Physics Beyond the Standard Model (experimental) - Part 3

CATERINA DOGLIONI - LUND UNIVERSITY

Outline for these three BSM lectures

Lecture 1

The Standard Model has no apparent major problem!

Why should we look beyond, and how? Direct and indirect BSM searches

Lecture 2

The Standard Model has some problems!

Solving many problems at once: *supersymmetry*

Solving one problem at a time: *generic dark matter searches* (at the LHC, for today)

Lecture 3

Connecting DM@LHC with DM beyond the LHC (direct and indirect detection)

Darker matter: the rare and the unexpected (at the LHC and beyond)

One-slide of other BSM theories & results

(Almost) back to the SM: neutrino physics

Recap of Lecture 1

The SM has no problems (…just wait until today's lecture…)!

- Measurements and agreement with theory

✅Energy frontier => exploration of the unknown

"Generic" ***direct search strategies***:

look for (sizable) deviations signaling the presence of new particles

A simple BSM search in more detail

❌Energy frontier => but we're not upgrading the LHC energy anytime soon!

Indirect search strategies:

look for (small) deviations from the presence of new particles in loops

Recap of Lecture 2

The SM has some problems!

- the Higgs and the hierarchy problem [some solutions: this afternoon]
- dark matter and dark energy [some solutions: this afternoon]
- neutrino masses [problem & solutions: tomorrow]

Solving many problems at once: **Supersymmetry (SUSY)**

How to search for SUSY & interpret results

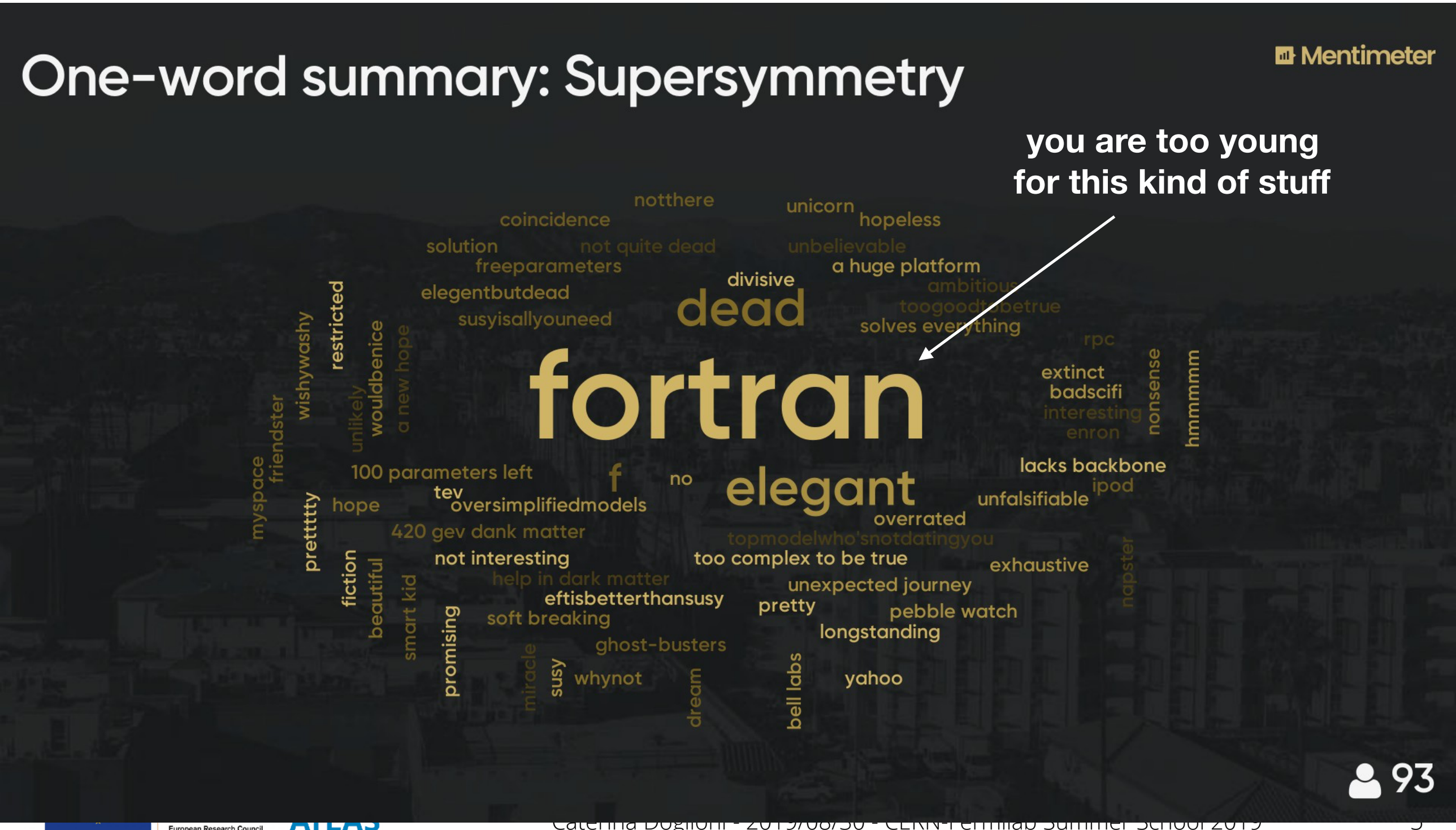
SUSY @ LHC: where we are, where we are going

Solving at least one big problem: not-necessarily-SUSY **Dark Matter, part 1**

~~Dark matter~~ Invisible particles at colliders

Benchmark models and searches

Wordcloud #1


Mentimeter
One-word summary: Supersymmetry
you are too young
for this kind of stuff
fortran
dead
elegant
notthere
coincidence
solution
not quite dead
freeparameters
elegentbutdead
susyisallyouneed
divisive
unicorn
hopeless
unbelievable
a huge platform
ambitious
toogoodtobetrue
solves everything
rpc
extinct
badscifi
interesting
enron
nonsense
hmmmmm
lacks backbone
ipod
unfalsifiable
overrated
topmodelwho'snotdatingyou
exhaustive
napster
wishywashy
restricted
wouldbenice
a new hope
unlikely
myspace
friendster
prettttty
100 parameters left
tev
oversimplifiedmodels
hope
420 gev dank matter
not interesting
too complex to be true
help in dark matter
unexpected journey
pretty
pebble watch
longstanding
eftisbetterthansusy
soft breaking
ghost-busters
fiction
beautiful
smart kid
promising
miracle
susy
whynot
dream
bell labs
yahoo
f
no
93

Wordcloud #2


One-word summary: Dark matter
Mentimeter
cool
cold
cosmos-constrained
too many candidates
invisiblesearches
butwimpsdontexistor
astrophysics
interdisciplinary
invisible
elusive
entropic gravity
nonluminous
cosmology
entropicgravity
met
useful
fascinating
wru
whyshoulditinteract
z and met
icecube
intriguing
intersting
wimp
exciting
abundant
cantwait
30

End of Lecture 2

~~DM~~ invisible particles at colliders

Let's start simple: Higgs portal models

arXiv:1903.03616

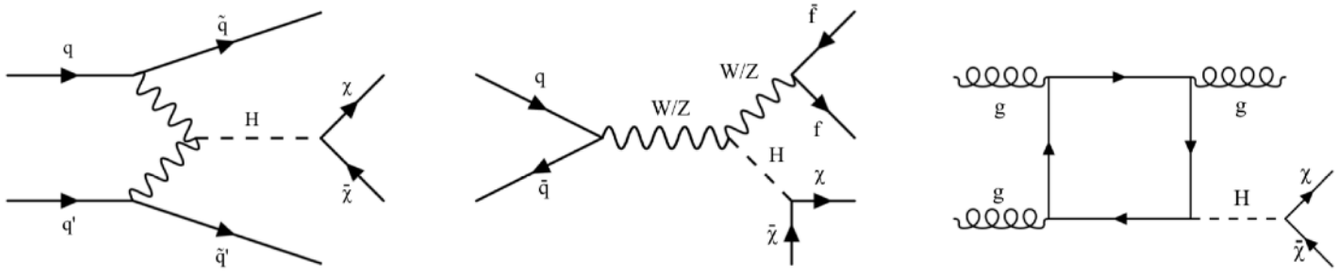
$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi \,.$$

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2 \,,$$

Lambda for fermion EFT: assumed 1 TeV

- Only add the DM particle to SM
- Test different kinds of dark matter
  - Majorana fermion/scalar
  - Vector not there for historical reasons

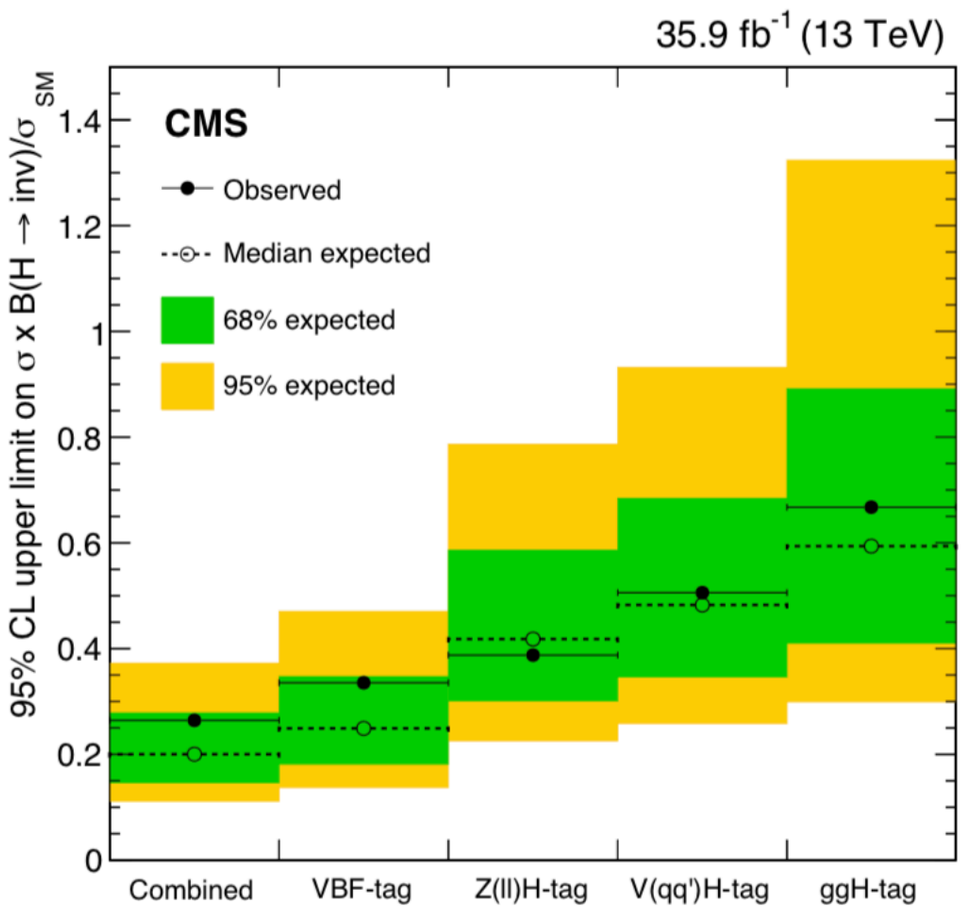
- How to detect invisibly decaying Higgs:
- **directly** (MET searches)

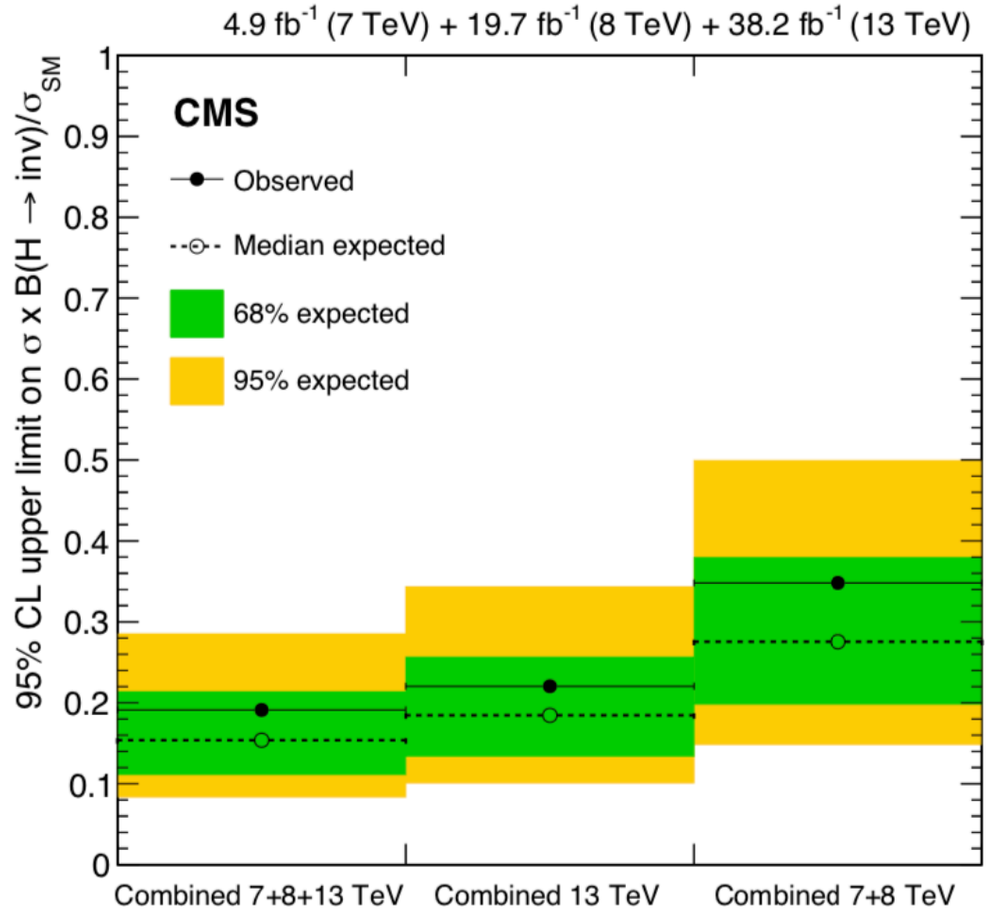


- **indirectly** (deviation of SM coupling through fits, using κ-framework)
  - including only σ x Branching Ratio (BR) measurements/ratios, no high-pT Higgs keeping SM BR fixed, only allow invisible BR to float in the fit (subtracting SM)

Higgs portal DM results with partial Run-2 data

https://arxiv.org/abs/1809.05937





LHC sensitive to a Higgs to invisible BR of ~0.2

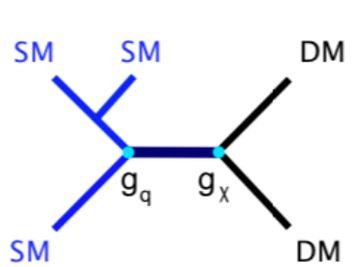
(SM value: invisible BR ~ 10^{-3}, reachable by future colliders)

Add a BSM mediator: s-channel vector/scalar models

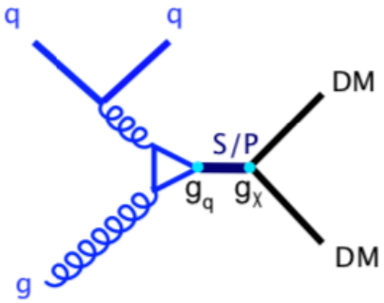
arXiv:1708.02245 & references Ann.Rev.Nucl.Part.Sci. 68 (2018) 429-459

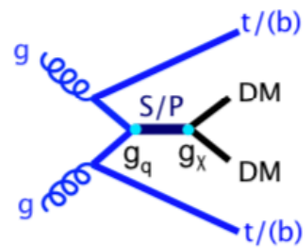
Map possible types of s-channel mediator exchanges between DM and SM: vector, axial-vector, scalar, pseudo-scalar mediators

- How to detect them:
  - **invisible decays** (MET searches)



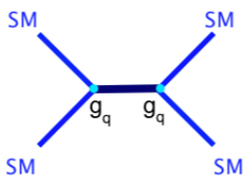
Mono-jet search (or mono-photon)



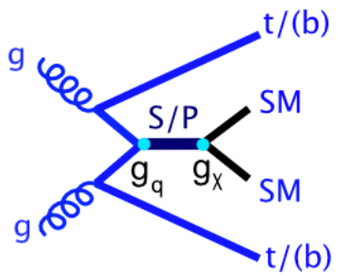


MET in association with heavy flavor quarks
(also: single top, Wt signatures)

- **visible decays of mediators**



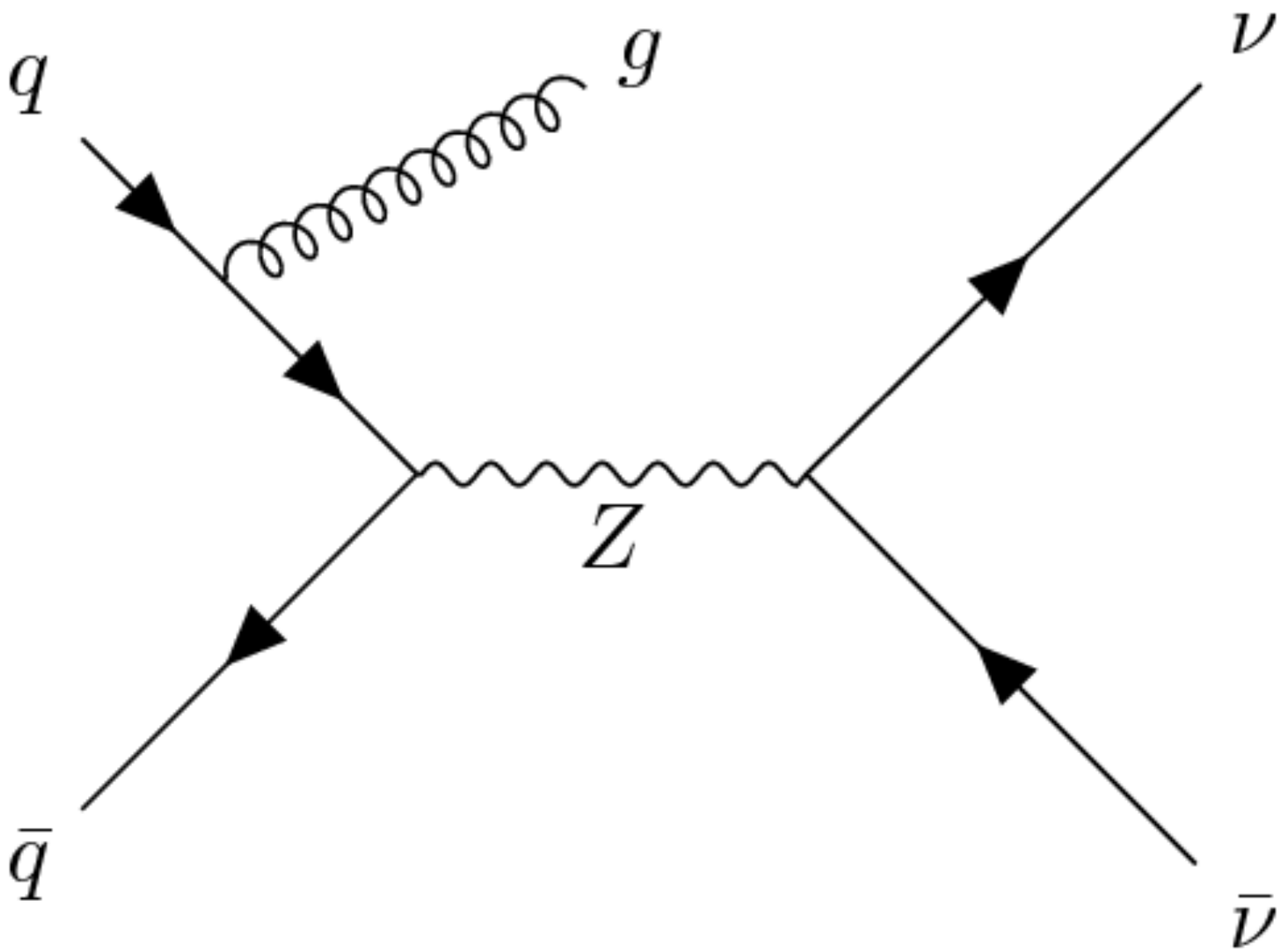
Di-object searches



Rare 4-top signatures

LHC production of invisible particles

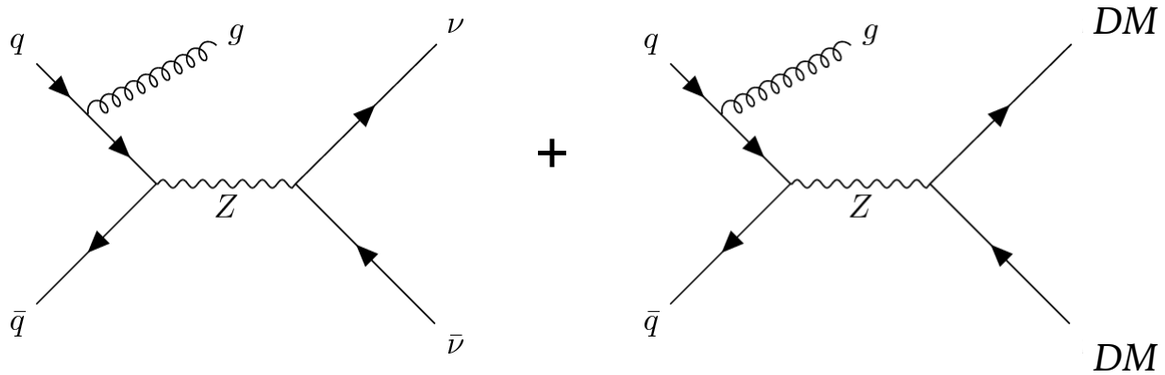
Production of invisible particles is common in the SM

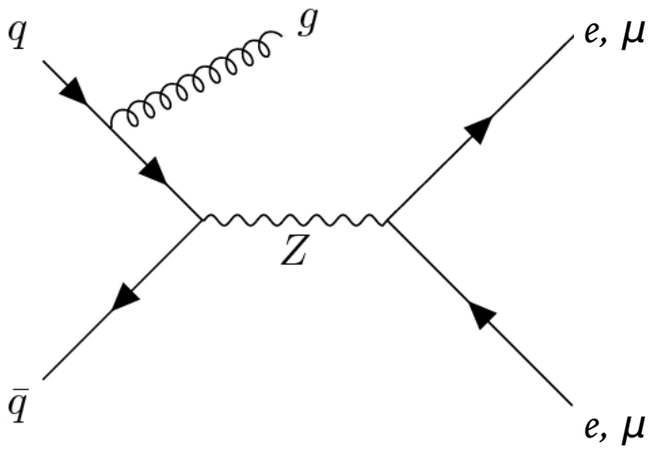


Eur. Phys. J. C 77 (2017) 765

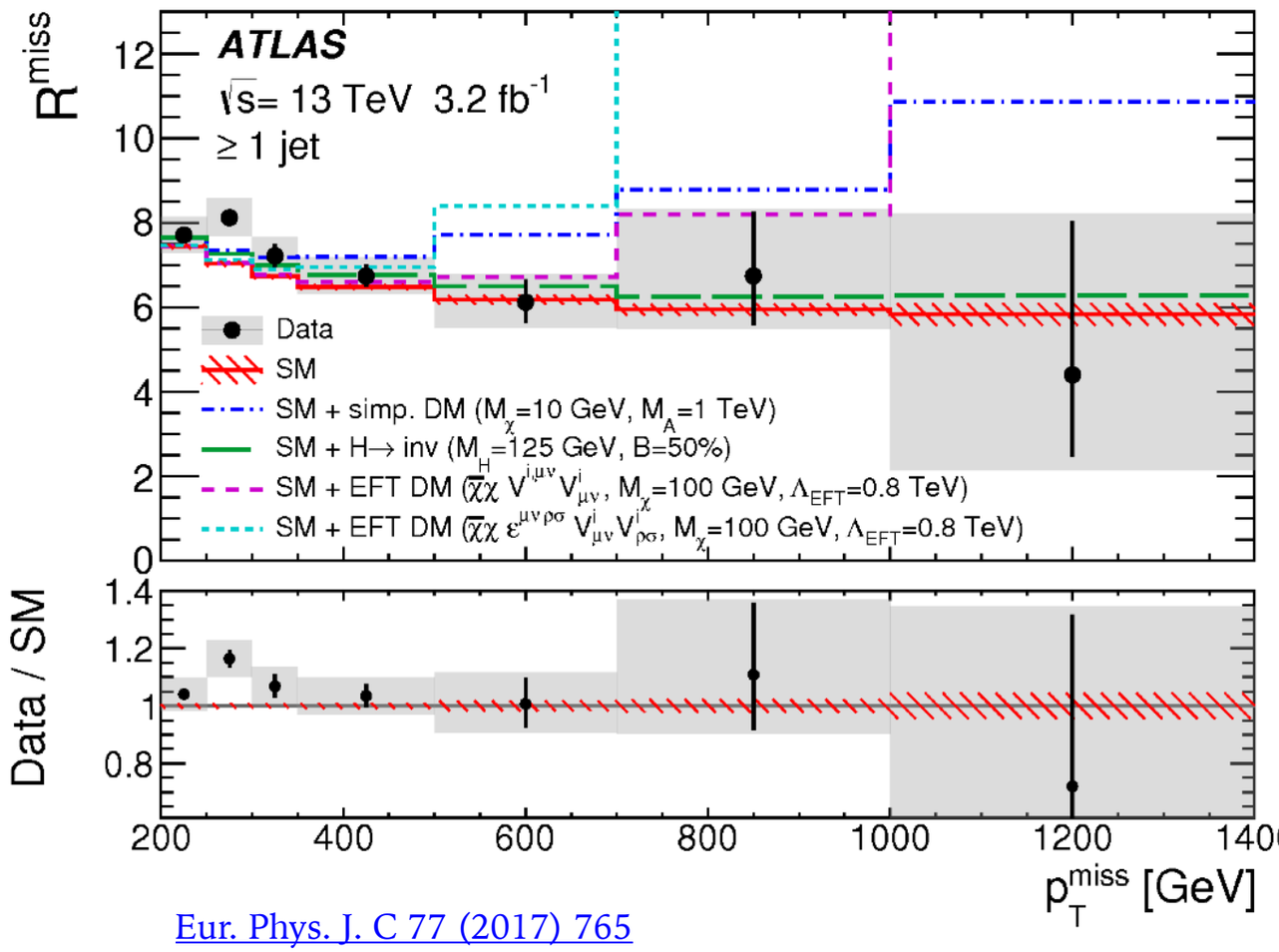
LHC production of new invisible particles

Production of invisible particles can be common in the SM
use **standard candles** (Z boson) to search for non-SM production





$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}\left(p_{\text{T}}^{\text{miss}} + \text{jets}\right)}{\sigma_{\text{fid}}\left(\ell^{+}\ell^{-} + \text{jets}\right)}$$



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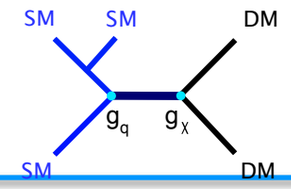
Generic searches for DM: "*X+MET*"



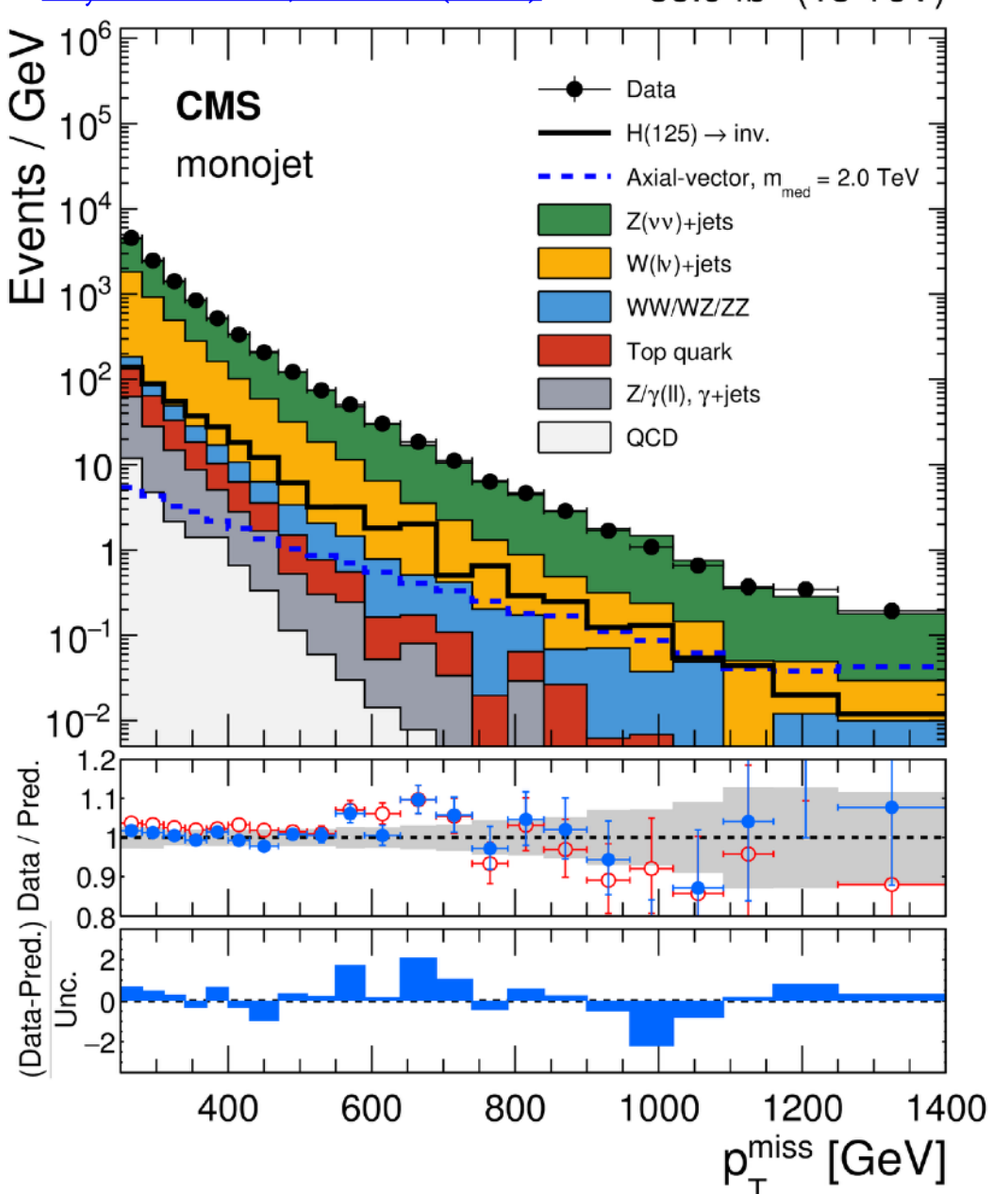
ISR (jet, photon, V boson…) + MET signature

Background normalized using data

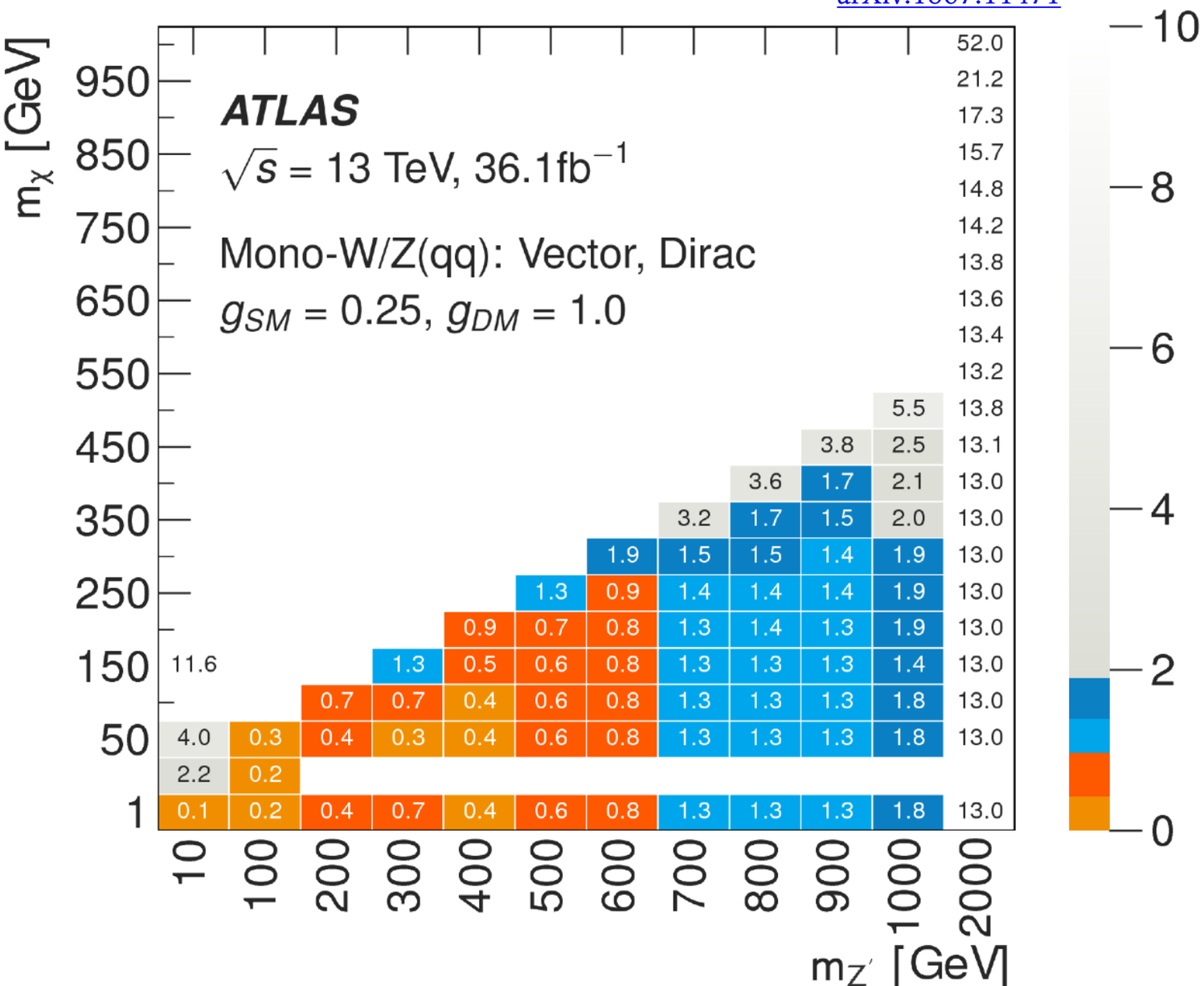
Background shapes need precise theory predictions [EPJC 2017 77:829]

Results can be interpreted in a variety of models

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



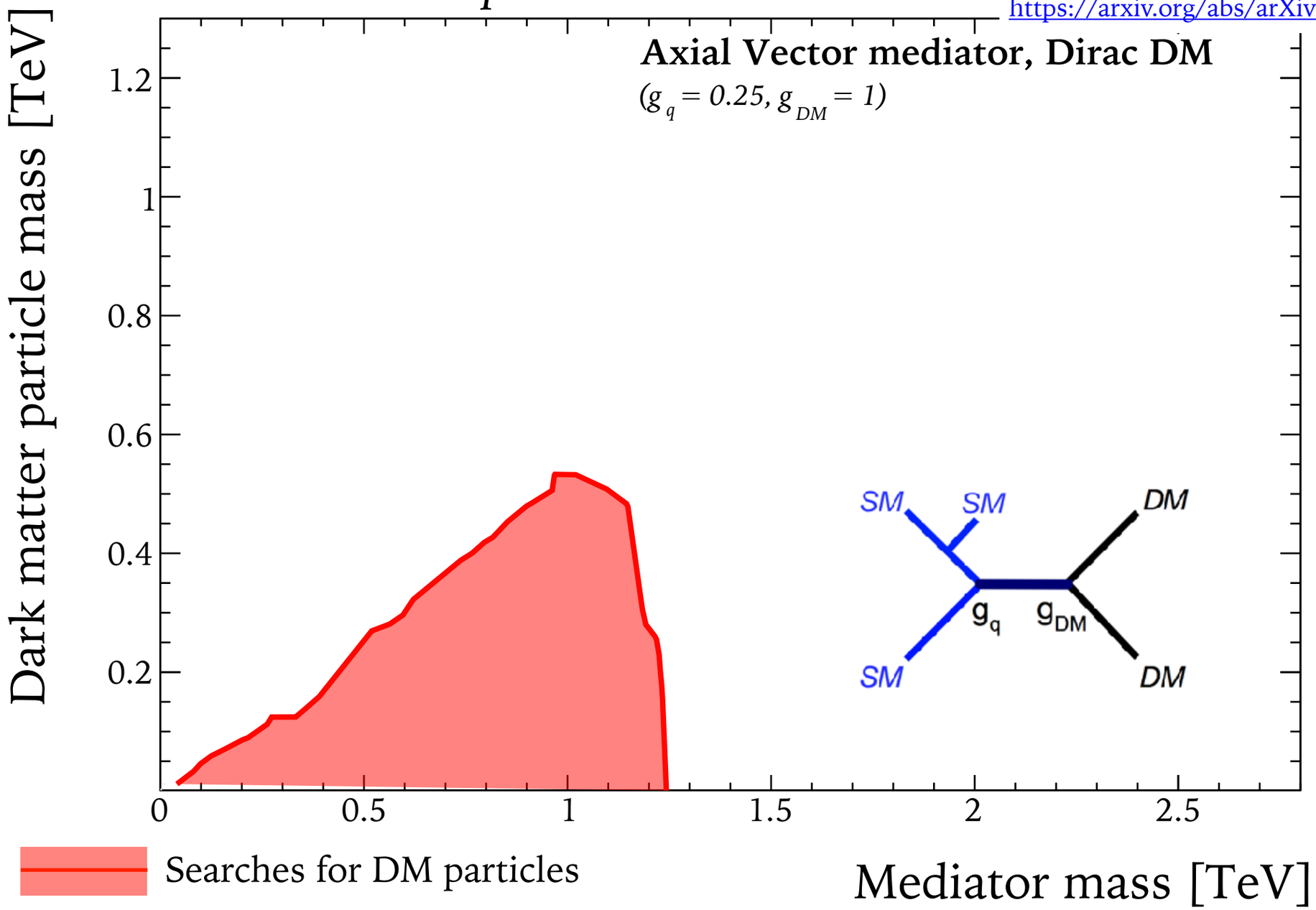
[arXiv:1807.11471]



Complementarity of visible/invisible searches

Illustrative example

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



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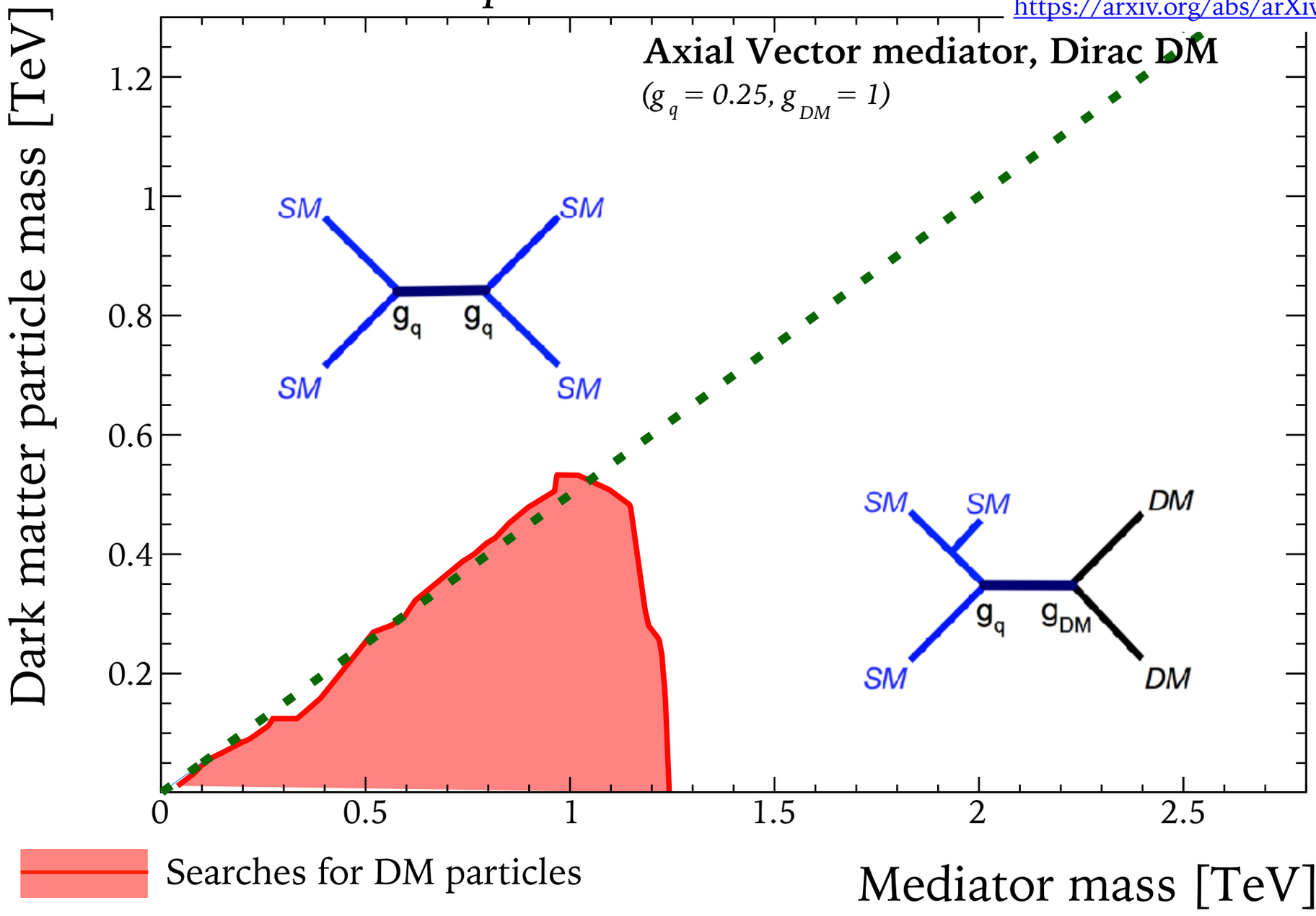

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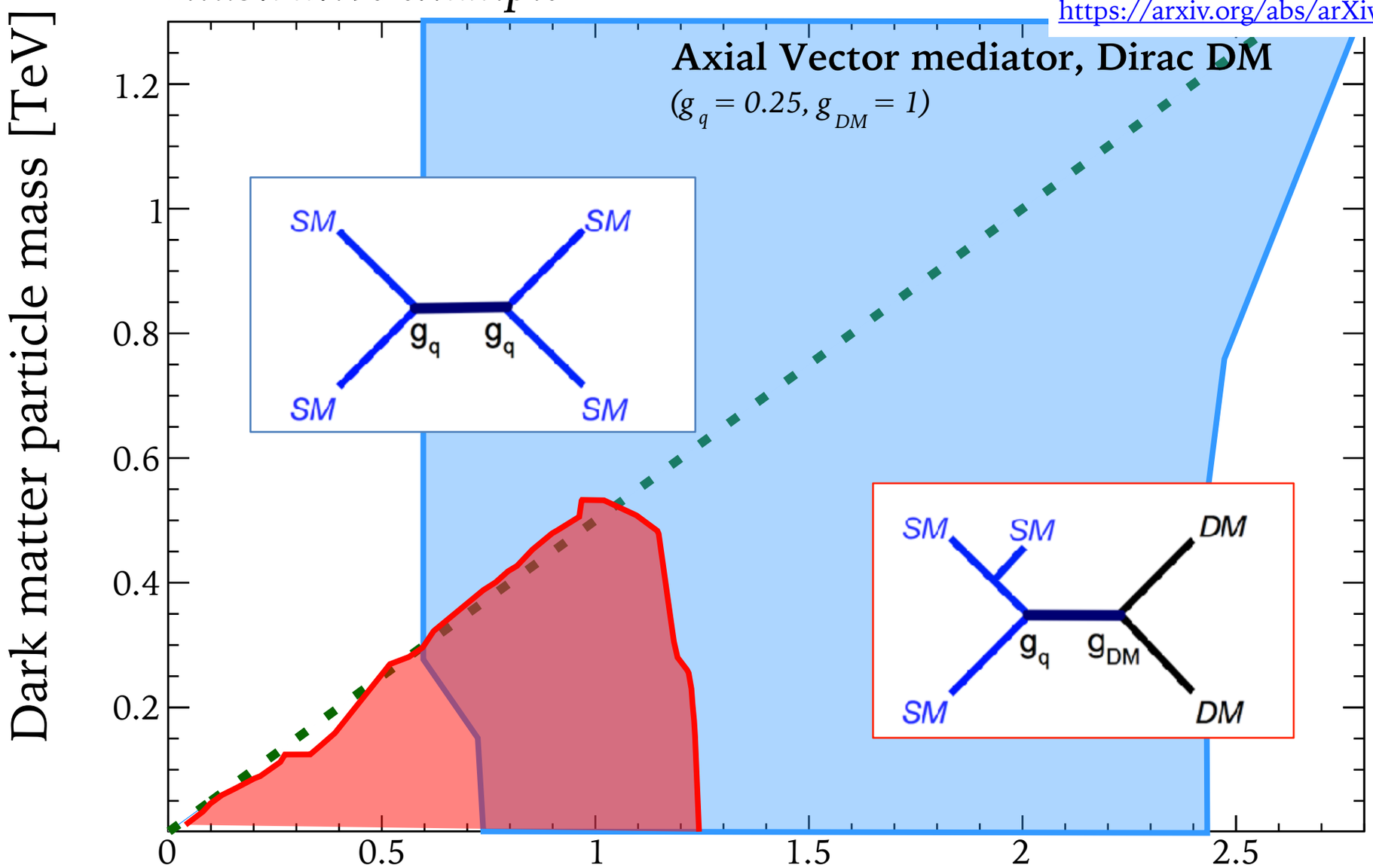

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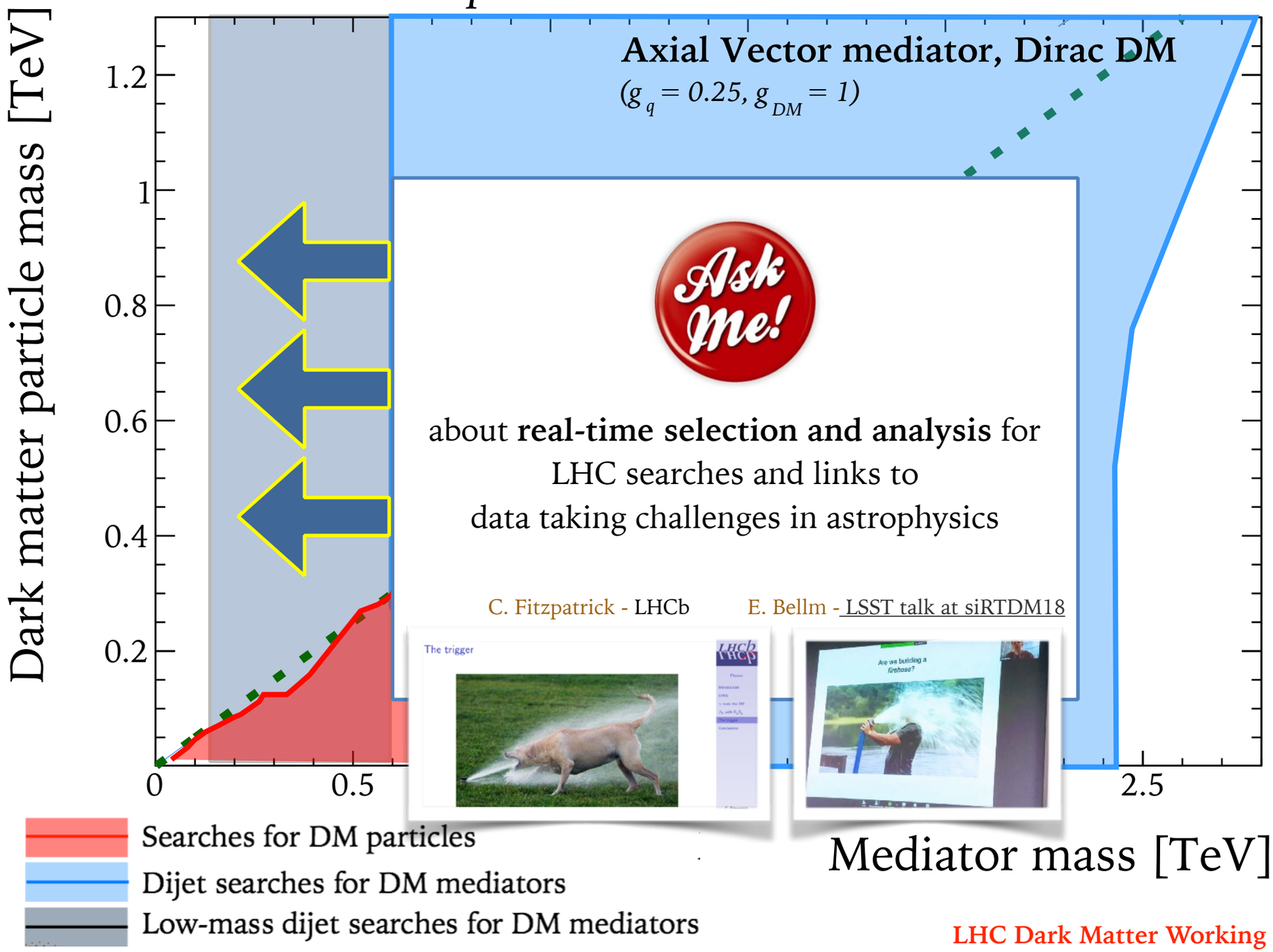
Collider strength for these models: searches for visible mediator decays

Complementarity of visible/invisible searches

Illustrative example



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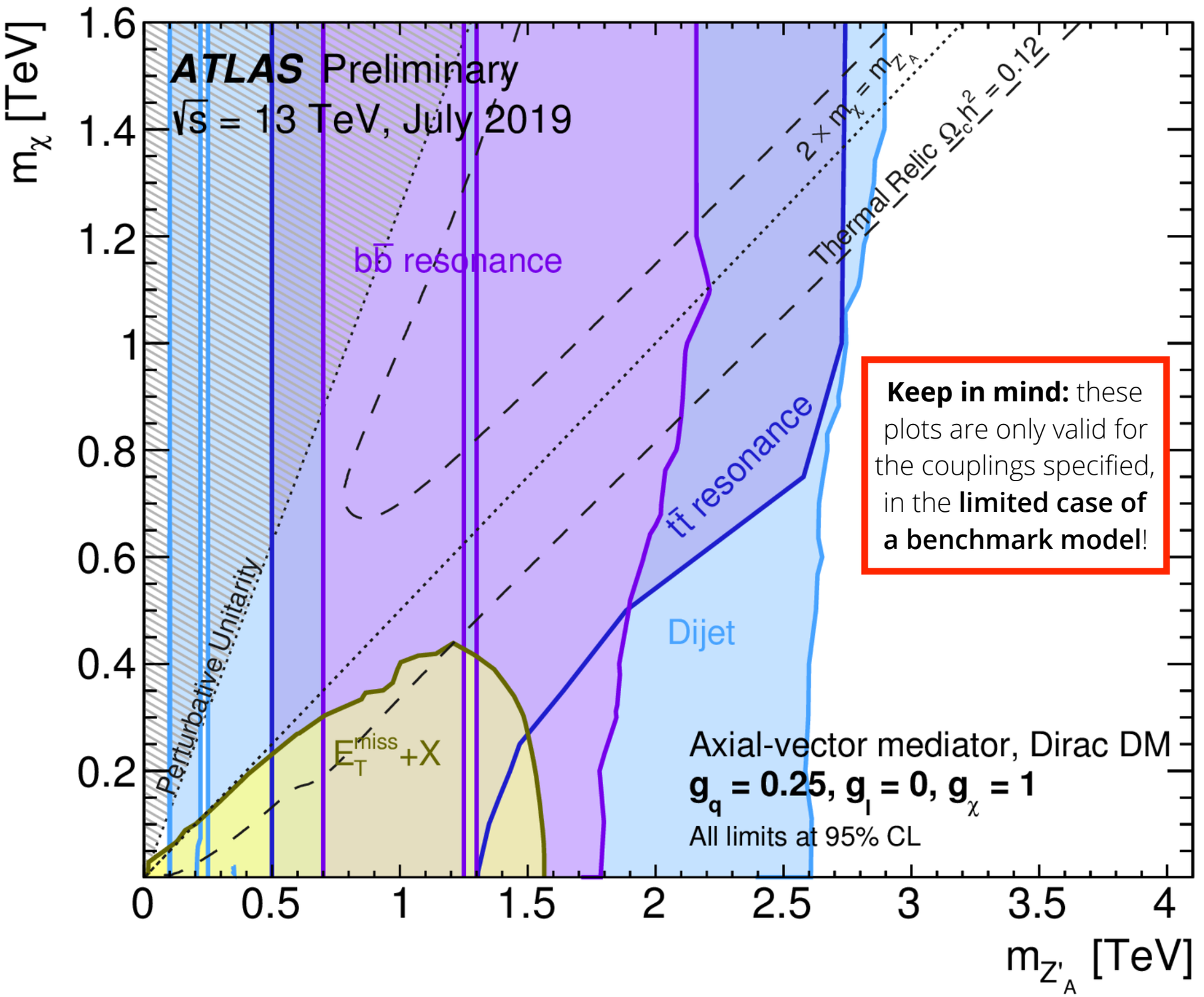
Collider strength for these models: searches for visible mediator decays

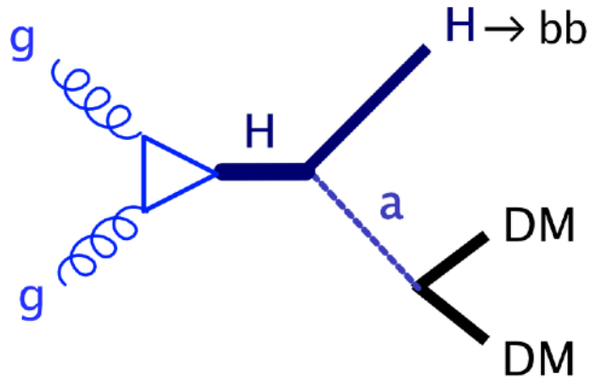
State of the art for s-channel A-V mediator



More complex models: pseudo/scalars in 2HDM

Compelling searches with increase of LHC dataset involve
new particles interacting with DM, alongside **Higgs boson**

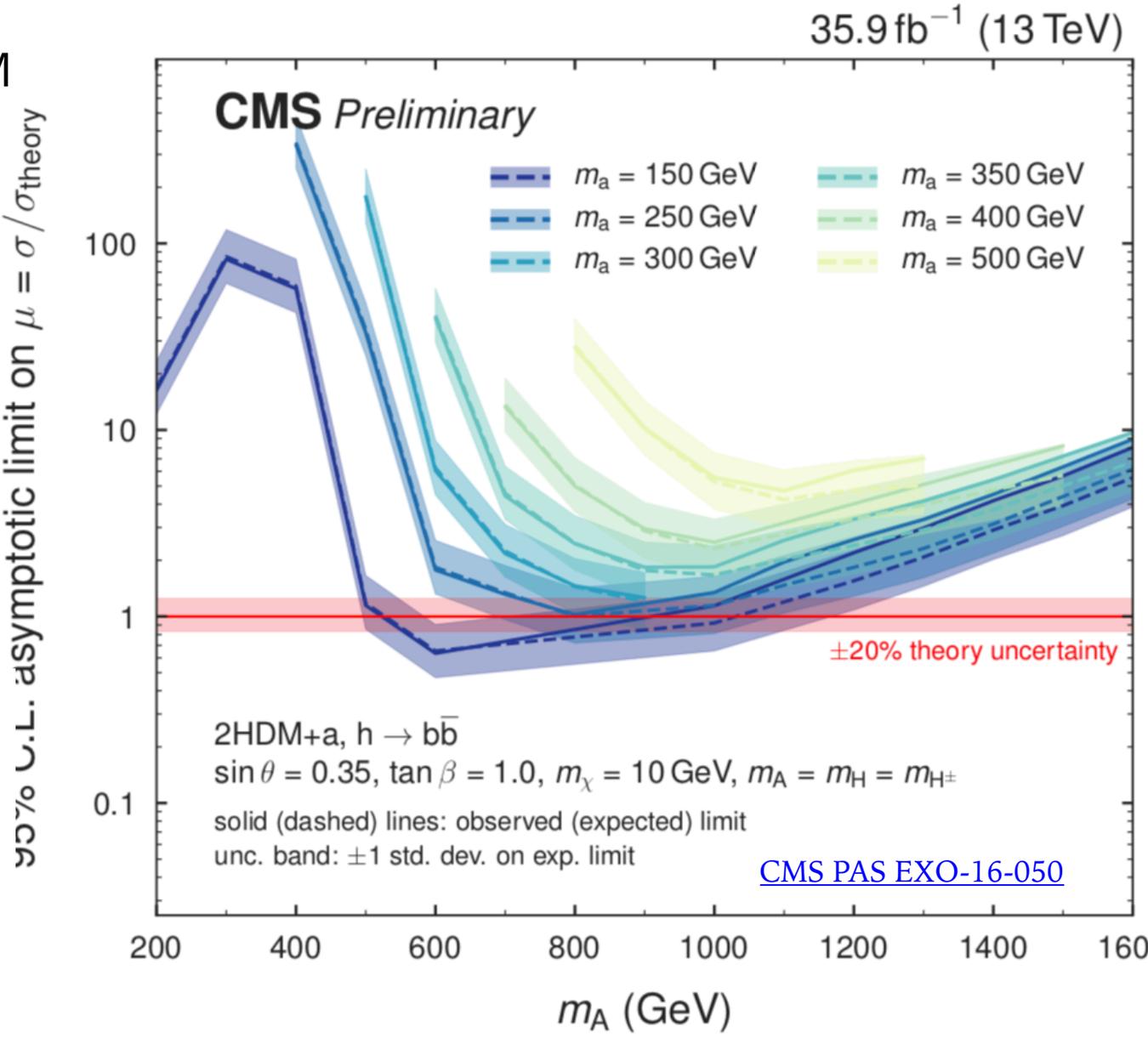
Example: pseudoscalar interacting with DM in a Two (2)-Higgs Doublet Model



LHC Dark Matter Working Group
https://arxiv.org/abs/1810.09420

E.g. search for MET + two b-quarks
ATLAS / CMS
No excess observed yet

LHC dataset sufficient to start being sensitive to this kind of processes, Run-3 dataset needed for more



Take-home point #1:

Generic searches for DM particles targeting simple (simplified) models show the unique LHC ability to look into the SM-DM interactions,
but they are only a starting point

Lecture 3

Detailed outline of Lecture 3

DM in a global context

- LHC searches, and what we know from astrophysics
- Comparing collider, direct and indirect detection experiments + status

Darker matter: WIMPs are not the only way

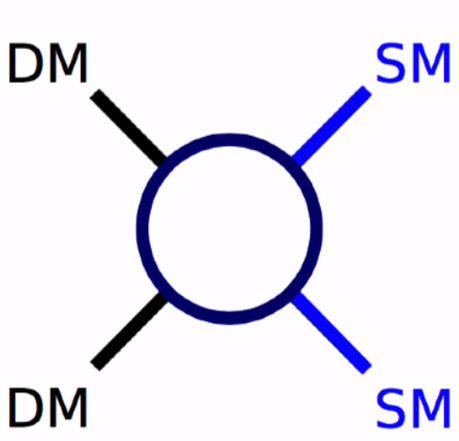
- The relic density as a guiding principle (or not)
- Other models (with long-lifetime particles), searches, experiments

One slide of other BSMs (and **leptoquarks**)

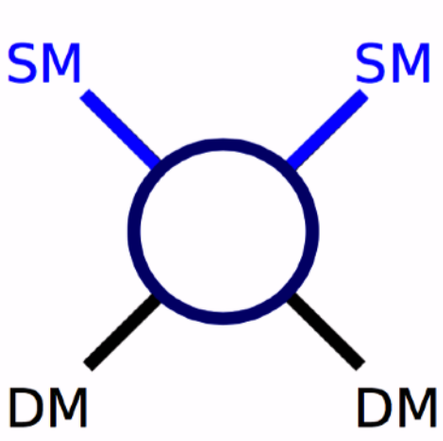
A very quick tour of BSM in the **neutrino sector**

The global landscape of DM

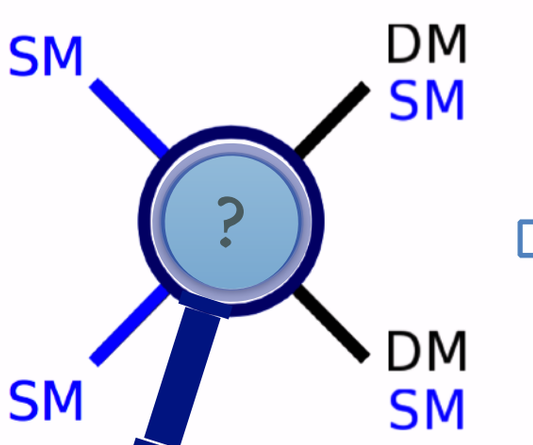
Collider, direct and indirect detection



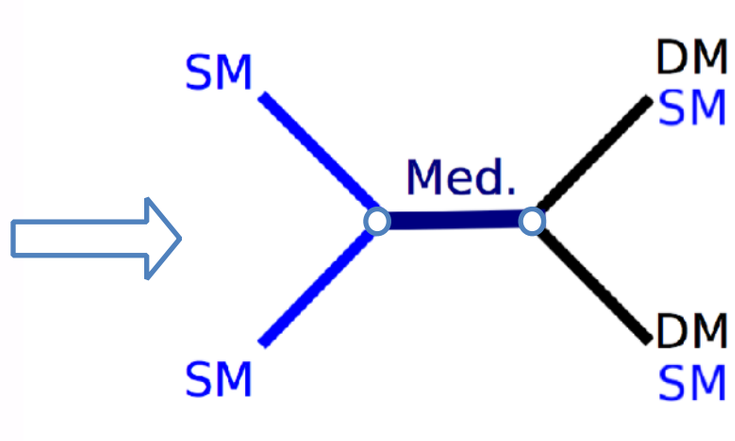
Indirect Detection



Direct Detection



Particle Colliders



See **C. De Los Heros**'s talk @ EPSHEP'19

See **I. Pellmann**'s talk @ EPSHEP'19

See **M. Genest**'s talk @ EPSHEP'19

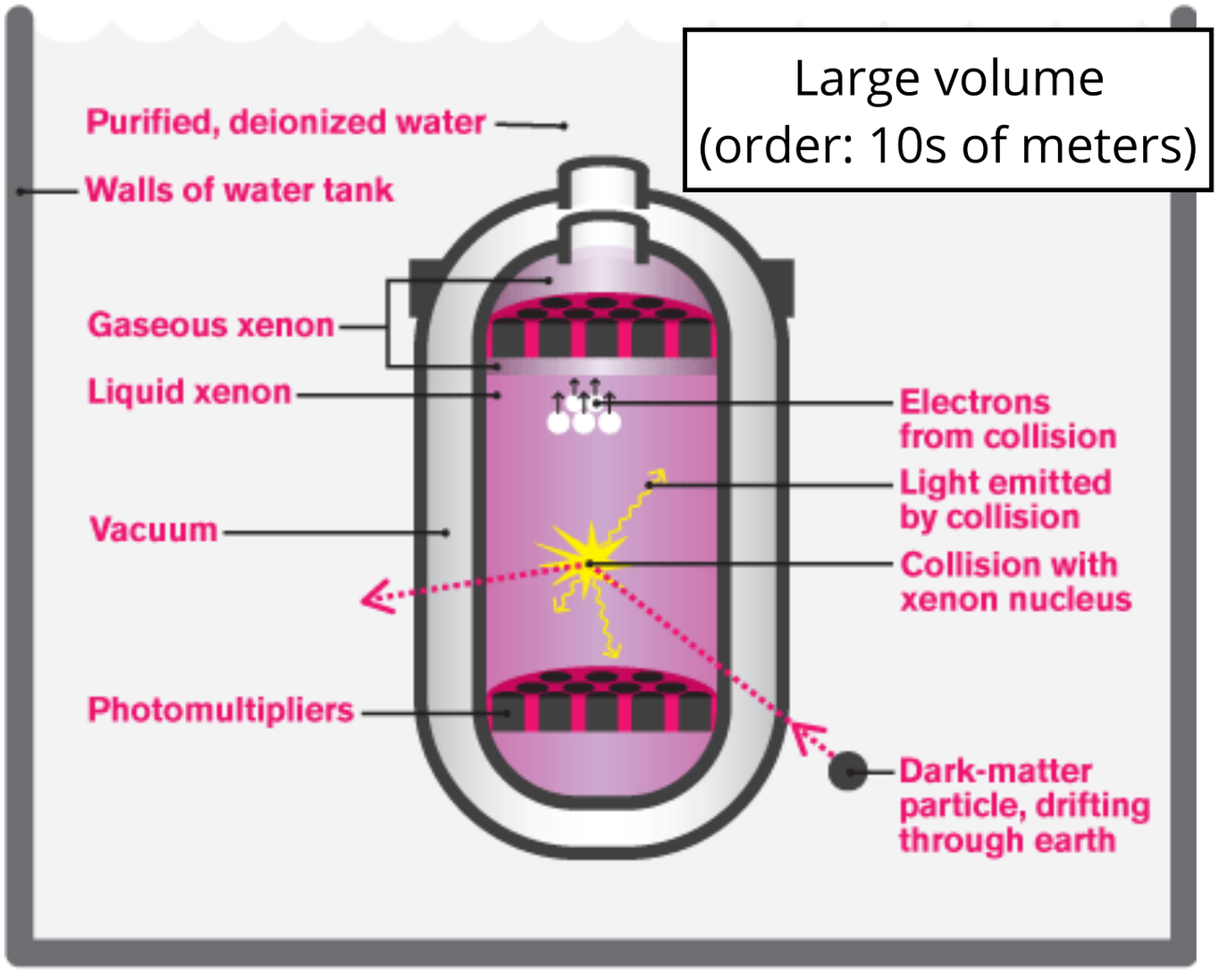
Complementary experiments tackling DM problem commonality: small signals (**WI**MP)

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

Examples of direct detection experiments: LUX/CRESST

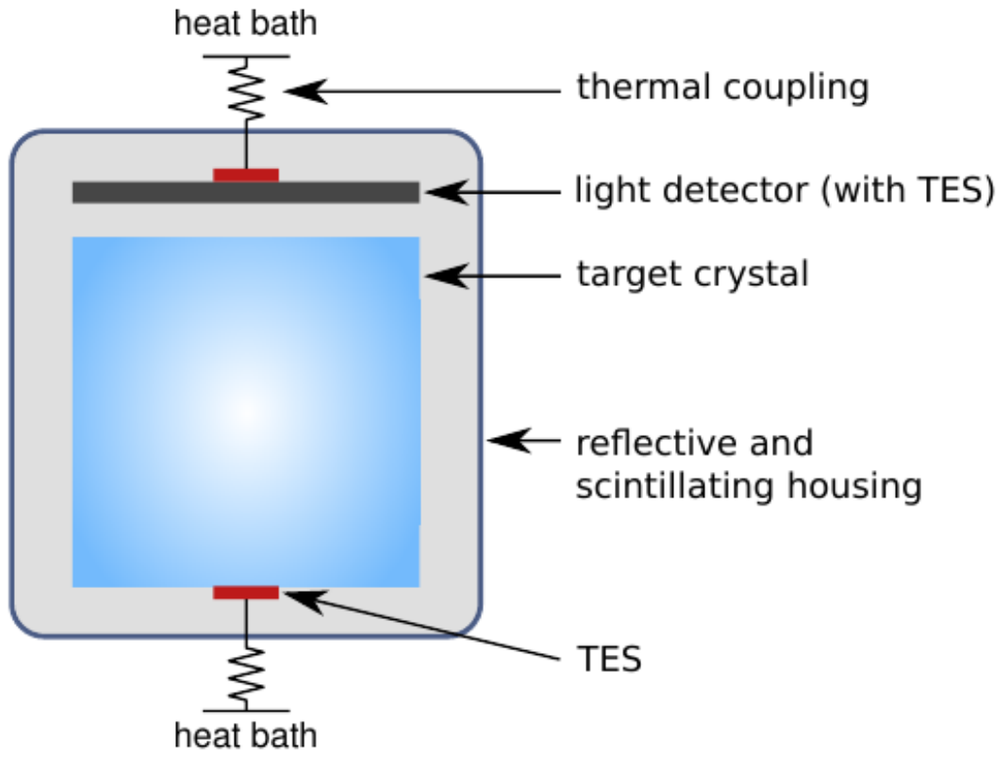
Search for Dark Matter: **LUX**

Large volume
(order: 10s of meters)



Search for Dark Matter: **CRESST**

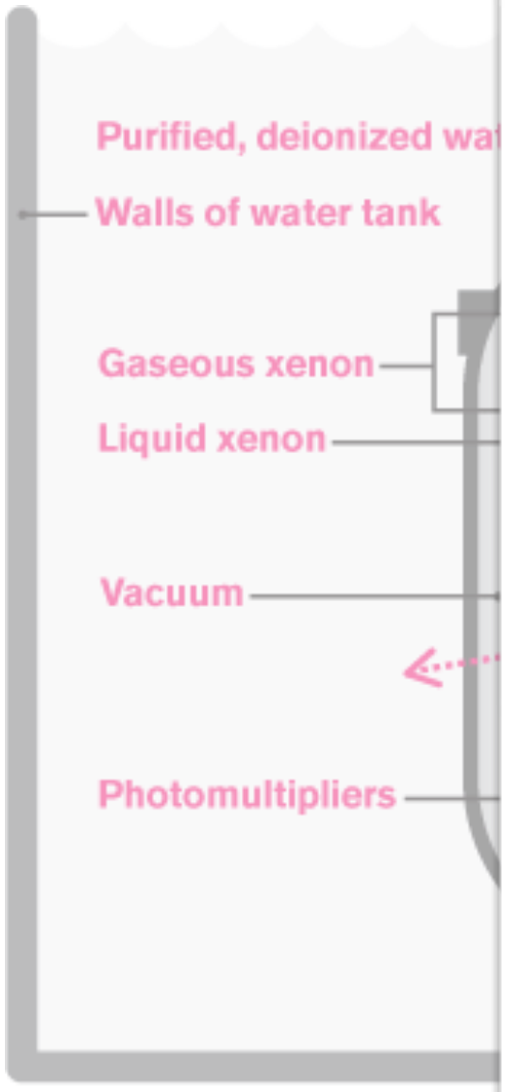
Very sensitive, smaller volume
(order: 10s of centimeters)



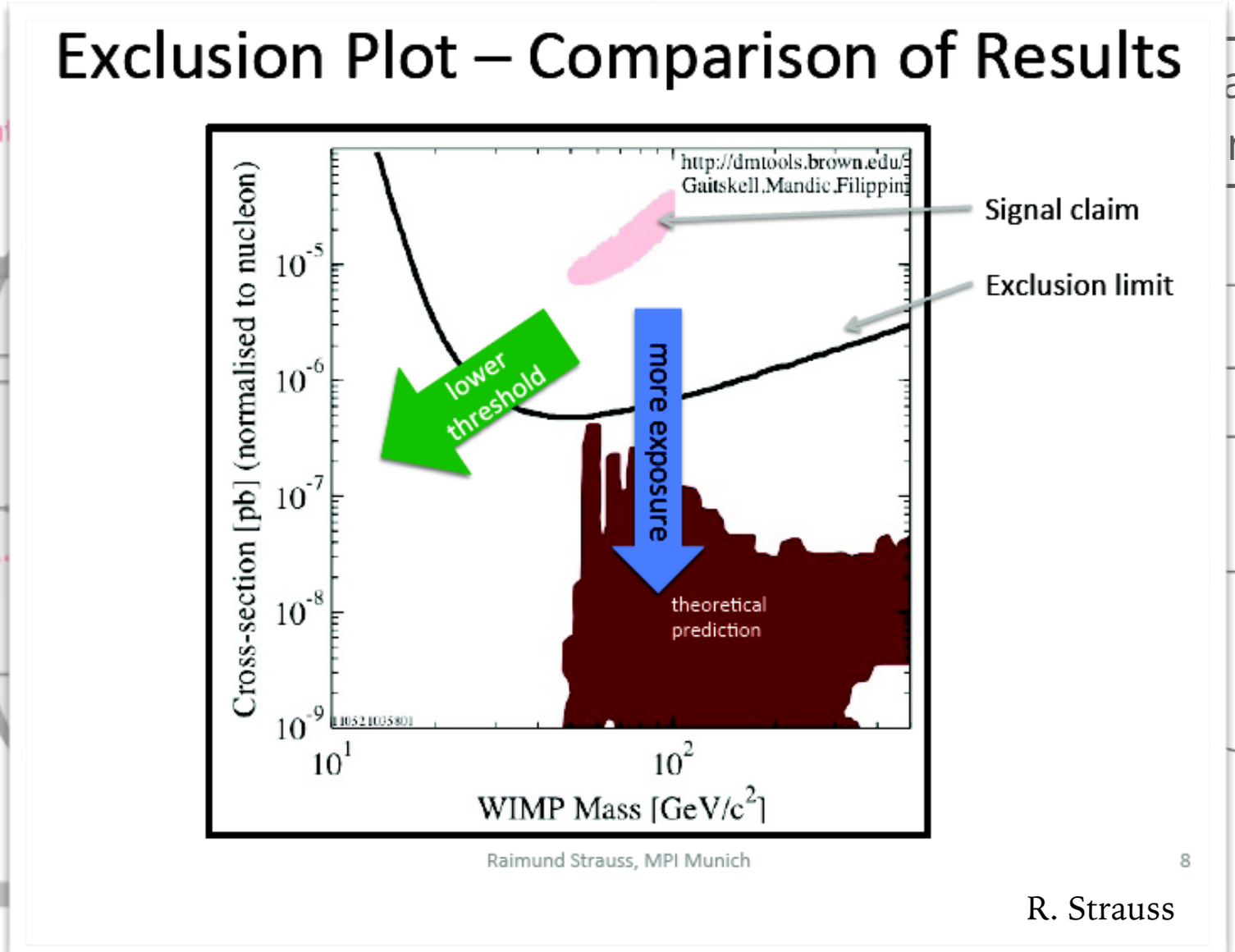
Many more experiments operational/planned for this decade

Examples of direct detection experiments: results

Search for Dark Matter: **LUX**



Search for Dark Matter: **CRESST**



aller volume
ntimeters)

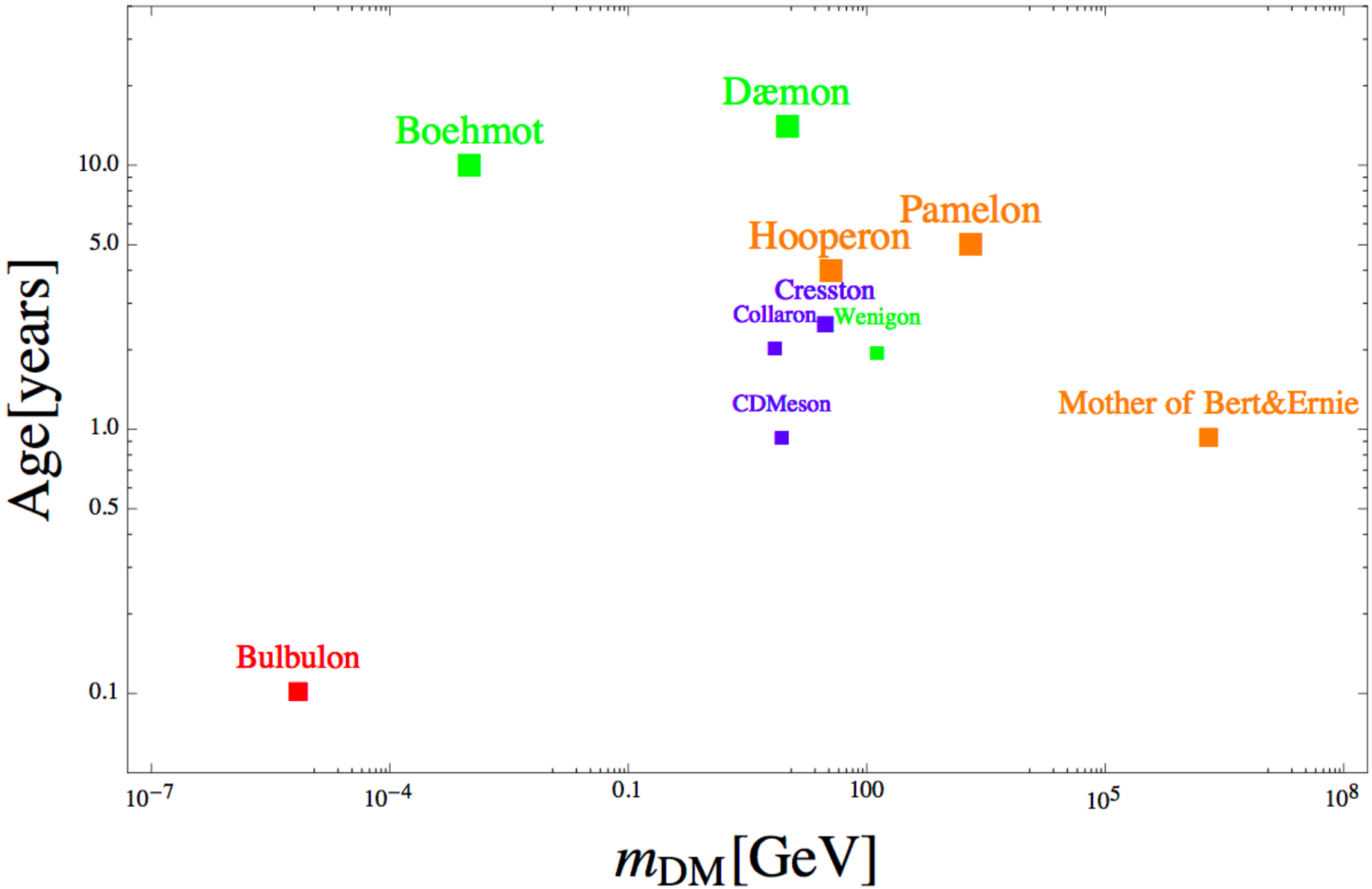
- thermal coupling
- light detector (with TES)
- target crystal
- reflective and scintillating housing
- TES

R. Strauss

Many more experiments operational/planned for this decade

Are we finding something?

http://resonaances.blogspot.com.br/2014/03/weekend-plot-all-of-dark-matter.html



Fictional (?) Dark Matter candidates on this blog have the names of the paper authors

Are we going bananas?

Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla E. Jeltema, Stefano Profumo

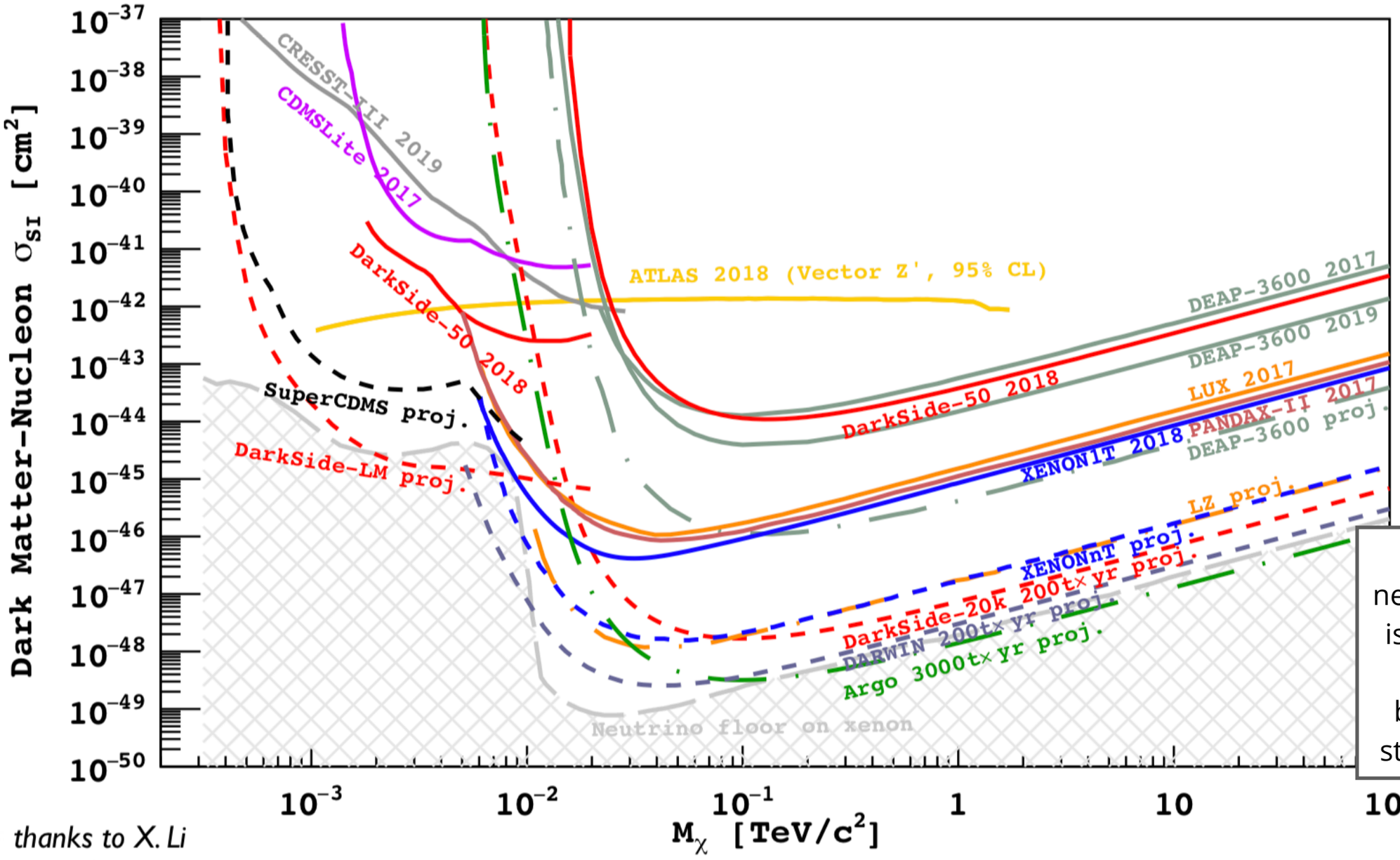
(Submitted on 7 Aug 2014 (this version), latest version 8 Apr 2015 (v2))

We examine the claimed excess X-ray line emission near 3.5 keV with a new analysis of XMM-Newton observations of the Milky Way center and with a re-analysis of the data on M31 and clusters. In no case do we find conclusive evidence for an excess. We show that known plasma lines, including in particular K XVIII lines at 3.48 and 3.52 keV, provide a satisfactory fit to the XMM data from the Galactic center. We assess the expected flux for the K XVIII lines and find that the measured line flux falls squarely within the predicted range based on the brightness of other well-measured lines in the energy range of interest. We then re-evaluate the evidence for excess emission from clusters of galaxies, including a previously unaccounted for Cl XVII line at 3.51 keV, and allowing for systematic uncertainty in the expected flux from known plasma lines and for additional uncertainty due to potential variation in the abundances of different elements. We find that no conclusive excess line emission is present within the systematic uncertainties in Perseus or in other clusters. Finally, we re-analyze XMM data for M31 and find no statistically significant line emission near 3.5 keV to a level greater than one sigma.

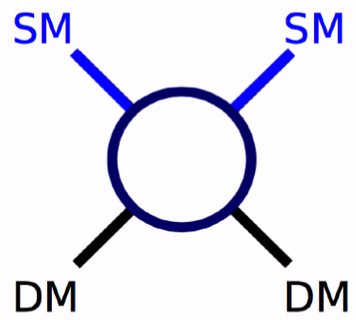
Why are bananas a problem for direct detection experiments?

Status & prospects of direct detection

J. Monroe's talk



thanks to X. Li



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

Direct detection + colliders in scalar mediator model

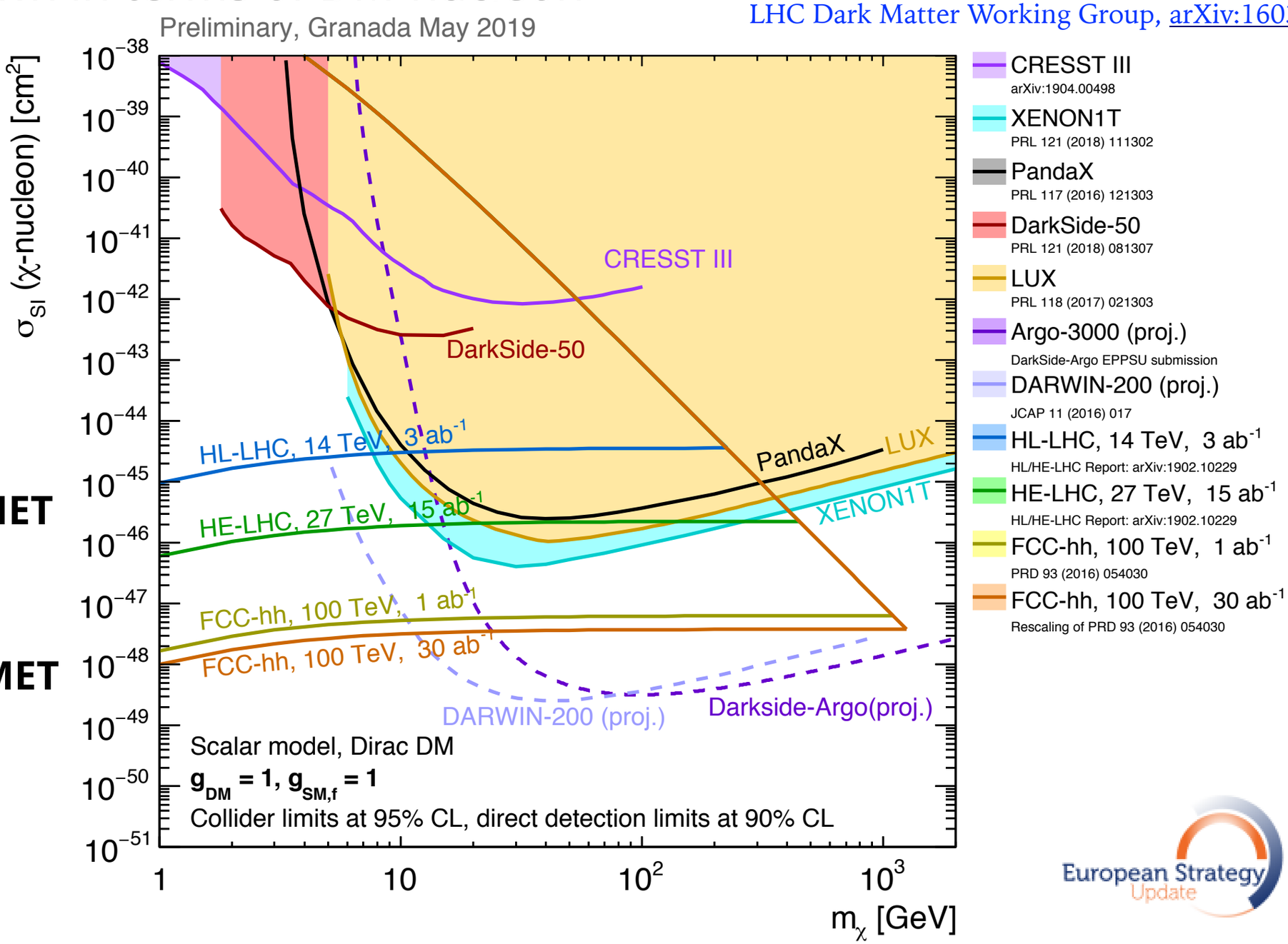
- (Hadron) collider constraints on simple models of DM can be shown in terms of DM-nucleon interactions

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

LHC Dark Matter Working Group, arXiv:1603.04156

ttbar+MET

V/jet+MET



European Research Council
Established by the European Commission

European Strategy Update

Direct detection + colliders in scalar mediator model

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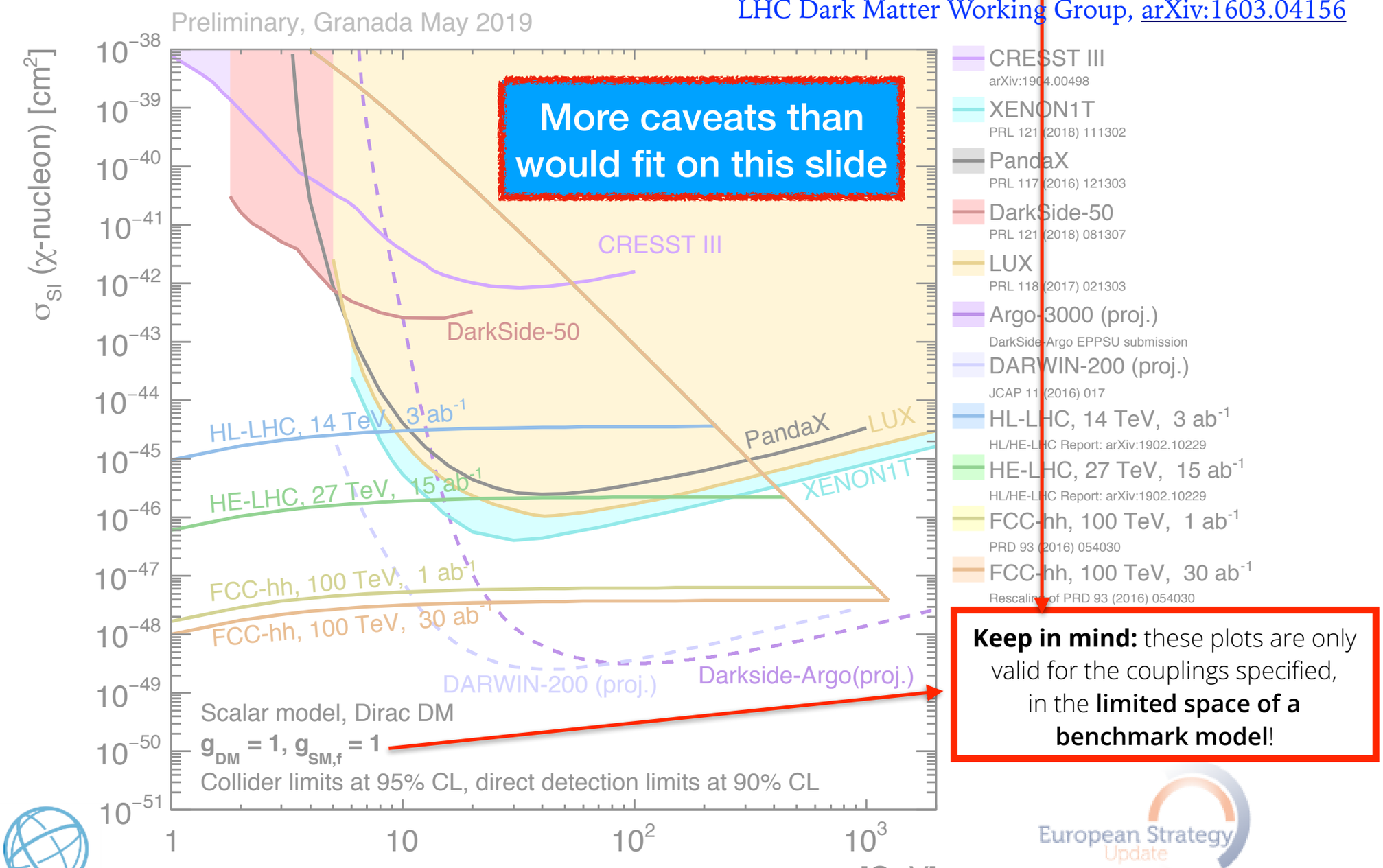
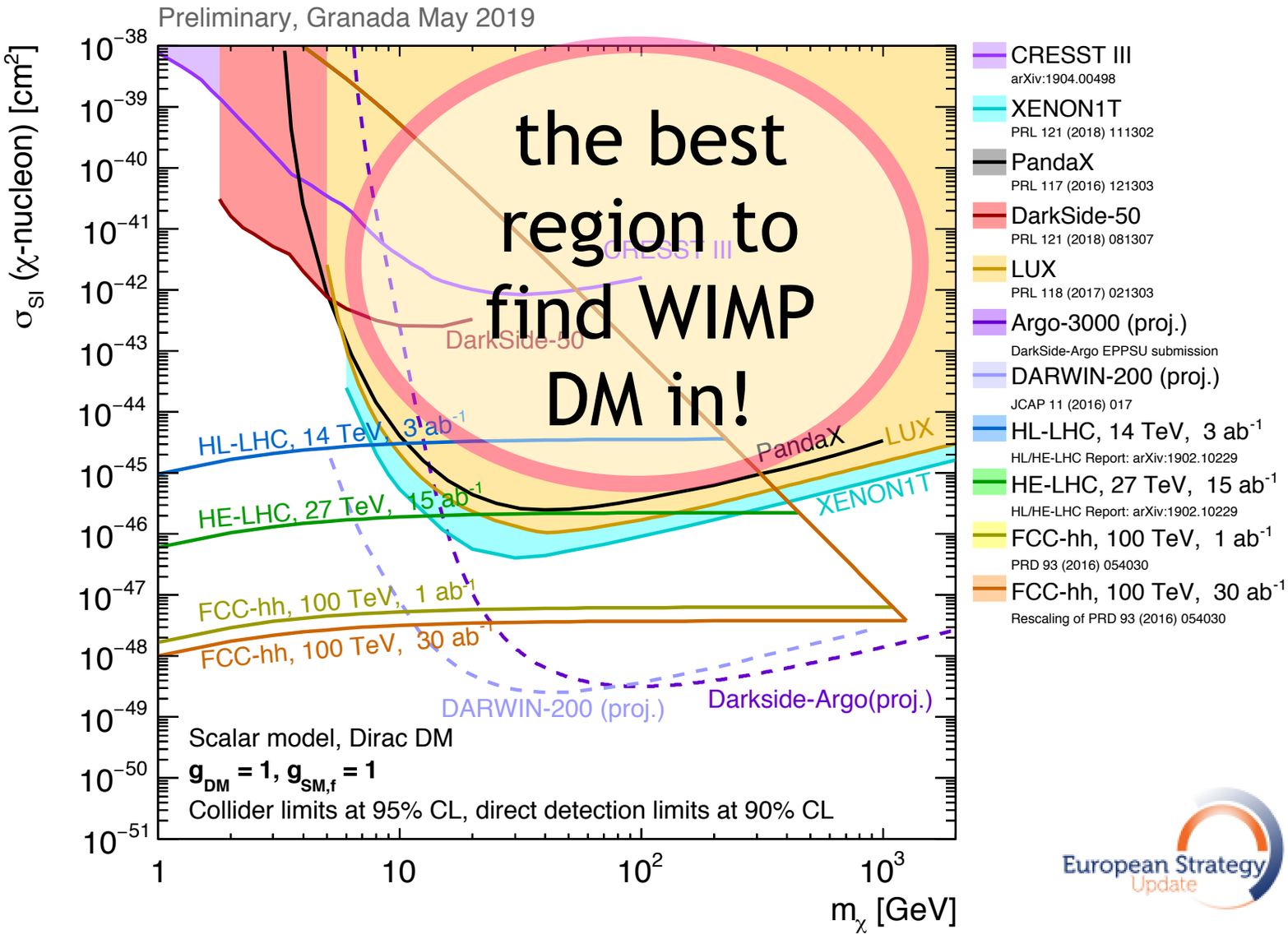


Keep in mind: these plots are only valid for the couplings specified, in the **limited space of a benchmark model**!

Direct detection + colliders in scalar mediator model

Synergy: complementary reach for future colliders and direct detection



- **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

See **V. Dutta**'s talk @ EPSHEP'19

- Synergies with also in non-WIMP DM, for DD and beam dump experiments

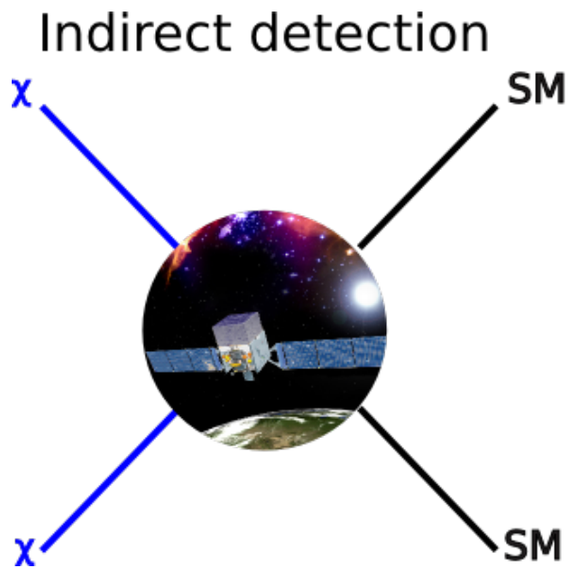
See **S. Stapnes**'s talk @ EPSHEP'19

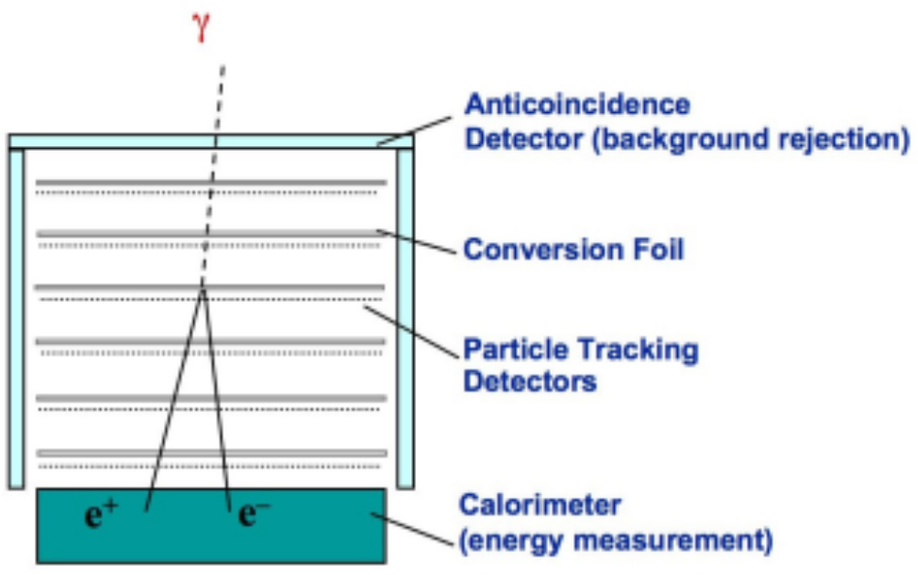
Indirect Detection example/excess: Fermi-LAT

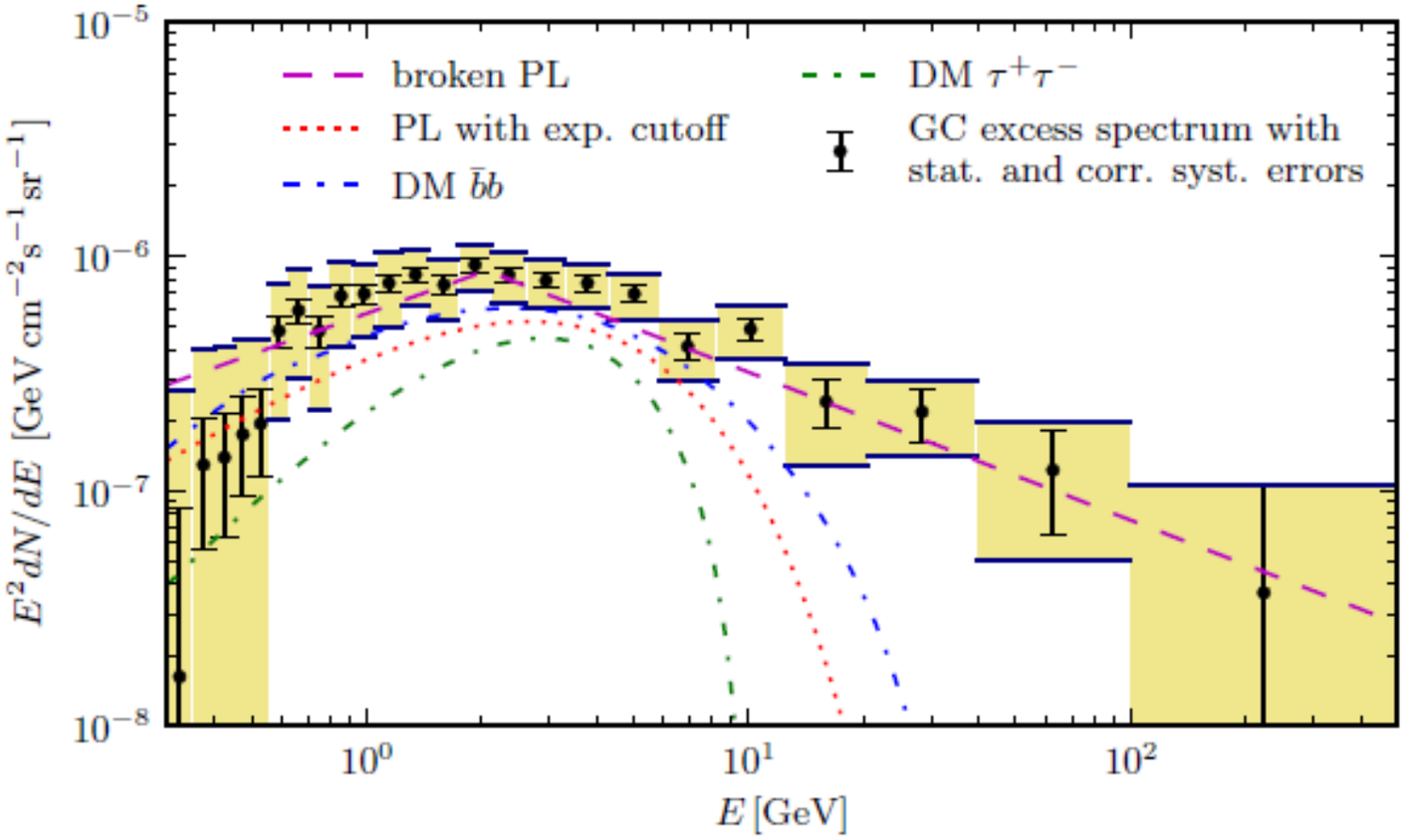
Dark Matter annihilates in the GC / dwarf galaxies (a place) to photons (some particles), which are detected by Fermi, HESS, … (an experiment).

Fermi Large Area Telescope

https://www-glast.stanford.edu/

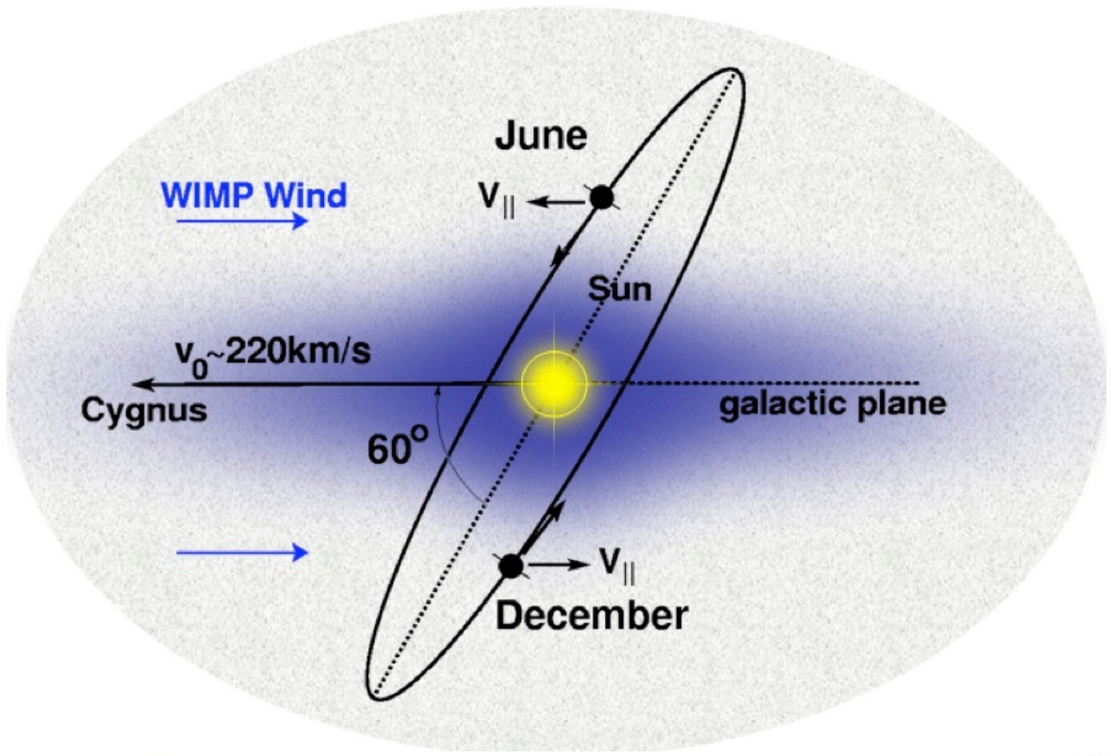






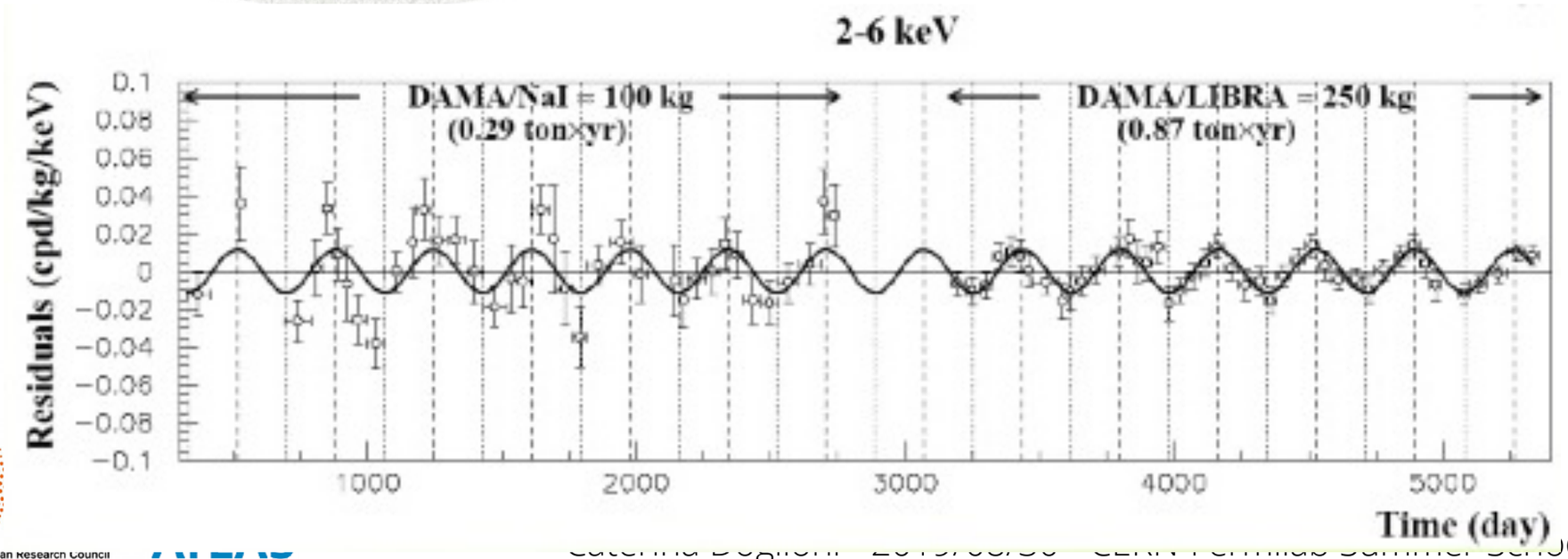
Many possibilities for interpretation, floor still open

More controversial indirect detection hints: DAMA



Dark Matter flows from the source where it annihilates:

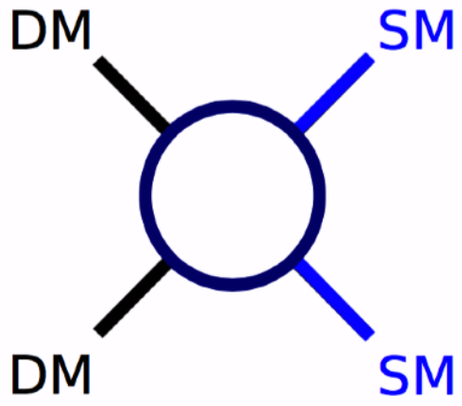
- Rotation of the earth wrt sun would allow to see **annual modulation**
- Verification needed: building SABRE experiment in Southern hemisphere

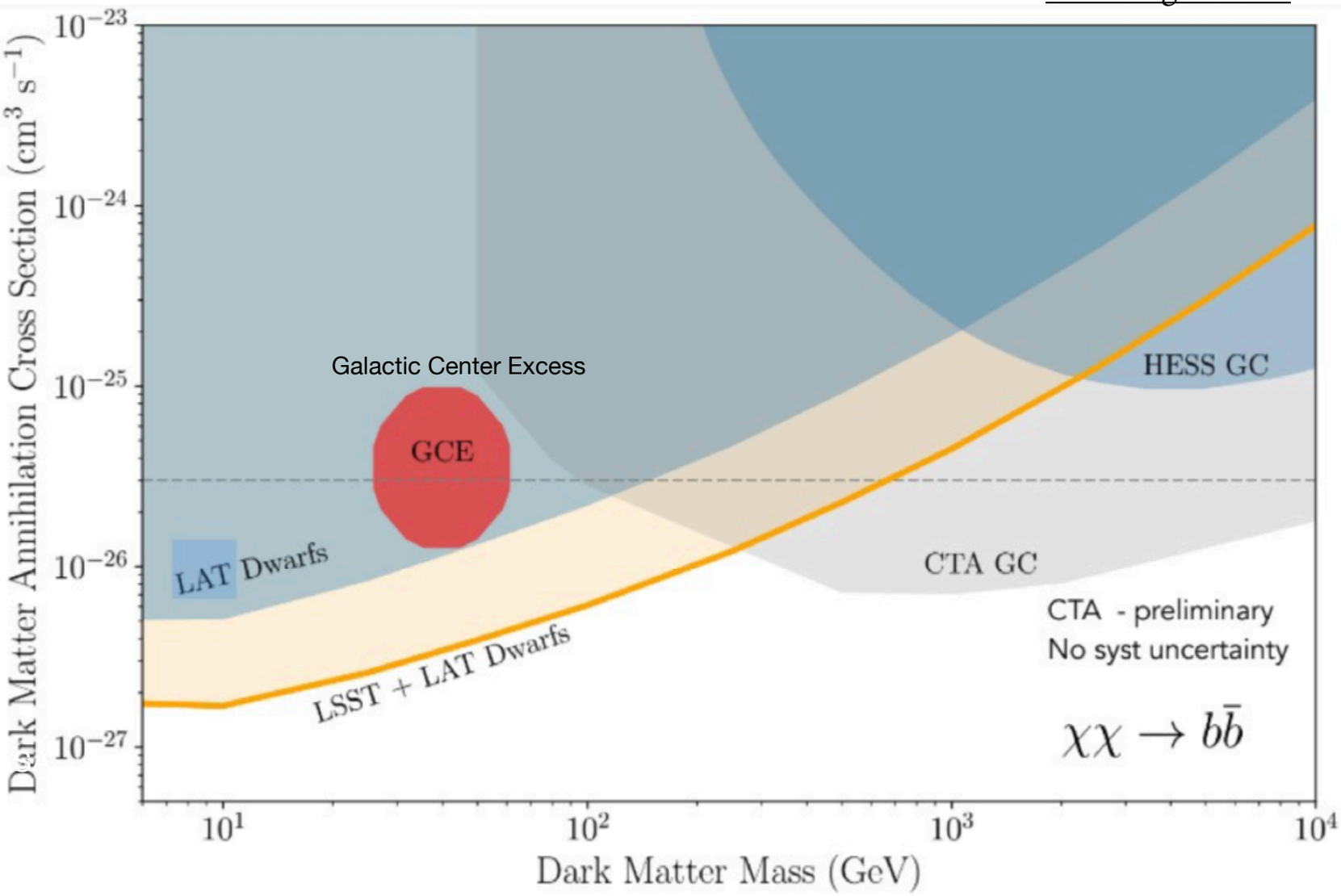


Is it conclusive evidence? **No**

Status & prospects of indirect detection

C. Weniger's talk

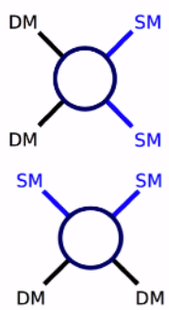




From Drlica-Wagner, A. & Others. arXiv [astro-ph.CO] (2019).
See also Carr, J. & Others. PoS ICRC2015, 1203 (2016).

Synergies in dark matter searches

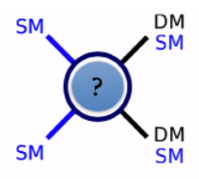
Huge progress planned for **direct and indirect detection** for **WIMP DM**
Future colliders and experiments can follow:
essential **complementarity** between



cosmological origin
astrophysics

and

nature of the DM-SM interaction
particle physics



Similarly, **combination of complementary experiments + theory** needed to identify nature of DM in case of **non-WIMP DM**

How to **strengthen common foundations**?
Many **common challenges**, e.g.
strategies to handle **large amounts of data,**
particle **detectors and instrumentation**

Take-home point #2:

The ideal WIMP DM discovery includes simultaneous observations in Direct and Indirect Detection

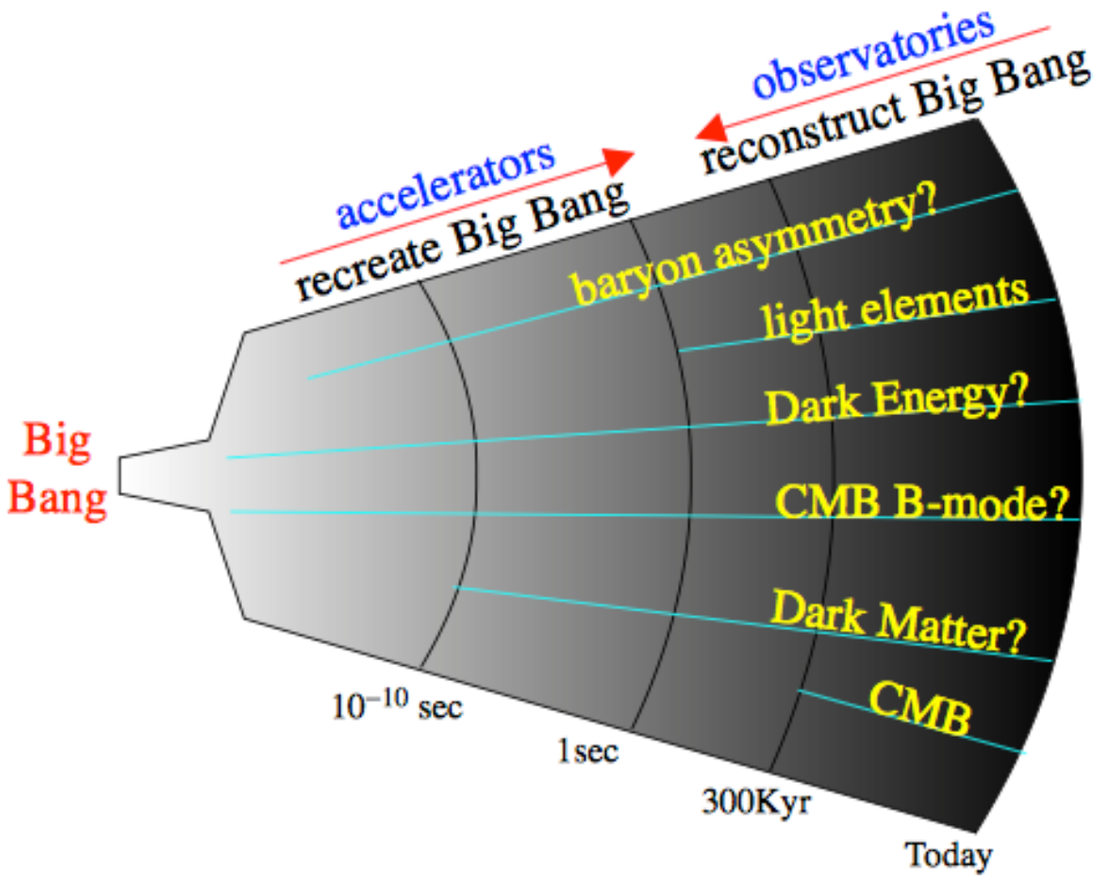
(detection from astrophysical phenomena: cosmological connection)

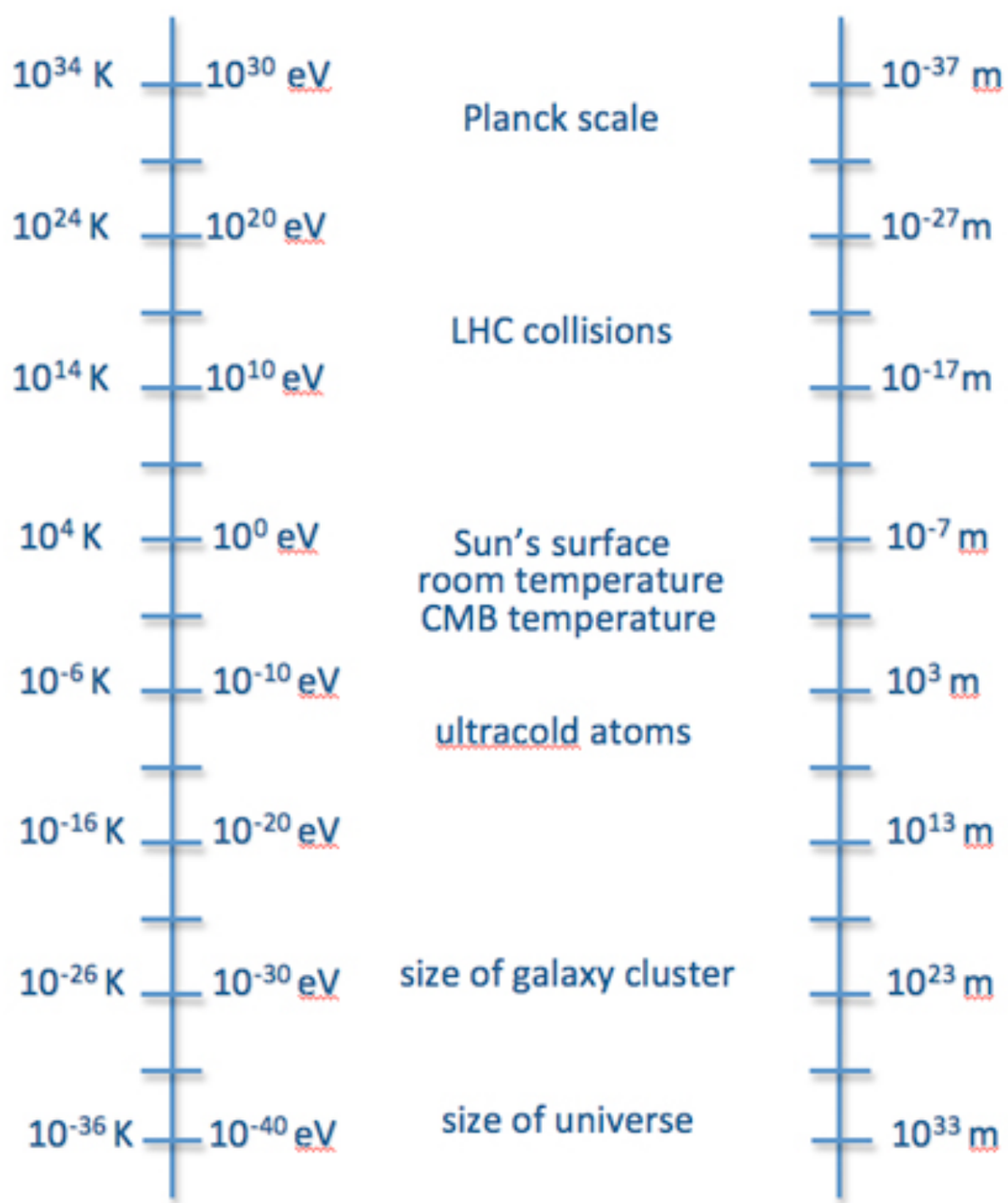
+ invisible particle found @ collider

(creation in controlled condition: understanding nature of interaction)

Darker matter & connections with astrophysics (to go beyond WIMPs)

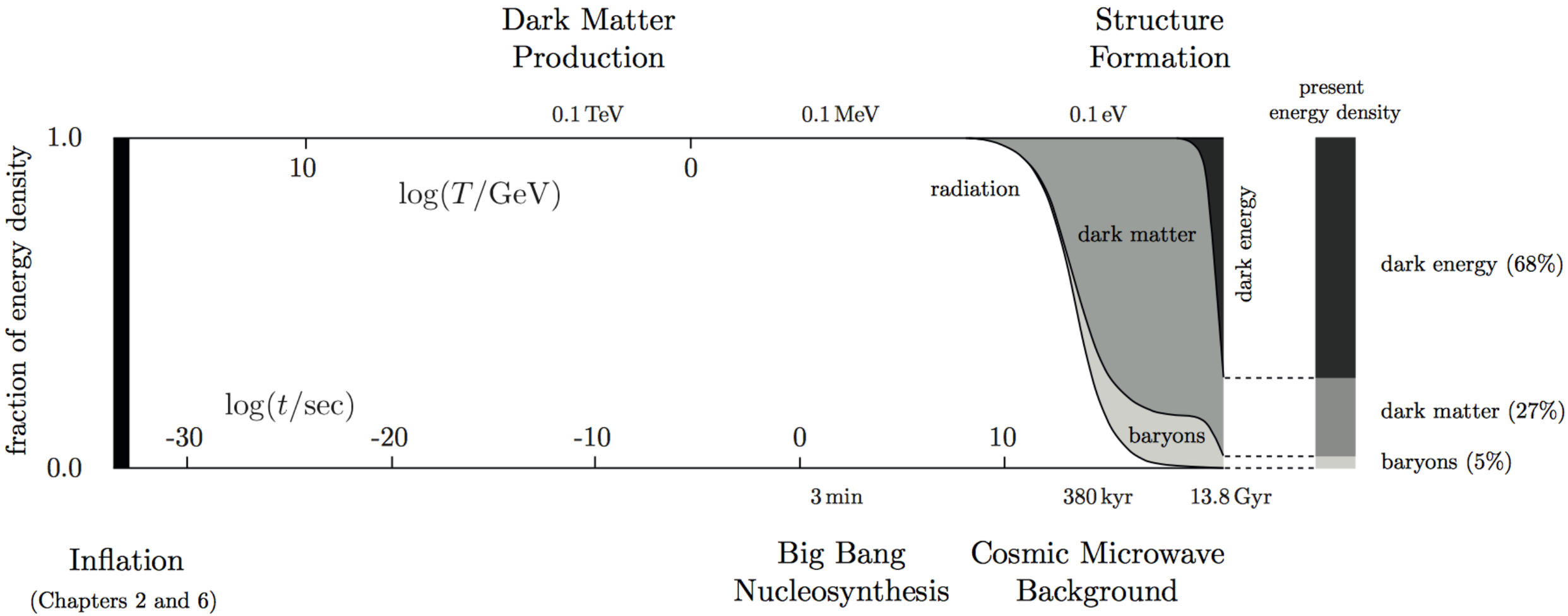
Many connections between particle physics and cosmology





Has the universe always been the same?

http://www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf

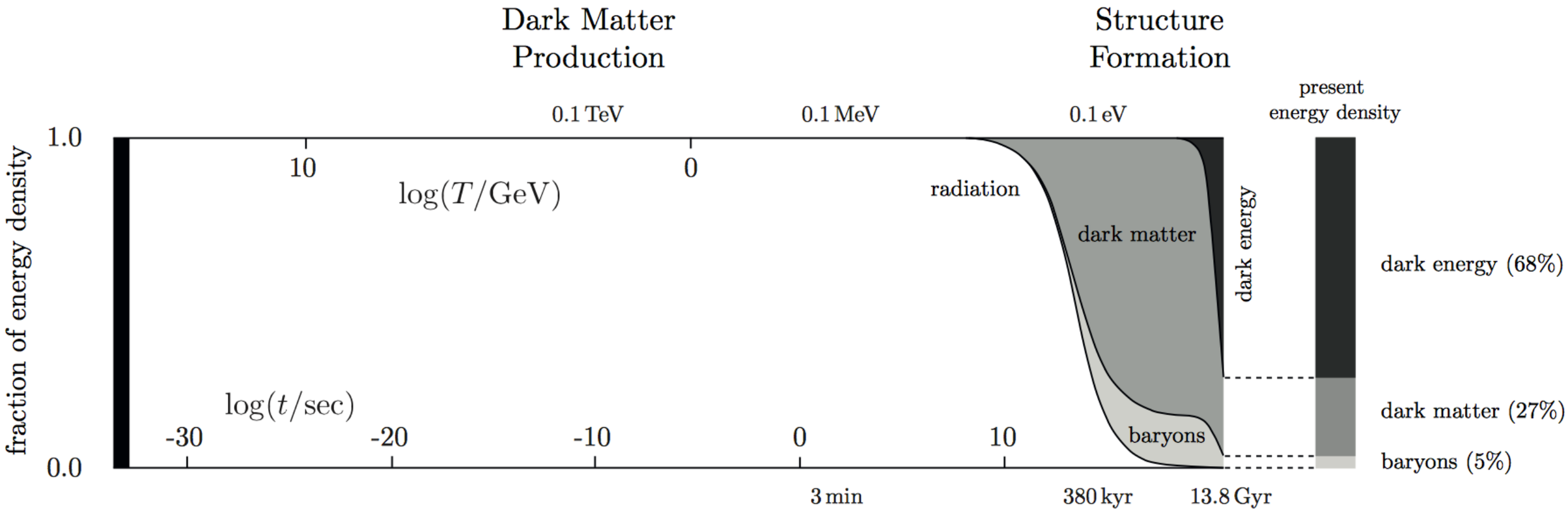


We only know 5% of the universe and we only care about 0.5% of it as the rest is interstellar gas

P. Fox, Dark Matter FCC workshop 2015

Has the universe always been the same?

http://www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf



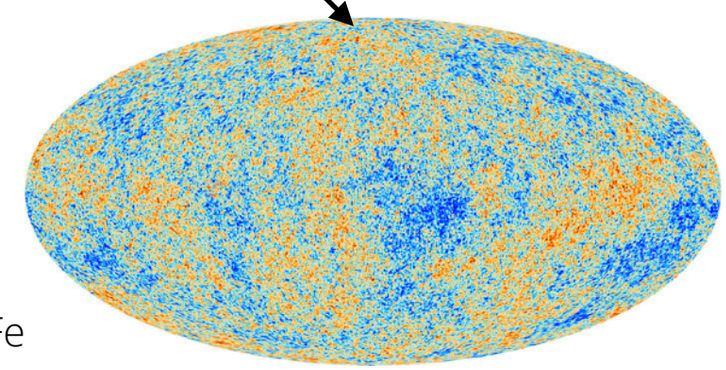
Inflation
(Chapters 2 and 6)

Big Bang
Nucleosynthesis

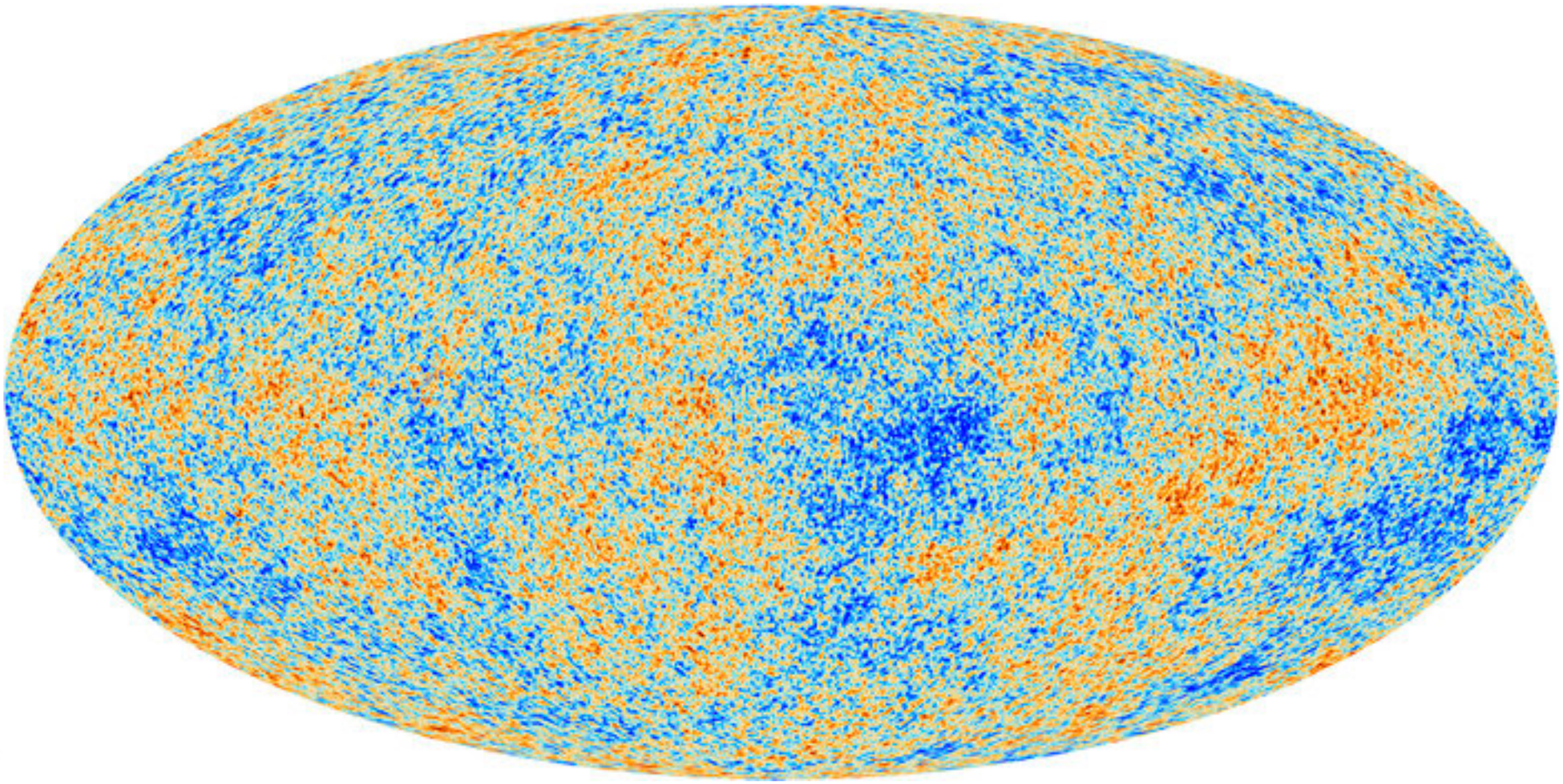
Cosmic Microwave
Background

Planck

What we see today



Cosmic microwave background



Cosmic microwave background

Cosmic microwave background

Read more at:
http://cosmology.berkeley.edu/Education/CosmologyEssays/The_Cosmic_Microwave_Background.html

On a cold winter morning
In the time before the light
In flames of death's eternal reign
We ride towards the fight

CMB = radiation released when universe **cooled down** enough to become **transparent to light**

As the red day is dawning
And the lightning cracks the sky
They'll raise their hands to the heavens above
With resentment in their eyes

So now we fly ever free
We're free before the thunderstorm
On towards the wilderness
Our quest carries on

The microwaves we see today are a **redshifted** version of the visible and UV light initially emitted

Deviations = small temperature fluctuations corresponding to regions of different densities

Measurements of these fluctuations using cosmological models as a guide tell us about the percentage of **DM** in the universe

X

Running back through the mid morning light
There's a burning in my heart
We're banished from a time in a fallen land
To a life beyond the stars

Are we certain about the relic (& connection to particle

DM relic density is one of the best clues we have about DM

For ideas on others: https://arxiv.org/abs/1712.06615, also galaxy formation & structure, which in turn rabbit-holes to: the Dark Matter flowchart, definitely worth reading

Galaxy Structure, Dark Matter, and Galaxy Formation

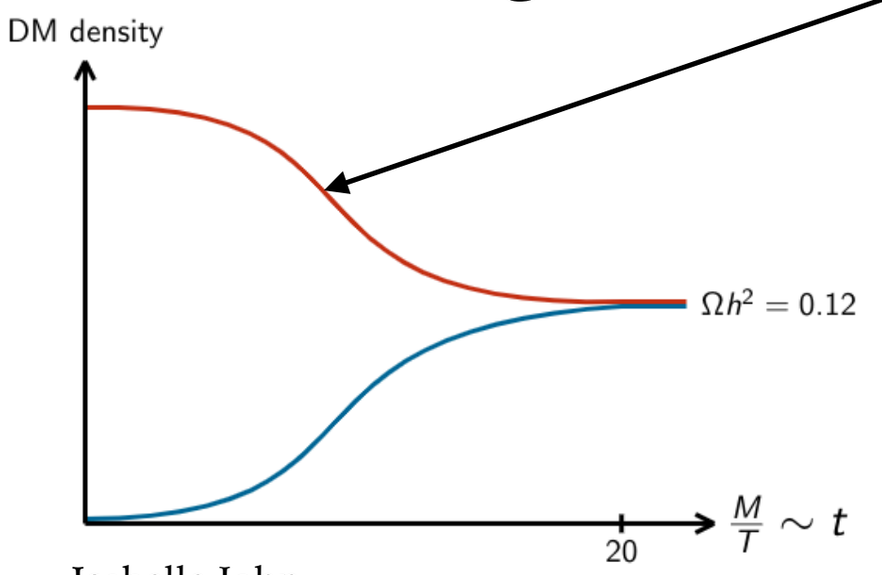
David H. Weinberg

Ohio State University, Department of Astronomy, 174 W. 18th Ave., Columbus, Ohio, 43210, U.S.A.

Abstract. The structure of galaxies, the nature of dark matter, and the physics of galaxy formation were the interlocking themes of *DM 1996: Dark and Visible Matter in Galaxies and Cosmological Implications.* In this conference summary report, I review recent observational and theoretical advances in these areas, then describe highlights of the meeting and discuss their implications. I include as an appendix the lyrics of *The Dark Matter Rap: A Cosmological History for the MTV Generation.*

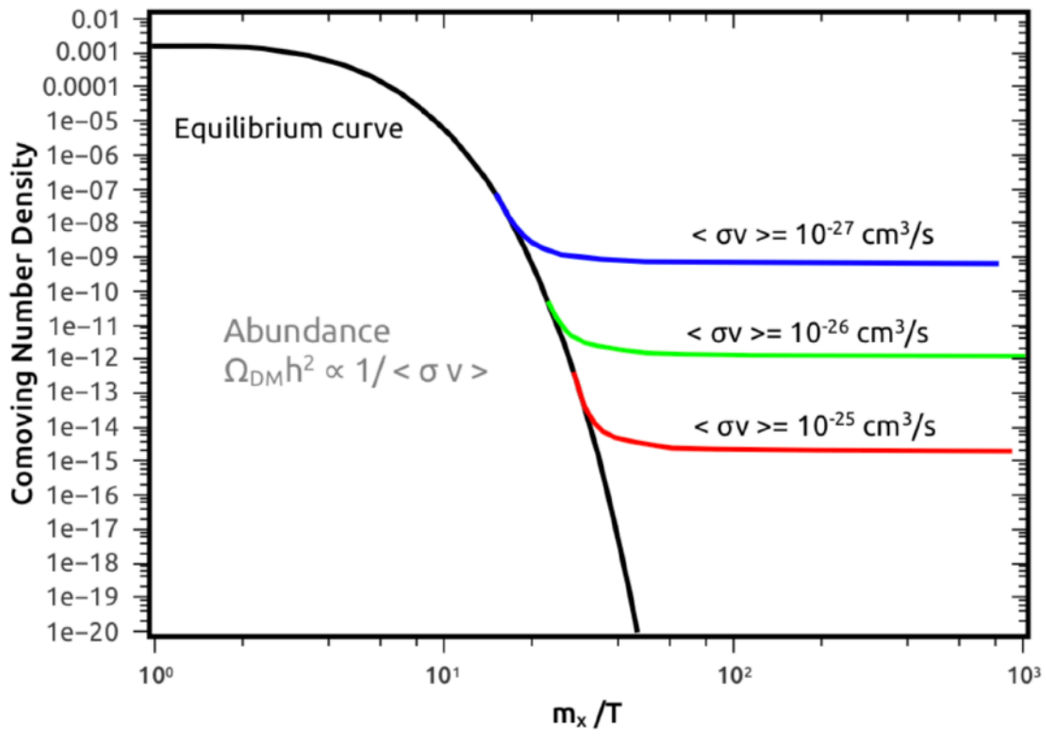
Still, its connection to DM particle models has **assumptions & uncertainties**, e.g.:

Freeze-**out** or freeze-**in** (or other mechanism altogether?)



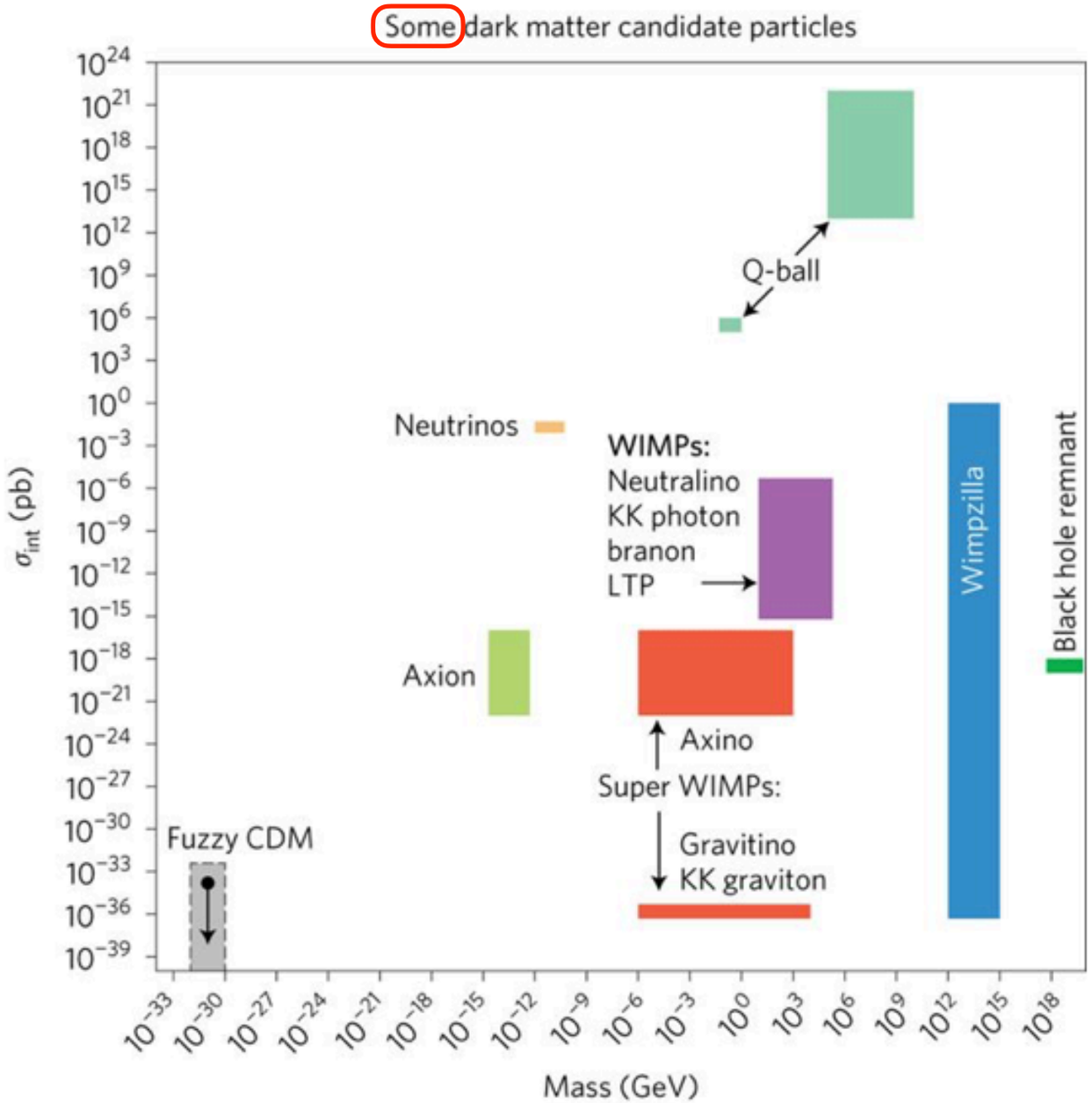
Isabelle John

Canonical "WIMP miracle" picture



https://arxiv.org/abs/1703.07364

Are we missing something in our WIMP paradigm? Probably...



CAN'T SEARCH FOR EVERY DM CANDIDATE

https://www.nature.com/articles/nphys4049, adapted from The Dark Matter Scientific Assessment Group

More models needed!

More models with DM as a thermal relic
but **lighter and with weaker couplings** wrt WIMPs

- Examples: dark ~~photon~~ boson (and dark Higgs) models
  Many searches in LHCb: http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

Models with **freeze-in DM** [hard to find @ LHC F. Kahlhoefer's talk/papers]

Models where **other mechanisms for relic** are needed:

- **Axions** (also solving the strong CP problem)
- More complex dark sectors, e.g. **dark QCD**
- More general models with **long lived particles**

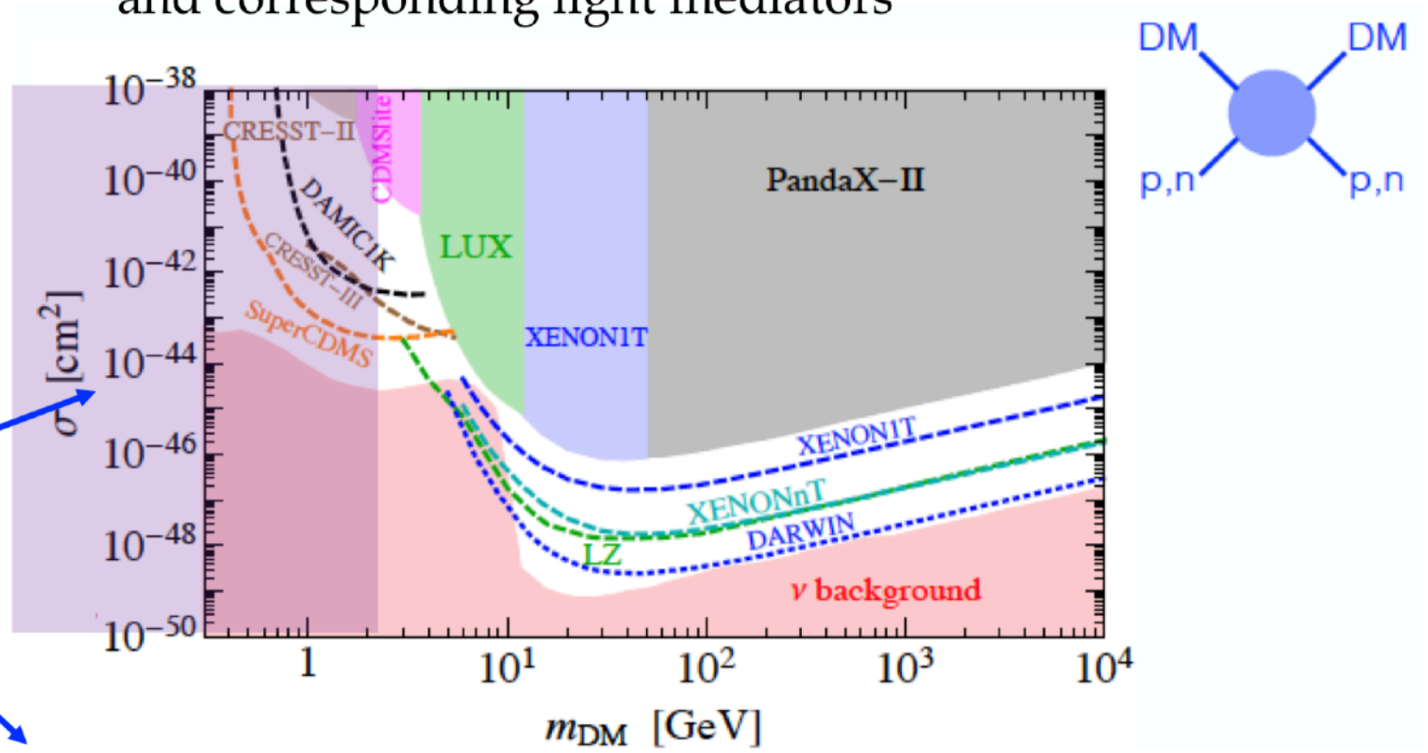
Or, DM is **black holes**. [In which case, no particles here, shuffle shuffle.]
but there is hope for not being this case: https://arxiv.org/abs/1701.02151

Light DM: other experiments will help the LHC

CERN launches Physics Beyond Colliders study group

https://home.cern/scientists/updates/2016/05/cern-launches-physics-beyond-colliders-study-group

Example n.1: Search for Light Dark Matter with thermal origin and corresponding light mediators

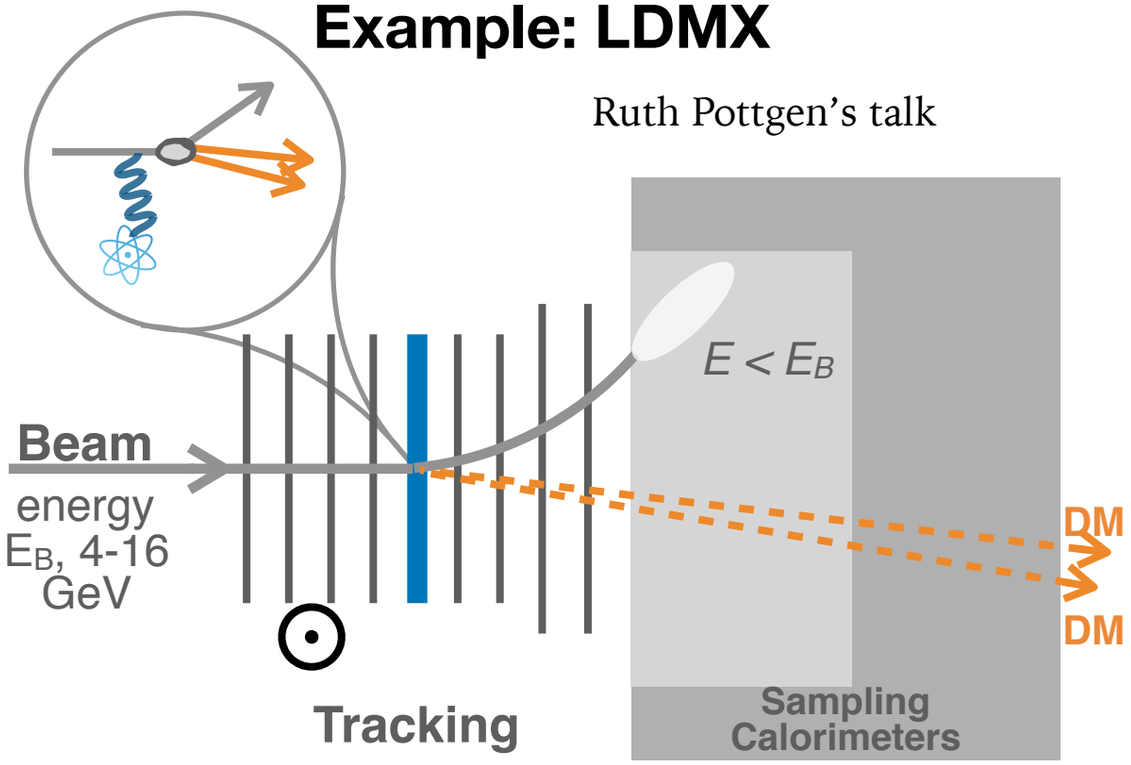


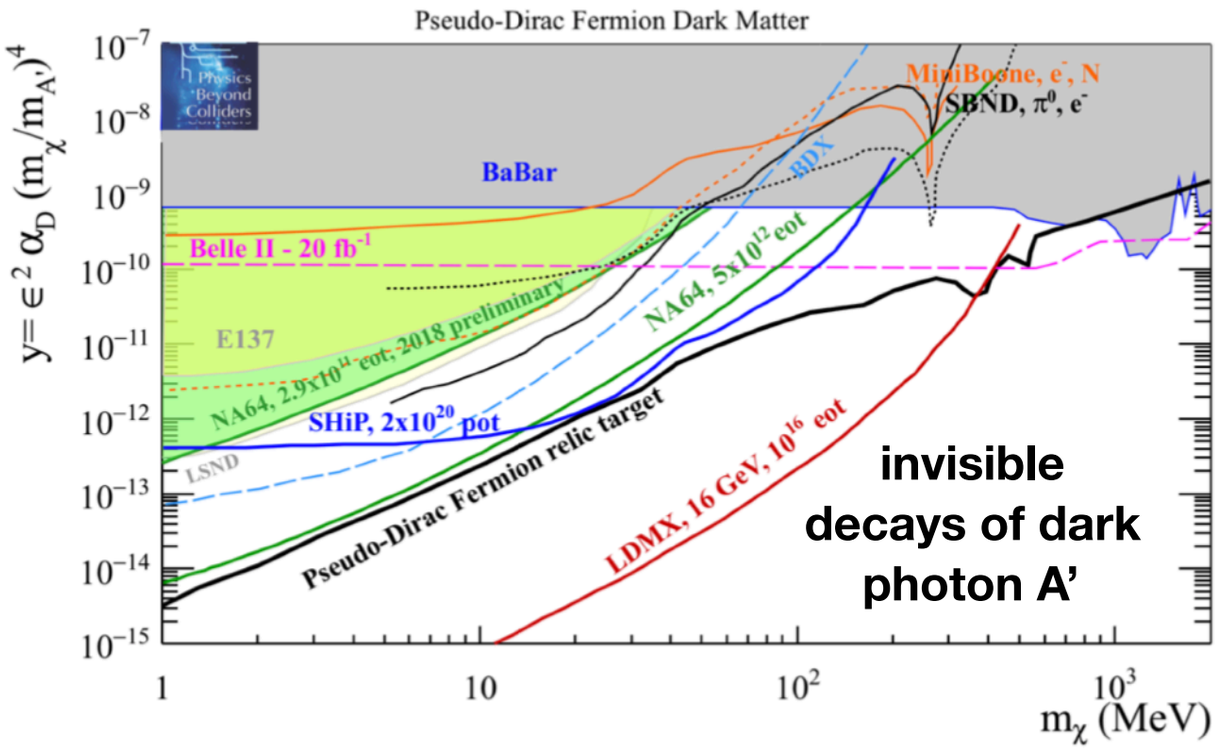
G. Lanfranchi, PBC meeting June 2018

Light DM: other experiments will help the LHC

Example: LDMX

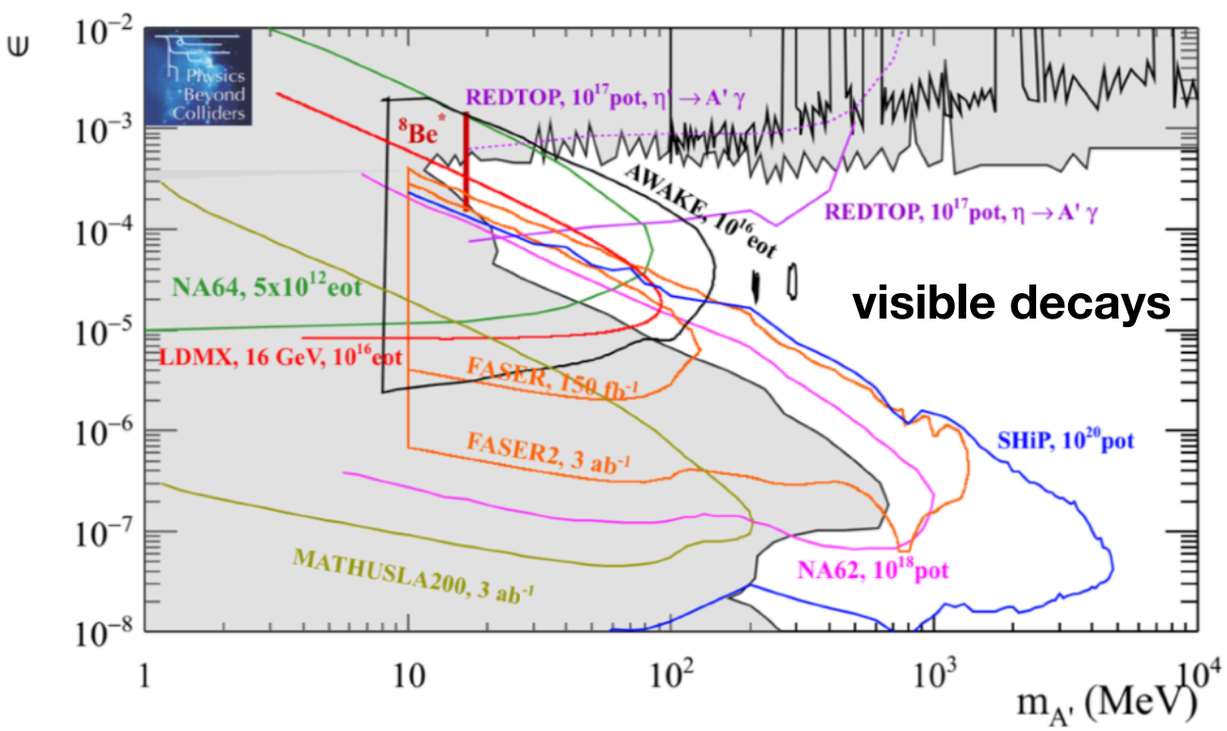
Ruth Pottgen's talk





Also see (only a selection of links for lack of time…):

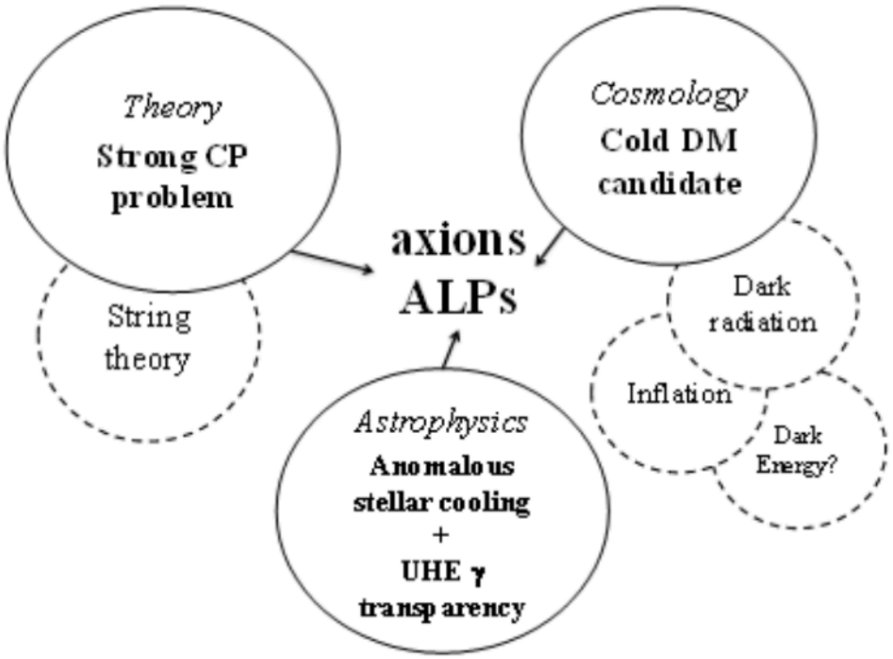
- Vision: Cosmic Visions report 2017
- Some new experiments: CODEX-b, MATHUSLA, FASER, SHIP, LDMX
- Some new accelerators: e-SPS Expression of Interest



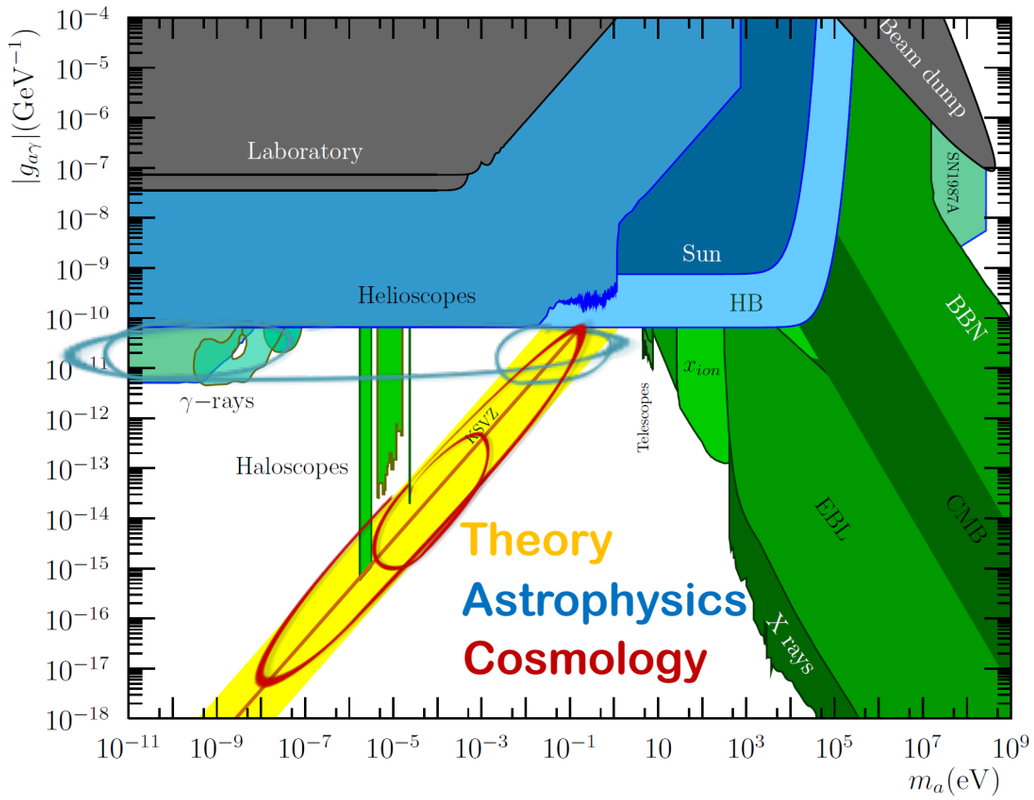
What if DM is an axion?

Figures taken From **I. Irastorza**'s talk @ EPSHEP '19

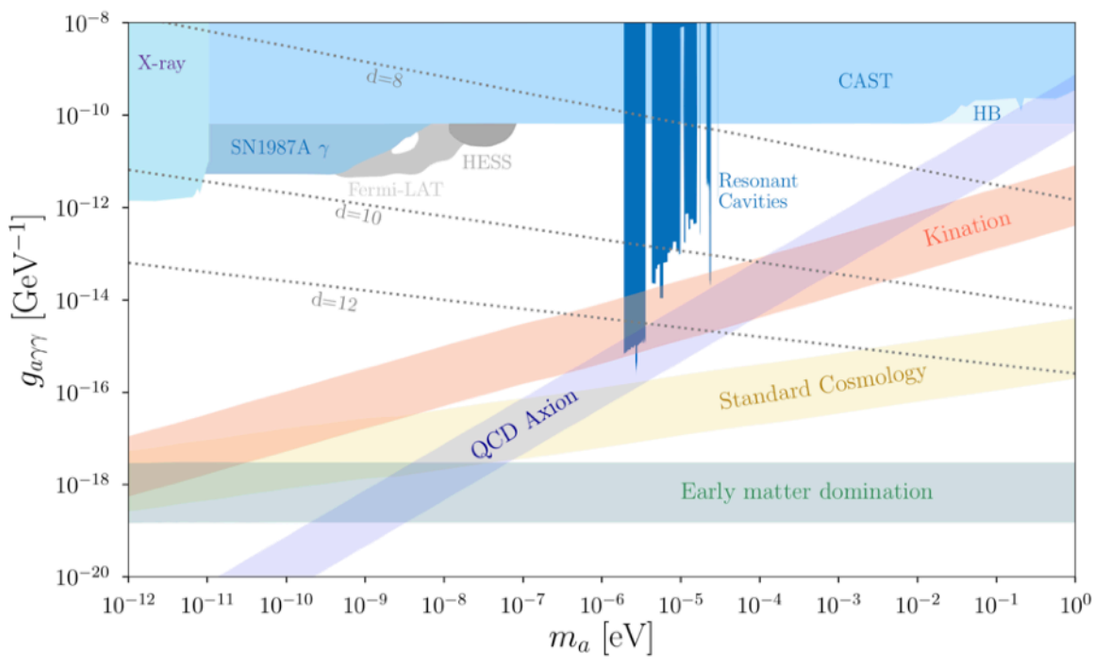
Axions/Axion-Like Particles (ALPs):
example of new particle
that solve many problems at once



can be produced in heavy ion collisions (ALICE, ATLAS, CMS)



https://arxiv.org/pdf/1905.06952.pdf



Why long lived particles @ LHC?

Why long-lived particles? (LLP)

S. Knapen's talk

Long lifetimes arise from a hierarchy of scales or a small coupling*

Three mechanisms:

- Off-shell decay
- Small splitting (phase space)
- Small coupling

Lessons from the SM:

- generic if there is more than one scale
- Often 3 body decays
- Weak theory prior on lifetime

(e.g. proton decay!)

small coupling

$$\Gamma \sim y^2 \left(\frac{m}{M}\right)^n m$$

Set by symmetry structure, typically n ≥ 4

hierarchy of scales

http://arxiv.org/abs/1903.04497
https://arxiv.org/abs/1810.12602

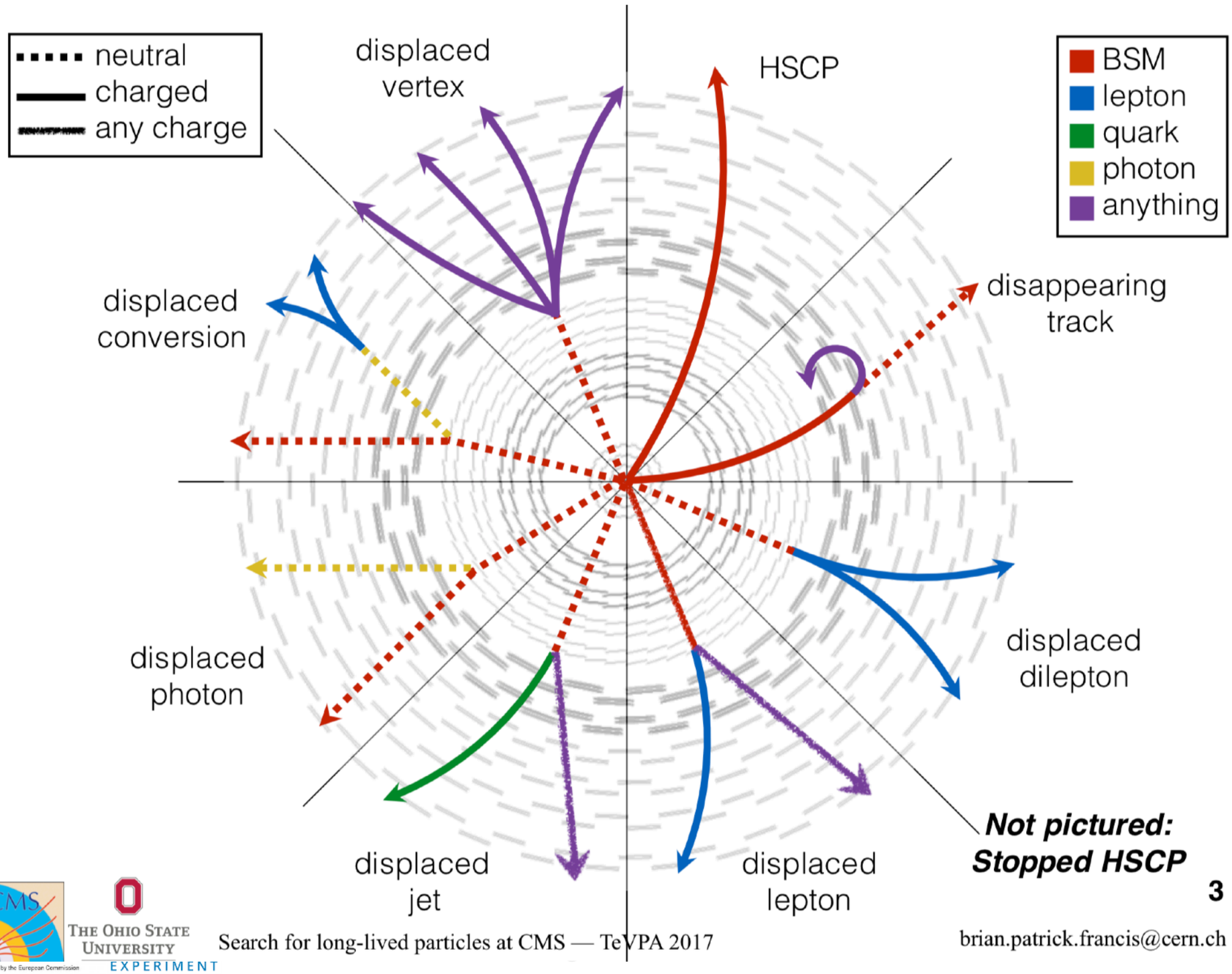
* could either be a hierarchy or loop suppression

Why are LLPs so interesting at this point?

- many theories predict these mechanisms
- some SM particles have a long lifetime, why shouldn't be BSM ones
- because they are harder to find!

(Too) many possibilities to detect long lived particles...

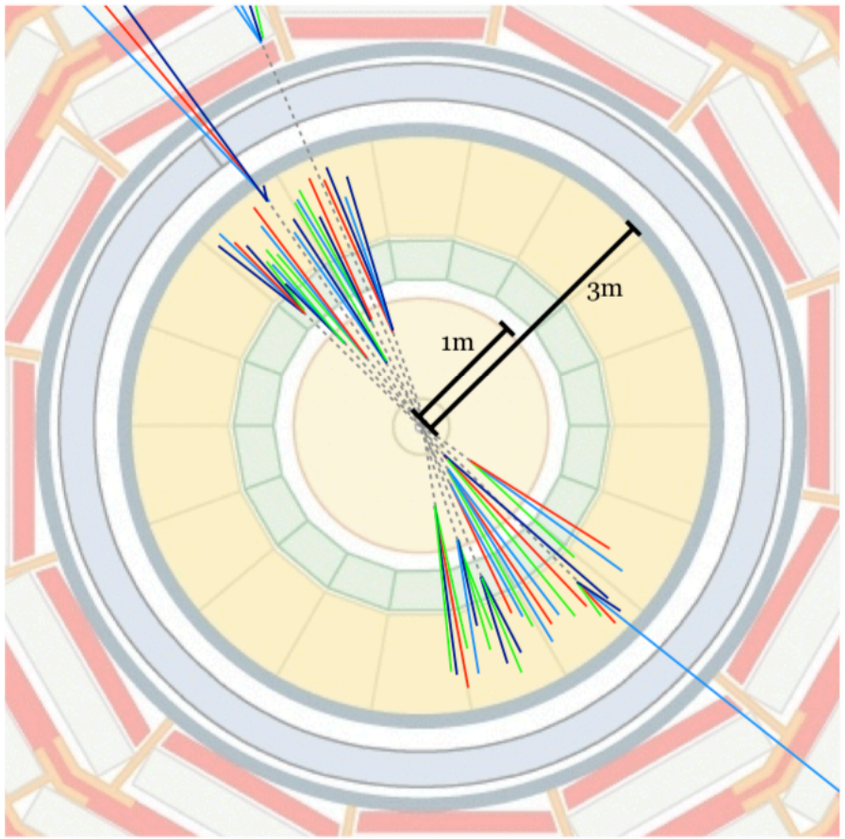
B. Francis' TeVPA talk, Original drawing by Jamie Antonelli



Example of a ”dark shower” search @ LHC

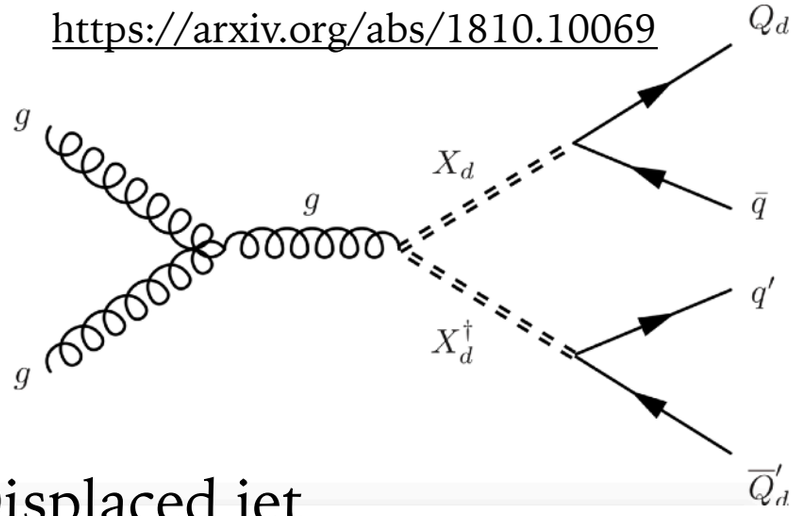
Theory: two emerging jets

https://arxiv.org/pdf/1502.05409.pdf



Experiment: select events w/help of a regular jet

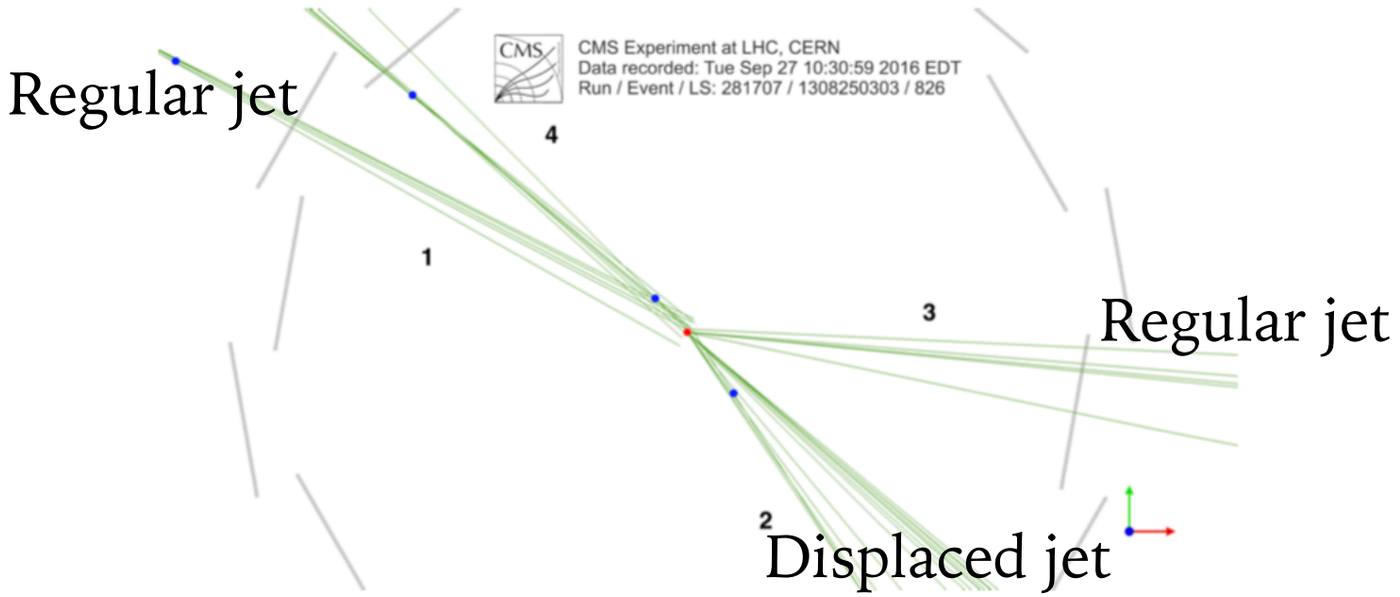
https://arxiv.org/abs/1810.10069



Regular jet

Emerging jet

Displaced jet



Regular jet

Regular jet

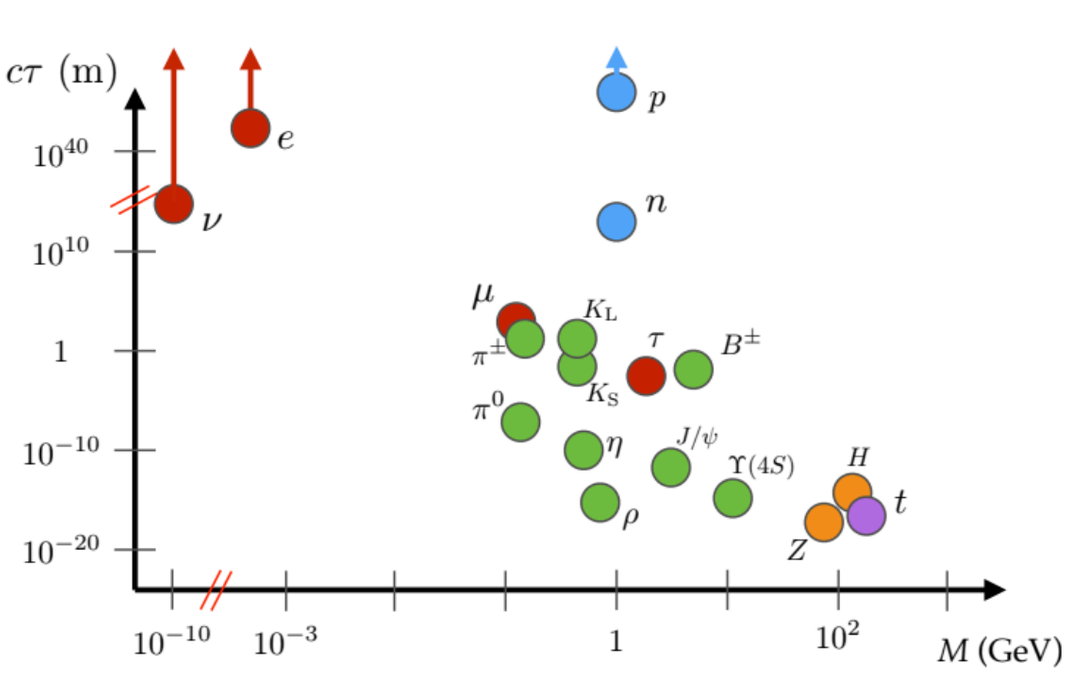
Displaced jet

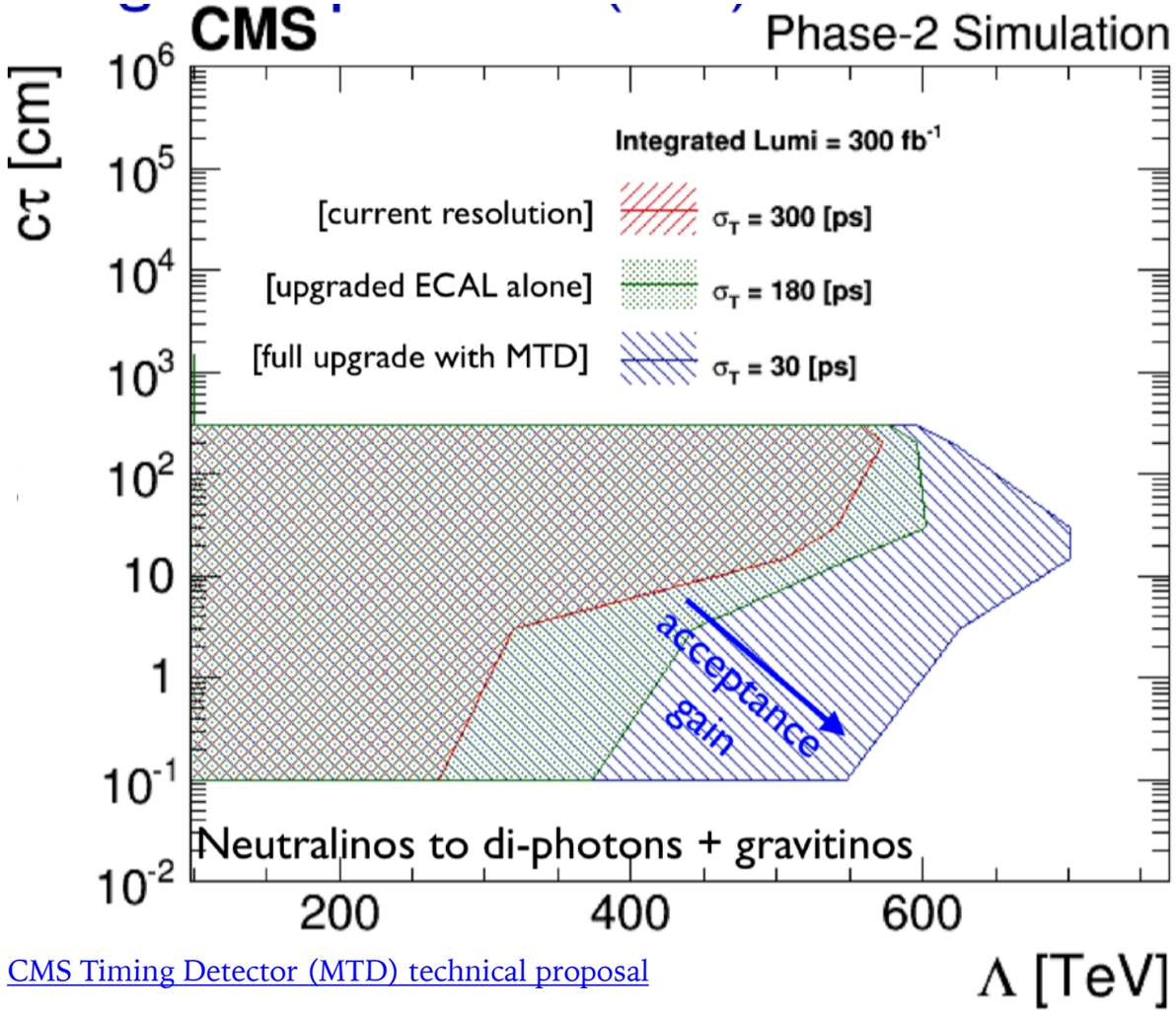
(no evidence for new phenomena)

LHC upgrades will help those searches

Measurement of **decay time** becomes possible with a timing detector in CMS barrel
More lifetime acceptance can translate into sensitivity to different models

Known example: range of masses and lifetimes of SM particles





CMS Timing Detector (MTD) technical proposal

Take-home point #3:

Modifying DM hypotheses

(e.g. thermal relic density, # of DM particles…)

leads to different search targets that are worth looking for,

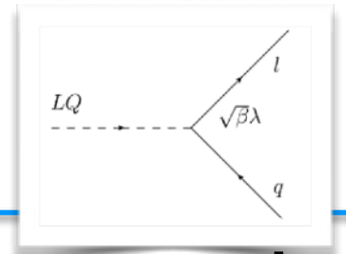
given our ignorance of dark sector

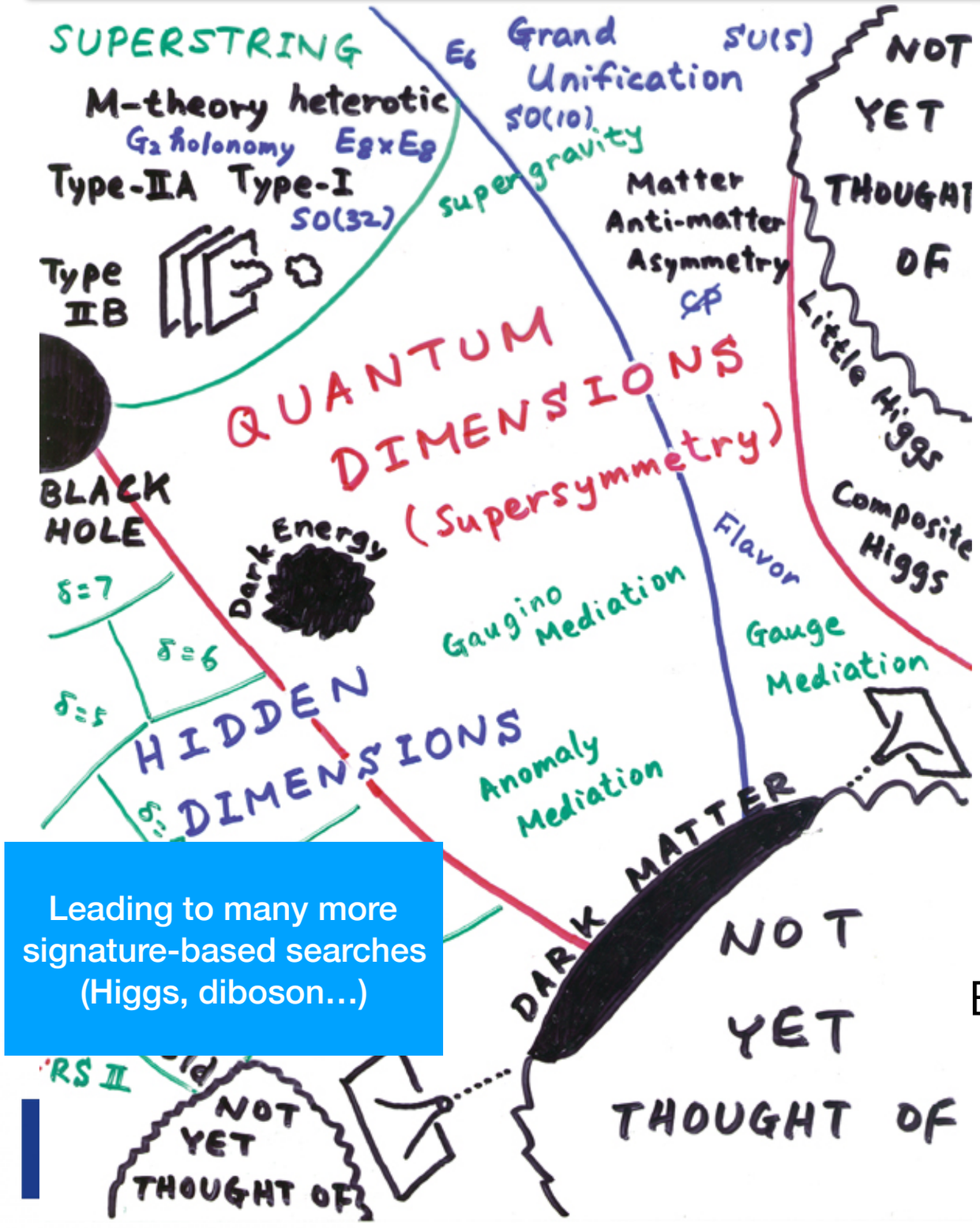
(plus, unexplored challenging signatures are fun for experimentalists)

1-slide for other BSM

(note that this is just a pick from a very long list)

Everything I didn't have time to cover





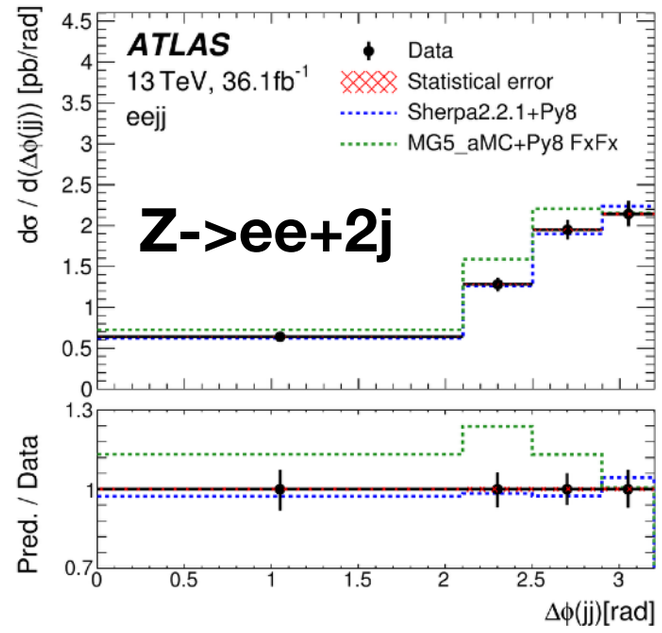
Leading to many more signature-based searches (Higgs, diboson…)

One example for all: leptoquarks

https://home.cern/news/news/physics/hunt-leptoquarks

ATLAS example from 1st gen LQ search that makes measurements out of CRs

https://arxiv.org/abs/1902.00377



BR

	Expected (m_{LQ1})	Observed (m_{LQ1})	Expected (m_{LQ2})	Observed (m_{LQ2})
1.0	1400	1400	1400	1560
0.5	1280	1290	1200	1230
0.1	1020	1010	960	960

Limit in GeV

3rd gen: connection to flavor anomalies

https://arxiv.org/pdf/1901.10480.pdf

(but also no evidence so far)

Take-home point #4:

Can I have another 1/2h? *Eilam Gross to Emanuele Re*

More seriously: there are many more well-motivated theories to search for, some giving unique LHC signatures that escape current searches

Let's search for those too, and make sure both data and the software are accessible,
maybe we won't have another high energy collider for a little while after the LHC

BSM in neutrino physics

Open Questions

What is absolute mass scale?

Details of neutrino oscillation?

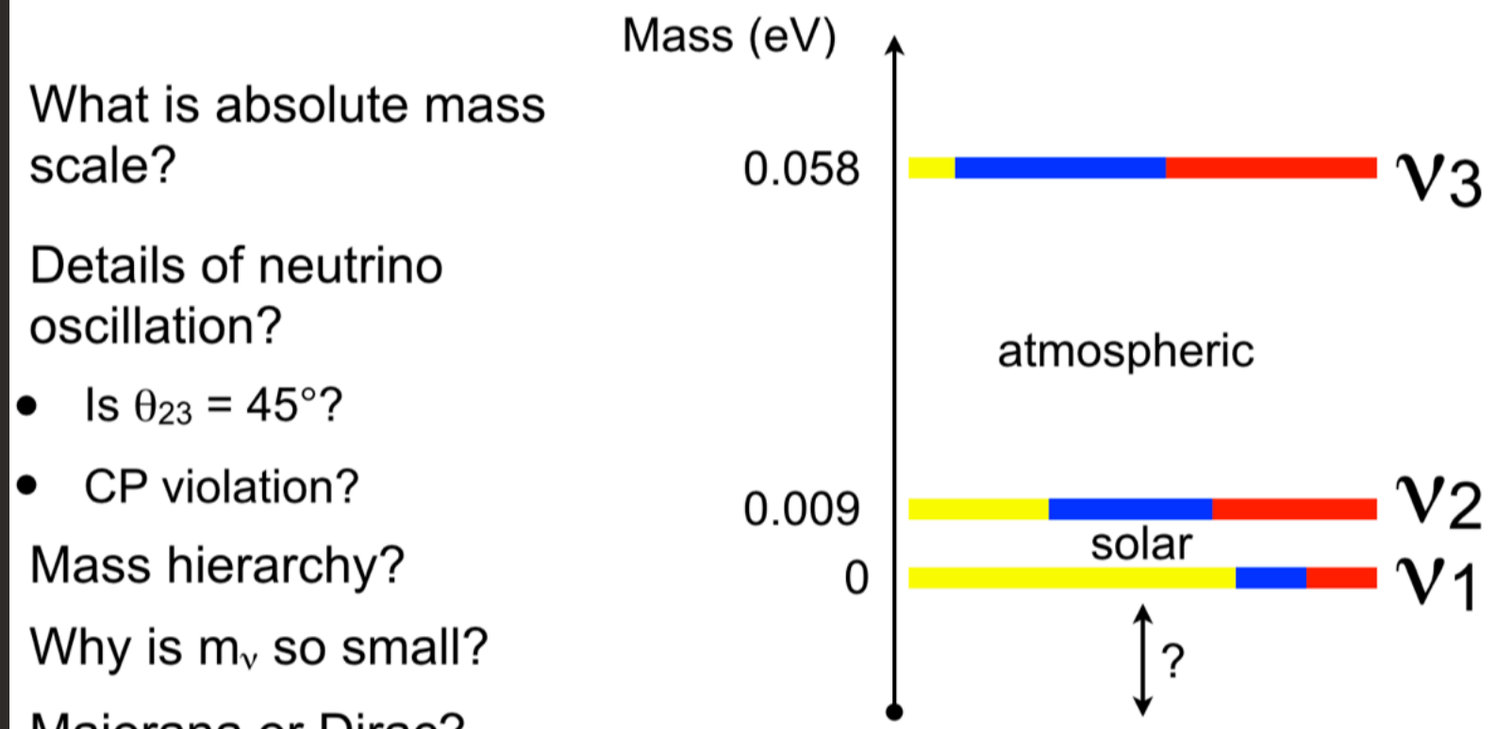
- Is $\theta_{23} = 45°$?
- CP violation?

Mass hierarchy?

Why is m_ν so small?

Majorana or Dirac?

Are there sterile neutrinos?



flavour key:

ν_e ν_μ ν_τ

Neutrino masses: a question out of many

Problem: Neutrinos have mass as we see through mixing, but they can't get it in the SM Y. Grossmann's TASI lectures

Solutions with minimal particle addition:

- There are other heavy fields —> new particles

$$\frac{\lambda}{M} H H \overline{L_L^c} L_L \quad \Rightarrow \quad m_\nu = \lambda \frac{v^2}{M}$$

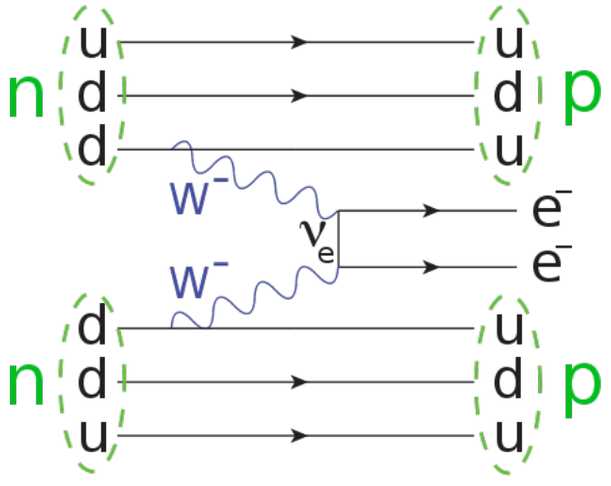
  - E.g. in the **Seesaw mechanism**
    - there is a right-handed neutrino and its presence generates a mass term for the SM right-handed one after EWSB

$$m_{\nu_R} = M_N \qquad m_{\nu_L} = \frac{m_D^2}{M_N}$$

  - If there is a **Majorana neutrino** (violation of lepton number) —> neutrinoless beta decay

- There is another Higgs

Symmetry Magazine

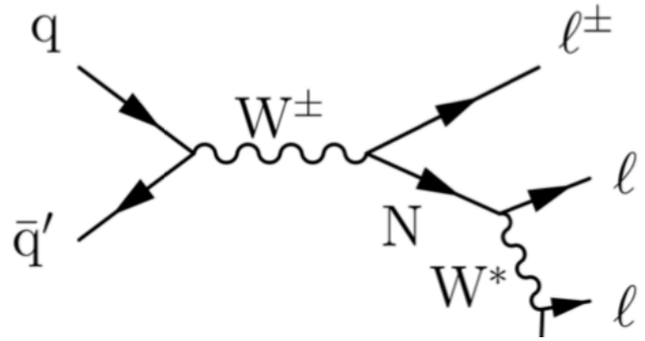


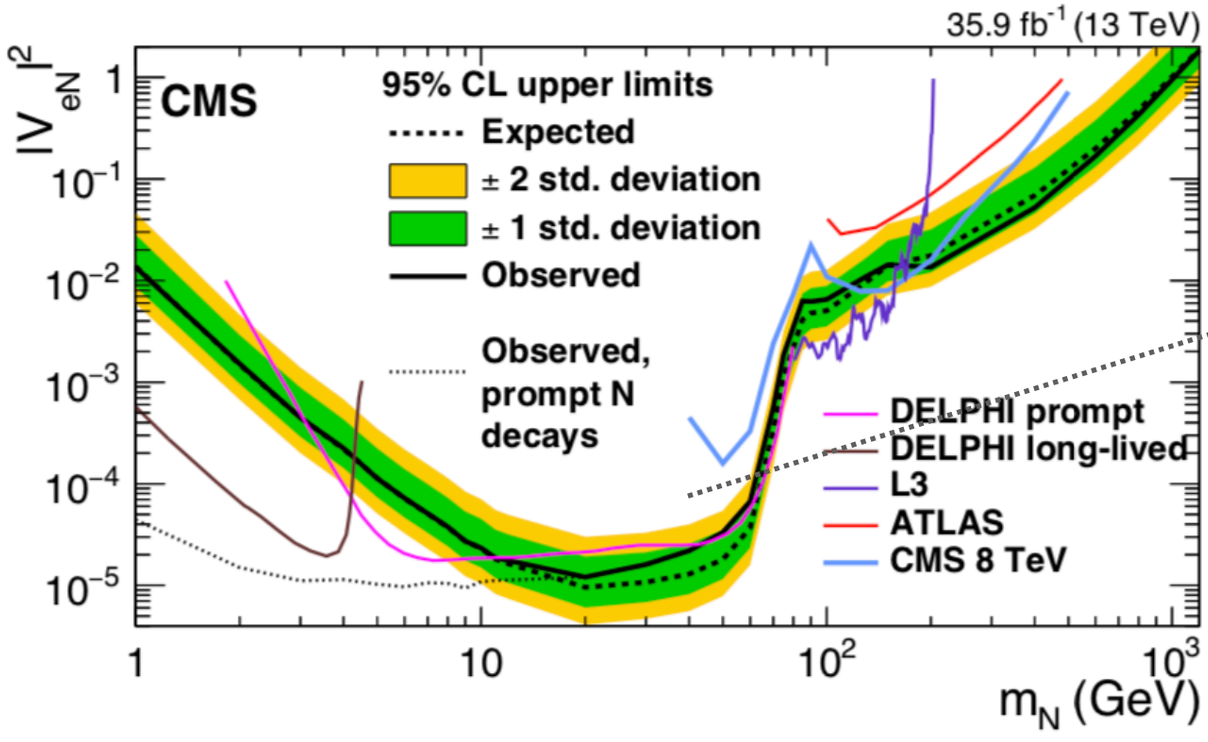
Some experimental searches for heavy neutral leptons

Example: CMS

https://arxiv.org/abs/1802.02965

Search for Heavy Neutral Leptons w/couplings to electrons and muons

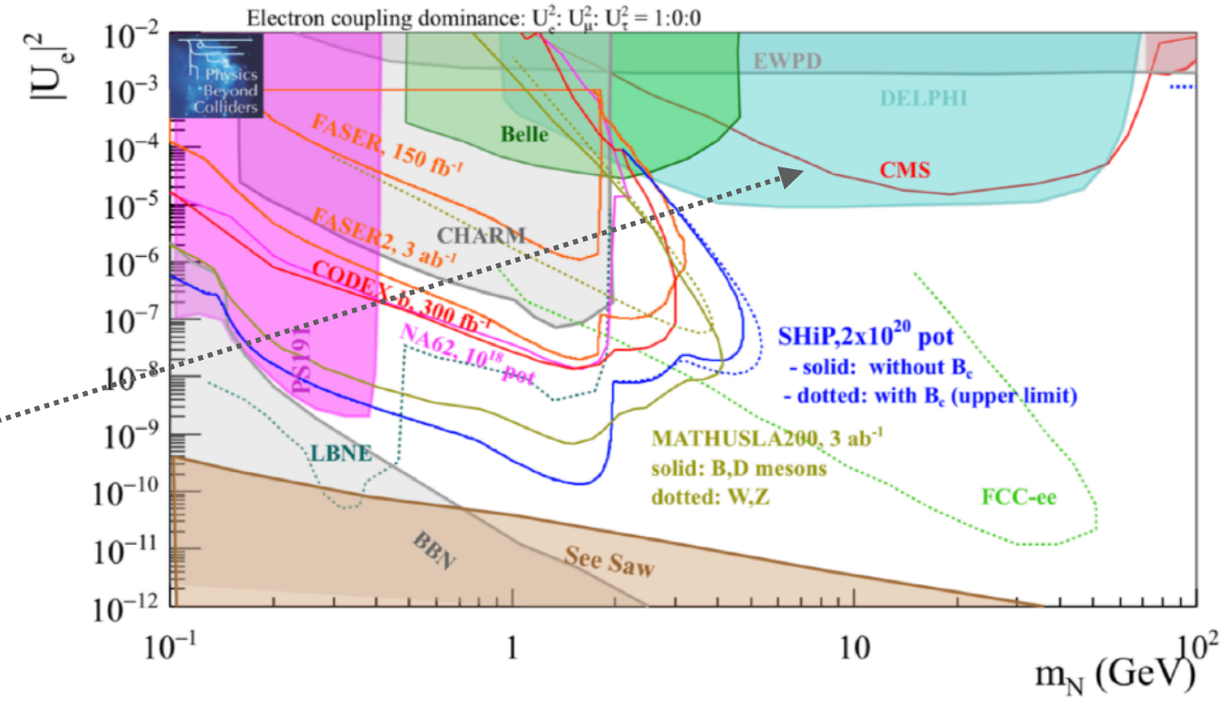




Beyond colliders

Sensitivity to Heavy Neutral Leptons w/coupling to the first lepton generation only (more in)

- Current bounds (filled areas)
- 10-15 years prospects for SHiP, MATHUSLA200, CODEX-b and FASER2
- Projections for LBNE near detector w/5 × 10^{21} proton on target
- Projection from FCC-ee with 10^{12} Z^0 decays

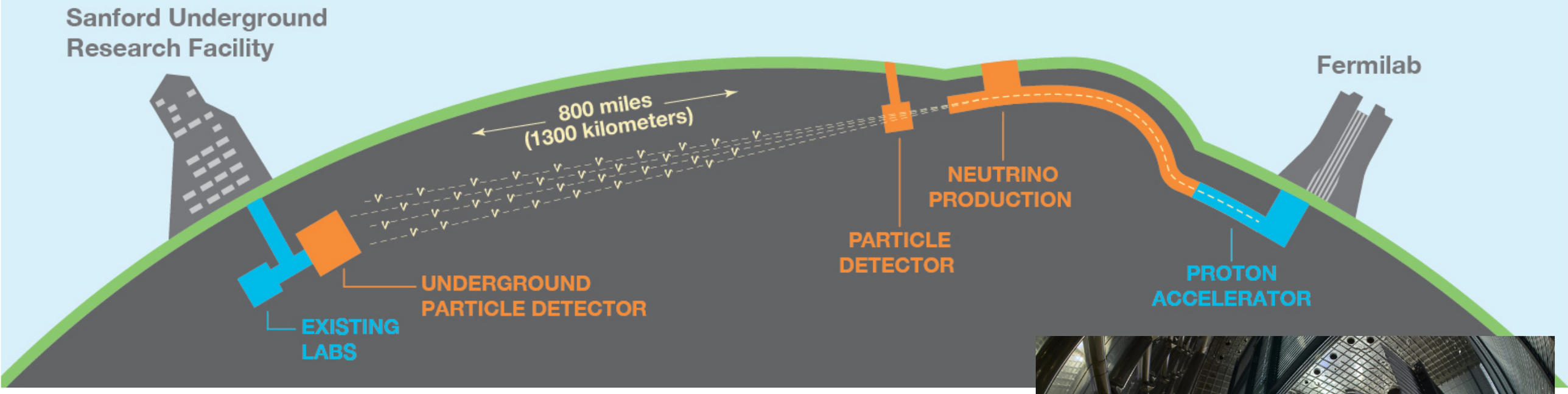


https://arxiv.org/abs/1901.09966

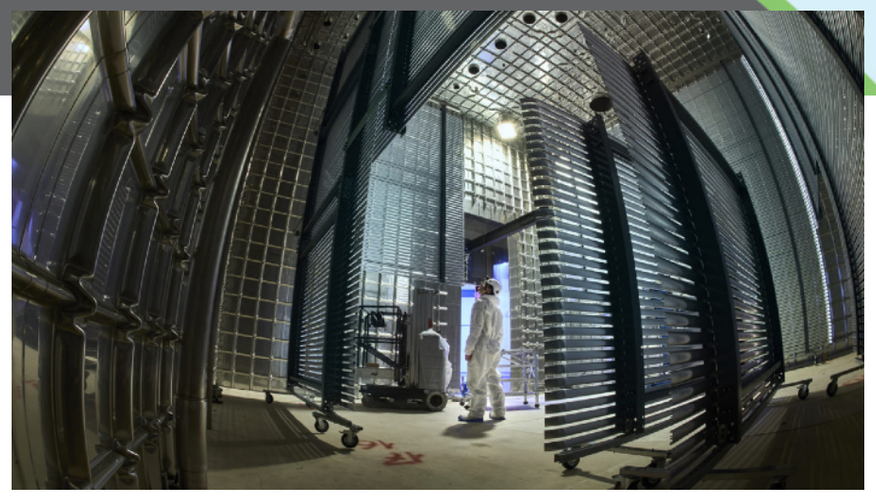
Neutrino masses: measuring through oscillations

https://www.dunescience.org **Neutrino platform @ CERN: http://cenf.web.cern.ch**

Also other experiments worldwide, e.g. SuperKamiokande, as well as in space



- An experiment for neutrino oscillations at Fermilab
  - Proto-Dune currently at CERN →
  - More than neutrinos!
    - proton decay, supernova dynamics



https://www.symmetrymagazine.org/article/protodune-in-pictures

Take-home point #5:

Neutrino physics is the BSM next door:
(or within, as billions of them/second traverse us right now)
ongoing and new exciting experiments with both Fermilab & CERN involvement will tell us more in the next decades

Recap of Lecture 3 & final poll

Take-home point #1:

Generic searches for DM particles targeting simple (simplified) models show the unique LHC ability to look into the SM-DM interactions,
but they are only a starting point

Take-home point #2:

The ideal WIMP DM discovery includes simultaneous observations in Direct and Indirect Detection

(detection from astrophysical phenomena: cosmological connection)

+ invisible particle found @ collider

(creation in controlled condition: understanding nature of interaction)

Take-home point #3:

Modifying DM hypotheses

(e.g. thermal relic density, # of DM particles…)

leads to different search targets that are worth looking for,

given our ignorance of dark sector

(plus, unexplored challenging signatures are fun for experimentalists)

Take-home point #4:

There are many more well-motivated theories to search for, some giving unique LHC signatures that escape current searches:

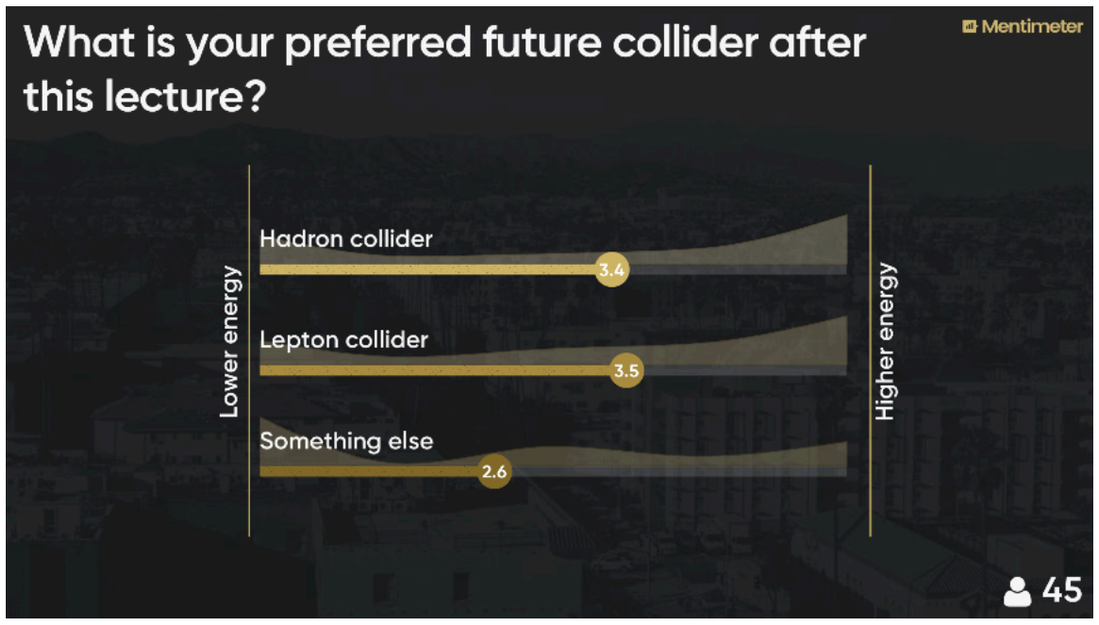
make sure both data and the software are accessible, maybe we won't have another collider for a little while

Take-home point #5:

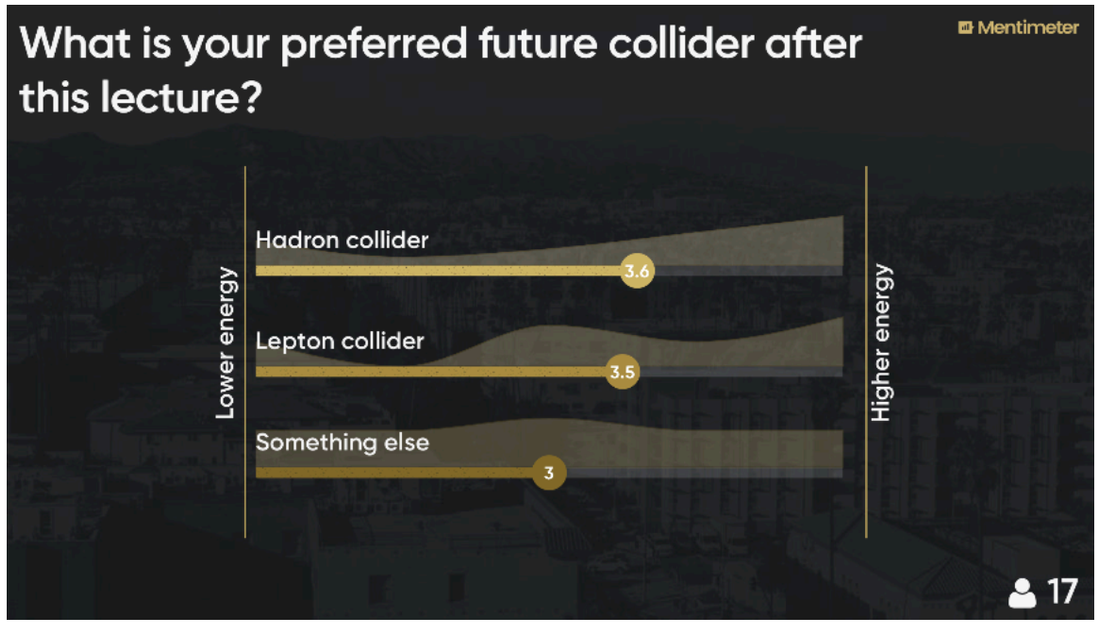
Neutrino physics is the BSM next door:
(or within, as billions of them/second traverse us right now)
ongoing and new exciting experiments with both Fermilab & CERN involvement will tell us more in the next decades

Future: poll results after each lecture

After lecture 1 (generic BSM)



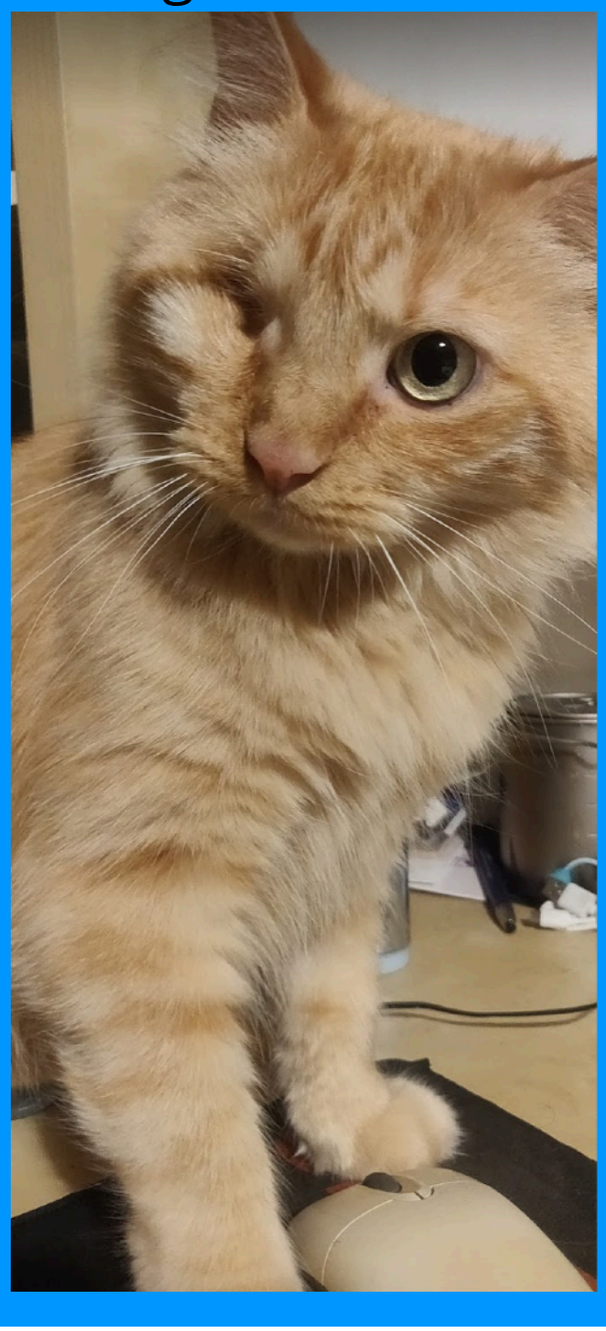
After lecture 2 (SUSY & DM)



After lecture 3 (More DM, other BSM, neutrino)….

Thanks for the attention
and for all the questions on the *mew* physics

the cat that helped
writing those lectures



Thinking about the Q from yesterday:
is there a correlation between
BSM people and cat people?

Happy to talk more!

e-mail: the usual CERN one hi spammers
Twitter: @CatDogLund