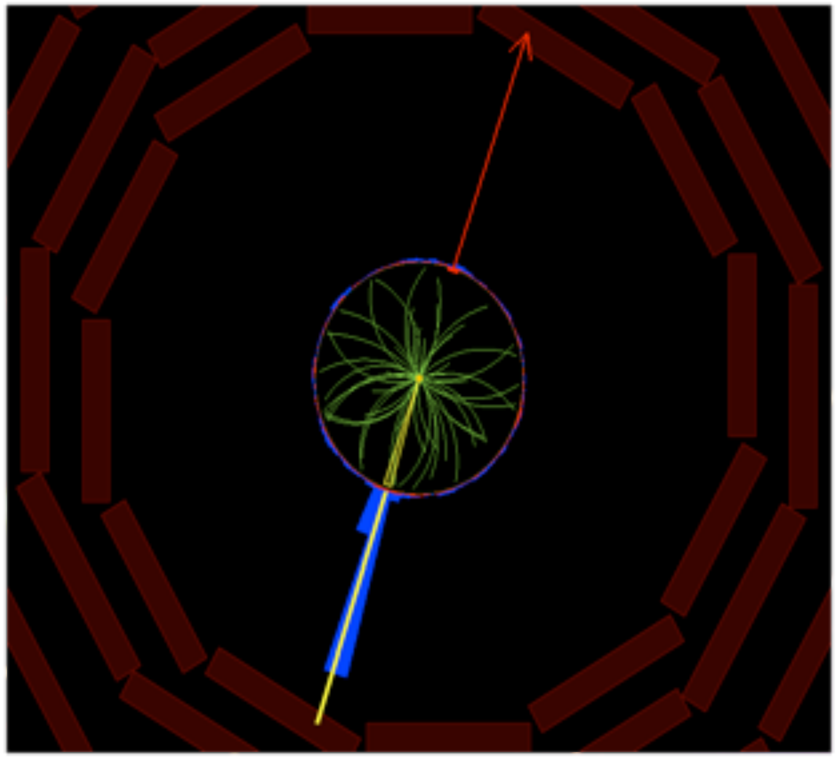
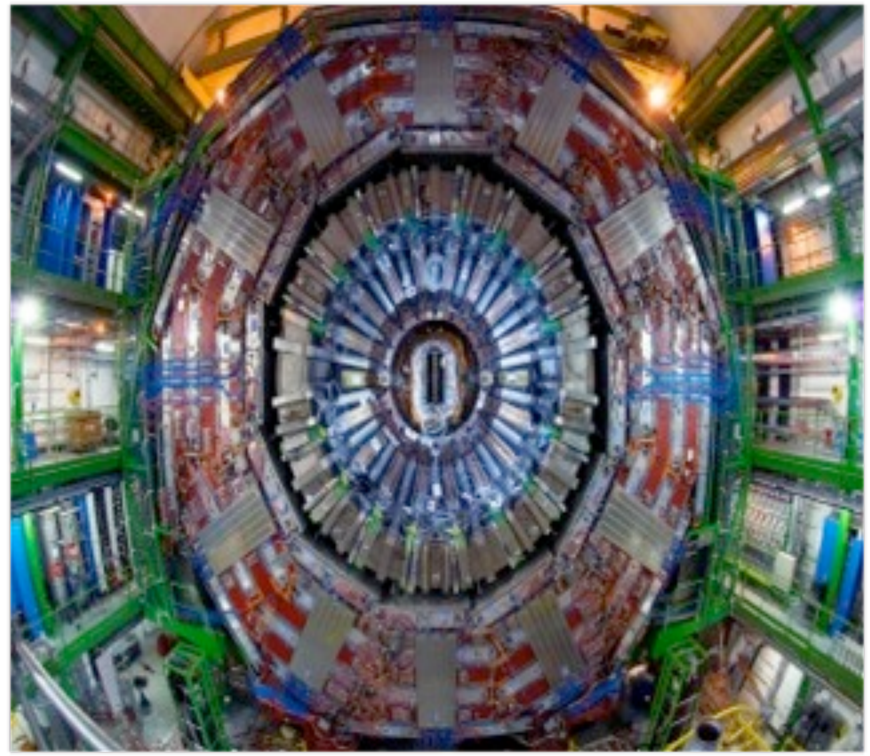
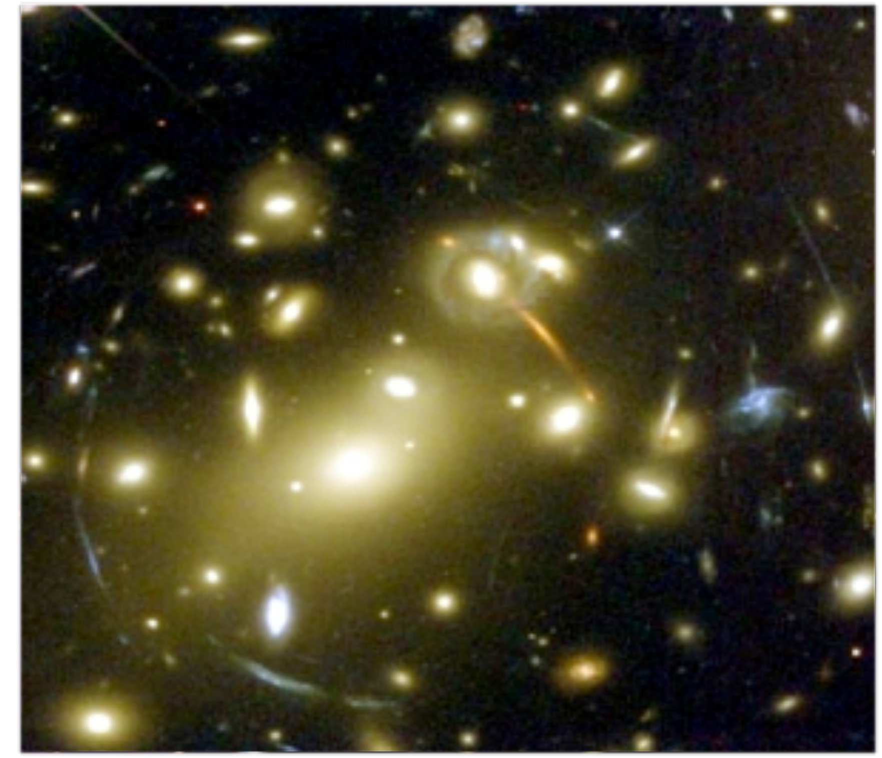






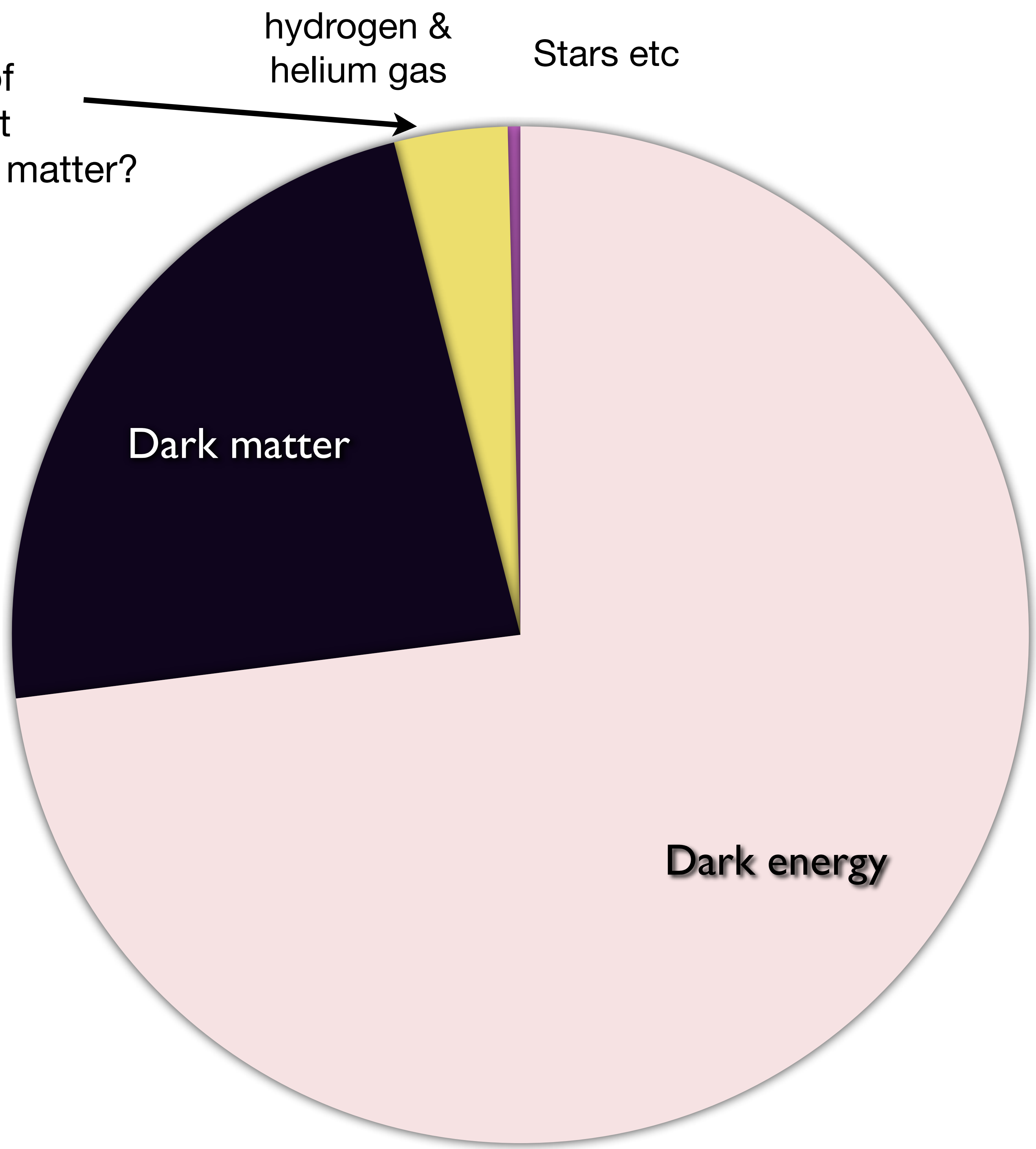
Where particle physics meets cosmology:

SHEDDING LIGHT ON DARK MATTER AT CMS

Sarah Alam Malik
Imperial College London

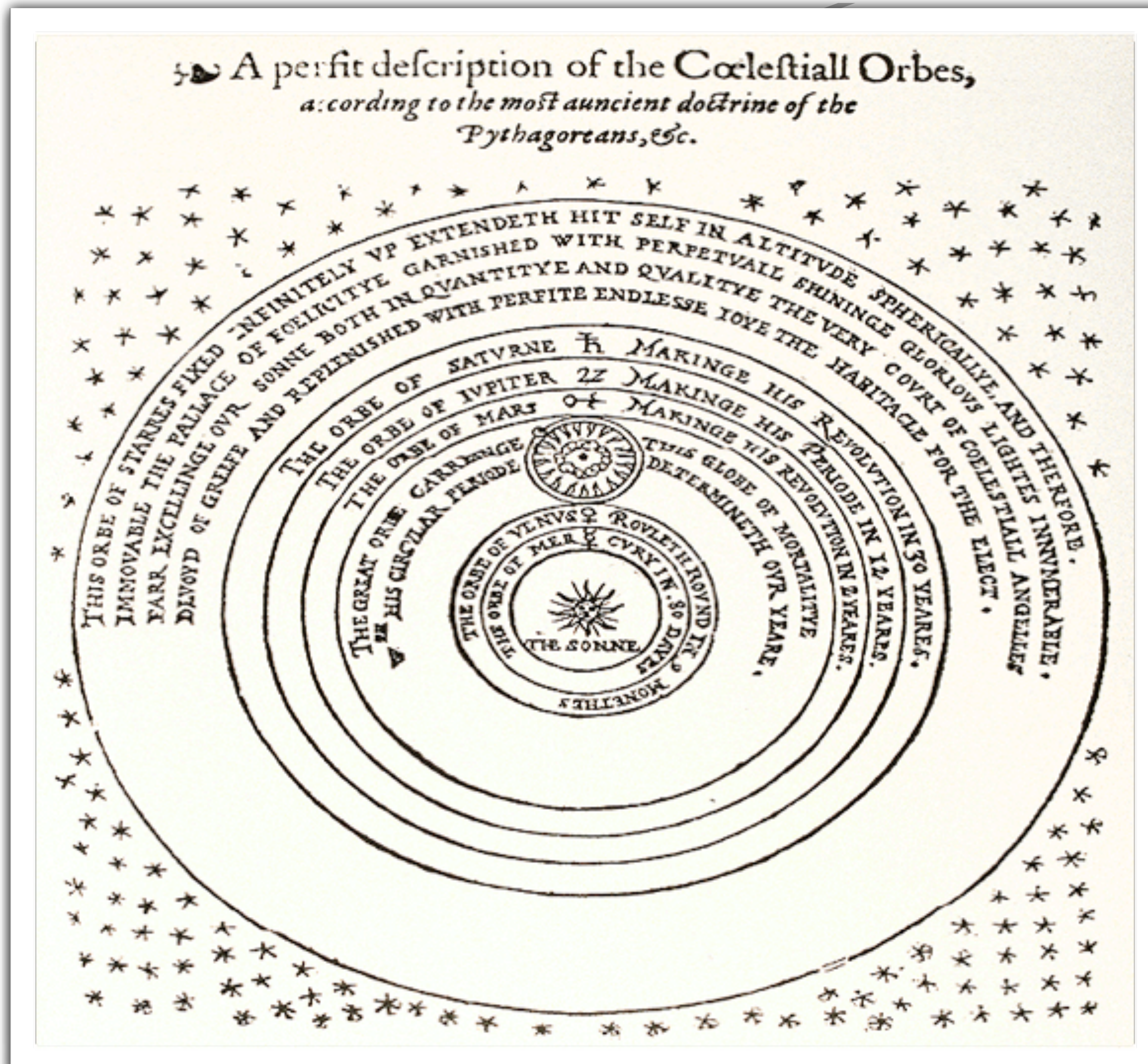
Composition of the Universe

-What we are made of
-What we know about
-Insignificant? Do we matter?



Our place in the Universe

Copernicus : Earth is not the center of the Universe!

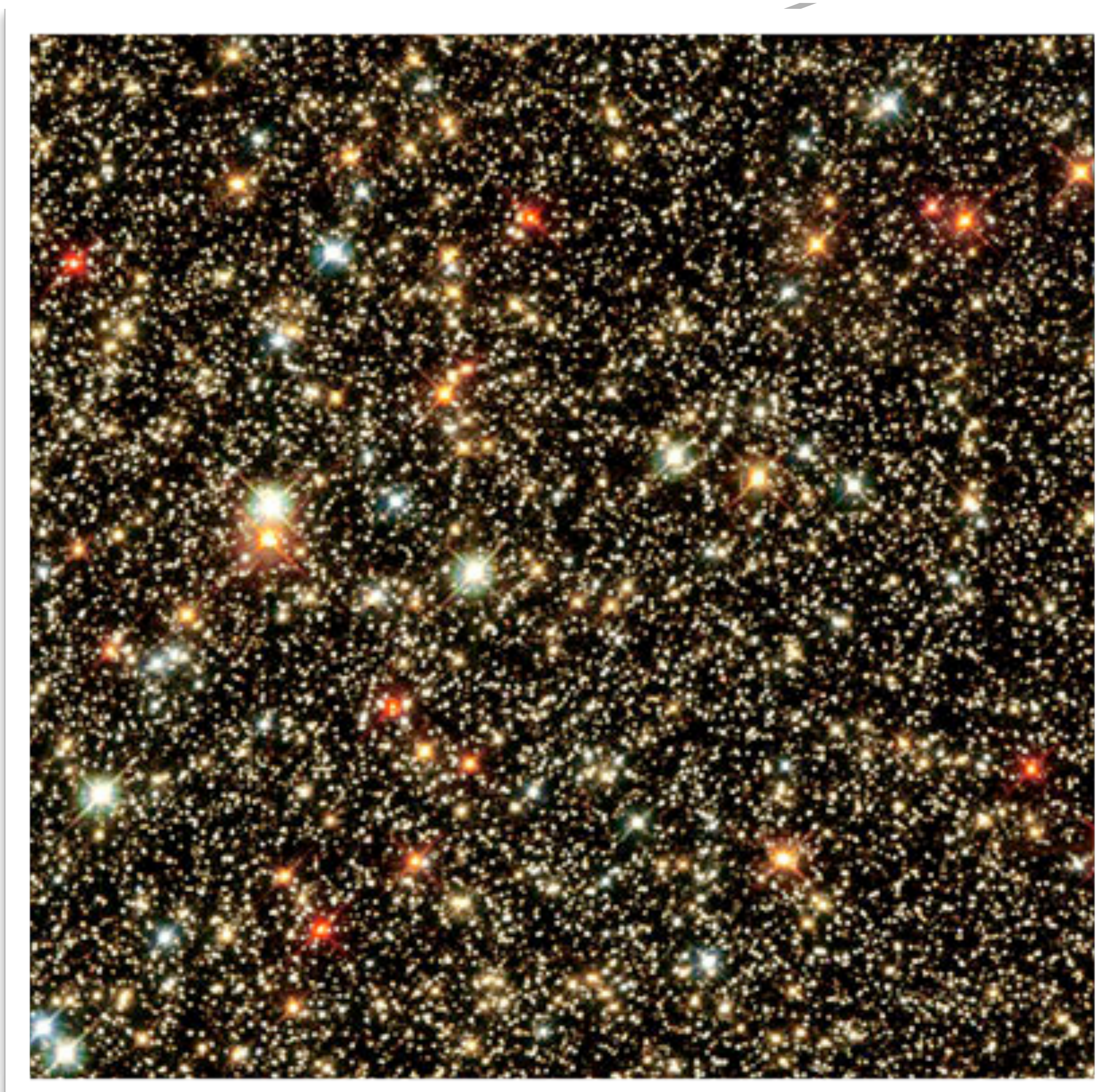


Our place in the Universe

Galileo: use of telescope, confirmed Copernican model,
Jupiter has orbiting moons, Earth just another planet

Our place in the Universe

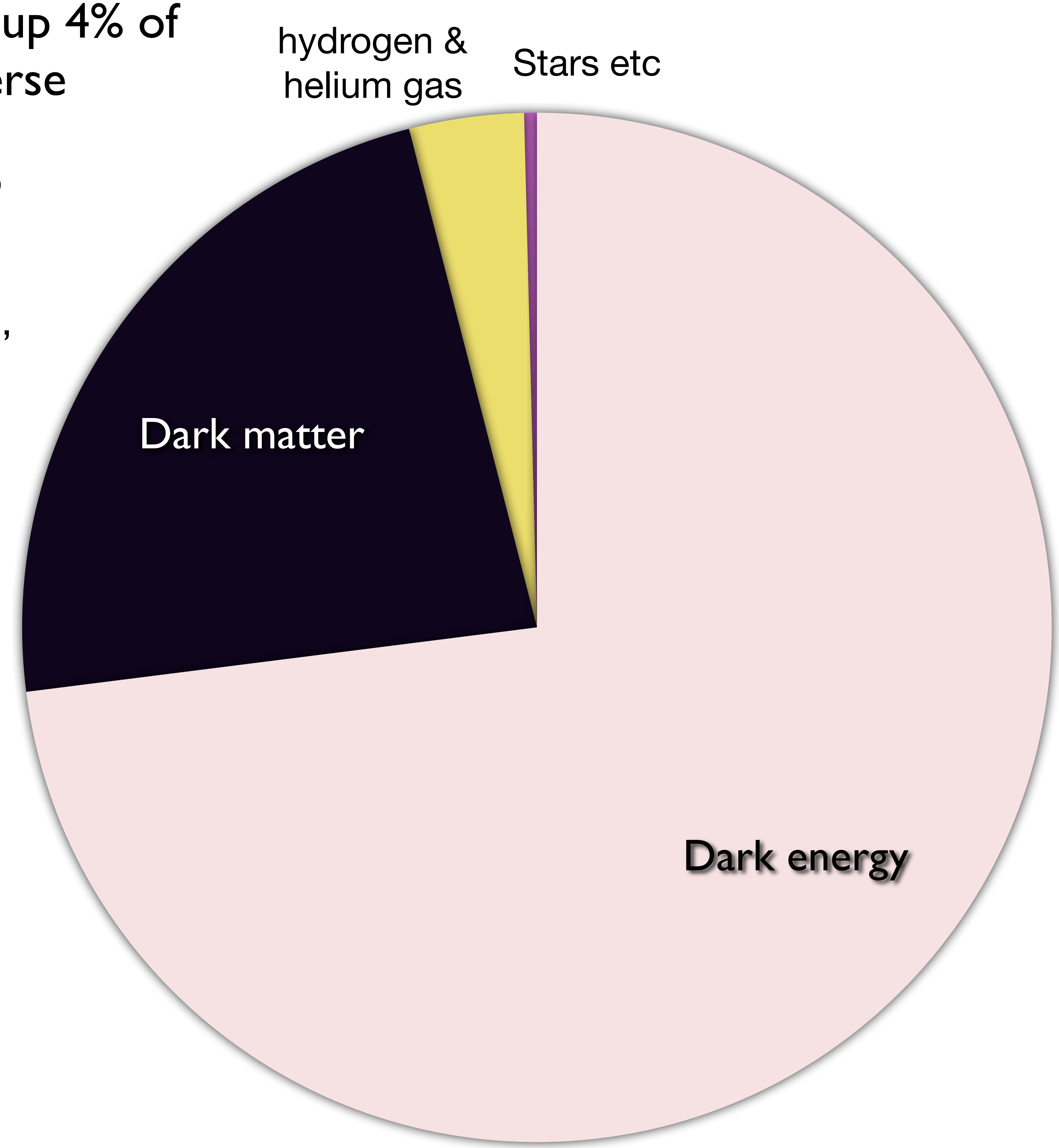
Hubble : each speck of light is another galaxy, our galaxy one of billions.

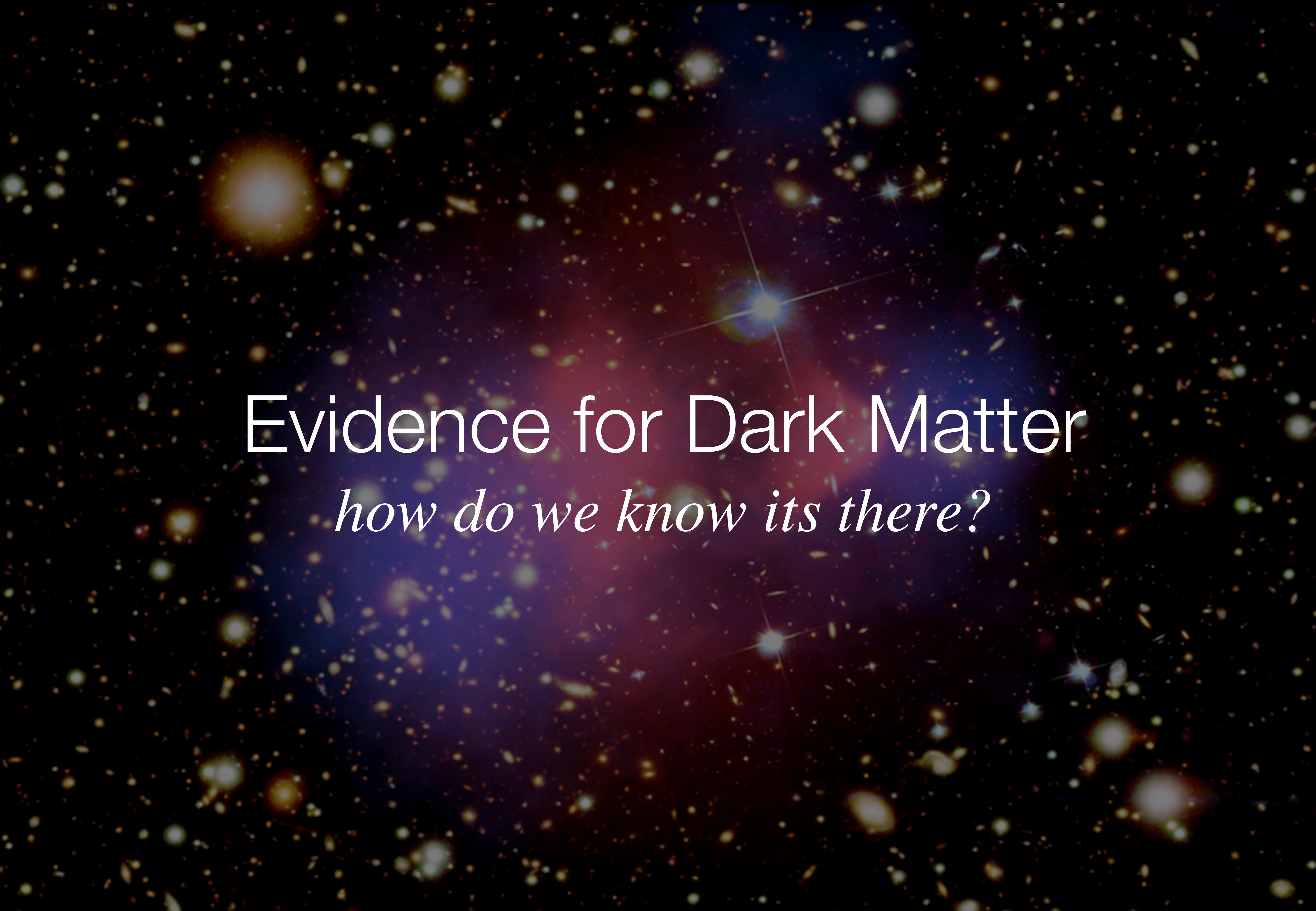


Our place in the Universe

We only make up 4% of the Universe

How did we come to know that the most common form of matter in the universe is 'invisible' to us?





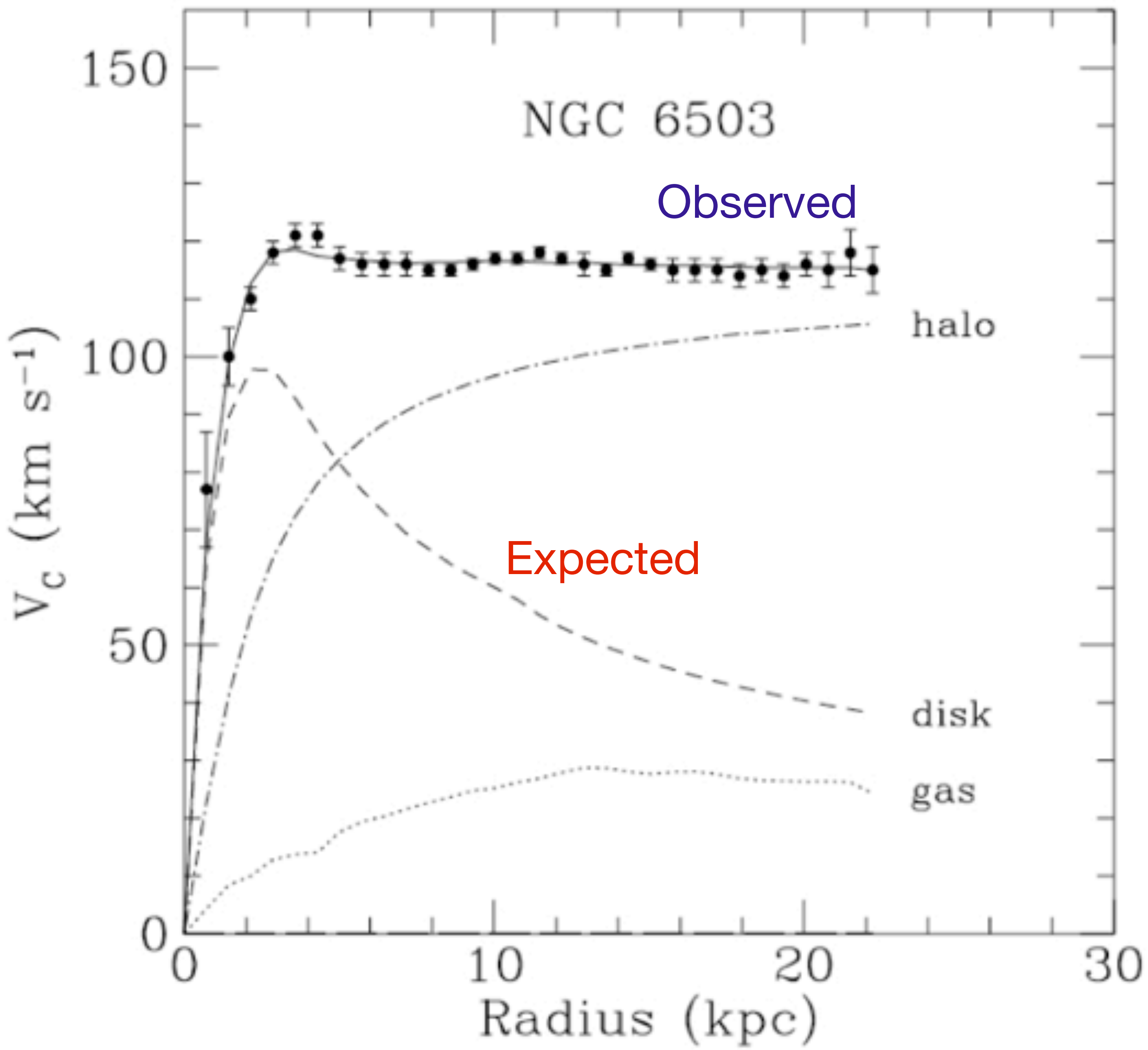
Evidence for Dark Matter

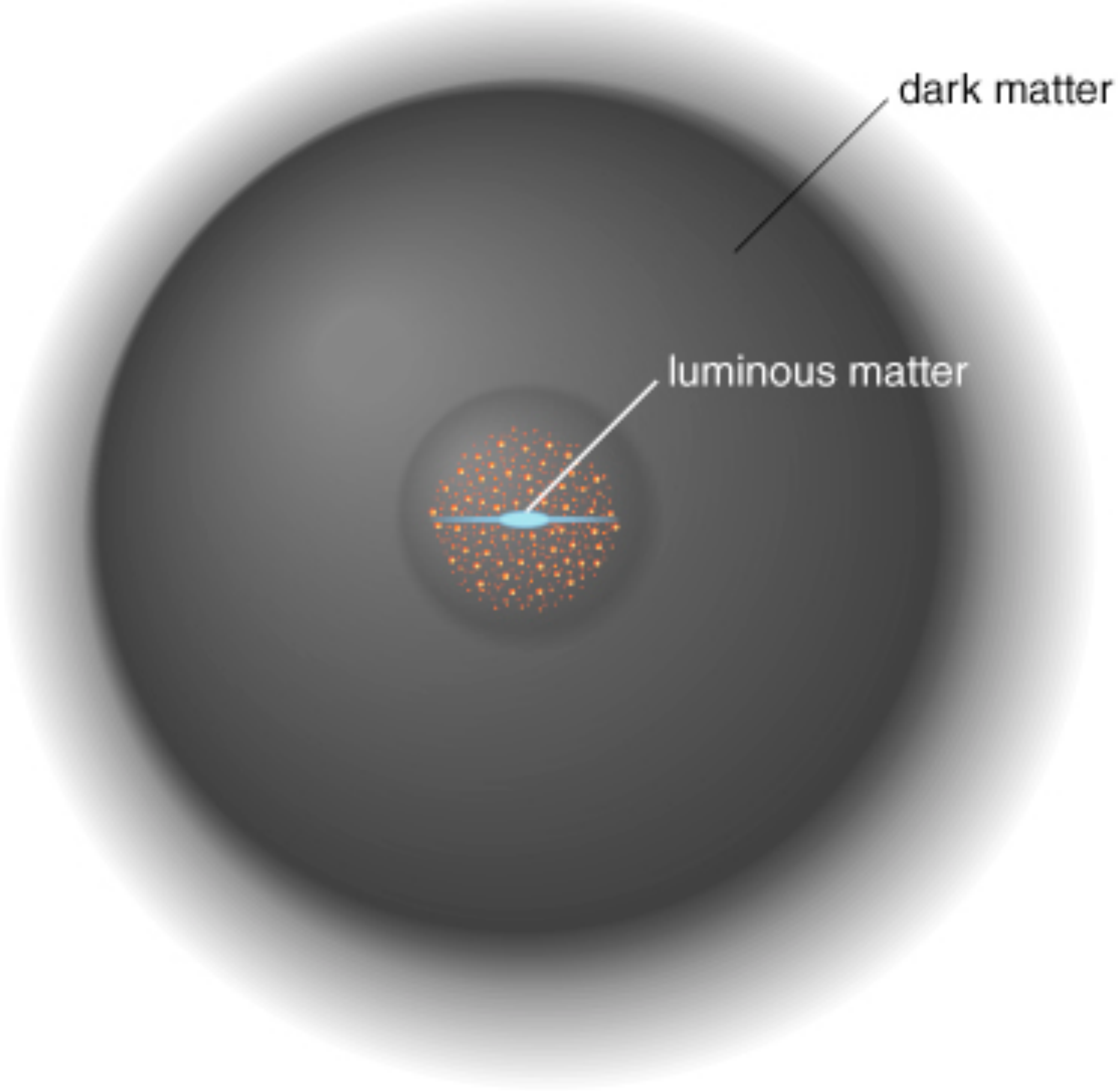
how do we know its there?

Not enough mass

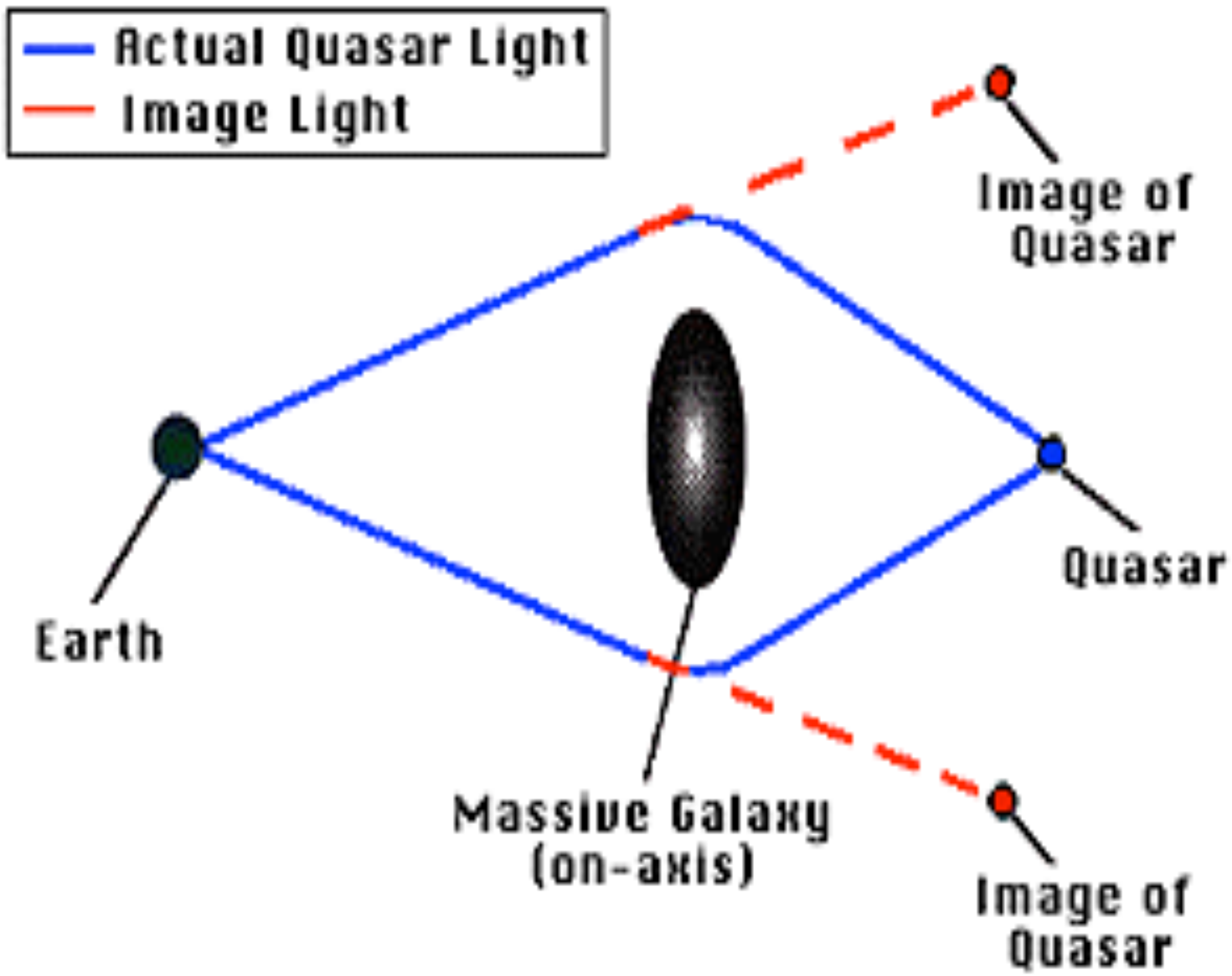
Fritz Zwicky

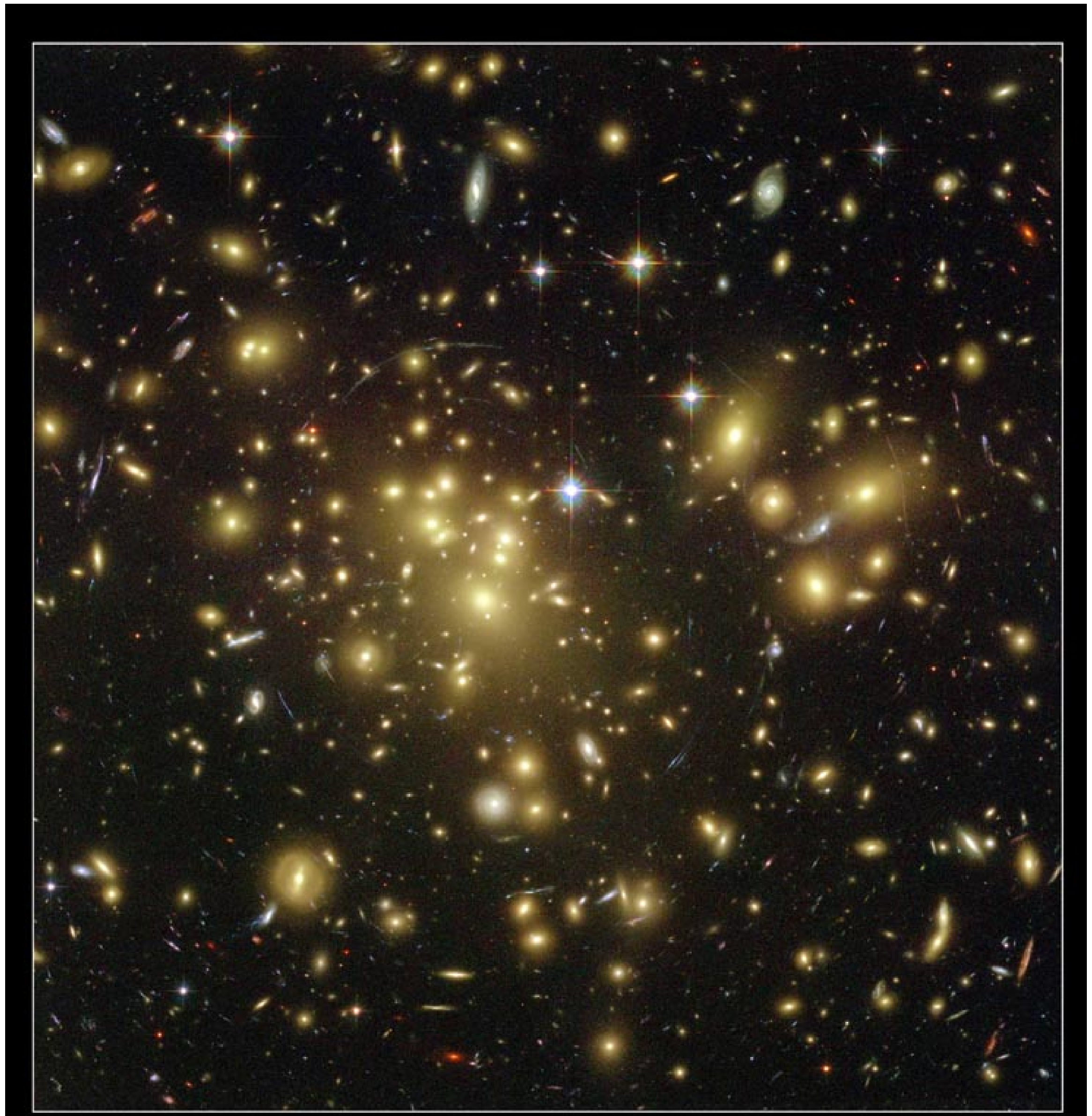
Rotation curves of galaxies





Gravitational lensing





Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

Gravitational lensing

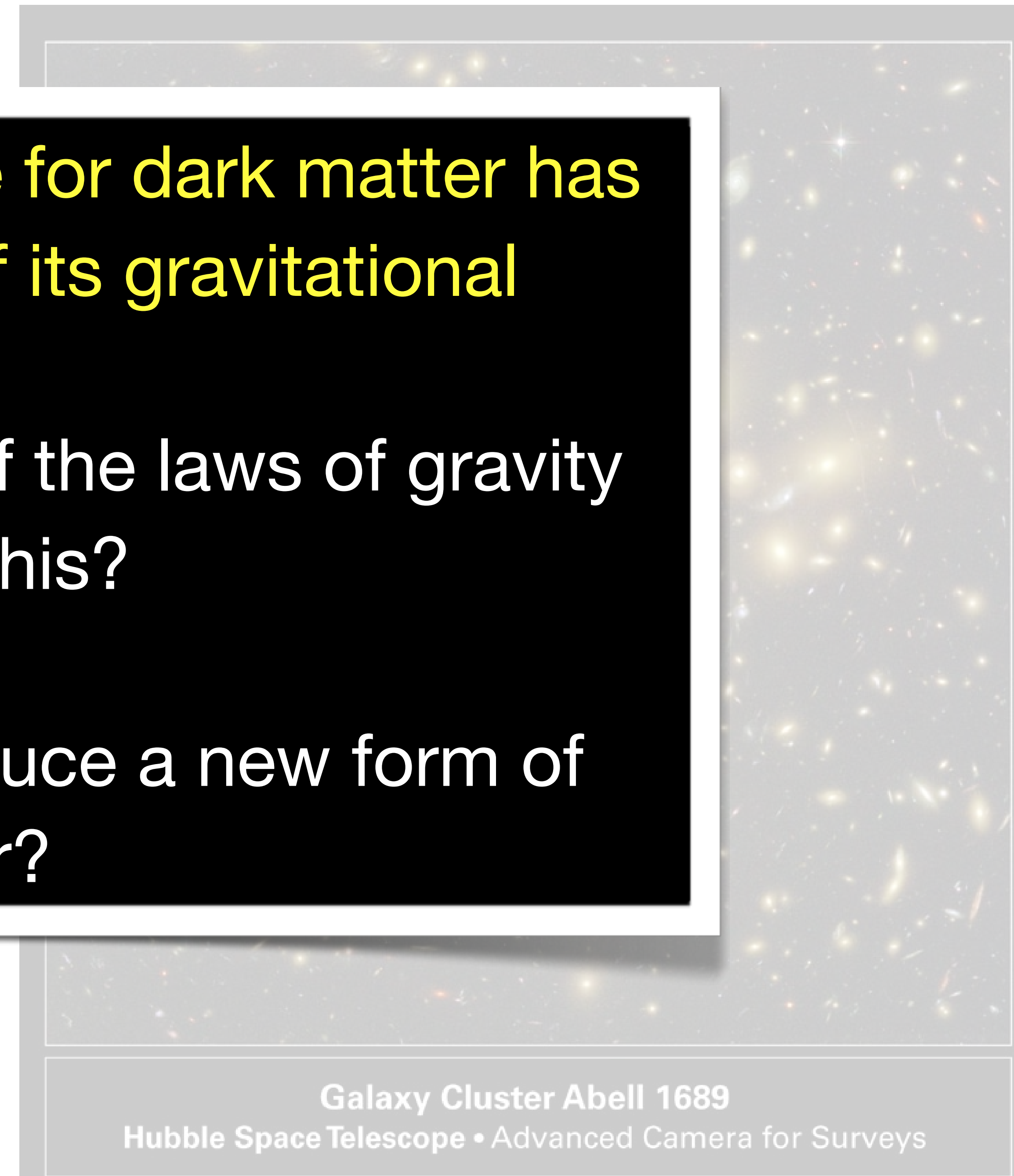
- foreground
- bending of l
give multiple

All experimental evidence for dark matter has come from observation of its gravitational influence :

- Can a modification of the laws of gravity explain this?

OR

- Do we need to introduce a new form of matter?



Bullet cluster

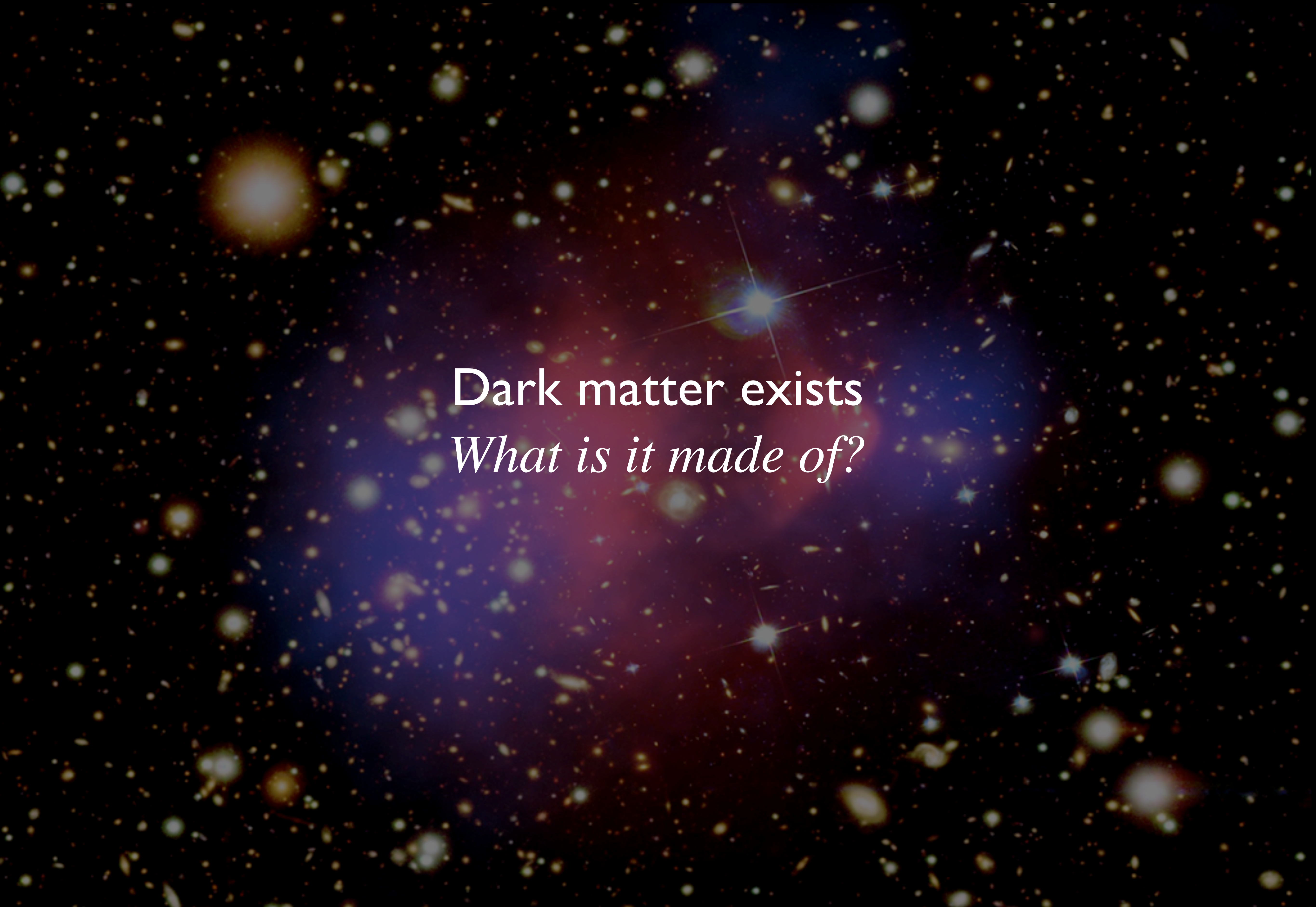
Optical image from Magellan and Hubble

Optical +X-ray

hot gas detected by Chandra, containing most of normal matter

Optical + gravitational lensing

Most of the mass in the cluster, measured by gravitational lensing, shown in blue

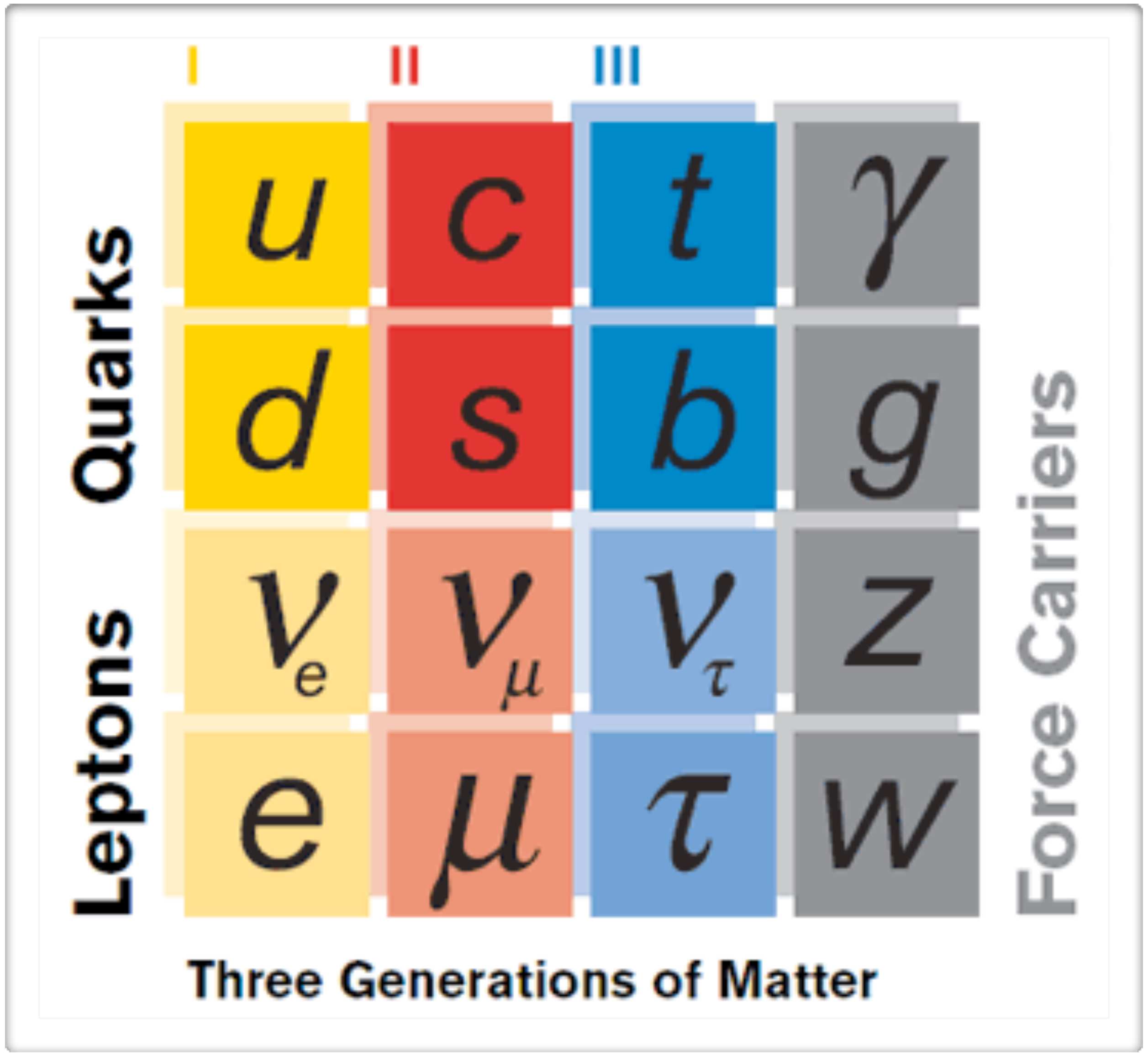

Dark matter exists
What is it made of?

What properties should a DM candidate have?

- non-relativistic
- long lived
- interacts gravitationally
- no electric charge or color charge

The Standard Model

Remarkably successful theory!
Passed rigorous tests performed by decades of experiments

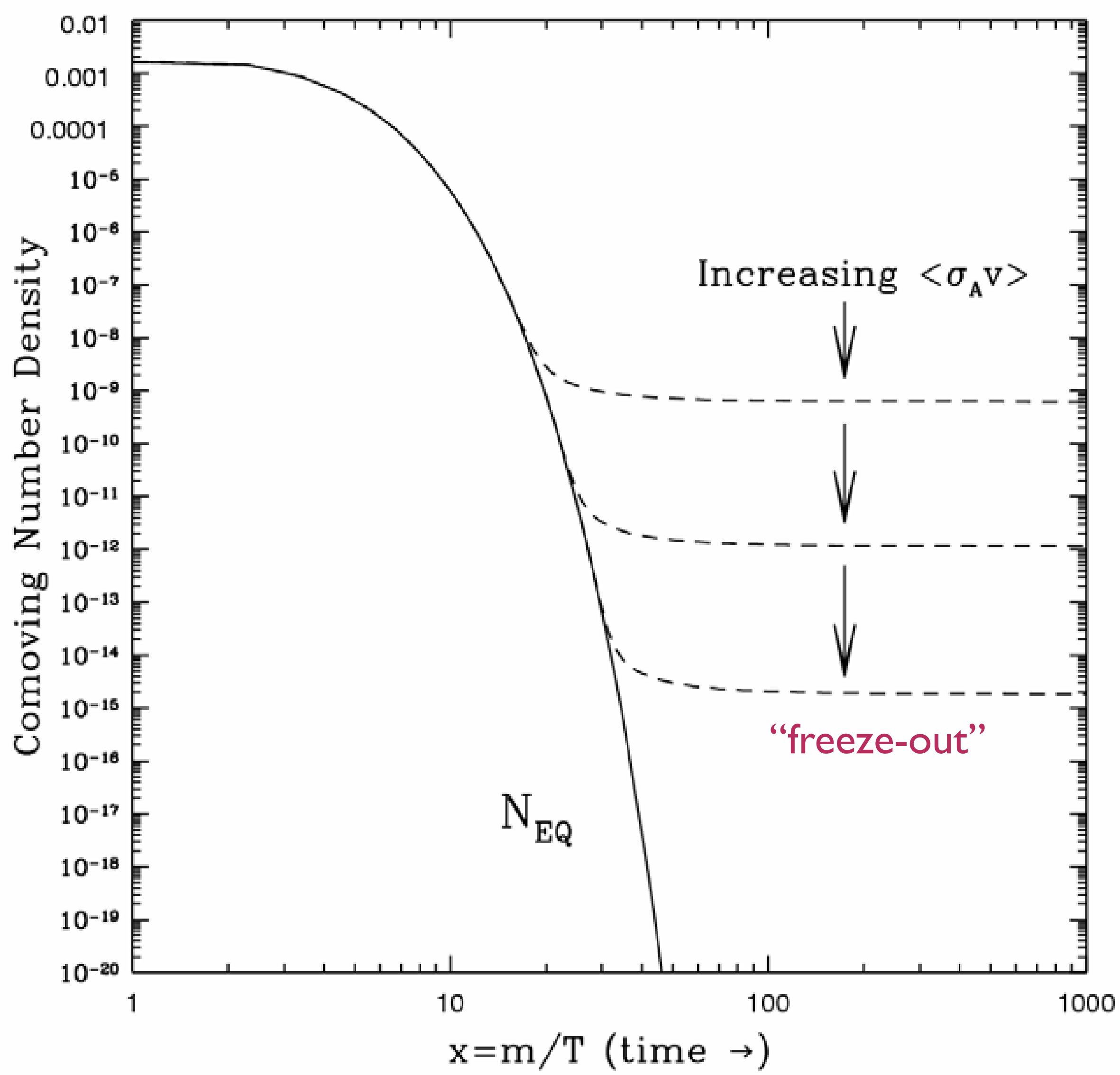


SM provides no candidate to explain the most common form of matter - no neutral, heavy, non-relativistic and long-lived particle

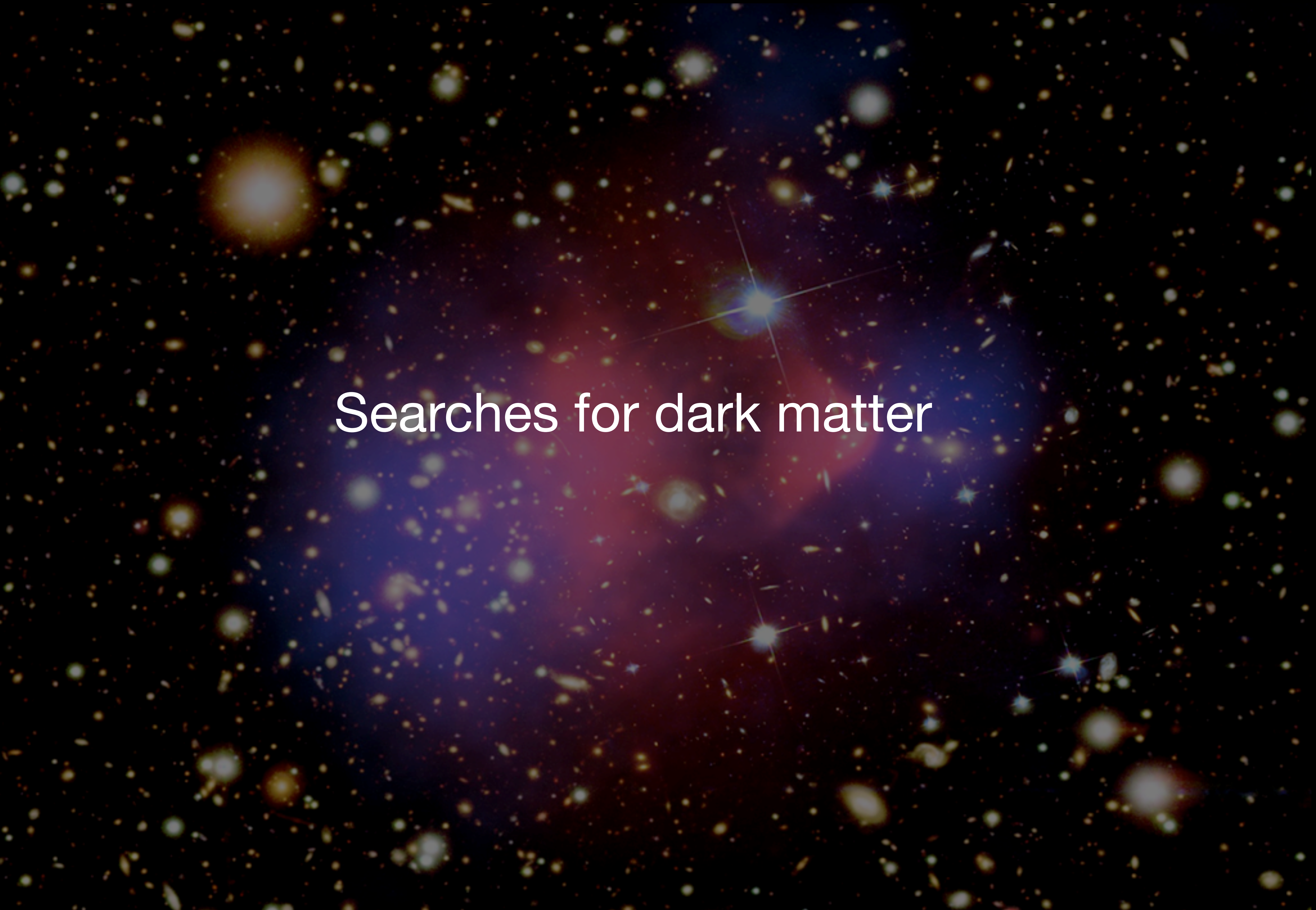
Weakly Interacting Massive Particles (WIMPs)

- Postulate a new species of elementary particles
- Weakly Interacting Massive Particles (WIMPs)
- They are produced in the Big Bang and interact via : $\chi + \chi \leftrightarrow SM + SM$.

- As the universe expands and the temperature falls, they become diluted, and eventually can't find each other, so they 'freeze out'.
- Their relic density is measured by their interaction strength, inversely proportional to the annihilation cross-section ($<\sigma_A v>$)



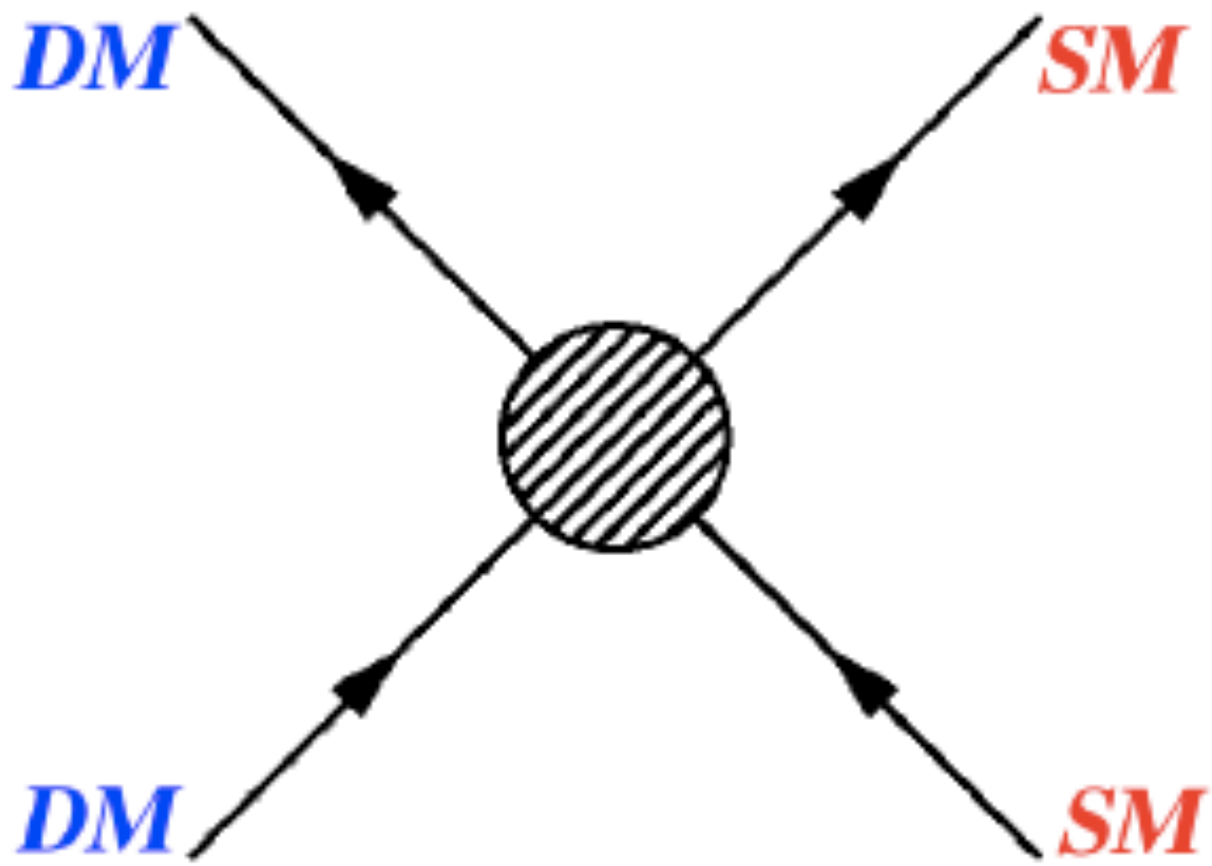
Weakly interacting particles with weak-scale masses naturally provide the right relic abundance - "WIMP miracle"



Searches for dark matter

Searching for dark matter

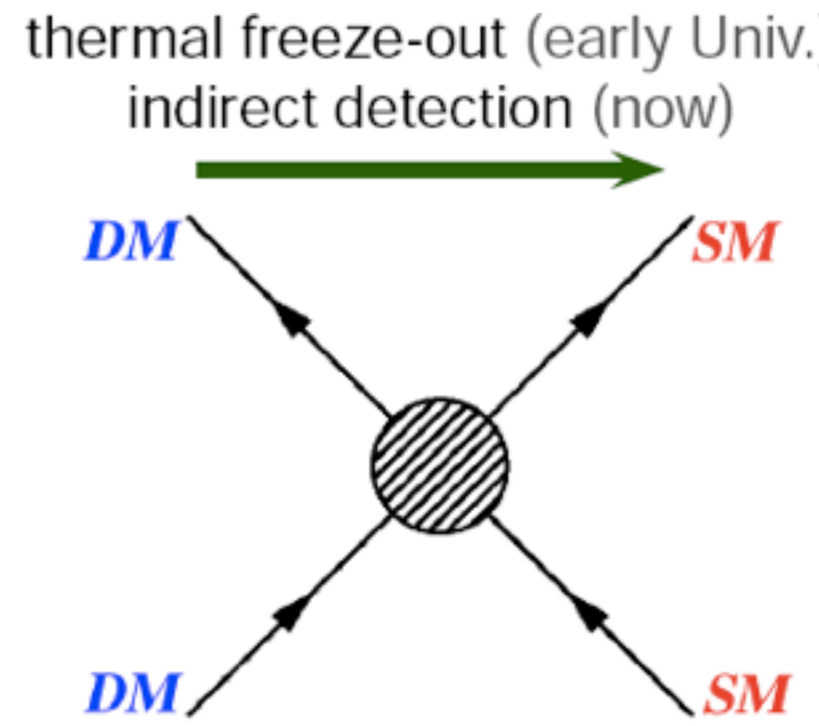
- $\chi + \chi \rightarrow$ SM + SM is the only process important for determination of relic abundance

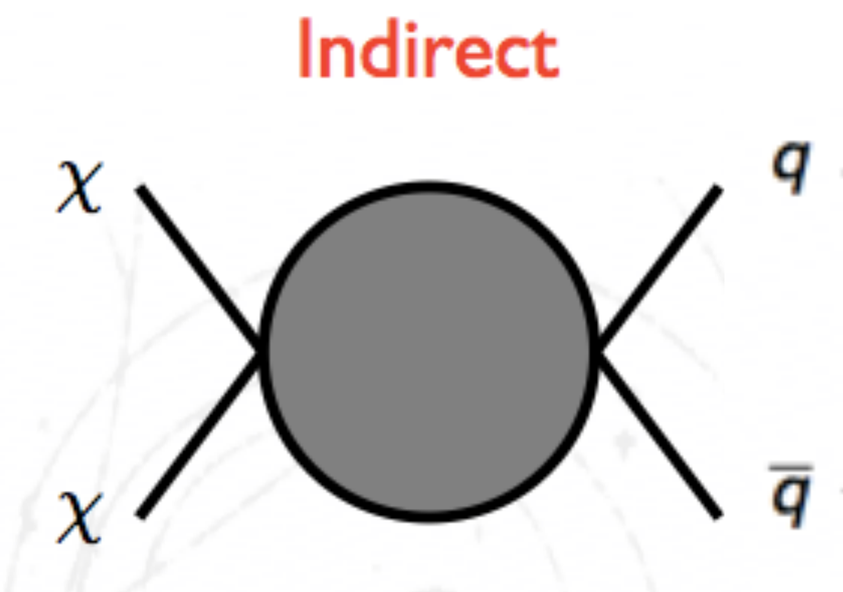


All three approaches to detecting dark matter probing the same interaction

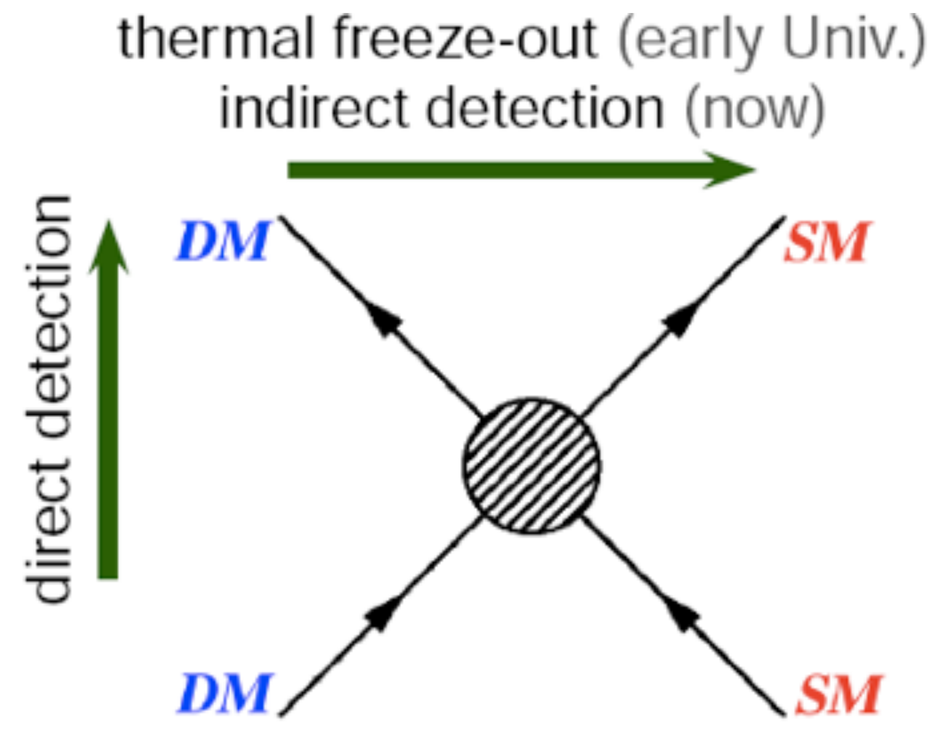
Searching for dark matter

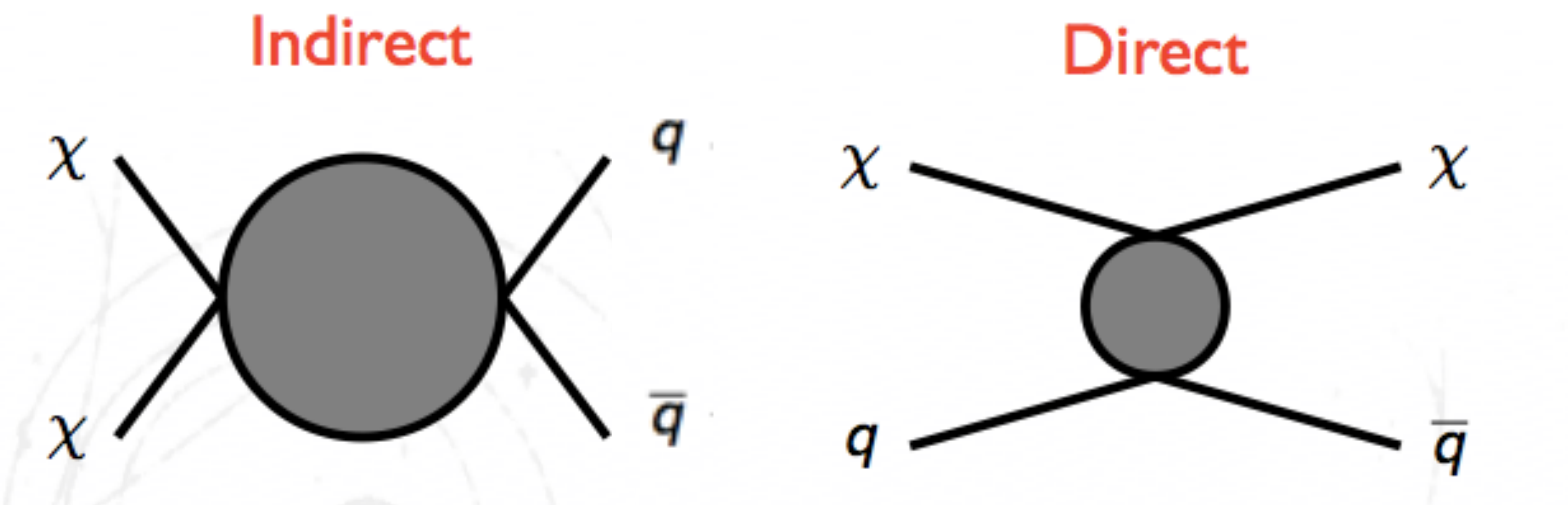
- $\chi + \chi \to$ SM + SM is the only process important for determination of relic abundance





- $\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$ is the only process important for determination of relic abundance





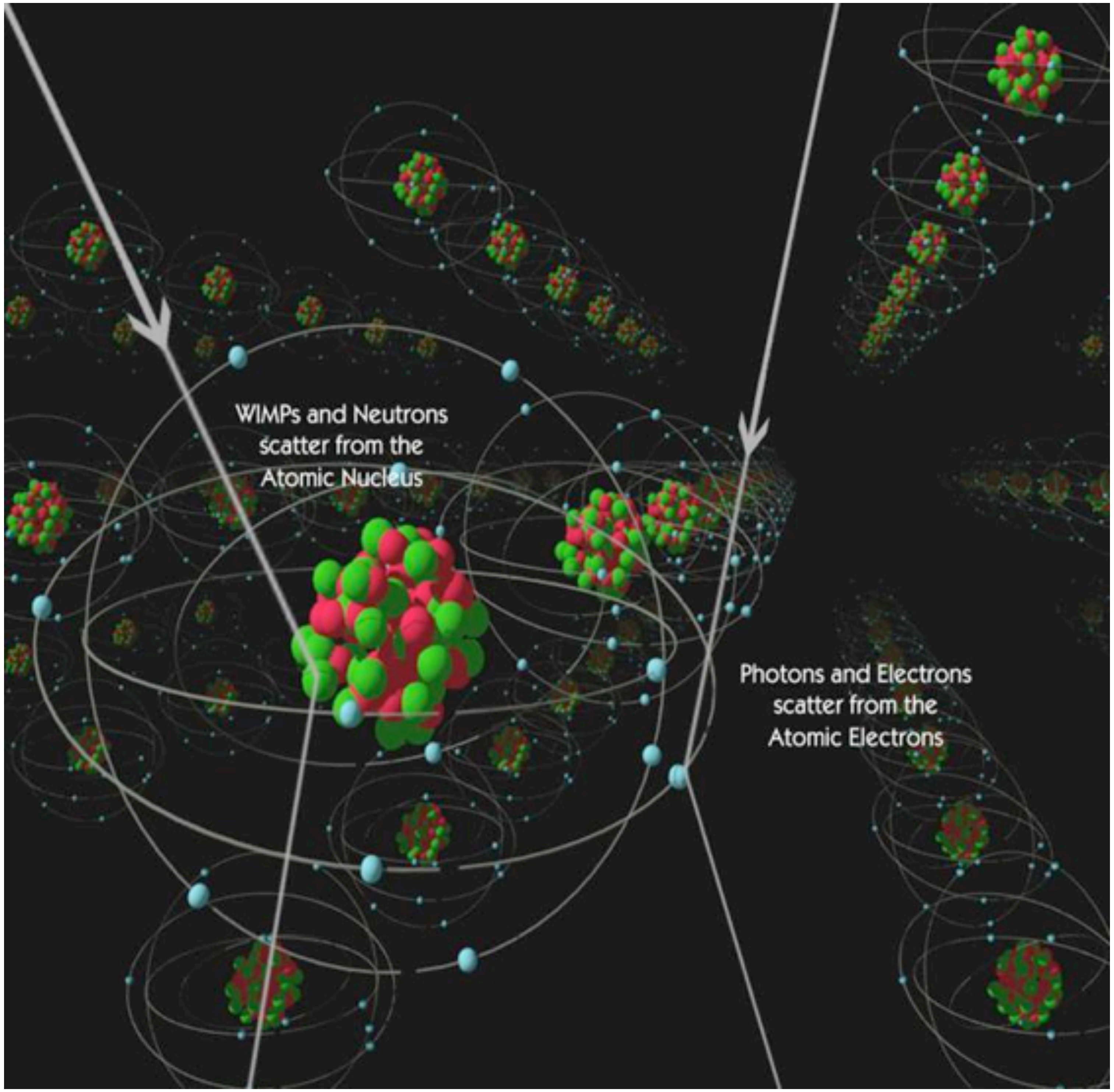
Direct detection

- aim to observe recoil of dark matter off nucleus, recoil energy 1- 100 keV

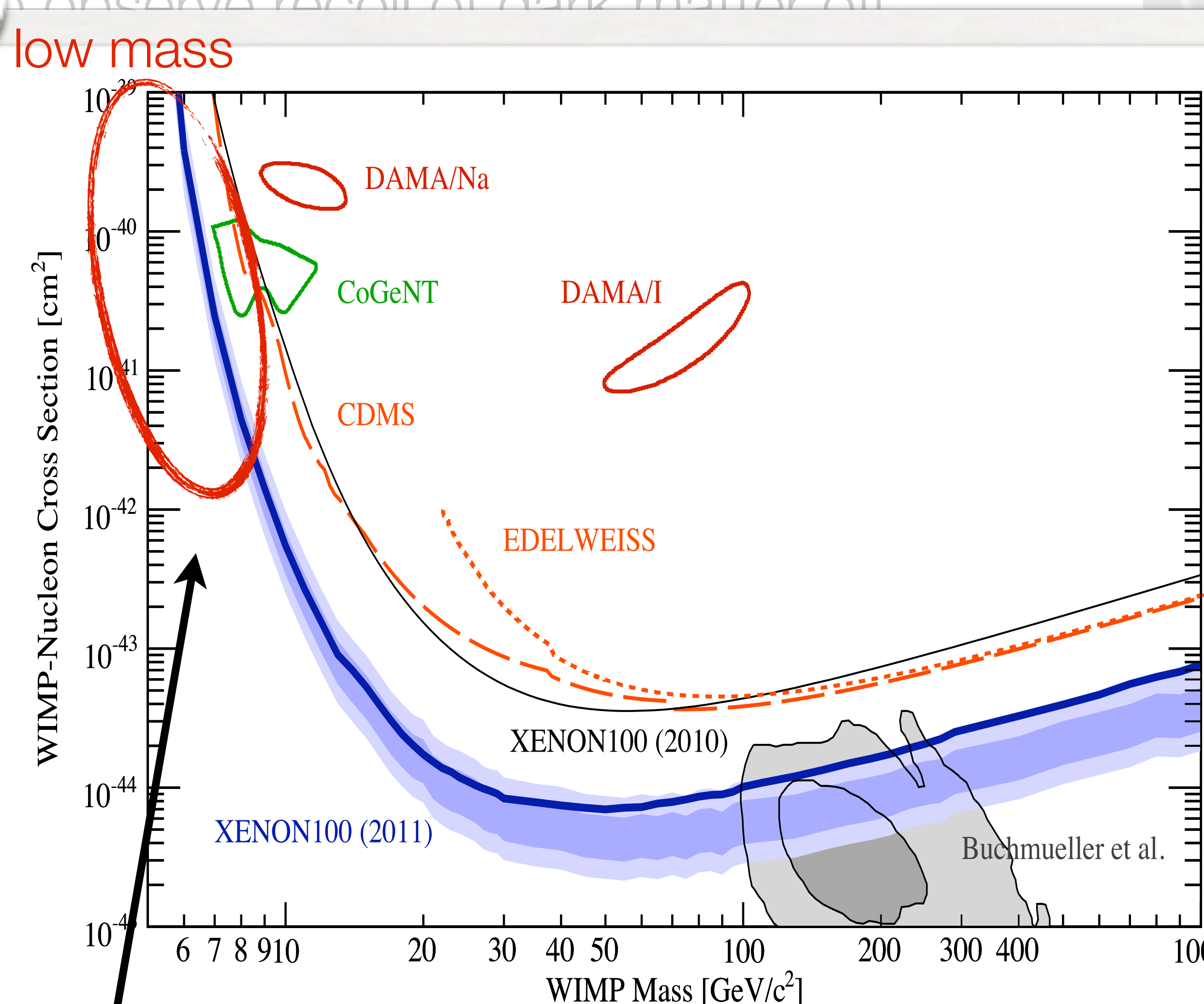
- recoil detected via scintillation, ionization and phonons

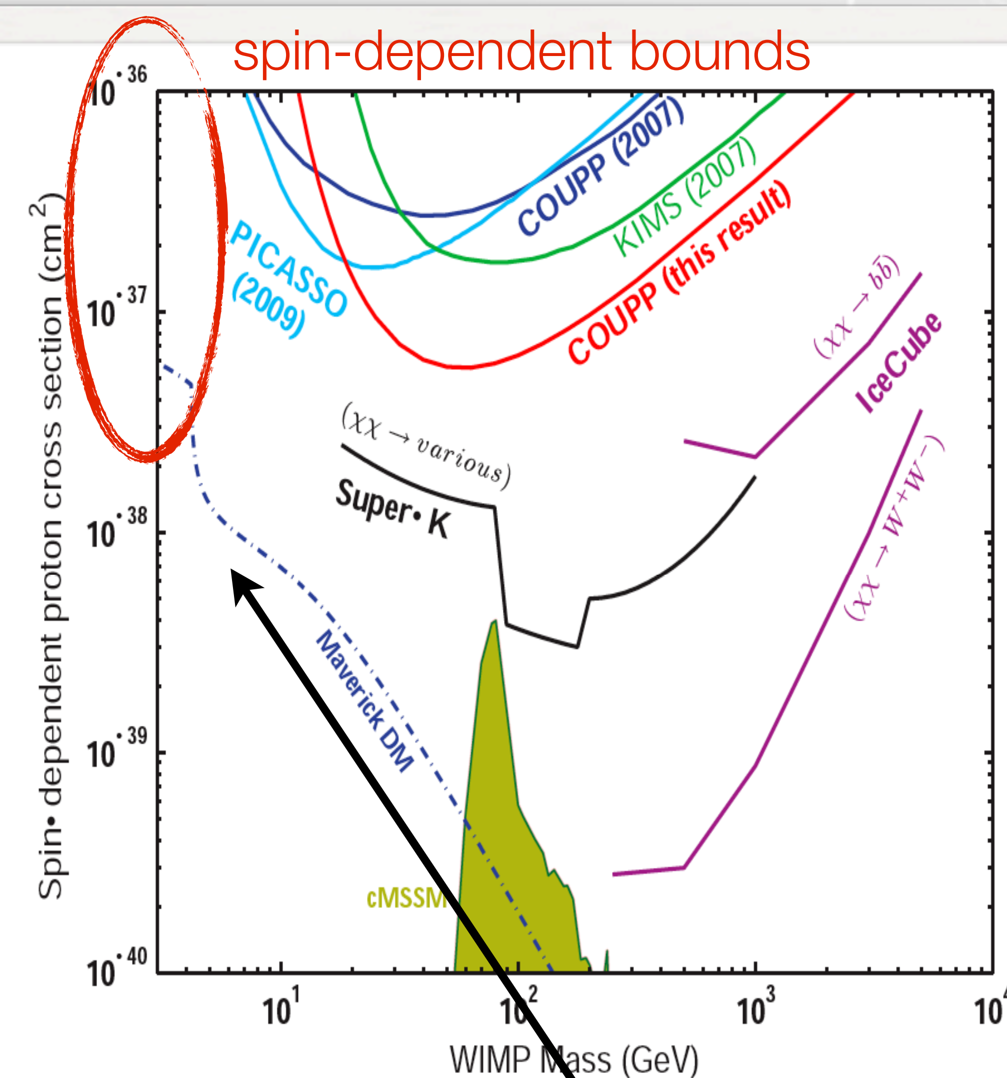
- current experiments use 10-100 kg heavy nuclei targets (Ge, Xe) located deep underground to minimize backgrounds

- sensitive to spin-dependent and spin-independent interactions.



Direct detection





Collider does not have low energy threshold

Challenges for direct detection experiments:

- low mass region not accessible
- limited by threshold effects, energy scale, backgrounds
- bounds from spin-dependent couplings weak

Collider- similar sensitivity to spin-dependent and spin-independent

Direct detection

- ai
reco

- rec
pho

- cu
targ
mini

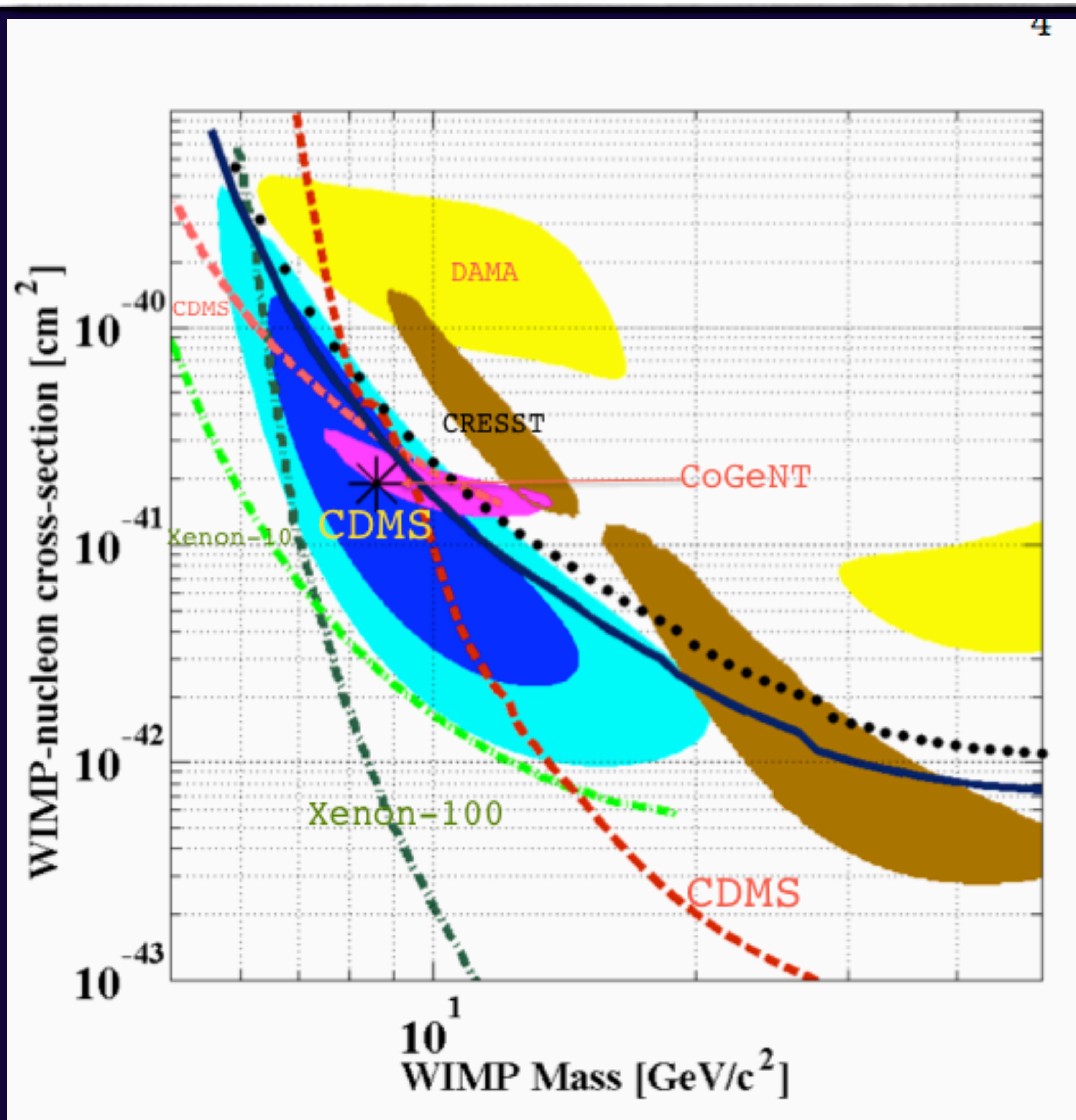
- ela
dep

Cha

- lov

- lim
bacl

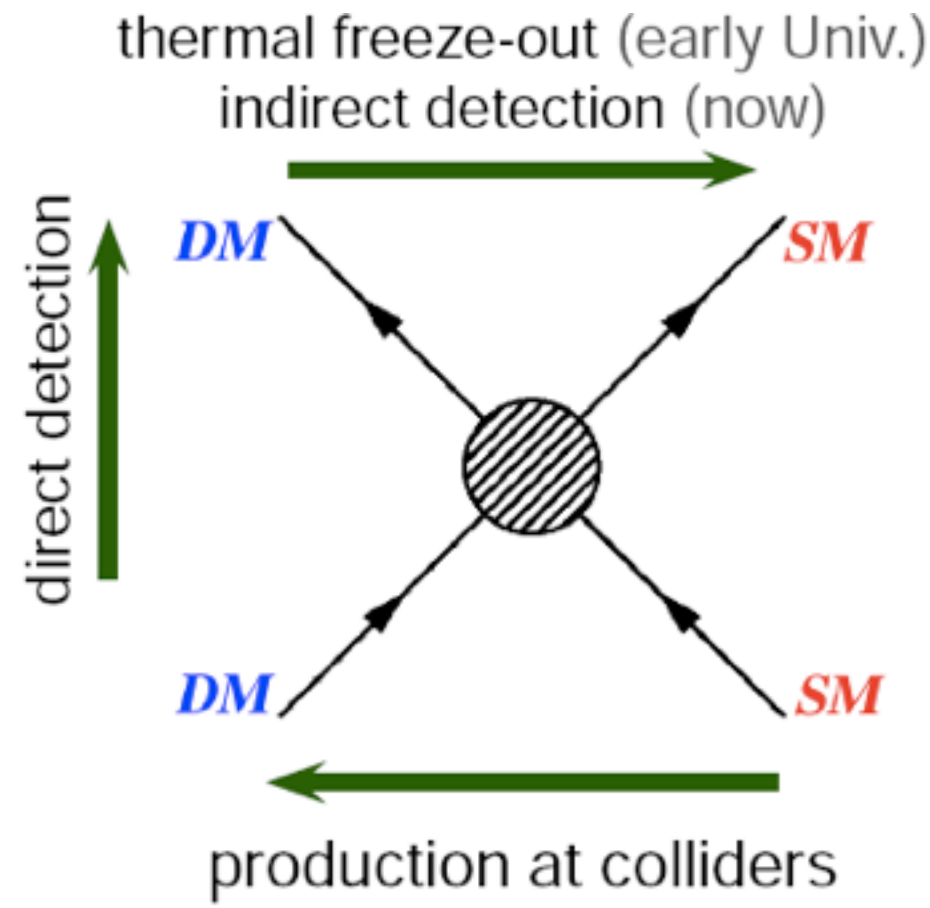
- bo

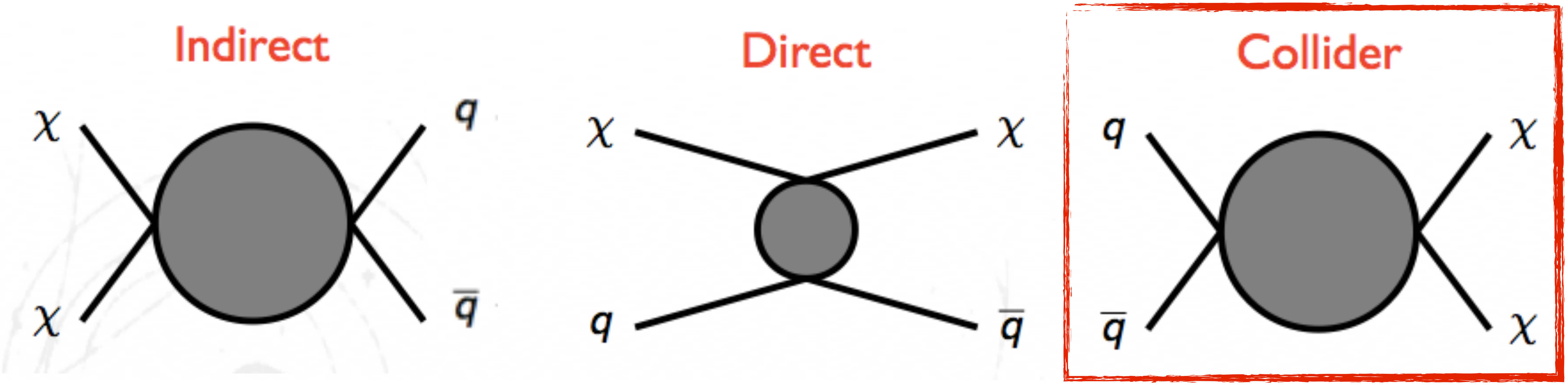


- excesses observed by several experiments, not confirmed by others

tremendous need for independent verification from non-astrophysical experiments!

- $\chi + \chi \rightarrow$ SM + SM is the only process important for determination of relic abundance

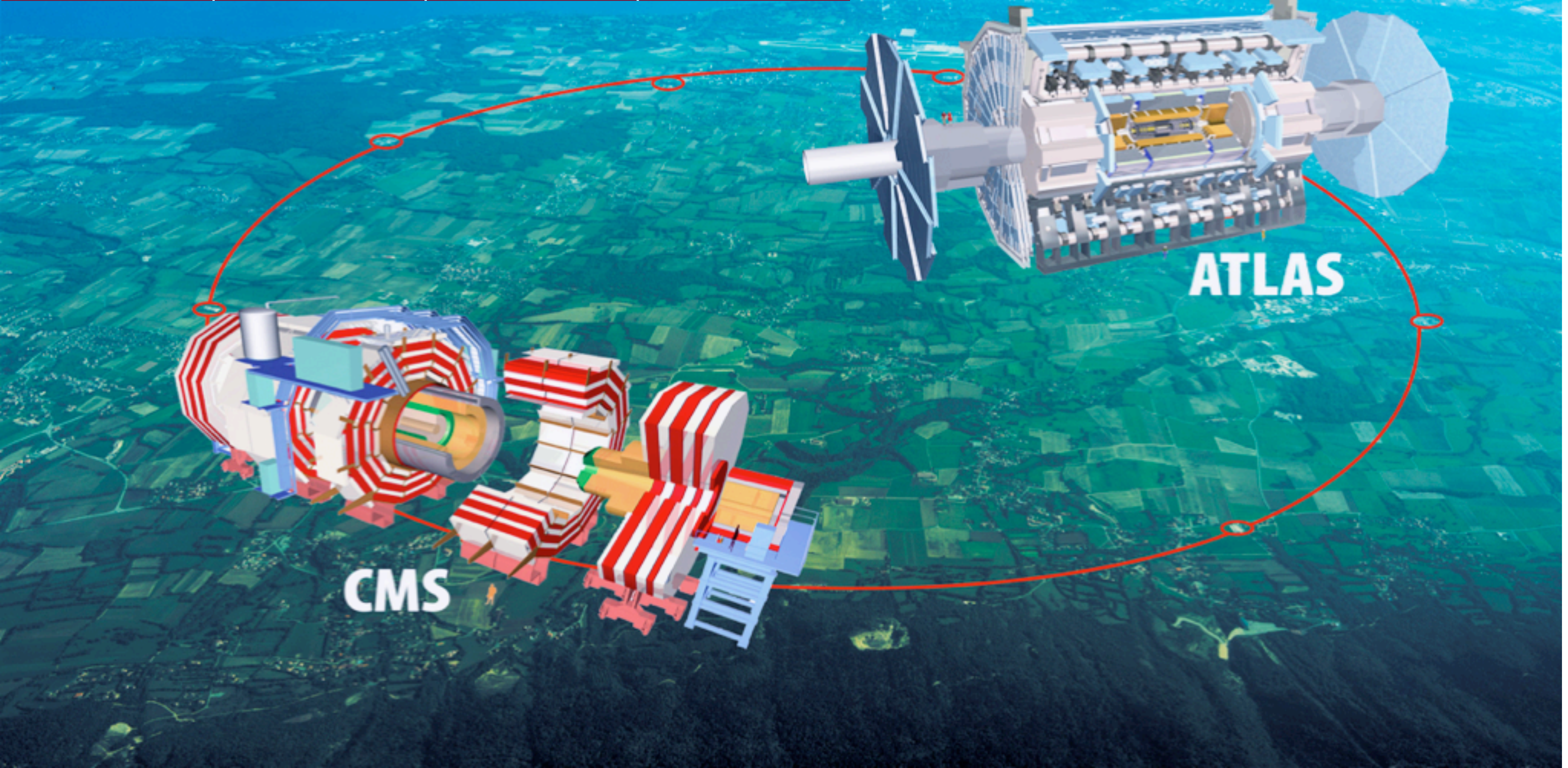




The Large Hadron Collider

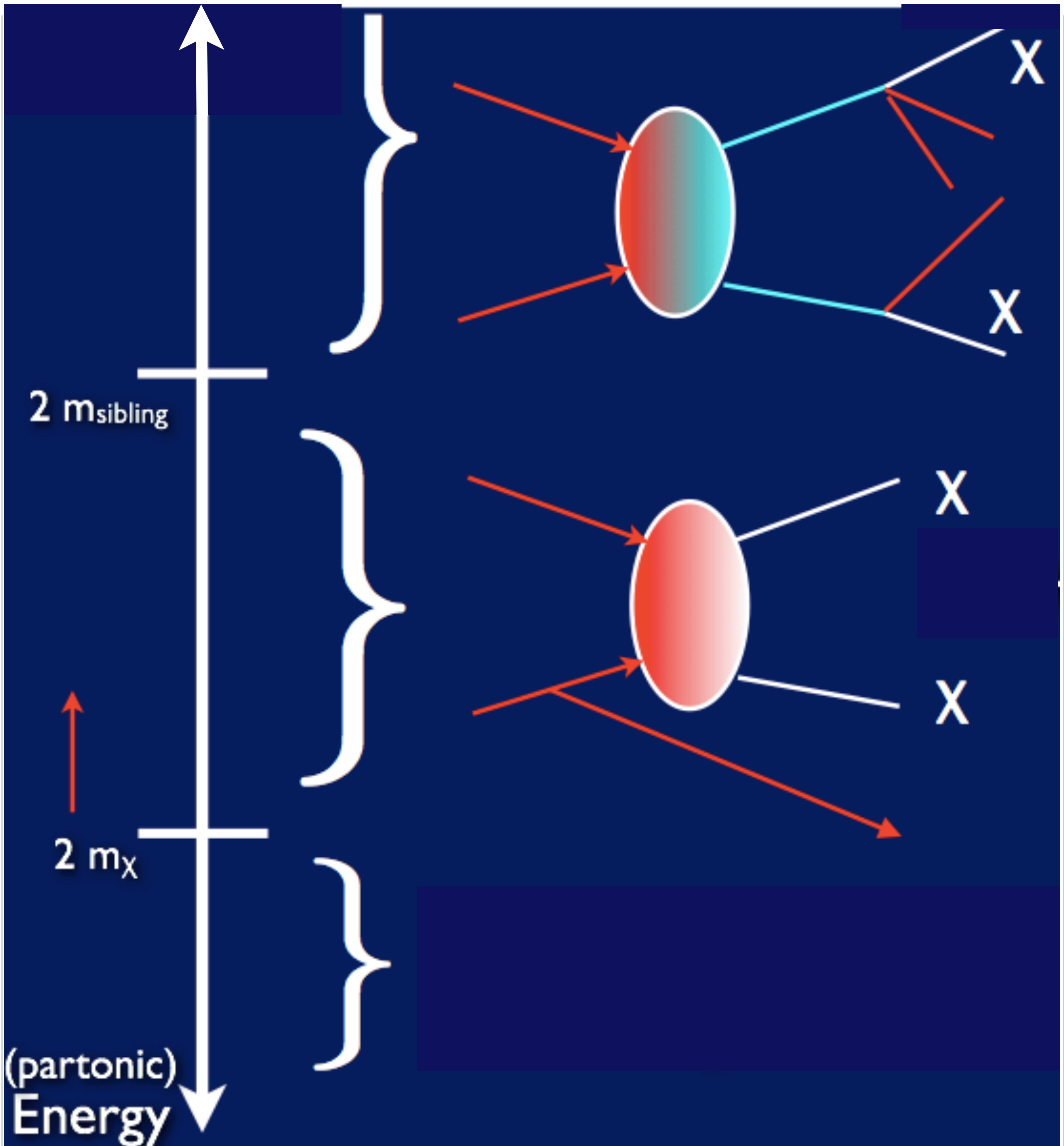
	2011	2012	2015
Energy	7 TeV	8 TeV	14 TeV
Integrated luminosity	5 fb^{-1}	20 fb^{-1}	40 fb^{-1} ?

- proton-proton collider
- two general, multi-purpose detectors
- ATLAS and CMS



Searches at colliders

Searching for dark matter at colliders



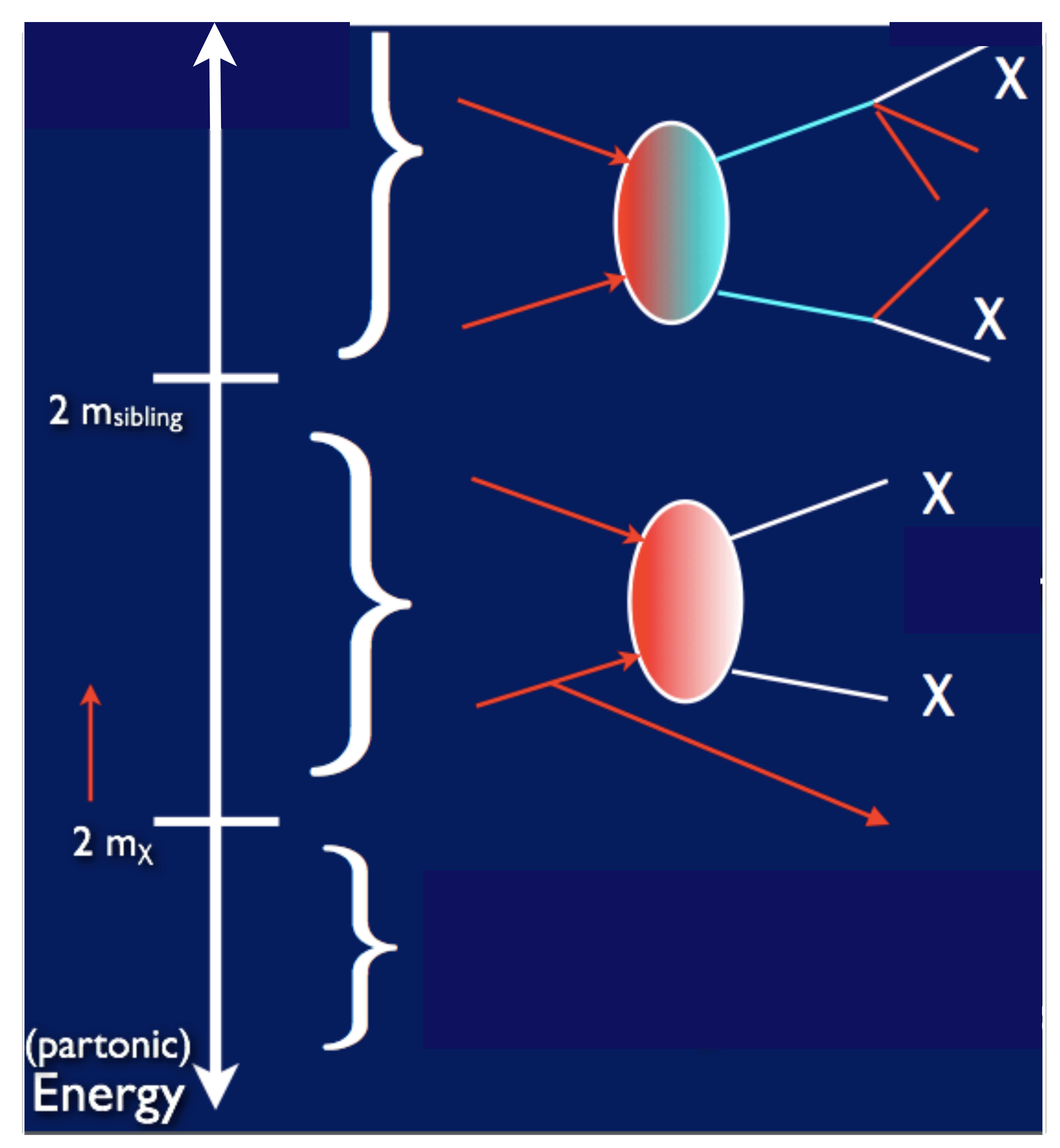
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Slide adapted from Tim Tait talk at Moriond

Searching for dark matter at colliders



LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Searching for dark matter at colliders

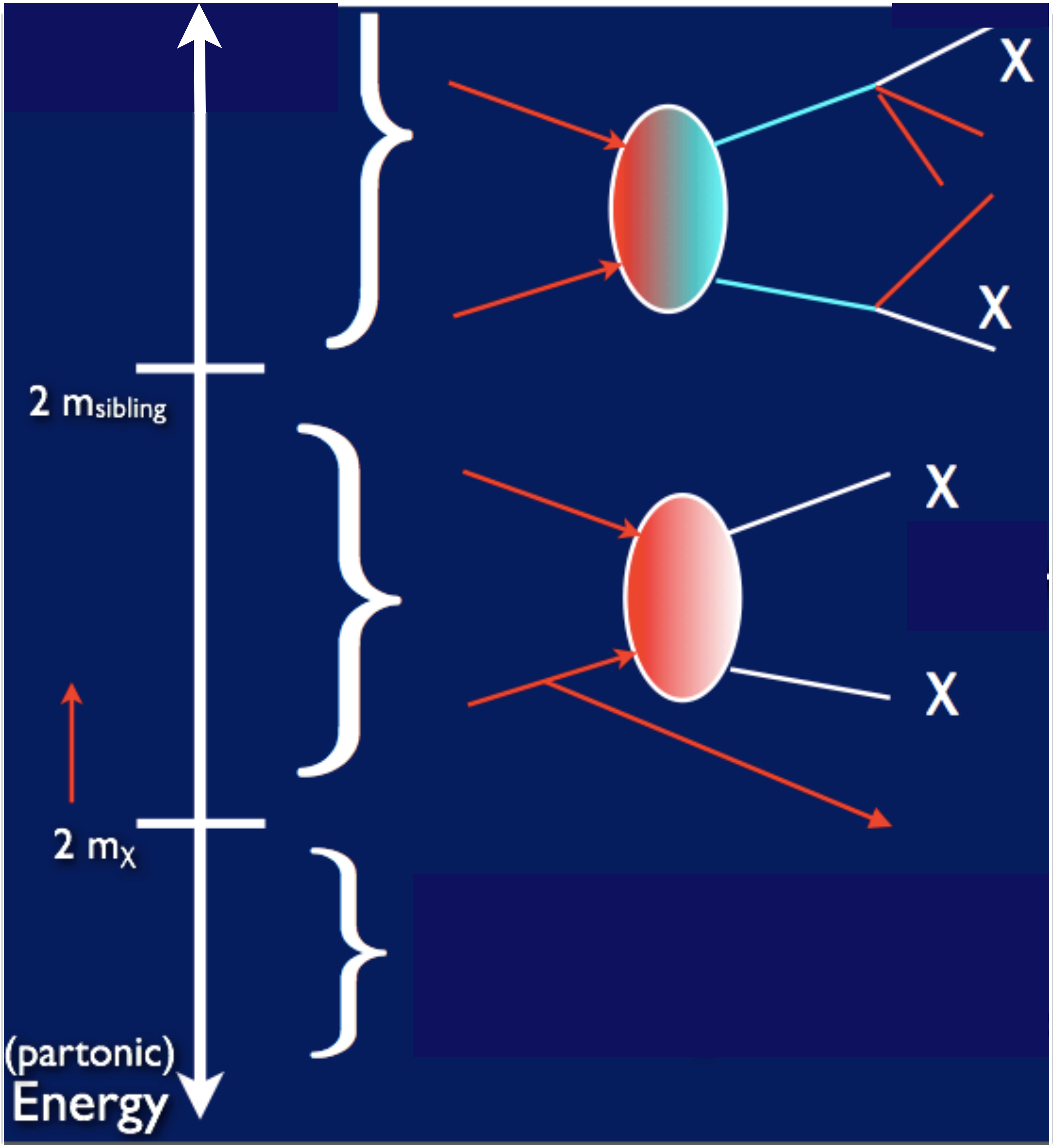
LHC can produce heavier

Supersymmetry
- symmetry between fermions and bosons
- heavy super-partners for each SM particle
- lightest SUSY particle (LSP) is neutral, stable. Good candidate for dark matter

Extra dimensions
-In UED, the dark matter candidate is a massive vector particle which is stable
- In Randall-Sundrum, the right-handed neutrino is stable

Theories designed to address the gauge hierarchy problem naturally
- predict stable, weakly interacting particles with mass ~ weak scale
- the correct relic abundance required to be dark matter.

Searching for dark matter at colliders



LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

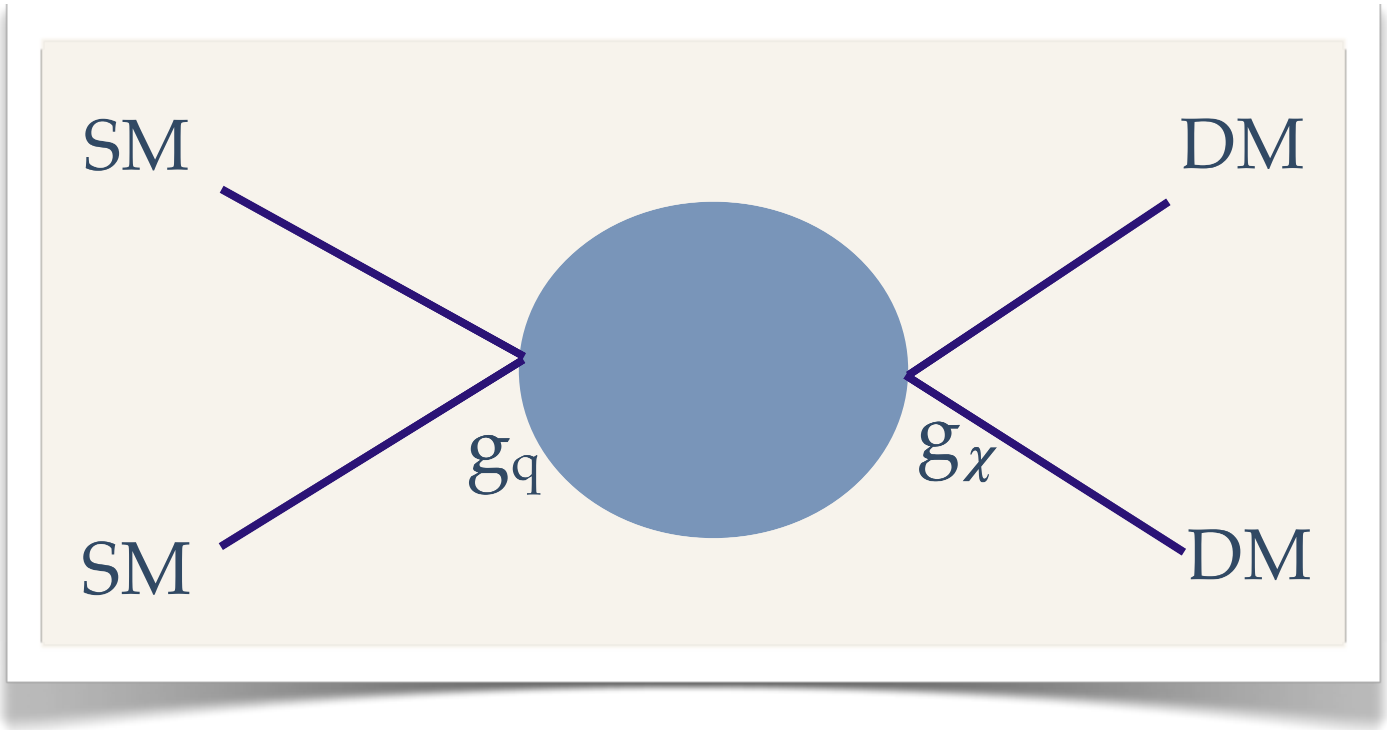
LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Phenomenology

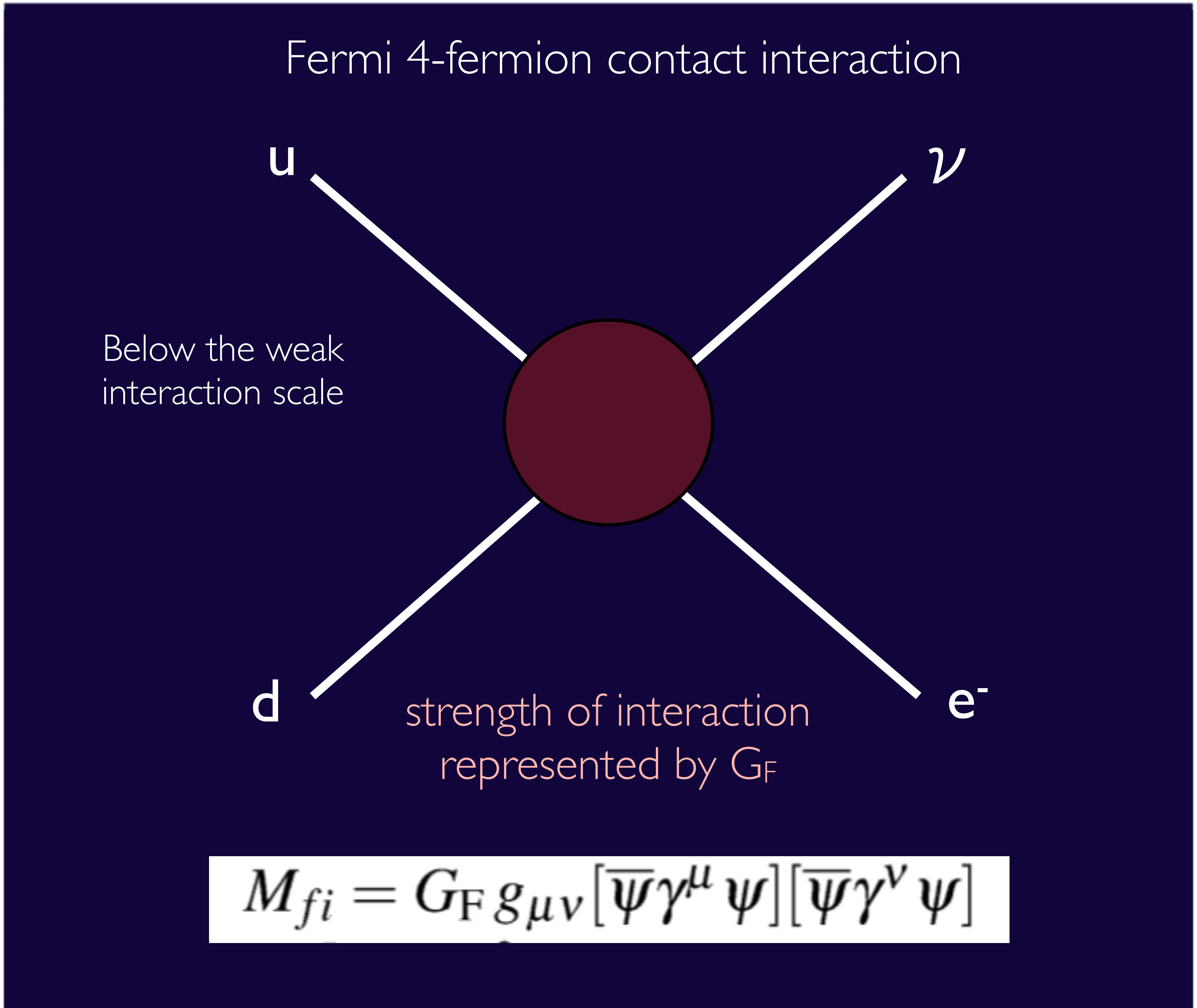
Assumptions:

- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction



Phenomenology

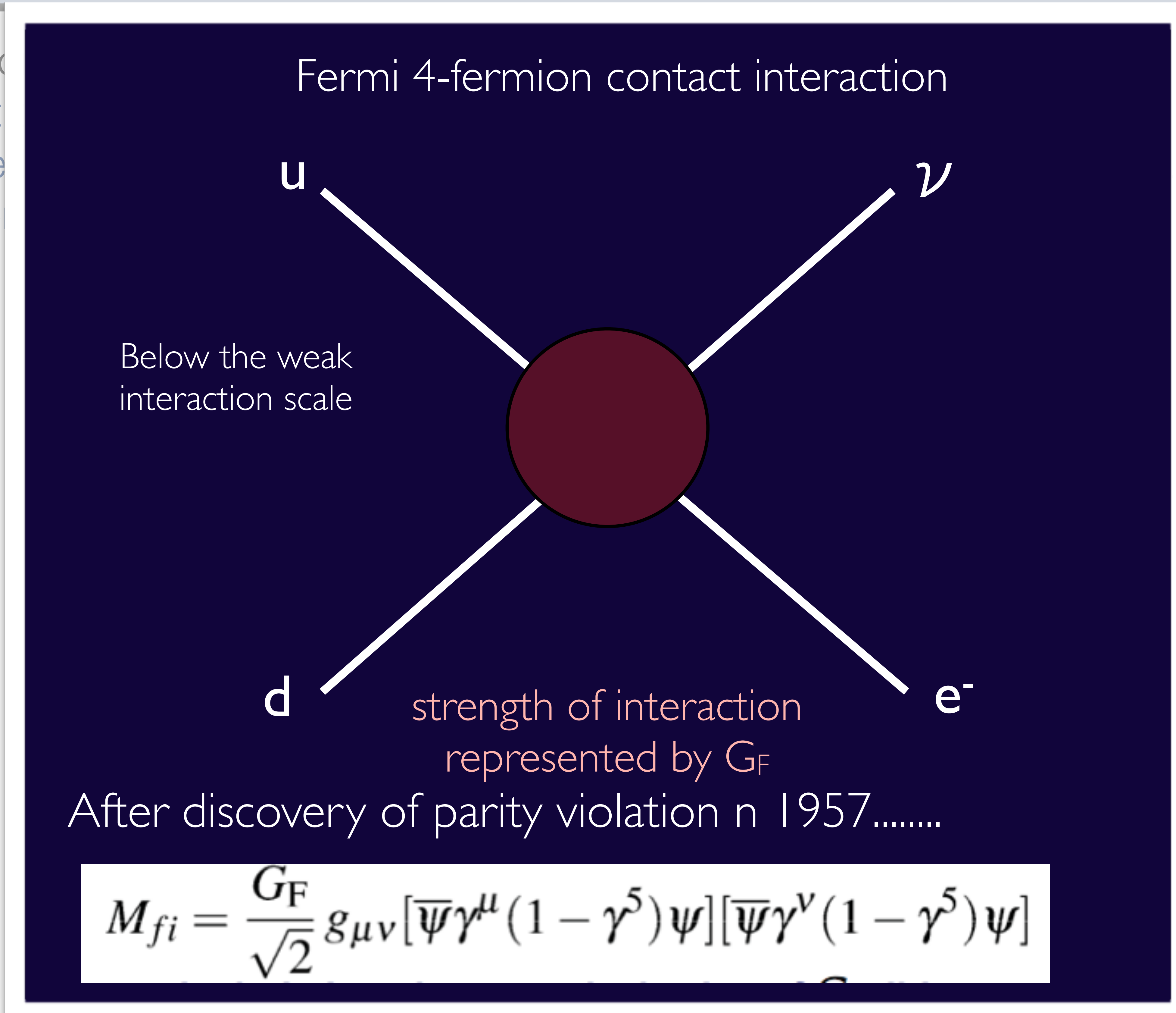
Assumpti
- DM part
- Effective   t interaction
- Mediato



Phenomenology

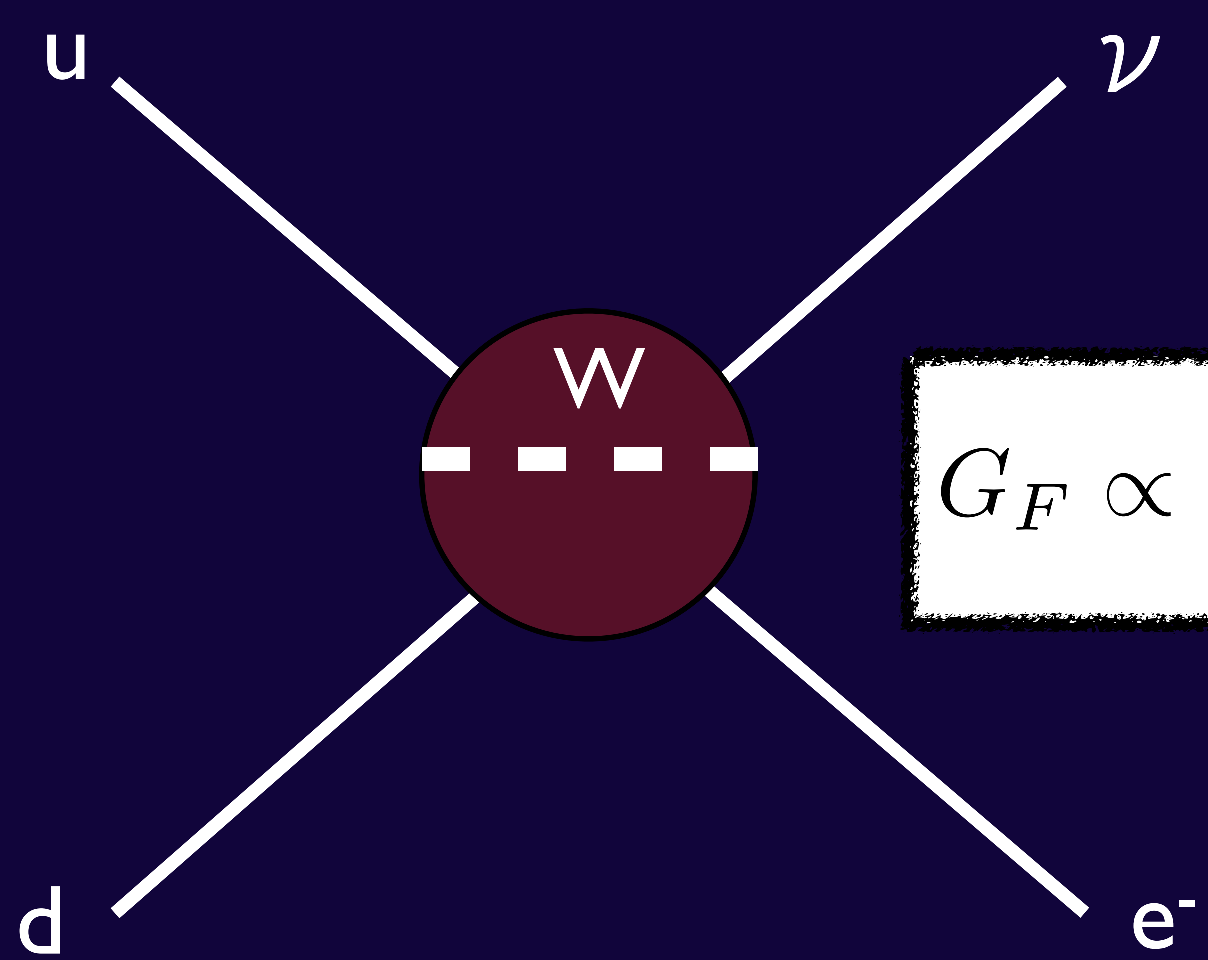
Assumpti

- DM part
- Effective … t interaction
- Mediato



Assumptio…
- DM part…
- Effective … t interaction
- Mediato…

After discovery of W boson.........



$$G_F \propto \frac{{g_w}^2}{{M_w}^2}$$

$$M_{fi} = \left[\frac{g_W}{\sqrt{2}}\overline{\psi}\frac{1}{2}\gamma^{\mu}(1-\gamma^5)\psi\right]\frac{g_{\mu\nu} - q_{\mu}q_{\nu}/m_W^2}{q^2 - m_W^2}\left[\frac{g_W}{\sqrt{2}}\overline{\psi}\frac{1}{2}\gamma^{\nu}(1-\gamma^5)\psi\right]$$

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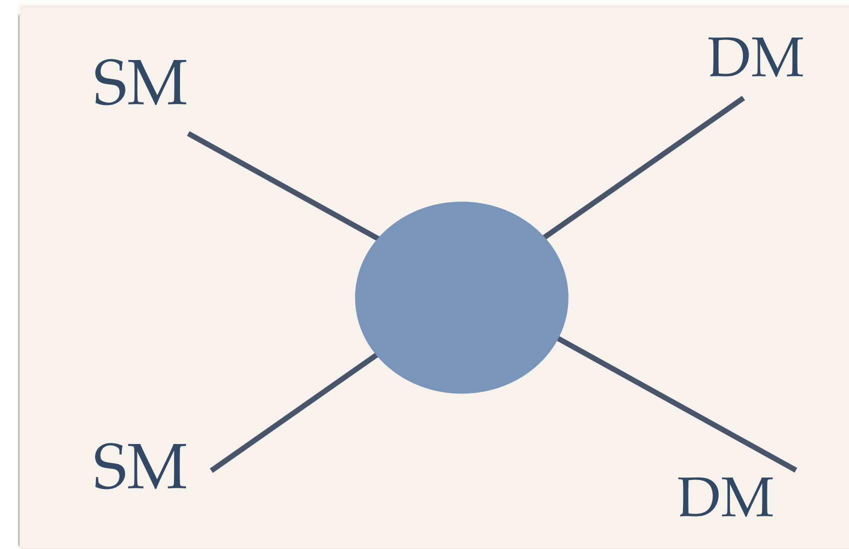


$$\mathcal{L} = \underbrace{\mathcal{L}_{SM}}_{\text{SM Lagrangian}} + \underbrace{i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X}_{\text{kinetic terms for DM}} + \underbrace{\sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \left[\bar{X}\Gamma_i^X X\right]\left[\bar{q}\Gamma_q^j q\right]}_{\text{set of 4-Fermion interactions between DM and SM quarks}},$$

Operators $\mathbf{\Gamma}$ describe scalar, pseudoscalar, vector, axial vector, tensor interactions

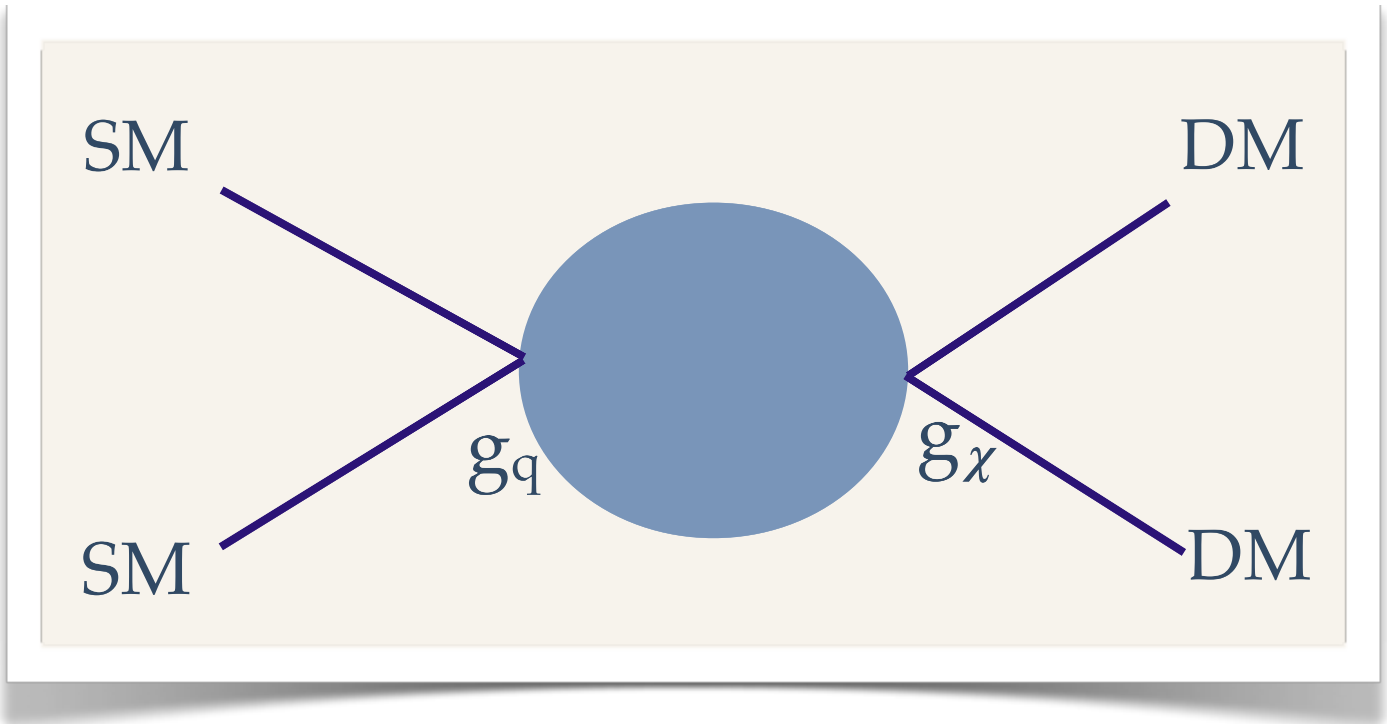
Literature

1. Beltran,Hooper,Kolb,Krusberg,Tait, 1002.4137
2. Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1005.1286
3. Bai, Fox, Harnik, 1005.3797
4. Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1008.1783
5. Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1009.0008
6. Fox, Harnik, Kopp,Tsai, 1103.0240
7. Fortin,Tait, 1103.3289
8. Cheung,Tseng,Yuan, 1104.5329
9. Shoemaker,Vecchi, 1112.5457
10. Haipeng An, Xiangdong Ji, Lian-Tao Wang

Phenomenology

Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik, JHEP 1012:048 (2010)

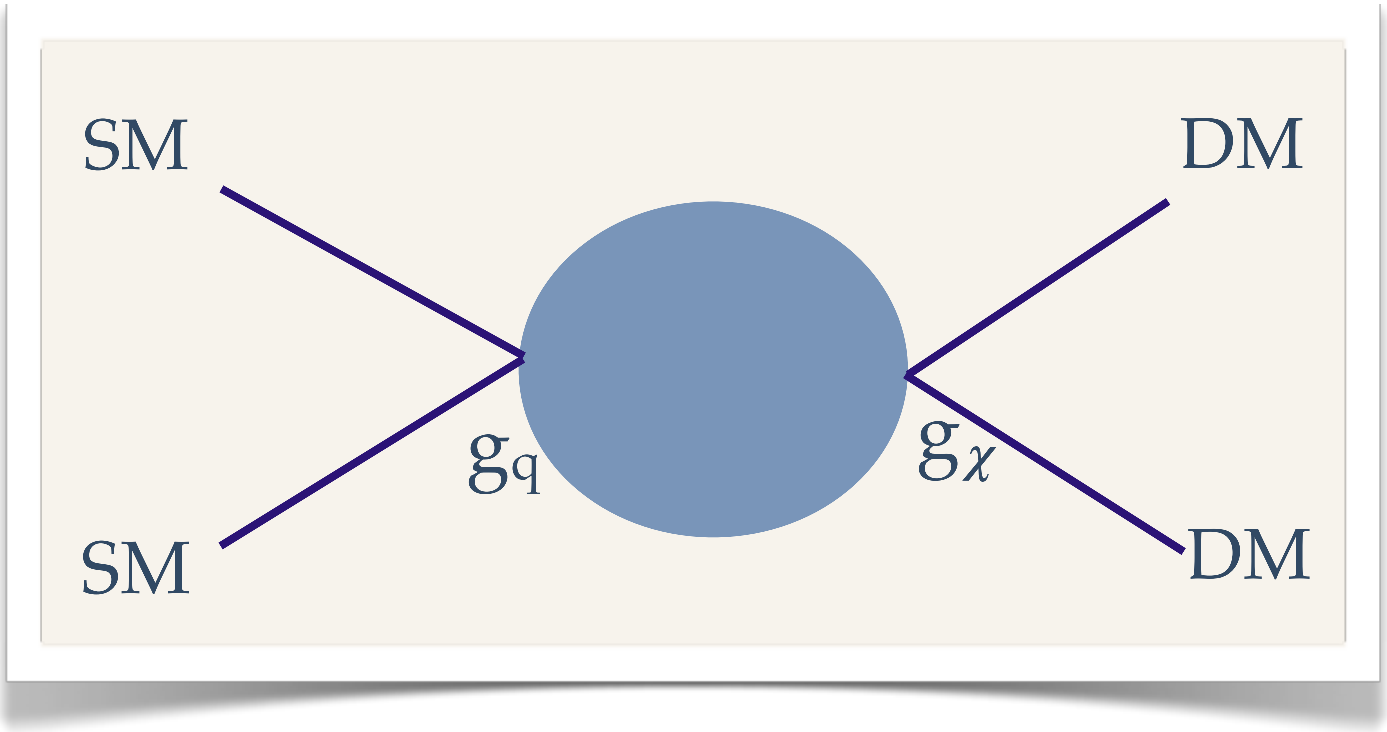


Phenomenology

Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik, JHEP 1012:048 (2010)

Set mass of mediator (M) to very high value



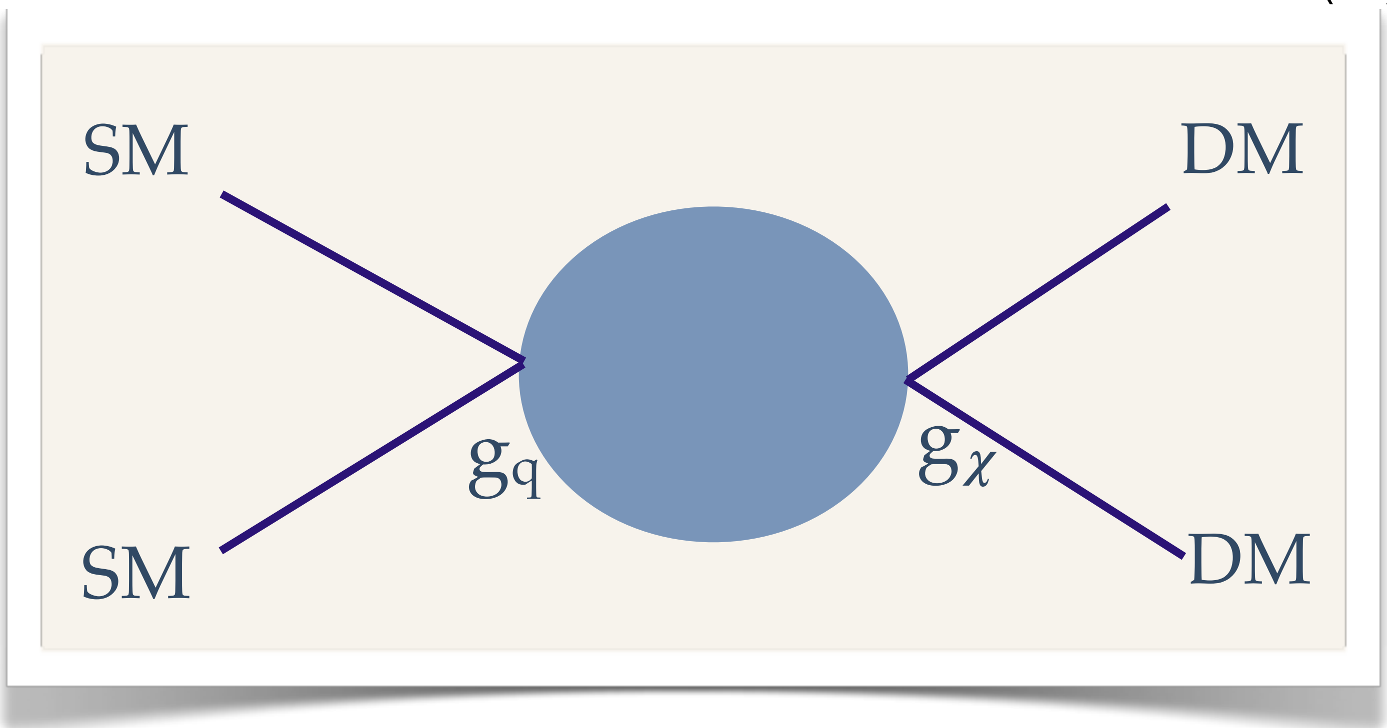
Operators describe nature of mediator and form of SM-DM couplings.

Consider three possibilities:
- (a) vector operator
- (b) axial-vector operator
- (c) scalar operator

Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik, JHEP 1012:048 (2010)

Set mass of mediator (M) to very high value



(a) For vector mediator, effective operator

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\Lambda = M/\sqrt{g_\chi g_q}$$

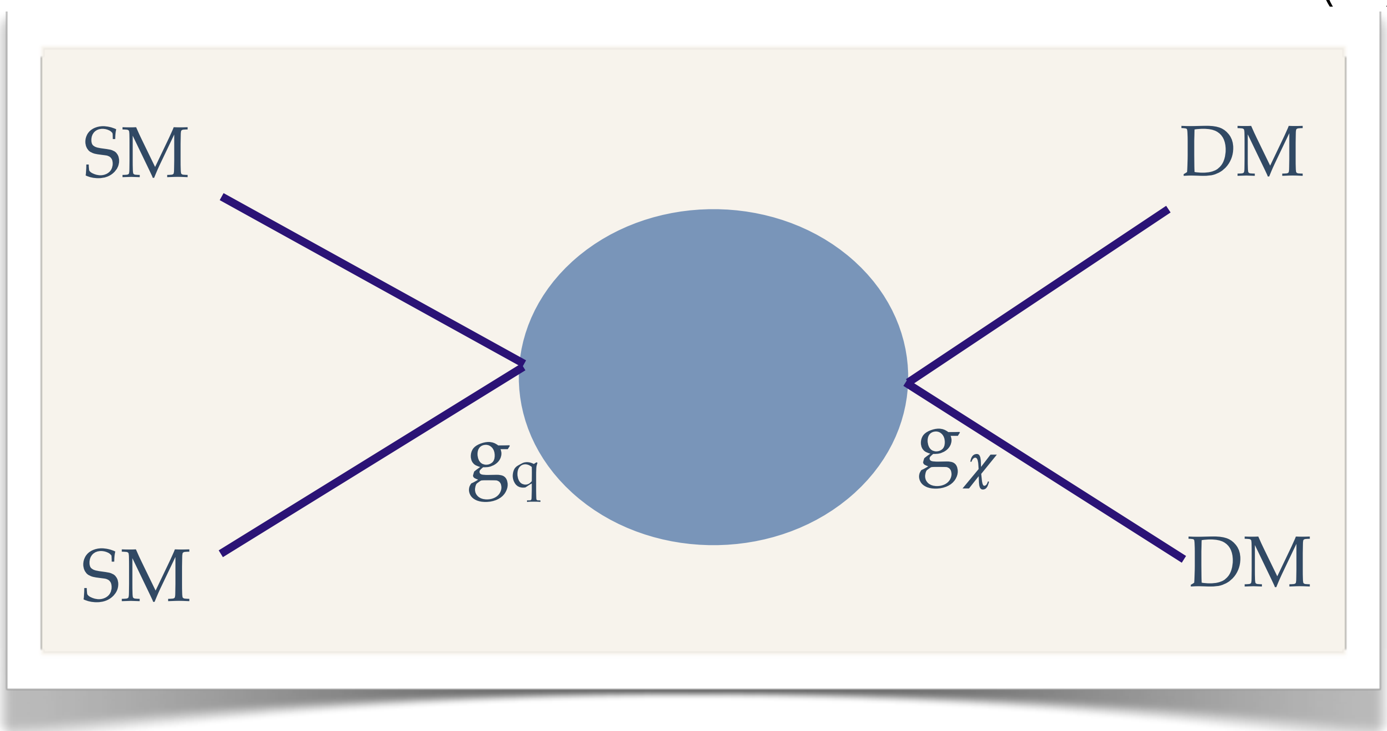
spin-independent

Phenomenology

Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik, JHEP 1012:048 (2010)

Set mass of mediator (M) to very high value



(b) For axial-vector mediator, effective operator

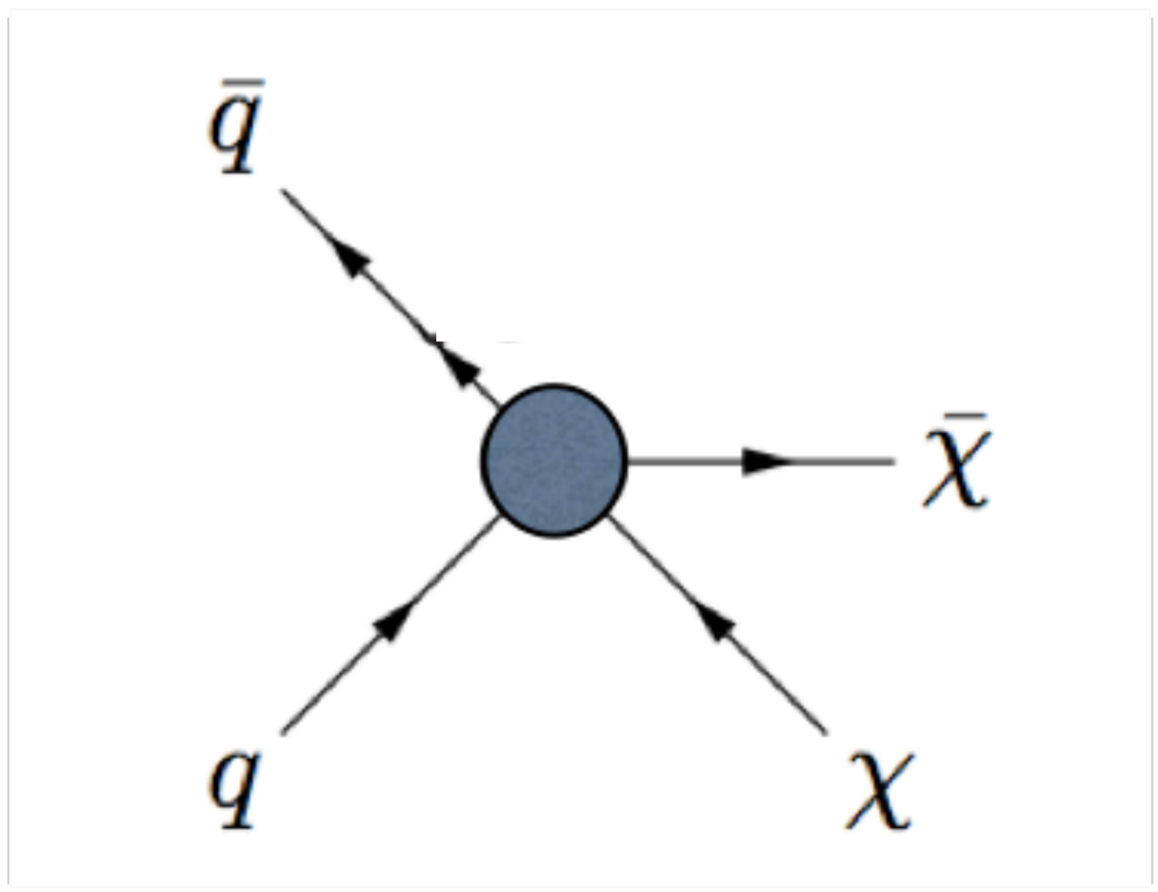
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

$$\Lambda = M/\sqrt{g_\chi g_q}$$

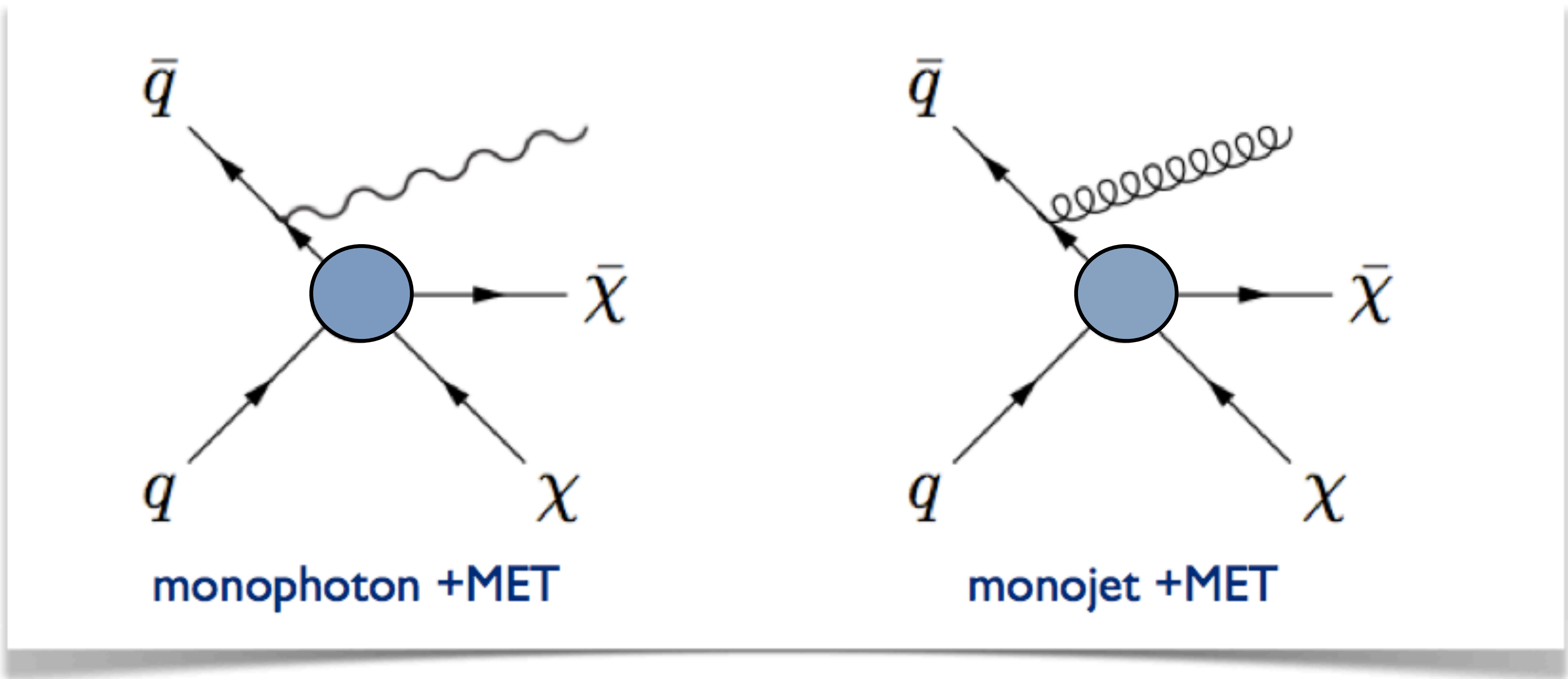
spin-dependent

Dark matter pair production at LHC
- DM particles produce missing energy

This process invisible to colliders!

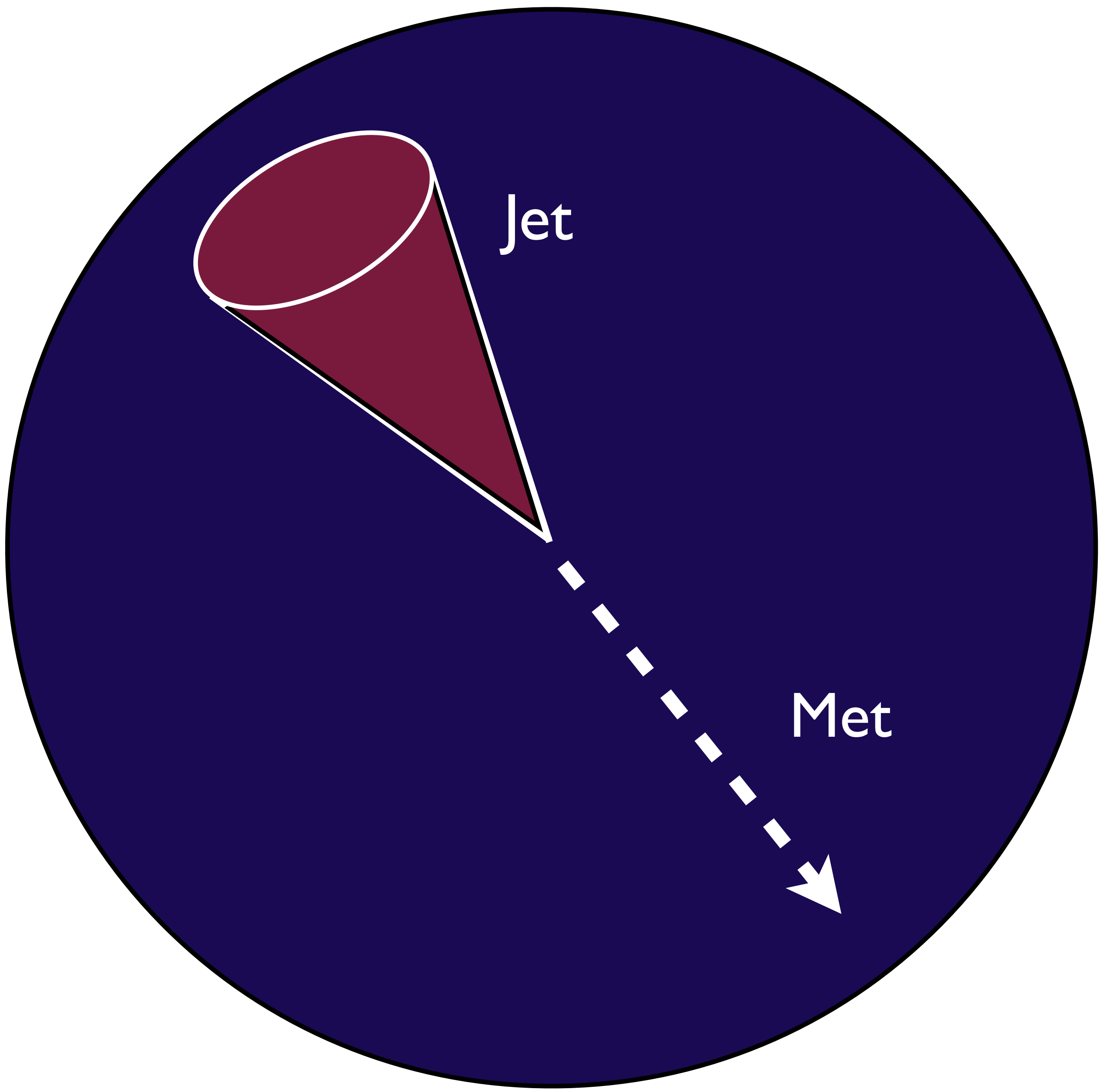


Dark matter pair production at LHC
- DM particles produce missing energy
- radiation of a photon/jet from initial state



Monojet Signature

Simple and striking signature



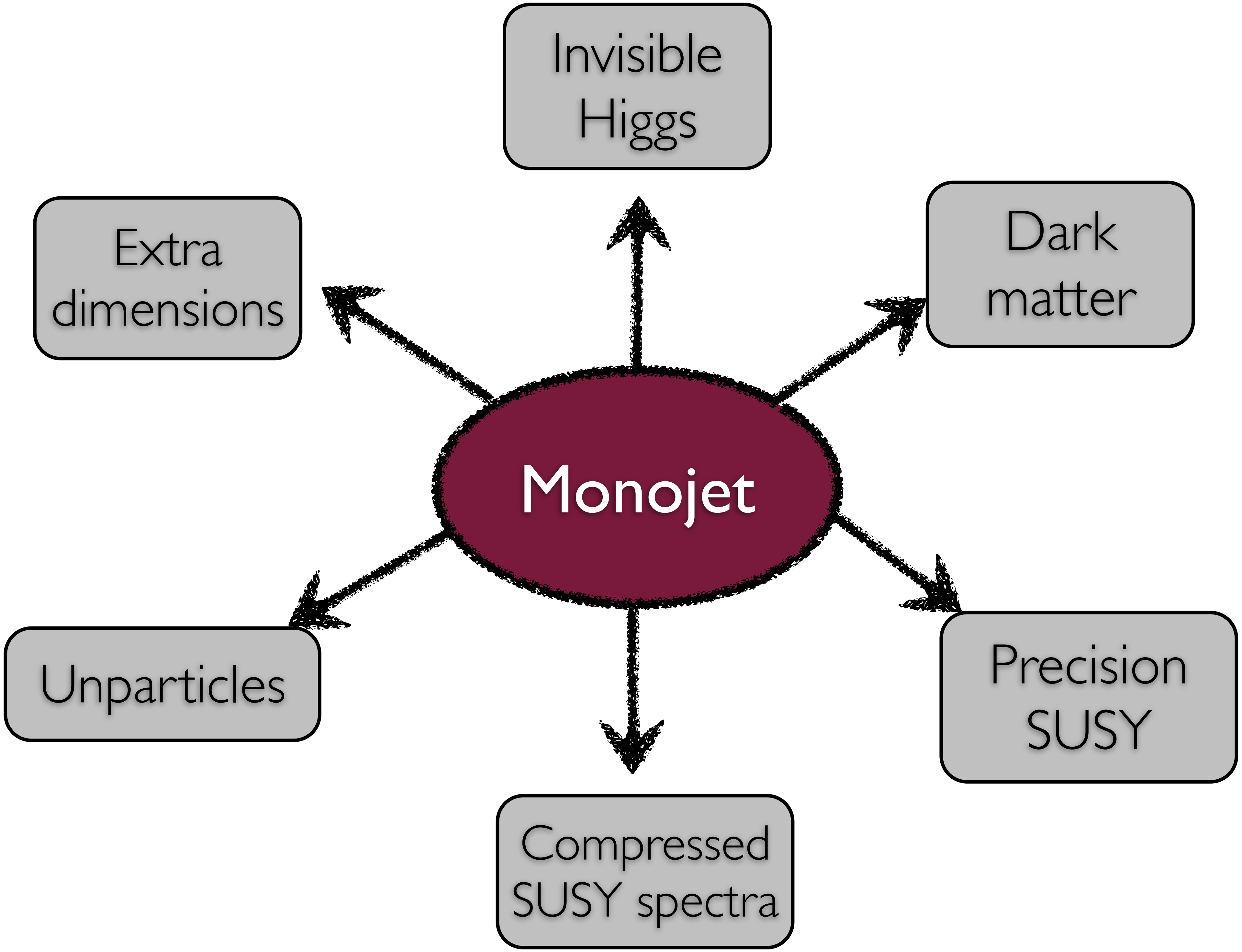
- Simplest collider signature

- visible energy from jet, recoiling against particle(s) that do not interact with detector

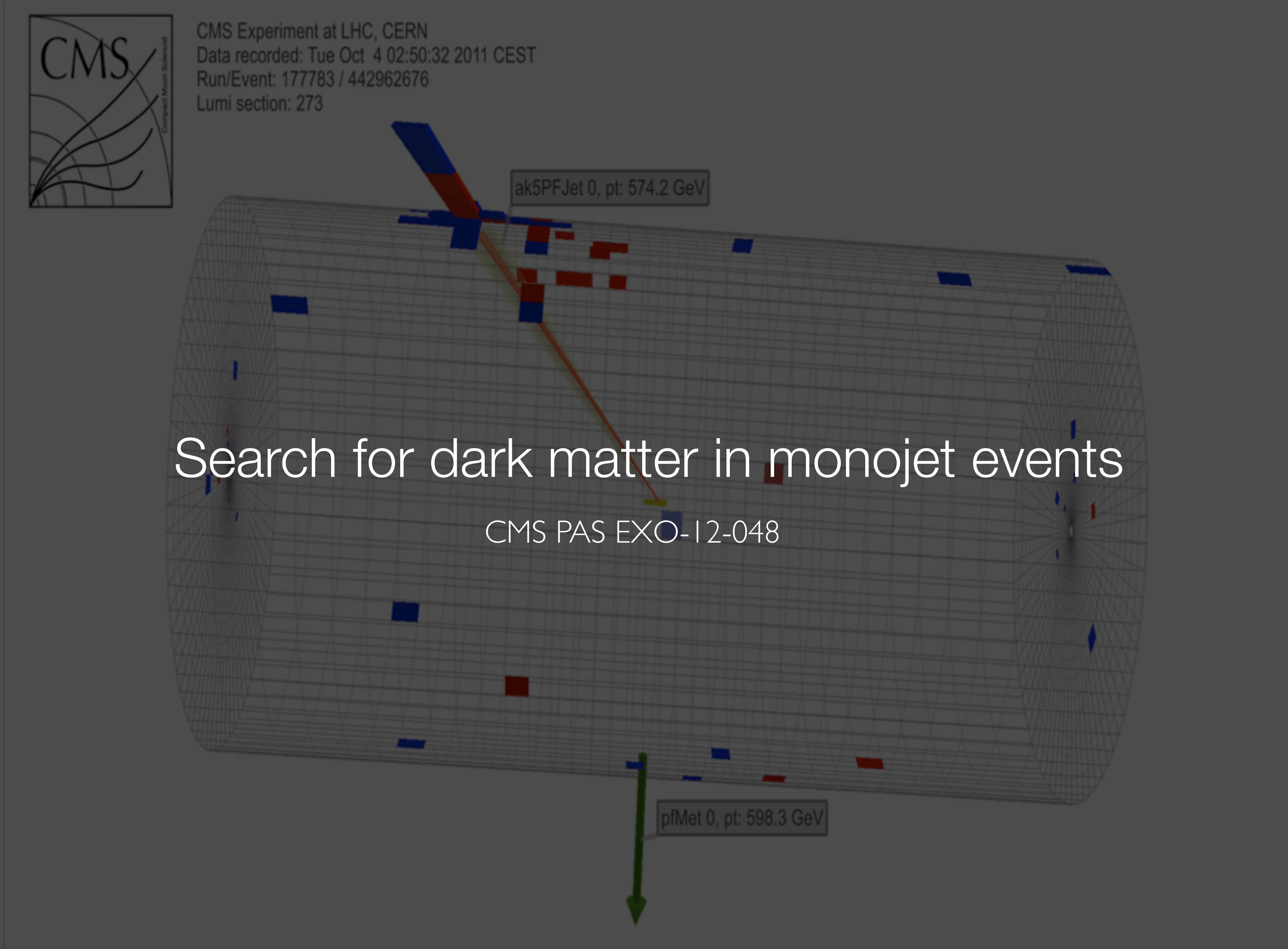
- In principle, generic search for new weakly interacting particle produced in pp collisions

Generic, simple topology → powerful search tool!

Discovery possibilities with Monojets



Wide range of different models predicting monojet signature



Search for dark matter in monojet events

CMS PAS EXO-12-048

Measurement Strategy

- ‘cut and count’ : apply event selection and count number of events in signal region
- look for excess of events above those expected from SM backgrounds
- understanding of backgrounds is crucial

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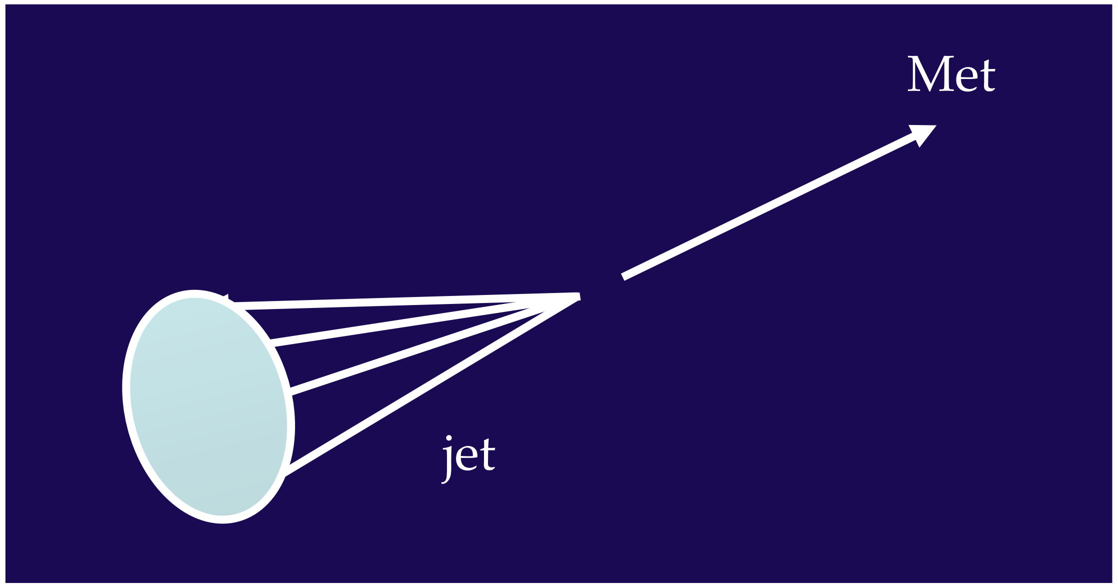
Signal



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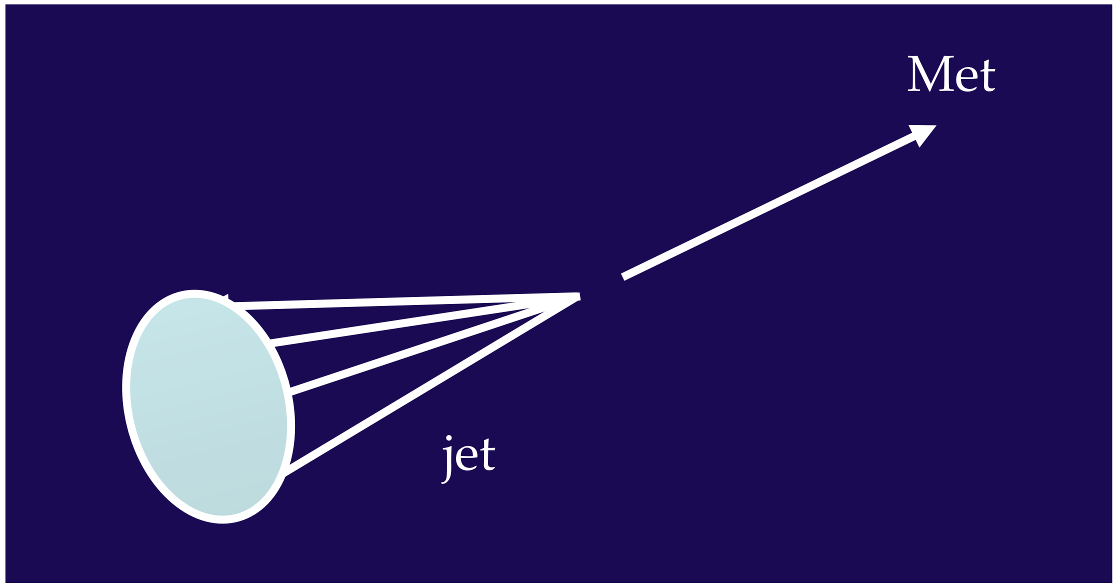
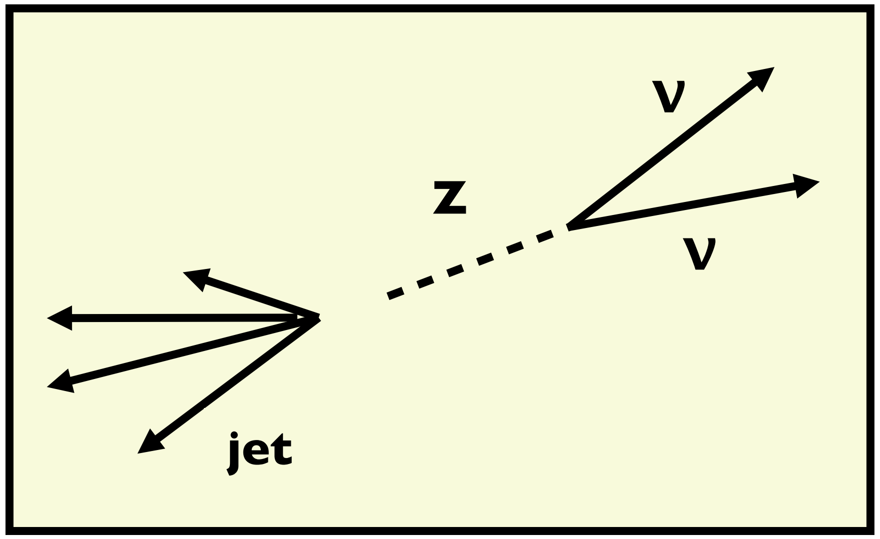


Backgrounds

Z→νν +jet, irreducible background,
looks just like signal



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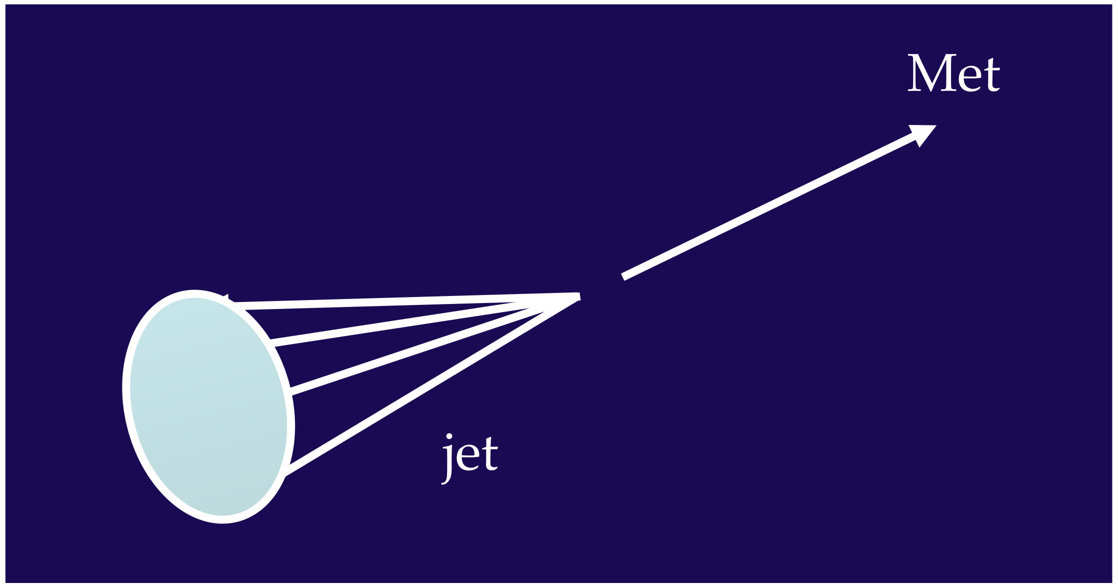
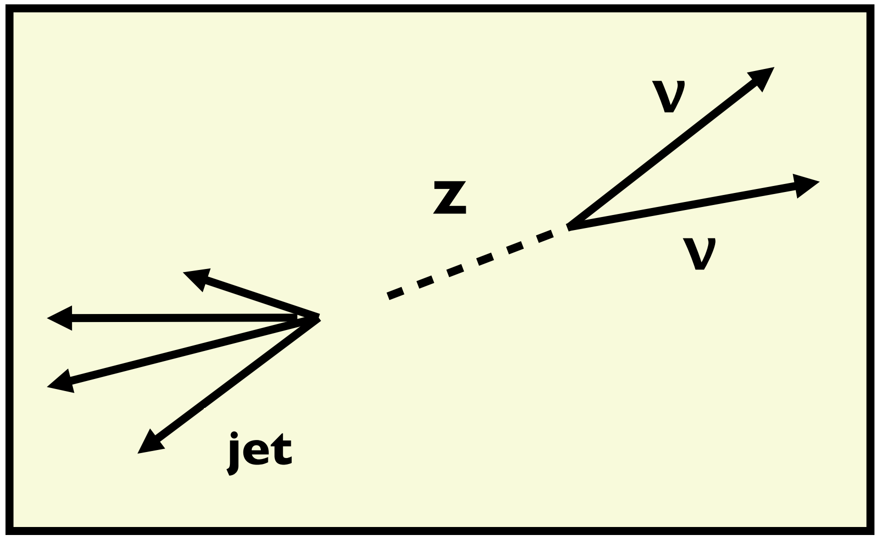
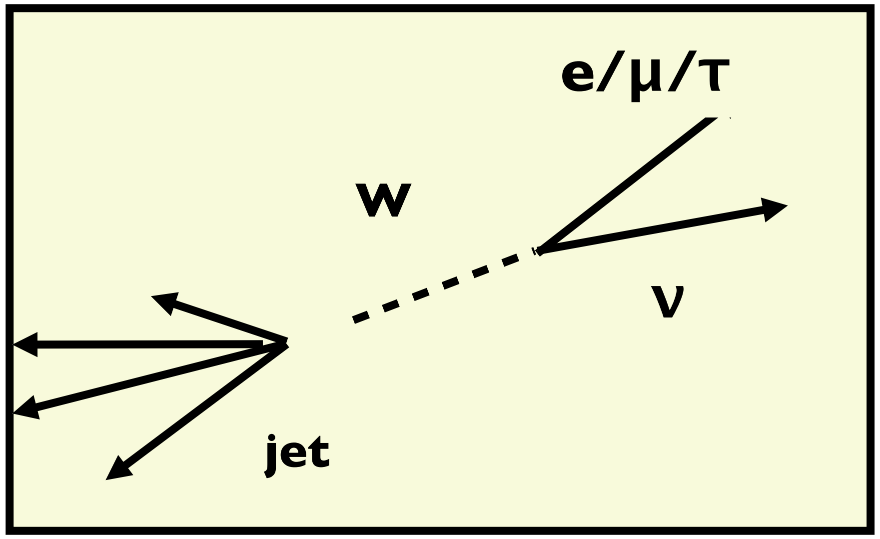


Backgrounds

Z→νν +jet, irreducible background, looks just like signal



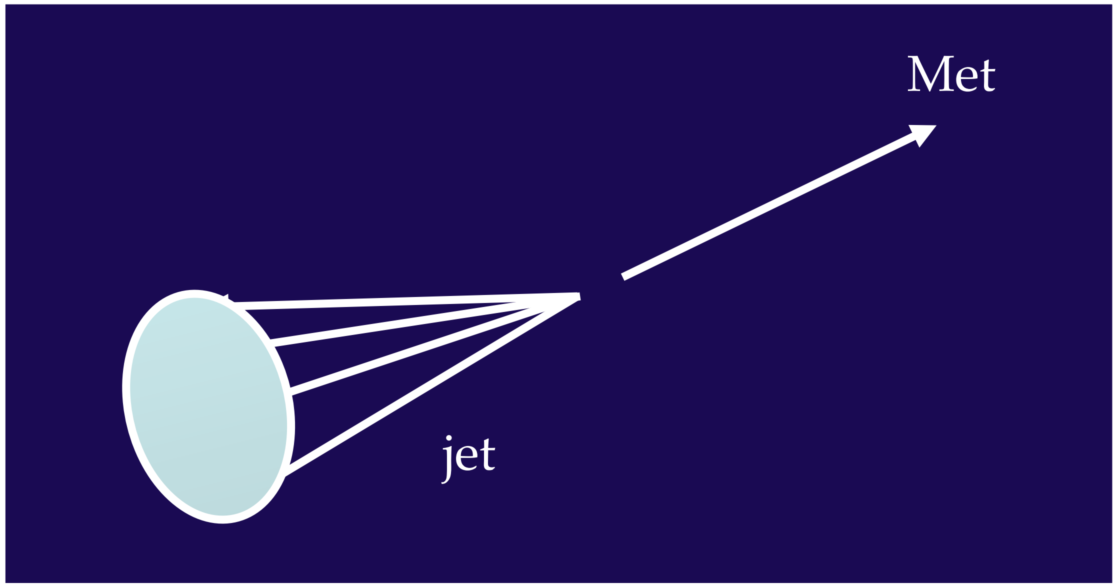
W+jets, e/u is not detected, tau decays hadronically



Measurement Strategy

- ‘cut and count’ : apply event selection and count number of events in signal region
- look for excess of events above those expected from SM backgrounds
- understanding of backgrounds is crucial

Signal

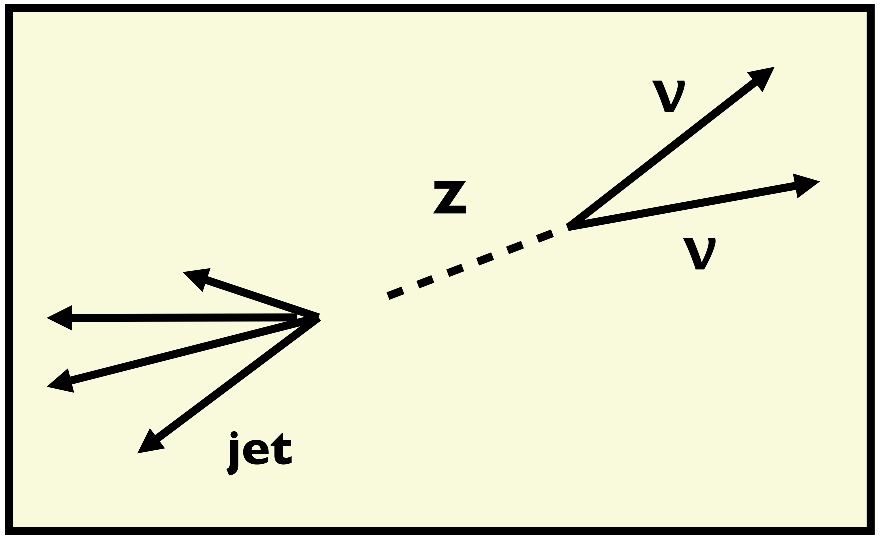


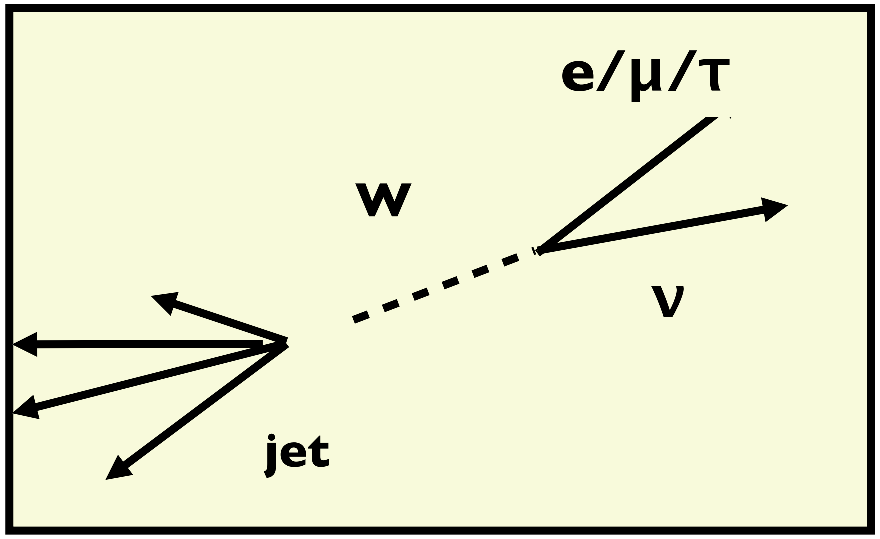
Backgrounds

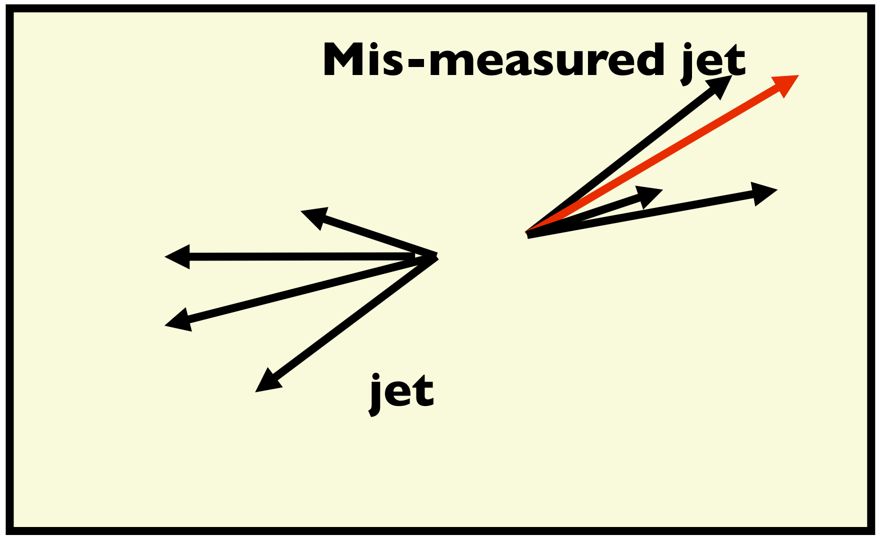
$Z \rightarrow \nu\nu$ +jet, irreducible background, looks just like signal

W+jets, e/u is not detected, tau decays hadronically

QCD, jet is mismeasured, producing Met.







Selecting monojet events

Basic Selection and Event Cleaning

- trigger requires p_T(jet) > 80 and Met > 80 (95) GeV
- cuts based on jet constituents (charged and neutral hadron and electromagnetic energies), removes cosmics, instrumental backgrounds

Select topology

- Large missing energy, Met > 200 GeV
- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4
- Allow one additional jet (if it has p_T > 30 GeV)
- Veto event if it has more than 2 jets

Reject background

- QCD

- $\Delta\varphi(j1,j2) > 2.5$

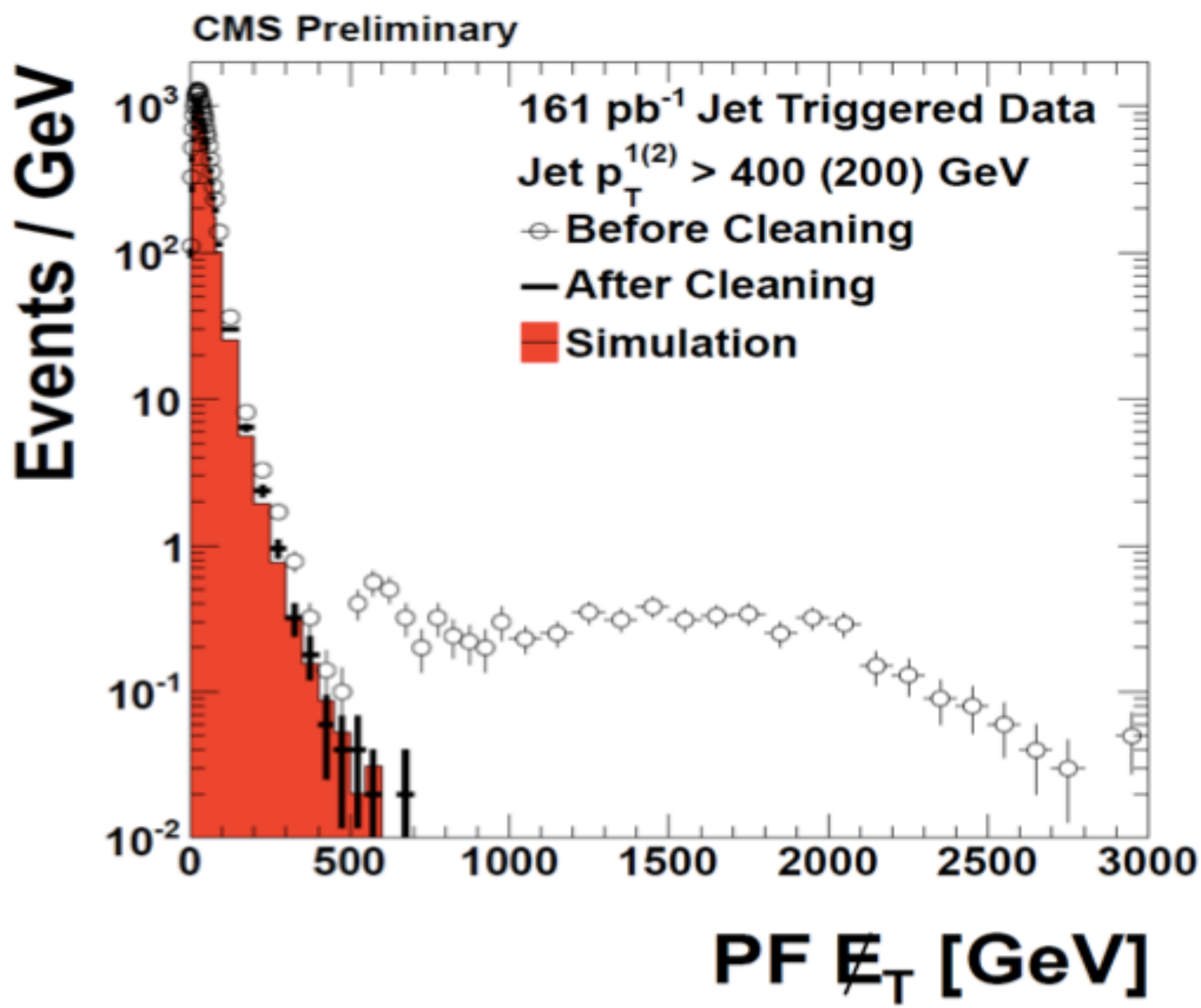
-remove events with back to back jets

- EWK

lepton rejection

-reject events with isolated electrons, muons

-veto events with isolated tracks



-veto events with isolated tracks

Selecting monojet events

Basic Selection and Event Cleaning

- Primary vertex
- cuts based on jet constituents (charged and neutral hadron and electromagnetic energies), removes cosmics, instrumental backgrounds

Select topology

- Large missing energy, Met > 350 GeV
- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4
- Allow one additional jet (if it has p_T > 30 GeV)
- Veto event if it has more than 2 jets

Reject background

- QCD

- $\Delta\varphi(j1,j2) > 2.5$

-remove events with back to back jets

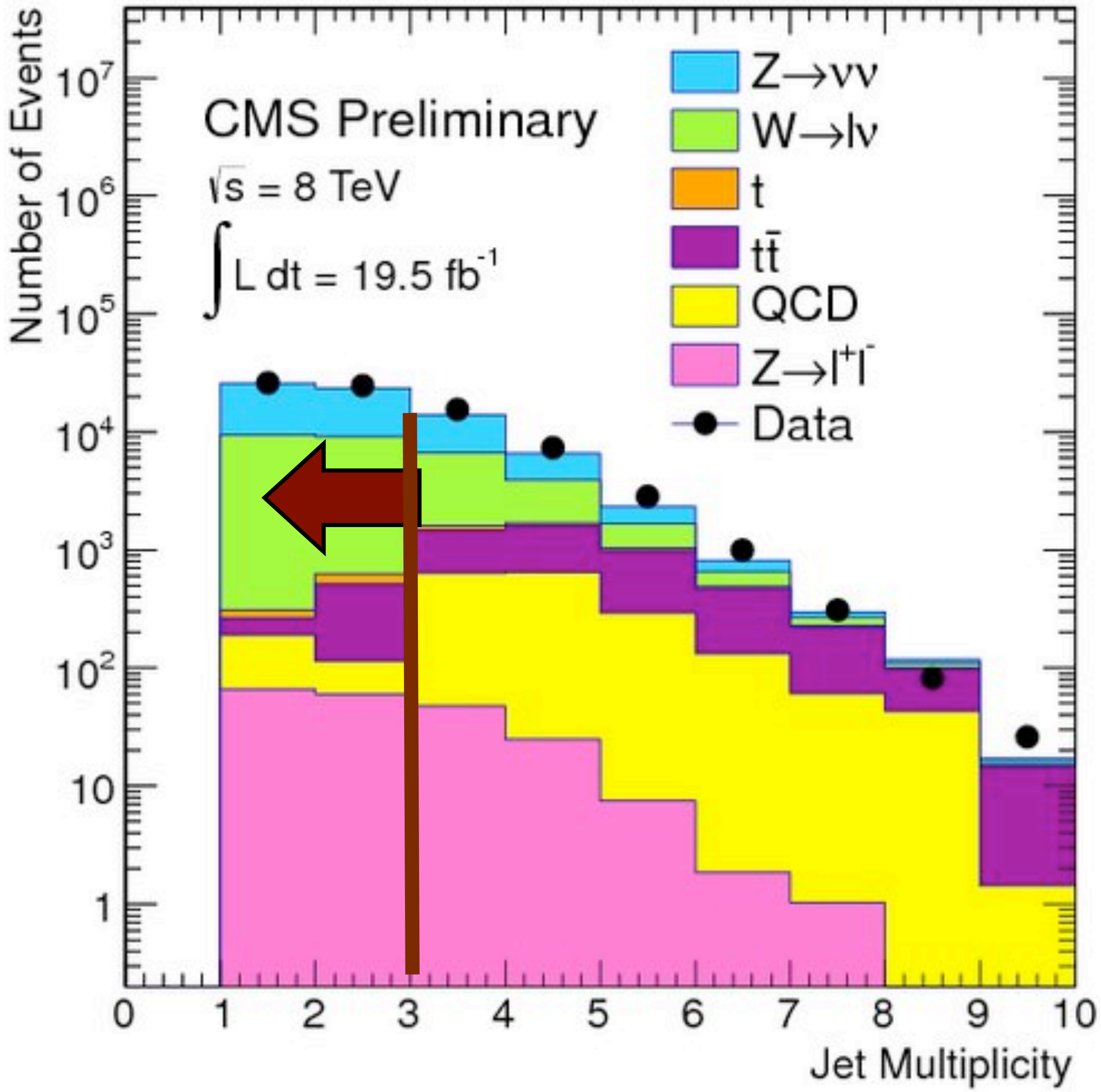
- EWK

lepton rejection

-reject events with isolated electrons, muons

-veto events with isolated tracks

Selecting monojet events



Selecting monojet events

Basic Selection and Event Cleaning

- Primary vertex
- cuts based on jet constituents (charged and neutral hadron and electromagnetic energies), removes cosmics, instrumental backgrounds

Select topology

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- Veto event if it has more than 2 jets

Reject background

- EWK

lepton rejection

-reject events with isolated electrons, muons

-veto events with hadronic taus

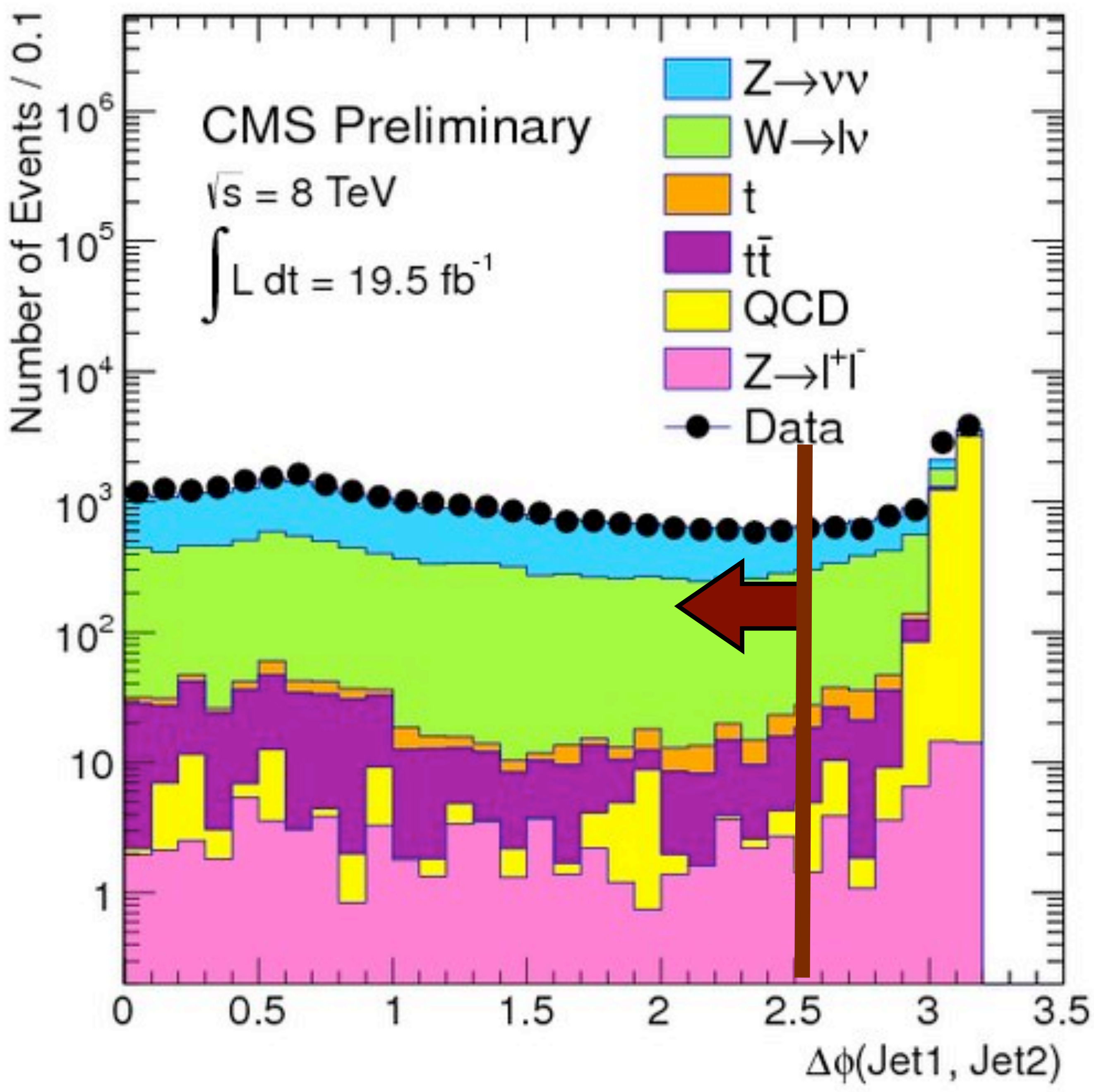
- QCD

- $\Delta\varphi(j1,j2) > 2.5$

-remove events with back to back jets

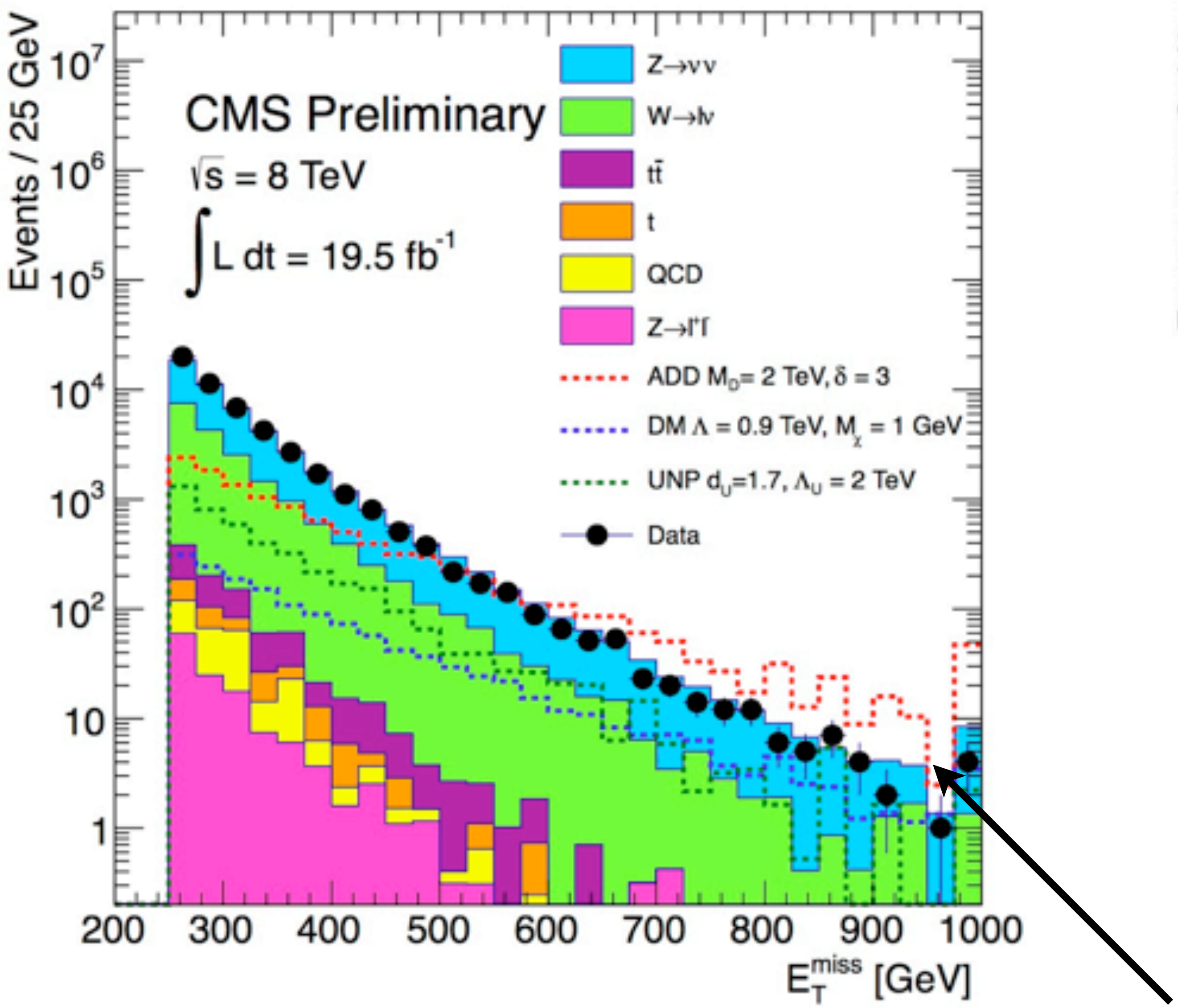
Selecting monojet events

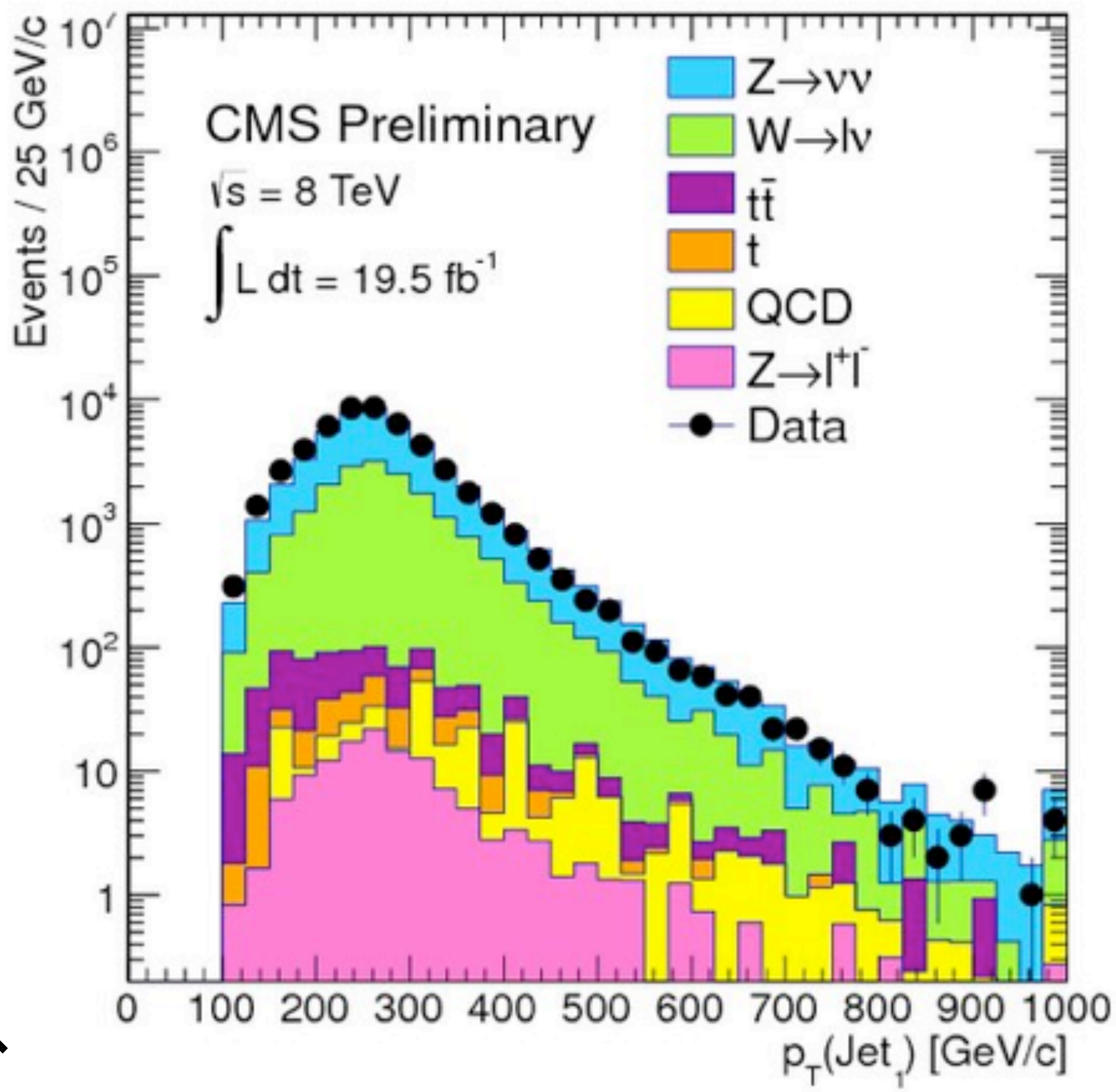
Basic Selection and Event Cleaning



-veto events with isolated tracks

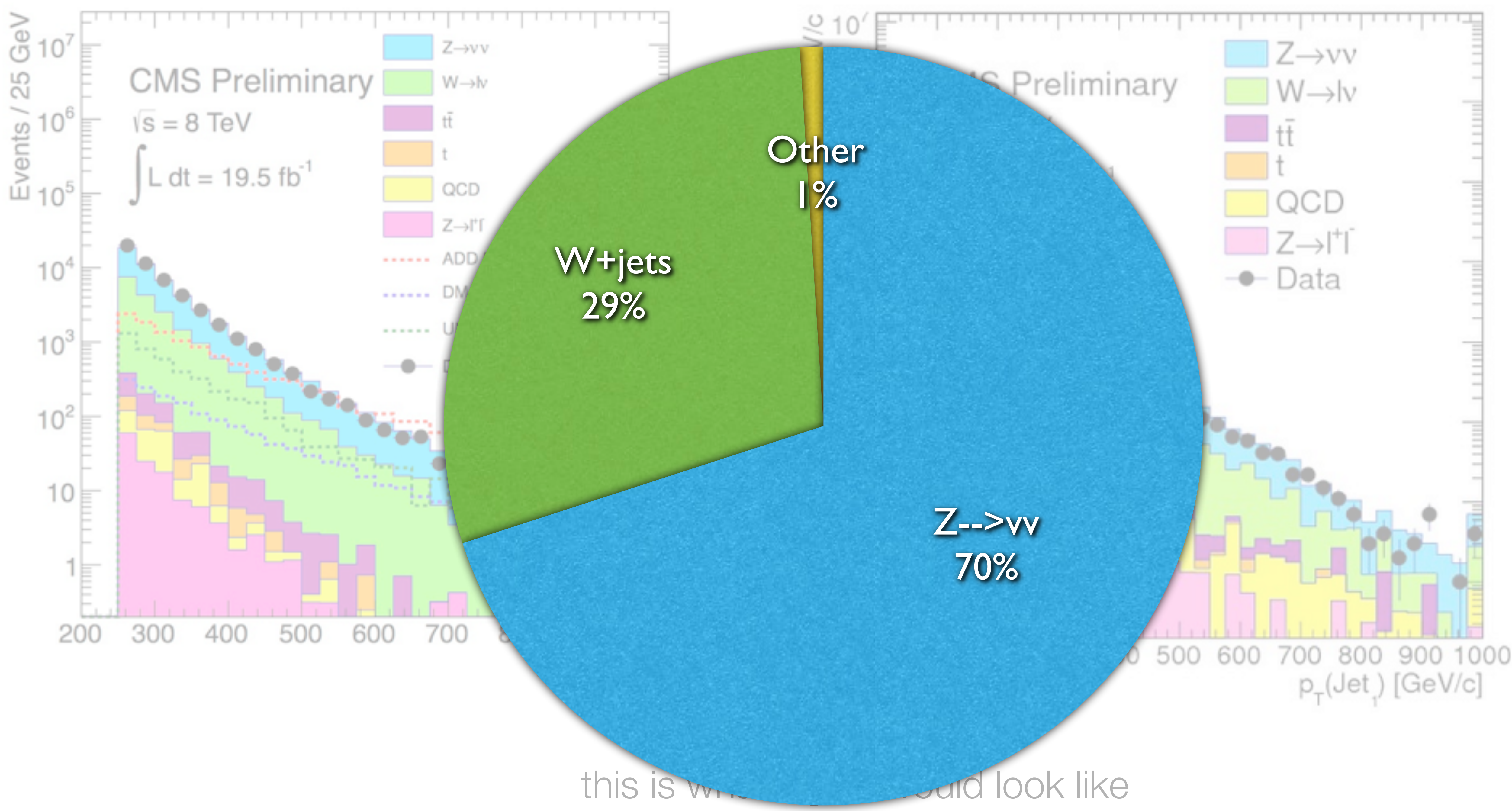
Selecting monojet events





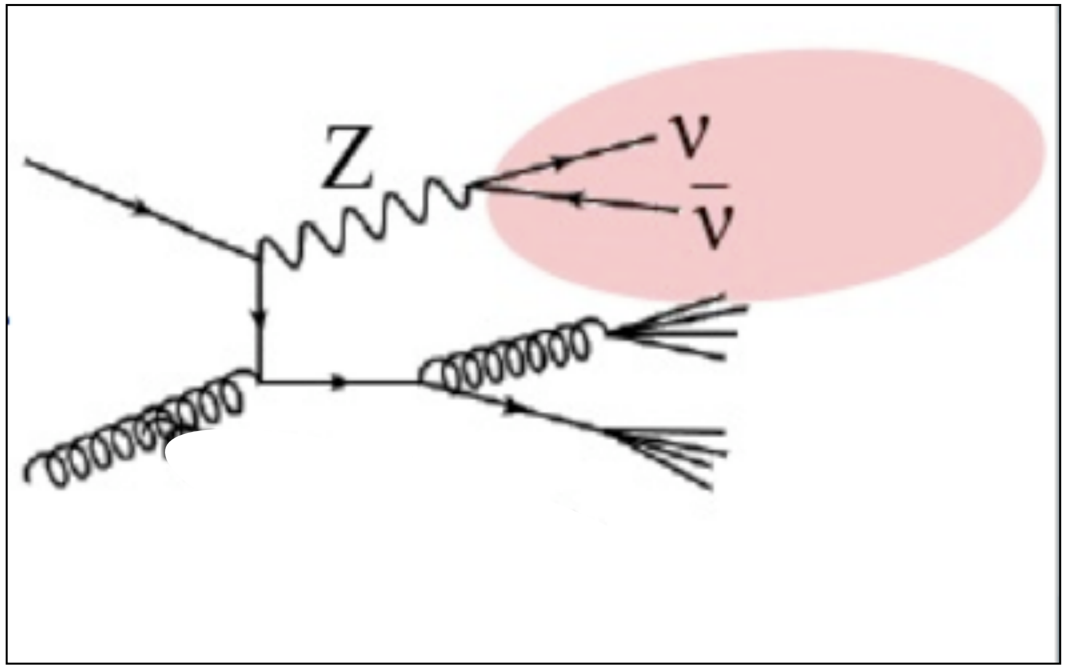
this is what signal would look like

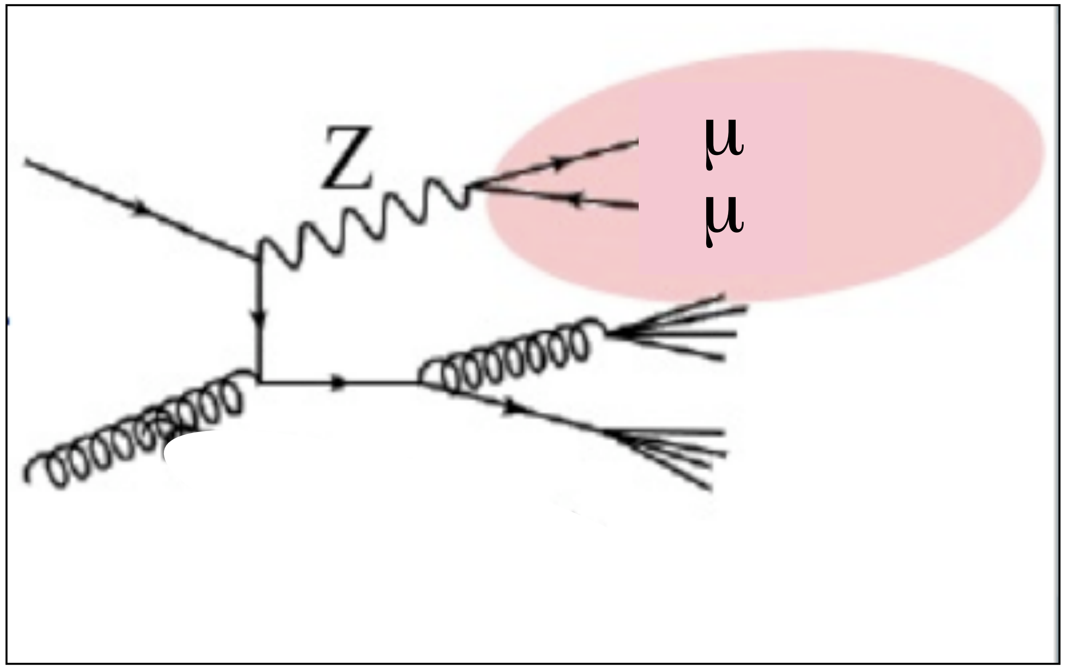
Selecting monojet events



Dominant backgrounds from Z-->νν and W+jets are estimated from data

Z→νν from Z→μμ





number of observed Z-->uu events

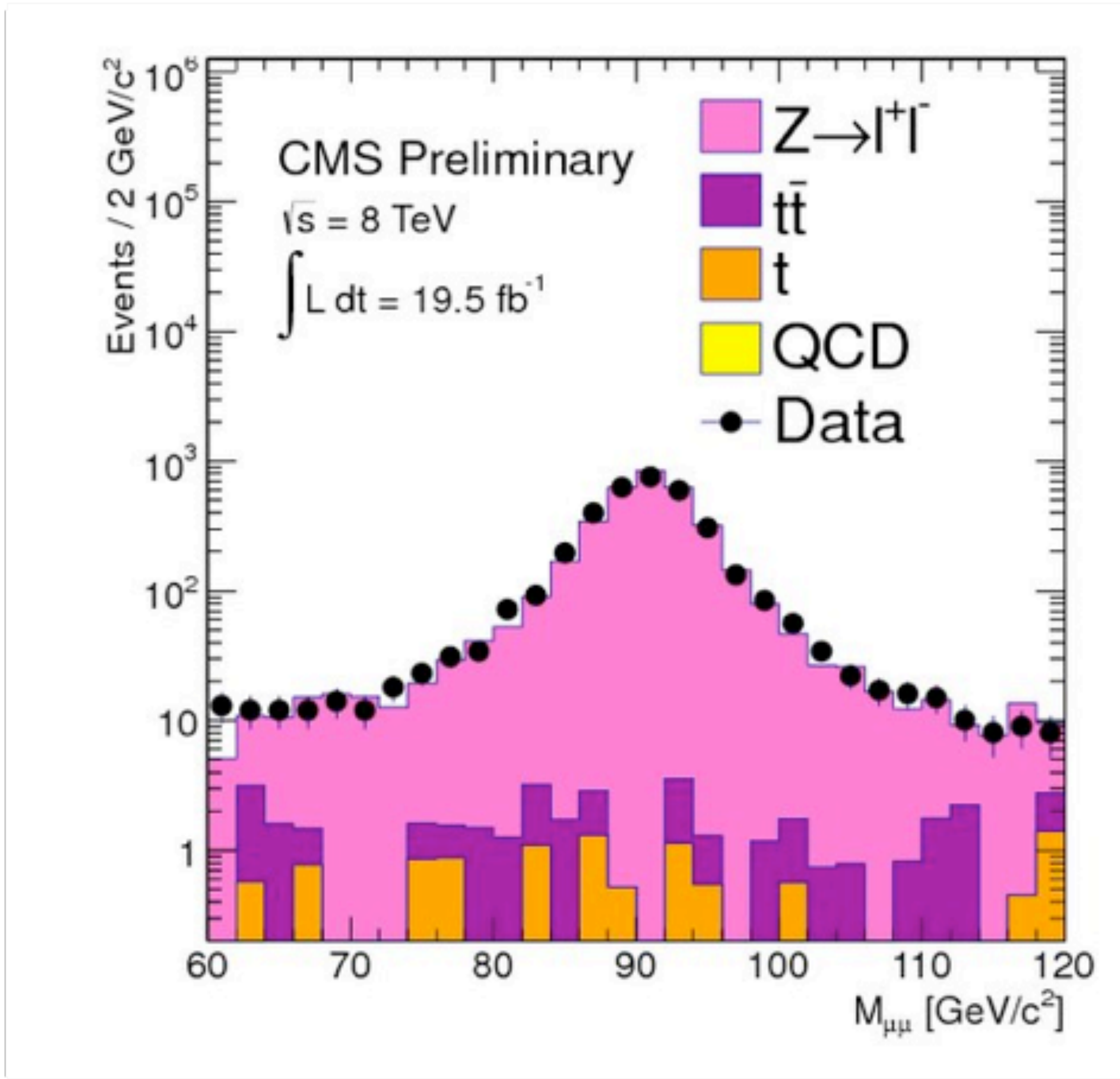
expected background events in Z-->uu sample

$$N(Z \rightarrow \nu\nu) = \frac{N_Z^{obs} - N_Z^{bgd}}{A_Z \bullet \varepsilon_Z} \bullet R\left(\frac{Z \rightarrow \nu\nu}{Z \rightarrow ll}\right)$$

detector acceptance (A_Z) and selection efficiency (ε_Z)

ratio of branching fractions

Select two isolated muons, opposite sign charge, with invariant mass 60-120 GeV



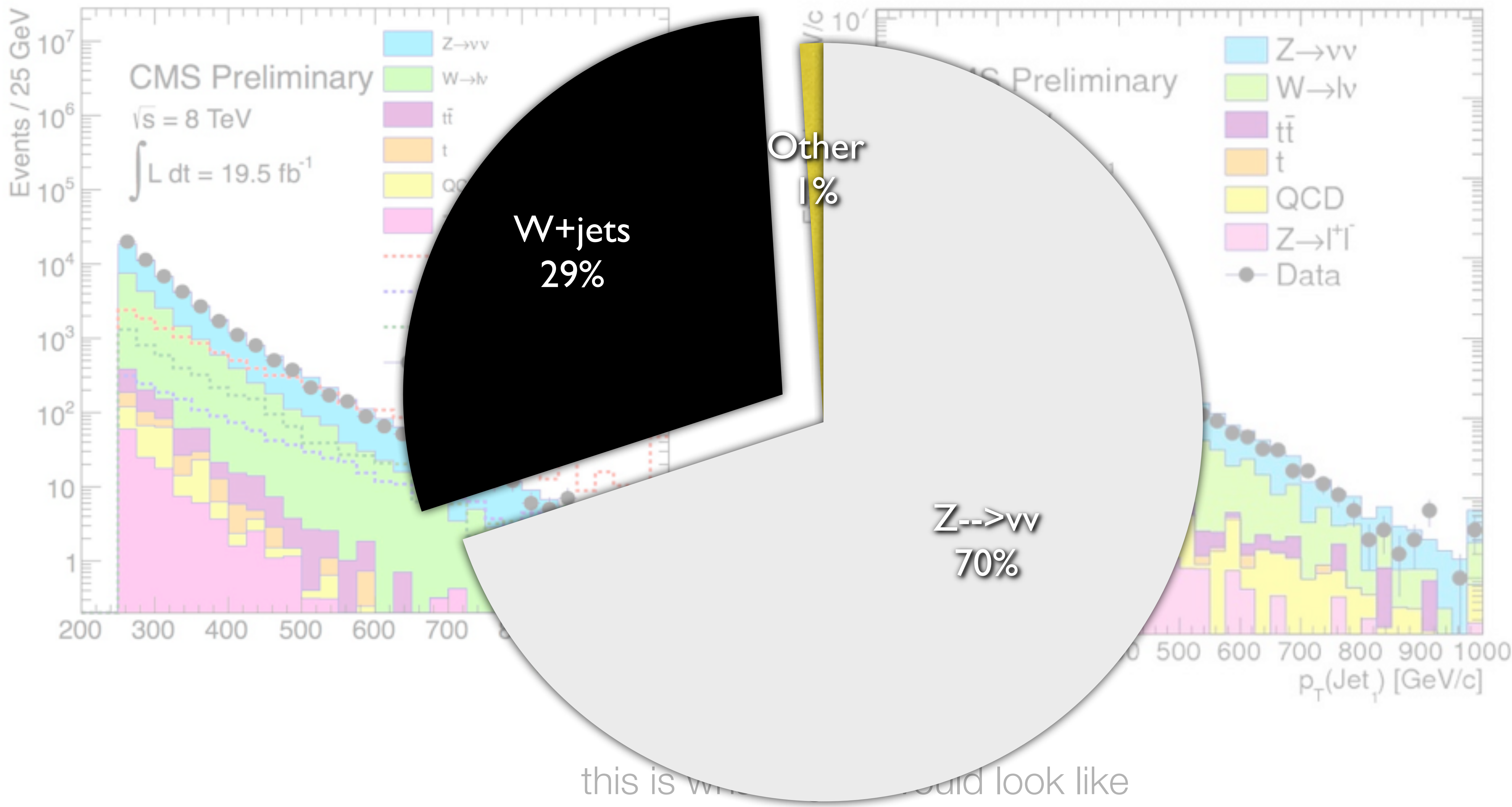
~340 events observed for Met cut of 400 GeV, negligible background

Data-driven background estimation

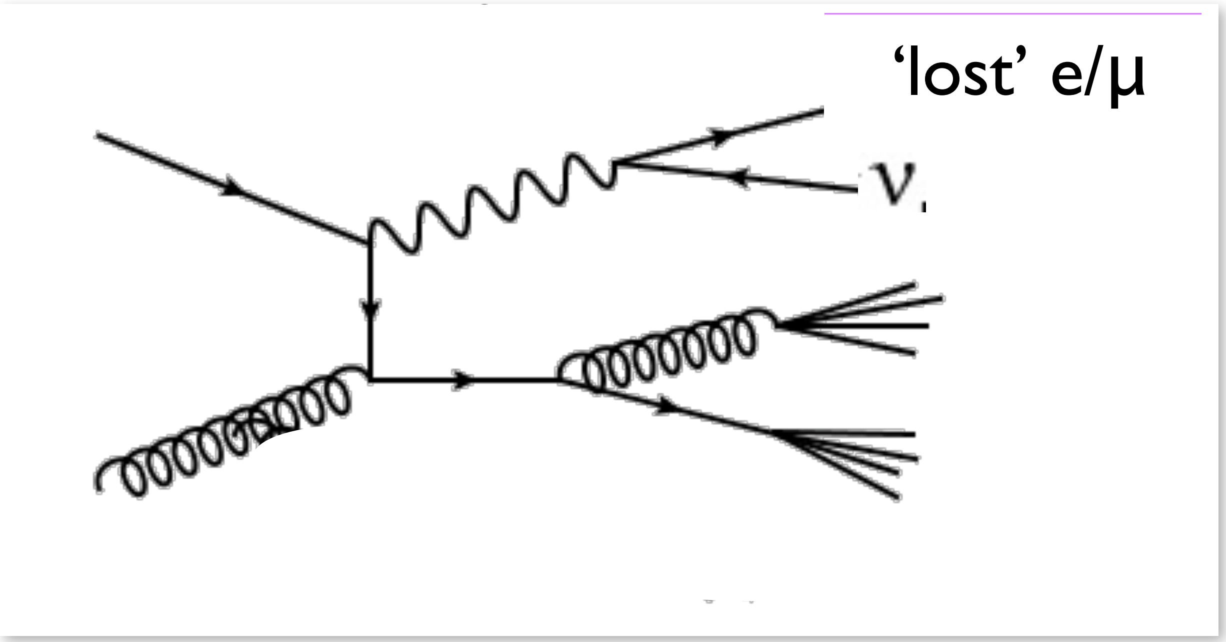
Predict Z-->vv background of 2569 +/- 188
(error dominated by statistical uncertainty, due to size of Z-->uu control sample)

E_T^{miss} cut (GeV)	400
Statistics (N_{obs})	5.6
Background (N_{bgd})	0.2
Acceptance (A)	2.1
Selection efficiency (ϵ)	2.2
Total	7.1

Selecting monojet events



W+jets background

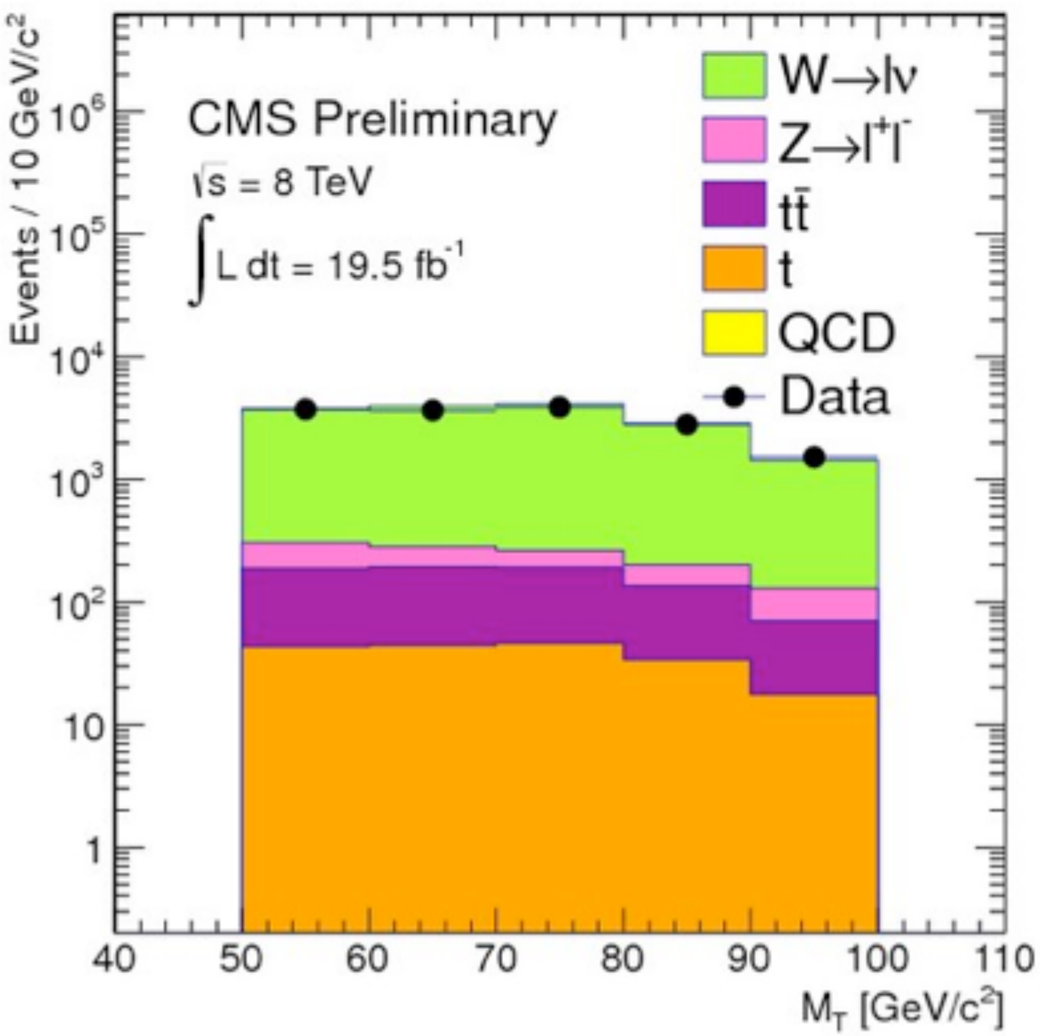


- lepton from W decay is ‘lost’ because
- its not within detector acceptance
- not reconstructed
- not isolated

Data-driven background estimation

W+jets from W→μν

- use muon+jets control sample, require $50 < M_T < 100$
- measure the efficiencies of the lepton acceptance and selection requirements
- correct for inefficiencies to estimate remaining W+jets background



$$N_{tot}^{\mu} = \frac{N_{obs} - N_{bgd}}{A'\epsilon'}$$

$$N_{lost\mu} = N_{tot}^{\mu} * (1 - A_{\mu}\epsilon_{\mu}).$$

- ~ 1400 W-->uv+jets events in data control sample
- Estimated W+jets background : 1044 ± 51

E_T^{miss} cut (GeV)	400
Statistics (N_{obs})	2.9
Background (N_{bgd})	2.1
Acceptance and efficiency	2.4
PDFs	2.0
Total	4.9

Results

Z(νν)+jets	2569 ± 188
W+jets	1044 ± 51
tt	32 ± 16
Z(ll)+jets	8 ± 4
Single top	7 ± 3.5
QCD multijets	3 ± 1.5
Total Background	3663 ± 196
Observed in data	3677

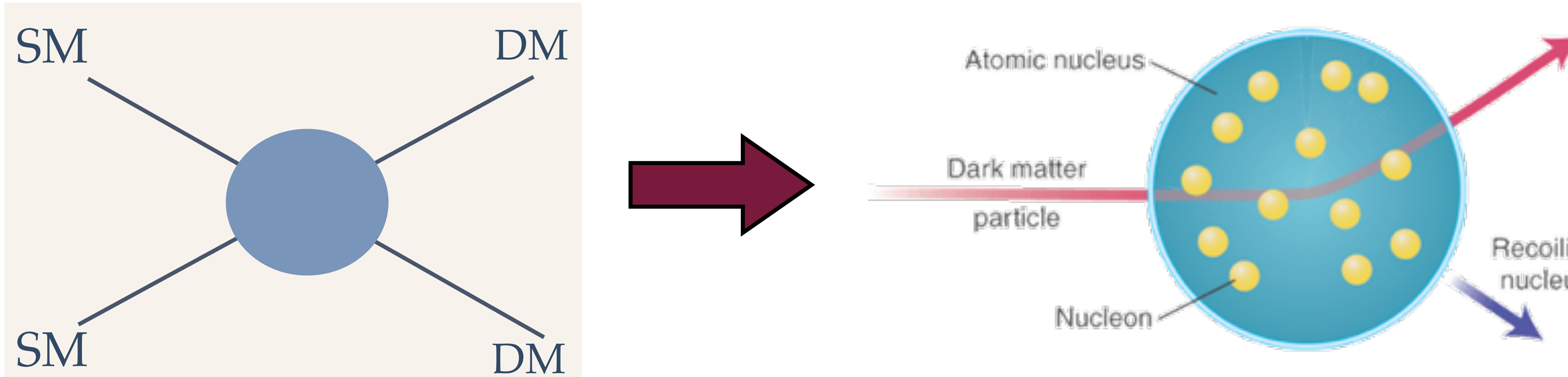
No excess of events over expected SM backgrounds

Setting limits on DM-nucleon cross section

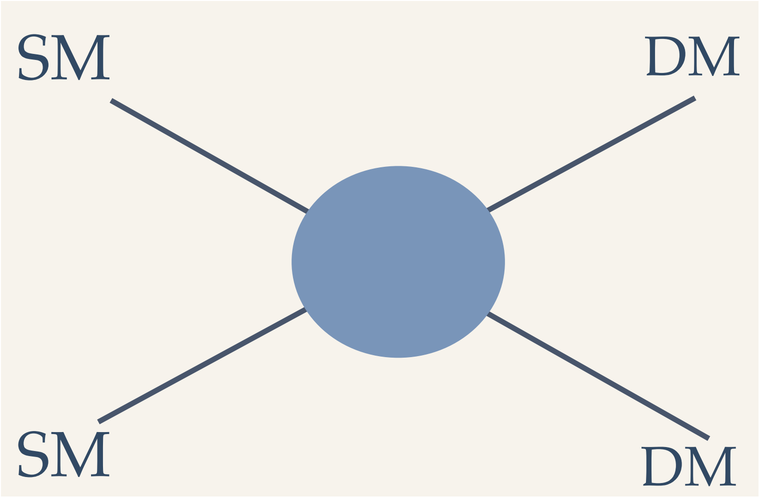
Translate collider limits to the same plane as direct detection experiments

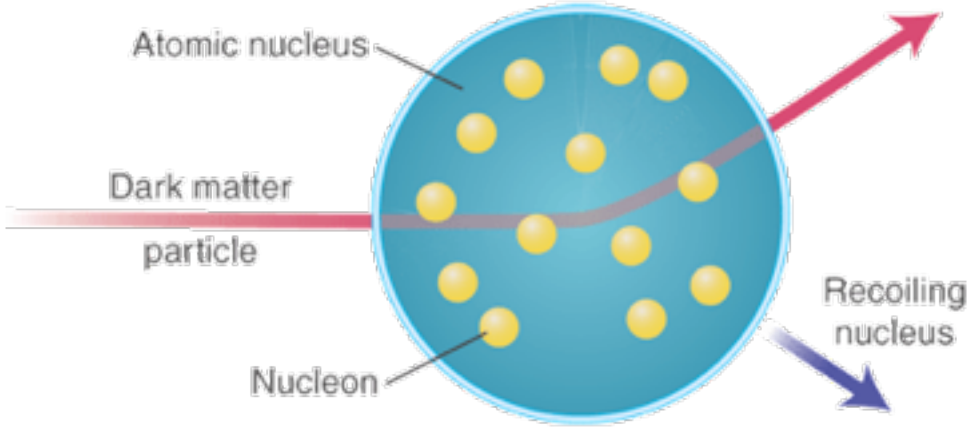
Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments



Translate collider limits to the same plane as direct detection experiments





For vector operator

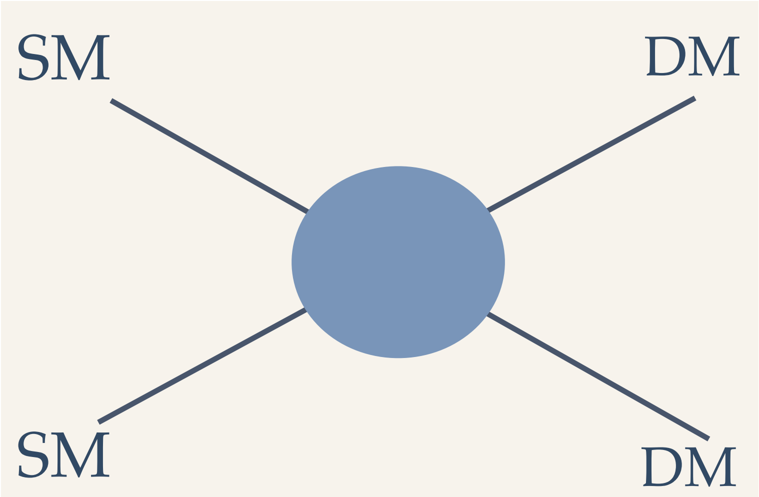
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

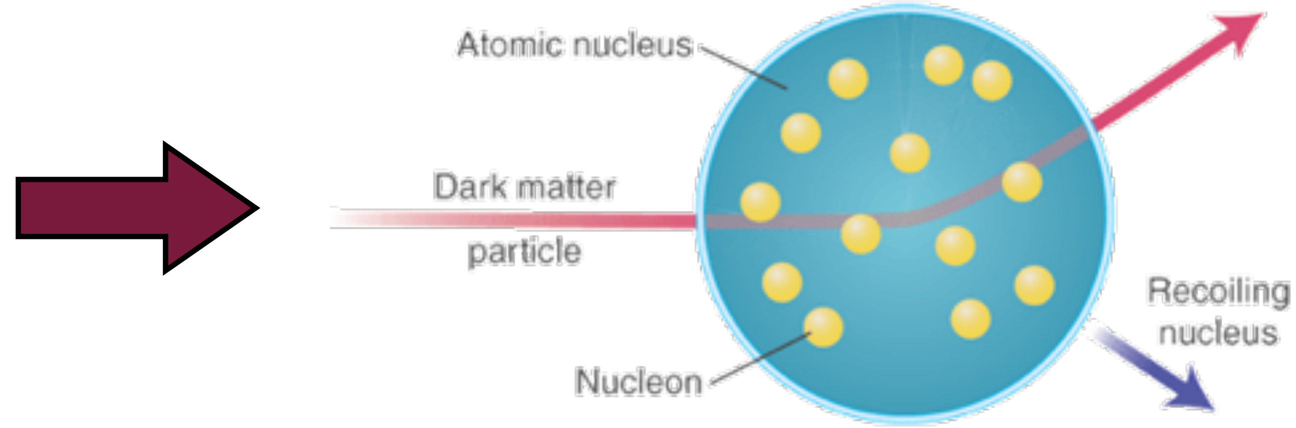
$$\mathcal{O}^N = f_q^N \frac{(\bar{N}\gamma^\mu N)\,(\bar{\chi}\gamma_\mu\chi)}{\Lambda^2}$$

coefficient relates nucleon and quark operator

Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





For vector operator

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}^N = f_q^N \frac{(\bar{N}\gamma^\mu N)\,(\bar{\chi}\gamma_\mu\chi)}{\Lambda^2}$$

coefficient relates nucleon and quark operator

need to know quark content of nucleon

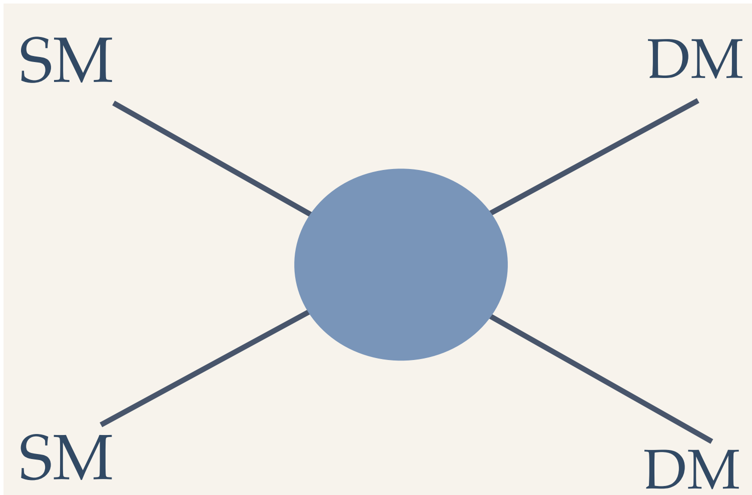
$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4} f_q^{N2}$$

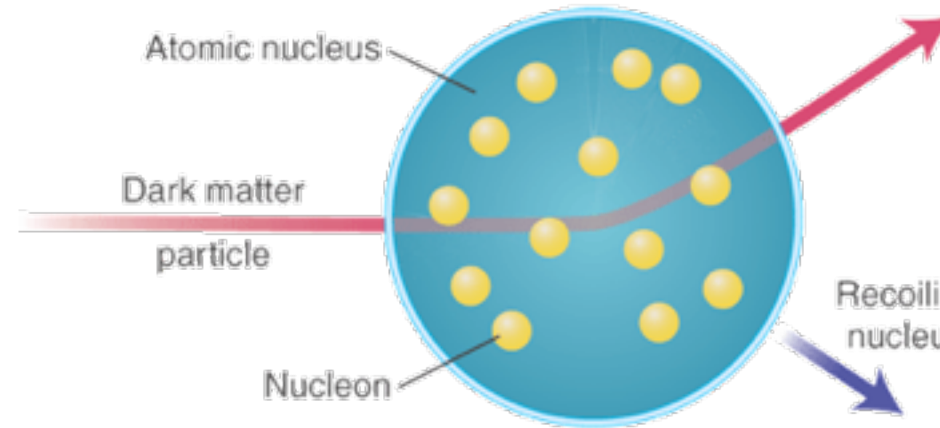
$$\text{where } \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

reduced mass of the DM-nucleon system

Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





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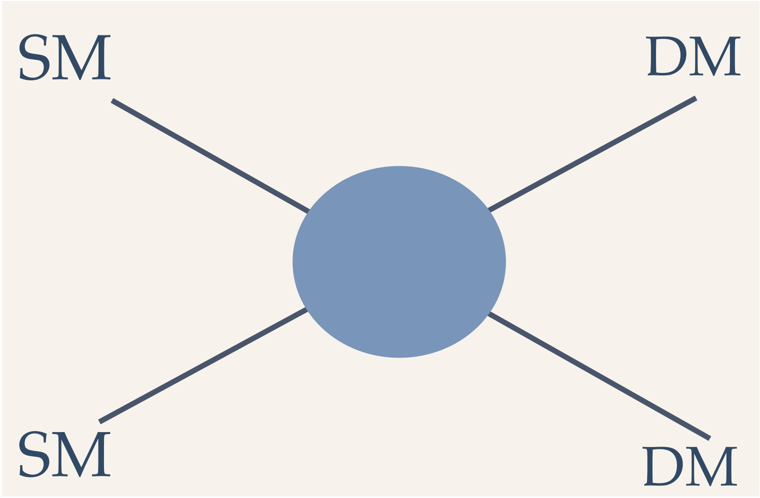
coefficient relates nucleon and quark operator

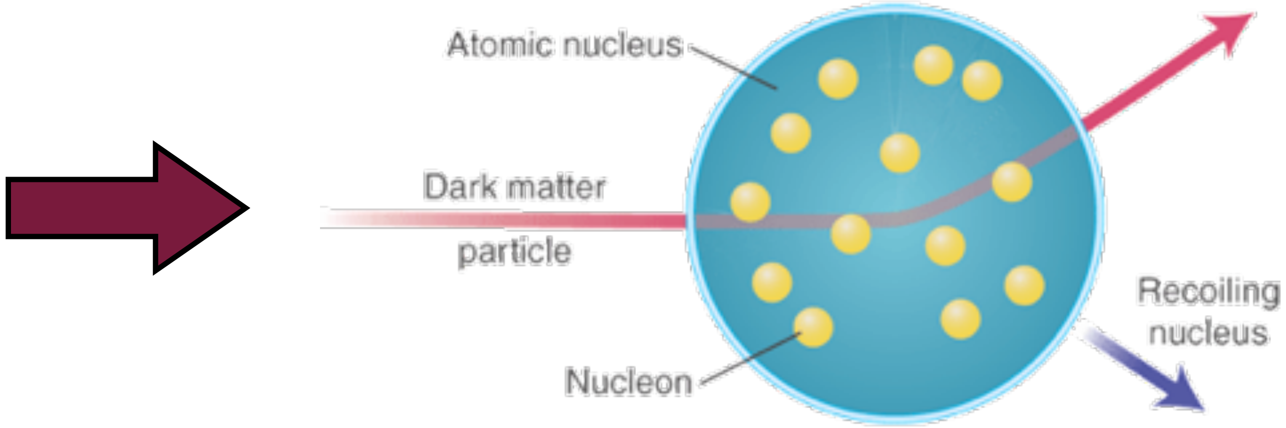
$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4} f_q^{N2}$$

- Upper limits on monojet cross sections converted to lower limits on Λ
- Lower limits on Λ then translated to spin-independent DM-nucleon cross-section

Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





For axial-vector operator

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

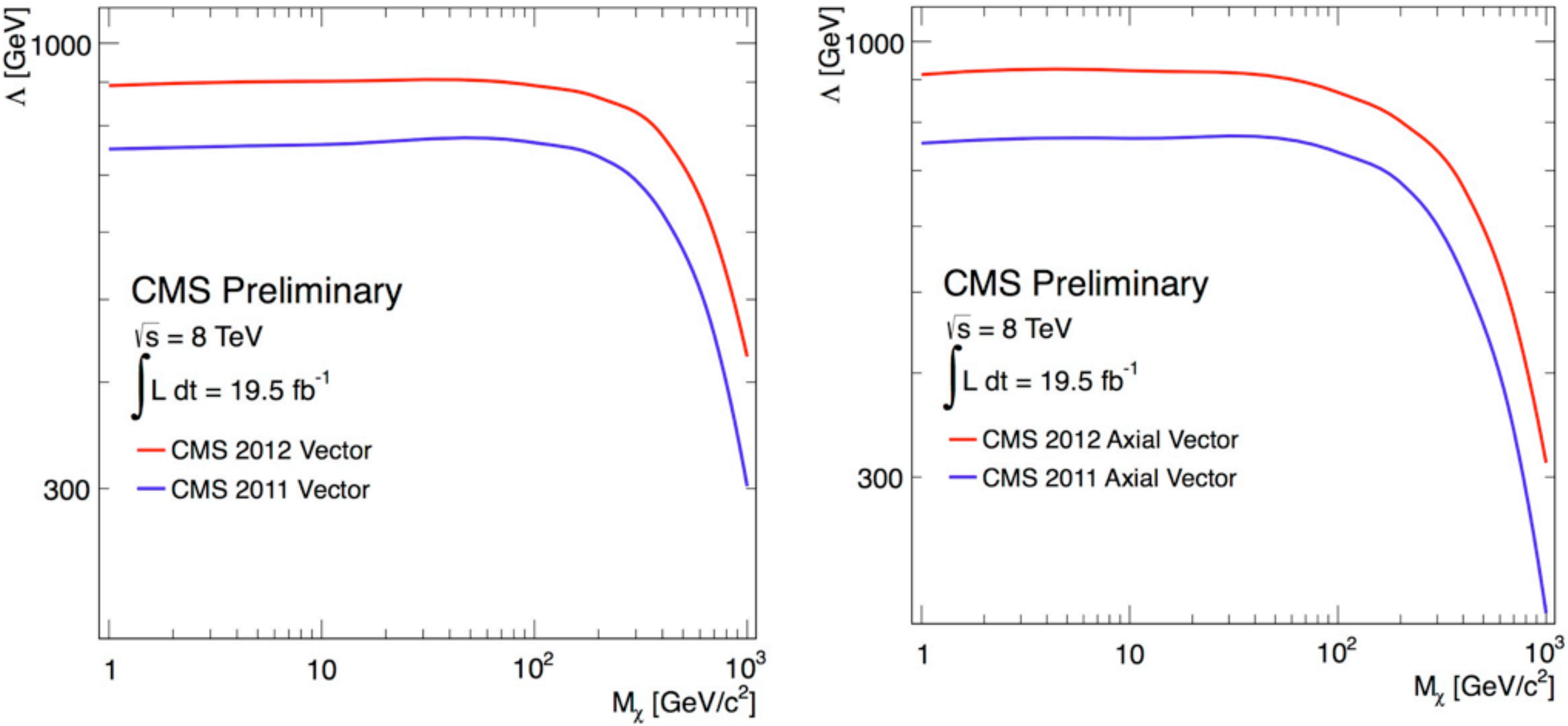
$$\mathcal{O}^{Nq} = \Delta_q^N \frac{(N\gamma^\mu\gamma_5 N)\,(\bar{\chi}\gamma_\mu\gamma_5\chi)}{\Lambda^2}$$

sum of quark helicities

$$\sigma^{Nq} = \frac{3\,\mu^2}{\pi\,\Lambda^4}\,(\Delta_q^N)^2\,.$$

- Upper limits on monojet cross sections converted to lower limits on Λ
- Lower limits on Λ then translated to spin-dependent DM-nucleon cross-section

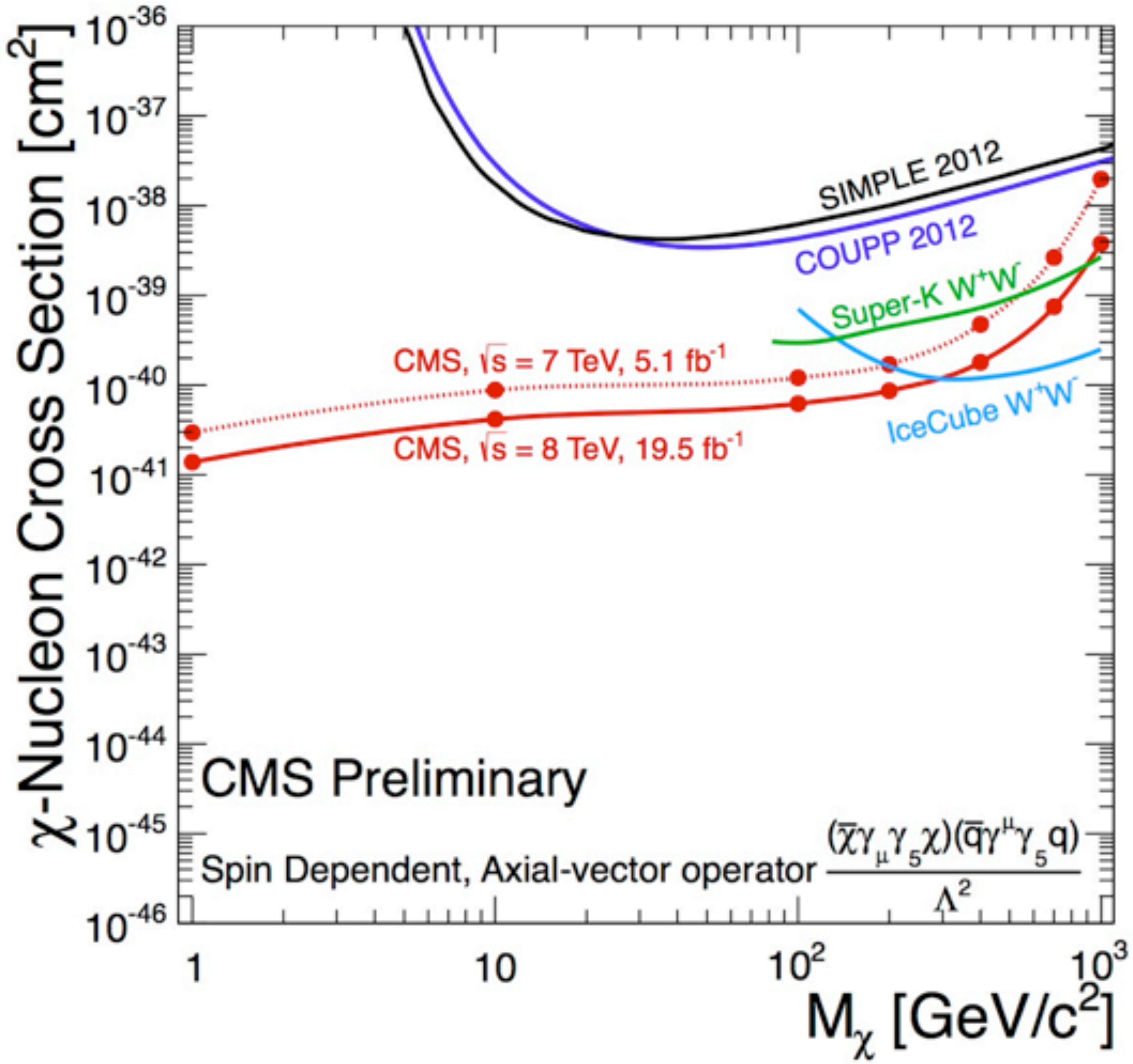
Limits on Λ



Λ [GeV]
1000
300
1
10
10^2
10^3
M_χ [GeV/c^2]
CMS Preliminary
$\sqrt{s}$ = 8 TeV
$\int$ L dt = 19.5 fb^{-1}
CMS 2012 Vector
CMS 2011 Vector
CMS 2012 Axial Vector
CMS 2011 Axial Vector

Dark matter spin dependent limits

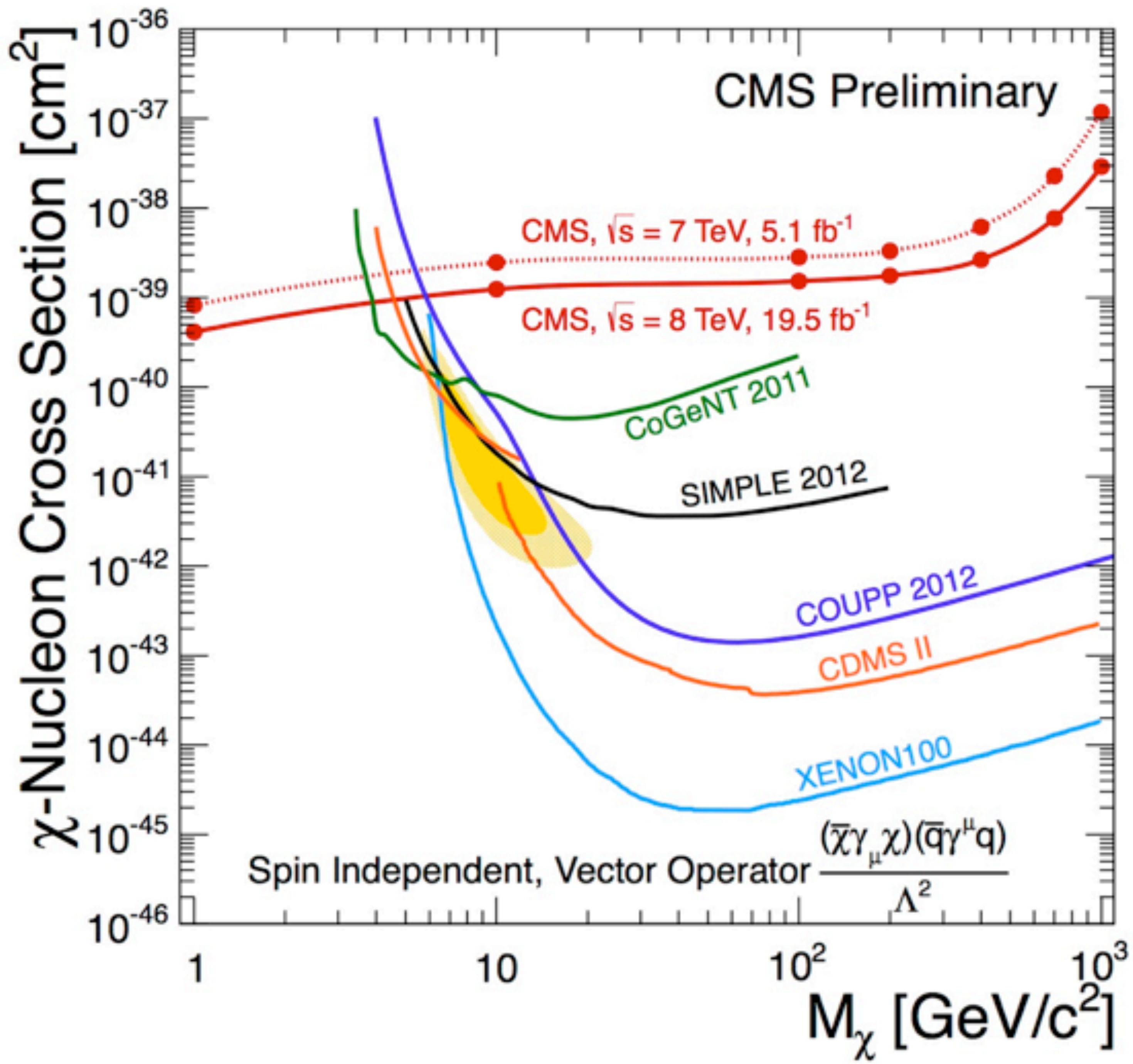
For axial-vector mediator, in context of EFT...



Stringent constraints by colliders over large DM mass range

Dark matter spin dependent limits

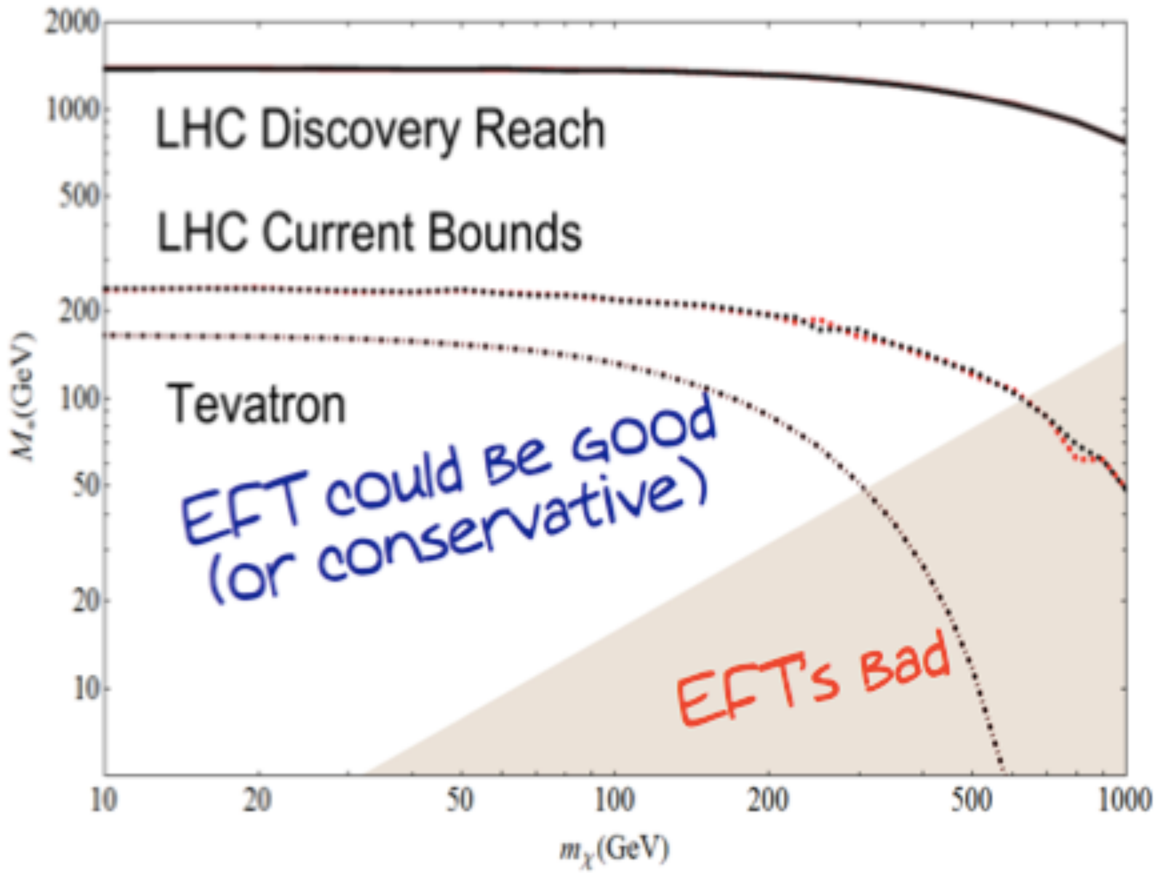
For vector mediator, in context of EFT...

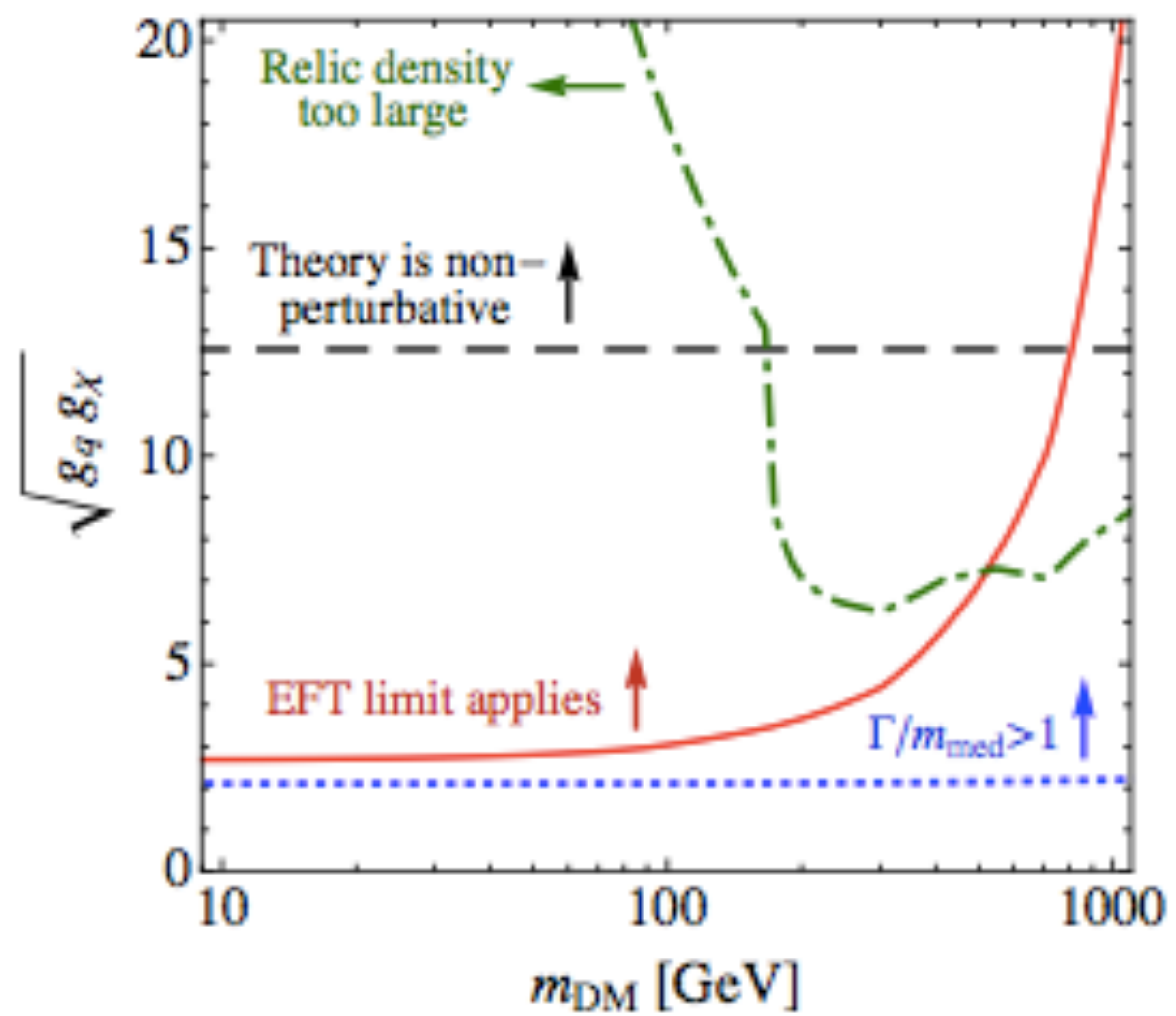


Constraining low mass dark matter, below 3.5 GeV, a region not as accessible to direct detection experiments

Limitations of EFT

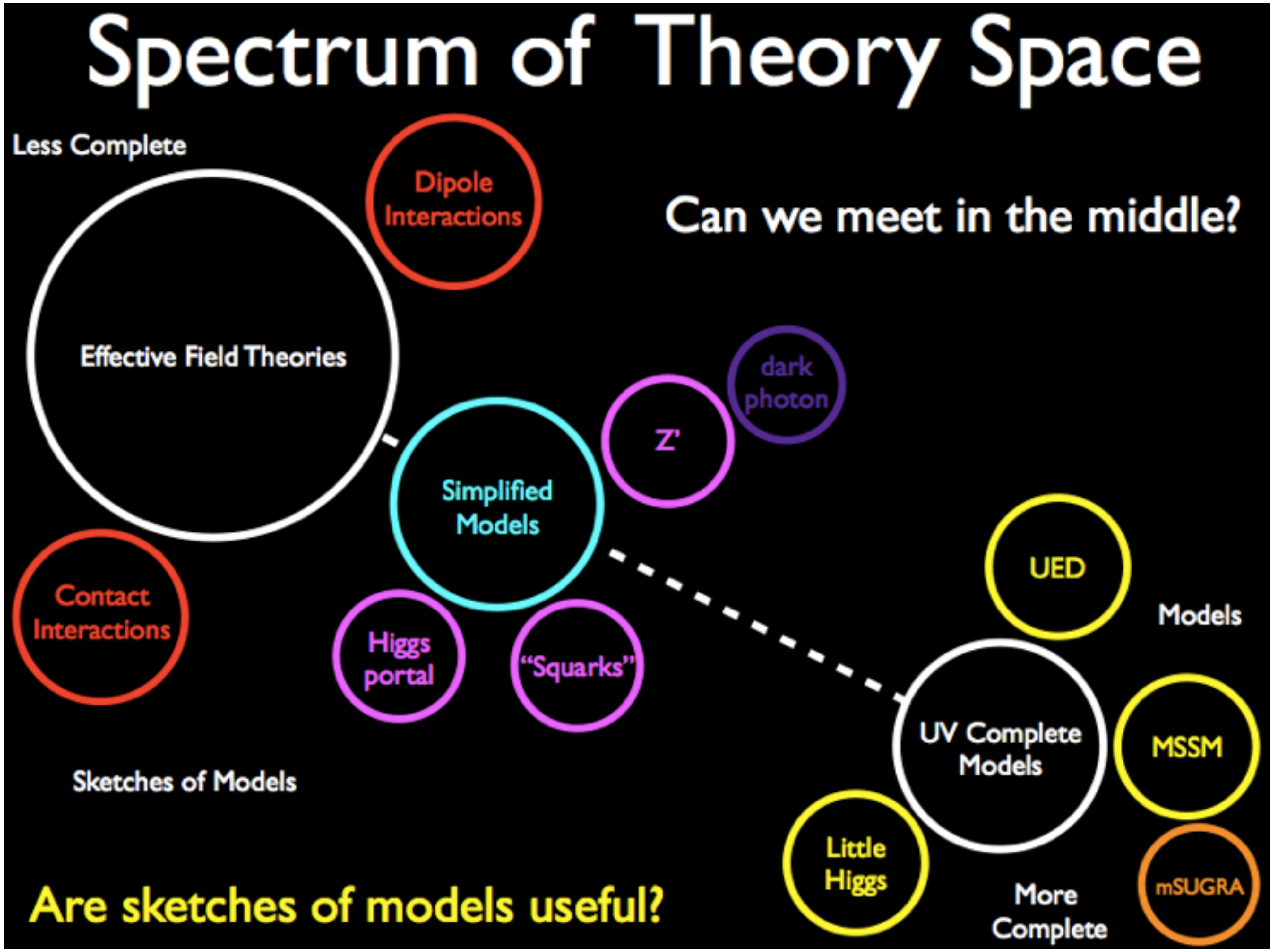
arXiv:1308.6799





R. Harnik, Dark Matter in Collision, UC Davis, 2012

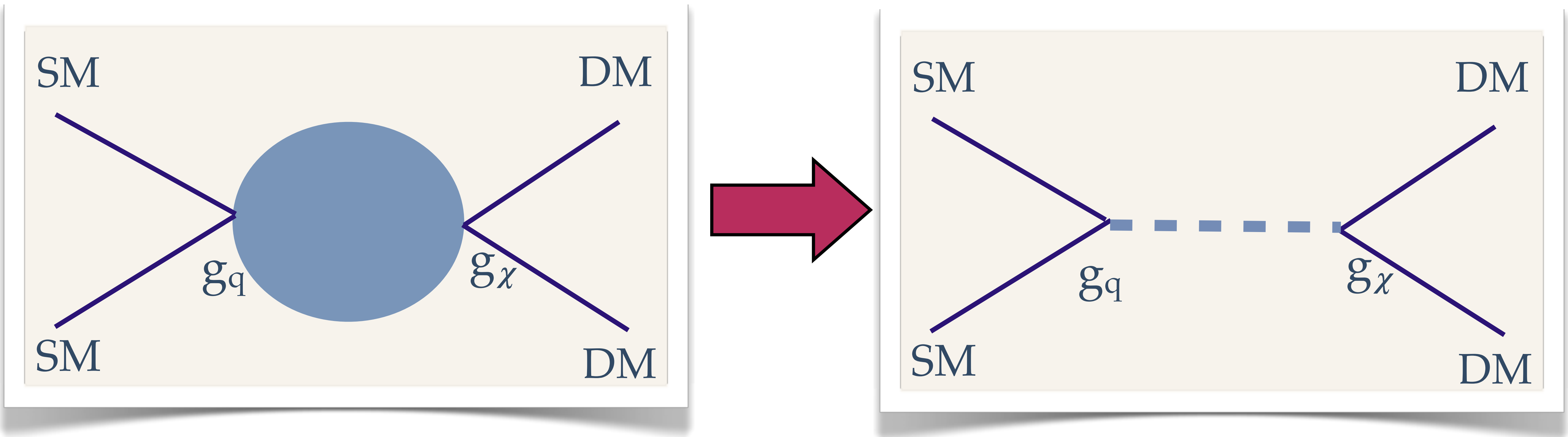
From Tim Tait



Phenomenology

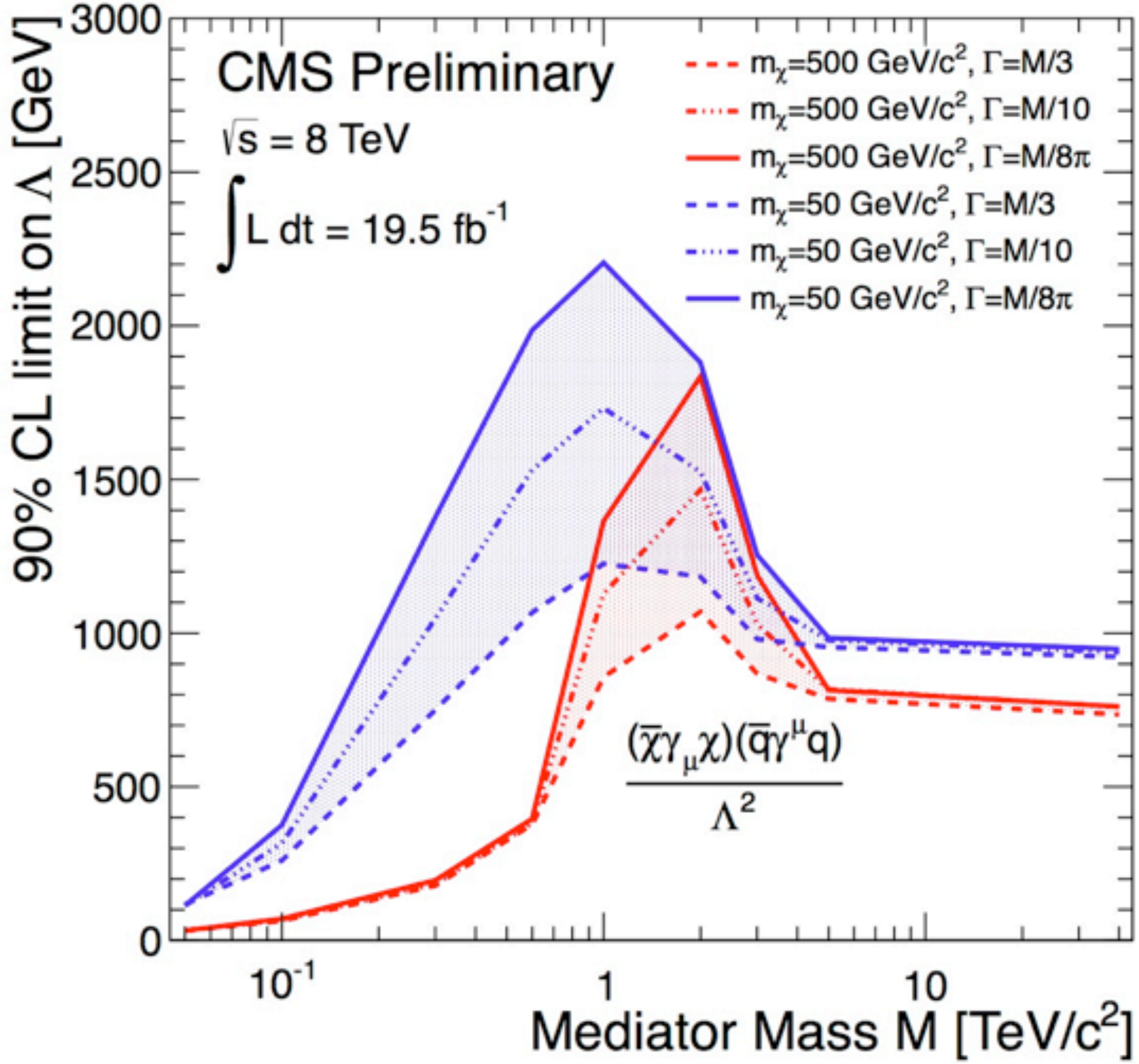
Light mediator

- Assume DM interaction is mediated by light particle
- Effective theory breaks down and explicitly have to include mediator mass.



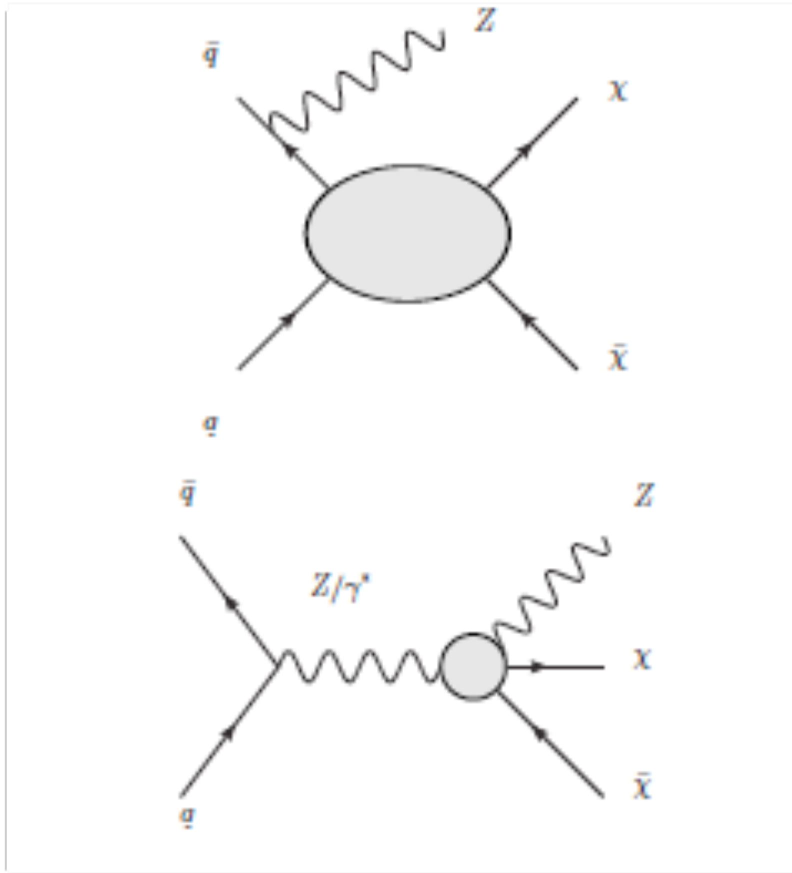
With 14 TeV collisions expected after the long shutdown, more important to consider case of low mass mediator

For light mediator.....

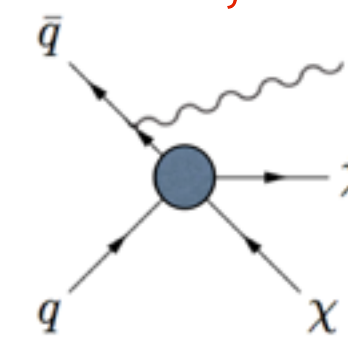


Mono-X

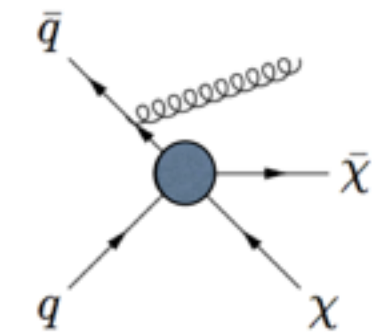
Mono-Z



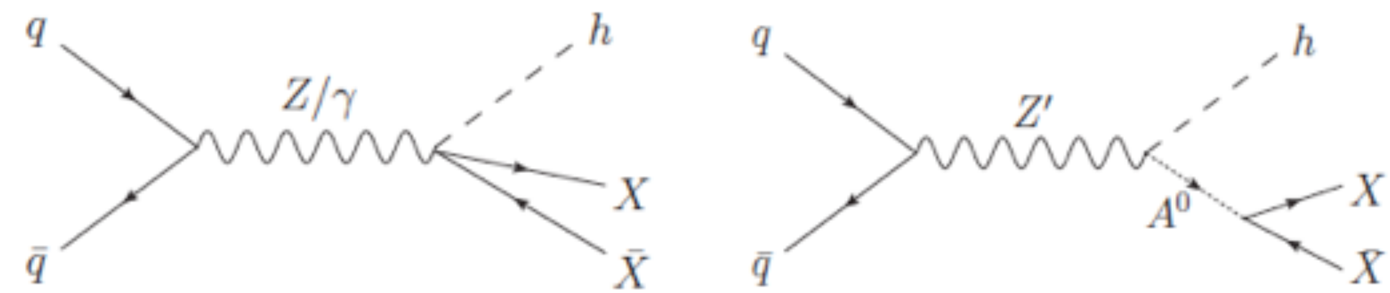
Mono-jet



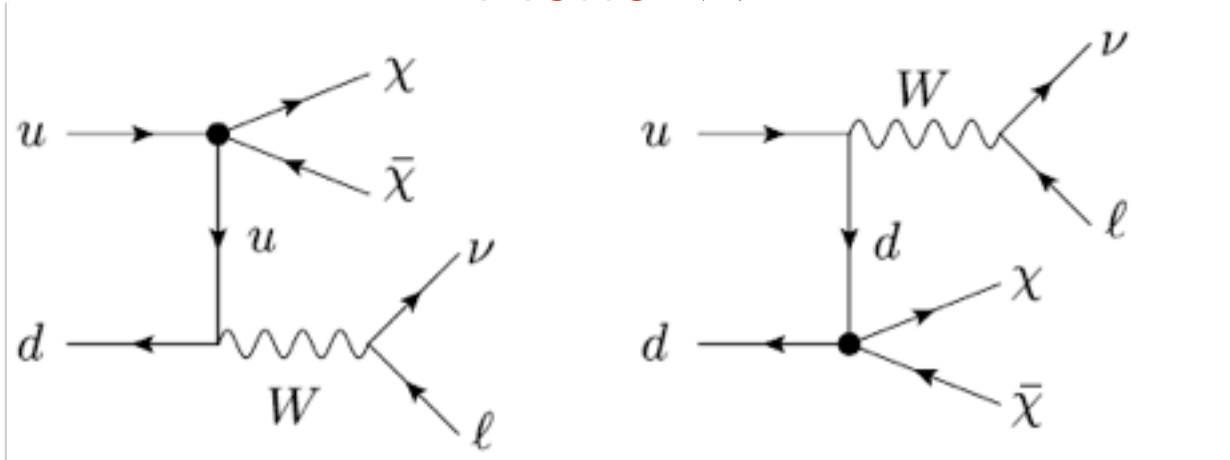
Mono-photon



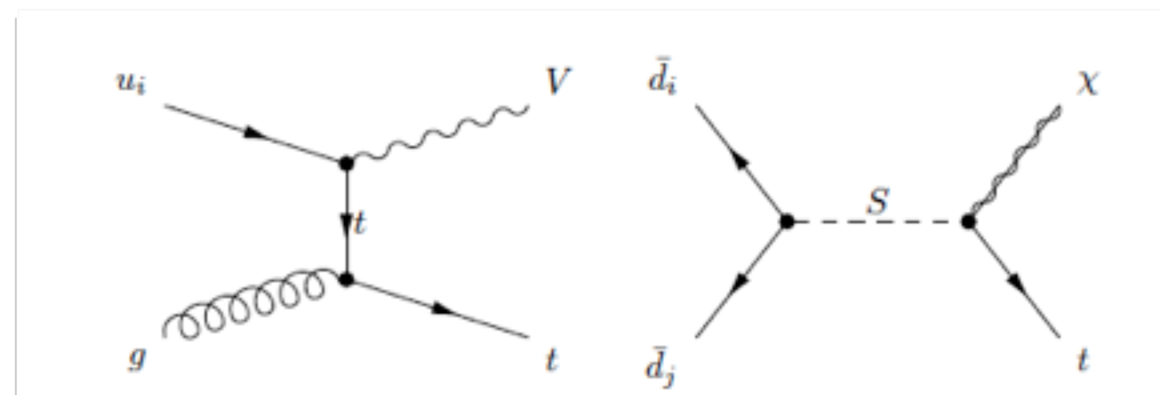
Mono-Higgs



Mono-W



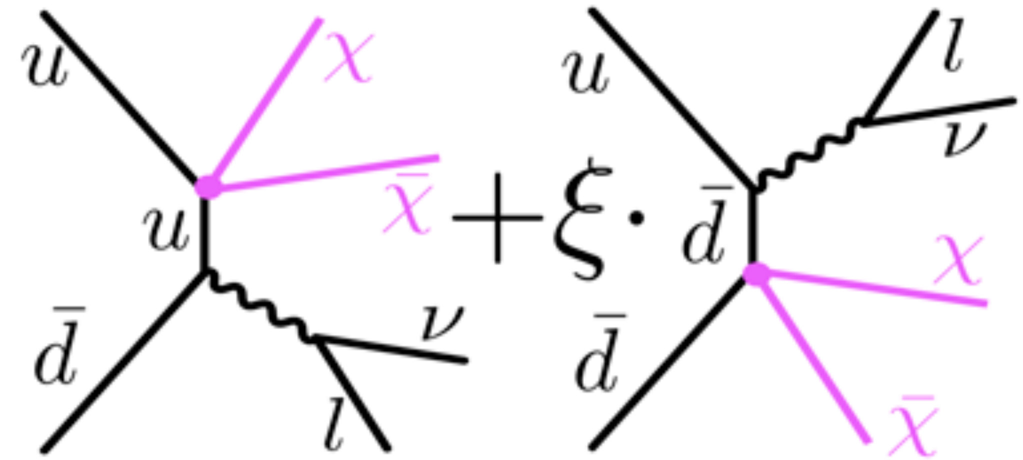
Mono-top

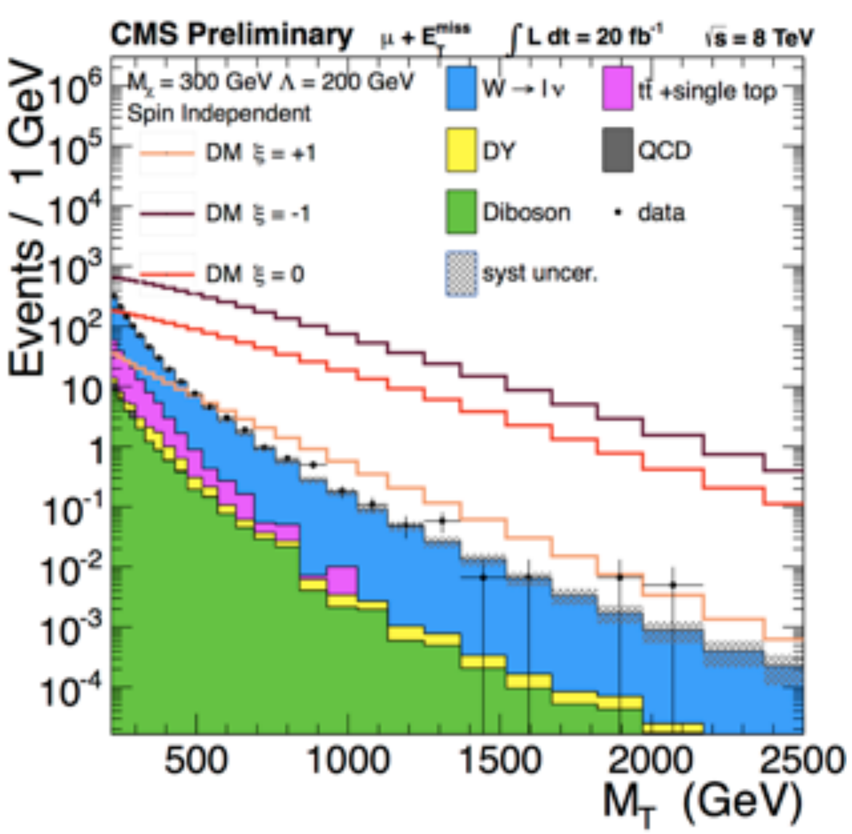


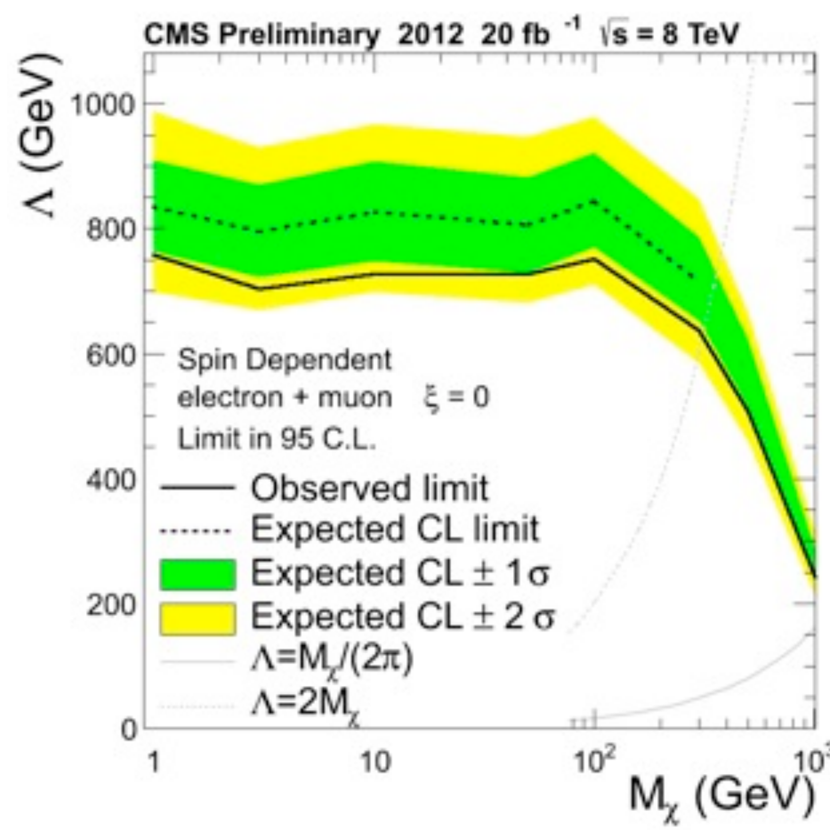
DM search in monoleptons

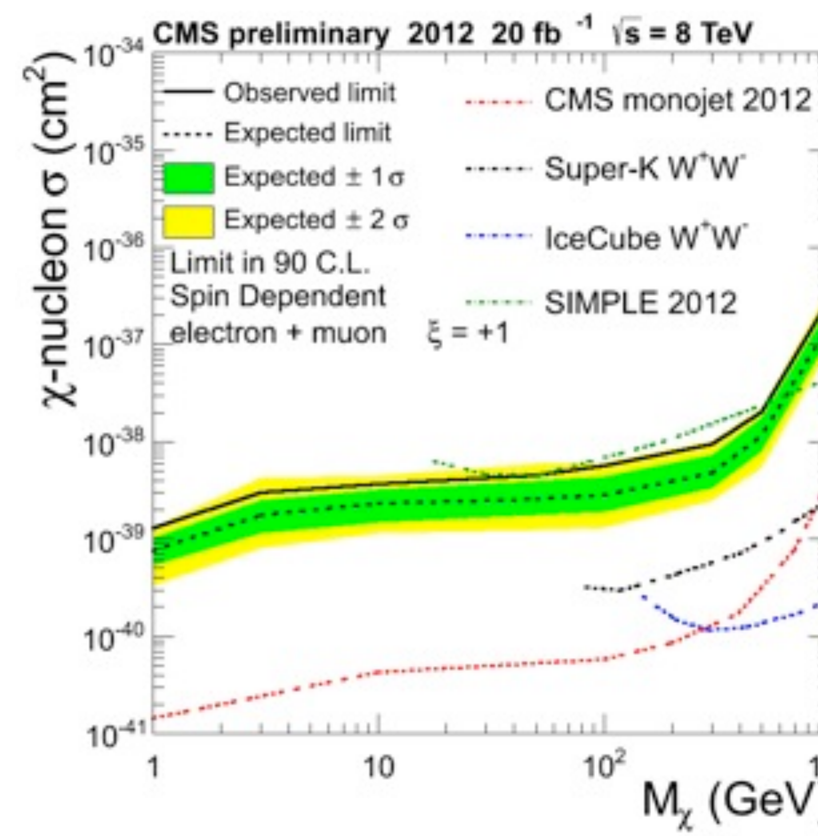
CMS-EXO-13-004

- DM produced together with W, which decays to lν
- Adapted from search for W'
- consider vector and axial-vector interactions









DM search in monophoton events

CMS-EXO-11-096

Photon selection

* p_T > 145 GeV
* Central region of detector, |η| < 1.4442
* Shower shape in calorimeter consistent with photon

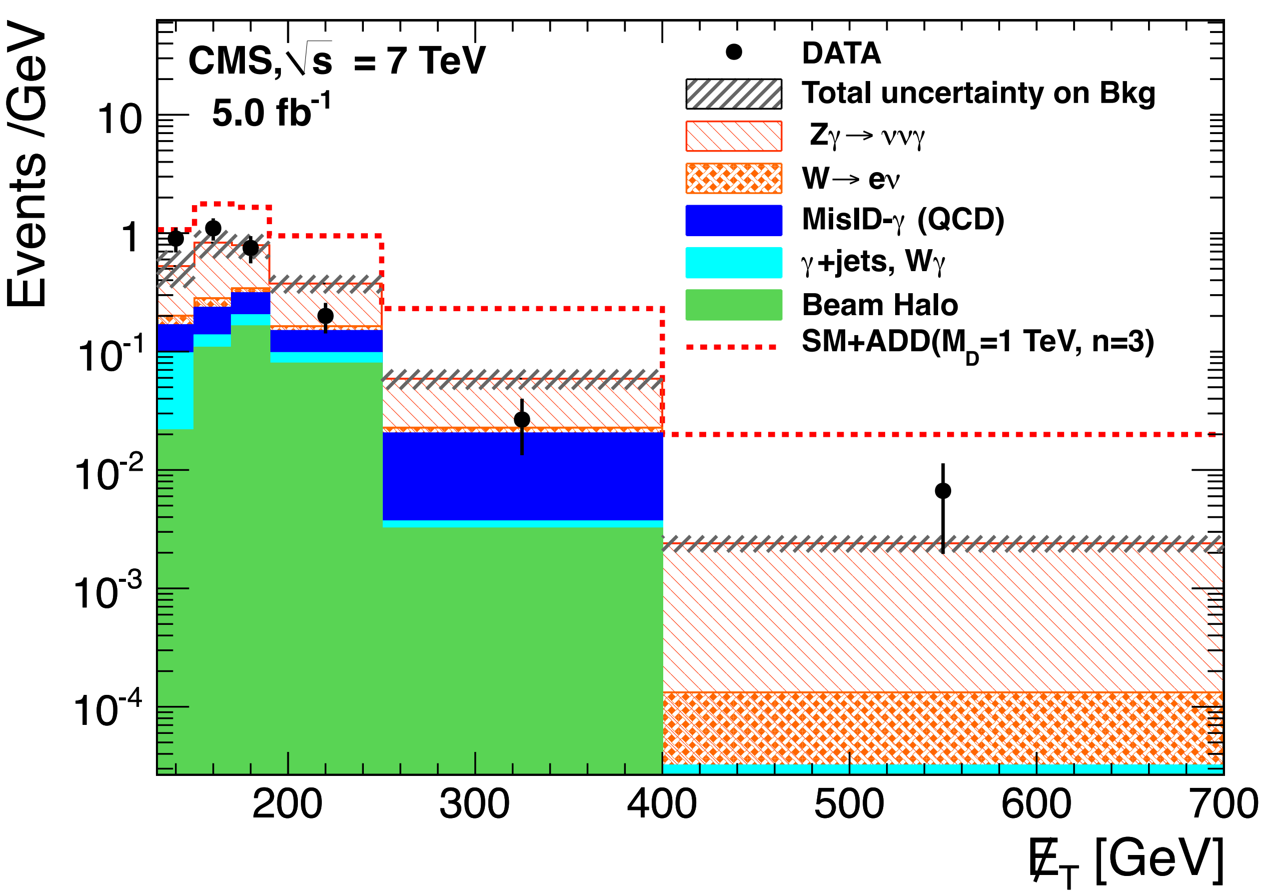
MET

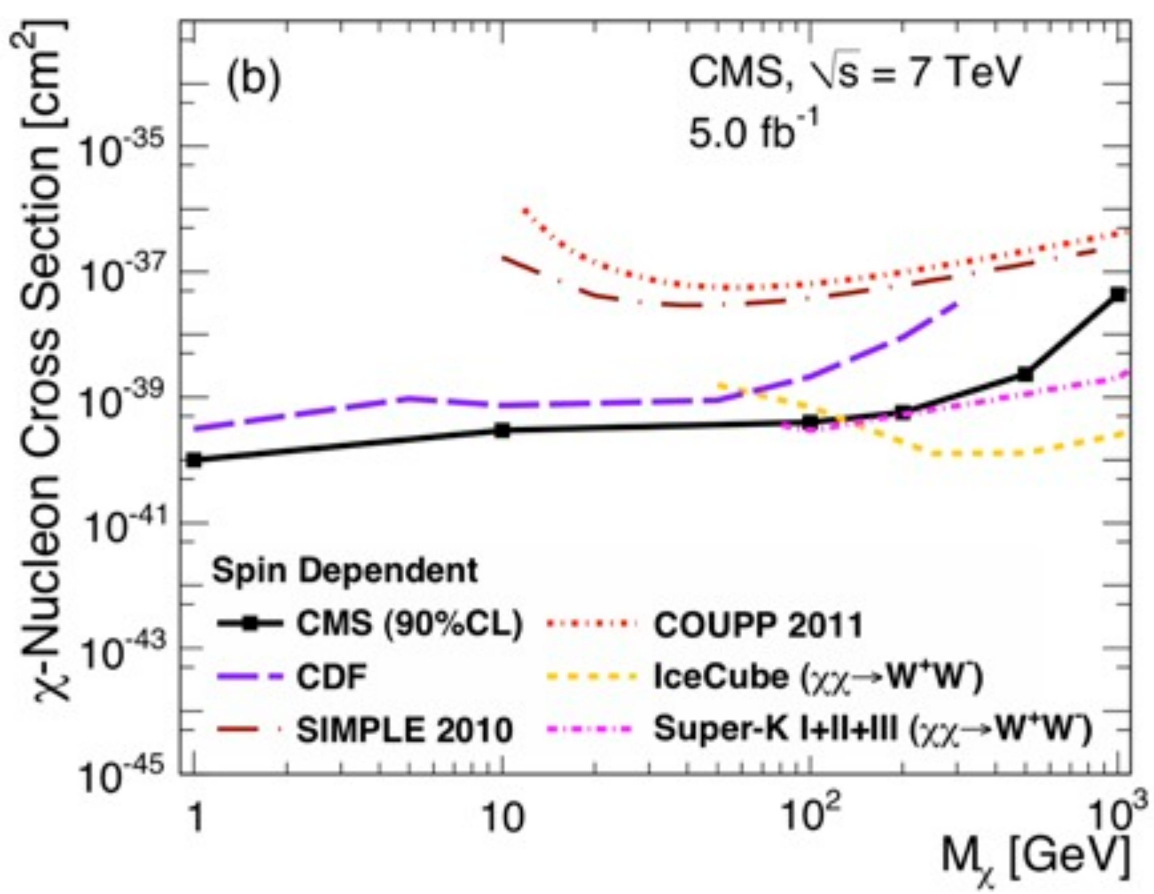
* MET > 130 GeV

Remove excessive hadronic activity

* No jet with p_T > 40 GeV and |η| < 3.0
* No track with p_T > 20 GeV with ΔR < 0.04 from photon

Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu\bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73





Summary

- Presented results from searches for dark matter at CMS using mono-X signatures
- Used to set limits on DM-nucleon scattering cross-section
- Competitive constraints for spin-dependent cross section over large DM mass range
- Extend the spin-independent bounds into low DM mass.
- Colliders provide constraints on DM that are competitive and complementary to those from direct detection experiments