Dark Matter:
an experimental perspective

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MEMBER OF THE ATLAS COLLABORATION AT CERN

Inputs and discussion:

European Strategy PPG BSM/DM/Higgs, Snowmass EF, RF and CF, ATLAS Collaboration, iDMEu proponents, Antonio Boveia, Boyu Gao, Isabelle John, Matt McCullough, Jocelyn Monroe, Marco Rimoldi, Ulrike Schnoor, Francesca Ungaro, Christoph Weniger, Jodi Cooley, Hugh Lippincott

@CatDogLund

http://www.hep.lu.se/staff/doglioni/

Outline

Introduction from a *particle experimentalist* [1] perspective

Dark matter experiments:

1. Dark matter at accelerators (particle colliders/intensity frontier experiments)

Disclaimer #1: My main expertise is in DM @ particle colliders, so this part will be more detailed than the others

2. Direct detection of dark matter
3. Indirect detection of dark matter (+ cosmic probes)

Synergies and complementarity between these different ways of detecting DM

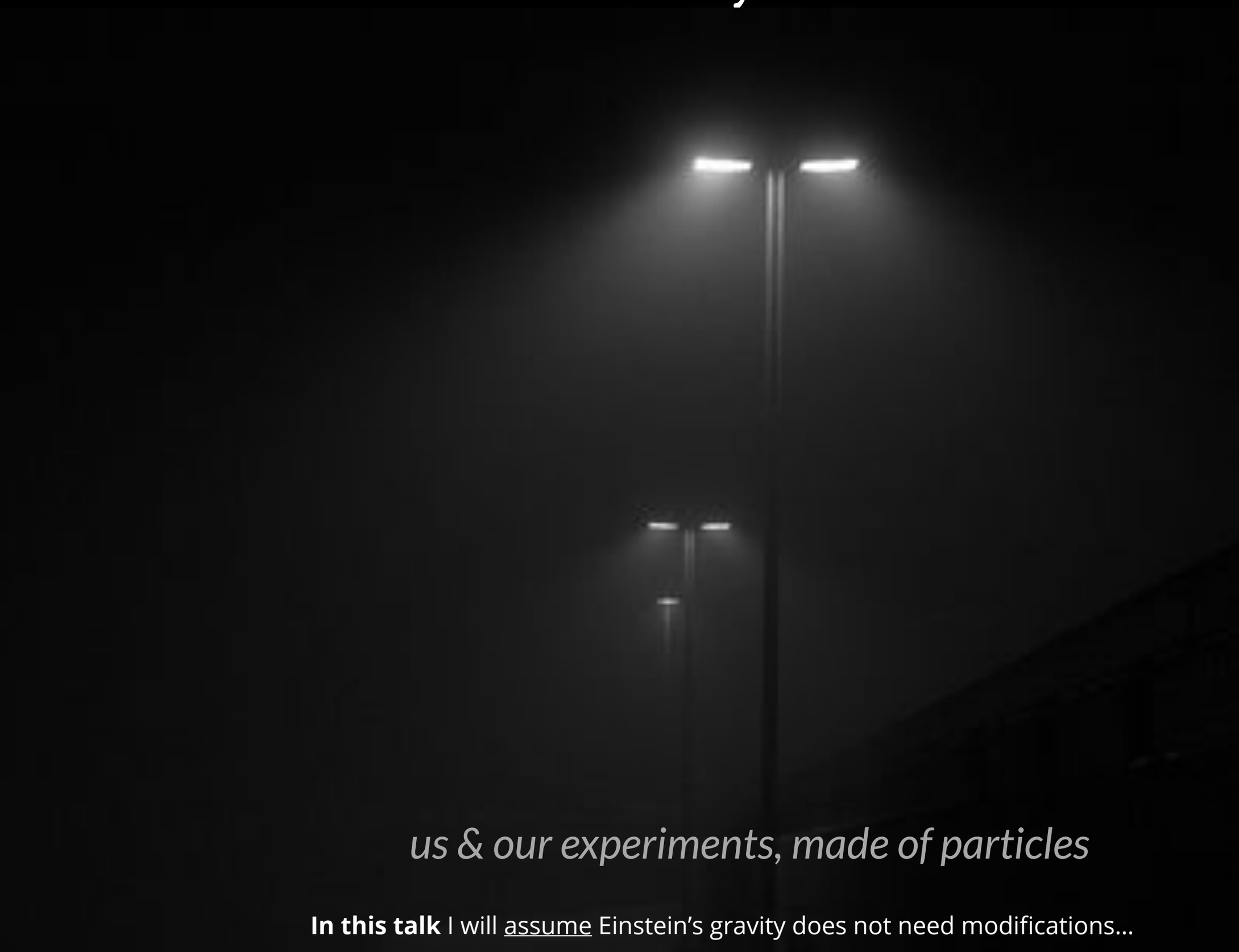
SnowMass2021 ⇒ link to the relevant Snowmass topical group

Disclaimer 2: this talk is not an inclusive talk for DM, but rather a personal perspective of things I've learned along the way as ATLAS Dark Matter Forum/WG organizer && in the European Strategy && in the Snowmass process

[1] for the perspective of a *dark matter experimentalist*, see page 3 of arXiv:1712.06615

Why should dark matter be a particle?

Why not?



us & our experiments, made of particles

In this talk I will <u>assume</u> Einstein's gravity does not need modifications…

The *relic density*

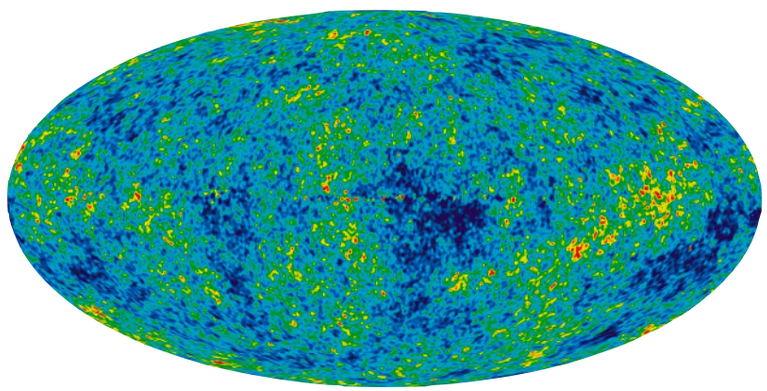
The Nobel Prize in Physics 2019

Ill. Niklas Elmehed. © Nobel Media.

James Peebles

Prize share: 1/2

"for theoretical discoveries in physical cosmology"



https://sci.esa.int/s/Wnqq4bw

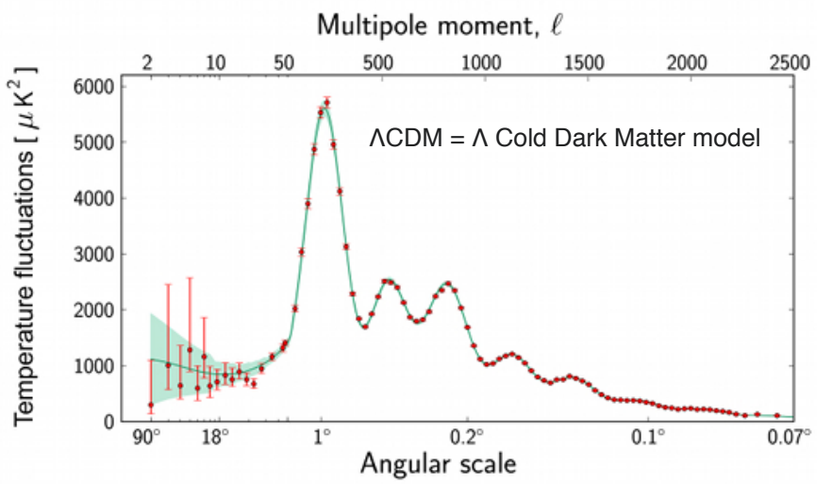
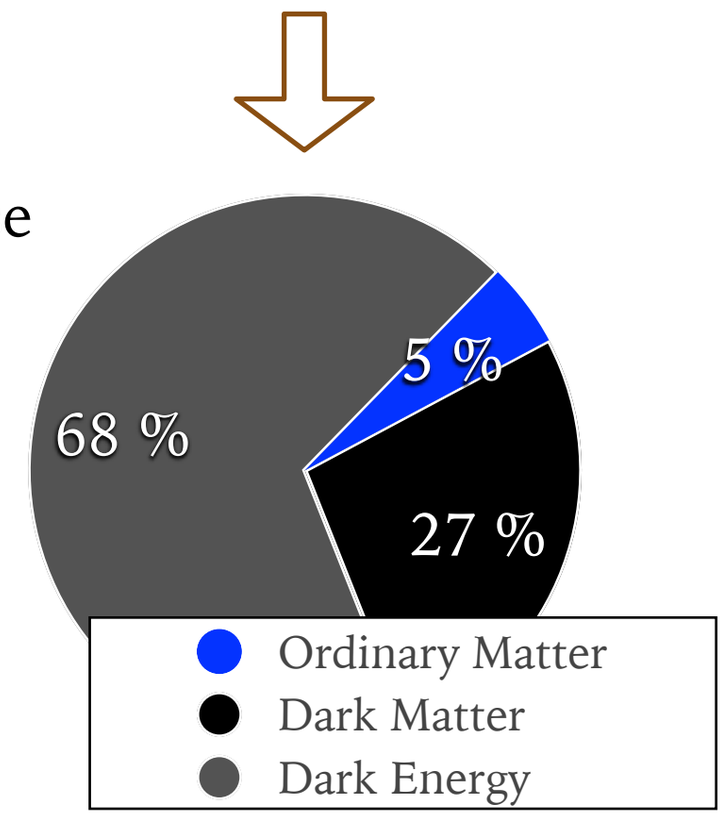


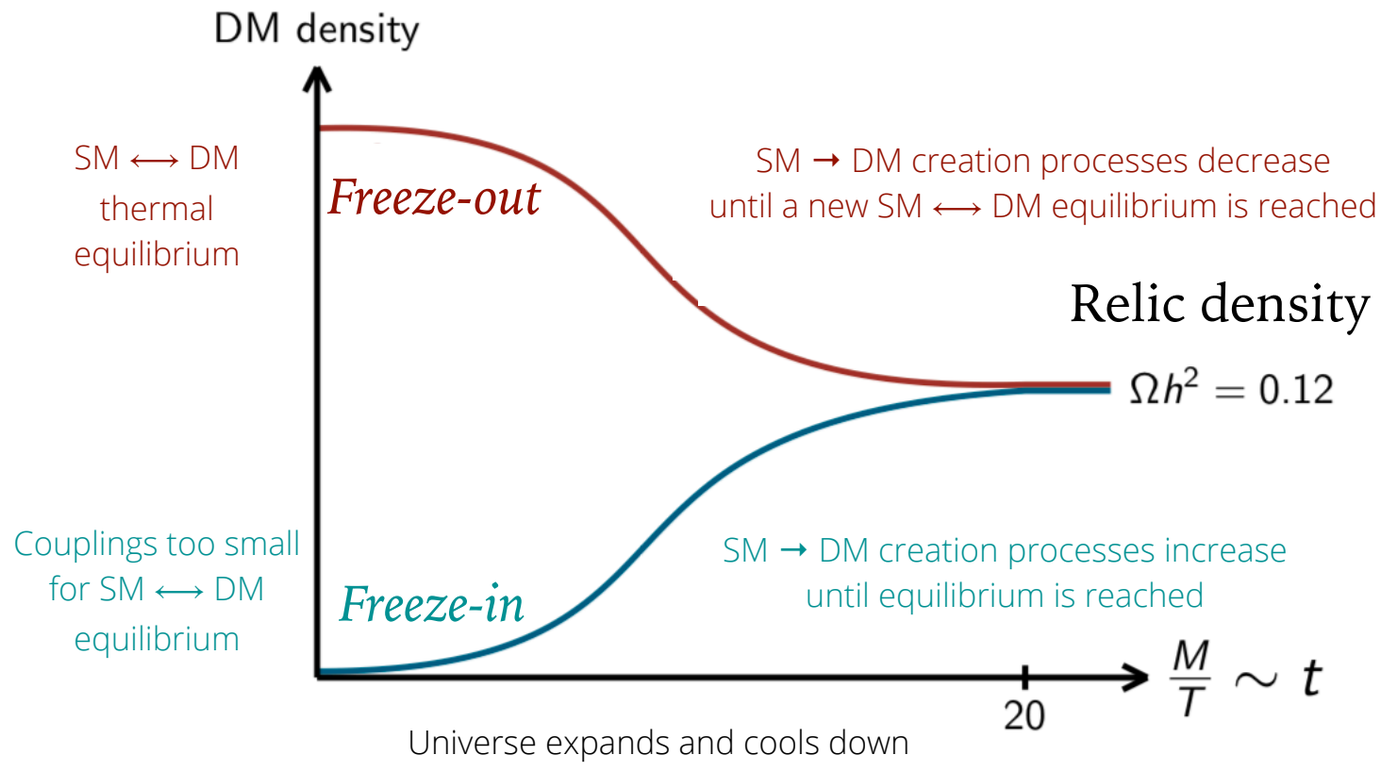
Image: Planck/NASA/ESA

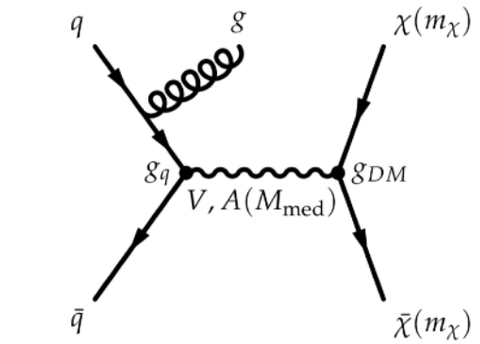
Dark matter constitutes **most of the matter** in the universe

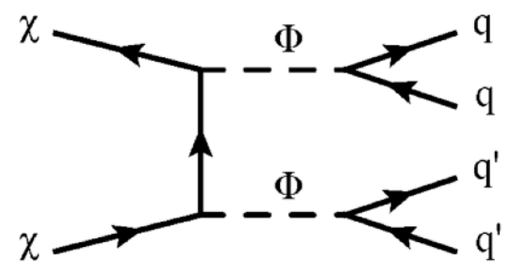
The DM we measure today **[relic DM density]**
already points at some properties of DM candidates
(e.g. dark, stable)
can it **guide us further**?



How did the relic density come to be?







Examples of DM ⟷ SM processes

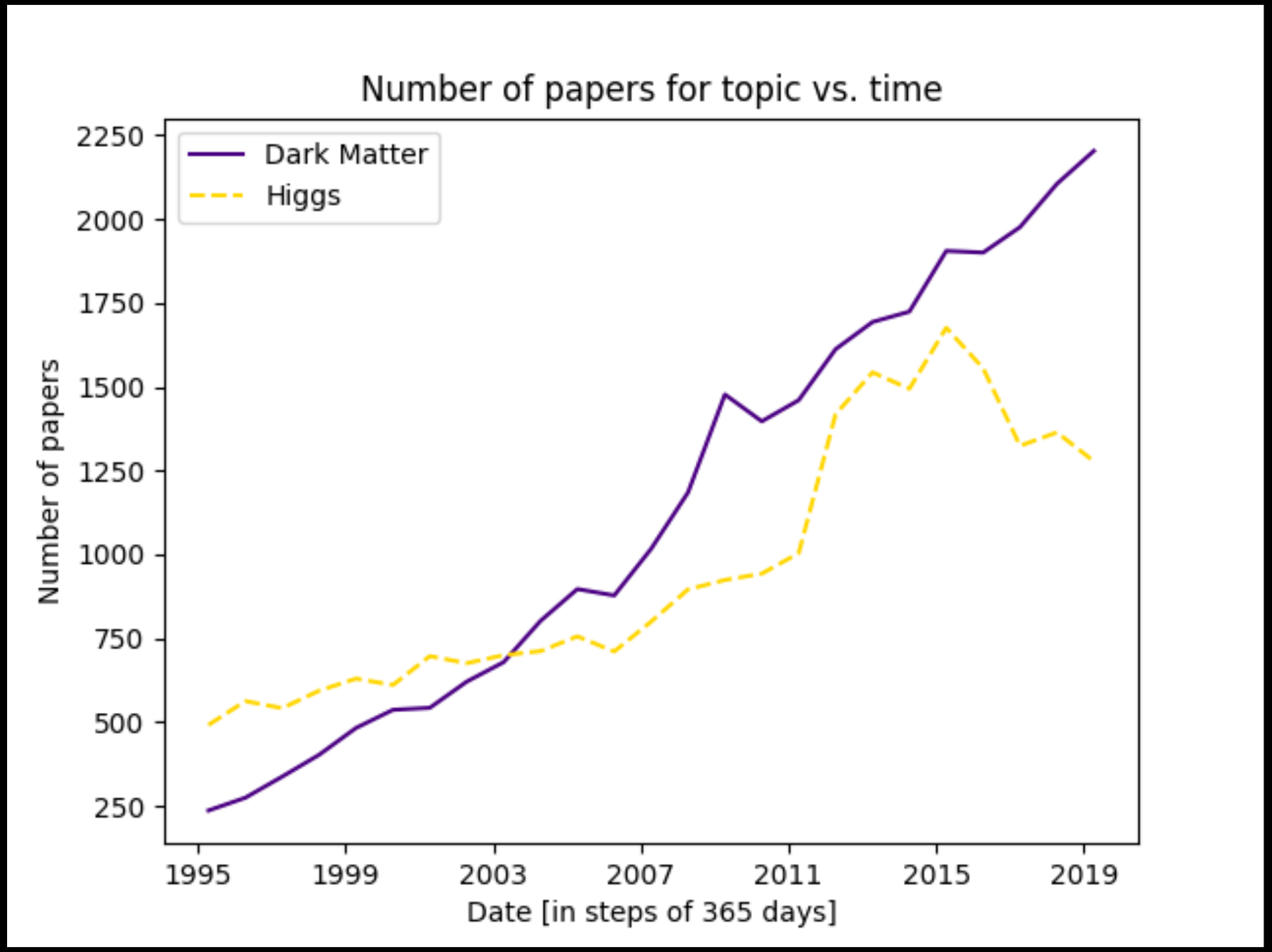
Isabelle John's thesis

Note: simplified picture, for a more complete one see https://arxiv.org/abs/1706.07442

Commonality of many of these models: they require **some form of interaction** (it can be more or less significant) between ordinary matter and dark matter

interaction ⇔ particles & forces

DM is a much-sought particle



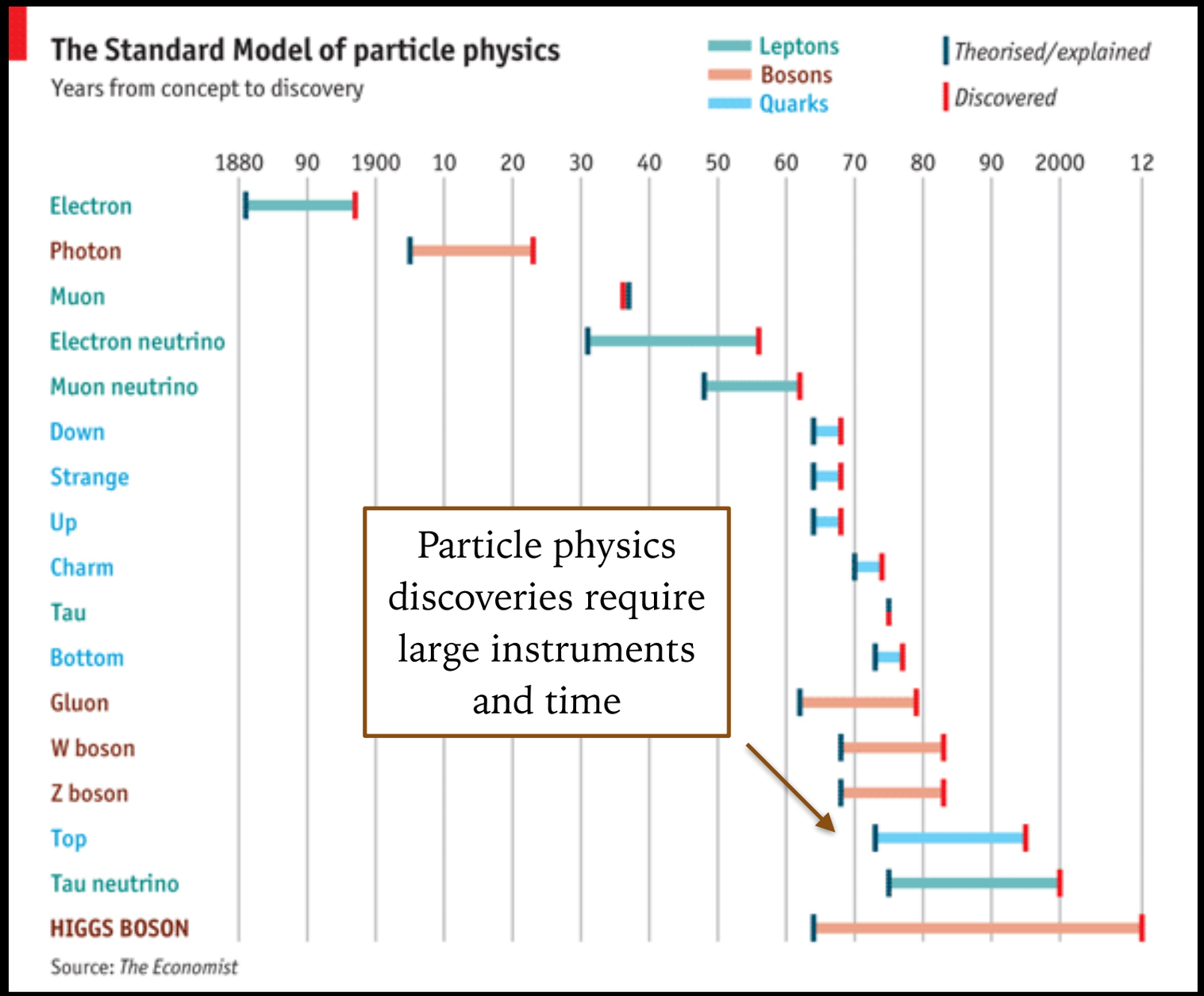
https://benty-fields.com/trending

Papers on the arXiv with the words in the title or abstract

Credits for finding it: Xenon1T, Twitter

Disclaimer: website not to be used as input by funding agencies

Finding new particles takes time



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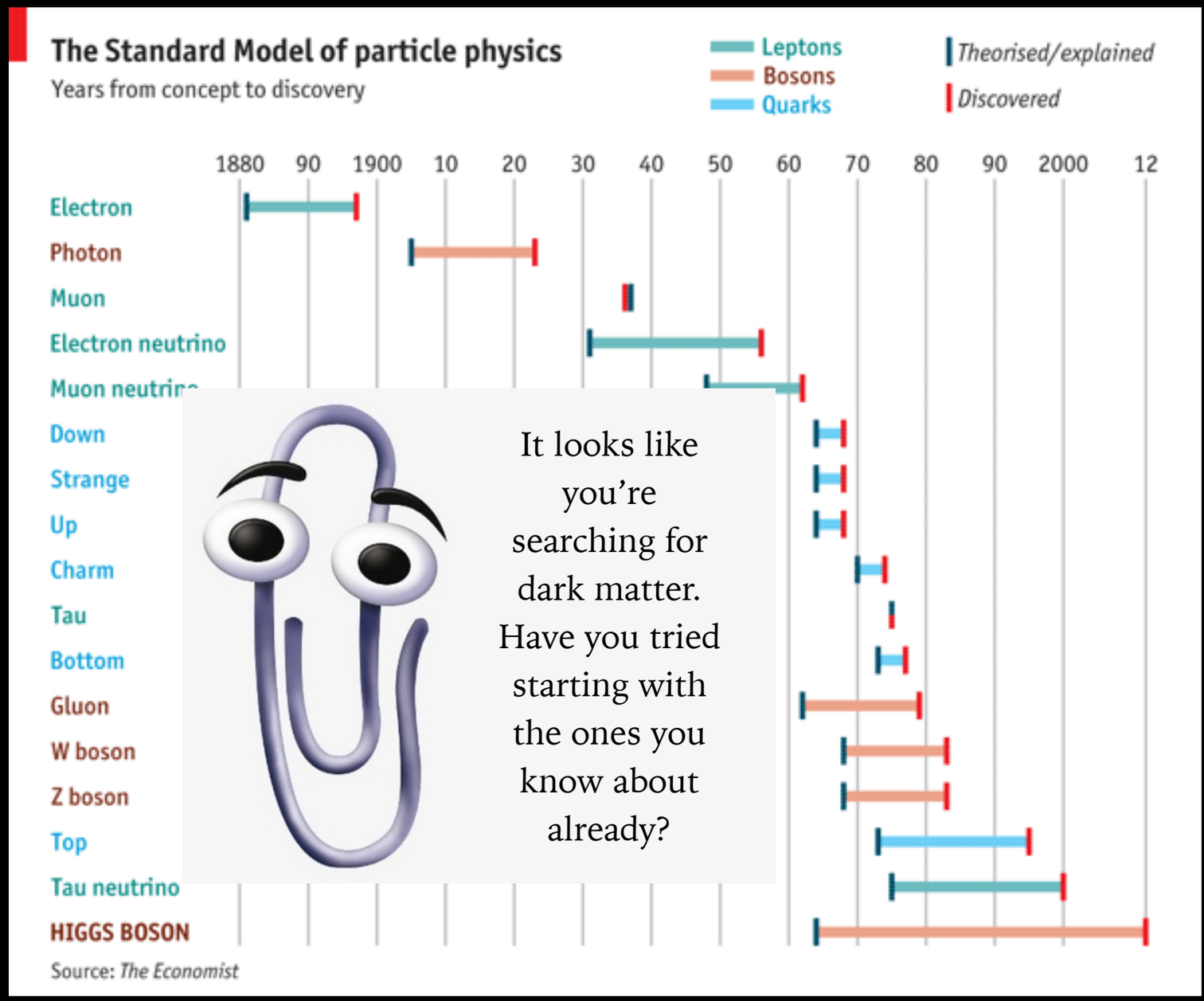
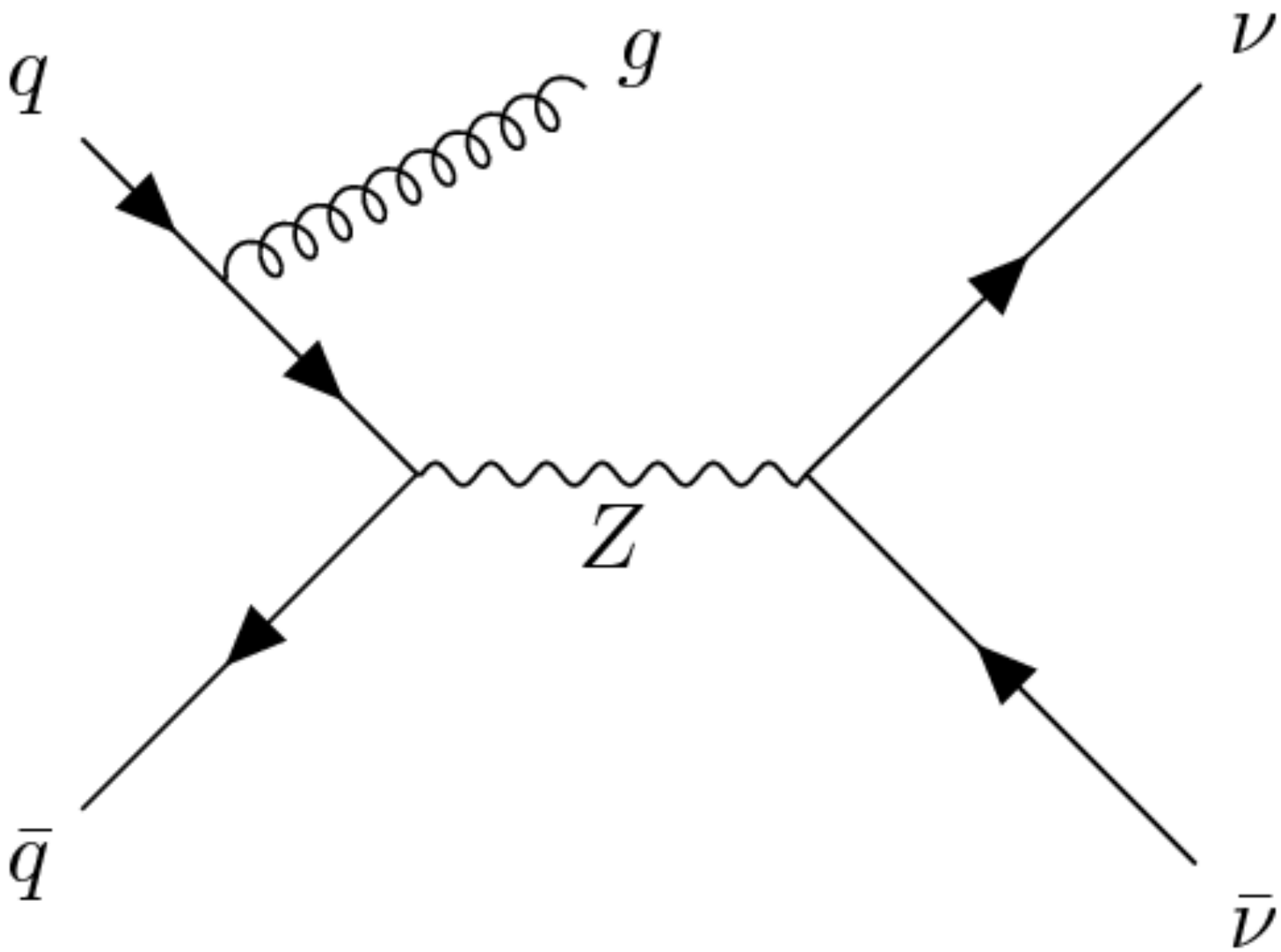


Generic production of invisible particles

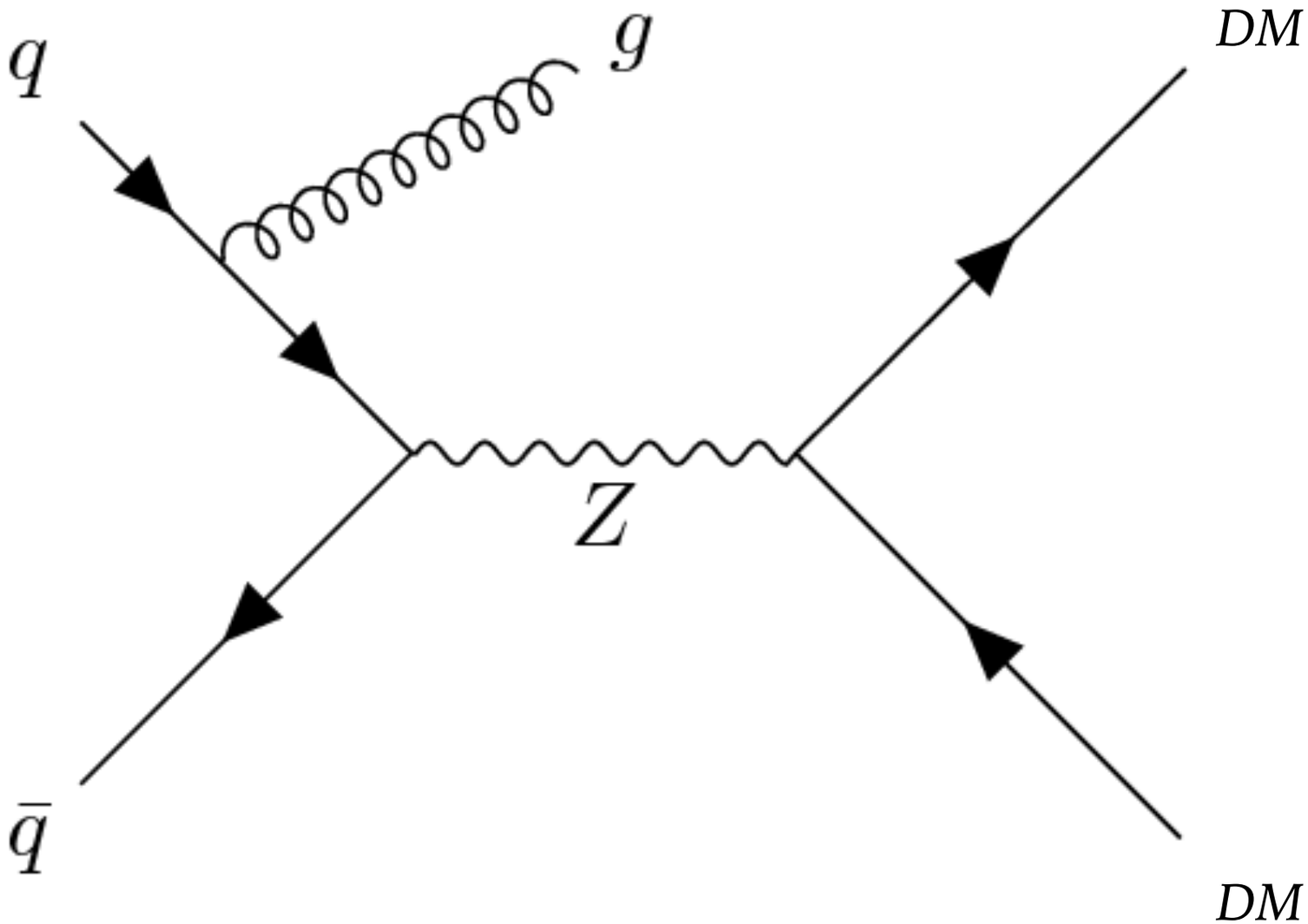
Production of invisible particles is common in the Standard Model...



Eur. Phys. J. C 77 (2017) 765

Generic production of dark matter?

What other invisible particles (that are suitable thermal relics) could we produce?



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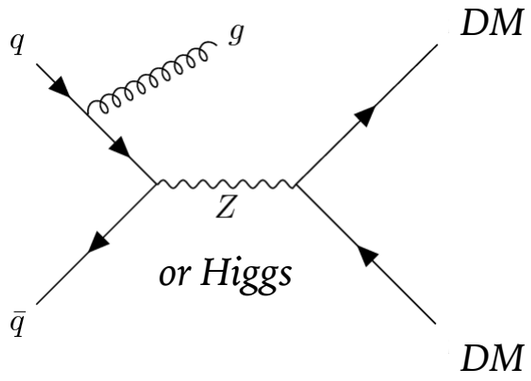
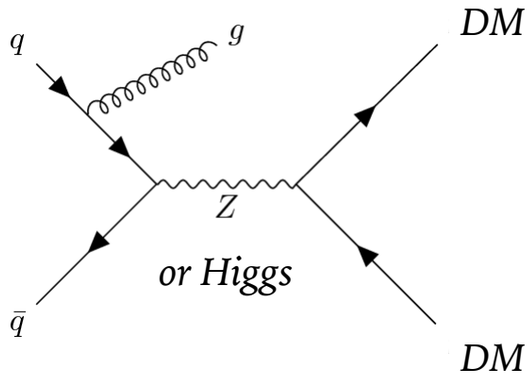
Weakly Interacting Massive Particles



The **minimal** option to make up 100% of the relic:

- only add one particle to the SM
- stable **TeV-scale** particle with **weak-force-sized** interactions
  - Weakly Interacting Massive Particle
- that particle conveniently appears in many SUSY models that also solve other problems in particle physics
- beautiful and simple, almost *miraculous!*

Weakly Interacting Massive Particles



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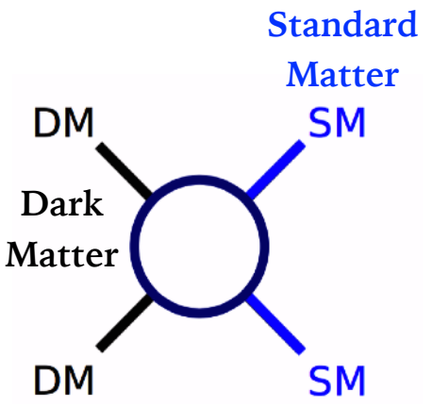
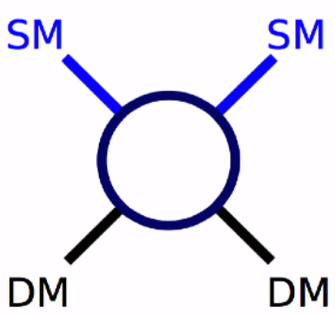
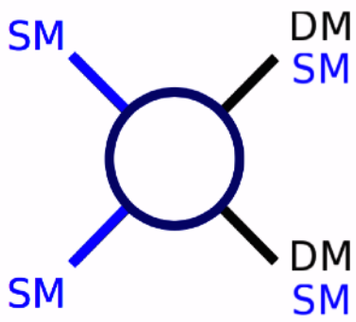
- beautiful and simple, almost *miraculous!*
- Experimental "advantage": many experiments can see it in different ways



Indirect Detection

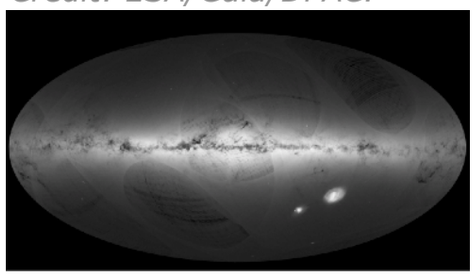


Direct Detection

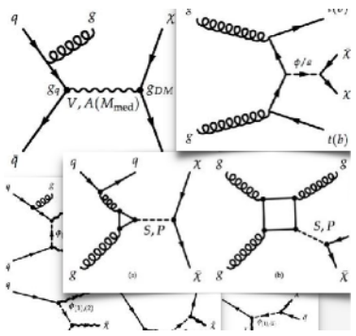


Colliders

Credit: ESA/Gaia/DPAC.



Astrophysics

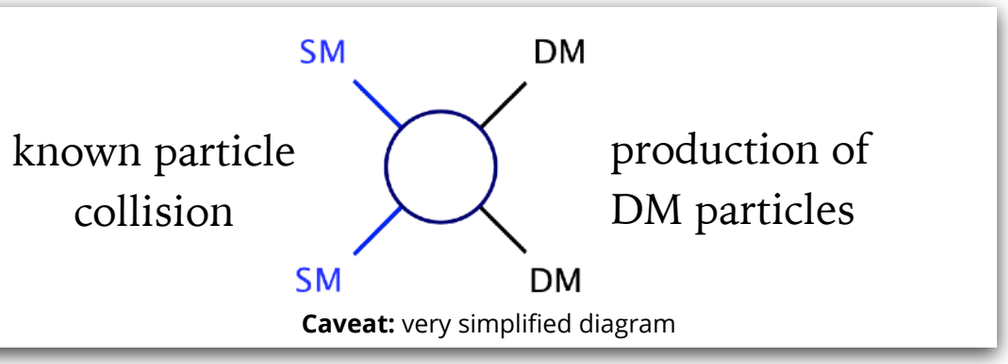


~~Dark matter~~ Invisible particles at colliders

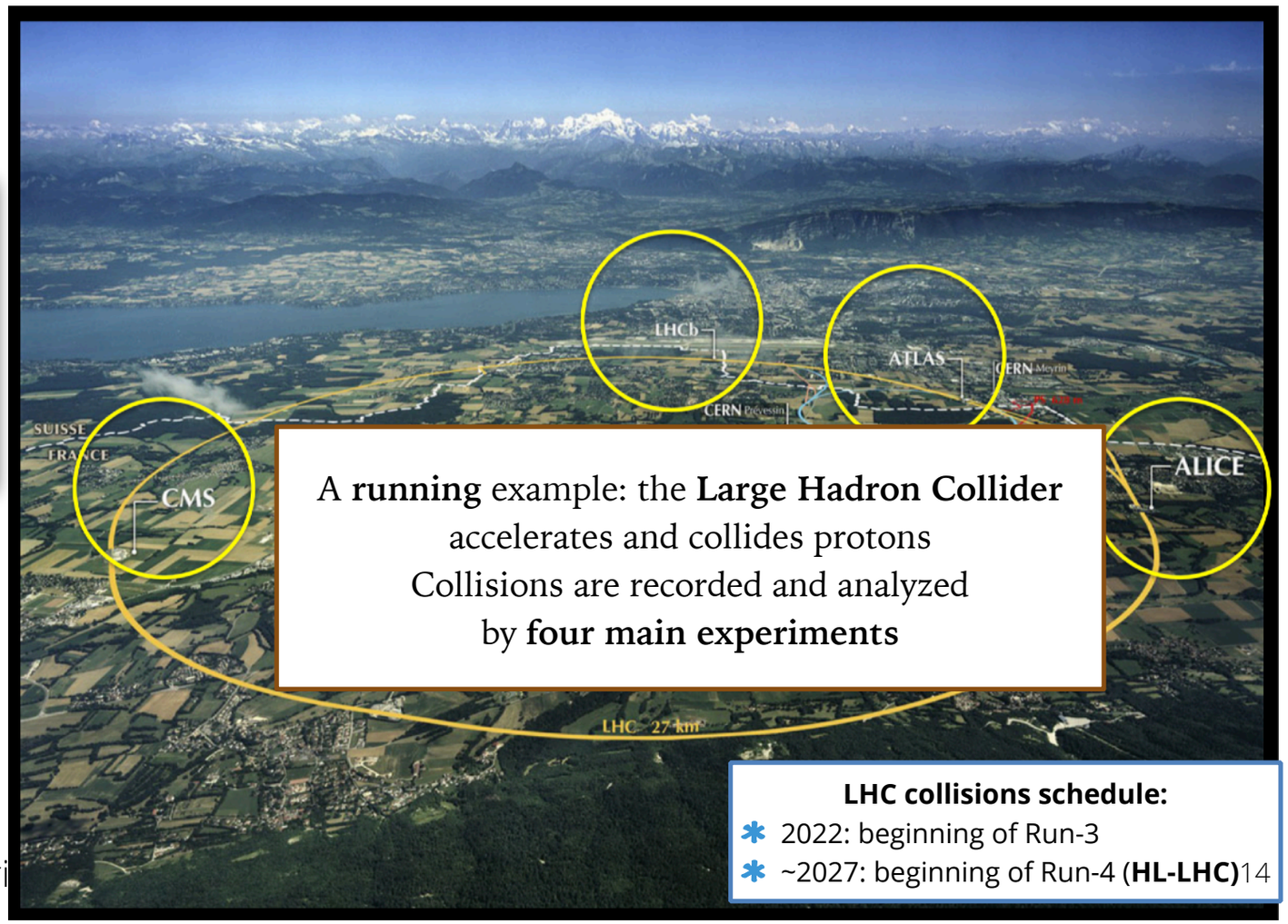
- Starting from our baseline assumption: WIMP DM
  - **interacts with SM** particles → we can **produce and detect it** at

Particle colliders { **LHC** (ATLAS, CMS, LHCb); KEK (Belle-2); ILC, CLIC, CEPC, FCC, muon … (Future) } Collider experiments

SnowMass2021 RF6
SnowMass2021 EF
SnowMass2021 AF3-5



Caveat: very simplified diagram

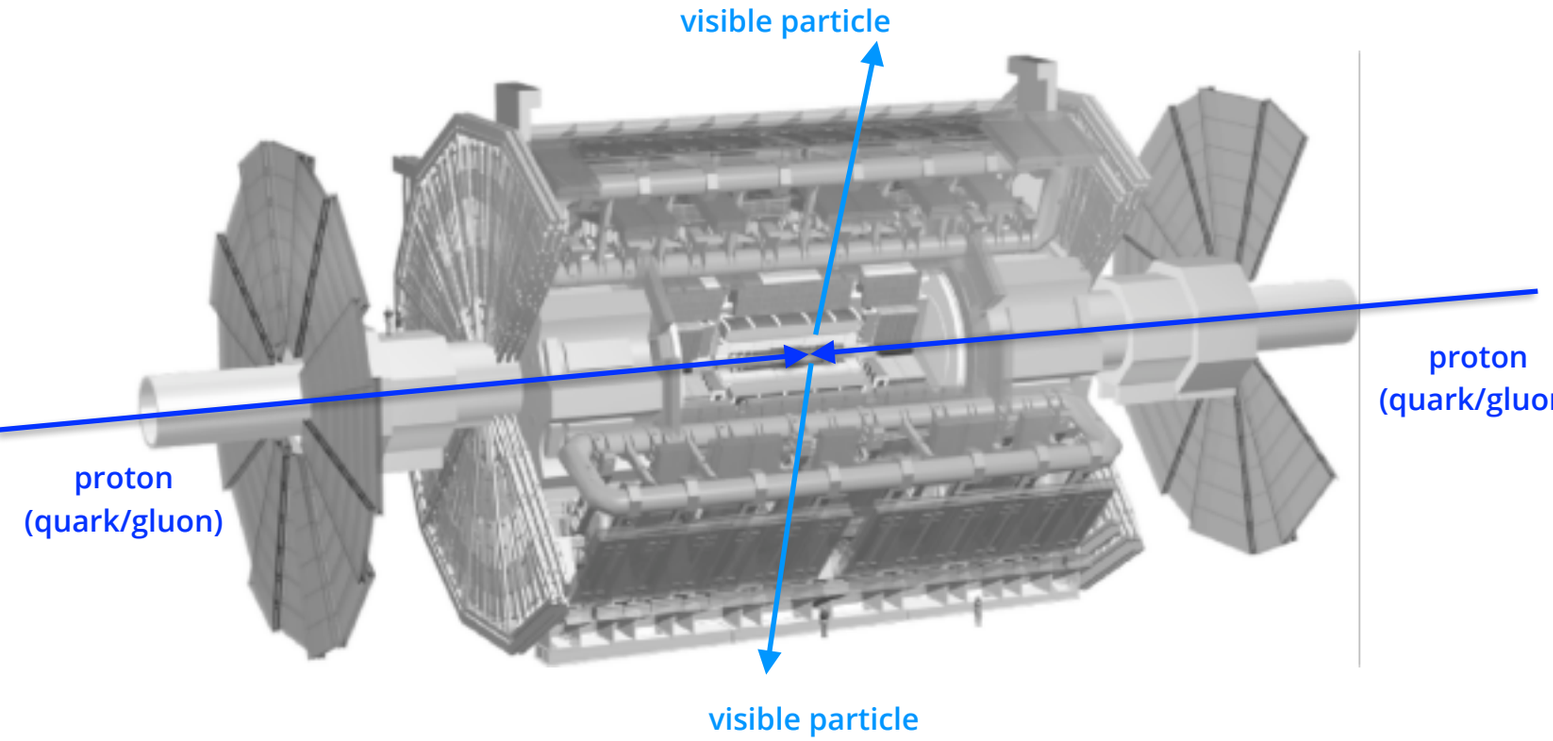


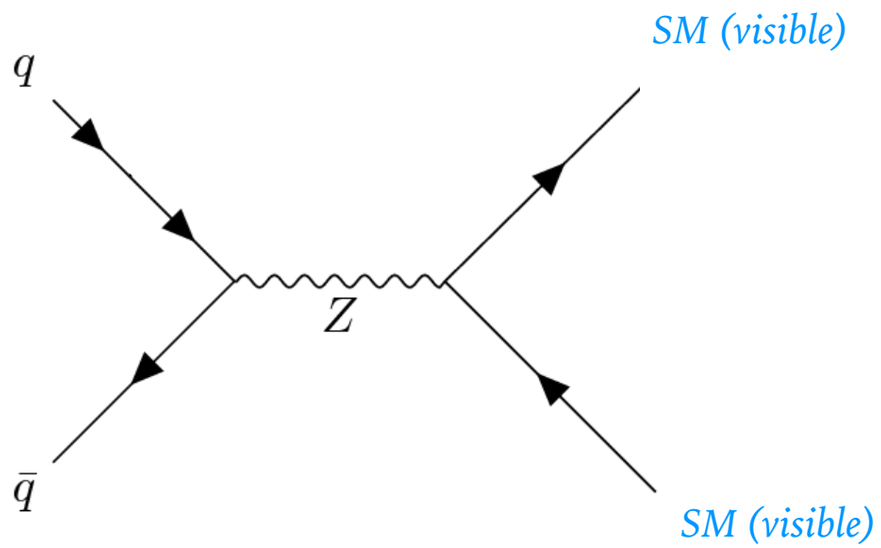
A **running** example: the **Large Hadron Collider** accelerates and collides protons
Collisions are recorded and analyzed by **four main experiments**

LHC collisions schedule:
- 2022: beginning of Run-3
- ~2027: beginning of Run-4 (**HL-LHC**)

Searches for ~~DM~~ invisible particles at colliders

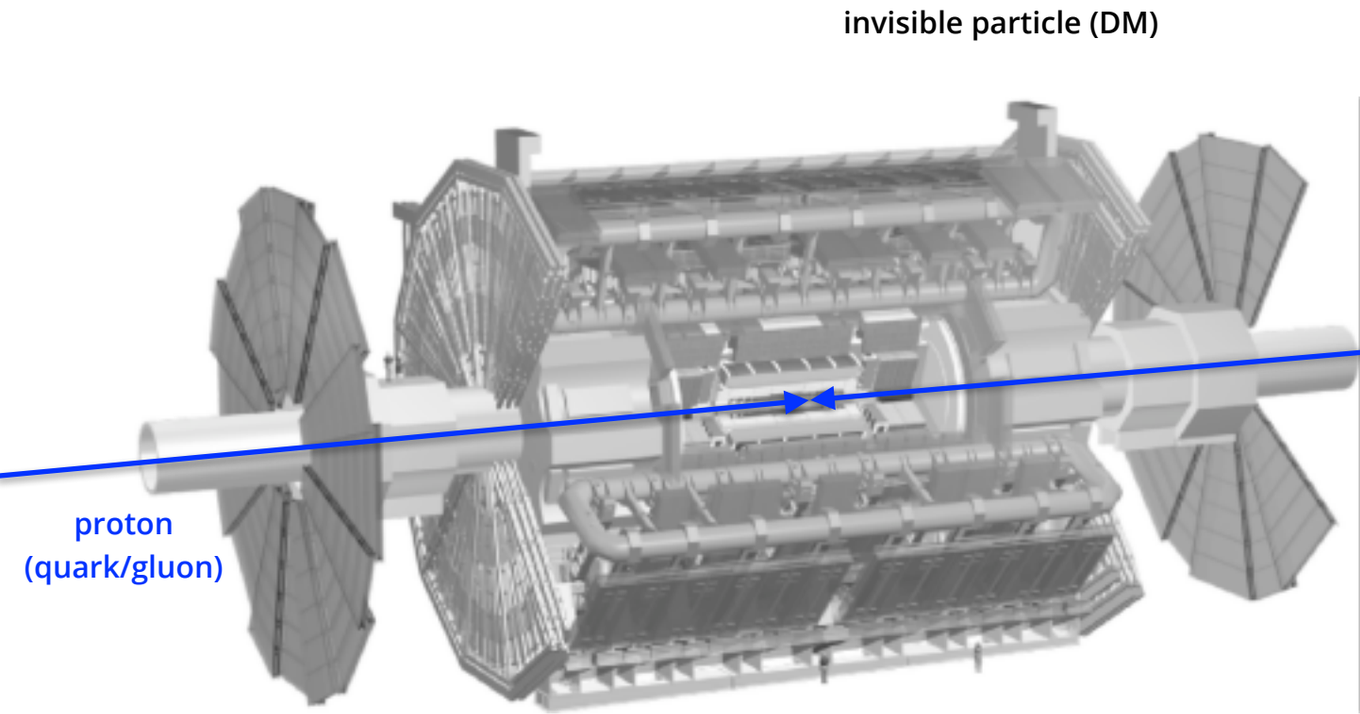
Detector covers all the solid angle and catches ~all visible particles

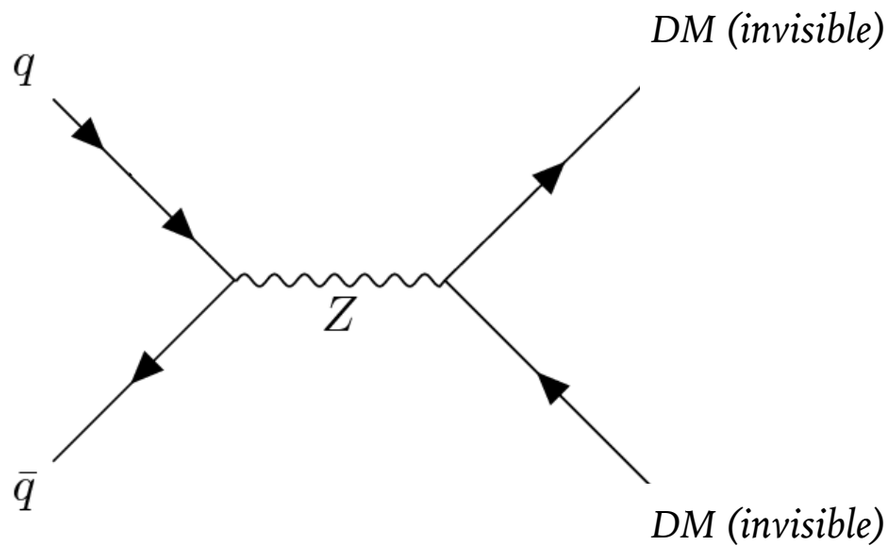




Searches for ~~DM~~ invisible particles at colliders

Dark matter doesn't interact significantly with our detectors → invisible





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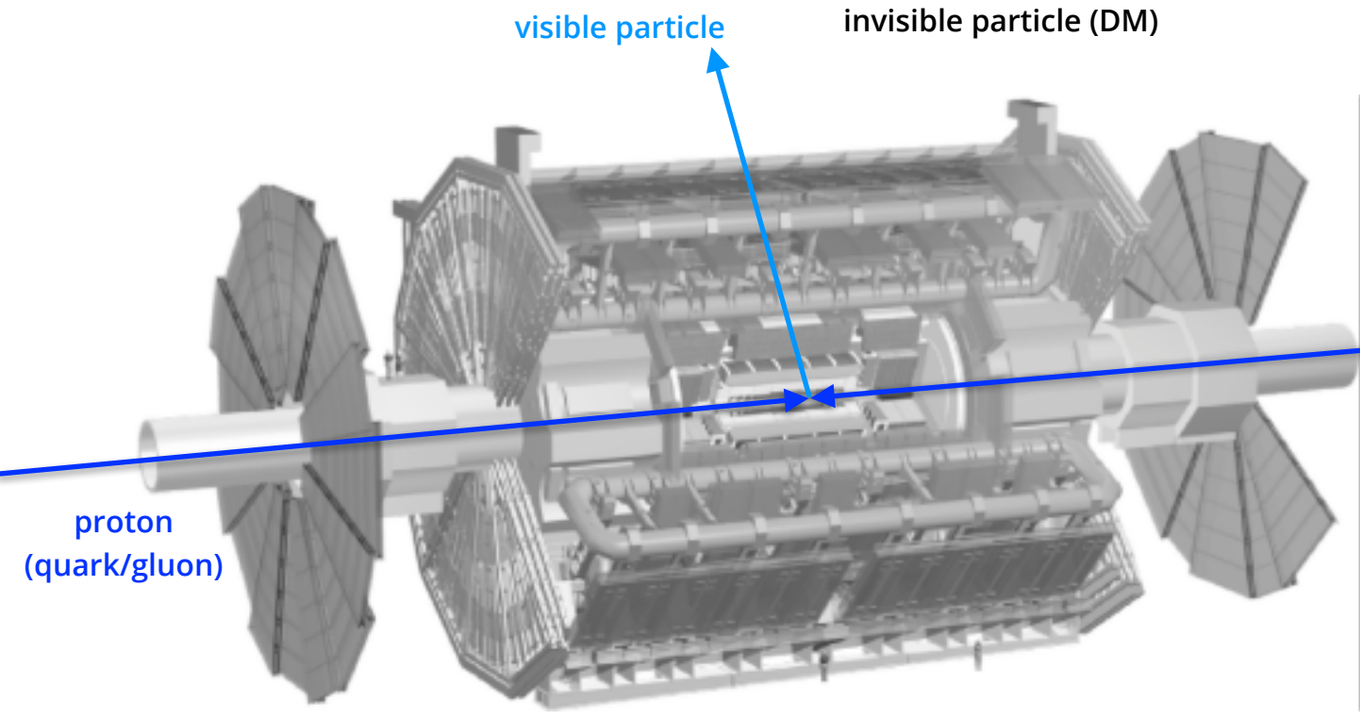
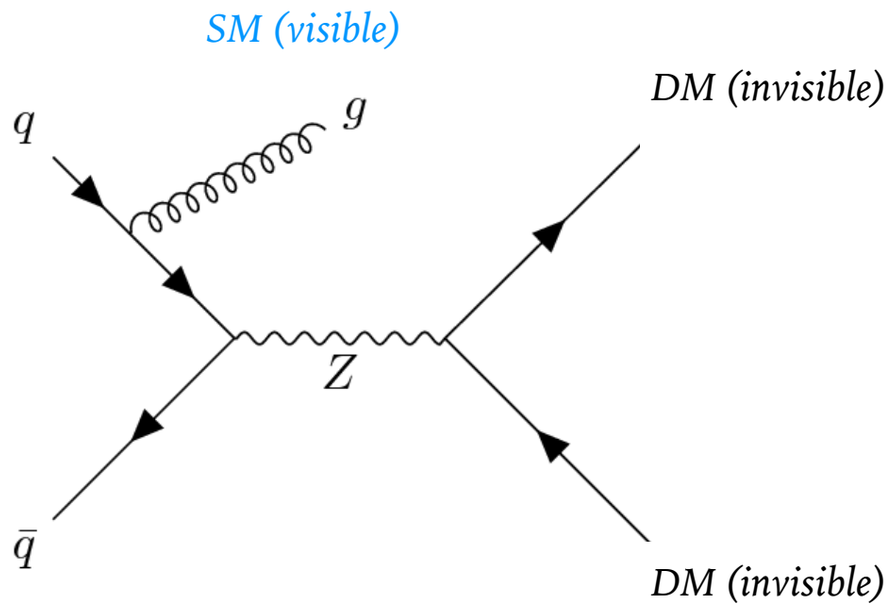
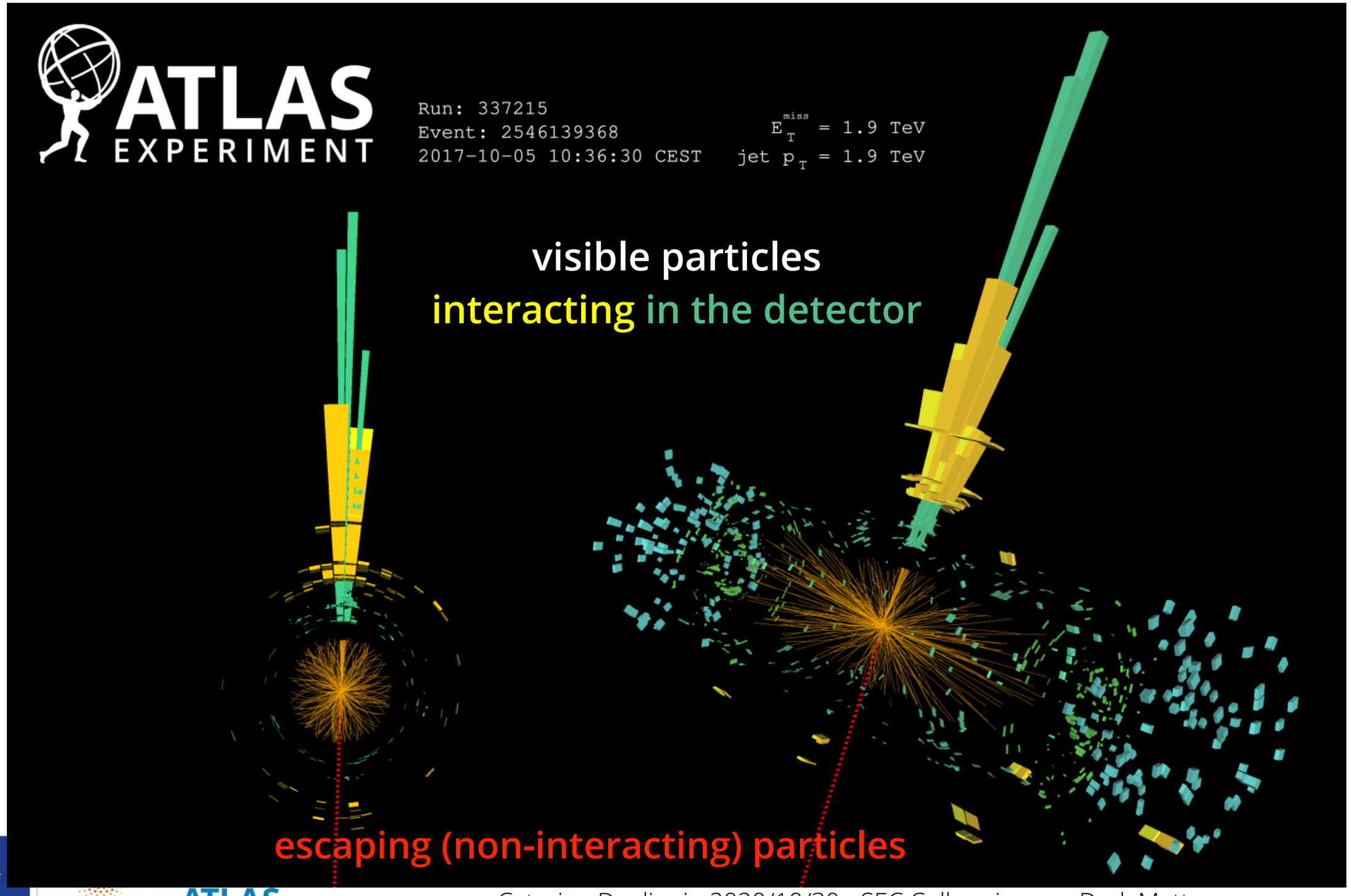


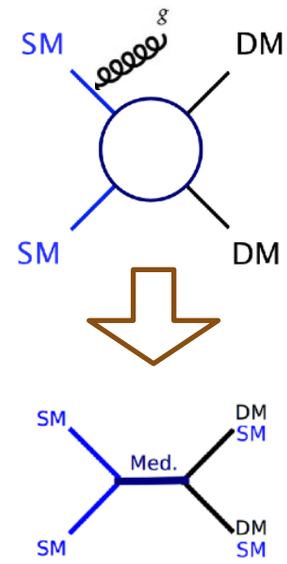


Signature of invisible particles
(like Dark Matter):
missing (transverse) momentum (E_T^{miss})

A “monojet event” at ATLAS

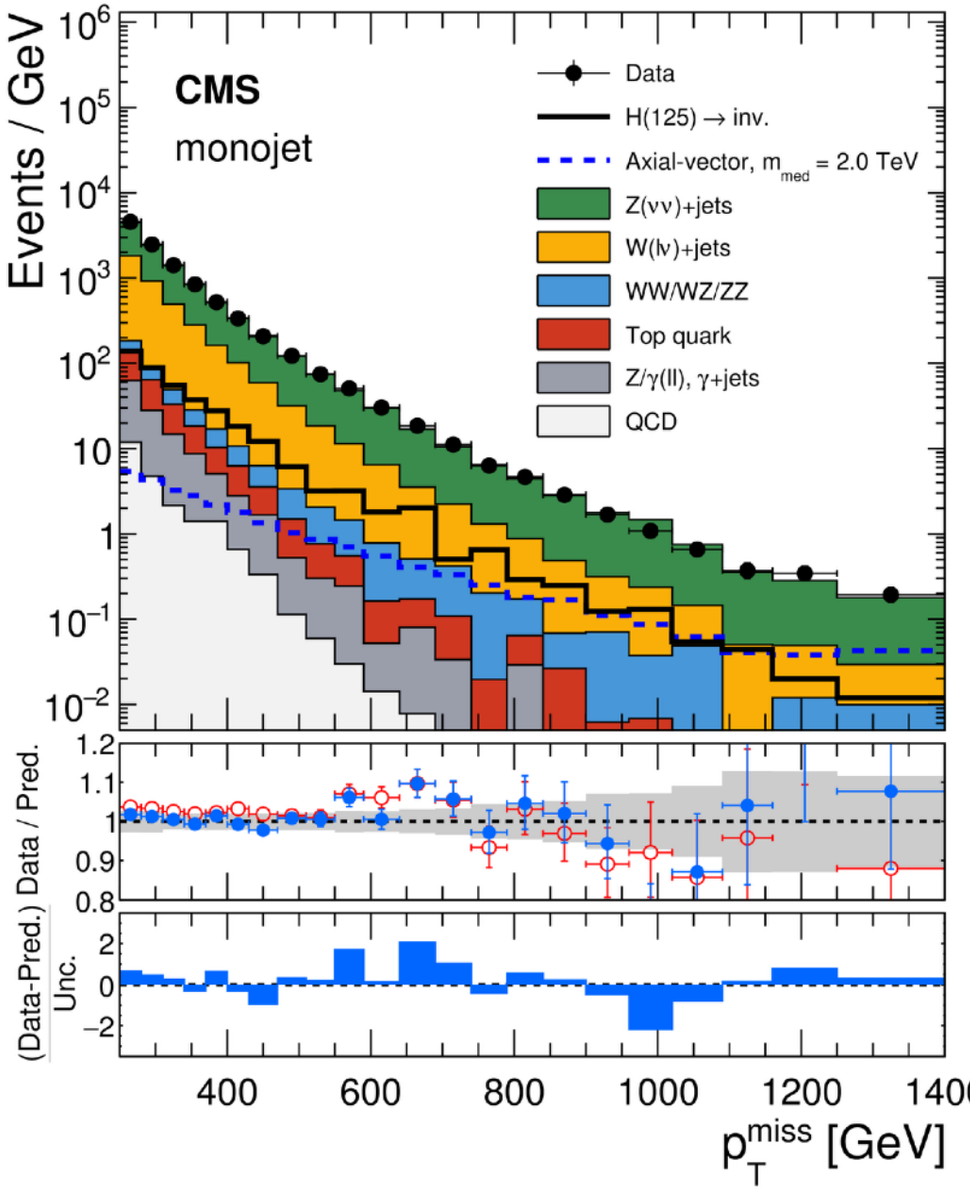


A generic search for DM: "*X+MET*"

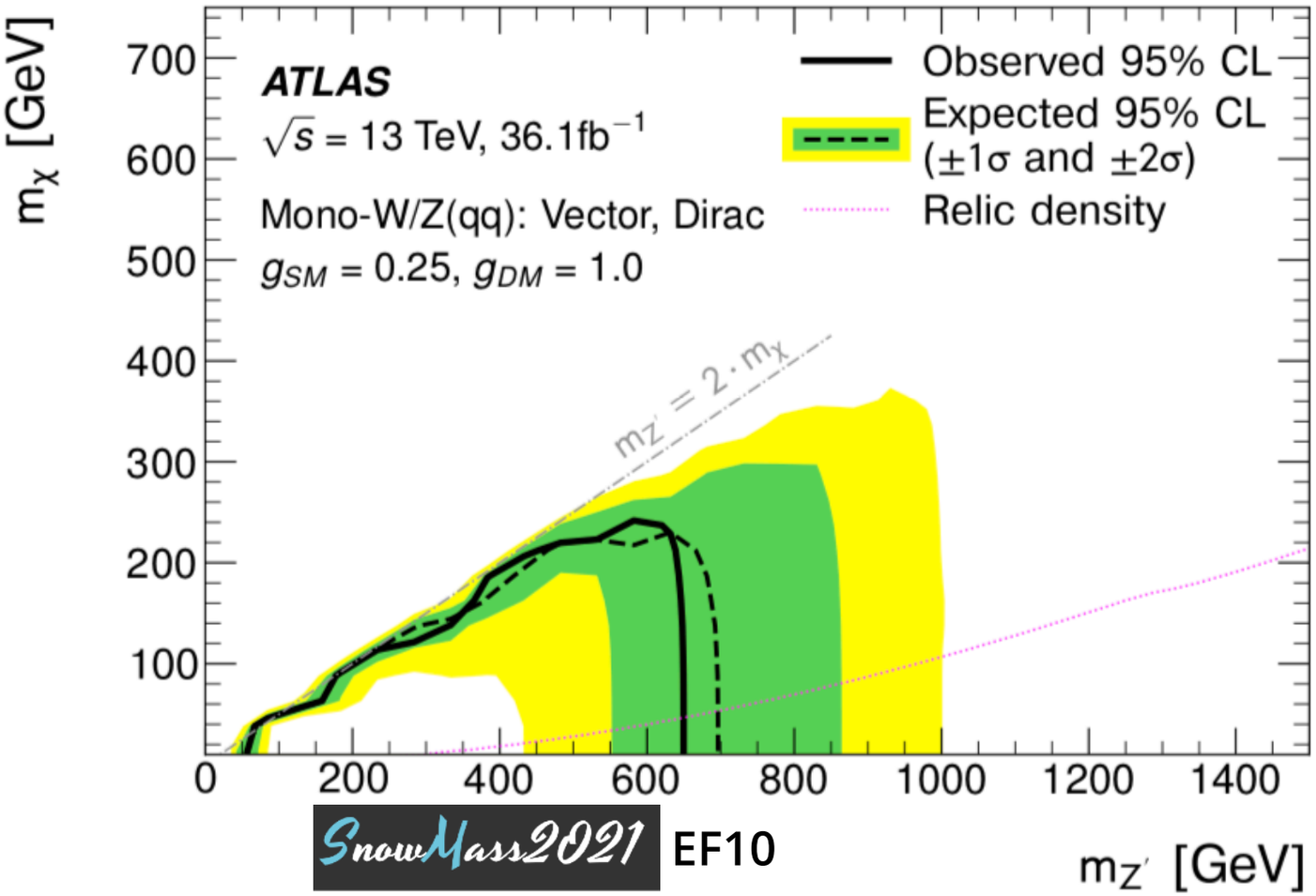


ISR (jet, photon, V boson...) + MET signature
- Background shapes need precise theory predictions [EPJC 2017 77:829]
- Results can be interpreted in a variety of models - here: vector mediator

[Phys. Rev. D 97, 092005 (2018)]



[arXiv:1807.11471]



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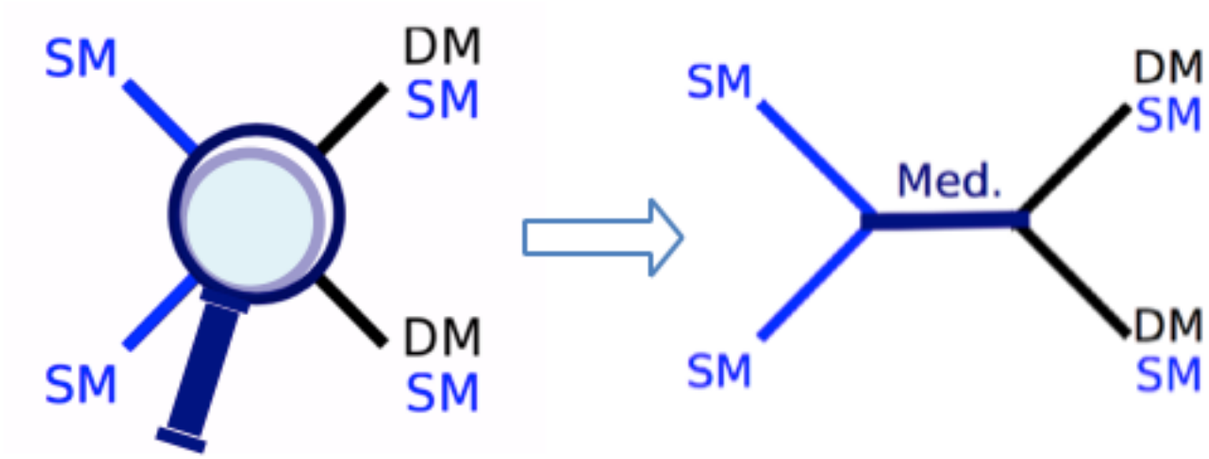
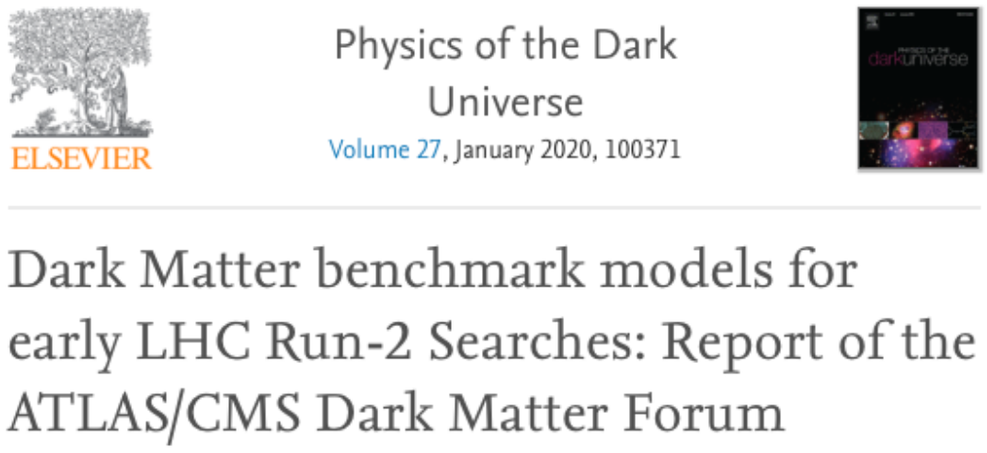
Is this the only way we can look for WIMP DM? No!

If there's a force other than gravity, there's a **mediator (/portal)**, and the LHC could **detect** its decays into **visible particles**:
simplified/portal models are popular collider & accelerator search benchmarks

SnowMass2021 EF10
SnowMass2021 RF6



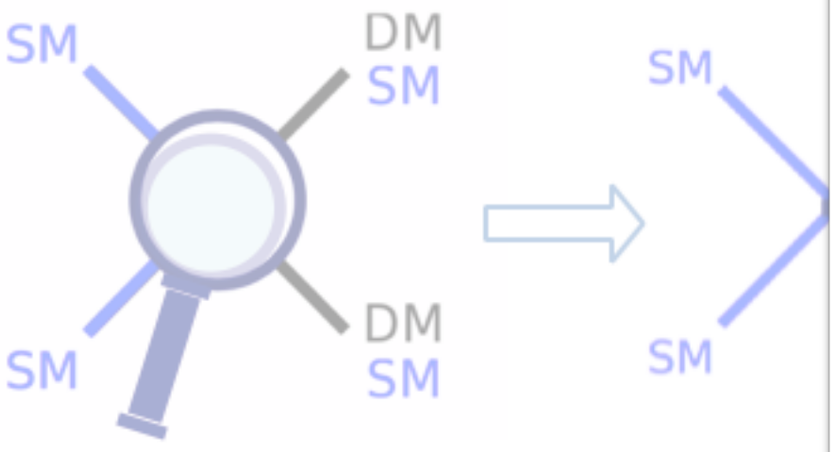


LHC Dark Matter Forum & Working Group

https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc
Phys. Dark Univ. 26 (2019) 100371 & references within, Ann. Rev. Nucl. Part. 68:429-459, 2018

Beware of simple models...

If there's a force other … s a **mediator (/portal)**, and the LHC could … to **visible particles**: *simplified/portal mode… …ler search benchmarks*



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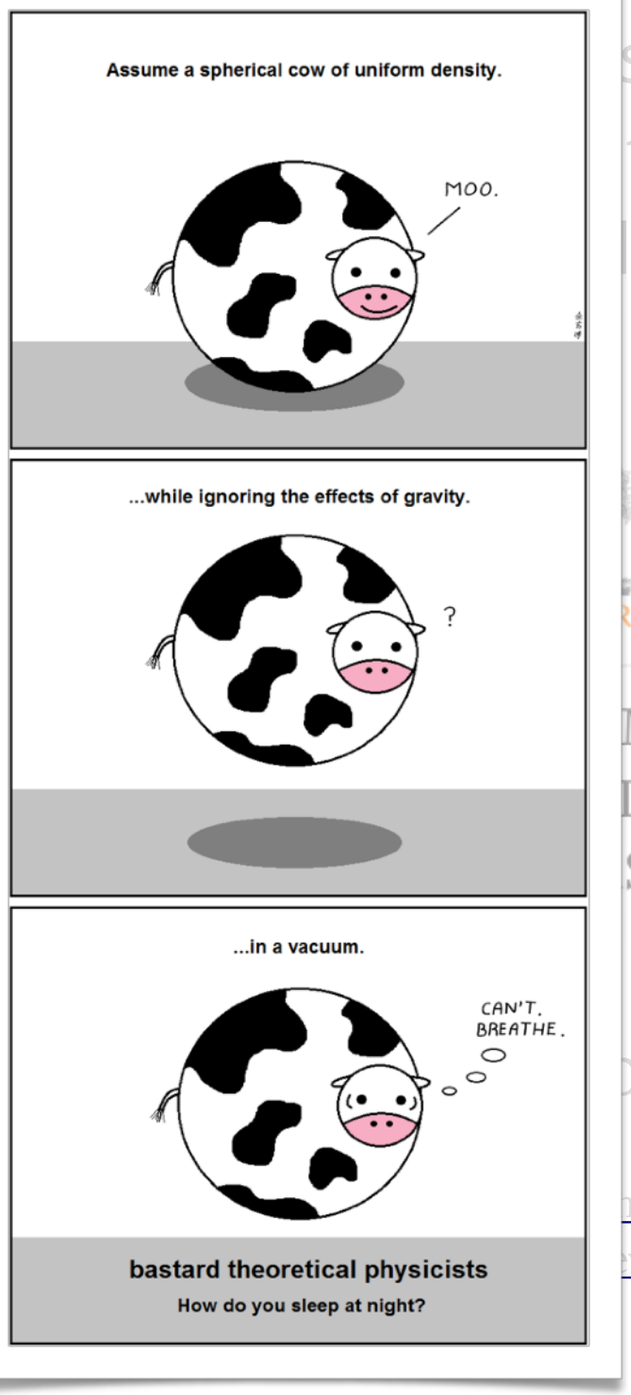


Physics of the Dark Universe
Volume 27, January 2020, 100371

…Matter benchmark models for LHC Run-2 Searches: Report of the …S/CMS Dark Matter Forum

LHC Dark M… …orking Group

https://lpcc.web… …matter-searches-lhc

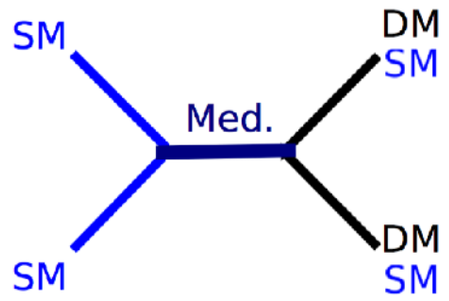
Phys. Dark Univ. 26 (2019) 1… …ev. Nucl. Part. 68:429-459, 2018

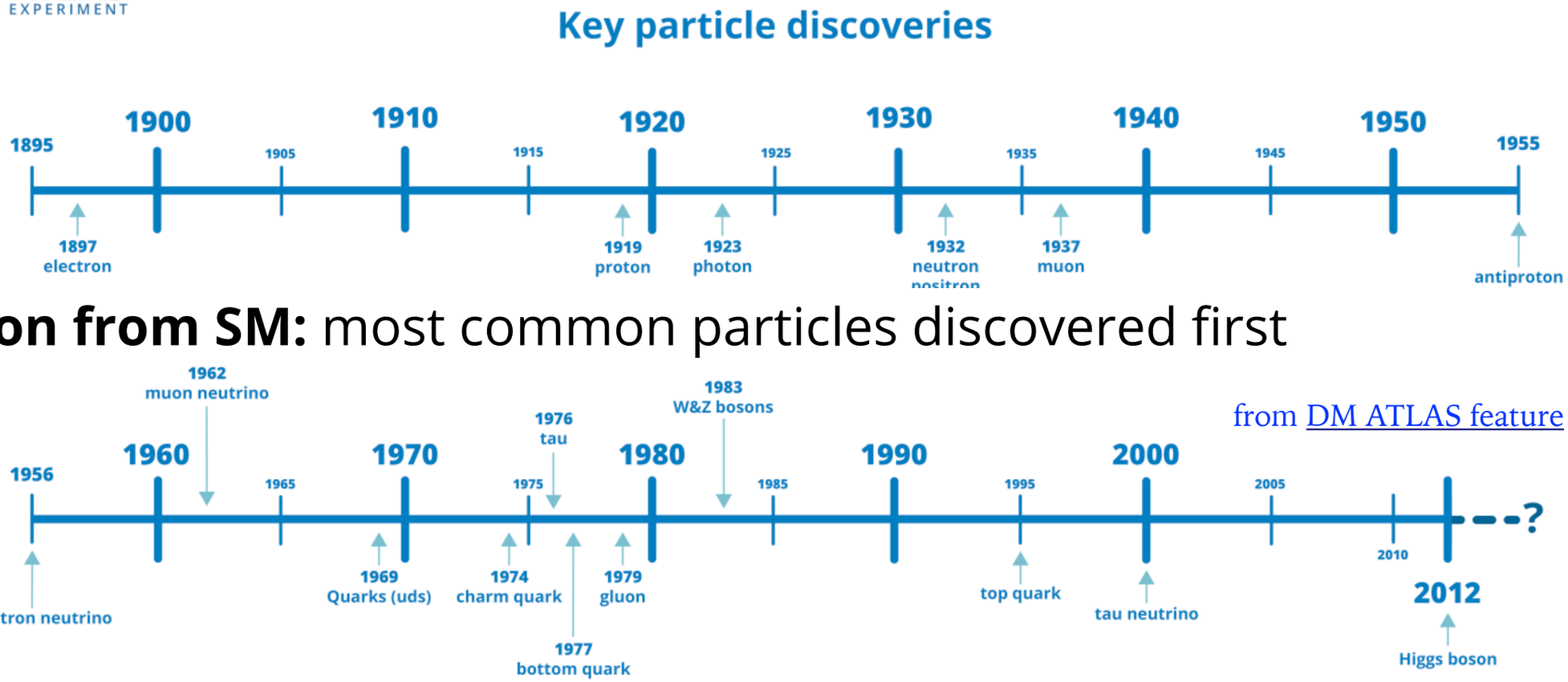
...but not all hope is lost!

"Why should we choose/believe the simplest models?"

"Do we think DM is all made of a single (WIMP) model?"

(not really…see dark sectors later!)





- **Lesson from SM:** most common particles discovered first

- Even simple models can encapsulate **relevant experimental characteristics** representing wider classes of theories

as long as we are aware that they can be more rare than what we choose as example

Beyond WIMP DM → beyond high-energy colliders

DM models with **light** particles && **very feeble interactions** w/SM benefit from high intensities, not only high energies

- Starting from our baseline assumption: DM
  - **interacts with SM** particles → we can **produce and detect it** at

Link to Suchita's CPM talk

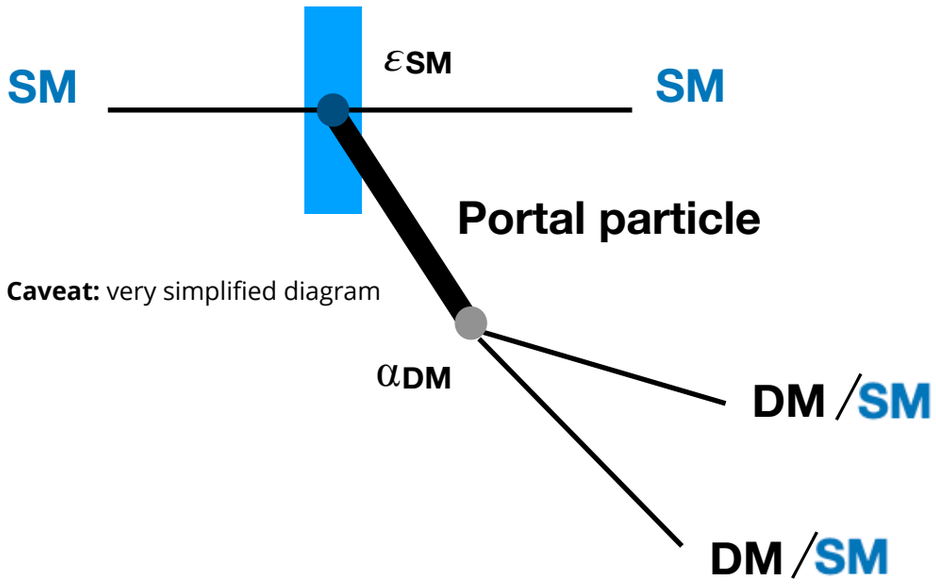
(Intense) beams from particle accelerators

- SPS
- LHC
- Fermilab Booster
- Future

NA62/4, LDMX, SHIP...
FASER, CODEX-b...
MiniBoone, ...
MANY more ideas...

Planned/proposed experiments

SnowMass2021 RF06
SnowMass2021 NF



→ production of DM/SM particles

Can we discover/rule out DM at accelerators in the next 50 years?

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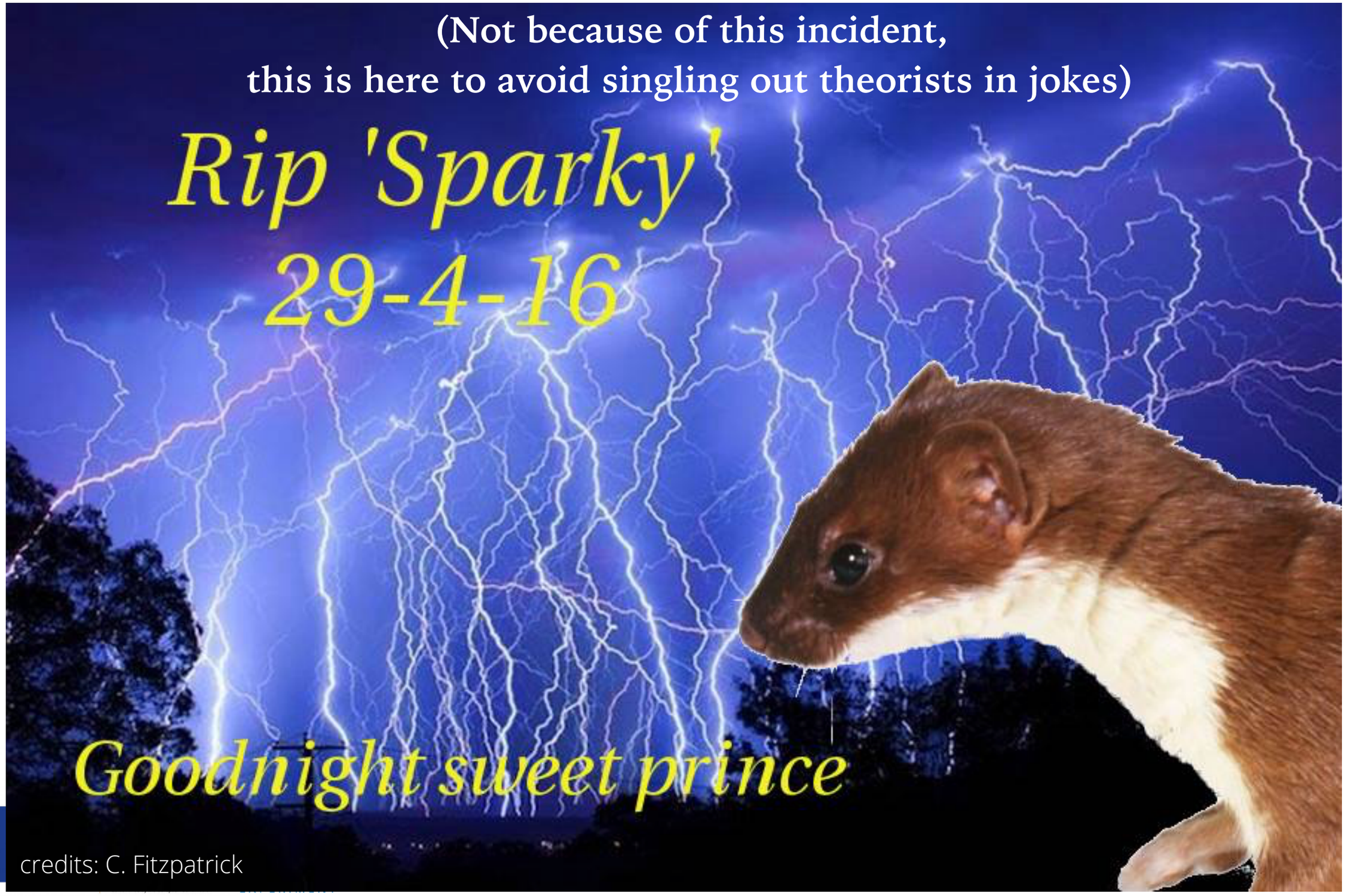

credits: C. Fitzpatrick

Can we discover/rule out DM at accelerators in the next 50 years?

🔥**Hot take**🔥: not with colliders/accelerators alone!

Particle accelerators, direct and indirect detection

- **Reason #1**: there are DM models that are not accessible at accelerator energies / intensities(SnowMass2021 CF01-03 & Chanda's talk)

Particle accelerators, direct and indirect detection

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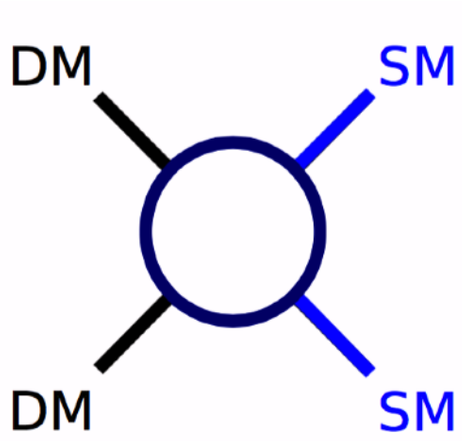
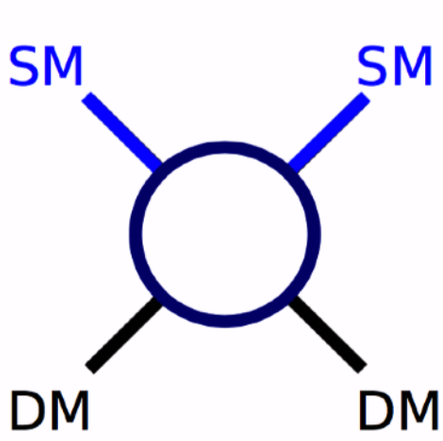
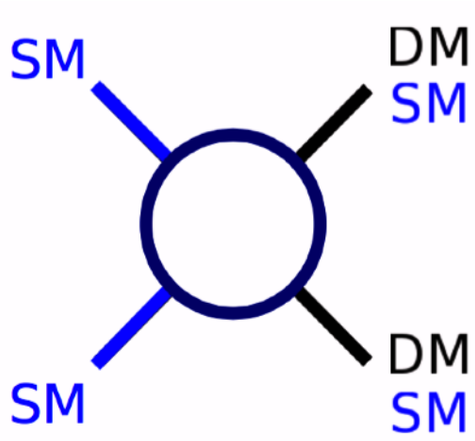
- **Reason #2:** DM discoveries need complementary experiments that involve DM with **cosmological origin**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays



Indirect Detection



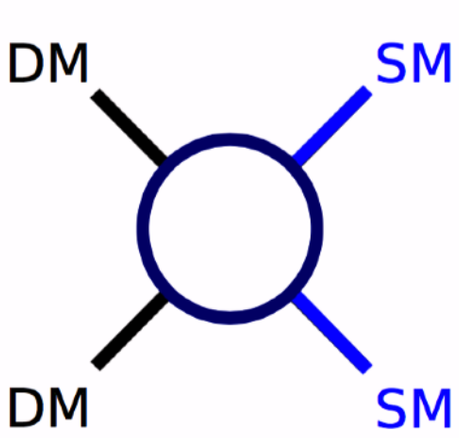
Direct Detection



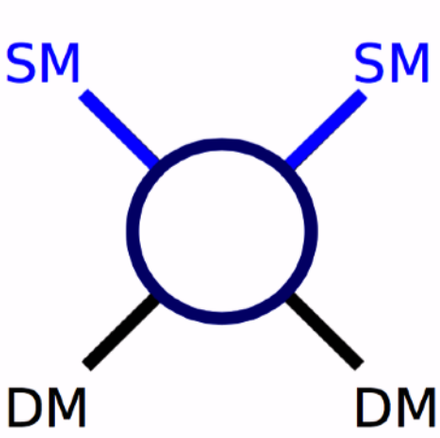
Particle Accelerators (colliders & extracted beam lines)

Particle accelerators, direct and indirect detection

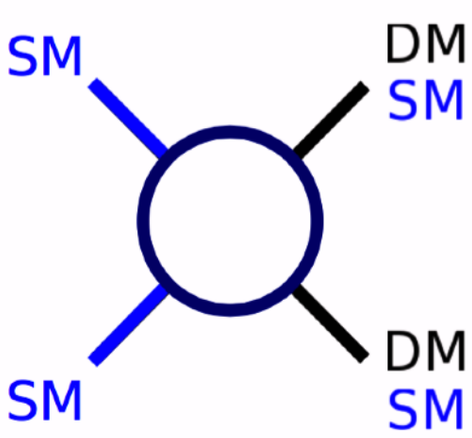
- **Reason #1**: there are DM models that are not accessible at accelerator energies / intensities(SnowMass2021 CF01-03 & Chanda's talk)
- **Reason #2:** DM discoveries need complementary experiments that involve DM with **cosmological origin**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays
  - Accelerators/colliders can produce DM and **probe the dark interaction**

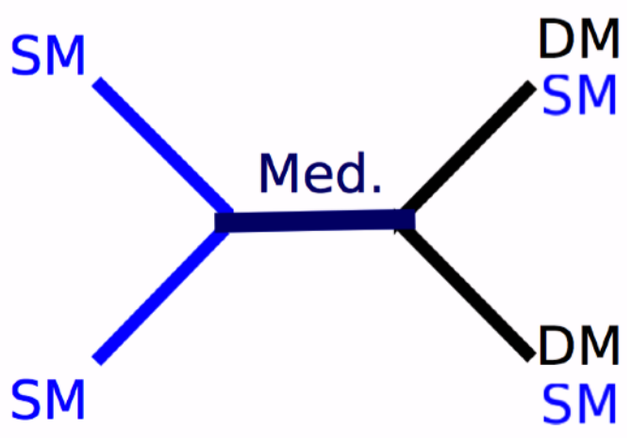


Indirect Detection



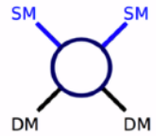
Direct Detection





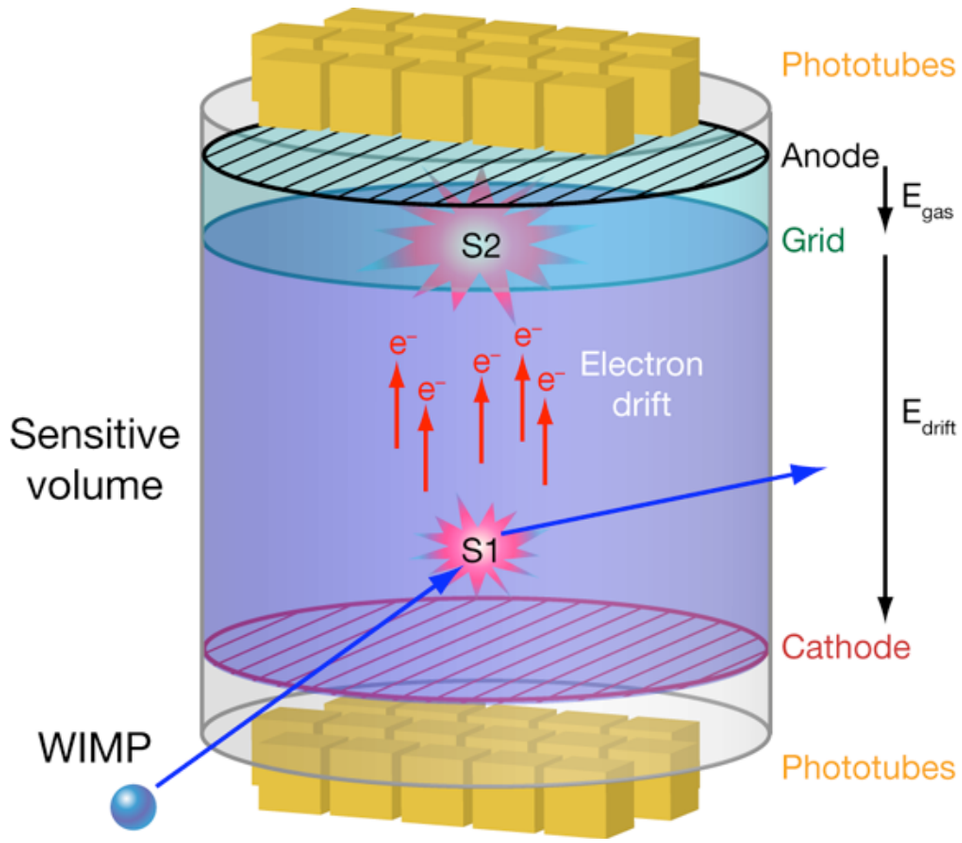
Particle Accelerators (colliders & extracted beam lines)

Direct detection experiments: examples



XENON/LZ

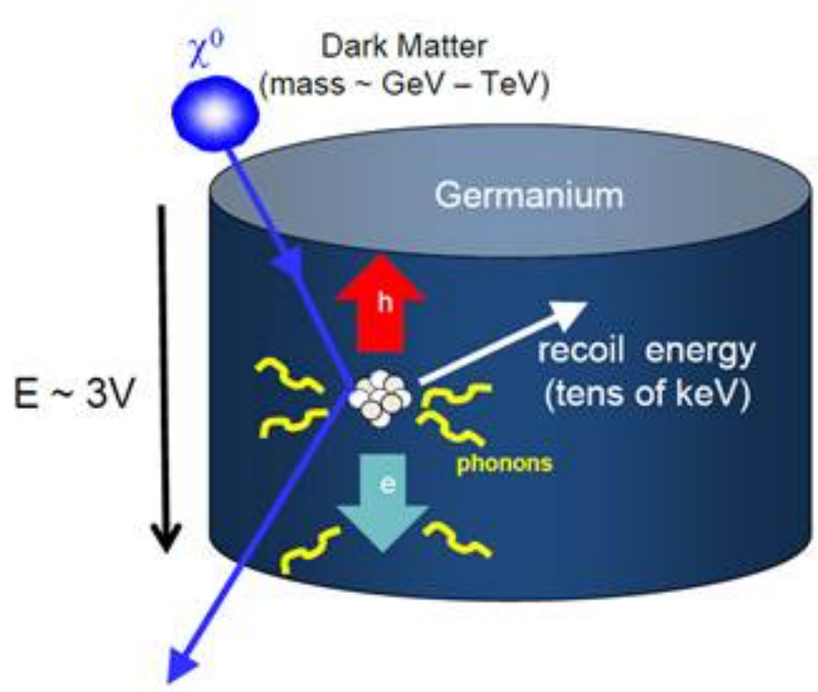
Large volumes (order: meters)



http://www.xenon1t.org
https://lz.lbl.gov

CDMS

Smaller volumes, lower threshold
(order: centimeter-meter)

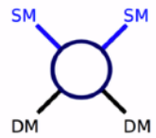


https://www.slac.stanford.edu/exp/cdms/

Many more experiments operational/planned for this decade:
from Generation-2 to Generation-3

SnowMass2021 CF1

Direct detection experiments: examples

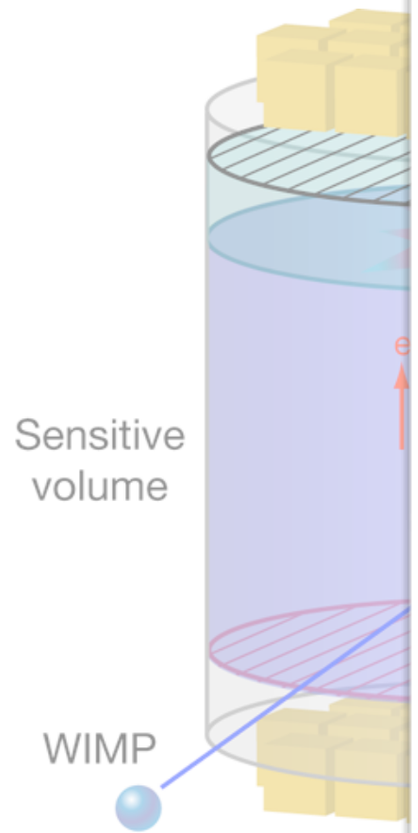


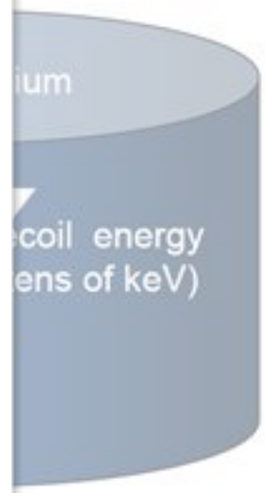
XENON/LZ

CDMS

Large vol

wer threshold
r-meter)





d.edu/exp/cdms/

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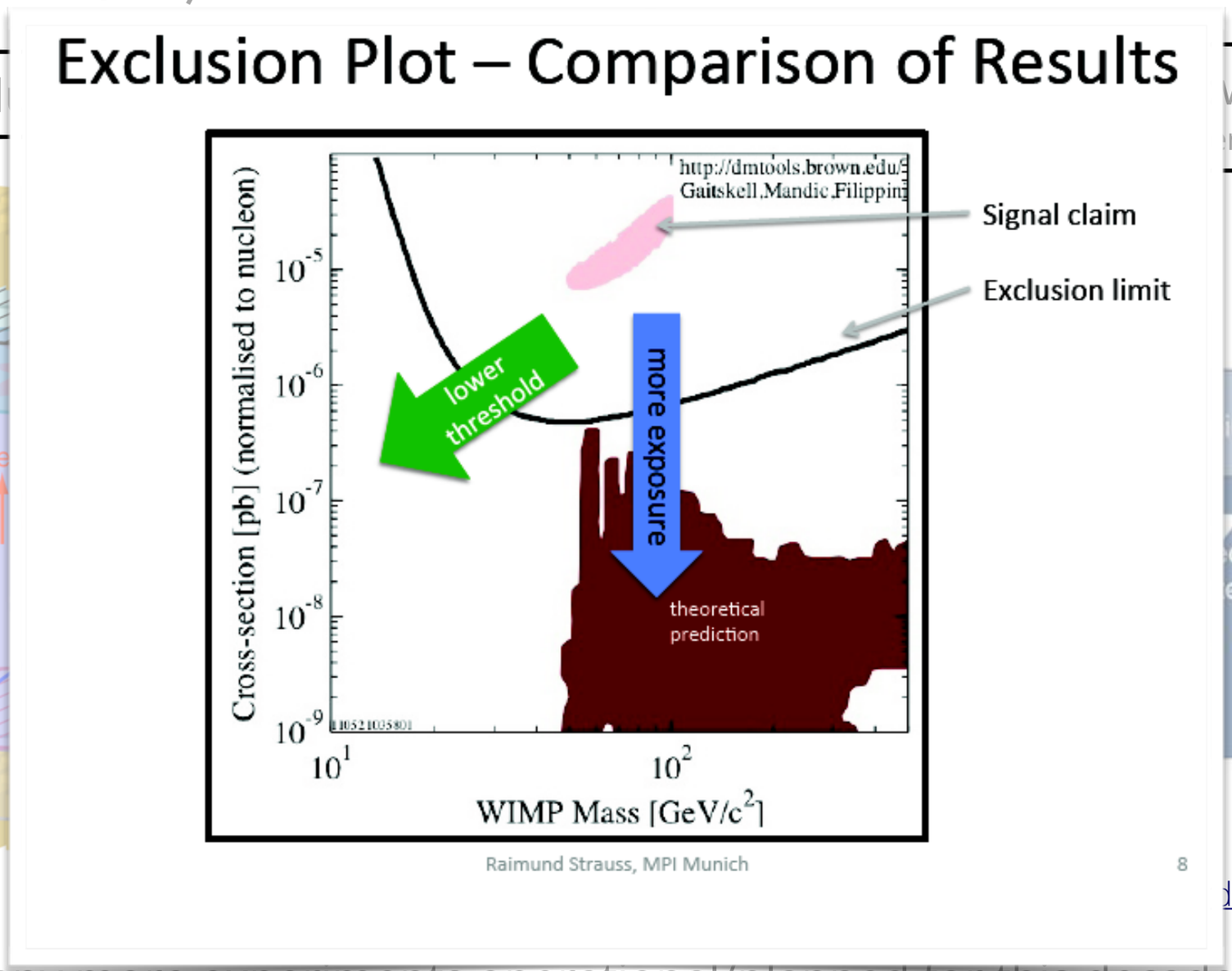
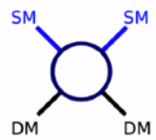


SnowMass2021 CF1

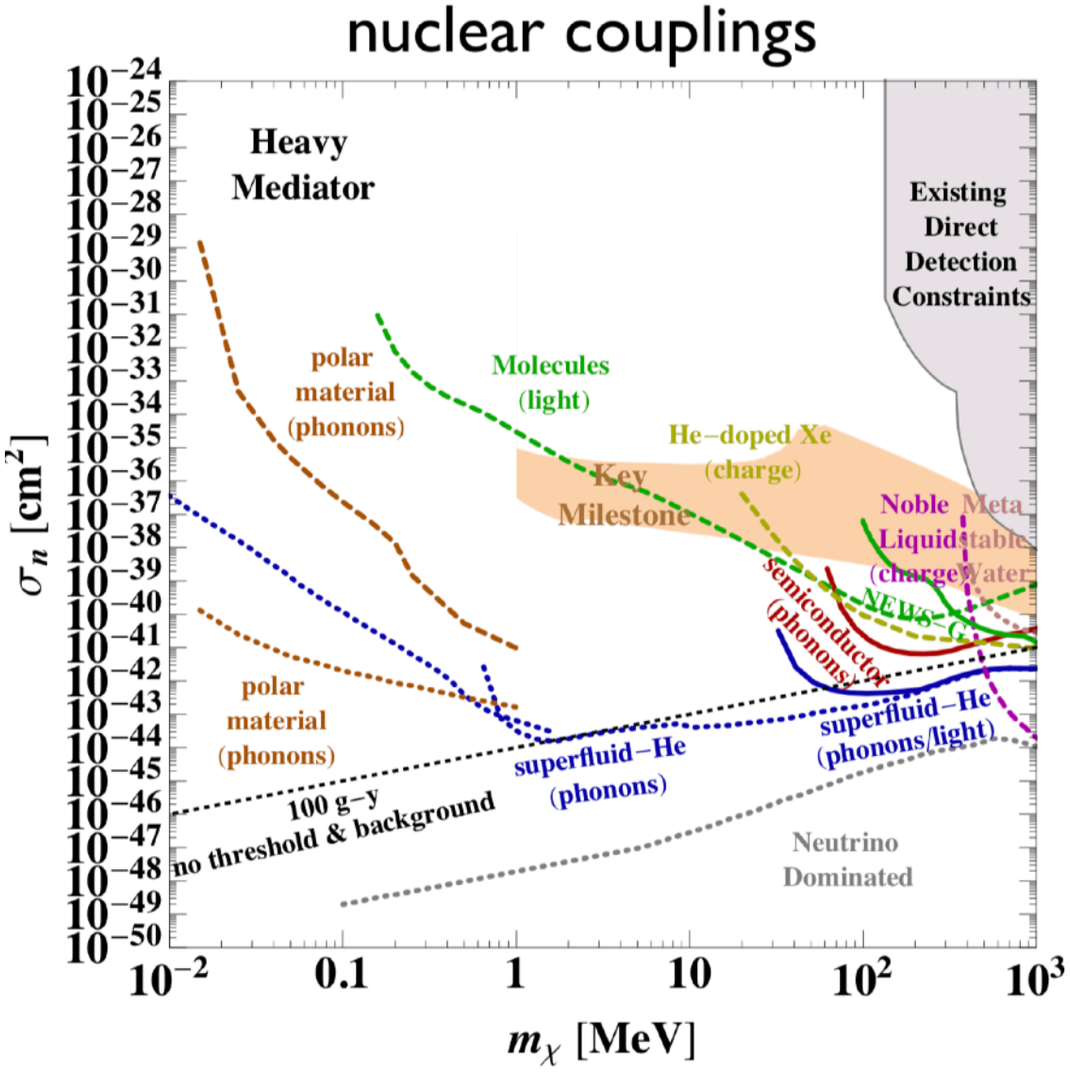
Direct detection for very light DM



"Traditional" DM-SM recoil direct detection searches lose sensitivity to low-DM masses, but...

- detectors can be made **more sensitive** to lower thresholds (e.g. phonon-based calorimeters) F. Petricca's talk @ GGI 2019
- **subdominant effects** can enhance "kick" from DM E.g. arXiv:1702.04730, 1707.07258, 1905.00046, 1810.07705, 1810.10543...
- can explore **new materials & detectors** → collaboration of **astro/ particle physics** & **solid state physics**
  - Including **quantum sensors**

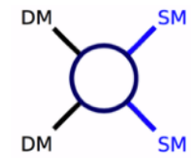
E.g. arXiv:1709.07882, CPM Session #77



BRN Report

SnowMass2021 CF1

Indirect Detection experiments: examples

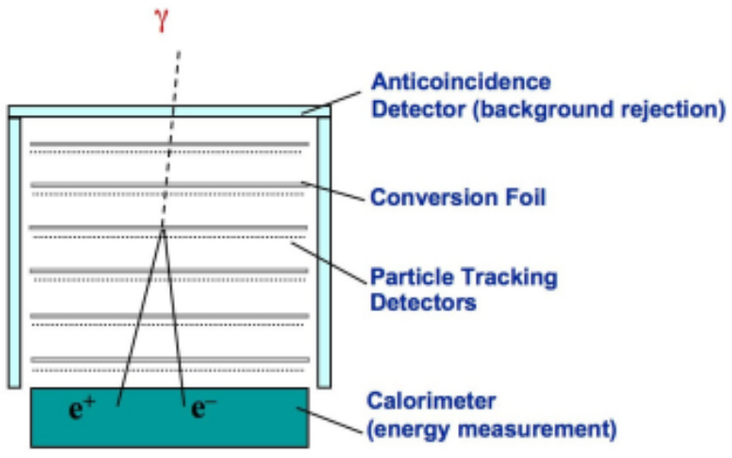


Dark Matter annihilates in the GC / dwarf galaxies (a place) to photons (some particles), which are detected by Fermi, HESS, ... (an experiment).

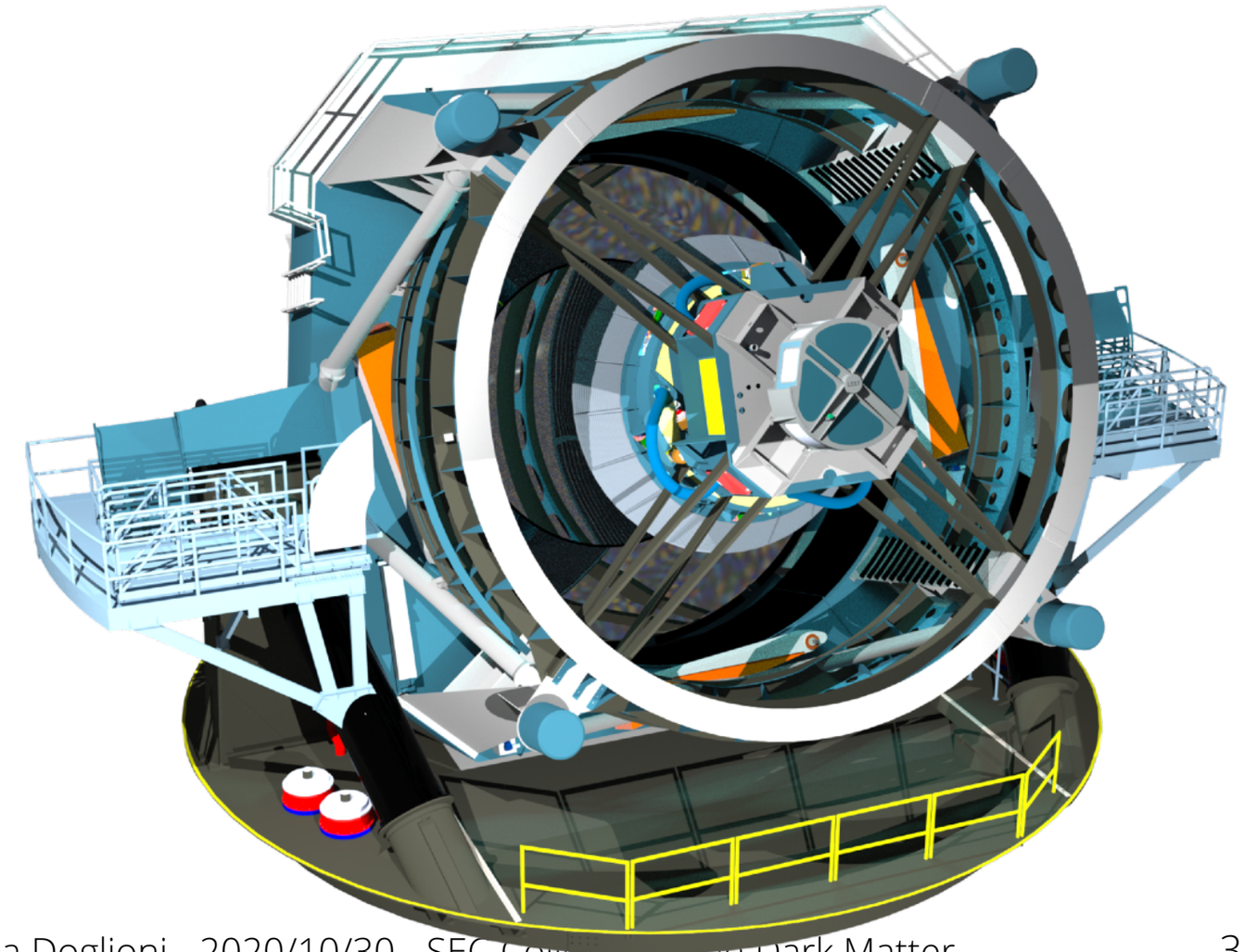
where to find DM:
galaxy surveys SnowMass2021 CF3
(e.g. LSST, SKA,...)
(also able to probe properties of DM & test DM models)

how to detect DM decays:
indirect detection experiments
(e.g. Fermi-LAT, CTA,...)

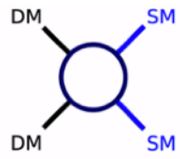
Fermi Large Area Telescope
https://www-glast.stanford.edu/

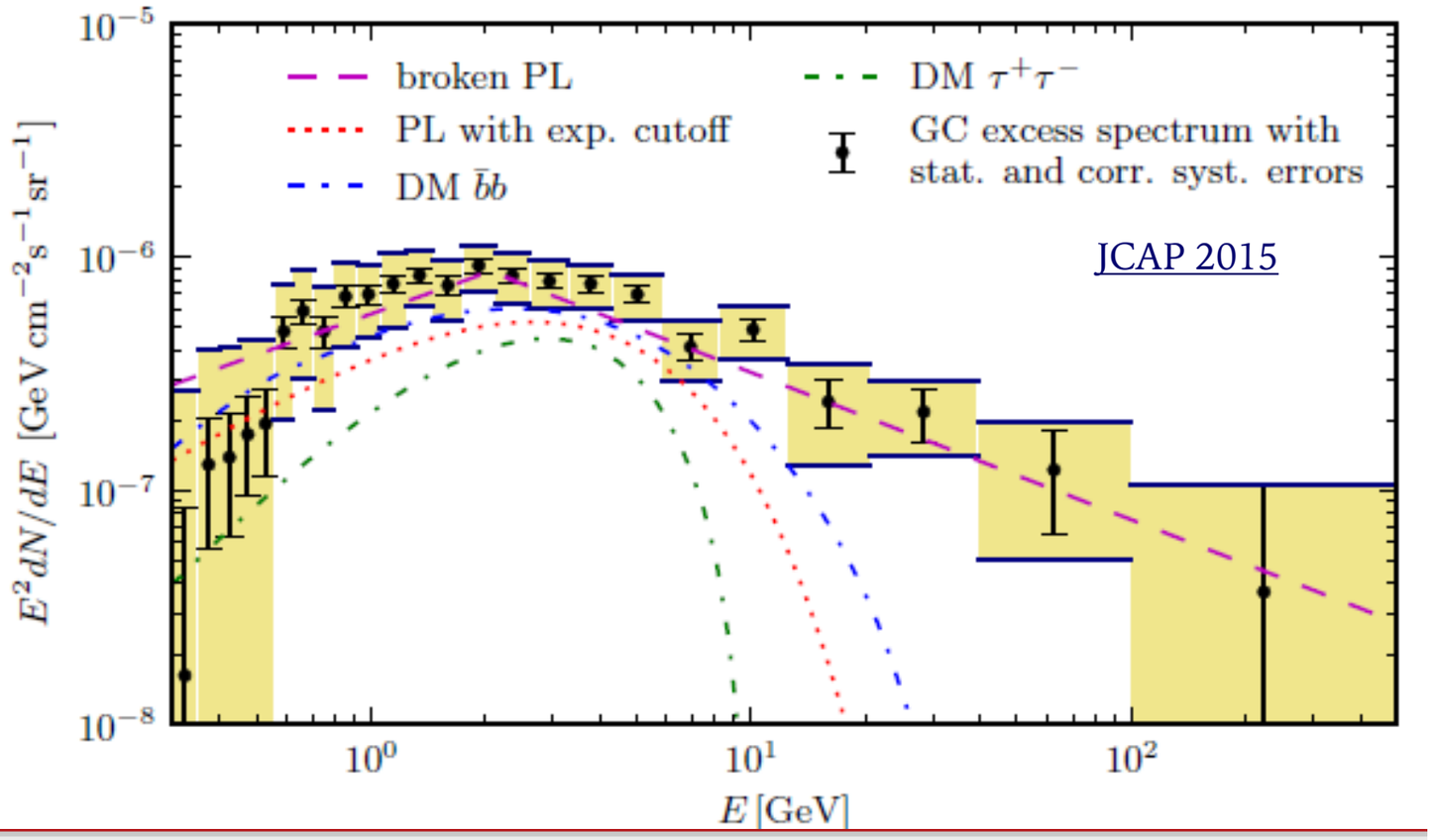


SnowMass2021 CF1



Indirect Detection example/excess: Fermi-LAT





Astrophysics > High Energy Astrophysical Phenomena

Dark Matter Strikes Back at the Galactic Center

Rebecca K. Leane, Tracy R. Slatyer

Phys. Rev. Lett. 123, 241101 (2019)

SnowMass2021 CF1-3

Many possibilities for interpretation, floor still open!

Looking for rarer DM (examples from direct detection)

- Major updates to direct/indirect detection experiments planned:
  - in terms of **detectors**
  - in terms of **reduction of challenging backgrounds**

SnowMass2021 CF1

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

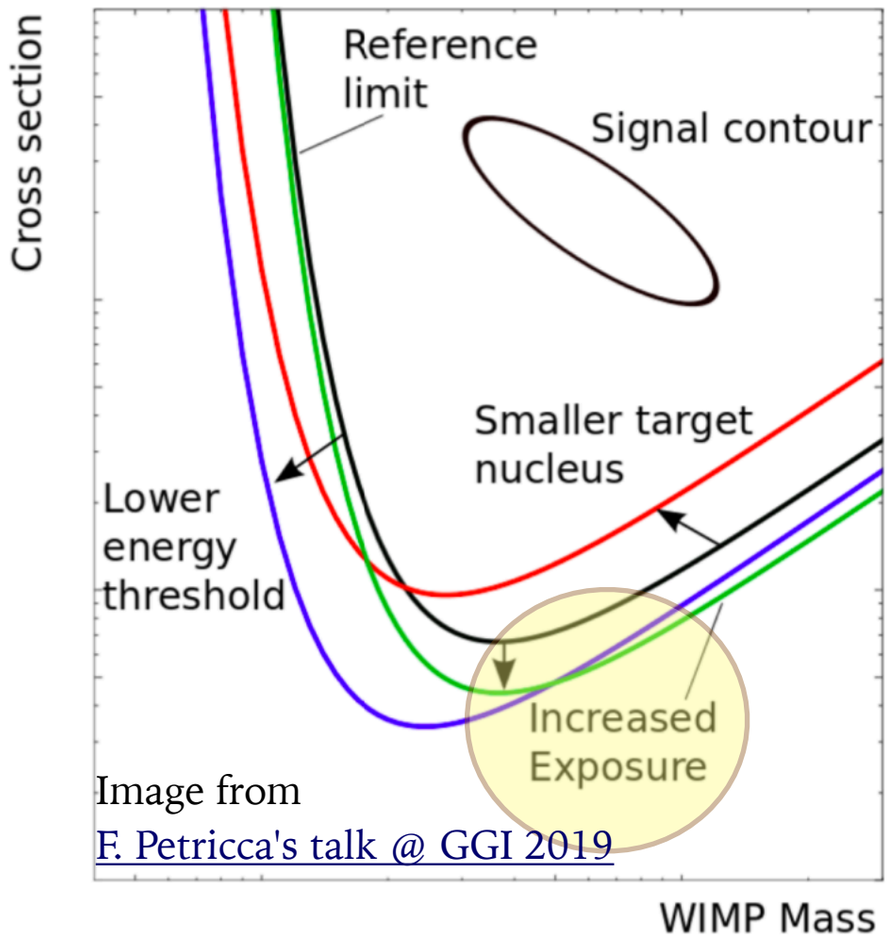
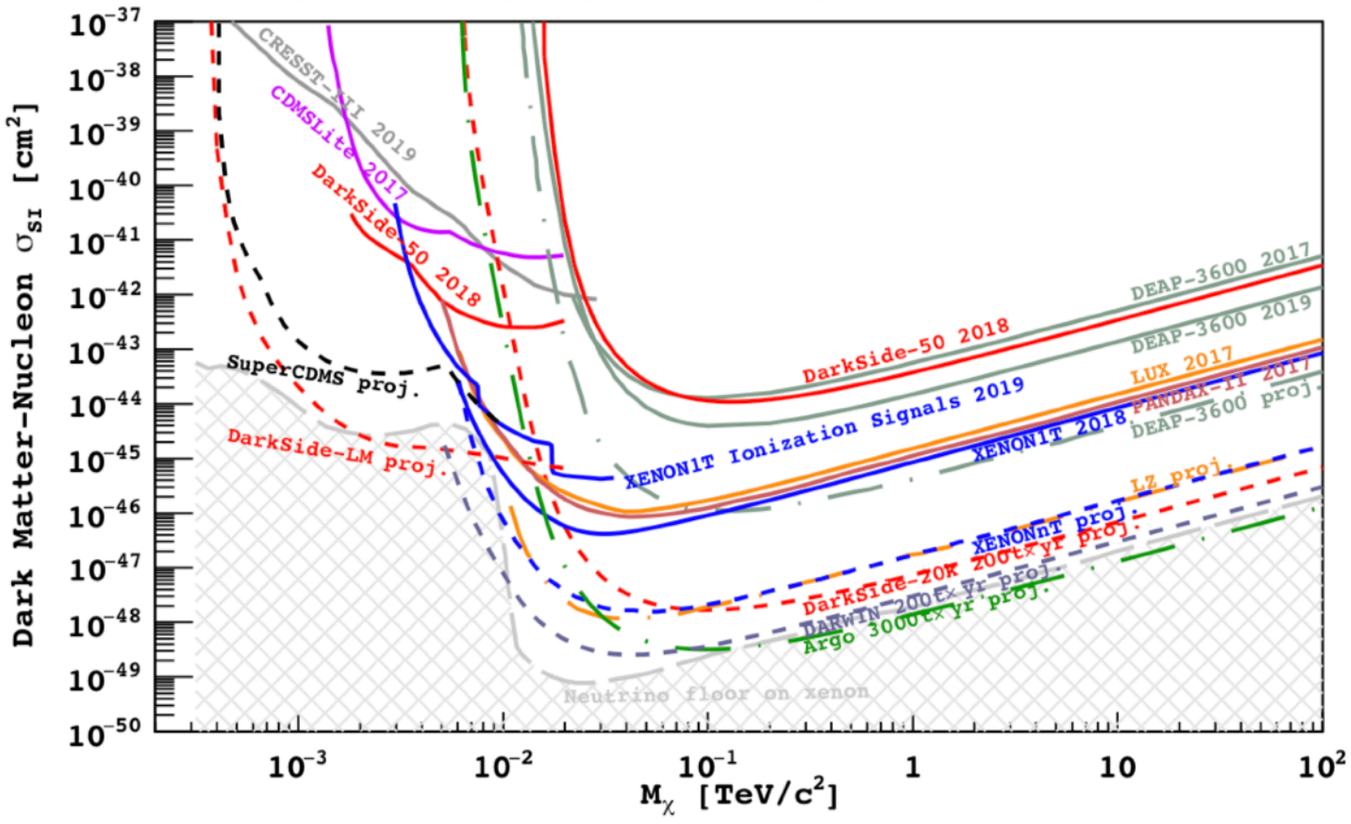


Image from
F. Petricca's talk @ GGI 2019

European Strategy Update Briefing Book



solar/cosmic neutrino scattering xsec may become larger than DM xsec
(but **irreducible backgrounds** haven't stopped anyone so far)

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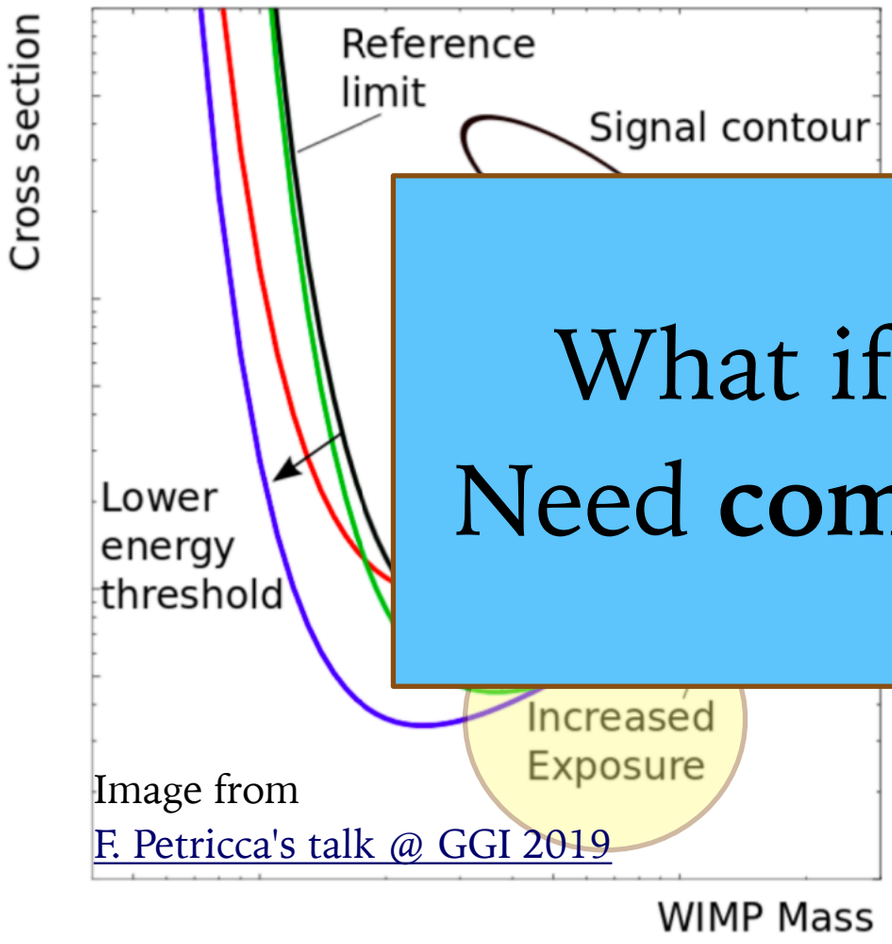

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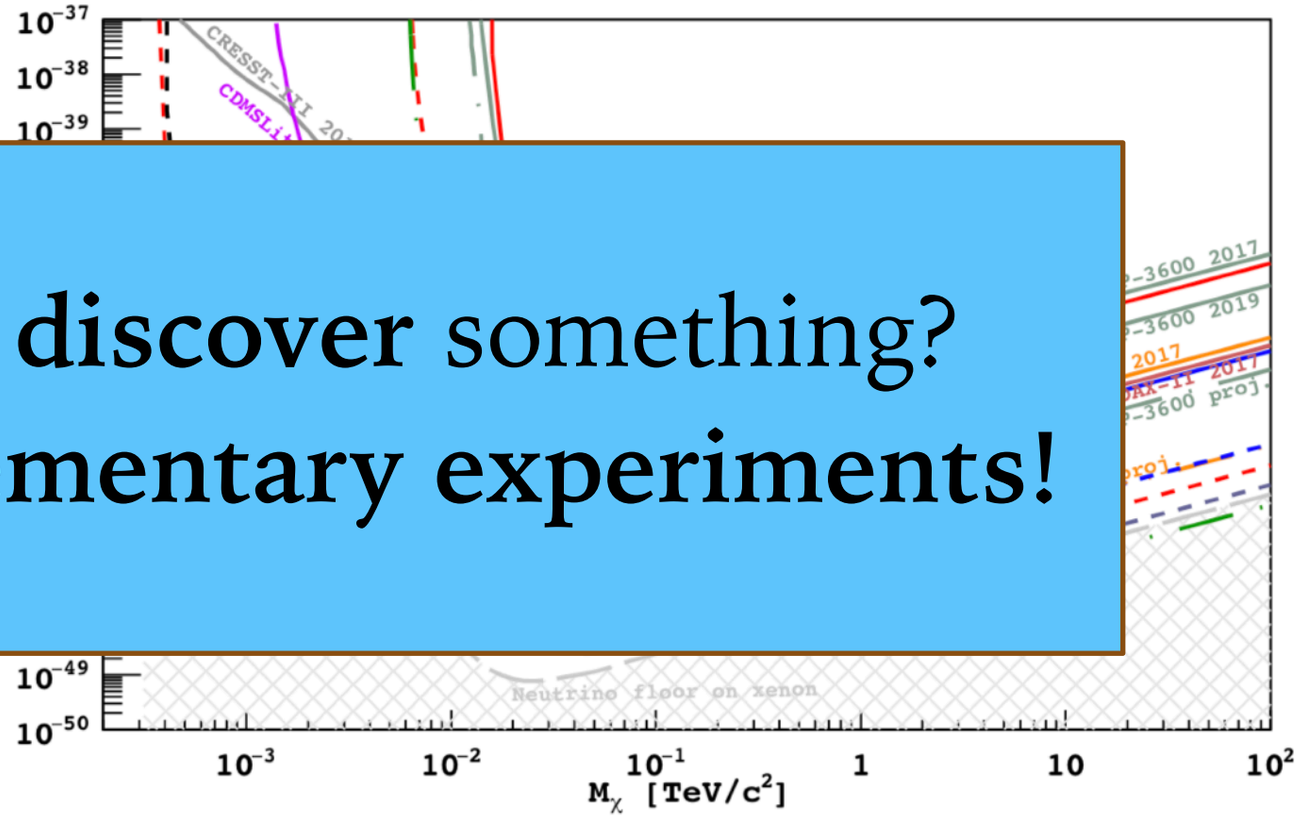


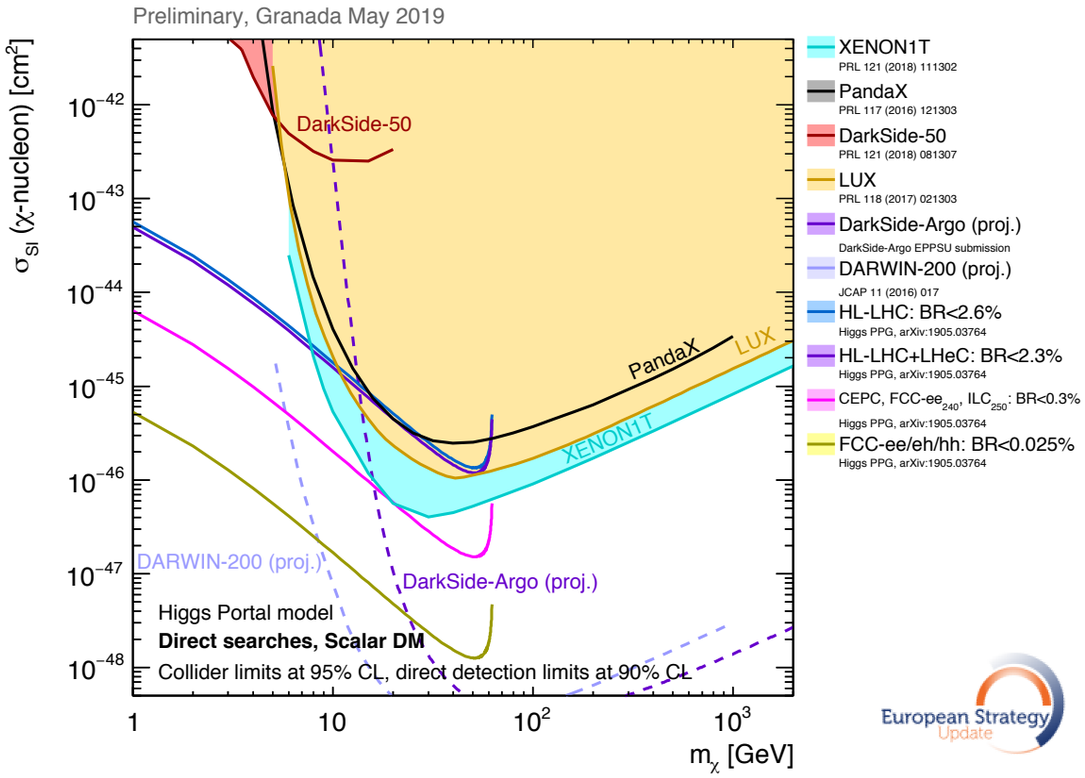
What if we **discover** something?
Need **complementary experiments!**

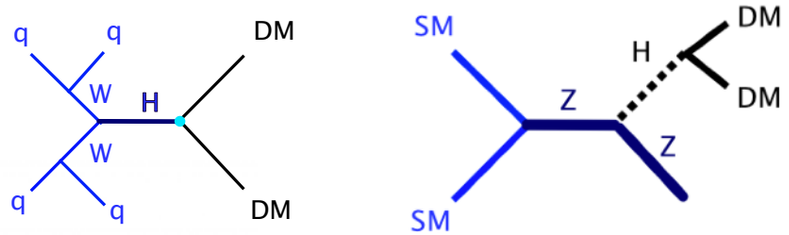
solar/cosmic neutrino scattering xsec may become larger than DM xsec
(but **irreducible backgrounds** haven't stopped anyone so far)

Complementarity so far: within WIMP frameworks

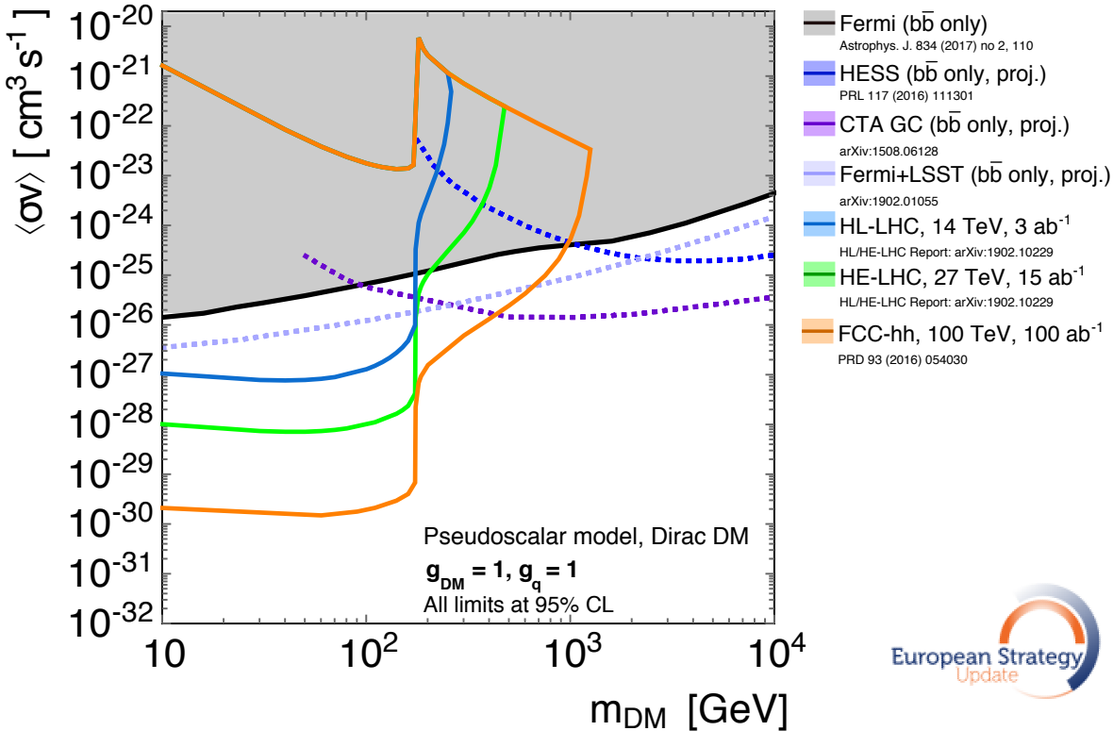
LHC DM Working Group, European Strategy Update Briefing Book, for non-WIMP examples, see Physics Beyond Colliders report

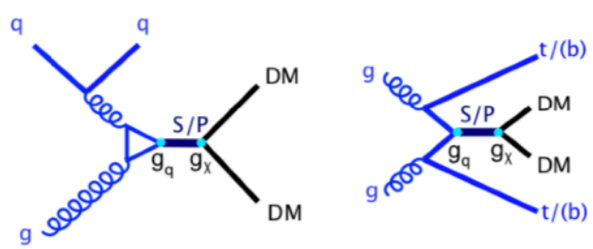
Invisible Higgs @ colliders and direct detection





Scalar mediators and indirect detection





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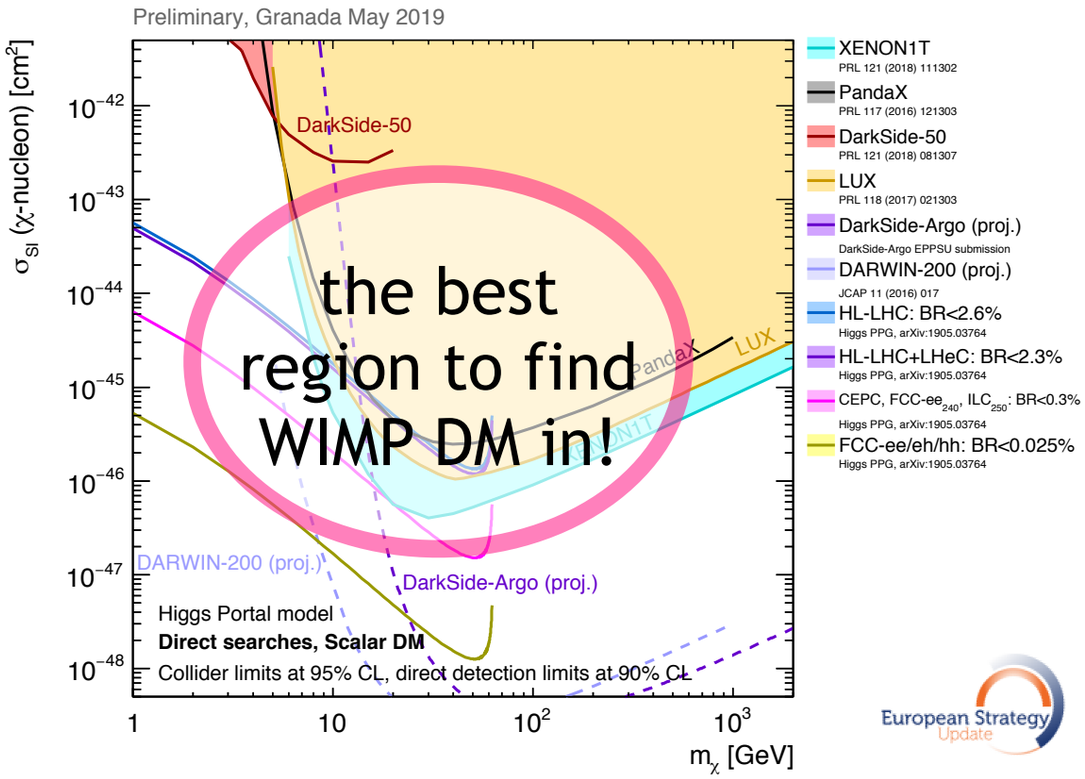

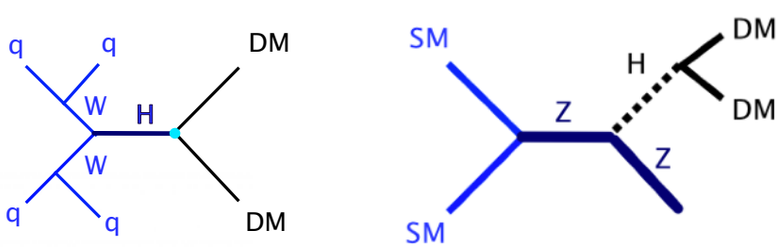

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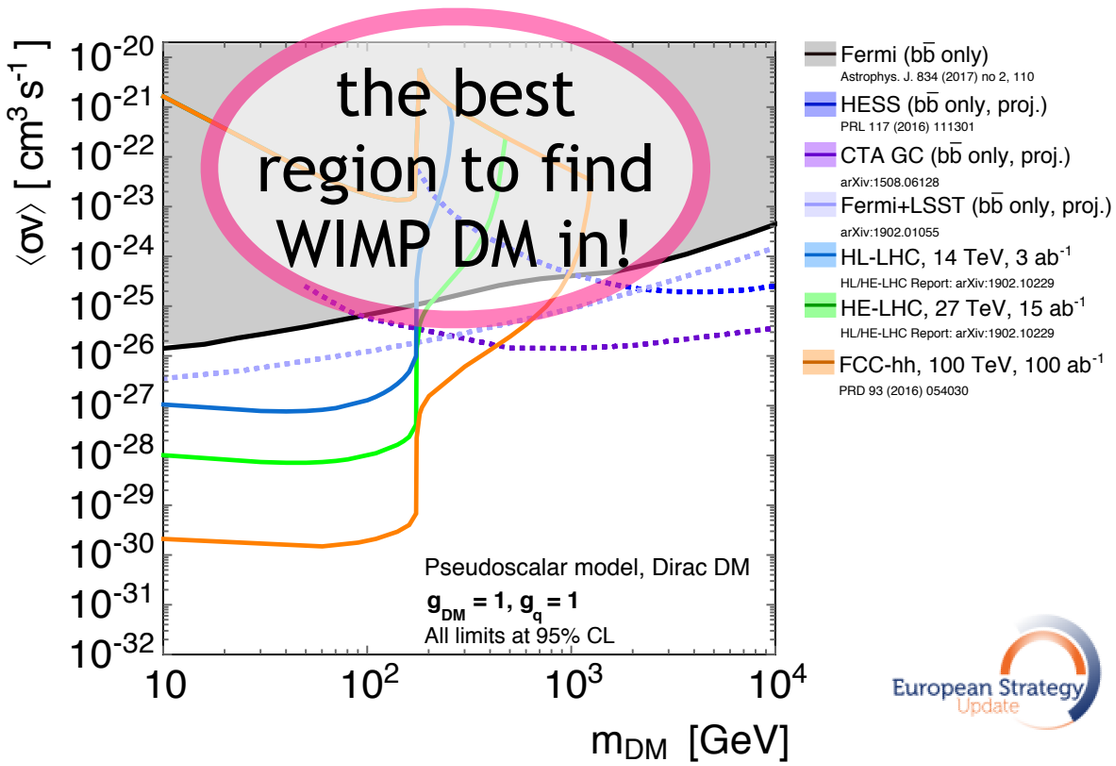


Health hazard : these plots are only valid for the couplings specified, in the **limited space of a benchmark model**!

Not to be used to deduce general things like:

"In the next 50 years we will exclude WIMP DM"

"Technique A is better than technique B to find DM"

Cate

Complementarity thoughts from Snowmass

Link to CPM session #150 - DM complementarity

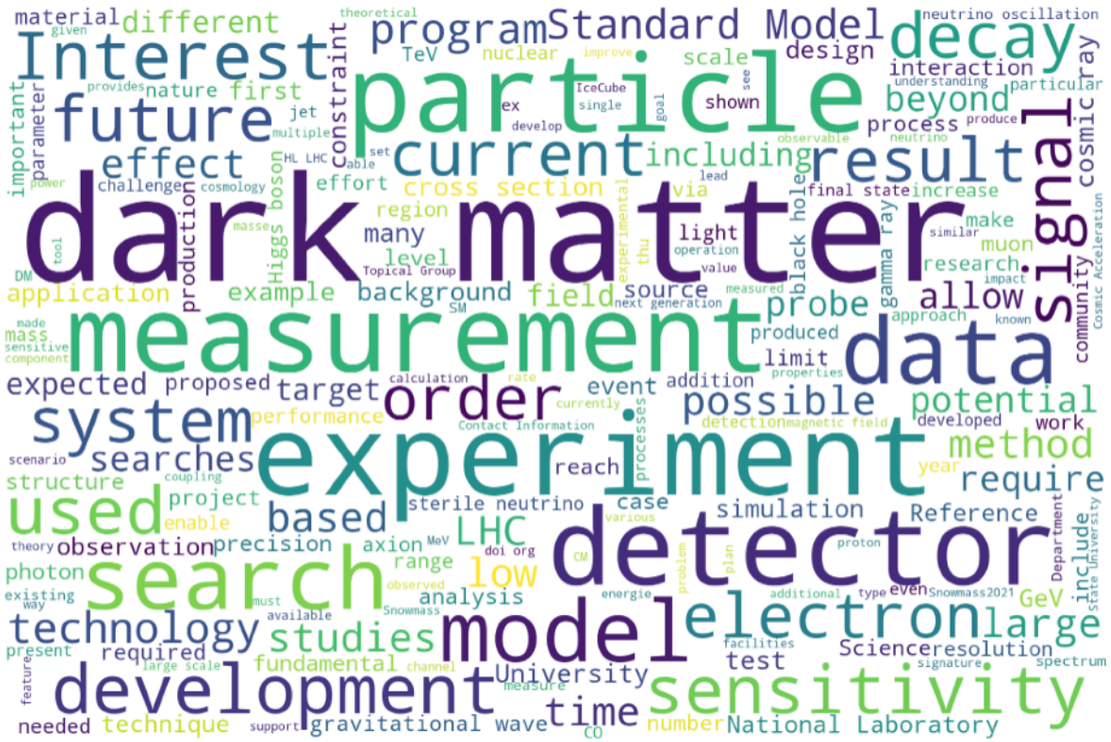
- Since the last Snowmass, there has been a fundamental shift in how we think about searches for dark matter.
- We are in an exciting exploratory phase where new ideas can be implemented on short timescales.
- Dark matter crosses **every** frontier.
- In order to get a full picture of the “elephant”, we need to combine information (more about this later)
- CF Conversation Starter: Dark matter could be *the* focal topic of this Snowmass Report.
- **How do we portray this complementarity?**
  - You can join us in thinking (e-mail me for a new mailing list!)

https://gordonwatts.github.io/snowmass-loi-words

Word Clouds

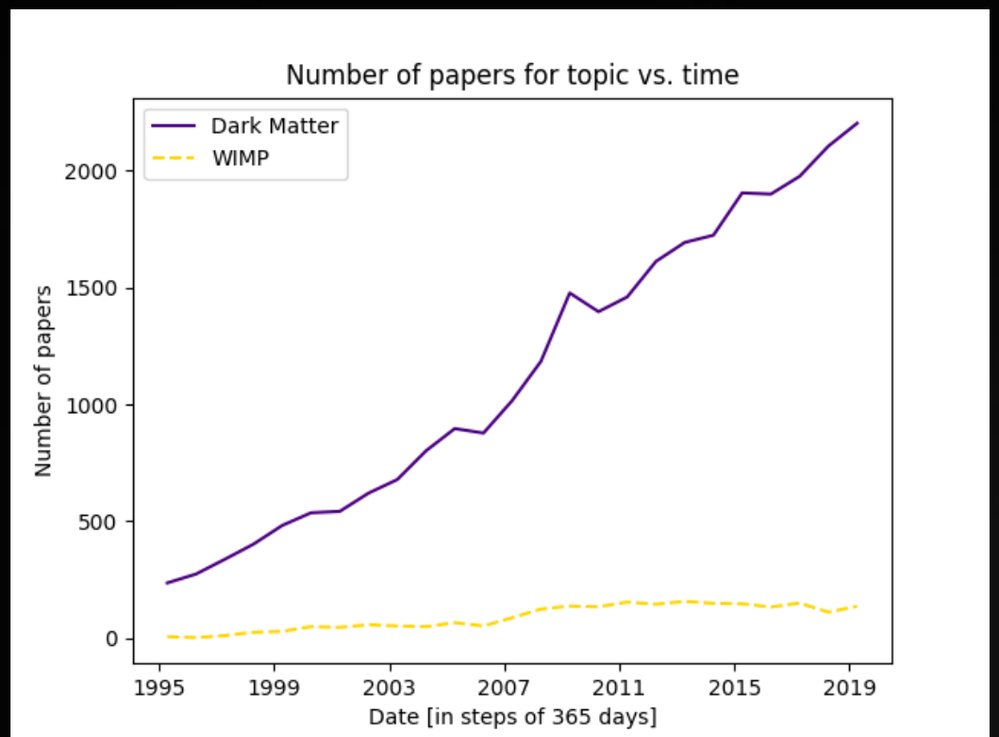
Word clouds are made by looking at the word frequency in the LOI’s. The more frequent the word, the larger the font-size in the word cloud.

All LOI’s



SnowMass2021 CF / EF / NF / RF

Last take-home point: look everywhere!

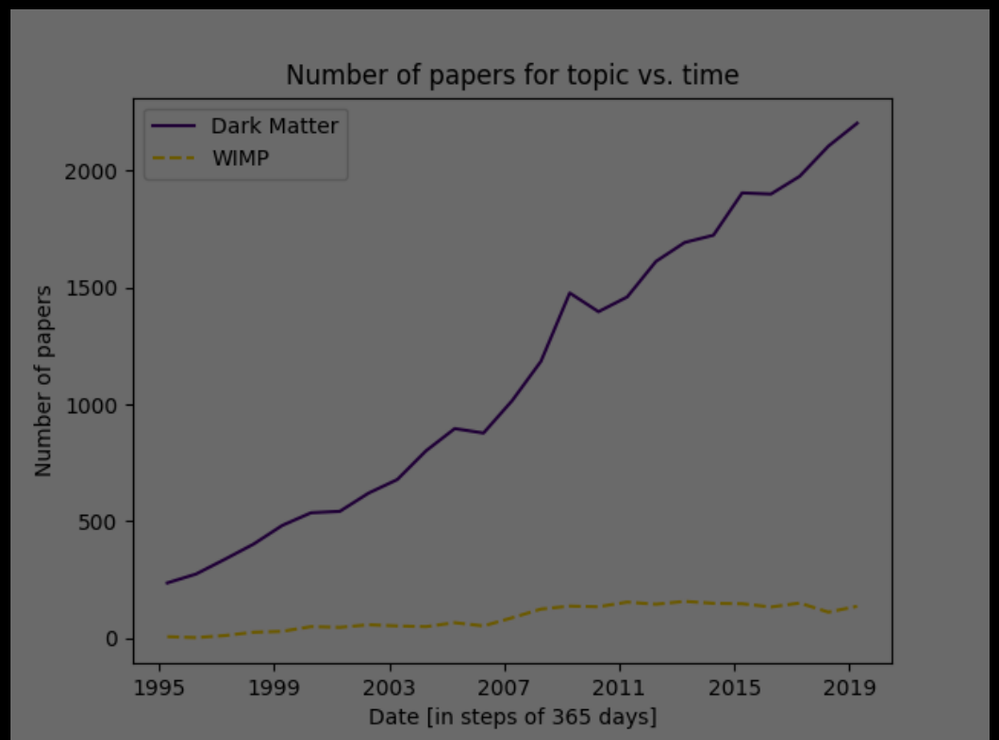


What might we learn from lines of research that are off the beaten track? They check accepted ideas, always a Good Thing, and there is the chance Nature has prepared yet another surprise for us.

J. Peebles

WIMP

Are we looking everywhere?



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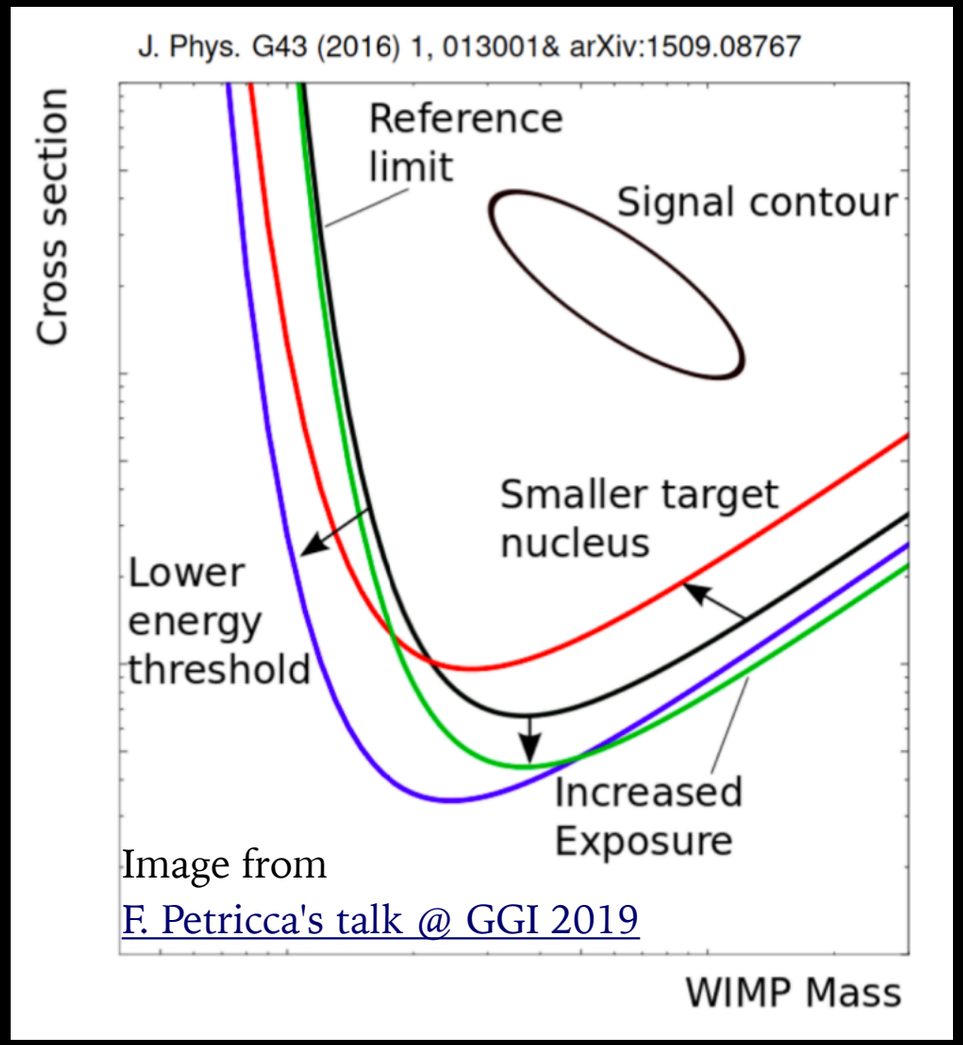
J. Peebles

left: much lighter DM

up: stronger interactions



right: more massive objects

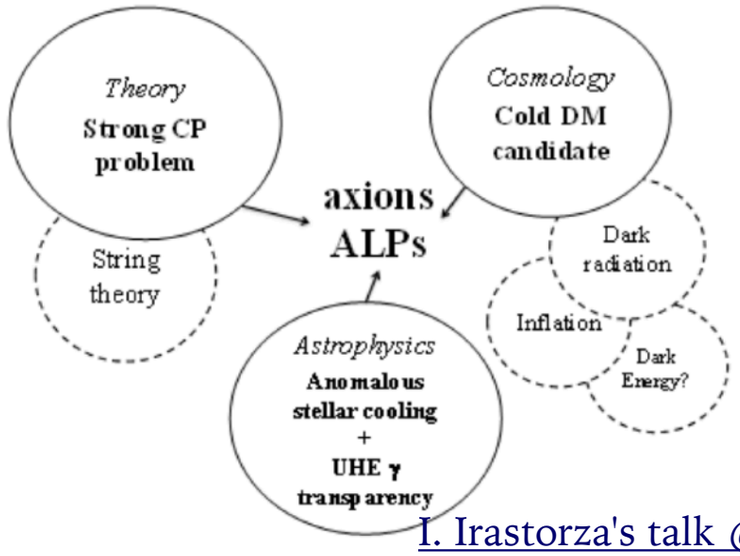
Note: not mentioning sterile-neutrino-like DM for lack of time!

Even lighter DM: axions

SnowMass2021 CF2

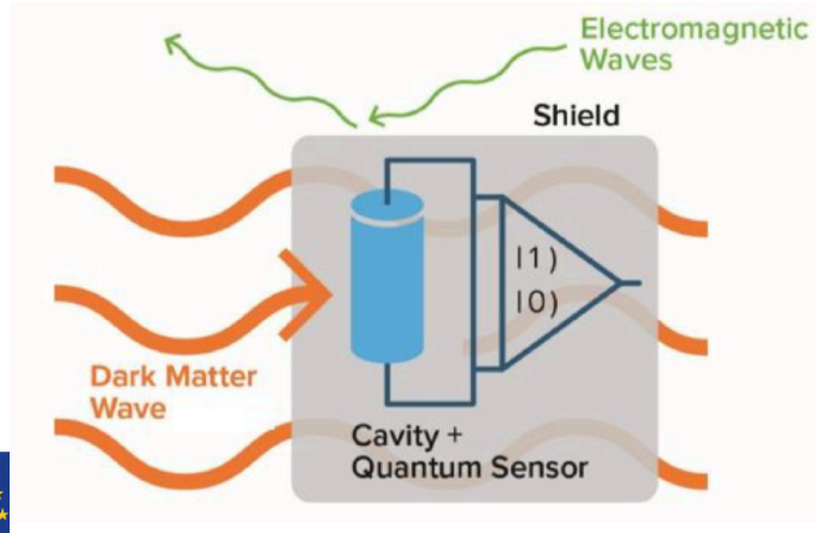
Axions/Axion-Like Particles (ALPs):

example of new particle with inter-field connections, solving more than the DM problem



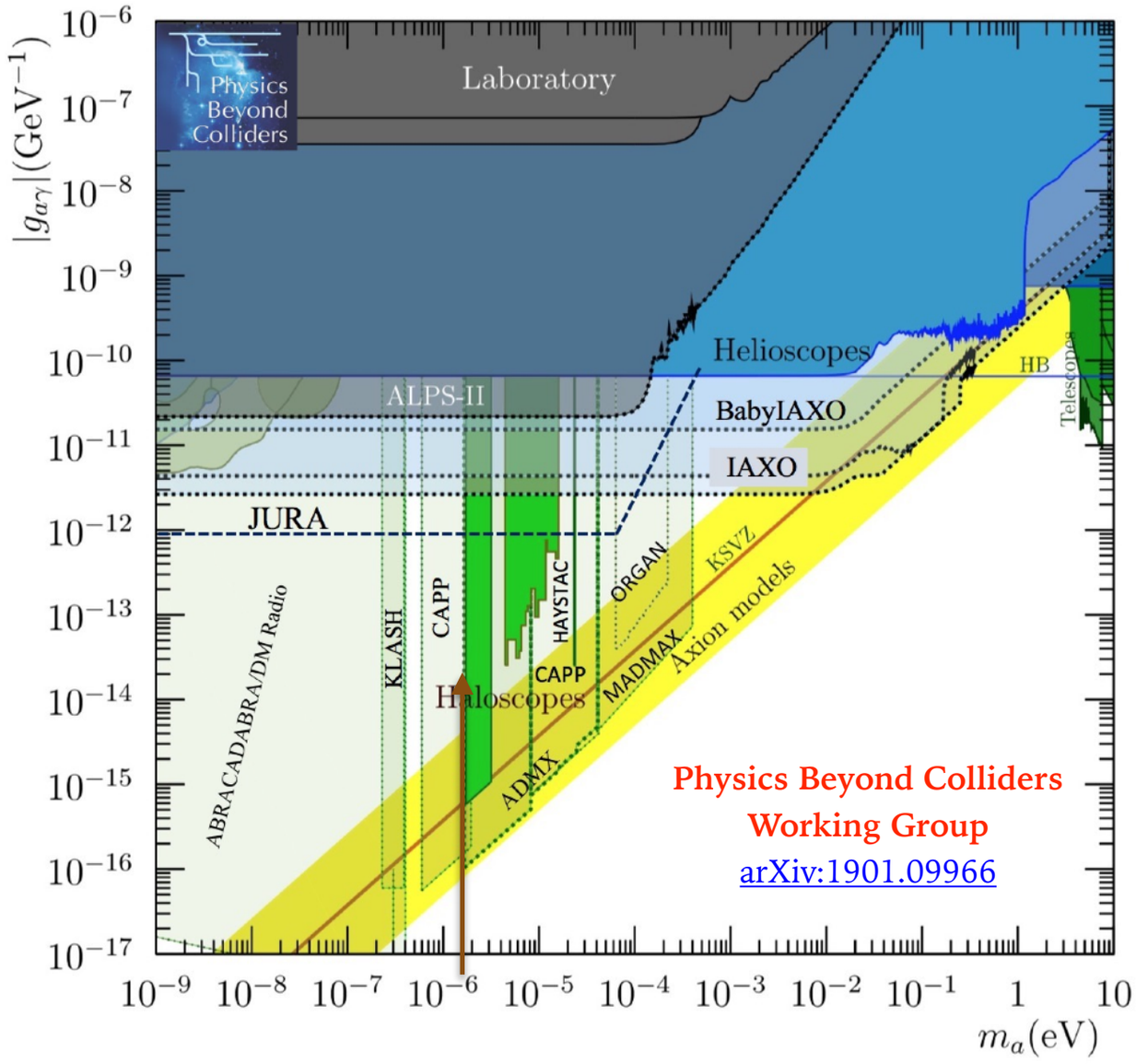
I. Irastorza's talk @ EPS-HEP 2019

New technologies (small experiments) now available



EXPERIMENT

BRN Report



Physics Beyond Colliders Working Group

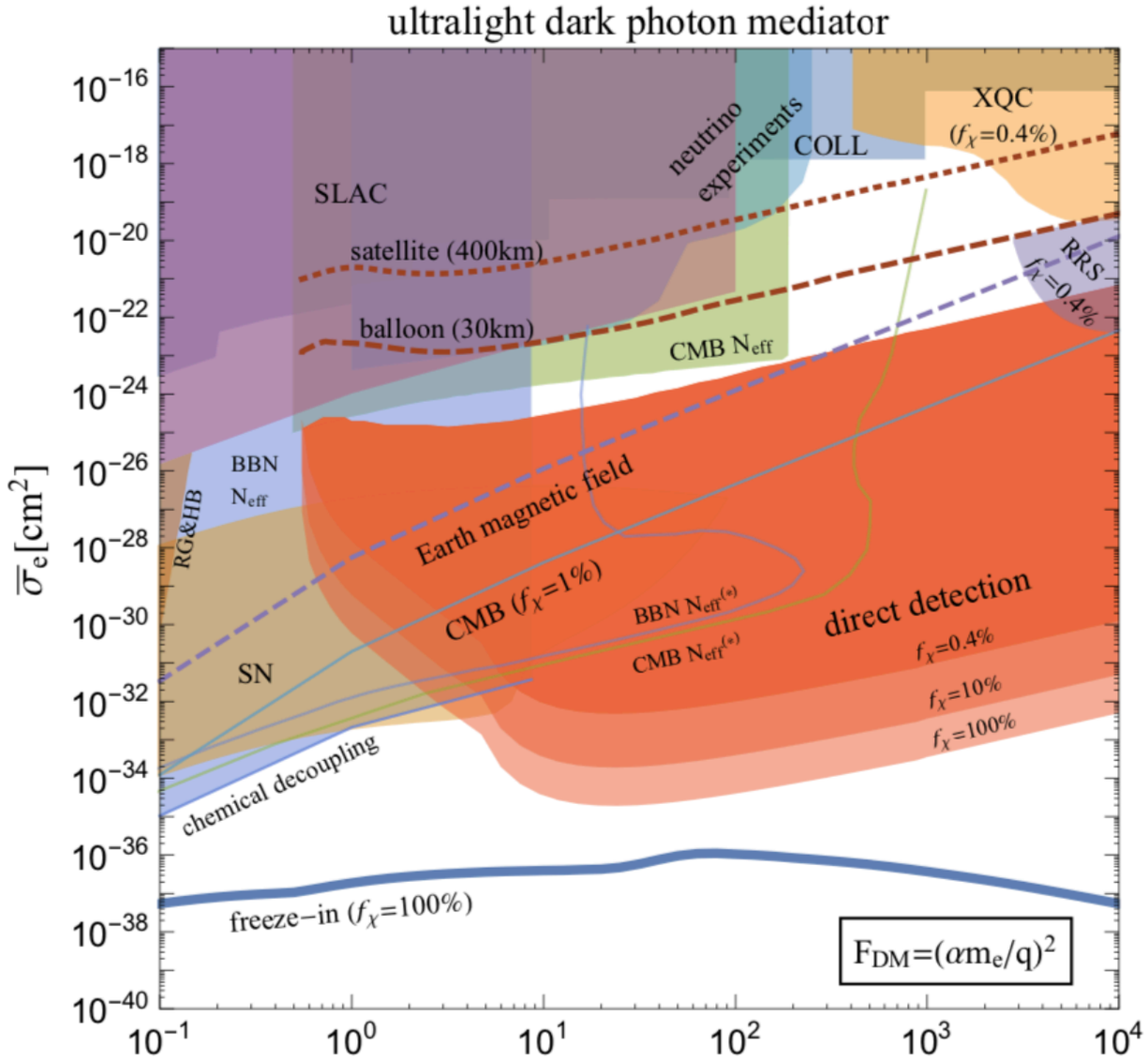
arXiv:1901.09966

New: sensitivity of haloscopes to "dark matter" axions

Looking *up* (to hints from astrophysics & more)

"Looking up" as a consequence of "looking left":

change of paradigm from "DM == invisible particles"



https://arxiv.org/abs/1905.06348

potentially low-mass & "strongly interacting" DM particles will

- interact with **detectors**
  - need to take this into account for collider searches!
- interact with **atmosphere & earth**
  - use/send detectors higher up!
- leave **astrophysical signals**
  - Supernova (SN), BBN, CMB...
- be part of more **complex dark sectors**
  - with interesting collider / cosmological signatures!

SnowMass2021 CF1,7
SnowMass2021 EF9
SnowMass2021 TF

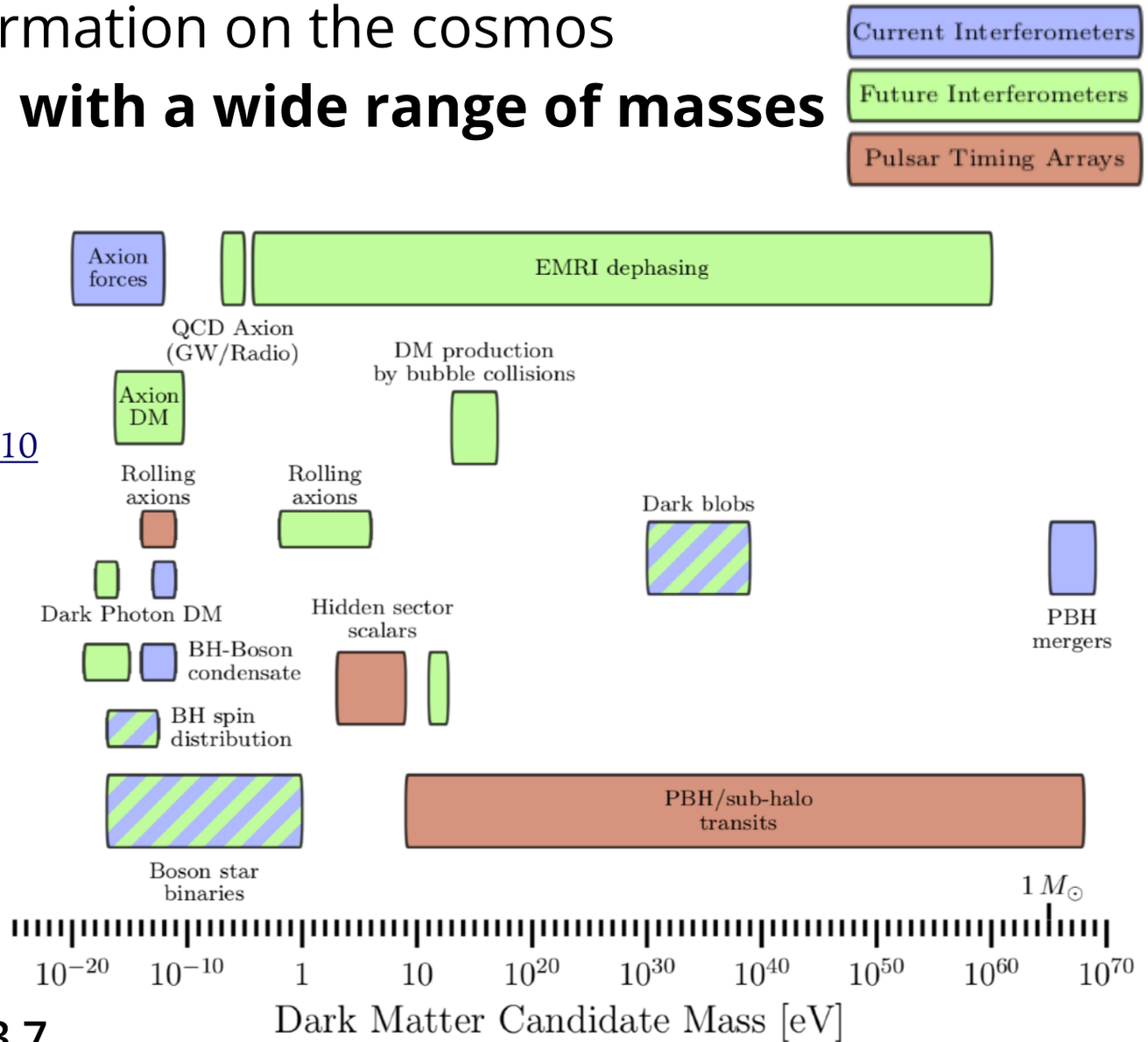
Looking *right* (to much more massive objects)

G. Losurdo's talk @ JENAS 2019

Gravitational wave experiments / **multimessenger** astronomy:

- Revolutionary combination of information on the cosmos
- experiments can shed light on **DM with a wide range of masses**

arXiv:1907.10610



SnowMass2021 CF3,7

Conclusions and take-home points

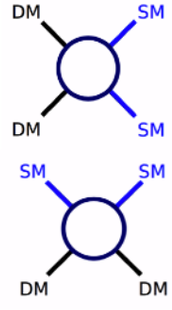
The search for Dark Matter, even for WIMPs alone, is **not yet over…**

…it's the perfect time to **search everywhere, including for the rare & unusual**

much larger datasets,
"precision searches"
at colliders and accelerators

new / improved detectors & techniques,
backgrounds & analysis tools

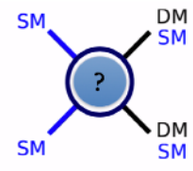
Now and future: essential **physics complementarity** across different experiments



cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
accelerators / colliders



but also on **tools**, given **shared theory, experimental & computing challenges**

Snowmass: one of the best ways to **help steer**
how DM discoveries will happen in the next 50 years!

Thanks for your attention (and thanks to the Early Career scientists who worked to produce many of these results)!

Some of the ATLAS DM results: the DARKJETS Team (Lund)

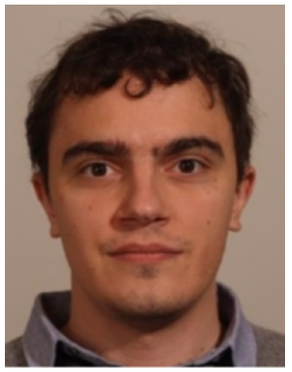
William Kalderon, Eric Corrigan, Eva Hansen, Per Alexander Ekman (not pictured: Jannik Geisen)

Project acronym	DARKJETS
Project	Discovery strategies for Dark Matter and new phenomena in hadronic signatures with the ATLAS detector at the Large Hadron Collider
Researcher (PI)	Caterina Doglioni
Host Institution (HI)	LUNDS UNIVERSITET
Call Details	Starting Grant (StG), PE2, ERC-2015-STG

Direct Detection plots: Isabelle John (Lund, now Stockholm)

with Emma Tolley, Antonio Boveia, Jocelyn Monroe, Maria Benito

Scalar mediator plots: Marco Rimoldi (DESY)



with Francesca Ungaro, Hideki Okawa, Oleg Brandt

Indirect Detection plots: Boyu Gao (OSU)

(still working on DM for Snowmass!)

with Emma Tolley, Linda Carpenter, Antonio Boveia, Christoph Weniger