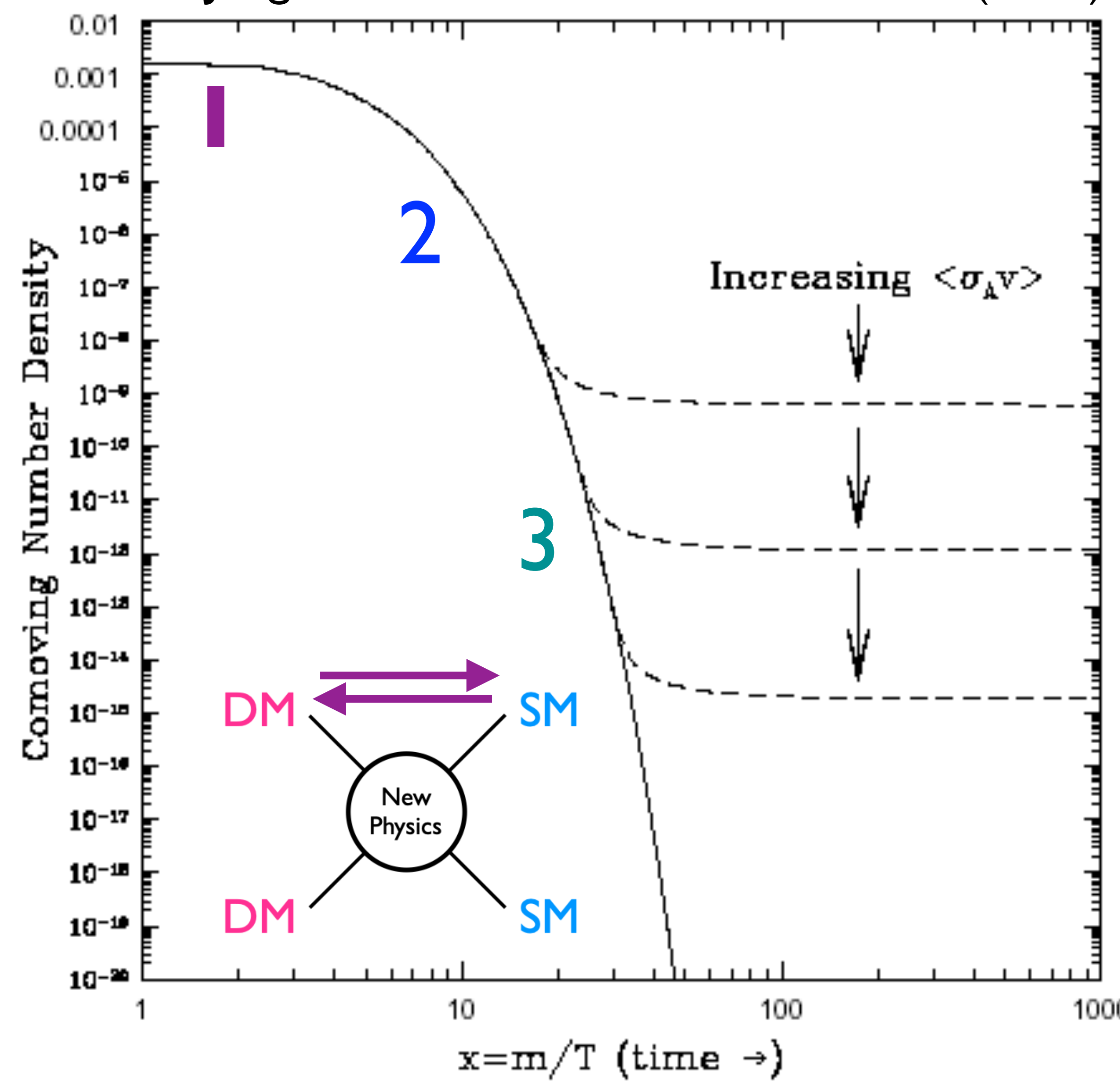
Jungman, Kamionkowski & Griest, PR (1996)



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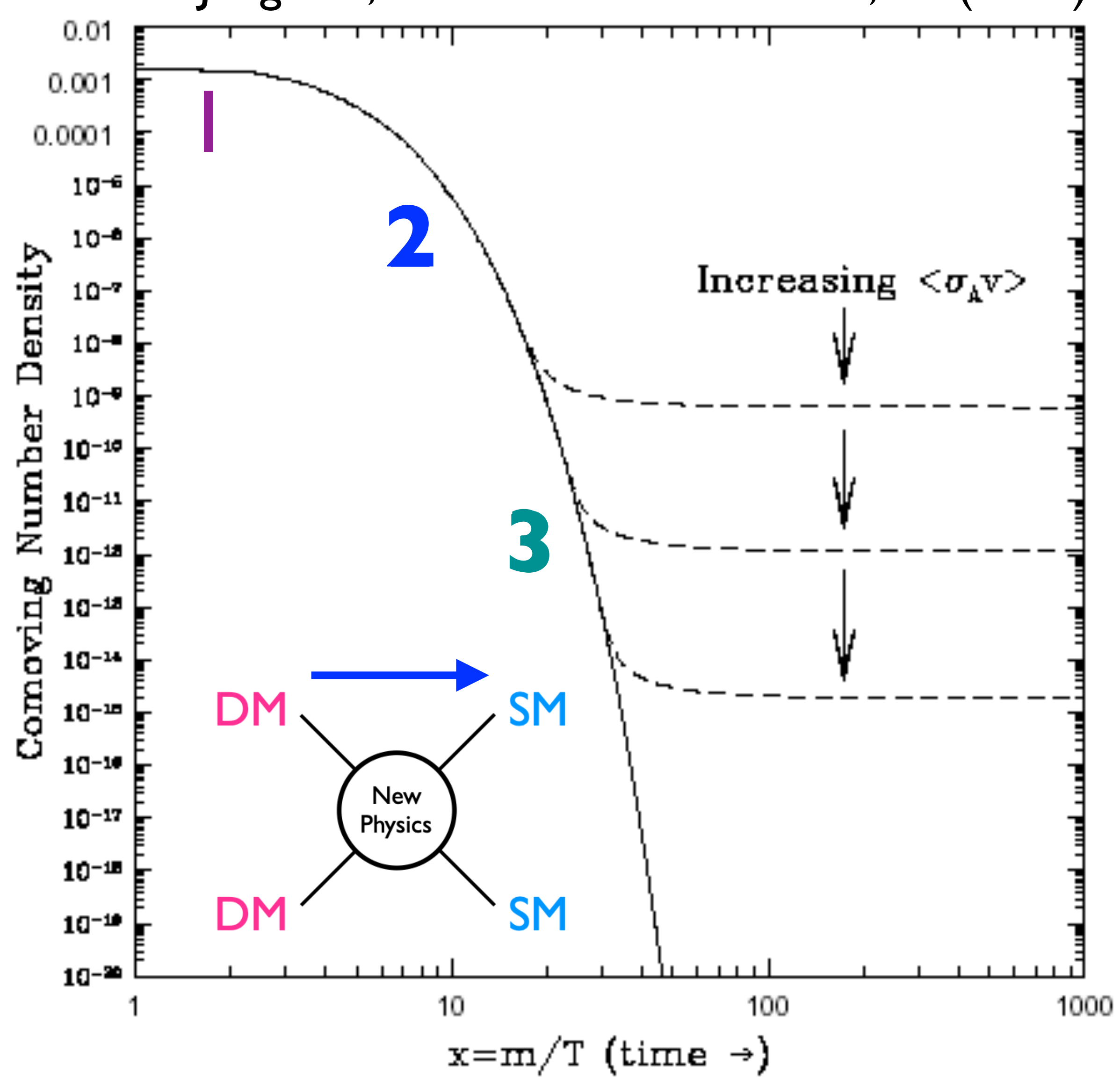


Relic Abundance

The **Boltzmann Equation** describes the evolution of the dark matter number density.

Expansion and annihilation compete to determine the number density:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

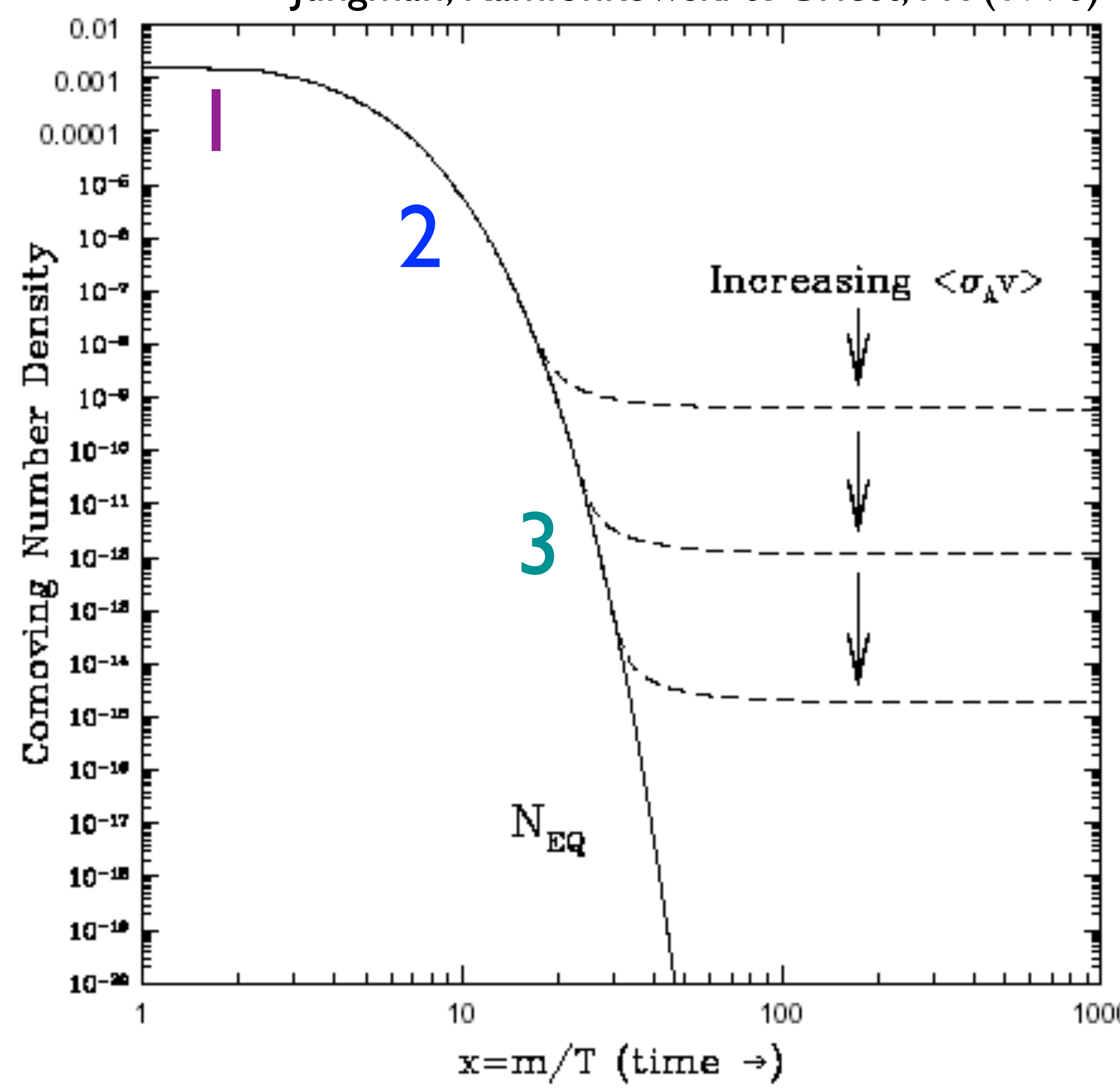
Equilibrium Number Density:

$(T \ll m_\chi)$

$$n_\chi^{eq} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-(m_\chi - \mu_\chi)/T}$$

When $\Gamma = n_\chi^{eq} \langle \sigma v_{rel} \rangle < H$ the annihilations that maintain equilibrium can't keep up with expansion. WIMPs can't find each other to annihilate.

Jungman, Kamionkowski & Griest, PR (1996)



Relic Abundance

WIMP "Coincidence"

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Back of envelope:

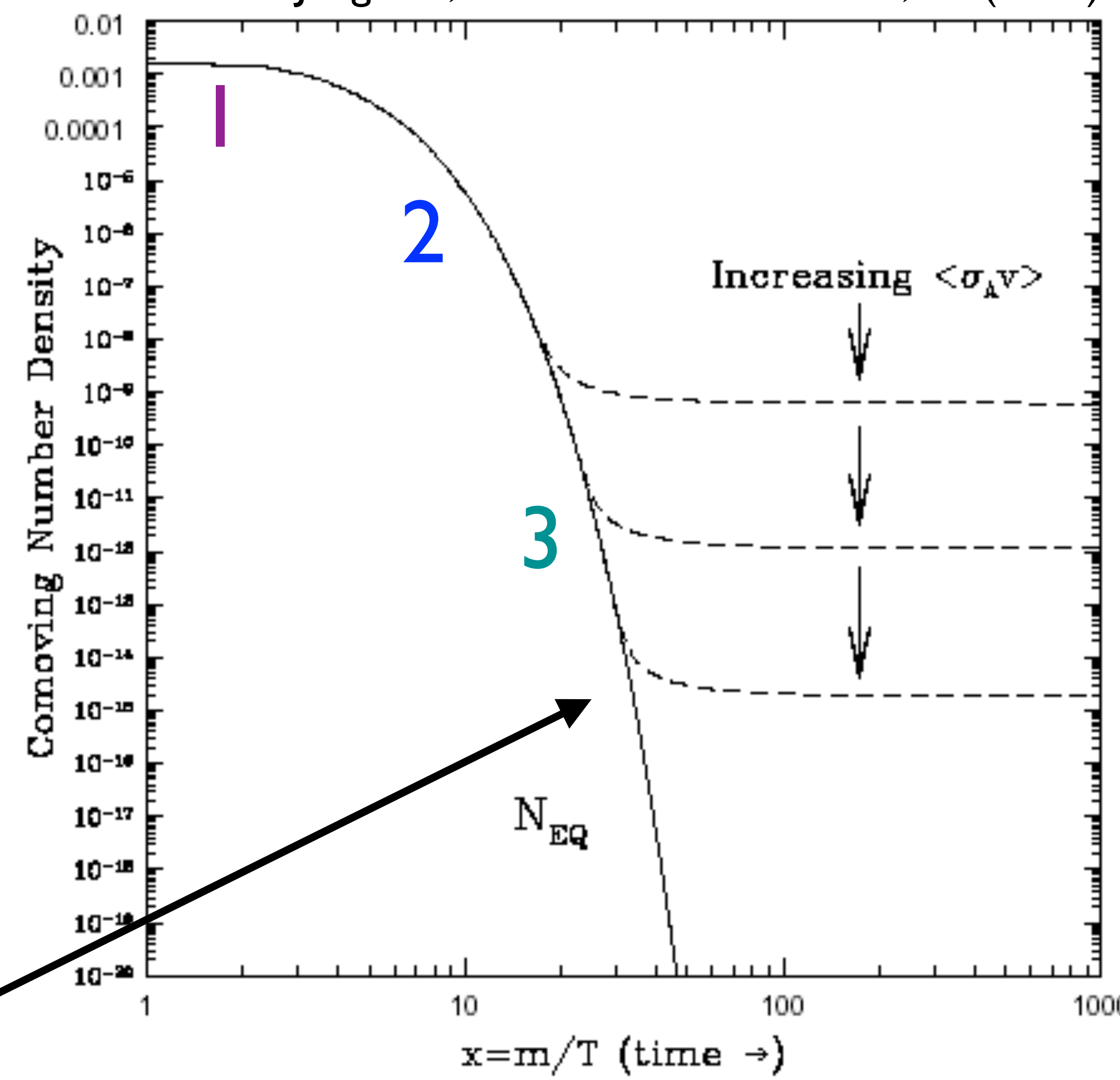
$$n_\chi^{eq} \langle \sigma v_{rel} \rangle \sim H$$

$$\left((m_\chi T)^{3/2} e^{-m_\chi/T} \right) \left(\frac{g^4}{m_\chi^2} \right) \sim \left(\frac{T^2}{M_{Pl}} \right)$$

$$\frac{m_\chi}{T} \sim \log \left(\frac{M_{Pl}}{m_\chi} \right) + \ldots$$

So a weakly-interacting 100 GeV WIMP means $\frac{m_\chi}{T} \sim 40$

Jungman, Kamionkowski & Griest, PR (1996)



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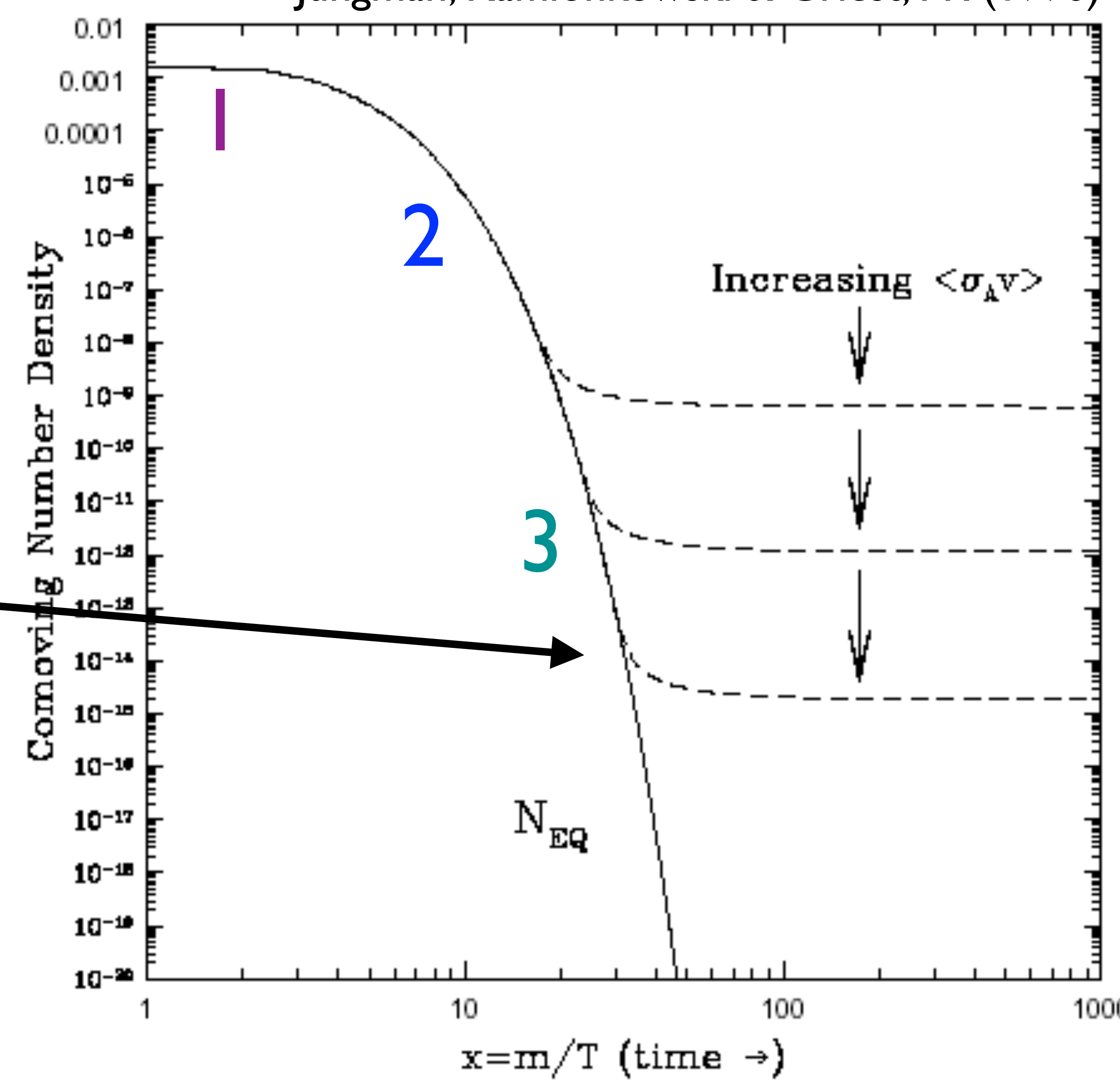

- Stable matter with GeV-TeV mass and weak-scale annihilation cross section yield $\Omega_\chi h^2 \approx 0.1$
- Mass and cross section completely determine abundance today.
- Wiggle room in mass and cross section

WIMPless, too!

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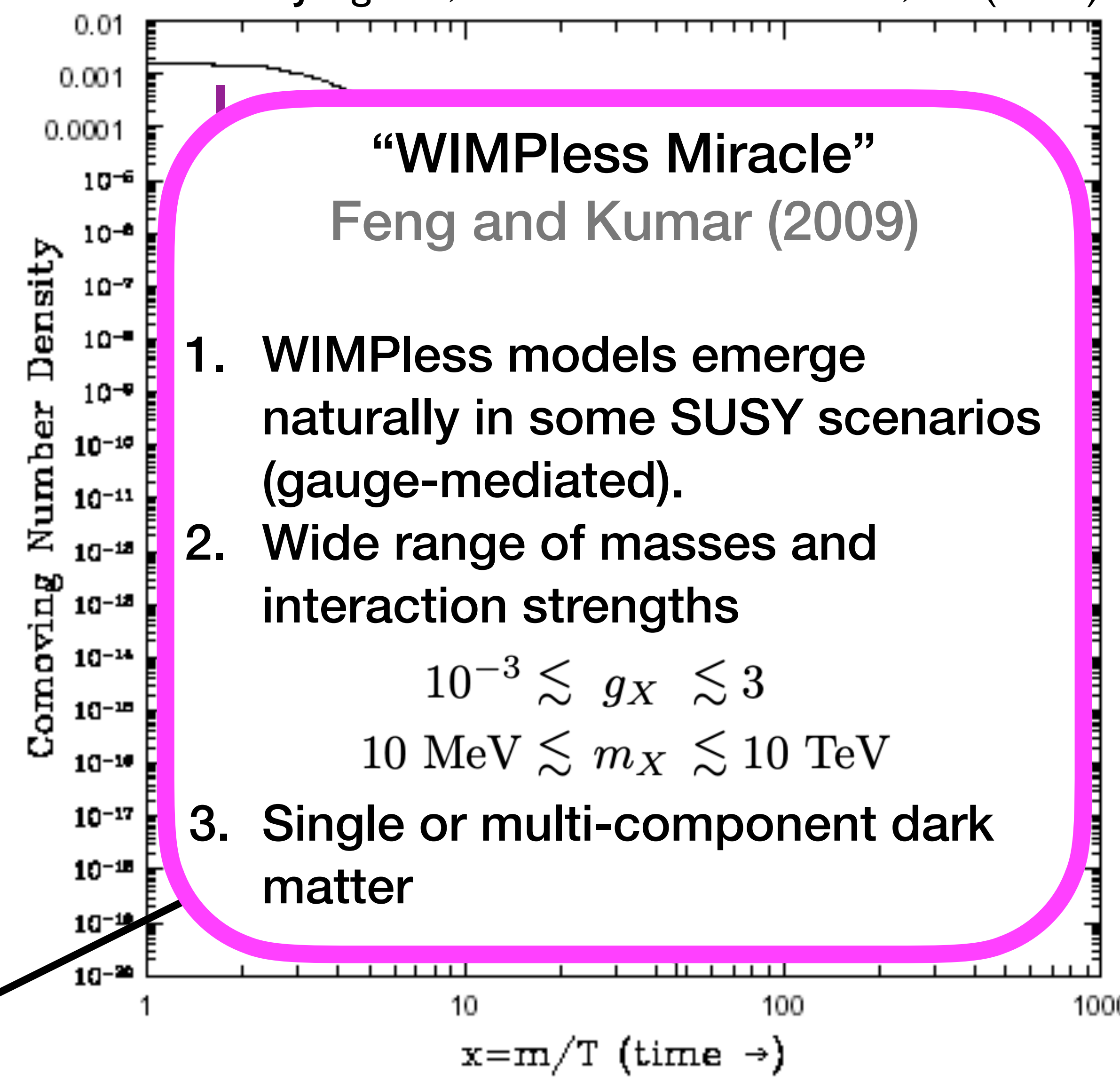


"WIMPless Miracle"

Feng and Kumar (2009)

1. WIMPless models emerge naturally in some SUSY scenarios (gauge-mediated).
2. Wide range of masses and interaction strengths

$$10^{-3} \lesssim g_X \lesssim 3$$

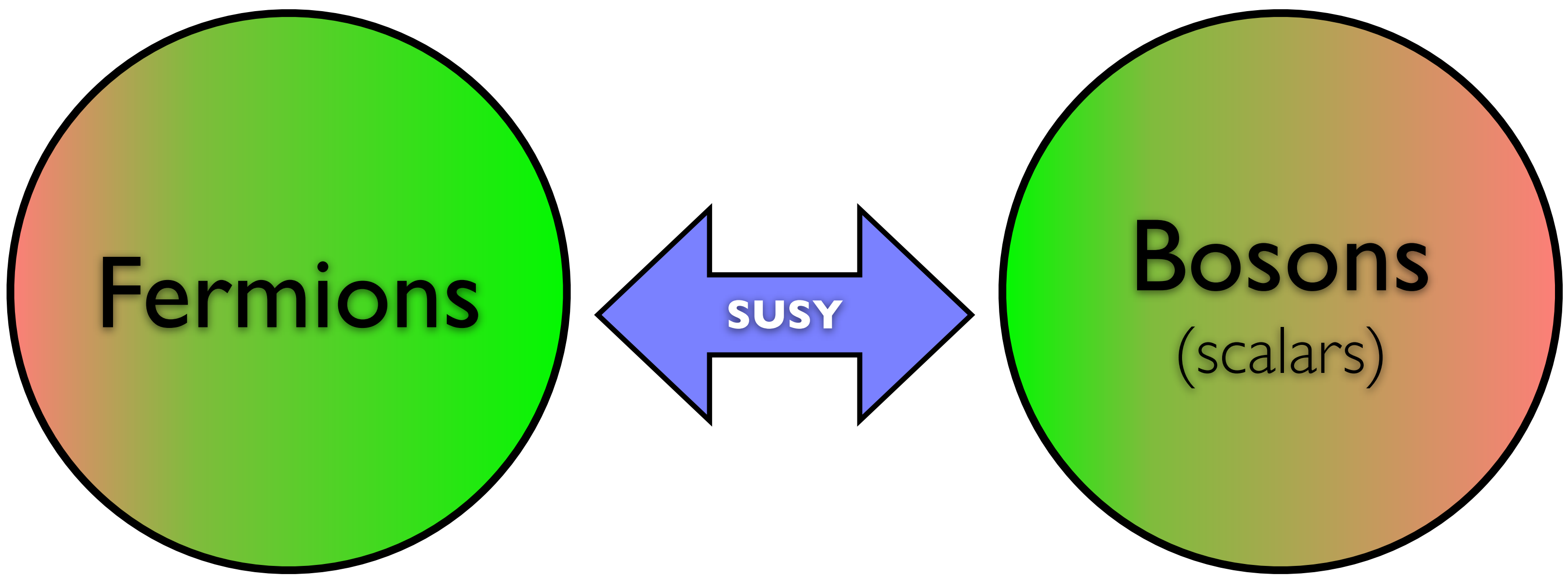
$$10 \text{ MeV} \lesssim m_X \lesssim 10 \text{ TeV}$$

3. Single or multi-component dark matter

WIMP Candidates

- Supersymmetric Neutralino
- Lightest KK Particle (LKP) from Universal Extra Dimensions
- Lightest T-odd Particle (LTP) from Little Higgs Models

Supersymmetry



Supersymmetry is the only possible extension of the Poincare algebra in a consistent 4d quantum field theory. Haag, Lopuszanski, & Sohnius (1975)

Each Standard Model particle gets a Supersymmetric partner!

The MSSM

Also…

axion (a, 0)
saxion (s, 0)
axino (ã, 1/2)
graviton (G, 2)
gravitino (G~, 3/2)

	particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
quarks and squarks	$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	3	2	$\frac{1}{6}$
	u_i^c	$\tilde{u}_i^c$	$\bar{3}$	1	$-\frac{2}{3}$
	d_i^c	$\tilde{d}_i^c$	$\bar{3}$	1	$\frac{1}{3}$
leptons and sleptons	$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
	e_i^c	$\tilde{e}_i^c$	1	1	1
gauge bosons and gauginos: W boson & wino	W	$\tilde{W}$	1	3	0
gluon & gluino	g	$\tilde{g}$	8	1	0
B boson & bino	B	$\tilde{B}$	1	1	0
Higgs bosons and higgsinos	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	1	2	$\frac{1}{2}$
	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1	2	$-\frac{1}{2}$

neutralinos

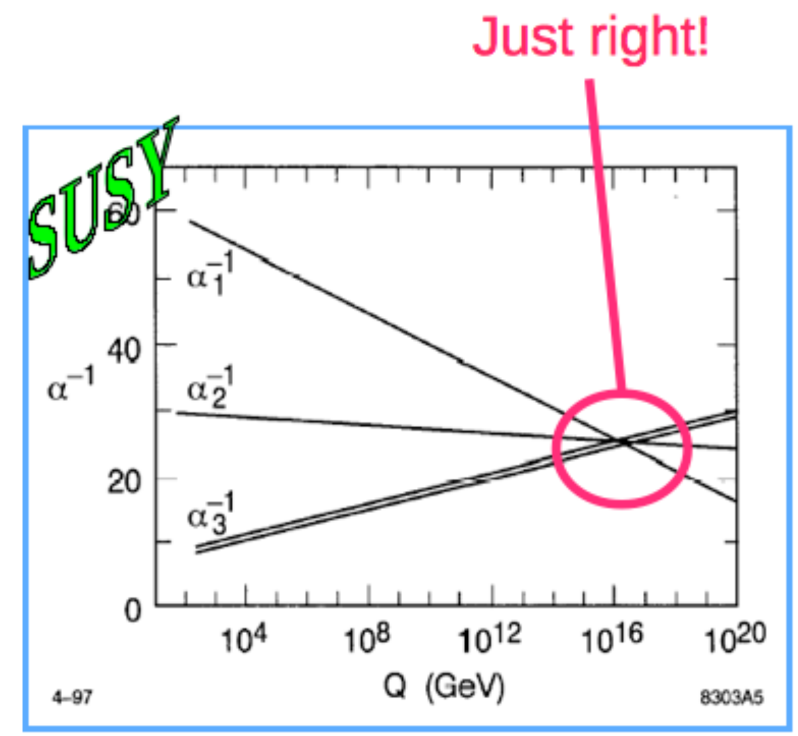
← wino mass, M_2

← bino mass, M_1

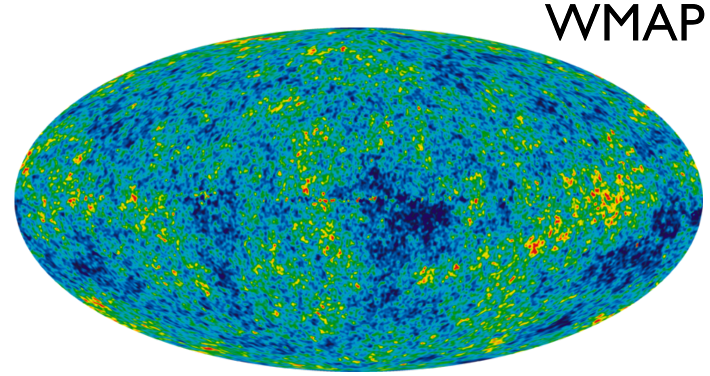
← Higgs mixing parameter, μ

Virtues of Supersymmetry

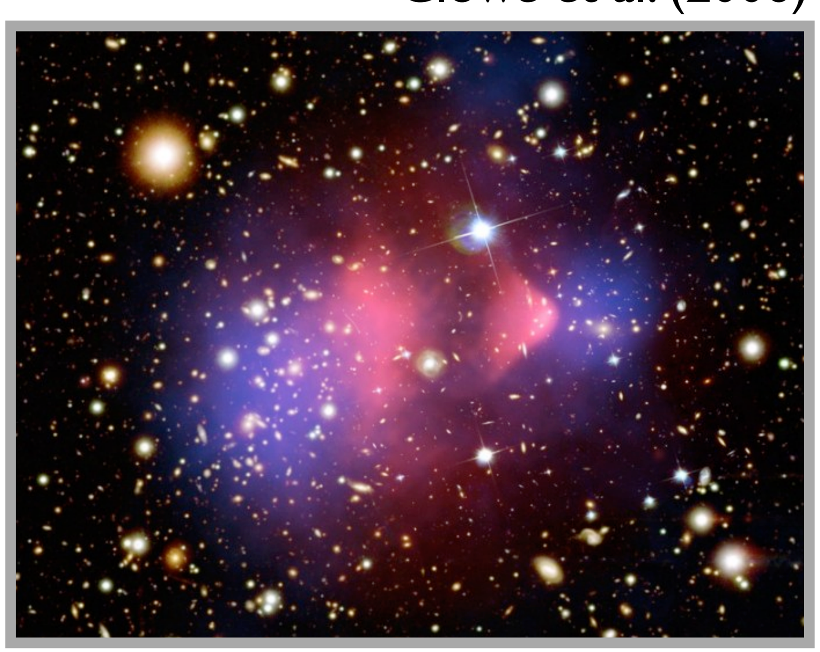
- Elegance (!)
- Gauge Coupling Unification
- Hierarchy Problem Addressed
- Light Higgs Boson
- **Dark Matter**



WMAP



Clowe et al. (2006)



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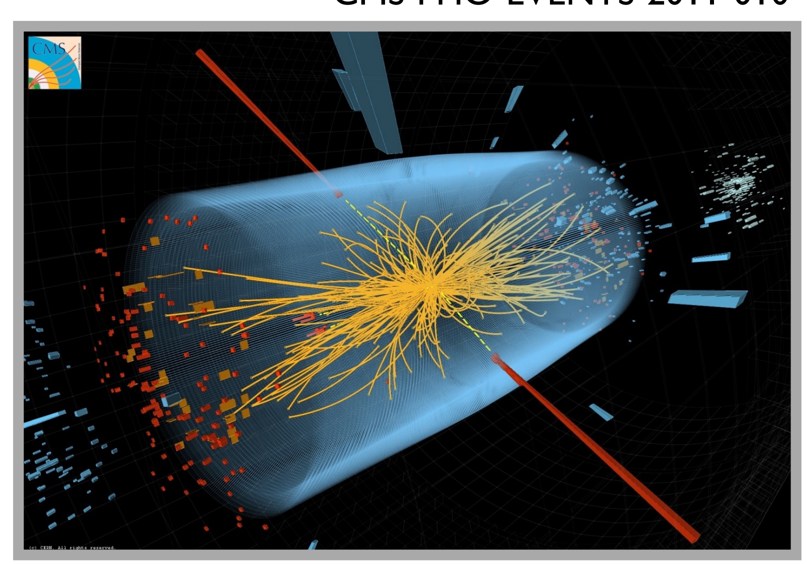
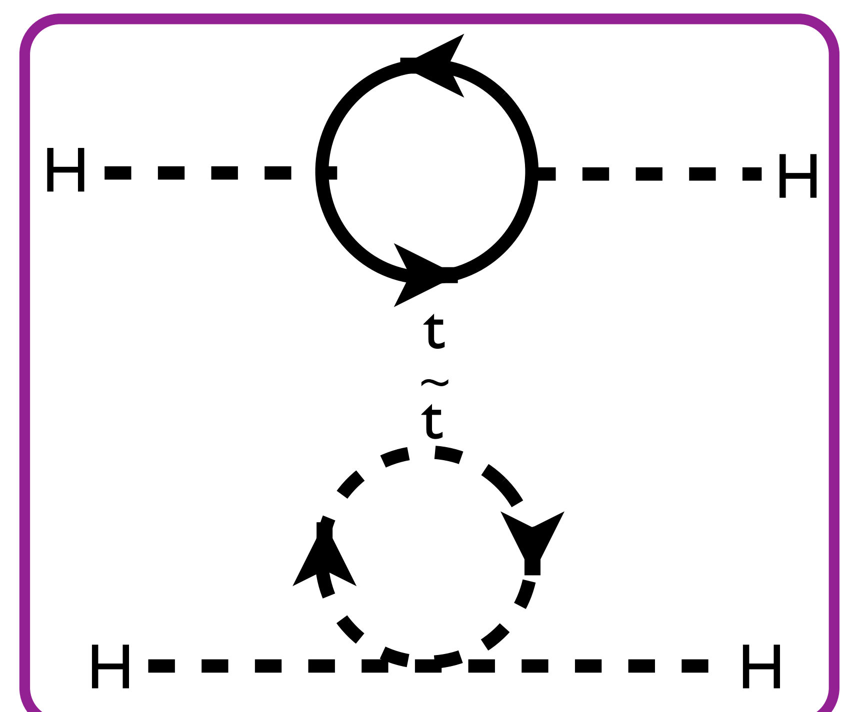




From Theory to Predictions

???

Supersymmetry

MSSM

Non-Minimal Model

Gravity Mediation

Gauge Mediation

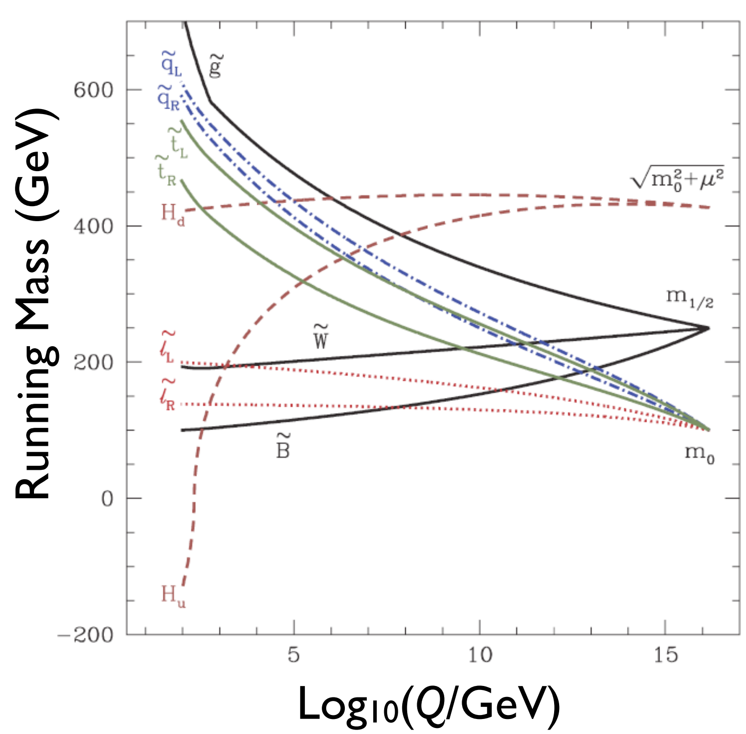
...

EW-Scale Inputs

mSUGRA

CMSSM

NUHM

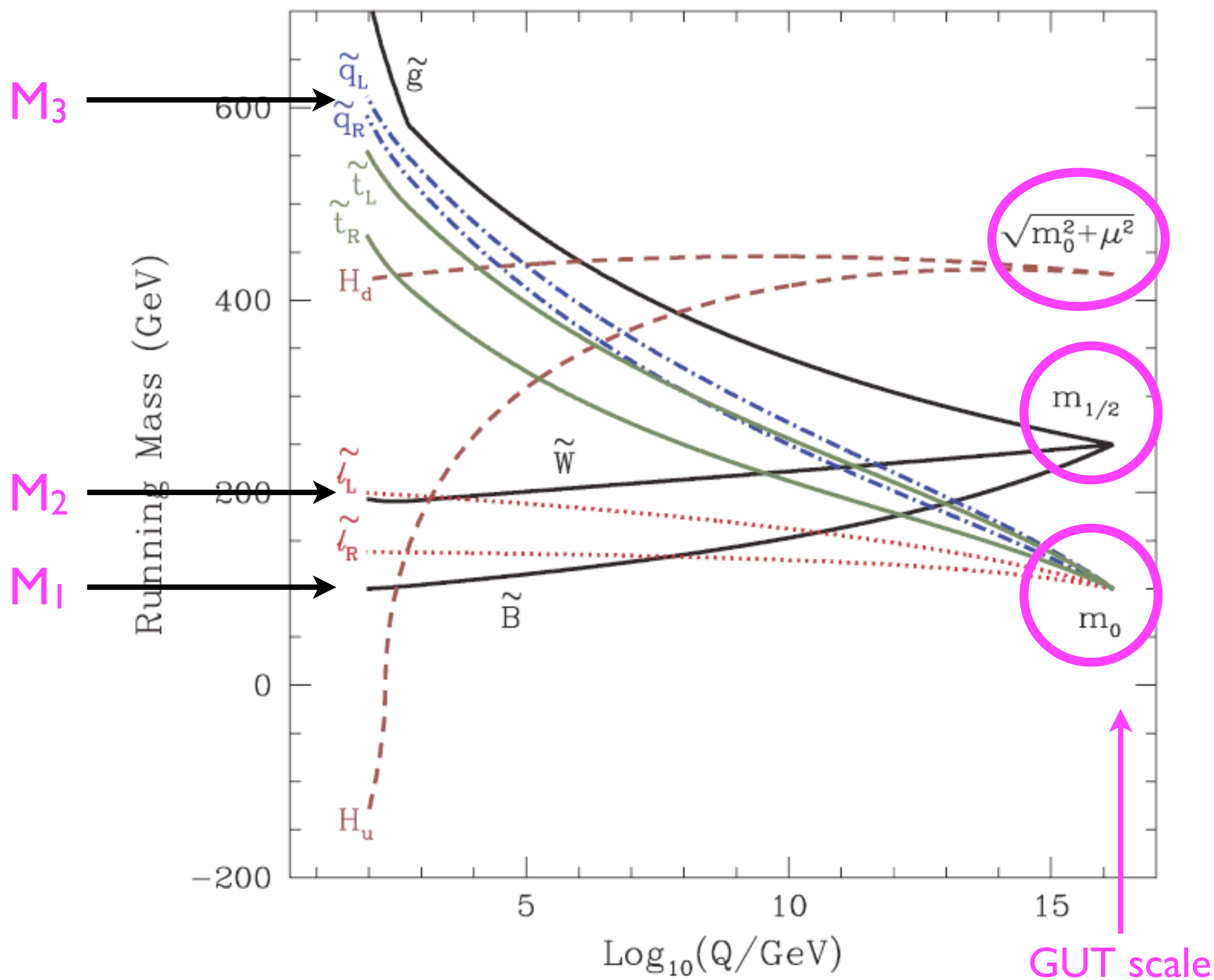


pMSSM

MSSMn (n=7,9,etc.)

Relevant Parameters for Specific Interaction(s) (simplified models)

Motivated by Minimal Supergravity…



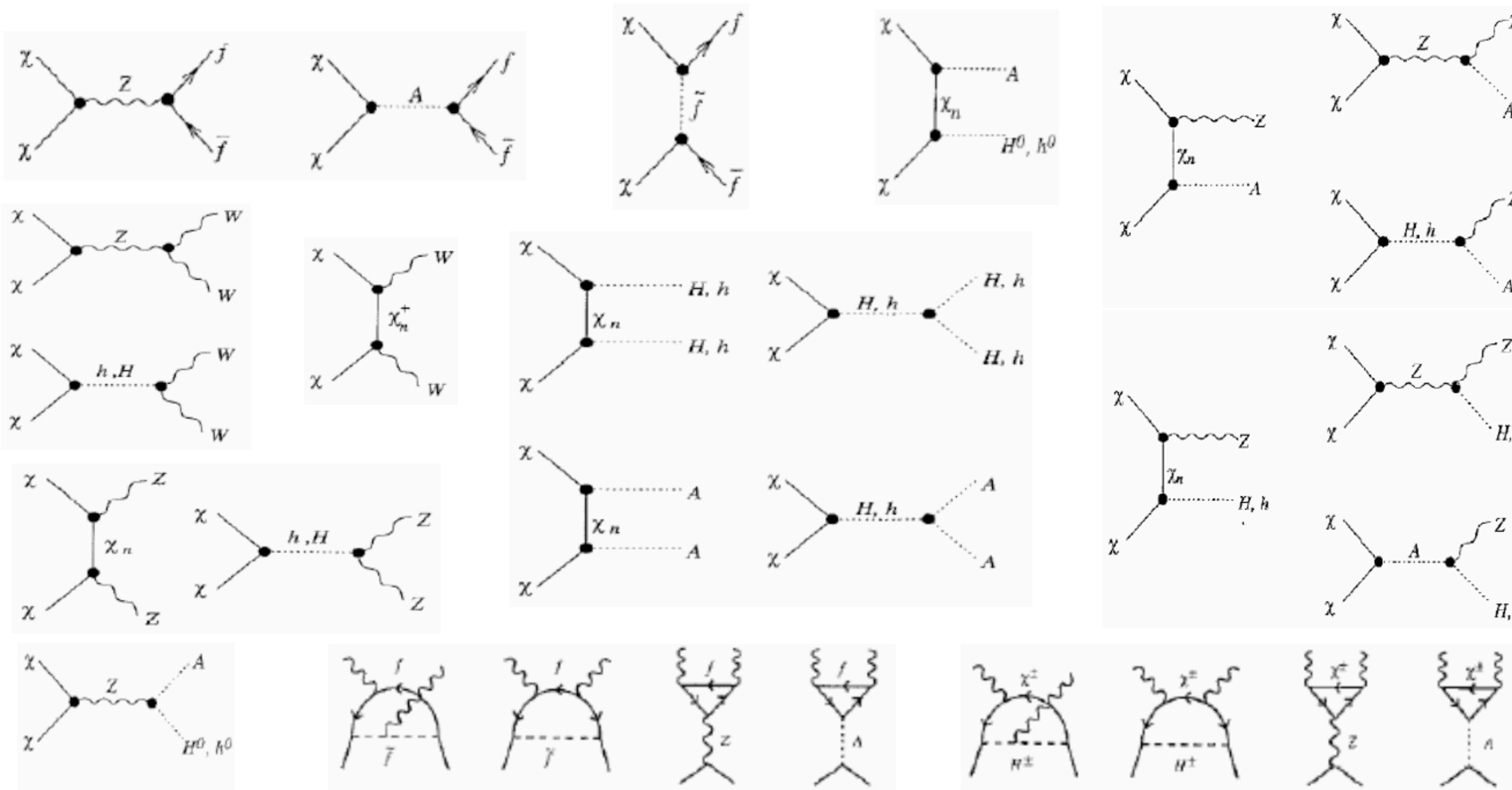
Constraints

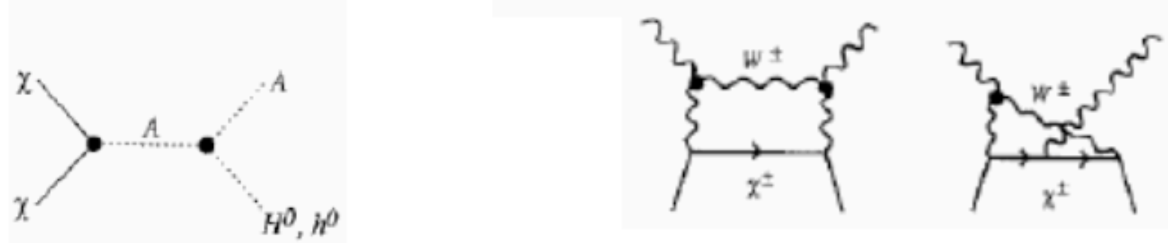
- Higgs mass
- Sparticle mass limits from collider searches
- Flavor constraints (eg. $b \to s\gamma$)
- Lepton dipole moments, etc.
- DM abundance
- Indirect and Direct dark matter searches

Lightest Supersymmetric Particle (LSP):

$$\tilde{\chi}_i^0 = \alpha_i \underbrace{\tilde{B}}_{\text{(bino)}} + \beta_i \underbrace{\tilde{W}^3}_{\text{(wino)}} + \underbrace{\gamma_i \tilde{H}_1^0 + \delta_i \tilde{H}_2^0}_{\text{(higgsino)}}$$

Now we calculate…

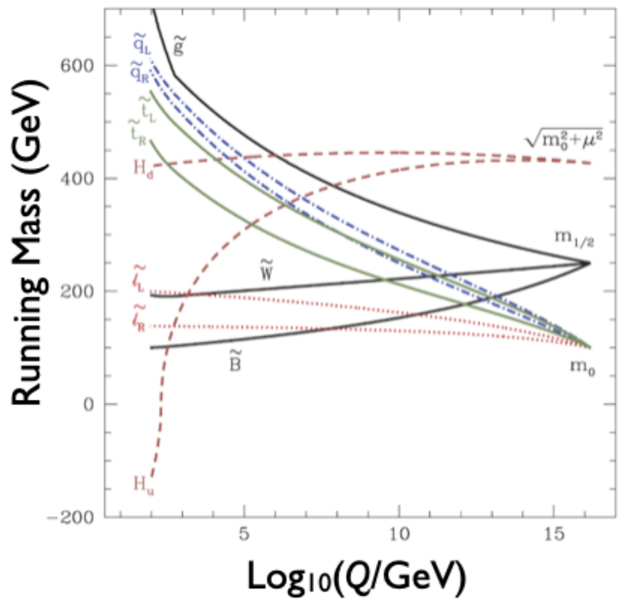




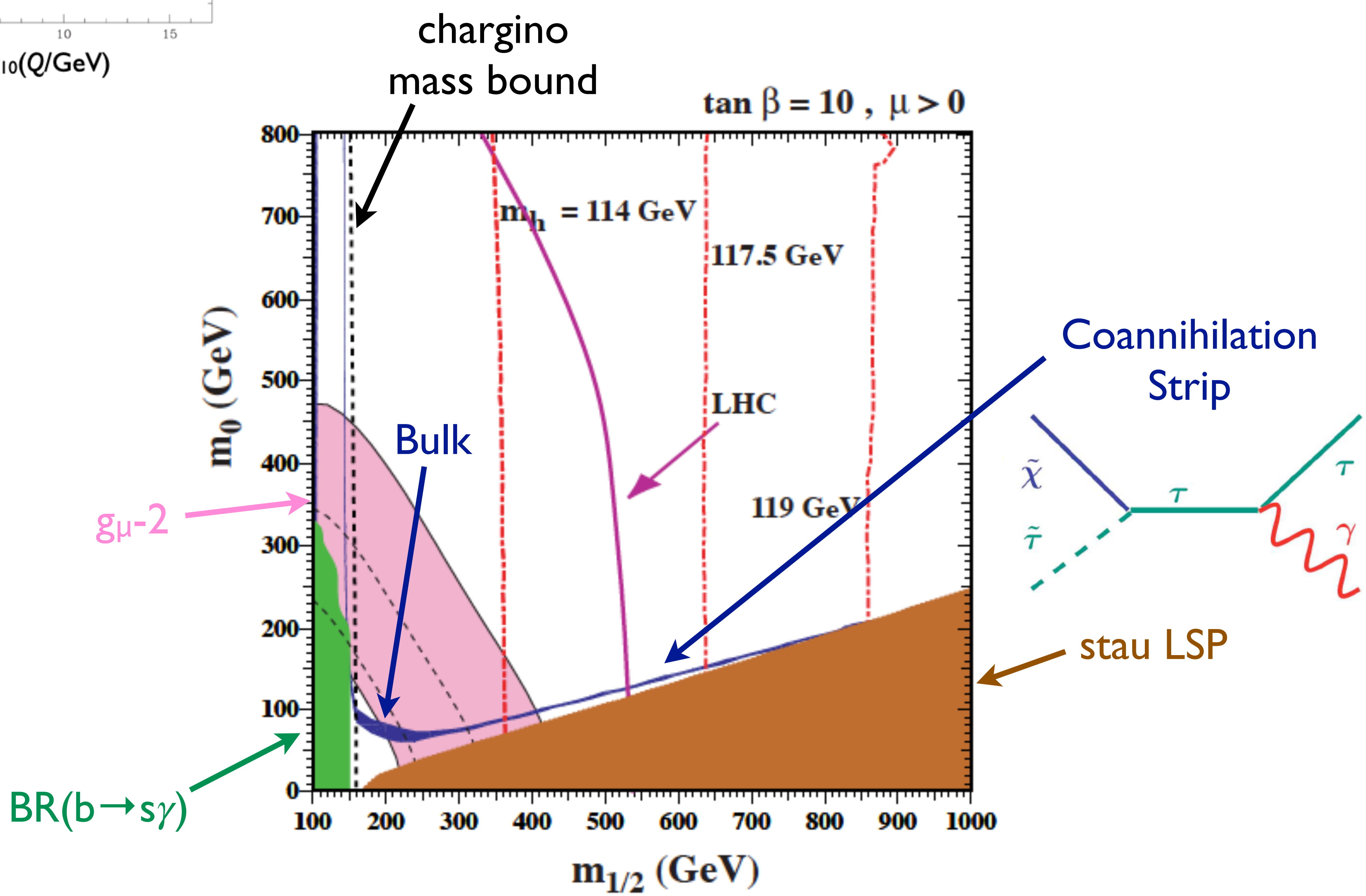
- These are just the simple ones…
- Take care of coannihilations, if relevant.
- Don't forget all the other particles in the model! Check consistency with current constraints/measurements.

Kolb & Turner (1997)
Srednicki, Watkins & Olive (1988)

CMSSM

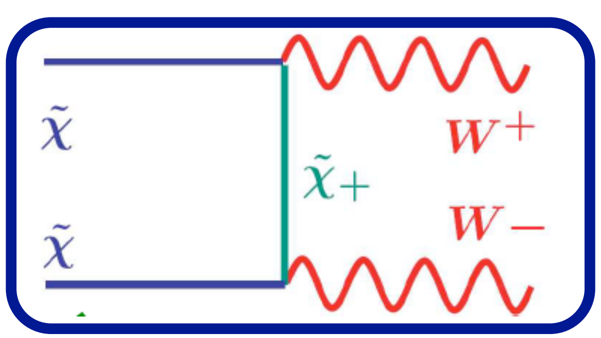


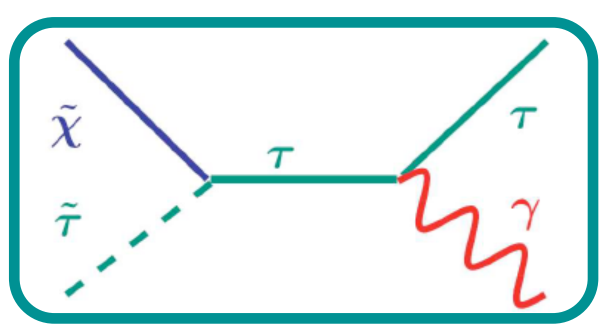
Ellis & Olive (2012)



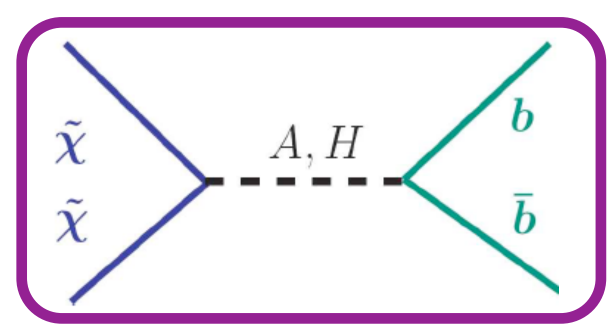
Neutralino Dark Matter

- **Dark matter abundance**
  - It's typical that $\Omega_\chi > \Omega_{CDM}$. Some mechanism(s) necessary for $\Omega_\chi \approx \Omega_{CDM}$.
    - Pure wino (~3 TeV)
    - Pure higgsino (~1 TeV)
    - Bino-higgsino or bino-wino mixture ("well-tempered", "focus point")
    - Coannihilations with sleptons or squarks (need nearly degenerate masses)
    - Coannihilations with neutralinos or charginos (need nearly degenerate masses, wino- or higgsino-like LSP)
    - Resonant annihilations ("funnel" or "pole")
    - t-channel charged scalar exchange ("bulk")



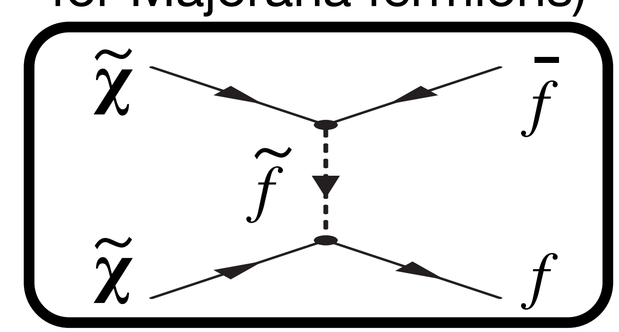


$m_{\tilde{\chi}_1^0} \approx m_{\tilde{\tau}_1, \tilde{t}_1, \tilde{\chi}_1^\pm}$



$2m_{\tilde{\chi}_1^0} \approx m_{h,A}$

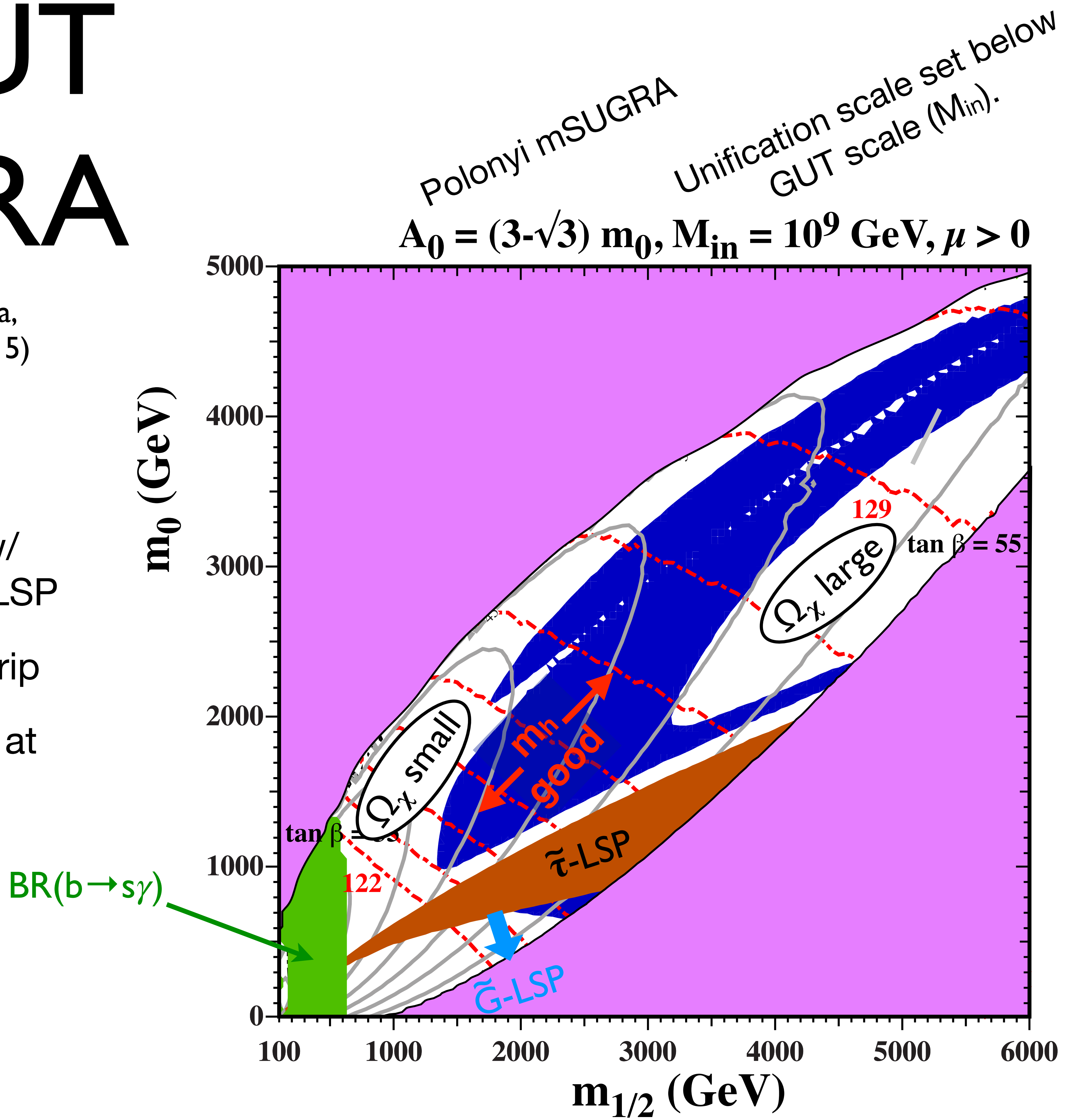
(chirality-suppressed for Majorana fermions)



sub-GUT mSUGRA

Ellis, Evans, Luo, Nagata,
Olive, & **Sandick** (2015)

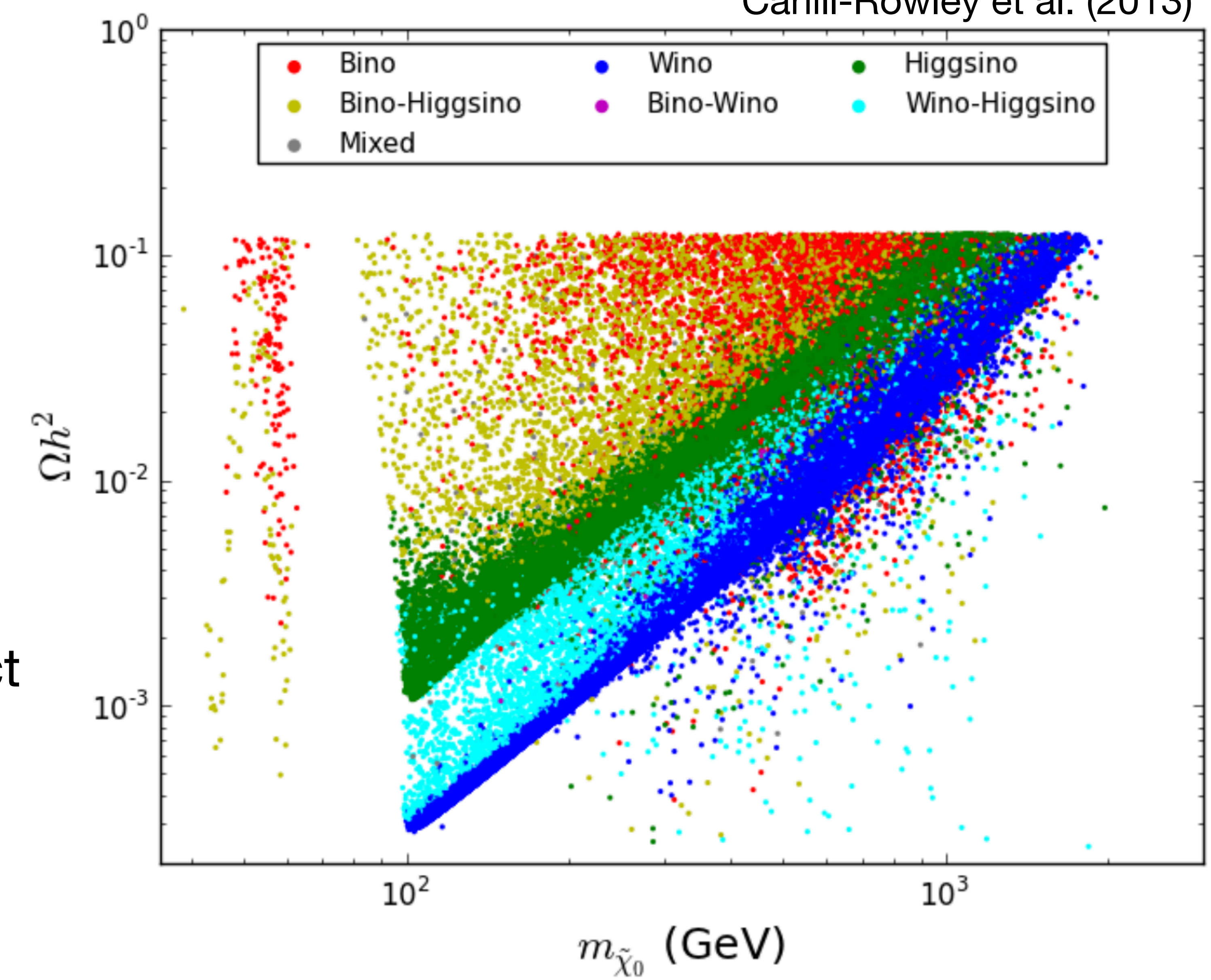
- Broad "focus point" w/ mixed bino-higgsino LSP
- Stau coannihilation strip
- "Bulk" (sort of) region at large masses



MSSM and Beyond

- 19 parameter pMSSM (and that's still pretty simplified!)
- 225k model points survive preliminary collider, flavor, precision measurement, dark matter, and theoretical constraints
- Each model point makes specific predictions for collider searches and direct and indirect dark matter searches.
- Mapping signals to parameter space is a complex problem

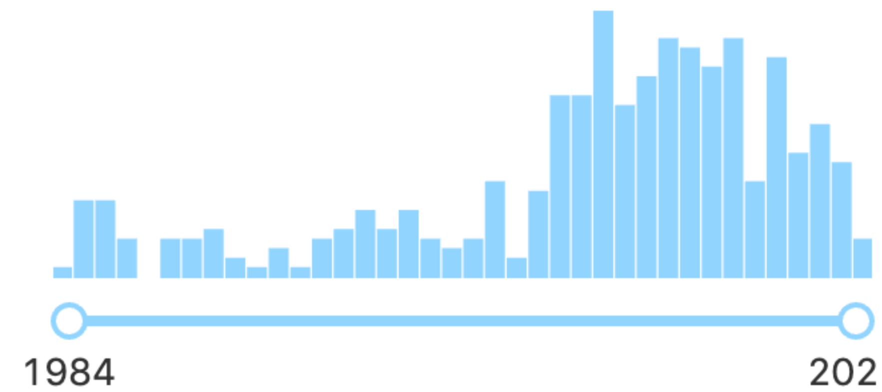
Cahill-Rowley et al. (2013)



Sneutrinos

- L-handed neutrinos have **L-handed sneutrino** superpartners in the MSSM
  - Large coupling to Z boson leads to low relic abundance and larger-than-observed scattering rates with nuclei. Falk, Olive, & Srednicki (1994)
  - Low mass window closed by limits from invisible Z decays at LEP. LEPEWWG (2003)
- R-handed neutrinos can be added to the SM to explain the origin of neutrino masses, so then also have **R-handed sneutrino** superpartners
  - L-R mixed sneutrinos have reduced coupling to Z (note that significant L-R mixing is only possible in some susy-breaking scenarios)
  - Pure R-handed sneutrinos could be CDM, but can't be thermal relics because they don't couple strongly enough to SM. Can be viable DM candidates in SUSY models with extended gauge or Higgs sectors (and therefore additional matter interactions).

Sneutrino DM



- Example: MSSM + gauged U(1)B-L Allahverdi et al. (2007, 2009)
    - DM could be R-sneutrino if U(1)B-L broken at TeV scale
- Example: MSSM + singlet superfield *s* for μ problem + singlet superfield *N* for R-(s)neutrino states Cerdeno & Seto (2009)
    - DM is pure R-sneutrino with couplings to MSSM fields, so it has the properties of a thermally-produced WIMP
- Example: MSSM + 6 complex neutrino fields (12 mixed L/R sneutrino mass eigenstates) March-Russell, McCabe, & McCullough (2009)
    - DM could be lightest sneutrino or combination of long-lived sneutrinos
- Message: Sneutrino DM must be substantially R-handed to suppress coupling to Z, so generally arises in extended versions of the MSSM
- Properties of sneutrino depend on MSSM extension - many possibilities.

Delle Rose et al. (2018) 1804.07753

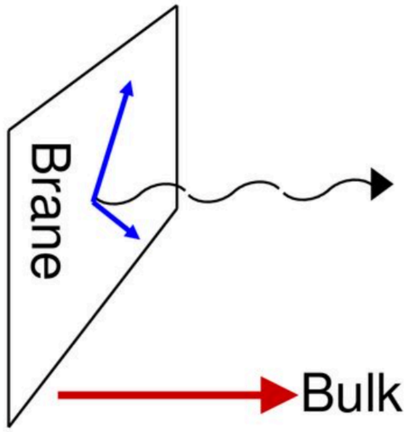
Break

Non-SUSY WIMPs?

- Lessons learned from SUSY neutralinos:
  - New physics near the weak scale + a symmetry that stabilizes the lightest new particle -> intriguing possibilities for WIMP dark matter candidate
  - Model dictates dark matter interactions.
- Similar for WIMP candidates from models with **Extra Dimensions** and Little Higgs models.

Extra Dimensions

- History: Kaluza and Klein (1920s) proposed extra dimensions to unify electromagnetism and gravity.
- 1990s: Extra dimensions that are small or strongly-curved compared to the “normal” 4-d.
  - Why 3+1d? Could be more…!
  - Necessary (along with supersymmetry) for consistent string theory.
  - Can solve the Hierarchy Problem, make some predictions.
- Size characterized by compactification scale, R



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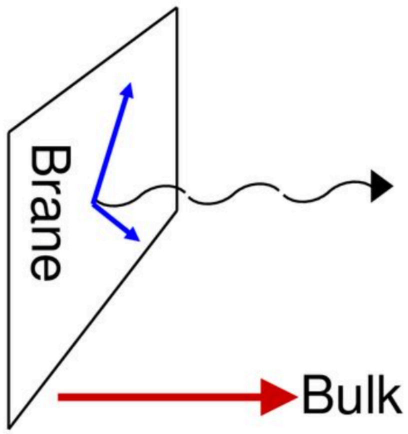


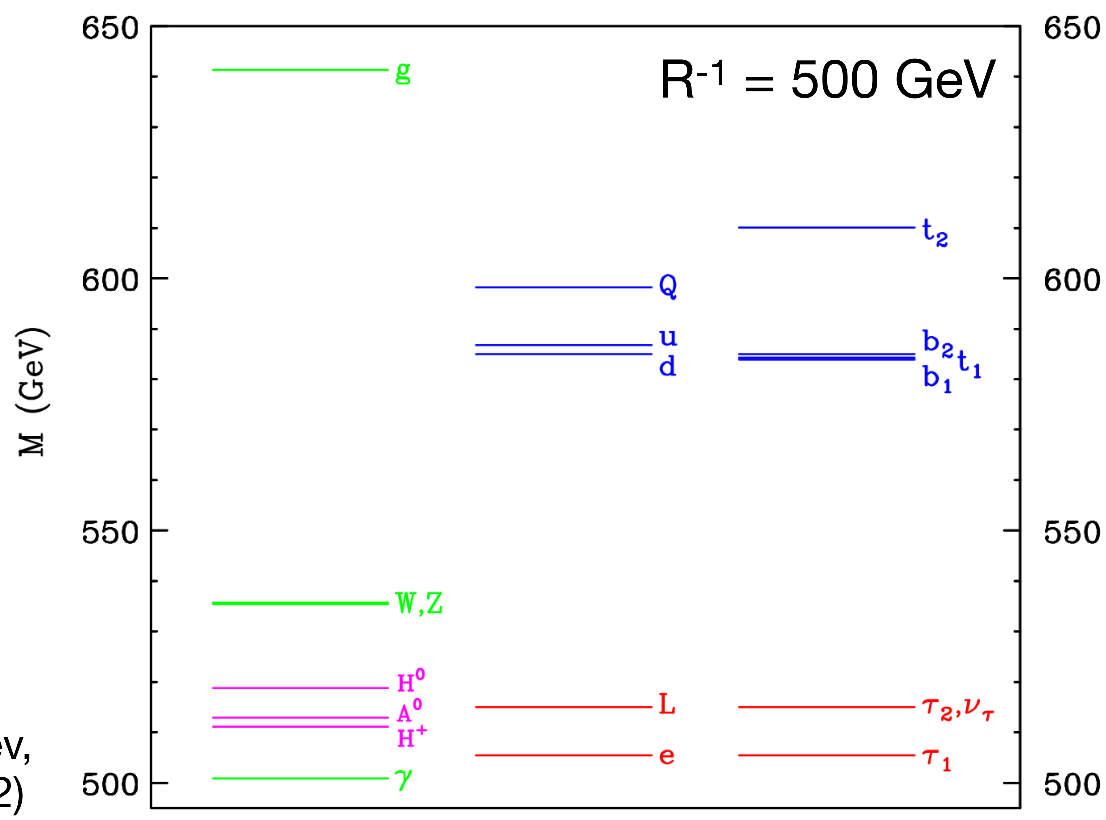
- Size characterized by compactification scale, R
  - **UED (Universal)**: All fields propagate universally in all dimensions, but extra dimensions are tiny. Appelquist, Cheng, and Dobrescu (2001)
    - R ~ 10^{-18} m
    - New particle mass scale M_{KK} ~ 1/R. So M_{KK} ~ ? GeV.
  - **ADD/LED (Large)**: SM fields are confined to 4-d brane and only gravity propagates in the bulk. R large relative to inverse of new scale, and decreases with number of extra dimensions.   Arkani-Hamed, Dimopolous, and Dvali (1998)
  - **WED (Warped)**: Similary to ADD, but SM fields are confined because extra dimensions have large curvature. Gravity can be strong away from our brane, but is weak where we live. Randall and Sundrum (1999)

DM from UED

- All quantum fields X are functions of coordinates (x^μ, y)
- Minimal UED is 5-d and has two parameters: R, Λ (cutoff)
- Tree-level mass for the nth KK excitation of a SM field $X^{(n)}$ is

$$m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}}$$

    - For large n or small SM mass, this looks like a “tower” of mass states.



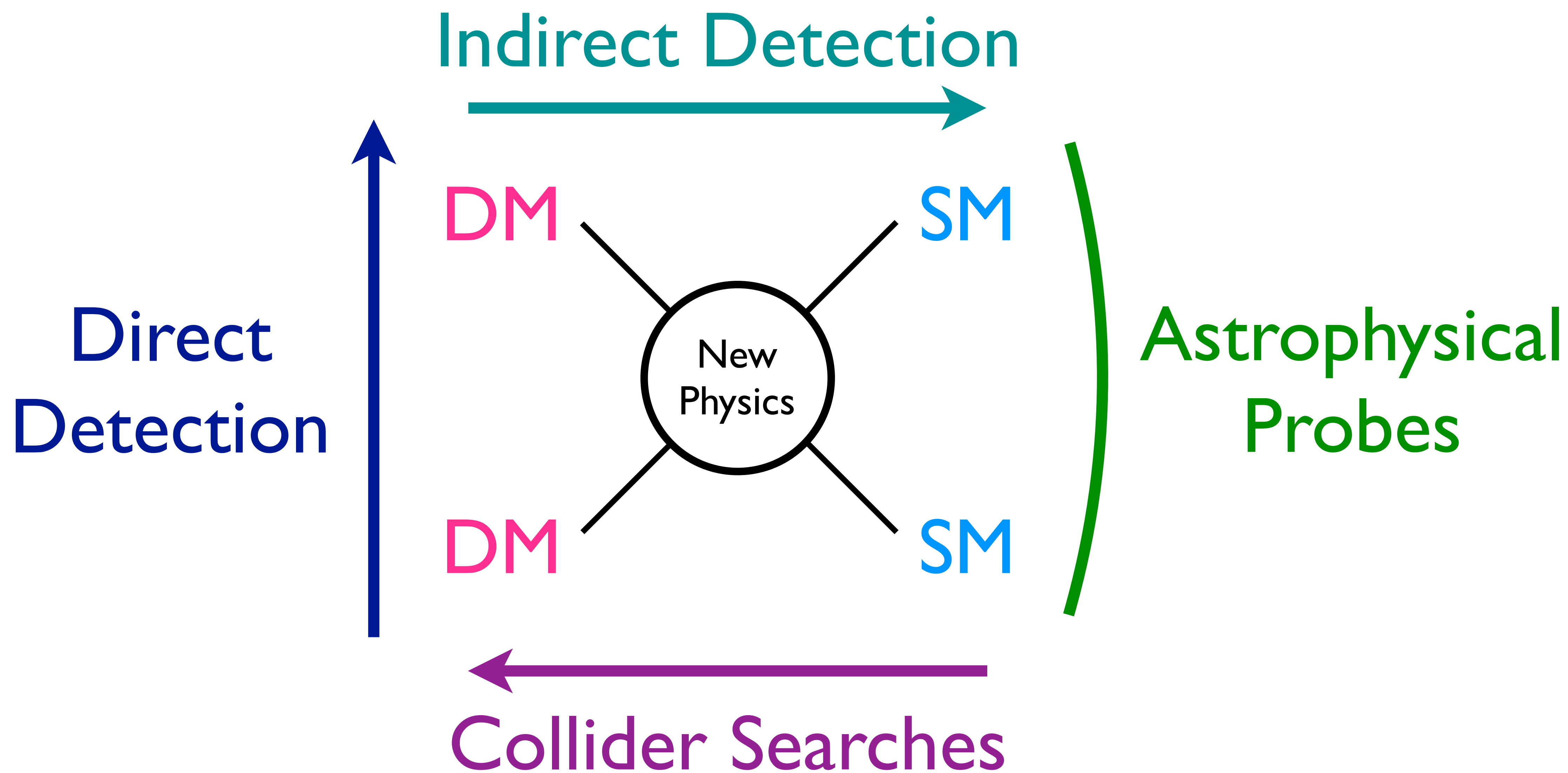
Cheng, Matchev, Schmaltz (2002)

- LKP is KK photon ($B^{(1)}$) or KK graviton ($G^{(1)}$)
- Similar to SUSY, coannihilations and resonant annihilations (w/ n=2 modes) are important for $B^{(1)}$
- $B^{(1)}$ is spin 1 (unlike the susy bino)

Non-SUSY WIMPs?

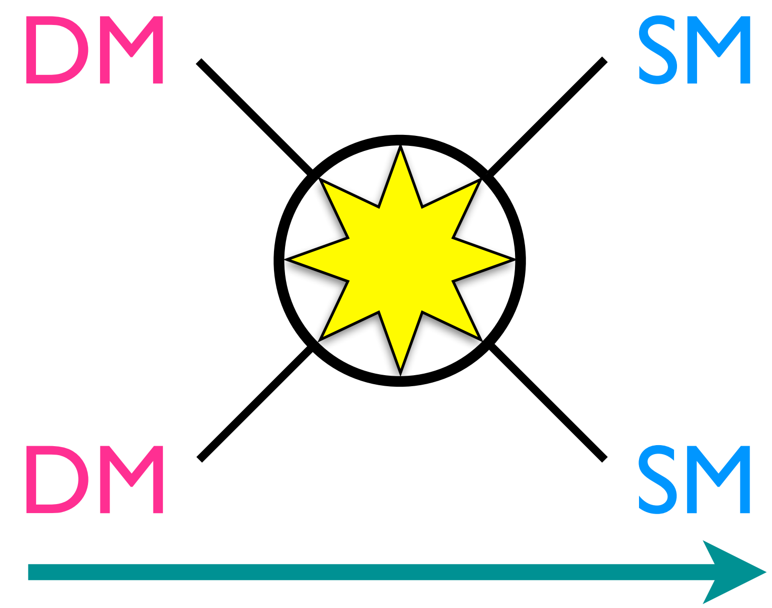
- Lessons learned from SUSY neutralinos:
  - New physics near the weak scale + a symmetry that stabilizes the lightest new particle -> intriguing possibilities for WIMP dark matter candidate
  - Model dictates dark matter interactions.
- Similar for WIMP candidates from models with Extra Dimensions and Little Higgs models.
- Since we don’t know what the fundamental theory is, we can also take a more phenomenological (bottom up / ad hoc) approach rather than top down.

WIMP Hunting

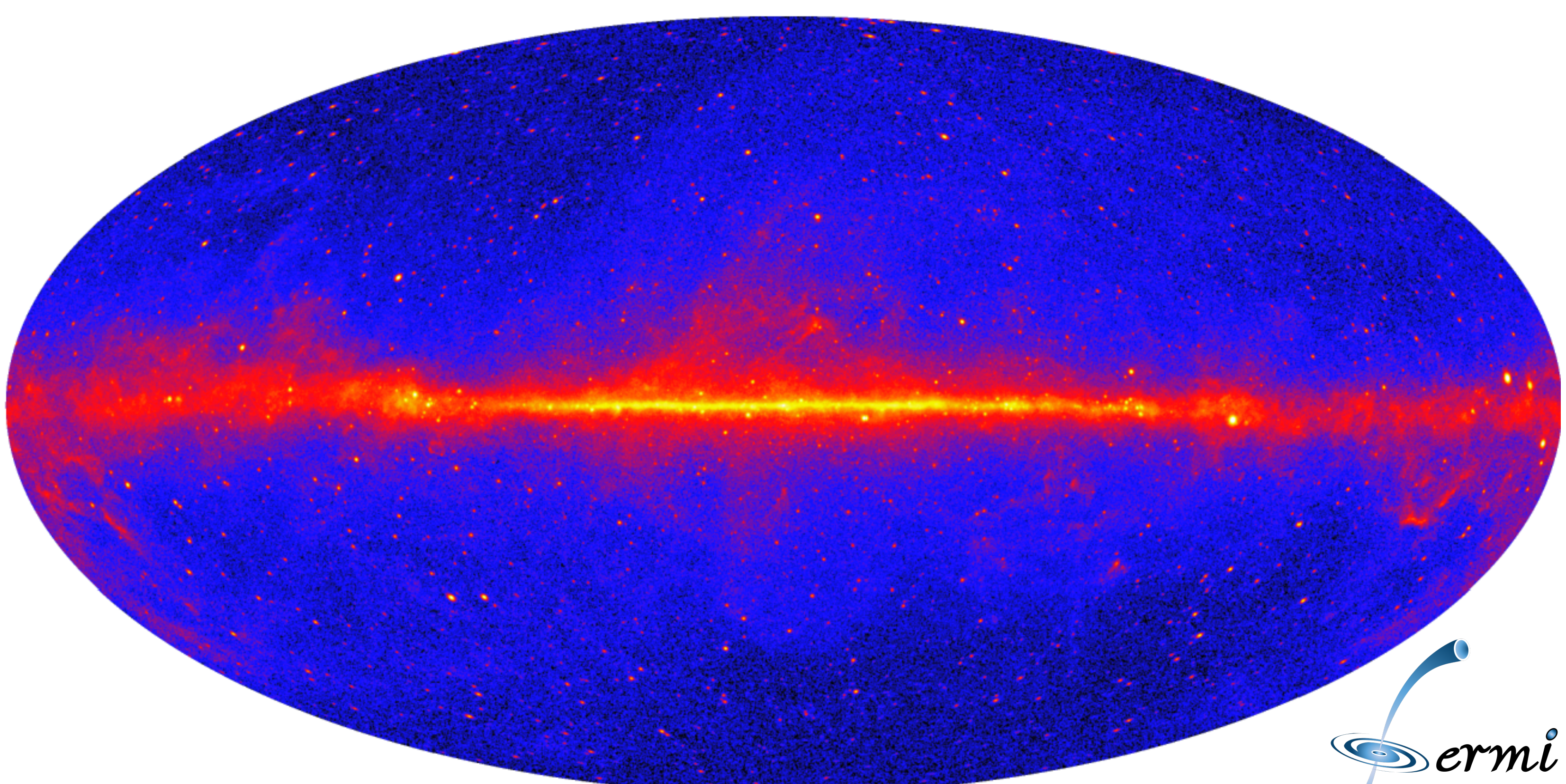


Goal: determine WIMP mass, spin, and couplings to SM particles.

Indirect Detection



- Look for end-products of DM annihilation
- If DM annihilated in the early universe, this process should still be occurring today: possible *link between present and early Universe physics.*

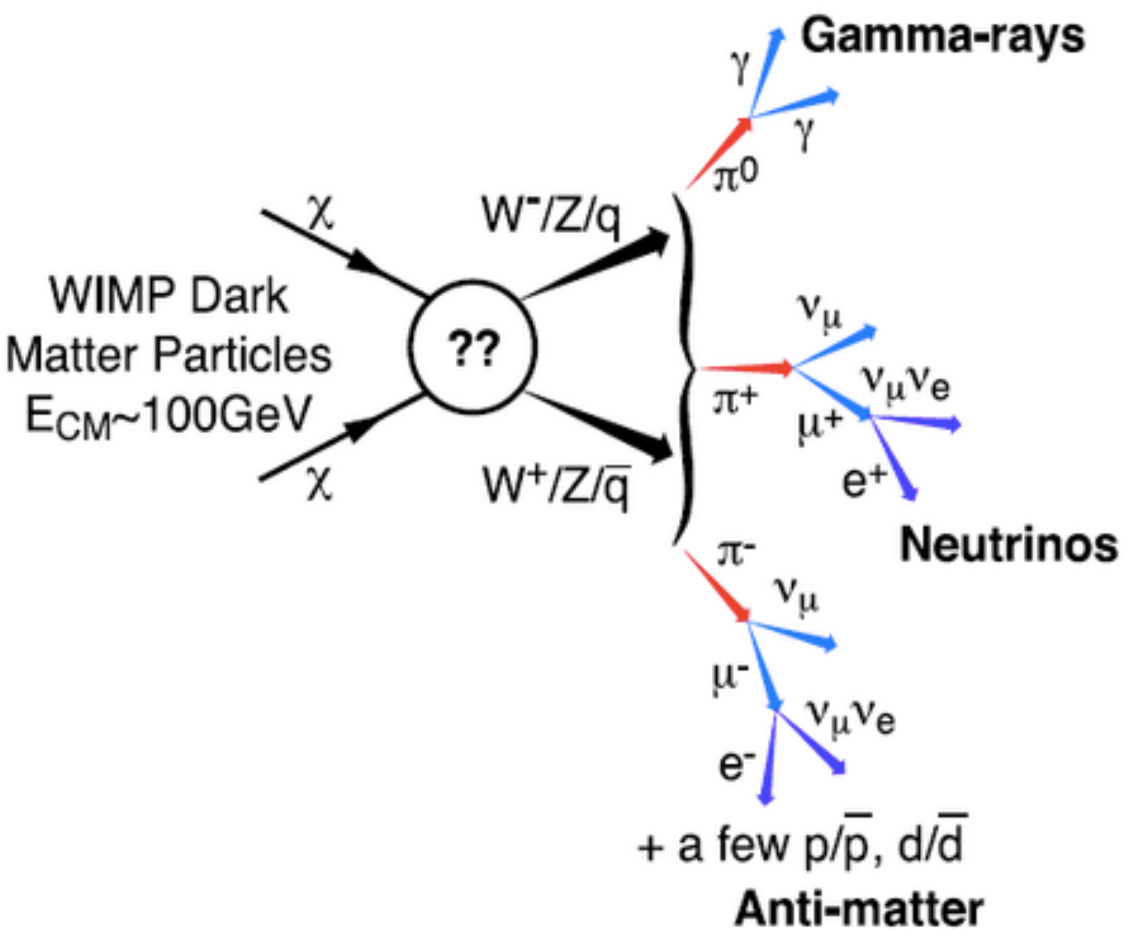


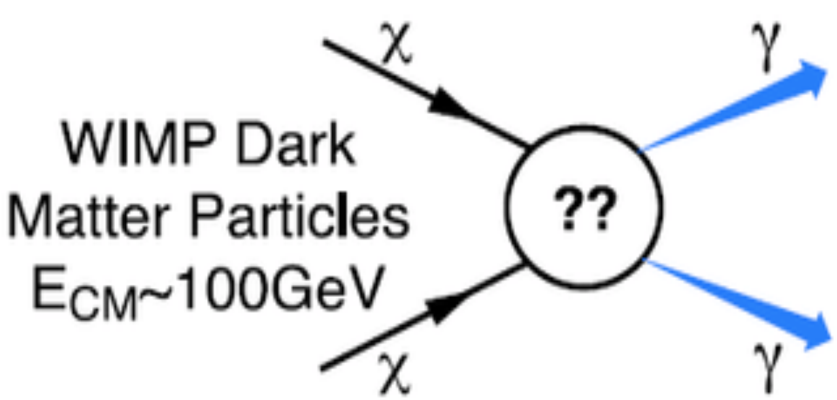
NASA/DOE/Fermi-LAT Collaboration

Fermi Gamma-ray Space Telescope

- **Challenges:**
  - Sensitive to the distribution of dark matter along the line-of-sight to a target.
  - Propagation - magnetic fields, dust, etc.
  - Difficult to exclude astrophysical explanations.
- **Good news:** Many places to look, many experiments looking(ed)

WIMP Annihilation



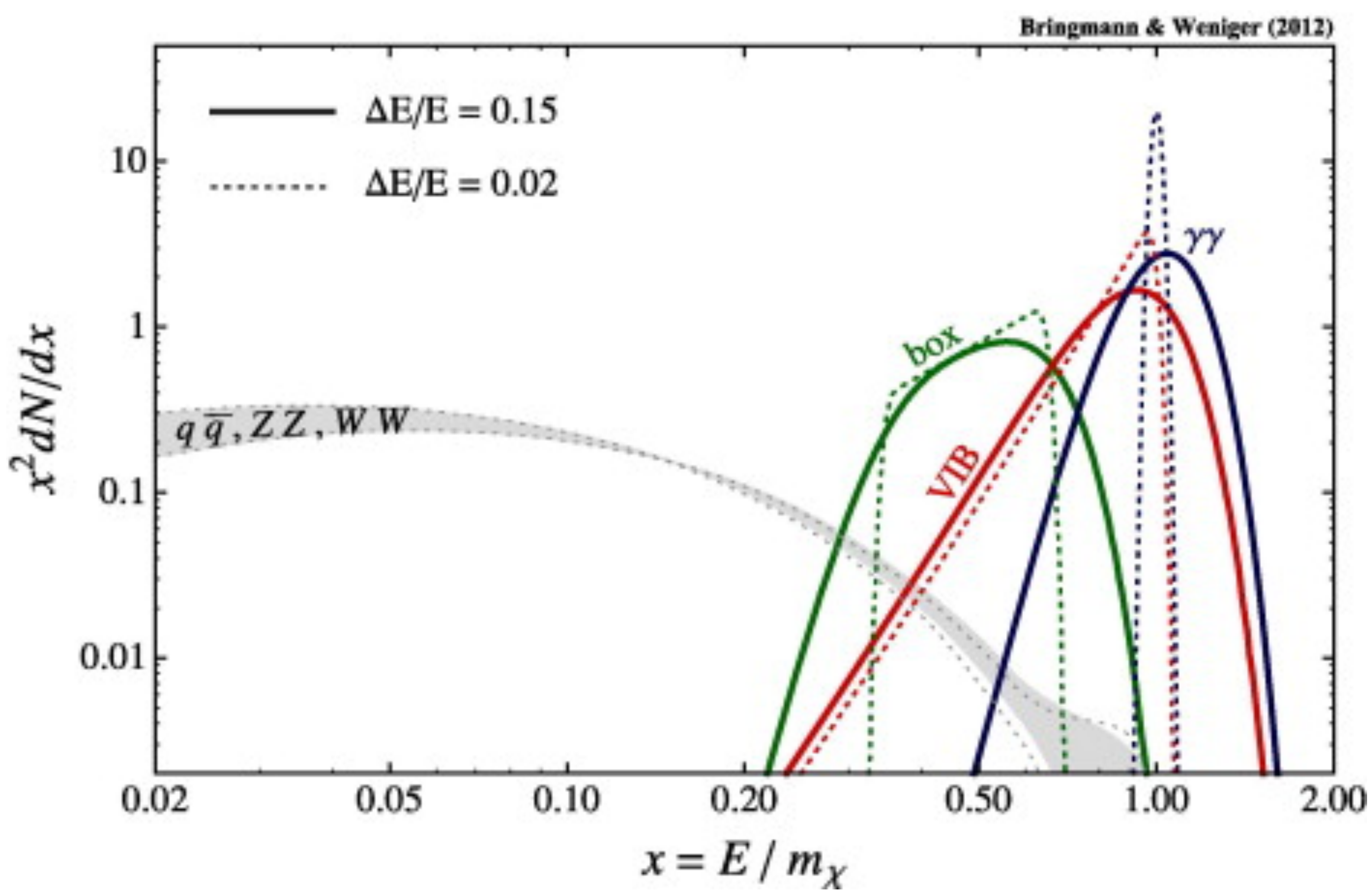


- Photons:
  - Direct annihilation
  - Radiation (Internal Brem.)
  - Decays/Hadronization/Cascades
  - Synchrotron, Inverse Compton Scattering of e^+/e^-…
- Neutrinos
- Electrons/Positrons
- Protons/Antiprotons
- Nuclei/Antinuclei

Ingredients

- Dark matter annihilation flux (neutral):

$$\frac{d\Phi}{dE}_{\rm ann} \propto \frac{1}{m^2} \sum_f B_f \boxed{\frac{dN_f}{dE}(E)} \int d\Omega \int d\ell \, (\sigma_{\rm ann} v) \, \rho^2_{\rm DM}(r)$$



- **Spectral features:** spectral shape, radiation (model-dependent)…
  - Line
  - Continuum from decays
  - Radiation

Ingredients

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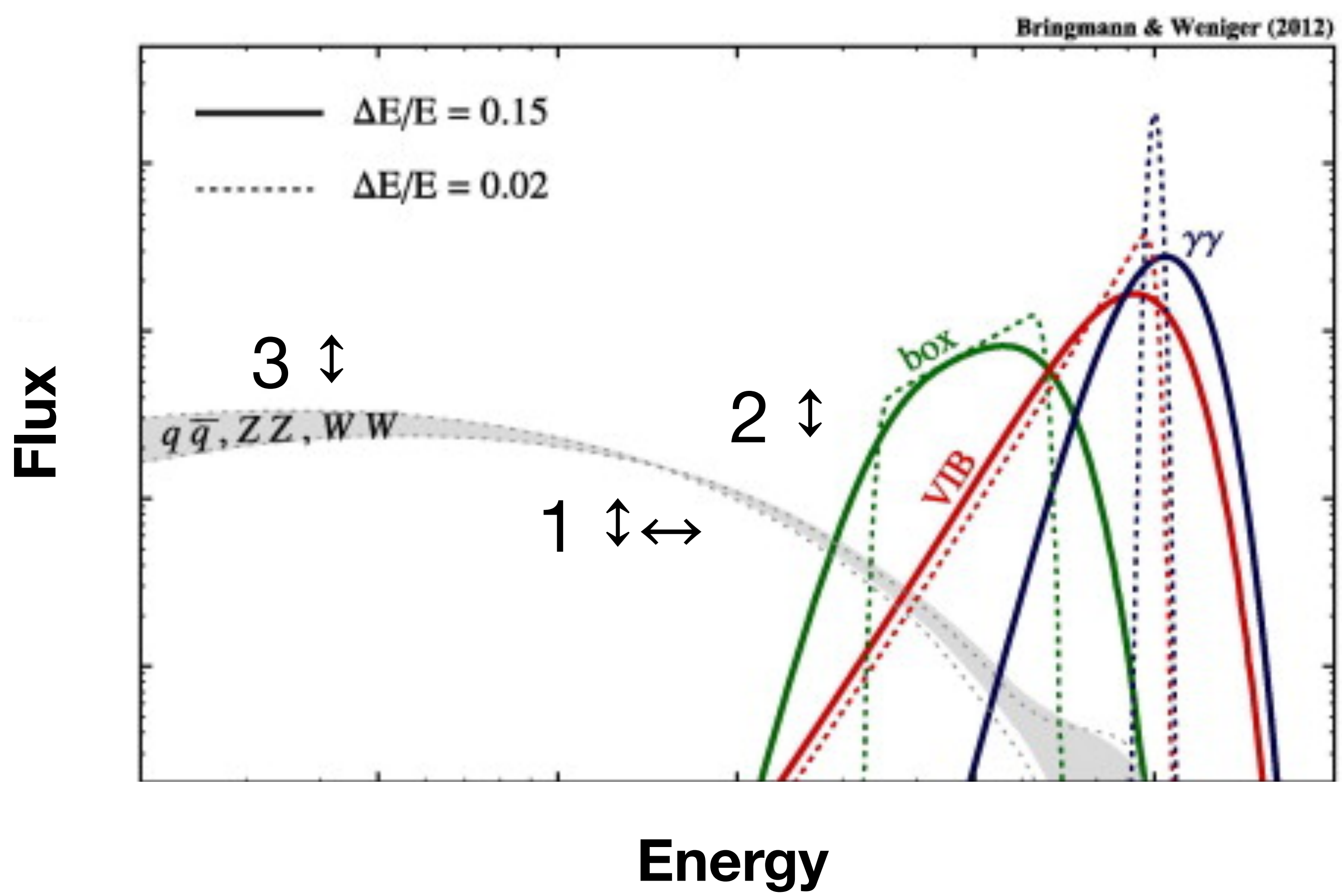

- **Dark Matter Properties:**
  1. mass
  2. branching fractions to different final states
  3. annihilation cross section

Ingredients

- Dark matter annihilation flux (neutral):

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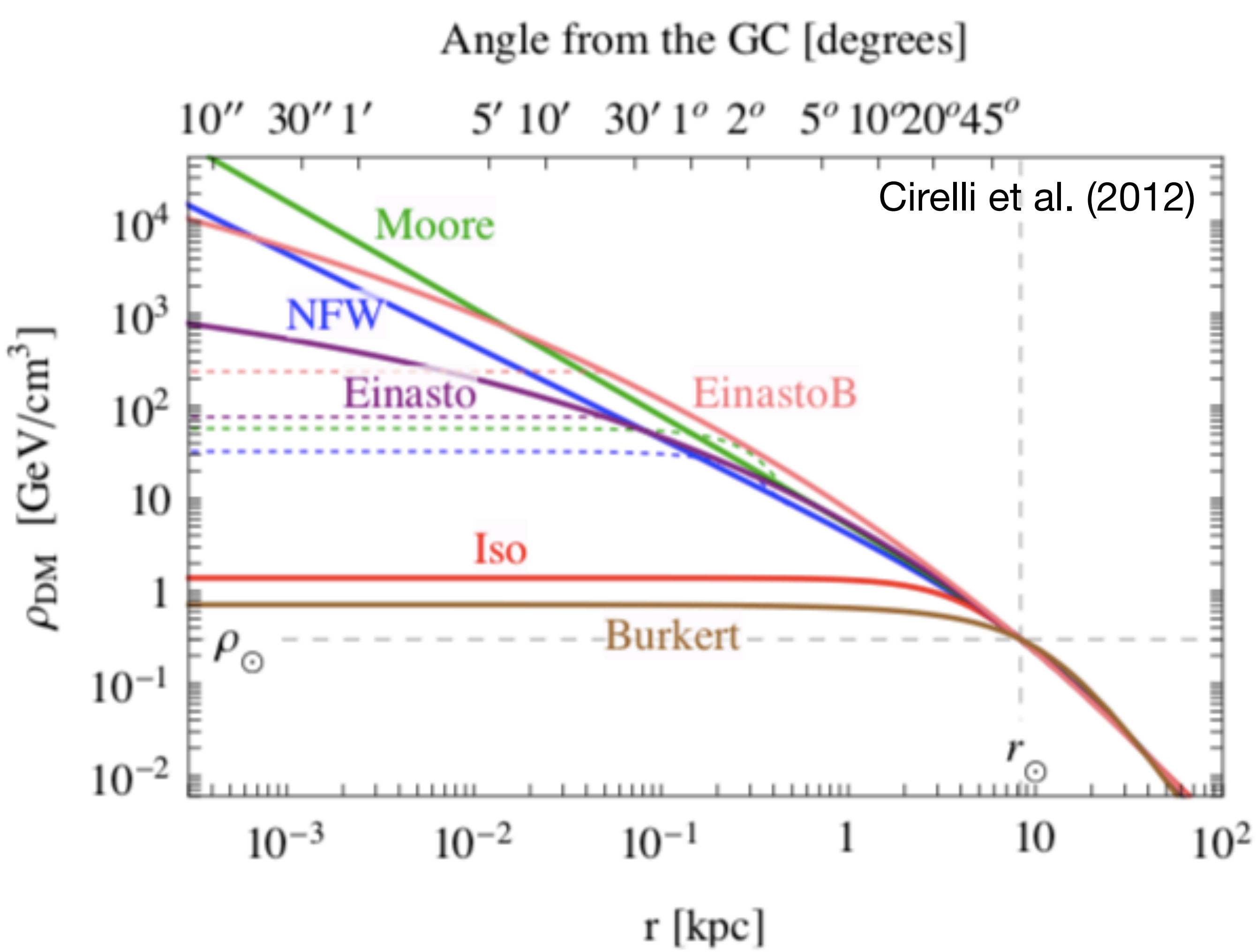

- **Dark Matter Distribution:**
  - "J factor"

    $$J = \int_{\Delta\Omega} d\Omega \int d\ell \, \rho^2_{\rm DM}(r)$$

  - Affected by velocity-dependence of annihilation cross section

Ingredients

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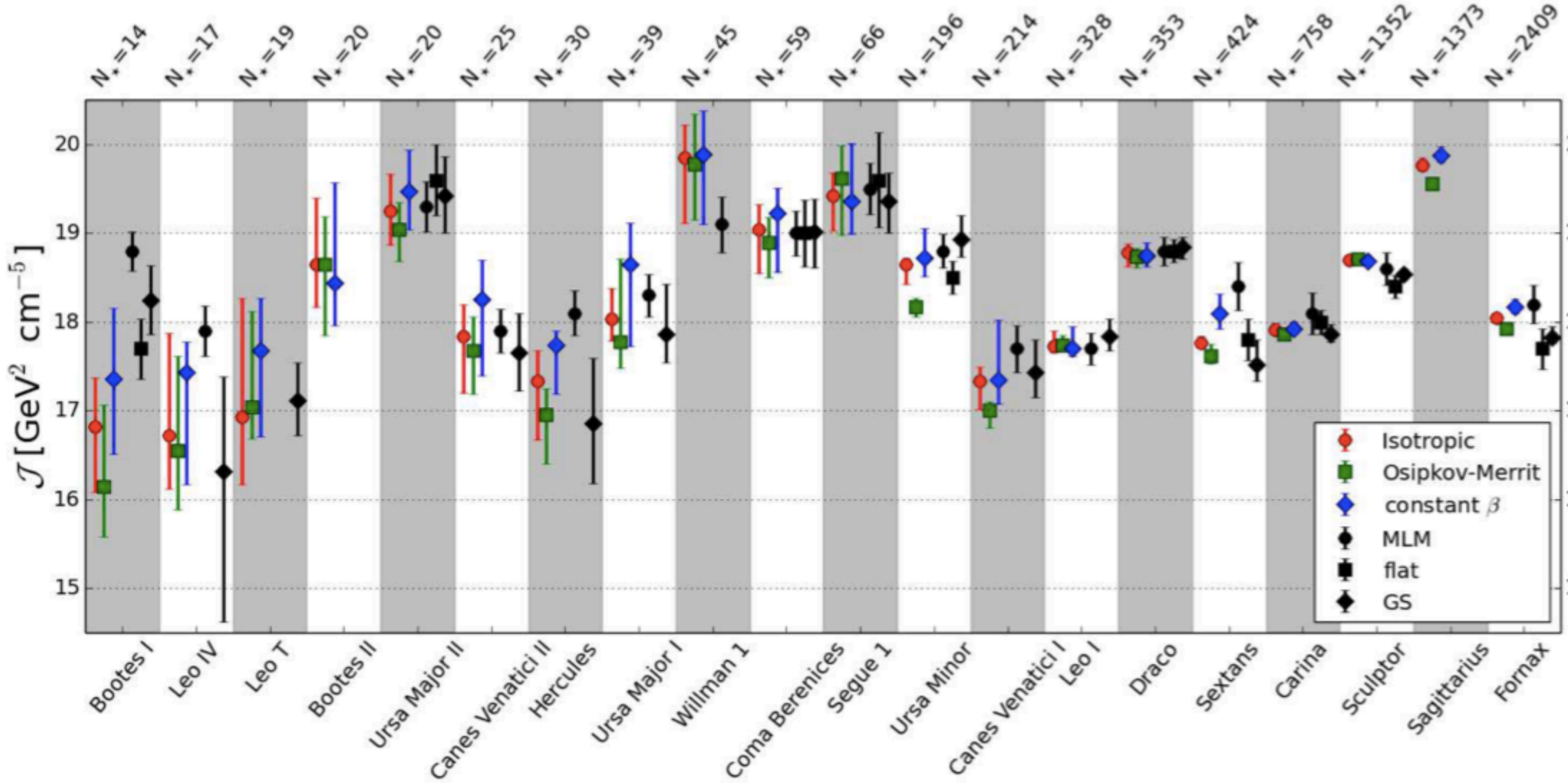
Chiappo et al. (2017)



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  - "J factor"

    $$J = \int_{\Delta\Omega} d\Omega \int d\ell \, \rho^2_{\rm DM}(r)$$

  - Affected by velocity-dependence of annihilation cross section

Note: for **decay**, $(\sigma v)_0 / 2 m_X \to \Gamma$

and $J \to J_D \equiv \int_{\Delta\Omega} d\Omega \int d\ell \, \rho$

Neutral vs. Charged Products

- Neutral: Propagate directly from source

$$\frac{d\Phi}{dE}_{\rm ann} \propto \frac{1}{m^2} \sum_f B_f \frac{dN_f}{dE}(E) \int d\Omega \int d\ell \, (\sigma_{\rm ann} v) \, \rho^2_{\rm DM}(r)$$

- Charged: Path and energy altered along the way

$\frac{\partial\psi(\vec{r},p,}{\partial t}$

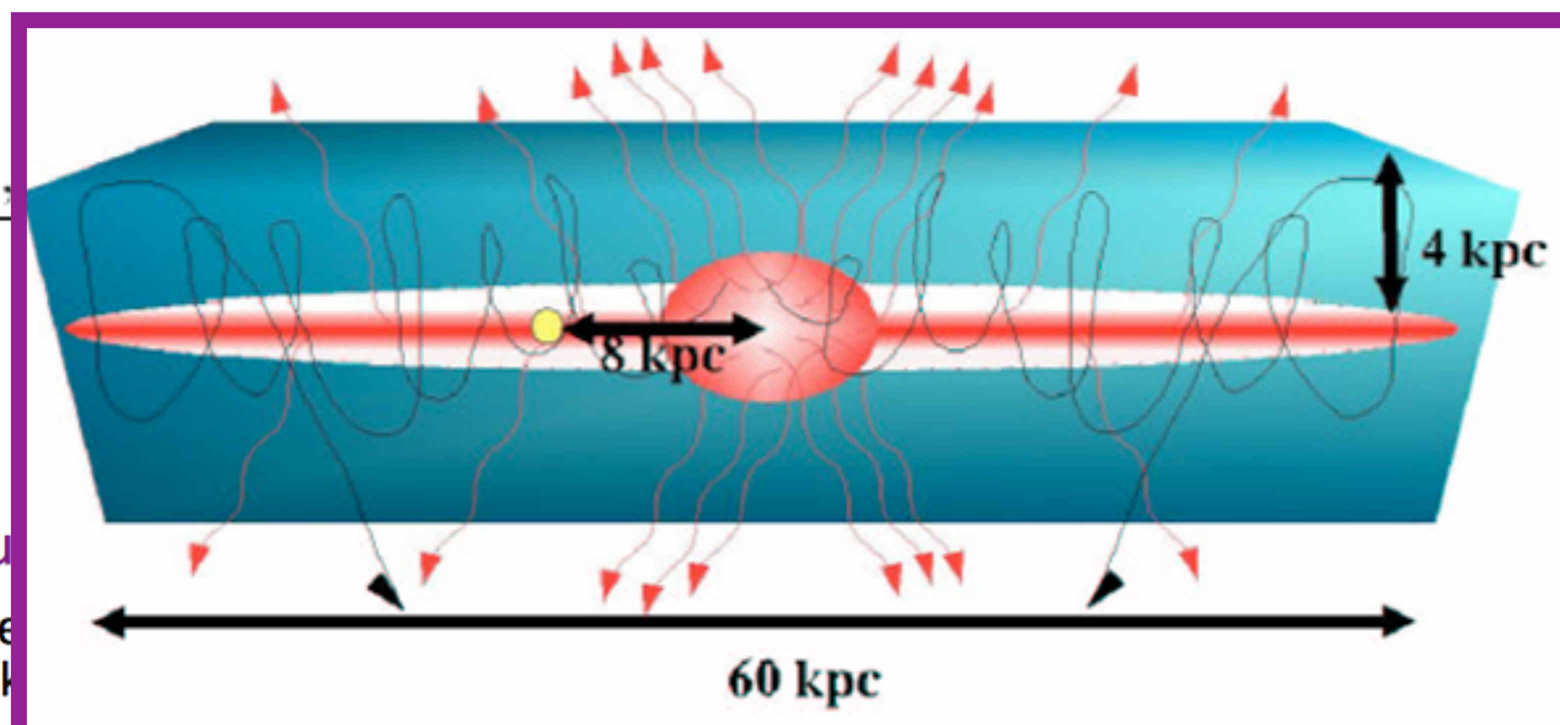
dioactive
decay

$\psi - \frac{1}{\tau_r}\psi$

diffu

ntation
ses

See
Moskalenk



ID Targets

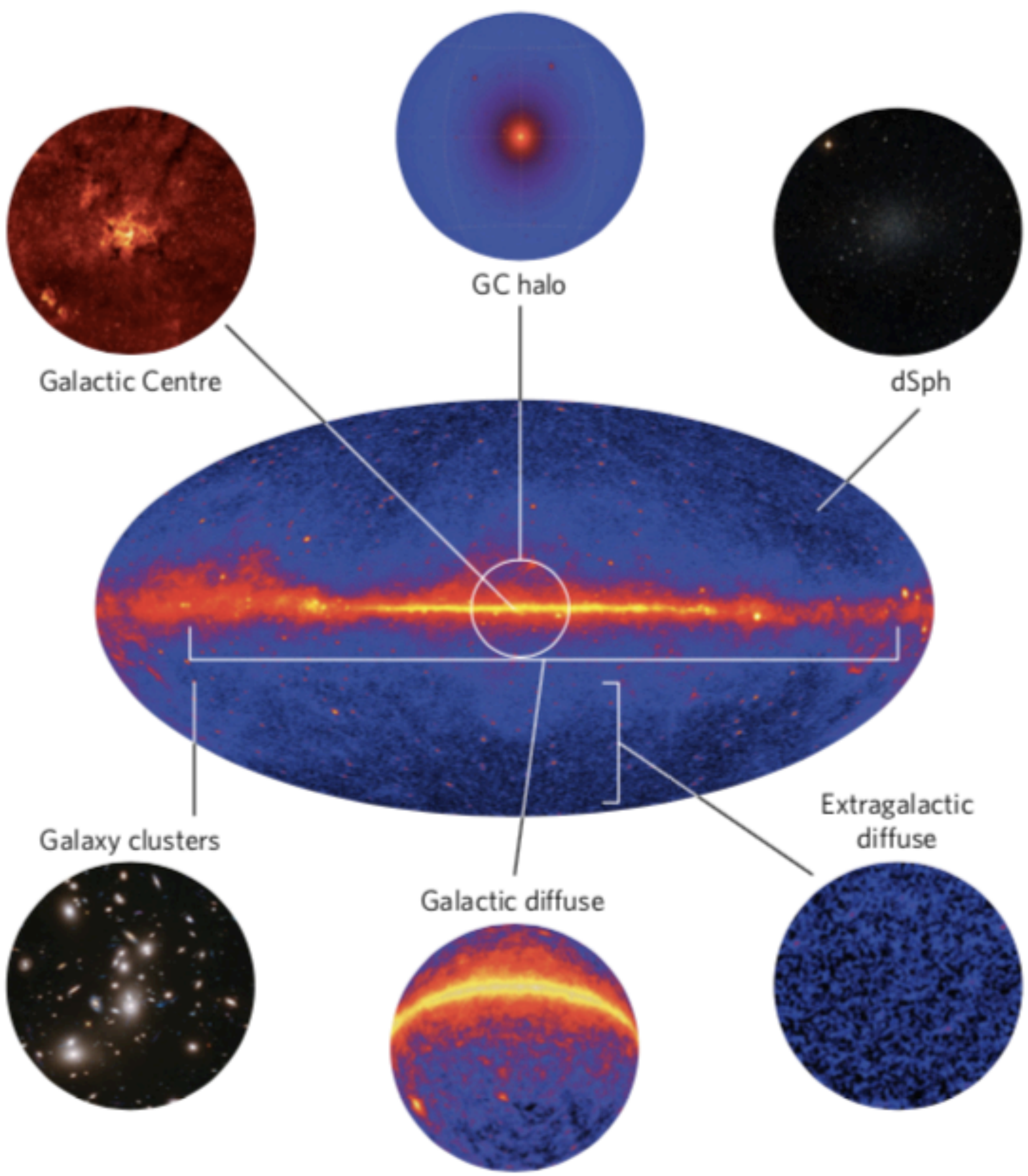
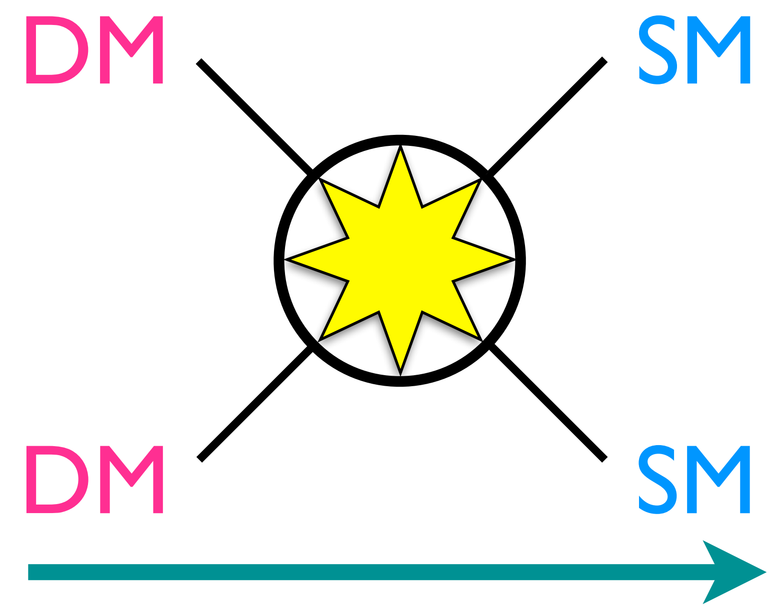


Image: Conrad & Reimer (2017)

- In the Milky Way halo
  Ellis, Freese et al. 1987; Feldman & Sandick, 2013; Kumar & Sandick, 2013
- Near the Milky Way GC
  Gondolo and Silk, 2000; Kumar, Sandick, Teng, & Yamamoto, 2016; Sandick, Sinha, & Yamamoto, 2017; Elagin, Kumar, Sandick, & Teng, 2017
- In the Sun or the Earth
  Silk et al. 1985; Kraus et al. 1986; Freese 1986; Kumar & Sandick, 2015; Ellis et al., 2016
- In nearby dwarf galaxies
  Evans, Ferrer & Sarkar 2004; Sandick et al. 2010; Feldman & Sandick, 2013, Kumar, Sandick, Teng, & Yamamoto, 2016; Sandick, Sinha, & Teng, 2016; Boddy, Kumar, Marfatia, & Sandick, 2018; Boddy, Hill, Kumar, Sandick, Shams Es Haghi, 2021
- In nearby galaxies or clusters of galaxies
  Colafrancesco, Profumo, & Ullio 2006
- In Milky Way substructure
  Evans, Ferrer & Sarkar 2004; Sandick et al. 2010; 2011a,b; 2012; Sandick & Watson, 2011, Ghosh, Kumar, Marfatia, & Sandick, 2018

Probes

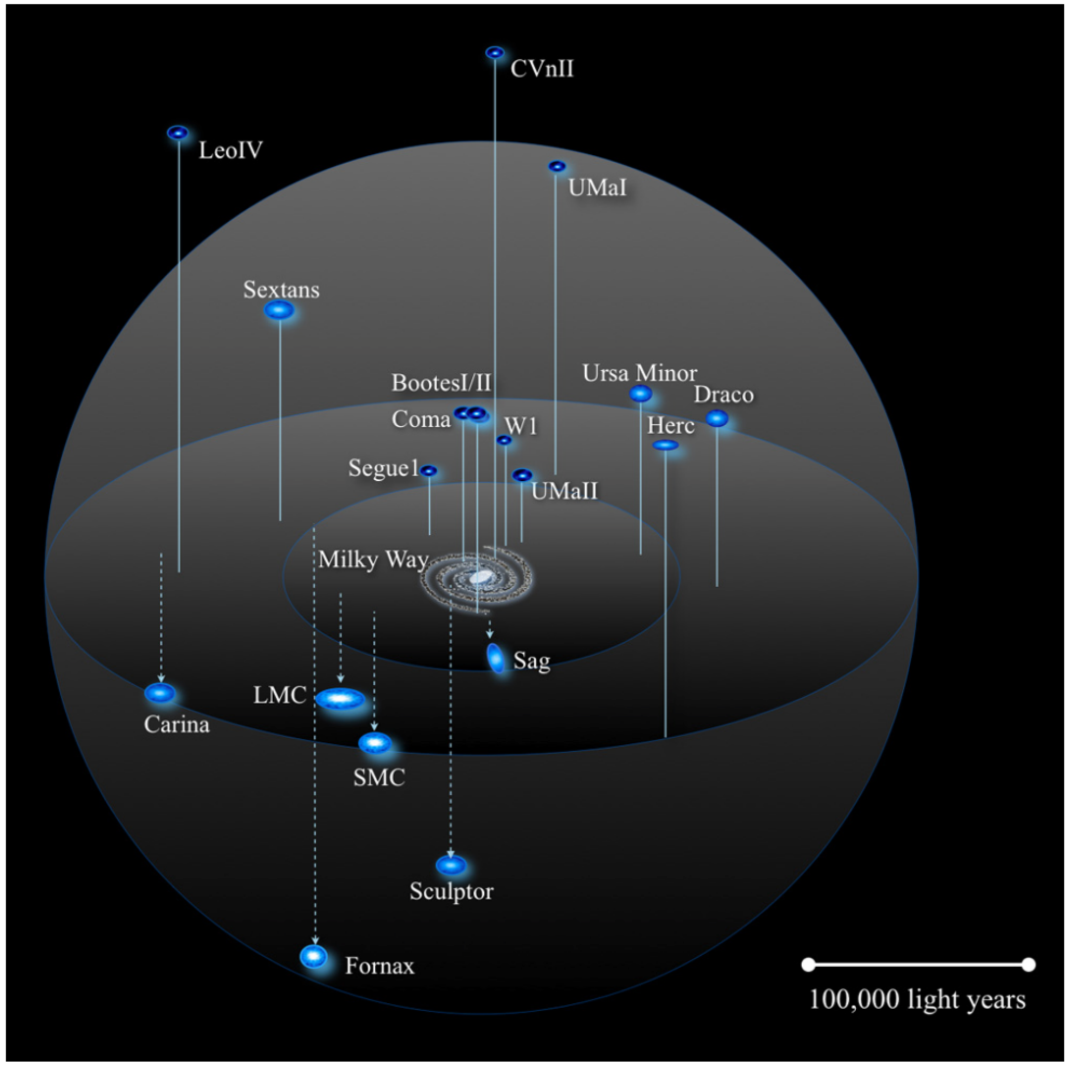


- Continuum x/gamma-ray photons
- Continuum neutrinos
- Line signals (photons and neutrinos)
- Positrons
- Antiprotons
- Deuterium
- Anti-He-3 and -4

- CMB
- 21 cm observations
- Cross correlations
- Dark Stars
- Dark Substructure
- Radio signatures (ARCADE-2 excess)
- …

Model Independence

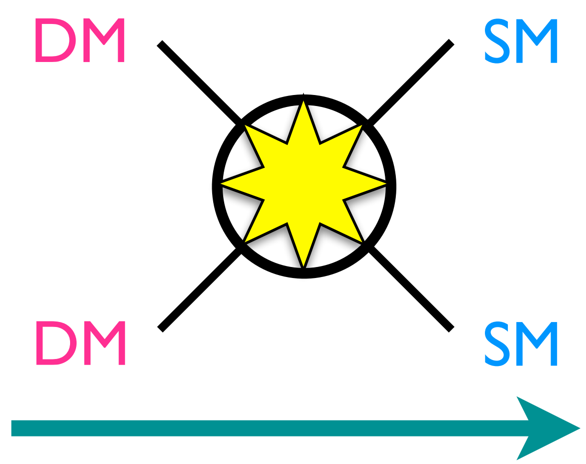
- **Can't blindly apply indirect detection limits to any DM model!**
  - Spectrum, J-factor, propagation
  - multi-body annihilation final states, final-state cascades, multi-component DM, nontrivial velocity dependence, etc.
- **MADHAT provides model-independent constraints on the number of photons from non-standard/unknown astrophysics**



Boddy, Kumar, Marfatia, & Sandick

arXiv:1802.03826

Indirect Detection



- Dark matter annihilation flux (photons):

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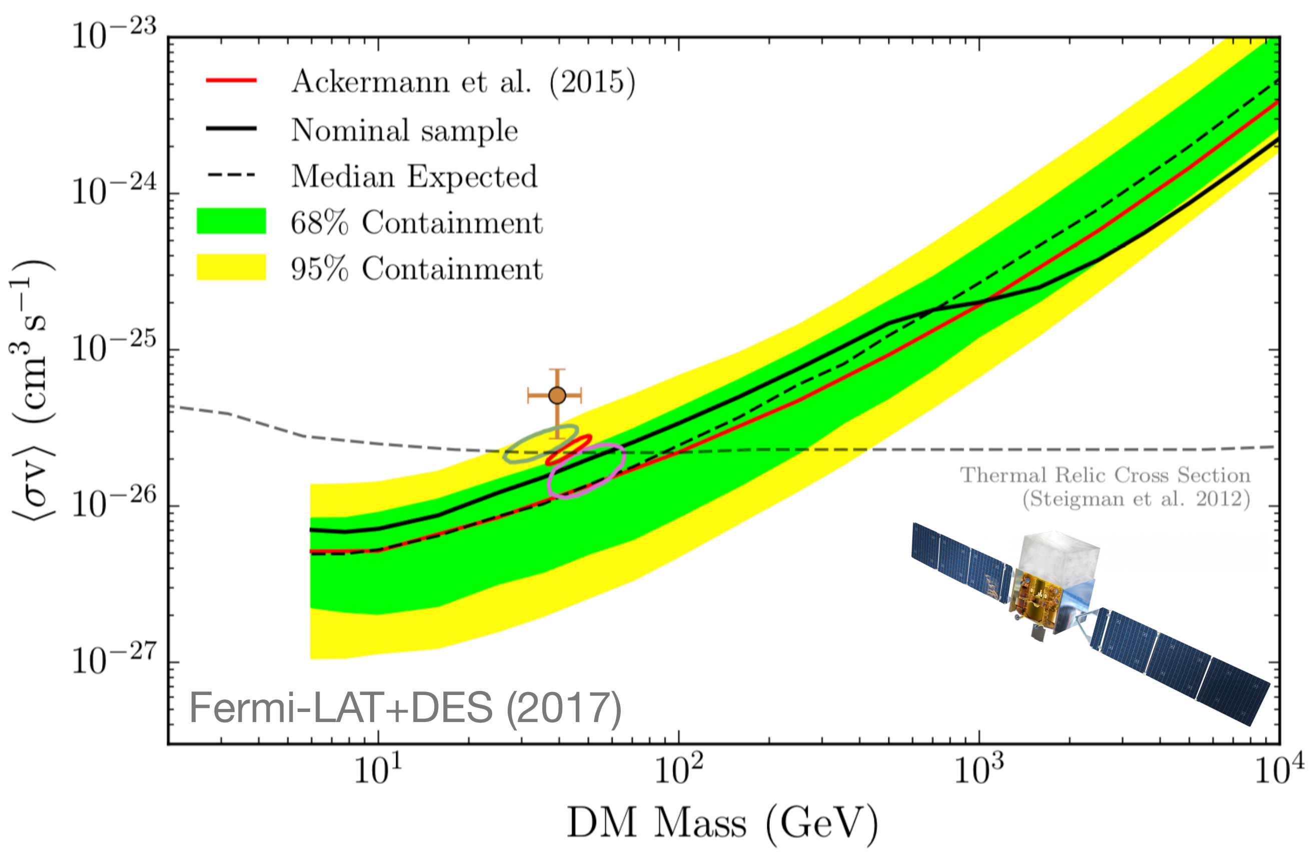
measure

assume

limit



<u>Key Assumptions</u>:

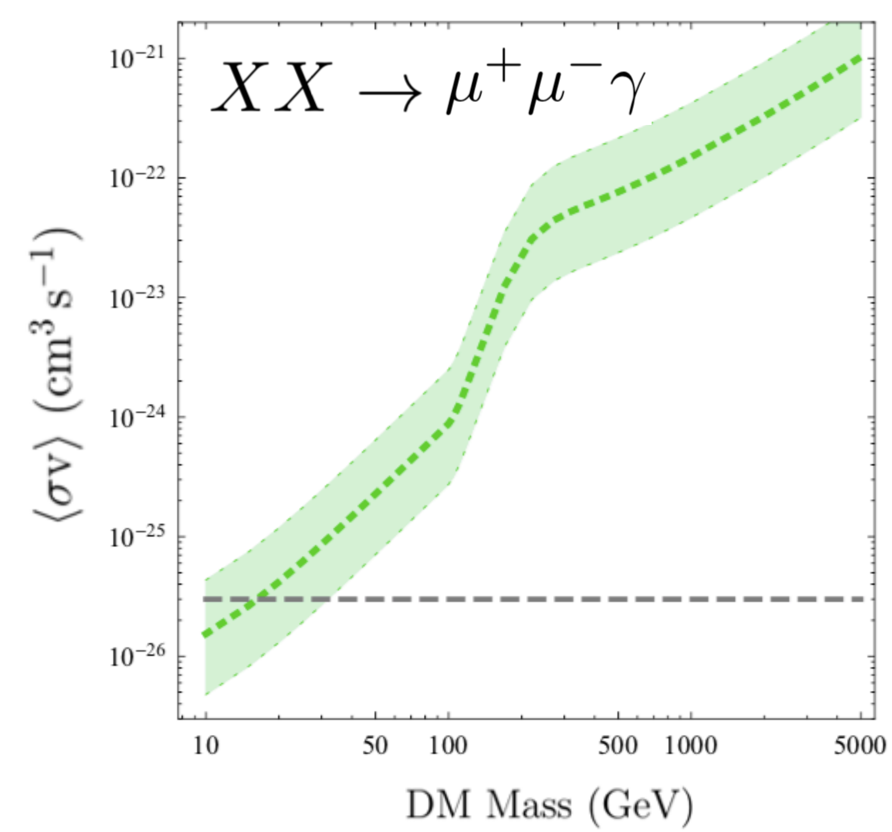
1. DM annihilates to b quark+antiquark
2. dark matter halo density
3. specific speed-dependence of annihilation

This limit can *only* be applied to a very specific dark matter model.

MADHAT: Model-Agnostic Dark Halo Analysis Tool

Boddy, Hill, Kumar, Sandick, & Shams Es Haghi,
Comput. Phys. Commun. 261 (2021) 107815

- **Facilitates comparison of dark matter models with astrophysical data**
- **Calculates constraints on the number of excess photons, *completely independent of dark matter particle physics model or dark matter astrophysics.***
    - determine the background (+foreground) distributions empirically - *no modeling*
    - use only number of photon counts - *no spectrum assumed*
    - simple stacking - *all photon events weighted equally*
- **Separation of observational data, dark matter distribution, and details of dark matter microphysics**



https://github.com/MADHATdm

Constraining Dark Matter

- **In the absence of signal, can place limits on models that could have produced an excess over background.**

$$\overline{N}_{\rm DM} = \boxed{\Phi_{\rm PP}} \times \boxed{J(\Delta\Omega)} \times (T_{\rm obs}\bar{A}_{\rm eff})$$

$$\boxed{\Phi_{\rm PP} = \frac{(\sigma v)_0}{8\pi m_X^2}\int_{E_{\rm th}}^{E_{\rm max}} dE_\gamma \frac{dN_\gamma}{dE_\gamma}\frac{A_{\rm eff}(E_\gamma)}{\bar{A}_{\rm eff}}}$$

$$\sigma v = (\sigma v)_0 \times S(v)$$

$$\boxed{J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int d\ell \int d^3v_1 f(r(\ell,\Omega),\vec{v}_1)\int d^3v_2 f(r(\ell,\Omega),\vec{v}_2) \times S(|\vec{v}_1 - \vec{v}_2|)}$$

Note: for decay, $(\sigma v)_0/2m_X \to \Gamma$ and $J \to J_D \equiv \int_{\Delta\Omega} d\Omega \int d\ell\, \rho$

arXiv:1802.03826, 1910.02890

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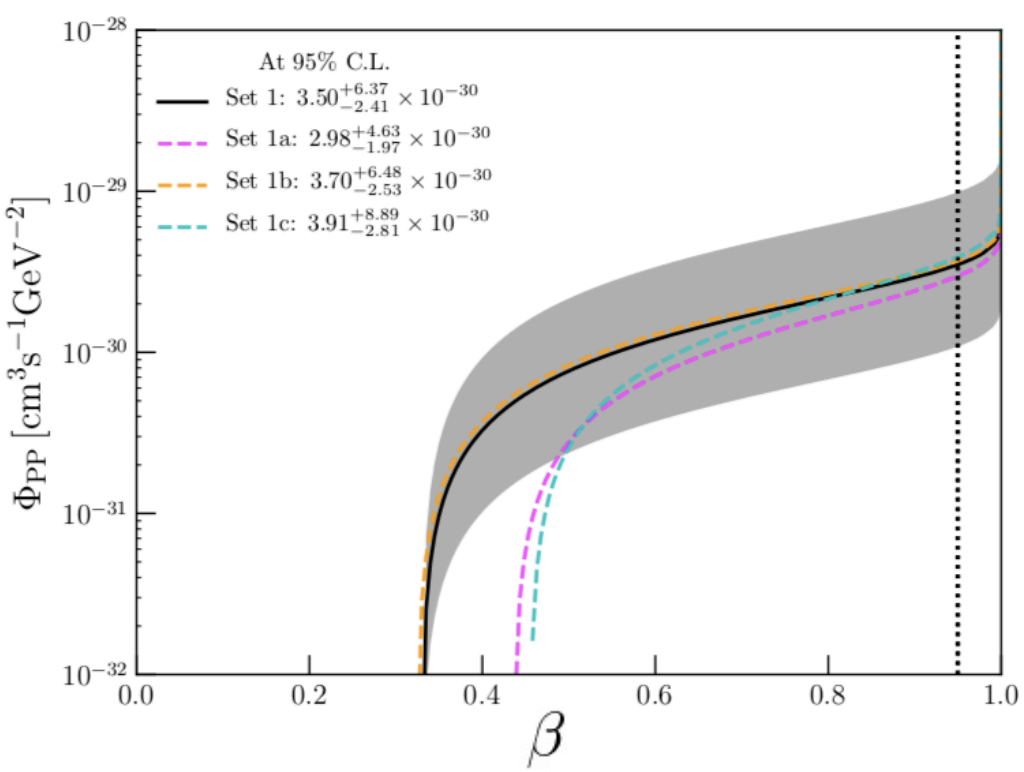
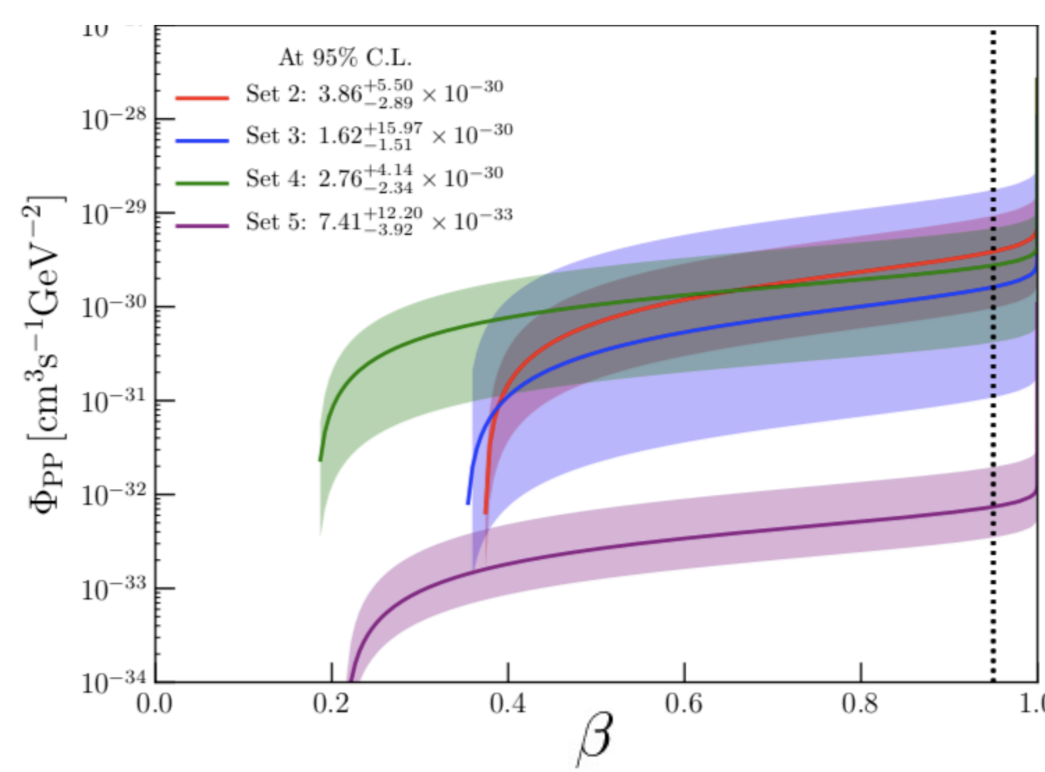
$$\overline{N}_{\rm DM} = \Phi_{\rm PP} \times J(\Delta\Omega) \times (T_{\rm obs}\bar{A}_{\rm eff})$$

$$\Phi_{\rm PP}^{\rm bound}(\beta) \equiv N_{\rm bound}(\beta)\left[\sum_i J^i \times (T_{\rm obs}\bar{A}_{\rm eff})^i\right]^{-1}$$

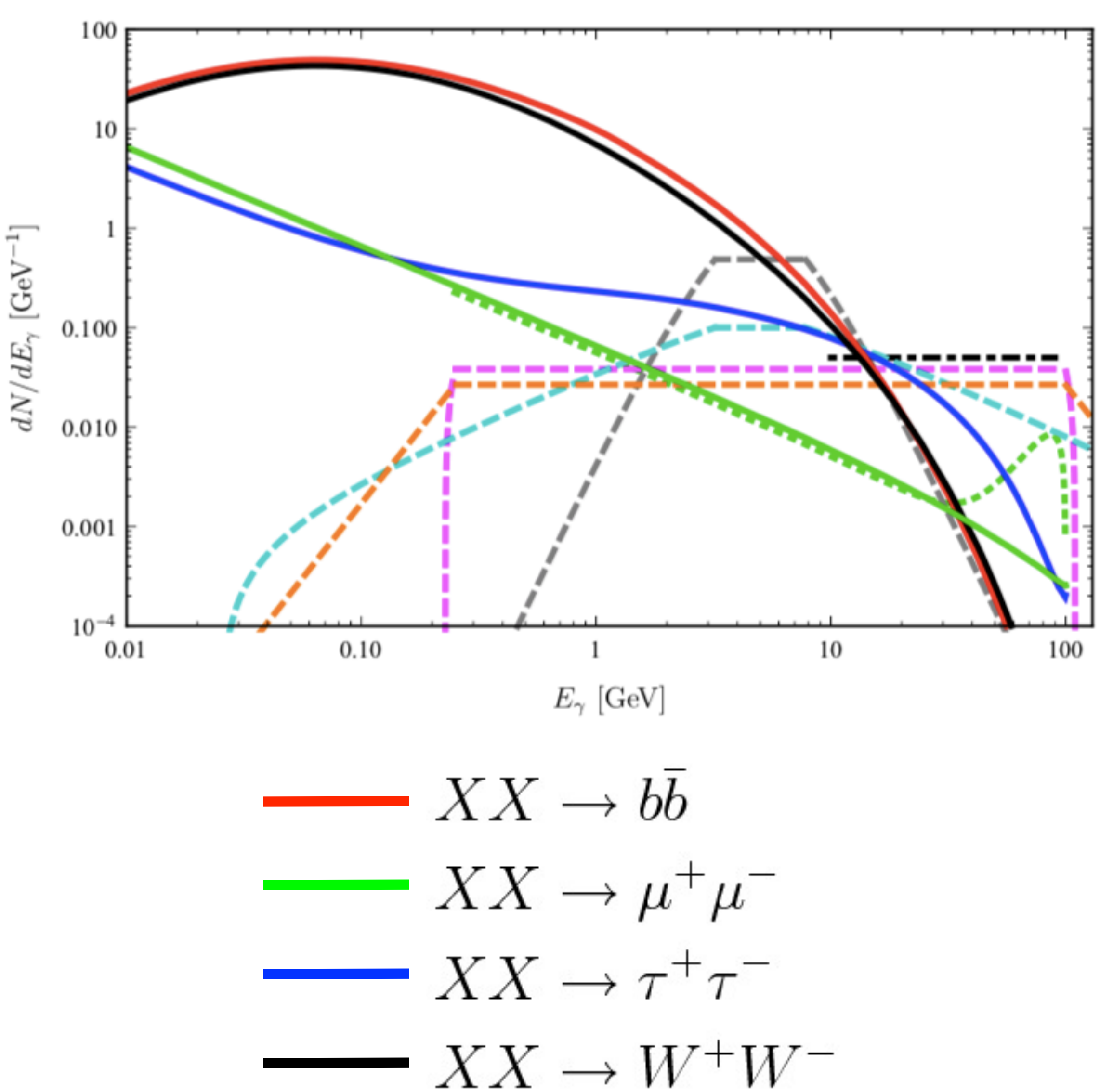




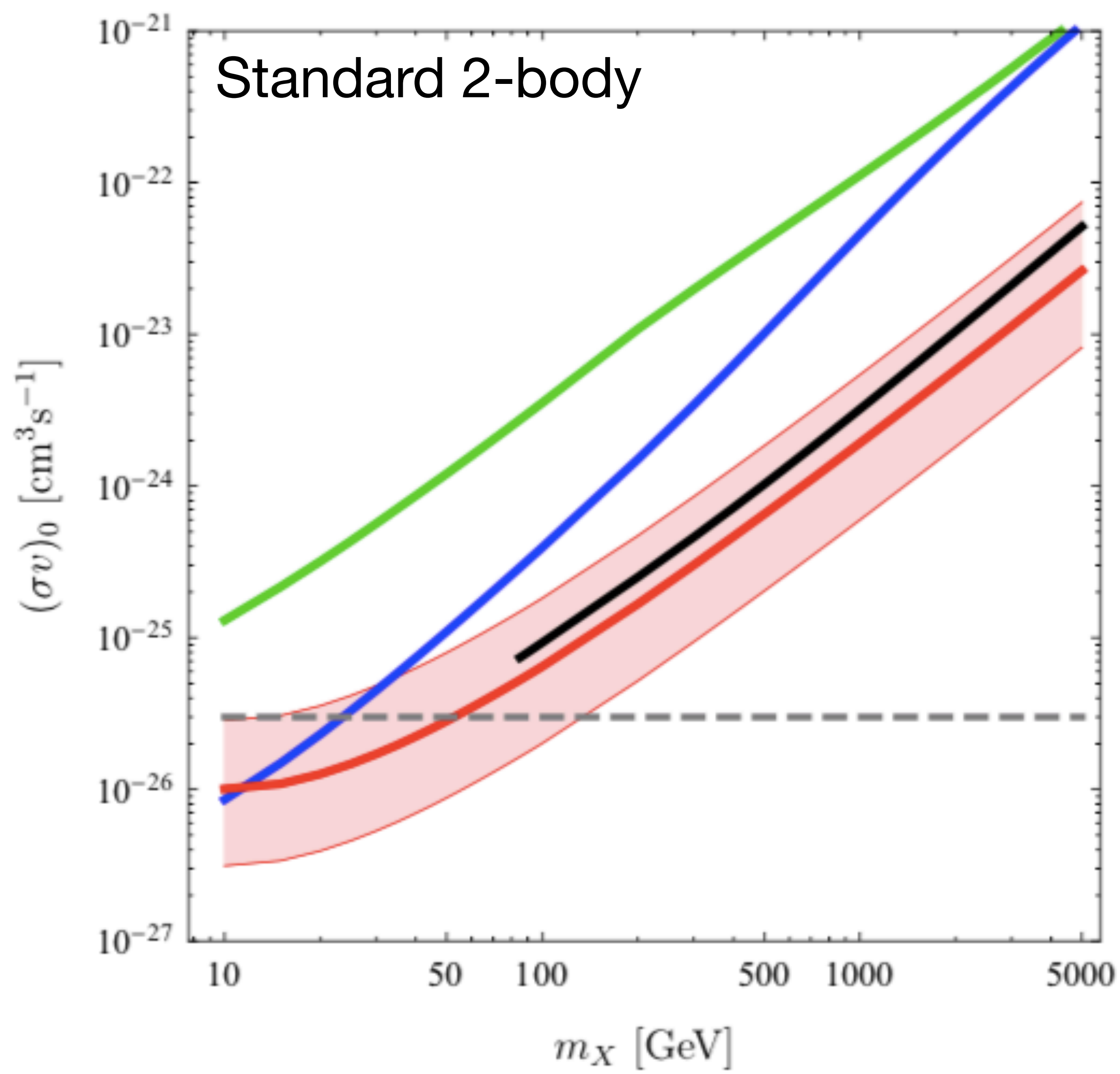
arXiv:1802.03826, 1910.02890

Results

- Constrain DM properties: $$\Phi_{\rm PP} = \frac{(\sigma v)_0}{8\pi m_X^2} \int_{E_{\rm th}}^{E_{\rm max}} dE_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{A_{\rm eff}(E_\gamma)}{\bar{A}_{\rm eff}}$$



arXiv:1012.4515



arXiv:1802.03826, 1910.02890

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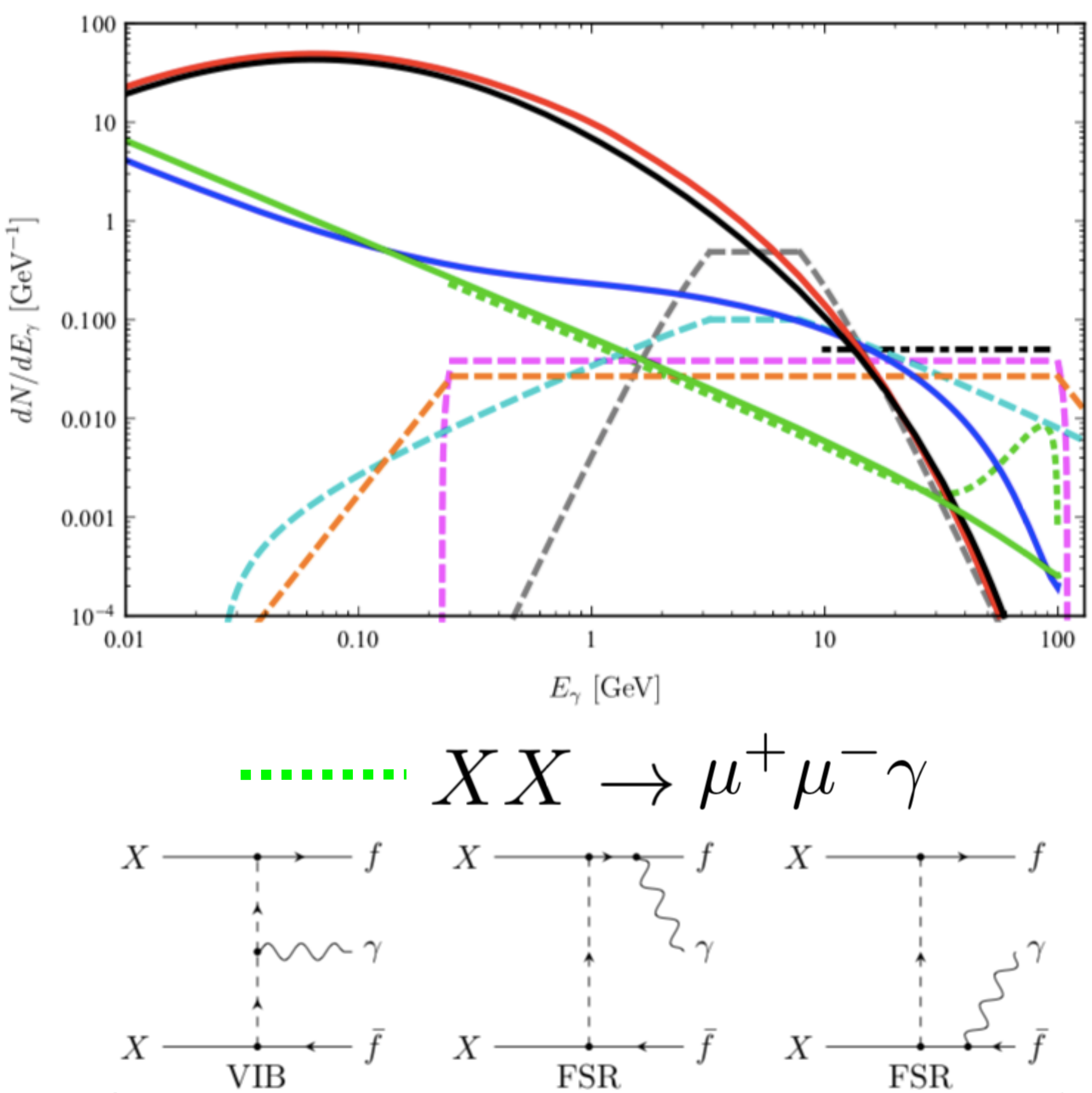
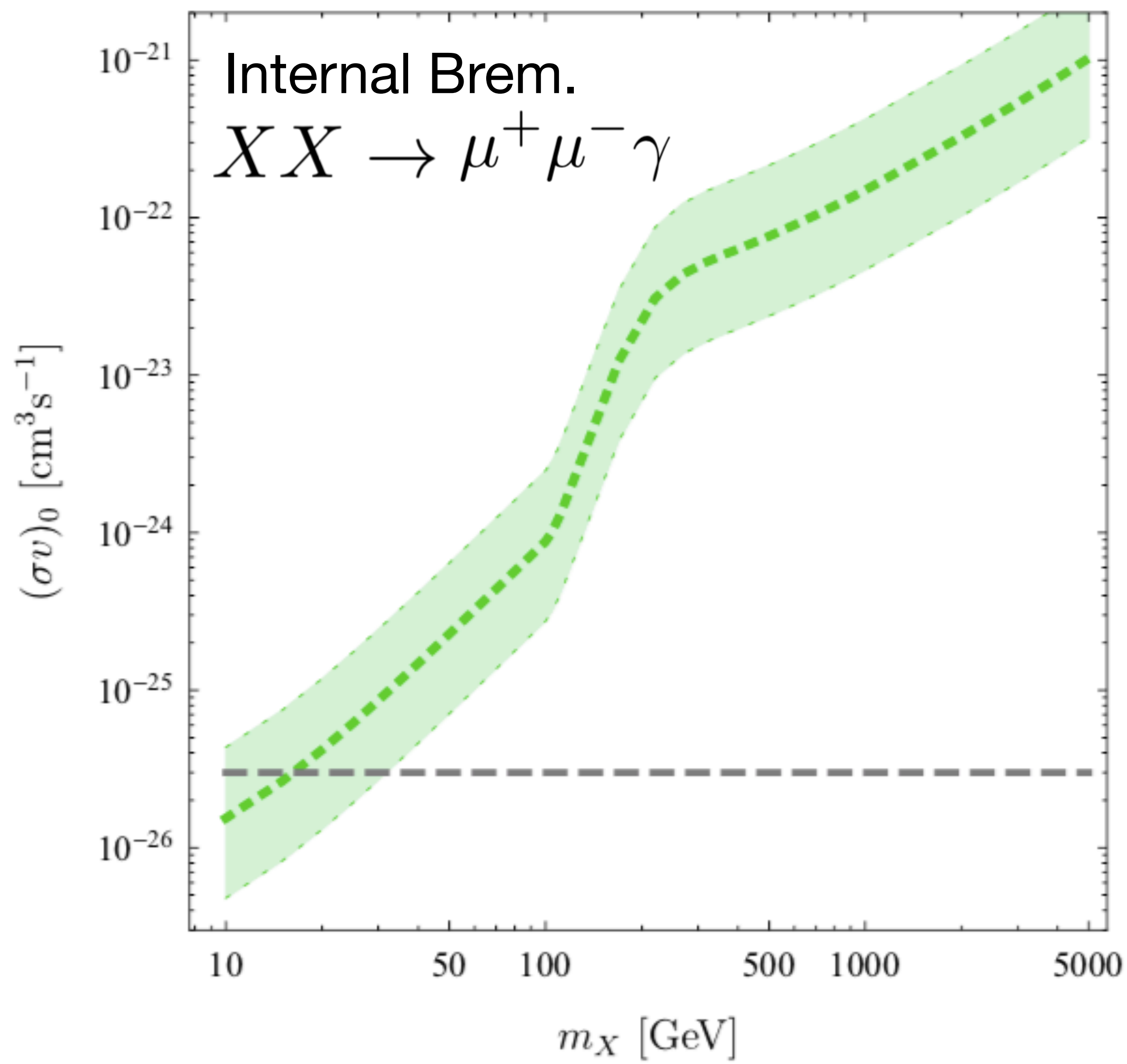


arXiv:1605.03224



P. Sandick

arXiv:1802.03826, 1910.02890

Results

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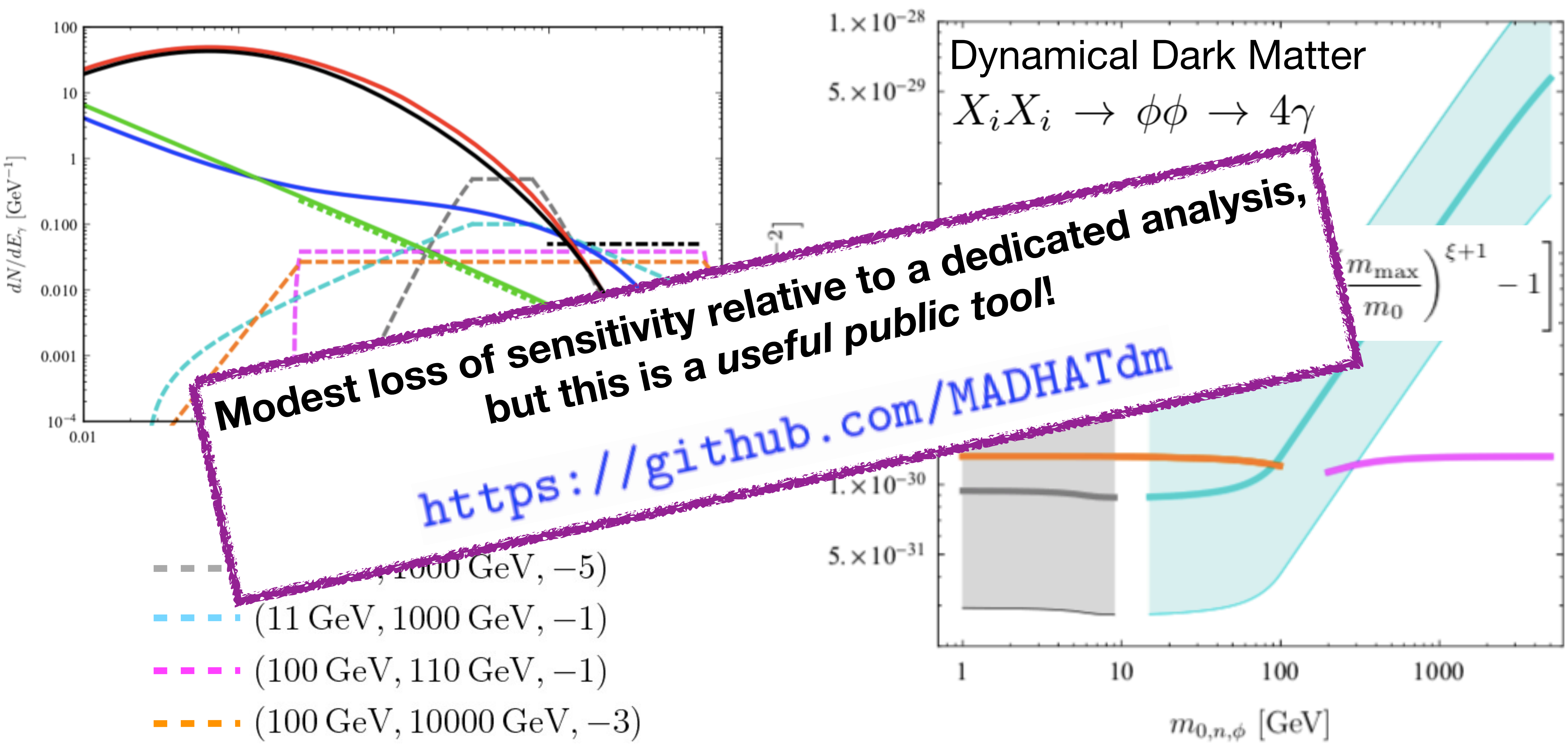


arXiv:1609.09104

P. Sandick

arXiv:1802.03826, 1910.02890

Candidates

- Weakly Interacting Massive Particles (WIMPs): neutralinos, LKP, LTP, …
- **Light bosons: Axions, Axion-Like Particles (ALPs), Fuzzy Dark Matter (FDM)**
- E-WIMPs/super-WIMPs/FIMPs: gravitino, axino, KK graviton
- Sterile neutrino
- Strongly Interacting Massive Particles (SIMPs)
- Asymmetric Dark Matter (ADM)
- WIMPzilla
- Primordial Black Hole (PBH)

Axions

- Strong CP Problem: QCD is observed to conserve CP, but CP violating operators are allowed. Why are they suppressed?
- $L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$ violates CP. Limit from neutron EDMs: $\theta < 10^{-9}$
- Peccei Quinn Mechanism (1977): Allows theta to be basically zero by promoting it to a field with a new global (PQ) symmetry.
- PQ symmetry is spontaneously broken at some scale f_a.
- Weinberg (1978) & Wilczek (1978): spontaneously broken symmetry means there must be a Goldstone boson! Axion.
- QCD vacuum effects: $m_a \approx \frac{f_\pi m_\pi}{f_a}$
- WMAP: $f_a < 3 \times 10^{11} \mathrm{GeV}$ and $m_a > 2.1 \times 10^{-5} \mathrm{eV}$ — Fox, Pierce, & Thomas (2004)
- Small mass??? Thermal production would result in hot axions, but several non-thermal production mechanisms yield cold axions that form a condensate at the QCD phase transition.

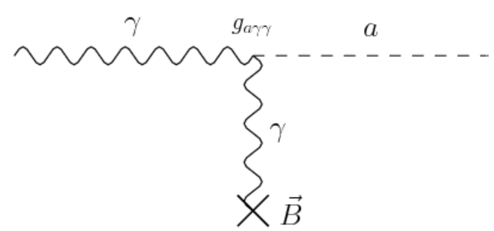
Axions, ALPS, and FDM.. Oh my!

- **QCD Axion** solves the strong CP problem.
- **Axion Like Particles (ALPs)** are scalars that behave similarly to the QCD axion, but might not solve the strong CP or DM problems.
- **Ultra-Light Axions (ULAs)** can be as light as 10^{-33} eV.
- **Fuzzy Dark Matter (FDM)** is a sort of generic term for ULAs/ALPs that contribute to DM. Preferred mass is near 10^{-22} eV, which has galaxy-scale deBroglie wavelength and therefore explains the cored profiles of galaxies.

Credit: Chanda Prescod-Weinstein

Detecting Axions

- Primakoff Effect



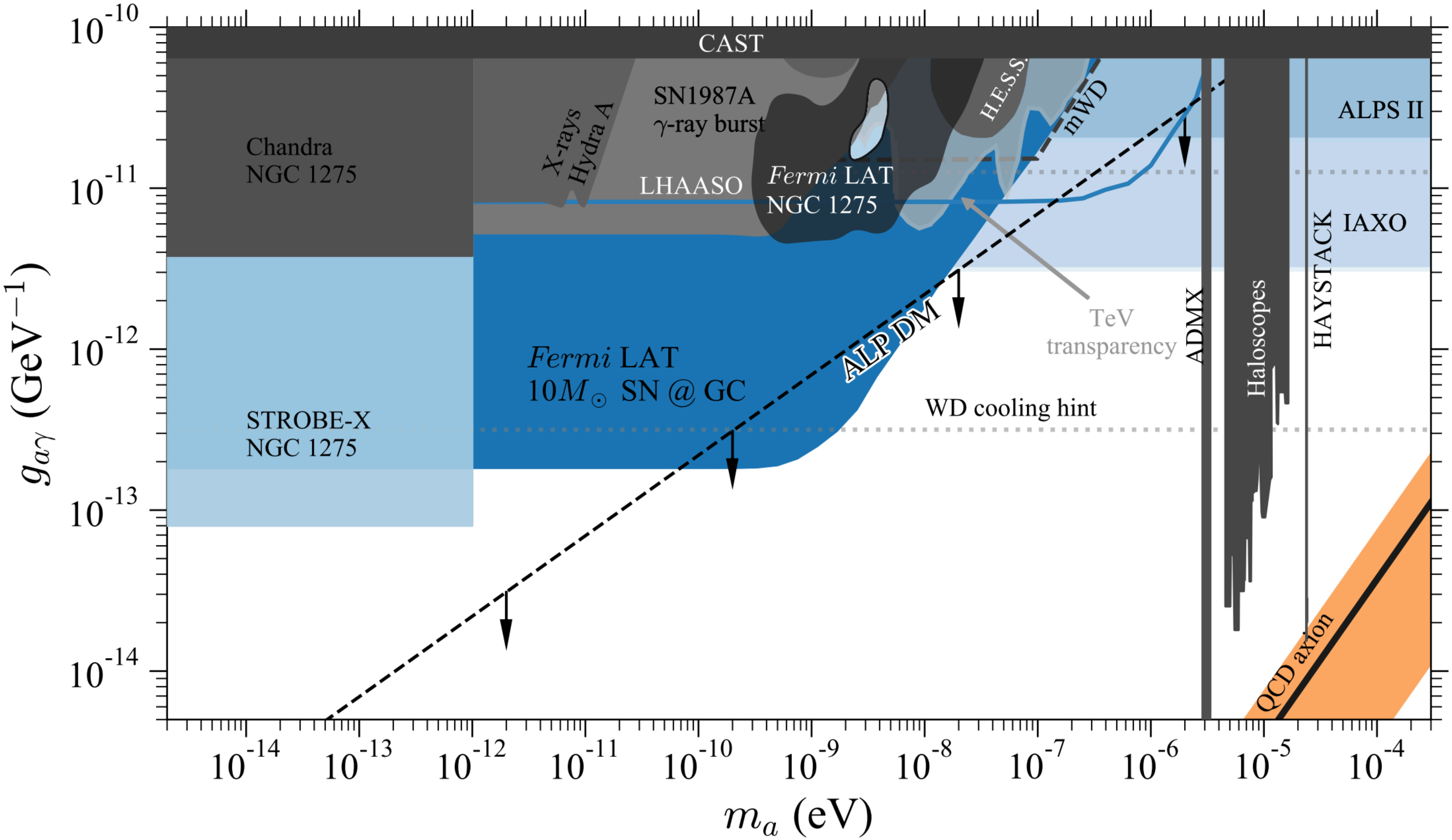
$$L_{a\gamma\gamma} = \underbrace{g_\gamma \frac{\alpha}{\pi} \frac{a(x)}{f_a}}_{g_{a\gamma\gamma}} \vec{E} \cdot \vec{B}$$

Note: for QCD axion, mass and coupling are not independent! But for generic ALP, they can be.

- Light through walls (ALPS)
  - Laser light is shined at a wall. Magnetic field: some photons converted to axions. Axions travel through wall. Magnetic field: some convert back to photons.
- Microwave cavity searches (ADMX)
  - Axions passing through cavity + magnetic field. Some convert to photons.
- Solar axion searches (CAST)
  - Photon converts to axion in sun, travels to Earth. Magnetic field: axion converts back to photon.
- Use astrophysical magnetic fields!

Axion Search Prospects

STROBE-X. arXiv:1903.03035



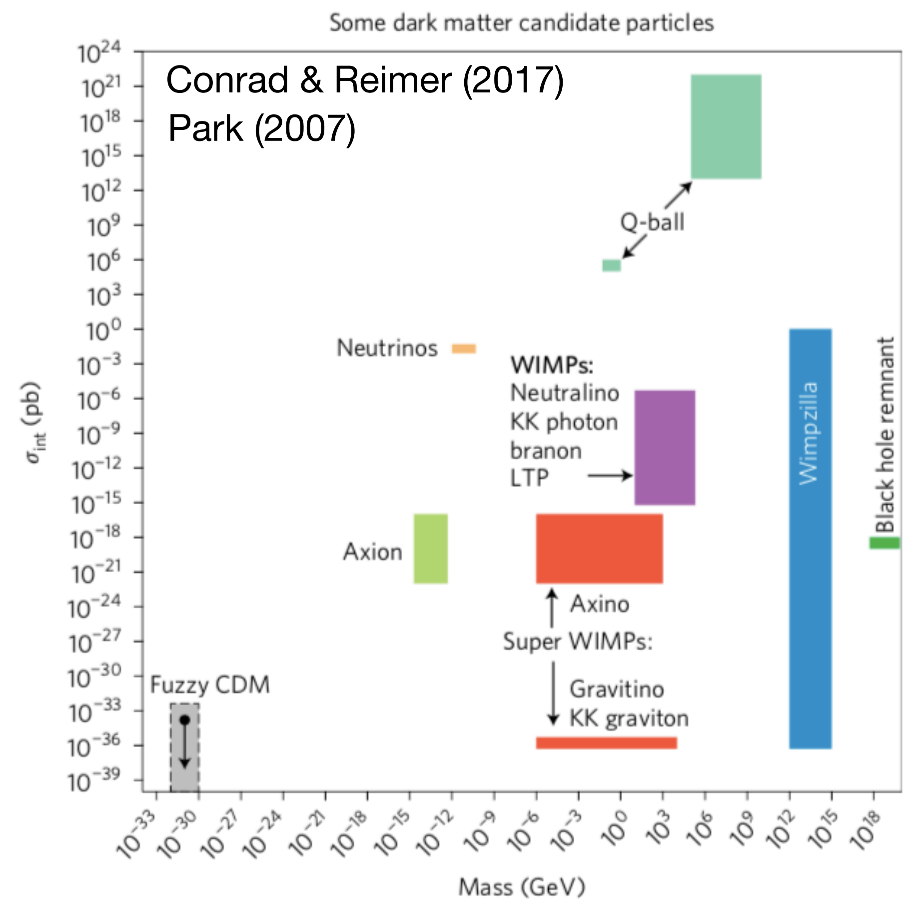
Break

Candidates

- Weakly Interacting Massive Particles (WIMPs): neutralinos, LKP, LTP…
- Light bosons: Axions, Axion-Like Particles (ALPs), Fuzzy Dark Matter (FDM)
- **E-WIMPs/super-WIMPs/FIMPs: gravitino, axino, KK graviton**
- Sterile neutrino
- Strongly Interacting Massive Particles (SIMPs)
- Asymmetric Dark Matter (ADM)
- WIMPzilla
- Primordial Black Hole (PBH)

E-WIMPs/Super-WIMPs/FIMPs

- Tiny interactions with SM particles
- Interaction scale with ordinary matter suppressed by a large mass scale.
  - gravitino: $M_{Pl} \sim 10^{19}$ GeV
  - axino: $f_a \sim 10^{11}$ GeV
  - Other candidates: KK graviton, sterile neutrinos…
  - Production: many possible mechanisms, including freeze-in



Axinos

- In supersymmetry, the axion is in a chiral multiplet with the saxion and axino:
$$\Phi_a = (s + \mathrm{i}a)/\sqrt{2} + \vartheta\tilde{a} + (F \text{ term})$$
- The axion gets its mass from QCD effects: $m_a \approx \frac{f_\pi m_\pi}{f_a}$
- Before SUSY breaking, axion multiplet is light (protected by PQ symmetry, so no susy mass parameter is allowed)
- SUSY breaking splits saxion and axino masses from the axion mass
    - $m_s \approx M_{SUSY}$ (saxion is not the LSP)
    - $m_{\tilde{a}}$ unconstrained! (could be LSP and DM)

Covi & Kim (2009) 0904.3218
Choi, Kim, & Roszkowski (2013) 1307.3330

Axino Dark Matter

- If the axino is the LSP, expect

$$\Omega_{a\tilde{a}}h^2 = \Omega_{\tilde{a}}^{NTP}h^2 + \Omega_{\tilde{a}}^{TP}h^2 + \Omega_a h^2$$

non-thermally produced axinos from NLSP decay

$$\tilde{\chi}_1 \to \tilde{a}\gamma$$

$$\Omega_{\tilde{a}}^{NTP}h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1}}\Omega_{\tilde{\chi}_1}h^2$$

thermally produced axinos from radiation off MSSM scattering processes

$$\Omega_{\tilde{a}}^{TP}h^2\,(g_s, f_a, N, m_{\tilde{a}}, T_R)$$

axions from vacuum misalignment mechanism

$$\Omega_a h^2 \approx \frac{1}{4}\left(\frac{f_a/N}{10^{12}\mathrm{GeV}}\right)^{7/6}\theta_i^2$$

- TP axinos are CDM for $m_{\tilde{a}} > 0.1\,\mathrm{MeV}$

- NTP axinos are WDM for $m_{\tilde{a}} < 1\,\mathrm{GeV}$ (but abundance is typically tiny)

Gravitino Dark Matter

- Like the axino, there are both thermal and non-thermal production mechanisms.

$$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{NTP} h^2 + \Omega_{\tilde{G}}^{TP} h^2$$

- NTP: $\Omega_{\tilde{G}}^{NTP} h^2 = \frac{m_{\tilde{G}}}{m_{\mathrm{NLSP}}} \Omega_{\mathrm{NLSP}} h^2$
    - Late decays (during/after BBN) are constrained, so this population is usually negligible.

- TP: Assuming the gravitino is sufficiently lighter than the other superpartners,

$$\Omega_{\tilde{G}}^{TP} h^2 \approx 0.3 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}} \right) \left(\frac{1\,\mathrm{GeV}}{m_{\tilde{G}}} \right) \sum_i c_i \left(\frac{M_i}{100\,\mathrm{GeV}} \right)^2$$

    - Interplay of reheat temperature and gravitino mass (also gaugino masses)
    - Superpartners likely beyond LHC reach, low reheat temperature (lower than that required by thermal leptogenesis)

- Gravitino DM could be stable or unstable (RPV)

Baer, Choi, Kim, & Roszkowski (2014) 1407.0017

Gravitino Masses

- The gravitino mass depends on how SUSY breaking is mediated:

SUSY breaking	Gravitino Mass	LSP?
Gravity mediation	100 GeV - few TeV	Maybe LSP
Anomaly mediation	10 TeV - 100 TeV	Not LSP
Gauge mediation	10 eV - 1 GeV	Probably LSP
Gaugino mediation	10 GeV - TeV	Maybe LSP

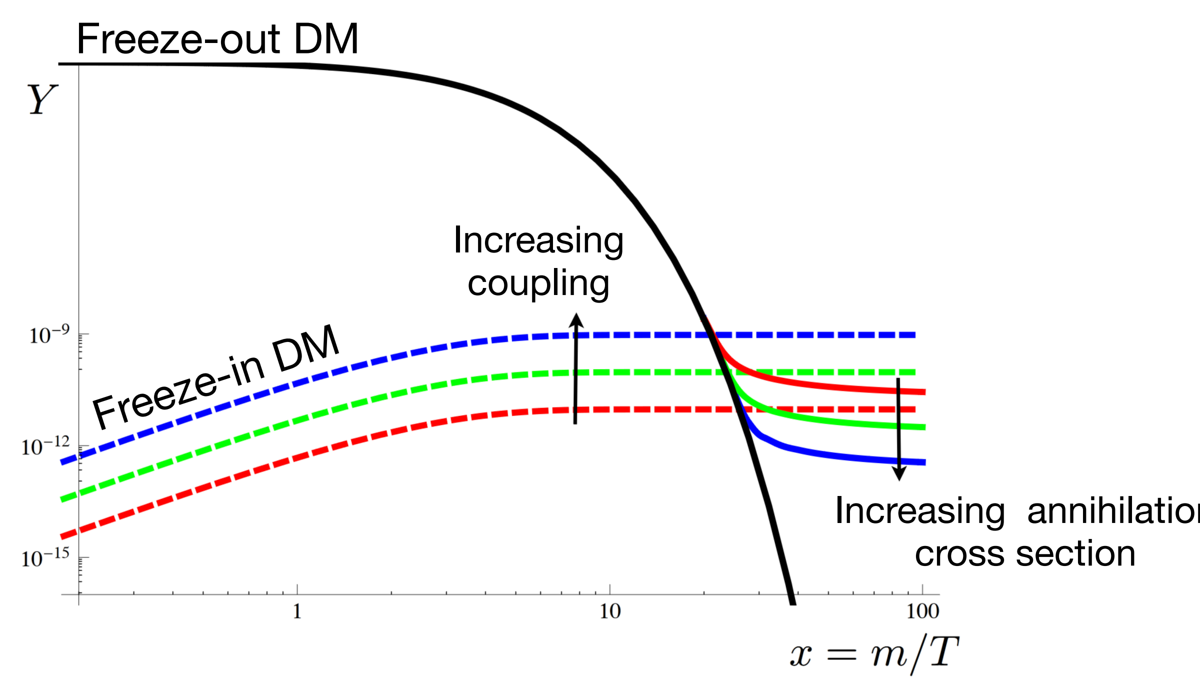
- Predictive power from fundamental theory

Freeze-In (for FIMPs)

- Collisional processes lead to production of out-of-equilibrium particles. Particles have extremely weak interactions, so once they're produced, they stick around.

1. Bath of SM particles at high T
2. SM particle interactions produce DM particles
3. Universe cools such that SM particles no longer have enough energy to produce heavier DM particles
    - **DM is "frozen-in"**

- Some differences from Freeze-out:
    - Larger coupling → more DM produced
    - Small initial thermal population



Hall, Jedamzic, March-Russell, & West (2009)

Detecting FIMPs

- Detection is challenging due to very weak interactions with SM, but there are still many possibilities!
- Could be produced during reheating after inflation, could impact BBN and CMB…
- Probed by low-threshold direct dark matter searches in the keV-MeV mass range
- Indirect signals from decay, or annihilation to an unstable light mediator ($\chi\chi \to \phi\phi$) that decays to SM particles
- Collider search for long-lived particles (eg. NLSP), anomalous scattering at fixed-target experiments, anomalous decays.
- Stars and supernovae

Bernal et al. (2017) 1706.07442

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- **Sterile neutrino**
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Sterile Neutrinos?

- SM (L-handed) neutrinos have masses, but because there are no R-handed neutrinos in the SM, there is no consistent way to write a term that gives them mass.

- Simple solution: add R-handed neutrinos, which are gauge singlet fermions, with Majorana mass M_{RH}, that interact with the corresponding LH neutrinos through a Yukawa term with coupling y_ν. After mixing, for M_{RH} large enough, the light (mostly LH) neutrinos will get a mass eigenvalue of

$$m_\nu \sim \frac{y_\nu^2 v_0^2}{M_{RH}}$$

  - Note: typical M_{RH} values are 10^{15} - 10^{16} GeV, but there are ways to get it much smaller.

  - Note: all other SM fermions are observed with both chiralities.

- There are other solutions besides this one (Minimal Type 1 Seesaw). Point is that adding RH neutrinos is reasonable.

- If RH (sterile) neutrinos are light (keV mass range) and not too strongly mixed with LH (active) neutrinos, they can be the DM.

Sterile Neutrino DM

- **O(keV) masses** are viable, though if sterile neutrinos are more decoupled from the SM then they can be much heavier.

- Sterile does not mean *completely* sterile - interactions with SM particles happen via mixing with active neutrinos, or may arise through new gauge interactions at high energies.

  - Sterile neutrinos have extremely weak interactions, so were never in thermal equilibrium in the early Universe

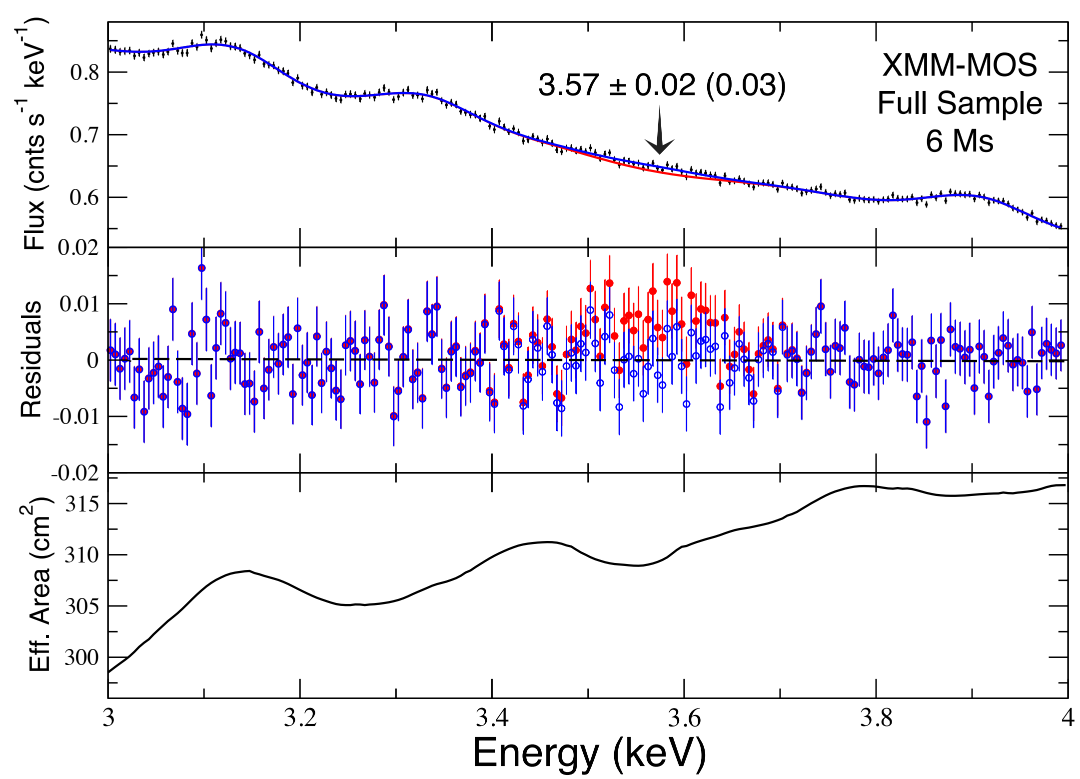
  - Possible production mechanisms: Freeze-in, oscillate-in (Dodelson-Widrow or Fuller-Shi), decays of heavy bosons… (all model-dependent)

- Not stable, but very long-lived (related to active-sterile mixing) - can have lifetimes longer than the age of the Universe

Boyarsky et al. (2018)

Sterile Neutrino DM

- Main decay mode is to 3 neutrinos
- More important (for observations) decay mode is $N \to \nu\gamma$
    - Monochromatic photon line signal at $E_\gamma \approx m_N/2$
- Anomalous emission at 3.5 keV observed in
    - Andromeda, Perseus, stacked clusters [Boyarsky et al. (2014)] and [Bulbul et al. (2014)]
  - Since observed in many galaxies and clusters
  - **Decaying 7 keV sterile neutrino DM?**
  - NOT observed in all targets where you'd expect to see it if it were DM. E.g. Draco, Milky Way halo [Dessert, Rodd, Safdi (2020)]
  - Additional observations will tell…



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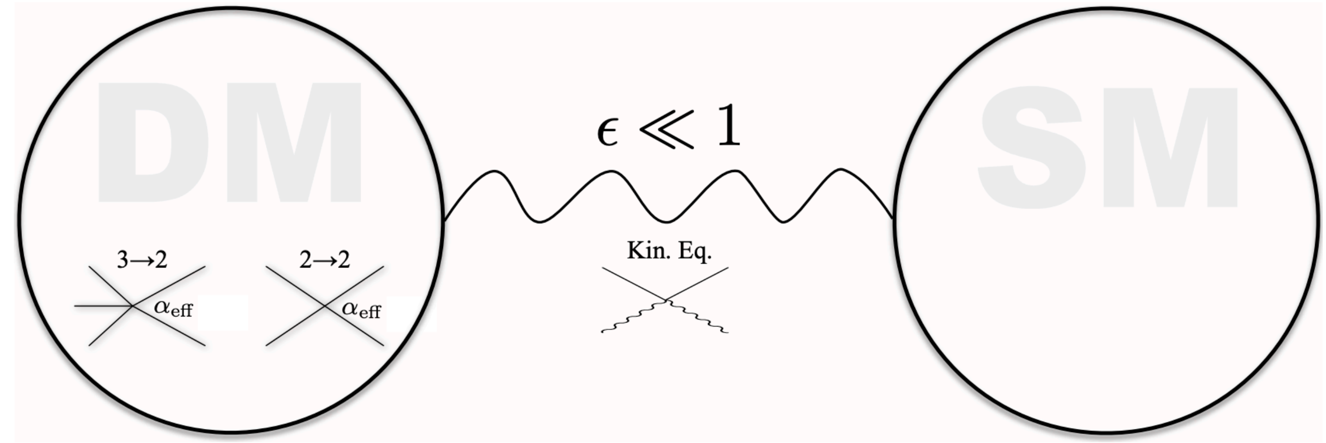
SIMP DM

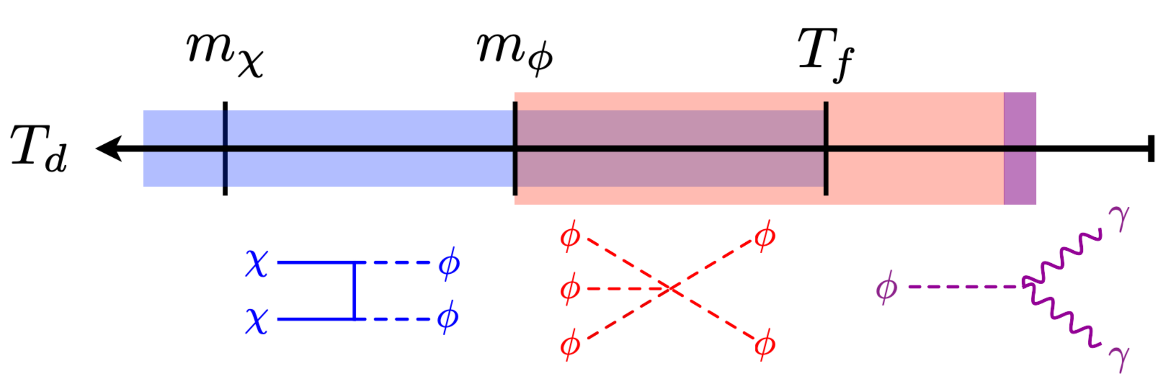


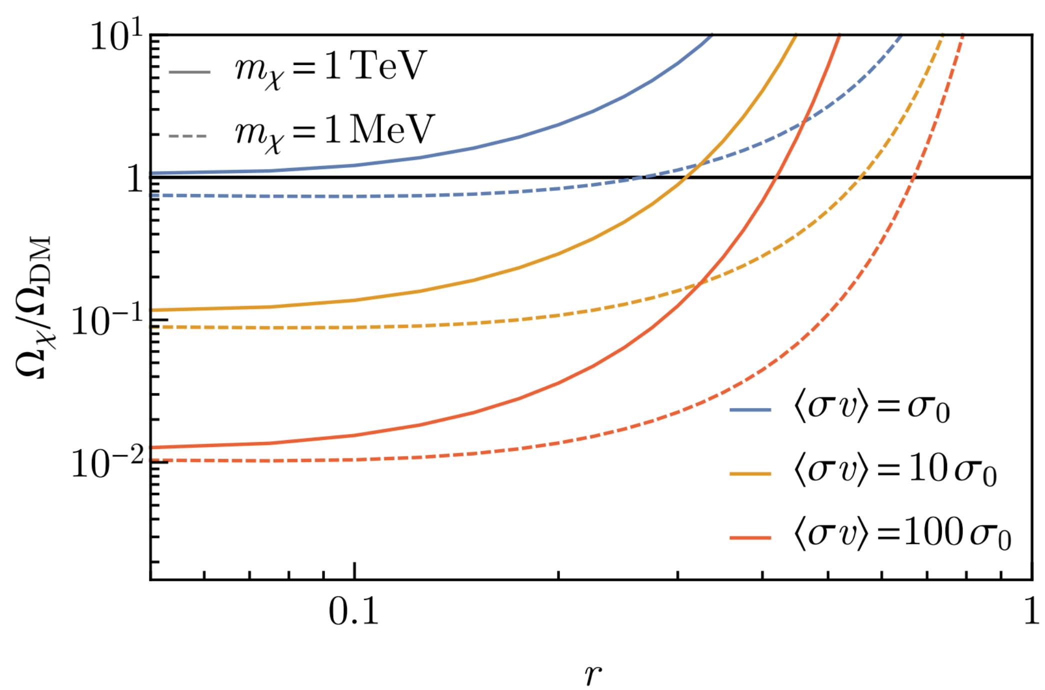
- Strongly Interacting Massive Particles (SIMPs)
- DM is feebly-coupled to the SM, but **strongly-coupled to itself**
    - 2DM → 2SM annihilations are suppressed (negligible compared to DM number-changing processes)
    - 2DM → 2DM interactions don't change the DM number density
    - 3DM → 2DM or 4DM → 2DM interactions decrease the DM abundance
- 3→2 mechanism leads to **m_{DM} below 1 GeV**
- 4→2 mechanism leads to **m_{DM} in the keV to MeV range**
- Small coupling to SM allows heat transfer (rather than DM heating up as number is reduced)
- Consequences for structure formation, and interesting direct and indirect detection prospects

Hochberg, Kuflik, Volansky, Wacker (2014)

SIMPs and Cannibals

- SIMPs are in thermal equilibrium with radiation, allowing heat transfer
- **Cannibal DM**: dark sector is decoupled from radiation
    - Temperatures scale as $T_\gamma \propto 1/a$ and $T_d \sim 1/\log a$
    - 3→2 processes heat up dark sector while the universe is expanding, so the dark sector temperature stays relatively constant (SM particles become exponentially colder than dark sector)
    - Relic abundance is largely set by freeze-out of 2→2 annihilations of DM to a metastable state, while 3→2 cannibalism maintains chemical equilibrium until decoupling or metastable lifetime





$$r = \frac{m_\phi}{m_\chi}$$

$$\sigma_0 = 3 \times 10^{-26}\,\frac{\mathrm{cm}^3}{s}$$

Carlson, Machacek, & Hall (1992)
Pappadopulo, Ruderman, & Trevisan (2016)

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Asymmetric DM

	Baryons	**Dark Matter**
Mass	$m_N \approx 1\,\mathrm{GeV}$	??
Number Density	$n_b/n_\gamma \approx 6 \times 10^{-10}$ not thermally produced	??
Abundance	$\Omega_b \approx 0.049$	$\Omega_{\mathrm{DM}} \approx 0.26$

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_b} \approx 5$$

Is DM like baryons?

Credit: Mattias Blennow

Asymmetric DM

	Baryons	Dark Matter
Mass	$m_N \approx 1\,\mathrm{GeV}$	??
Number Density	$n_b/n_\gamma \approx 6 \times 10^{-10}$ not thermally produced	??
Abundance	$\Omega_b \approx 0.049$	$\Omega_{\mathrm{DM}} \approx 0.26$
	Dirac Fermions	Dirac Fermions
	Abundance tied to baryon number, B	DM number, X
	Asymmetry seeded in early Universe	X related to B

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_b} \approx 5$$

Is DM like baryons?

Now DM and baryons would have similar number densities, so

$$\frac{m_{\mathrm{DM}}}{m_b} \approx \frac{\Omega_{\mathrm{DM}}}{\Omega_b} \approx 5$$

Credit: Mattias Blennow

Asymmetric DM

- DM-antiDM asymmetry may or may not be related to the baryon-antibaryon asymmetry.

- Asymmetry could be *transferred* or *generated*.

1. Electroweak sphalerons
2. Higher dimension and renormalizable interactions

1. Simultaneous generation = ***cogenesis***
   - Modifications to baryo- or lepto-gesis that incorporate generating a DM asymmetry
2. Asymmetry generation in the dark sector, then communication via a transfer mechanism = ***darkogenesis***

- Wide range of models, wide range of phenomenological implications for dark matter detection and cosmology.

Zurek (2013) 1308.0338

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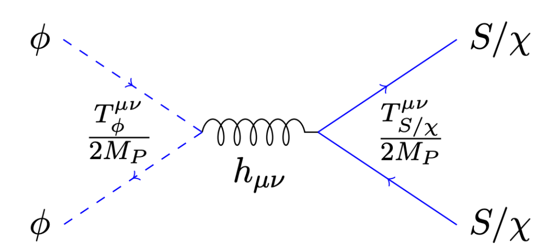
WIMPwhat?

- **WIMPzilla** = “superheavy” dark matter
  - Not thermally produced, not weakly interacting, but very massive
- Maximum WIMP mass is O(100) TeV
- Freeze-in can be an effective production mechanism for heavier DM with a small SM coupling (FIMP)
- Superheavy DM can be produced purely *gravitationally*
  - Mass range: ~ 10^8 - 10^{18} GeV (related to inflaton mass and reheating temp)
- Production mechanisms:
  - Gravitational particle creation $\mathcal{L} = \frac{1}{2M_P} h_{\mu\nu} T^{\mu\nu}_{\phi} + \frac{1}{2M_P} h_{\mu\nu} T^{\mu\nu}_{S/\chi}$



  - During reheating (at the end of inflation through inflation decay) or preheating (through inflaton field oscillations)
  - In bubble collisions in a 1st order phase transition that completes inflation
- We’ve already seen some: heavy gravitinos produced during reheating would be considered WIMPzillas
- Detection prospects? Low number density makes this challenging. Neutrino experiments could be sensitive to decays.

Kolb, Chung, & Riotto (1998) 9810361

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PBH Formation

- Proposed in the 60's, studied extensively by Hawking and others in the 70s
- Primordial Black Holes (PBHs) formed in the very early universe
- Various mechanisms:
    - collapse of large density perturbations
    - collapse of cosmic string loops
    - bubble collisions
    - …
- Can happen during a radiation- or (early) matter-dominated era
- Possible that PBHs themselves come to dominate the energy density of the universe

- Formation requires increased energy density at early times → connection between PBH mass and horizon mass at formation

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

    - Planck time → 10^{-5} g (Planck mass)
    - 1 second → 10^5 m_sun
- Formation over a long time period means a range of masses at formation.
- Dimensionless initial energy density in PBHs (at formation time t_i):

$$\beta(M) \equiv \frac{M\, n_{\mathrm{PBH}}(t_i)}{\rho(t_i)}$$

(P)BH Properties

"Black holes have no hair." -John Archibald Wheeler

- Mass (M) — Schwarzschild
  - Spin ($a^*=L/M^2$) — Kerr ("astrophysical")
  - Charge (Q) — Reissner-Nordström

Kerr-Newman

NASA/ESA and G. Bacon (STScI)

PBH Evaporation

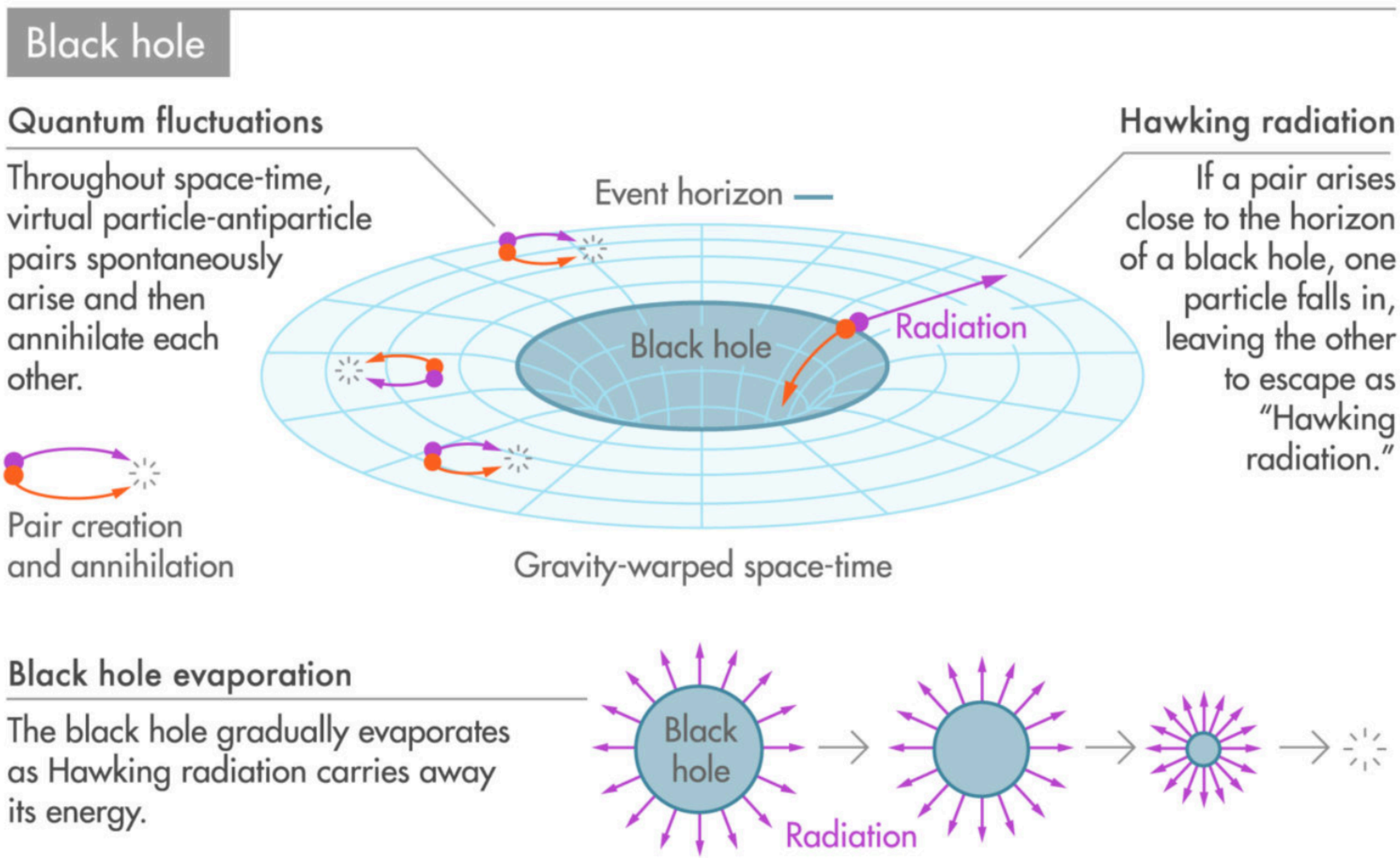


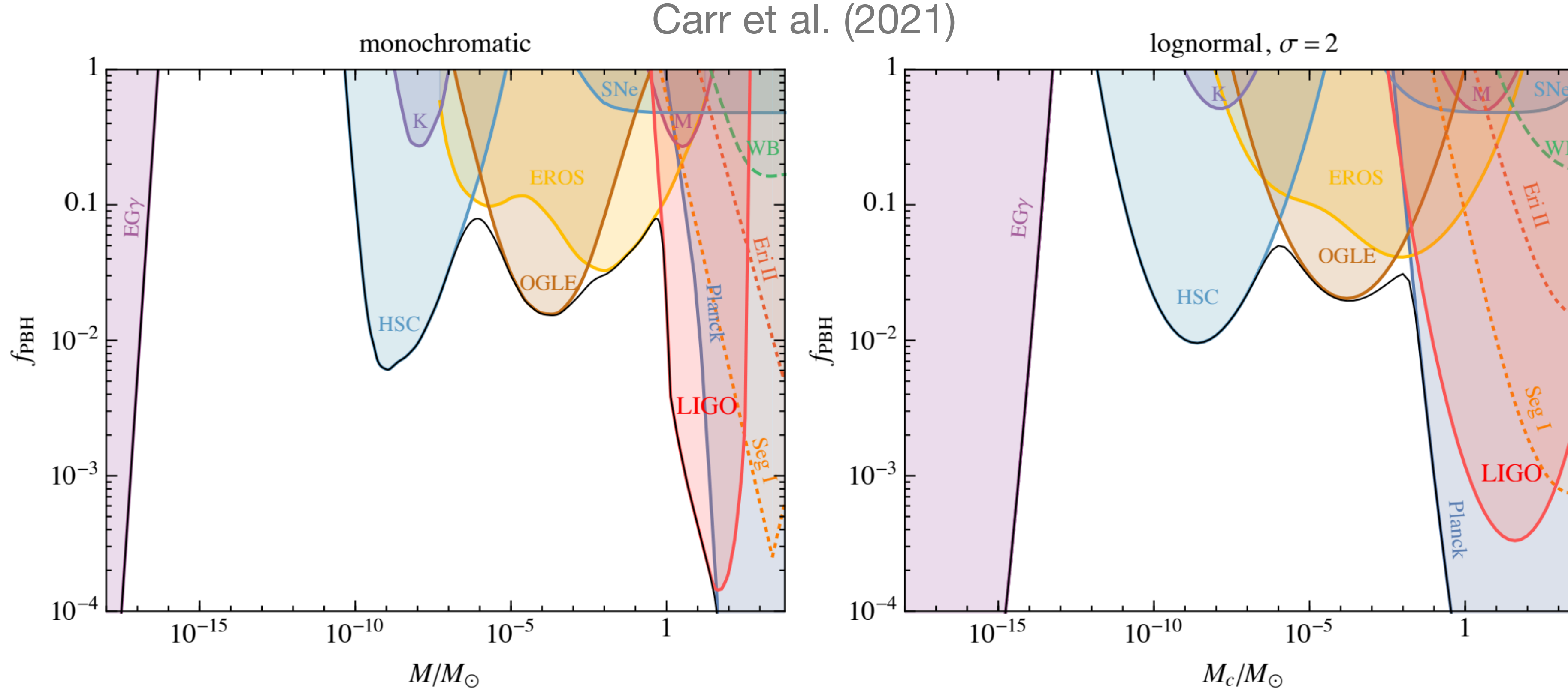
Image: Lucy Reading-Ikkanda for Quanta Magazine

PBH Evaporation

- Black Holes evaporate through continuous emission of degrees of freedom, losing mass and angular momentum.
    - Lifetime = time required to evaporate
- **Low Mass range**: 10^{-5} g - 10^{-1} g - 10^{9} g
    - Mass range defined by CMB and BBN. These are not the dark matter, but they are important to the dark matter story.
- **High Mass range**: 10^{16} g (asteroid mass) - 10^{24} g (sublunar)
    - Still around today
    - DM candidates
    - Monochromatic mass function?

        ➡ asteroid mass
- Other masses possible if mass function is not monochromatic

Carr et al. (2021)



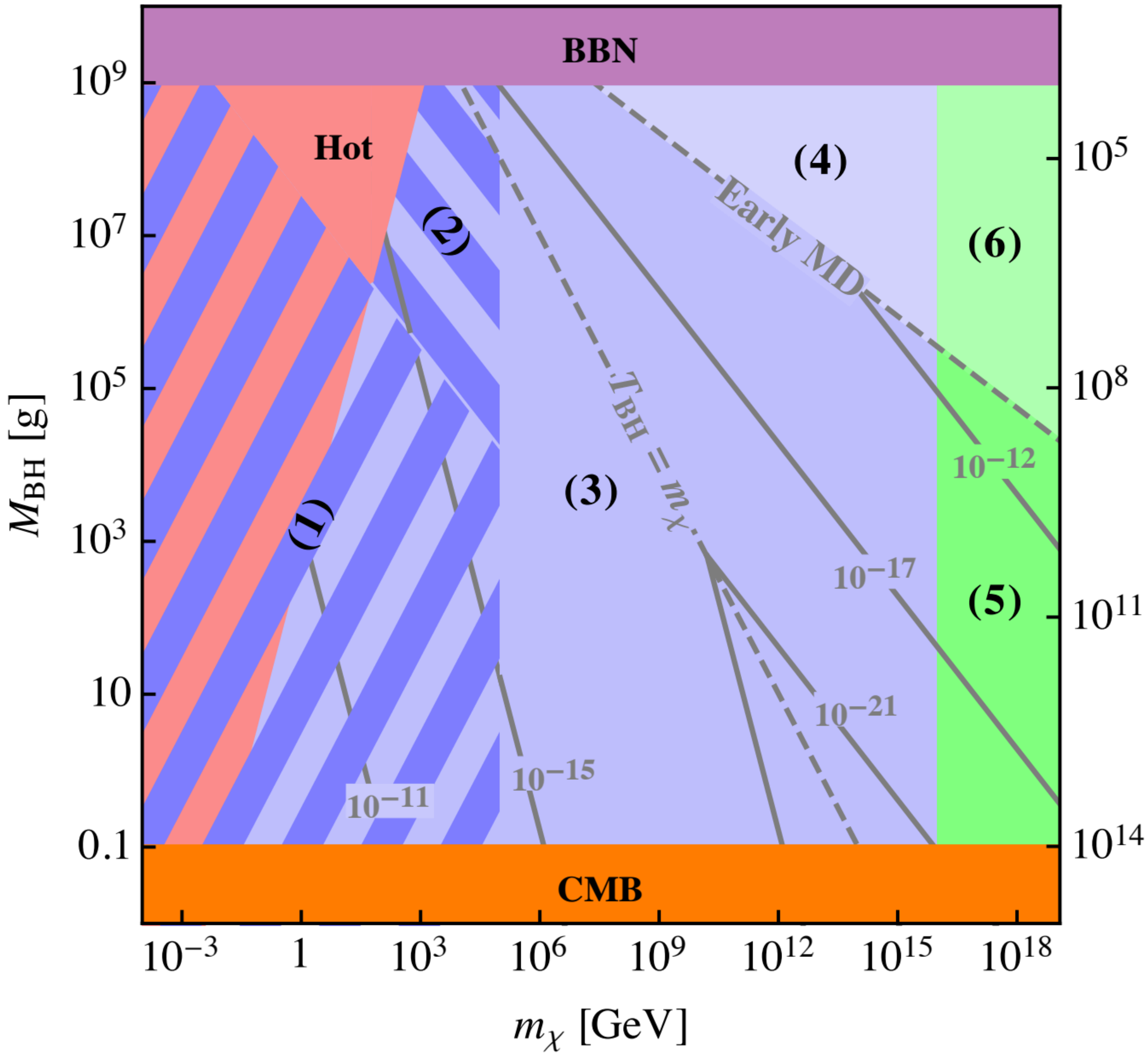
PBH Evaporation and Dark Matter

- If PBHs evaporate after the abundance of DM is set by another mechanism, PBH evaporation will provide a second inevitable contribution to the DM abundance.

	PBH evap. *before* DM production	**PBH evap. *after* DM production**
• **Freeze-out production** • WIMPs: 2-2 annihilation • SIMPs: 3-2 self-annihilation • Stronger interactions lead to less DM	no effect on DM abundance	extra source of DM
• **Freeze-in production** • e.g. FIMPs: produced via decay, scattering, or pair production • Weaker interactions lead to less DM	extra source of DM	extra source of DM
• **Gravitational production** • e.g. WIMPzilla: particle creation by the expansion of the universe acting on quantum fluctuations of the vacuum (also many other mechanisms)	extra source of DM	extra source of DM

Gondolo, Sandick, & Shams Es Haghi (2020)

Results



Sources of Dark Matter:

(1): freeze−out only

(2): freeze−out and/or PBH

(3): freeze−in and/or PBH

(4): freeze−in required plus PBH

(5): WIMPZILLA and/or PBH

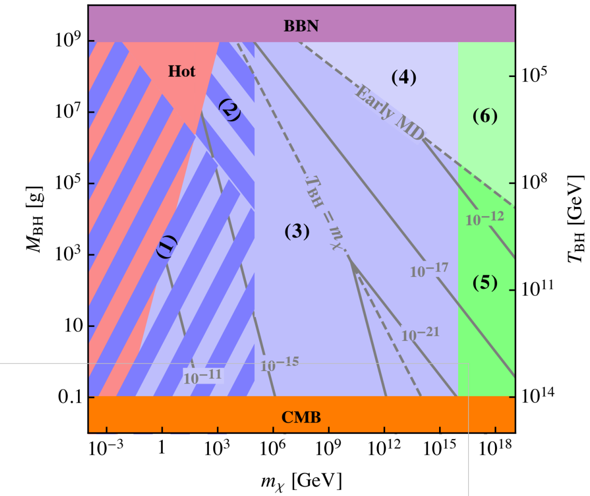
(6): WIMPZILLA required plus PBH

Note: effect depends on energy density in PBHs:

$$\beta(M) \equiv \frac{M\, n_{\rm PBH}(t_i)}{\rho(t_i)}$$

Gondolo, Sandick, & Shams Es Haghi (2020)

PBH evaporation and DM models



Summary

	PBH evap. *before* DM production	PBH evap. *after* DM production	DM Properties?
Freeze-out	no effect on DM abundance	extra source of DM	If there is an extra DM source, larger annihilation cross sections are consistent (improved detection prospects).
Freeze-in or Gravitational Production, **no EMDE**	extra source of DM	extra source of DM	Less DM needed from other production mechanism (even feebler couplings are viable).
Freeze-in or Gravitational Production, **EMDE**	extra source of DM	extra source of DM	Amount of DM produced by PBHs is independent of PBH abundance. Definitely need second production mechanism (PBHs can't do it alone).

Important to understand **interplay** of PBHs and other sources/production mechanisms for dark matter

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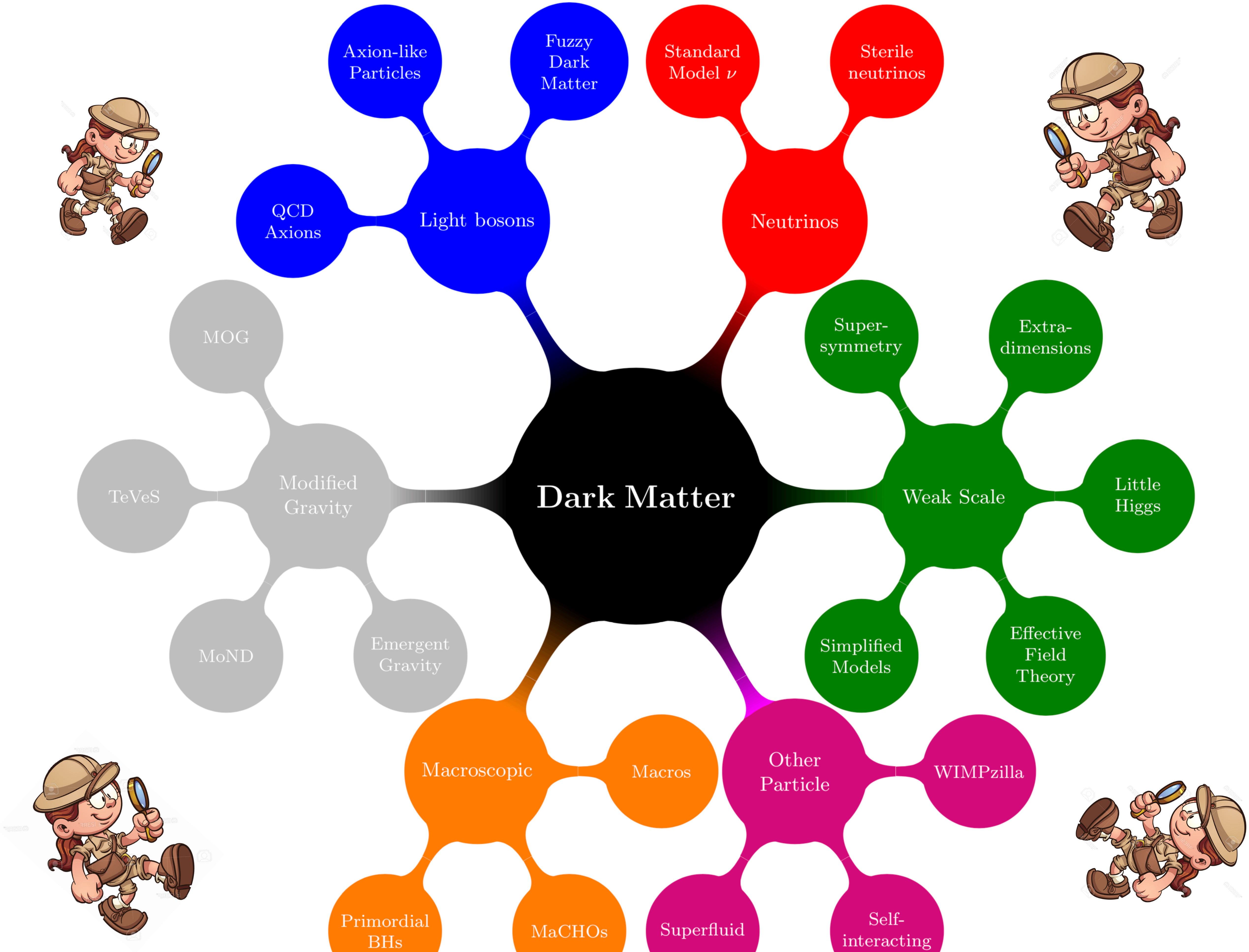

Bertone and Tait (2018)