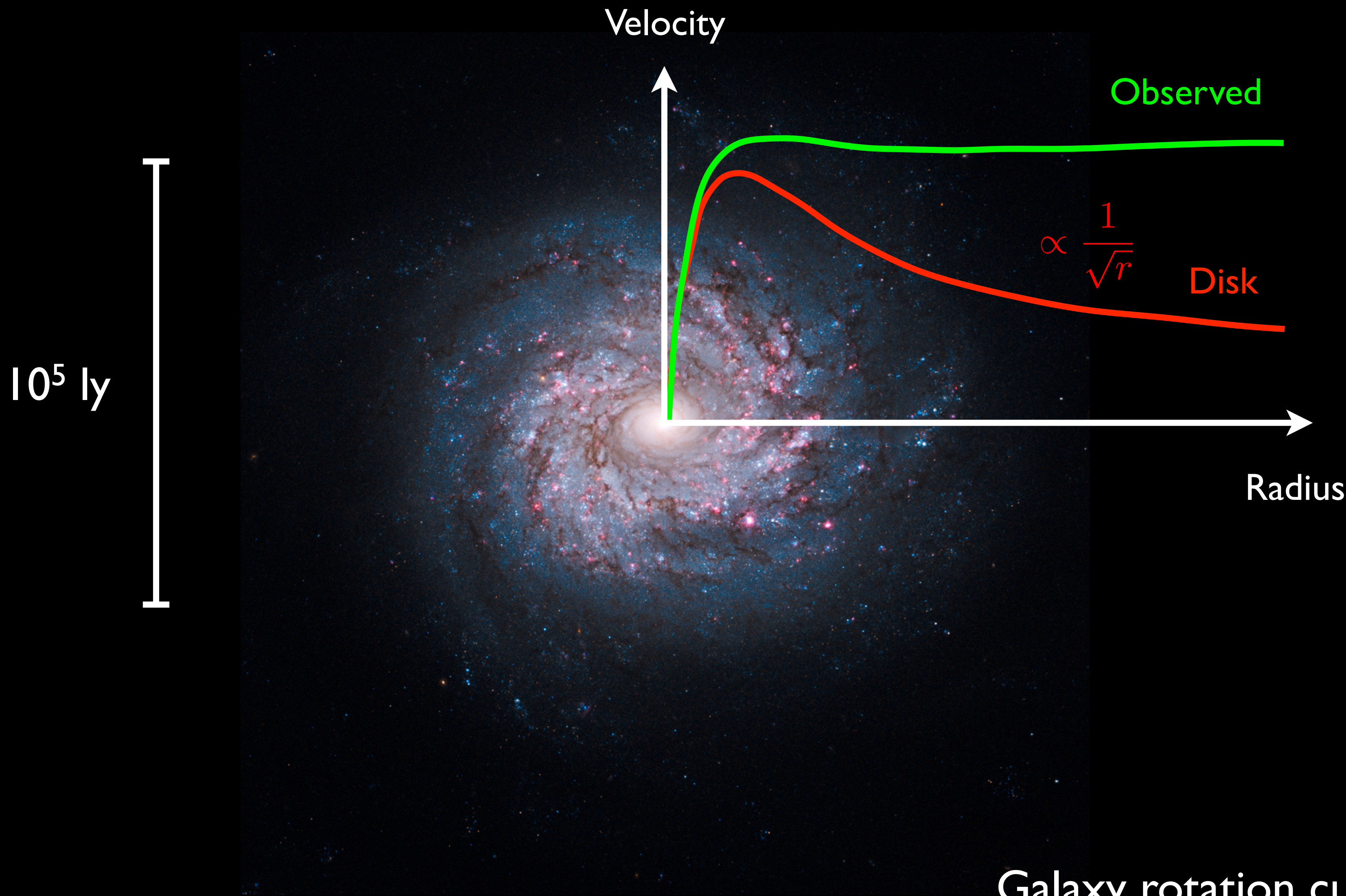
LHC searches for dark matter

Uli Haisch

Evidence for dark matter

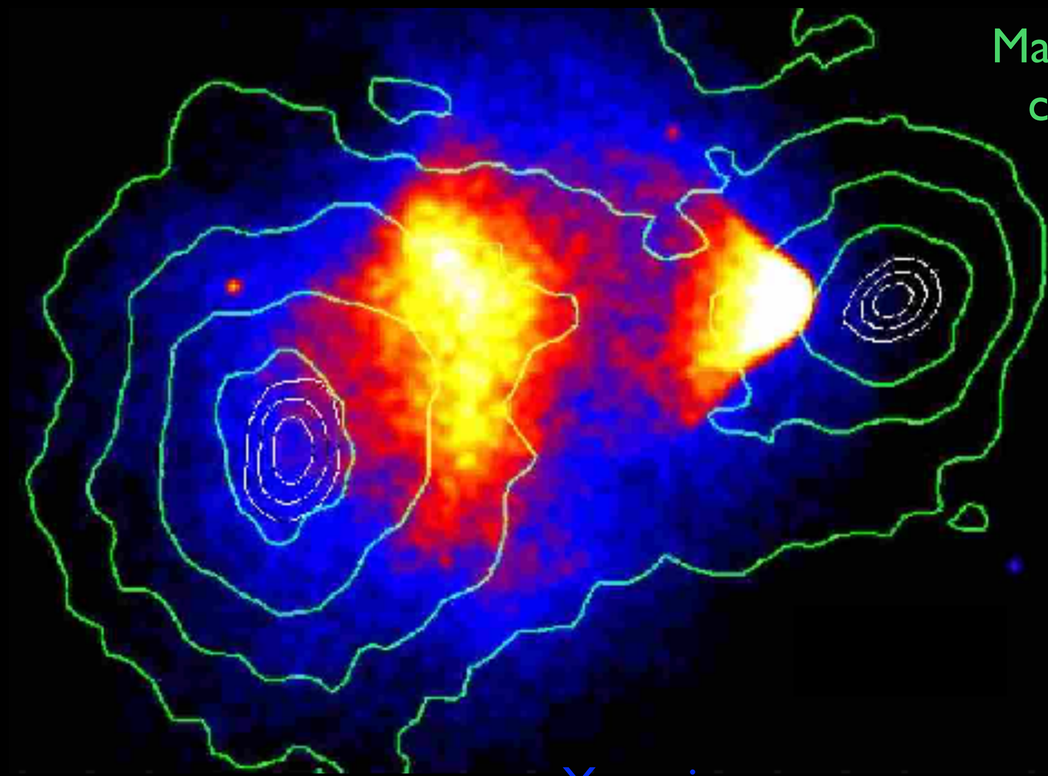


Galaxy rotation curves

Evidence for dark matter

Bullet cluster

10^7 ly

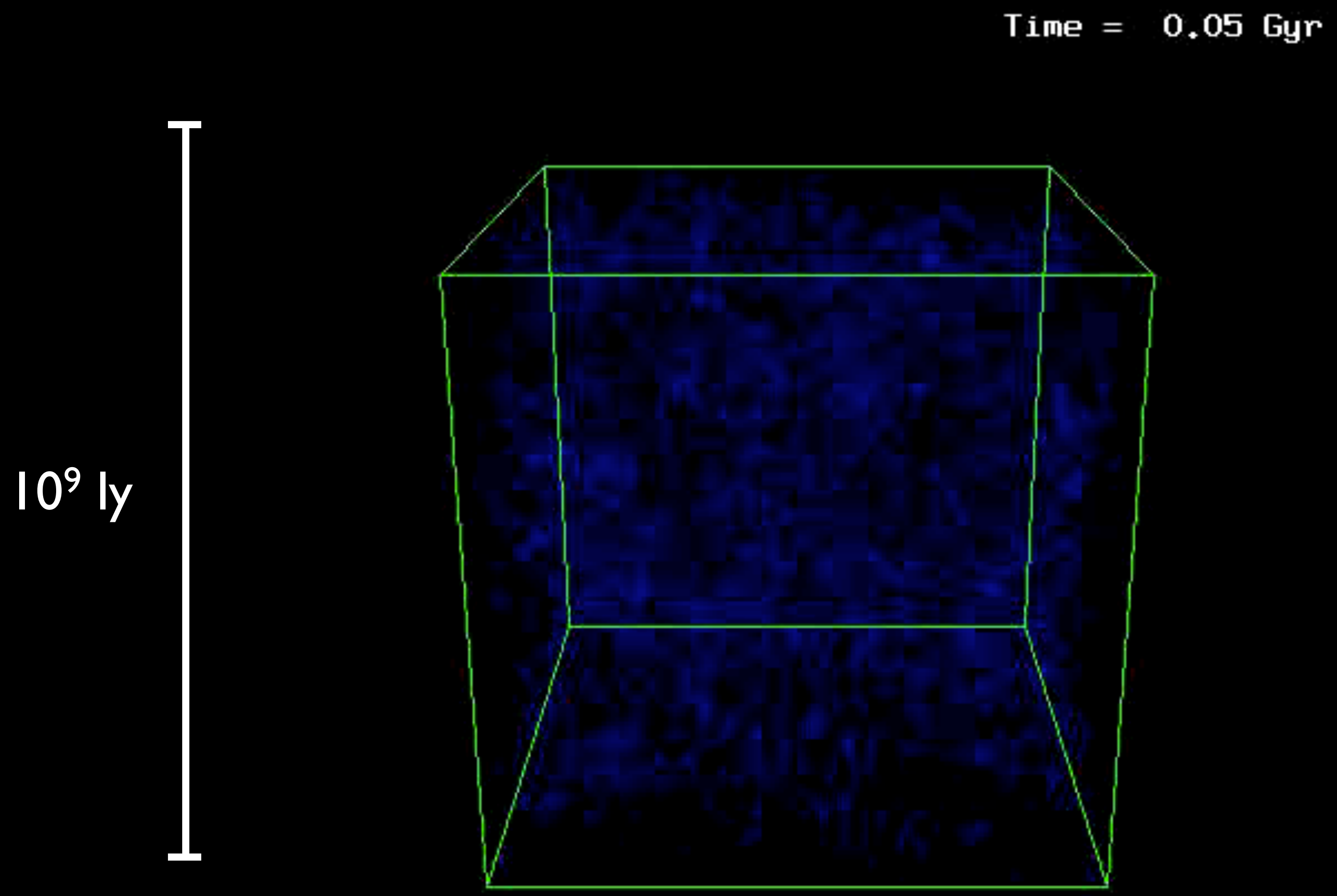


Mass density contours

X-ray image

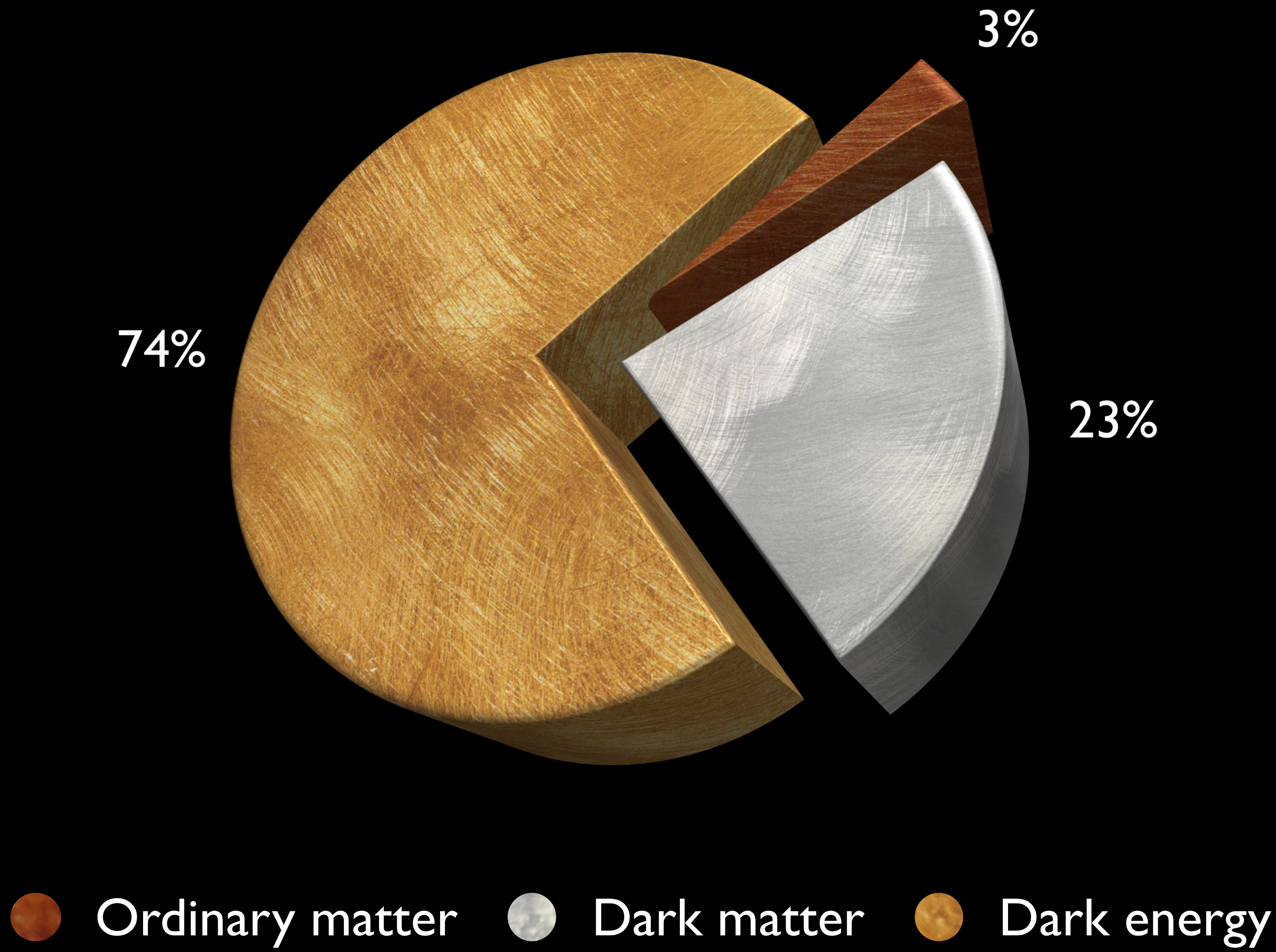
Gravitational lensing

Evidence for dark matter



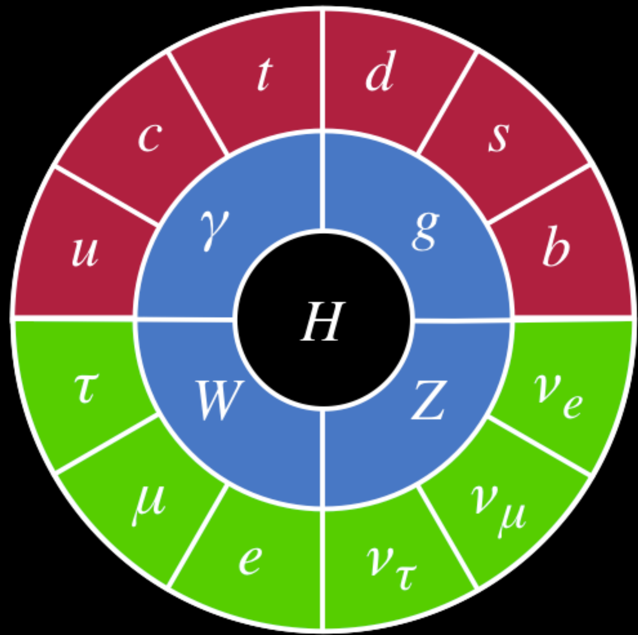
Structure formation

Content of Universe



But what is dark matter?

- As a particle physicist I want to know how dark matter (DM) fits into a particle description
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime exceeding the age of the Universe)
- Nothing in the Standard Model of particle physics fits the profile



Standard Model (SM)

DM questionnaire

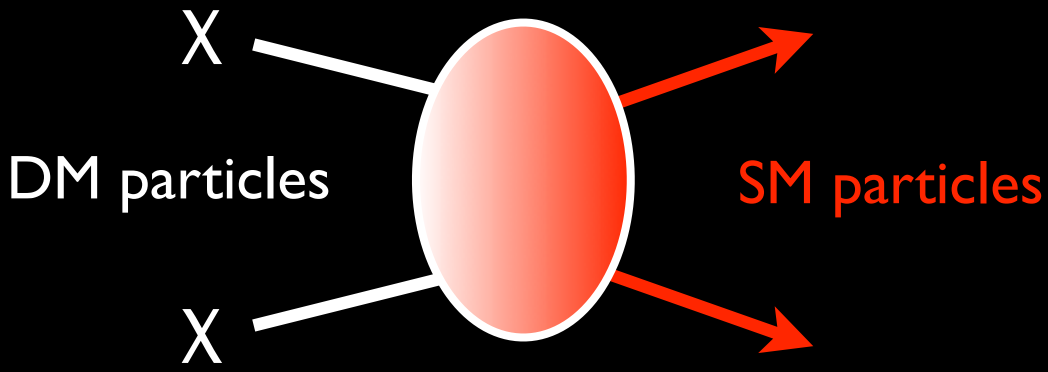
- [ ] Mass: ________
- [ ] Spin: ________
- [ ] Lifetime: ________

Couplings:

- [x] Gravity
- [ ] Weak interaction?
- [ ] Higgs?
- [ ] Quarks/gluons?
- [ ] Leptons?
- [ ] Thermal relic?

  - [ ] Yes
  - [ ] No

Particle probes of DM

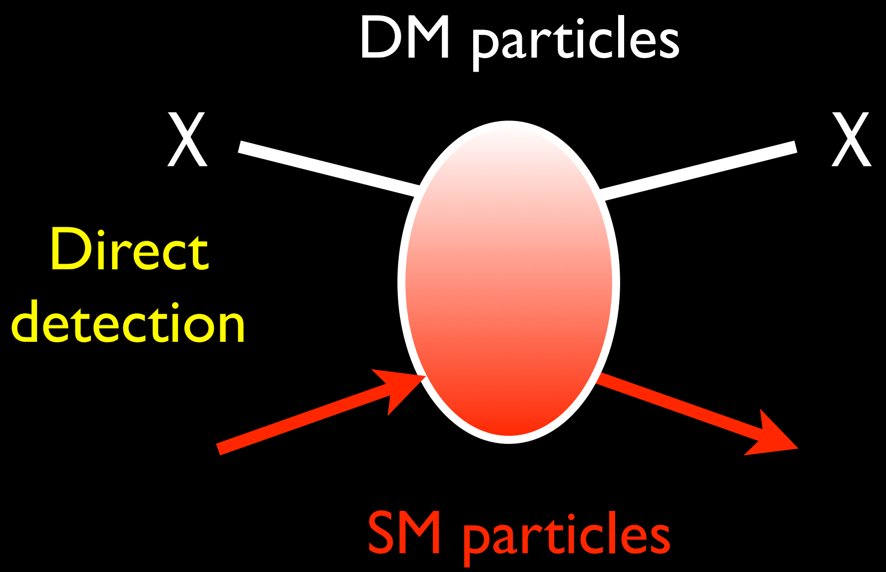


Indirect detection

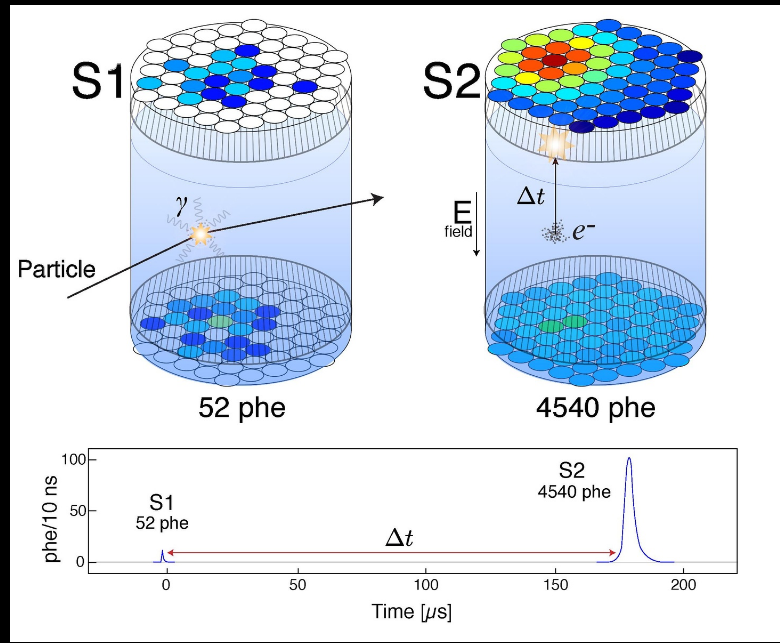
Fermi telescope

- The common theme of searches for DM is that all methods are determined by how the DM particles interact with the SM

Particle probes of DM

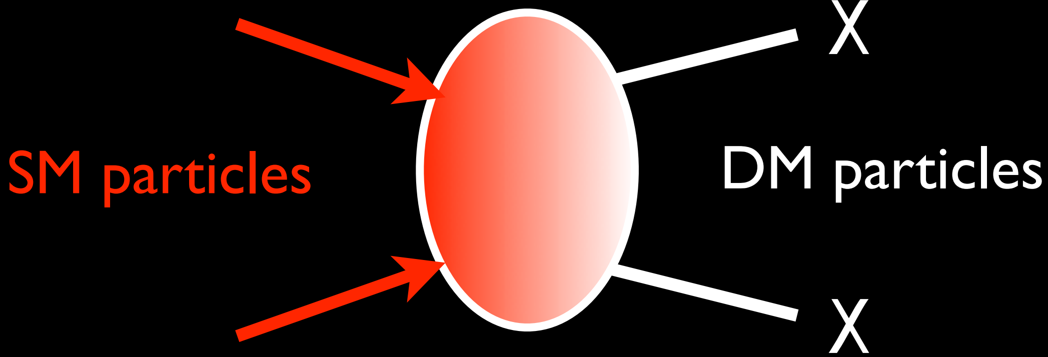


LUX detector



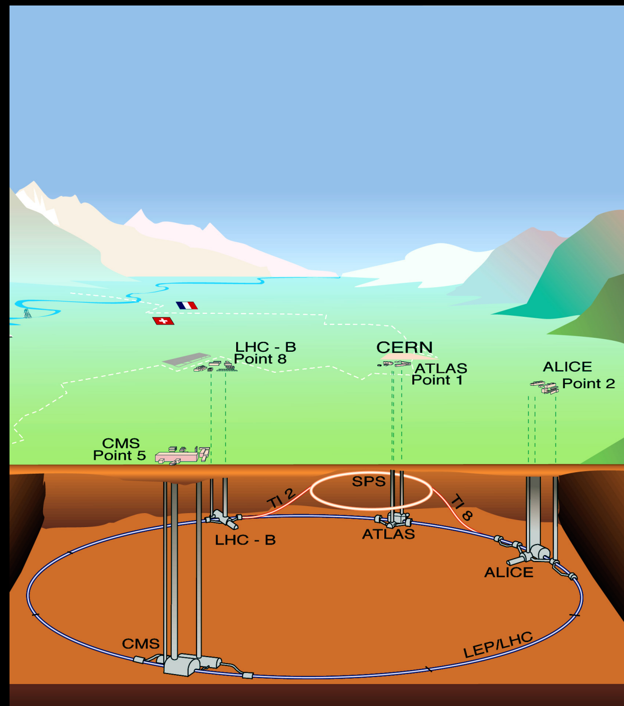
- The common theme of searches for DM is that all methods are determined by how the DM particles interact with the SM

Particle probes of DM



Collider searches

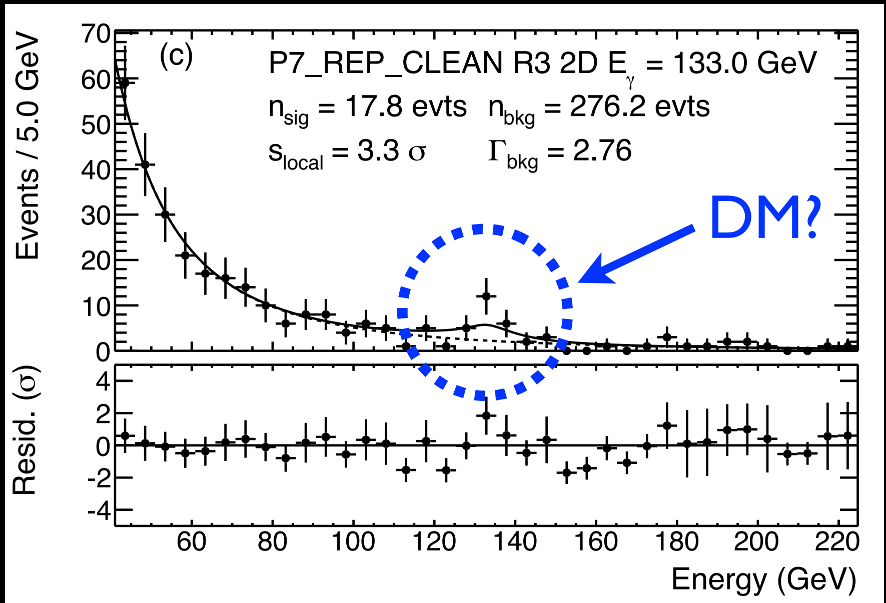
LHC at CERN



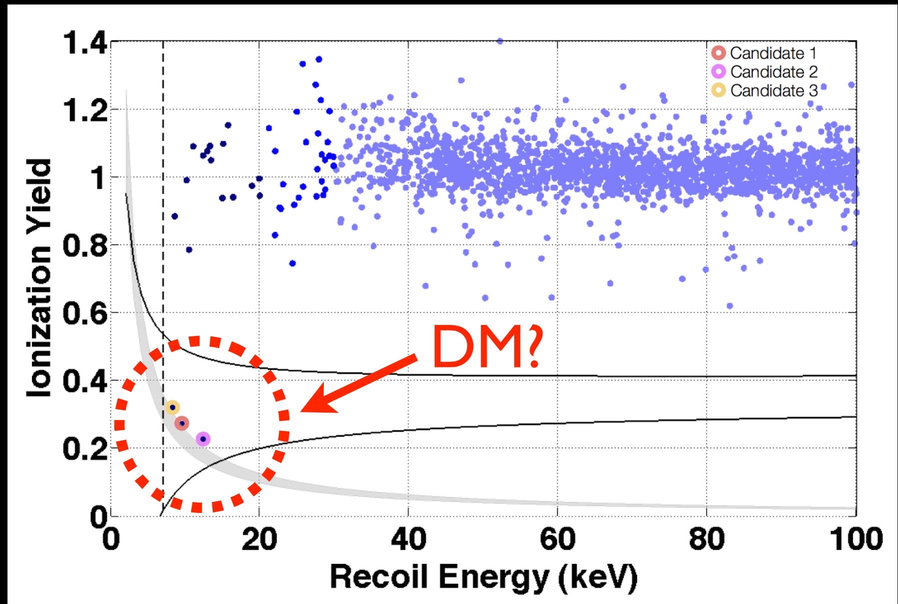
- The common theme of searches for DM is that all methods are determined by how the DM particles interact with the SM

Has DM already been seen?

Fermi-LAT



CDMS II

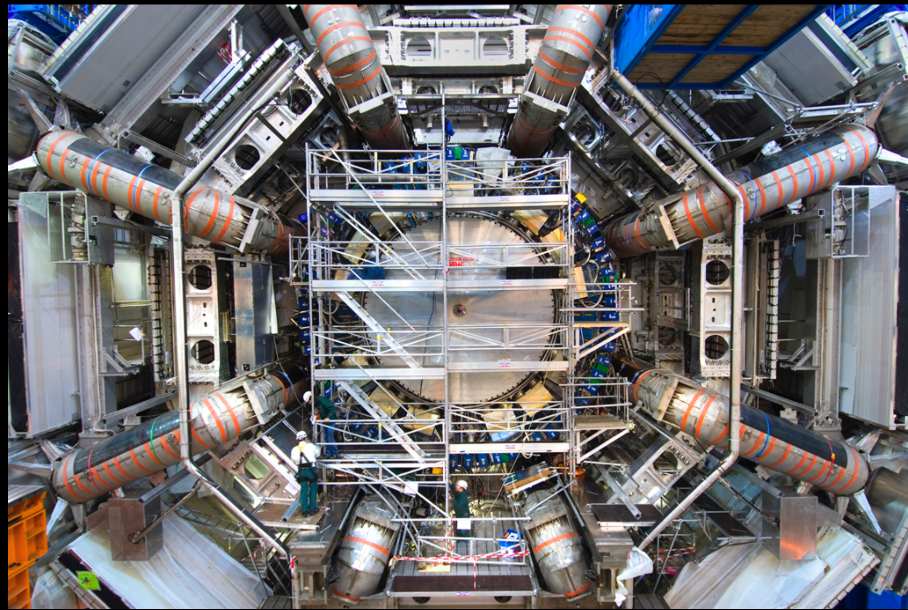


- Claims for DM discovery have been made based on the results of indirect and direct detection experiments. Since the backgrounds in both cases are large and uncertain (and given that we have no control over the signal), claims remain unsubstantiated

DM production at the LHC

- If DM particles are sufficiently light and couple to quarks or gluons, we should be able to produce them at the LHC
- By studying DM production in proton-proton collisions, we are testing the inverse of the process that kept DM in thermal equilibrium in the early Universe
- LHC may allow us to produce other states of "dark sector", which are no longer present in the Universe today

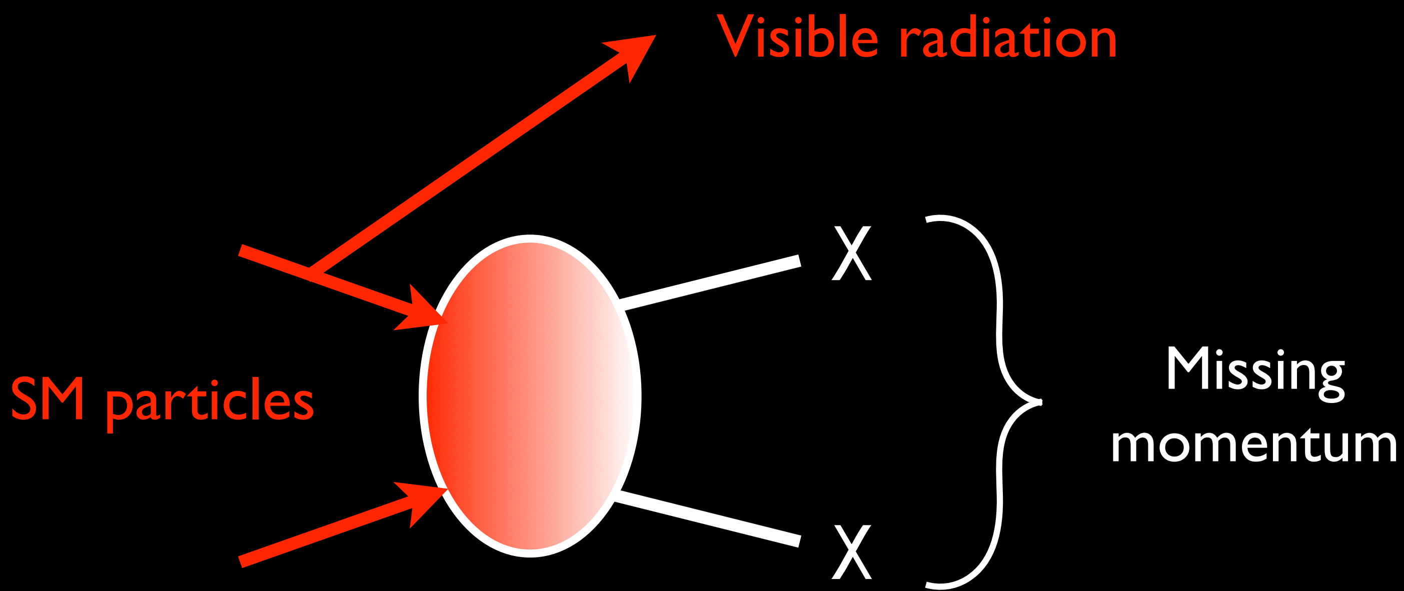
ATLAS detector



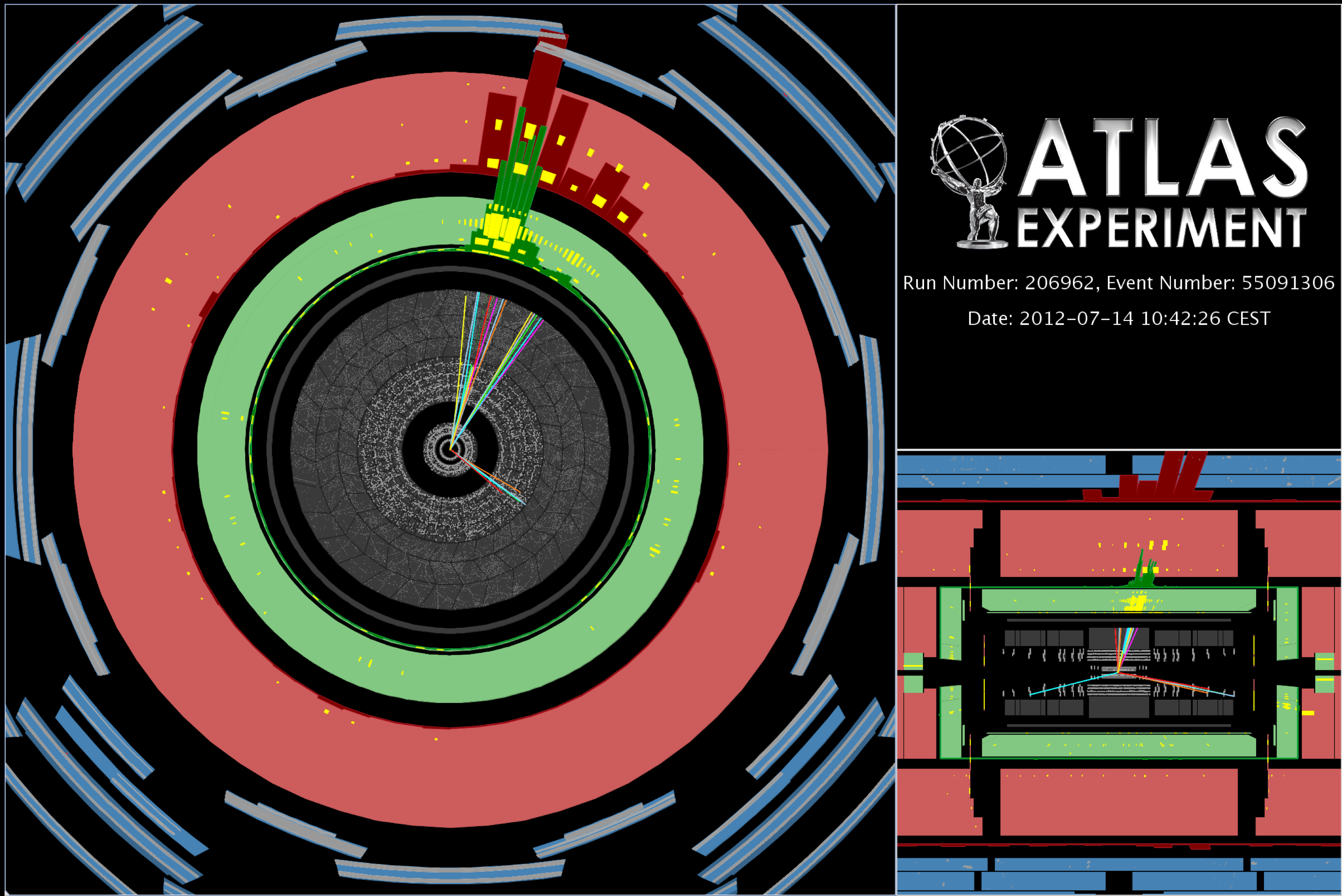
46 m $\times$ 25 m,
7000 t,
3000 km of cables, …

How to see the invisible?

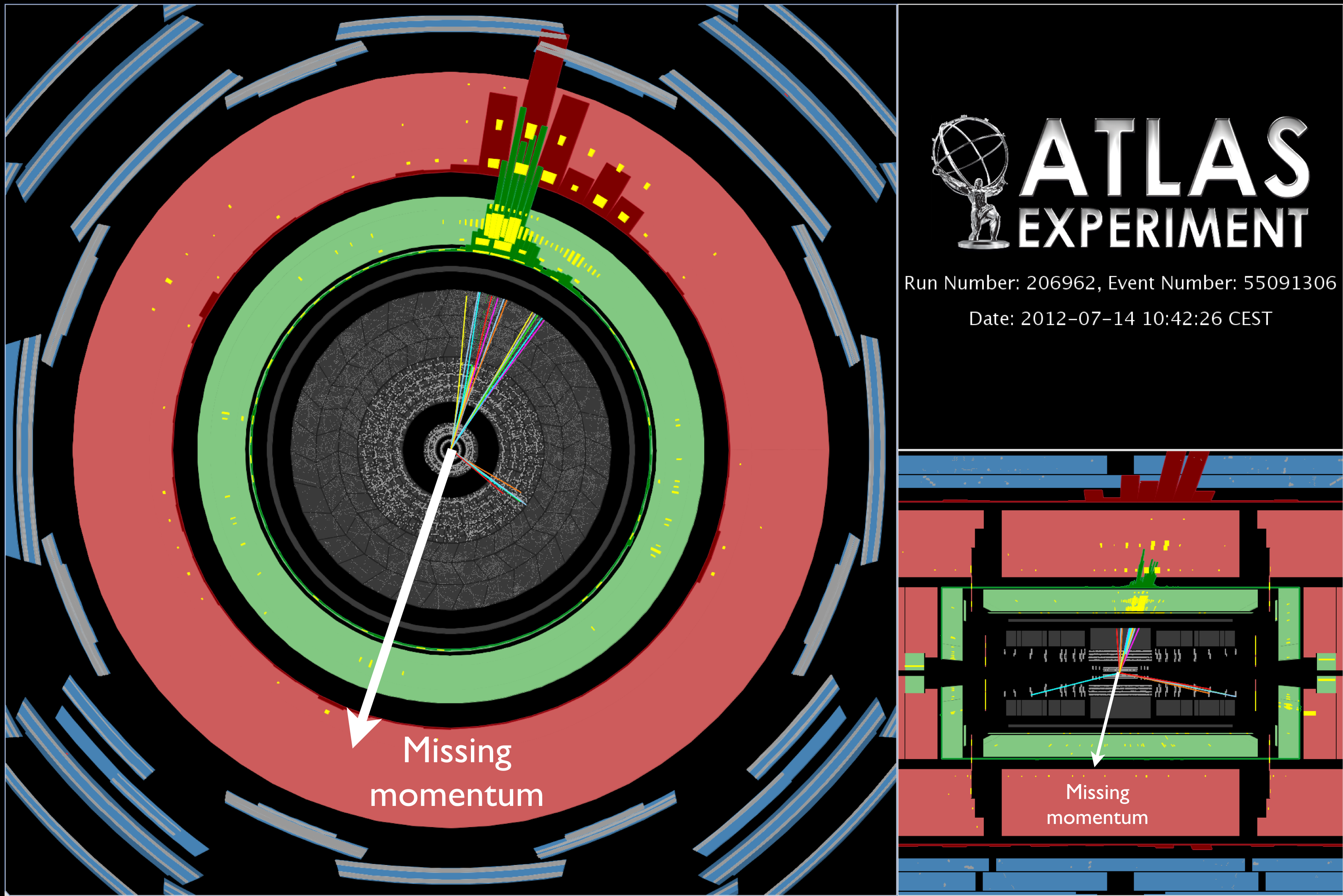
- The DM particles interact so weakly that they are expected to pass out of the detector components without any significant interaction, making them effectively invisible (much like neutrinos)
- One way to “see” DM particles nonetheless, works by looking for “missing momentum” and additional SM radiation



How to see the invisible?

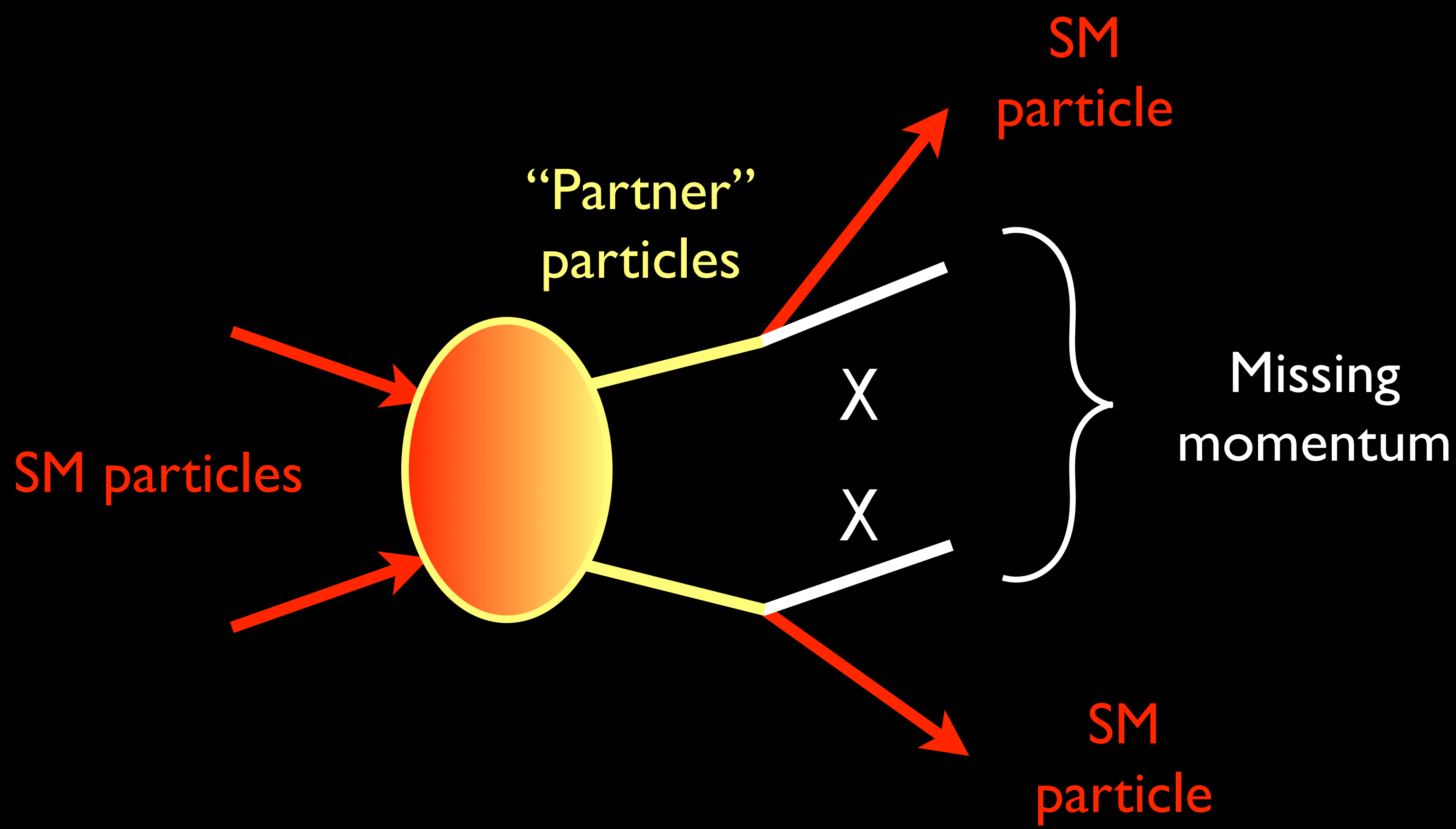


How to see the invisible?

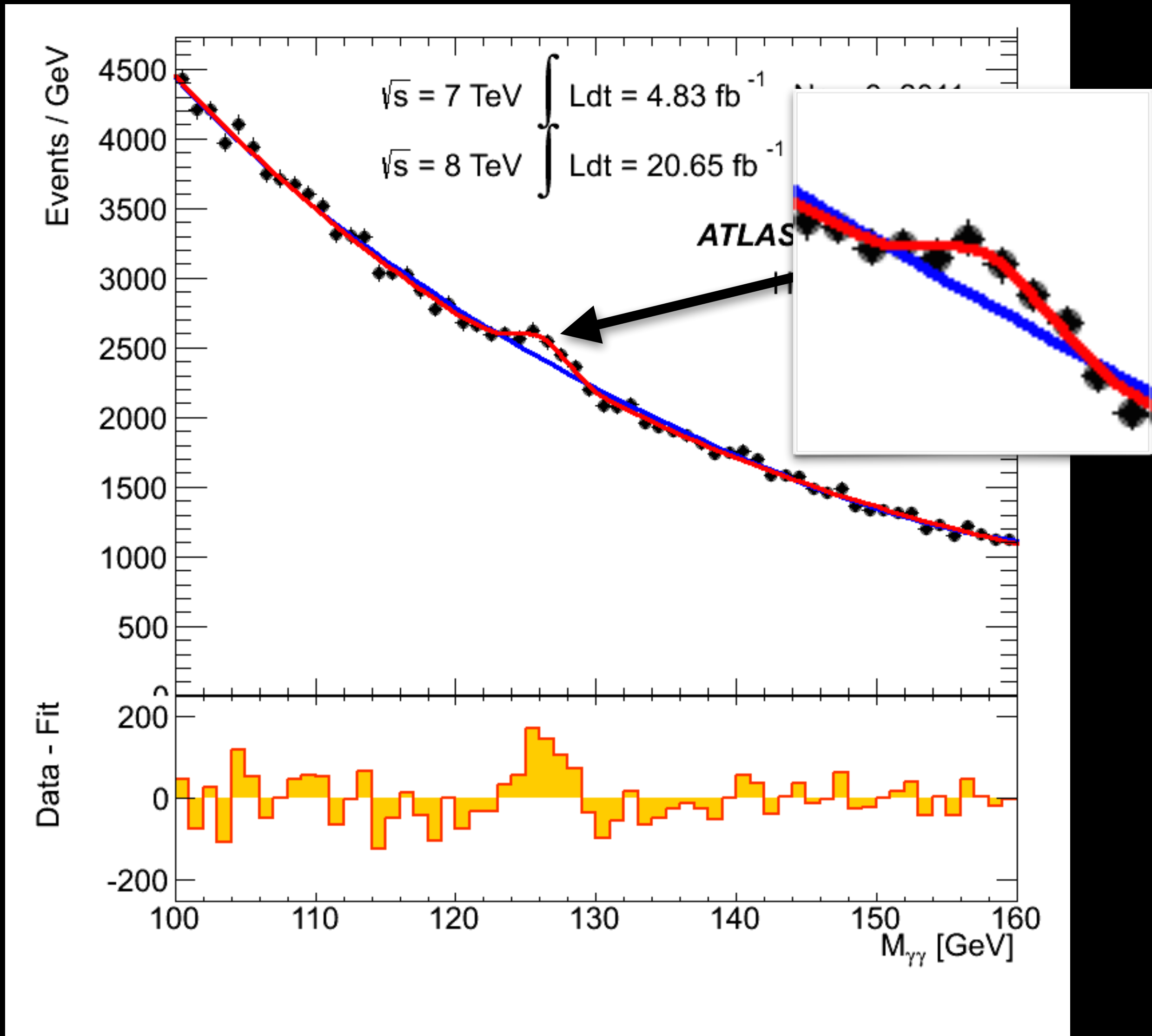


How to see the invisible?

- Second way to try to detect SM, based on production of "partner" particles that decay to DM and SM particles



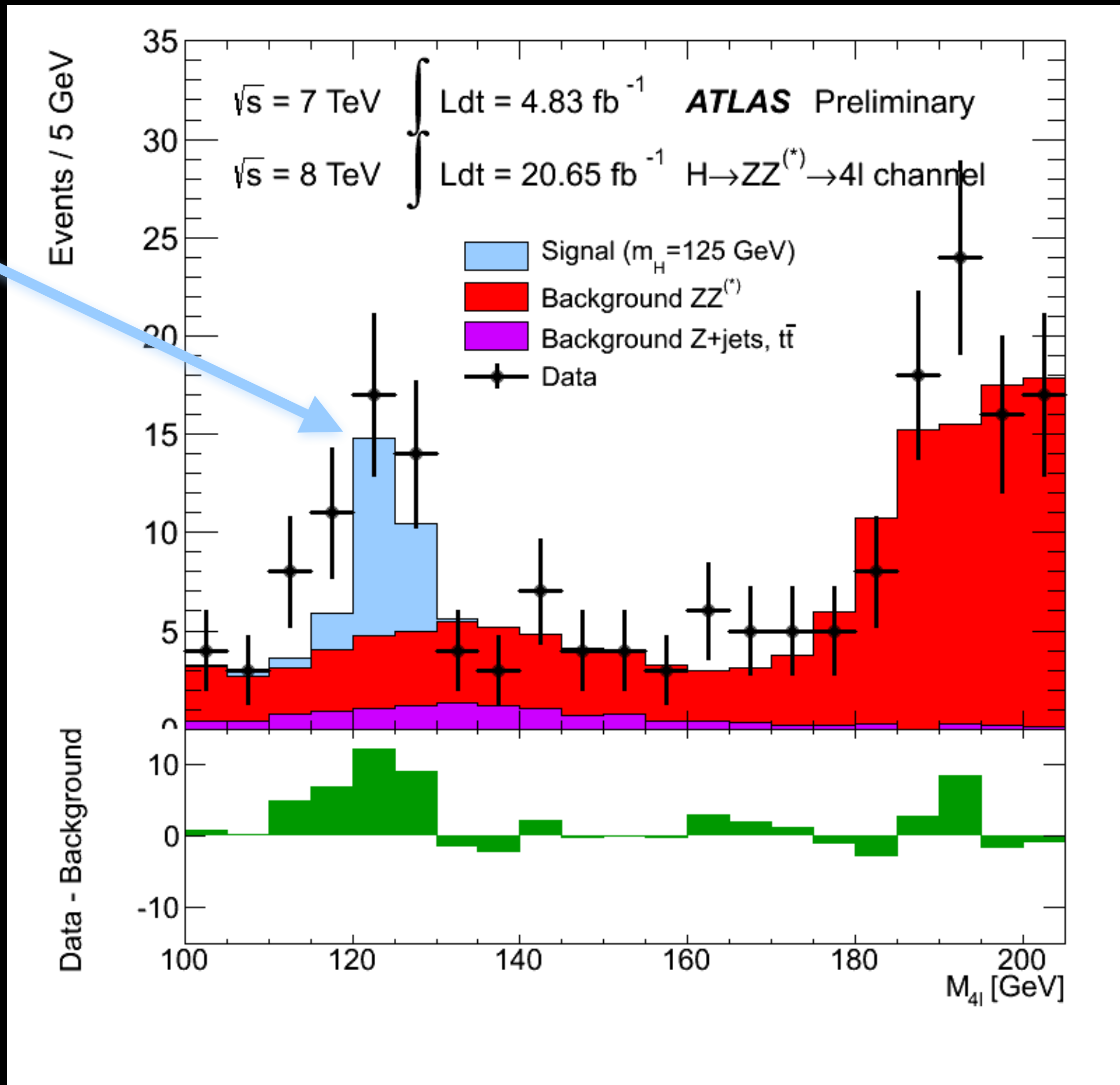
"Bump hunting" for the Higgs



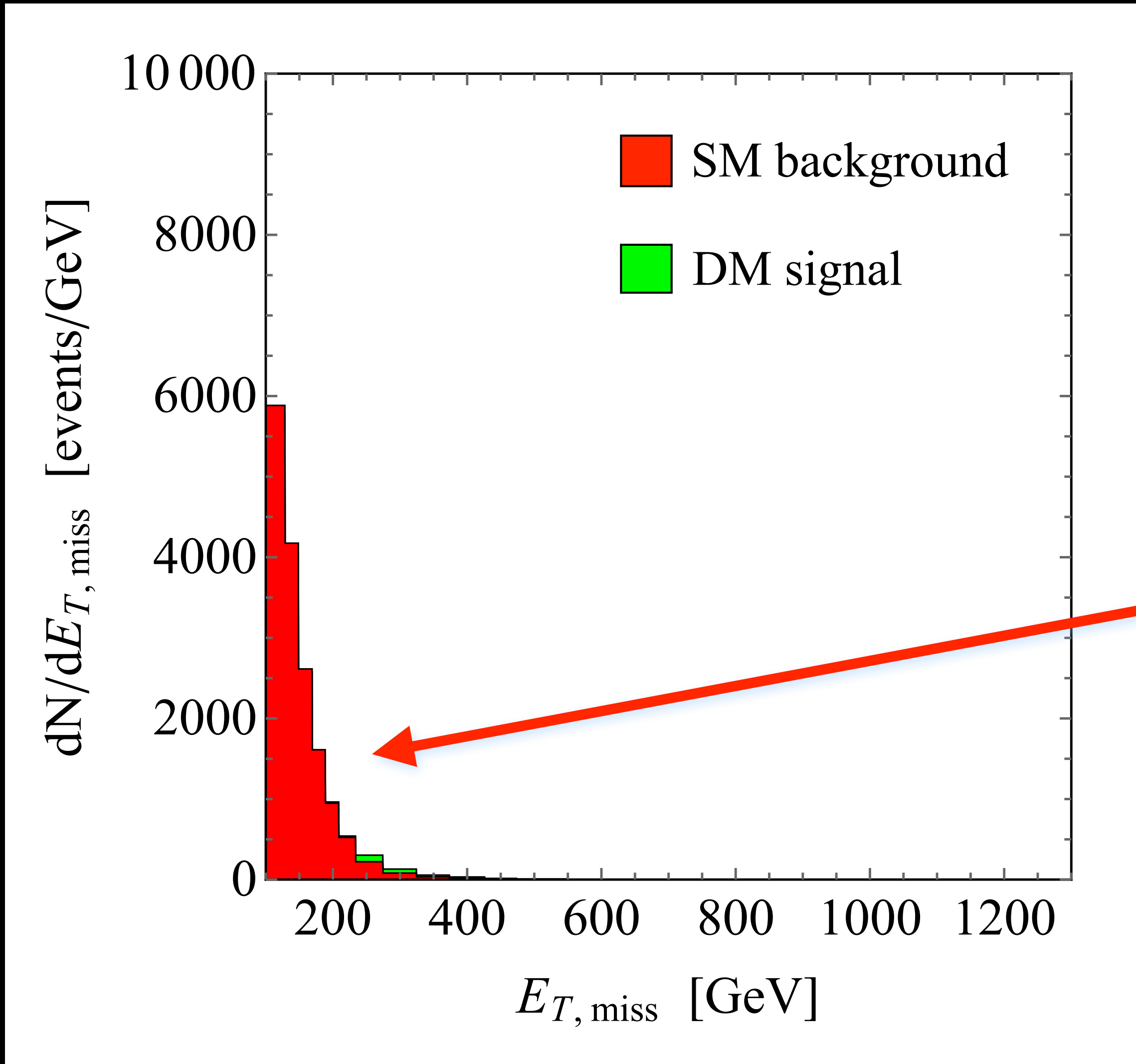
The di-photon decay of the Higgs leads to a nice bump in the invariant mass distribution

"Bump hunting" for the Higgs

To see the bump for the Higgs decaying to two Z bosons, one does not even have to zoom in

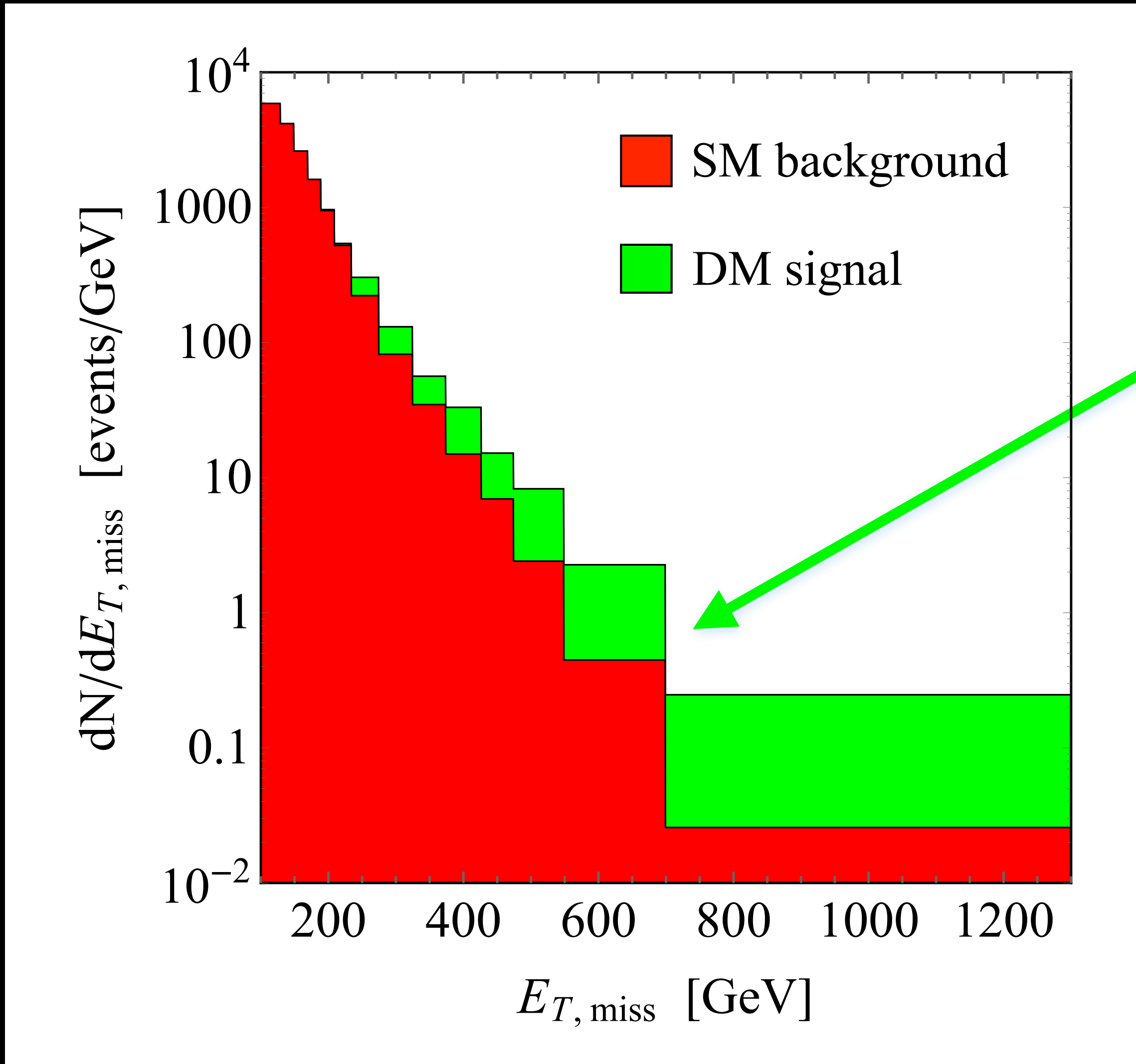


"Tail surgery" to find DM



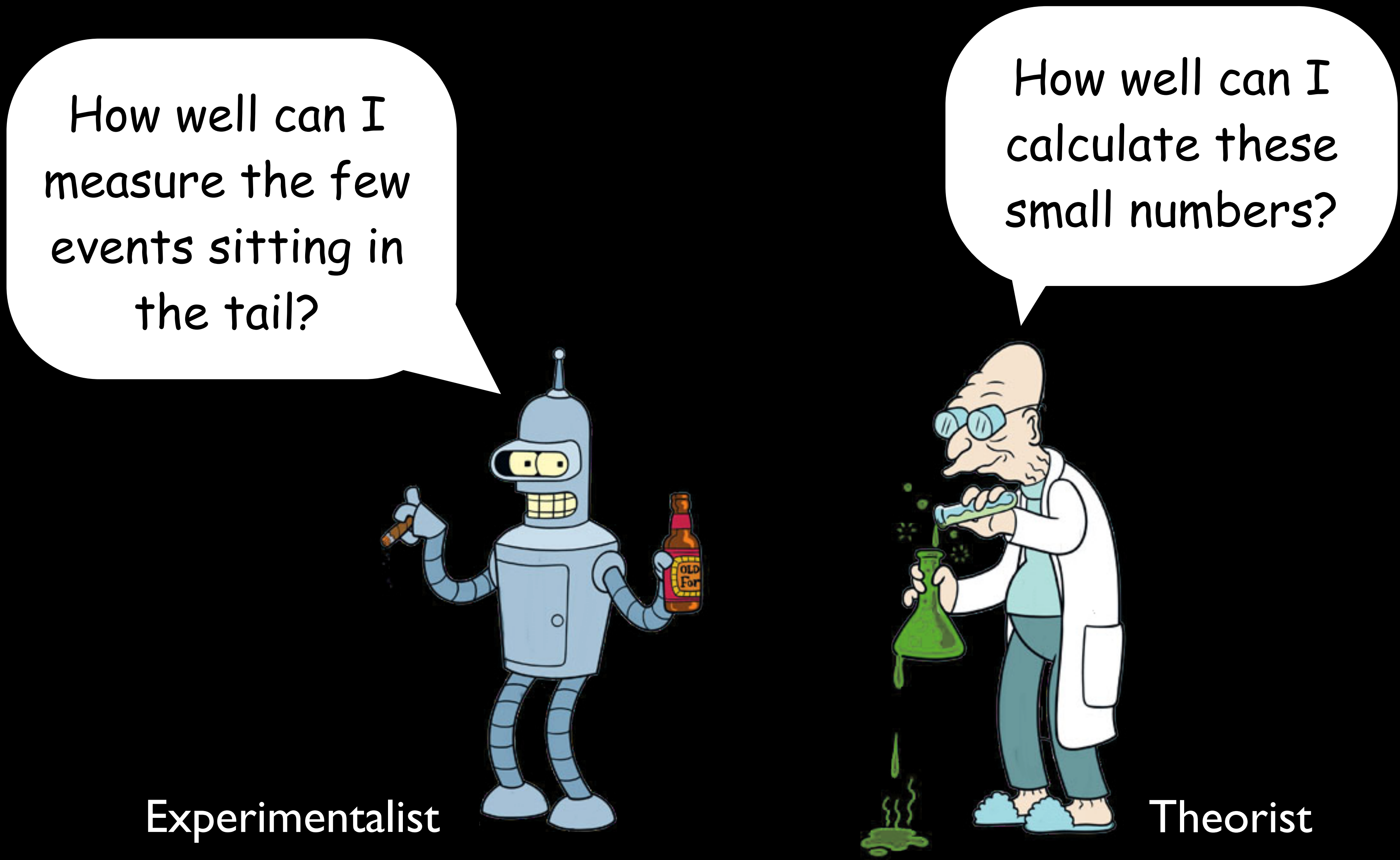
Overwhelming SM background, that arises in the case of mono-jet searches from Z + jet production with the Z boson decaying to neutrinos

“Tail surgery” to find DM

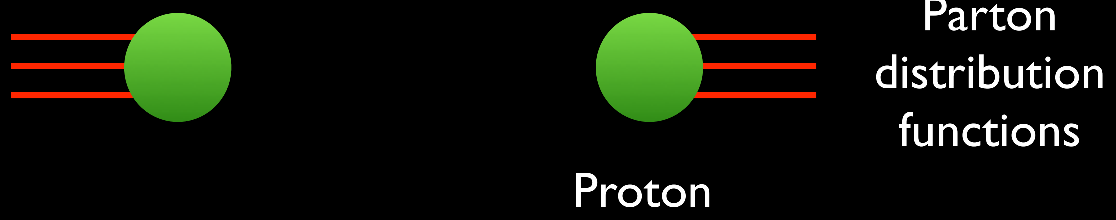


The presence of DM manifests itself in a small enhancement in the tail of the missing energy distribution

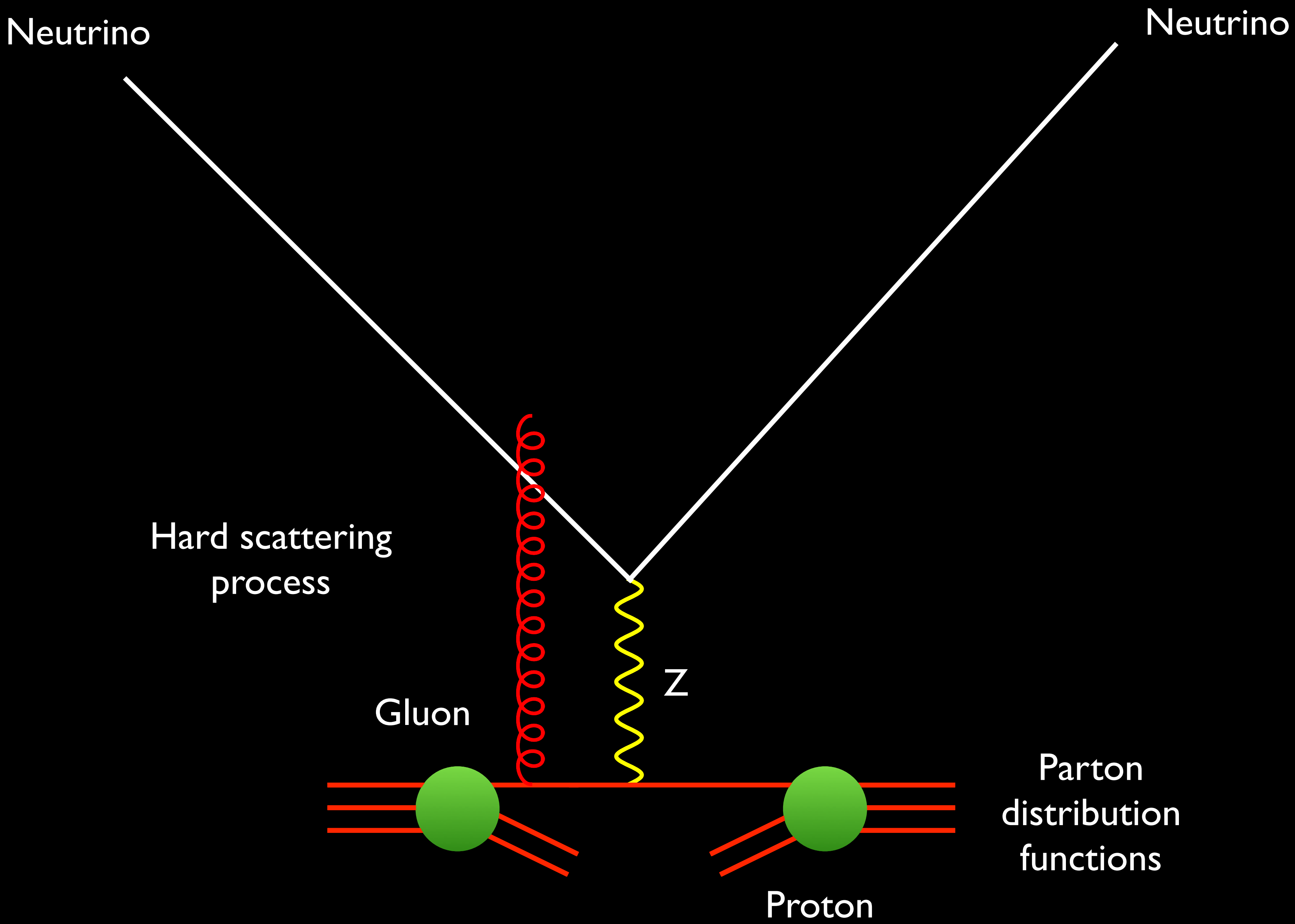
A big challenge indeed



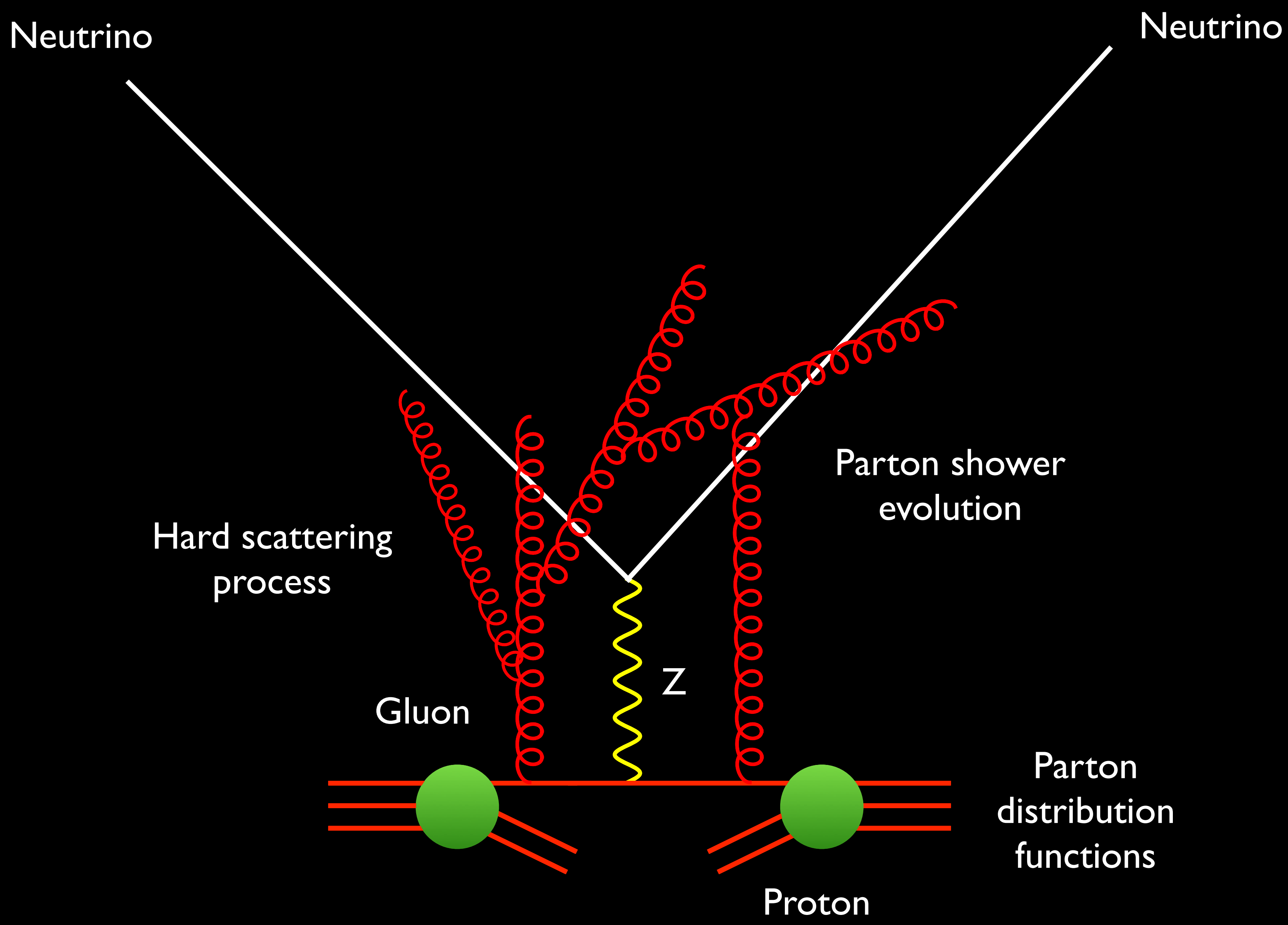
Precision QCD predictions



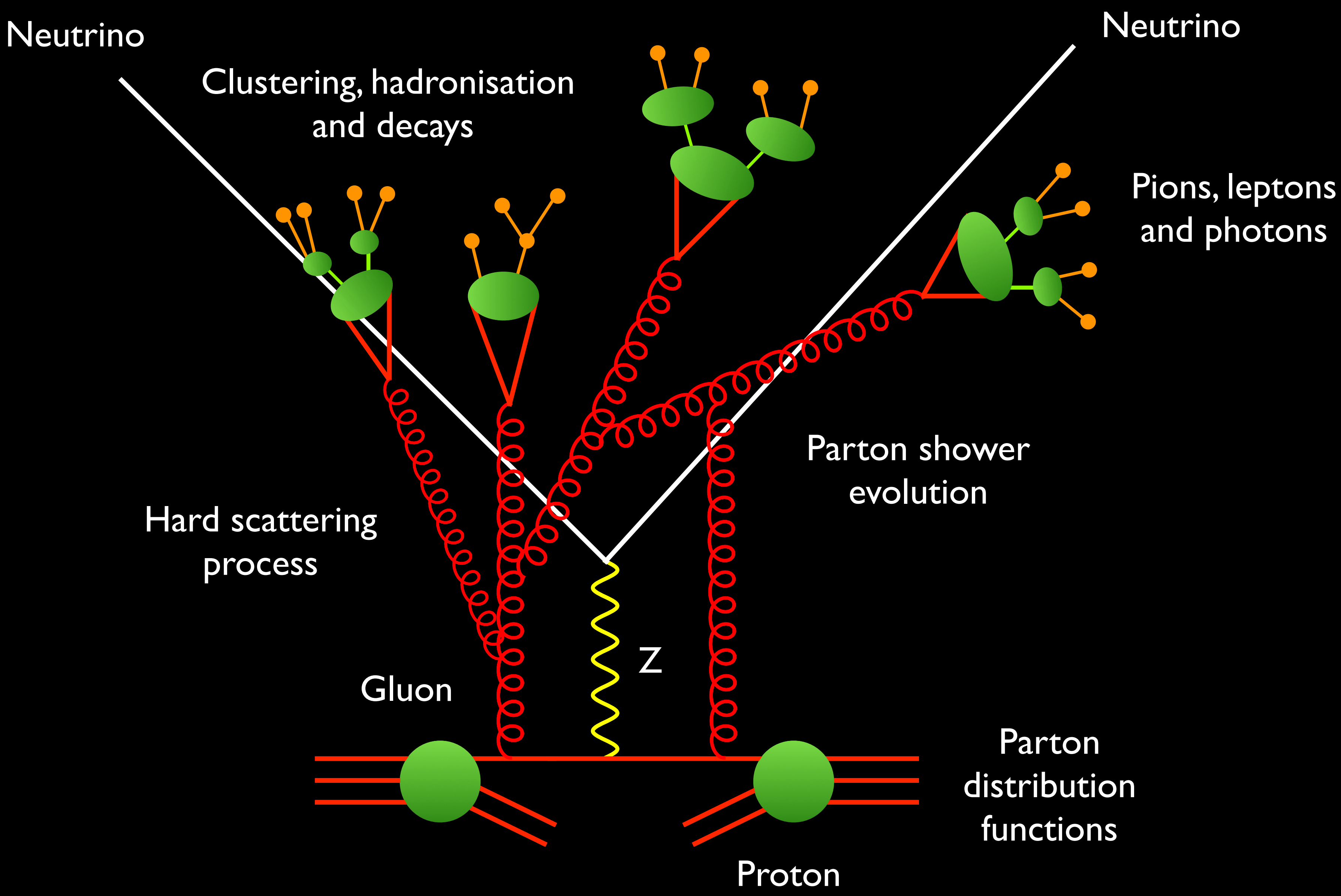
Precision QCD predictions



Precision QCD predictions

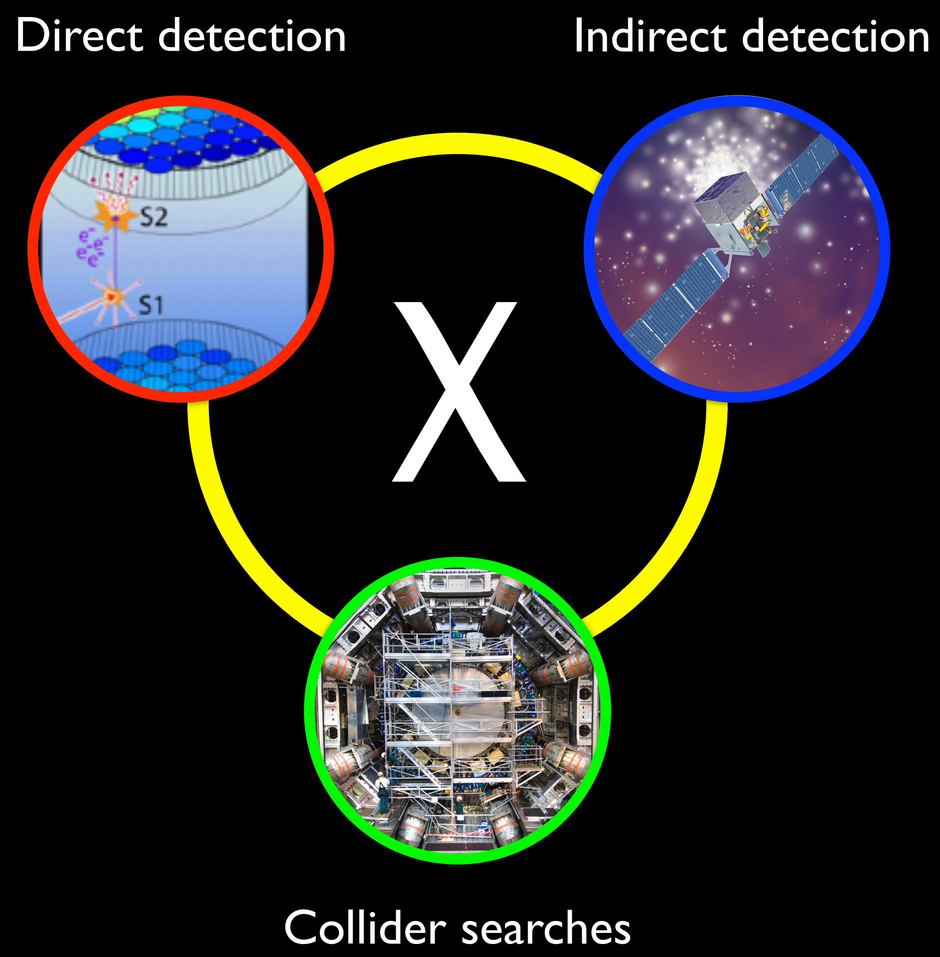


Precision QCD predictions

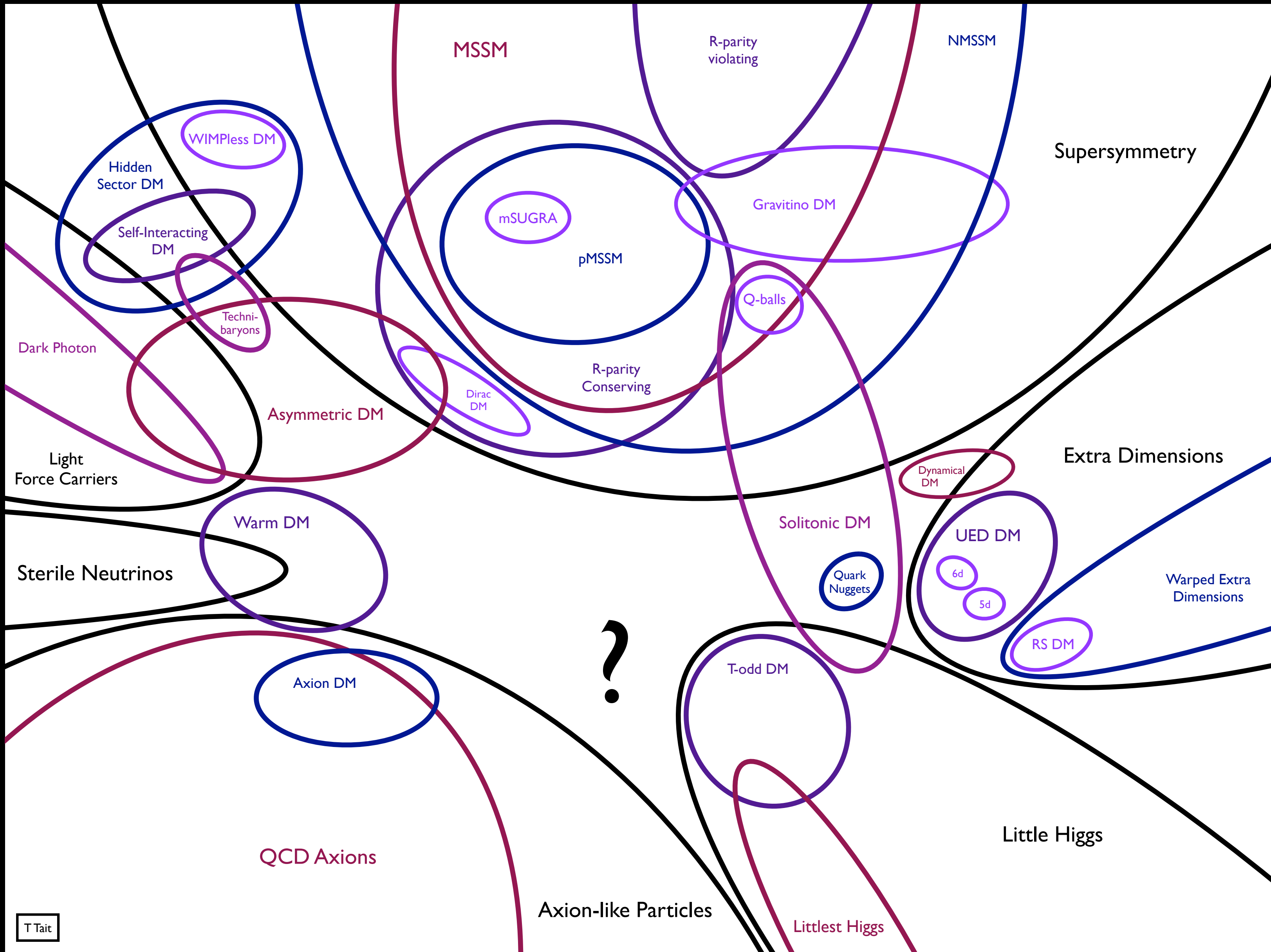


But we also need a DM theory

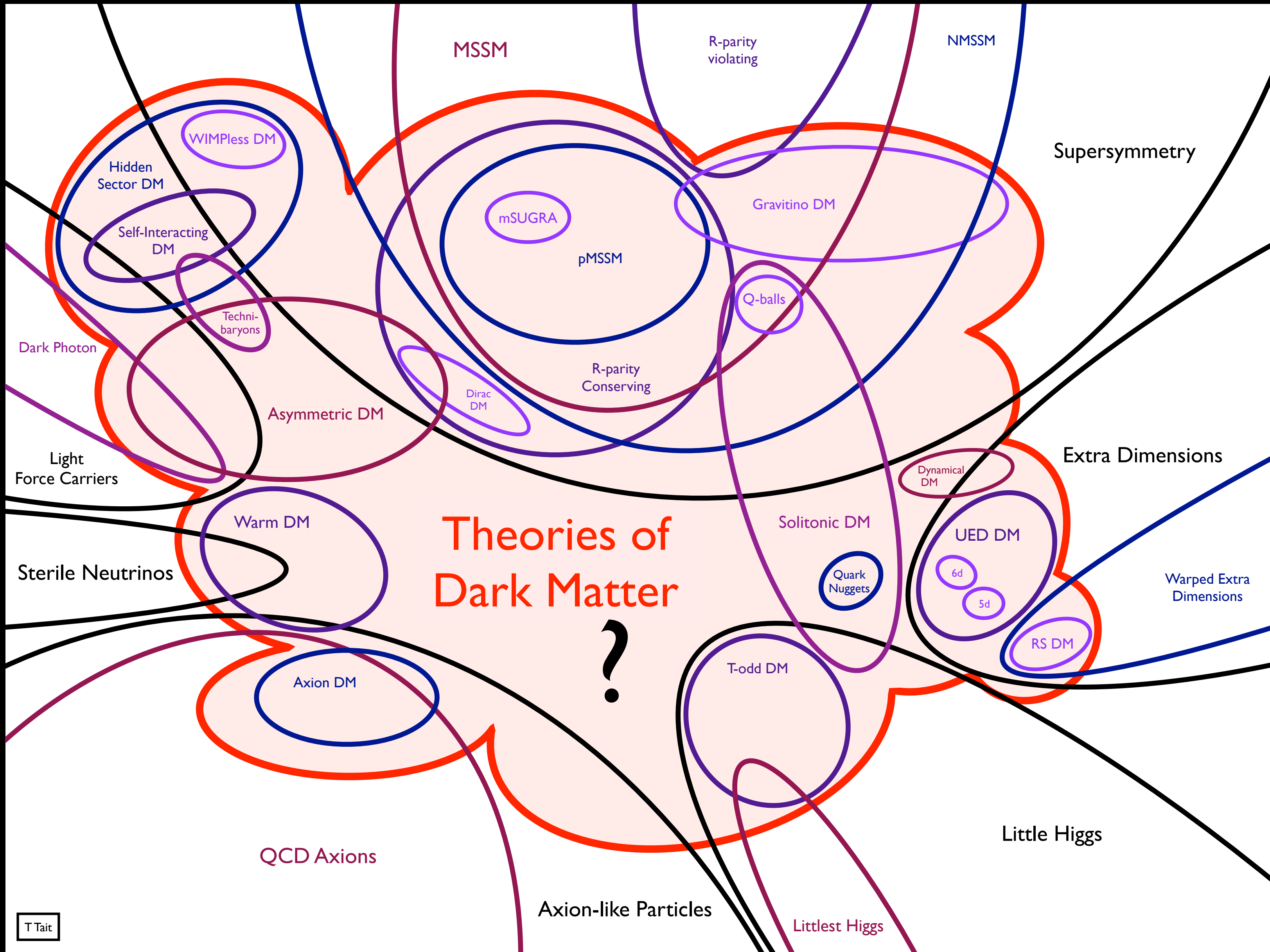
- The three main search strategies perform quite different measurements. Without a theoretical model of DM, we cannot compare the results
- If evidence for DM is found in one type of search, we can predict in a given model the signals that should be seen in other searches

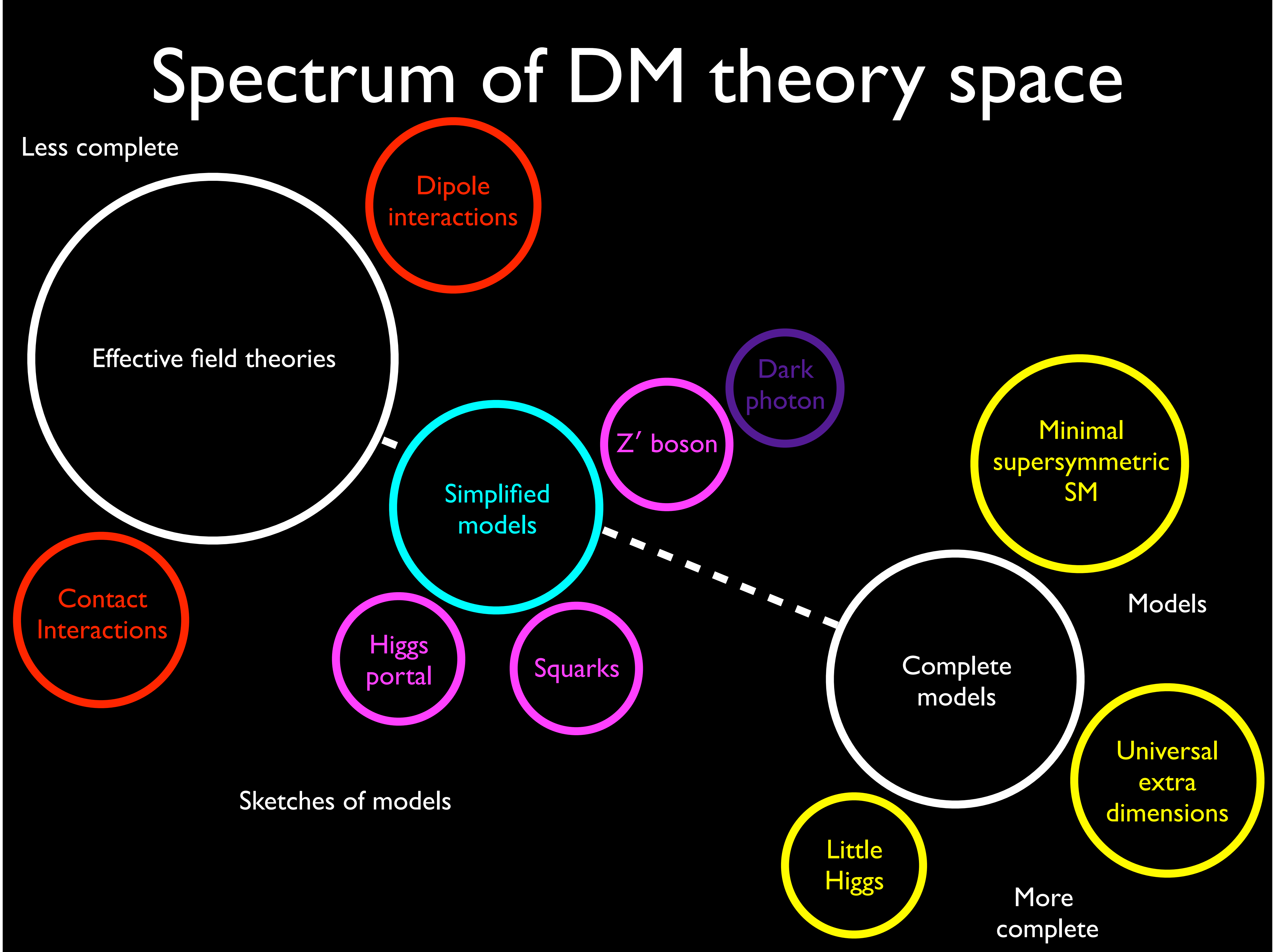


No lack of theoretical models

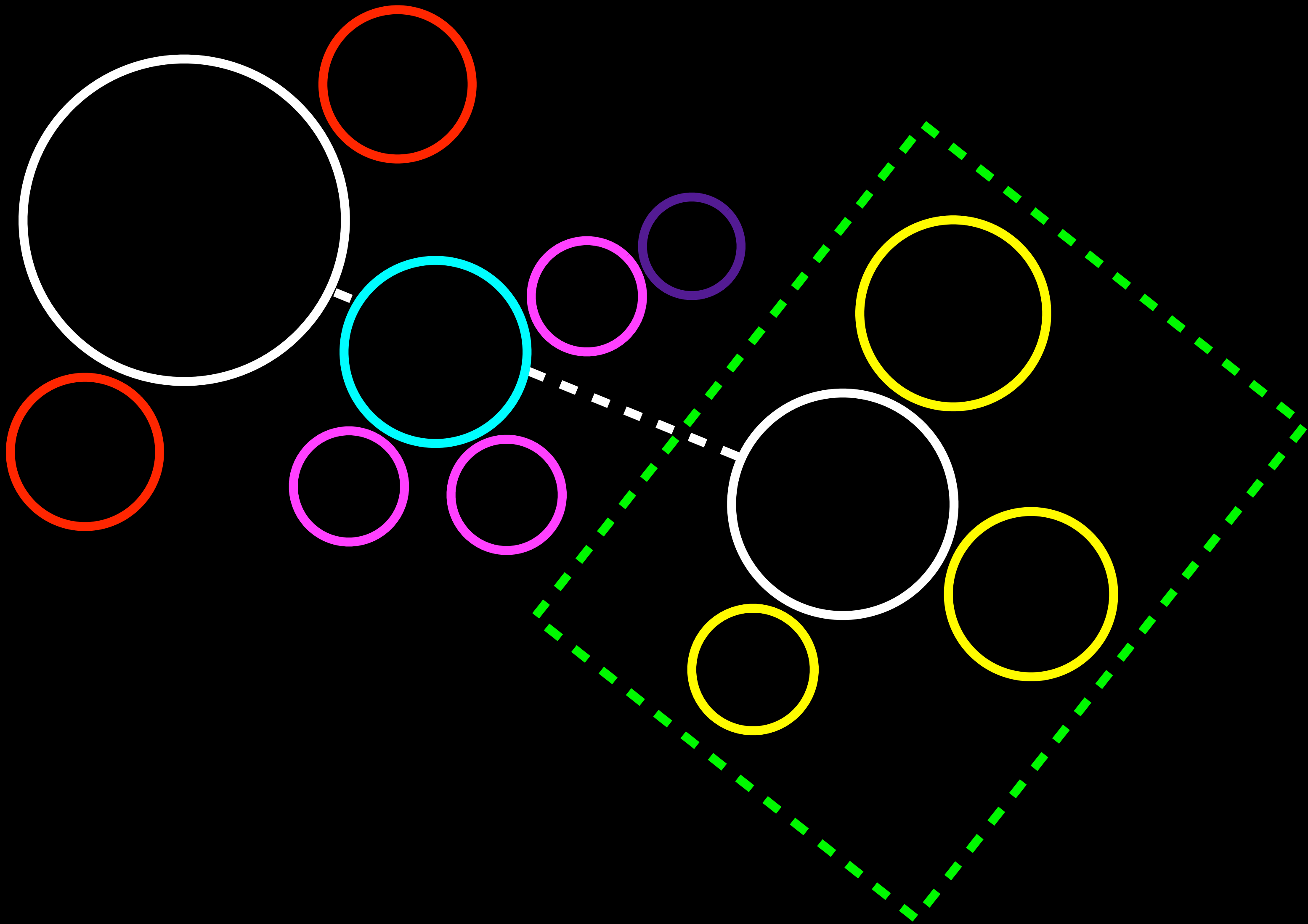


No lack of theoretical models



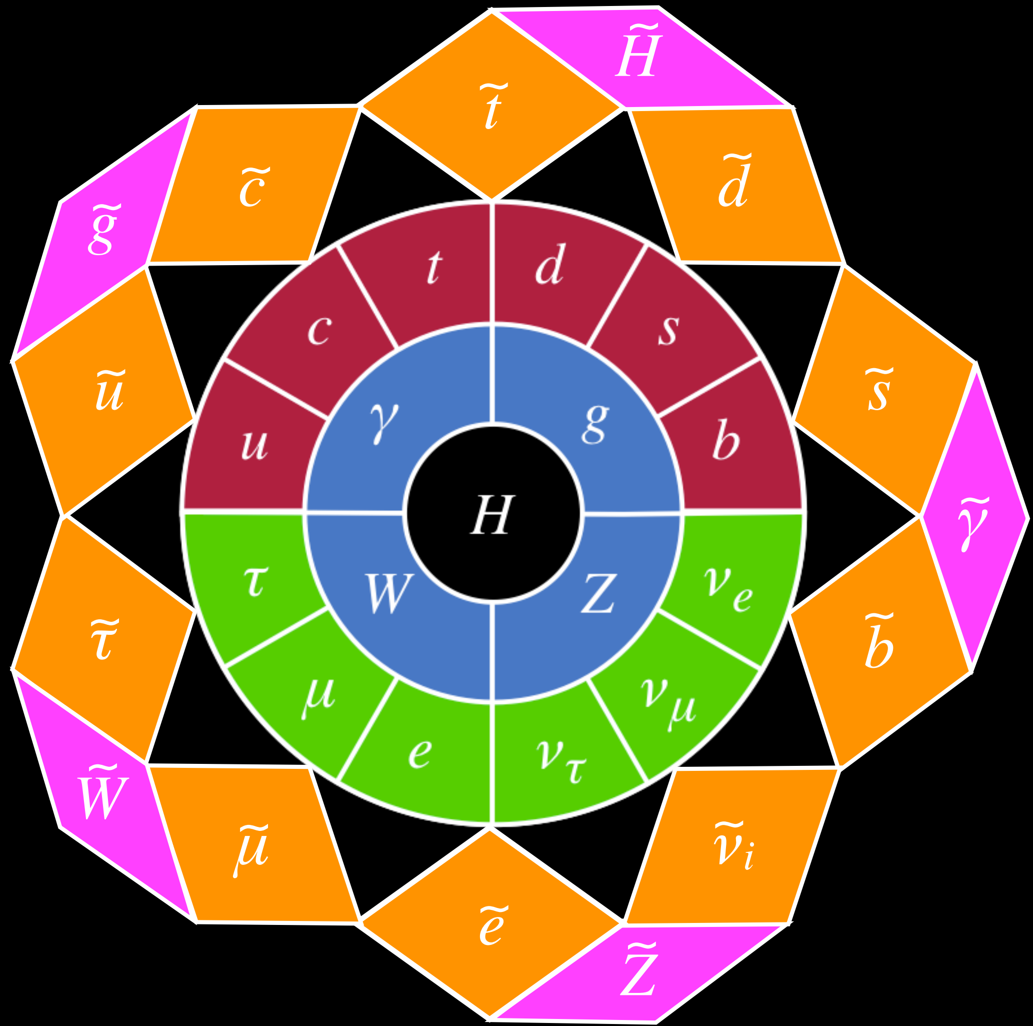

Spectrum of DM theory space
Less complete
Dipole interactions
Effective field theories
Dark photon
Z′ boson
Minimal supersymmetric SM
Simplified models
Contact Interactions
Models
Higgs portal
Squarks
Complete models
Universal extra dimensions
Sketches of models
Little Higgs
More complete

Complete DM theories



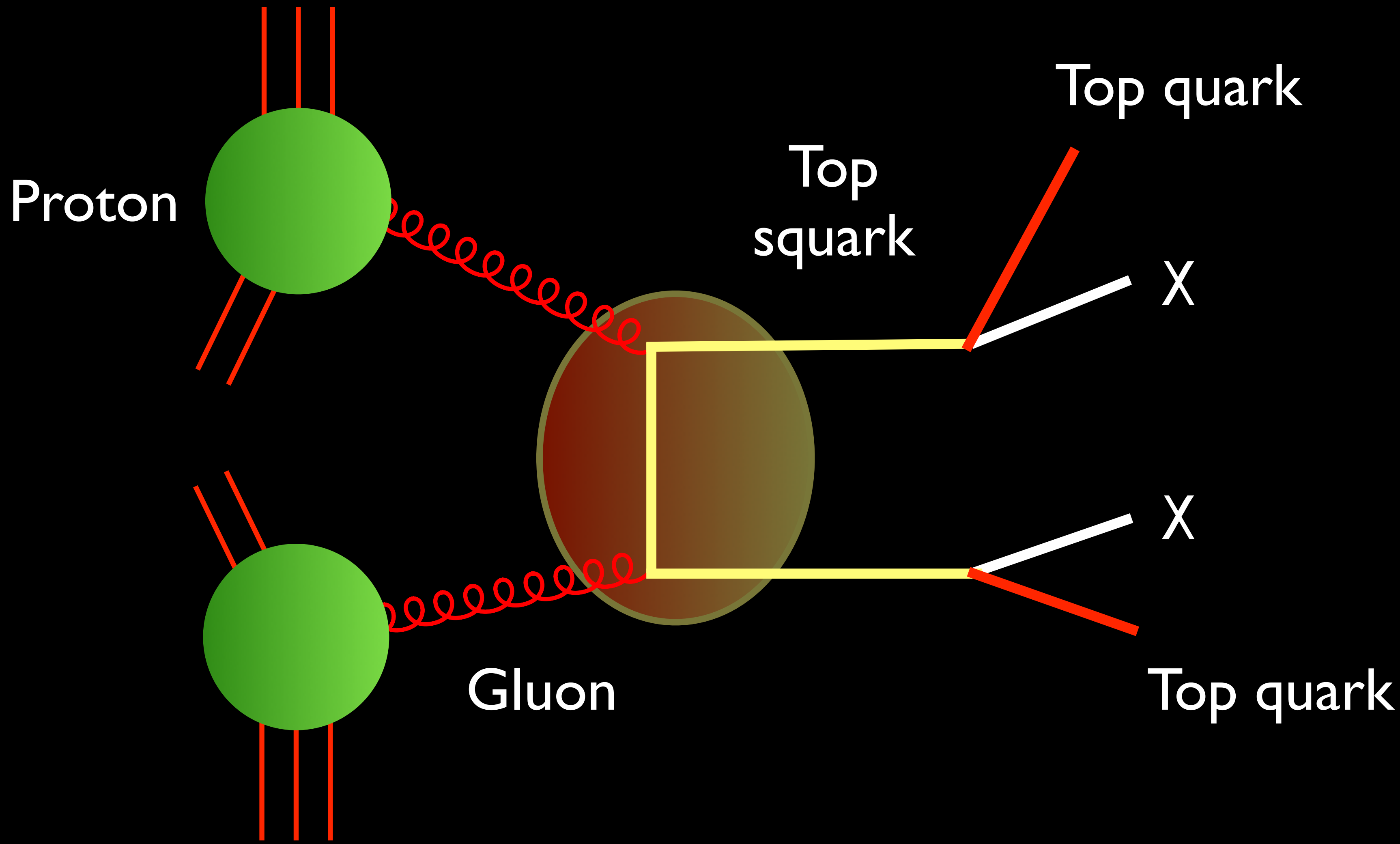
Complete = complicated

- All complete DM models add more particles to the SM, most of which are not viable DM candidates
- The classical example is the MSSM, in which each SM particle gets its own "superpartner"
- In the case of the MSSM there are 20 additional parameters that can be relevant for DM physics

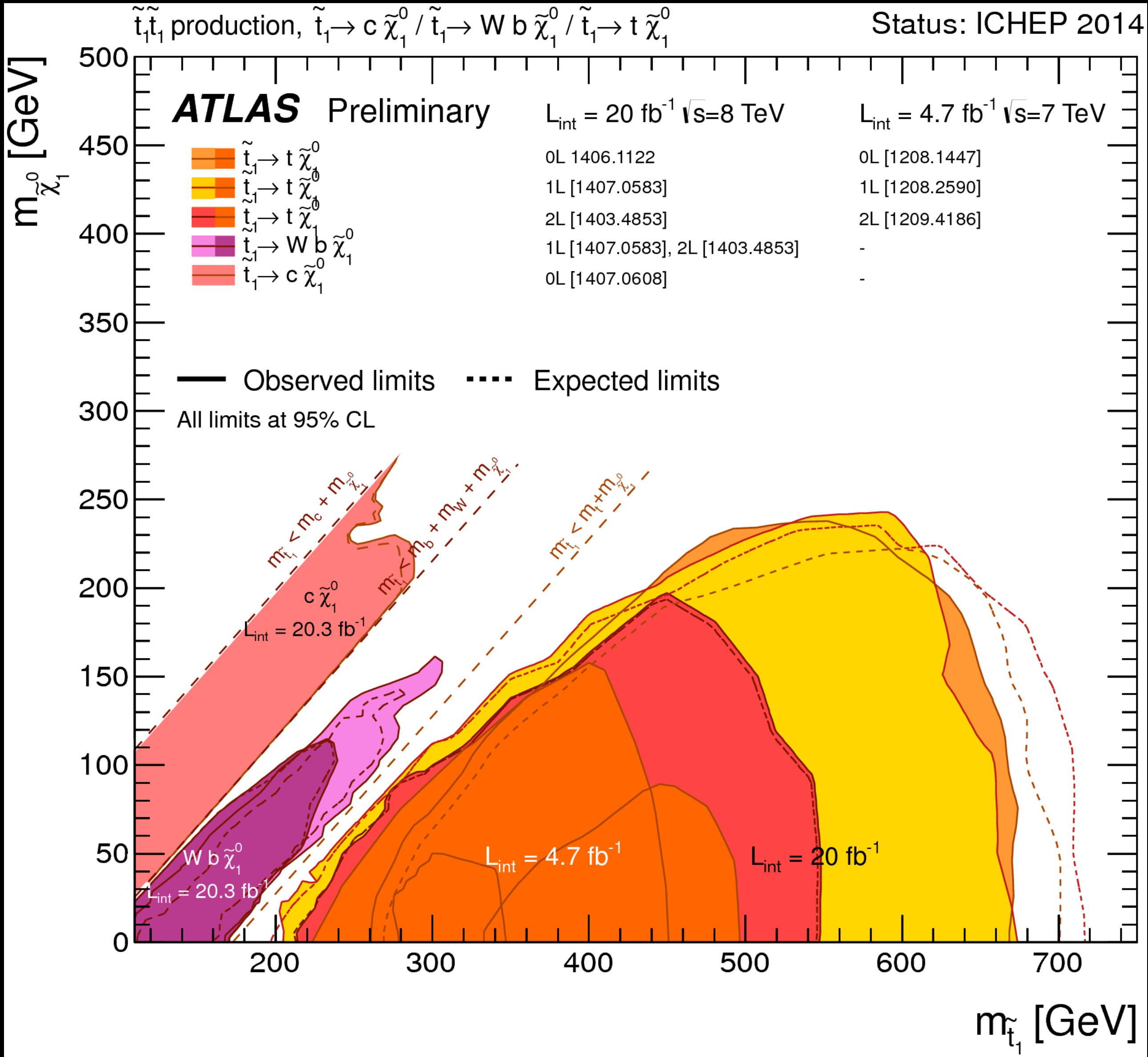


Minimal supersymmetric SM (MSSM)

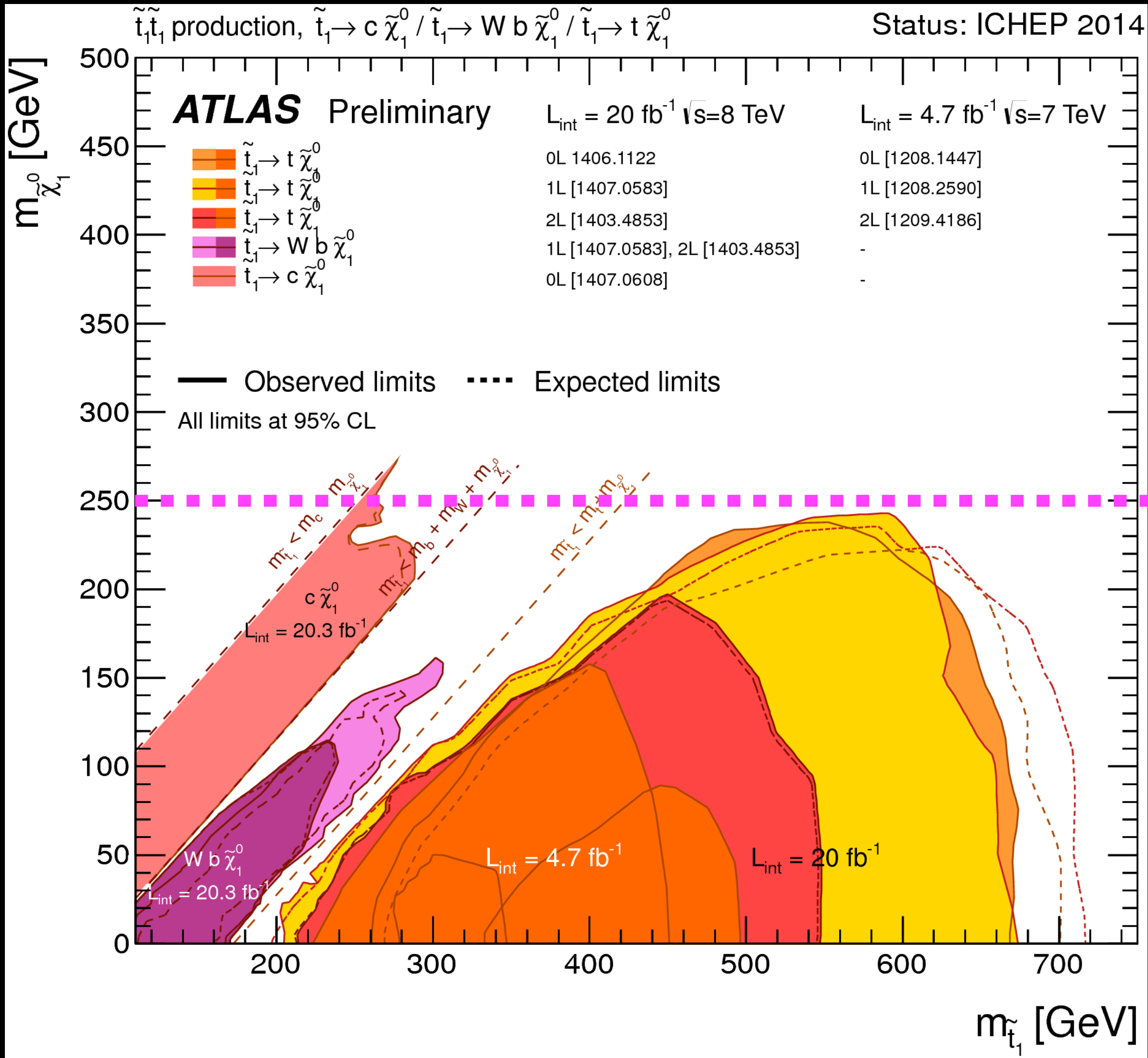
One way to produce DM in MSSM



LHC limits on DM mass in MSSM



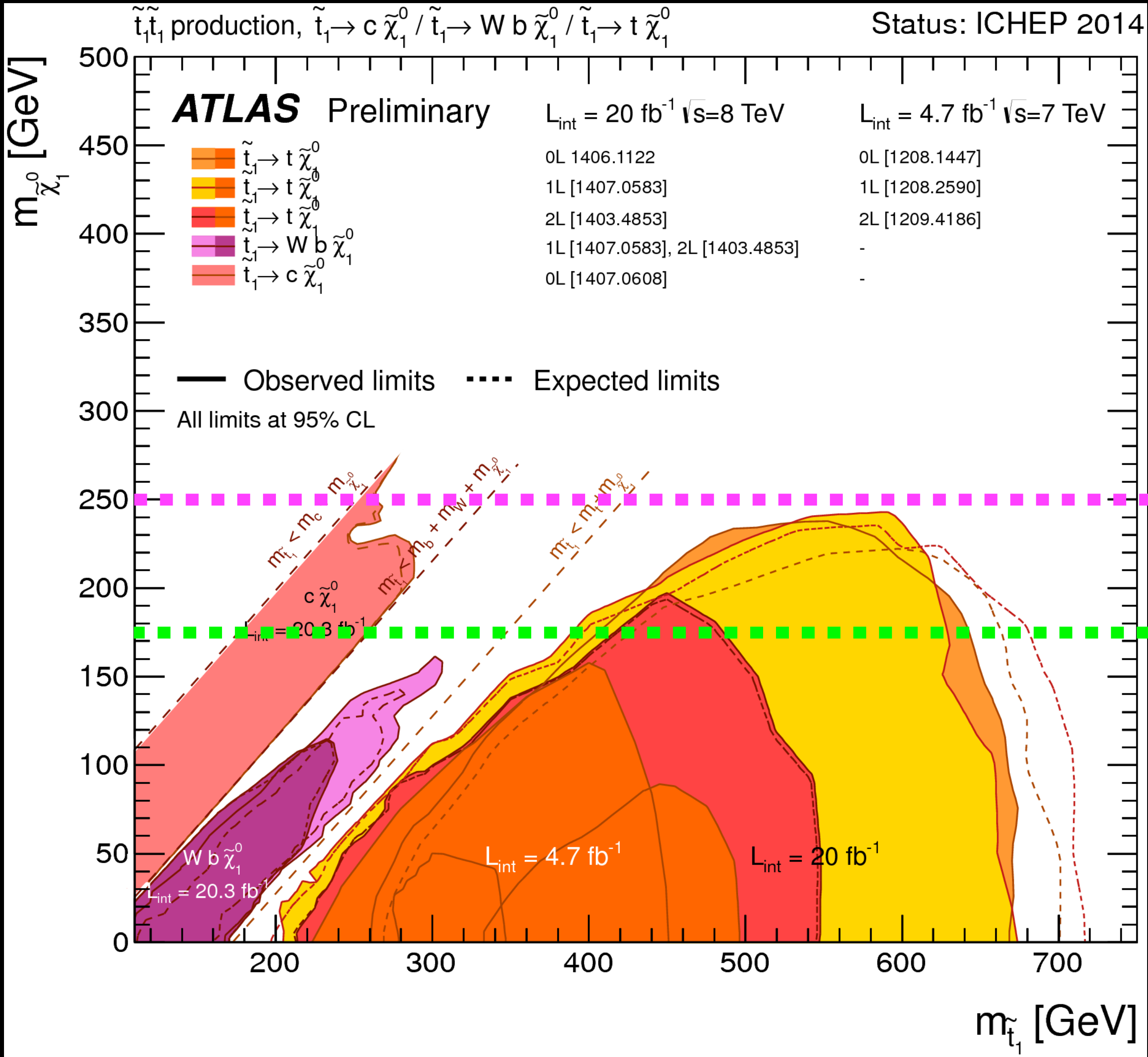
LHC limits on DM mass in MSSM



Range of DM masses unexplored by the first LHC run

250 GeV

LHC limits on DM mass in MSSM



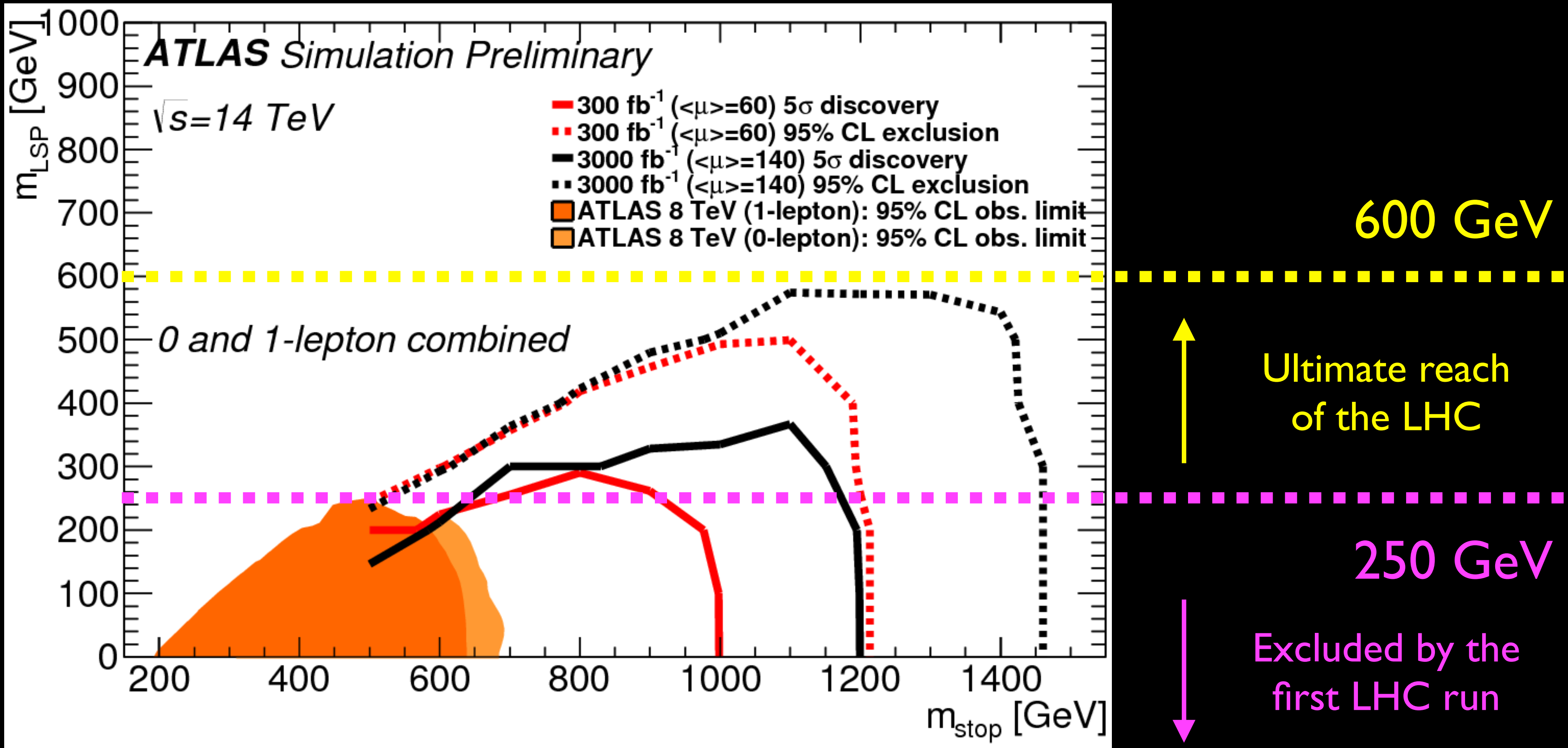
Range of DM masses unexplored by the first LHC run

250 GeV

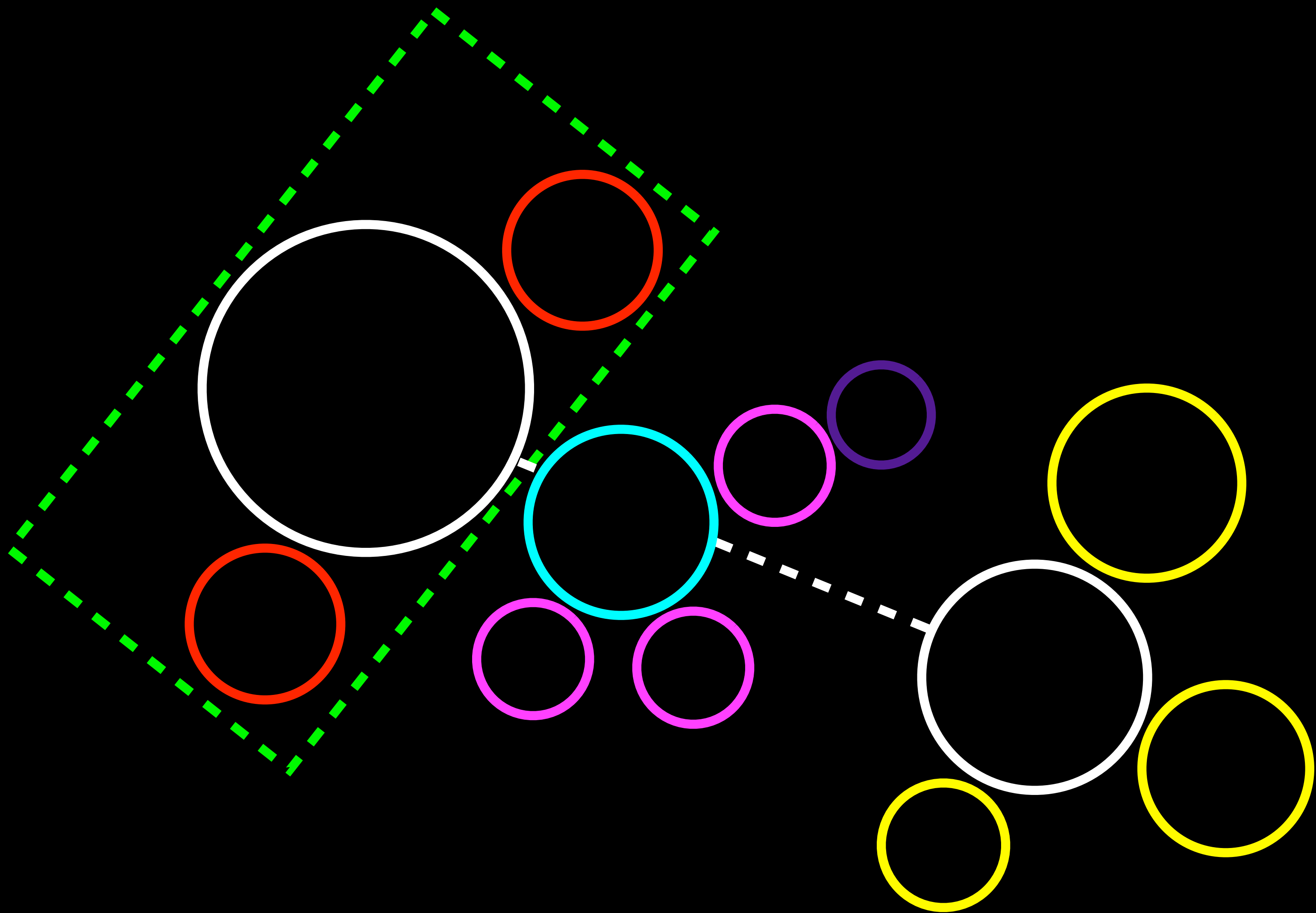
175 GeV

Masses of all the SM particles: top quark, Higgs, Z boson, …

LHC limits on DM mass in MSSM

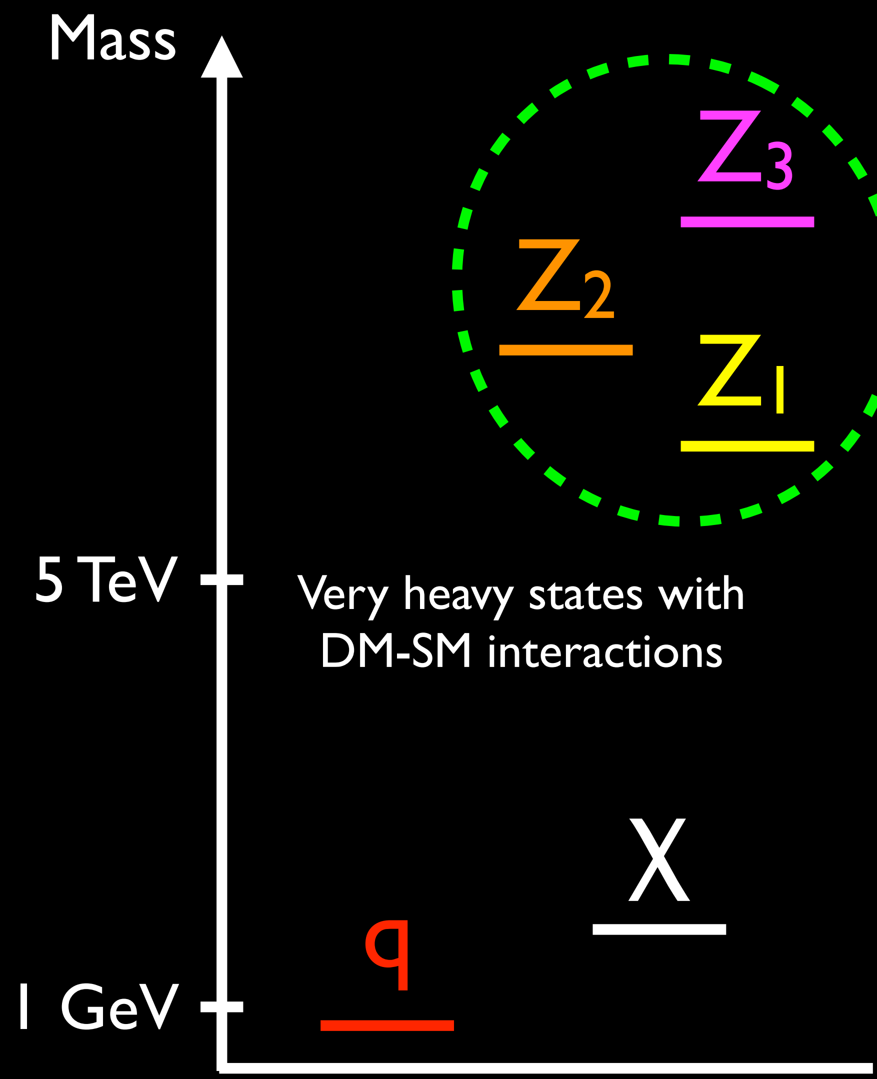


DM effective field theories

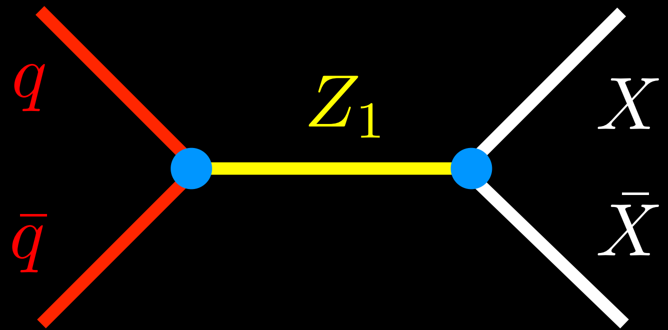


Effective = easy

- At the other end of complexity are models in which the DM particles are the only new states that can be produced at the LHC
- In such cases, effective field theory allows us to describe the DM-SM interactions mediated by all heavy particles in a simple and universal way



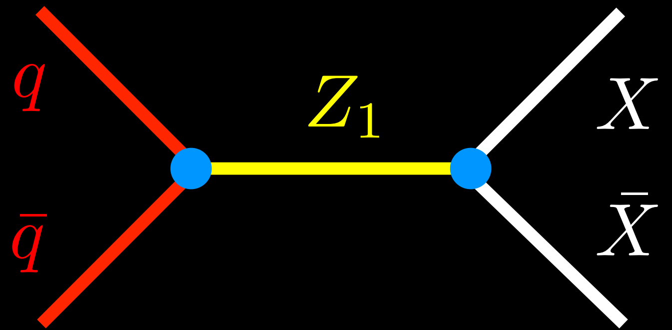
Effective field theory primer



$$= \frac{g^2}{p^2 - M_{Z_1}^2}(\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

$$p = p_{\bar{q}} + p_q = p_{\bar{X}} + p_X$$

Effective field theory primer



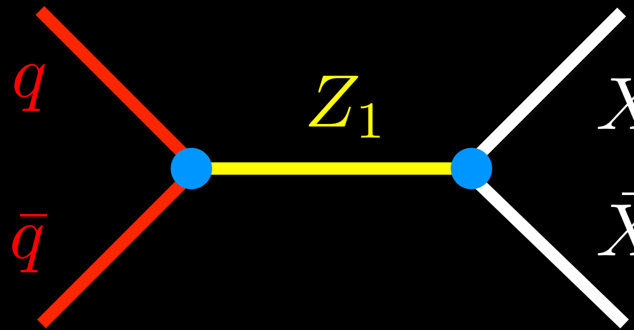
$$= \frac{g^2}{p^2 - M_{Z_1}^2}(\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

$$p = p_{\bar{q}} + p_q = p_{\bar{X}} + p_X$$

$$p^2 \ll M_{Z_1}^2$$

$$-\frac{g^2}{M_{Z_1}^2}(\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

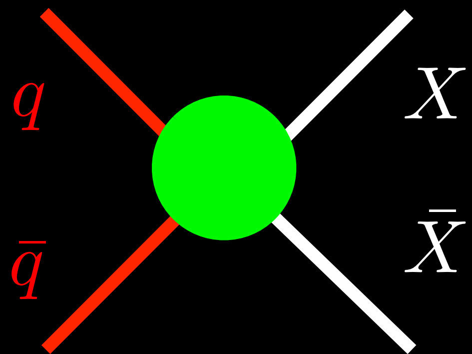
Effective field theory primer



$$= \frac{g^2}{p^2 - M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

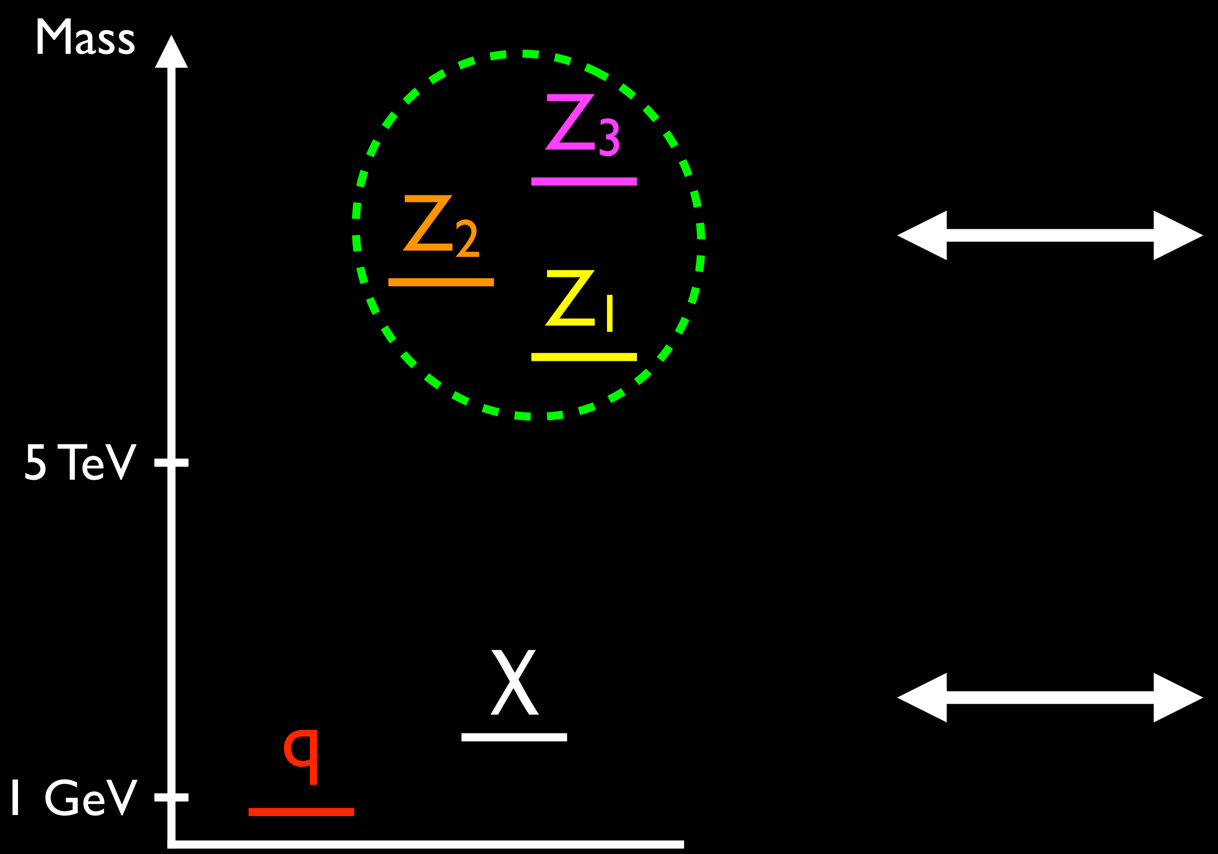
$$\Big\downarrow \quad p^2 \ll M_{Z_1}^2$$

$$-\frac{1}{M_*^2}$$



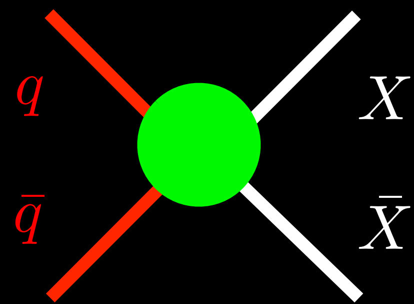
$$= -\frac{g^2}{M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

Effective field theory primer



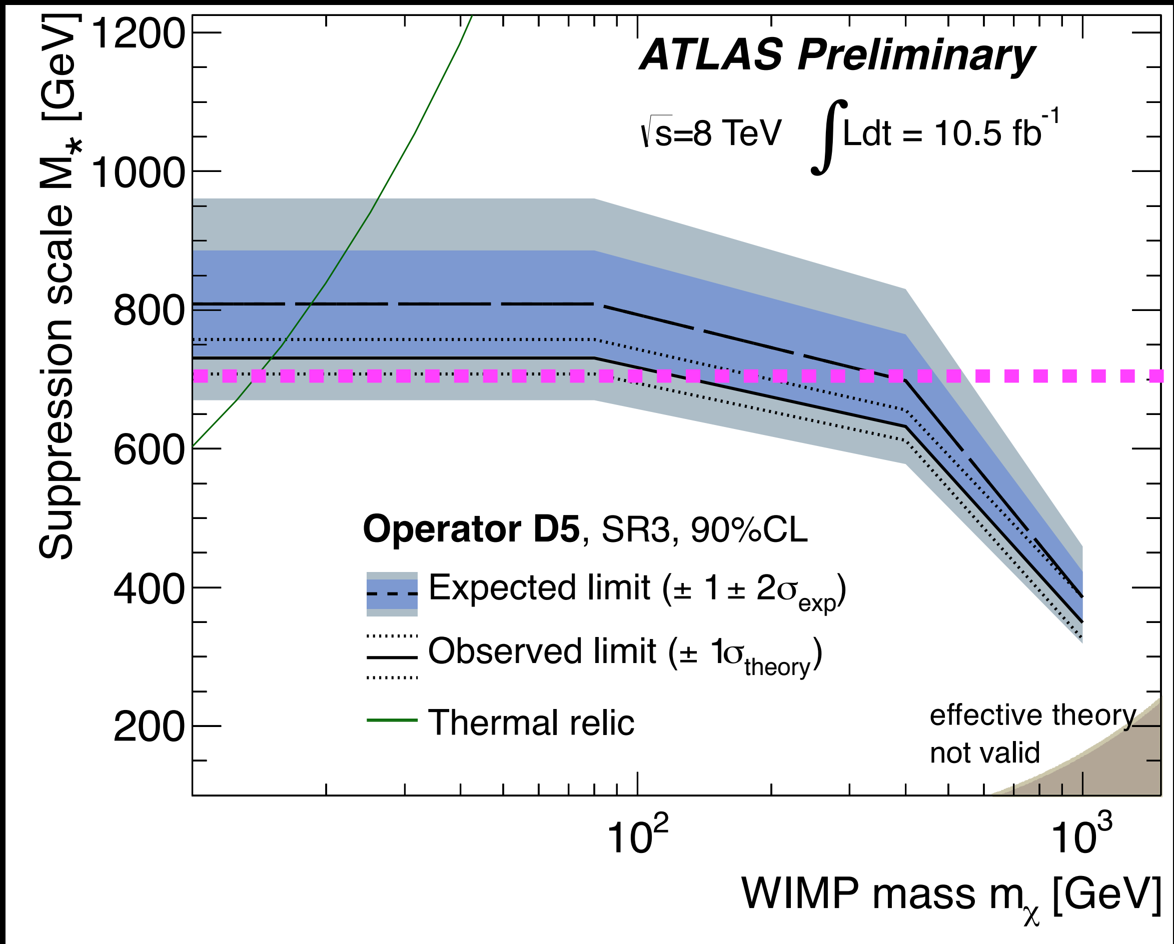
Information on heavy states encoded in a single coupling

$$\frac{1}{M_*^2} = \frac{g^2}{M_{Z_1}^2}$$



Independent of heavy physics

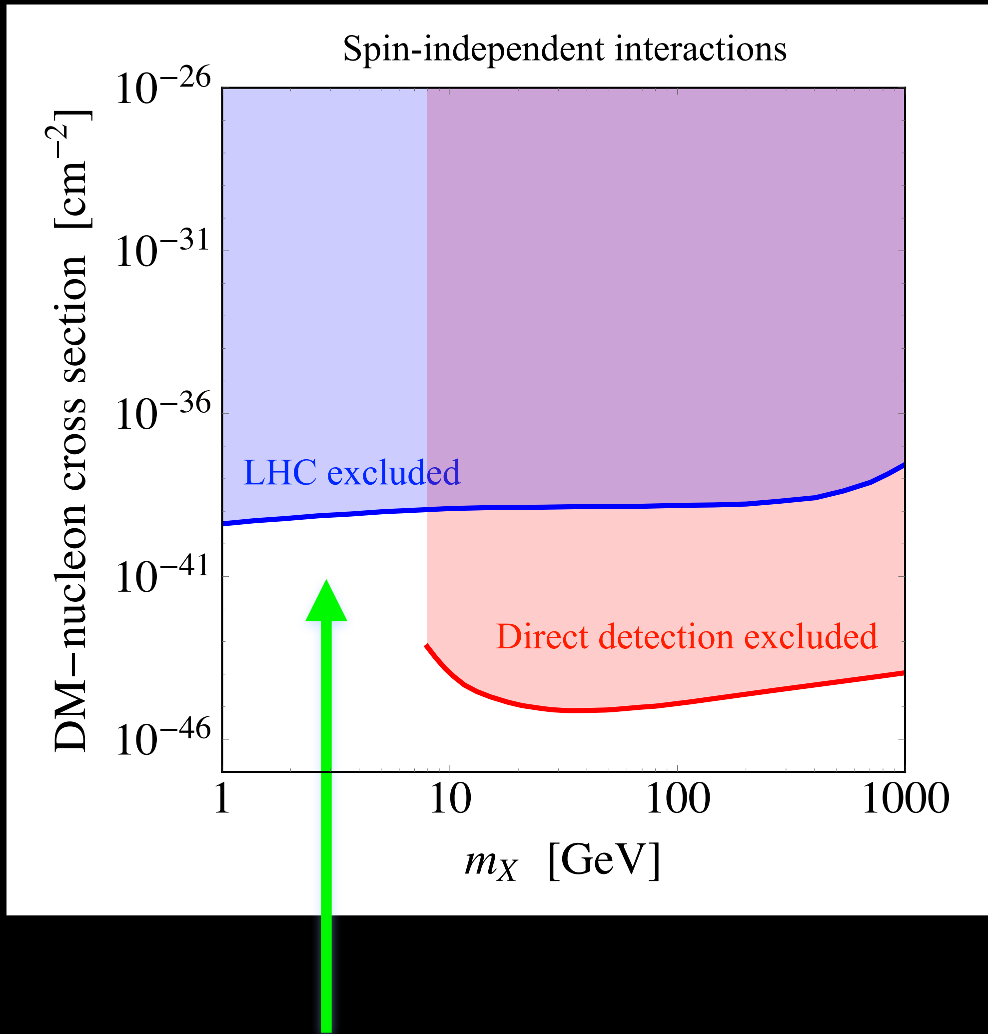
LHC limits on suppression scale



700 GeV

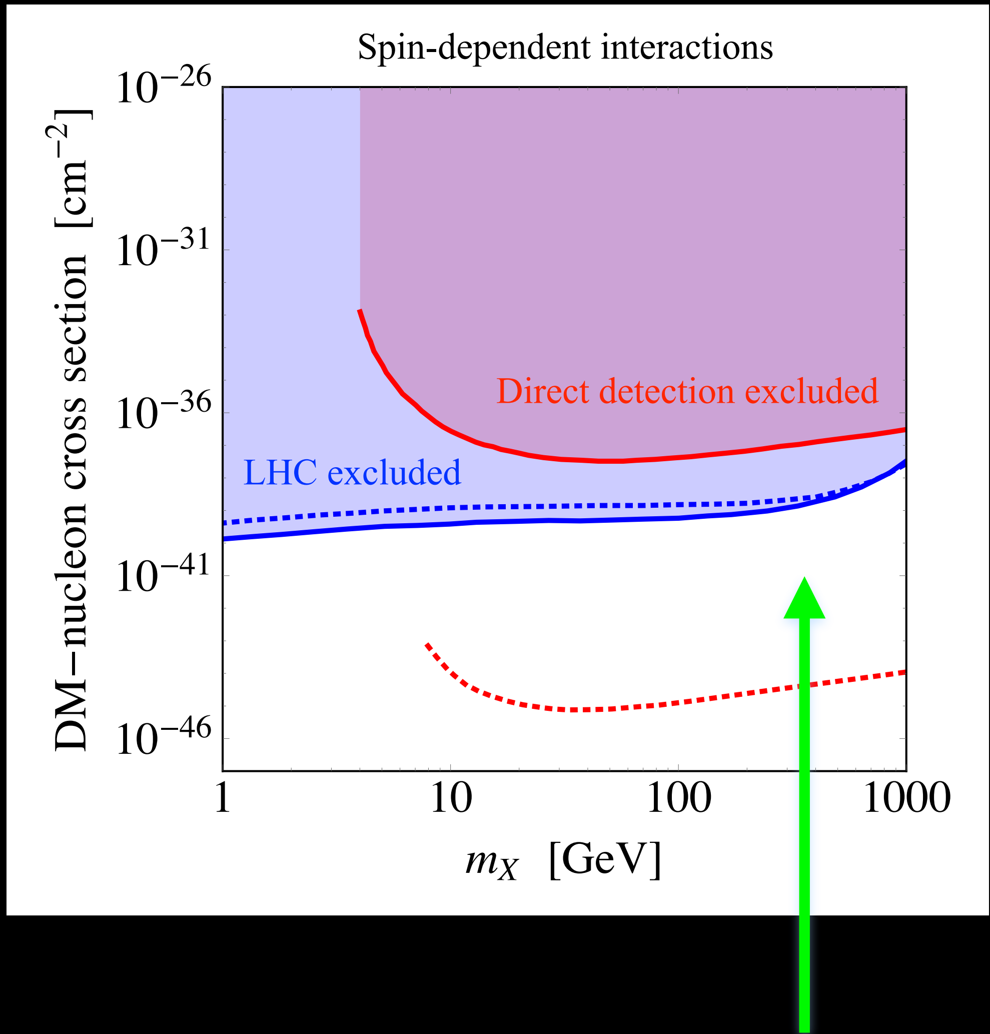
Excluded by the first LHC run

Comparison with direct detection



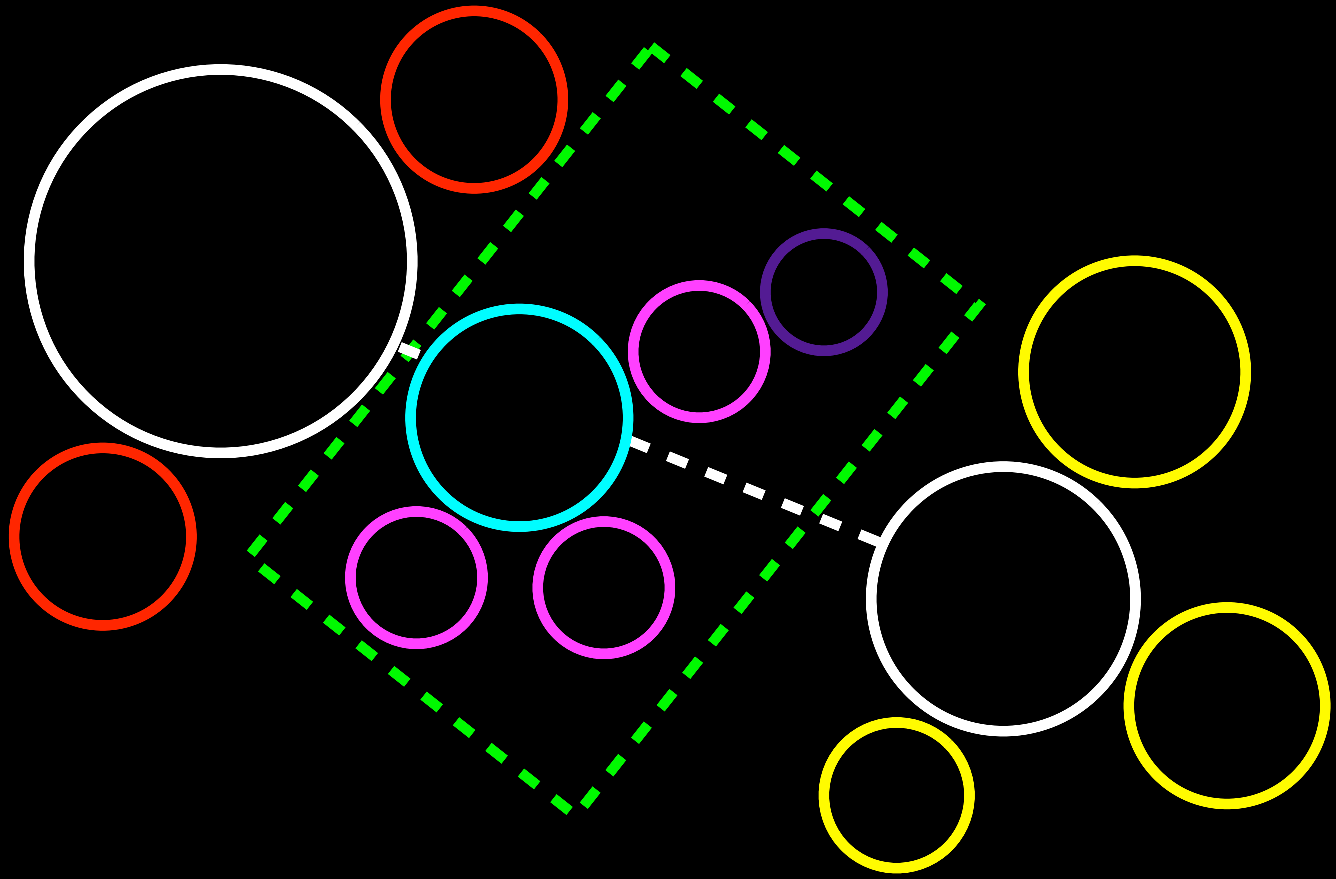
The LHC constraints are strongest at low DM mass, where direct detection is challenging due to the small nuclear recoil

Comparison with direct detection



The LHC is superior to any spin-dependent search for all DM masses, since DM-nucleon scattering is incoherent in this case

Simplified DM models

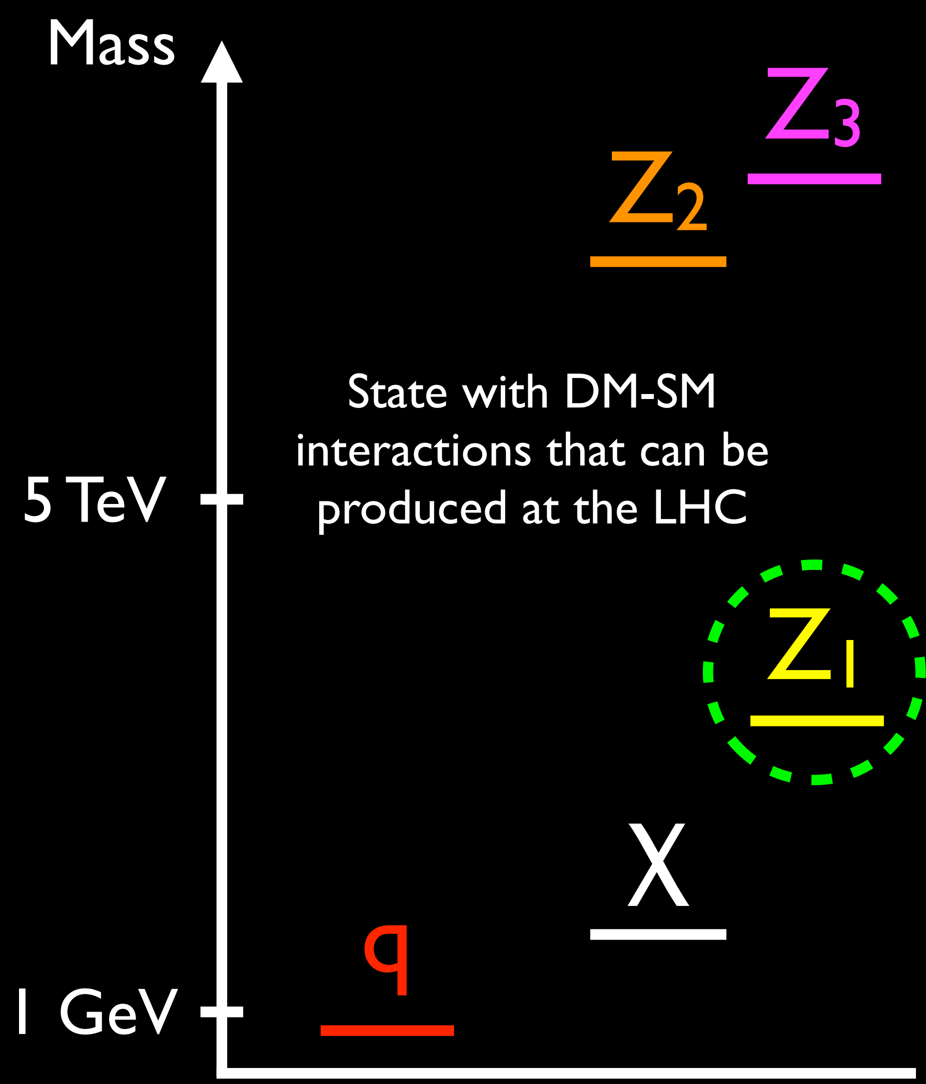


Simplified = in-between

- Another interesting option is to consider models that contain DM *and* the most important state mediating its interactions with the SM

- Unlike the effective field theories, these simplified models can describe the full kinematics of DM production at the LHC

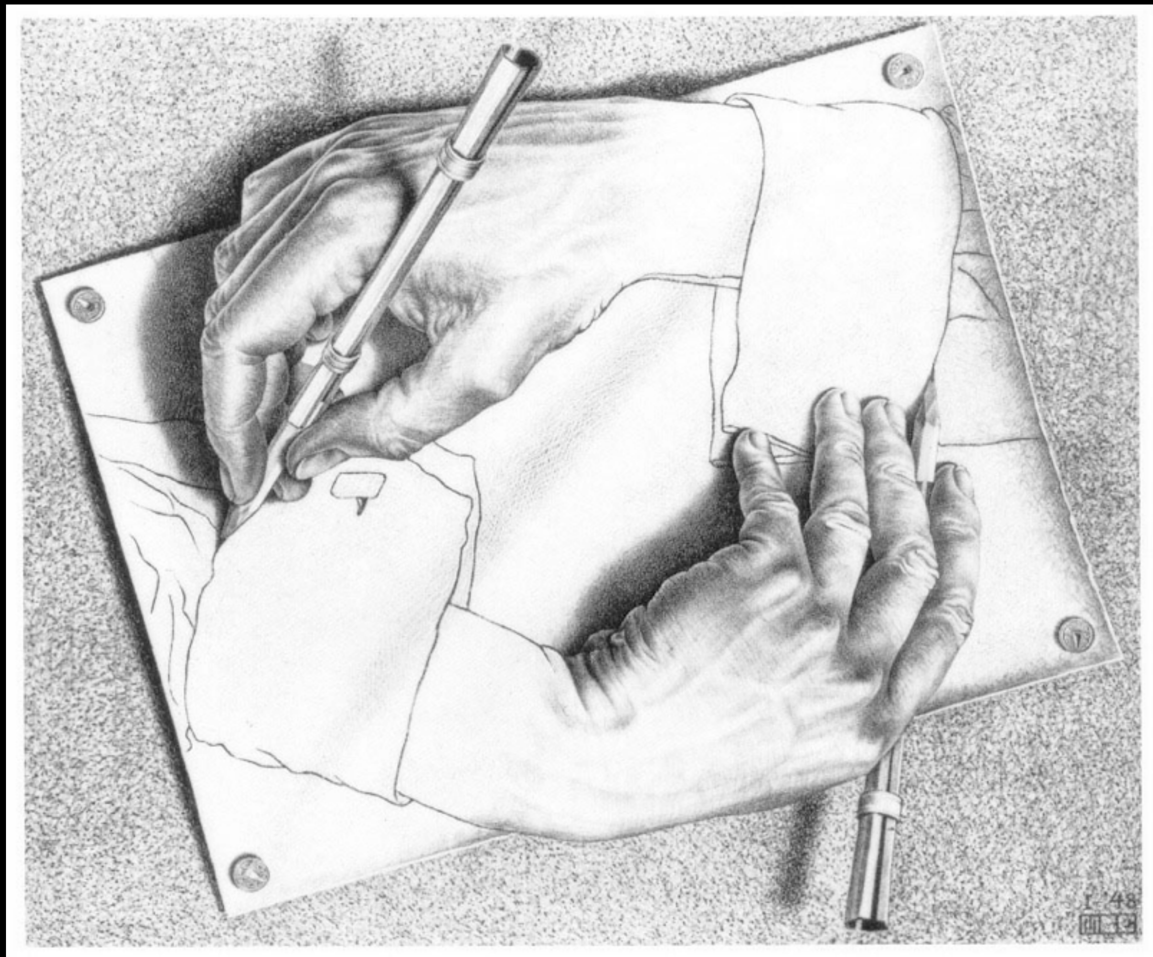
- Simplified DM models have typically a few parameters



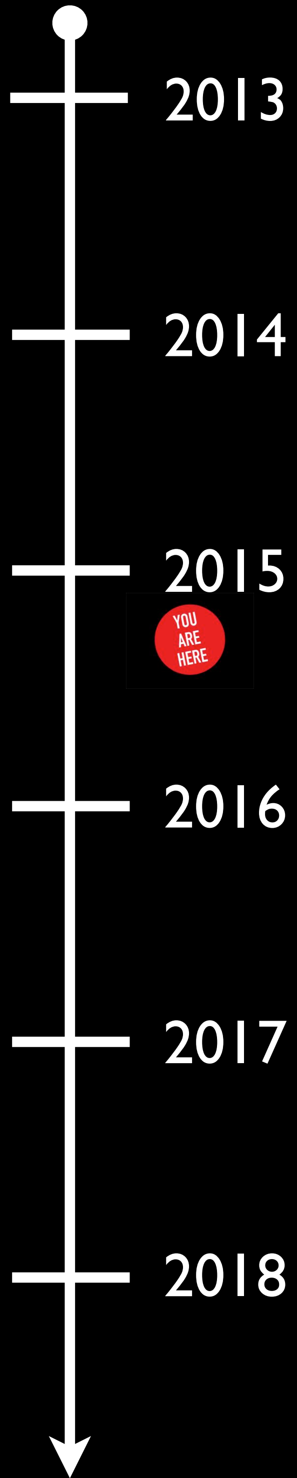
Outlook

- Dark matter implies physics beyond the Standard Model
- An understanding of dark matter thus requires new theoretical concepts. These can be complete models, but it is also fruitful to think about less defined, more hazy sketches of theories
- Searches at the LHC, in underground experiments and in astrophysical observations naturally target different parts of the dark matter theory space. They complement one another
- Once we have a detection, only the full suite of techniques will allow us to fully learn what dark matter really is

The LHC can bring sketches of dark matter to life!



A possible timeline

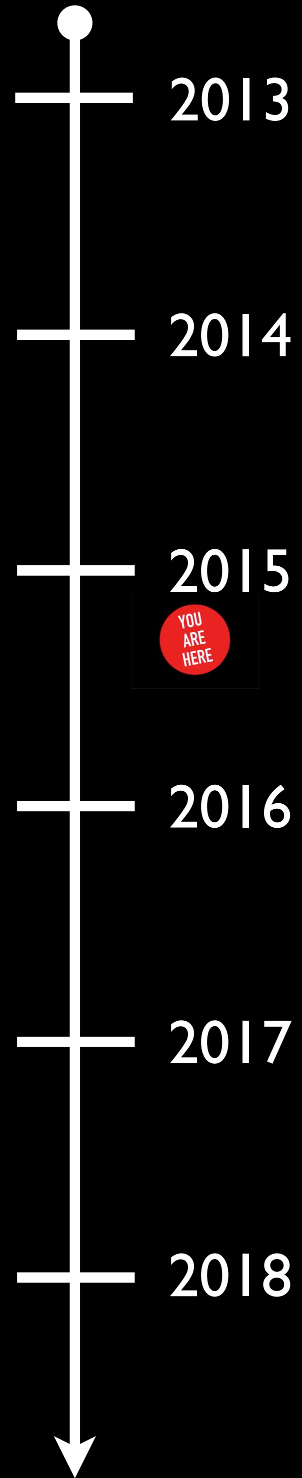


- [ ] Mass
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak interaction?
- [ ] Higgs?
- [ ] Quarks/gluons?
- [ ] Leptons?
- [ ] Thermal relic?

A possible timeline



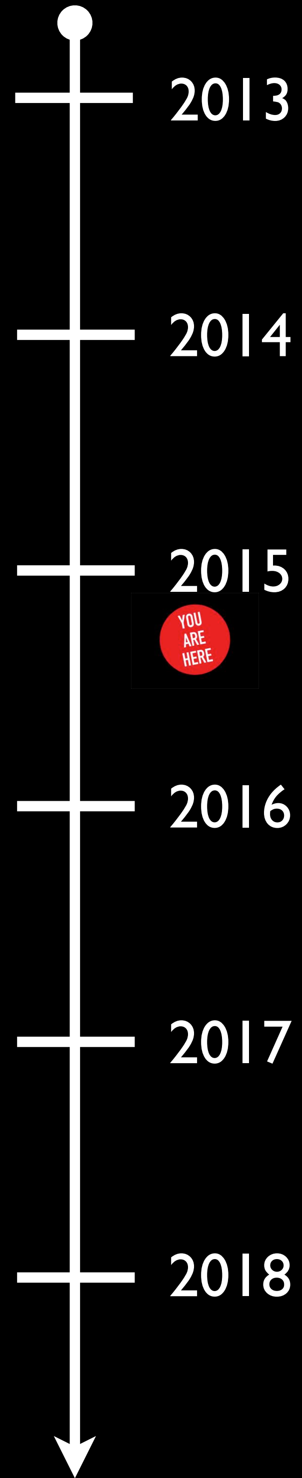
LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV

- [?] Mass: < 200 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak interaction?
- [ ] Higgs?
- [x] Quarks/gluons
- [ ] Leptons?
- [ ] Thermal relic?

A possible timeline



LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV

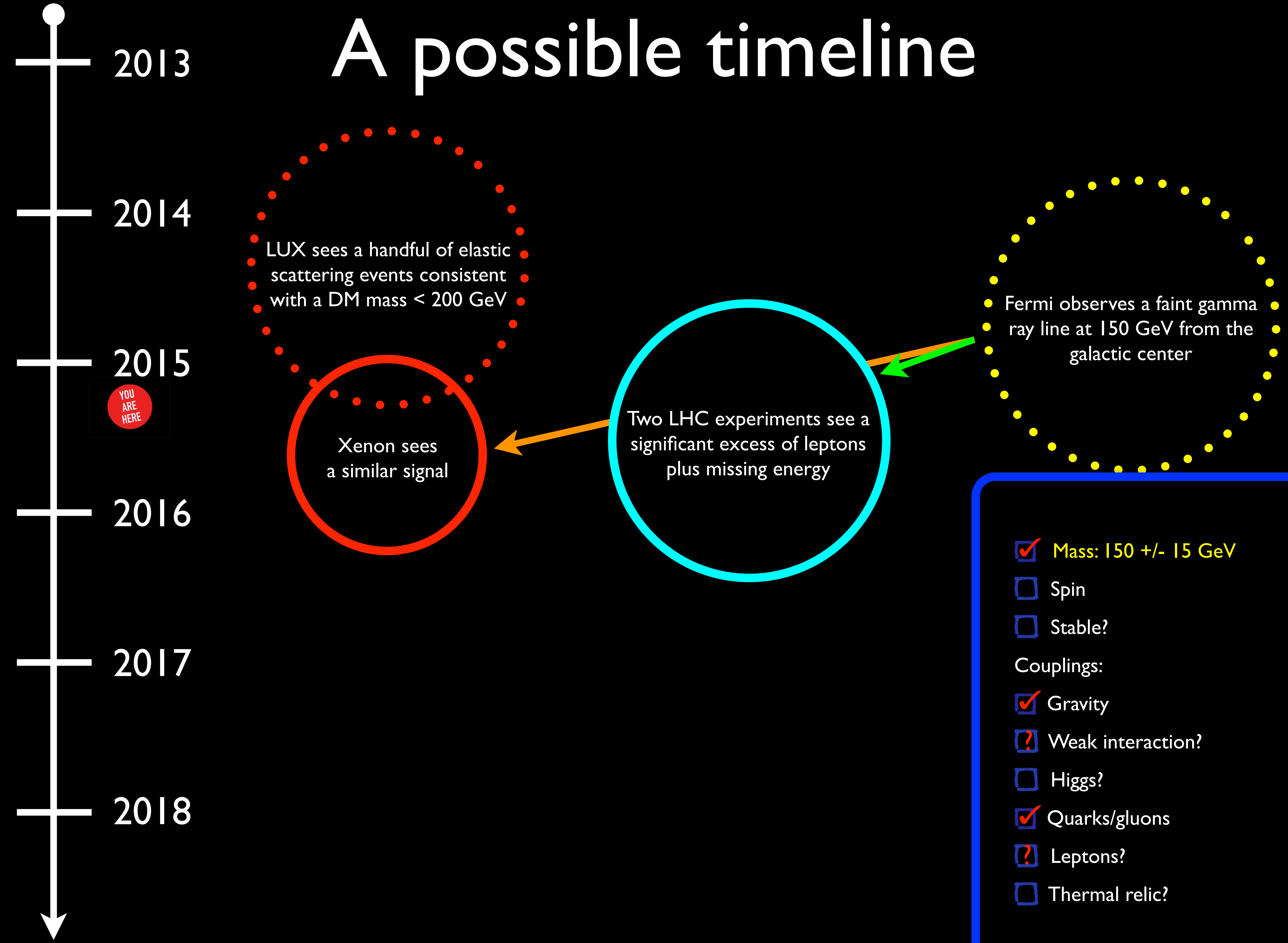
Fermi observes a faint gamma ray line at 150 GeV from the galactic center

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks/gluons
- [ ] Leptons?
- [ ] Thermal Relic?

A possible timeline

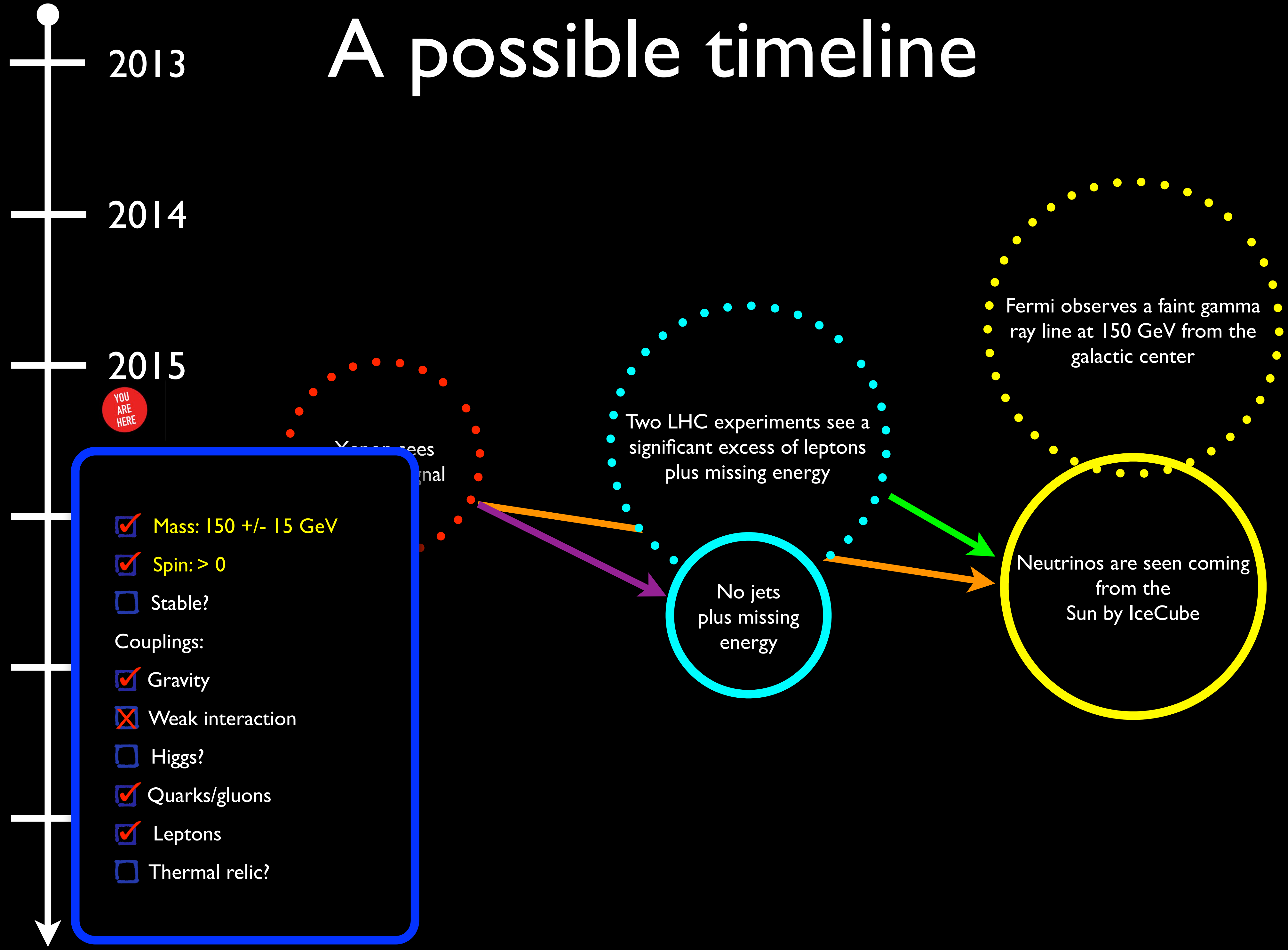


- ☑ Mass: 150 +/- 15 GeV
- ☐ Spin
- ☐ Stable?

Couplings:

- ☑ Gravity
- ? Weak interaction?
- ☐ Higgs?
- ☑ Quarks/gluons
- ? Leptons?
- ☐ Thermal relic?

A possible timeline



A possible timeline

2013

2014

2015

YOU ARE HERE

2016

2017

2018

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV

Xenon sees a similar signal

A positive signal of axion conversion is observed at an upgraded ADMX

Two LHC experiments see a significa[...] plu[...]

Fermi observes a faint gamma ray line at 150 GeV from the galactic center

- [x] Mass: 150 +/- 15 GeV
- [x] Spin: > 0
- [ ] Stable?

Couplings:

- [x] Gravity
- ☒ Weak interaction
- [ ] Higgs?
- [x] Quarks/gluons
- [x] Leptons
- [ ] Thermal relic?

- [x] Mass: 20 μeV
- [x] Spin: 0
- ☒ Stable

Couplings:

- [x] Gravity
- [x] Photon interaction
- [ ] Higgs?
- [ ] Quarks/gluons?
- [ ] Leptons?
- ☒ Thermal relic?

A possible timeline

2013

2014

2015

YOU ARE HERE

2016

2017

2018

????

✓ Mass: 150 +/- 0.1 GeV	✓ Mass: 20 μeV
✓ Spin: > 0	✓ Spin: 0
☐ Stable?	✗ Stable
Couplings:	Couplings:
✓ Gravity	✓ Gravity
✗ Weak unteraction	✓ Photon interaction
☐ Higgs?	☐ Higgs?
✓ Quarks/gluons	☐ Quarks/gluons?
✓ Leptons	☐ Leptons?
✓ Thermal relic	✗ Thermal relic

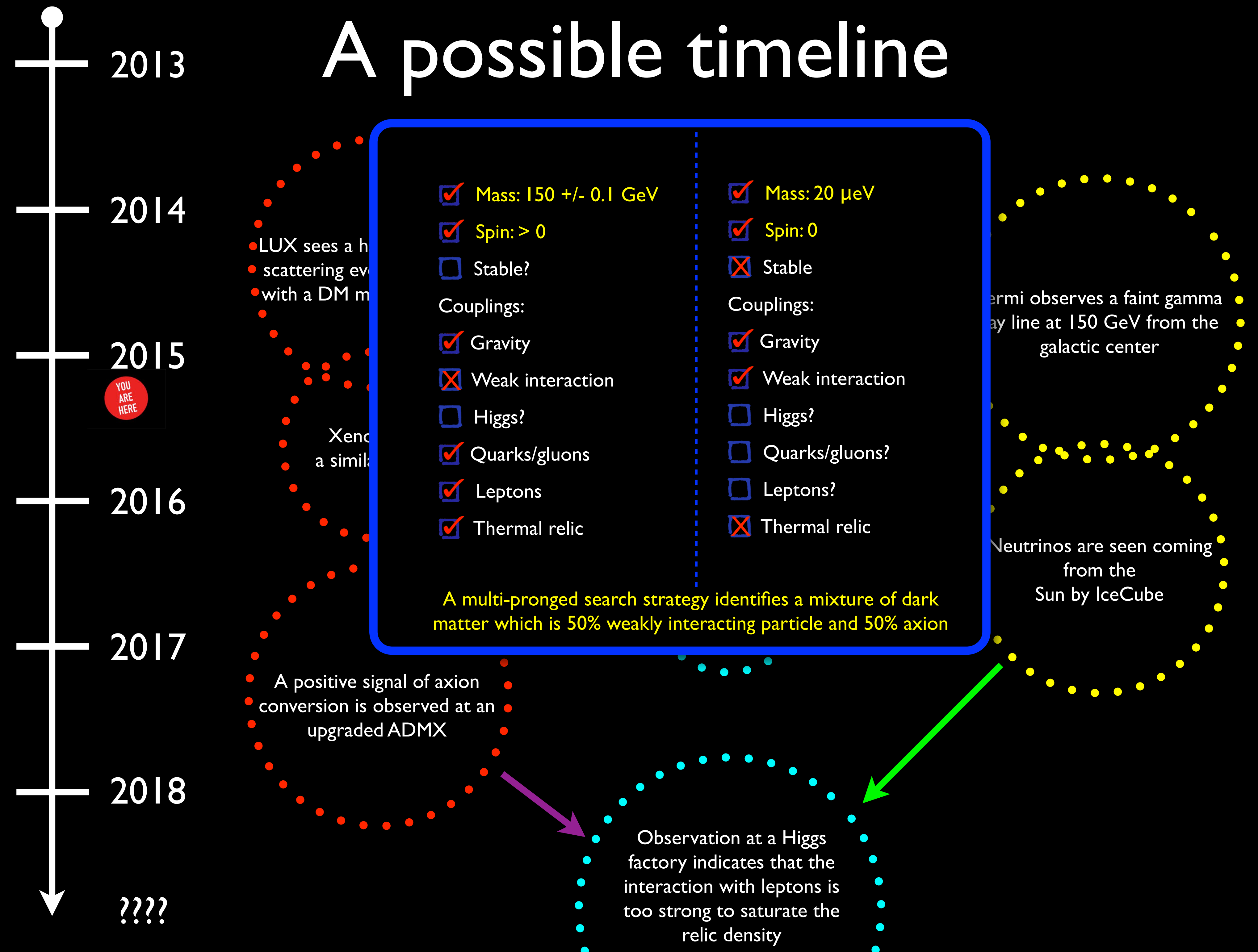
Fermi observes a faint gamma ray line at 150 GeV from the galactic center

Neutrinos are seen coming from the Sun by IceCube

A positive signal of axion conversion is observed at an upgraded ADMX

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density

A possible timeline



☑ Mass: 150 +/- 0.1 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☒ Stable
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak interaction	☑ Weak interaction
☐ Higgs?	☐ Higgs?
☑ Quarks/gluons	☐ Quarks/gluons?
☑ Leptons	☐ Leptons?
☑ Thermal relic	☒ Thermal relic

A multi-pronged search strategy identifies a mixture of dark matter which is 50% weakly interacting particle and 50% axion