DM-Stat: Statistical Challenges in the Search for Dark Matter

OVERVIEW: Dark Matter

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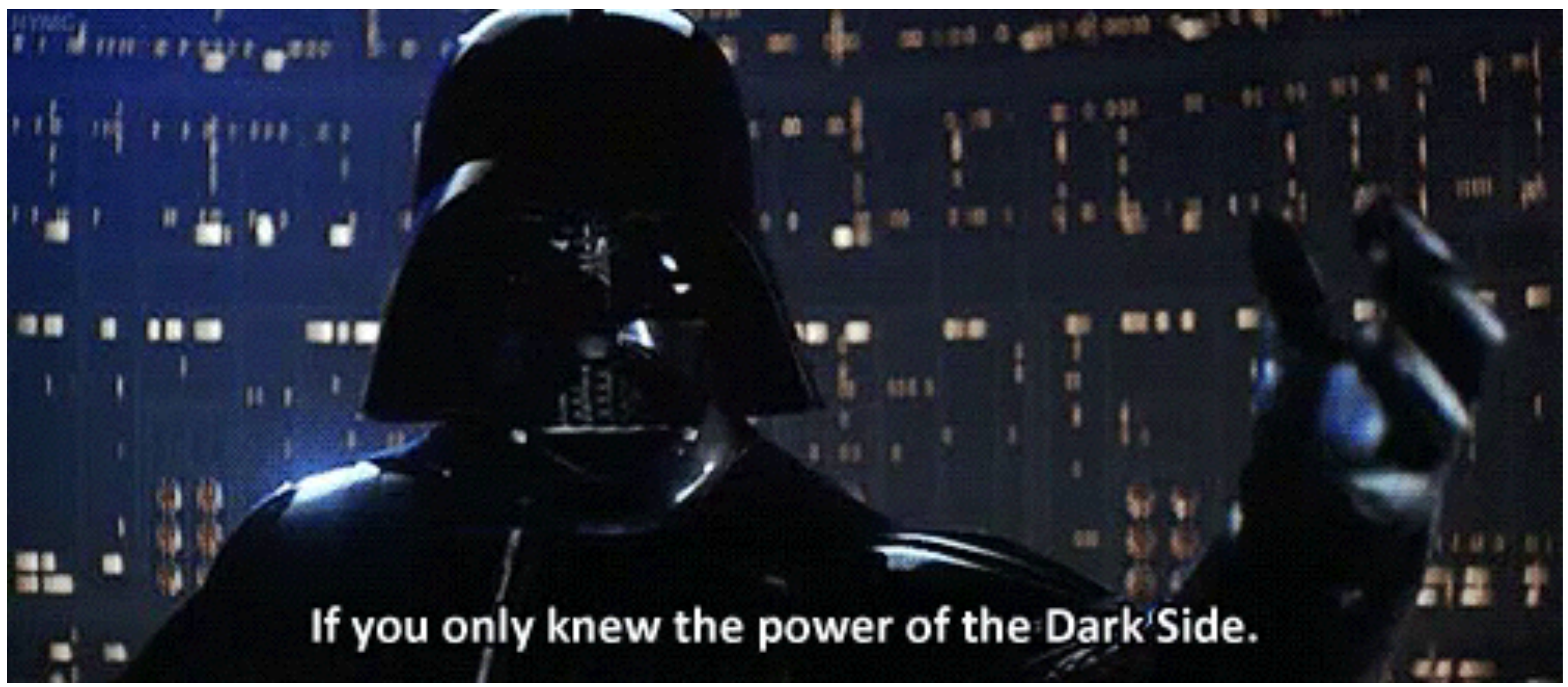
Dark Matter: Episode I
The Prequel Talk



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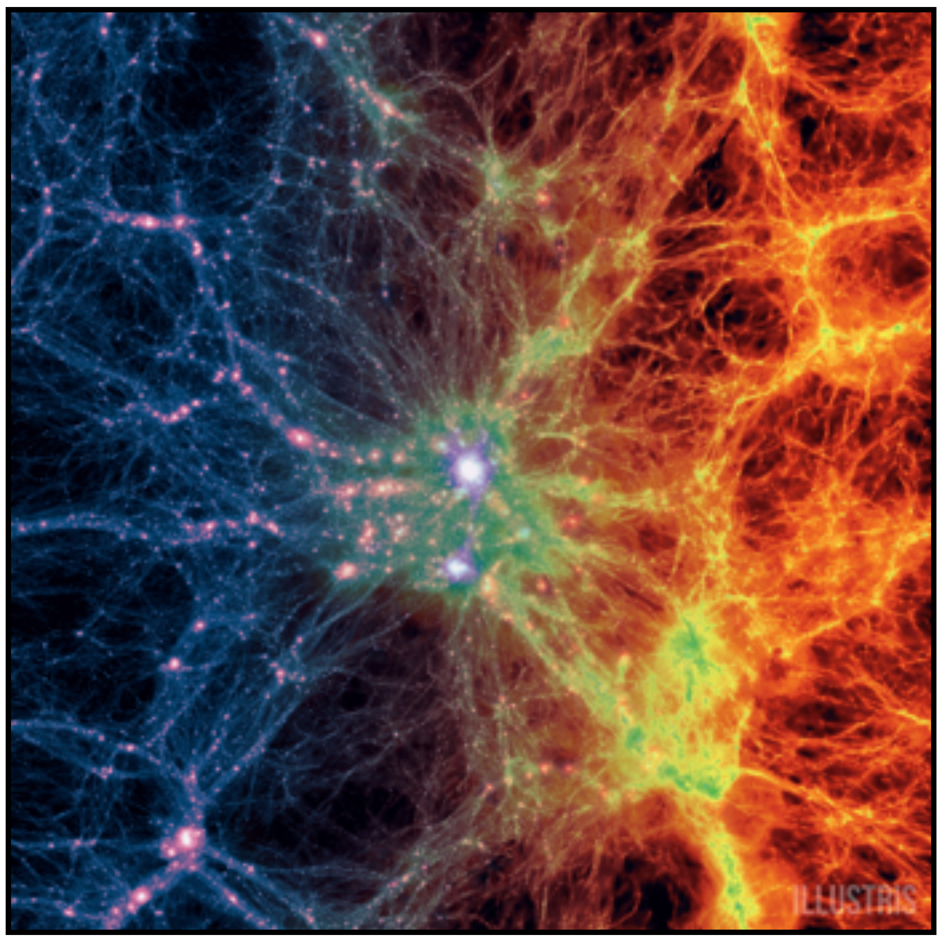
DM-Stat: Statistical Challenges in the Search for Dark Matter

An Introduction to Dark Matter



Illustris simulation

Xenon1T detector

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What is Dark Matter?

Nobody knows :(

Particles, or objects, or maybe something more diffuse

We've only ever identified it's gravitational interactions

It's everywhere in the Universe (to varying degrees…)

Dark Matter (DM) is everywhere, even in this room…
but how much?

In ‘ordinary’ units: $\rho_\chi \sim 5 \times 10^{-25}\,\mathrm{g/cm^3}$

In ‘particle physics’ units: $\rho_\chi \sim 0.3\,\mathrm{GeV/cm^3}$

In ‘astronomy’ units: $\rho_\chi \sim 0.008\,M_\odot/\mathrm{pc}^3$

In ‘British’ units:

1 DMPPP

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In ‘astronomy’ units: $\rho_\chi \sim 0.008\,M_\odot/\mathrm{pc}^3$

In ‘British’ units:

1 DMPPP = 1 **D**ark **M**atter **P**article **P**er **P**int

*depending on the Dark Matter mass

Evidence:

How do we know Dark Matter is everywhere?

Theory:

What is Dark Matter?

Searches:

How can we make it not-so-Dark Matter?

Evidence:
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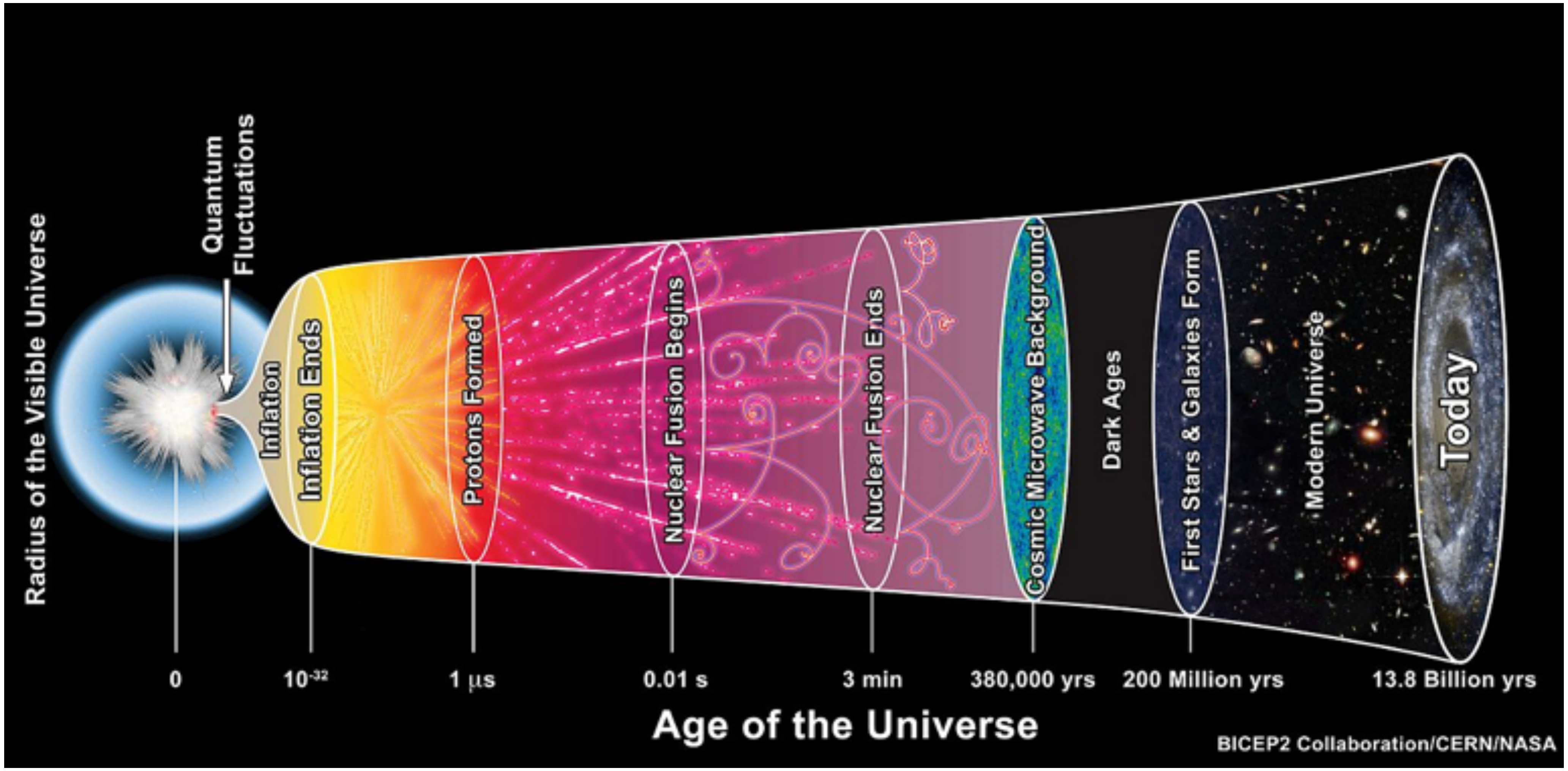
Timeline of the Universe

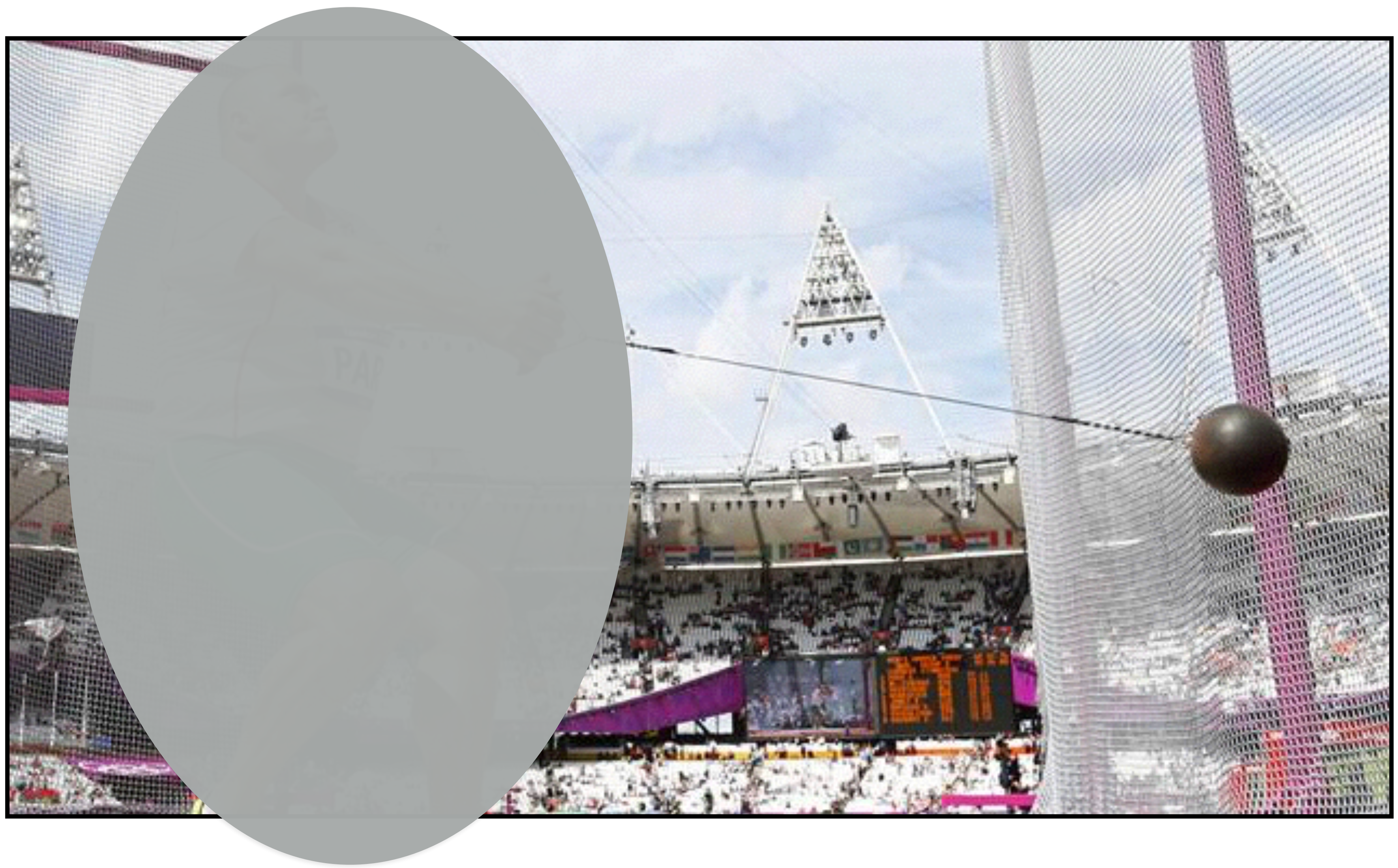


Time

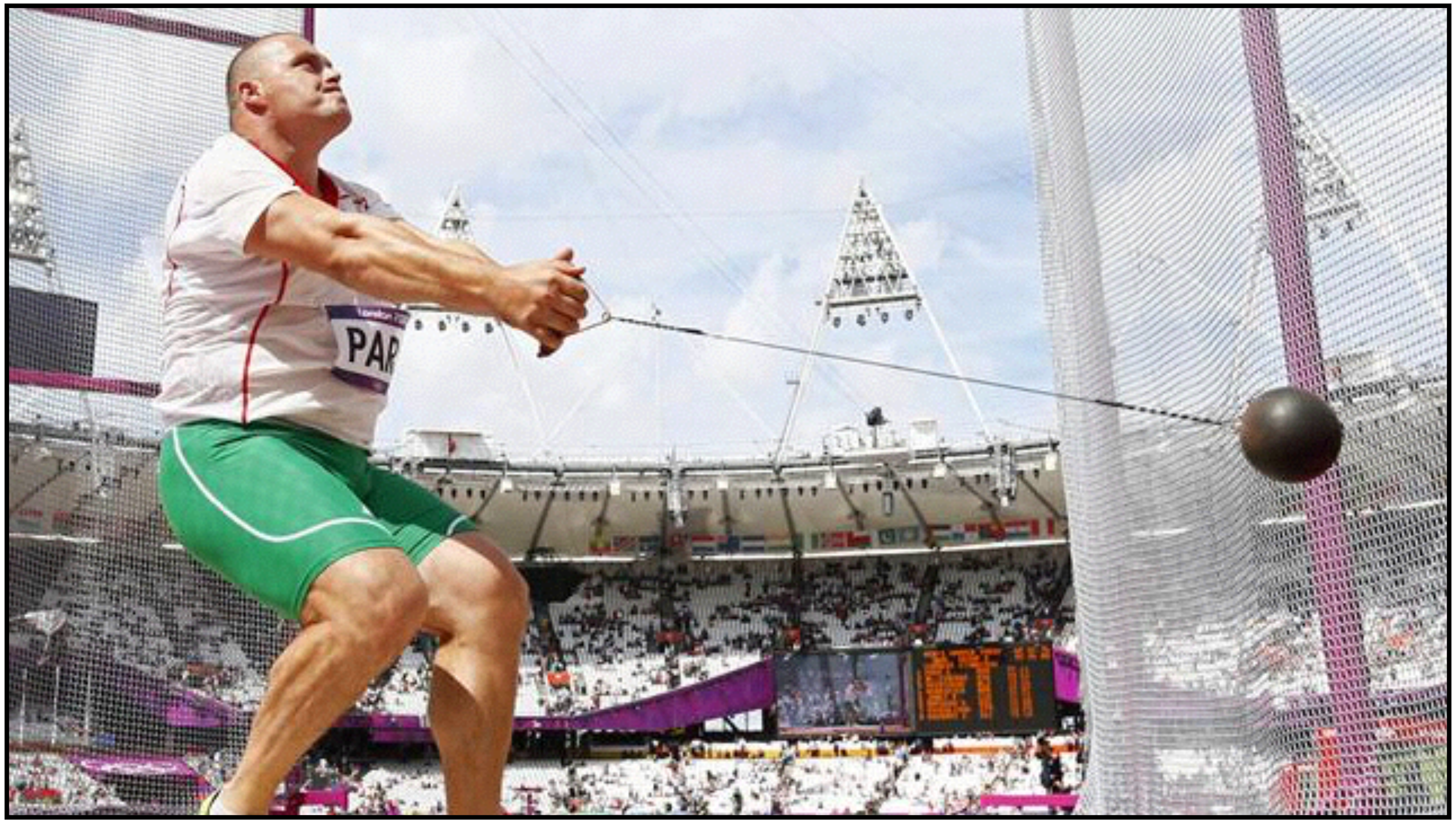
Size

Temperature

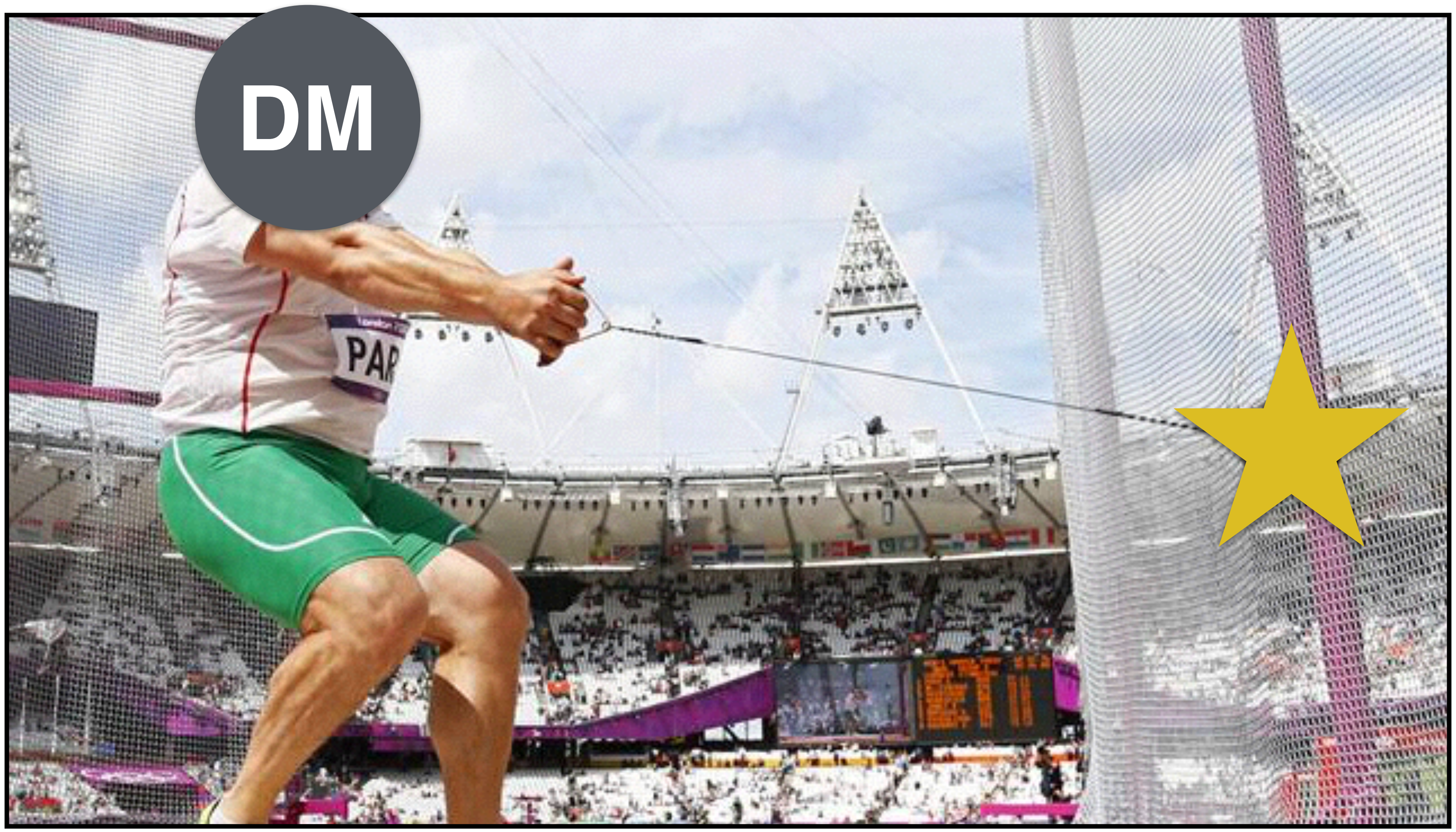
DARK MATTER IN GALAXIES AND CLUSTERS



DARK MATTER IN GALAXIES AND CLUSTERS



Dark Matter in Galaxies and Clusters



Dark Matter in Galaxies and Clusters

Abell 370
Galaxy Cluster

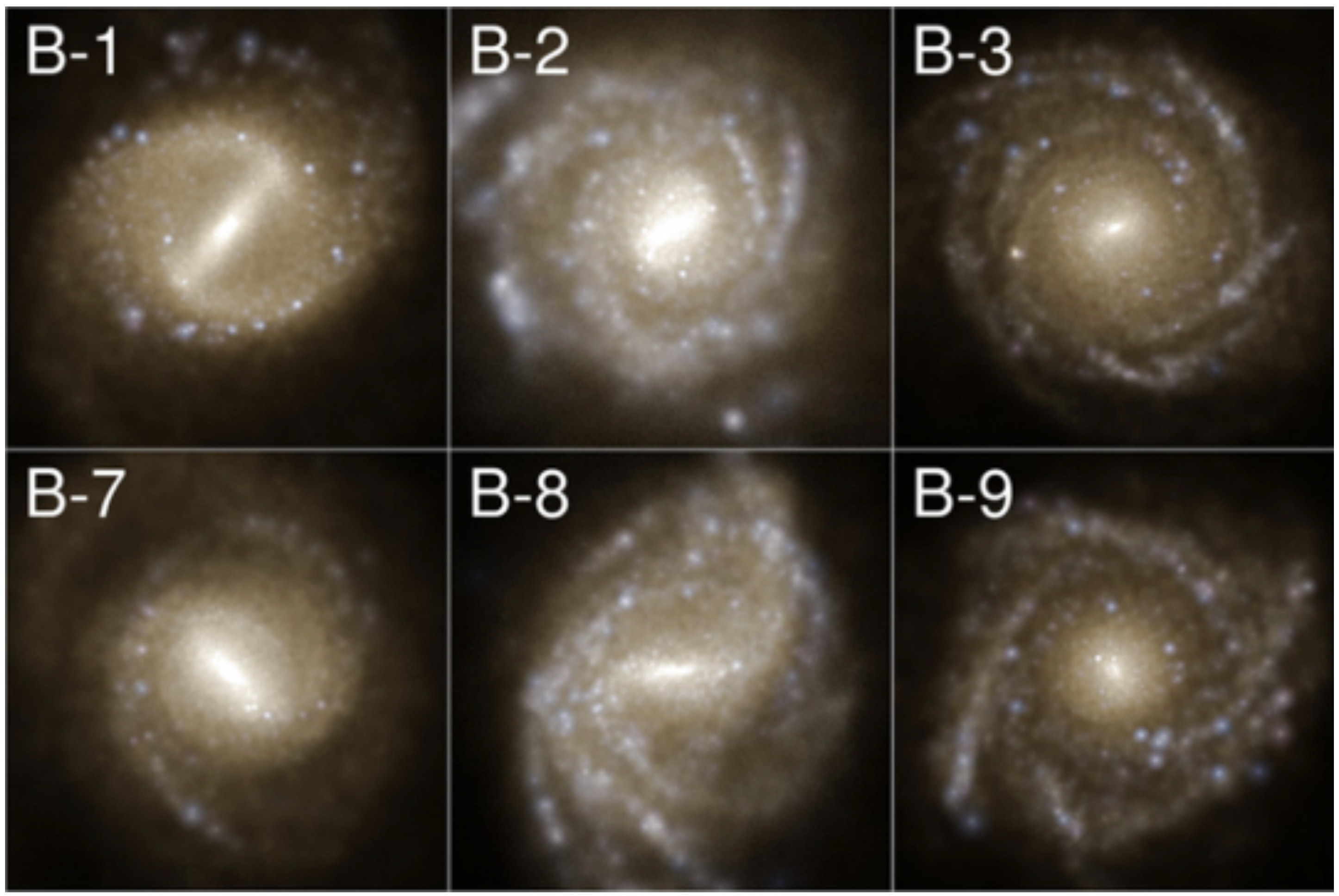
NGC 4414 Spiral Galaxy

[astro-ph/0006397]

[Rubin et al. (1980)]

STRUCTURE FORMATION WITH DARK MATTER

Dark matter has become an integral part of our understanding of how Galaxies form - seed for structure growth



[Illustris simulation - arXiv:1405.2921]

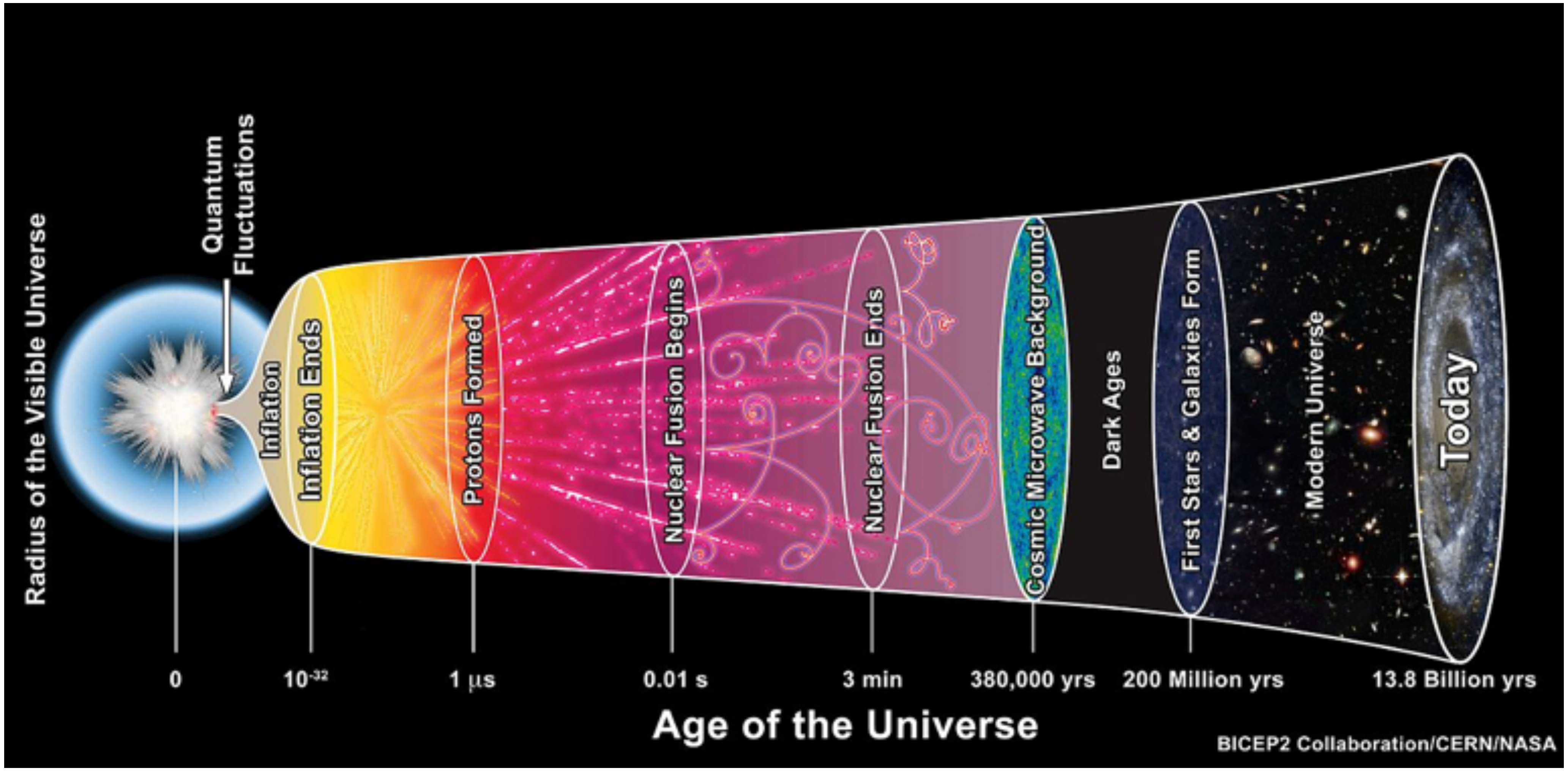
Cosmological simulations can now produce realistic (and beautiful) Galaxies

But Galaxy formation is messy and non-linear and still not fully understood

[arXiv:1609.05917 vs. arXiv:1610.07663]

[Alyson Brooks - Tuesday]

Timeline of the Universe



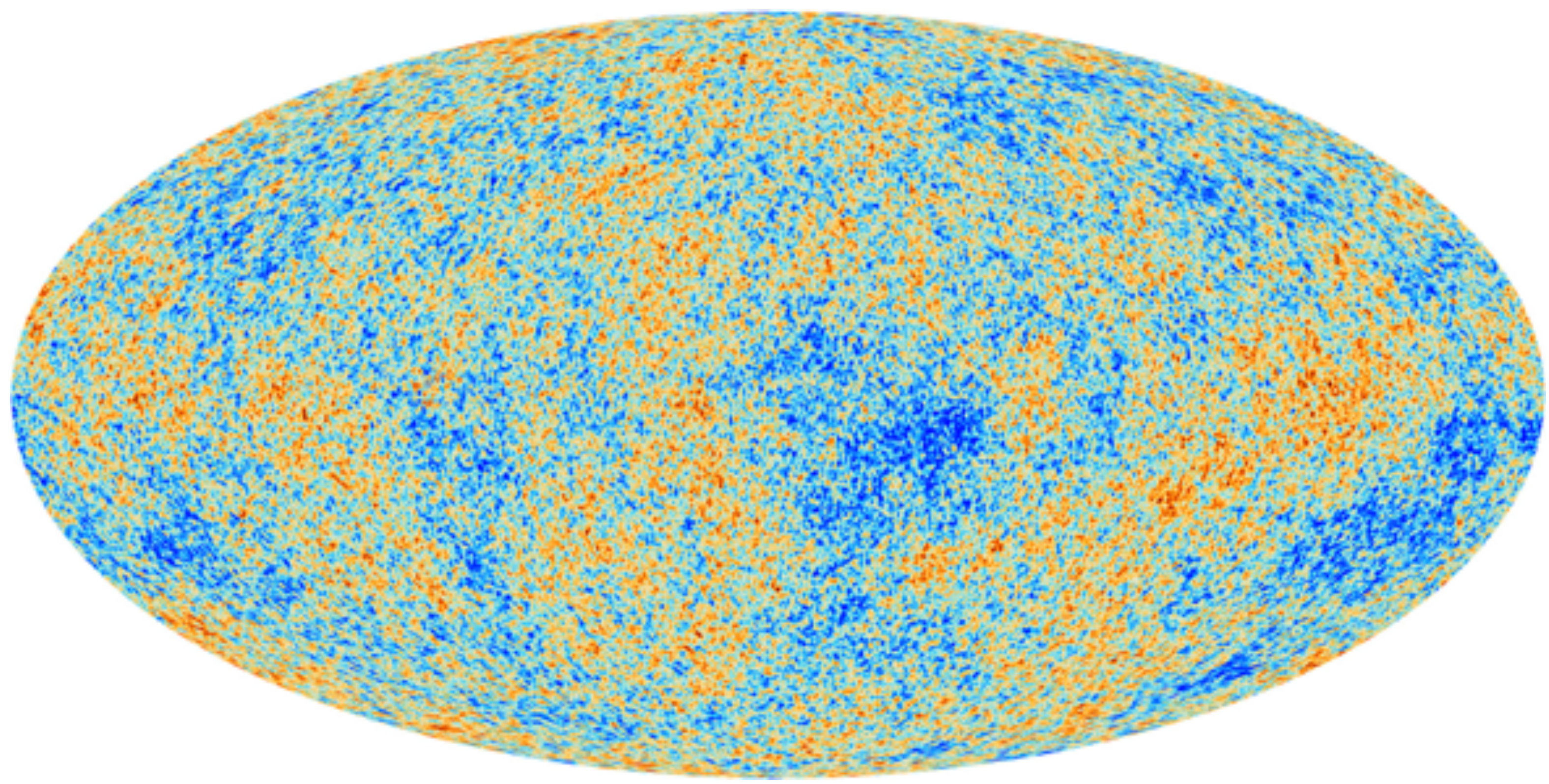
Time

Size

Temperature

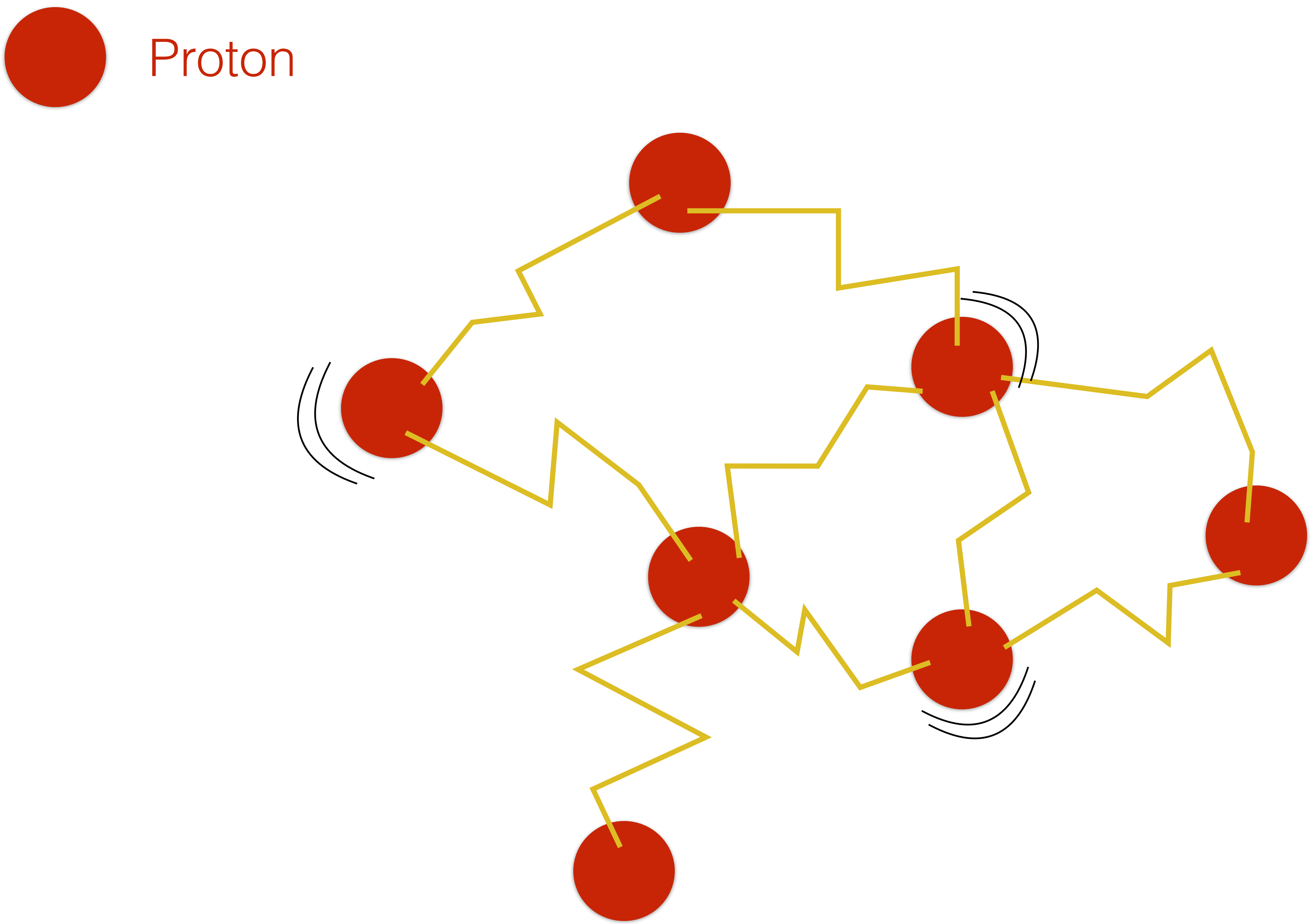
Cosmic Microwave Background (CMB)

PLANCK (2009 - 2013)

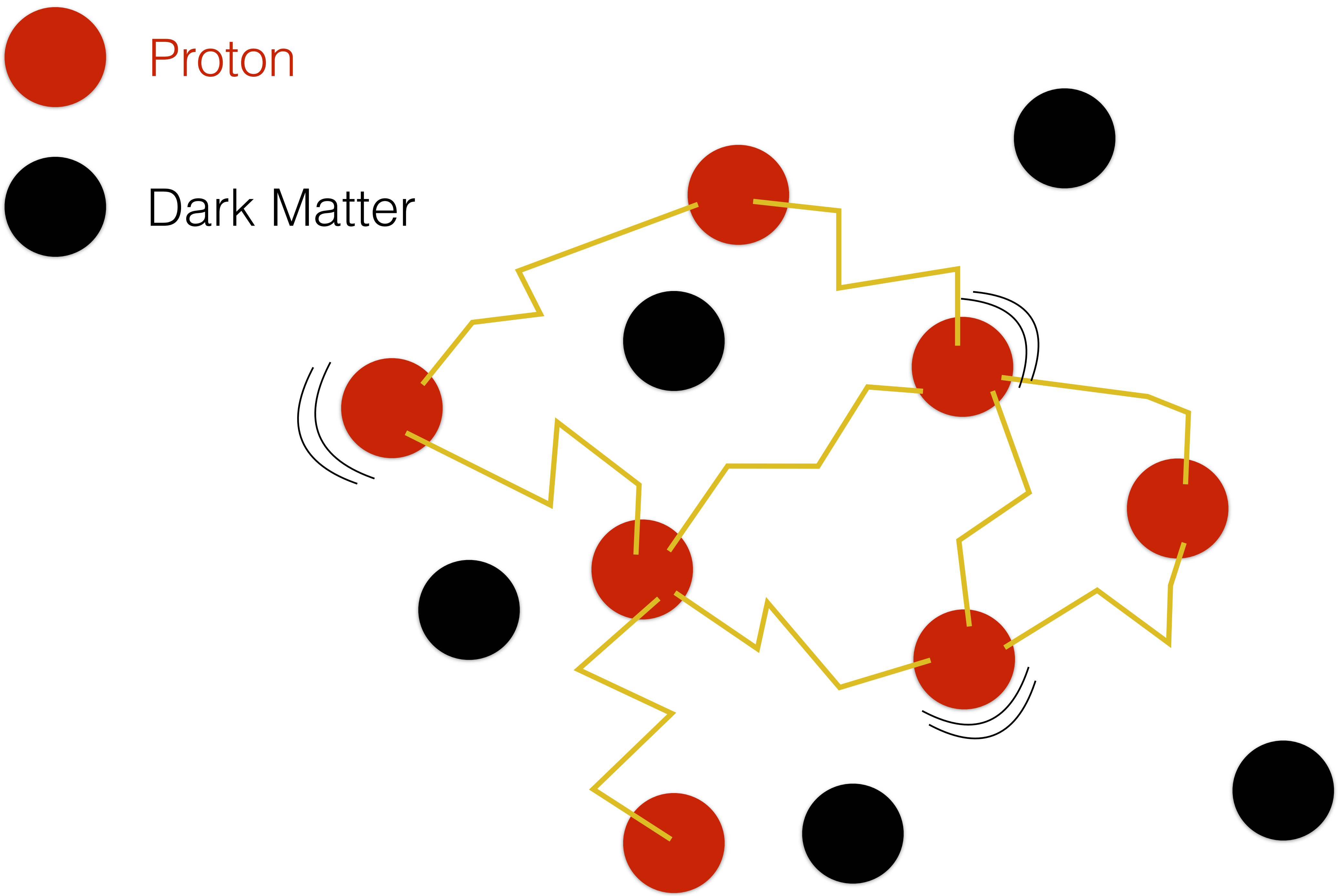


[arXiv:1502.01589]

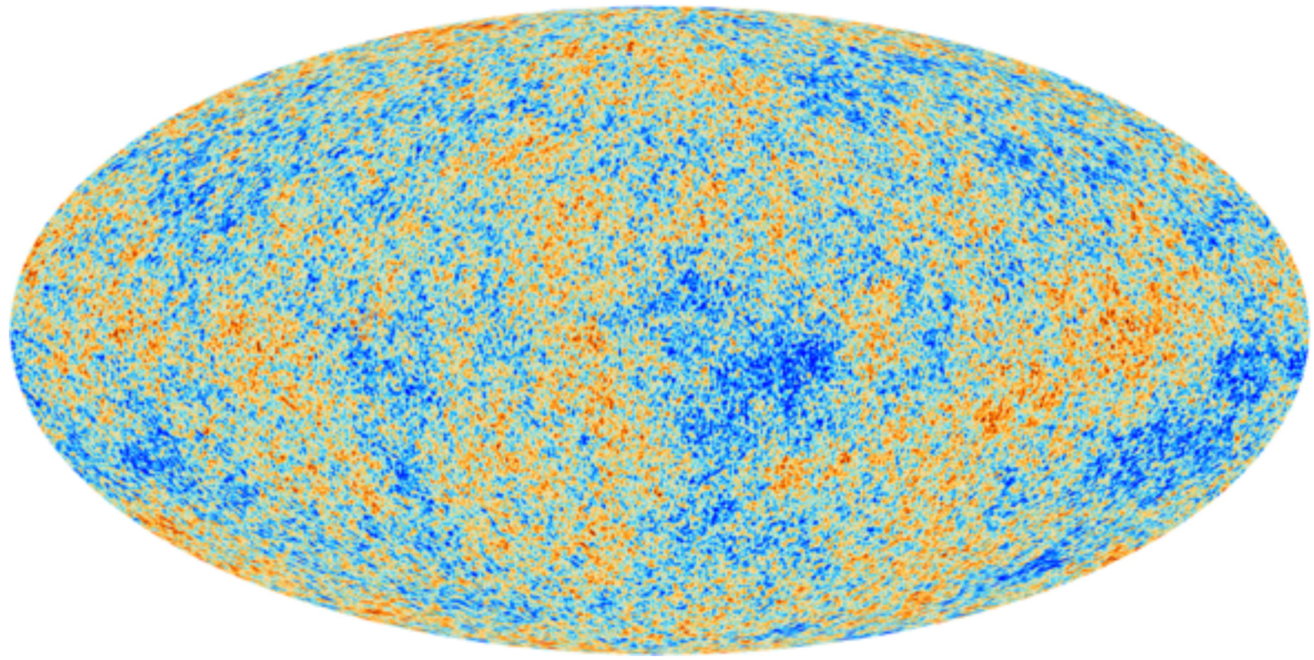
A HOT MESS!

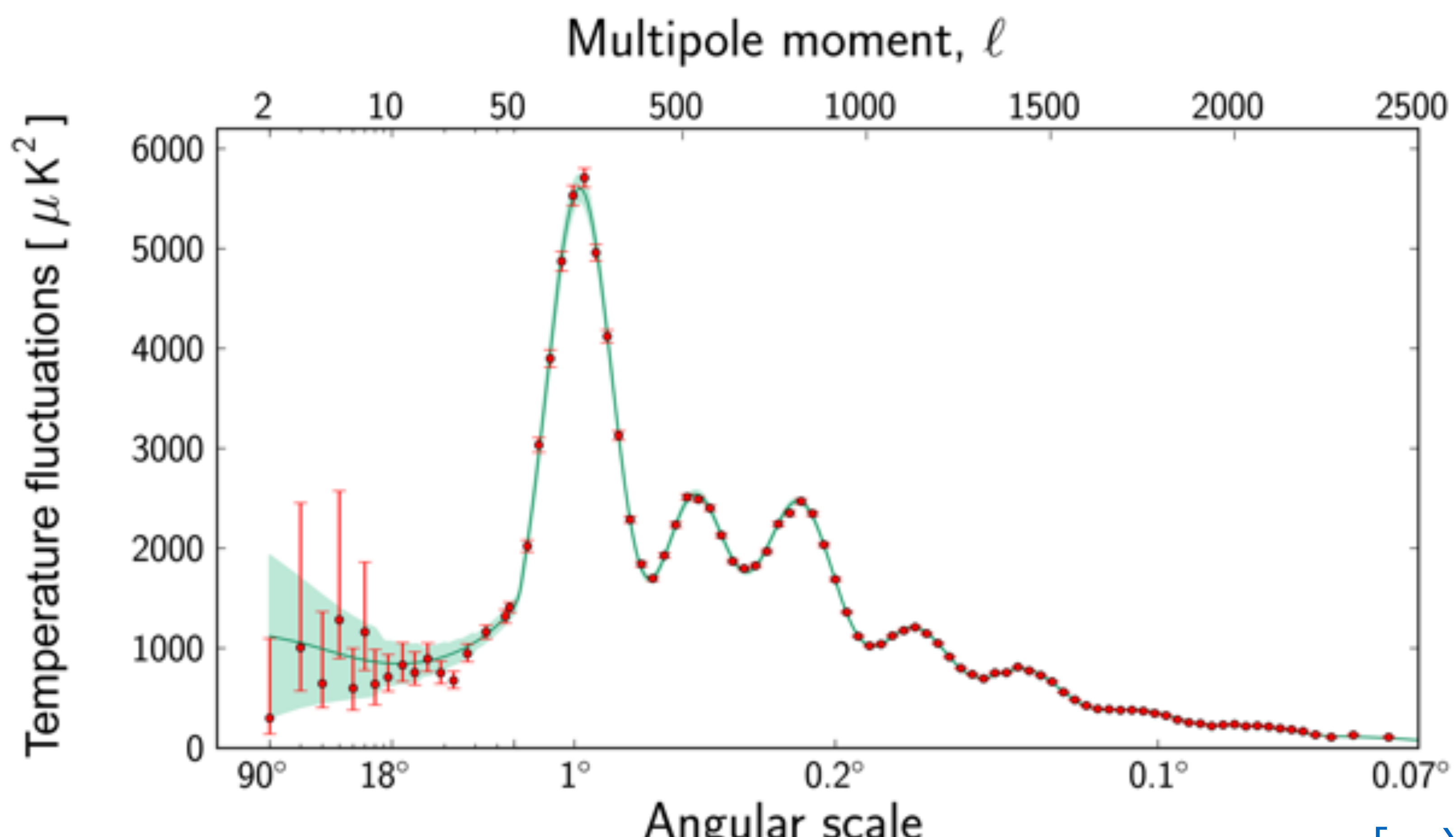


A HOT MESS + DARK MATTER!



CMB Temperature Anisotropies

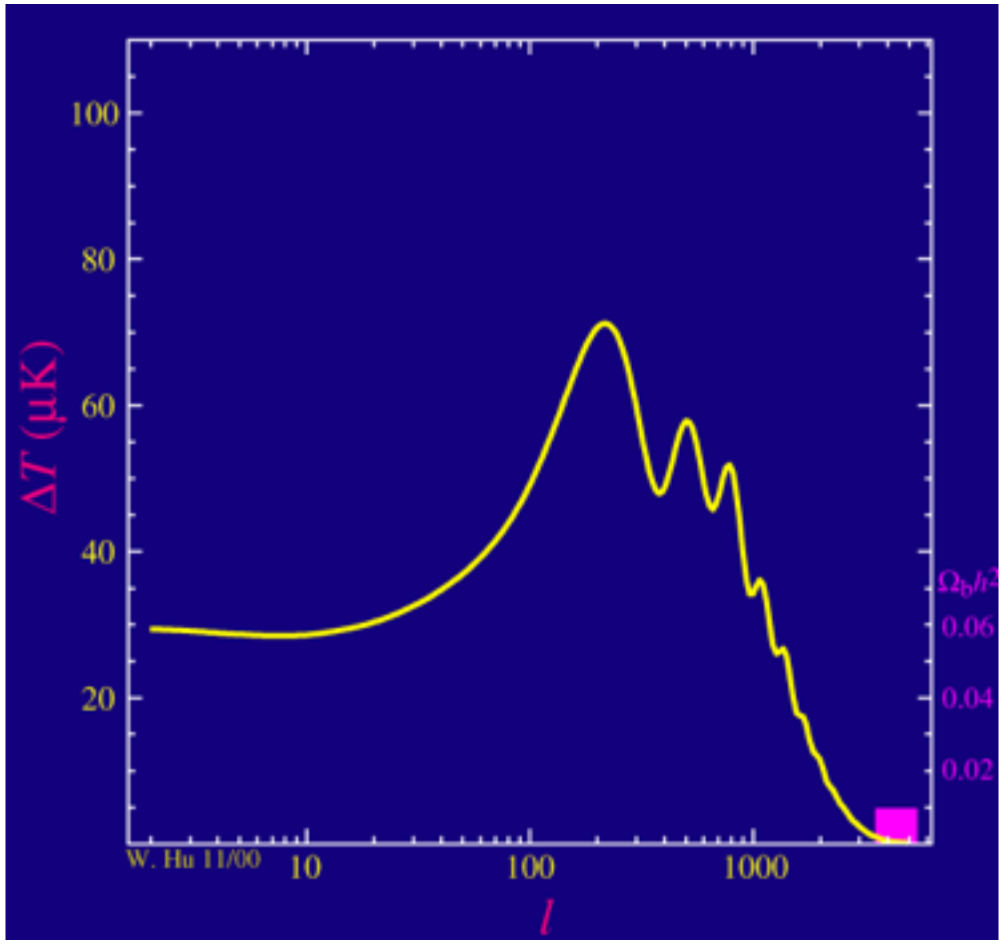




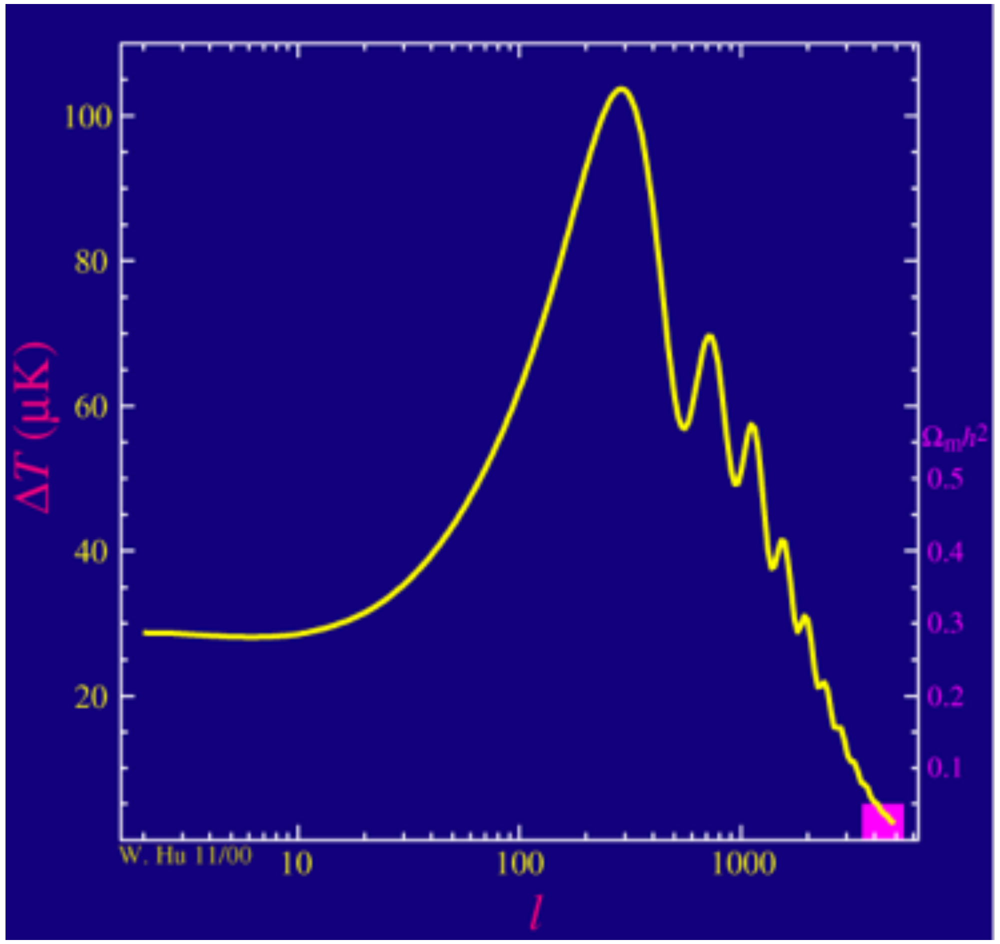
[arXiv:1502.01589]

Changing Cosmological Parameters

Changing amount of baryons
(i.e protons and neutrons)

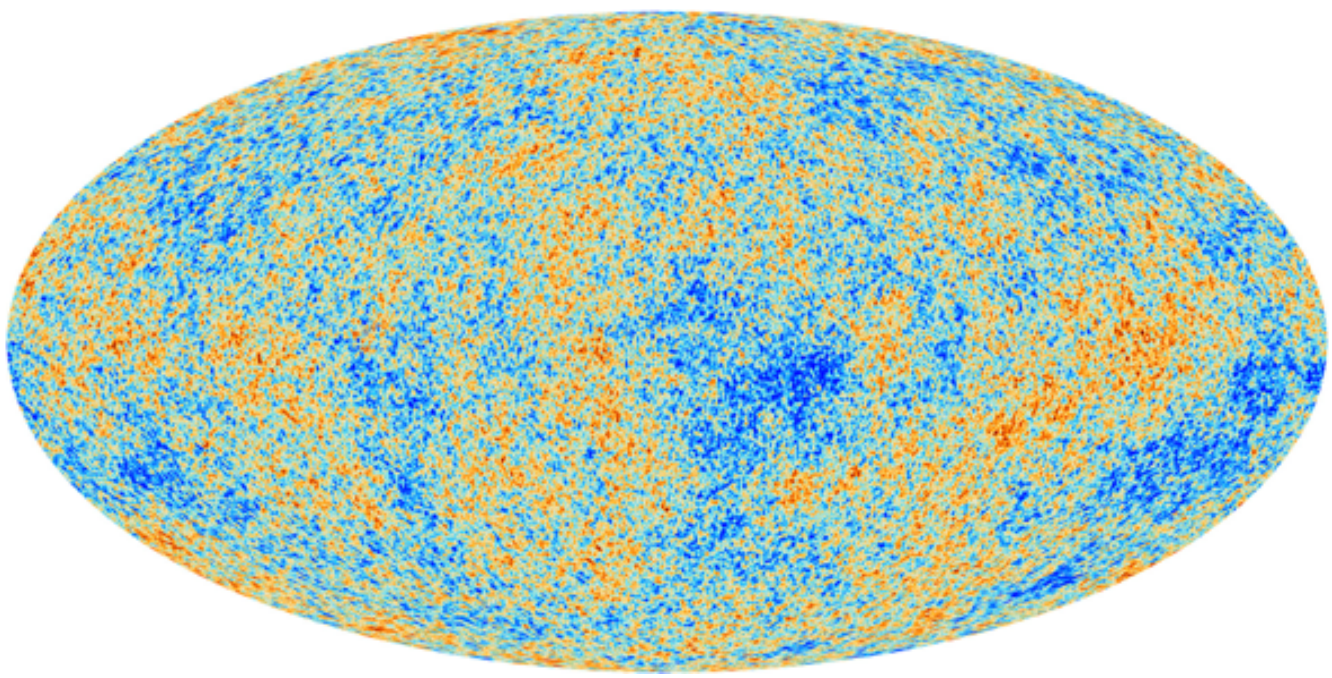


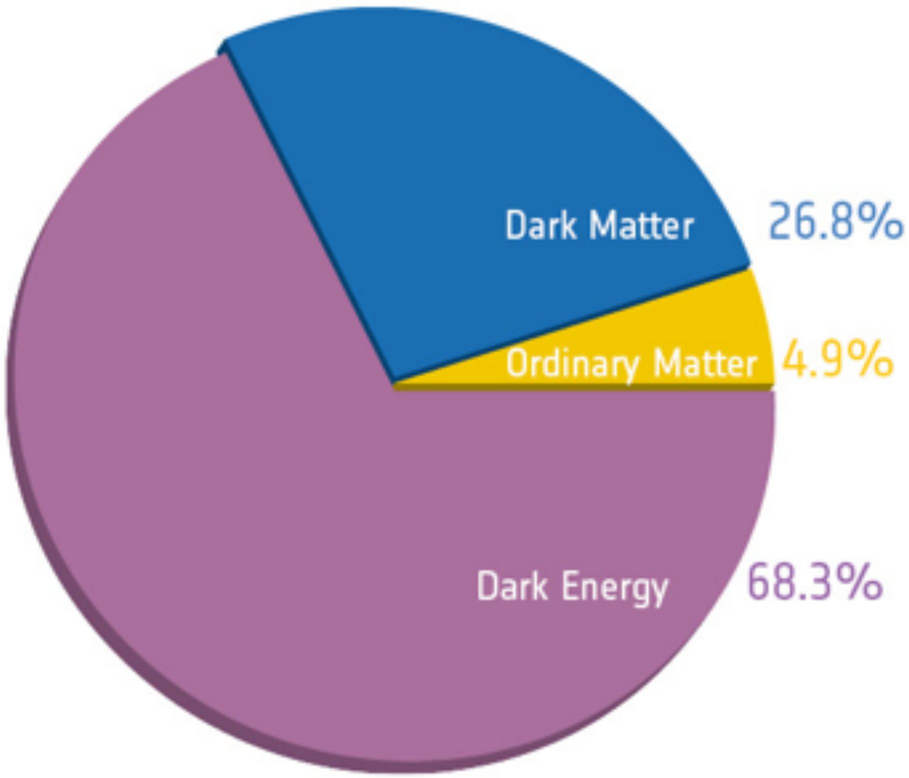
Changing total amount
of matter (DM + baryons)



http://background.uchicago.edu/~whu/animbut/anim1.html [astro-ph/0110414]

Energy Budget of the Universe





Anything you propose instead of Dark Matter still has to fit the CMB.
So it will end up looking almost exactly the same as Dark Matter…

[E.g. Skordis - https://tinyurl.com/DM-and-CMB]

Evidence:

How do we know Dark Matter is everywhere?

Theory:

What is Dark Matter?

Searches:

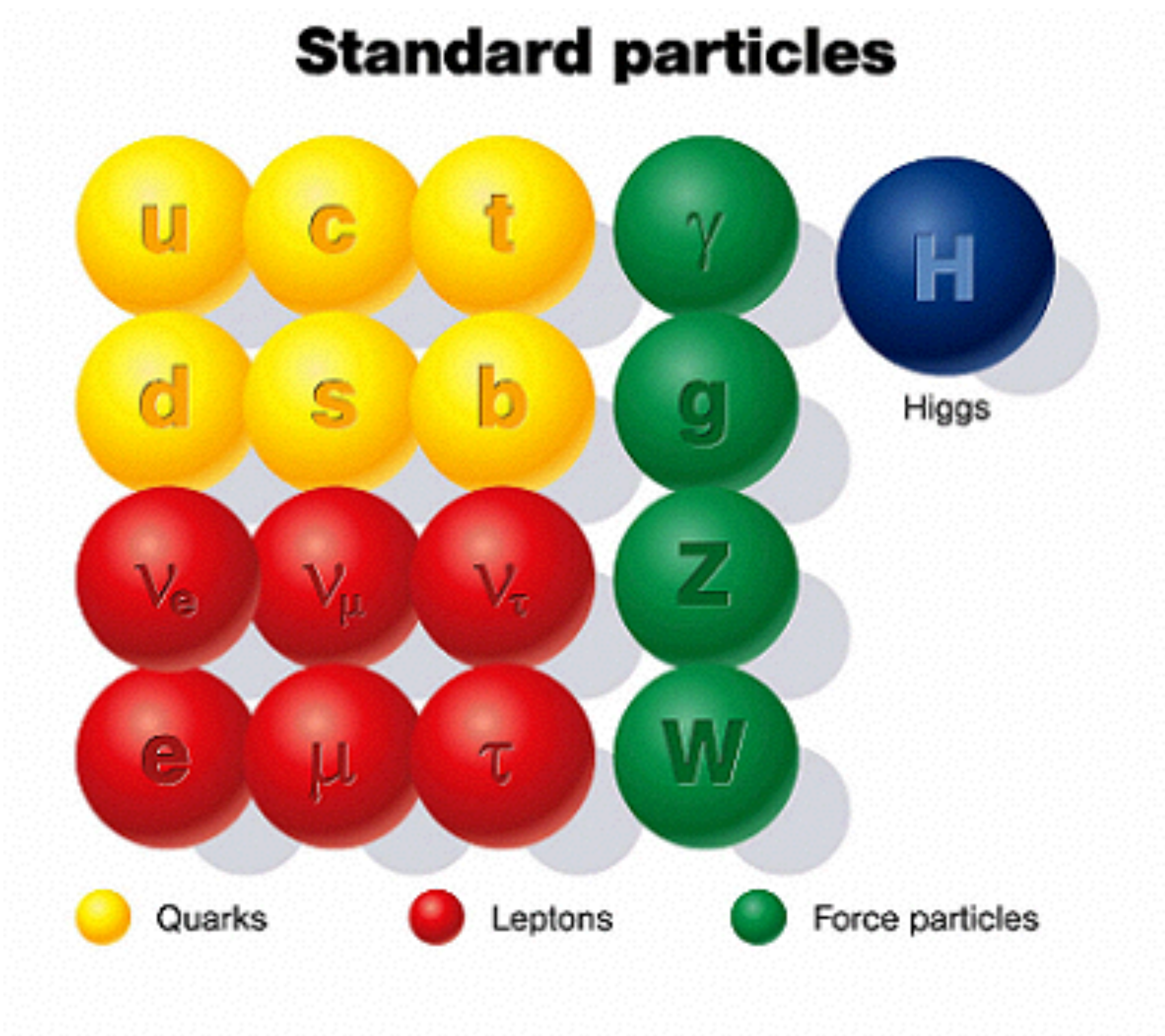
How can we make it not-so-Dark Matter?

Dark Matter Shopping List

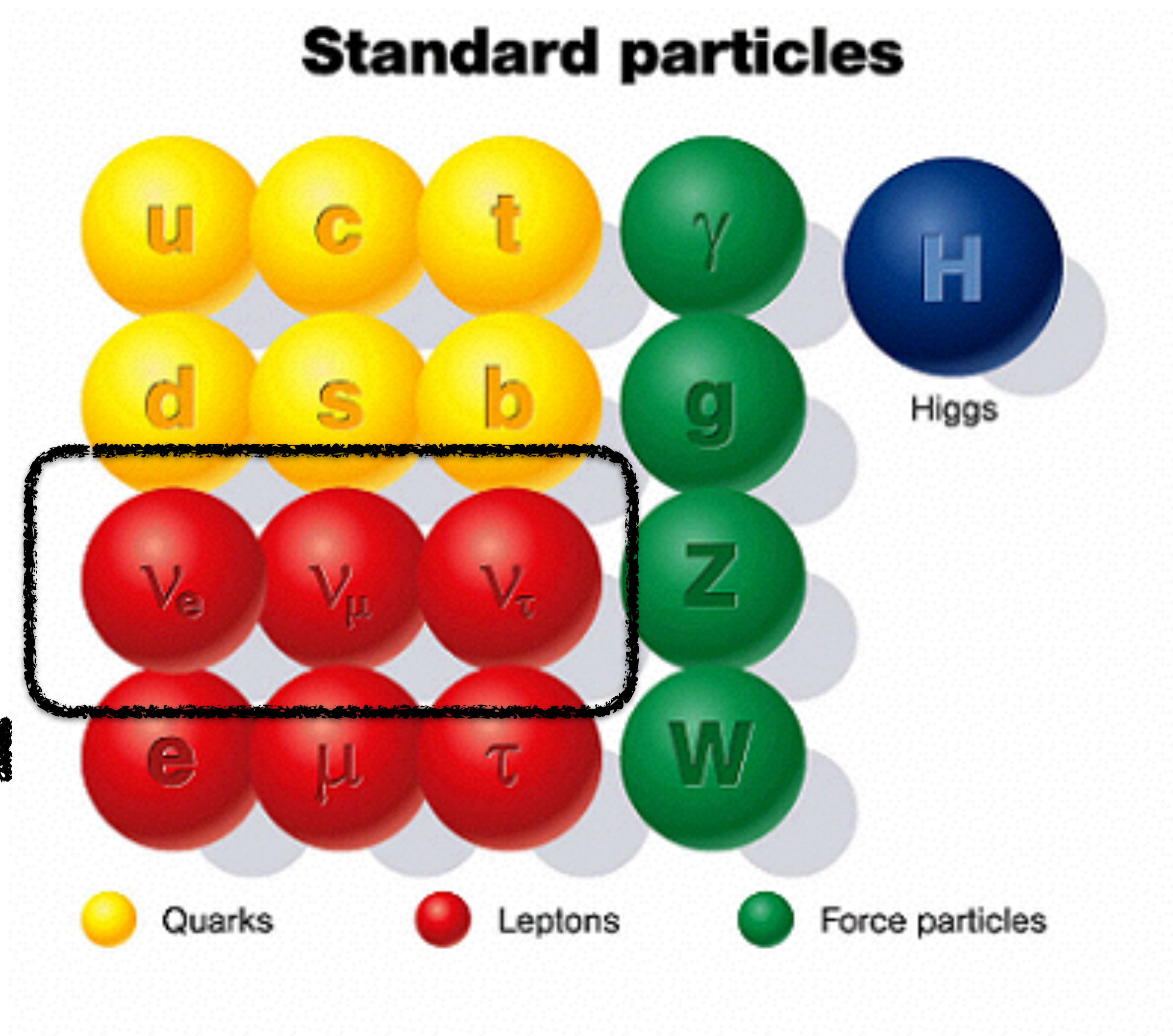
* Non-baryonic
* 'Cold' (i.e. slow moving)
* 'Neutral'
* Produced in sufficient amounts

[arXiv:0711.4996]

Standard Model (SM) of Particle Physics



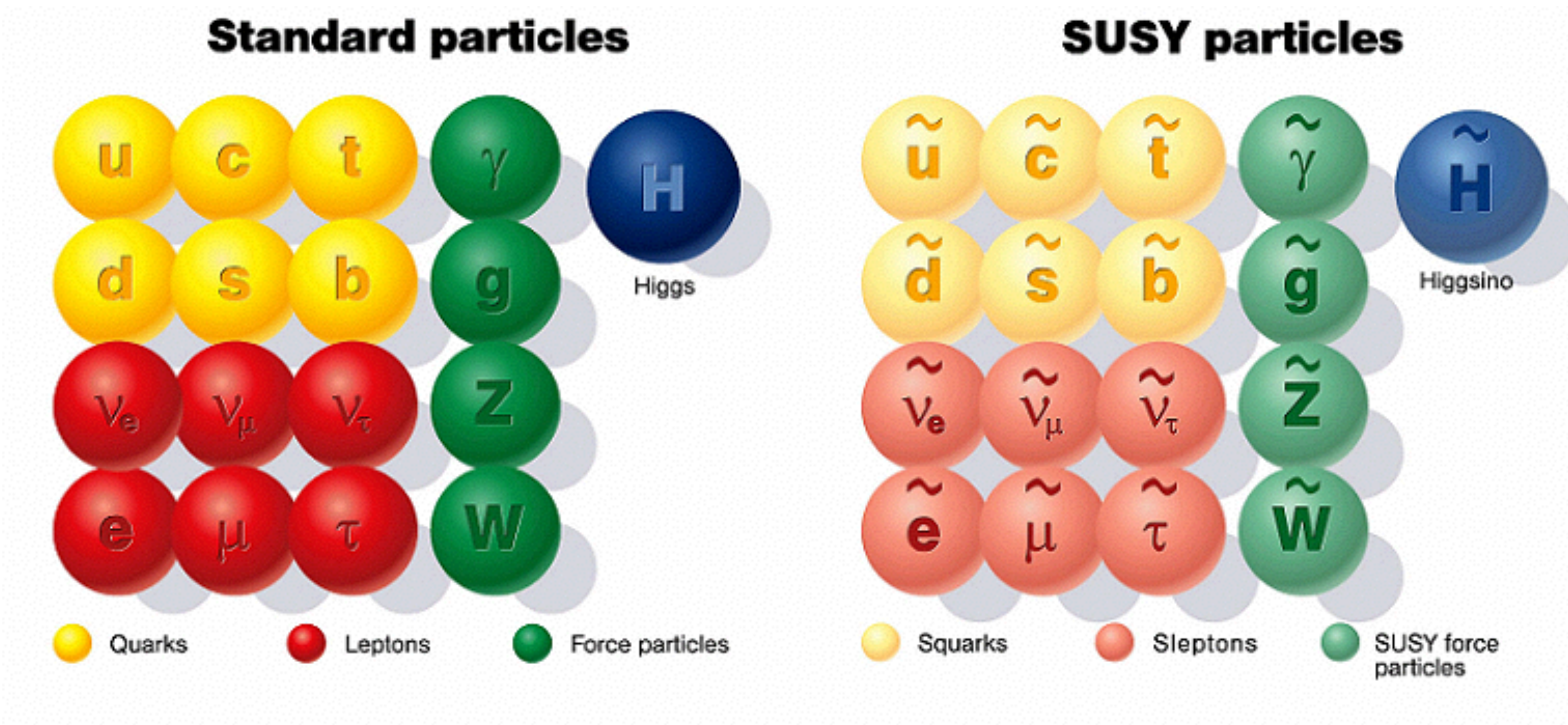
Standard Model (SM) of Particle Physics



Some Dark Matter but not nearly enough…

Supersymmetry (SUSY)

An example of a self-consistent high energy theory, which also gives you a DM particle



[hep-ph/9506380]

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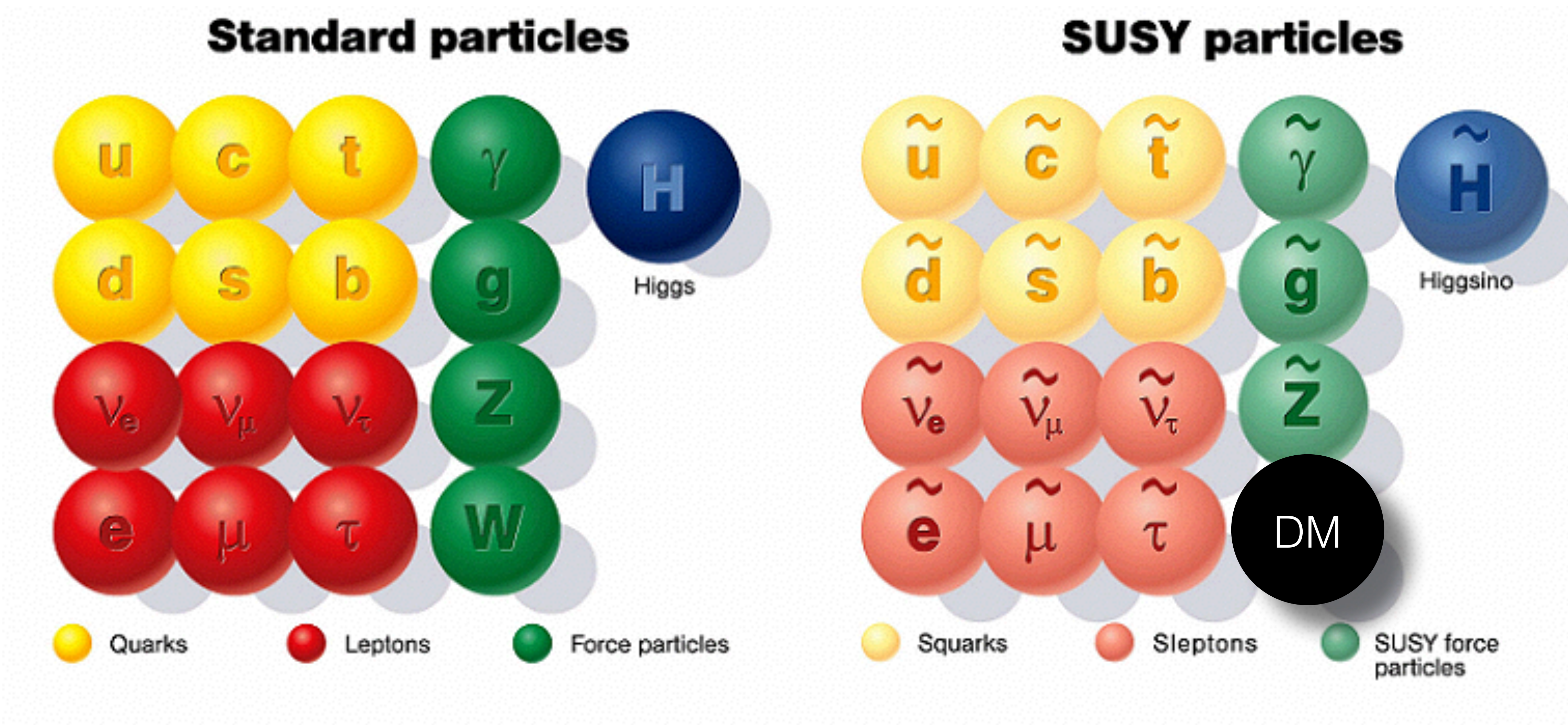
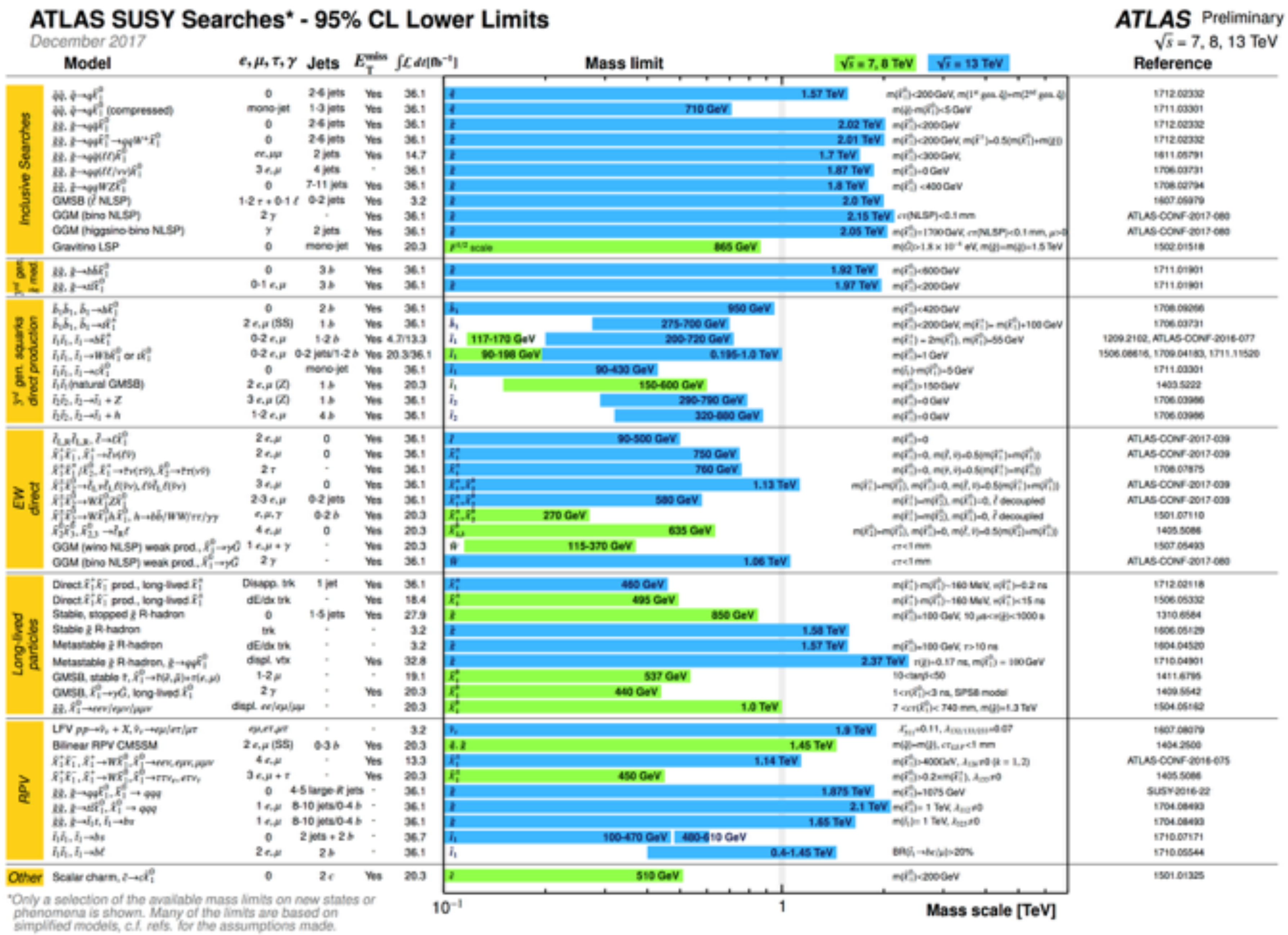


[hep-ph/9506380]

SUPERSYMMETRY CONSTRAINTS

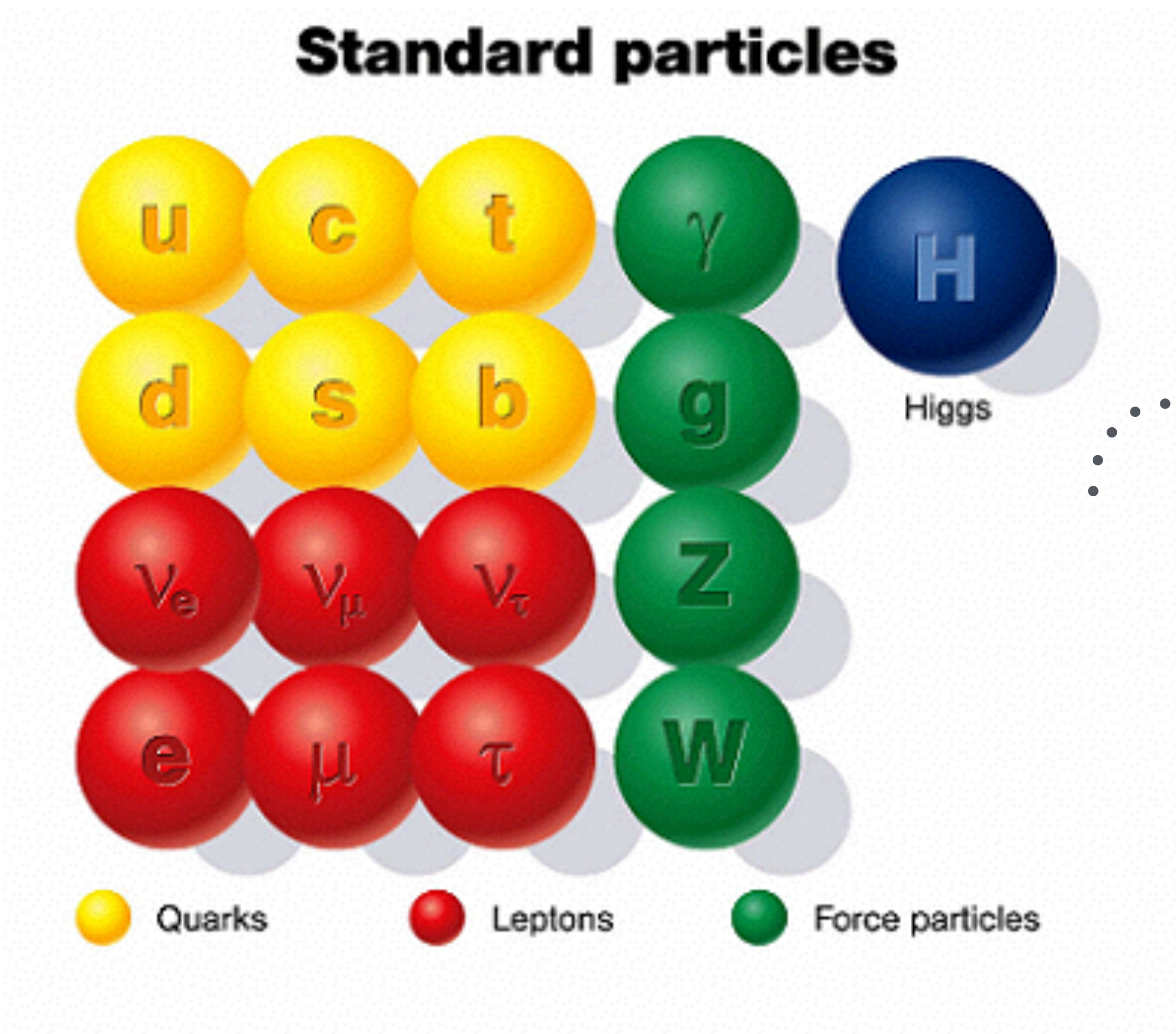
Falling out of favour - we haven't seen any of these new particles (yet)

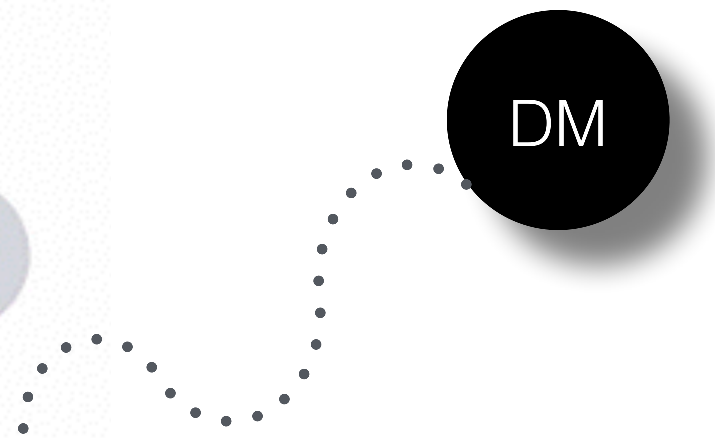


[But see e.g. arXiv:1507.07446]

Effective Field Theory (EFT)

Add a new particle and ask what kind of interactions it is allowed to have…



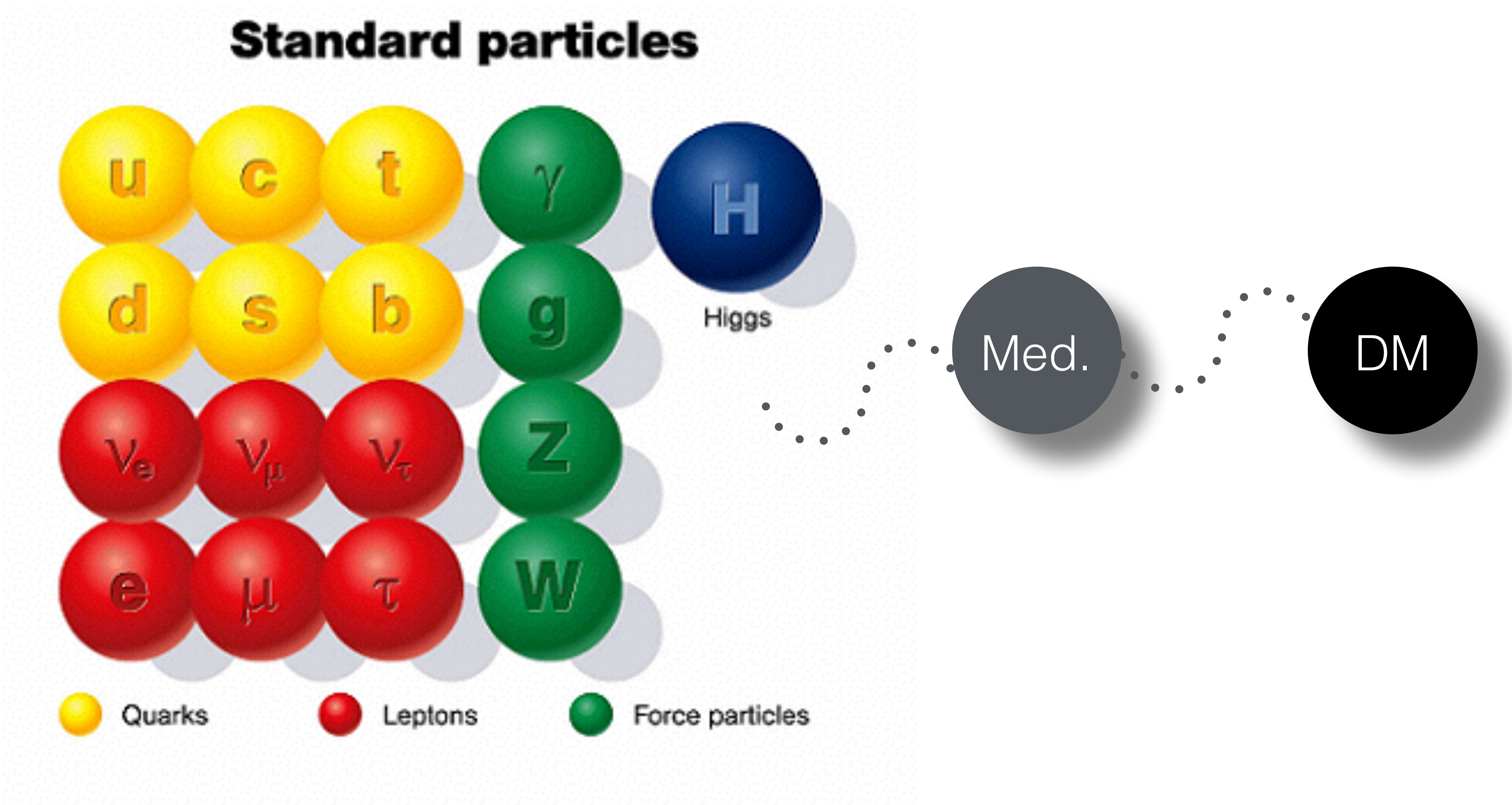


$$(m_{\rm DM},\, c_1,\, c_2,\, c_3\,, ...)$$

[arXiv:1008.1783]

Simplified Models

Add extra particles which mediate the interactions

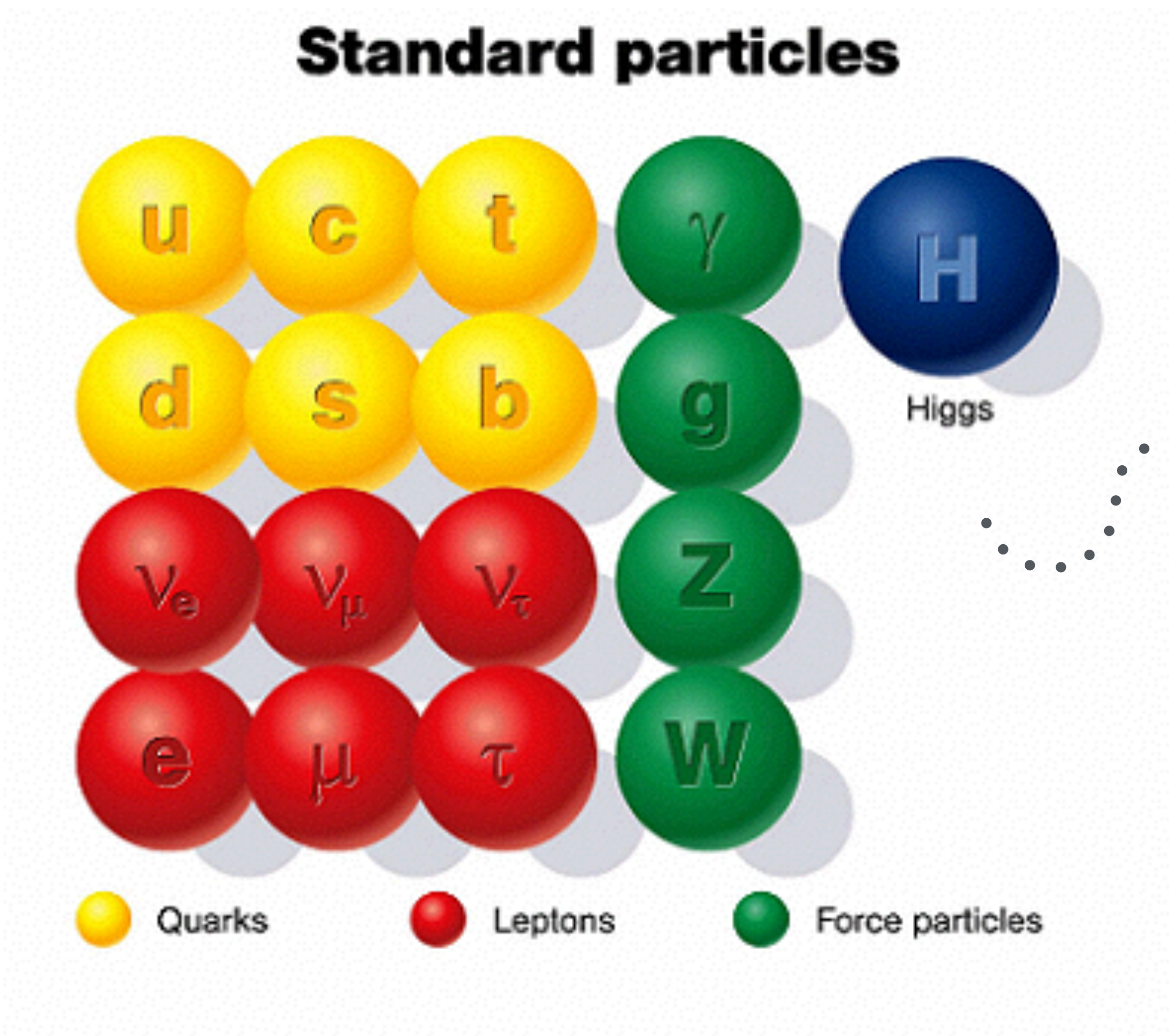


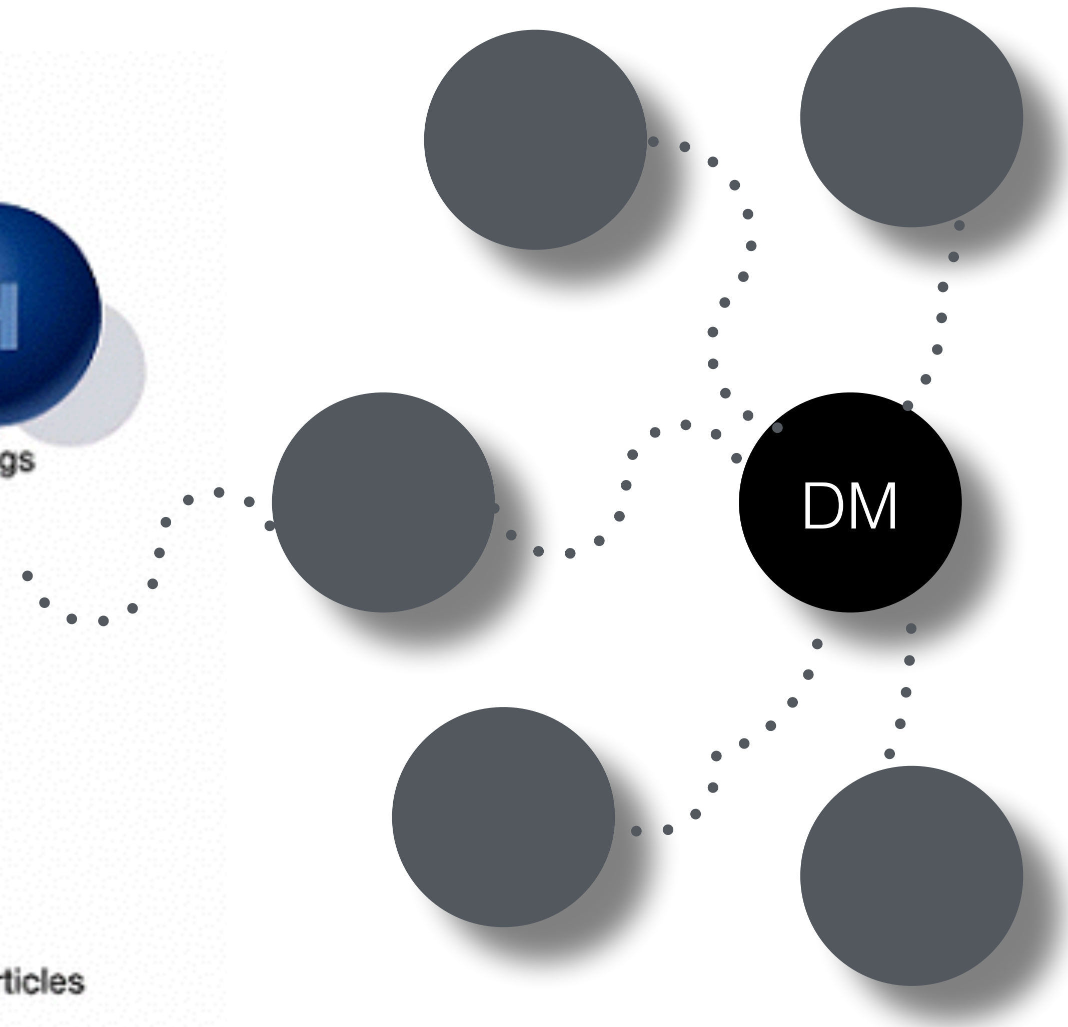
$$(m_{\rm DM},\, m_{\rm med},\, c_{\rm DM},\, c_{\rm med})$$

[arXiv:1506.03116]

DARK/HIDDEN SECTORS

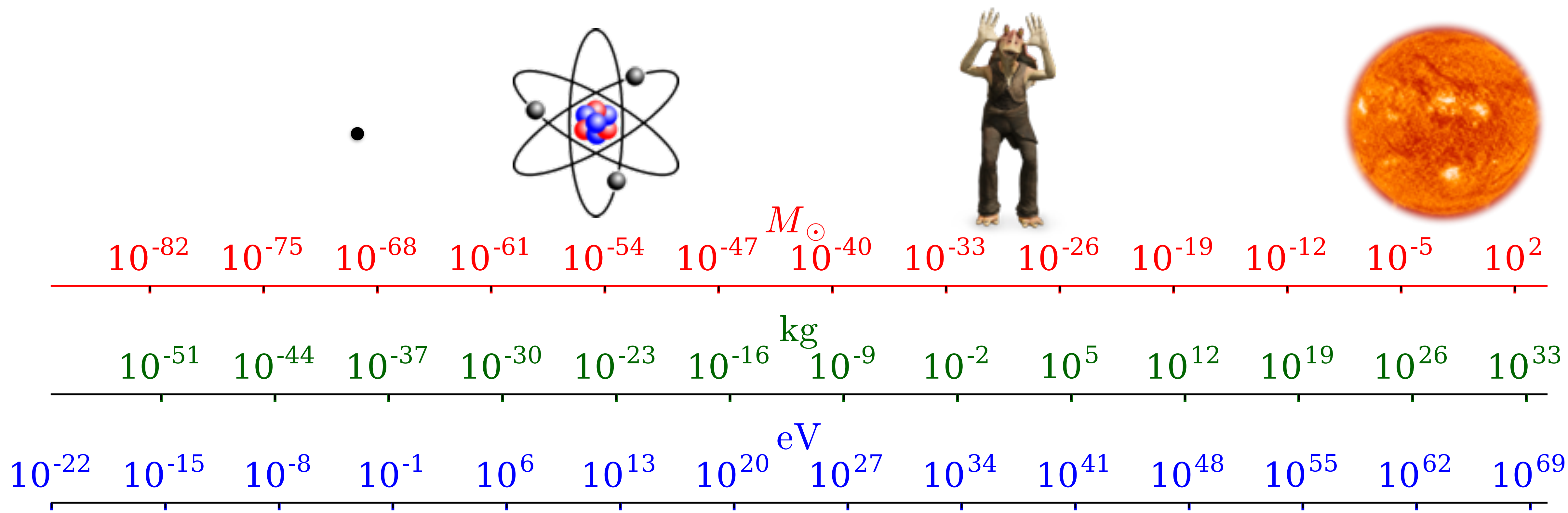
Add lots of extra particles which are hidden from us





[arXiv:0808.2318]

Dark Matter Mass "Priors"



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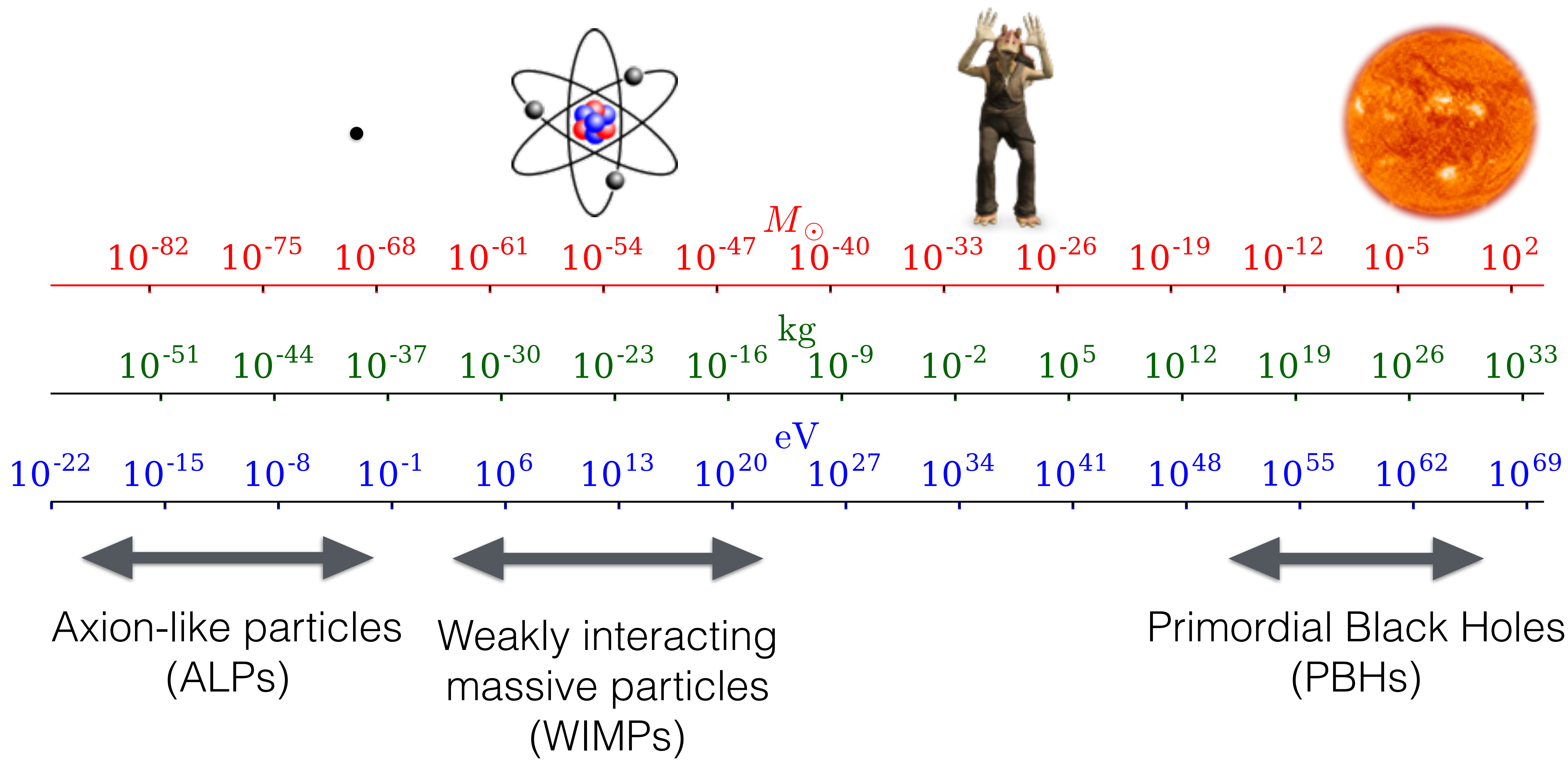

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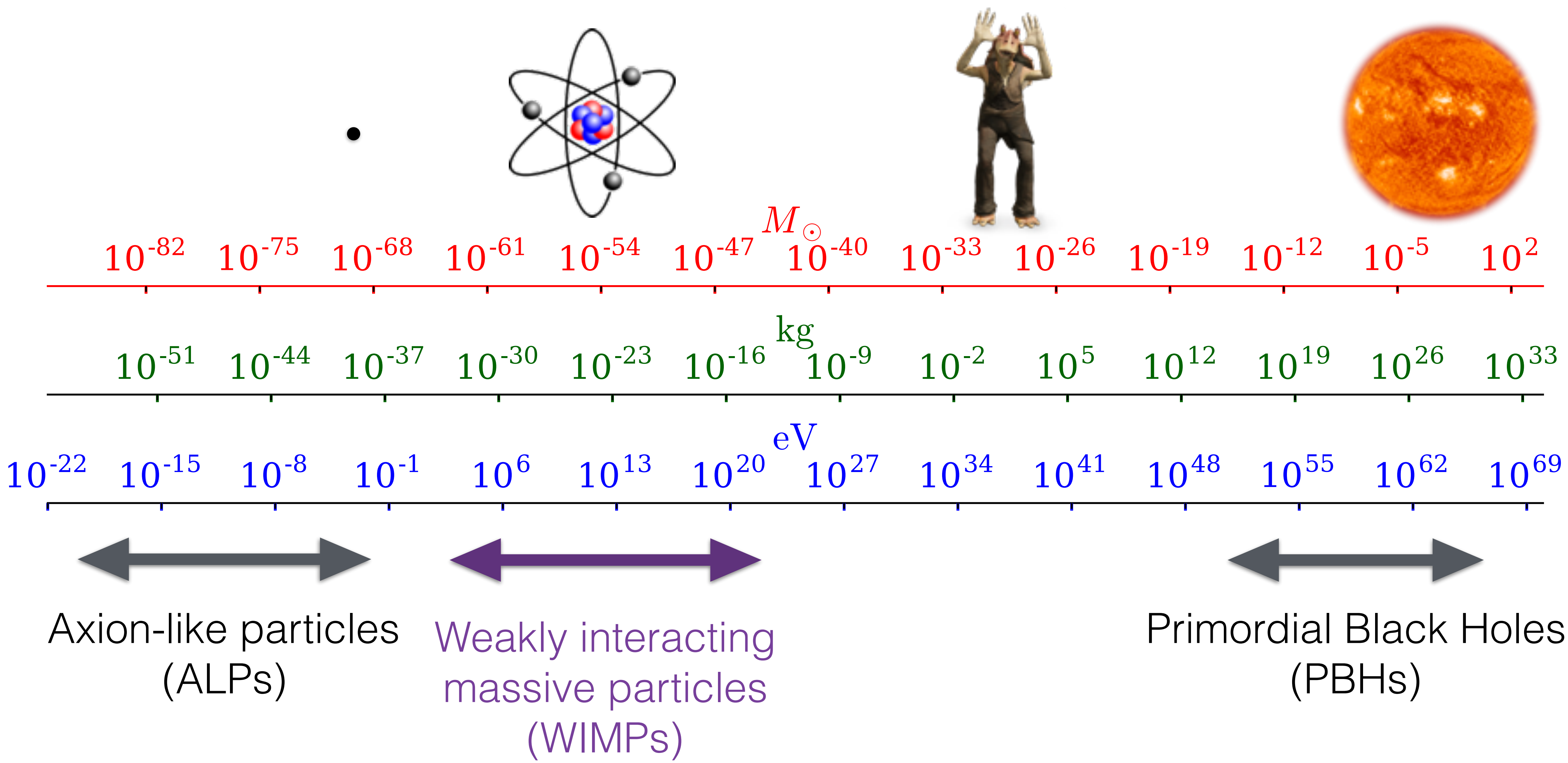
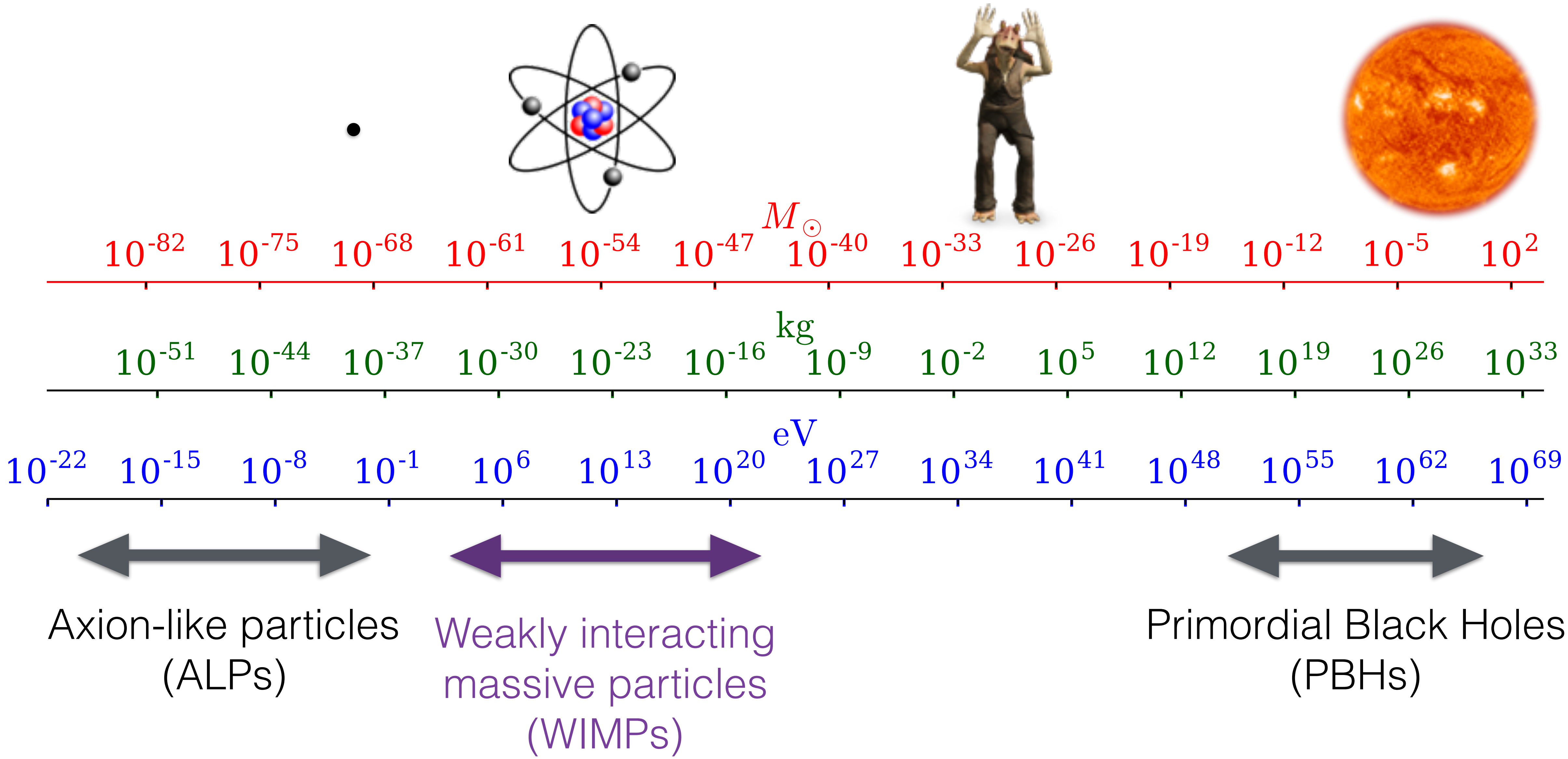


Focus is often on so-called WIMP Dark Matter (perhaps motivated by SUSY)

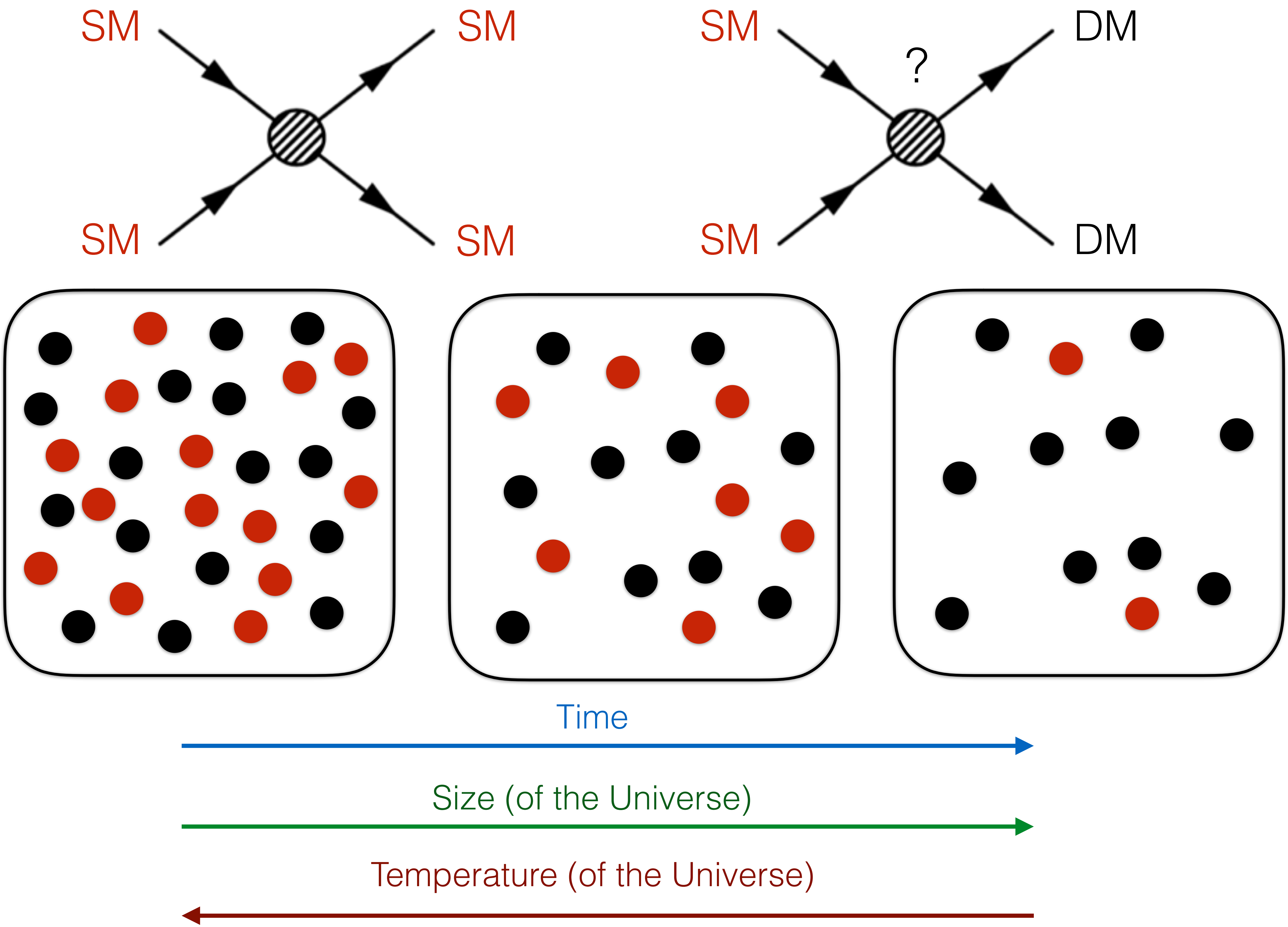
(Very) loosely speaking: $m_\chi \sim \mathrm{keV} - \mathrm{TeV} \sim [10^{-6}, 10^3]\, m_p$

Dark Matter Mass "Priors"



Perhaps the best 'prior' is whether or not you can come up with a sensible production mechanism.

Freeze-out



SM
SM
SM
SM
SM
?
DM
SM
DM
Time
Size (of the Universe)
Temperature (of the Universe)

FREEZE-OUT

It turns out that particles with TeV-scale mass (~1000 proton masses) and "weak-scale" interactions gives just the right amount of DM today!

The WIMP Miracle!

Sadly, we haven't seen these 'weak-scale' particles yet.
But not to worry…

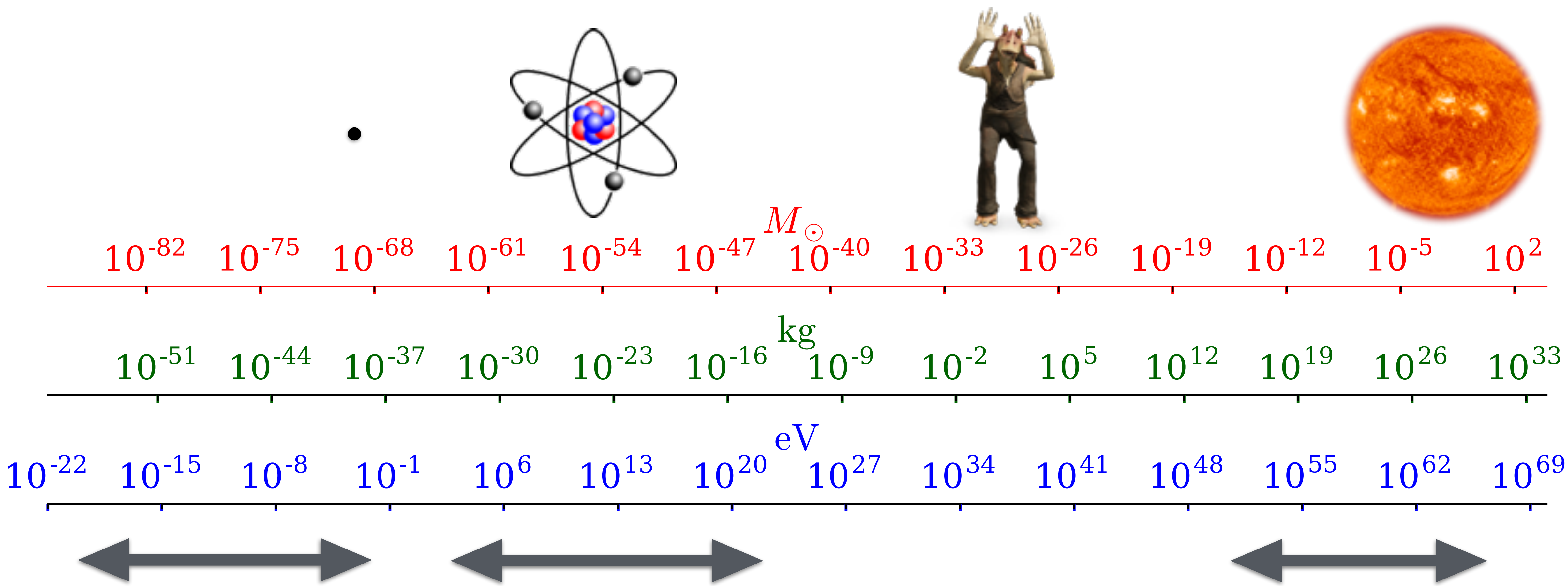
[arXiv:0903.3381]

Alternative production mechanisms

Freeze-out [Kolb & Turner (1990)]
Freeze-in [arXiv:0911.1120]
Asymmetric Dark Matter [arXiv:1305.4939]
Forbidden Dark Matter [arXiv:1505.07107]
Secluded Dark Matter [arXiv:0711.4866]
SIMP Dark Matter [arXiv:1402.5143]
Self-interacting Dark Matter [arXiv:1510.08063]
Misalignment Mechanism [arXiv:1105.2812]
Gravitational production (WIMPzillas!) [hep-ph/9810361]
Hidden sector freeze-out [arXiv:1712.03974]
Early kinematic decoupling [arXiv:1706.07433]
Elastically decoupling relics [arXiv:1706.05381]
Semi-annihilating Dark Matter [arXiv:1611.09360]

Necessity is the mother of invention!

Dark Matter Mass "Priors"



Axion-like particles (ALPs)

Weakly interacting massive particles (WIMPs)

Primordial Black Holes (PBHs)

Look everywhere we can…

Evidence:

How do we know Dark Matter is everywhere?

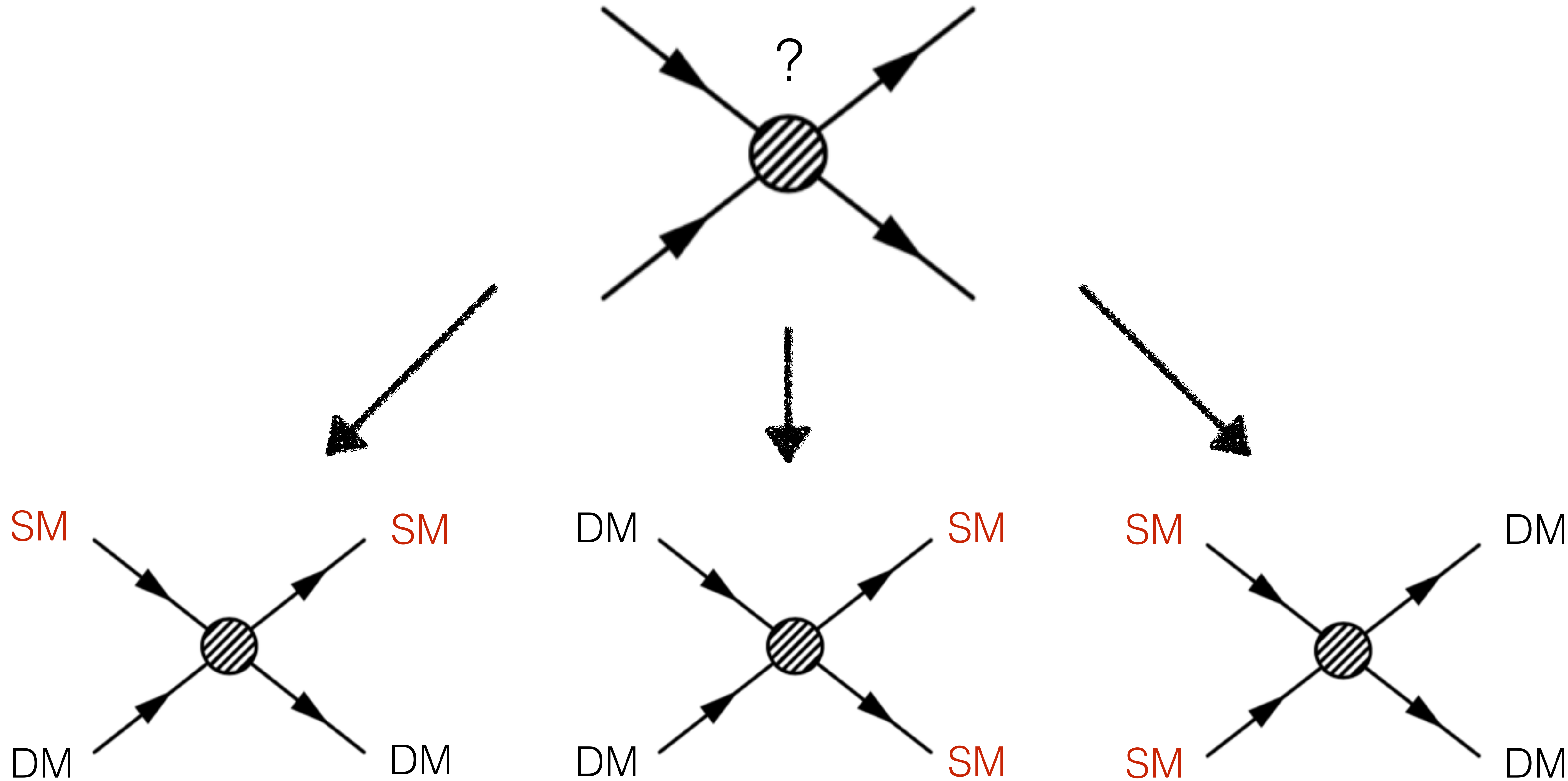
Theory:

What is Dark Matter?

Searches:

How can we make it not-so-Dark Matter?

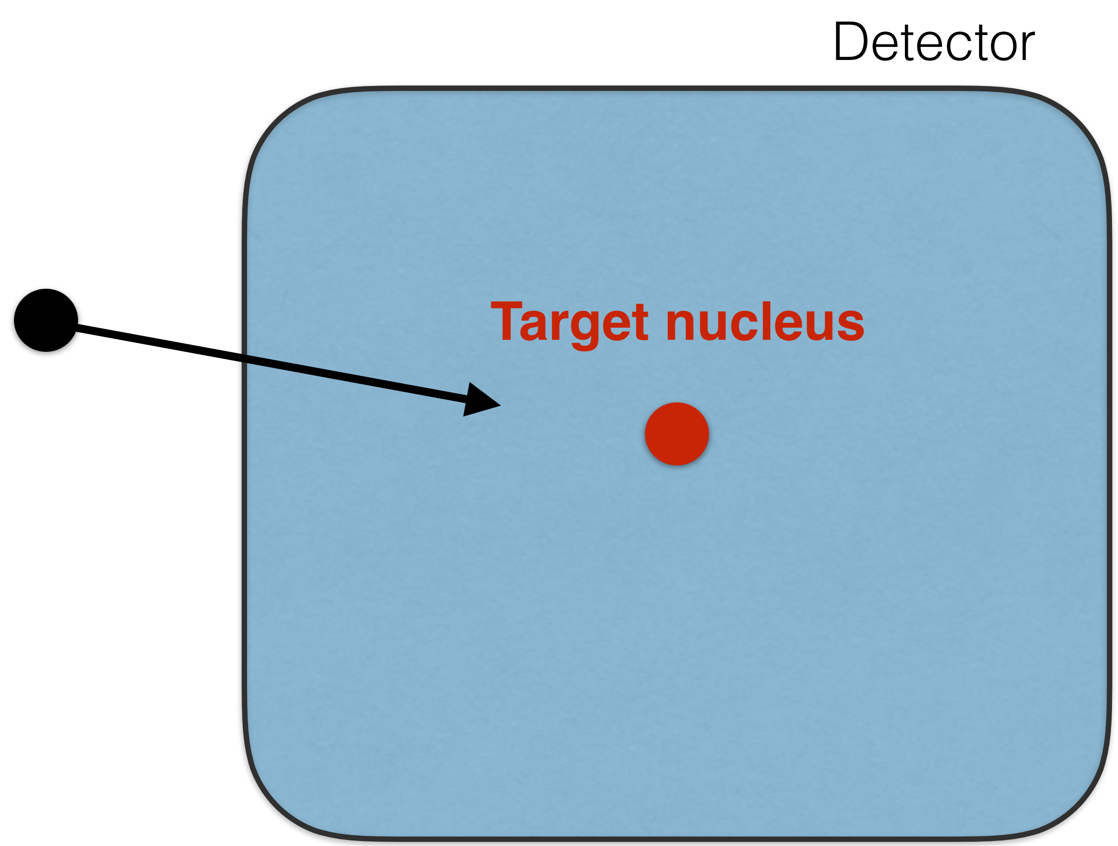
Dark Matter Interactions



“Direct”	“Indirect”	“Collider”
[Wolfgang Rau - Tuesday]	[Christoph Weniger - Wednesday]	[Christopher Anelli - Thursday]

DIRECT DETECTION

Look for the interaction of DM with nuclei:



Rare event searches with (sometimes) unknown BG…

Hope to compare recoil energy spectra with DM predictions!

Direct Detection

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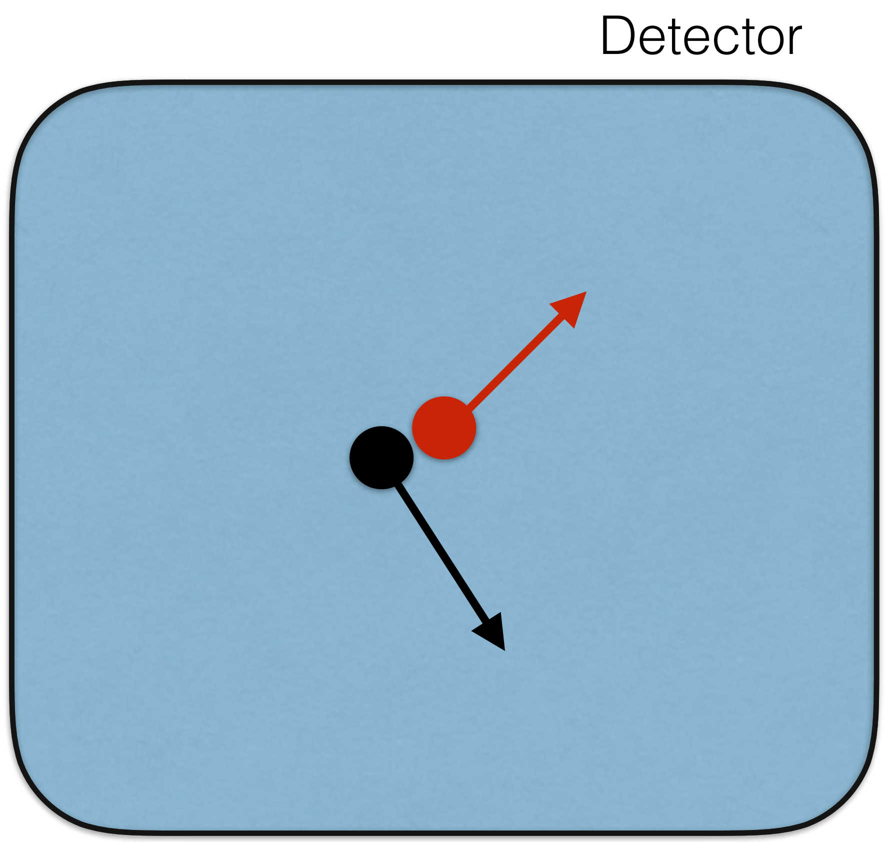

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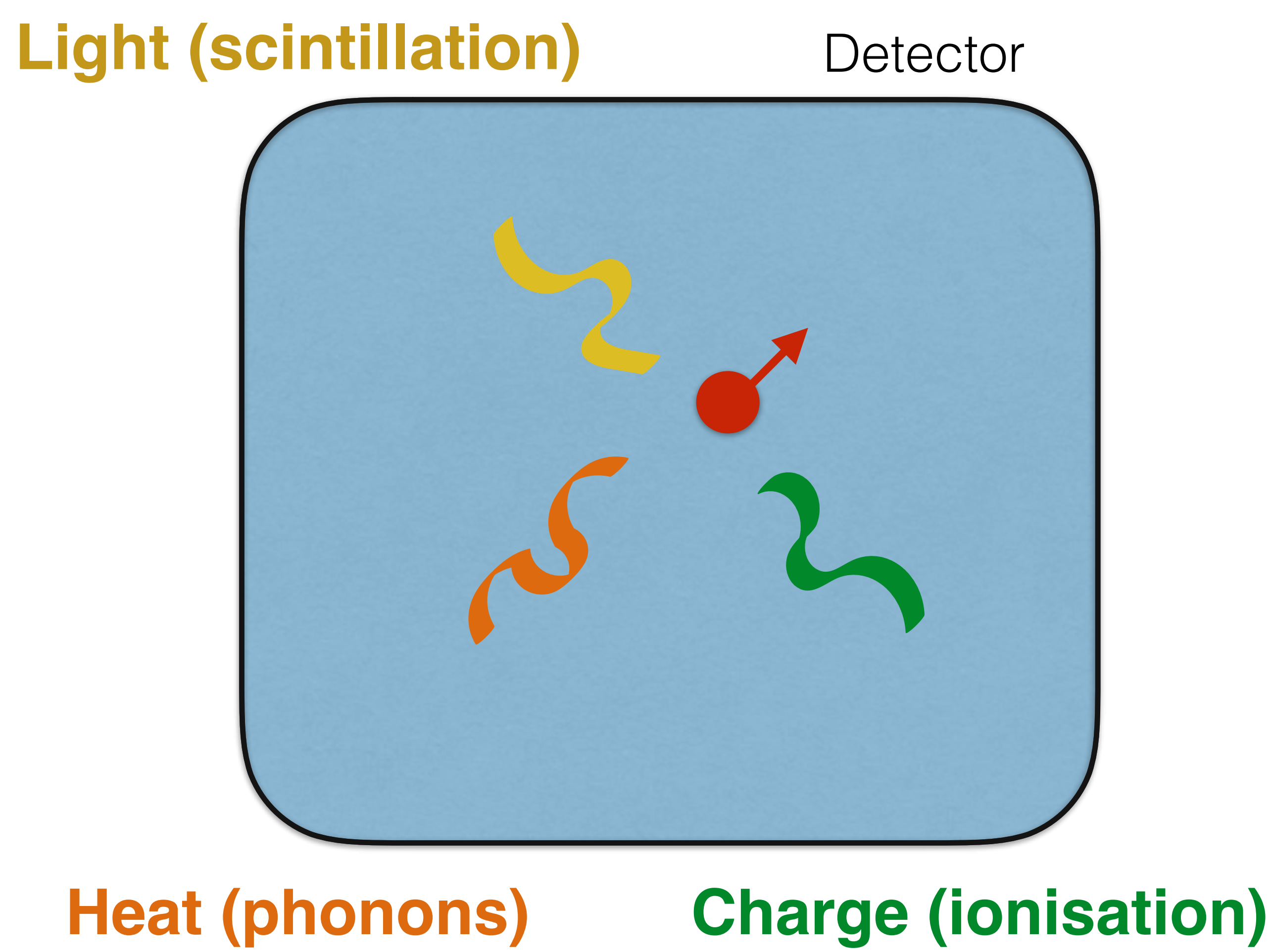


Rare event searches with (sometimes) unknown BG…

Hope to compare recoil energy spectra with DM predictions!

XENON1T

[See e.g. https://tinyurl.com/ycomgccl]

3.2 tons of liquid Xenon in a tank!

Deep underground - LNGS lab in Italy (3200 m.w.e.)

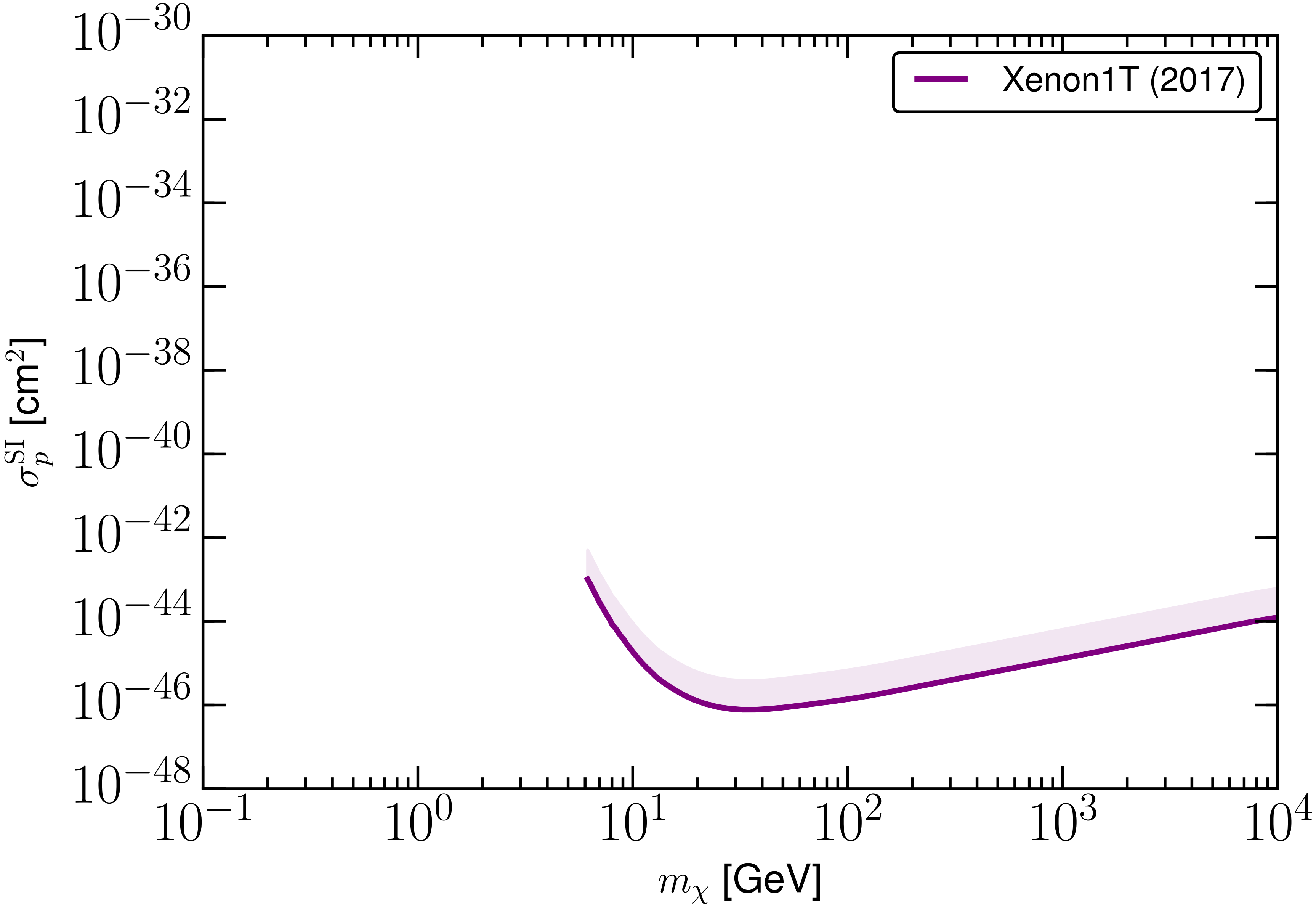
Low background, low threshold detector

[arXiv:1705.06655]

Direct detection constraints

Proton-proton cross section
is somewhere here

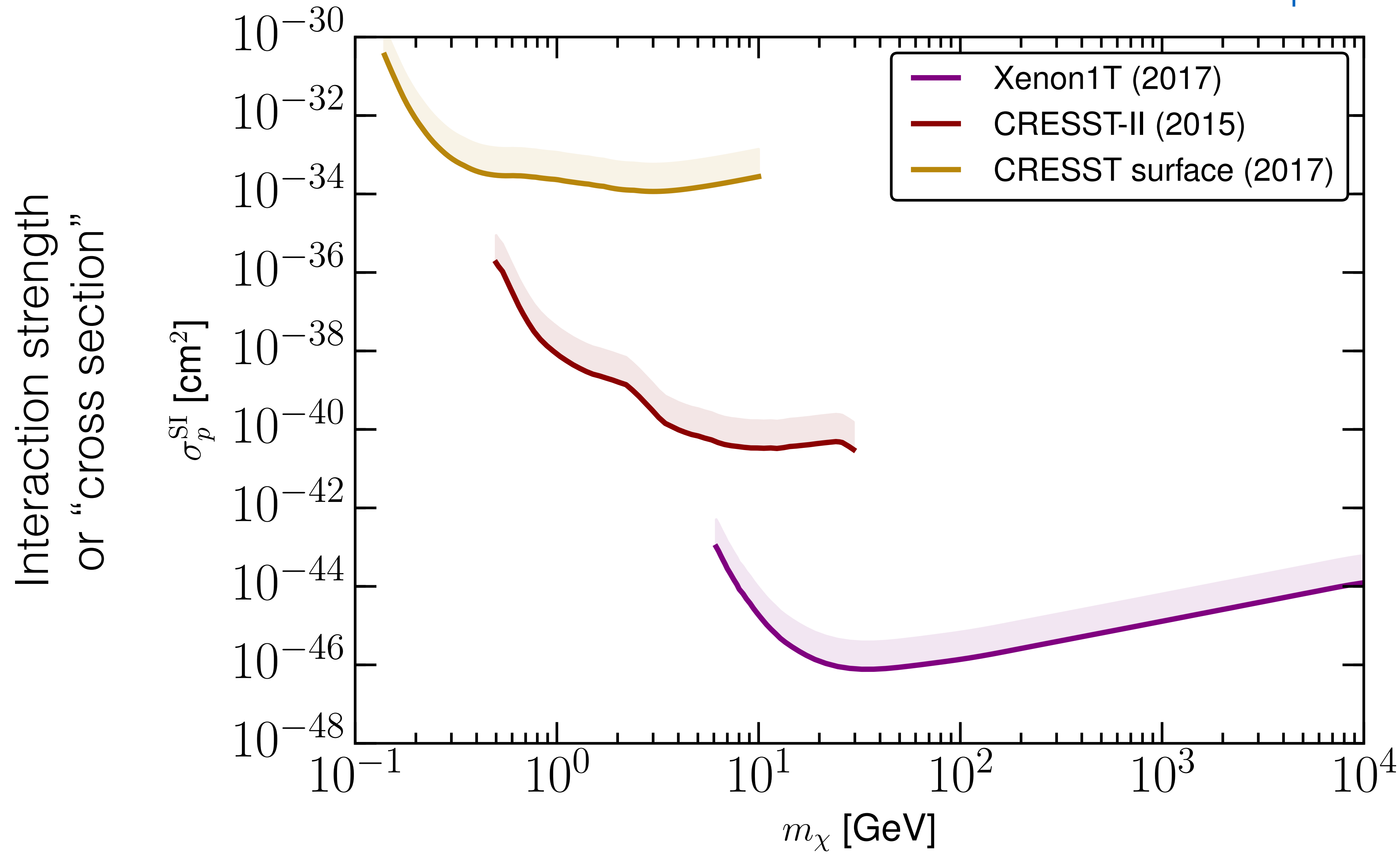
Interaction strength
or "cross section"



Dark Matter Mass

Direct detection constraints

+lots of other experiments

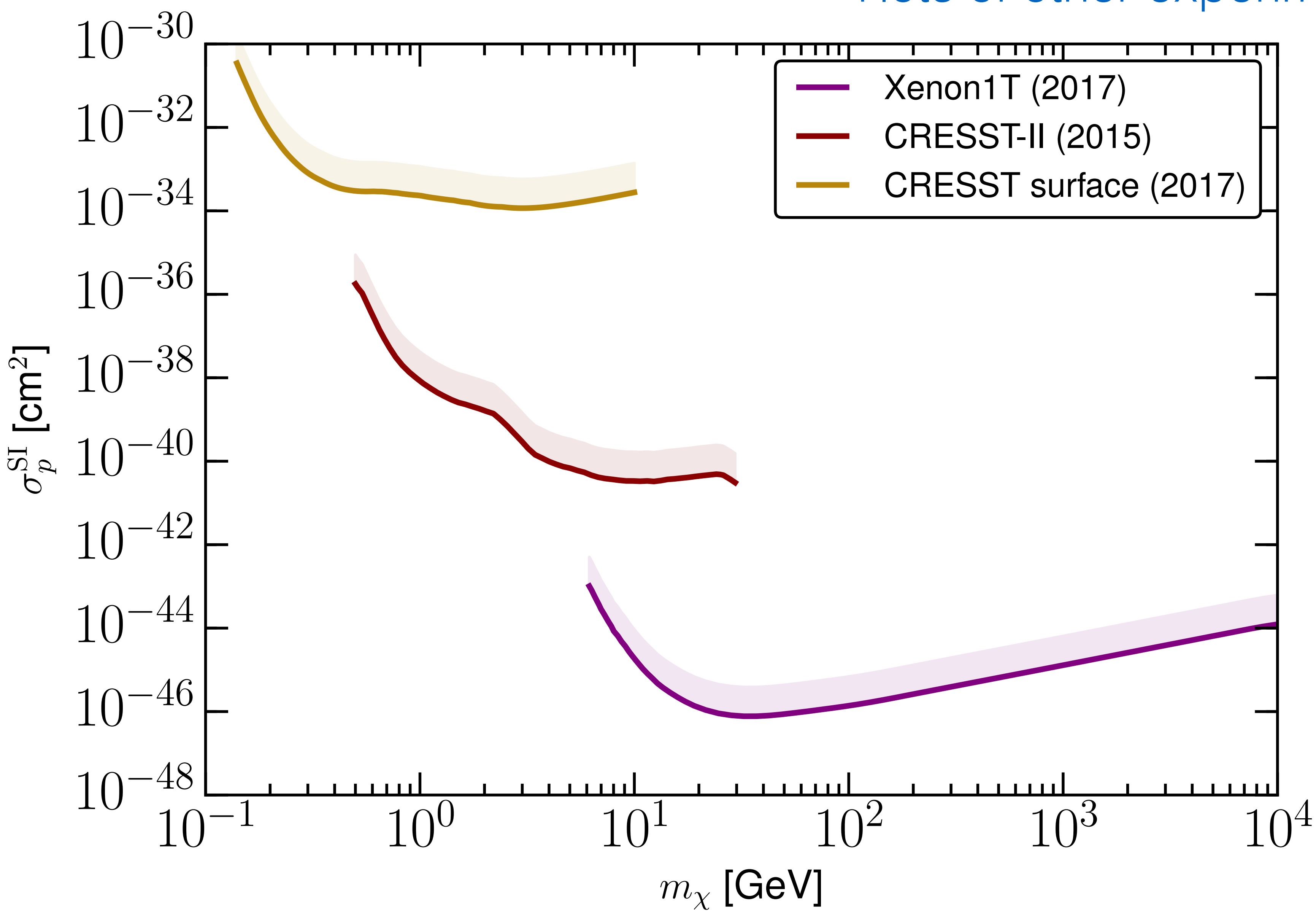


[arXiv:1509.01515, arXiv:1707.06749]

DIRECT DETECTION CONSTRAINTS

Low Threshold

+lots of other experiments



Interaction strength
or "cross section"

Large exposure

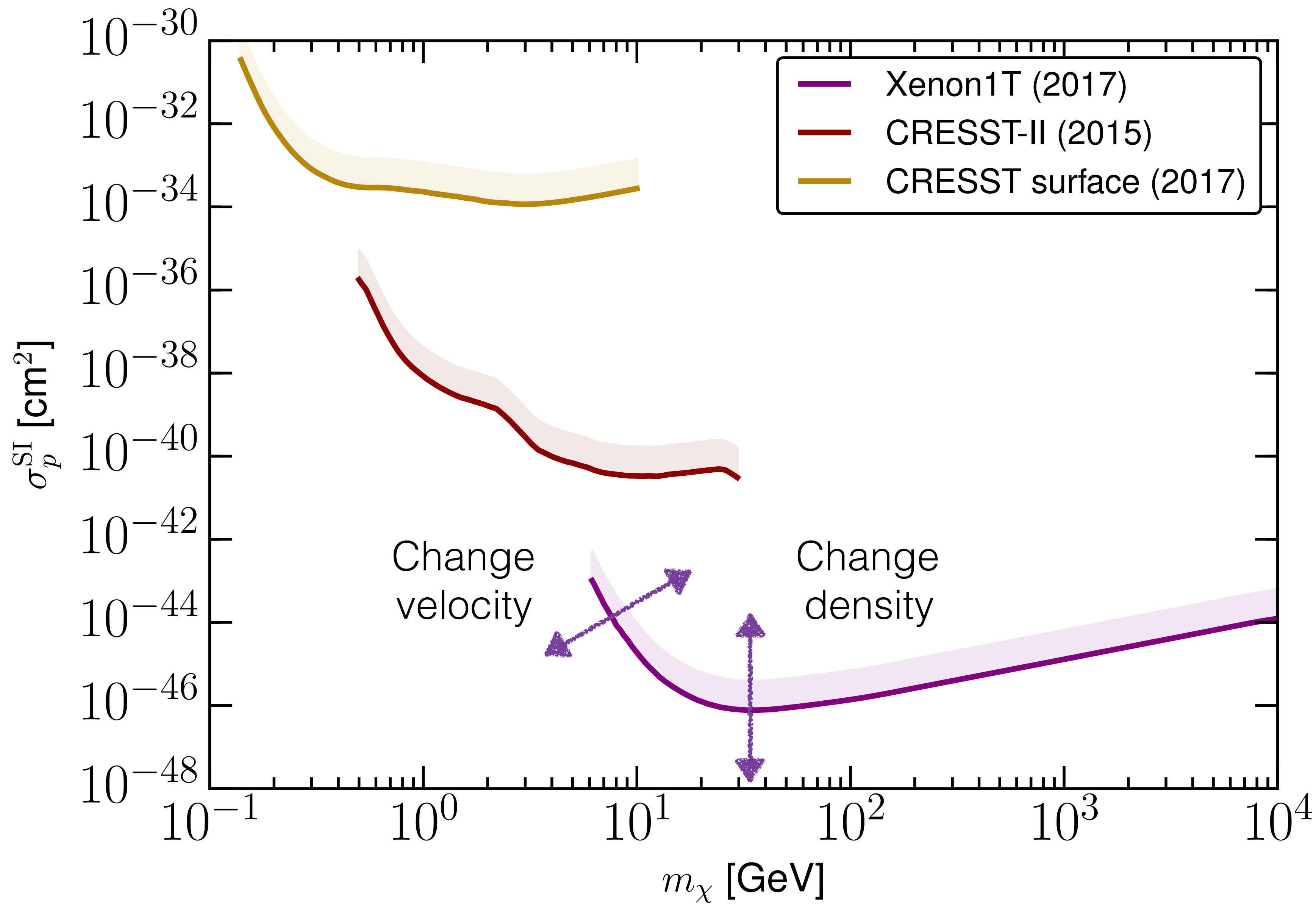
Dark Matter Mass

[arXiv:1509.01515,
arXiv:1707.06749]

Uncertainties in direct detection

Local distribution of Dark Matter is uncertain…

Interaction strength
or "cross section"



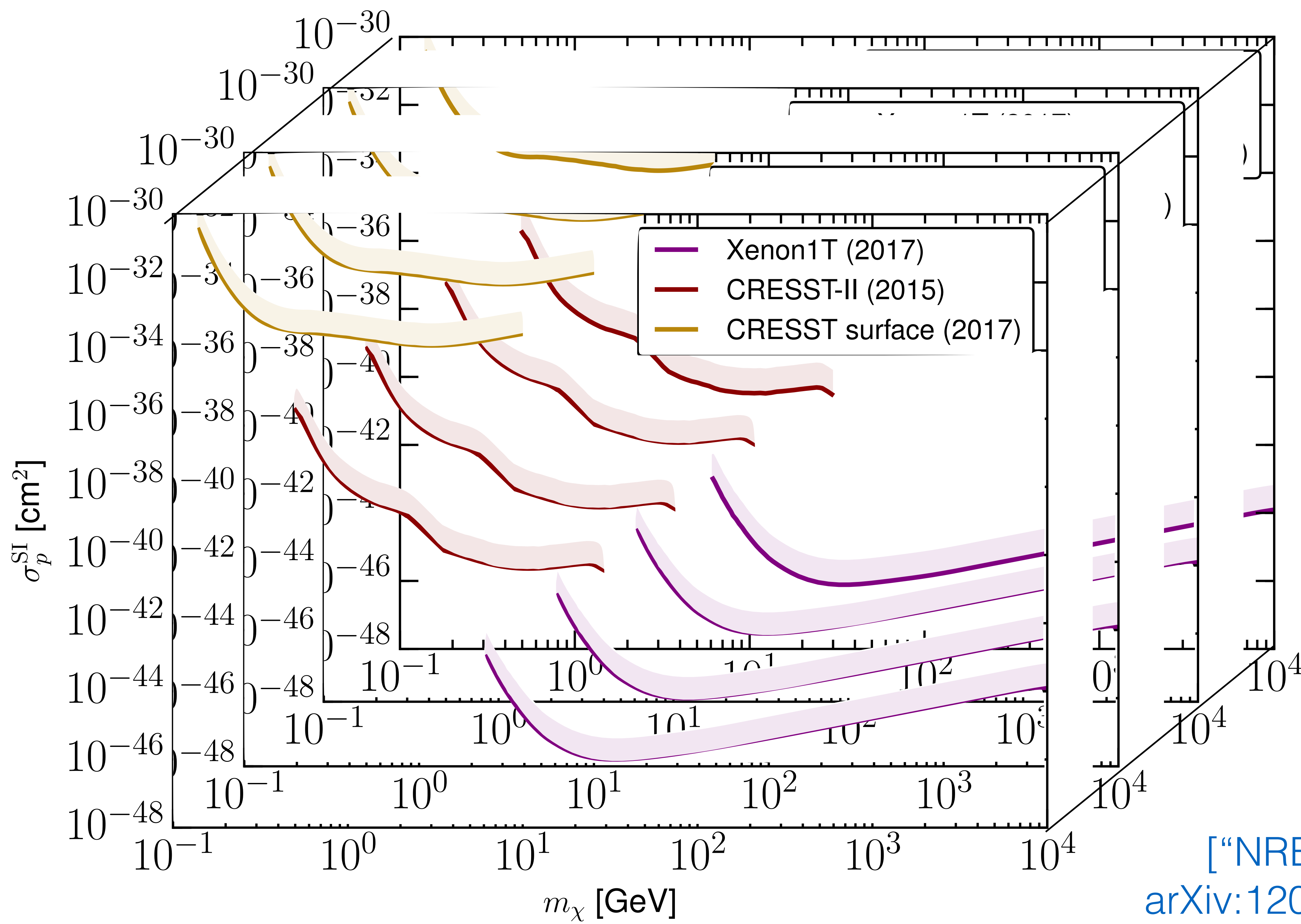
Dark Matter Mass

[Fabio Iocco - Tuesday]

Uncertainties in direct detection

Unknown form of the interaction…

Generalising, you could write down 30+ different interactions…

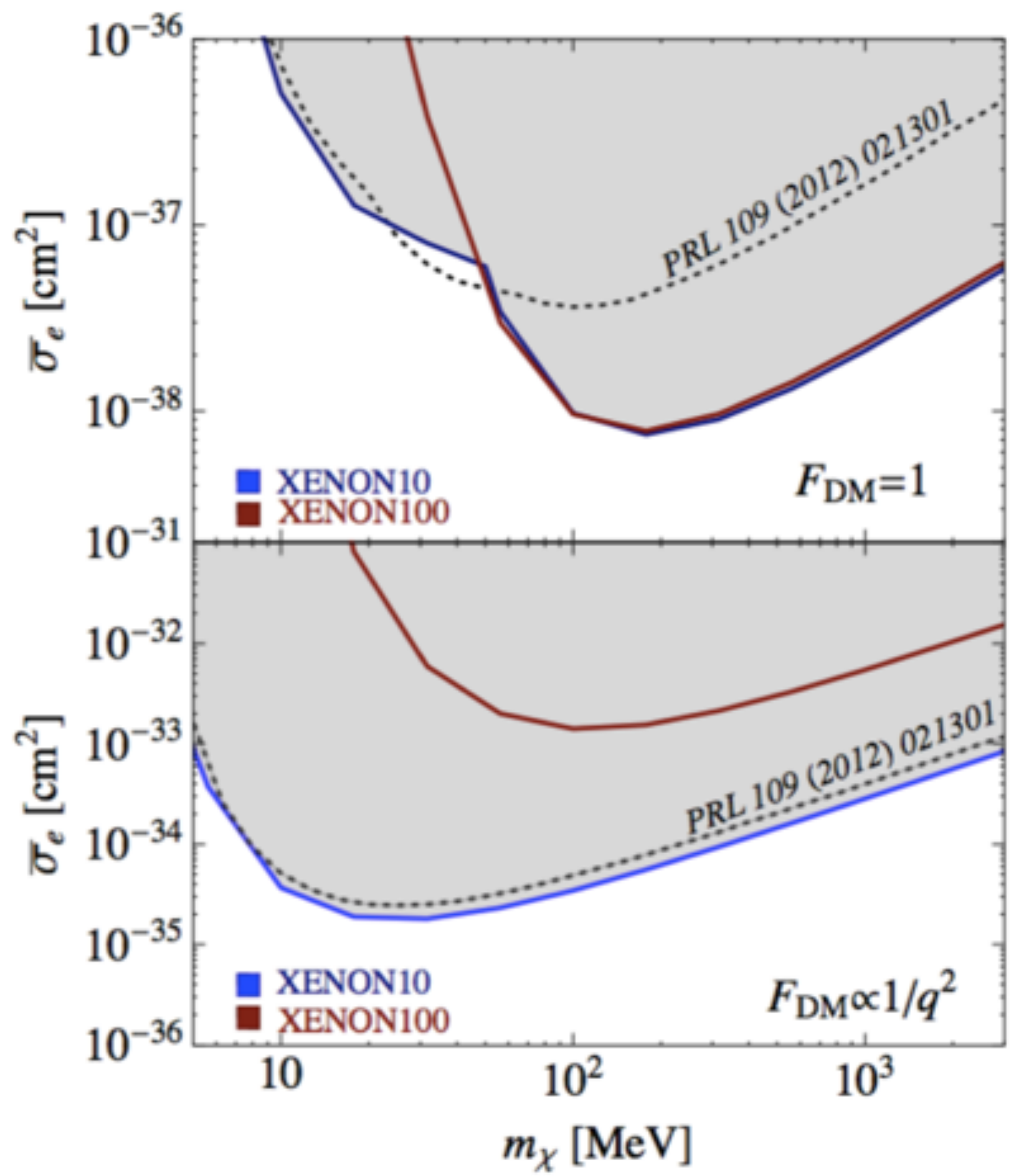


["NREFT", arXiv:1203.3542]

DARK MATTER ELECTRON SCATTERING

So far, we've only talked about DM-nucleus interactions.
Could also look for DM interacting with electrons in your detector:

Cross section

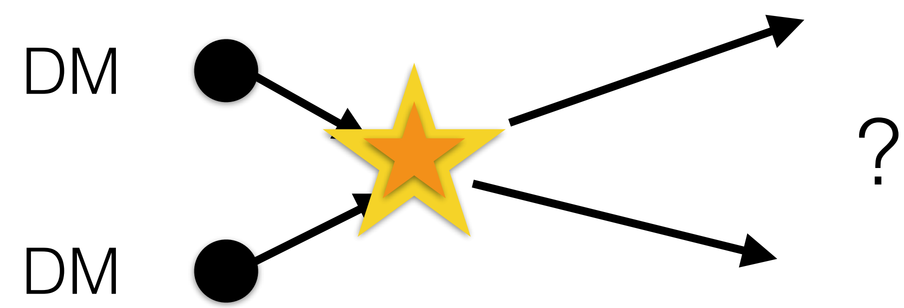


Dark Matter Mass

[arXiv:1703.00910]

INDIRECT DETECTION

Look for the products of DM annihilation



INDIRECT DETECTION

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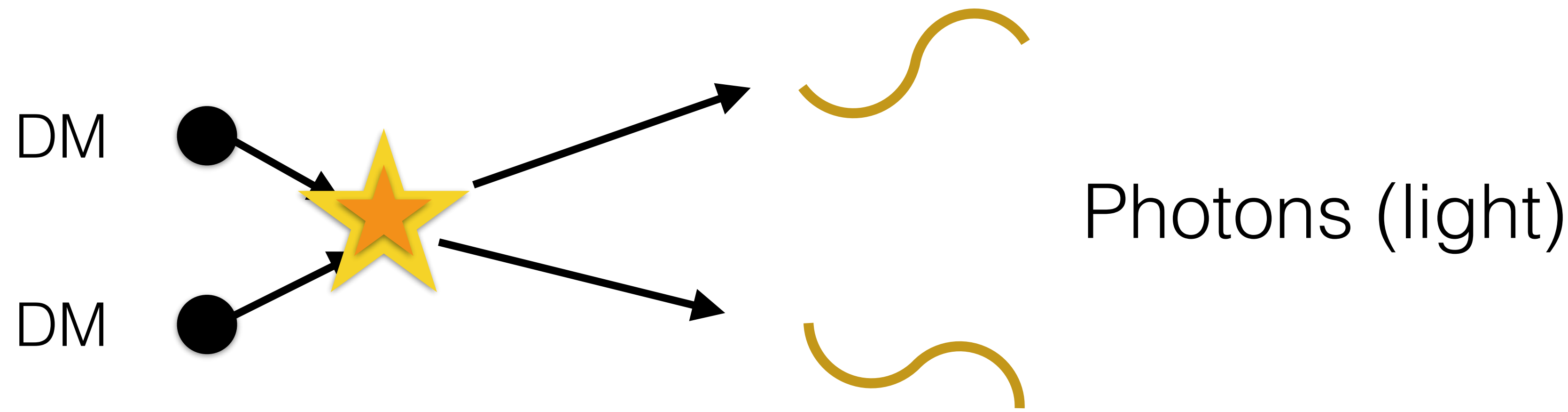
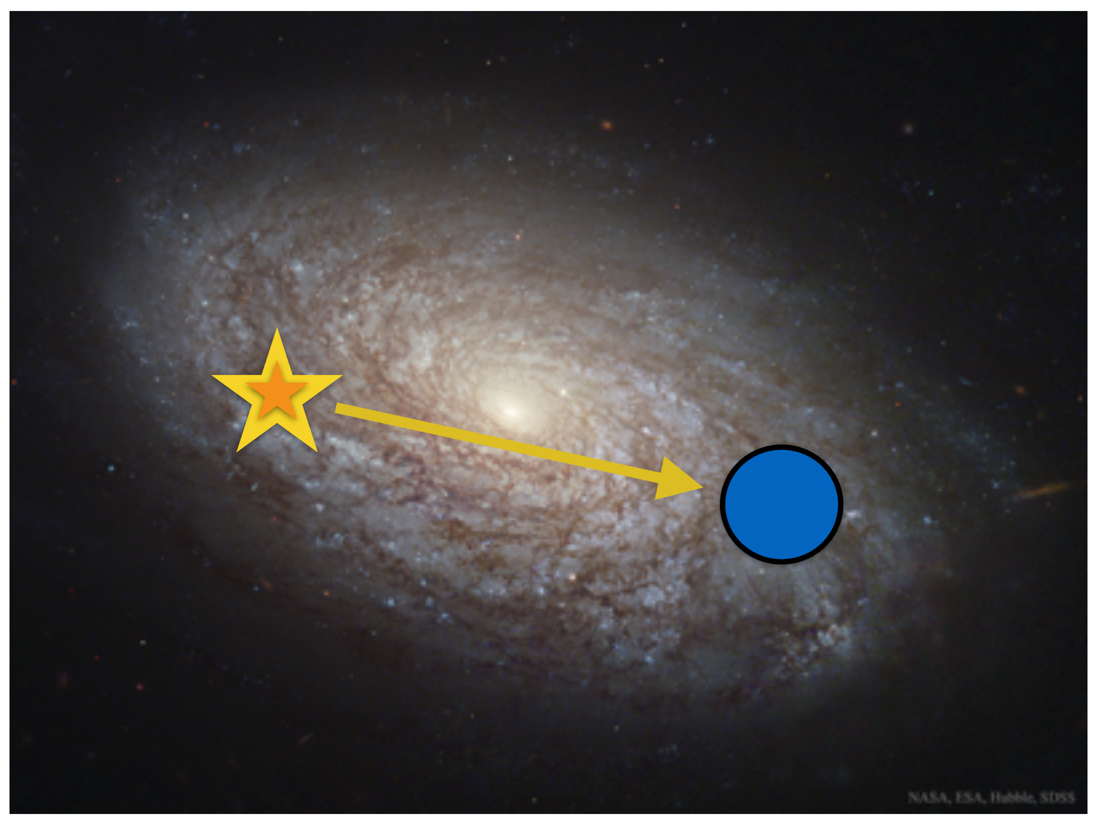
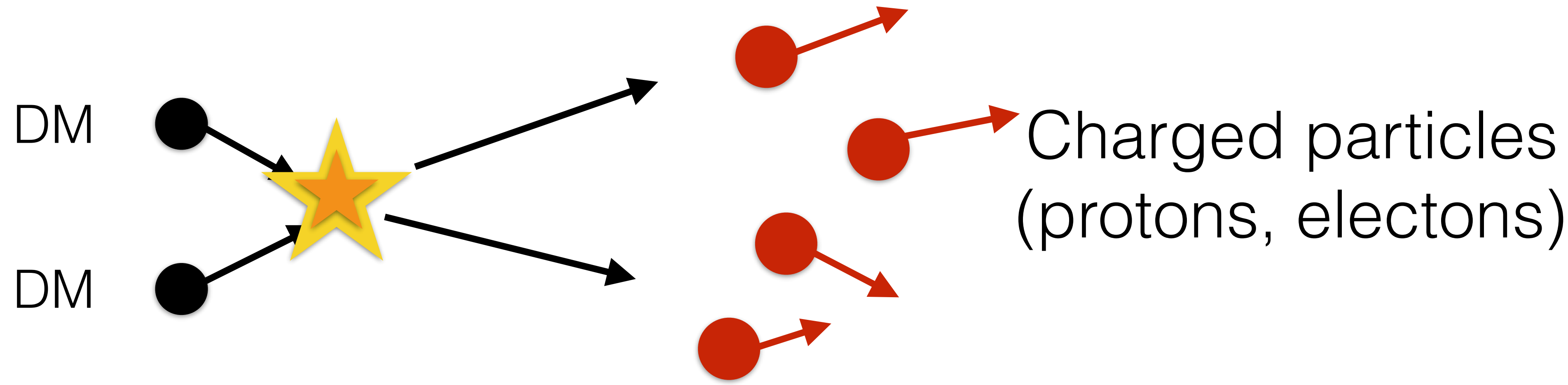


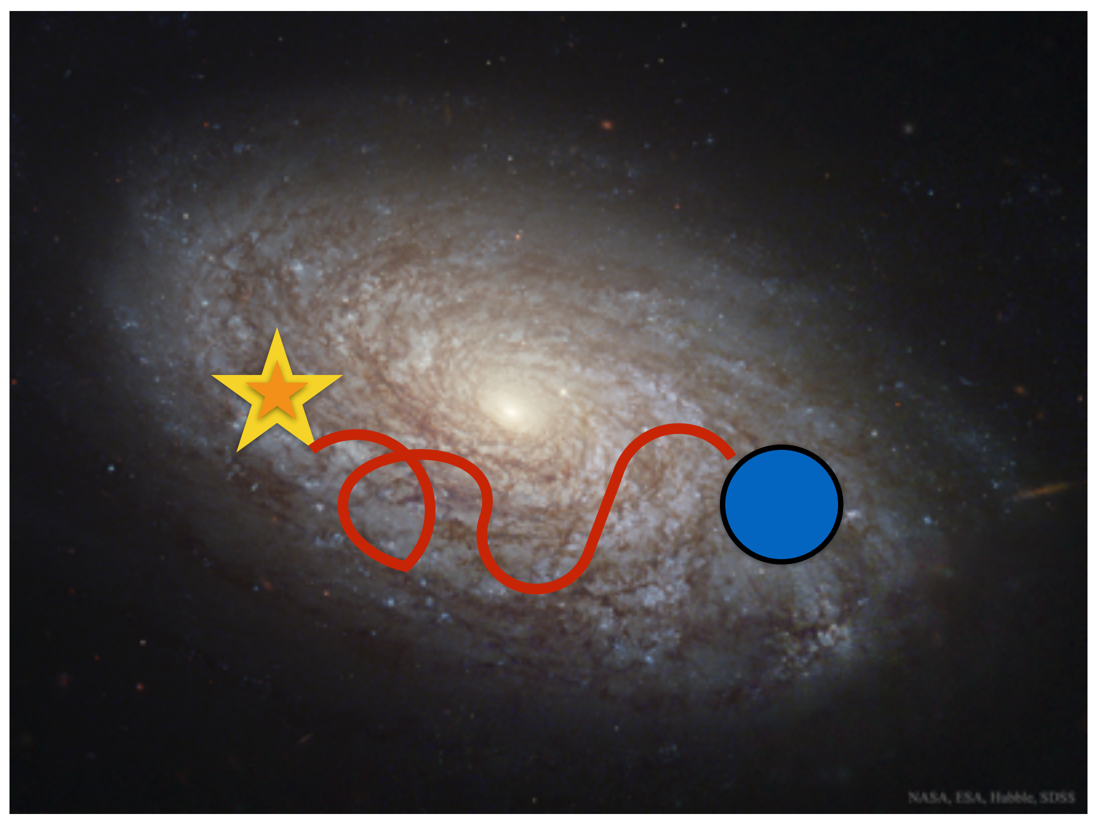


The light travels in a straight line
and we could observe it with telescopes

INDIRECT DETECTION

Look for the products of DM annihilation





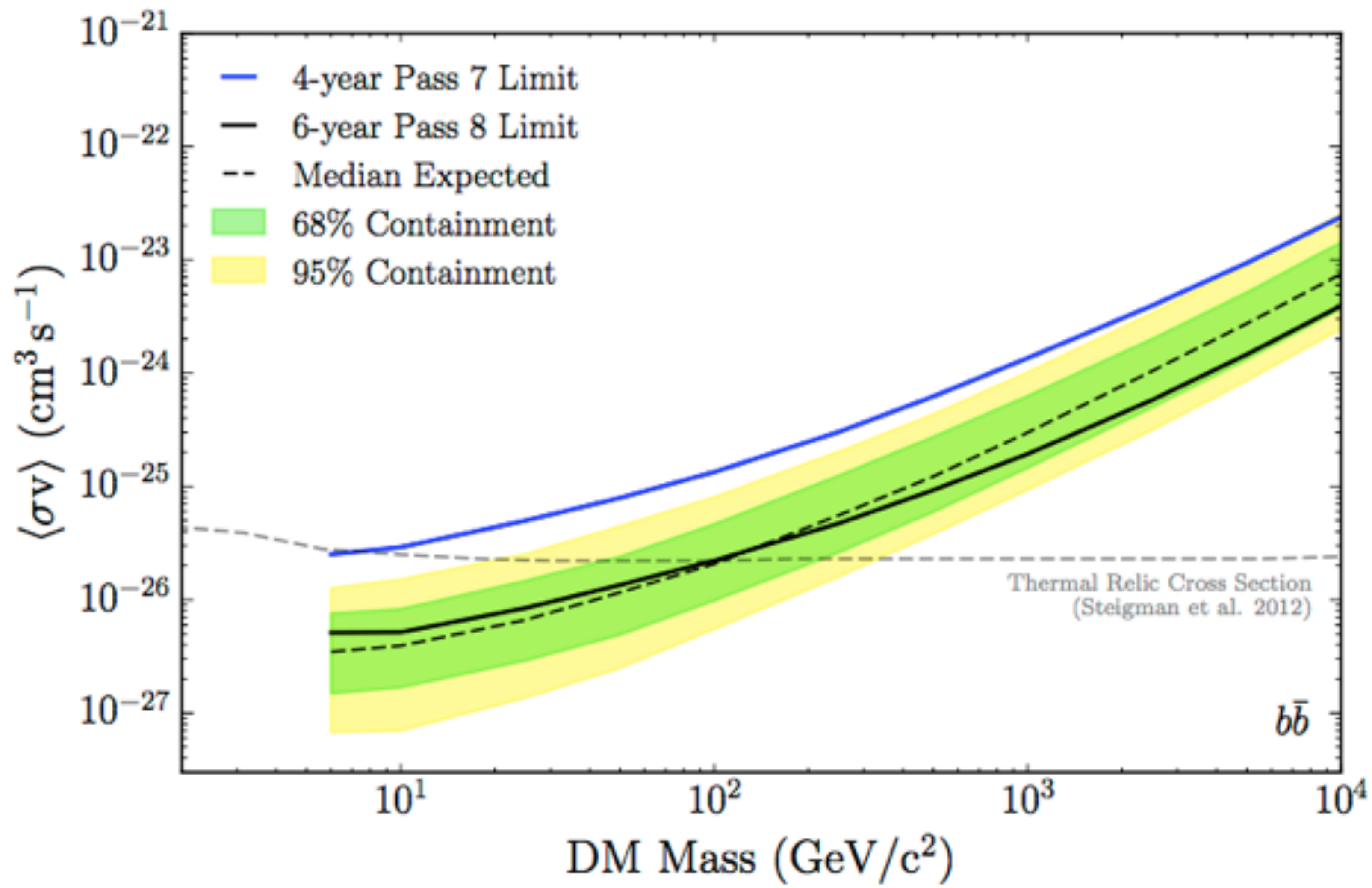
Charged particles (cosmic rays)
diffuse through the galaxy to get to us

INDIRECT DETECTION (WITH LIGHT)

Look for excess light coming from promising sources
(centre of the galaxy, Dwarf Spheroidal galaxies)

Fermi Large Area Telescope constraints
from Dwarf Spheroidal Galaxies

Annihilation cross section



Dark Matter Mass

[arXiv:1503.02641]

INDIRECT DETECTION (WITH LIGHT)

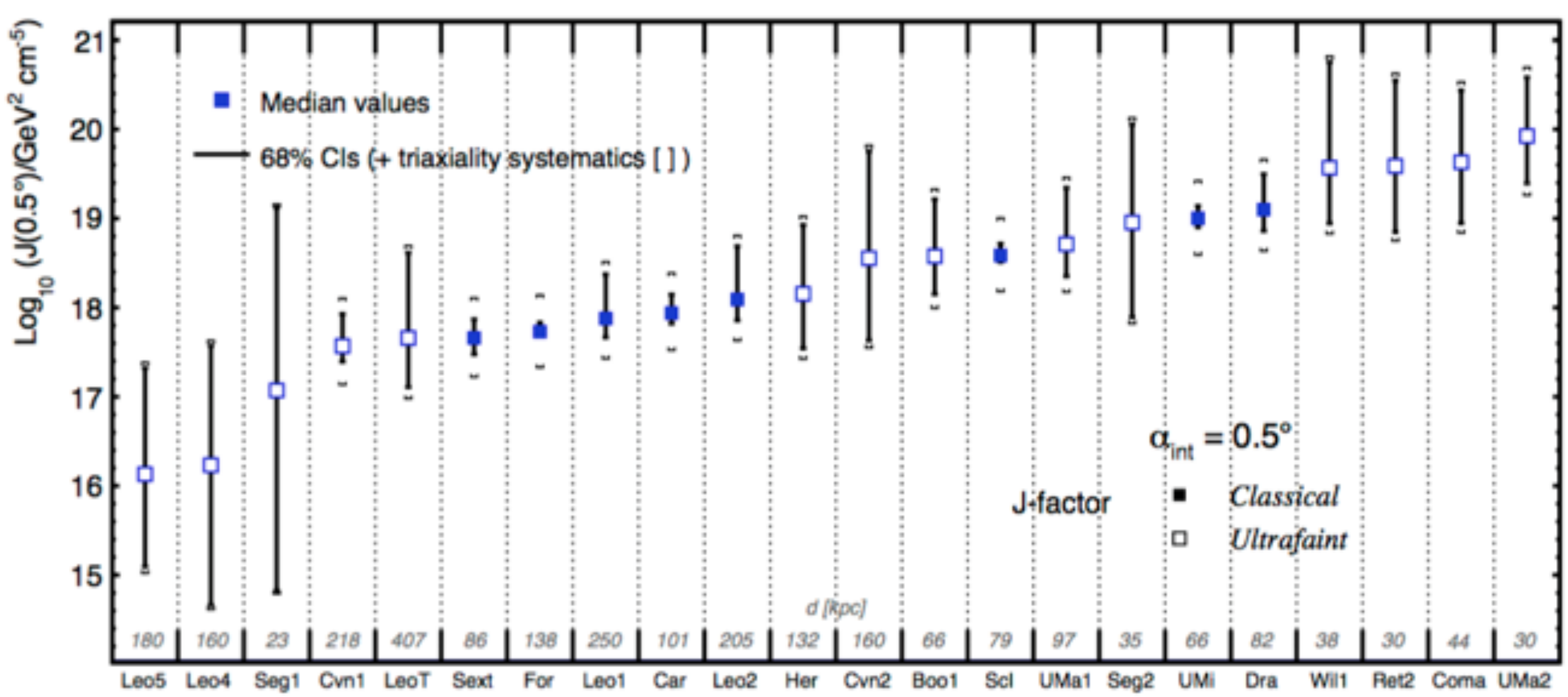
Look for excess light coming from promising sources (centre of the galaxy, Dwarf Spheroidal galaxies)

Not always clear which are the promising targets - efficient forecasting is important

[Tom Edwards - Thursday]

Not always clear how much Dark Matter there is:

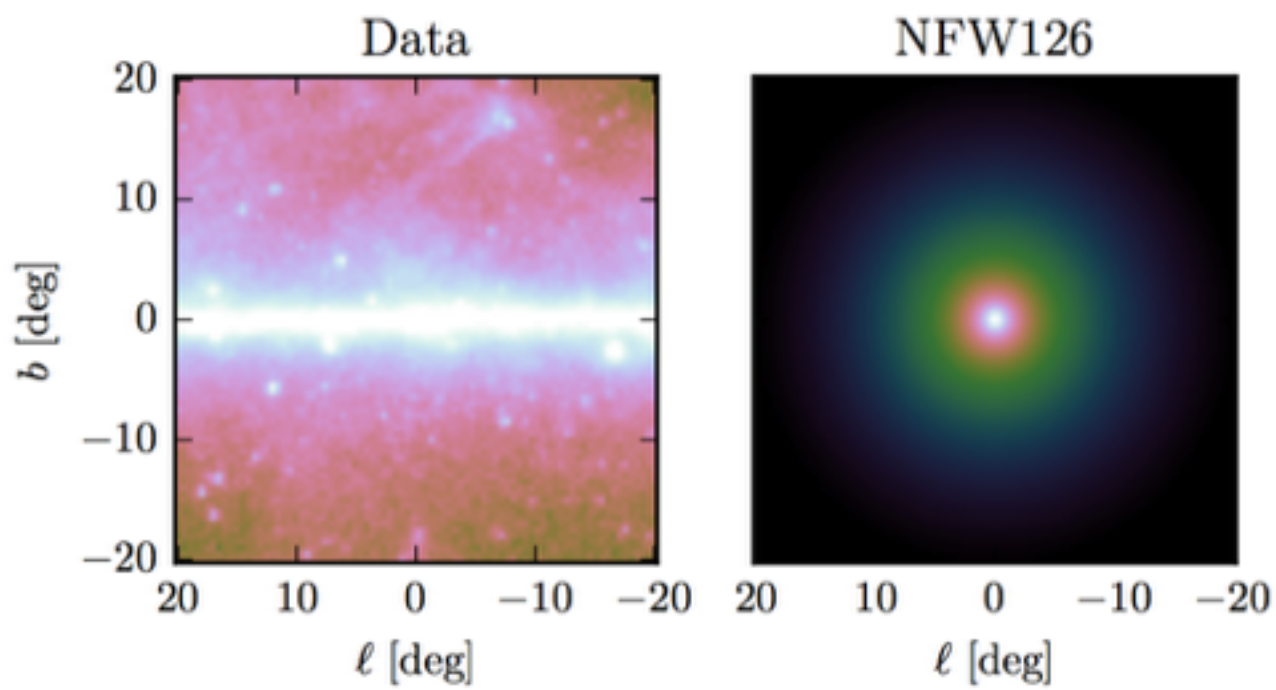
"Amount" of Dark Matter (log-scale)



Dwarf Spheroidal galaxies [Bonnivard et al. 2016]

Galactic centre excess

In recent years there was a promising ‘excess’ in the Galactic centre



DM-like profile fits well

Now generally accepted as a new population of point sources - owing the to the application of some new (for the DM community) statistical techniques

[Tracy Slatyer - Friday]

[arXiv:1506.05104, arXiv:1506.05124]

GALACTIC CENTRE EXCESS

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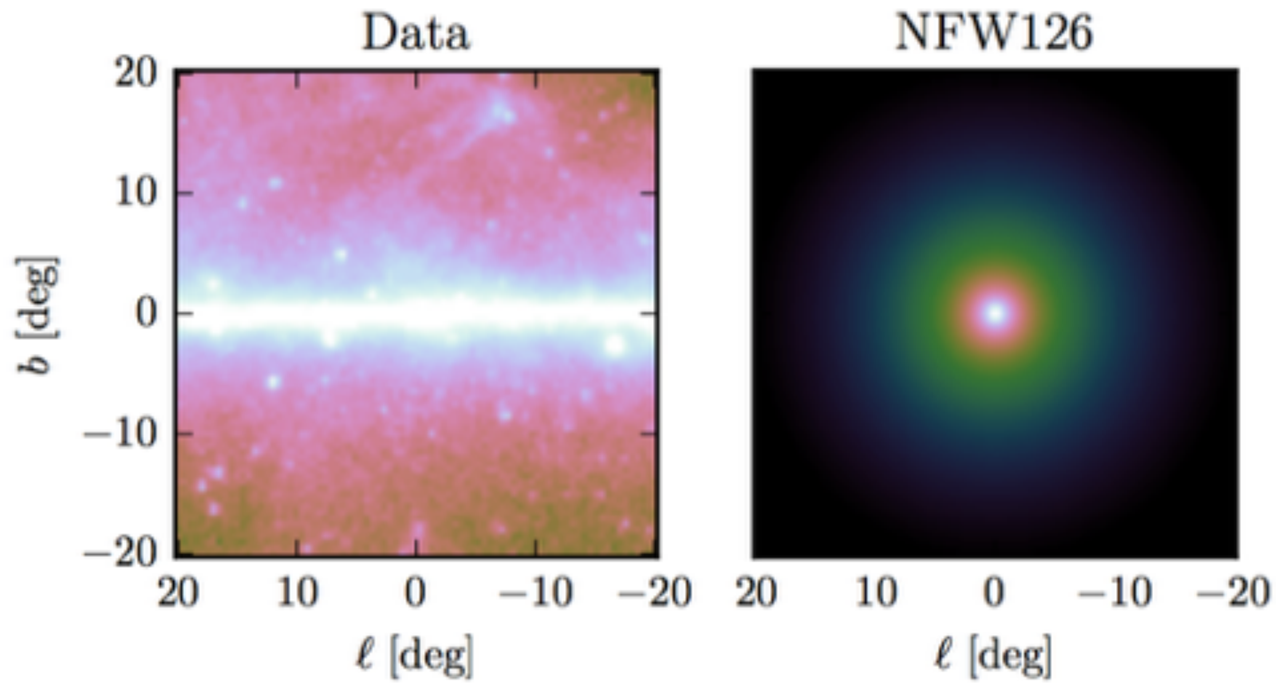


DM-like profile fits well

Now generally accepted as a new population of point sources - owing the to the application of some new (for the DM community) statistical techniques

or "How Statistics killed Dark Matter"

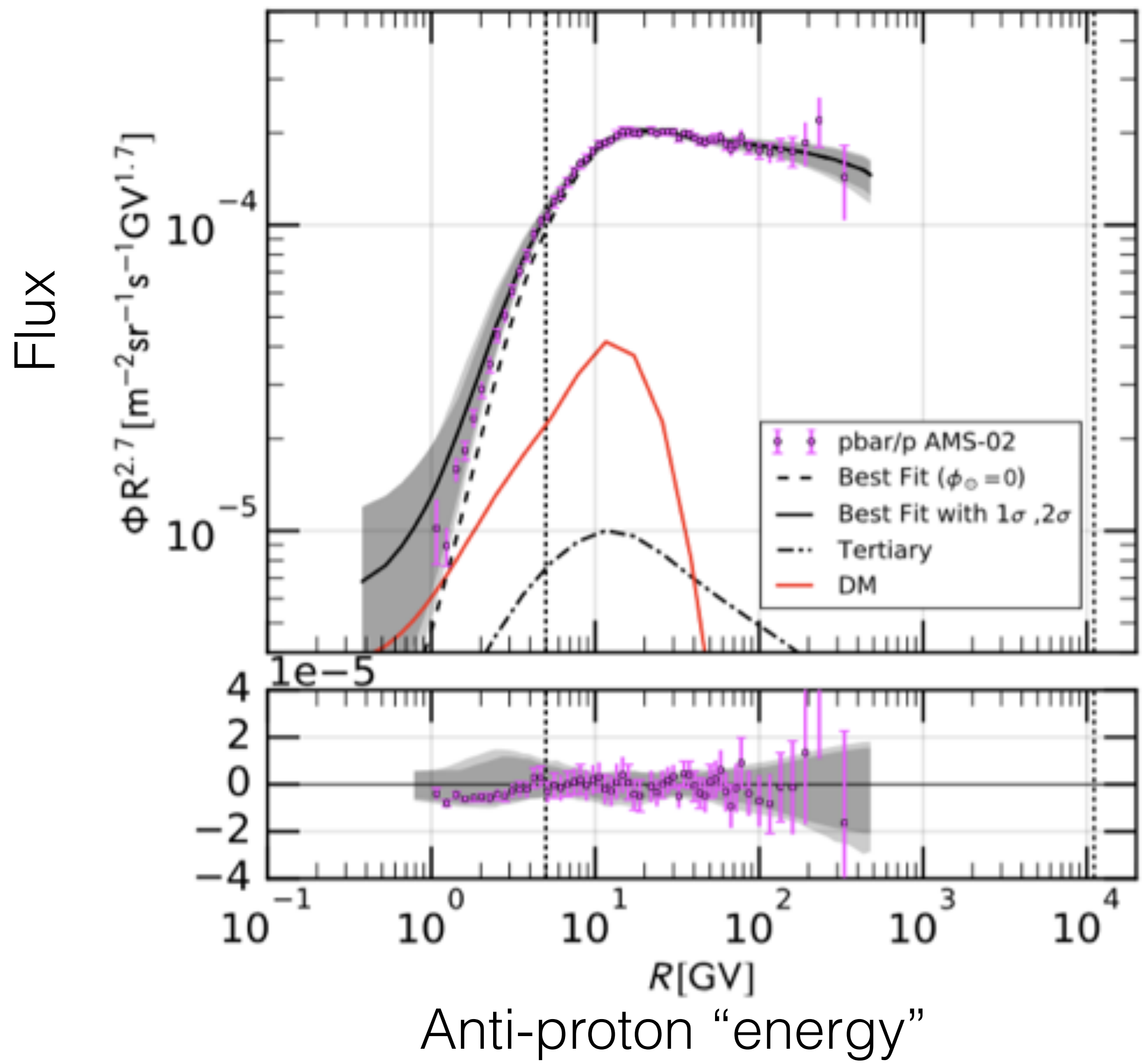
[Tracy Slatyer - Wednesday]

[arXiv:1506.05104, arXiv:1506.05124]

INDIRECT DETECTION (WITH CHARGED PARTICLES)

Charged particles diffuse through the galaxy under the influence of magnetic fields, Galactic winds, collisions…

Observe at (or near) Earth with detectors such as AMS-02



[arXiv:1504.04276, arXiv:1610.03071]

INDIRECT DETECTION (WITH CHARGED PARTICLES)

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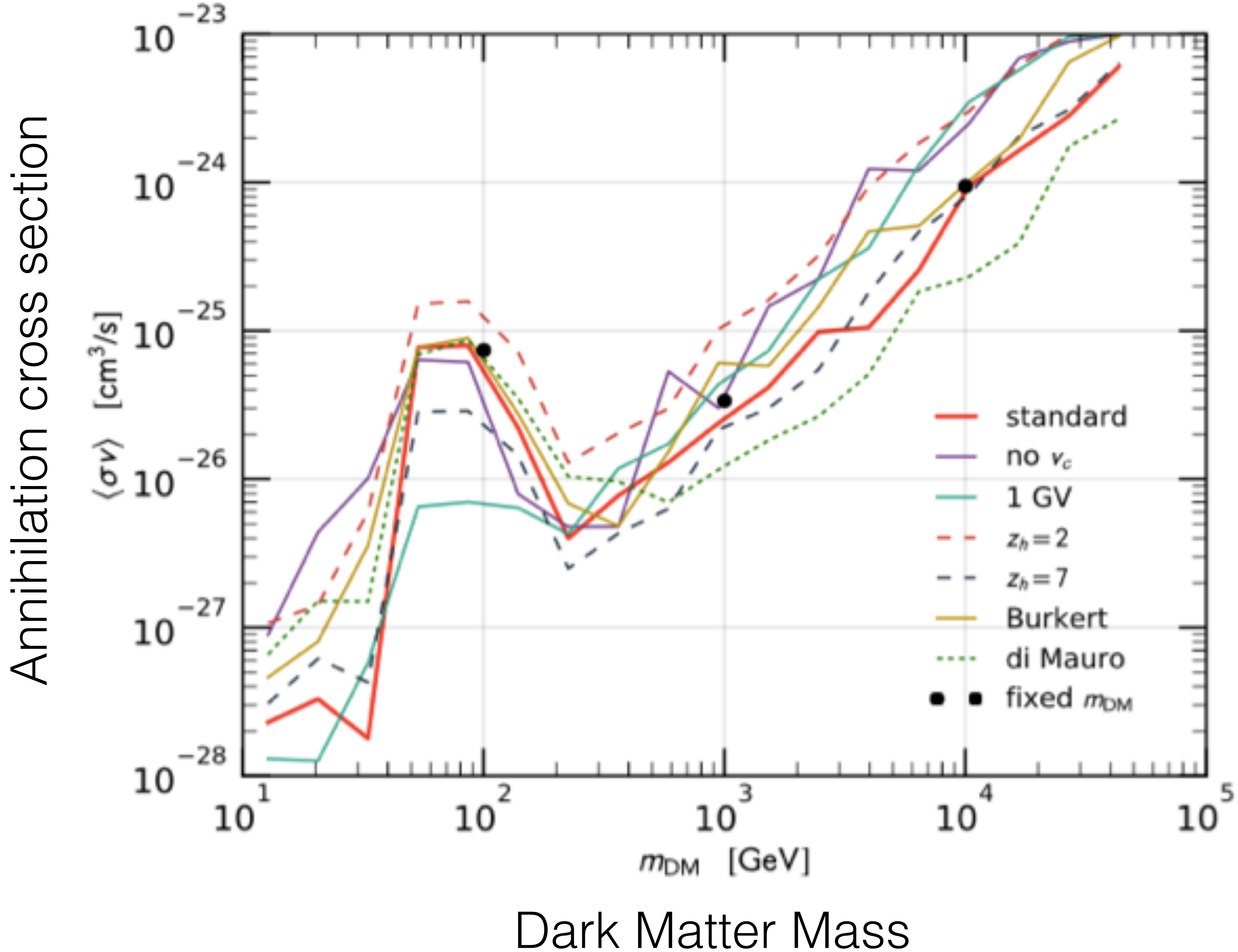
Many different uncertainties in this process…



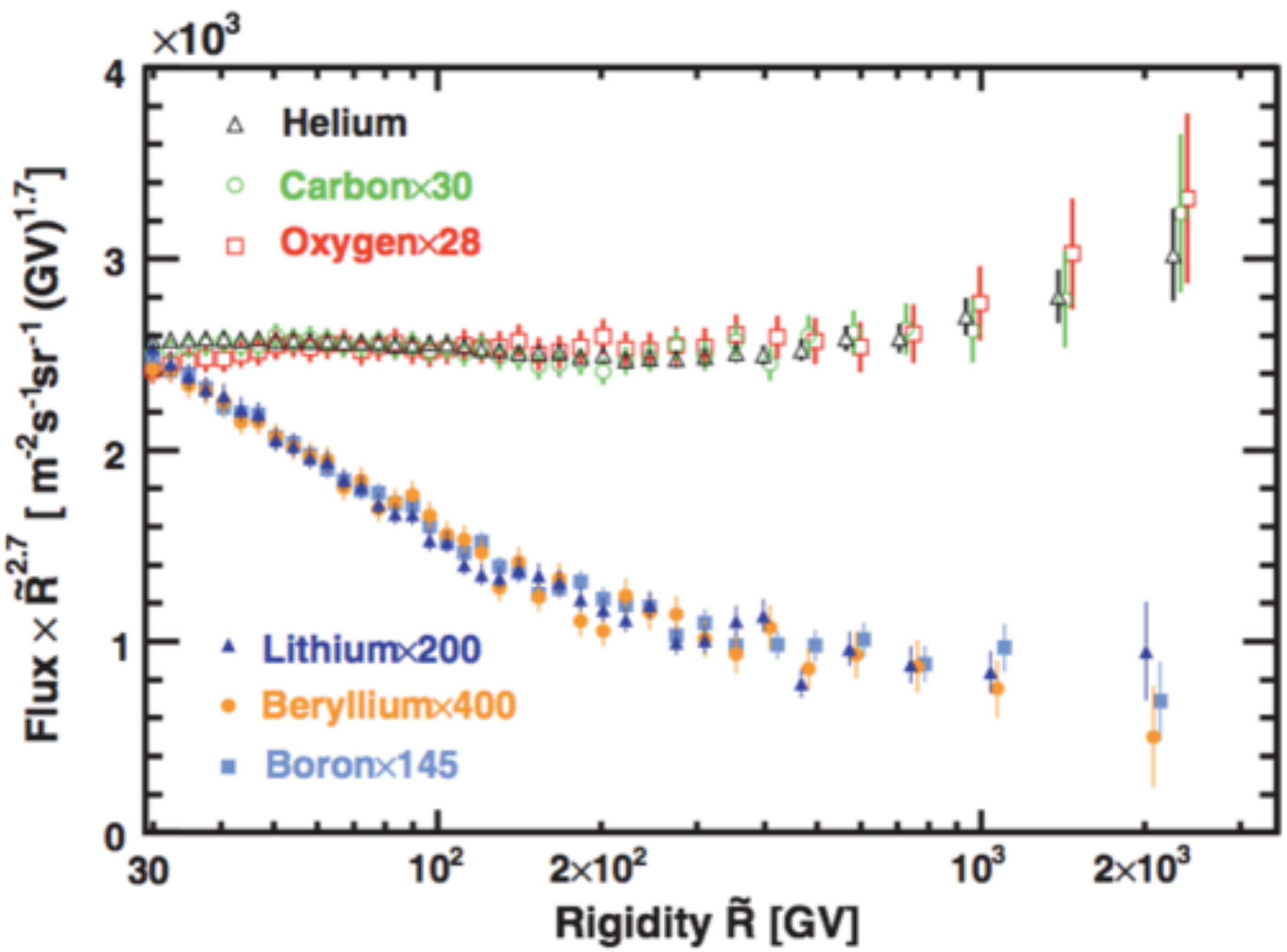
[arXiv:1610.03071]

INDIRECT DETECTION (WITH CHARGED PARTICLES)

Observed cosmic ray fluxes are not yet fully understood

Have to simultaneously fit diffusion parameters and possible DM signal (with pronounced degeneracies…)

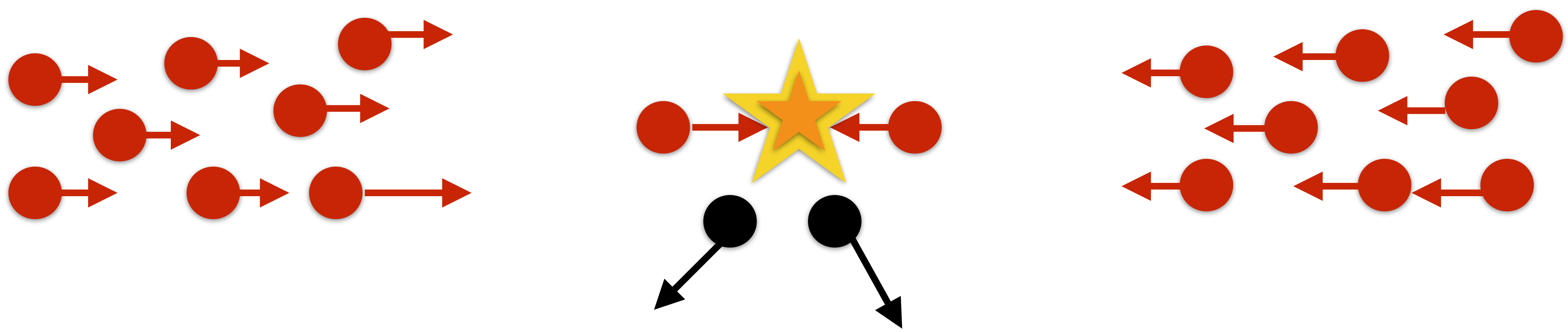
Flux



Cosmic ray "energy"

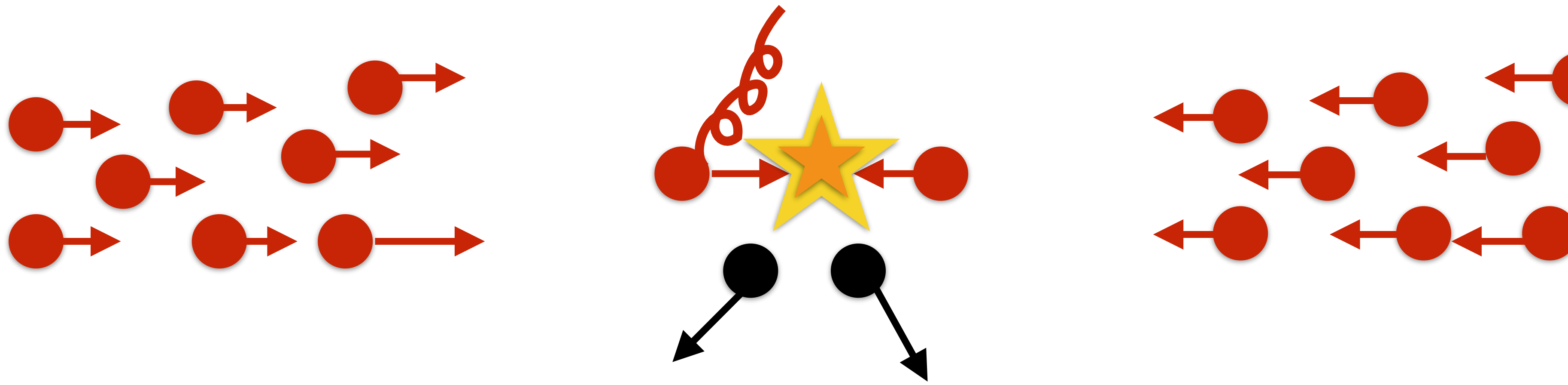
[PhysRevLett.120.021101]

Collider Searches



[arXiv:1702.02430]

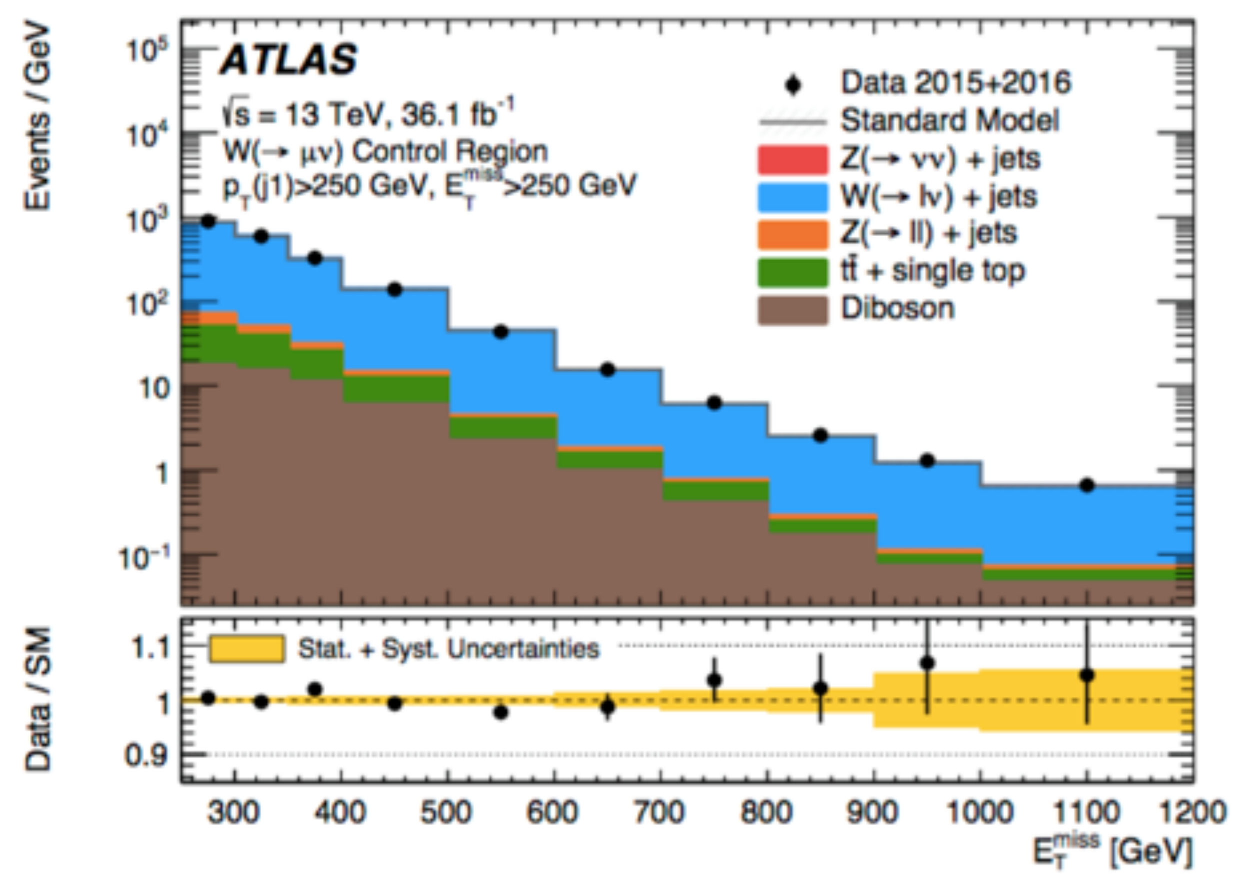
Collider Searches (at the LHC)



Most common signature is 'something' + missing energy
(which is carried away by the DM)

Complicated backgrounds…

Use a combination of Monte Carlo and control regions to fix background rates

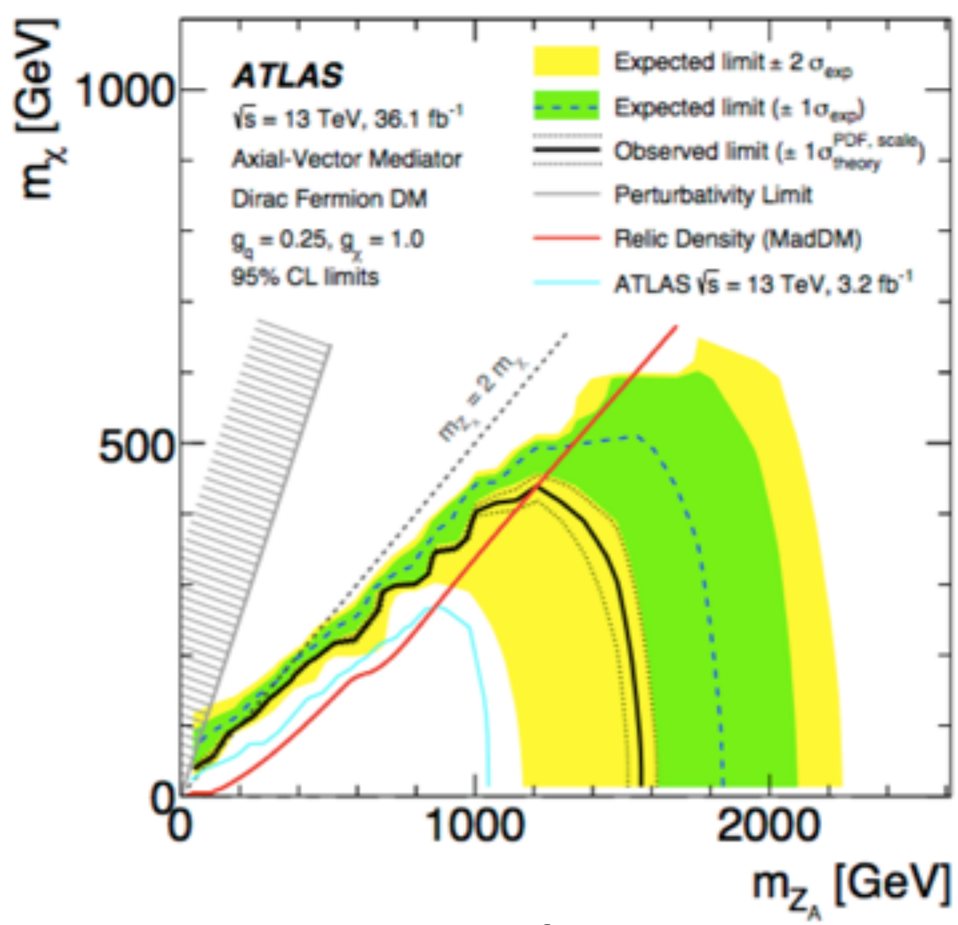


Missing energy [arXiv:1711.03301]

Collider Searches (at the LHC)

Most common signature is 'something' + missing energy (which is carried away by the DM)

Dark Matter Mass



Mass of mediator

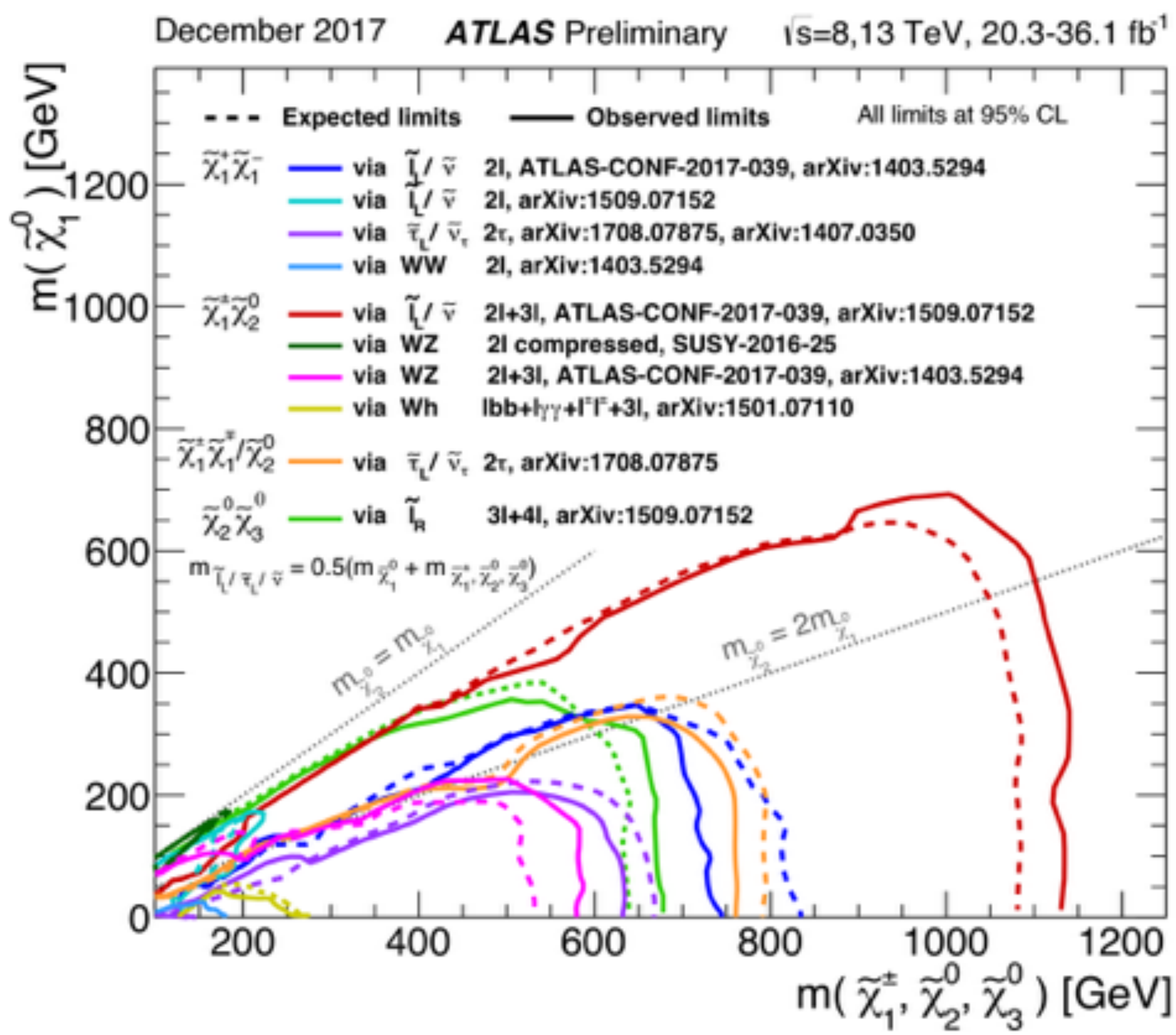
Jets + Missing energy search at ATLAS

[arXiv:1711.03301]

Collider Searches (at the LHC)

In more 'complete' models (e.g. SUSY), you know exactly what to look for:

Dark Matter mass



Mass of other new particles

But with more complete models come more particles, more constraints - global fits are important!

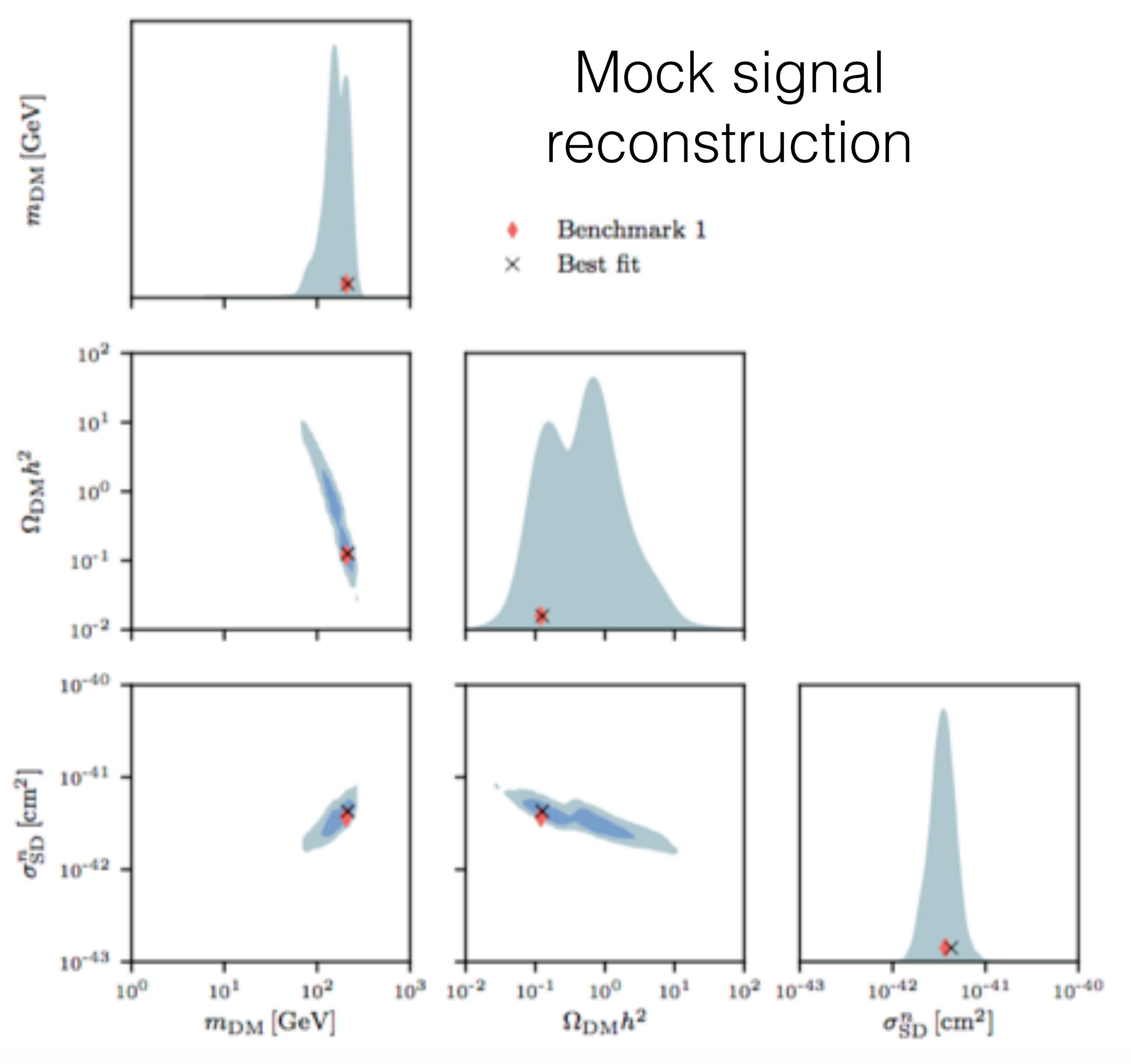
[e.g. GAMBIT - arXiv:1705.07908]

SIMULATING COLLIDER SIGNALS

To constrain Dark Matter, we have to determine what the signal should look like in the detector

But detector simulation is very expensive for (complicated) collider experiments

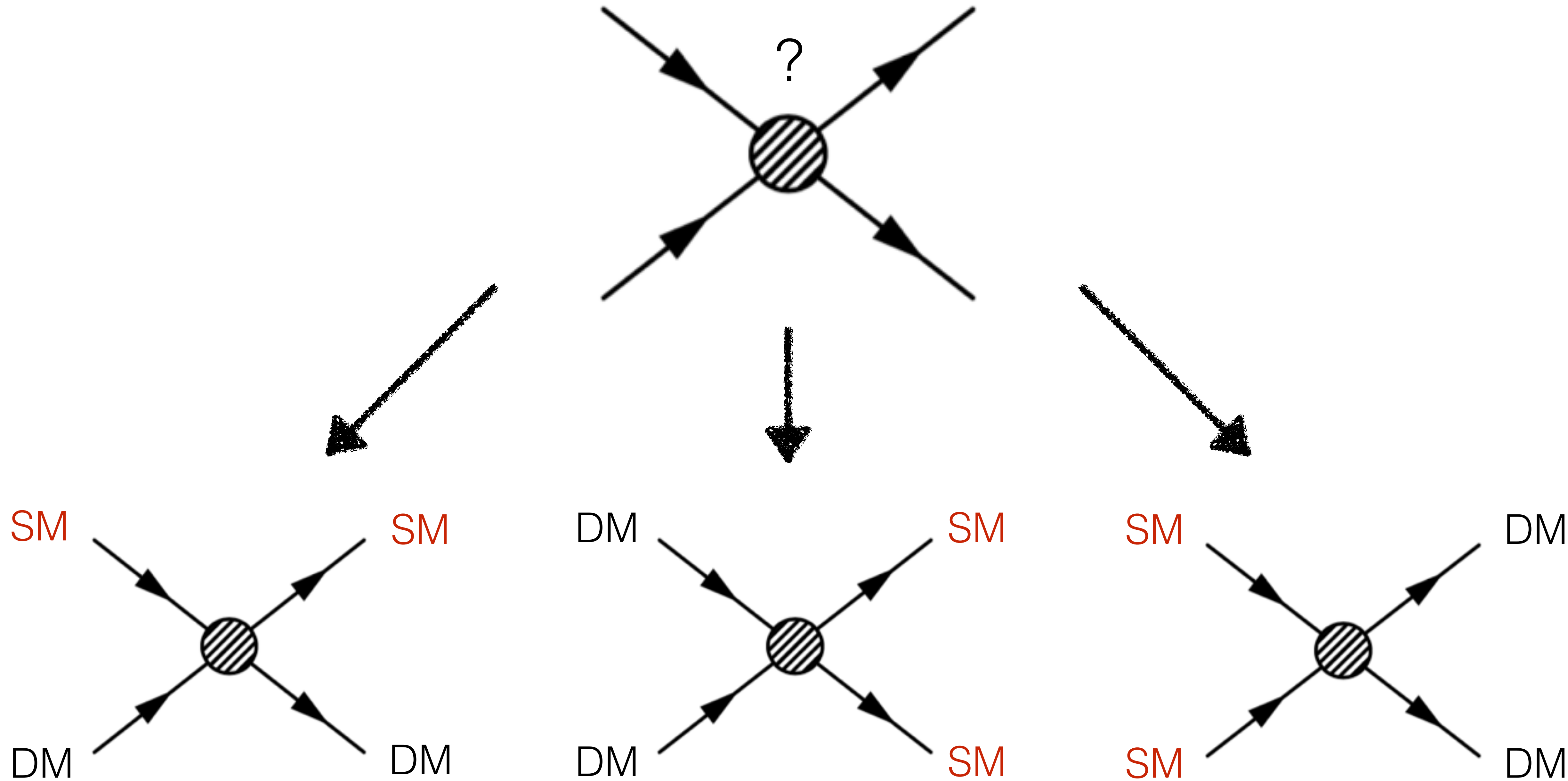
Mock signal reconstruction



Machine learning is already being used to accelerate detector simulation and parameter scans

[arXiv:1712.04793]

Dark Matter Interactions



“Direct”	“Indirect”	“Collider”
[Wolfgang Rau - Tuesday]	[Christoph Weniger - Wednesday]	[Christopher Anelli - Thursday]

“EXOTIC” SEARCHES

New ideas every day…

Fixed target experiments [arXiv:1702.02688]

Impact of DM interactions on CMB [arXiv:1801.08609]

Offsets between Galaxies and DM [arXiv:1504.06576]

Novel Direct Detection targets [arXiv:1611.06228]

to name just a few…

…and this is only for WIMPy Dark Matter…

We haven’t even started talking about axions, PBHs,…

Statistical Challenges in the Search for Dark Matter

How do we distinguish the faintest of signals from unknown backgrounds?

How do we obtain meaningful constraints on huge parameter spaces?

Which is the best target to look at or detector to build?

How do we accelerate the search for Dark Matter?

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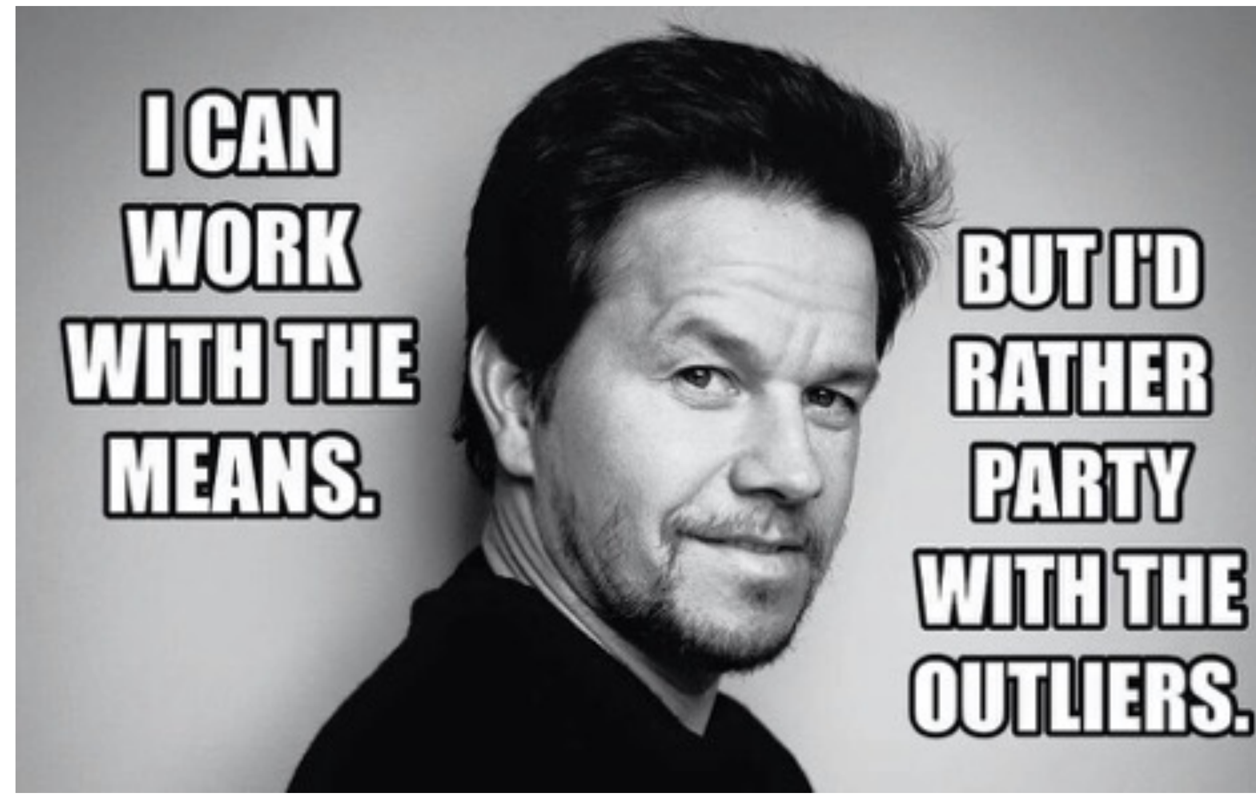
Prof. Wahlberg



Thank you!