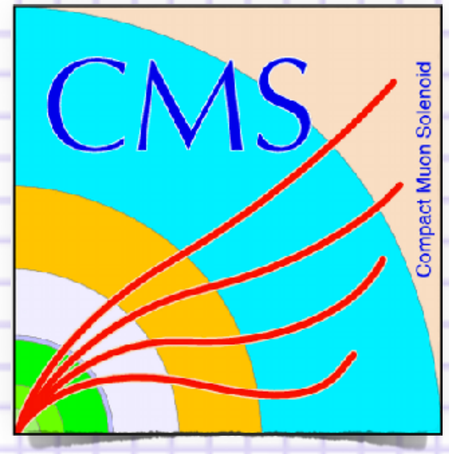
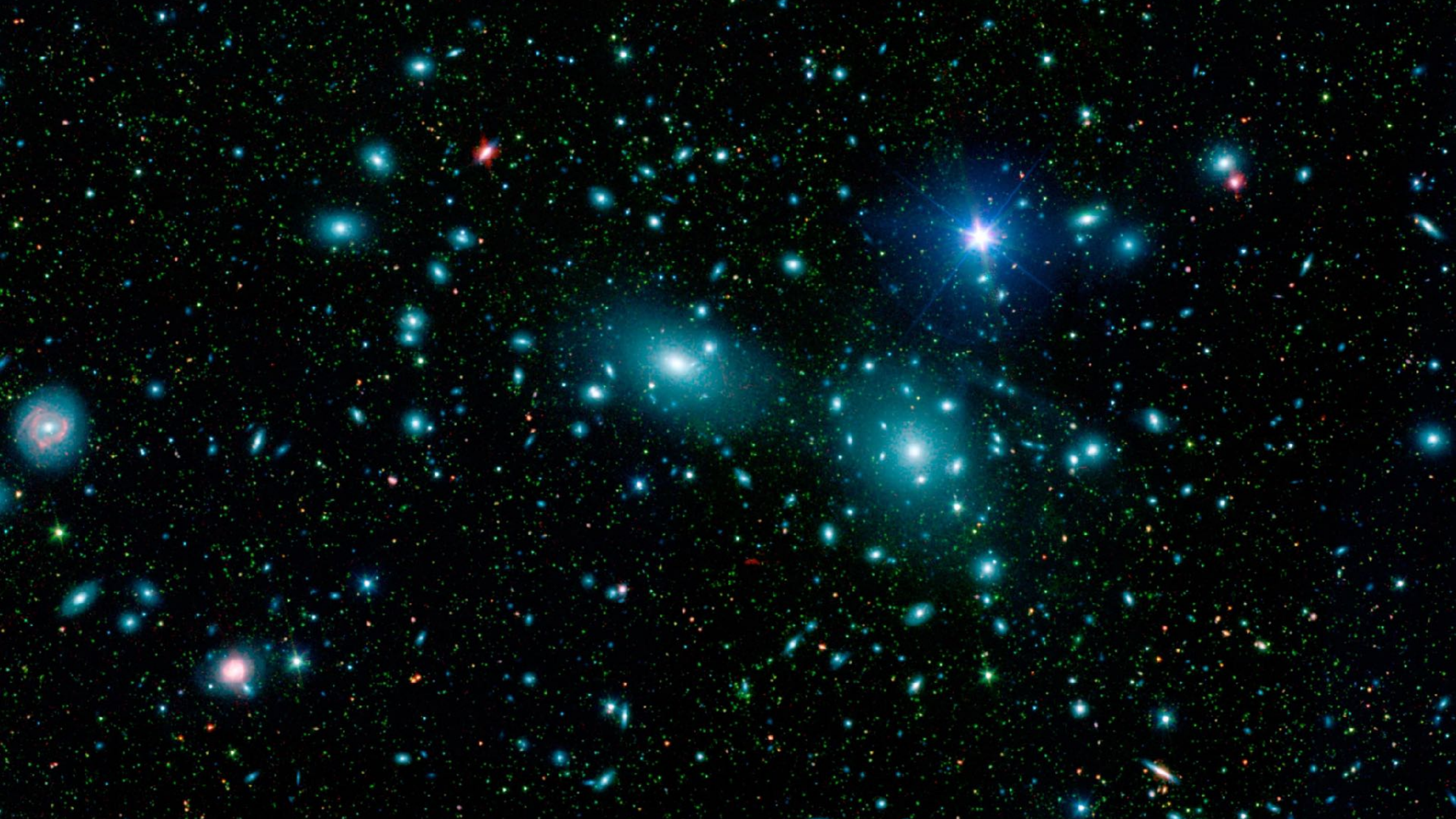
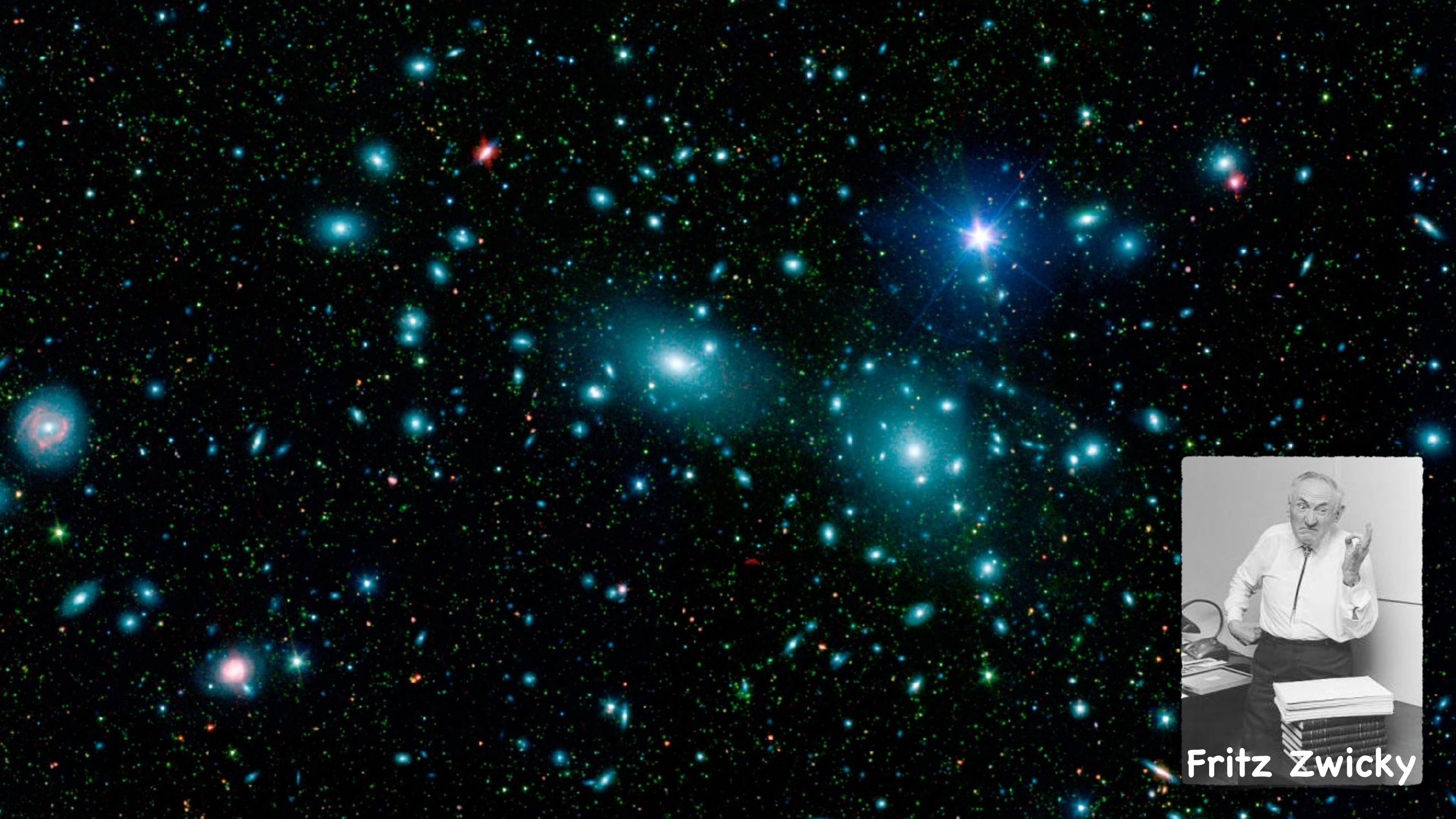
Search for Dark Matter and Supersymmetry at CMS

Carsten Hensel (CBPF) for the CMS Collaboration






Fritz Zwicky

Outline

01 The Case for Dark Matter

02 Model-dependent DM Searches: SUSY

'Model-independent' DM searches

03 Outlook / Summary

Evidence for Dark Matter

Evidence for Dark Matter

Rotational Curves

1970 Vera Rubin

Evidence for Dark Matter

Rotational Curv

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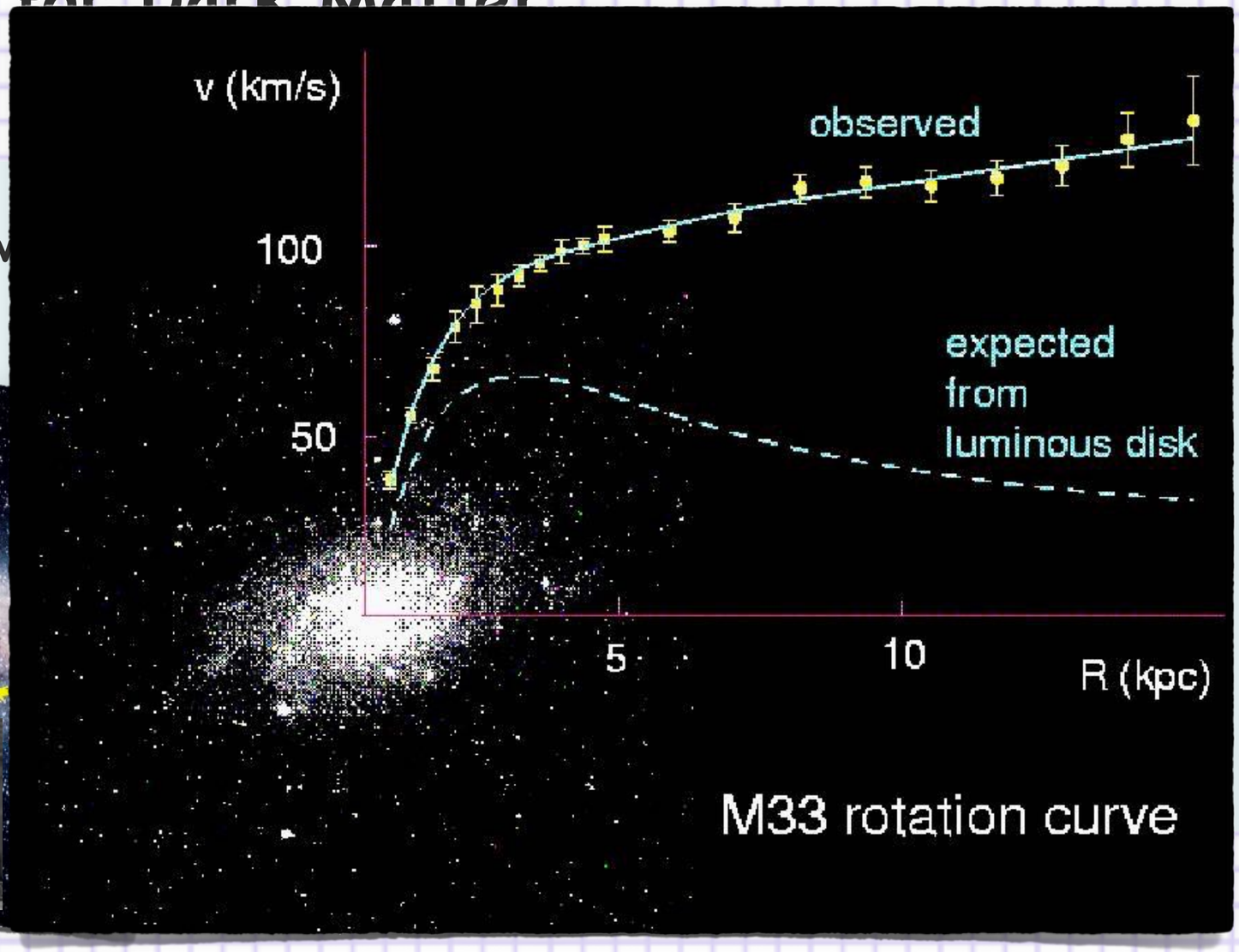

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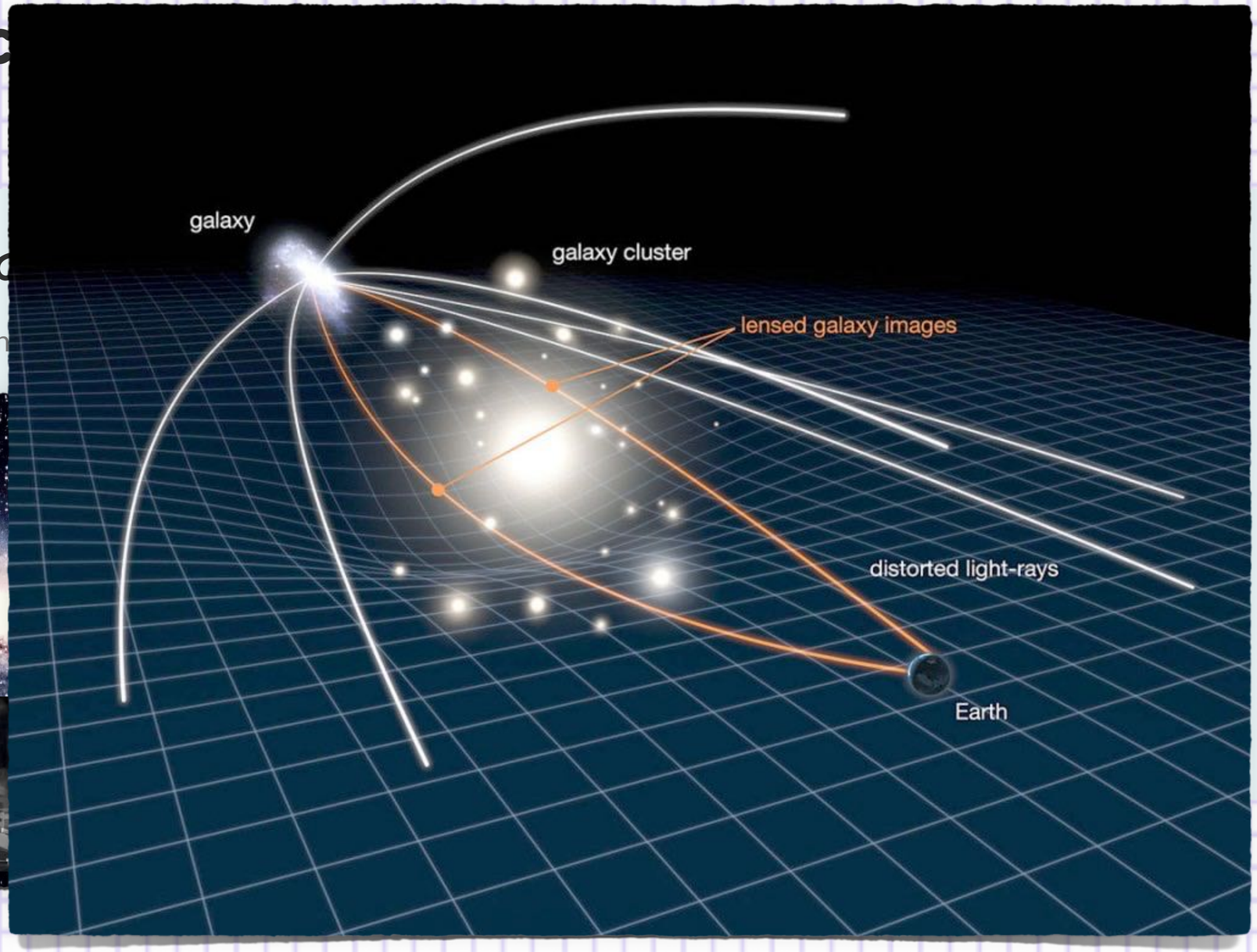

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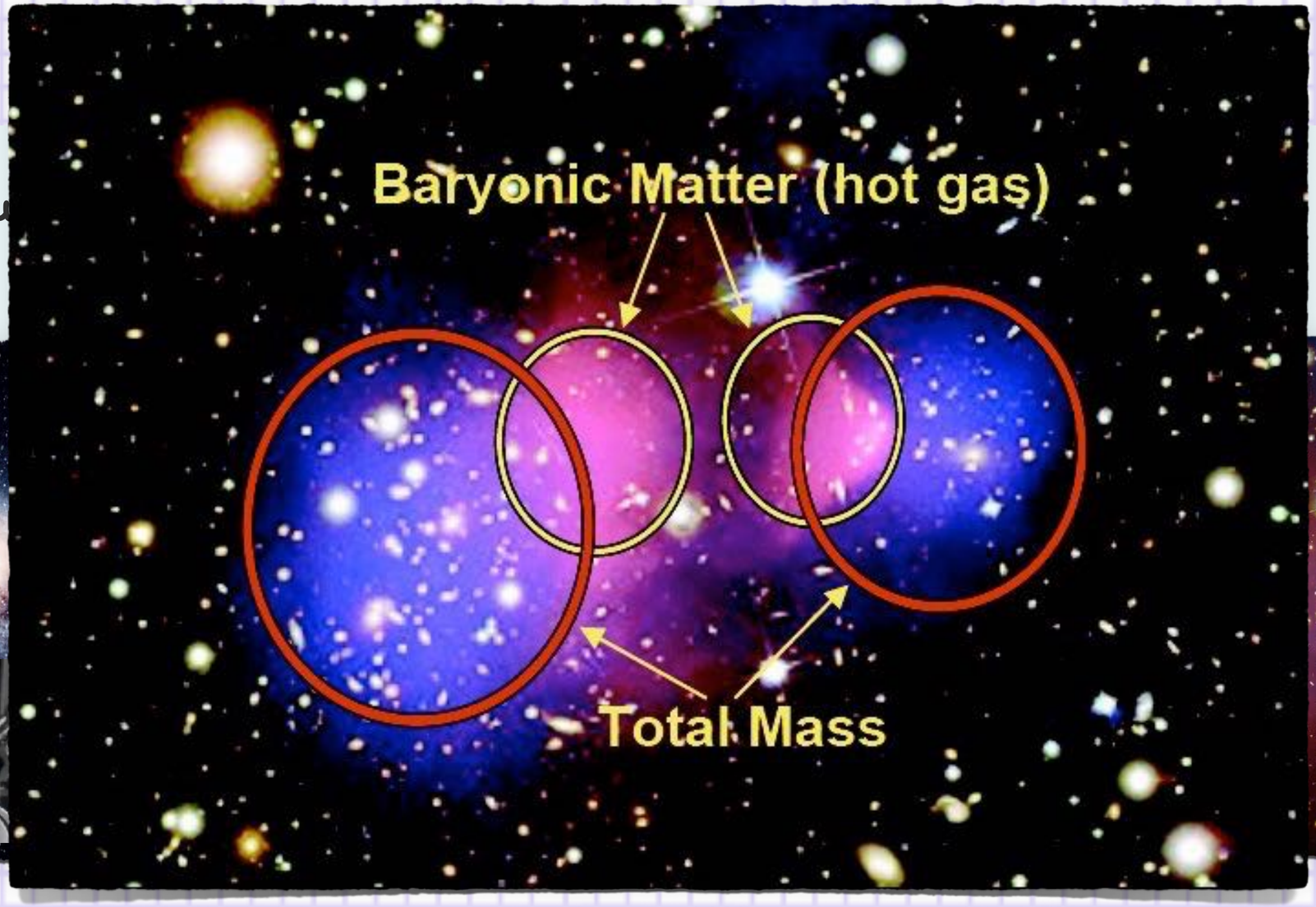

Evidence for Dark Matter

Rotational Curves

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Gravitational Lensing

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Bullet Cluster

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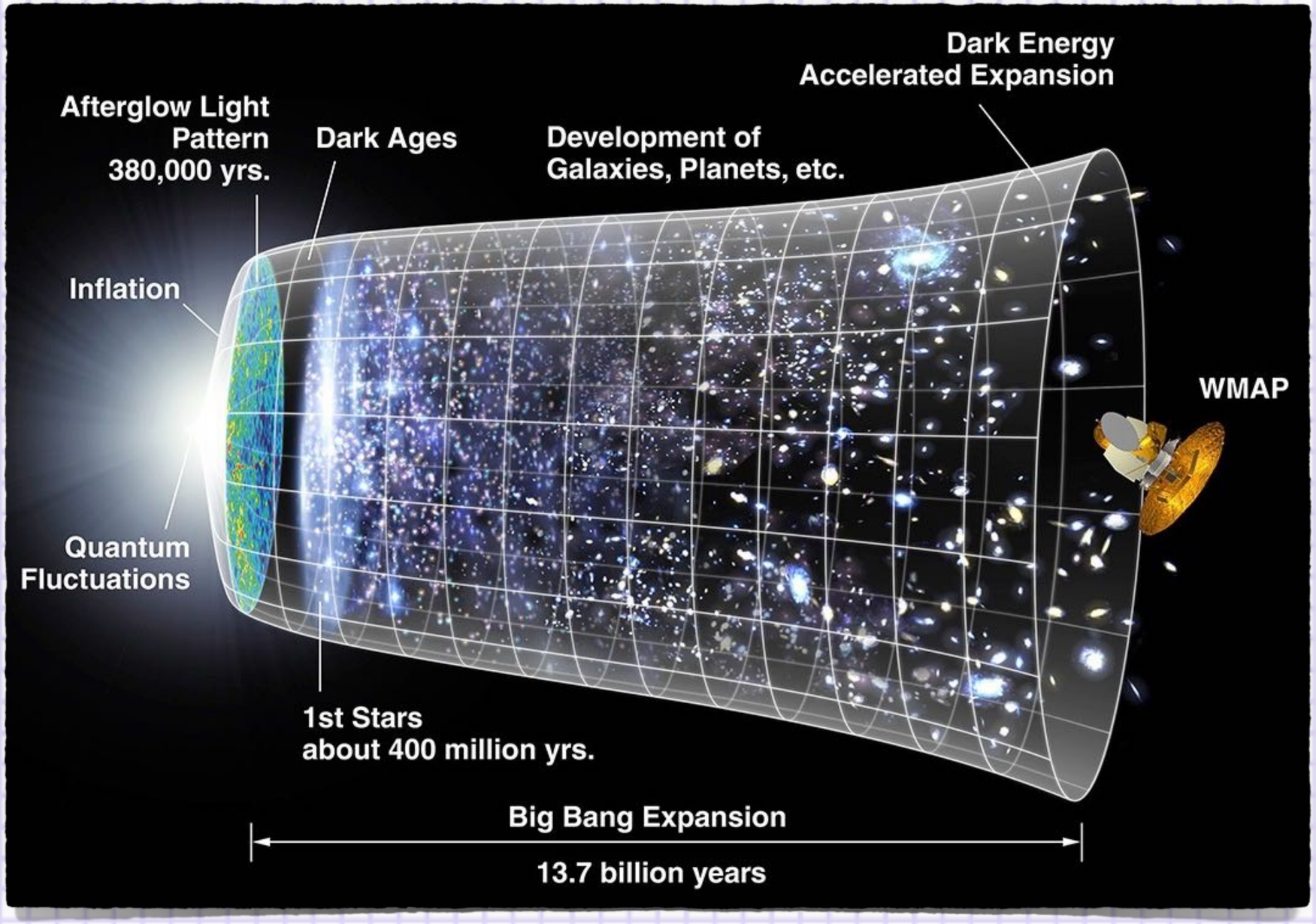
“

We have very good reasons to believe that there’s something out there that deserves the name Dark Matter.
We can even quantify how much there should be!

”

History of the Universe

History of the Universe



Dark Matter Contents of the Universe

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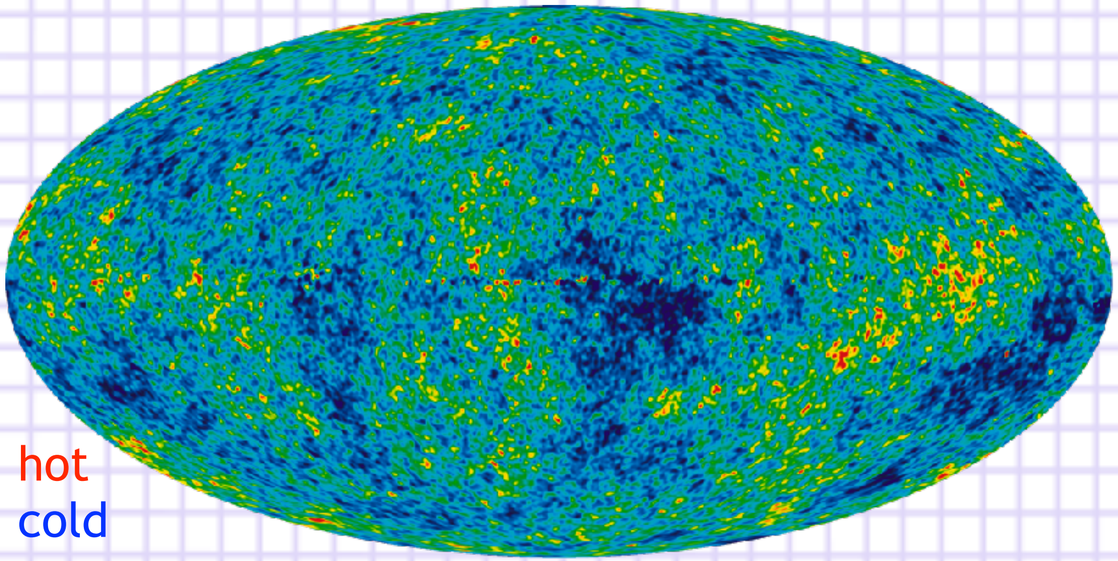

hot
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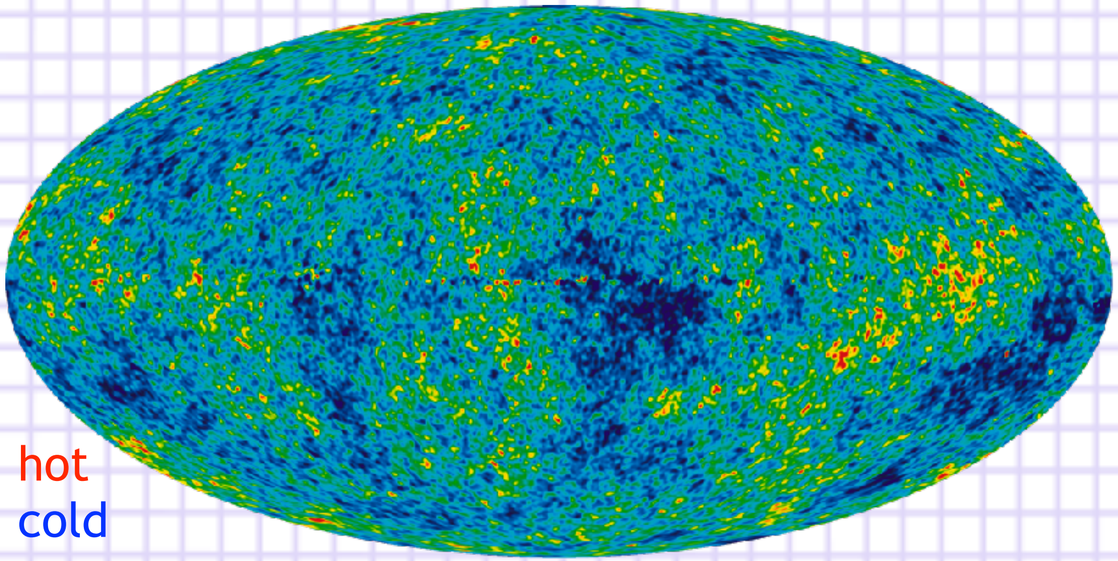

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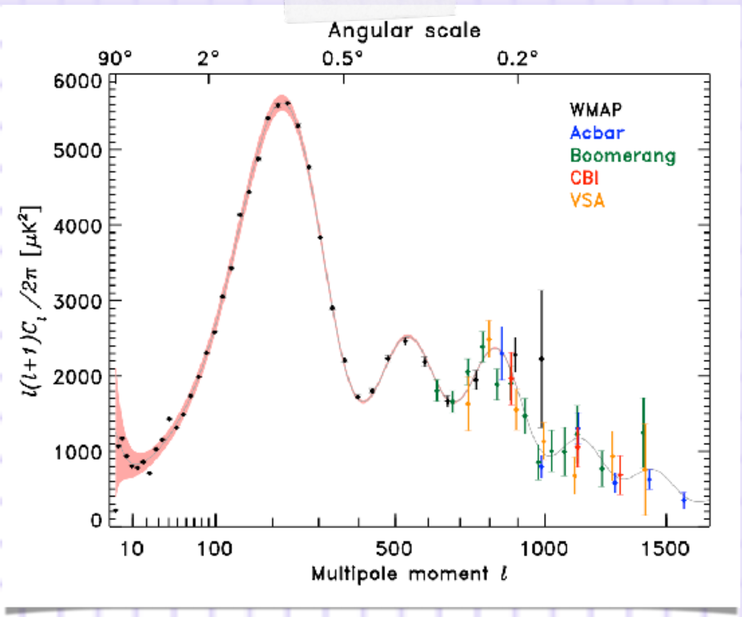

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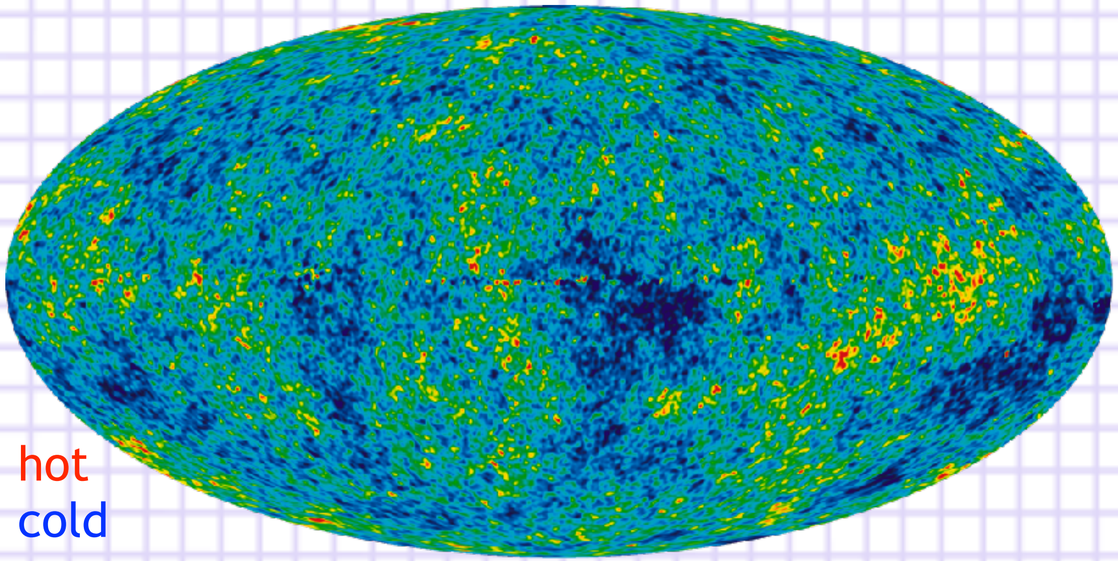

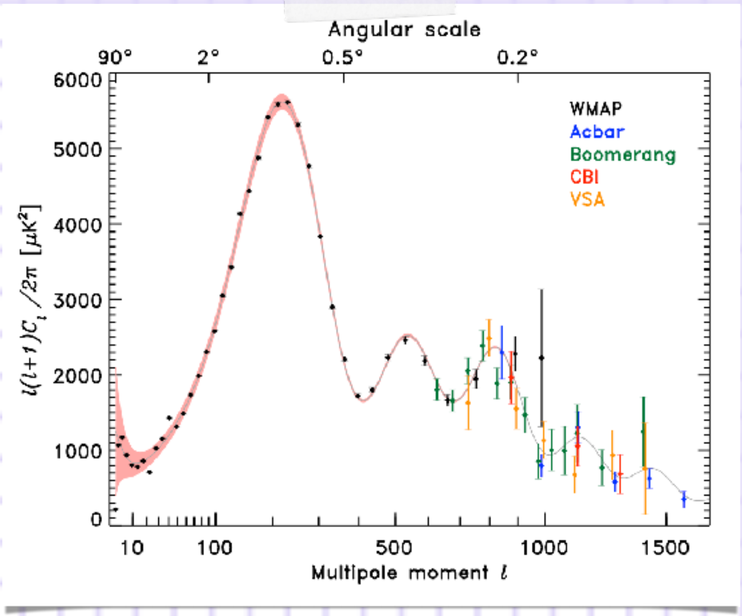

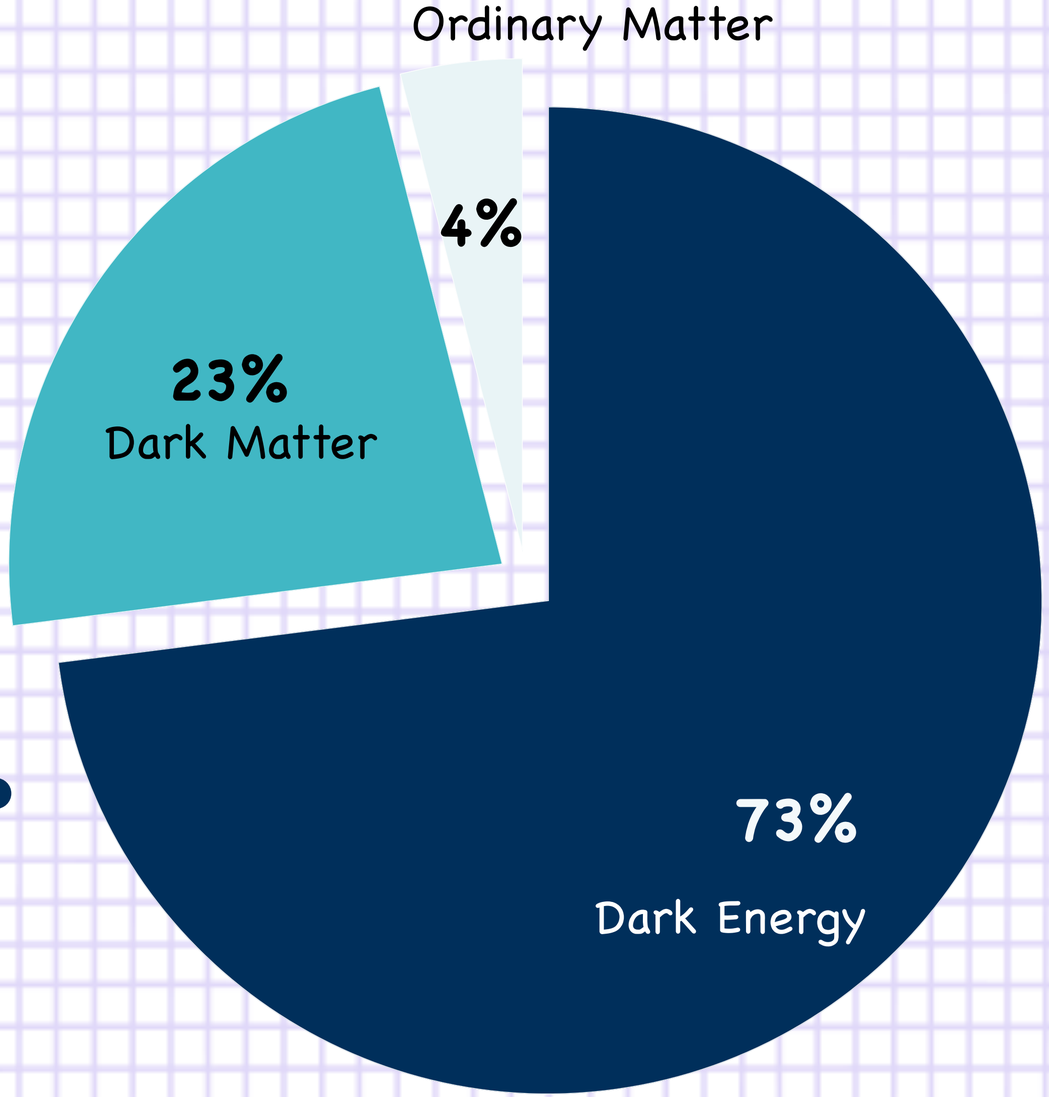

Standard Model and Dark Matter

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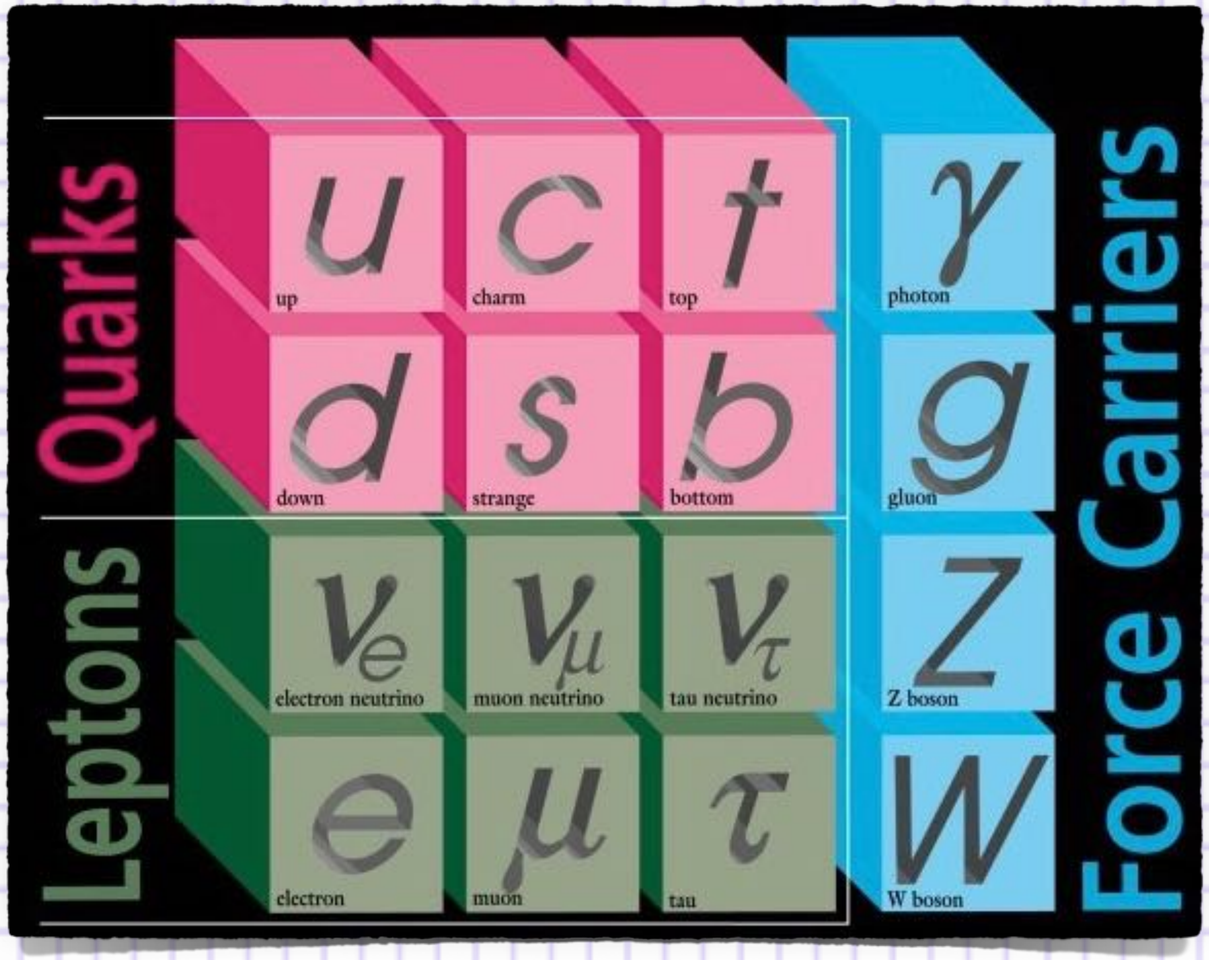

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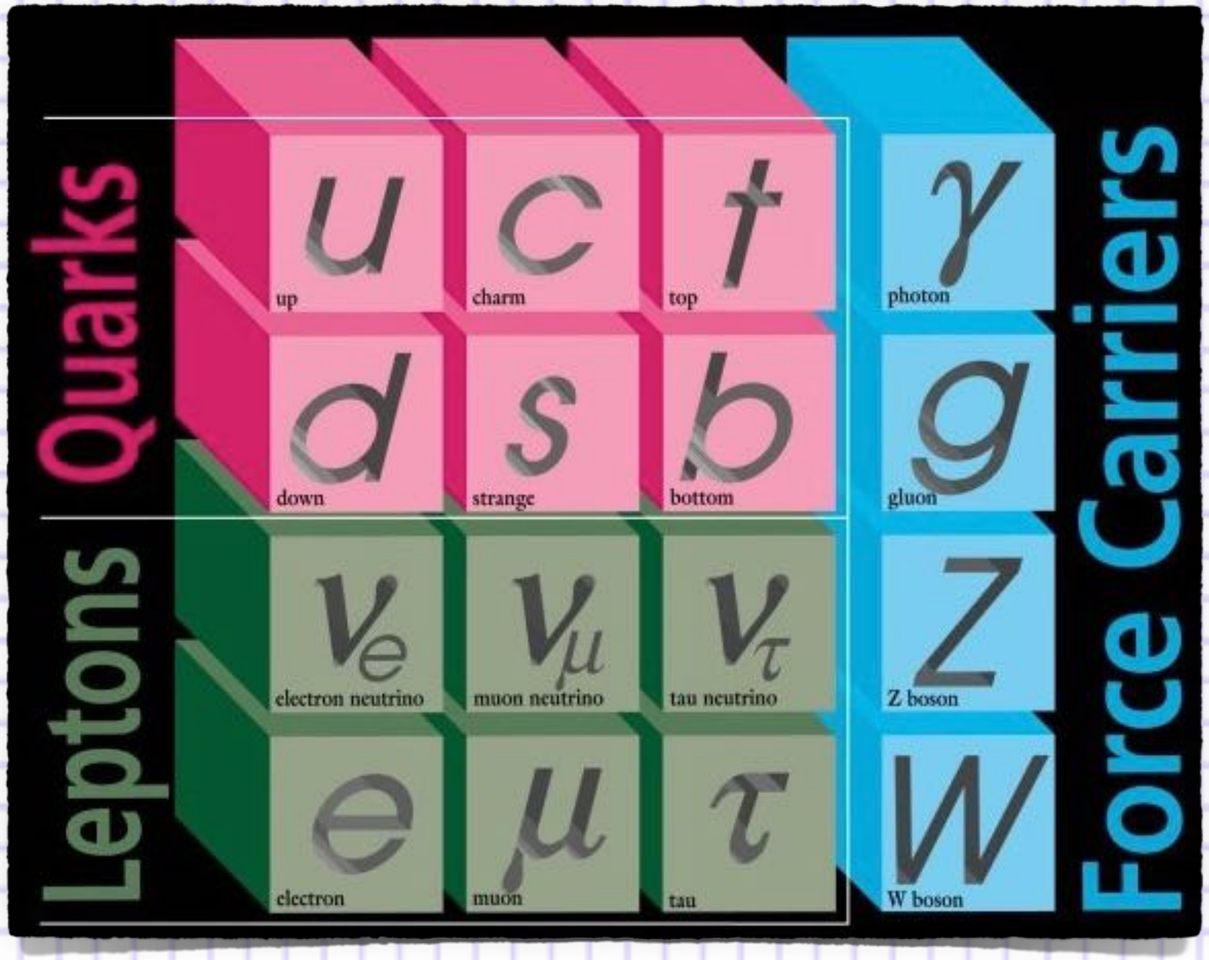
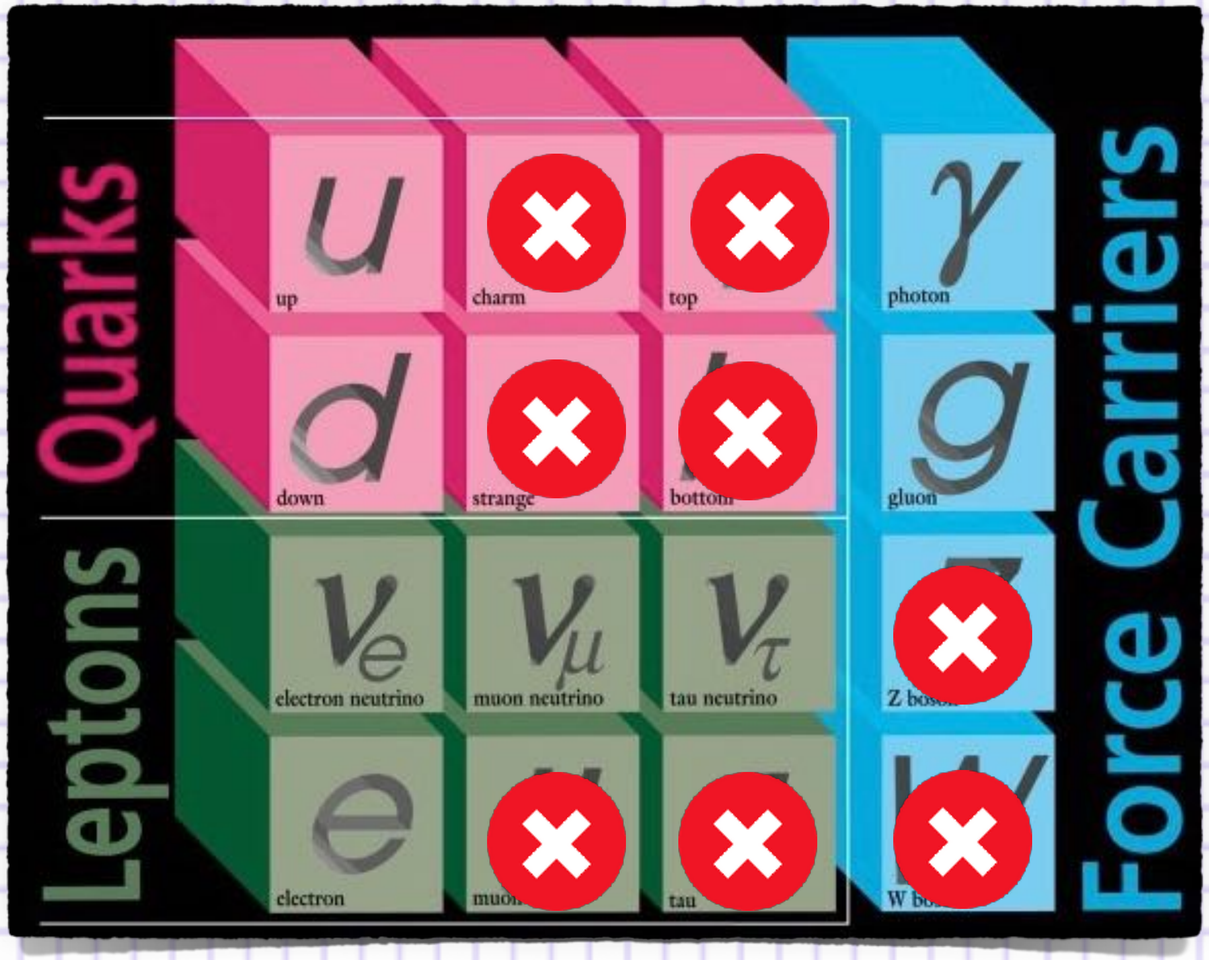


Dark Matter Properties

Standard Model and Dark Matter



Dark Matter Properties

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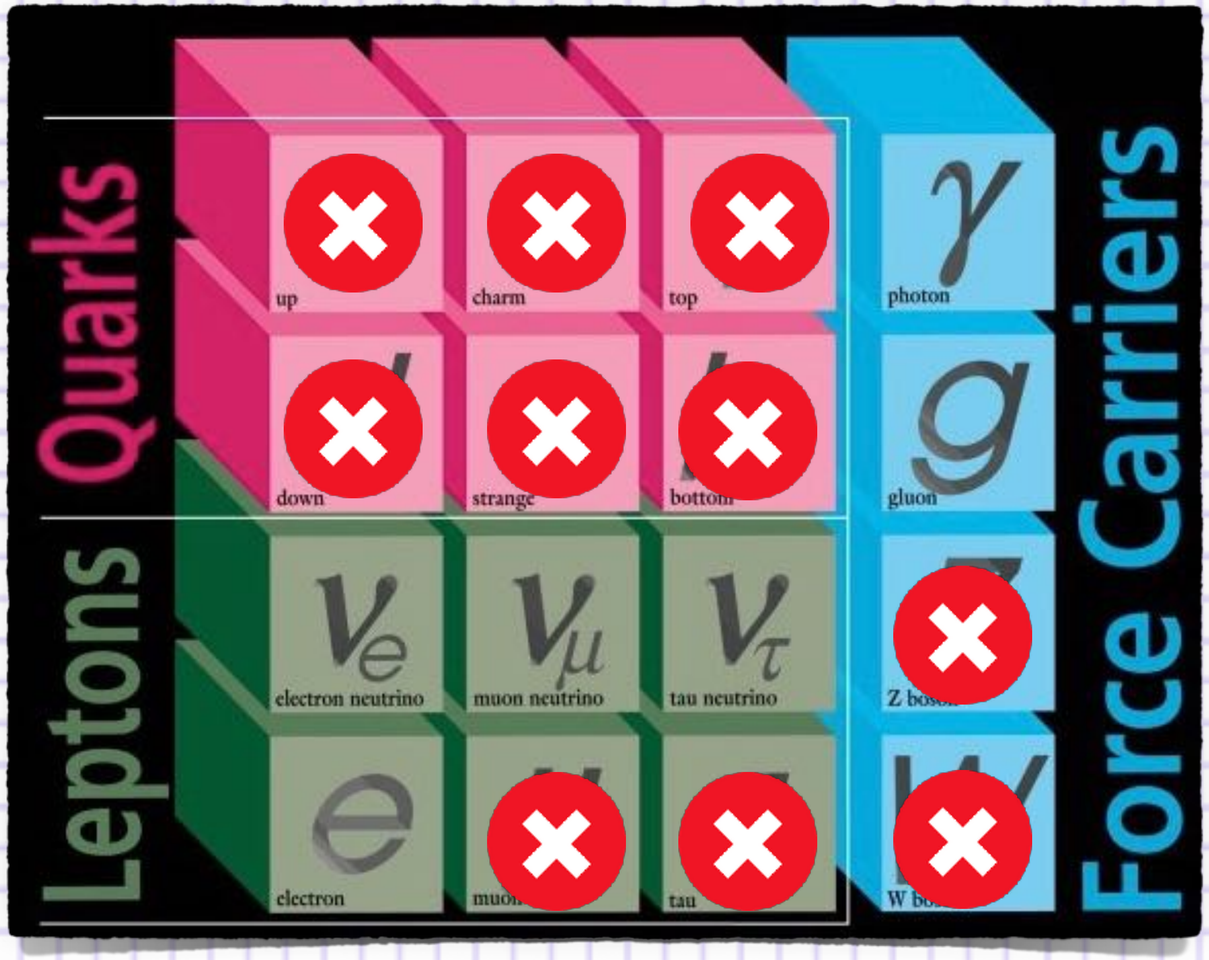

Dark Matter Properties

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- non-baryonic (baryogenesis)

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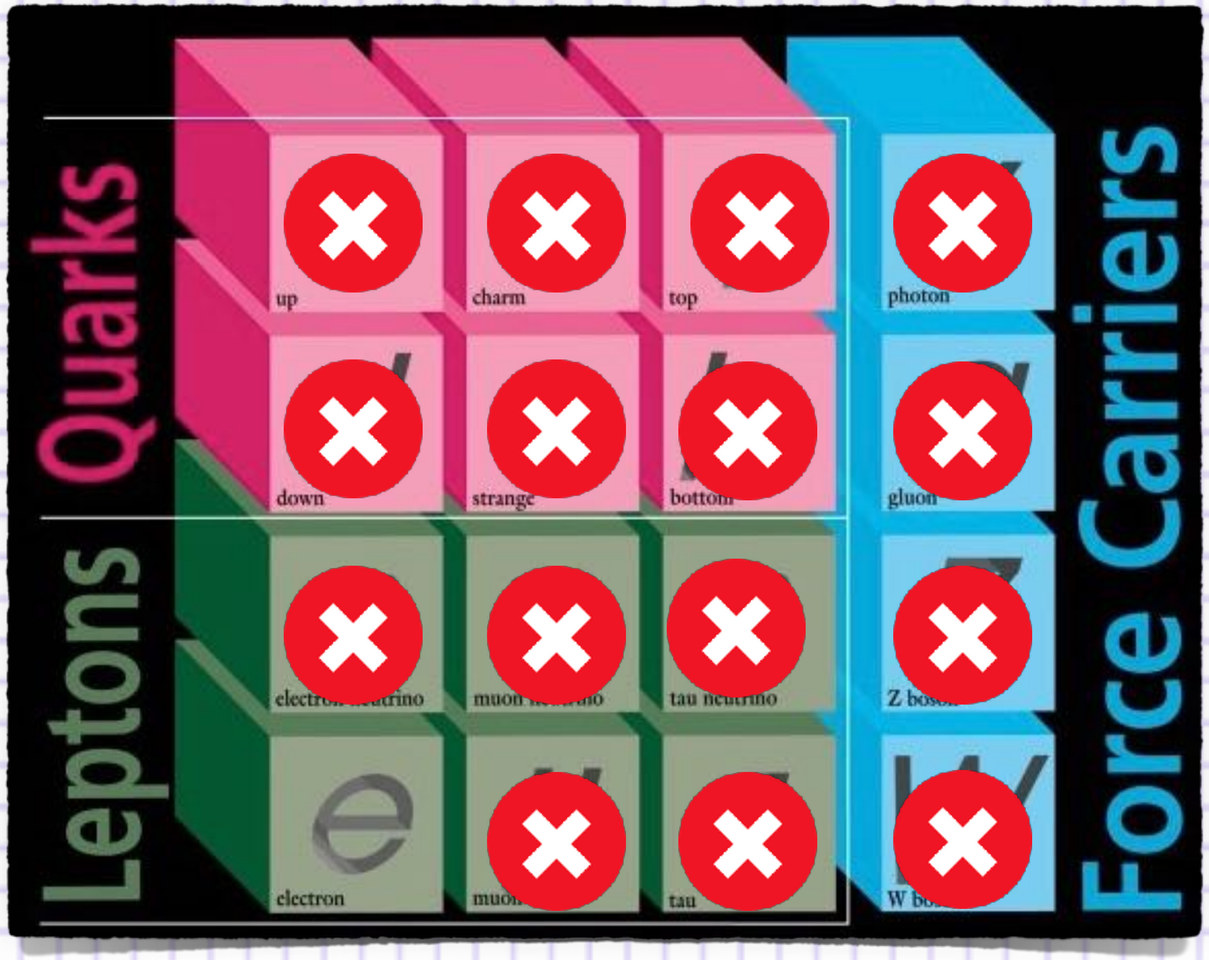

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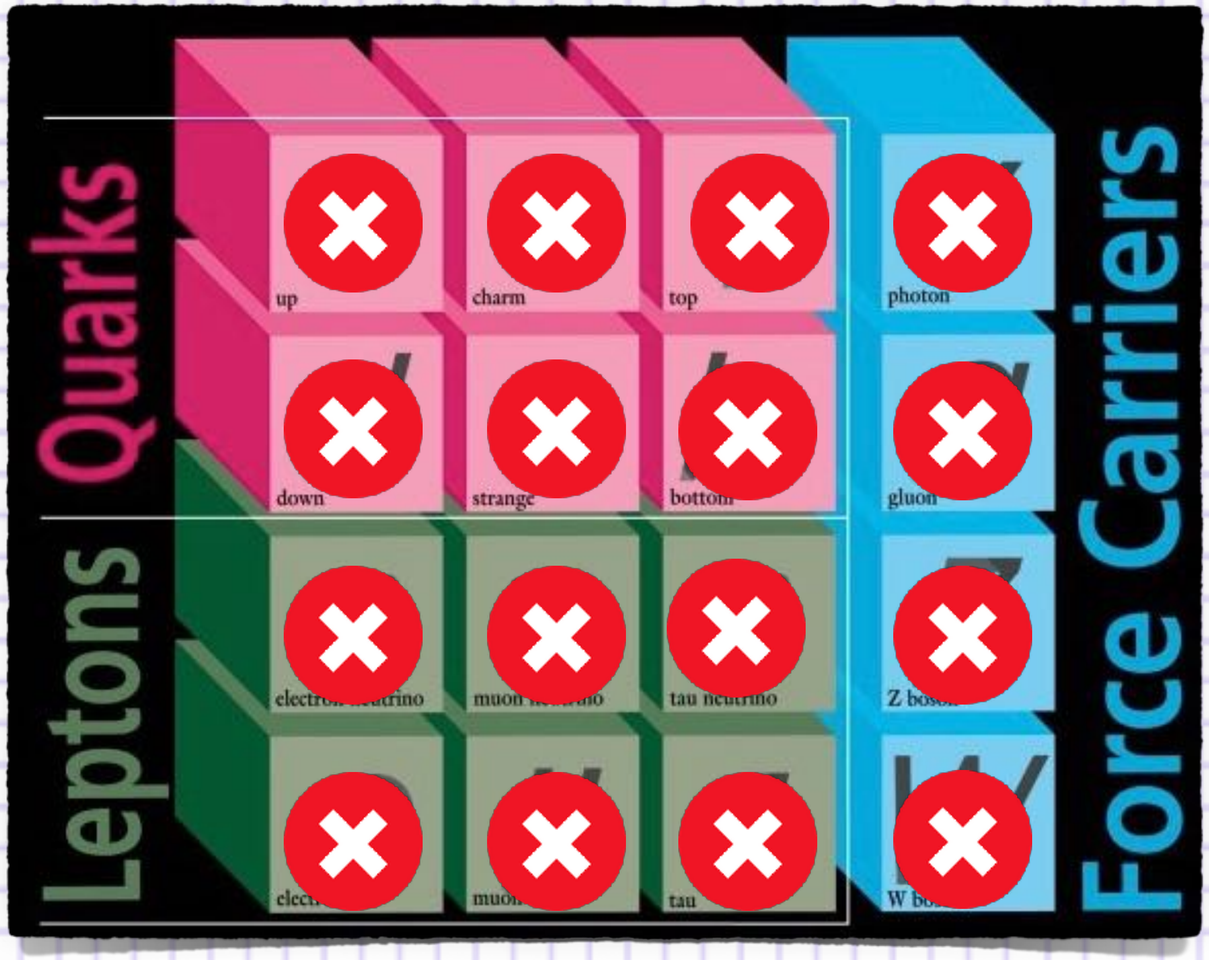

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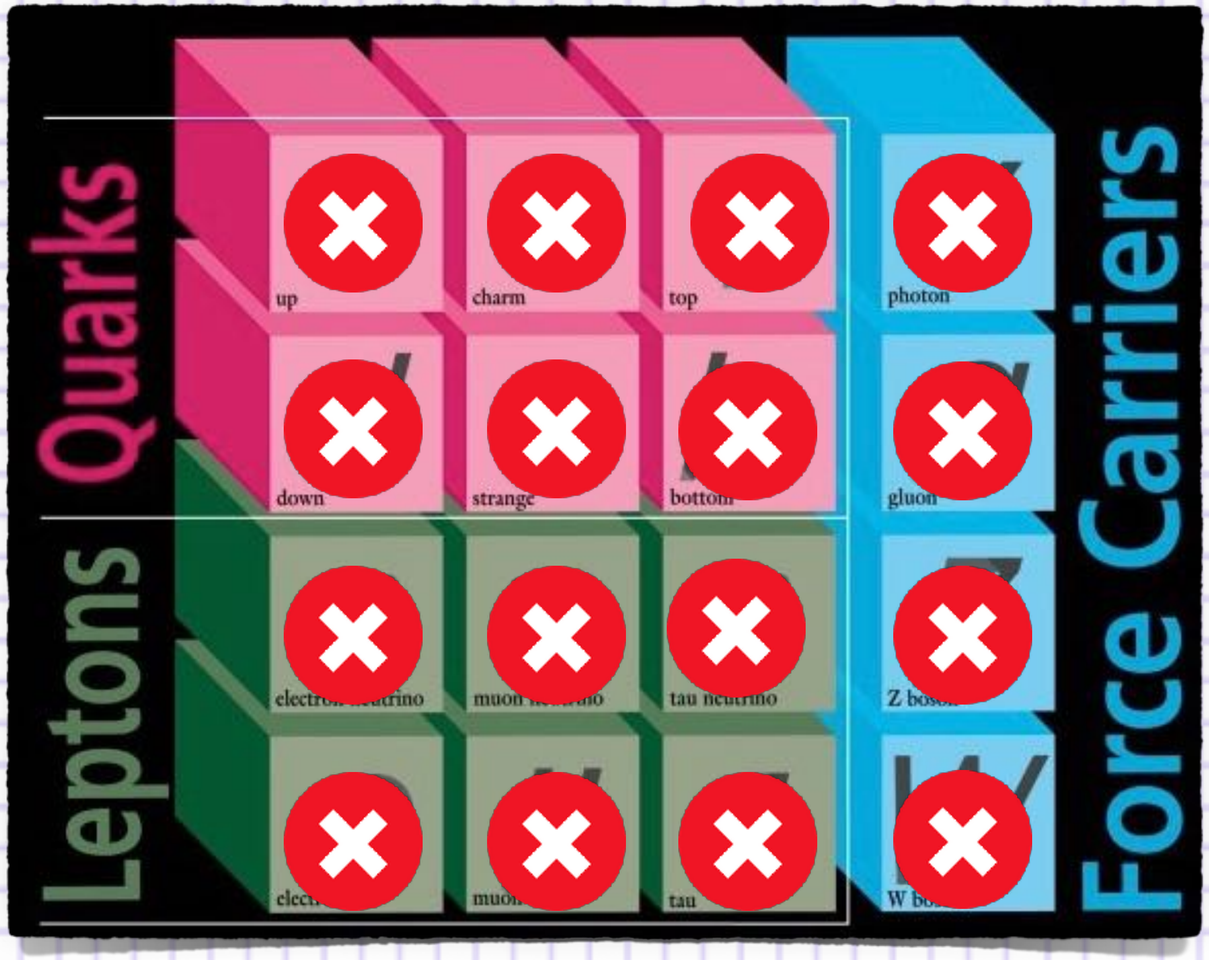

Dark Matter Properties

- stable
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If we want to explain DM with a particle we have to extend the Standard Model

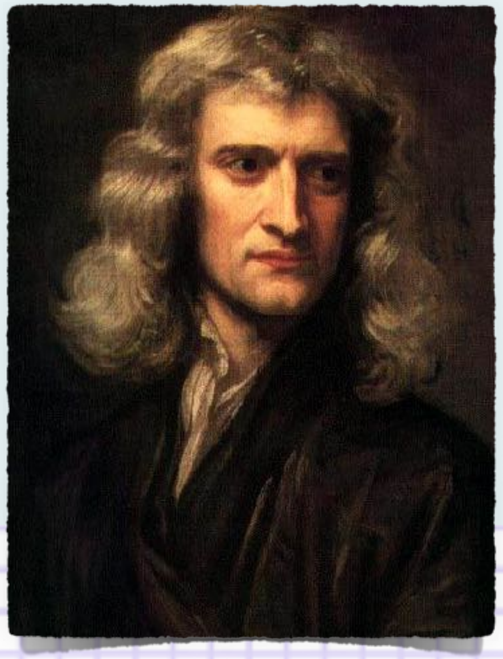
“
Wait a minute! Maybe there are other explanations for the observed effects. Do we really need (a) new particle(s)?
”

Explanation Attempts for Dark Matter

Explanation Attempts for Dark Matter

MOND

Modified Netownian Dynamics



MOND (MOdified Newtonian Dynamics)

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What if Newton’s Laws looked a little different?

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$$F = ma \quad \Leftrightarrow \quad F = m\mu(a/a_0)a$$

with

$$\mu(x) = 1 \quad \text{für} \quad x \gg 1$$

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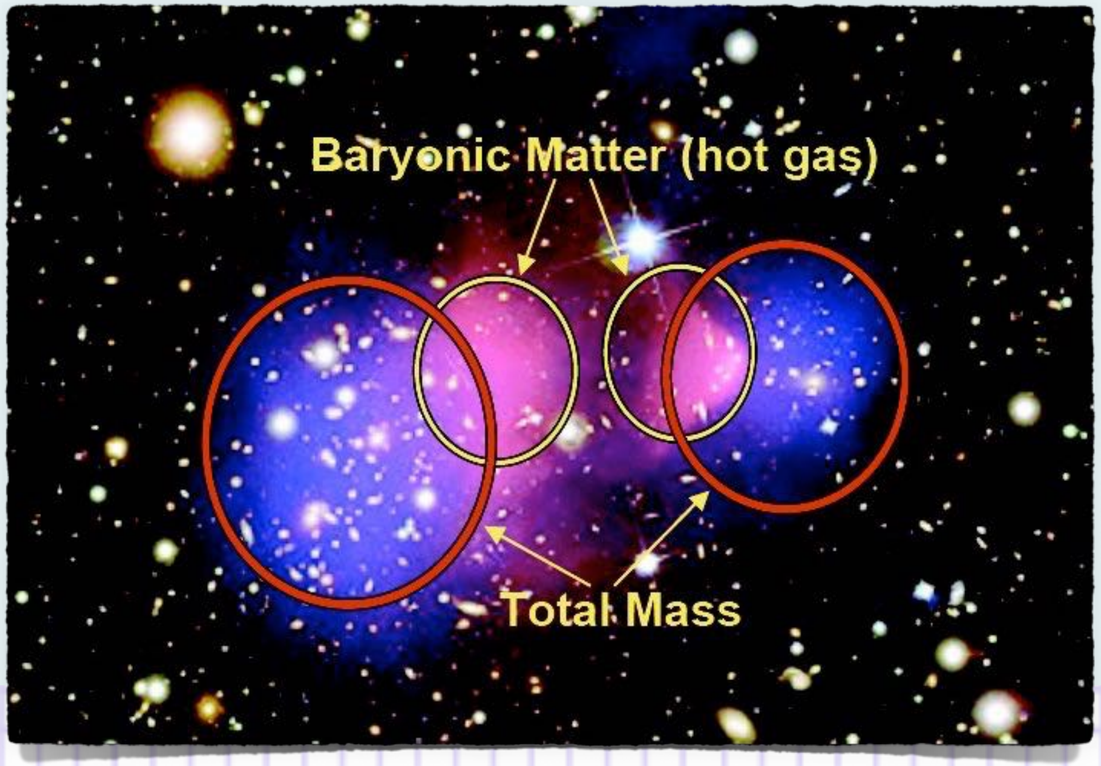
Could be an explanation for rotation velocity!

However, it fails to explain bullet cluster...



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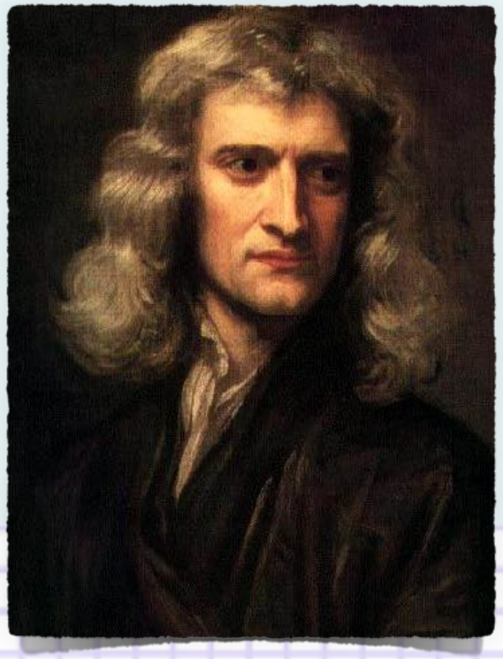

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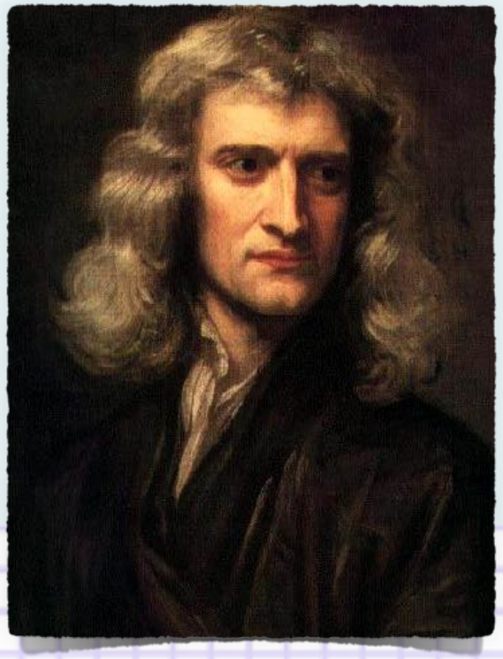
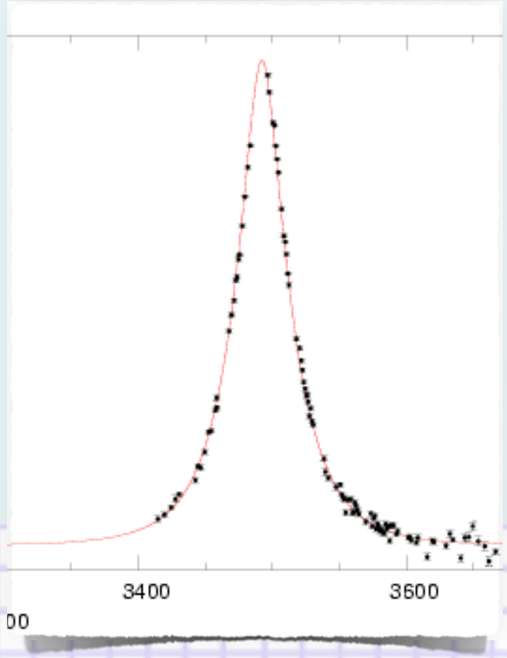


MACHOs

Massive Compact Halo Objects



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definition: **collection of baryonic matter**

- planets
- neutron stars
- brown dwarfs
- weak red dwarfs
- small black holes
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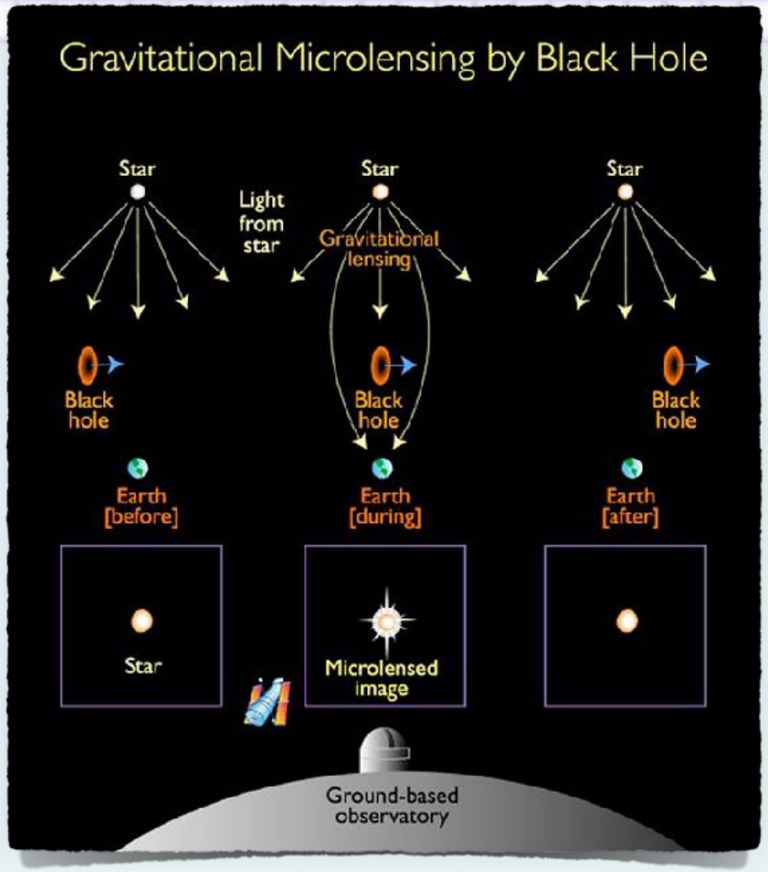

Indirectly observable: Gravitational Microlensing

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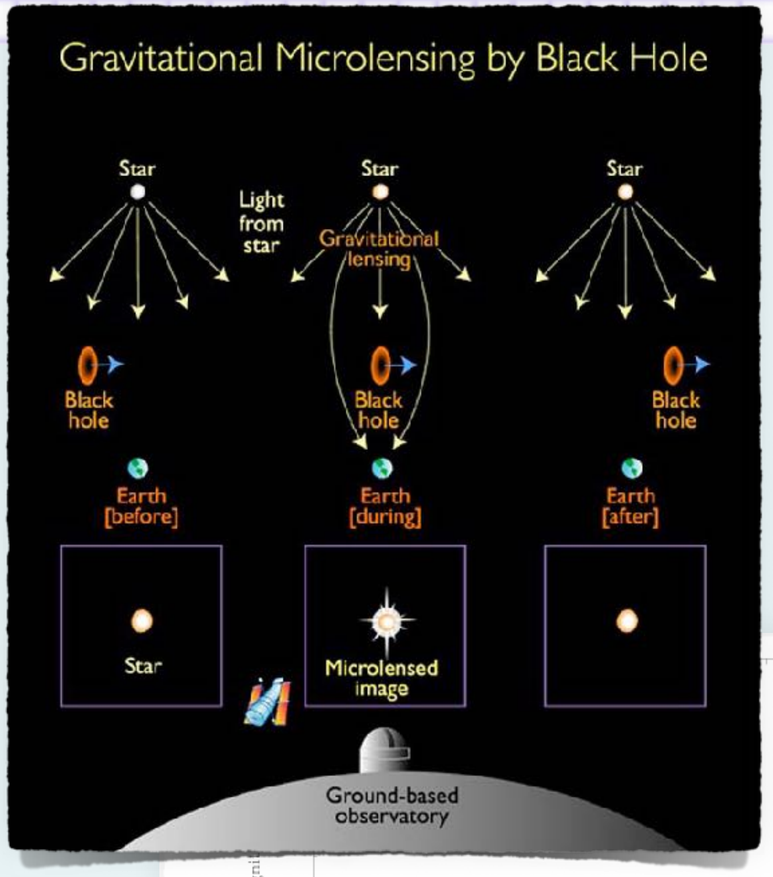

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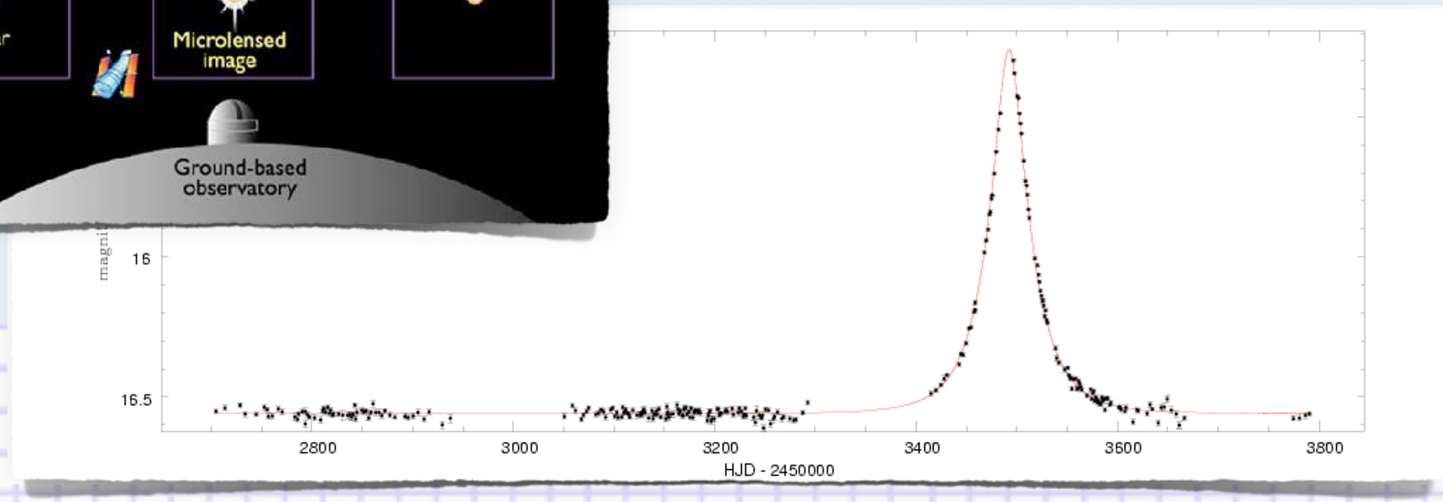

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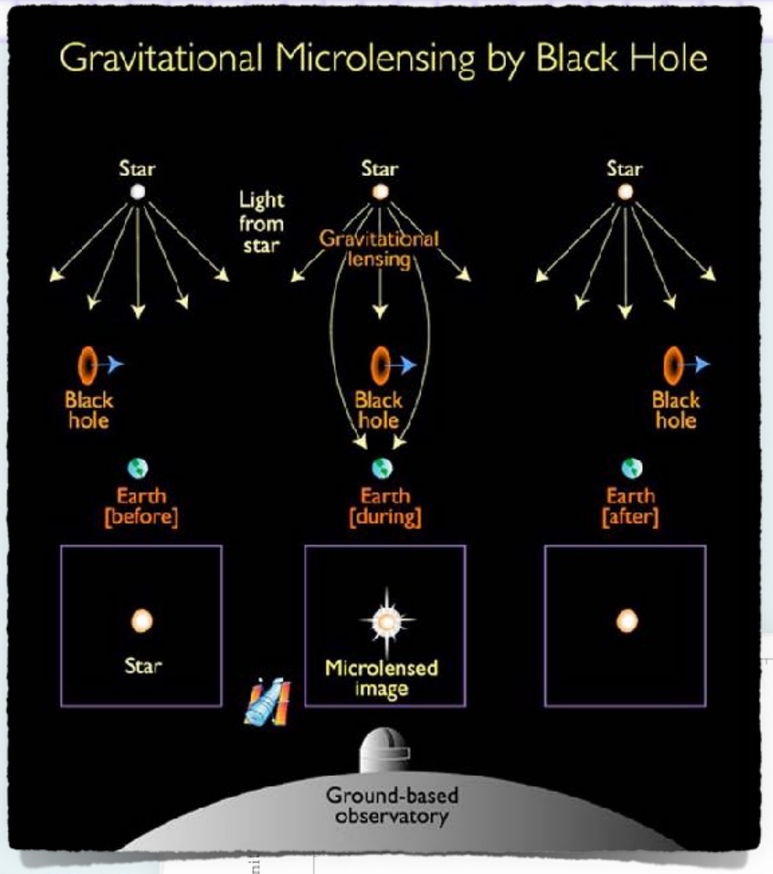

Indirectly observable:
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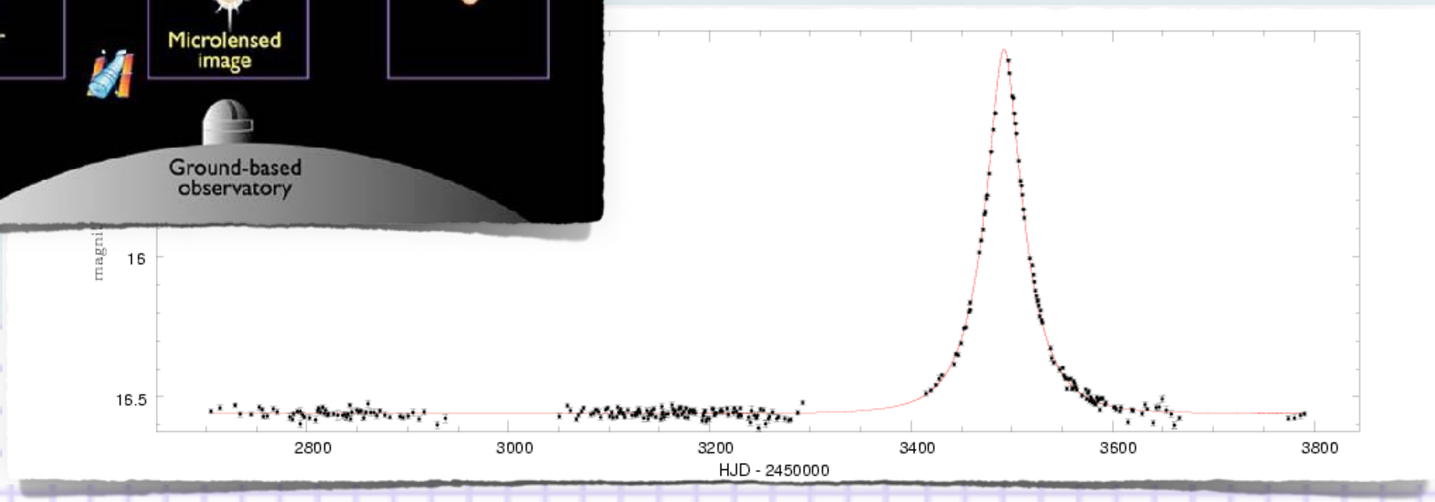
Gravitational Microlensing Survey:
MACHOs are excluded as Dark Matter for objects between 10^{-8} to 100 solar masses.



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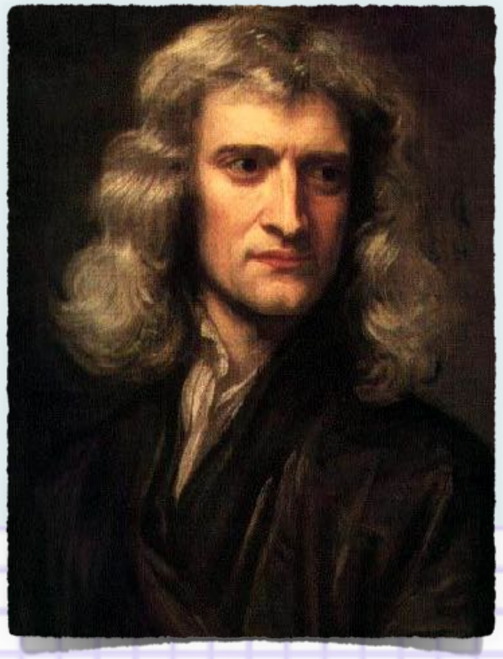

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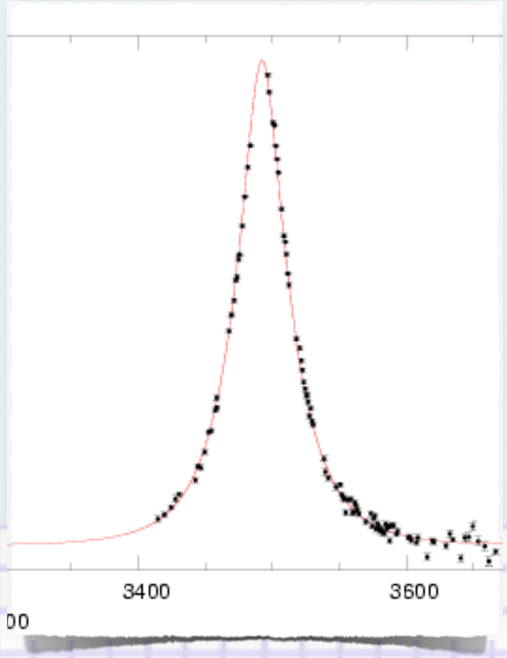

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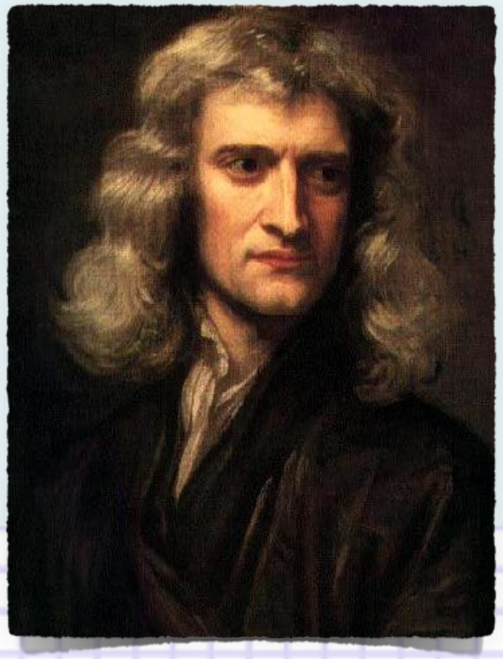

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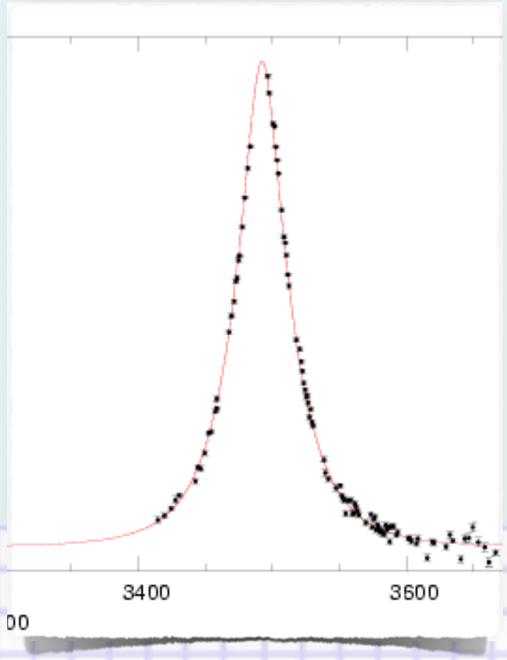

The simplest and most elegant explanation for all of our observations is the existence of new particles with DM properties!

“

If Dark Matter is some sort of particle and if none of the Standard Model particles has Dark Matter properties we need to extend the Standard Model!

”

Supersymmetry

Why are SUSY Searches Interesting in Terms of DM?

Supersymmetry

Why are SUSY Searches Interesting in Terms of DM?

Supersymmetry Crashcourse

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- SUSY is a concept that adds additional symmetry to SM (fermions <—>bosons)
- SUSY is key element in many SM extensions
- If SUSY is realised around 1 TeV scale:

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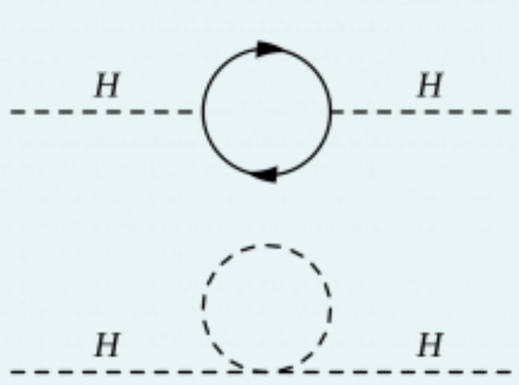
Stabilize Higgs Mass



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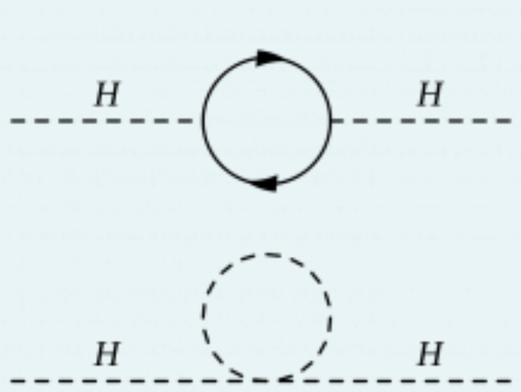
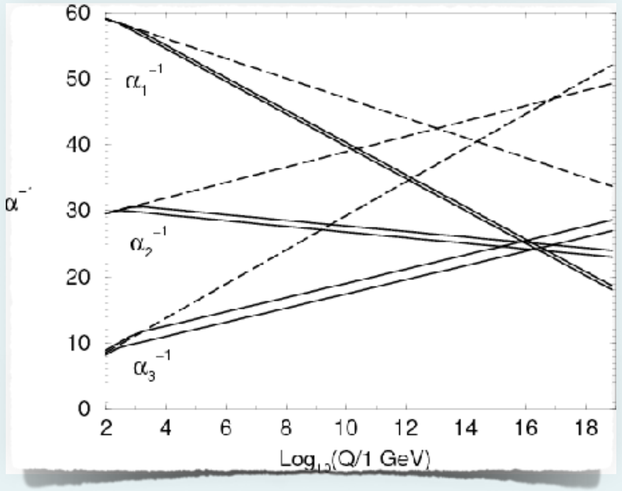


Gauge Unification



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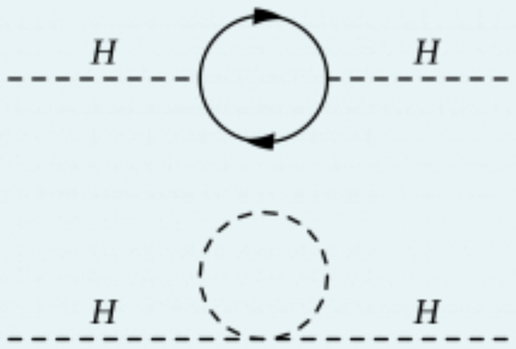

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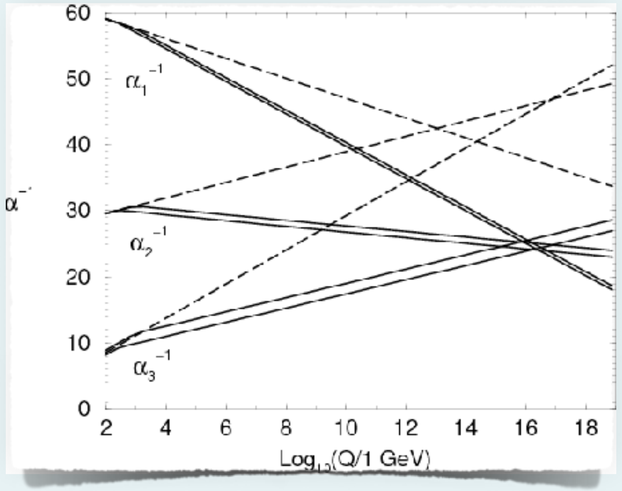

Dark Matter Candidate

LSP has DM properties

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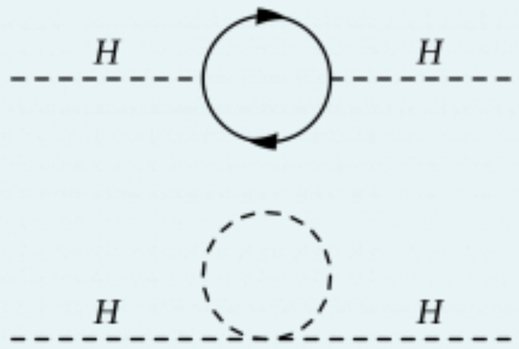

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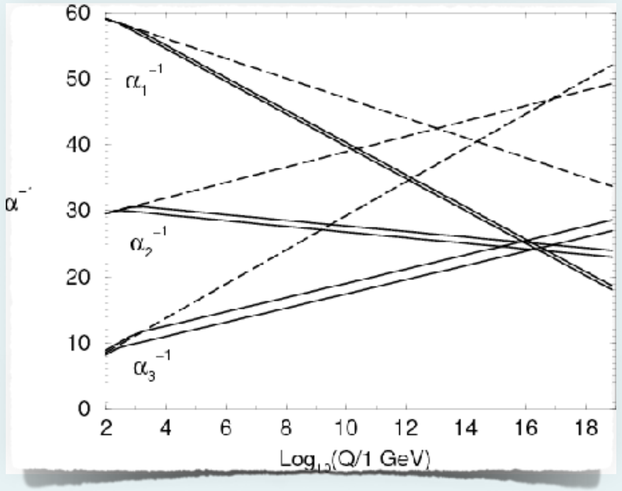

Dark Matter Candidate

LSP has DM properties

- SUSY has to be a broken symmetry (SUSY breaking requires parametrization)

The Minimal Supersymmetric Extension to the Standard Model

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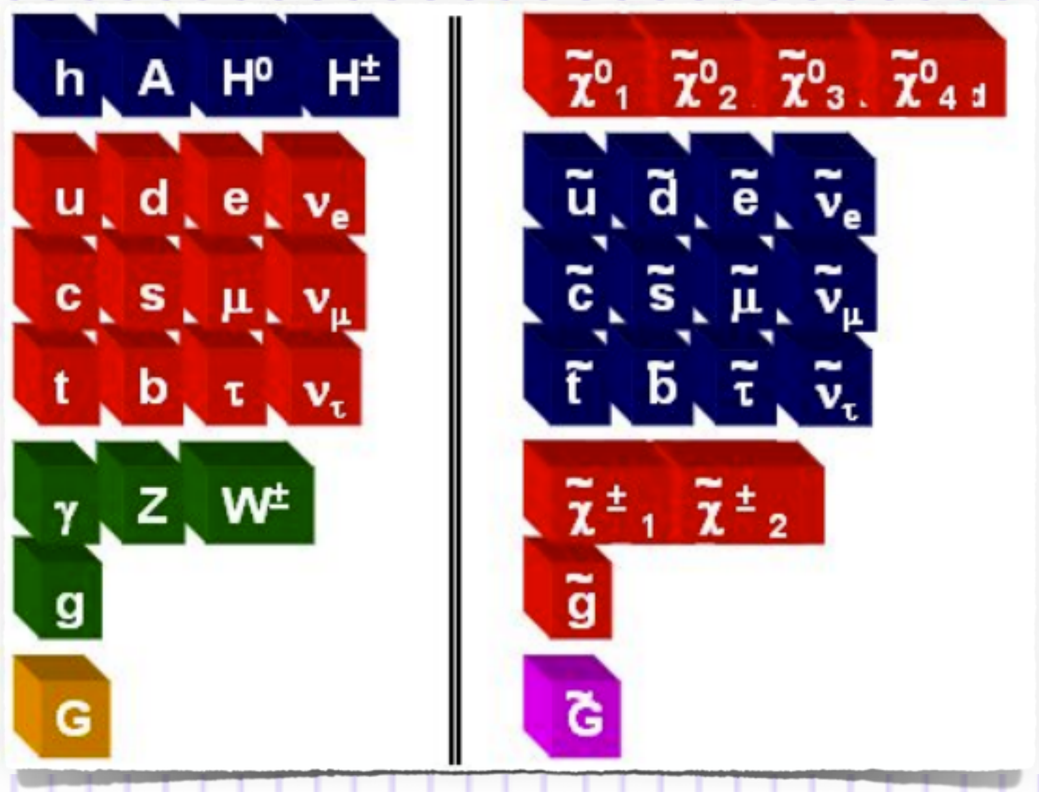
MSSM

- Minimal Supersymmetric Extension to the SM
- only one symmetry extension: **N=1 SUSY**
- minimal in its particle content
  - one SUSY partner for each SM particle: **fermion <—> boson**
  - two Higgs doublets: **generating mass for up- and down-type quarks**
- SUSY breaking: **124 parameters**
- **lightest supersymmetry particle (LSP) usually has DM properties**



“If the LSP has Dark Matter properties, then every search for Supersymmetry is also a search for Dark Matter.”

SUSY Signatures

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Design search strategy such that it enhances discovery potential!

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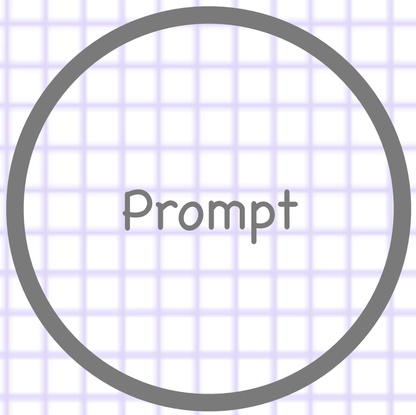

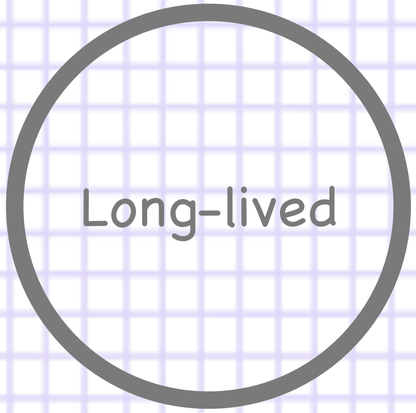

SUSY Signatures

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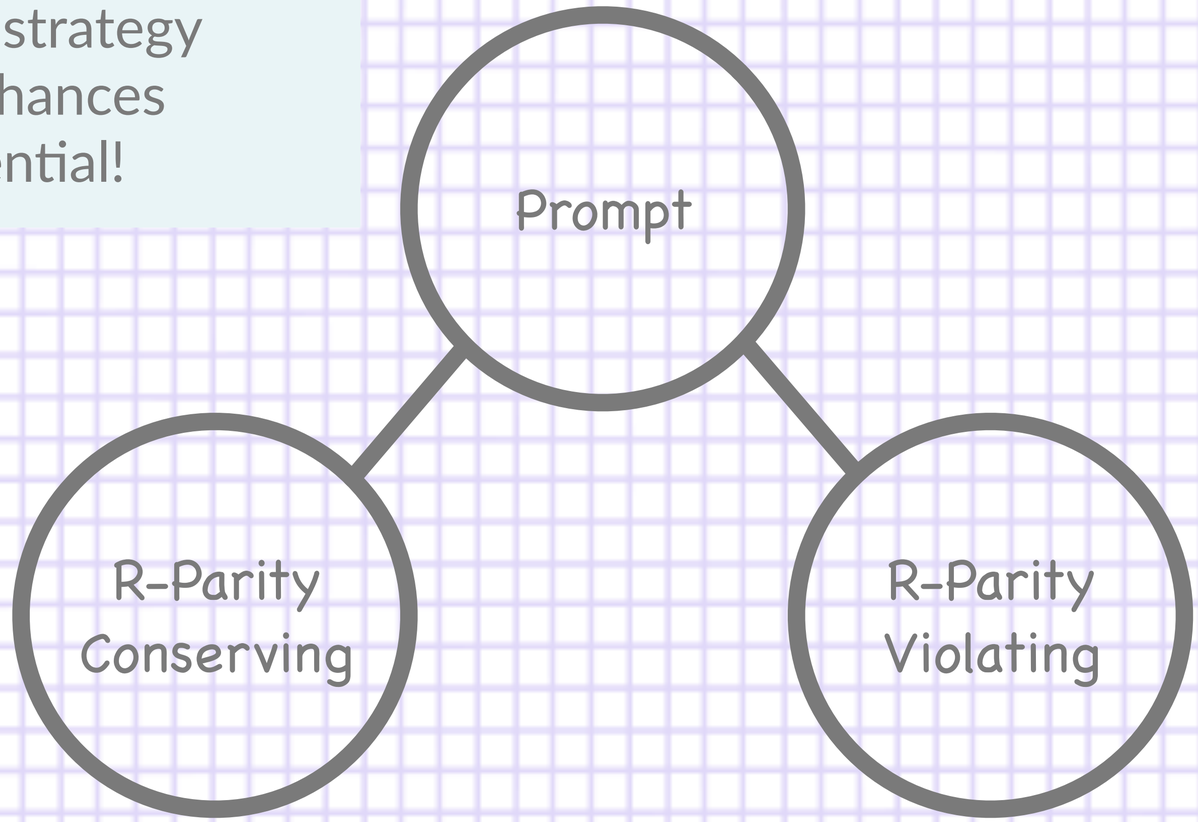

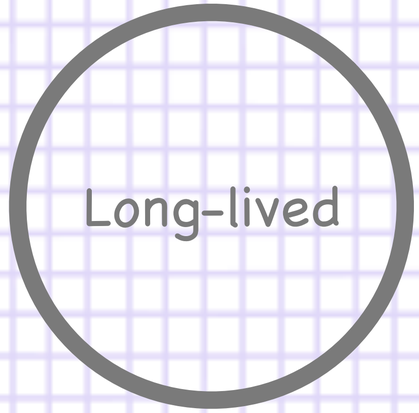

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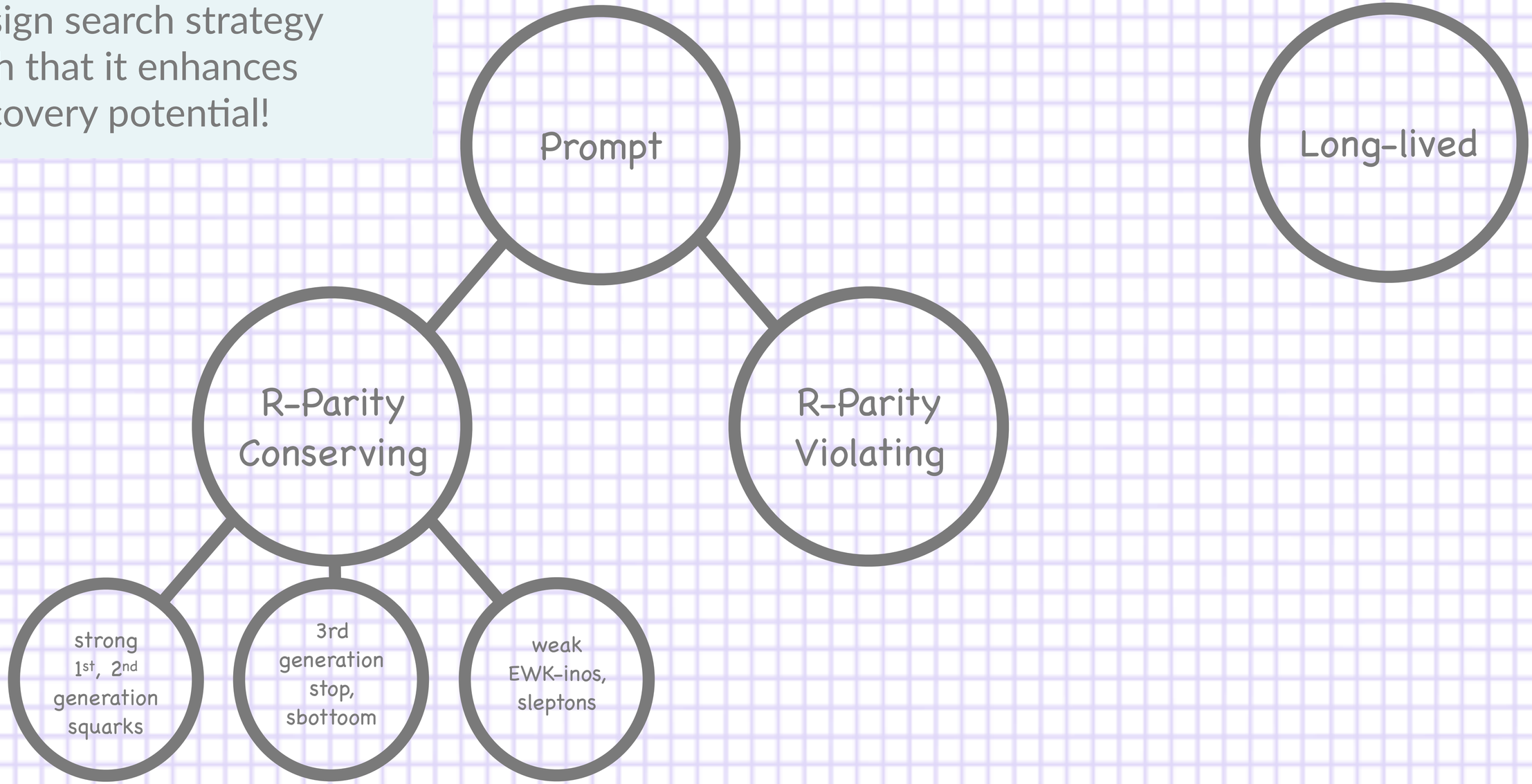

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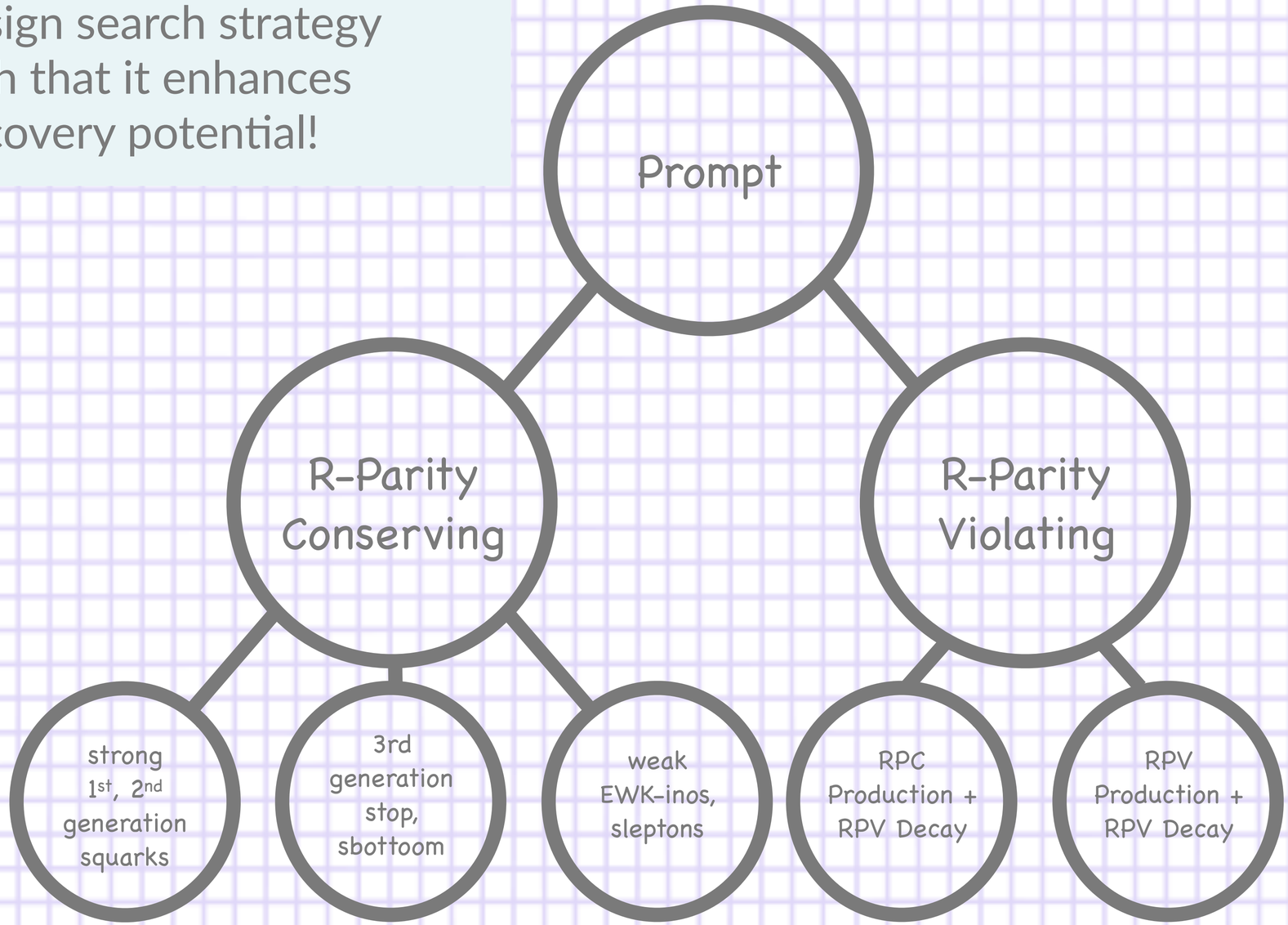

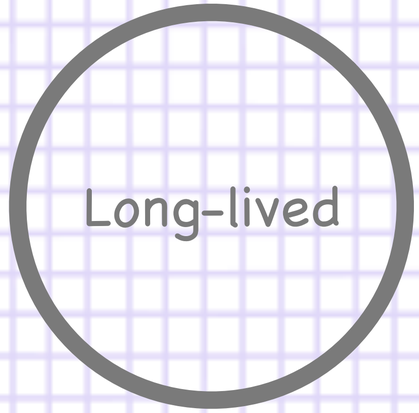

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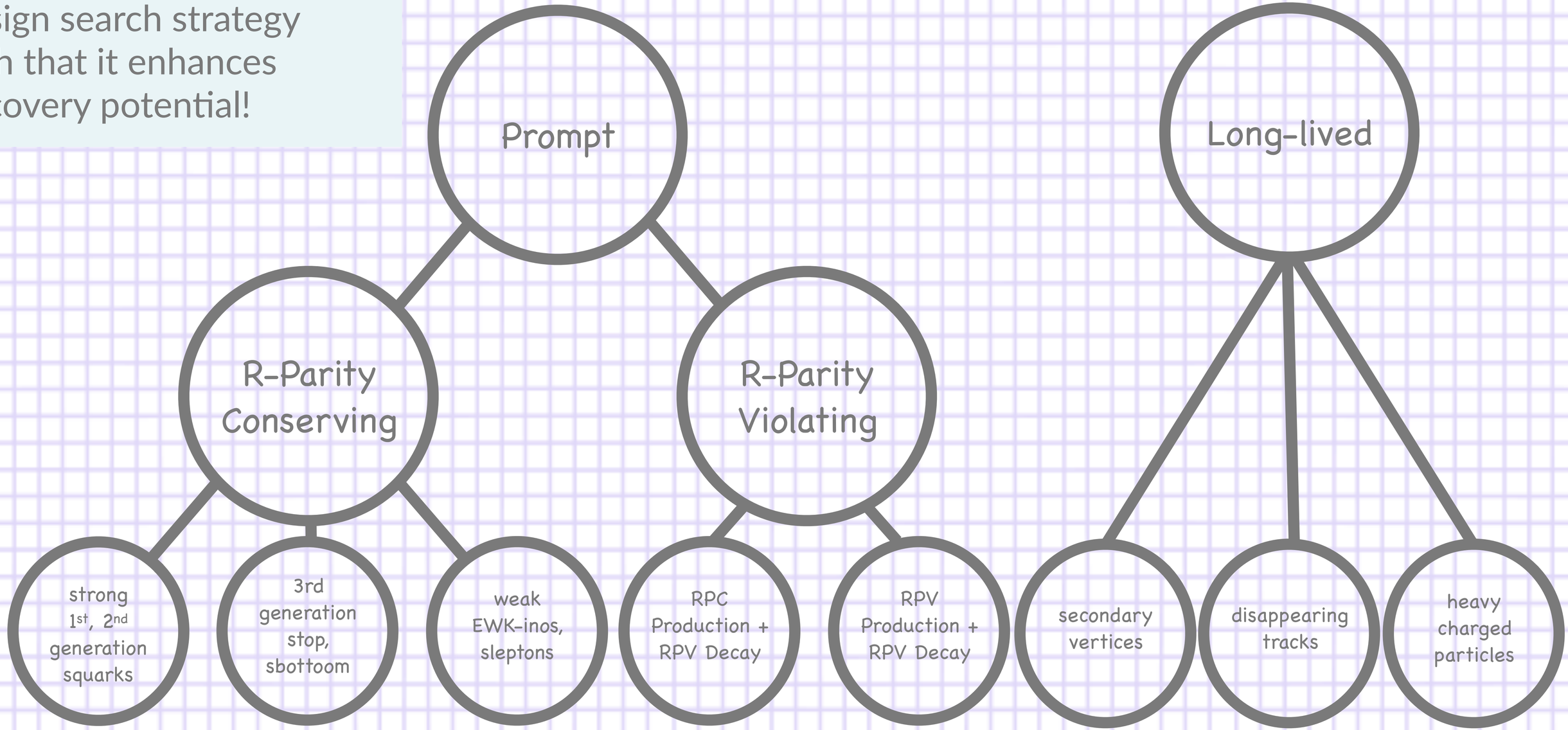

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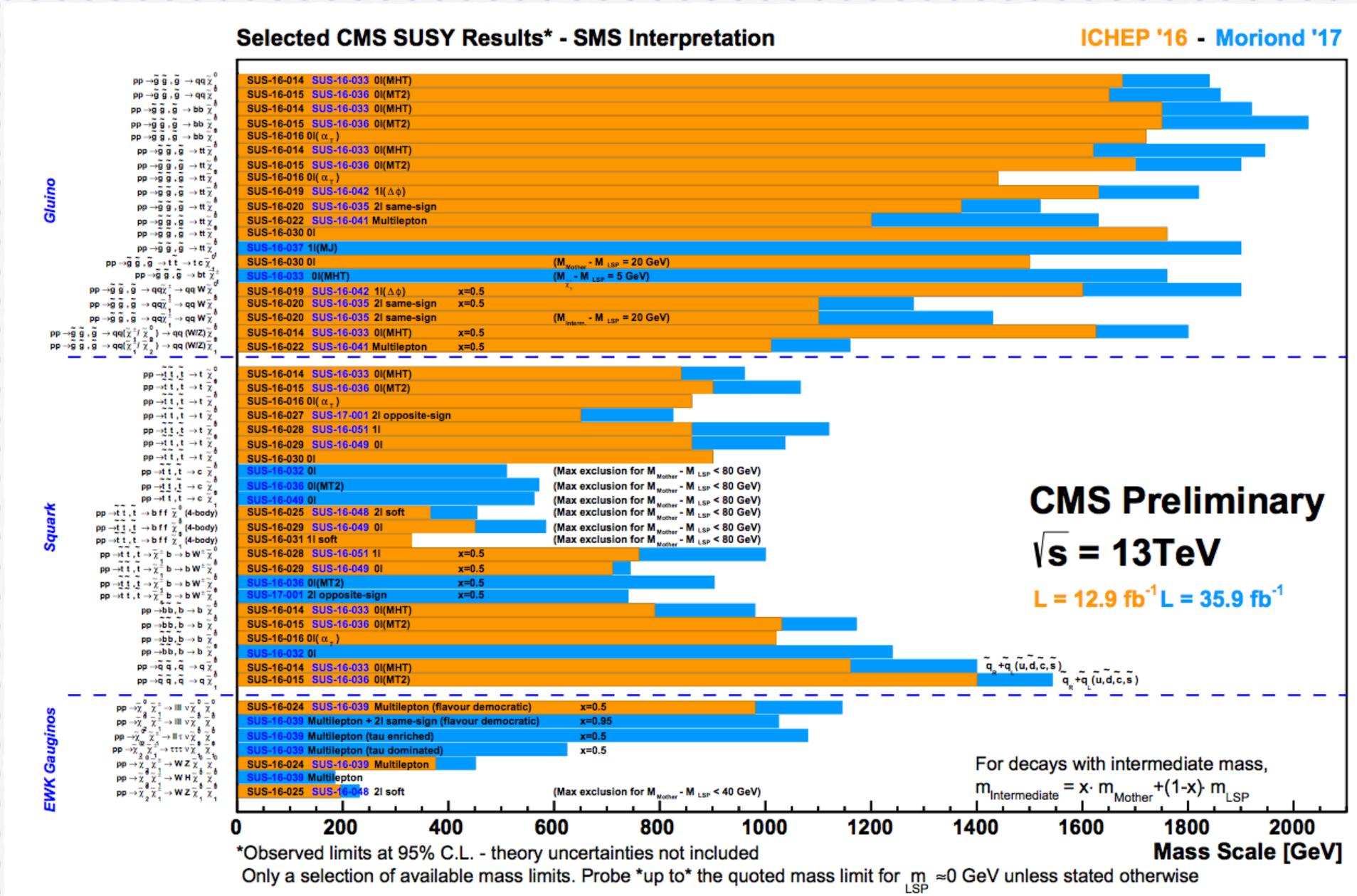

“
Haven’t we ruled out
SUSY by now?
Can we please move on?
”

Constraining the SUSY Parameter Phase Space

-or-

What is it we are setting limits on?

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Unconstrained MSSM

- explicit SUSY breaking
- parametrisation of SUSY breaking
- **requires 105 additional parameters**
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- gauge unification
- unification of gaugino masses
- universal scalar mass
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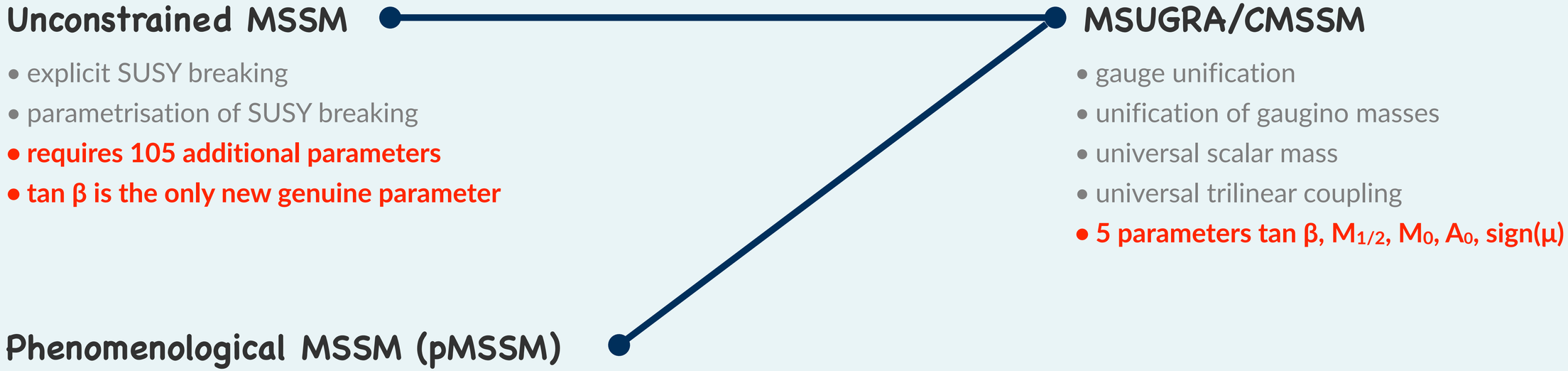

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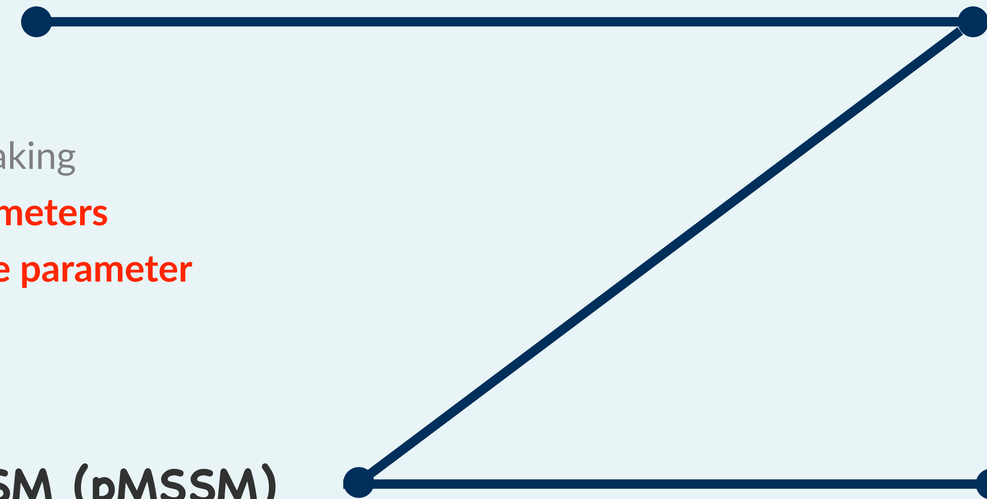

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Phenomenological MSSM (pMSSM)

- no new source of CP-violation
- NFNC
- 1st and 2nd generation universality
- **19 parameters**

Simplified MSSM

- effective models with minimal particle content
- parametrised directly in terms of particle masses
- complementary to pMSSM

So, is Supersymmetry still alive?

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YES!!!

- Results leave little room in current data samples.
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- Other more plausible models are far from being ruled out!
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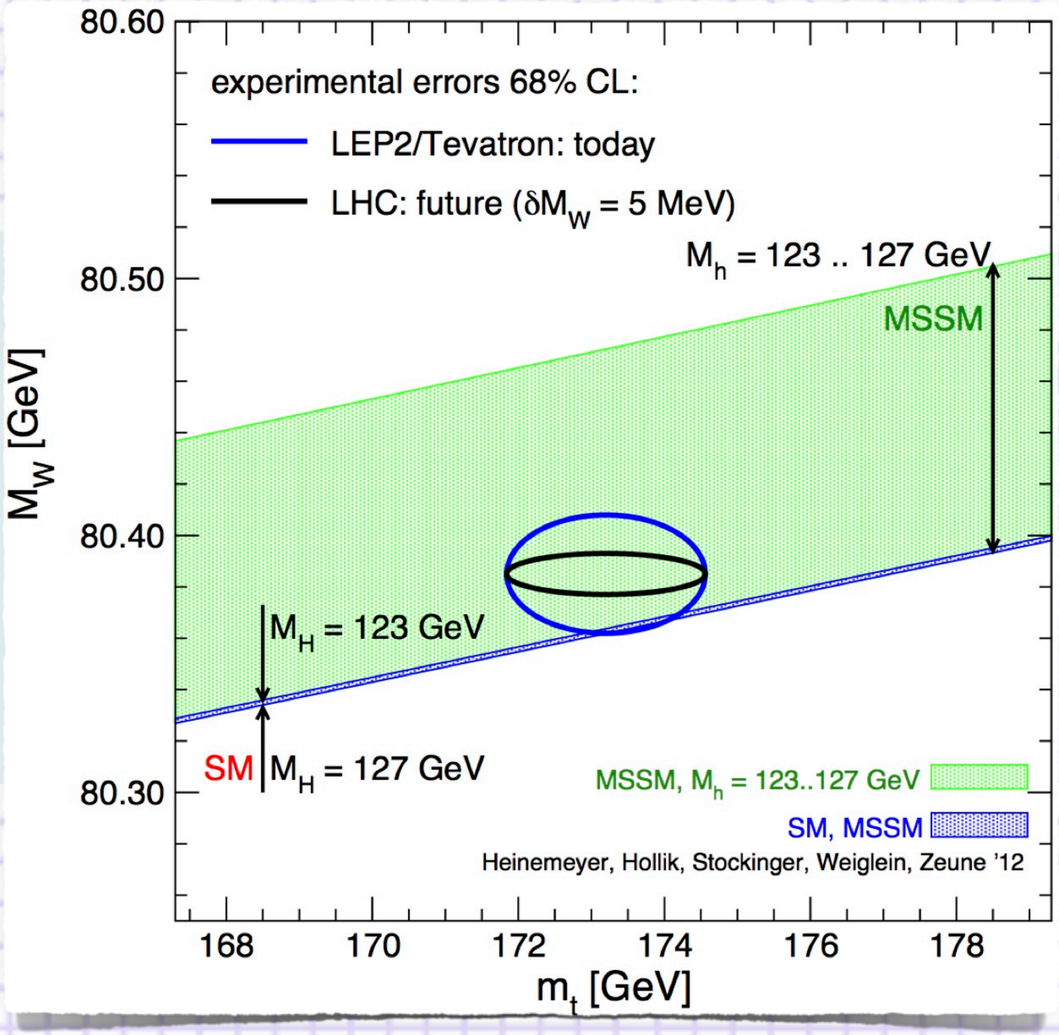

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SUSY is 'hiding'

- so far mainly covered 'standard' searches with our analysis strategies
- only recently we started to think 'outside the box' when it comes to SUSY searches
- **What if SUSY is hiding in plain sight and our analyses are not sensitive?**

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- But even the best analyses have blind spots.
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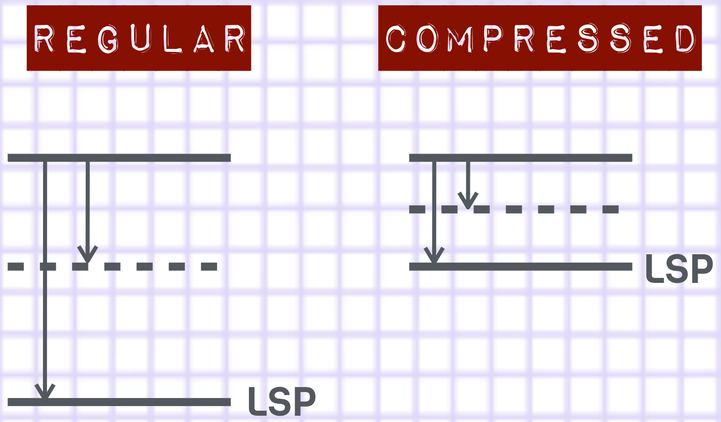

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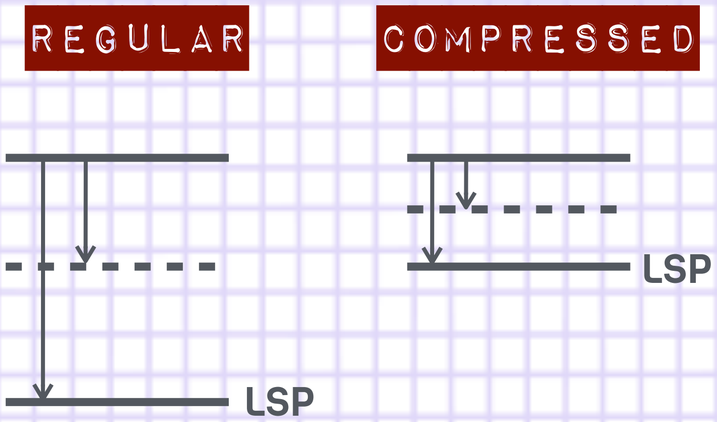
  - reconstruction might fail
  - might not even fire the trigger
- Obviously we need dedicated analyses!
- But our exclusion plots…?



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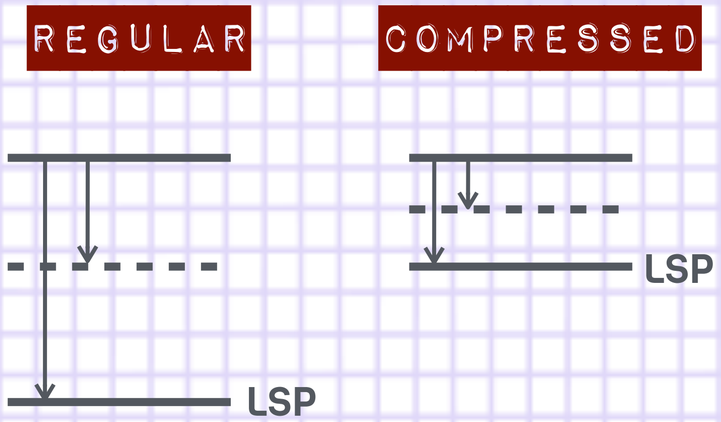

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“How are searches performed in those compressed mass hierarchy scenarios?”

Compressed SUSY Scenario 1

PLB 759 (2016) 9

- signature: soft leptons, low jet multiplicity, MET
- low ΔM (< 80 GeV) leads to 4-body decay
- 3 decay channels (W decay)
  - 0 leptons: BR 55%, huge irreducible background Z -> νν, W -> lν
  - 1 lepton: BR 38%, background from W -> lν
  - 2 lepton: BR 7%, being worked on
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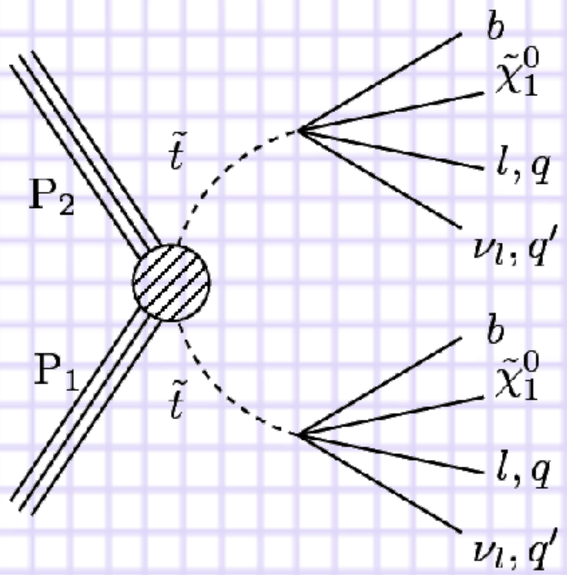

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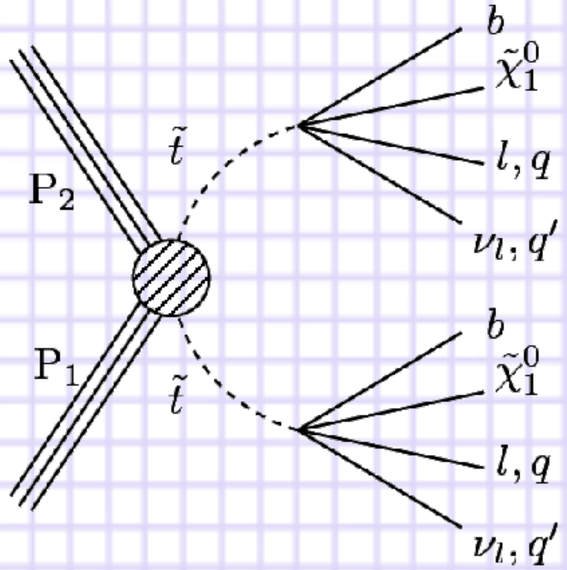

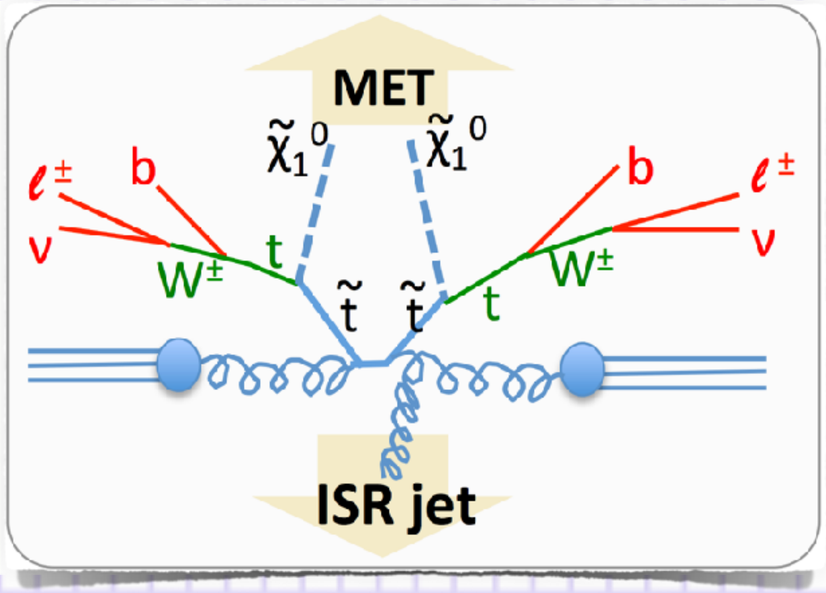

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- MET > 200 GeV (driven by trigger turn-on)
- p_T(jet1) > 150 GeV (driven by trigger turn-on)
- p_T(jet3) > 60 GeV, mono-jet and dijet events
- b-jet veto, signal b-jet: p_T < 30 GeV
- N(lep) = 2, Nμ >0, opposite sign μμ, eμ channels
- p_T(l1): [5(7), 25] GeV
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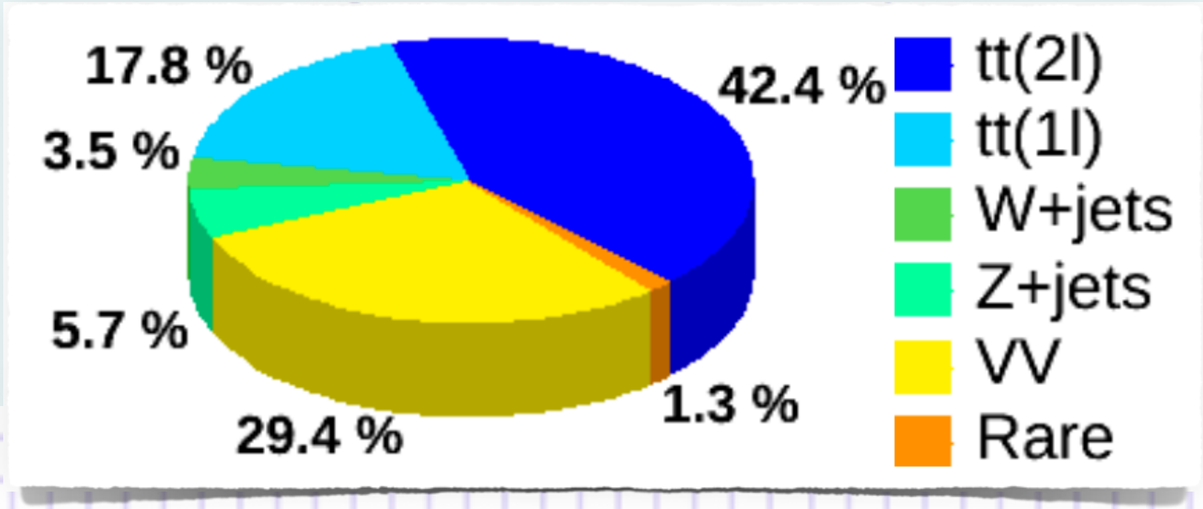
- SR region: 8 events (simulation)
- background composition:



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low pT bin most sensitive

Background	$p_T(\ell_1)$: 5–15 GeV	$p_T(\ell_1)$: 15–25 GeV	Inclusive
$t\bar{t}(2\ell)$	0.75 ±0.19	2.08 ±0.37	2.84 ±0.42
$t\bar{t}(1\ell)$,W+jets	0.60 ±0.33	1.32 ±0.69	1.92 ±0.76
Z/γ^*+jets	<0.30	0.48 ±0.45	0.48 ±0.45
VV	0.74 ±0.27	1.61 ±0.48	2.35 ±0.55
Rare backgrounds	0.03 ±0.01	0.08 ±0.04	0.11 ±0.04
Total SM	2.12 ±0.47	5.6 ±1.0	7.7 ±1.1
$\tilde{t}\tilde{t}$ signal (250,230)	10.0 ±1.5	3.41 ±0.90	13.5 ±1.8
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relative systematic uncertainties

Systematic effect	$p_T(\ell_1)$: 5–15 GeV	$p_T(\ell_1)$: 15–25 GeV
Statistical uncertainty	21.9	18.3
Jet energy scale	1.0	2.8
b tagging	1.5	1.4
Electron efficiency	1.3	1.1
Muon efficiency	6.0	4.5
$t\bar{t}$ background	5.1	5.4
NP background	10.1	5.6
Z/γ^* background	0.0	2.3
VV background	8.0	2.6
Rare backgrounds	3.7	3.3
Total uncertainty	26.9	21.1

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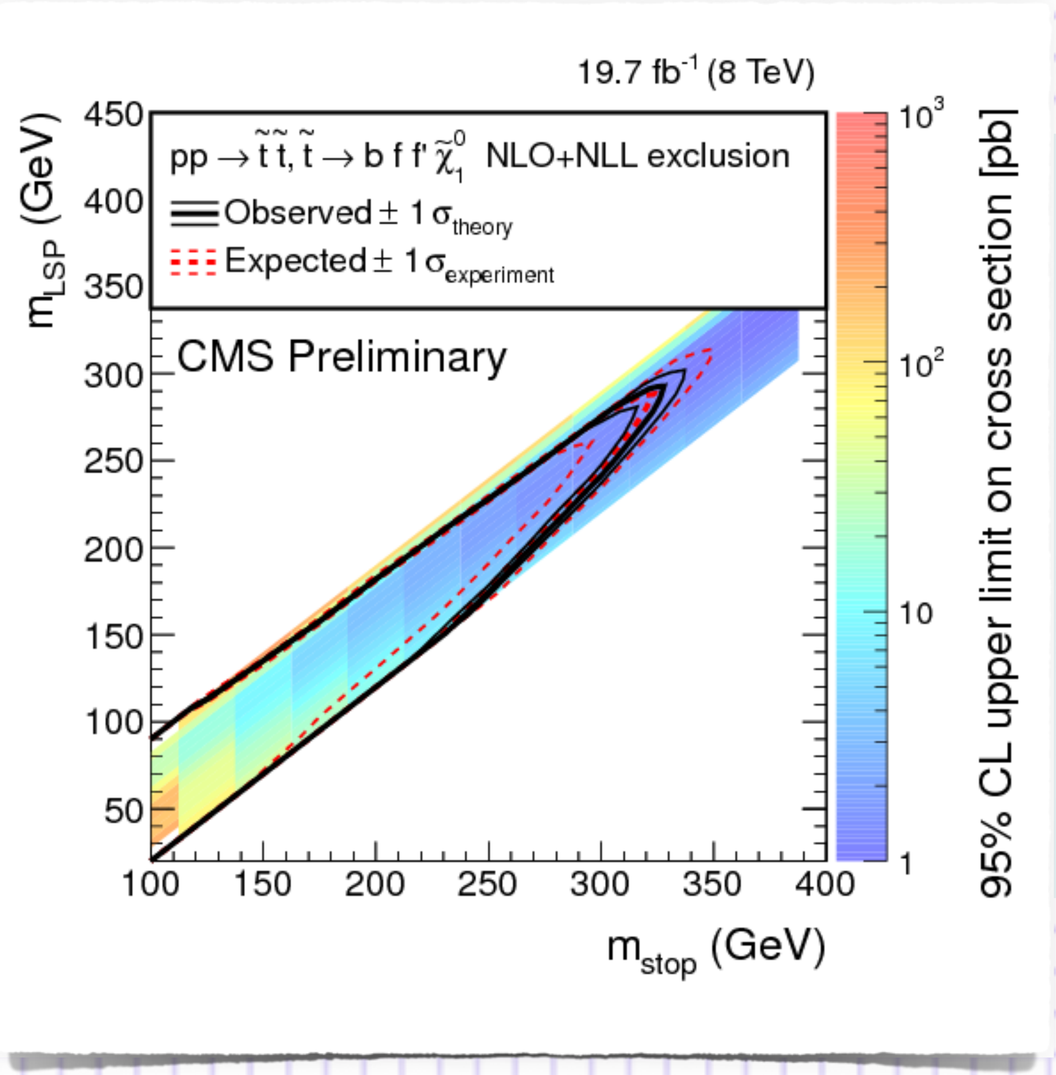

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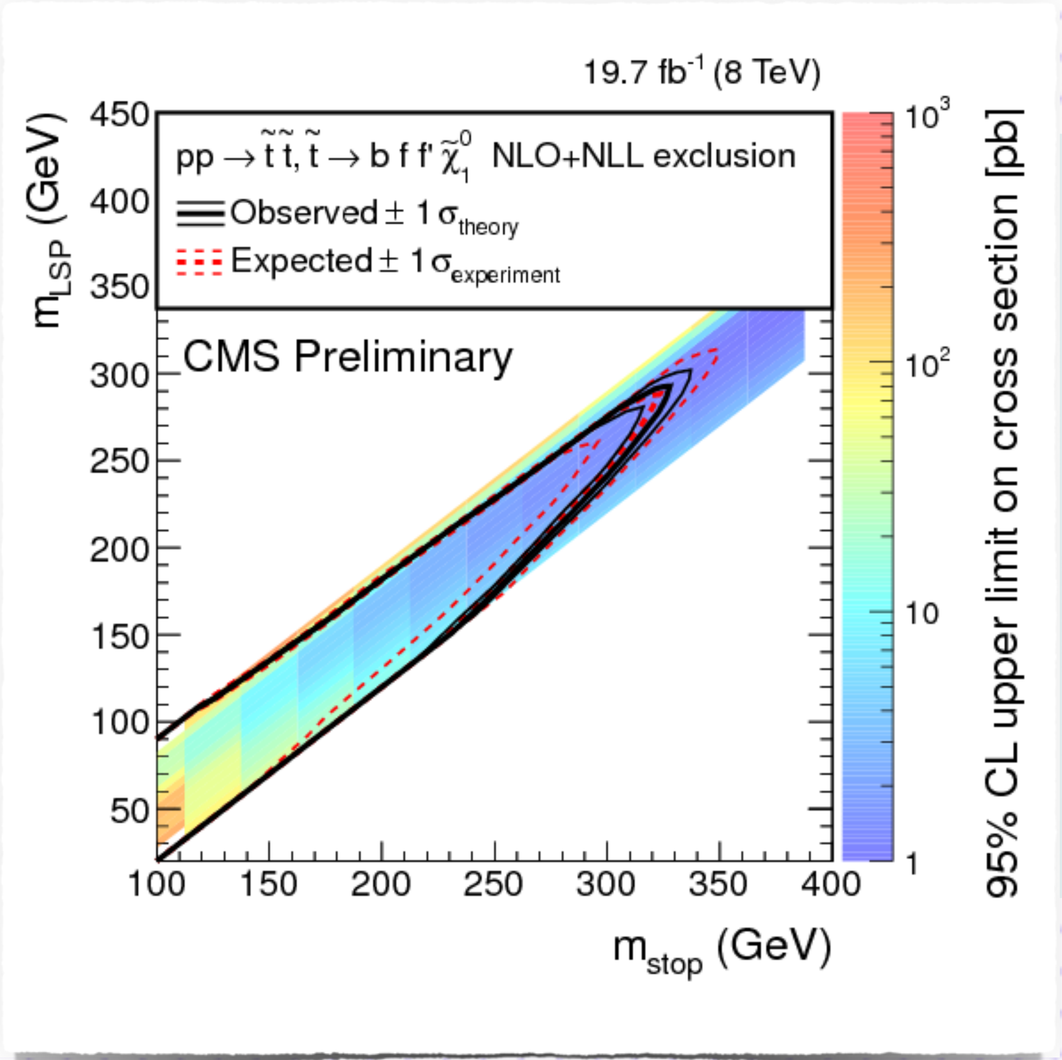

Compressed SUSY Scenario 2

JHEP 11 (2015) 189

- general idea: access compressed stau SUSY by tagging vector boson fusion (VBF) jets
- VBF production (2 examples shown) yields 2 high-pT jets in opposite hemispheres of the detector with large separation in η
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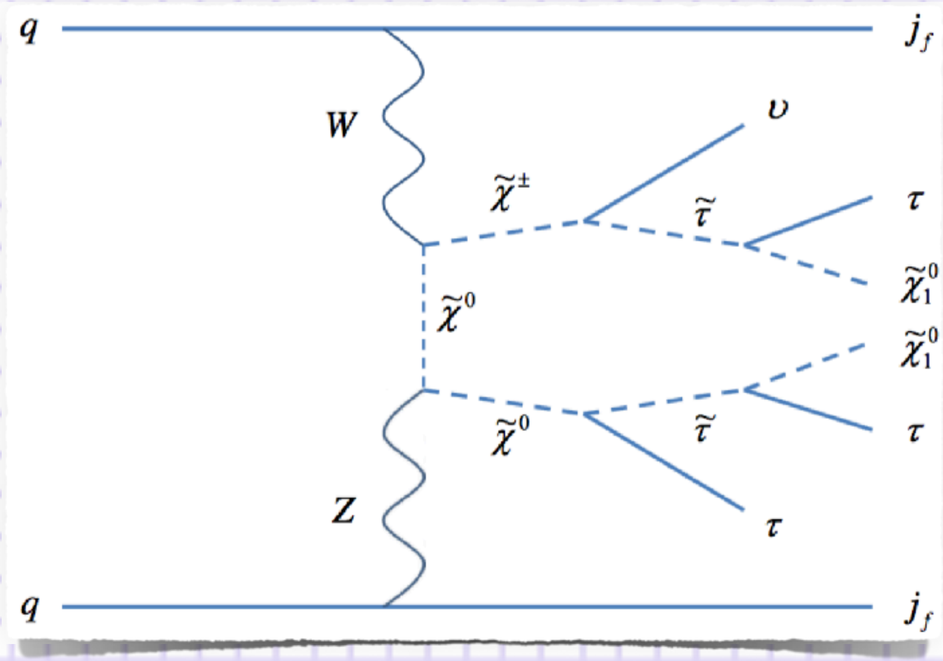

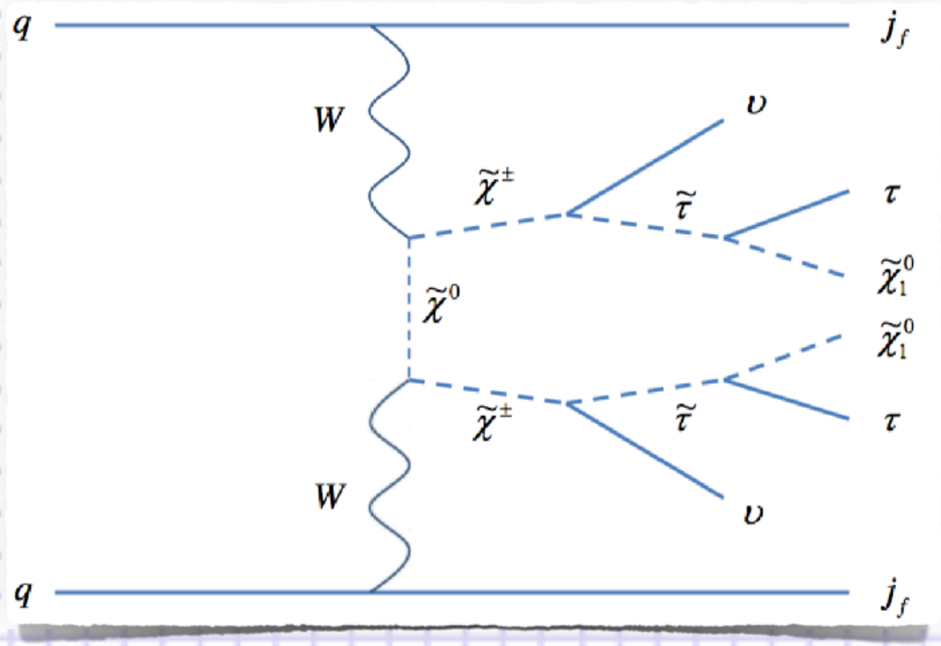

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Process	$\mu^{\pm}\mu^{\mp}jj$	$e^{\pm}\mu^{\mp}jj$	$\mu^{\pm}\tau_h^{\mp}jj$	$\tau_h^{\pm}\tau_h^{\mp}jj$
DY + jets	4.3 ± 1.7	$3.7\pm^{2.1}_{1.9}$	19.9 ± 2.9	12.3 ± 4.4
W + jets	< 0.01	$4.2\pm^{3.3}_{2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0\pm^{2.3}_{2.4}$	11.7 ± 2.8	–
QCD	–	–	–	6.3 ± 1.8
Higgs	1.0 ± 0.1	1.1 ± 0.5	–	1.1 ± 0.1
VBF Z	–	–	–	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1\pm^{4.6}_{4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

OS

Process	$\mu^{\pm}\mu^{\pm}jj$	$e^{\pm}\mu^{\pm}jj$	$\mu^{\pm}\tau_h^{\pm}jj$	$\tau_h^{\pm}\tau_h^{\pm}jj$
DY + jets	< 0.01	$0\pm^{1.7}_{0}$	0.5 ± 0.2	< 0.01
W + jets	$0.1 \pm 8.2 \times 10^{-4}$	$0\pm^{3.0}_{0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9\pm^{0.4}_{0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5\pm^{0.7}_{0.9}$	6.7 ± 2.8	$0.1 \pm 1.2 \times 10^{-2}$
Single top	–	–	–	< 0.1
QCD	–	–	–	7.6 ± 0.9
Higgs	–	–	–	< 0.01
Total	5.4 ± 0.3	$5.4\pm^{3.5}_{0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9

SS

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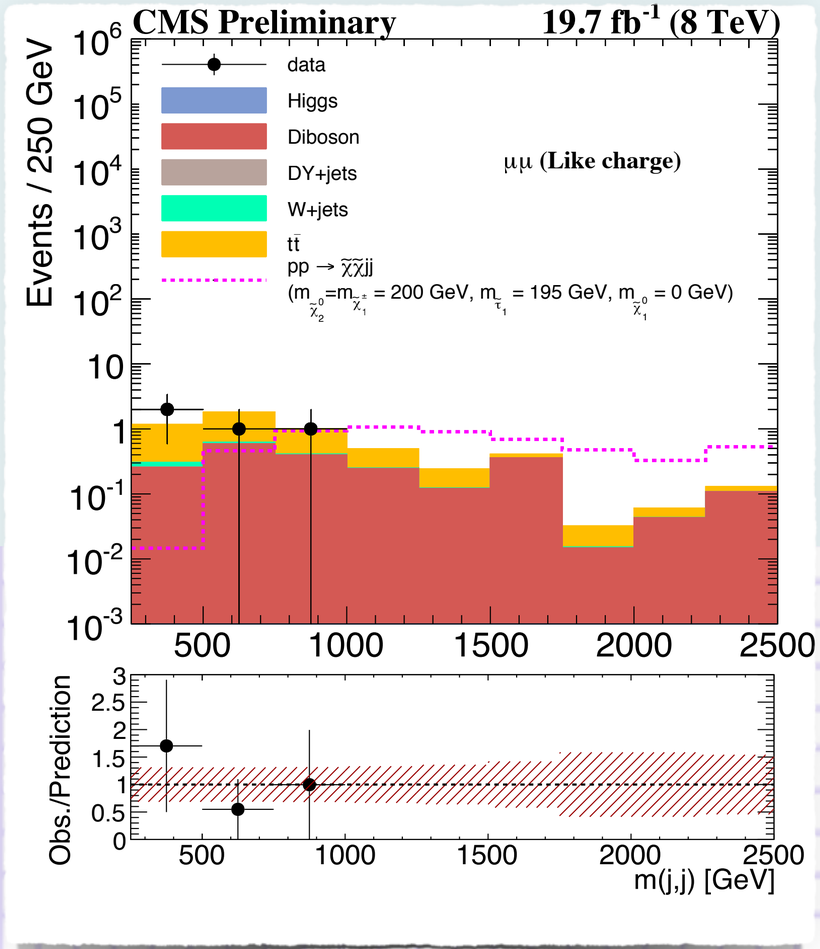

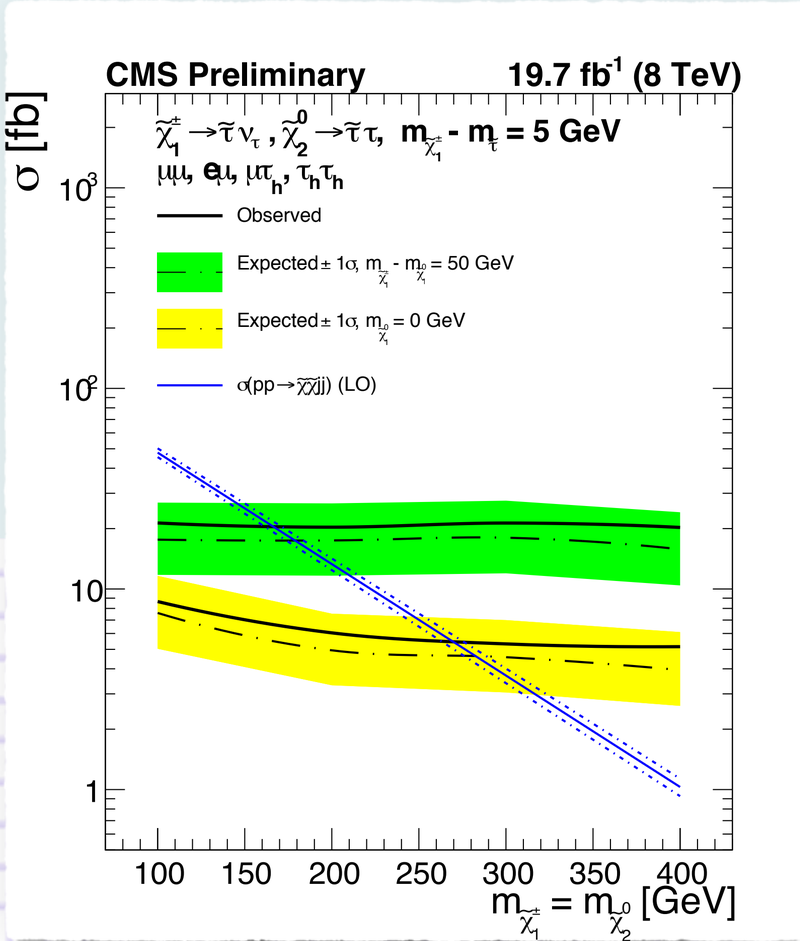

Non-SUSY Dark Matter Searches

Let’s start from first principles: We have no clue what DM is!

“How do we search for something that doesn’t interact and we don’t know what it is?”

Collider Dark Matter Searches

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The Problem With Non-interacting Particles

- assuming a generic DM particle pair production
- Such a process leaves no detector activity!
- Impossible to trigger on, let alone reconstruct.

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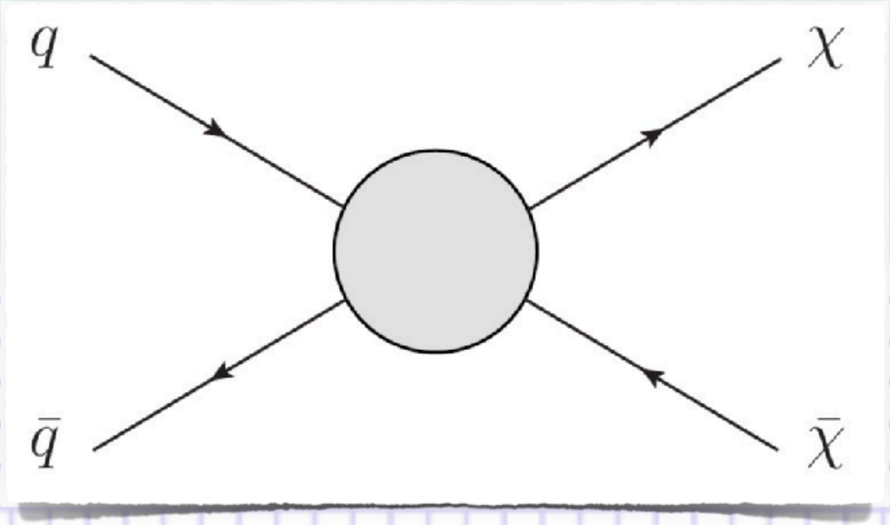

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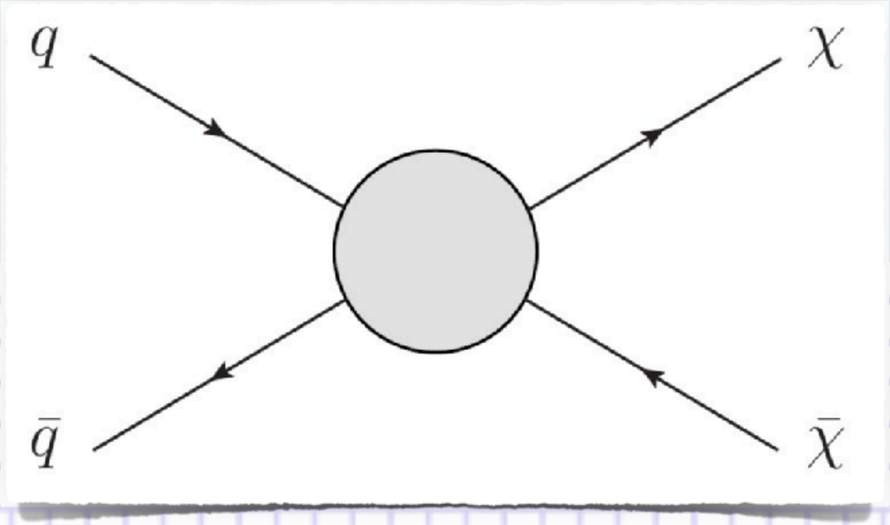

Make Non-interacting Particles 'Visible'

- Require that DM particles recoil against 'something'.
- Mono-X searches (MET + X)
- X: jets, photons, W/Z, Higgs, heavy-flavour

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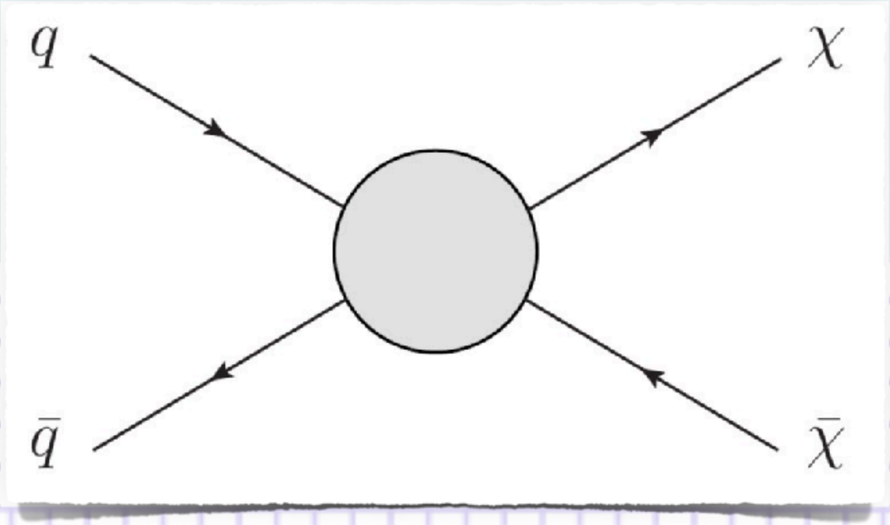

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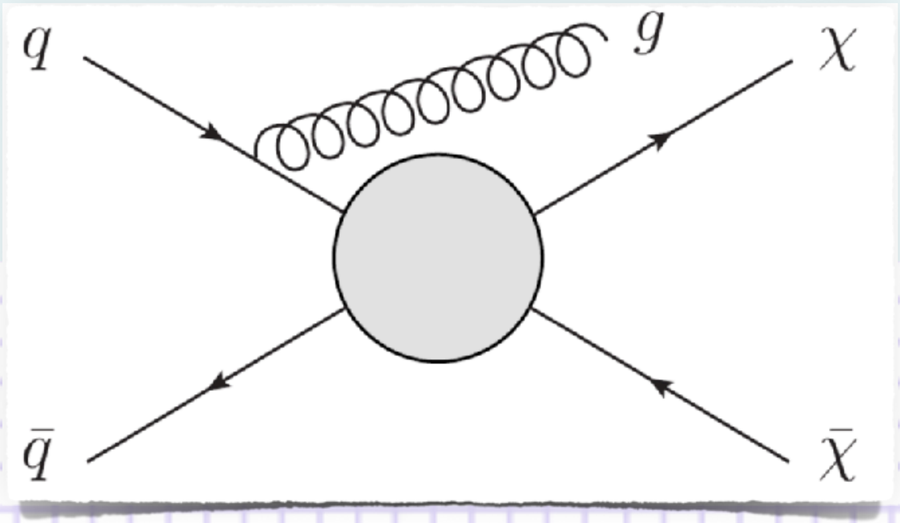

“

Well, we still need to plug in some sort of model, don’t we?

”

Collider Dark Matter Searches: Simplified Models

(A. Albert, ICHEP)

Collider Dark Matter Searches: Simplified Models

Spin-1 Mediator

(A. Albert, ICHEP)

Collider Dark Matter Searches: Simplified Models

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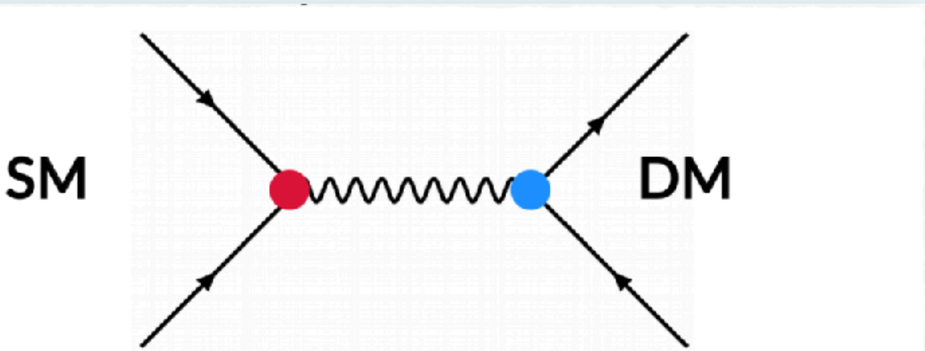
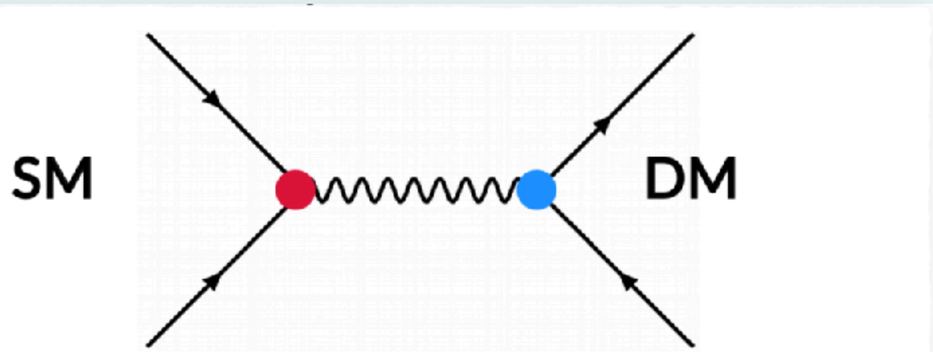


$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q$$

(A. Albert, ICHEP)

Collider Dark Matter Searches: Simplified Models

Spin-1 Mediator



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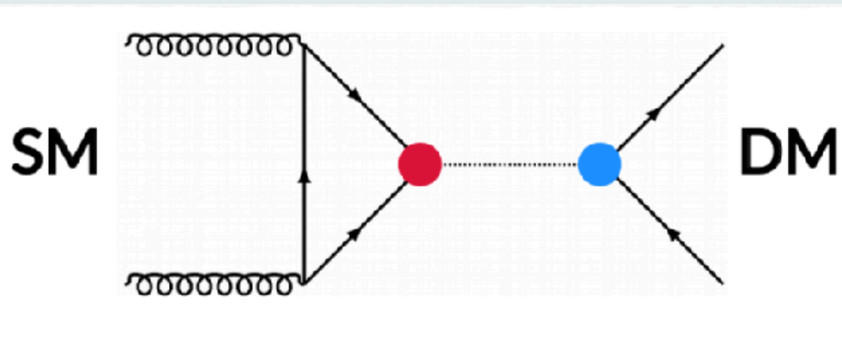
Spin-0 Mediator



$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}q$$

(A. Albert, ICHEP)

Collider Dark Matter Searches: Simplified Models

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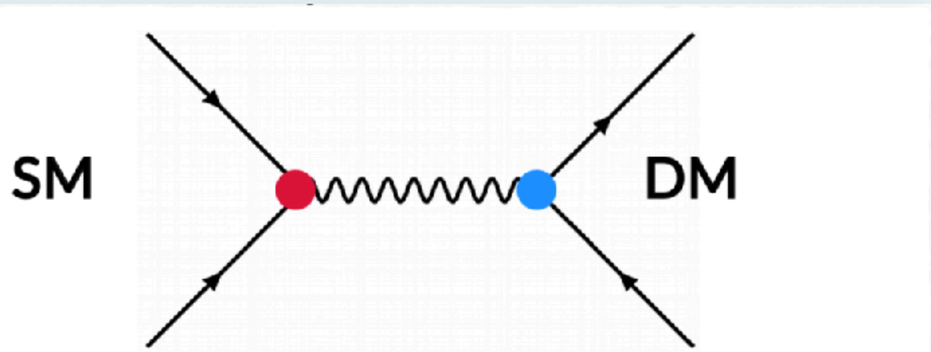

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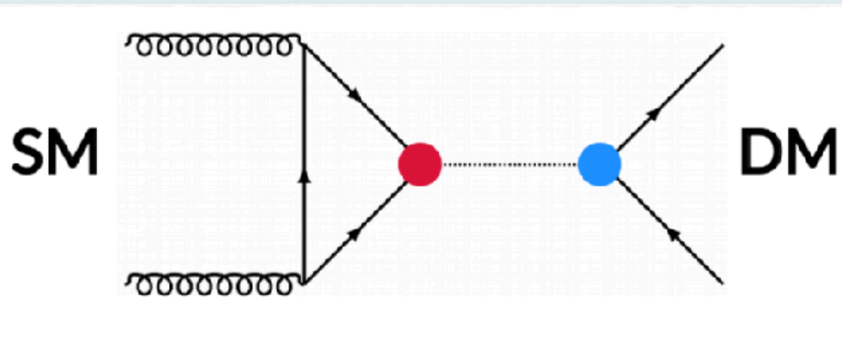

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- Model Parameters: mediator mass, DM particle mass, mediator-quark coupling, mediator-DM coupling
- minimal flavour violation
- benchmarks defined by LHC Dark Matter working group (1603.04156)

(A. Albert, ICHEP)

CMS Mono X Searches

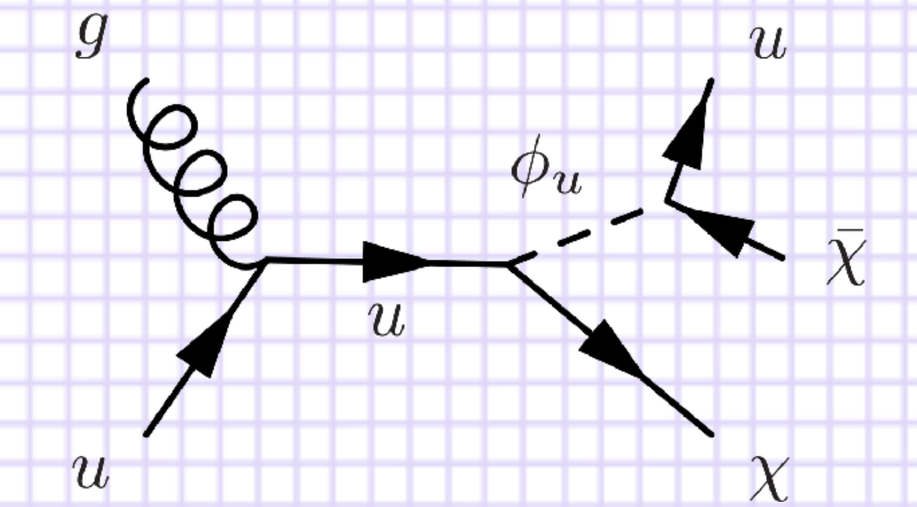
CMS Mono X Searches

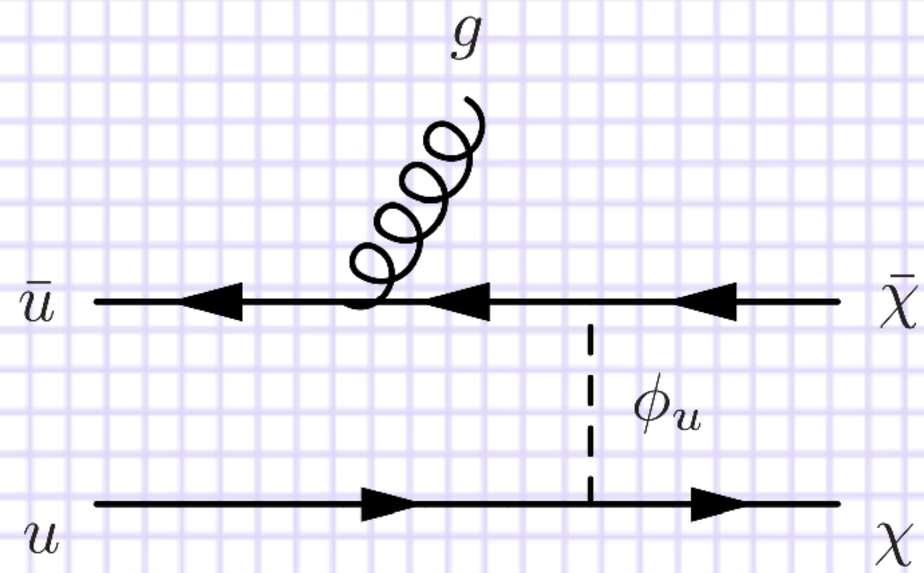
X	Dataset	Documentation
jet or hadronic V	2016, 35.9fb-1	EXO-16-048, 1712.02345
photon	2016, 12.9fb-1	EXO-16-039, 1706.03794
Z(ll)	2016, 12.9fb-1	EXO-16-038
Higgs (γγ)	2015, 2.3fb-1	EXO-16-012, 1703.05236
Higgs (bb)	2015, 2.3fb-1	EXO-16-012, 1703.05236
tt	2016, 2.3fb-1	EXO-16-028
t	2016, 12.9fb-1	EXO-16-040
b	2015, 2.2fb-1	B2G-15-007

Mono-jet Search

1712.02345

- flagship DM analysis
- results from last year
- still strongest DM limits.





Mono-jet Search: Event Selection

Mono-jet Search: Event Selection

Selection: large MET + at least one high-p_T jet

- MET > 250 GeV
- jet p_T > 100 GeV

Dominant Backgrounds

- Z(νν) + jets
- W(lν) + jets
- control regions constrain backgrounds at large MET:
  - Z(μμ), W(lν)
  - NLO + EWK γ/Z and W/Z transfer factors extrapolate CR to SR

Signal

- extract signal from binned likelihood MET fit

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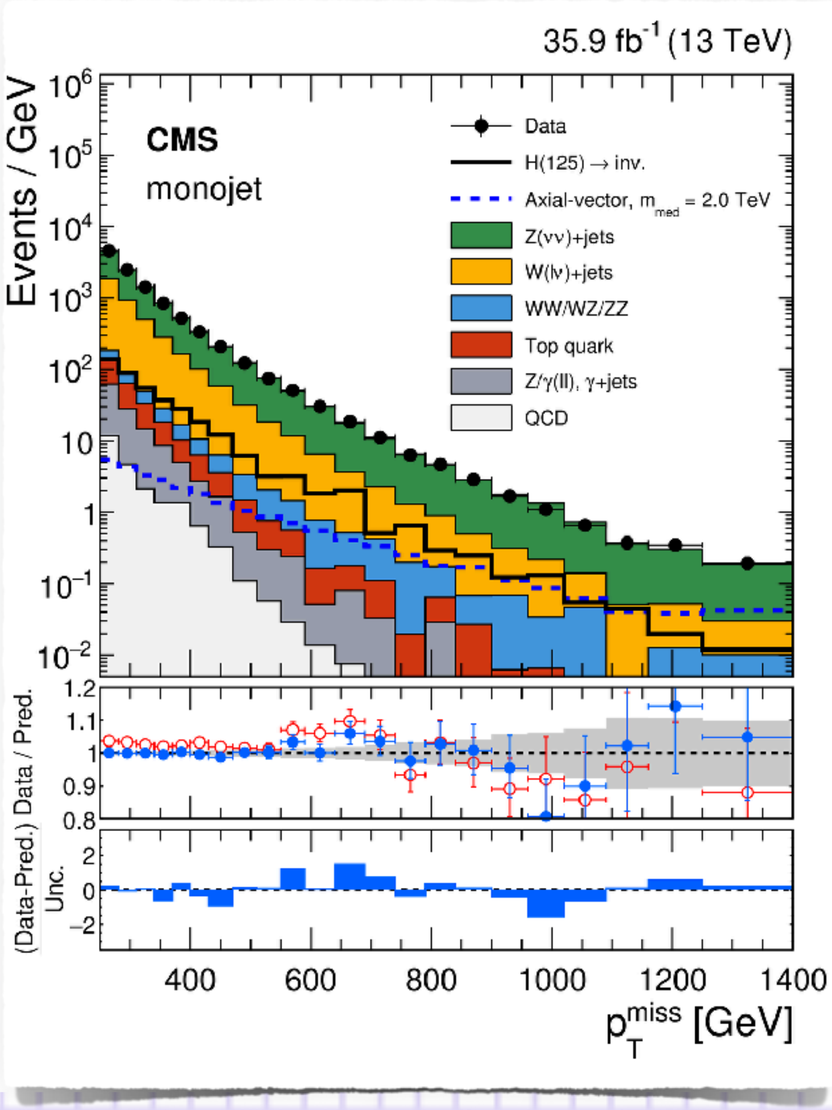
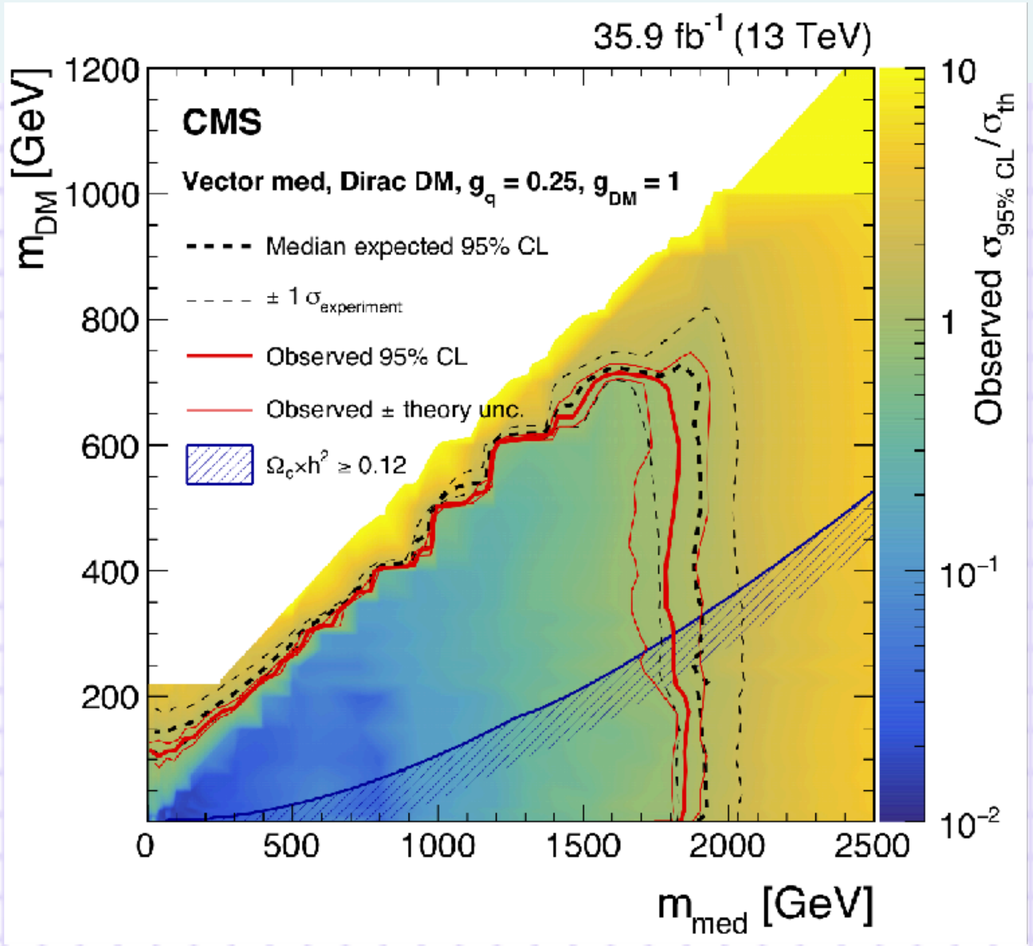
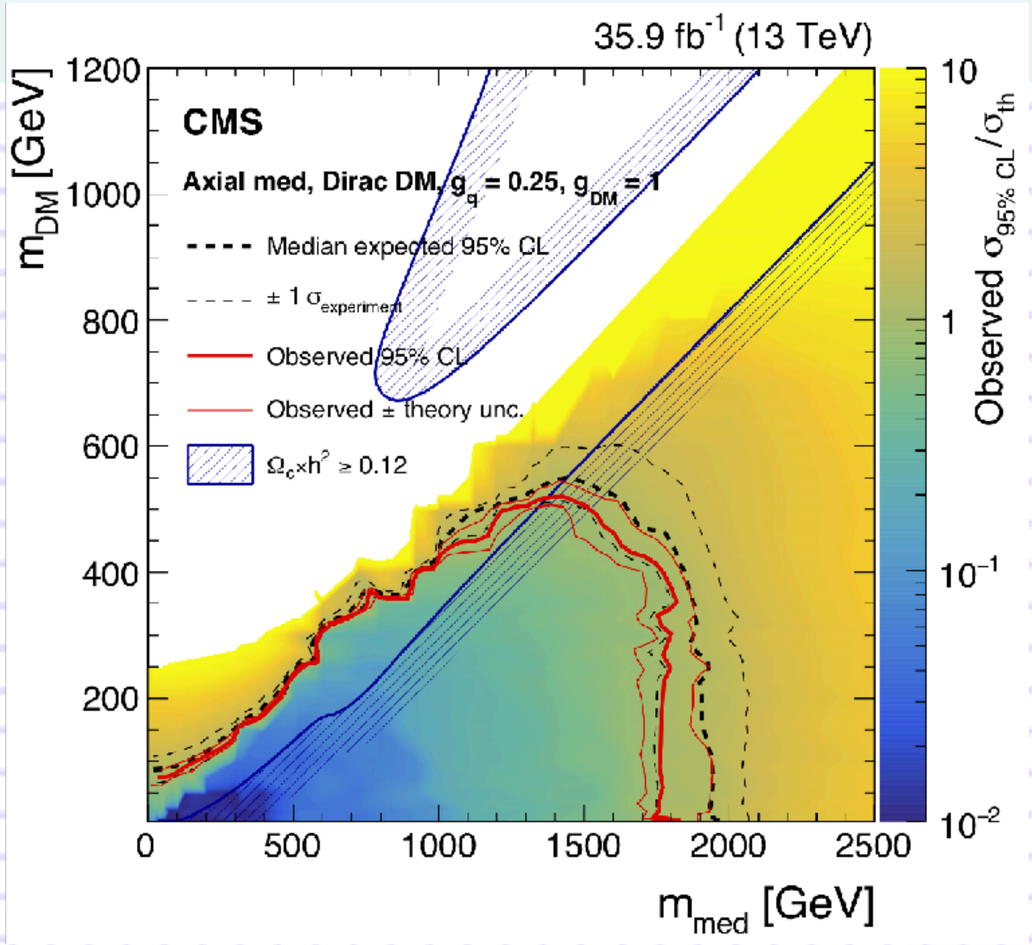


Mono-jet Search: Results

Both spin-1 and spin-0 mediators

- vector/axial exclusion up to 700 GeV/1.8 TeV
- scalar/pseudo up to 450 GeV/1.7 TeV
    - (scalar exclusion assuming mediator coupling to bosons)



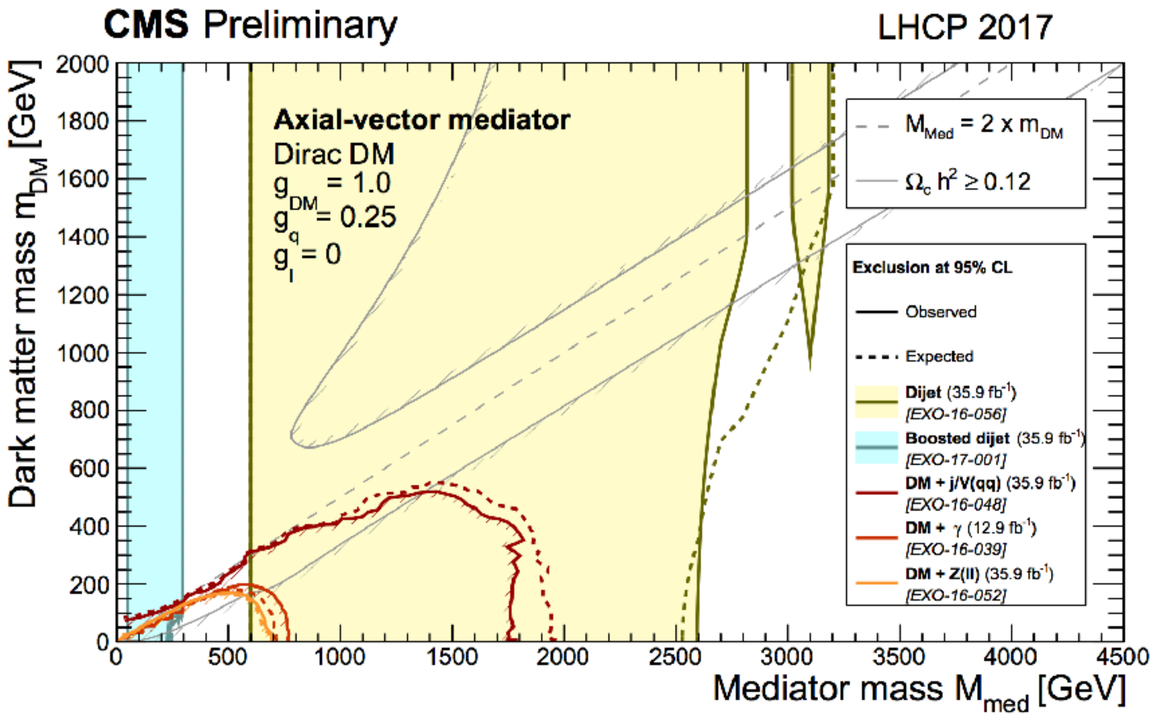


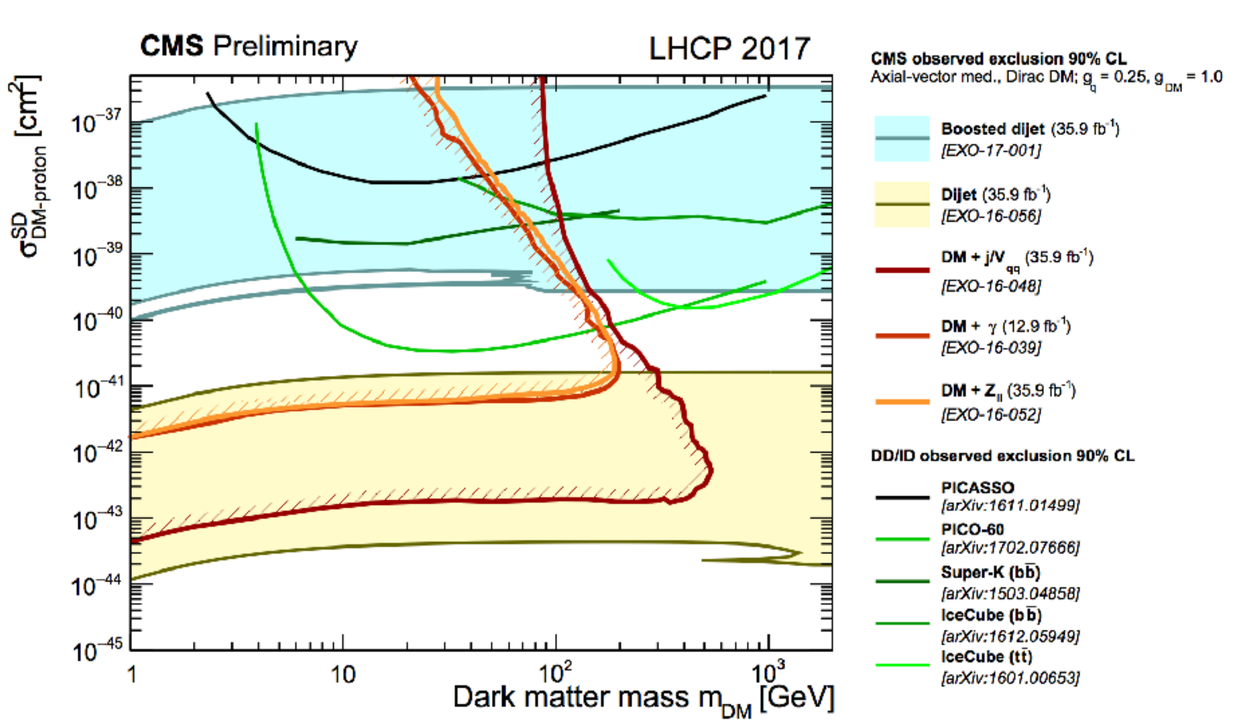
Dark Matter: Putting Everything Together

Dark Matter: Putting Everything Together

Comparison of various MET + X Channels

- here: axial vector mediator: mono-jet, mono-V, mono-Z(ll), mono-photon
  - including search for direct mediator production with diets
  - translation to SD DM-nucleon cross-section





“

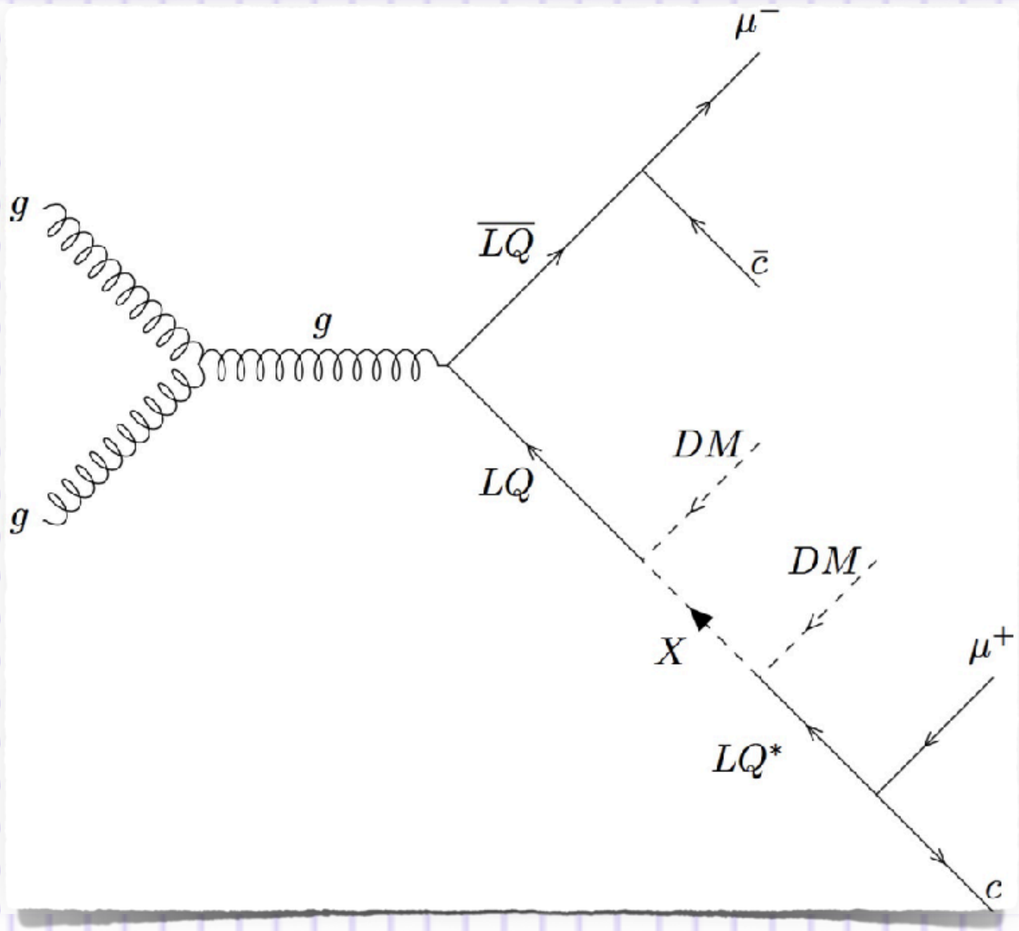
Are Mono-X Searches the only Dark Matter Searches we can perform?

”

Dark Matter from Leptoquark Decays

CMS-PAS-EXO-17-015

- one of the less conventional signatures
- co-annihilation between Majorana DM + Dirac X drives relic density
- consider small mass splitting between m_X and m_{DM} ~ 10%
- analysis based on full 2016-2017 data set: 77fb^{-1}



Dark Matter from Leptoquark Decays

Dark Matter from Leptoquark Decays

Analysis Sketch

- MT(μ, MET) > 500 GeV
- search for bump in mass of μ-jet system

Dominant Backgrounds

- W, ttbar

shape from simulation, norm from data

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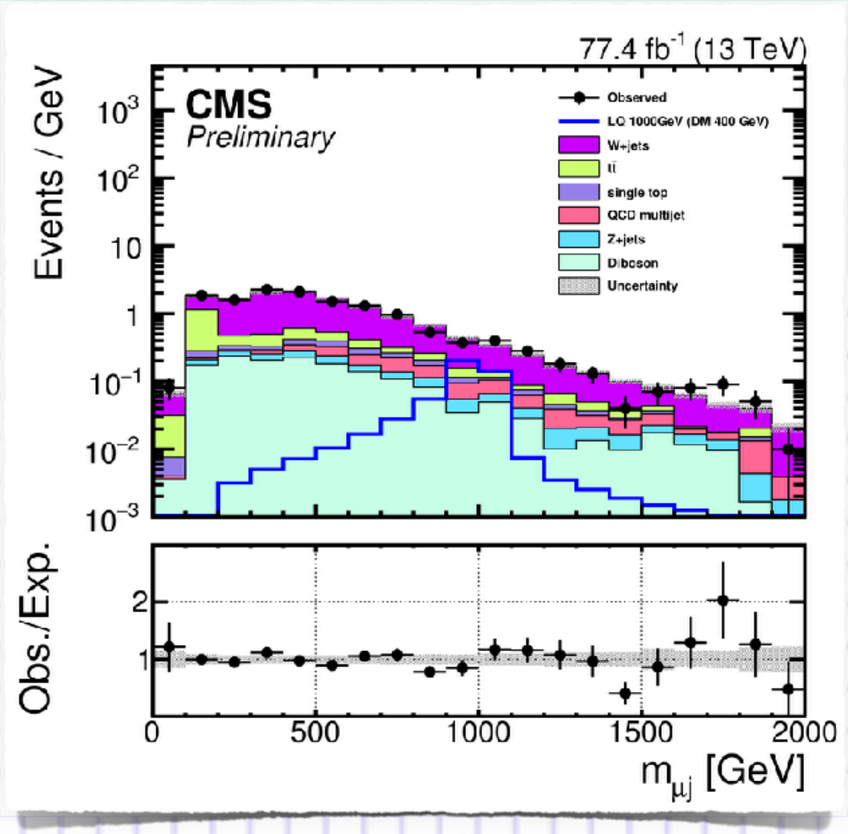

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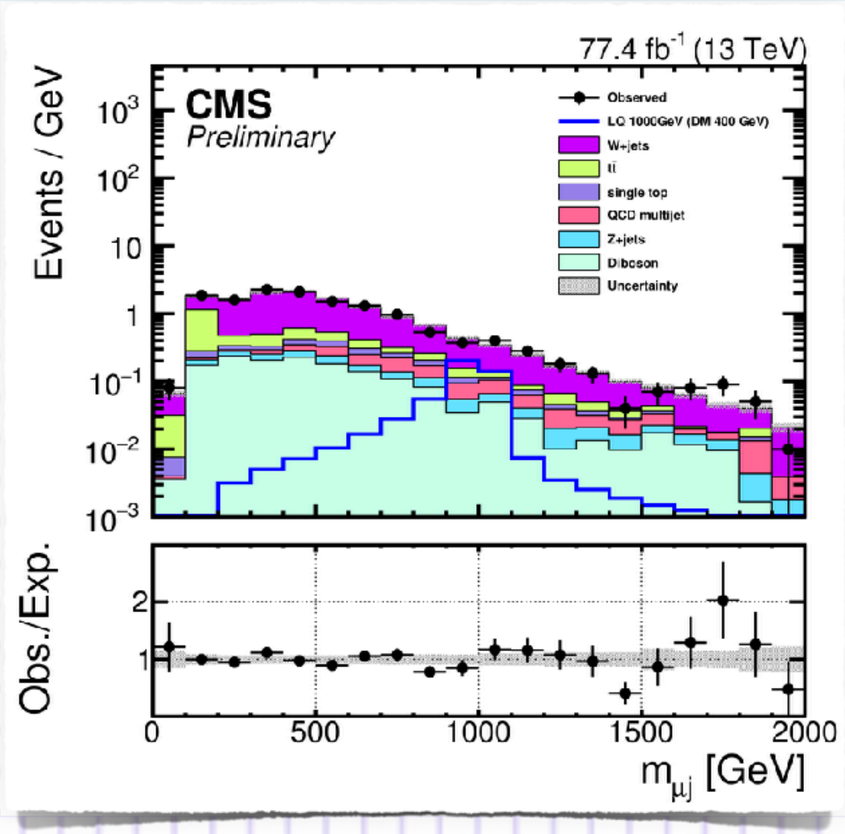

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- strong constraints from direct LQ search m_{LQ} < 820 GeV

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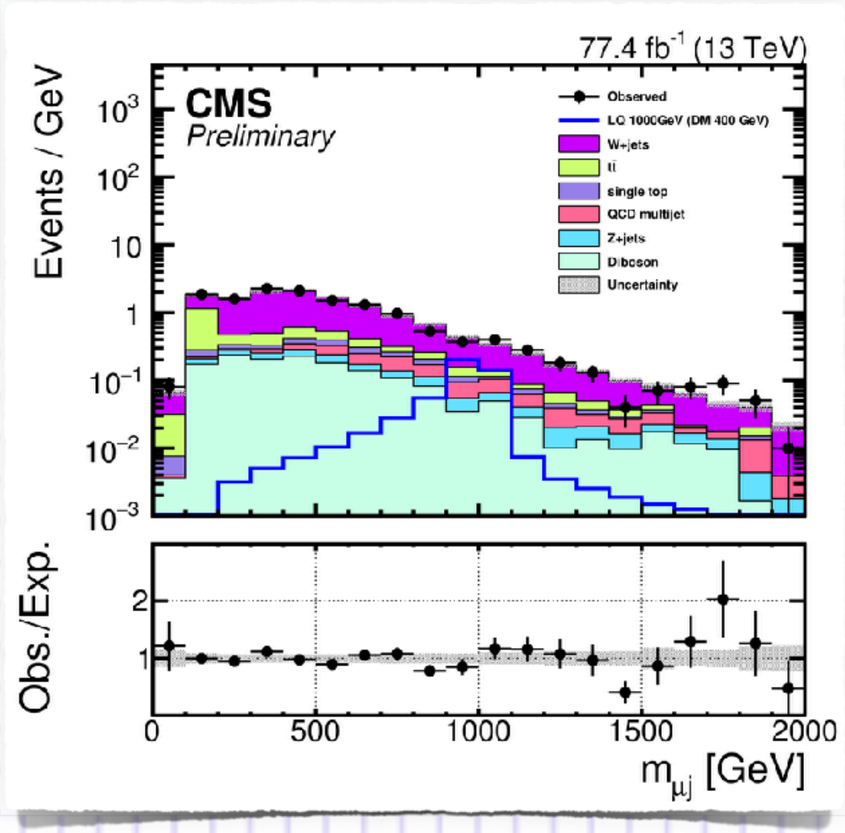

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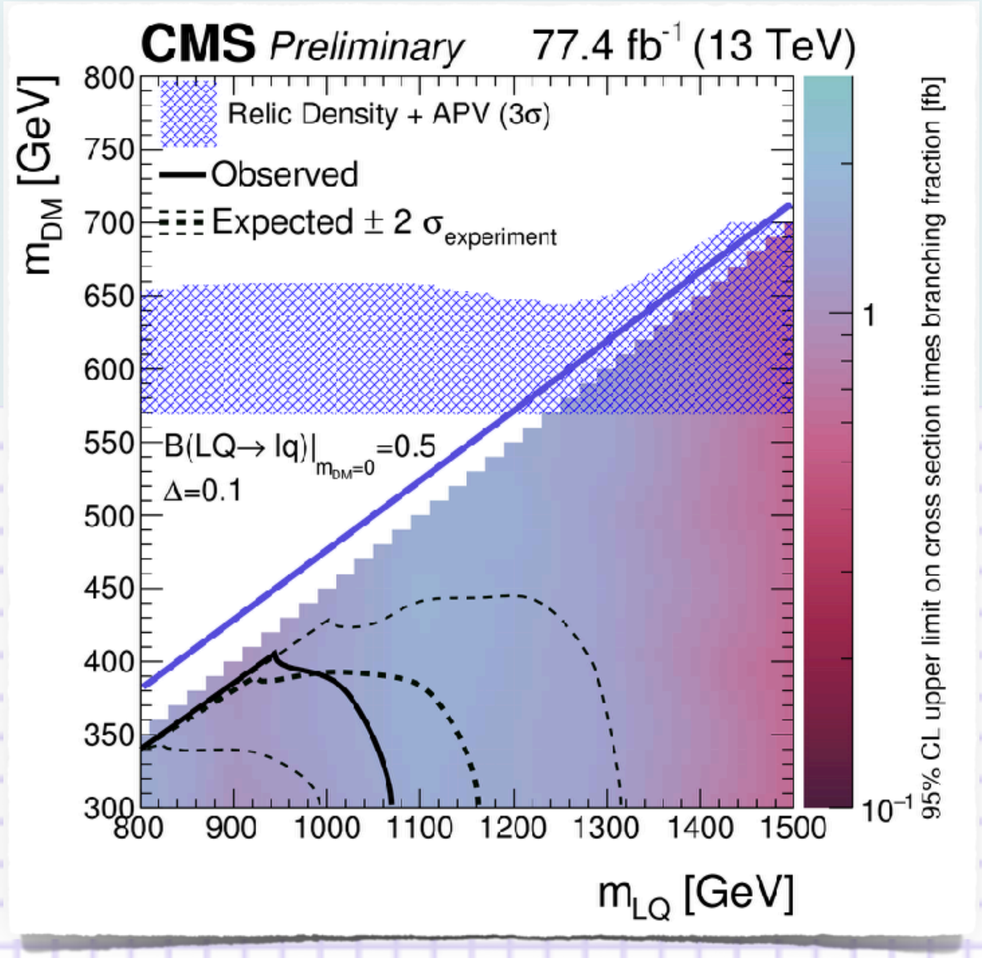
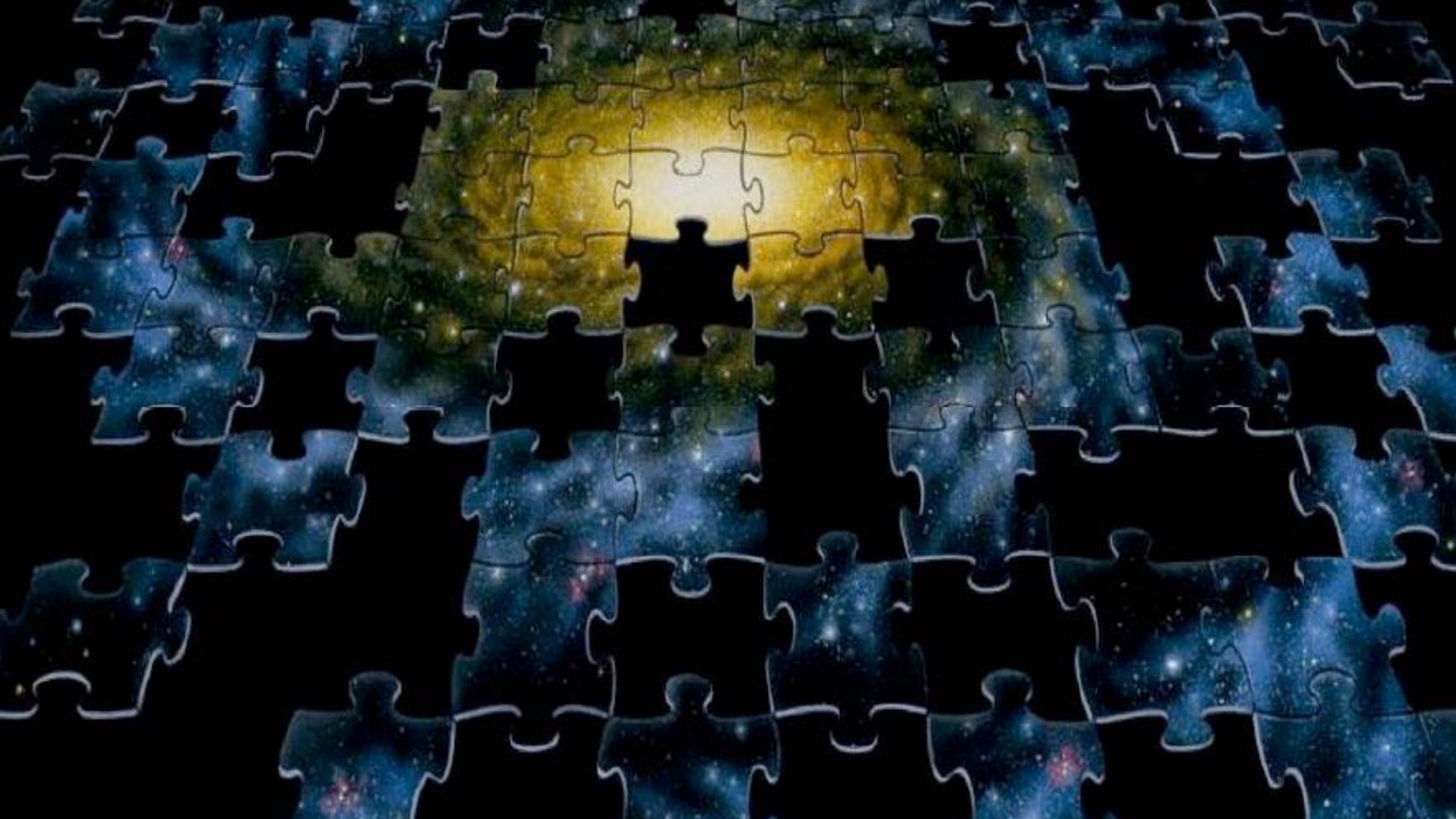
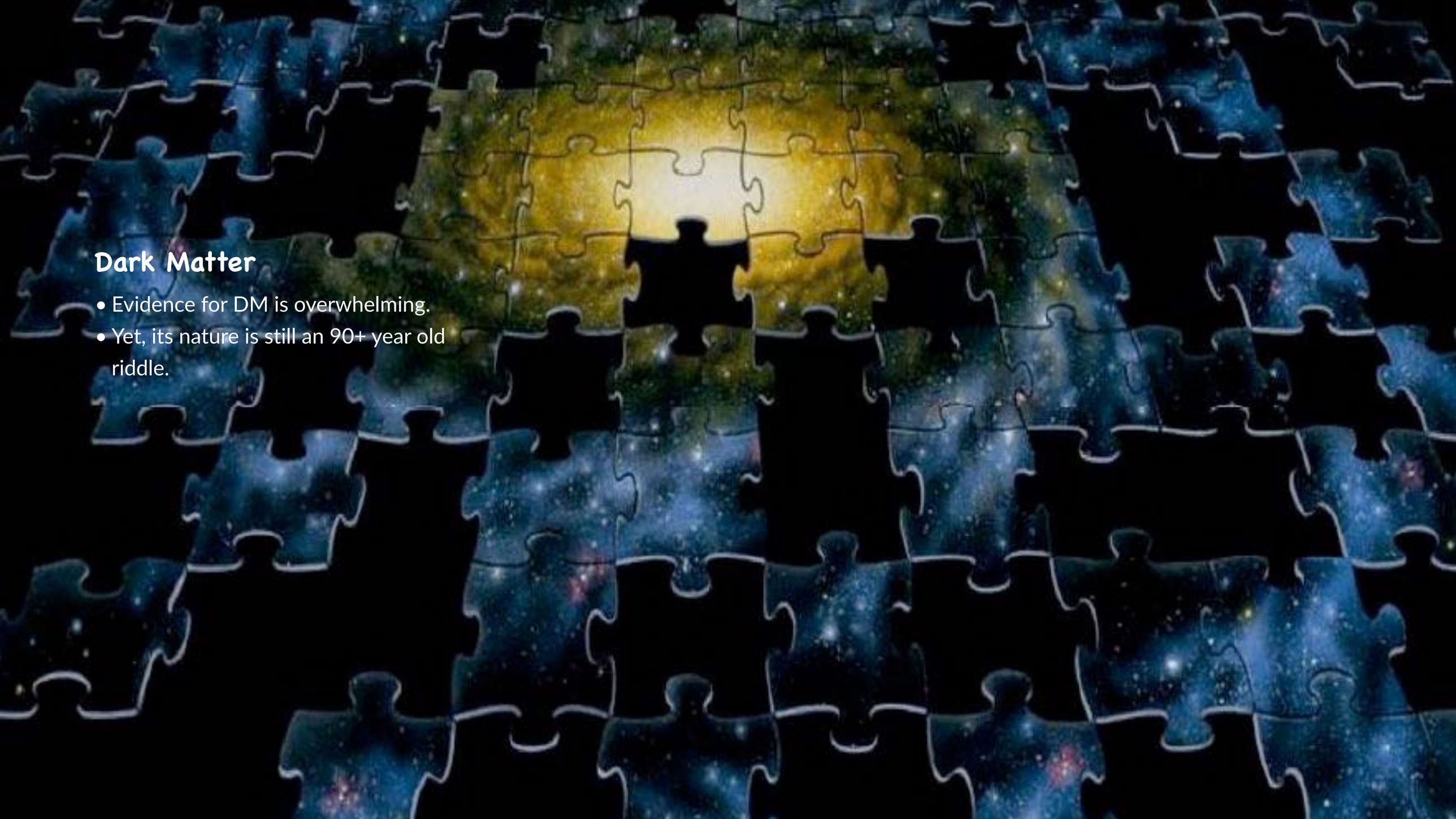


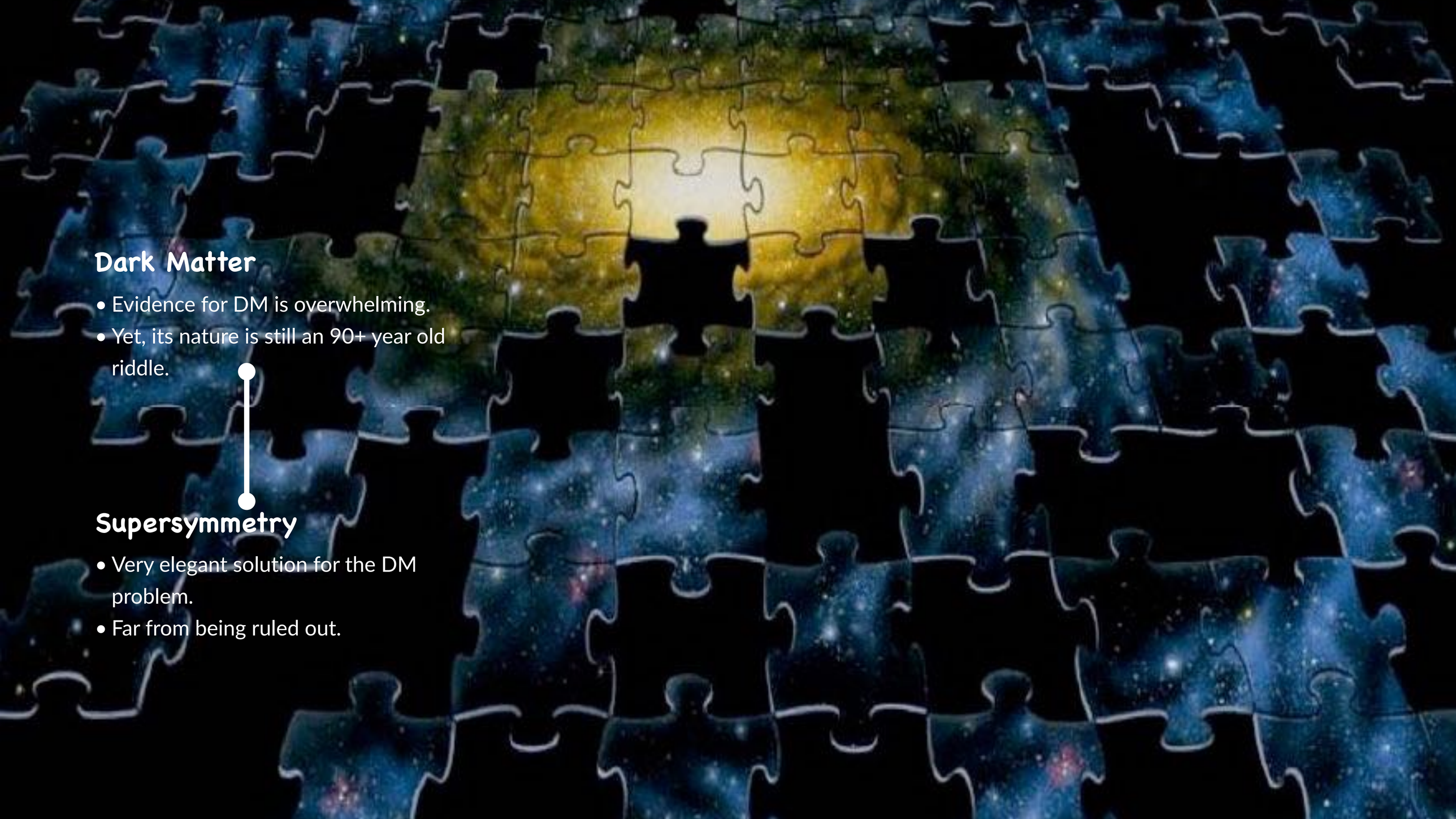
Summary/ Outlook





Dark Matter

- Evidence for DM is overwhelming.
- Yet, its nature is still an 90+ year old riddle.



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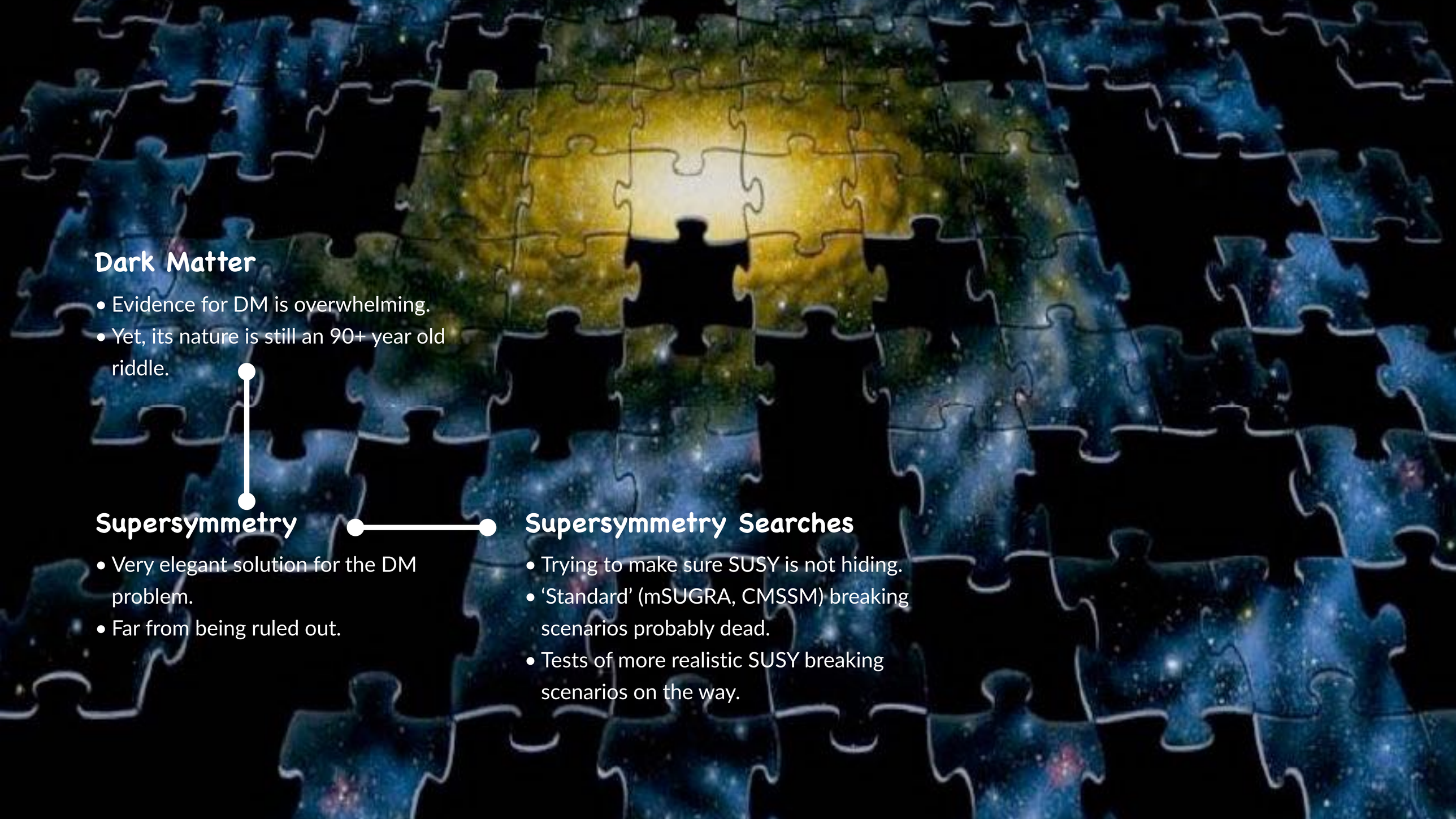
- Far from being ruled out.



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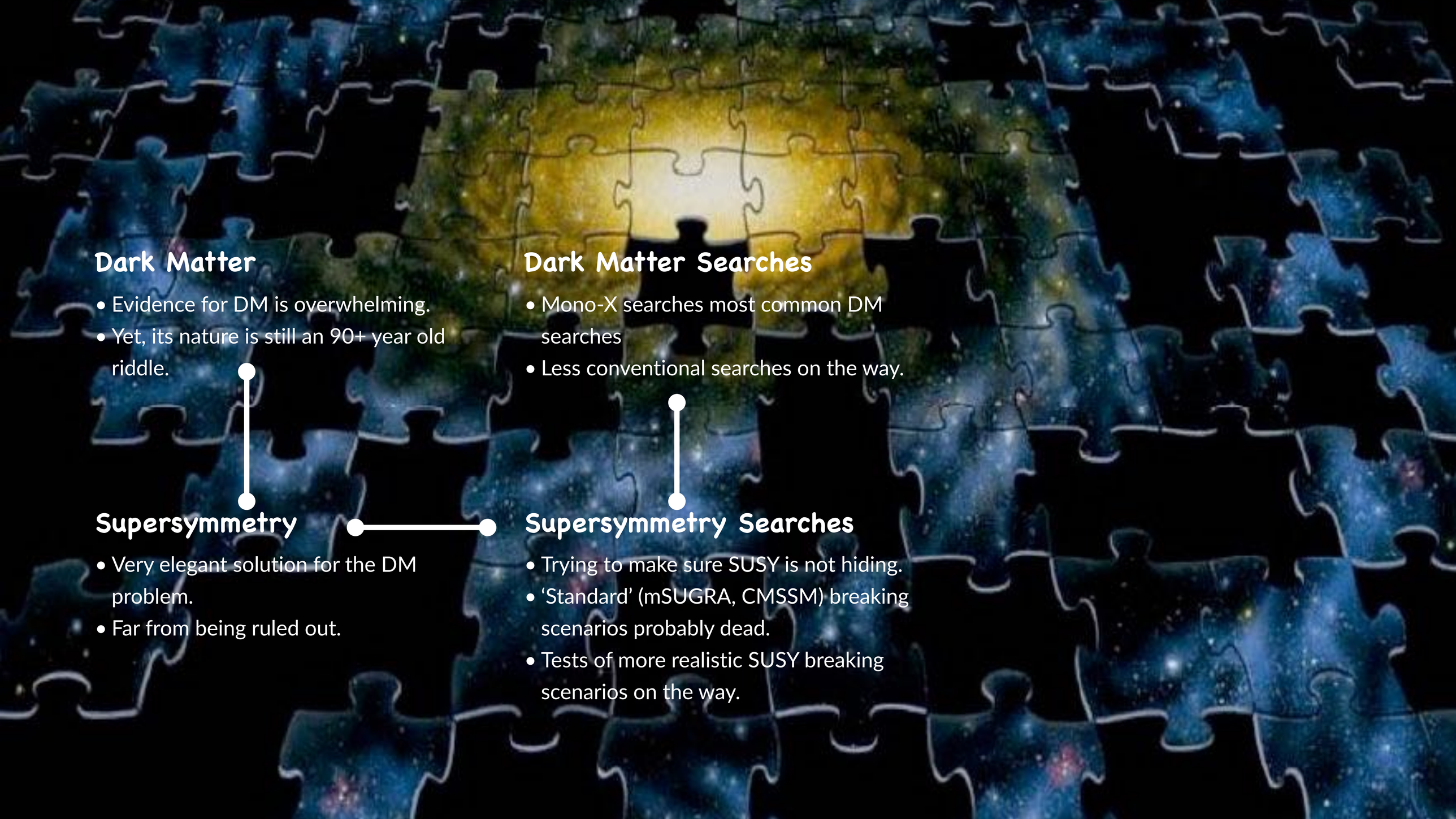
- Tests of more realistic SUSY breaking scenarios on the way.



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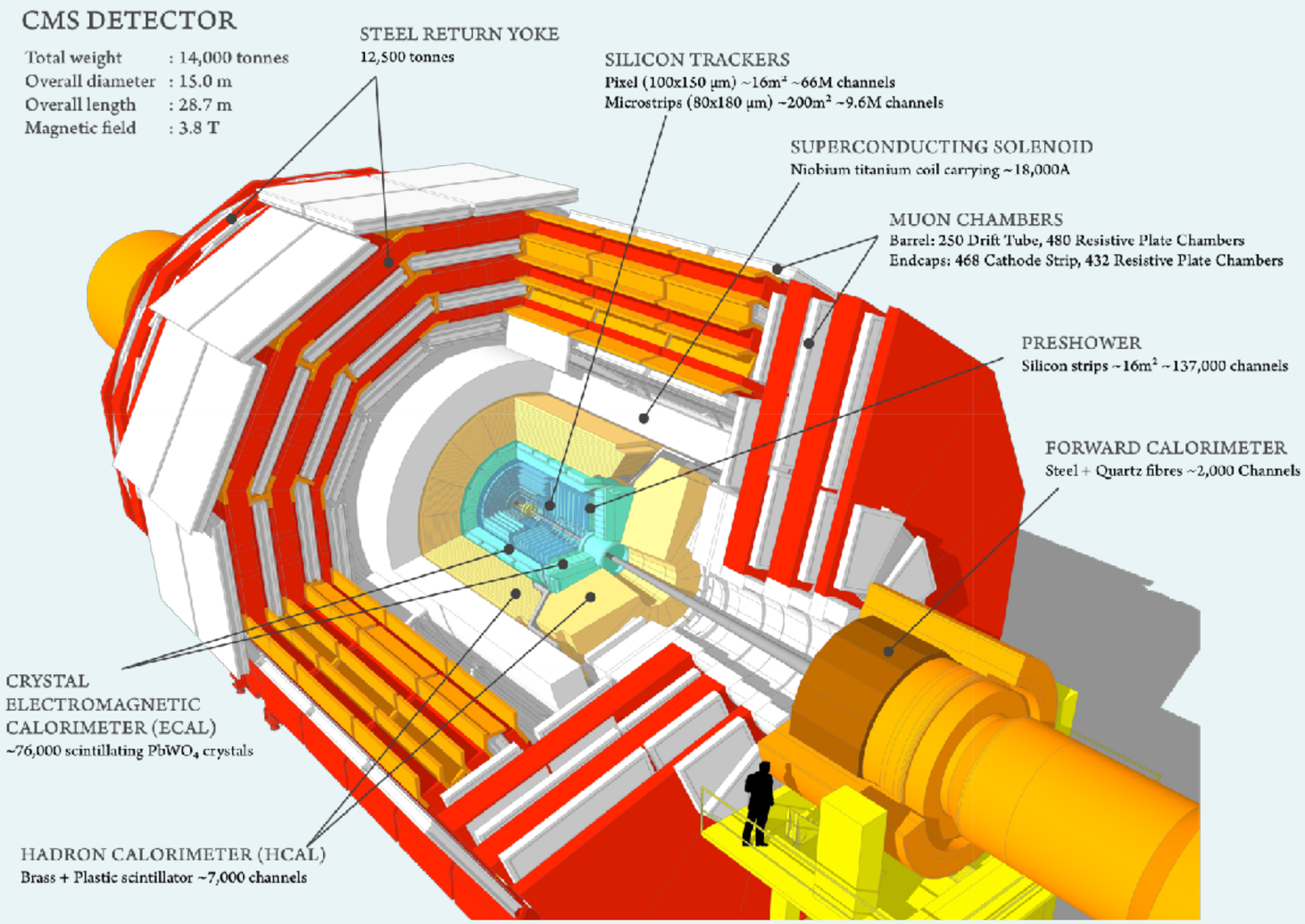
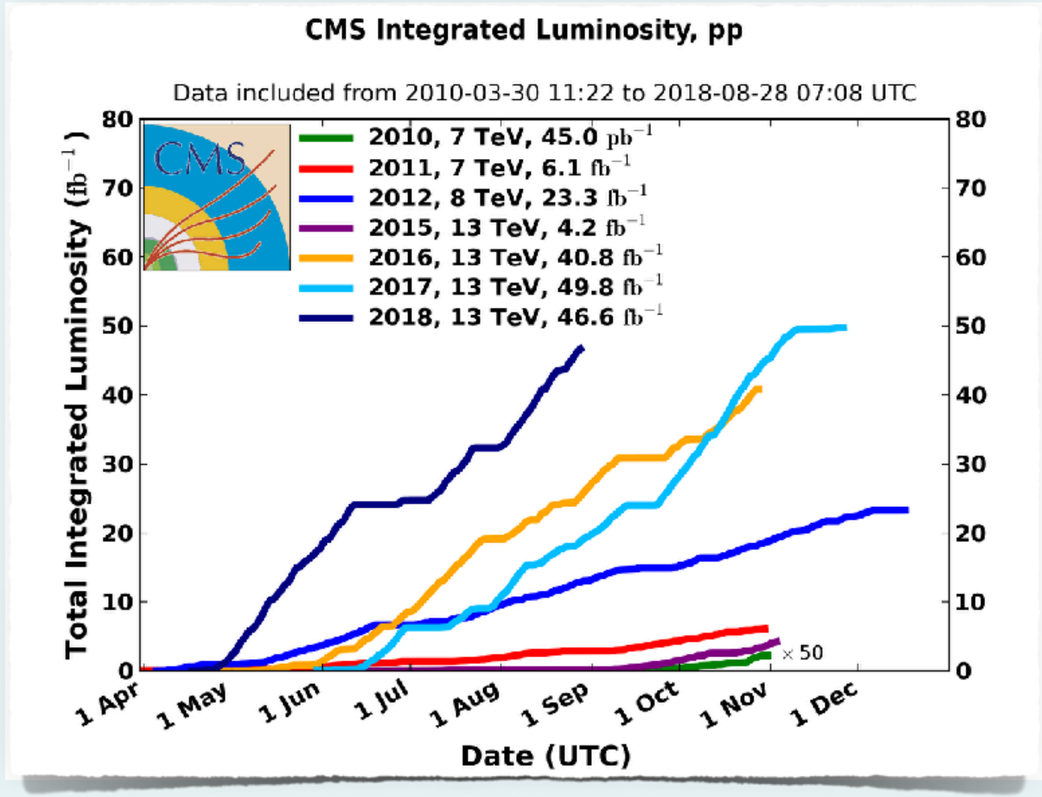
Outlook

- Plenty of work went into CMS SUSY and DM searches.
- But we are far from being done.
- New analysis ideas (and strategies) help us to explore even the tiniest bits of the search parameter space.
- In the end every analysis result is yet another puzzle piece that helps us form a better picture of truly cosmological scales.

Additional Information

The CMS Detector and CMS Data Samples





The Inverse Problem

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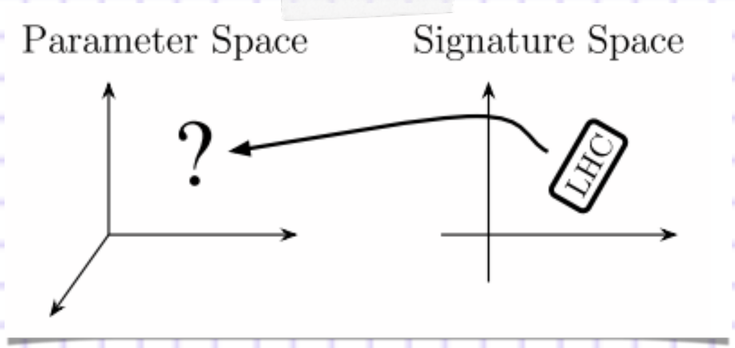

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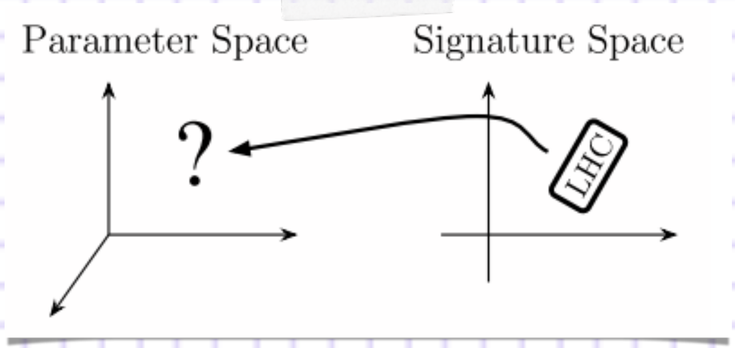
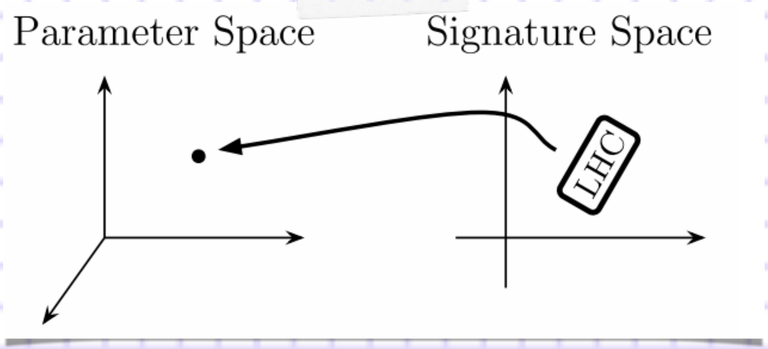


ideal scenario



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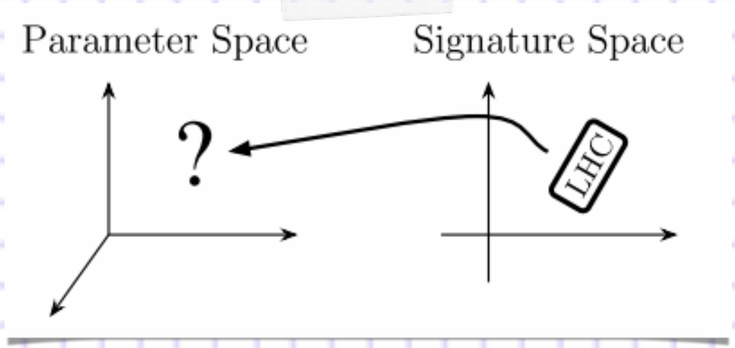

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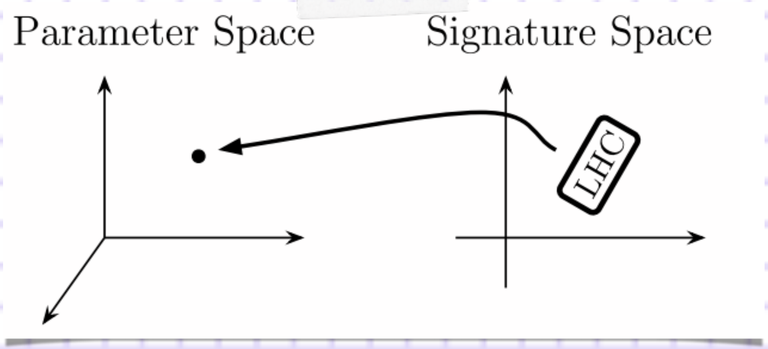
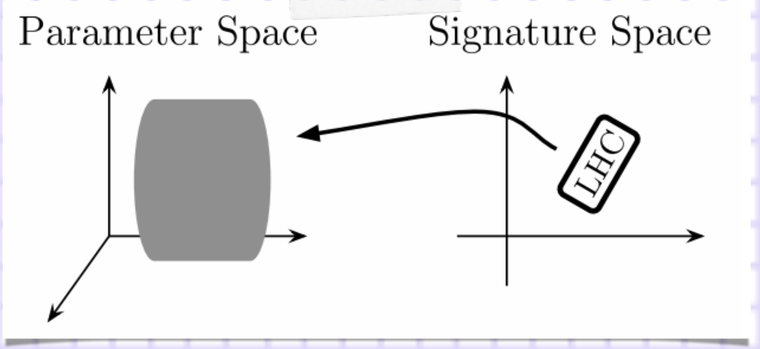


realistic scenario



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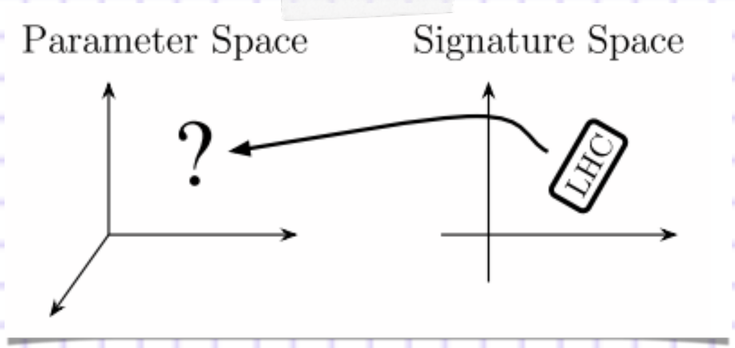

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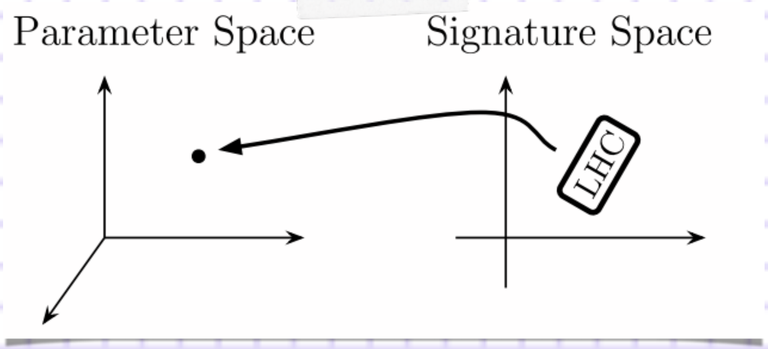


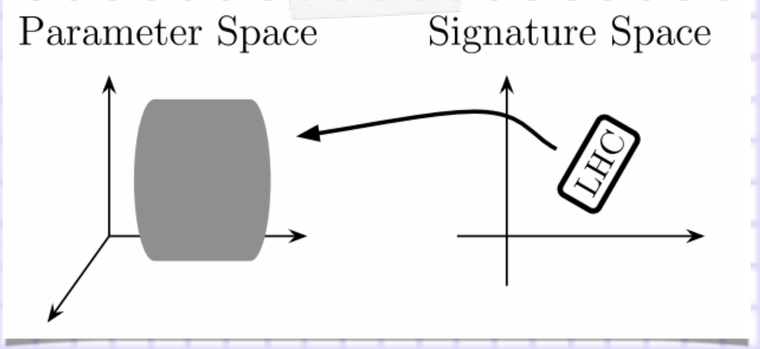
FITTINO

SUSY

-test models

-extract parameters

realistic scenario



Is the LSP Dark Matter?

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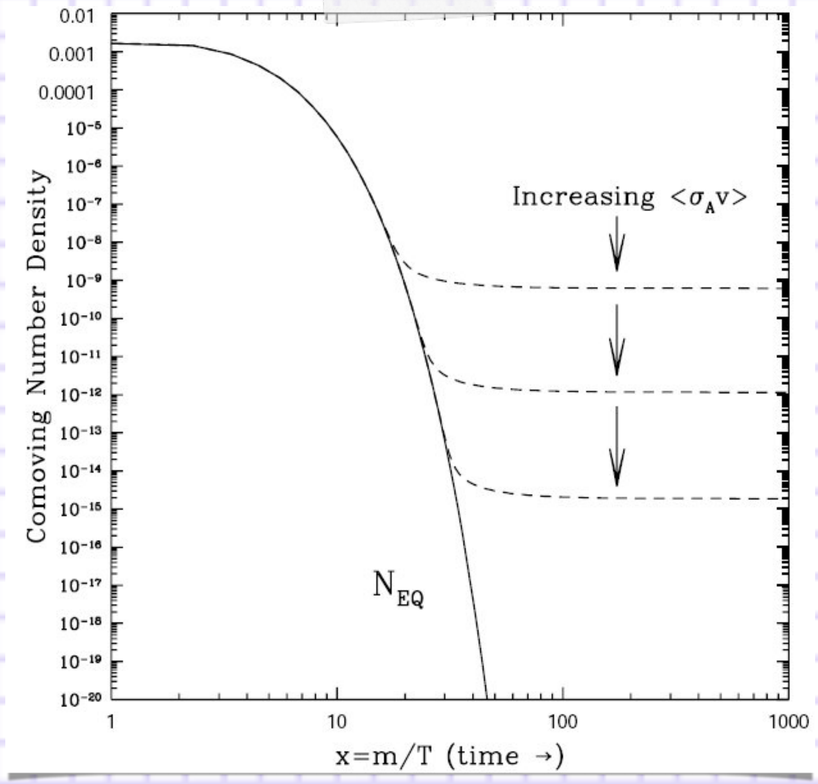

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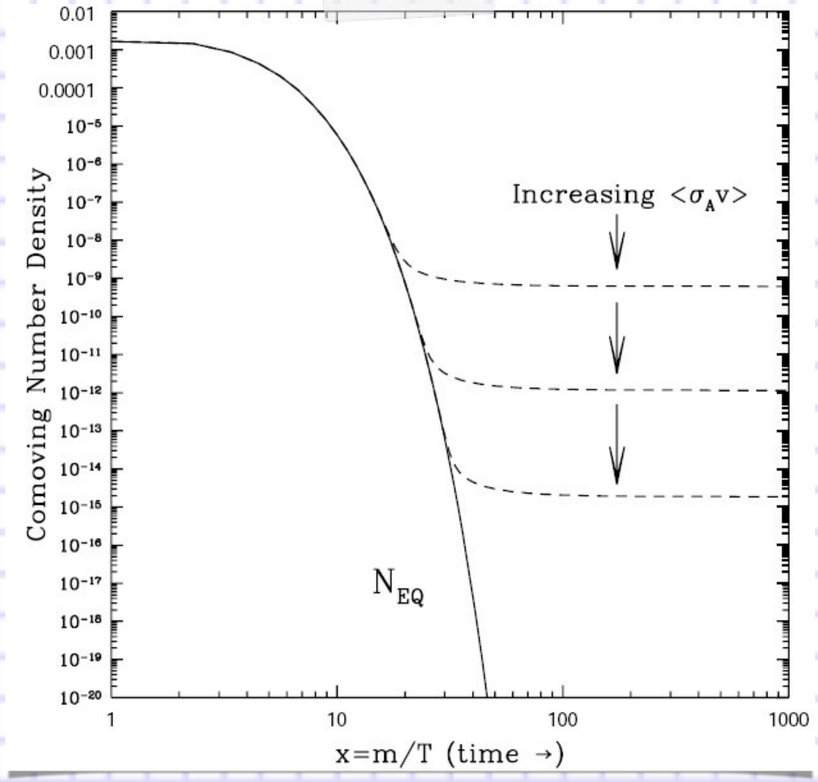

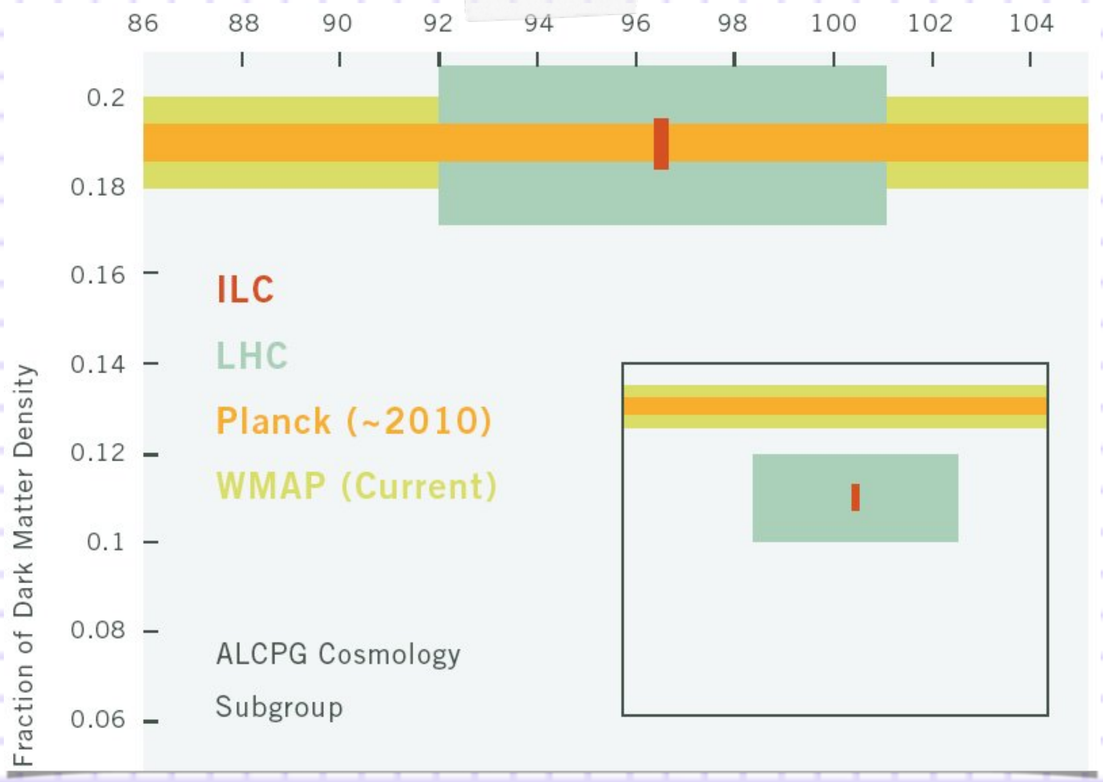

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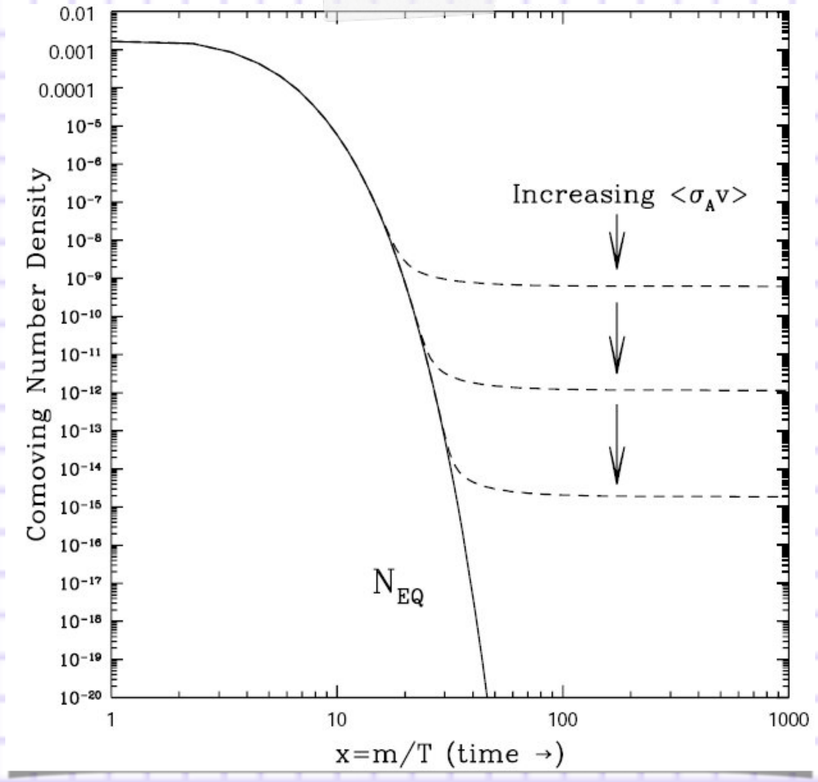
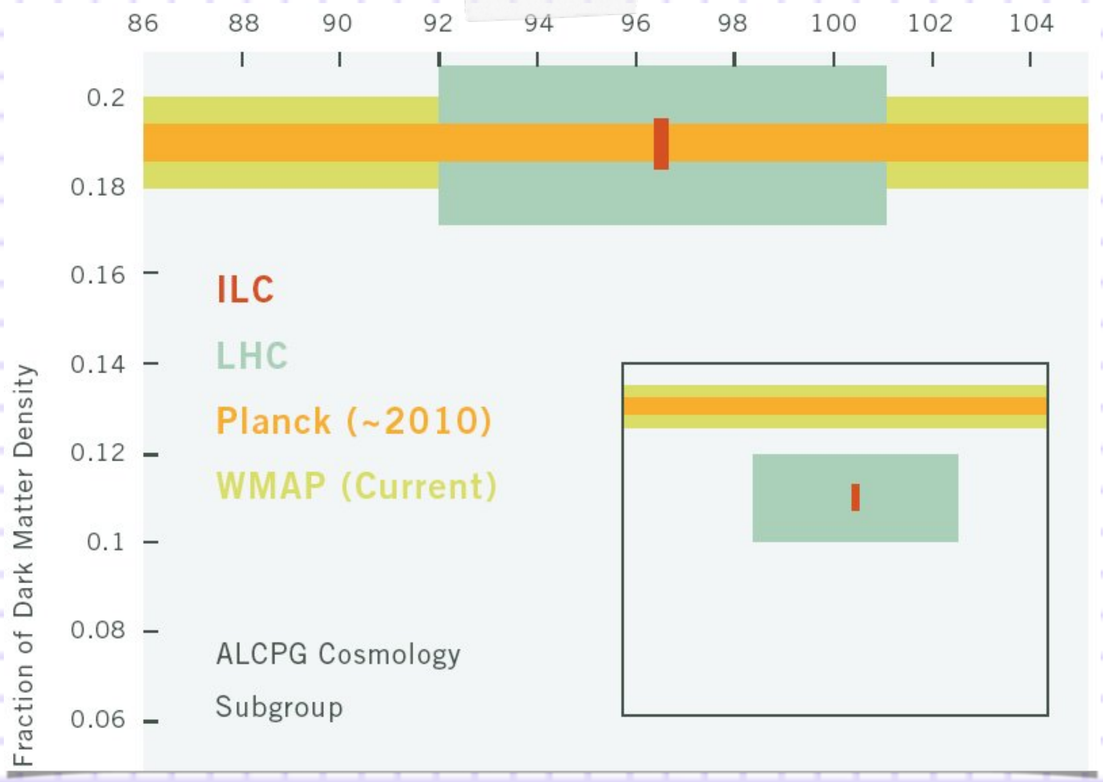


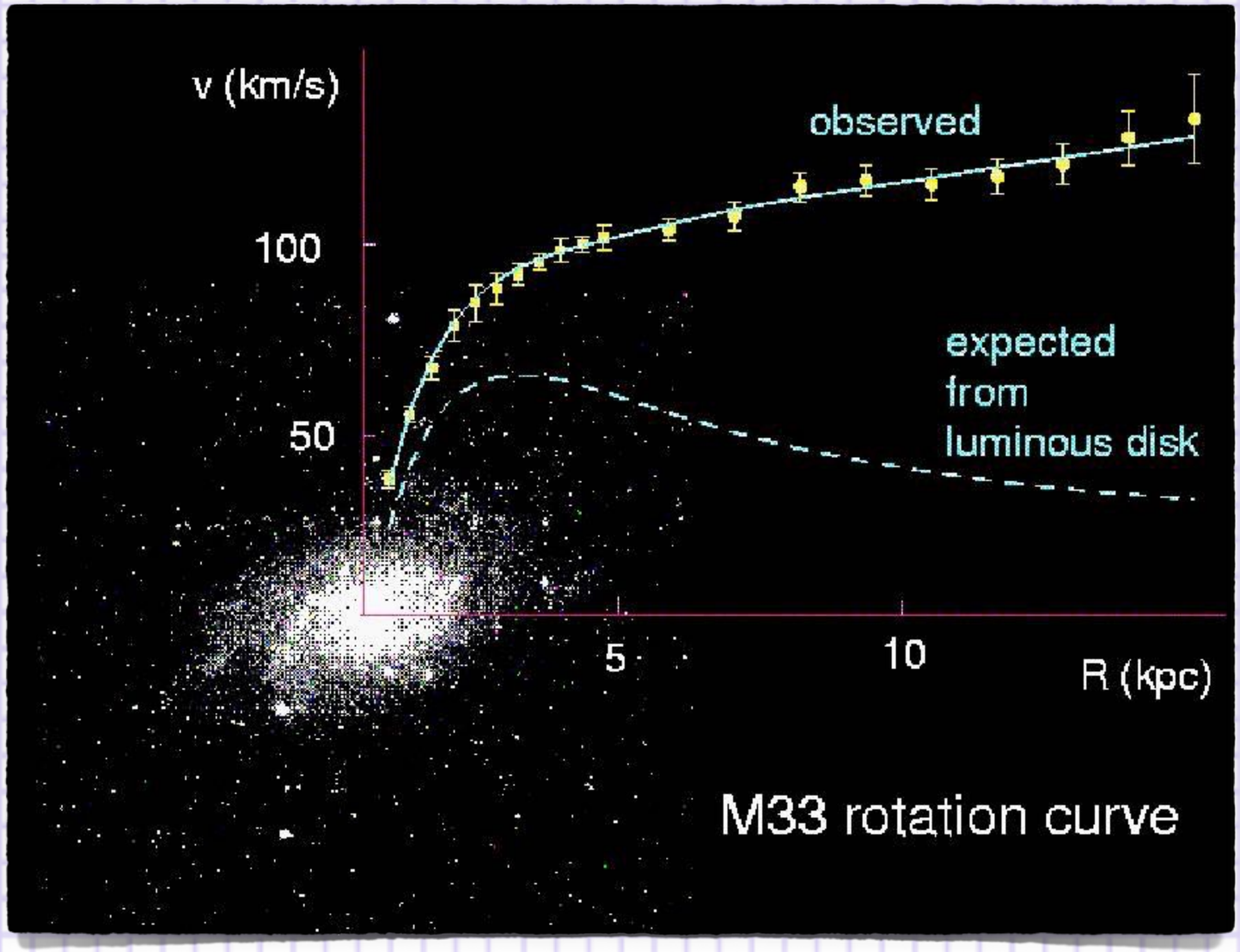


two options for the measurement:

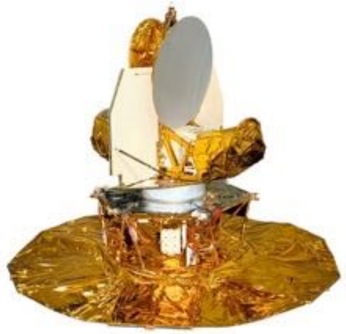
-measure all couplings: model independent, but dificult at LHC

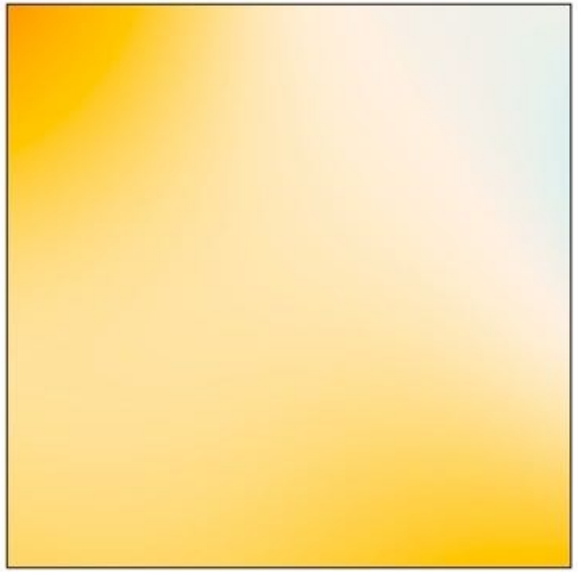
-measure particle Masses: model dependent, possible at LHC

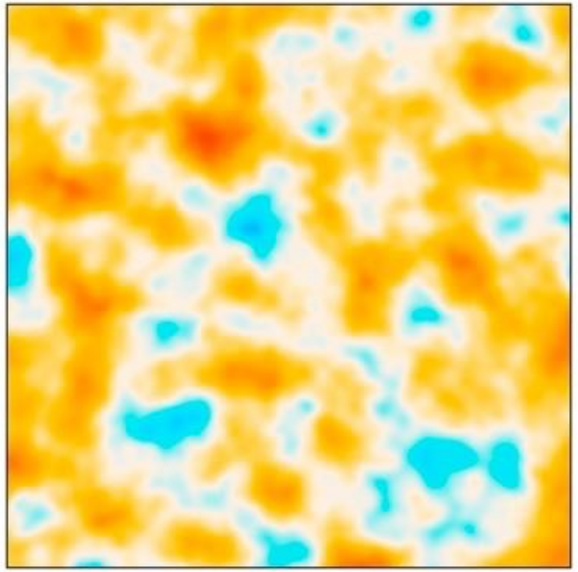
Rotational Curves

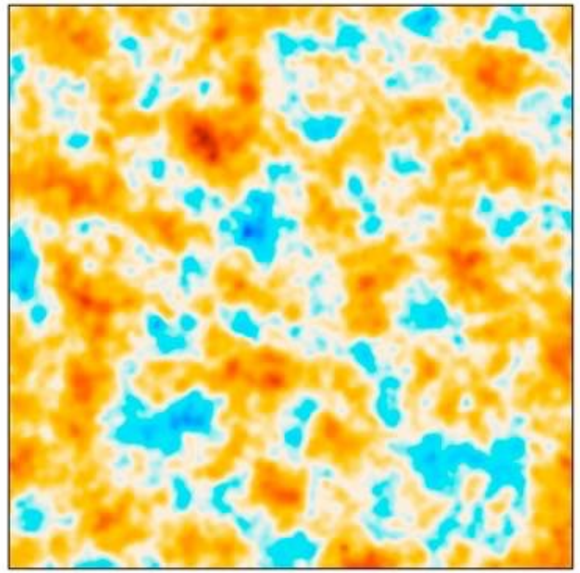


CMB Measurement Resolution









COBE

WMAP

Planck

SUSY Theory Phase Space

Let's not forget, SUSY is not just one theory.
It's rather a concept with a multitude of possible manifestations!