Another perspective on Dark Matter

CATERINA DOGLIONI - LUND UNIVERSITY

Inputs, discussion and inspiration:
EPPSU PPG BSM, PPG DM, PPG Higgs, ATLAS Collaboration, A. Boveia, O. Brandt, C. Fitzpatrick, U. Haisch, P. C. Harris, I. John, J. Jaeckel, G. La Rana, Matt McCullough, F. Petricca, M. Benito, T. Montaruli, J. Monroe, E. Rossi, M. Rimoldi, R. Poettgen, E. Tolley, F. Ungaro, T. Åkesson

I would also like to thank the Galileo Galilei Institute for the hospitality & for many of the ideas presented here

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

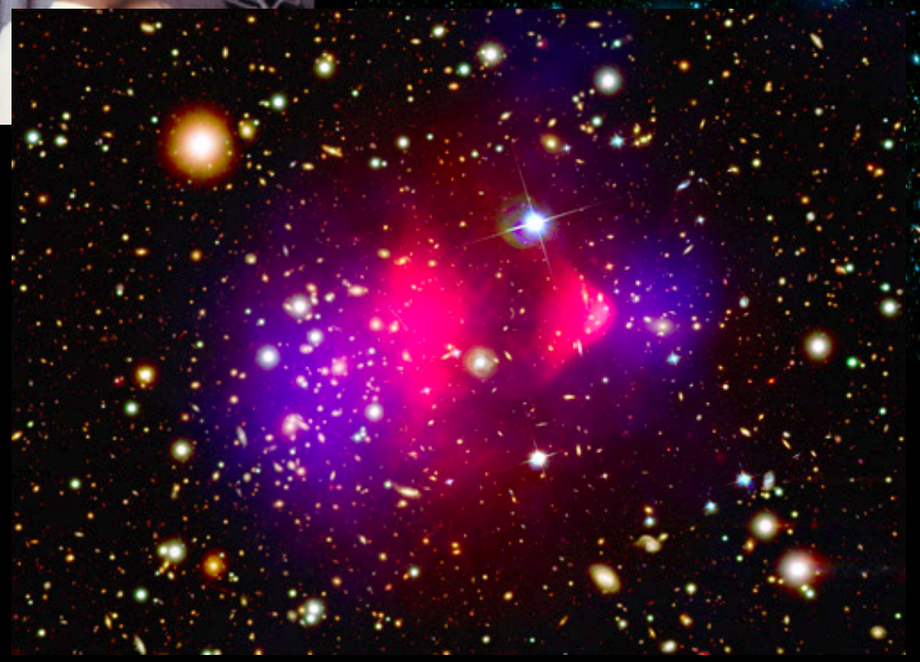
Outline

What do we know about **dark matter**? [quite a lot, after Jocelyn Monroe's talk!]

it is dark

it is dark

it has mass

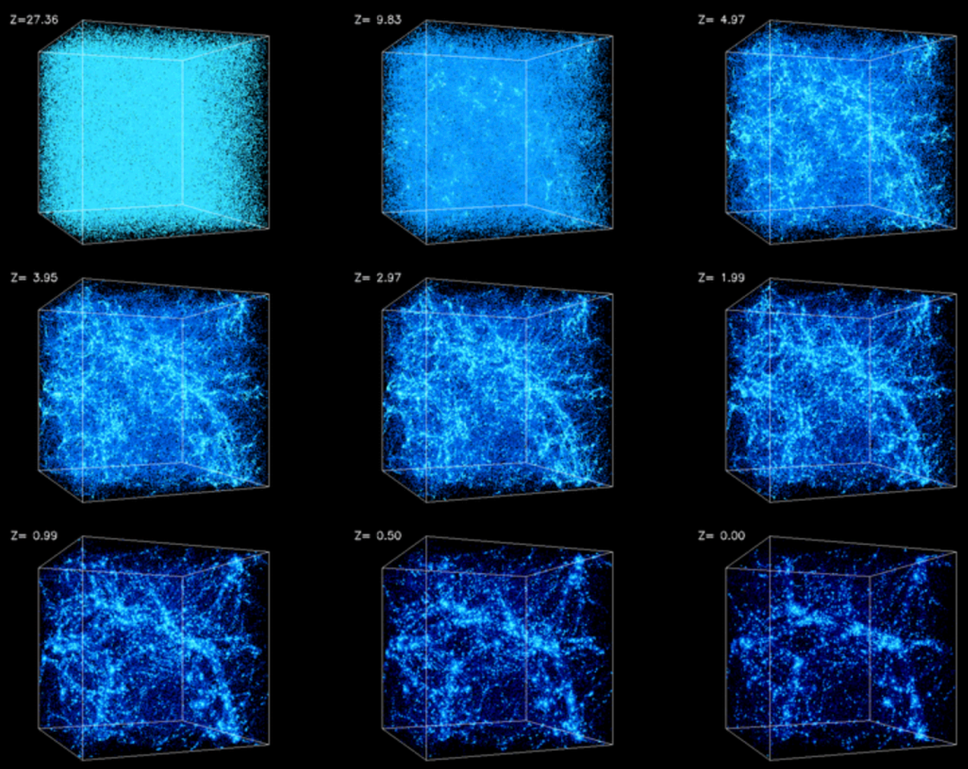


Images: NASA/ESA

it has mass

Images: NASA/ESA

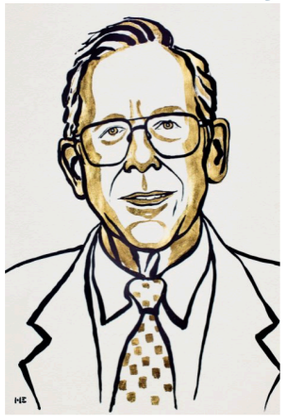
it is dark



it is needed to describe
galaxy structure formation

simulations were performed at the National Center for Supercomputer Applications by A. Kravtsov and A. Klypin.

The Nobel Prize in Physics 2019

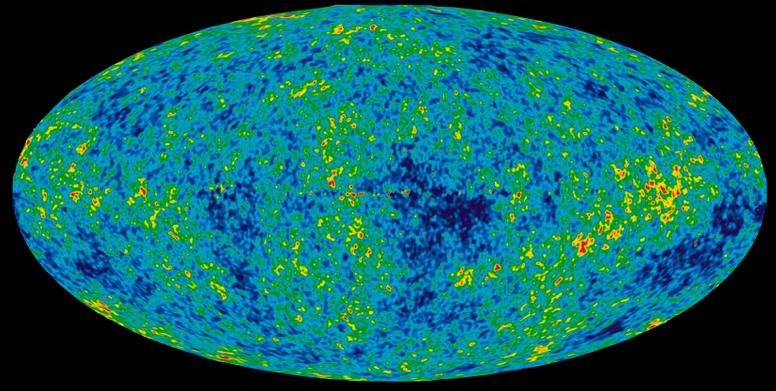


Ill. Niklas Elmehed. © Nobel Media.

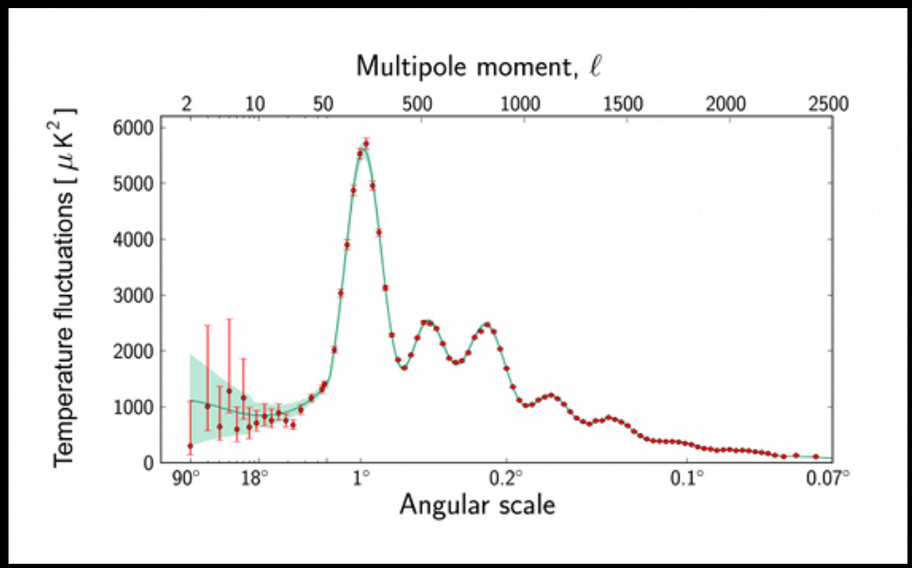
James Peebles

Prize share: 1/2

"for theoretical discoveries in physical cosmology"



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



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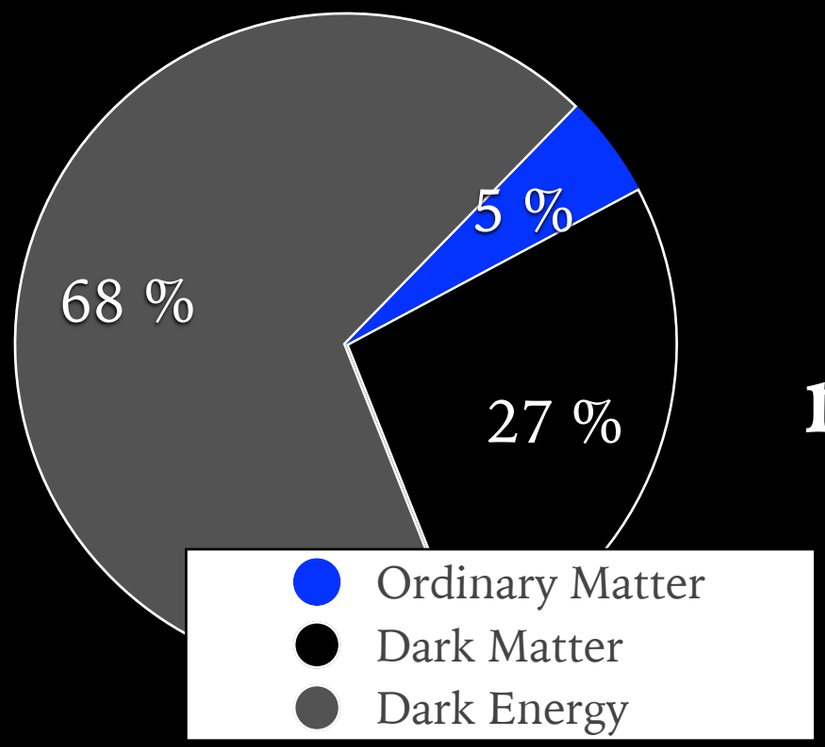
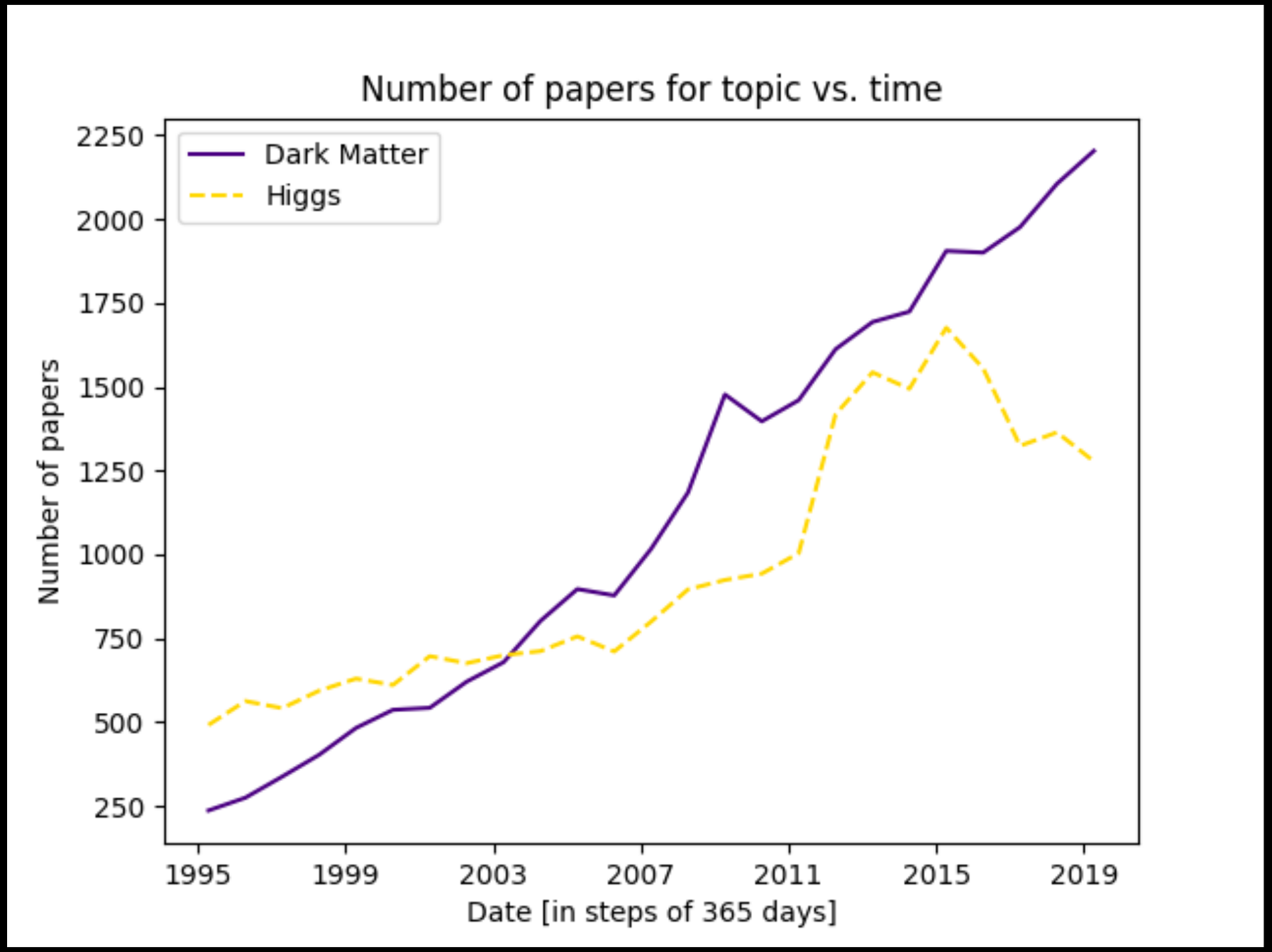


it constitutes most of the matter in the universe

many are writing about it



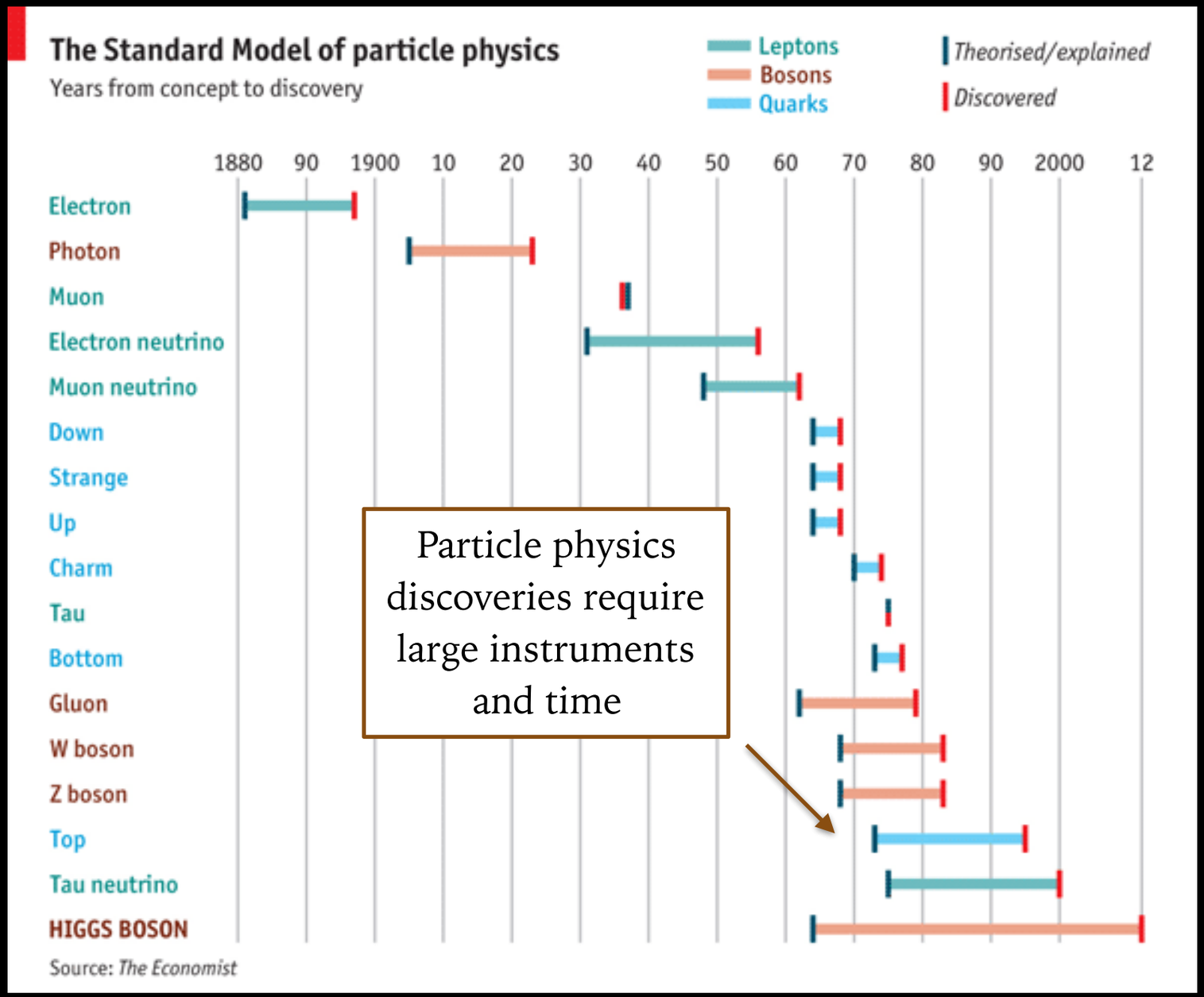
https://benty-fields.com/trending

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

it may be a new particle not yet in the Standard Model…

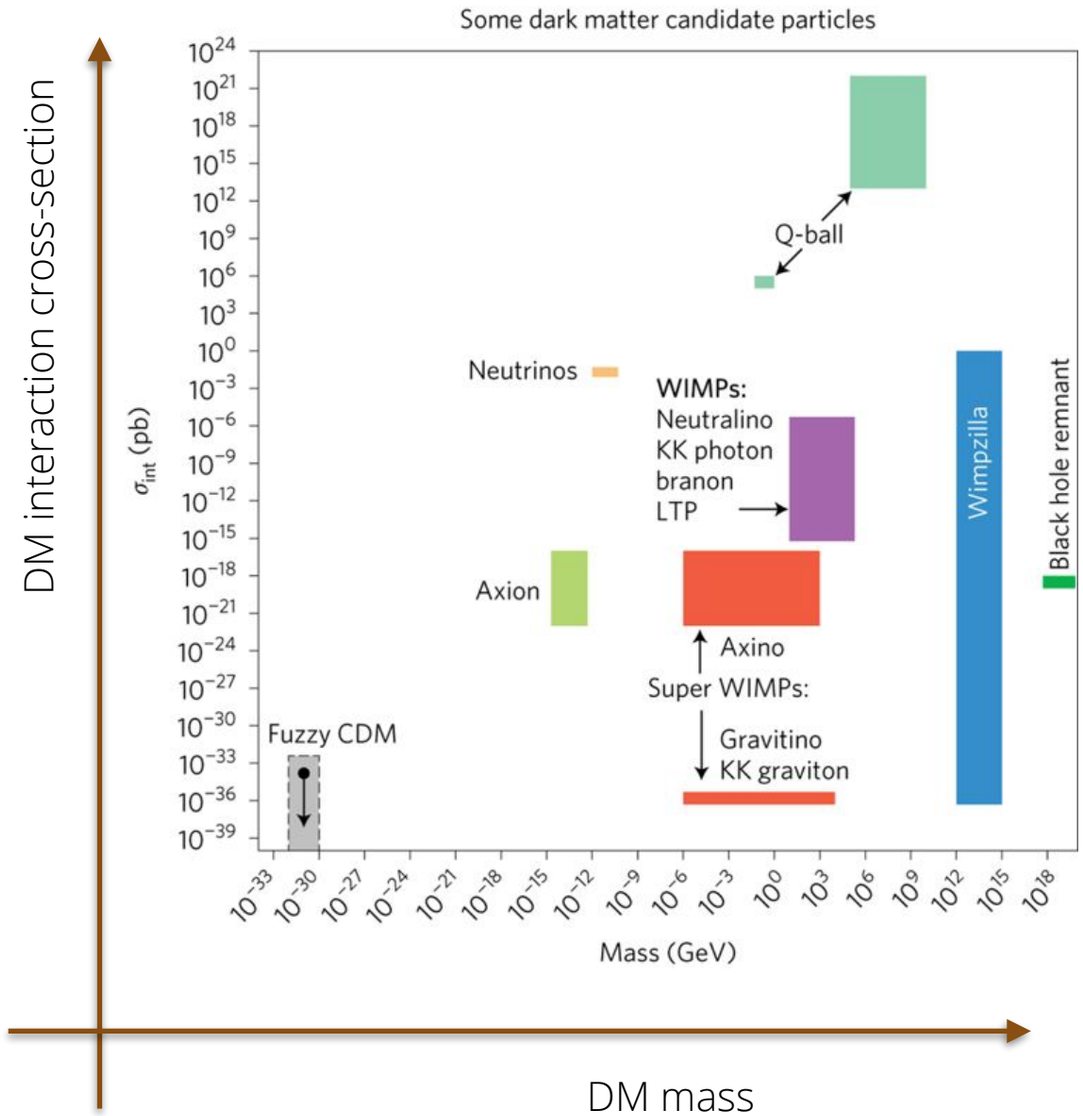


…but the only hints we have about it are from astrophysics → synergy needed

Outline

Topics selected for this talk:

1. A tour of complementarity in dark matter experiments, for Weakly Interacting Massive Particles and beyond



Disclaimer: not mentioning alternative gravity theories, focusing on DM = massive objects

Outline

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1. A tour of complementarity in dark matter experiments, for Weakly Interacting Massive Particles and beyond

2. How to make the most of the data:
   - data acquisition & selection
   - reinterpretation of results

Outline

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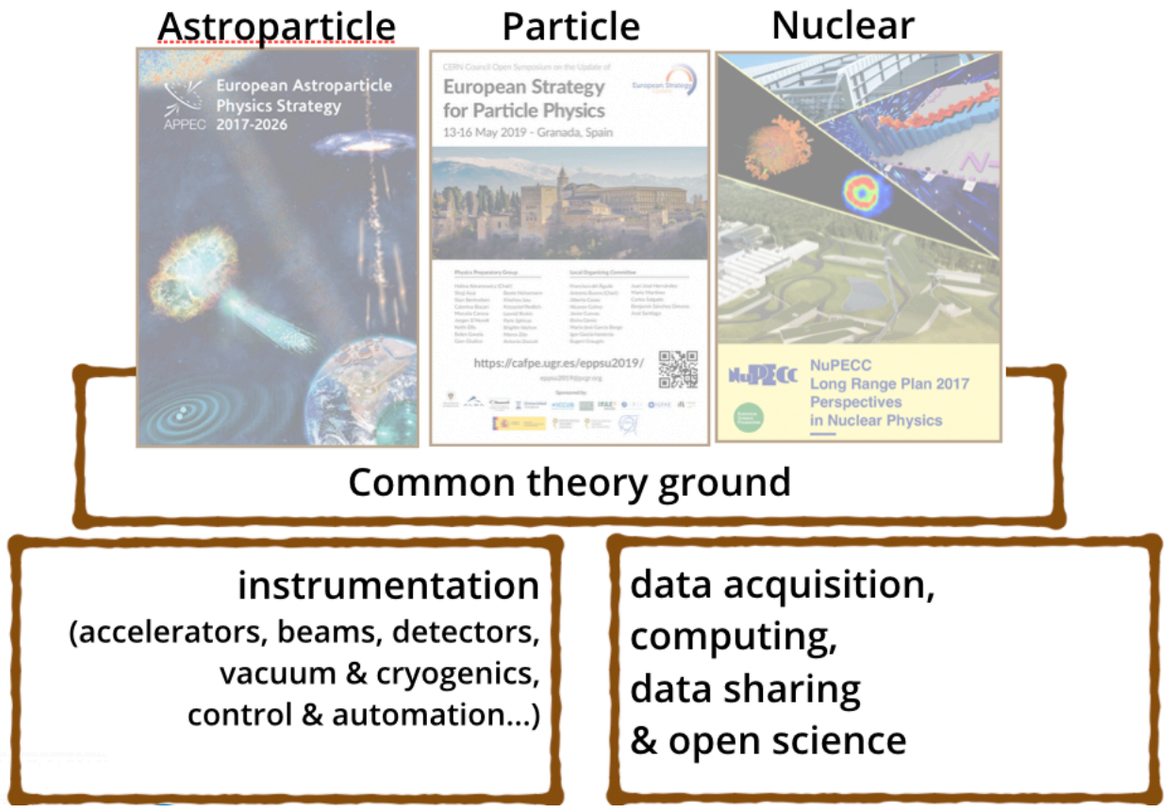
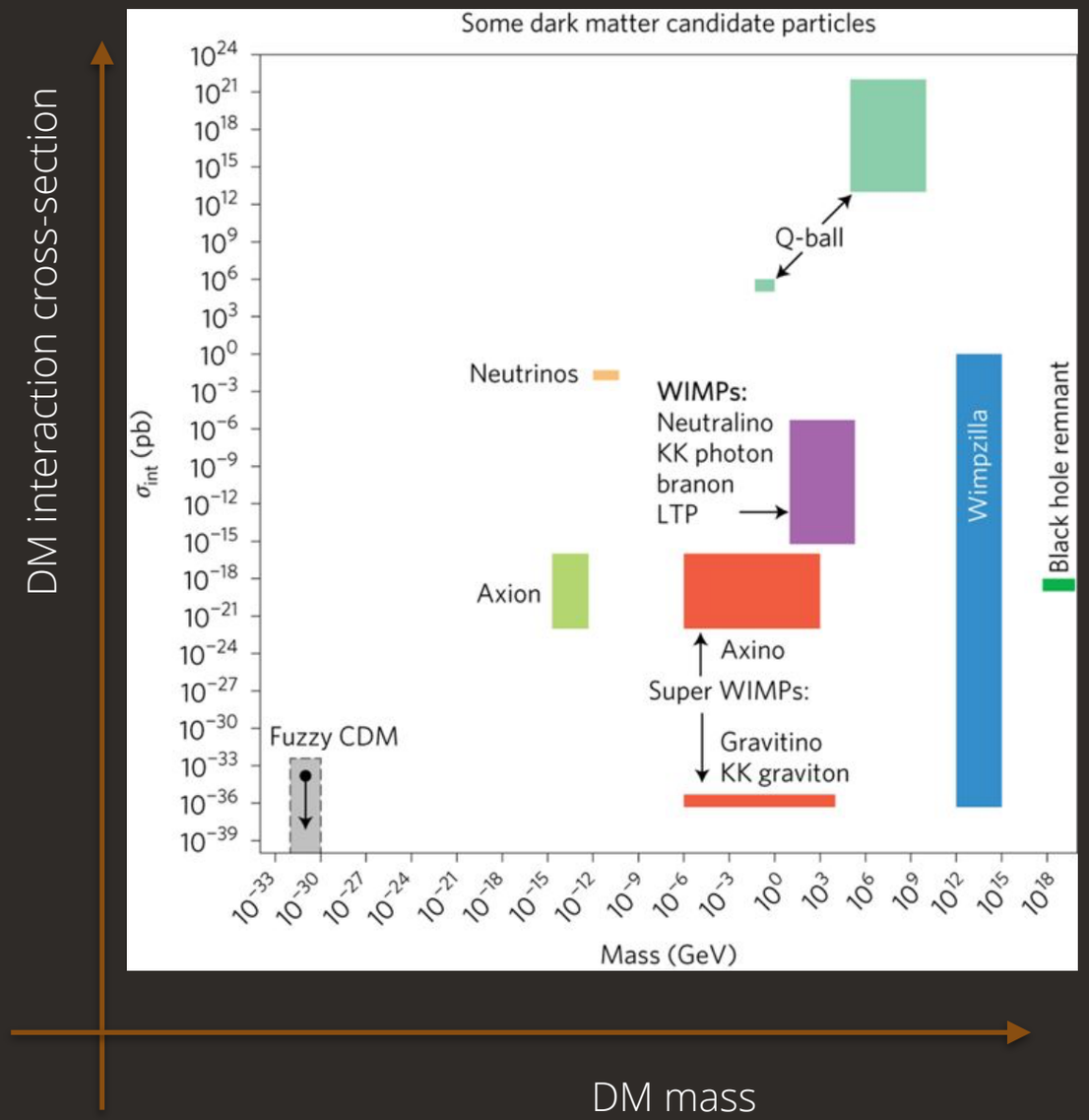
1. A tour of complementarity in dark matter experiments, for Weakly Interacting Massive Particles and beyond

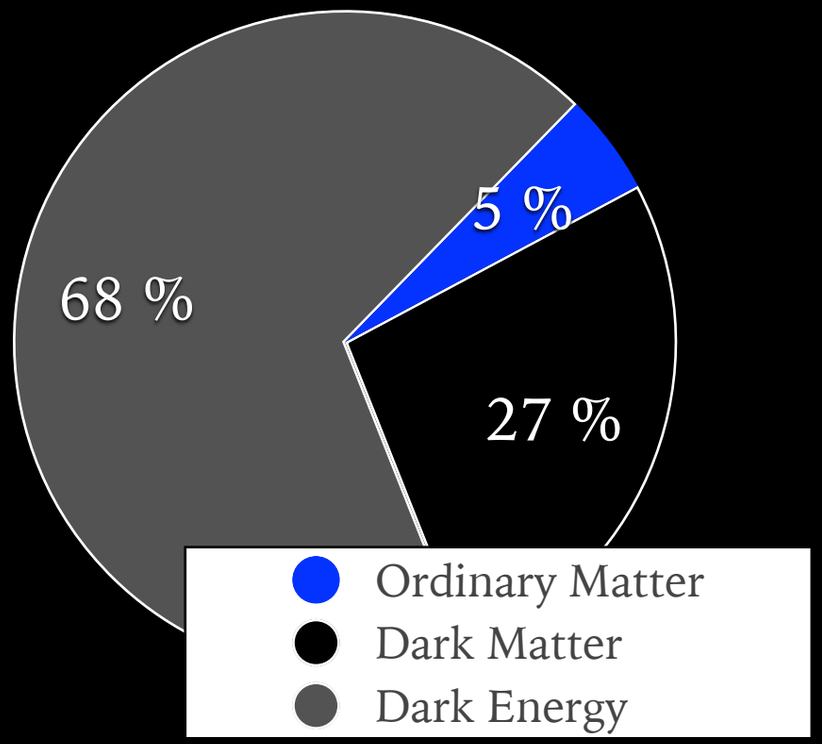
2. How to make the most of the data:
   - data acquisition & selection
   - reinterpretation of results

3. Outlook & wishlist for next steps



WIMP dark matter & beyond





Dark Matter

constitutes
most of the matter
in the universe

↓

relic density

This relic density can be explained with

a new particle

- that **interacts** only **weakly** with known matter
- with **mass** in the range of sensitivity of current experiments

(Weakly Interacting Massive Particle)

Complementarity for WIMP searches

R. Durrer's talk

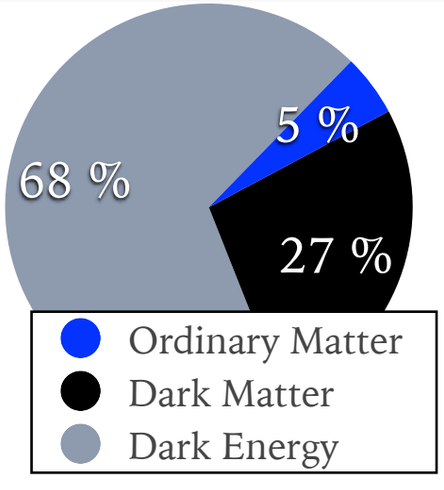
WIMP solution, guided by **thermal relic density**:

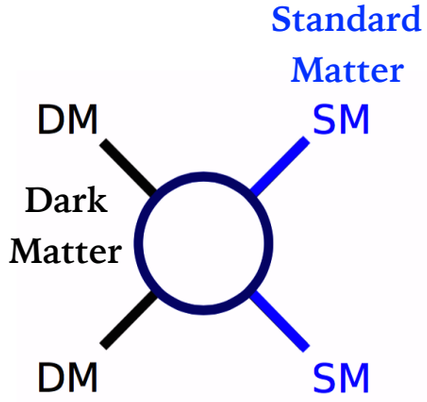
Weakly Interacting Massive Particles

=

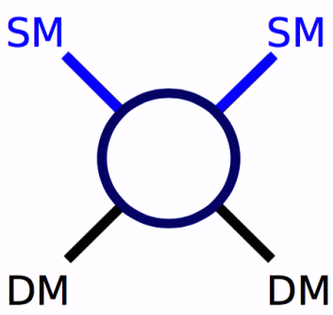
Dark Matter particles invisible to detectors,

with masses at the **TeV scale**

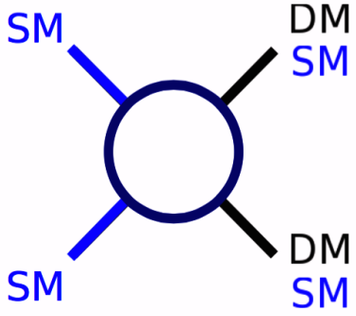




Indirect Detection

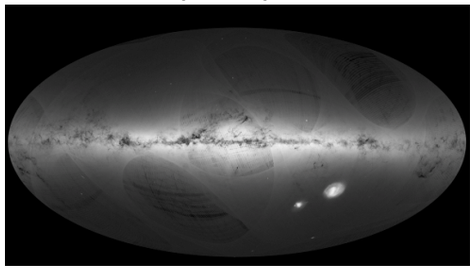


Direct Detection

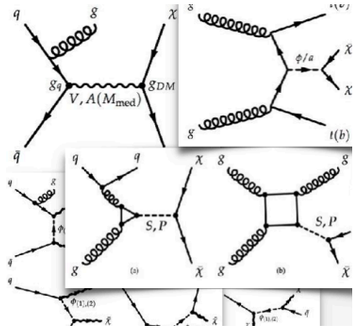


Colliders

Credit: ESA/Gaia/DPAC.



Astrophysics



Theory

Complementarity for WIMP searches

WIMP solution, guided by **thermal relic density**:

Weakly Interacting Massive Particles

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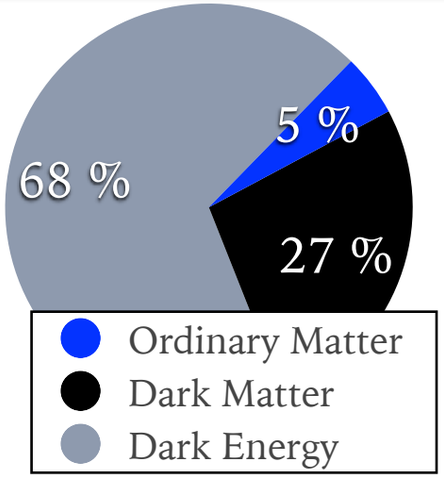
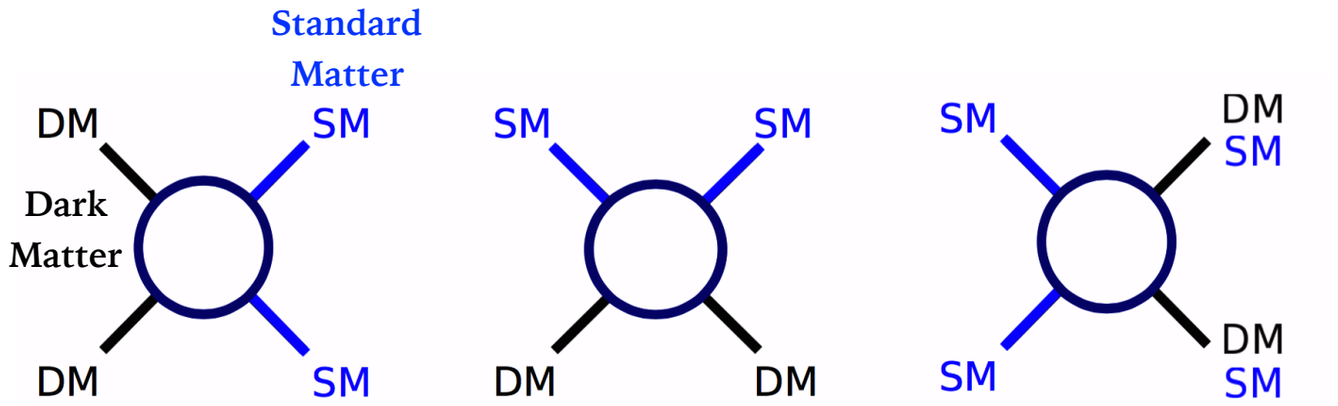
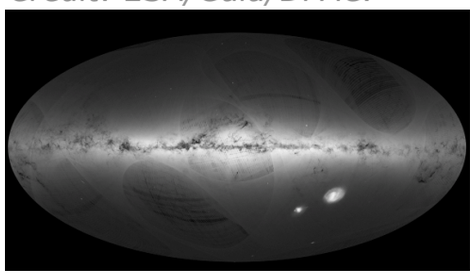
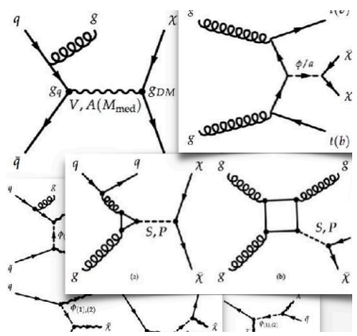




Indirect Detection | Direct Detection | Colliders

Credit: ESA/Gaia/DPAC.





Astrophysics | Theory

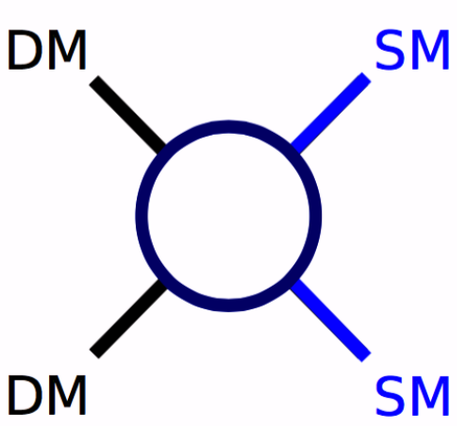
Complementary experimental strategies & inputs

All needed, given what we don't know about DM!

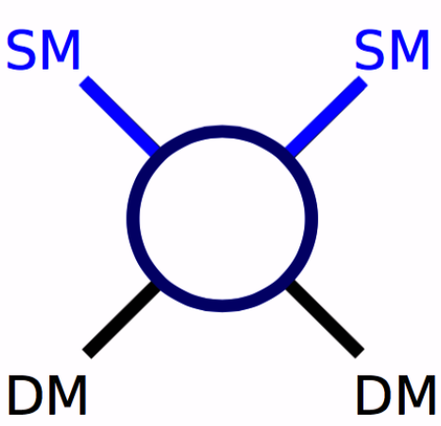
Colliders, direct and indirect detection

Big Question at Granada symposium:
How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

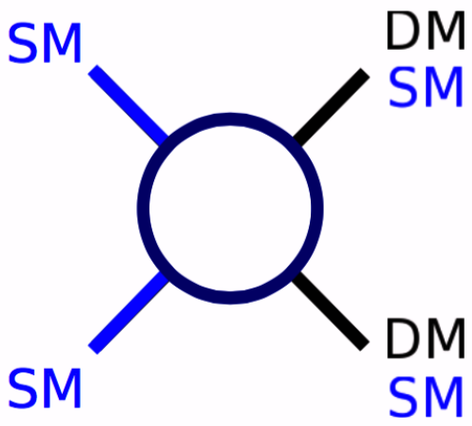
- Why we need complementarity:
  - DD/ID can discover DM with cosmological origin



Indirect Detection



Direct Detection

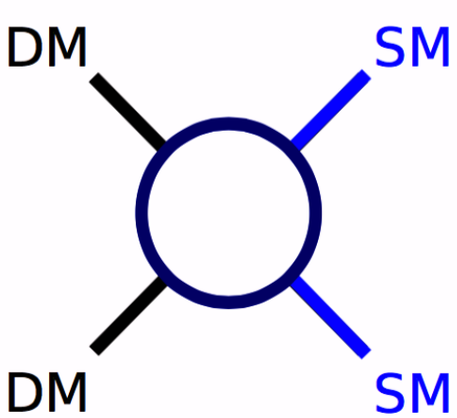


Particle Colliders

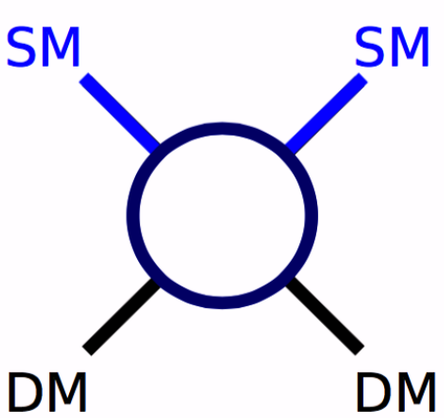
Colliders, direct and indirect detection

Big Question at Granada symposium:
How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

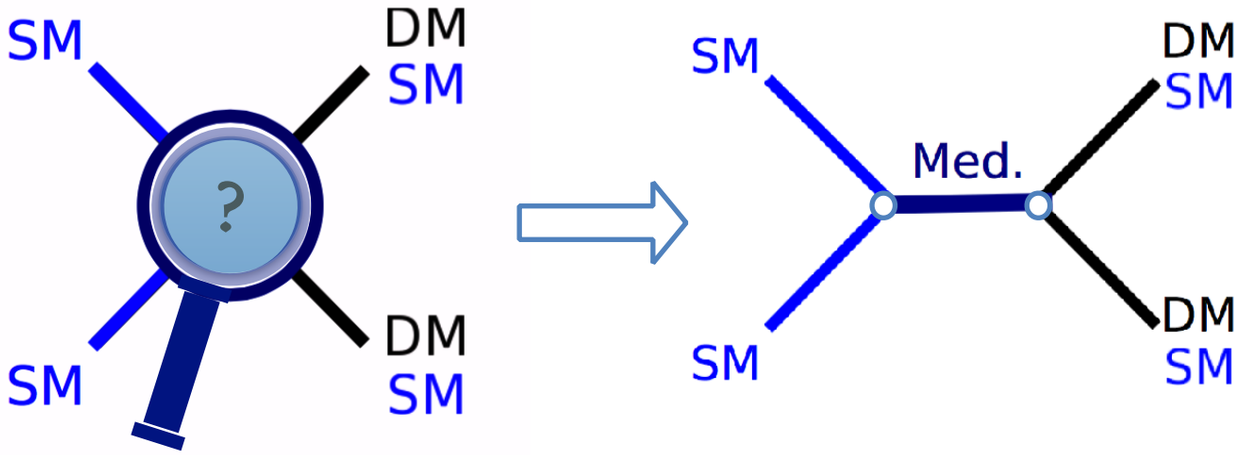
- Why we need complementarity:
  - DD/ID can discover DM with cosmological origin
  - Colliders can produce DM and probe the dark interaction



Indirect Detection



Direct Detection



Particle Colliders

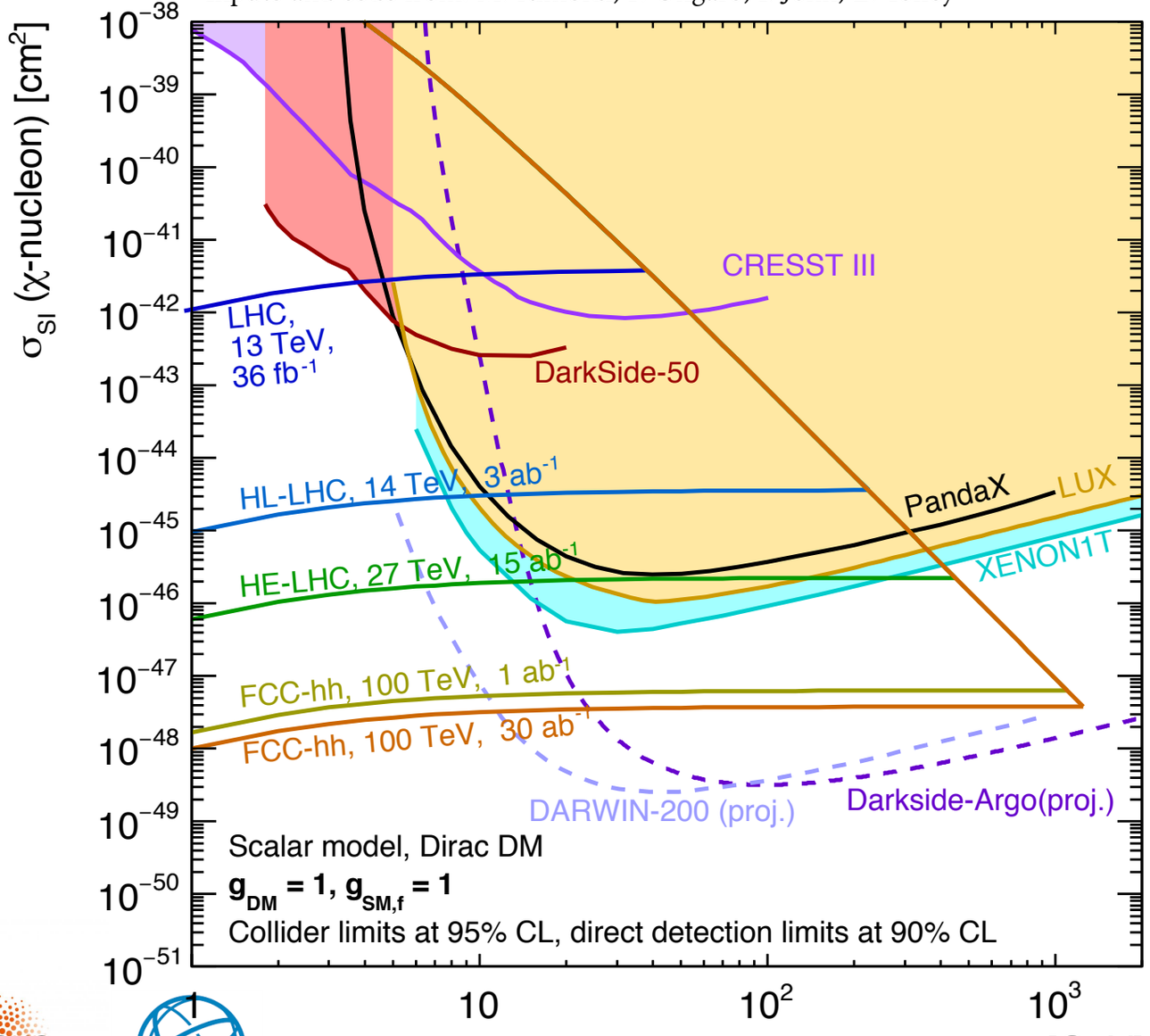
Example of collider/direct detection complementarity

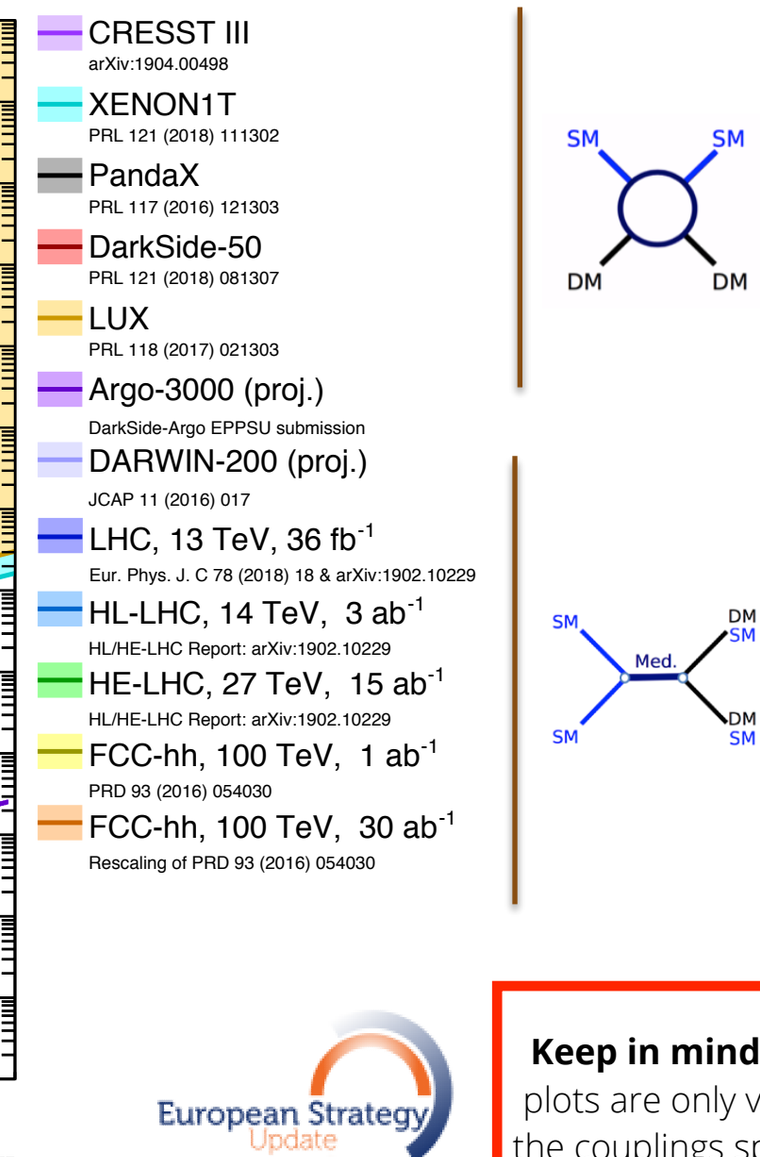
- **Collider constraints** on simple models of DM can be compared to **direct detection** ones

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\ {\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2 .$$

arXiv:1603.04156

Inputs and code from: M. Rimoldi, F. Ungaro, I. John, E. Tolley





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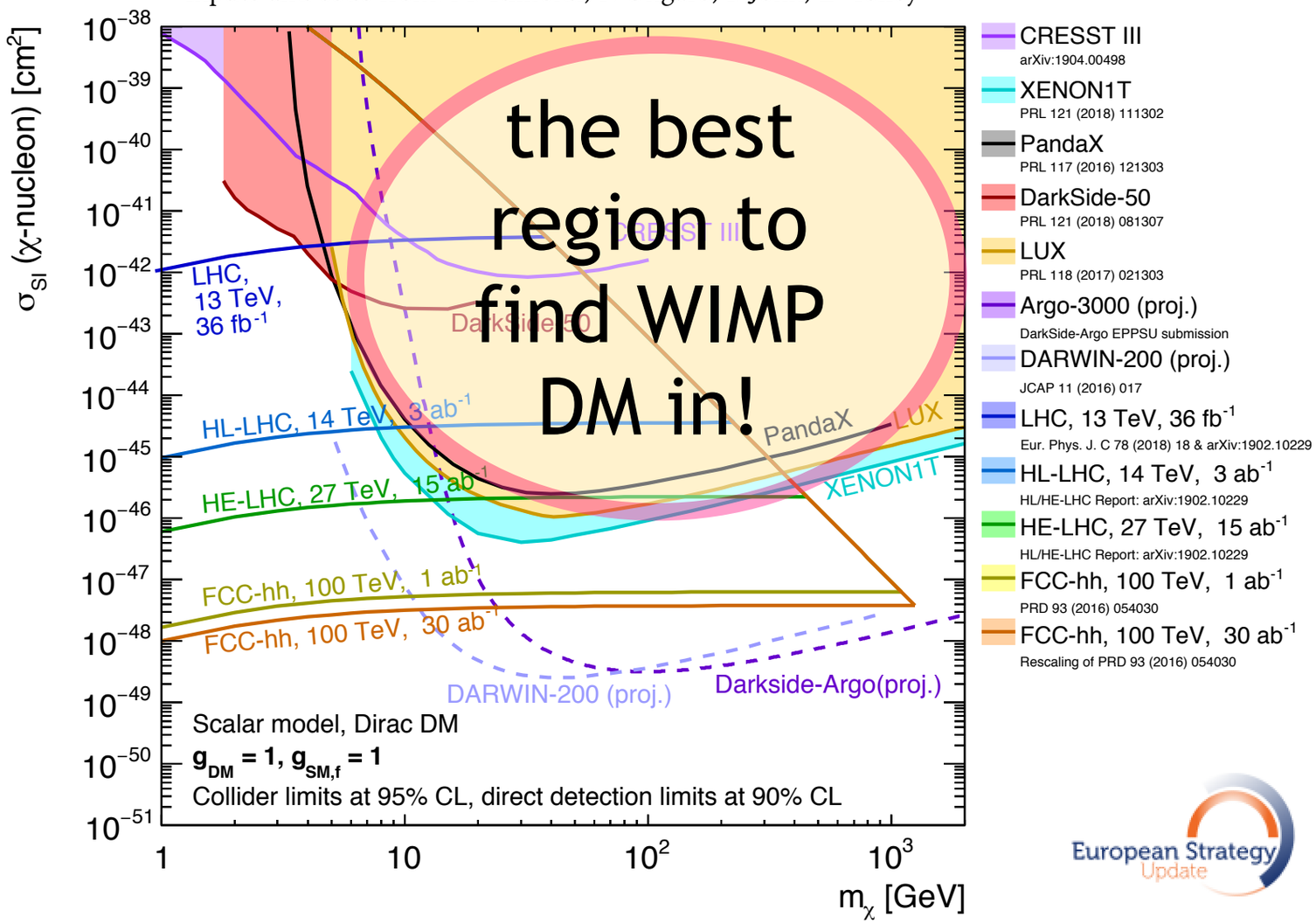
Keep in mind: these plots are only valid for the couplings specified, in the limited space of a benchmark model!

A popular slide: scalar mediator between SM and DM

Synergy: complementary reach for future colliders and direct detection

Inputs and code from: M. Rimoldi, F. Ungaro, I. John, E. Tolley



- **Collider discovery** of invisible particle needs **confirmation of cosmological origin** from DD/ID

- **DD/ID discovery** needs collider **understanding of nature of interaction**

- A **future collider program** that increases sensitivity to invisible particles **coherently with DD/ID** serves these purposes

European Strategy Update

- Synergies also in non-WIMP DM, for DD and beam dump experiments: see later slides for discussion on **Physics Beyond Colliders WG**

European Research Council
Established by the European Commission

ATLAS EXPERIMENT

Increasing understanding between communities

Often said about Direct (Indirect) Detection results: ”DD experiment subject to astrophysical uncertainties, how much do they matter when comparing to collider searches?” Note: collider searches (not displayed) have uncertainties too

Isabelle John, Lund University Master’s thesis, with M. Benito’s help and inputs, updates in M. Benito's talk @ GGI 2019

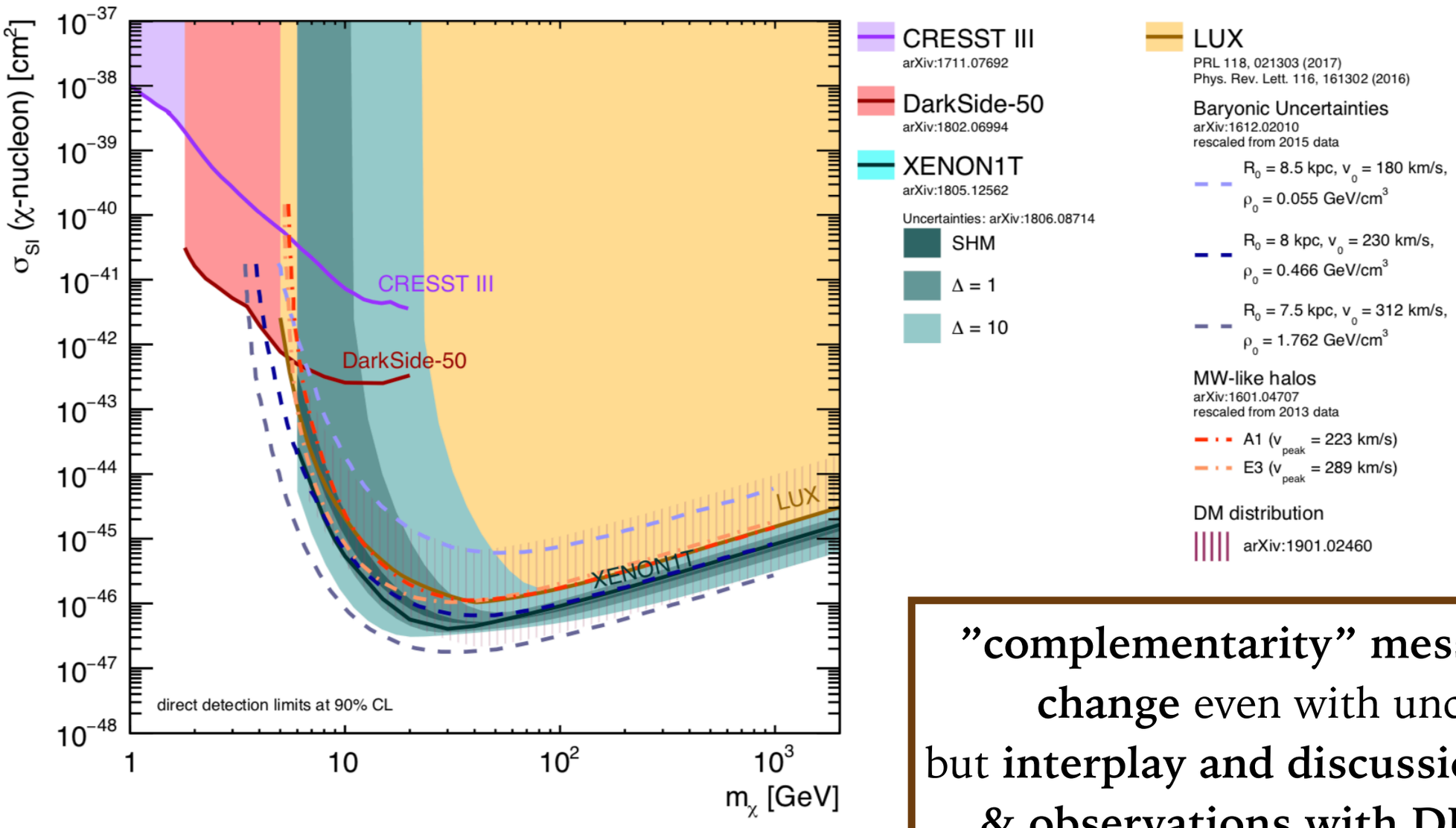


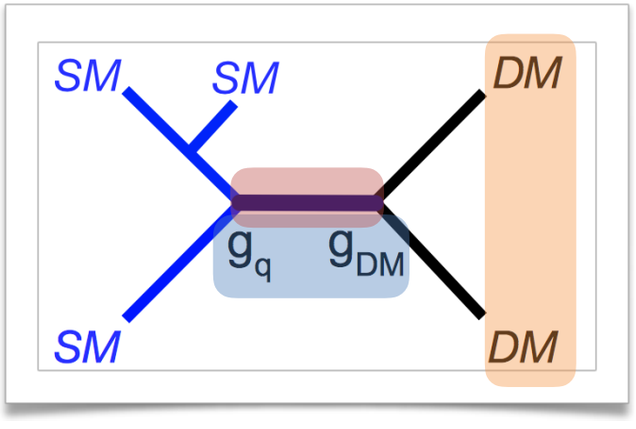
Figure 5.1: Exclusion plot with direct detection searches, including all deviations and uncertainty bands for direct detection limits.

”complementarity” message does not change even with uncertainties,
but **interplay and discussion astro theory & observations with DD/ID needed**

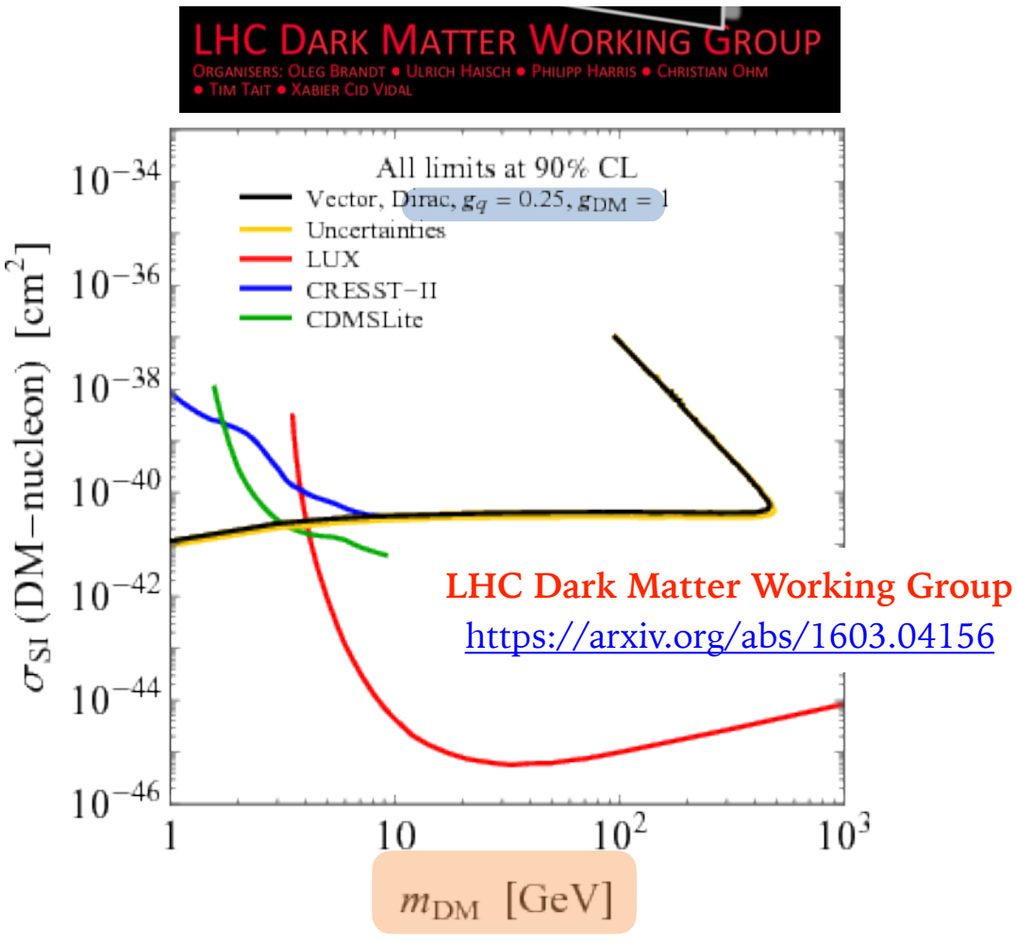
Increasing understanding between communities

Often said about collider results: "Collider results always require a model to compare with DD/ID, how much do model assumption matter?"

Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**



For more thoughts on upper bounds to collider sensitivity:
arXiv:1810.07705 and DMWG meeting June 2017



Possible solution: model/parameter scans…

Wish: let's find a platform for a common **discussion forum** that connects **colliders, direct and indirect detection** [see also: Phystat 2019 @ OKC, APPEC news]

Direct detection: looking *down* (to rarer WIMPs)

- Major updates to direct detection experiments planned
  - in terms of **detectors** F. Petricca's talk @ GGI 2019
  - in terms of **reduction of challenging backgrounds** E. Baracchini's talk @ GGI 2019

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

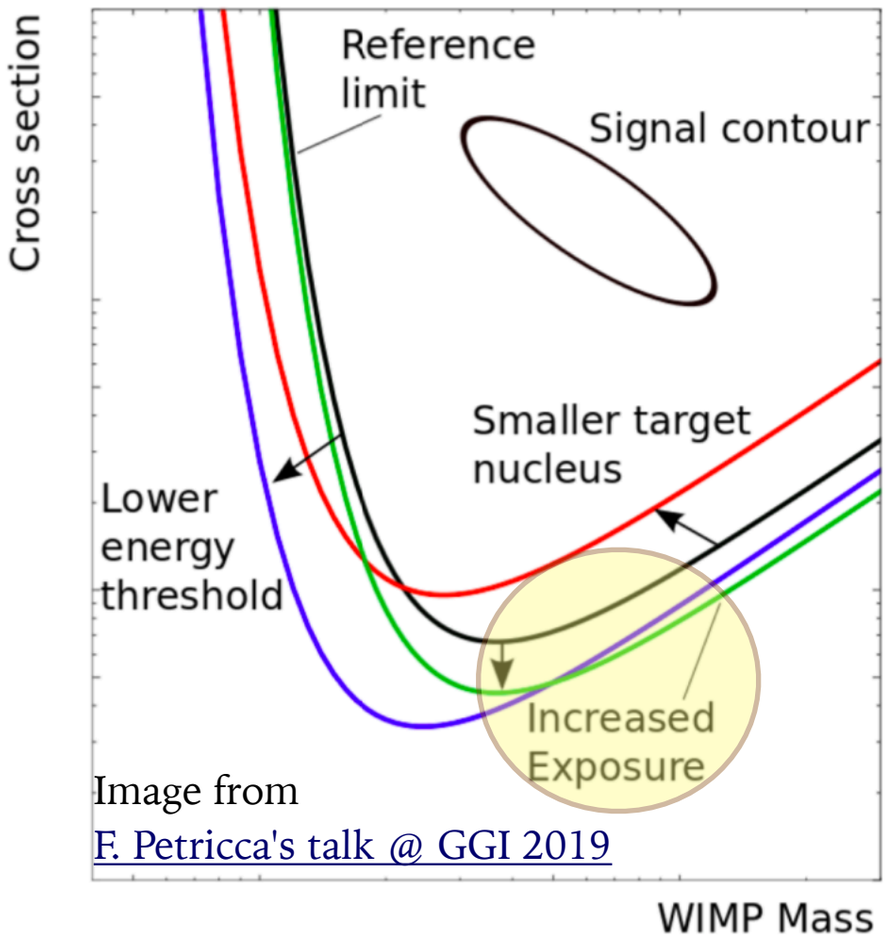


Image from
F. Petricca's talk @ GGI 2019

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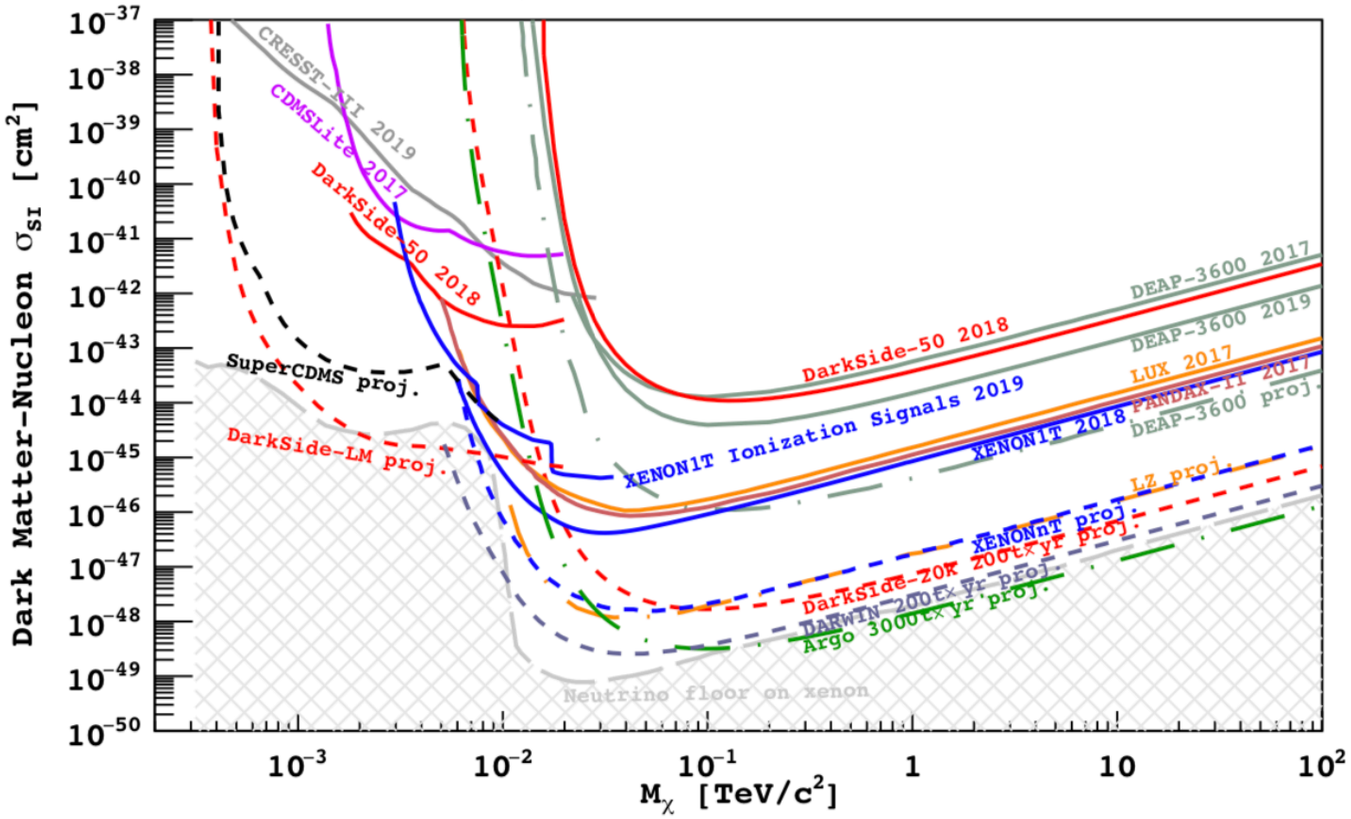
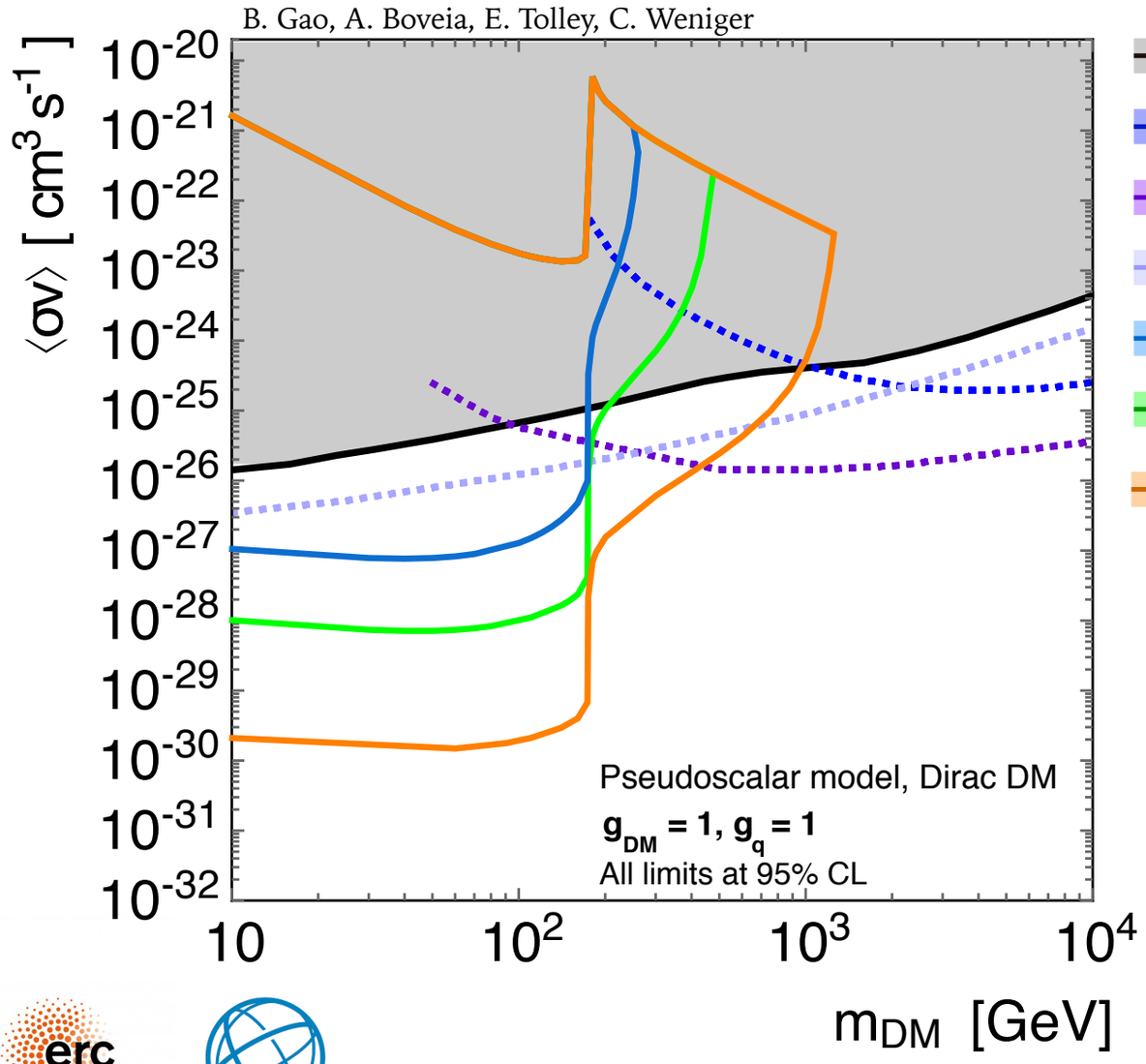
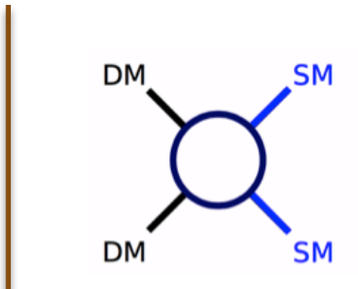


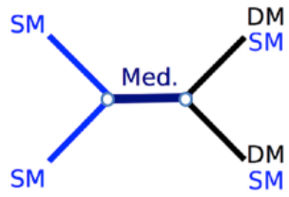
Wish: A common **detector technology forum / test beams** within CERN platform can **benefit the DD community**
[implementation needs agreement & discussion, as we heard yesterday in the Q&A]

Indirect detection: looking *down* (to rarer WIMPs)

- Major updates to indirect detection searches planned
  - in terms of **survey of DM-rich objects** A. Schneider's talk @ GGI 2019
  - in terms of **reduction of challenging backgrounds** F. Calore's talk @ GGI 2019, M. Cirelli's talk @ GGI 2019







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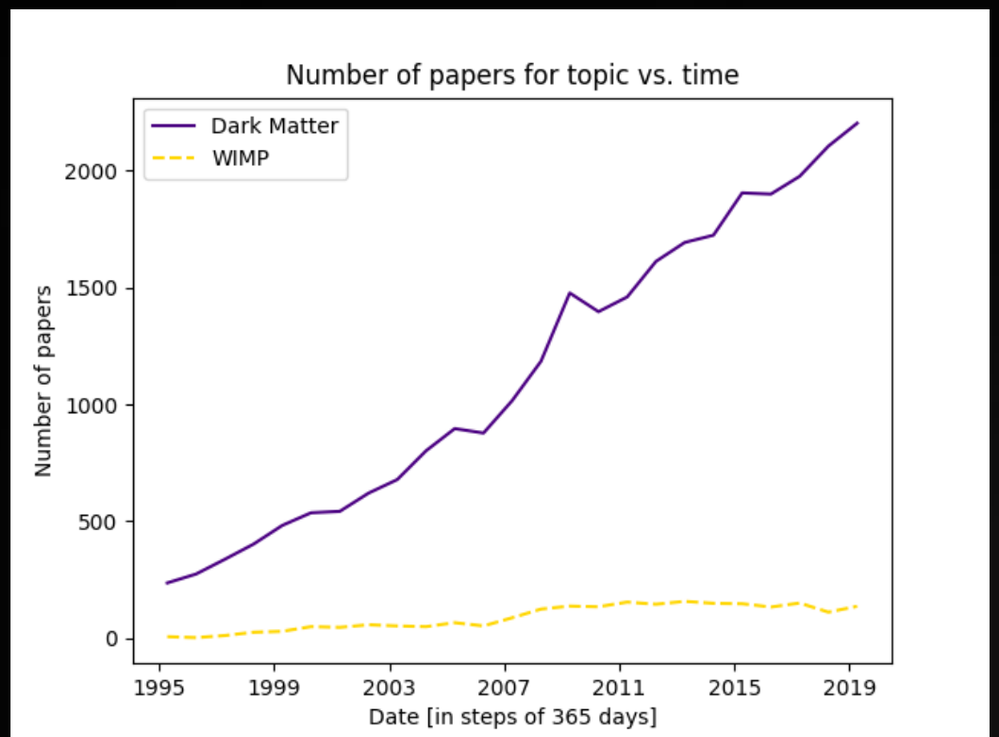
Are we looking everywhere?



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

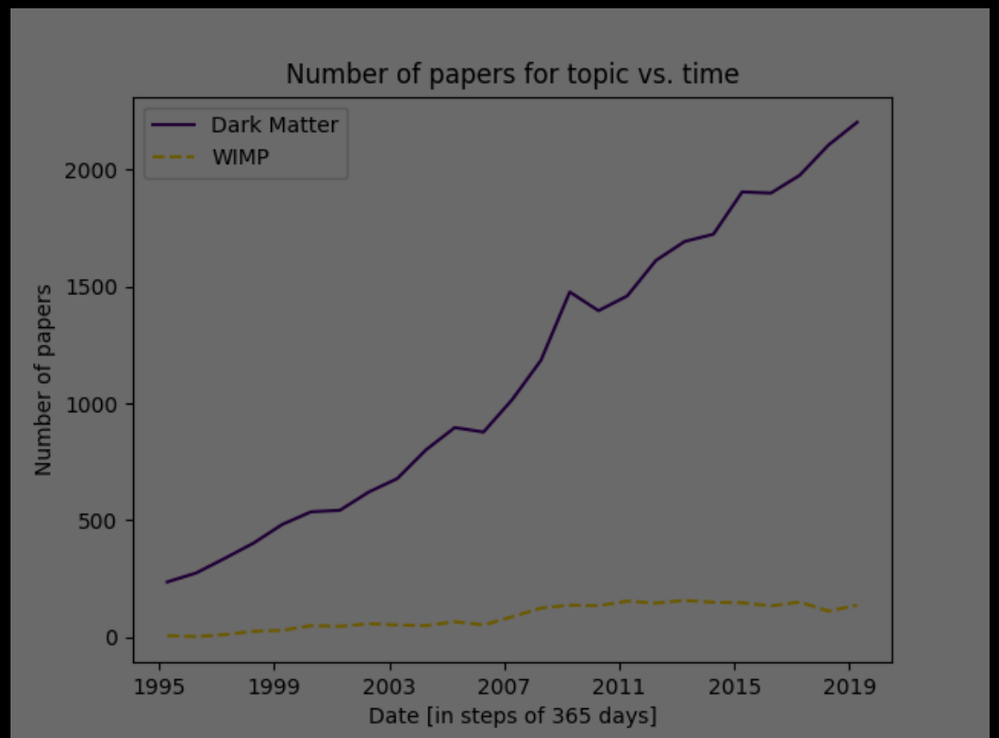
WIMP

Are we looking everywhere?

up: stronger interactions

left: lower masses

right: more massive objects



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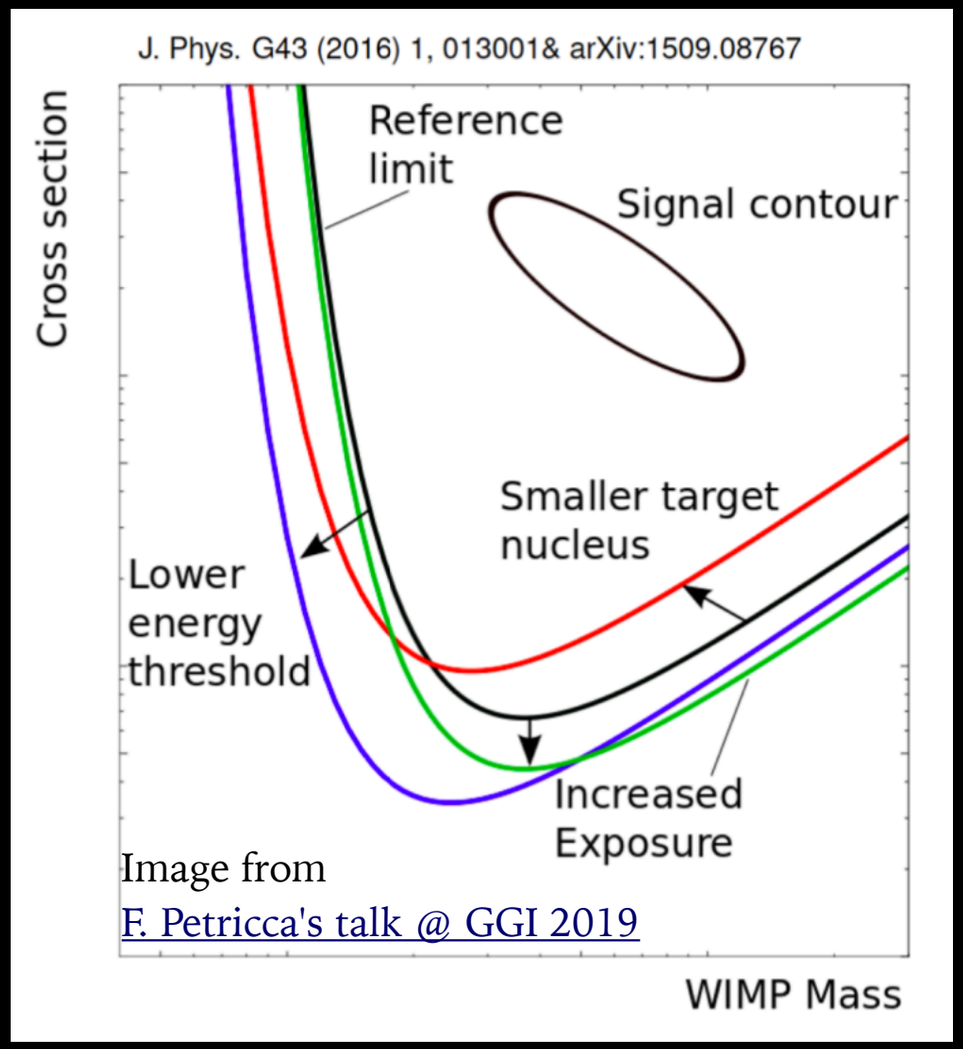


Looking *left* (to lower DM masses)

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

- detectors can be **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 **astrophysics** & **solid state physicists** E.g. arXiv:1709.07882

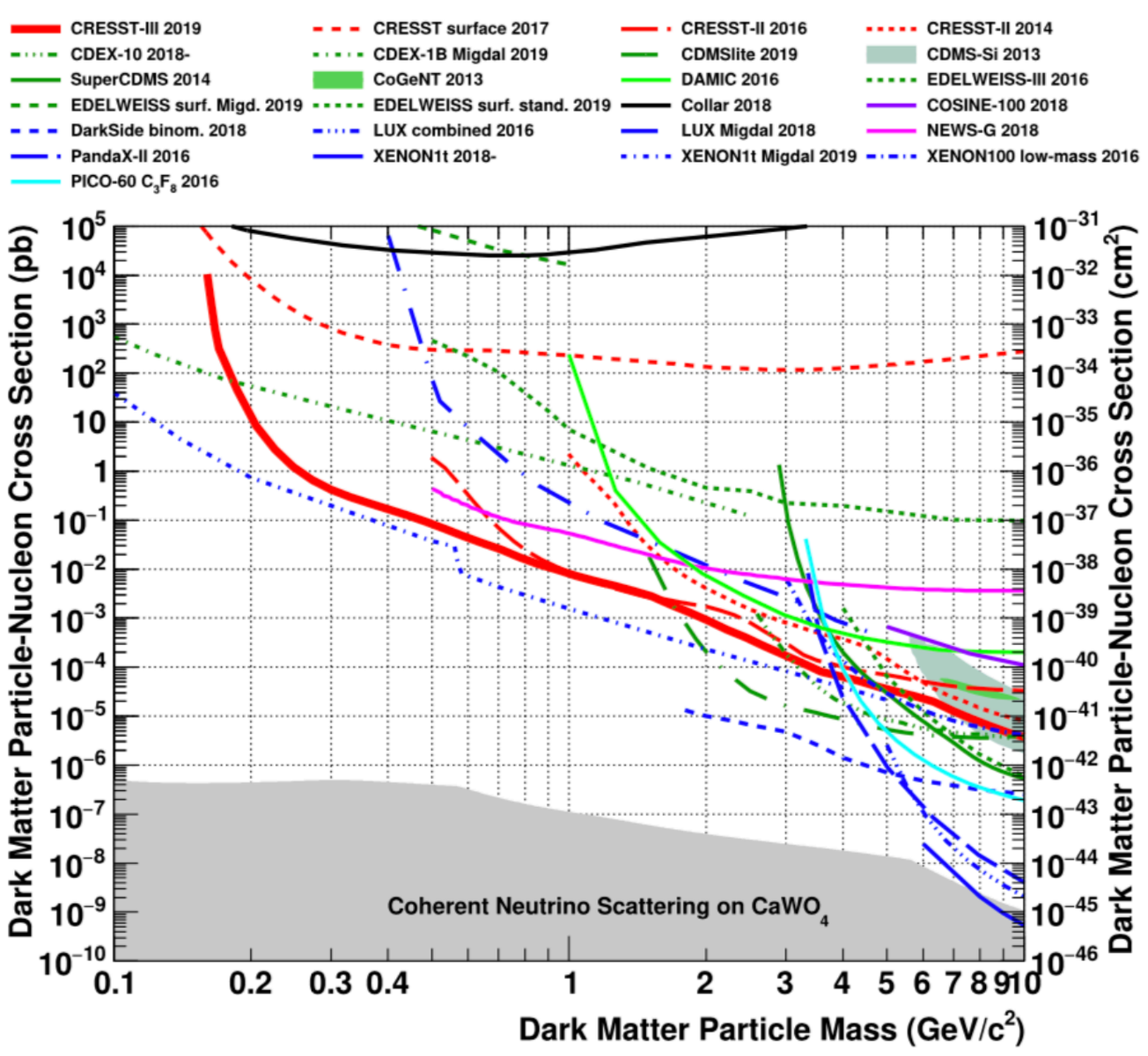


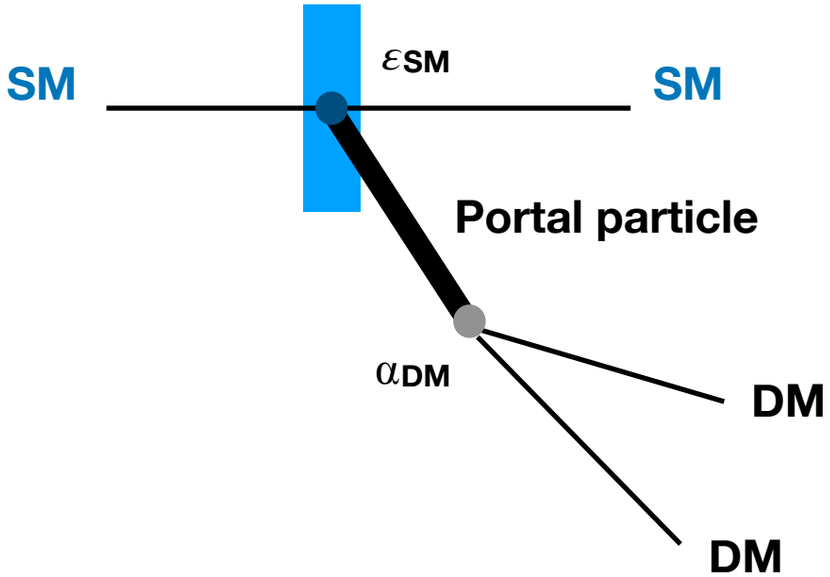
Image from F. Petricca's talk @ GGI 2019

Other light DM benchmarks & prospects

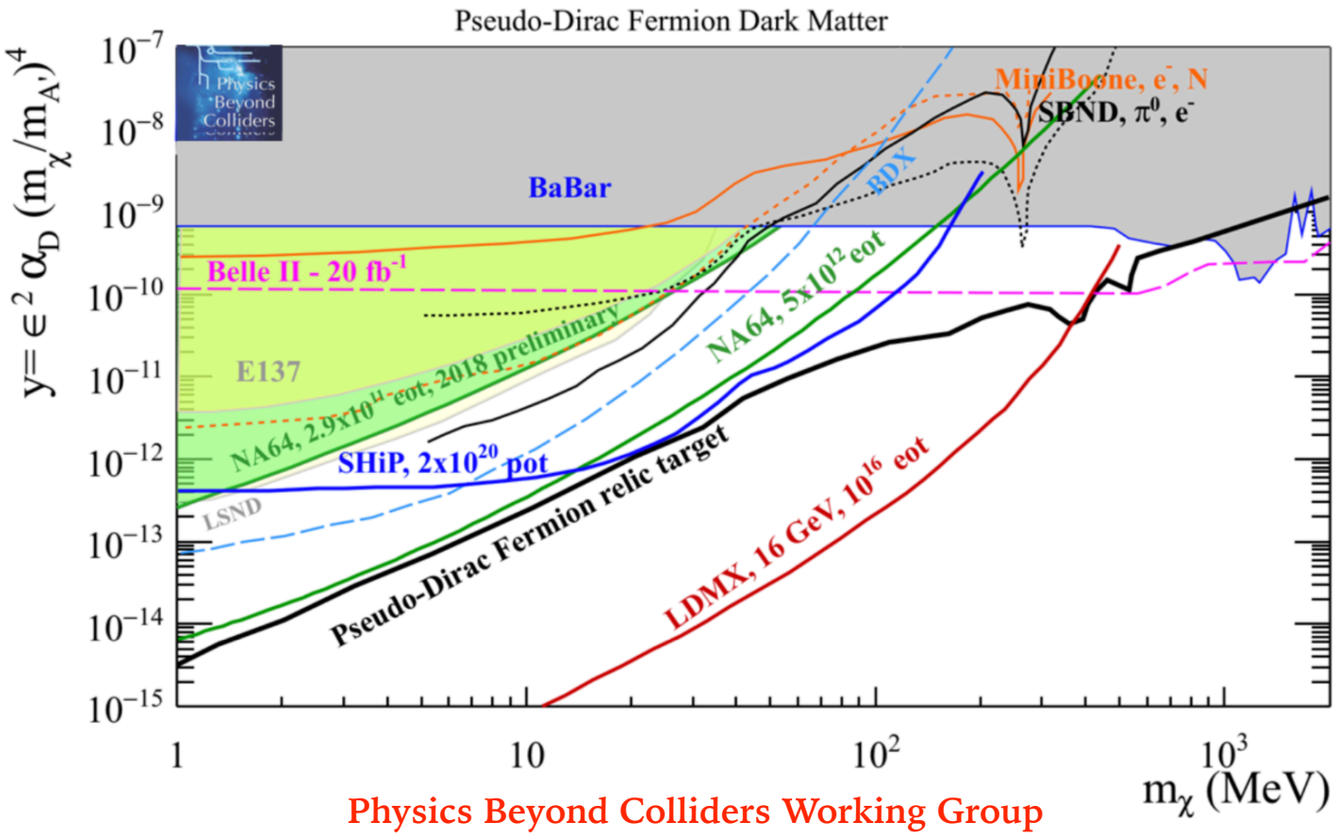
- Non-WIMP benchmark models for **dark sector** searches:
  - e.g. Dark photon, Heavy Neutral Lepton, Heavy Higgs, Axion-like particles
- Benchmark with thermal dark matter interpretation: dark photon

  → **complementarity of collider, non-collider and astro experiments**

mixing between SM and dark sector



Invisible dark photon decays

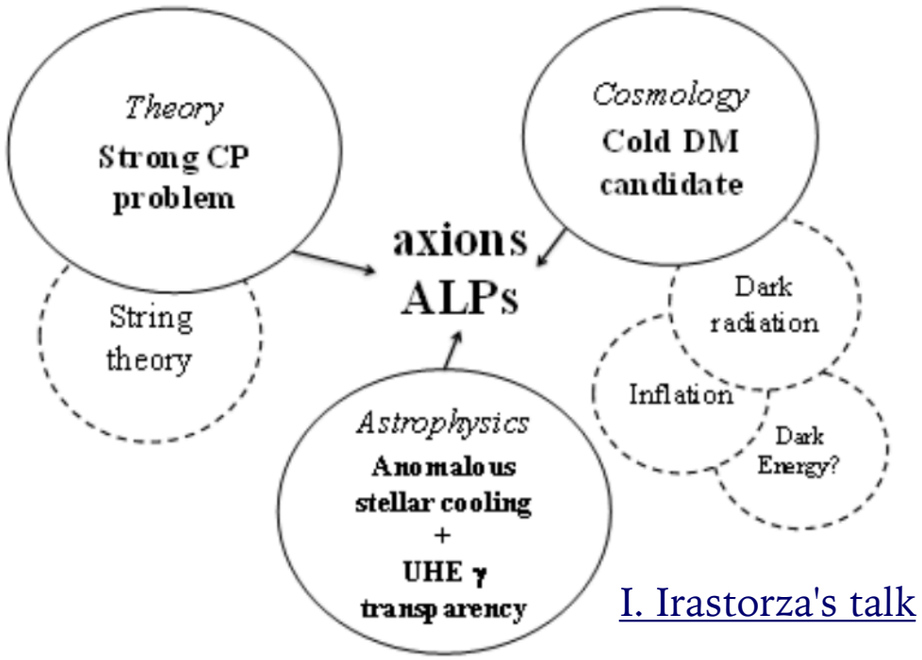


Physics Beyond Colliders Working Group

arXiv:1901.09966

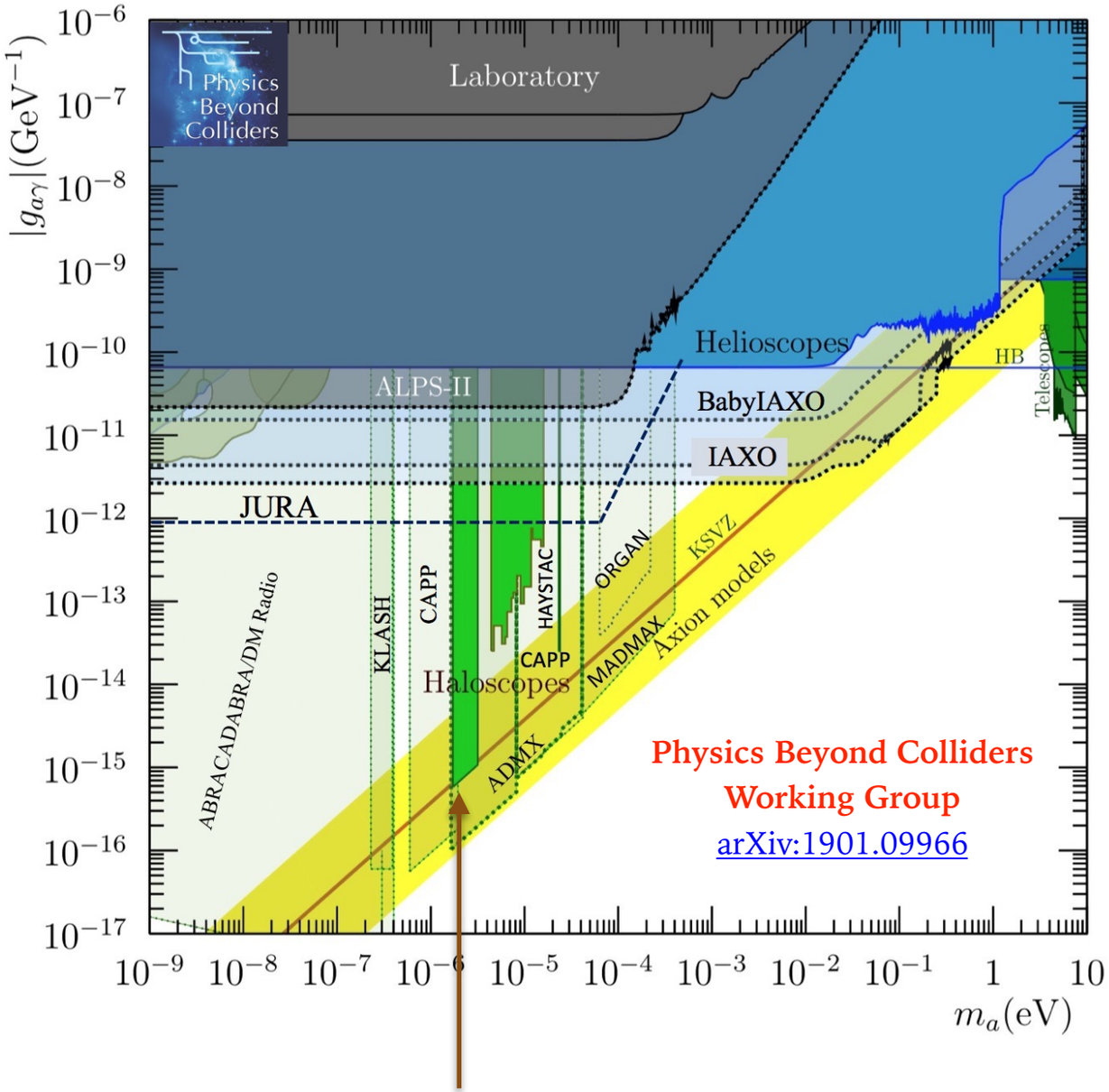
Even lighter DM: axions

Axions/Axion-Like Particles (ALPs):
example of new particle
with inter-field connections,
solving more than the DM problem



I. Irastorza's talk

also using nuclear physics experiments (EDM rings)
or novel dielectric materials



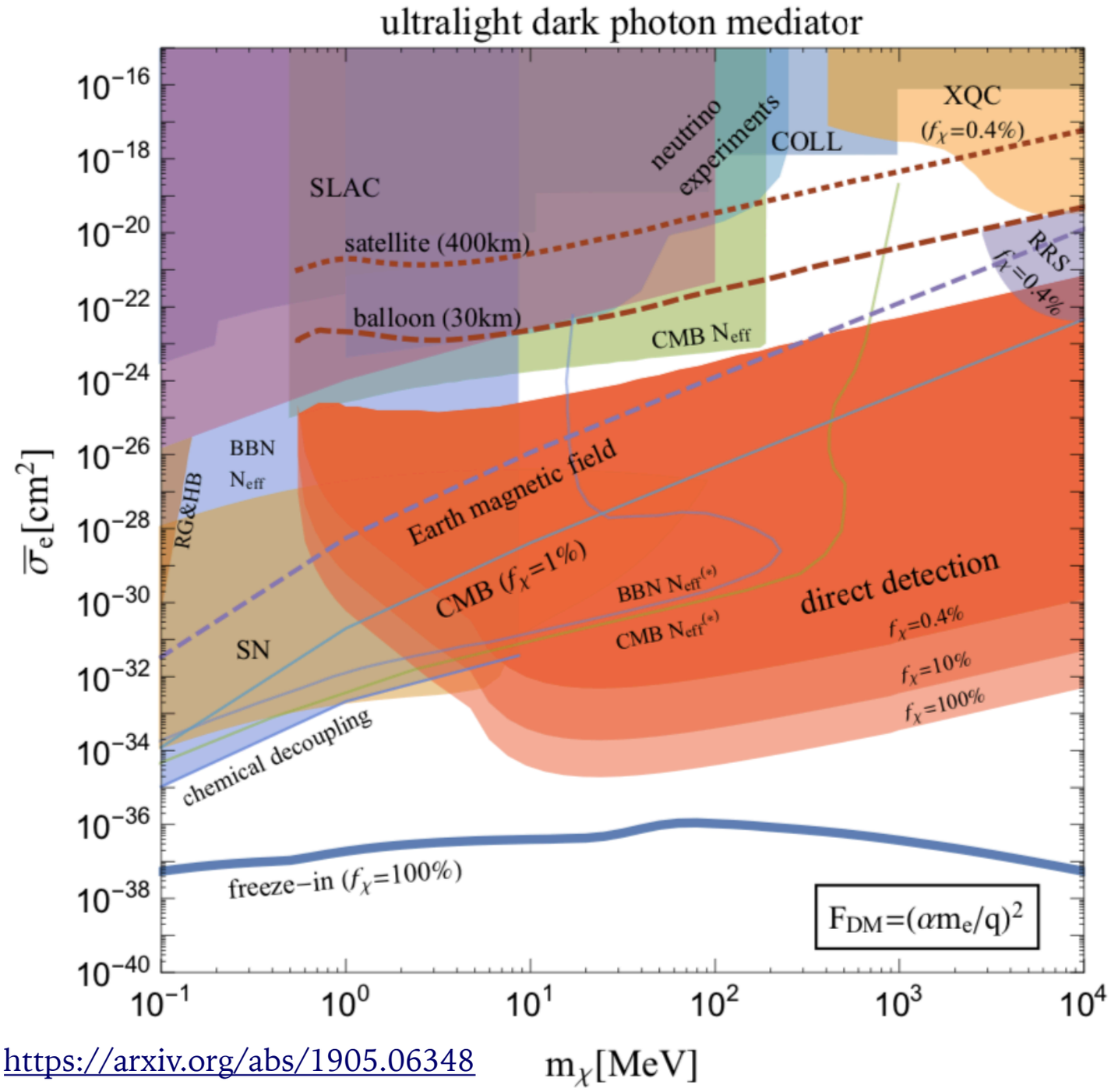
New: sensitivity of haloscopes
to **"dark matter" axions**

Wish: beneficial to connect many **smaller experiments,**
in terms of **joint expertise** and **common discussion platforms**

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

very low-mass but "strongly interacting" DM particles will

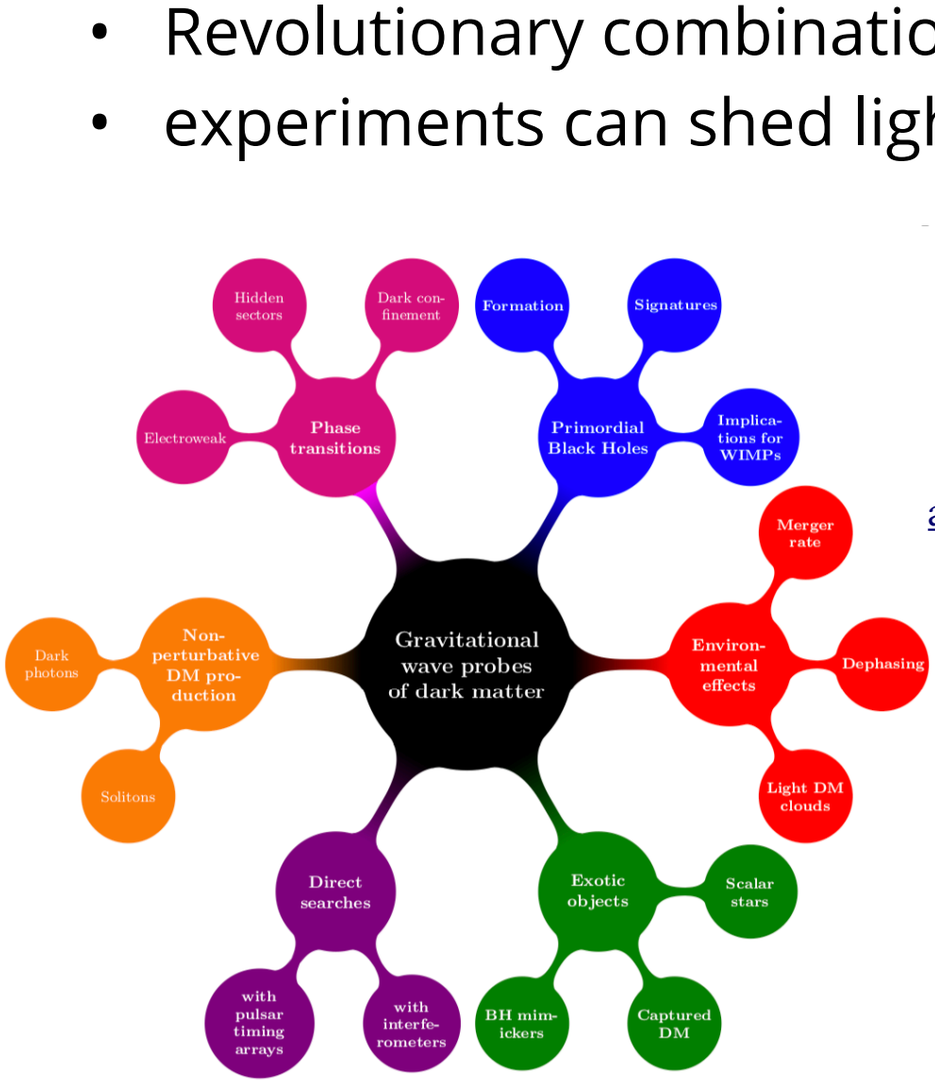
- interact with **detectors**
  - need to take this into account for WIMPs@colliders
- interact with **atmosphere & earth**
  - use/send detectors higher up!
- be detectable using **astrophysical signals**
  - SN (supernova), BBN, CMB...

Looking *right* (to much more massive objects)

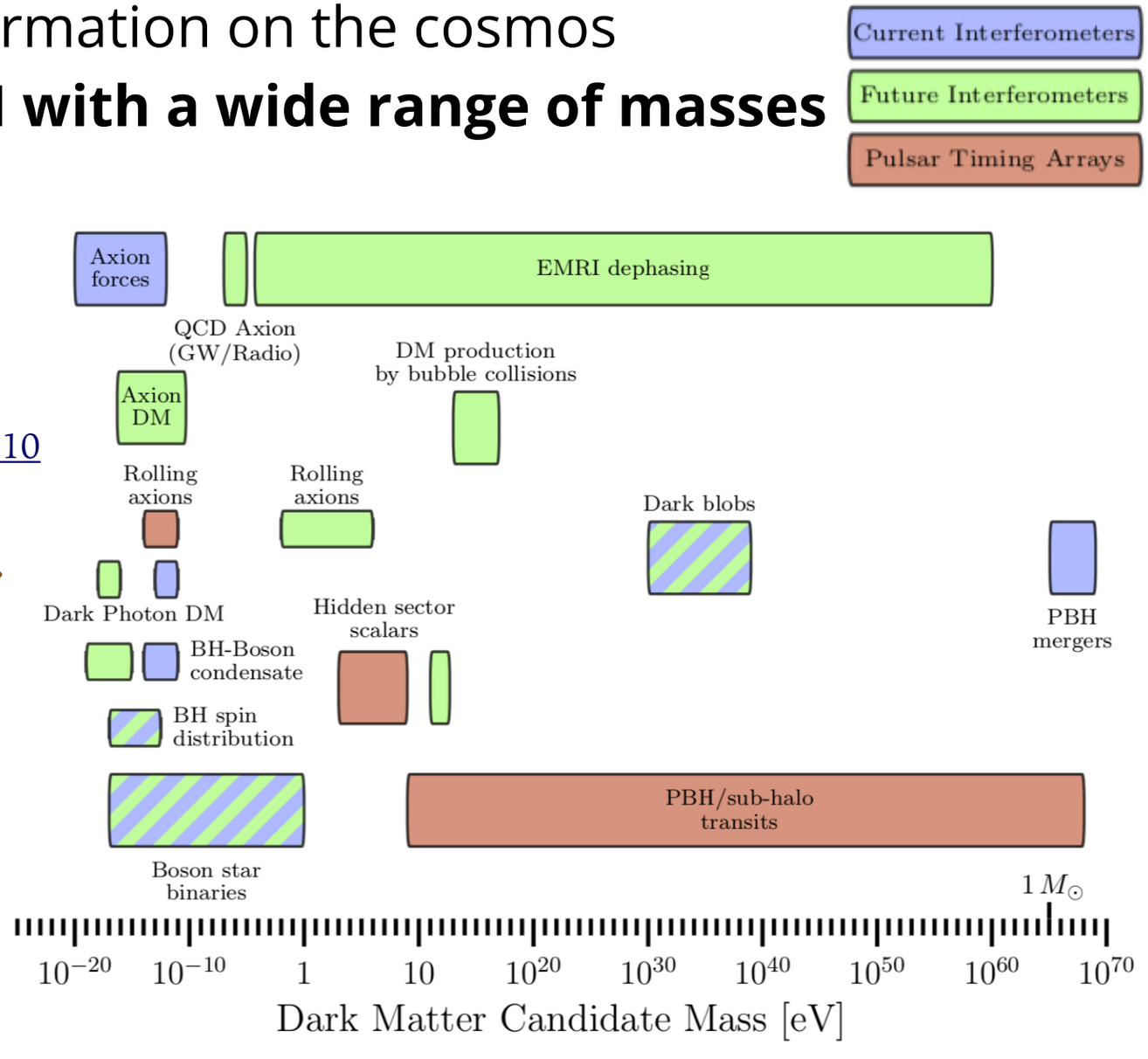
G. Losurdo's talk

Gravitational wave experiments / **multimessenger** astronomy:

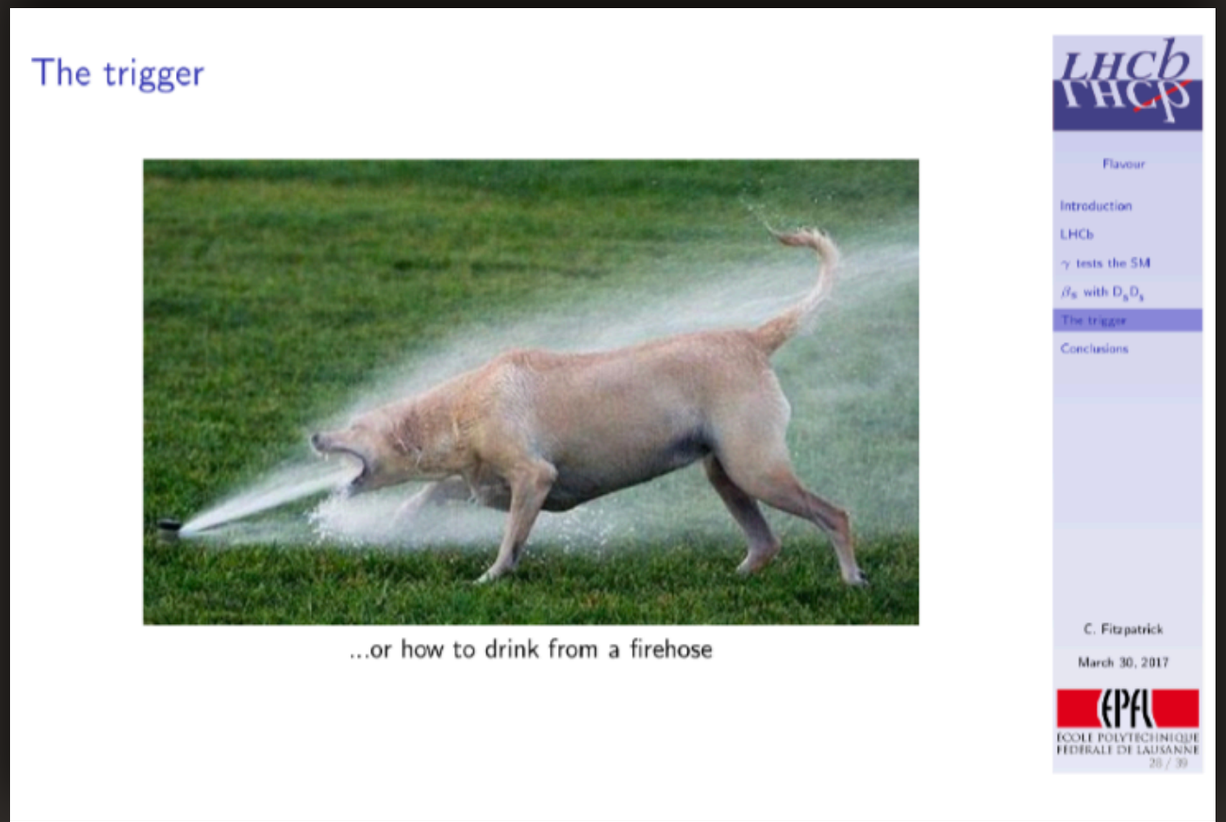
- Revolutionary combination of information on the cosmos
- experiments can shed light on **DM with a wide range of masses**



arXiv:1907.10610



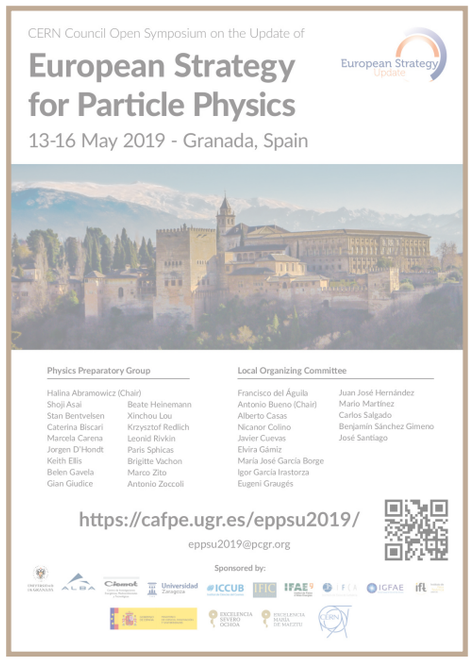
Back to earth: foundations
(or: making the most of the data)



More synergies: ”foundations” for common challenges

Astroparticle

Particle



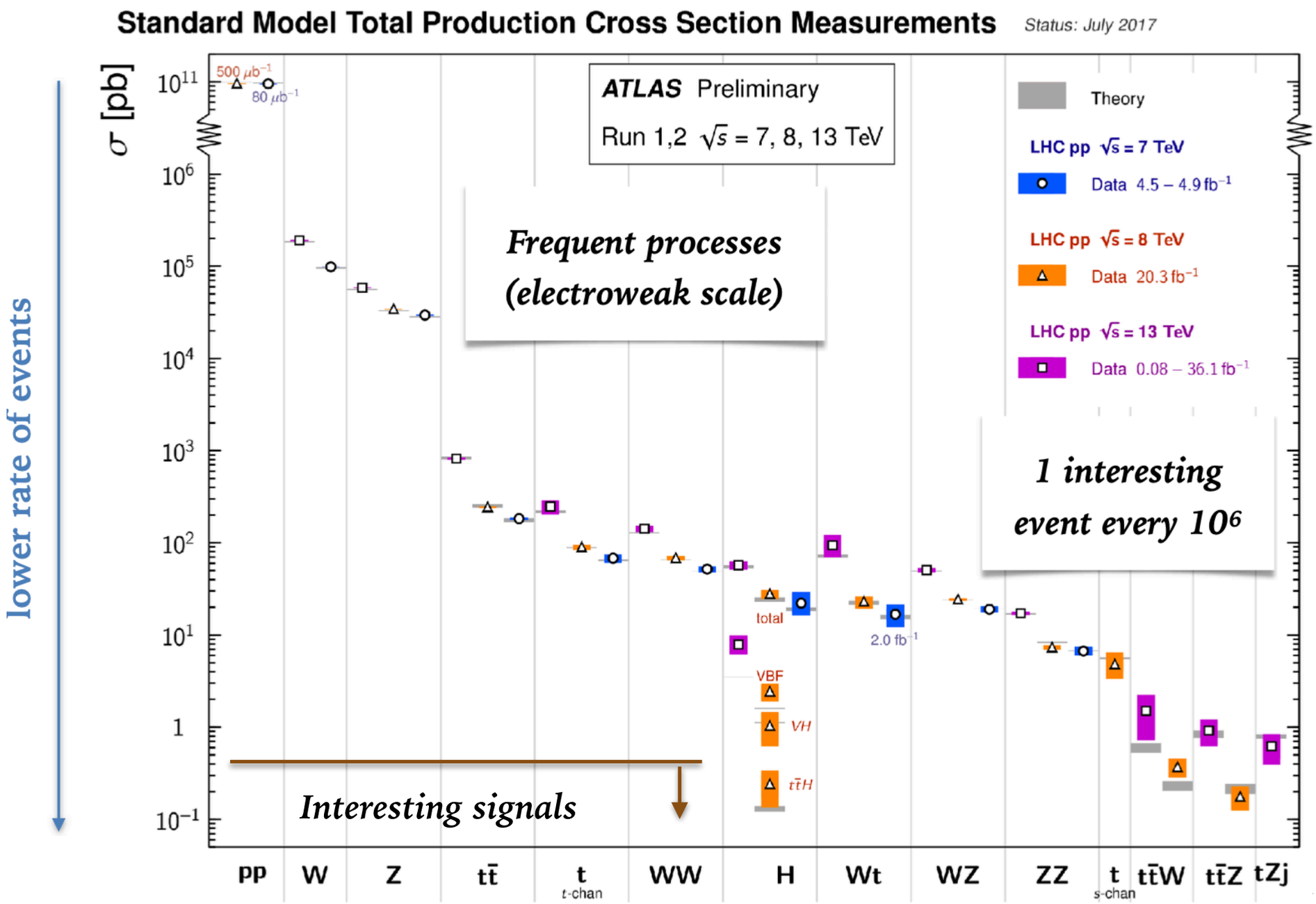
Nuclear

Common theory ground

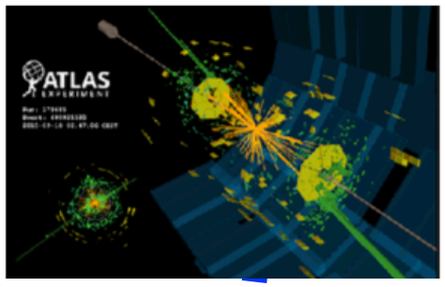
instrumentation
(accelerators, beams, detectors,
vacuum & cryogenics,
control & automation...)

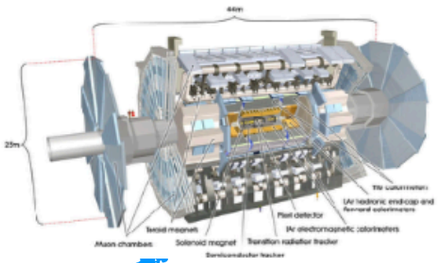
data acquisition & selection,
computing,
data sharing
& open science

Colliders: another look at the Standard Model



Online | Offline





Event selection (trigger) → Object reconstruction and calibration → Data analysis

Data produced by the LHC
(multiplied by large number)

Data I like

Data I would have used to like if I had been a data hipster

Data you like

What we can record after the trigger

Data ~nobody likes

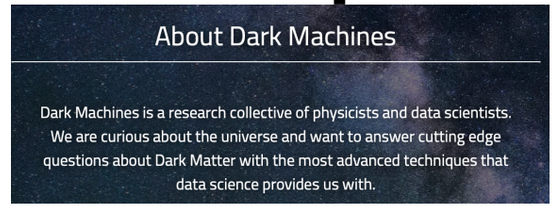
How LHC collaborations make the most of the data

Interesting time for high energy accelerator physics:
we don't know what to expect from DM/new physics
(but we have a prior: it should be *somewhere*)
we have the **LHC running now**,
and the data we discard is **gone**

1. Analyze as much data as possible, **as fast as possible**
2. Save data for **further reconstruction, later**
3. Implement more refined algorithms to **look for the unexpected**
   - Including unsupervised searches / novelty detection

Turbo stream (LHCb), Data Scouting (CMS), Trigger-level Analysis (ATLAS),

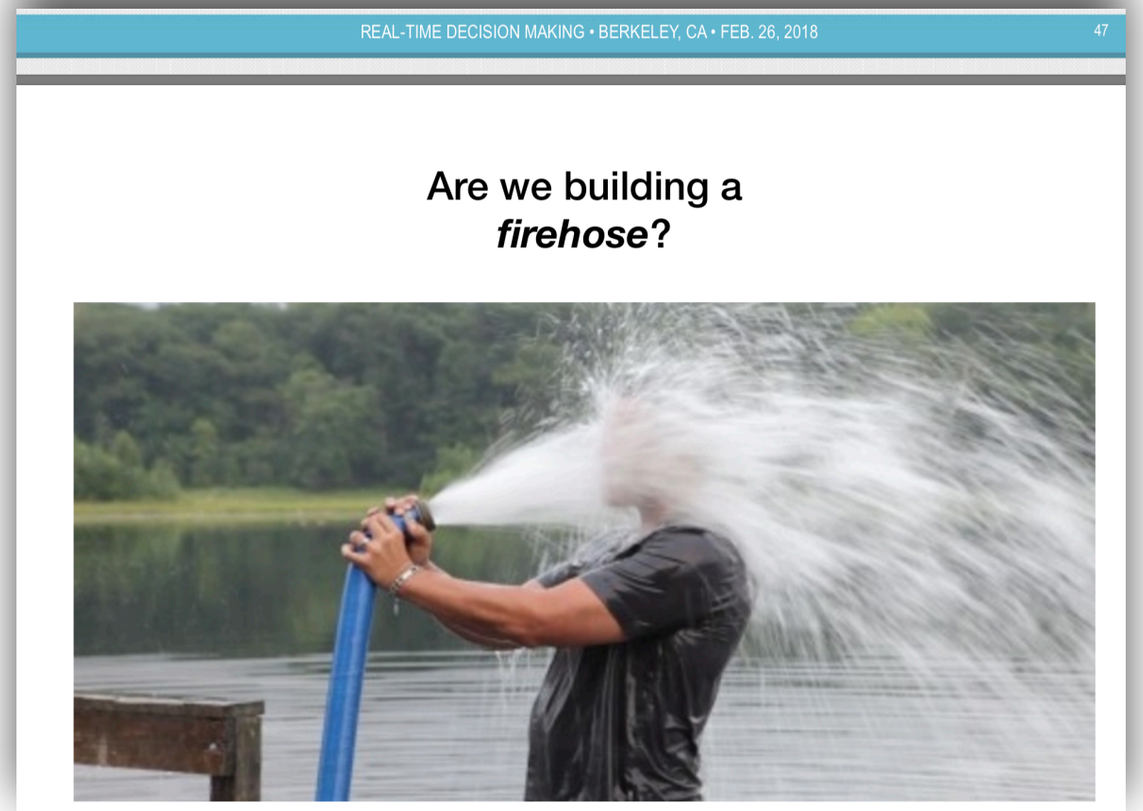
M. Pierini's talk



Extremely large datasets, in different contexts

C. Fitzpatrick, **LHCb**

E. Bellm, **Large Synoptic Survey Telescope**



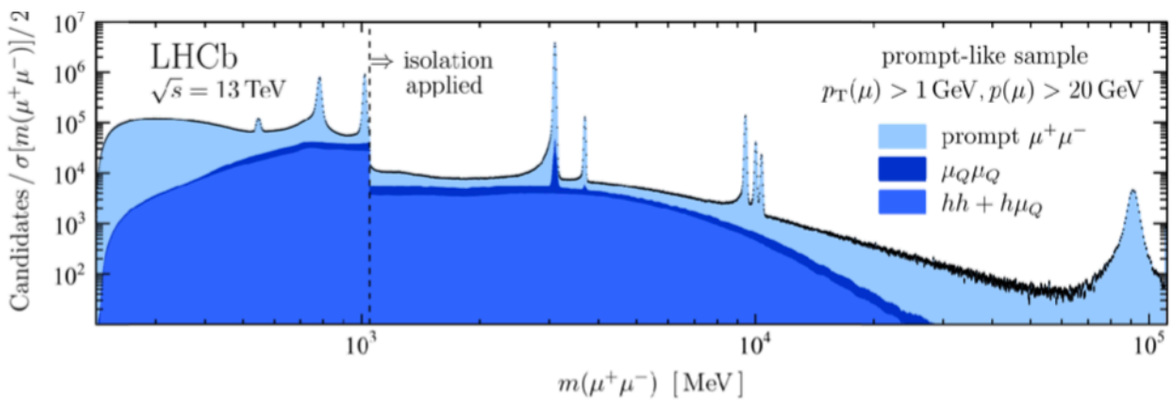
The LHC and modern astrophysics surveys are **data firehoses**

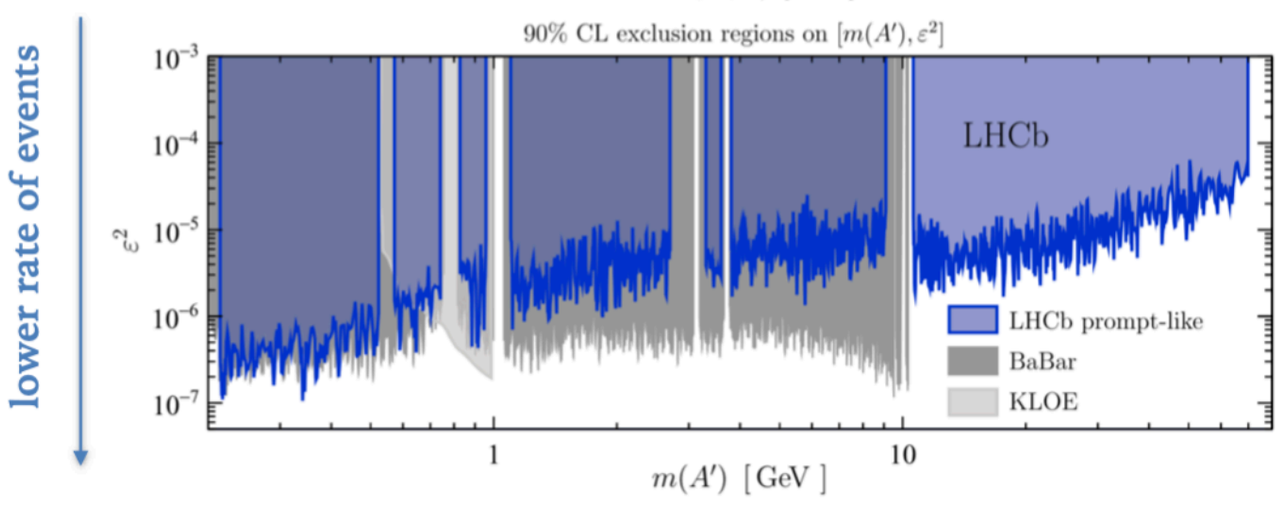
Wish: let's discuss **practical problems** where common techniques and tools for **data taking & data reduction** are useful

Visible decays of dark photon: CMS and LHCb

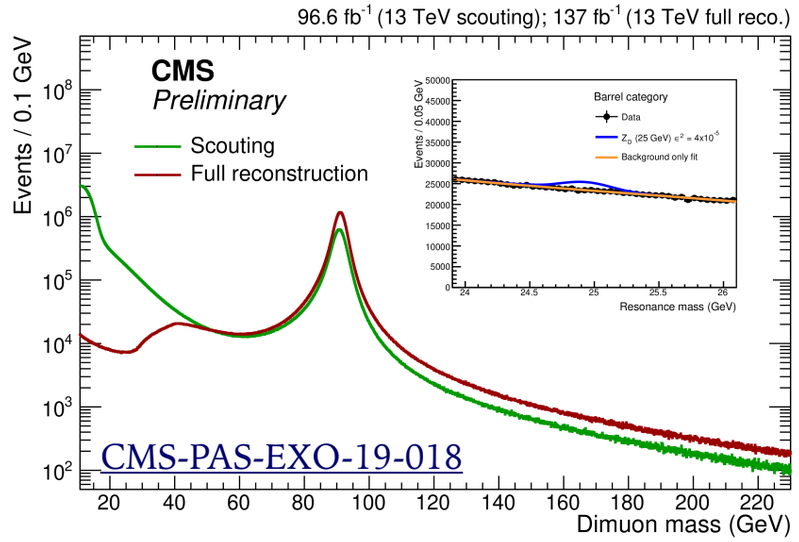
Using data-taking technique that allows to **overcome** (some) **storage limitations**:
Analyze physics objects **directly in real-time** from online data selection level

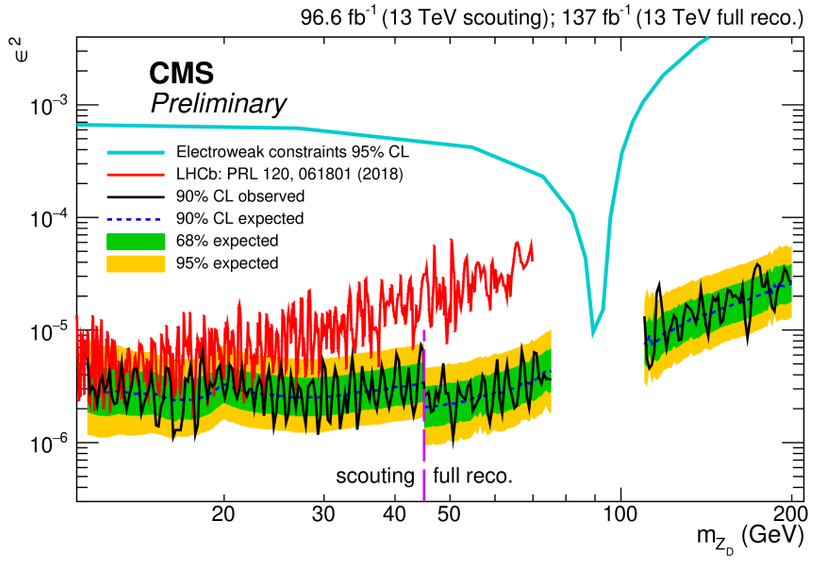
Phys. Rev. Lett. 120, 061801 (2018)





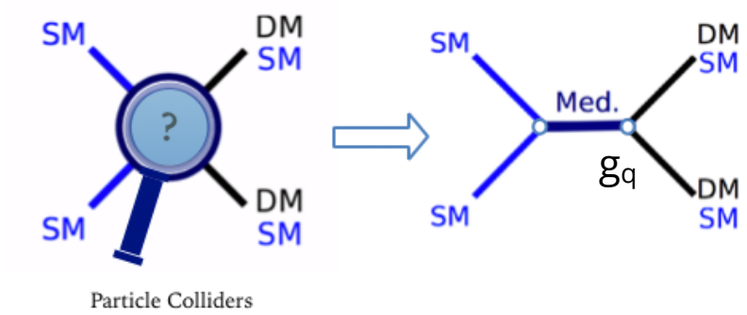
Run-3 prospects in arXiv:1509.06765



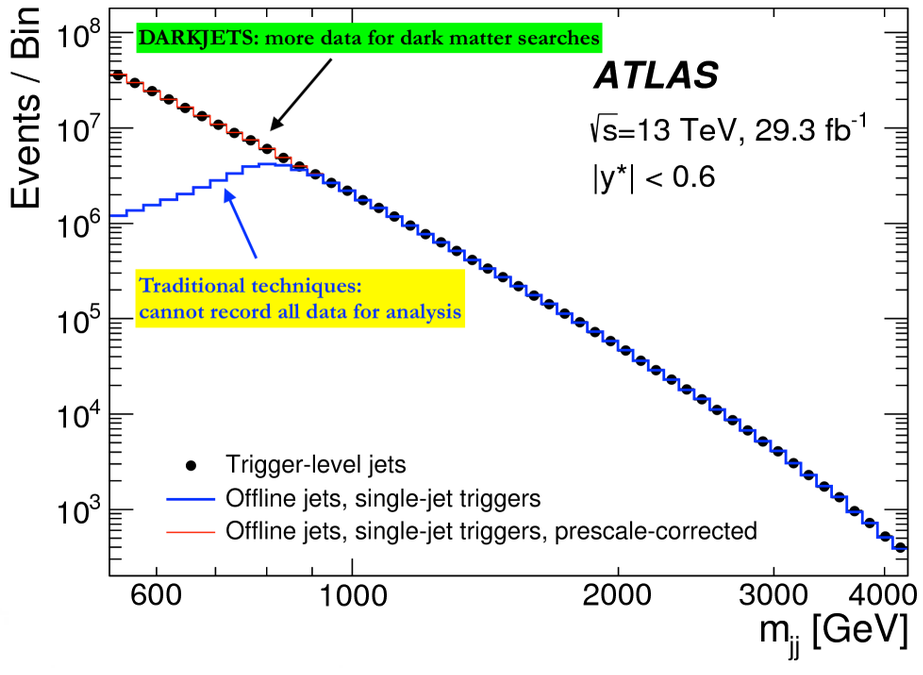


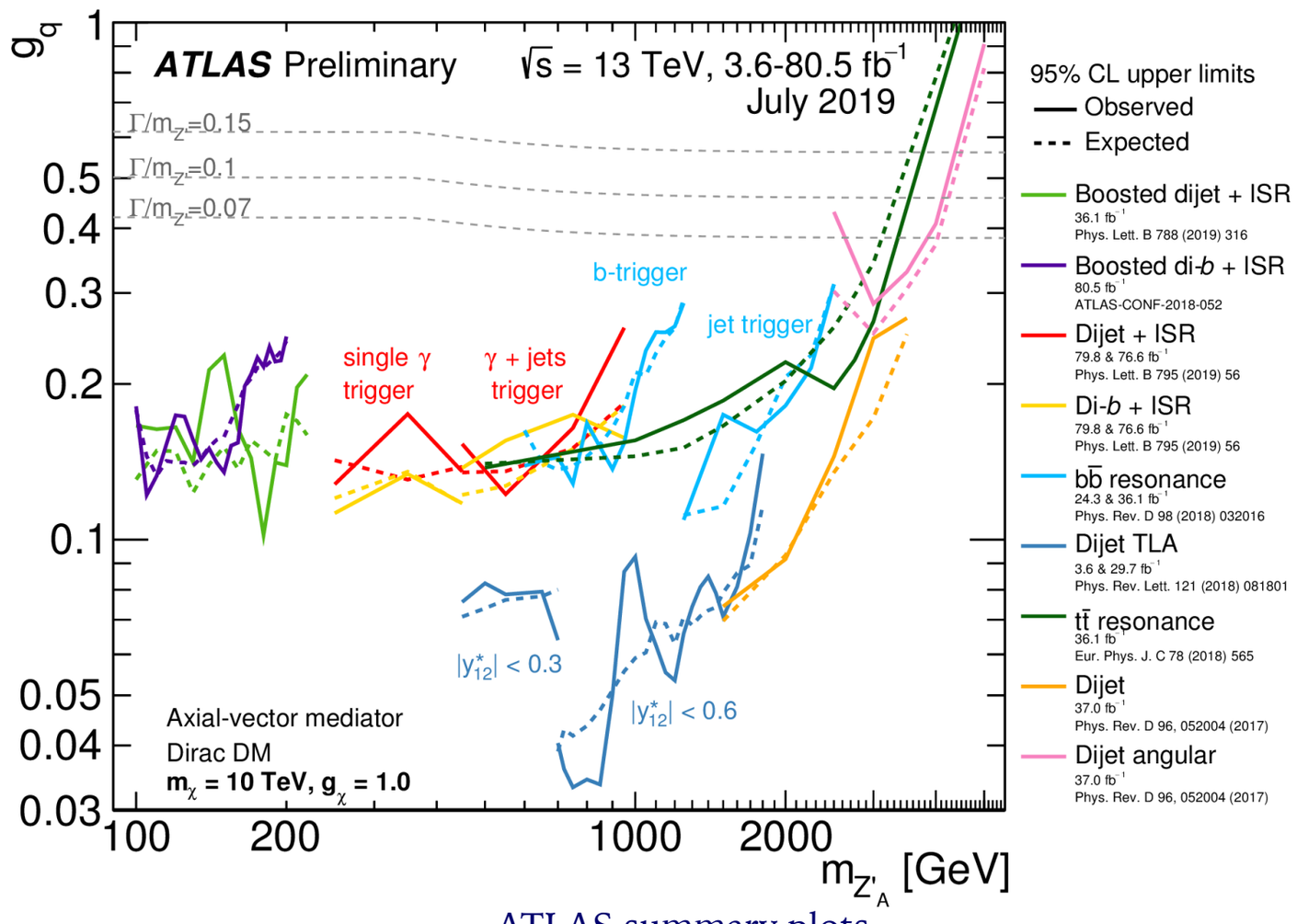
Dark matter *mediators*

Same ”real-time” analysis technique also used to look for
dark matter mediators (= dijet resonances) decaying to quarks



arXiv:1804.03496





ATLAS summary plots

arXiv:1810.12238 for more context

Reinterpretation & recasting

Let's not limit DM collider searches to a null result on a single model if we can...

Reinterpret & recast

ATL-PHYS-PUB-2019-032

ATLAS PUB Note
ATL-PHYS-PUB-2019-032
11th August 2019

RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two *b*-quarks

CMS-NOTE-2017-001] ATL-PHYS-PUB-2019-029

Available on the CMS information server CMS NOTE-2017/001

The Compact Muon Solenoid Experiment
CMS Note
Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2017/11/07

Simplified likelihood for the re-interpretation of public CMS results

The CMS Collaboration

Fit&combine

$$\mathcal{L} = \mathcal{L}_{\text{collider}}\mathcal{L}_{\text{DM}}\mathcal{L}_{\text{flavor}}\mathcal{L}_{\text{EWPO}}\cdots$$

Example: https://gambit.hepforge.org
Eur. Phys. J. C (2019) 79:395

Eur. Phys. J. C (2019) 79:395
https://doi.org/10.1140/epjc/s10052-019-6837-x

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Combined collider constraints on neutralinos and charginos

GAMBIT Collaboration: Peter Athron[1,2], Csaba Balázs[1,2], Andy Buckley[3], Jonathan M. Cornell[4], Matthias Danninger[5], Ben Farmer[6], Andrew Fowlie[1,2,7], Tomás E. Gonzalo[8], Julia Harz[9], Paul Jackson[2,10], Rose Kudzman-Blais[5], Anders Kvellestad[6,8,a], Gregory D. Martinez[11], Andreas Petridis[2,10], Are Raklev[8], Christopher Rogan[12], Pat Scott[6], Abhishek Sharma[2,10], Martin White[2,10,b], Yang Zhang[1,2]

Use precision measurements

arXiv:1902.03067 arXiv:1606.05296

JHEP

Published for SISSA by Springer

Received: *July 6, 2016*
Revised: *January 20, 2017*
Accepted: *February 23, 2017*
Published: *March 14, 2017*

Constraining new physics with collider measurements of Standard Model signatures

Jonathan M. Butterworth,[a] David Grellscheid,[b] Michael Krämer,[c] Björn Sarrazin[c] and David Yallup[a]

Wish: ensure these platforms are useful, by virtue of **feedback/support/dissemination** within collider & other communities

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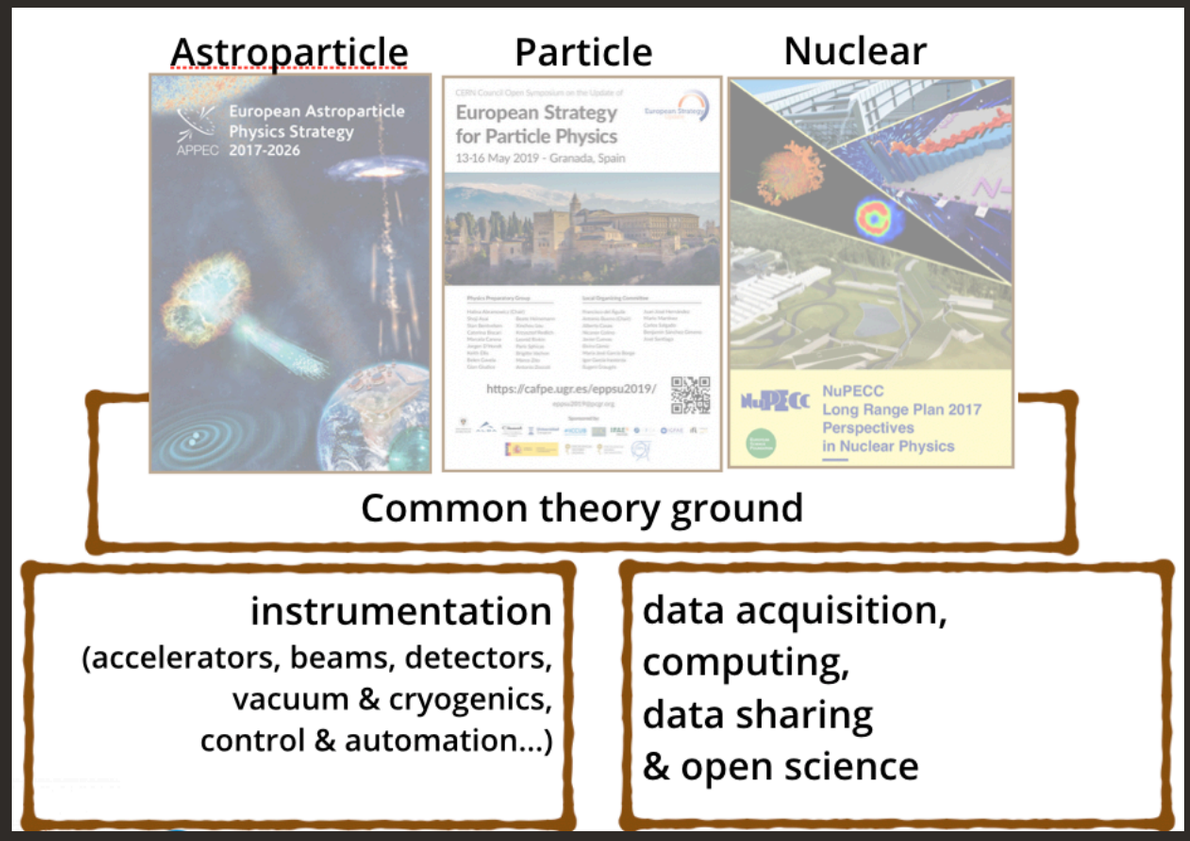
Conclusions & wishlist



A constellation of activities and initiatives

Astroparticle Particle Nuclear

2013 APPEC input to EPPSU: taking off in 2019 with CERN as first 5-year host

European Center for Astroparticle Theory (EuCAPT)

Common theory ground

instrumentation
(accelerators, beams, detectors, vacuum & cryogenics, control & automation...)

data acquisition, computing, data sharing & open science

HSF HEP Software Foundation

ESCAPE European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

European Research Council Established by the European Commission

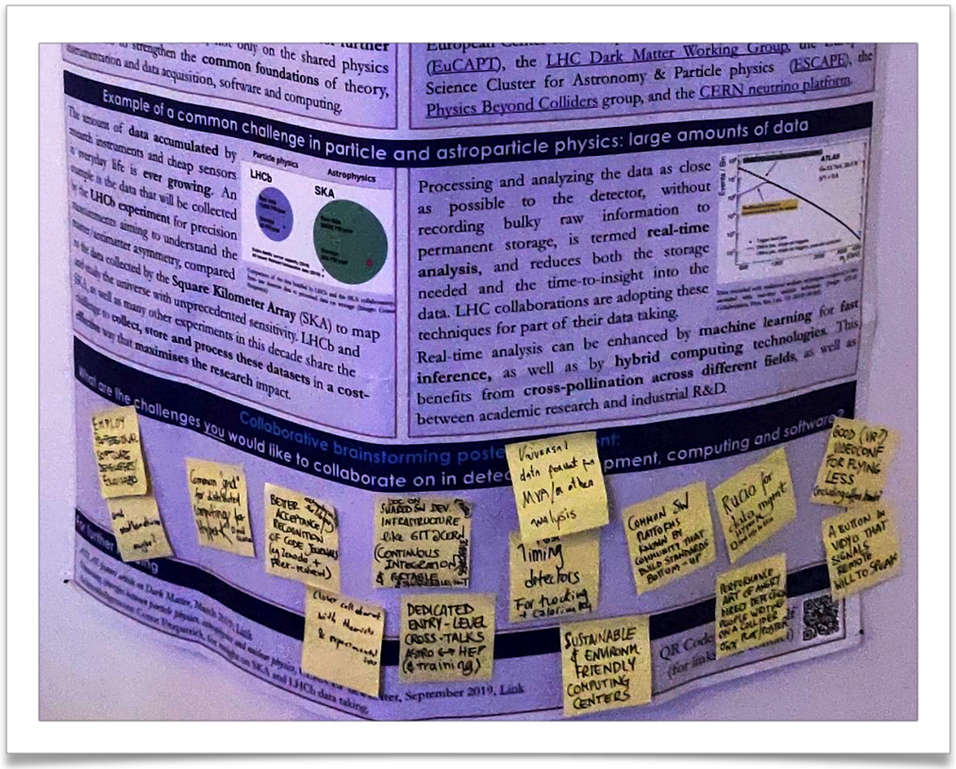
ATLAS EXPERIMENT

Tuesday morning talks

G. Lamanna's talk, F. Genova's talk

Today & tomorrow: (creative) steps to collaboration

Poster session today: a social experiment



Some ideas from Swedish community:

- Shared searchable software code-base/journals
- Working together towards sustainability of meetings and computing centers
- Shared R&D for timing detectors
- Dark matter posters performance art (?!?)

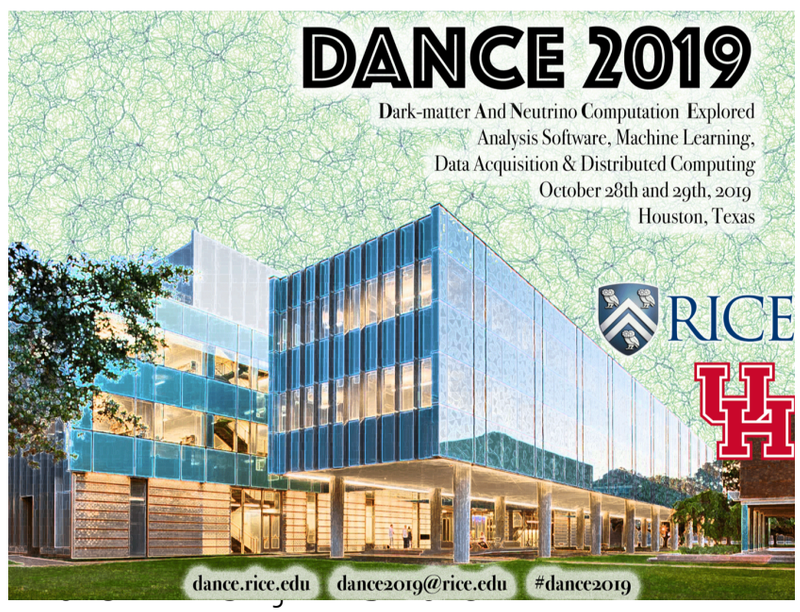
High Energy Physics Software Foundation

Meeting tomorrow at 16:00 (Blue Room)

[JENAS is] *"The beginning of a process to work on & support projects together"* (M. Lewitowicz, Monday Q&A)

Goal: start discussing common **challenges & needs** of the community, in order to benefit from joint work on **solutions**

Stay tuned also for:

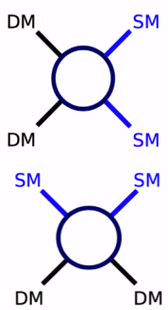


C. Tunnell's talk @ IRIS-HEP meeting

Outlook and wishlist

Dark matter present & future:

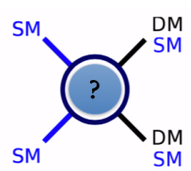
essential **physics complementarity** across different experiments



cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
colliders/beyond colliders (accelerators)



as well as on **tools**, given **shared theory, experimental & computing challenges**

Dark matter wishlist (partial/collected so far):

• a **platform** or a common **discussion forum** focused on **dark matter**
(collider, direct and indirect detection, as well as GW & other astro probes)

- for **analysis** and **interpretation** of results
- for common **technology** challenges and solutions
- for **data sharing, software** & **computing**

HSF HEP Software Foundation

ESCAPE

European Center for Astroparticle Theory (EuCAPT)

CERN Physics Beyond Colliders

LHC Dark Matter Working Group
Organisers: Oleg Brandt • Ulrich Haisch • Philipp Harris • Christian Ohm • Tim Tait • Xabier Cid Vidal

A personal view: **bottom-up/community-driven** approach beneficial

→ let's keep **reaching out** to each other!

Thanks for your attention
(and thanks to the junior physicists who worked on many of the European Strategy plots)!

CLICdp projections: Ulrike Schnoor (CERN)

with Andrea Wulzer, Philipp Roloff, Jean-Jacques Blaising

Scalar projections: Marco Rimoldi (DESY)

with Francesca Ungaro, Hideki Yukawa, Oleg Brandt

Direct Detection: Isabelle John (Lund)

with CD, Emma Tolley, Antonio Boveia, Jocelyn Monroe

Indirect Detection: Boyu Gao (OSU)

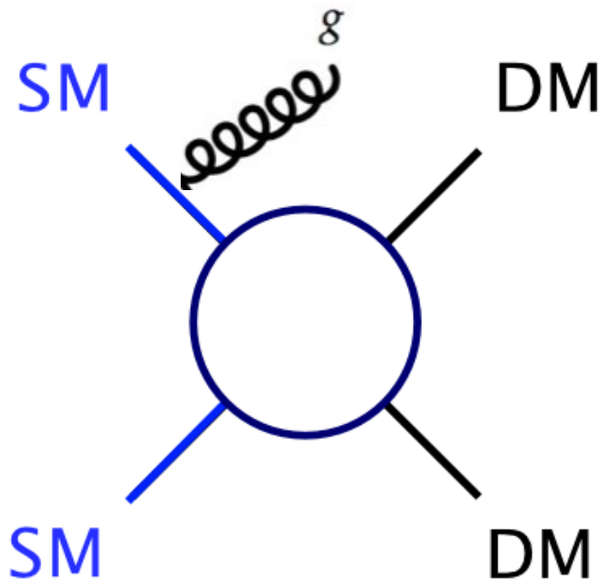
with Emma Tolley, Linda Carpenter, Antonio Boveia, Christoph Weniger

Backup slides

Broad categories of collider searches

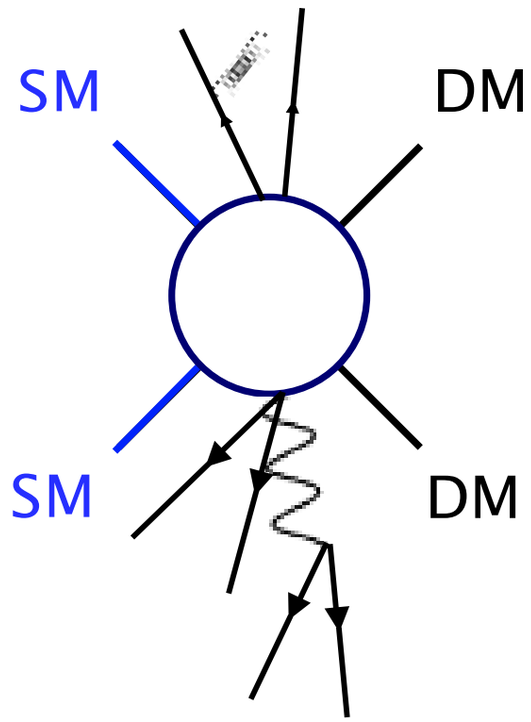
Generic searches ⟵ ⟶ More specific searches

- Good for **simple models** with **sizable cross-sections**
- **Fewer assumptions** on specific model characteristics



- More sensitive to **specific models**
- More reliant on **model assumptions**

p, π, … → jets



→ the way we think of benchmark models **influences collider searches**

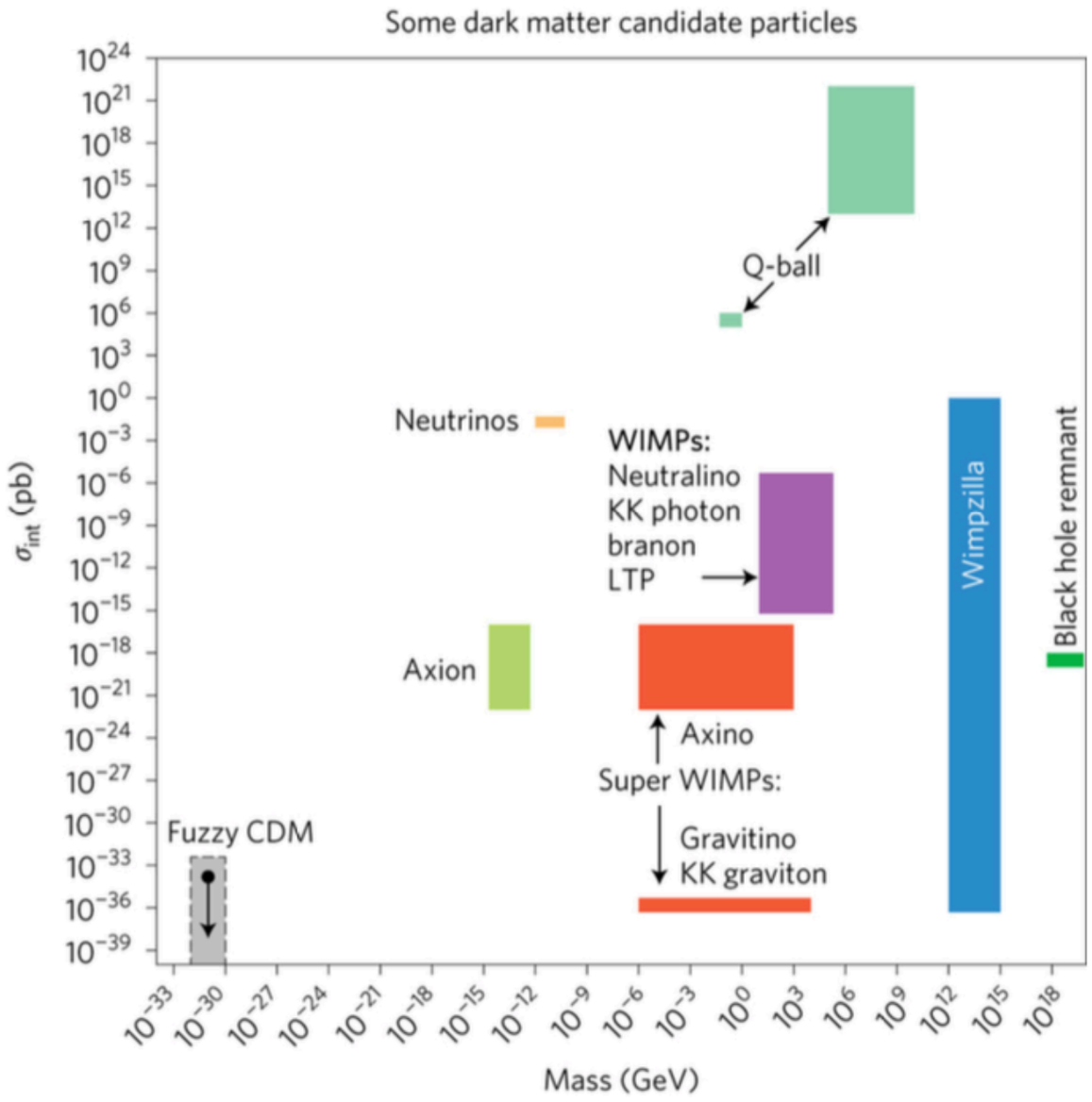
Simple models ⟵ ⟶ More complex/complete models

48

F. Calore's talk @ GGI 2019

The dark matter landscape

10^{-22} eV — 10^{-2} eV — 1 GeV 1 TeV — 10^{19} GeV (10^{-5} g) — 10^{57} GeV (10^{33} g)



- Identification strategies are necessarily (more or less) model dependent
- The **theoretical prejudice in dark matter searches** is also set by what we can probe with available data
- You always need some sort of signature of your model!

Conrad & Reimer, Nature Physics 13 (2017) 224-231

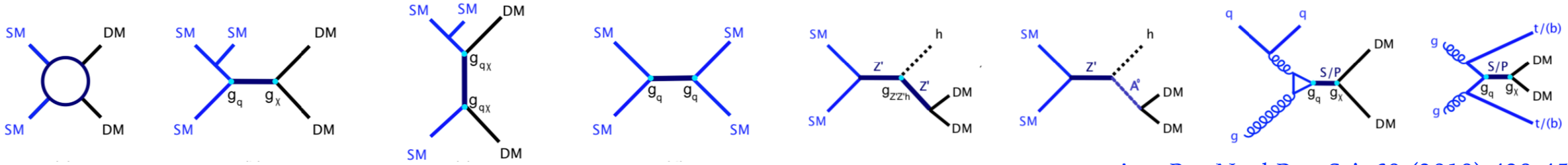
Benchmarks of choice (for heavy WIMP DM)

"Big question" for the update of the European Strategy of Particle Physics

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

Problem: unable to cover all cases!

- Large number of model possibilities for WIMPs, even limiting to the simplest models (see e.g. LHC Dark Matter Forum/WG documents)



Ann.Rev.Nucl.Part.Sci. 68 (2018) 429-459

- Any benchmarks chosen will be **only examples -** what to choose and why?
  - **Wino/Higgsino DM:** simple extension of SM portals, within SUSY framework
  - **Higgs portal DM:** newly discovered Higgs, simple interaction
  - **Simplified models of vector/scalar-mediated DM:**
    - Vector/axial vector: visible and invisible signatures
    - Scalar: cross-sections are small → good collider probes
-

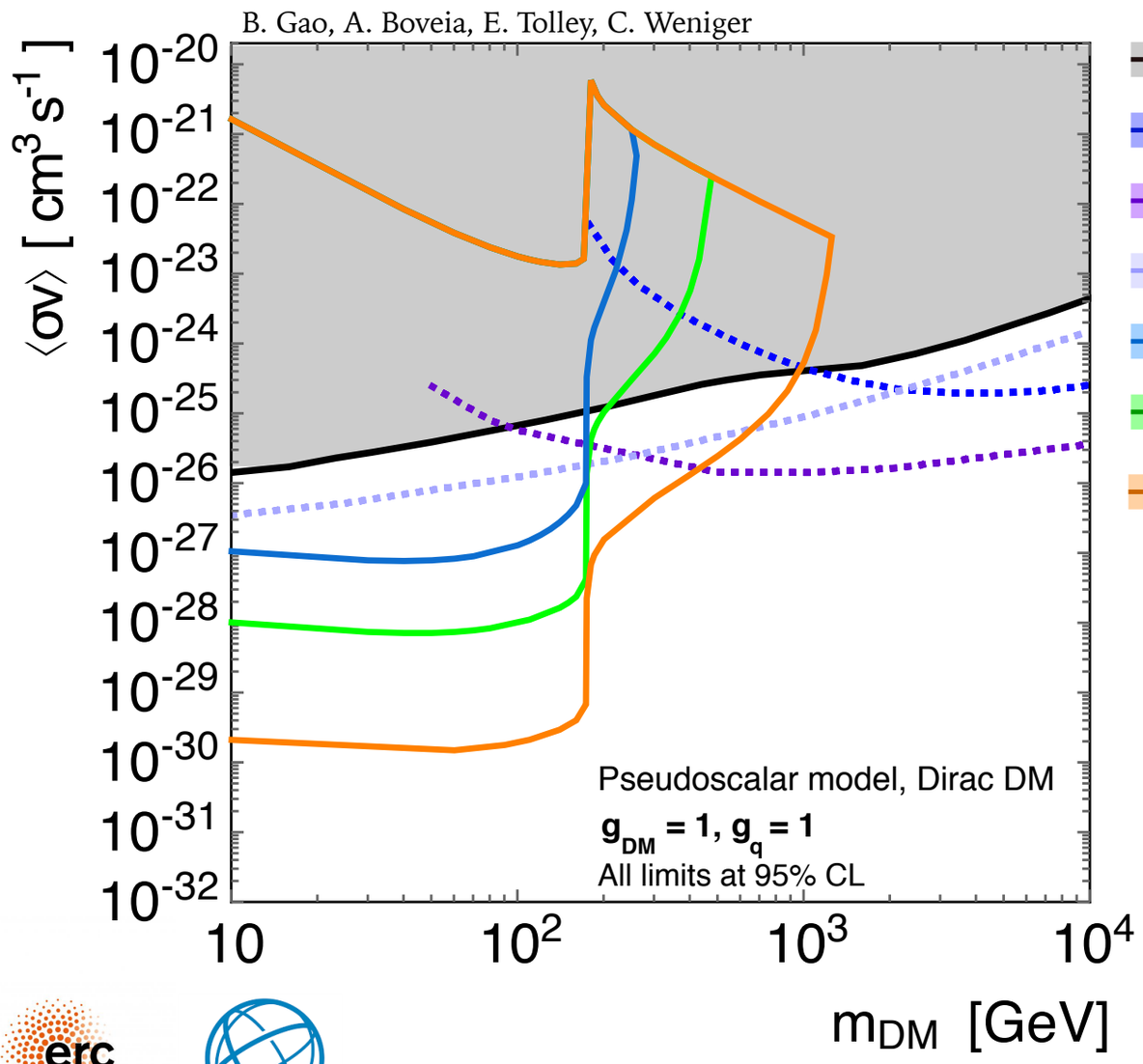
Pseudoscalar mediator: indirect detection plots

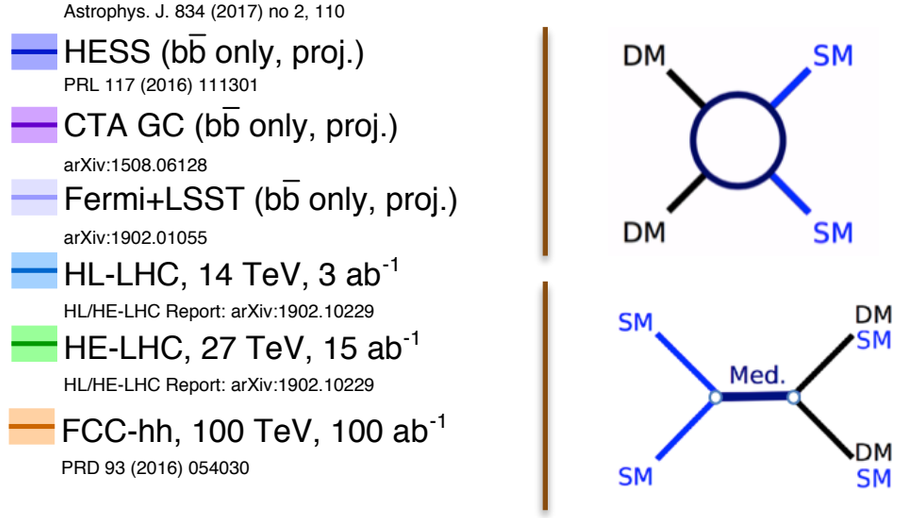
- Limits on pseudoscalar mediator mass/scale can be translated to limits in the velocity-averaged DM annihilation plane

$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

$$\langle \sigma v_{\rm rel} \rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \left| \sum_q m_q^2 \, f_{\text{pseudo-scalar}} \left(\frac{m_q^2}{m_\chi^2} \right) \right|^2$$

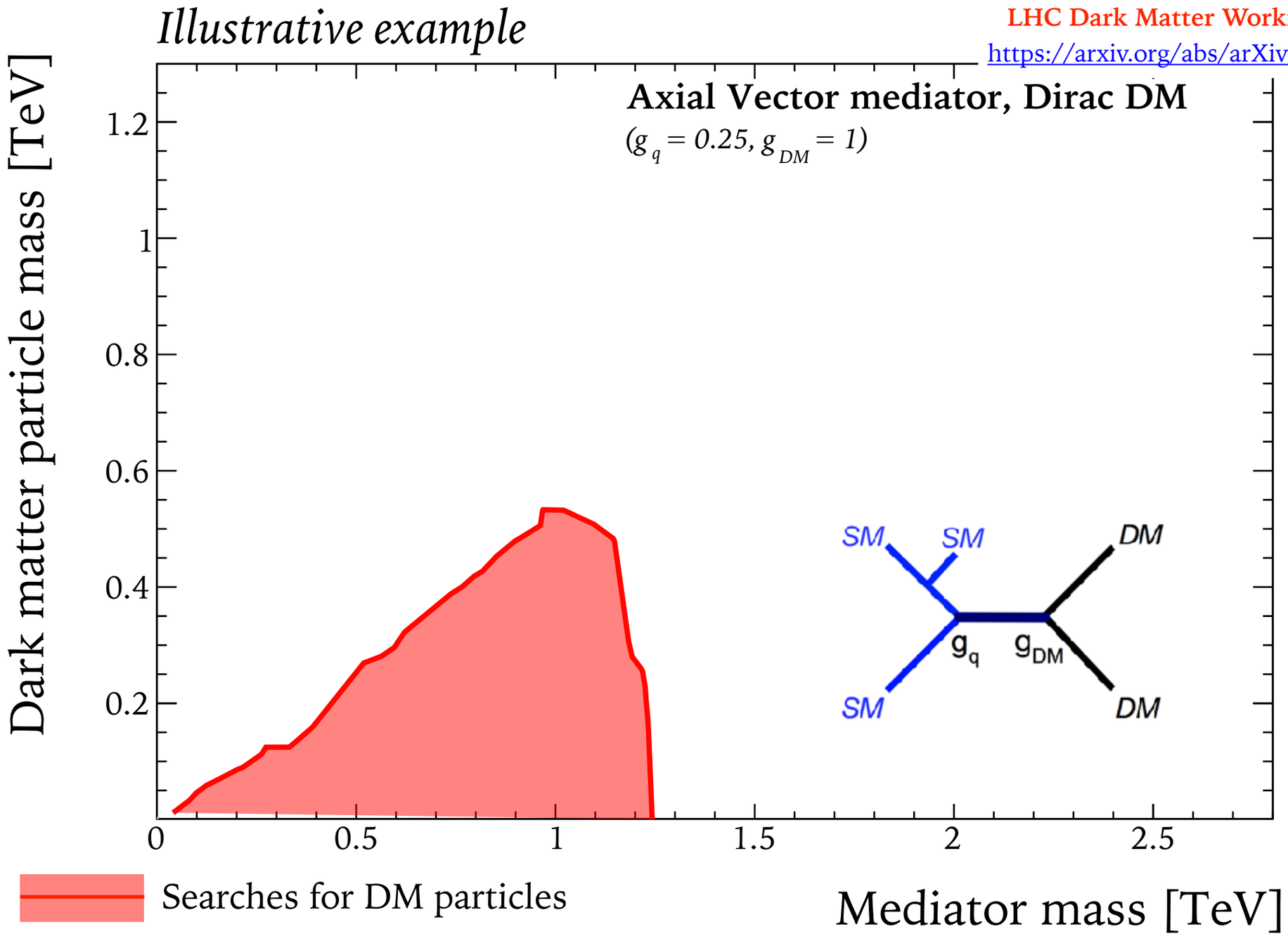
arXiv:1603.04156





European Strategy Update

Complementarity of visible/invisible searches



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European Union funding
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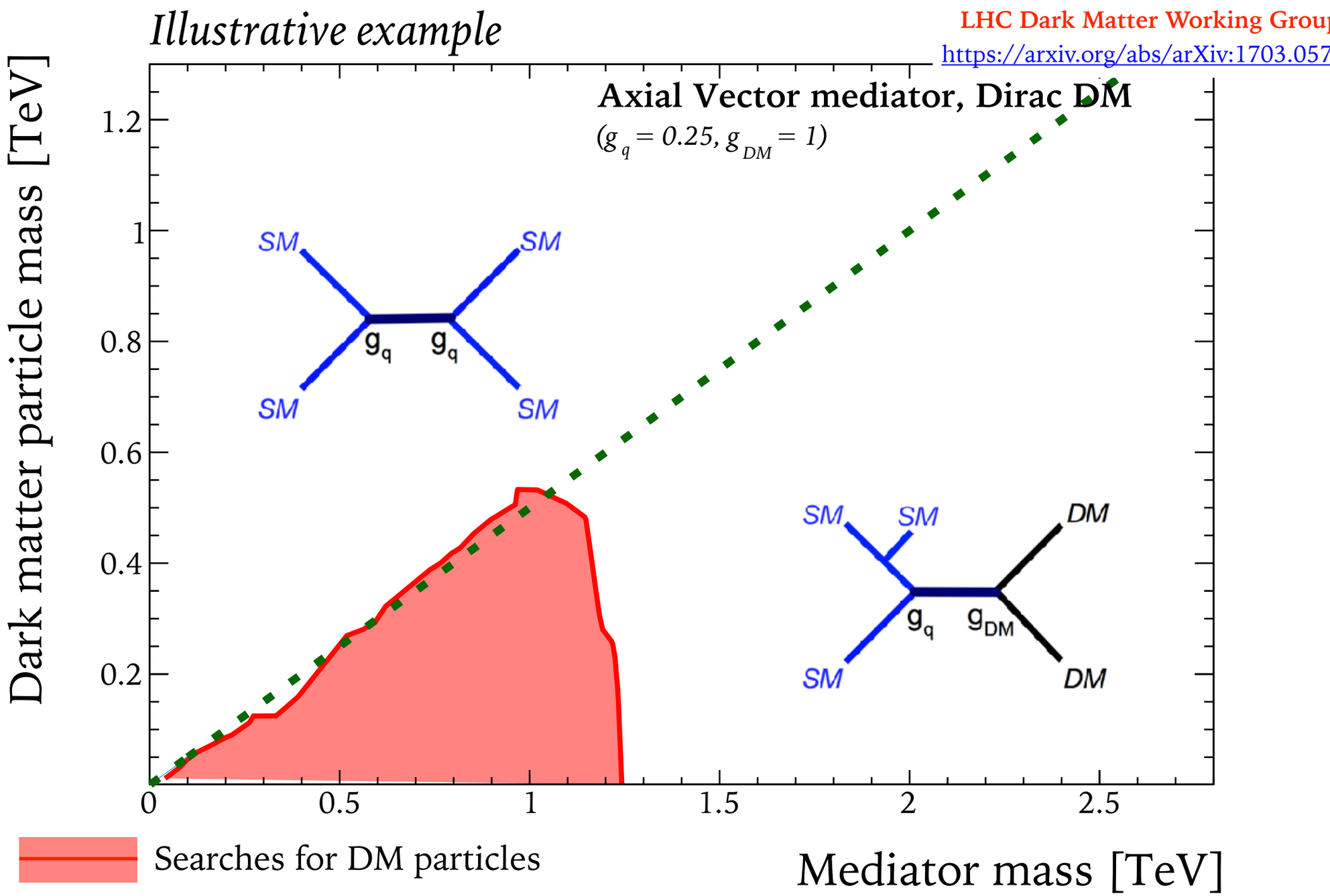
LUND UNIVERSITY

Complementarity of visible/invisible searches



LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

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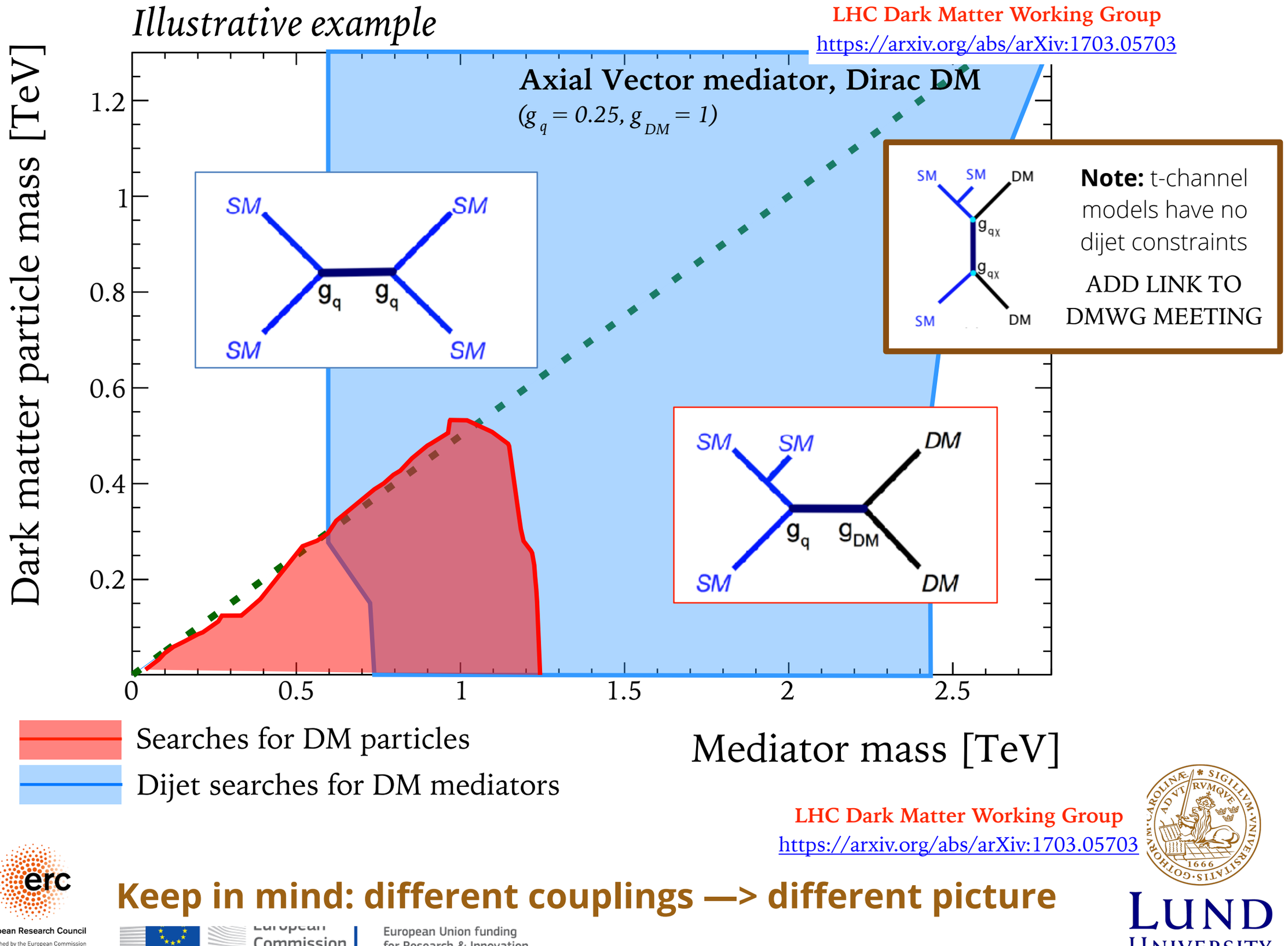
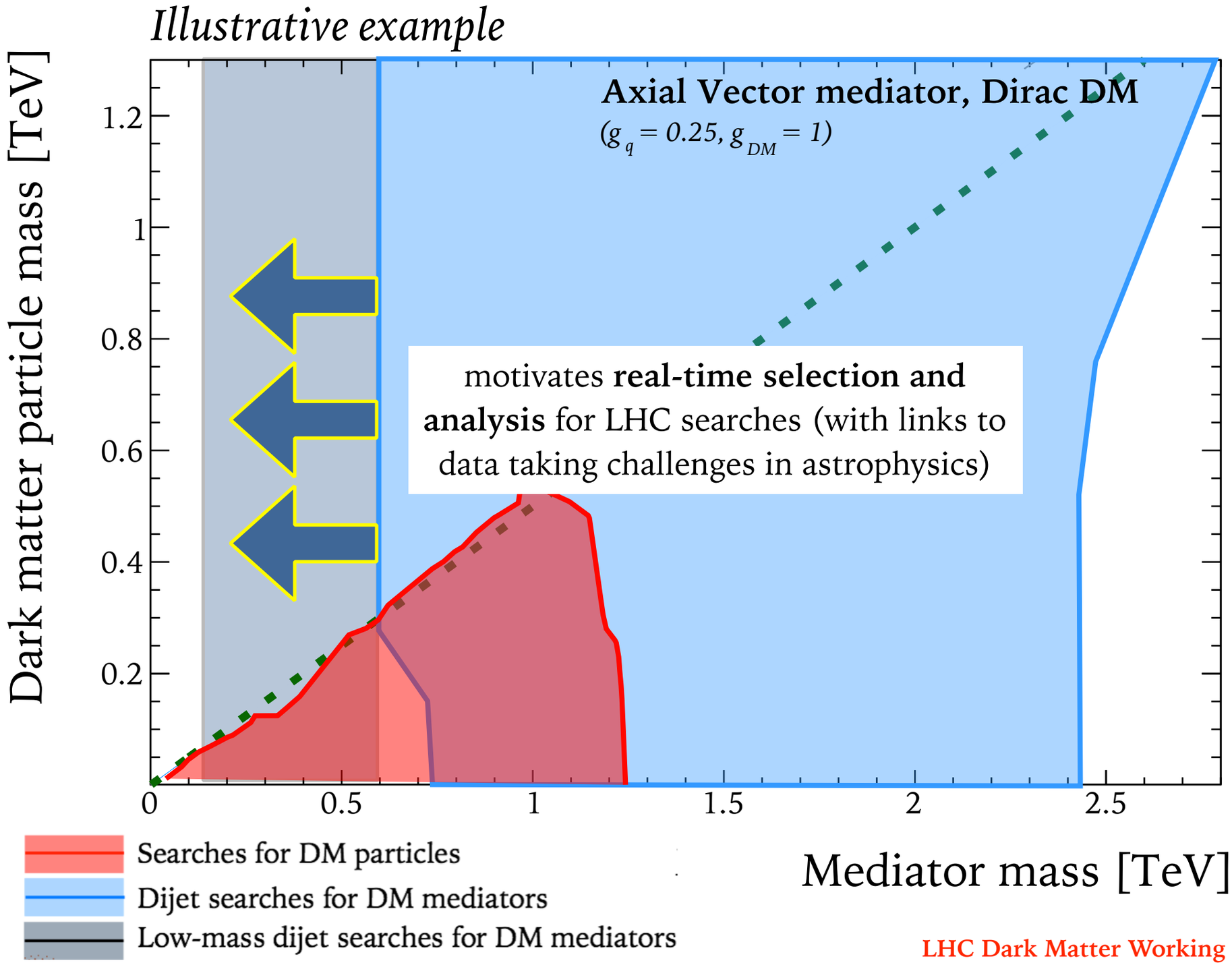
Complementarity of visible/invisible searches



LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

Keep in mind: different couplings —> different picture

Complementarity of visible/invisible searches



LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

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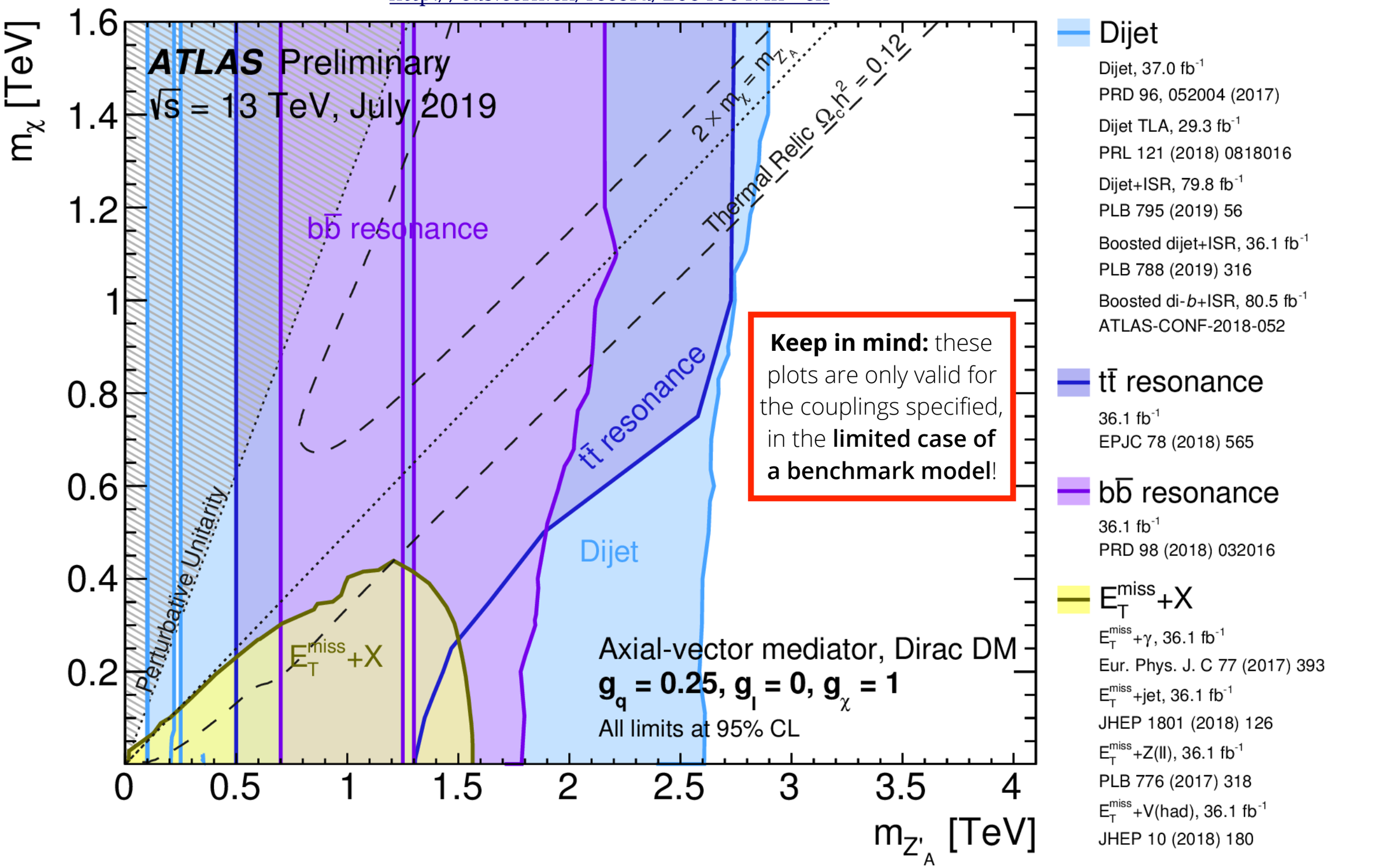
Horizon 2020
European Union funding
for Research & Innovation
LUND UNIVERSITY

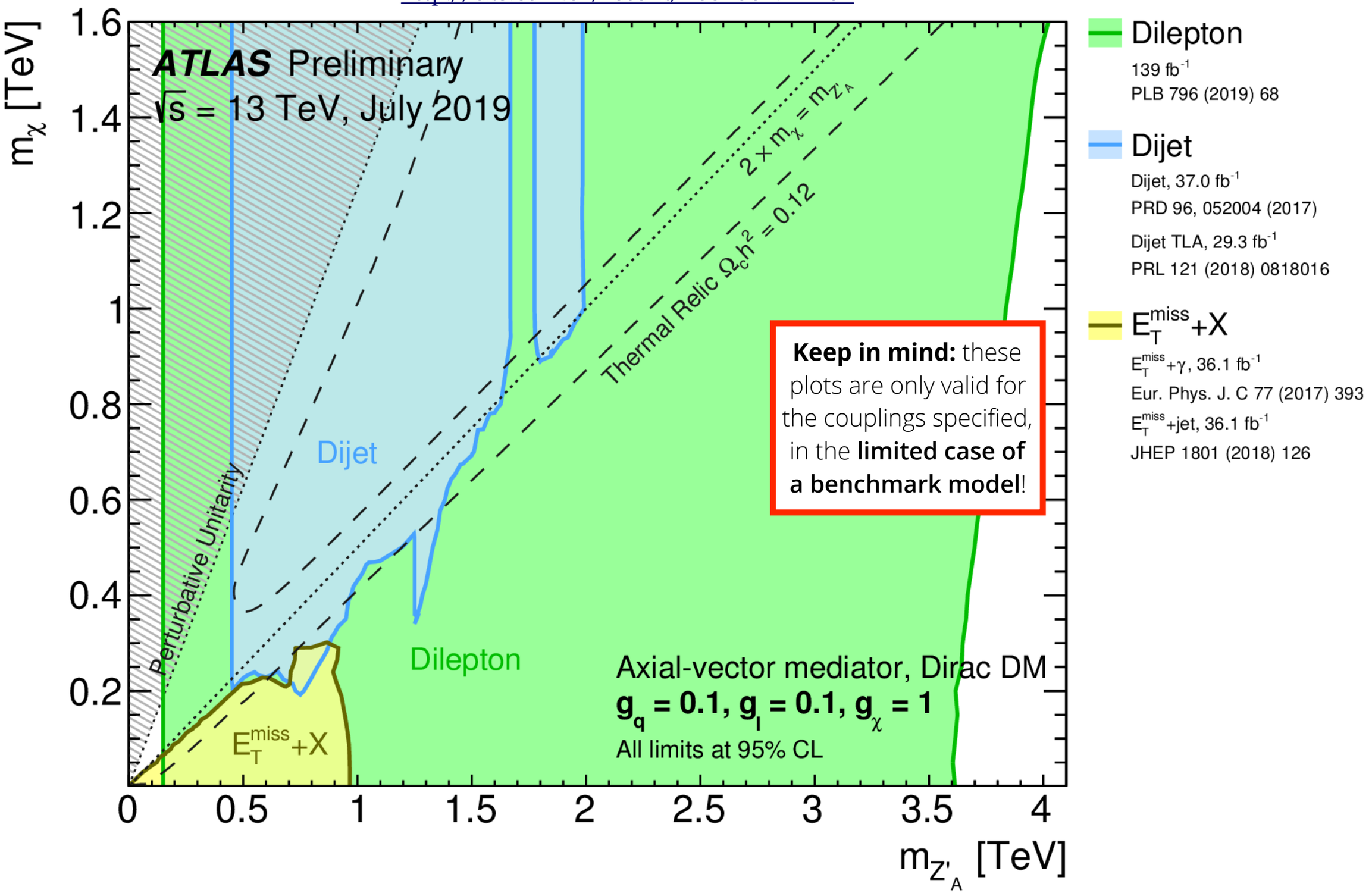
S-channel A-V mediator: coupling to quarks = 0.25

http://cds.cern.ch/record/2684864?ln=en



S-channel A-V mediator: coupling to quarks = 0.1

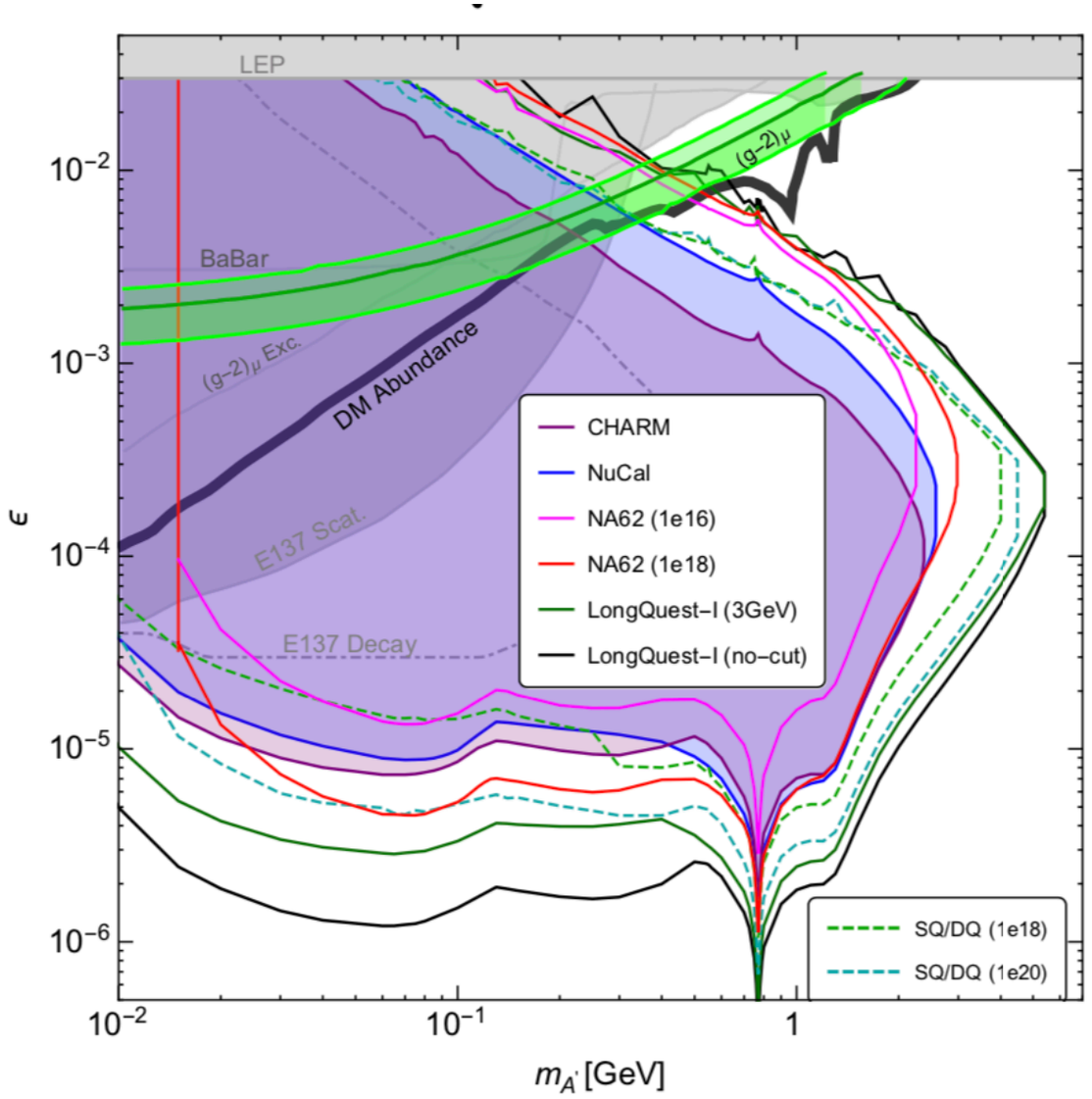
http://cds.cern.ch/record/2684864?ln=en



Inelastic DM as g-2 motivated model

See also: arXiv:1804.00009

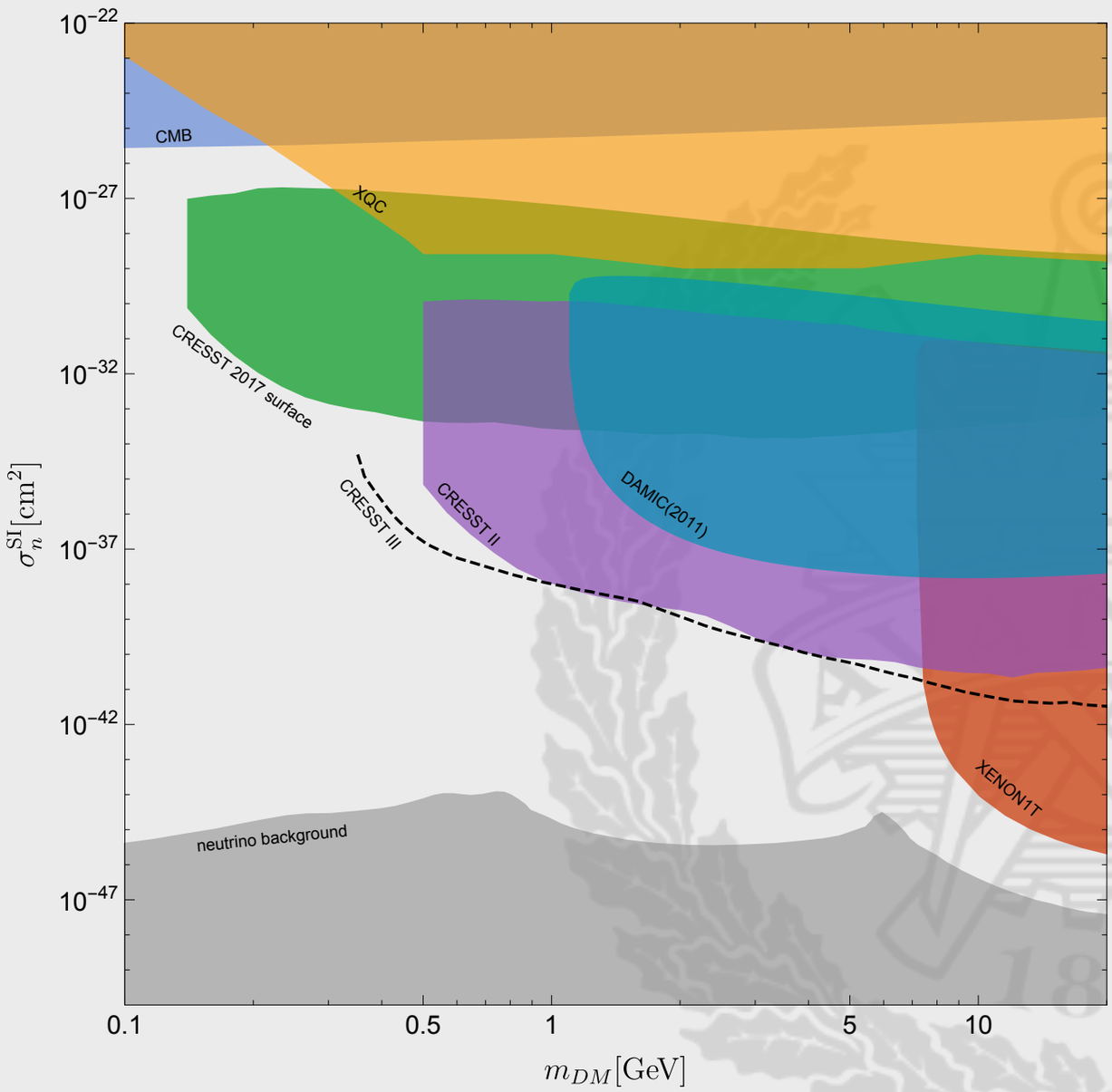
Mass splitting between DM and other new particle: 0.4, α_D=0.1



arXiv:1908.07525

Timon Emken's talk

Constraints on the DM-nucleon scattering cross-section



PBH/MACHO constraints

M. Cirelli's talk @ GGI 2019