Dark Matter:
in the Sky, under Ground, at Colliders

探测暗物质：上天，入地，看人间

Shufang Su (苏淑芳) • U. of Arizona

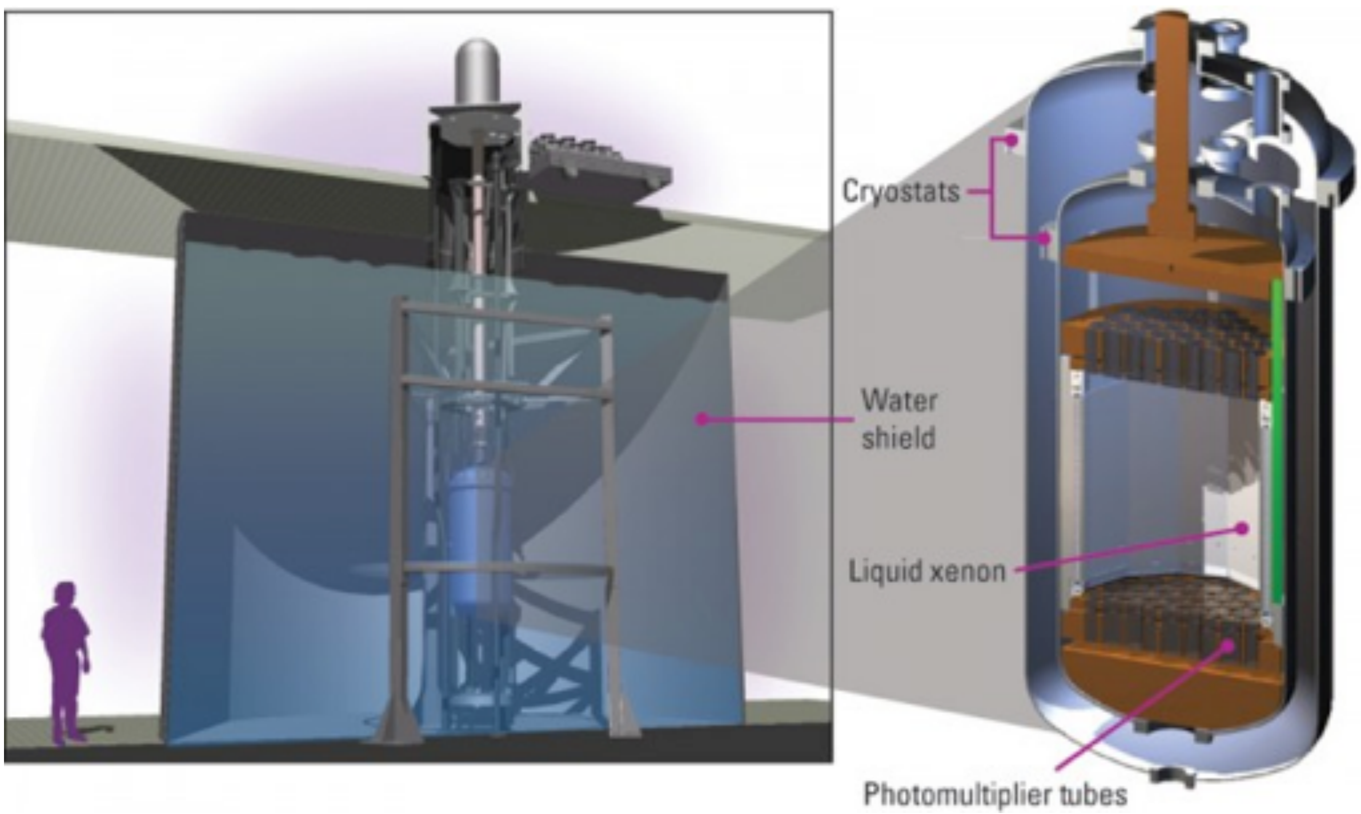
Tsinghua University

Feb 28, 2014

2013

Direct detection update: LUX

Oct 30, 2013



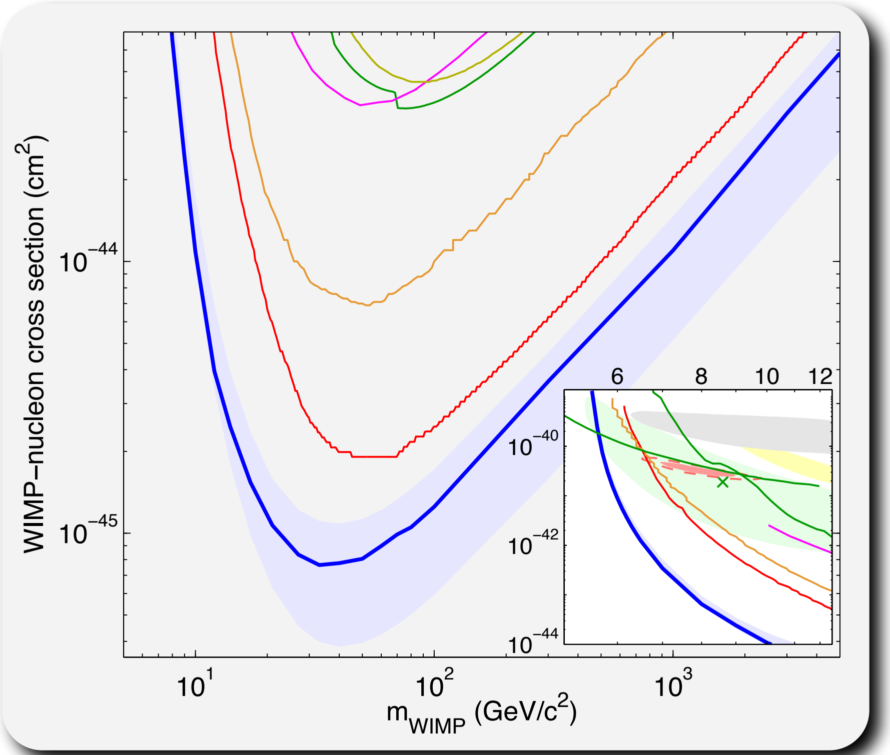
Direct detection update: LUX

LUX 2013

Oct 30, 2013

Edelweiss II
CDMS II
ZEPLIN-III
ZENON100 100d
ZENON100 225d

CoGeNT
DAMA/LIBRA
CRESS
Si @ CDMS II



- Xe detector, 85.3 days, 118 kg fiducial volume
- 90% C.L. limit of 7.6 x 10^{-46} cm^2 @ 33 GeV

Direct detection update: LUX

Google | LUX dark matter | **Oct 30, 2013**

Web · Images · Maps · Shopping · **News** · More · Search tools

About 3,180 results (0.22 seconds)

Add "**LUX dark matter**" section to my Google News homepage


New York Ti...

LUX Dark matter detector finds no WIMPs, so why are scientists ...
Los Angeles Times - by Amina Khan - Oct 30, 2013
Scientists at an ambitious **dark matter** experiment in operation at an underground gold mine in South Dakota have discovered exactly what they ...

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First results from **LUX dark matter** detector rule out some candidates
Phys.Org - Oct 30, 2013

Dark Matter Experiment Has Detected Nothing, Researchers Say ...
Highly Cited - New York Times - Oct 31, 2013

Huge **Dark Matter** Experiment Finds Nothing but More Mysteries
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Where the heck is **dark matter**? The initial run of a fancy new xenon ...
Blog - Houston Chronicle (blog) - Oct 30, 2013

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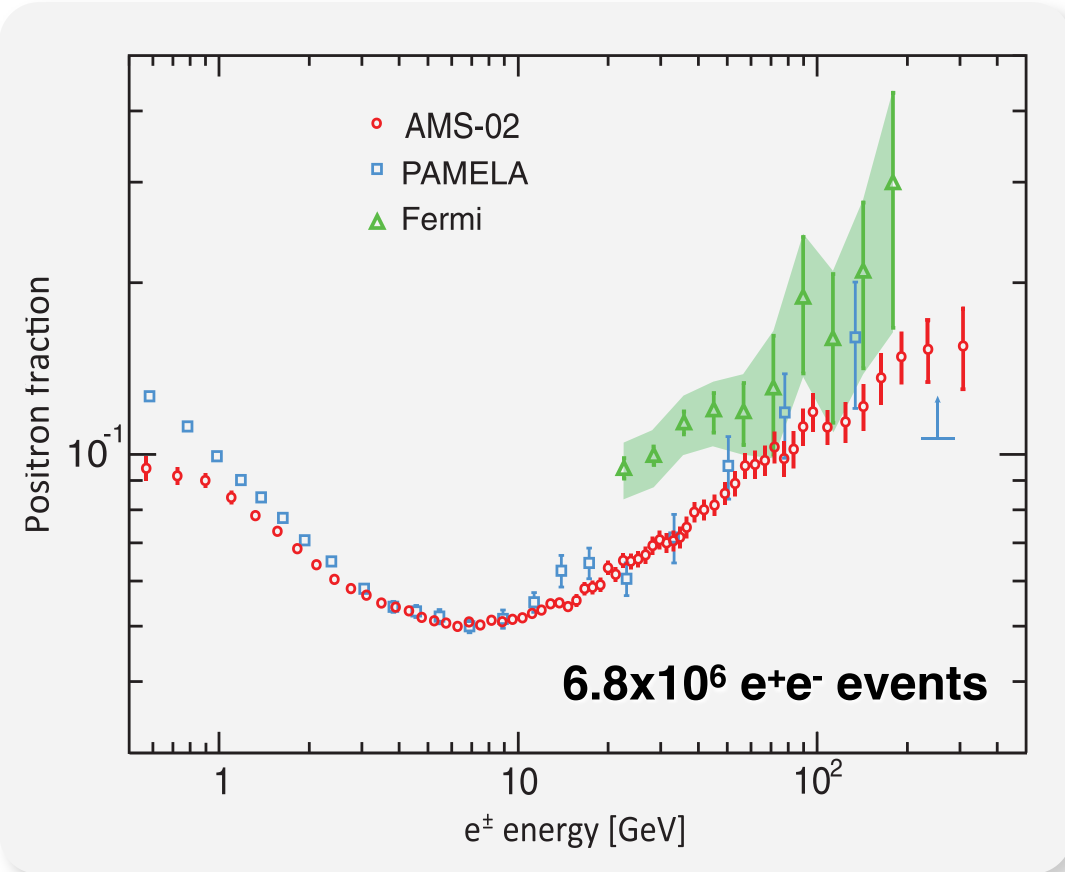
Indirect detection update: AMS

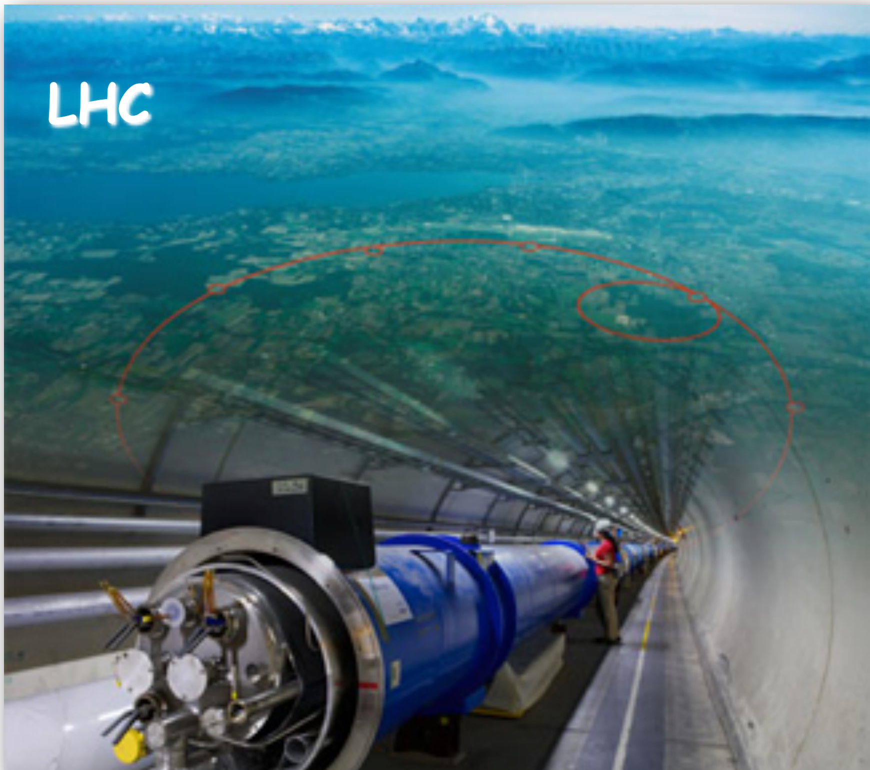
April, 2013

AMS, PRL110, 141102 (2013)

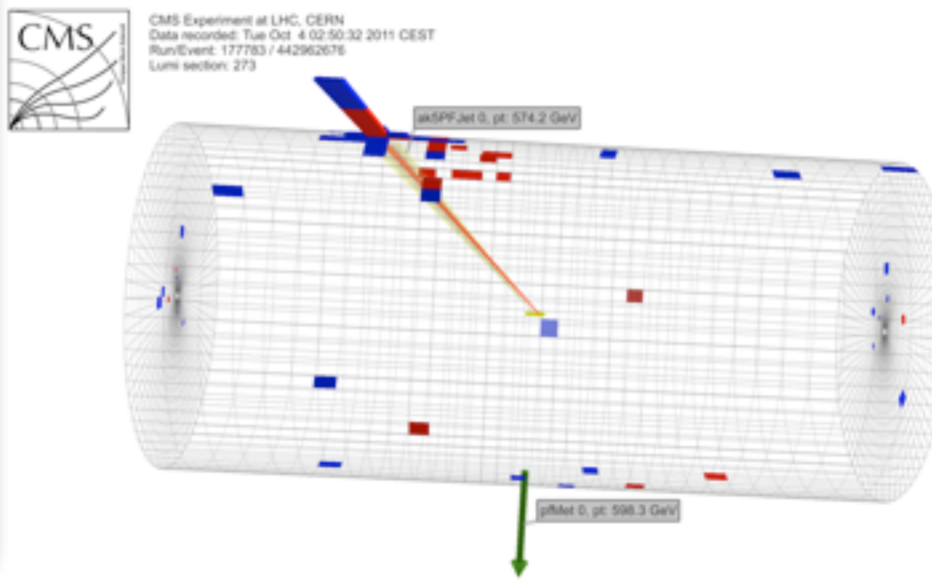


- dark matter annihilation? decay?
- nearby pulsar?
- ...

Collider updates



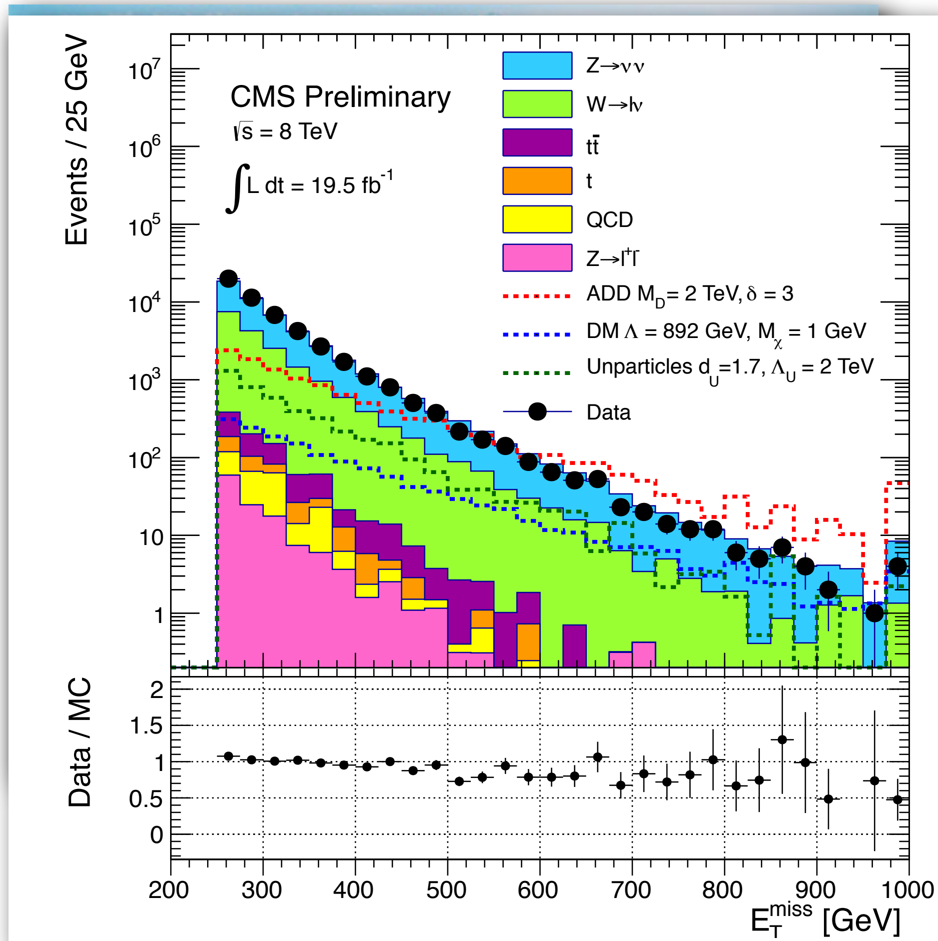
monojet



March, 2013

Collider updates

CMS, EXO-12-048



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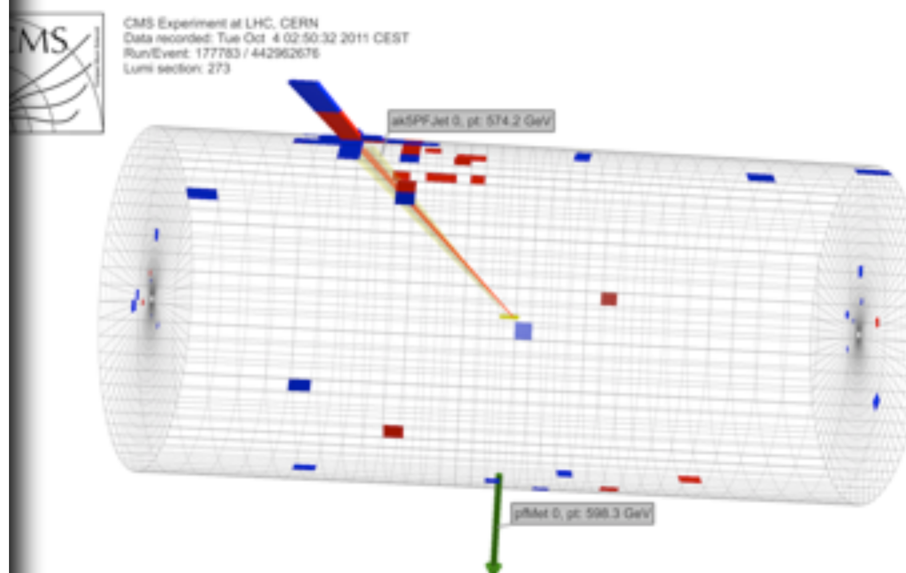
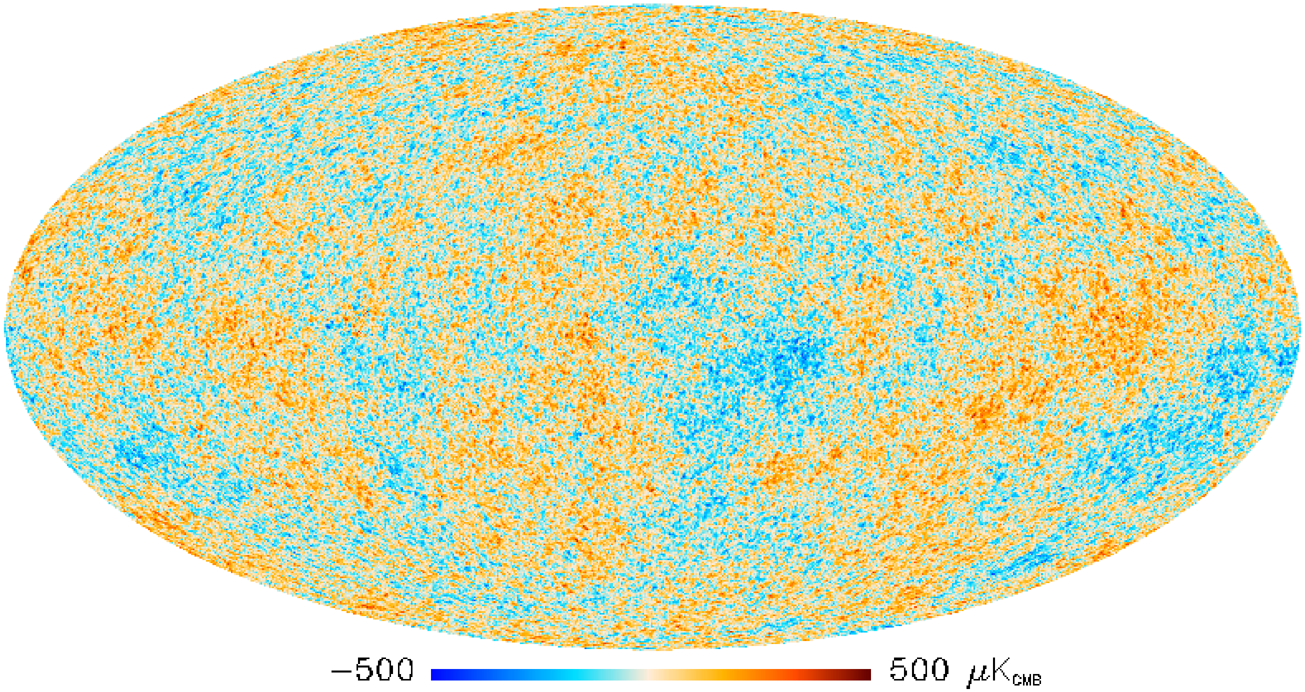


PLANCK

Planck Collaboration,
1303.5062, 1303.5076

March, 2013



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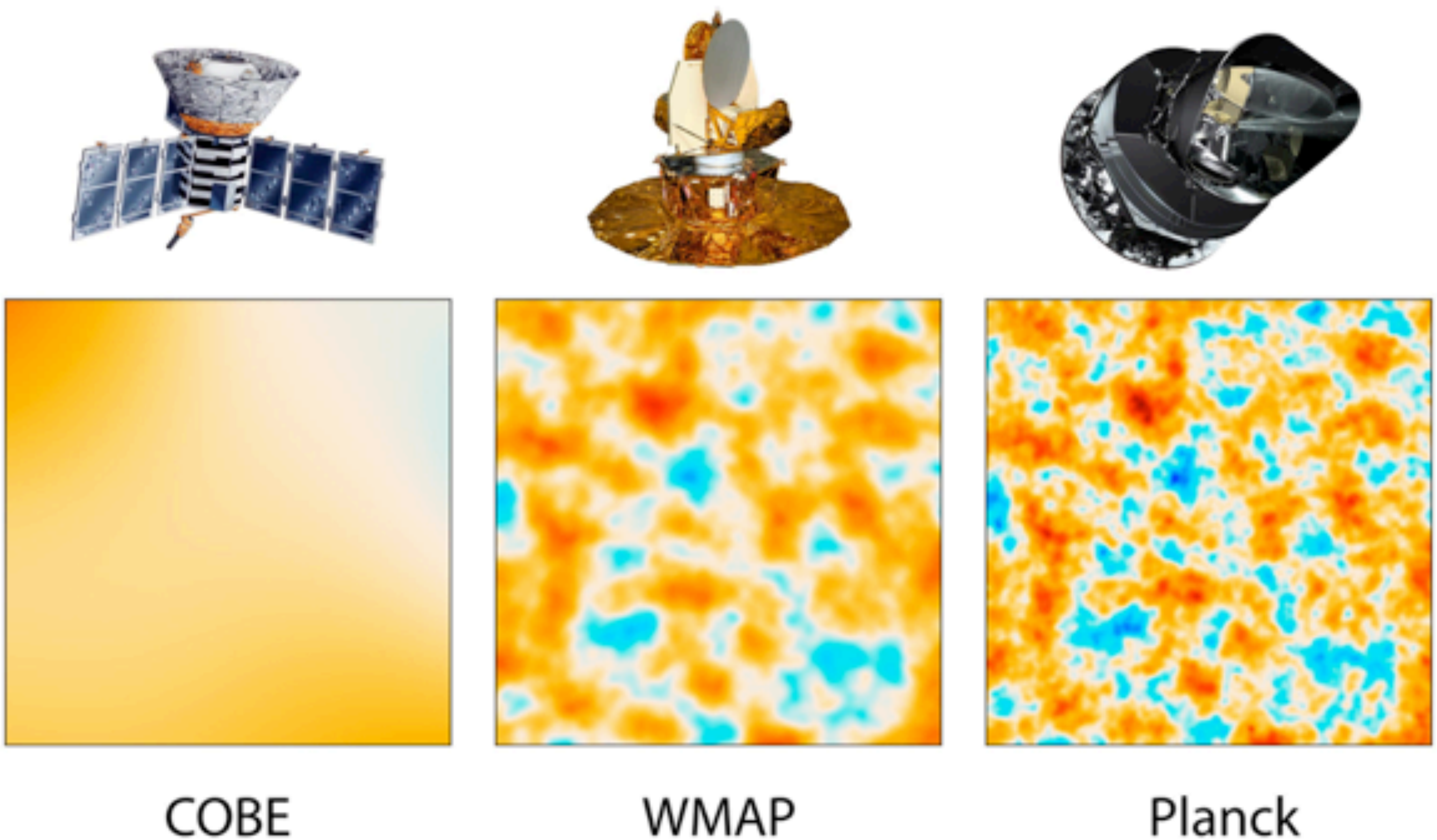

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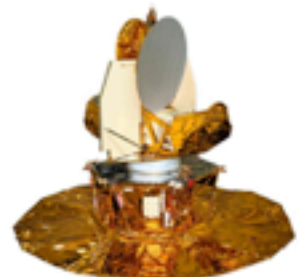
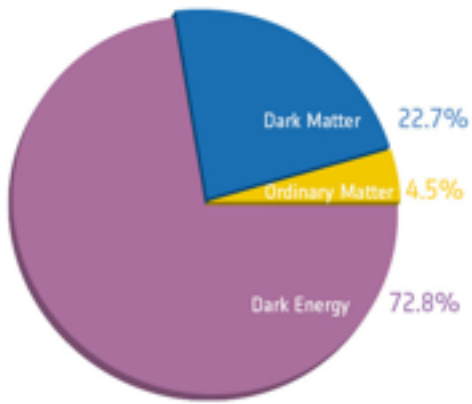
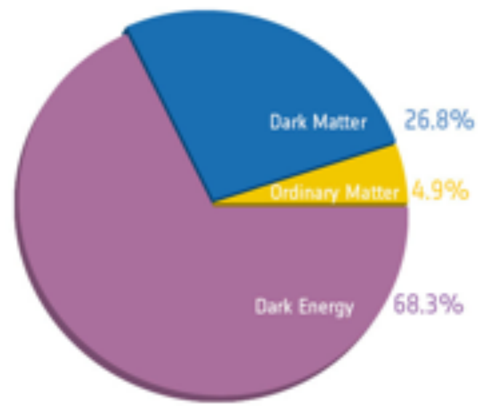


COBE



Before Planck



After Planck

S. Su

We are living through a revolution in our understanding of the Universe

on the largest scales

For the first time in history,

we have a complete picture of the Universe

Outline

为什么? ◉ The evidence of dark matter

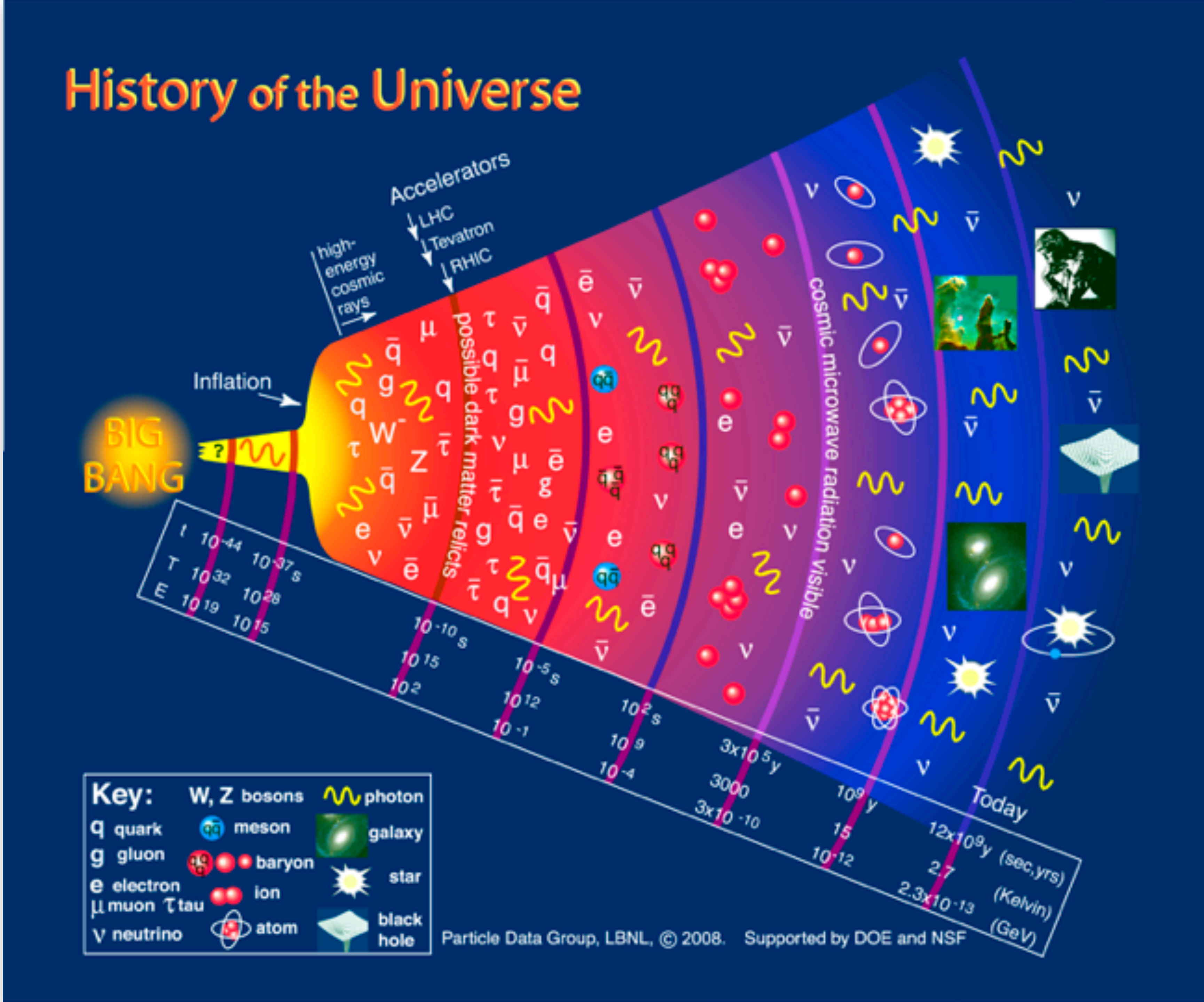
是什么? ◉ What is dark matter?

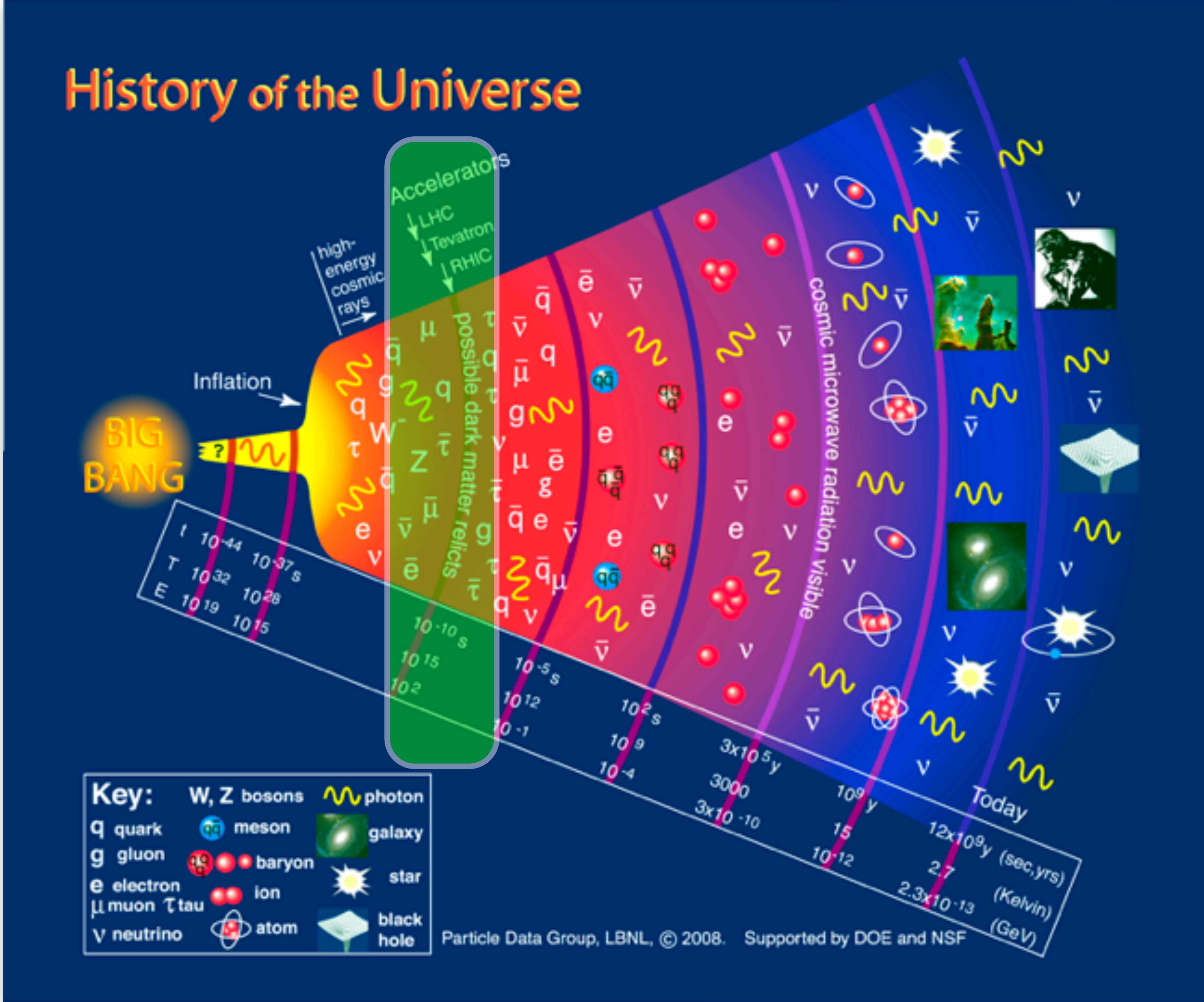
– dark matter and new physics

看什么? ◉ Dark matter detection

– Direct detection
– Indirect detection
– Search at colliders

Evidence


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t
T
E
10 -44
10 -37 s
10 32
10 28
10 19
10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF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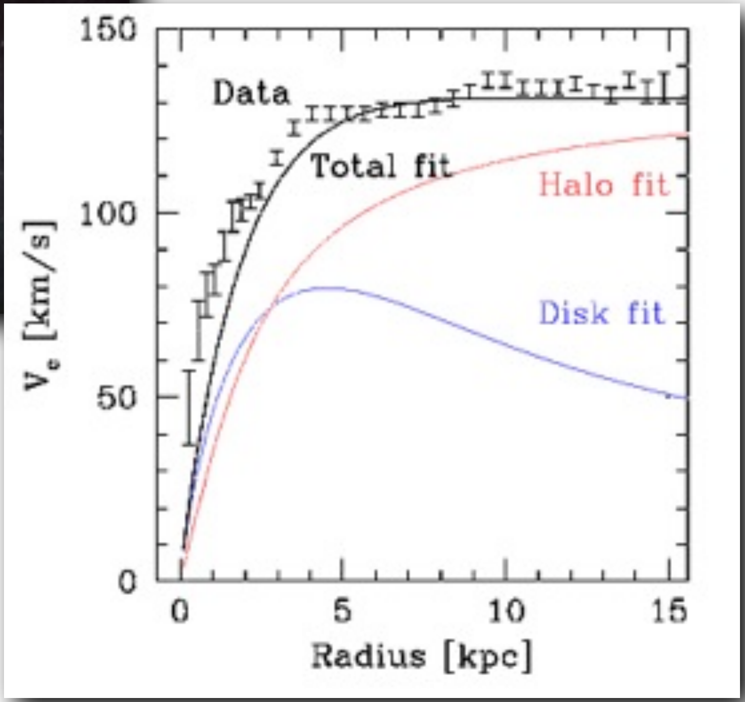
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Exp evidence: rotation curves

Rotation curves of galaxies and galactic clusters



Constrain Ω_m

$\Omega_i = \rho_i / \rho_c$

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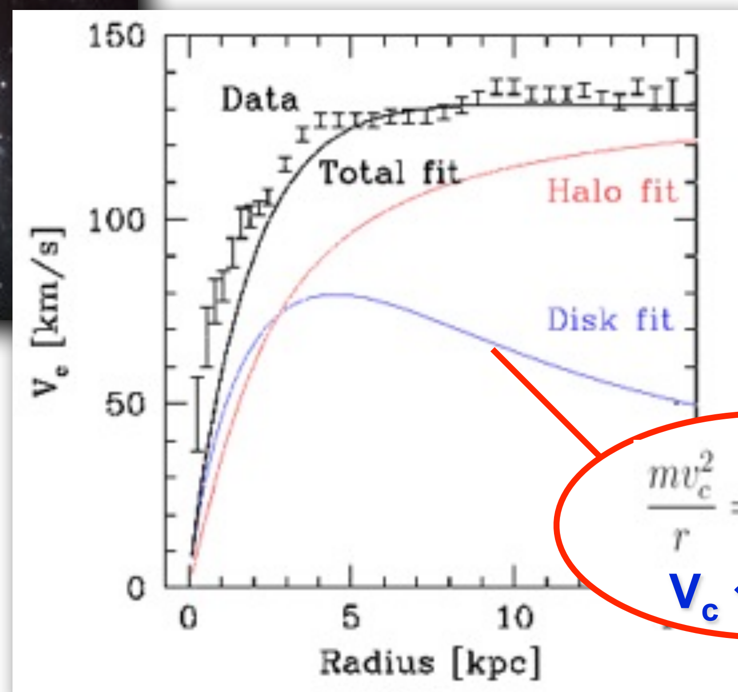
Rotation curves of galaxies and galactic clusters



$$\frac{mv_c^2}{r} = G_N \frac{mM}{r^2}$$

$V_c \sim 1/r^{1/2}$

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$\Omega_i = \rho_i / \rho_c$

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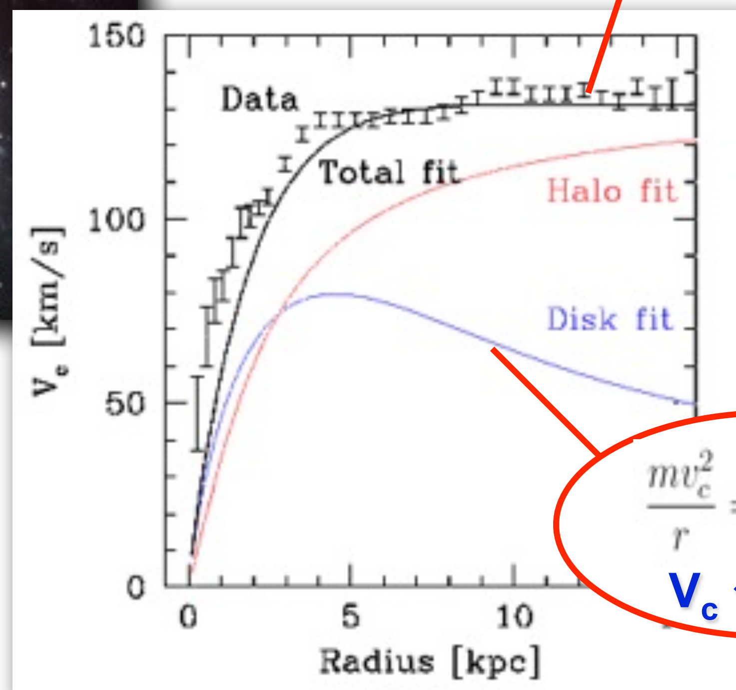

$V_c \sim$ const

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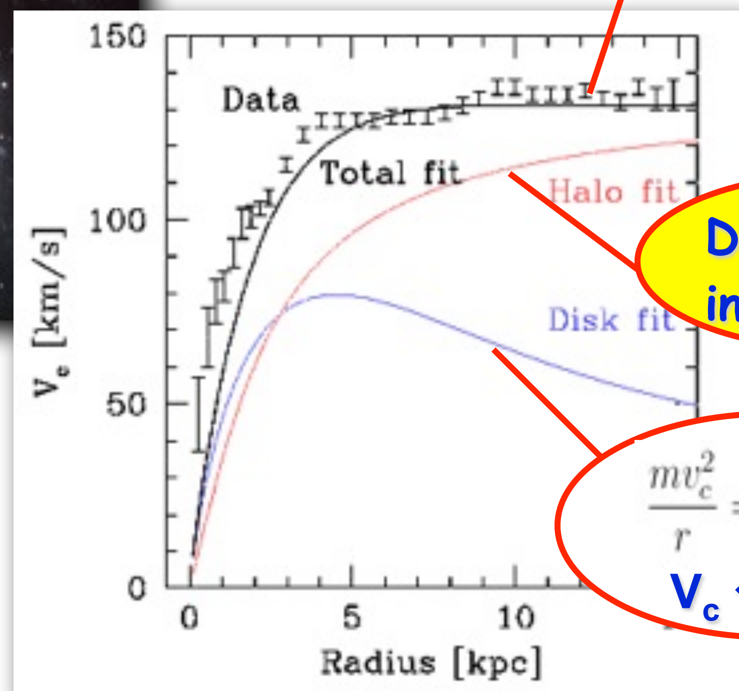


$V_c \sim$ const

Dark matter in halo

$$\frac{mv_c^2}{r} = G_N \frac{mM}{r^2}$$

$V_c \sim 1/r^{1/2}$

Constrain Ω_m

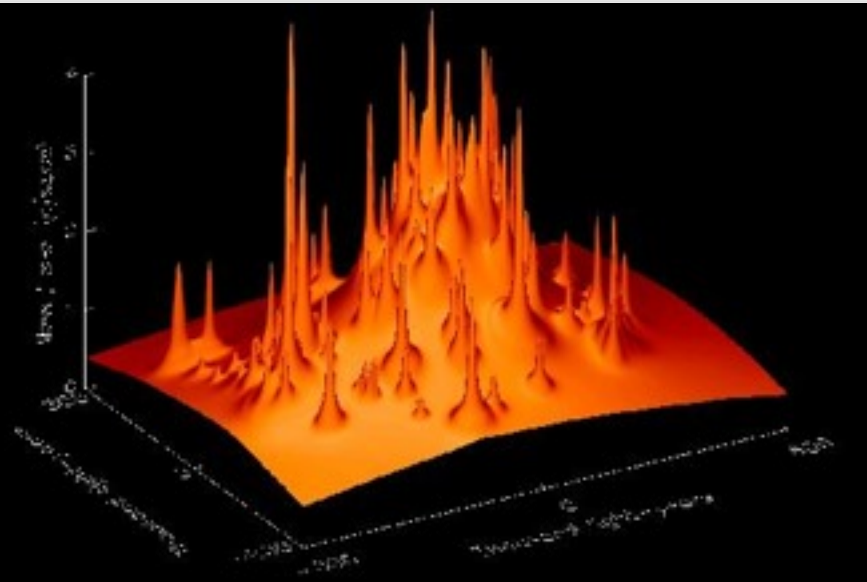
$\Omega_i = \rho_i / \rho_c$

Exp evidence: lensing

Gravitational lensing

Constrain Ω_m

Hubble Space Telescope image of a cluster of galaxies. An irregular blue galaxy in the background is multiply-imaged.



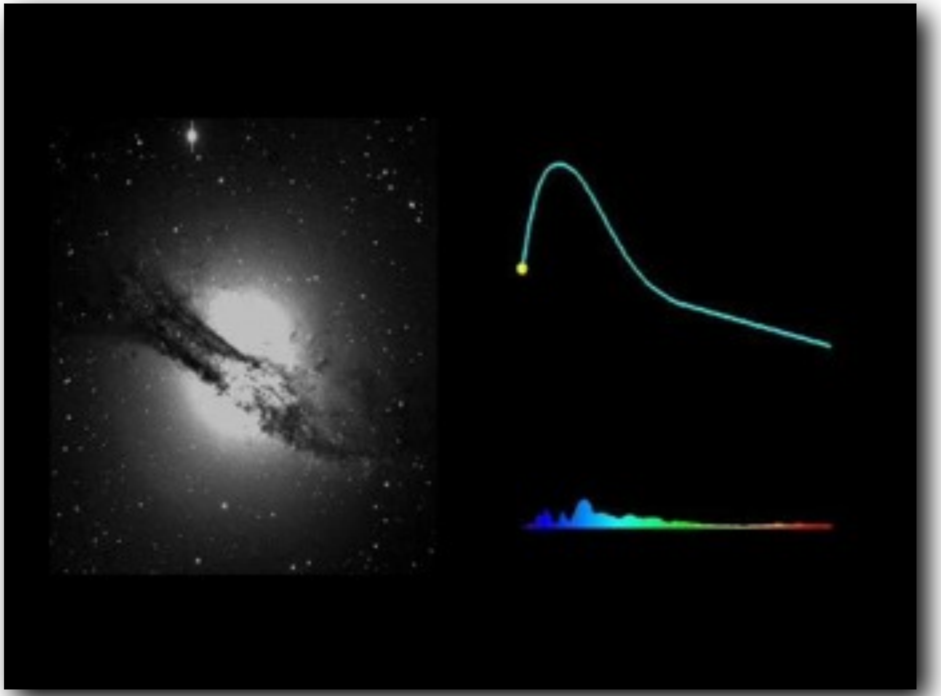
Mass reconstruction of the cluster. Note the large, smooth distribution of (apparently invisible) matter.

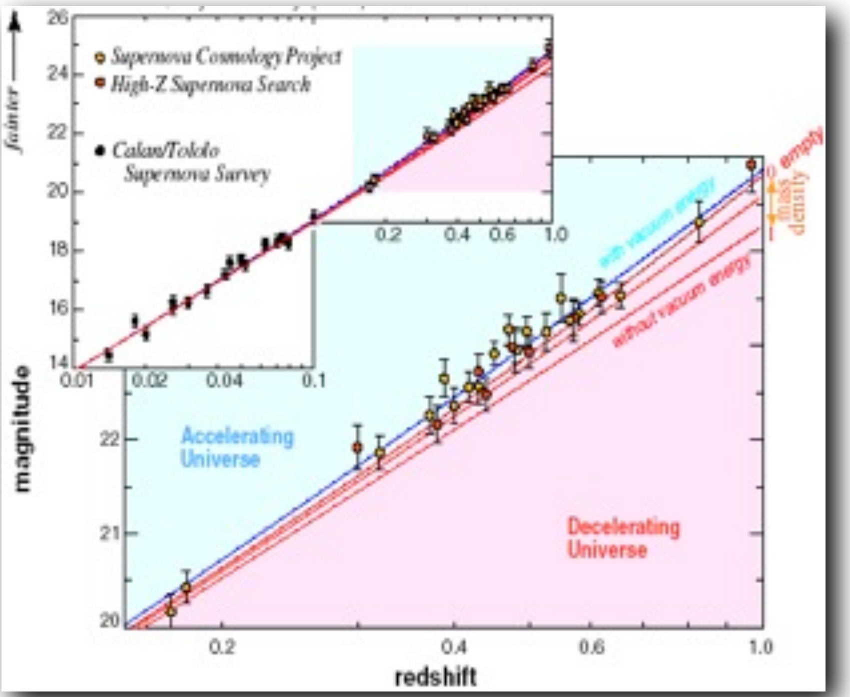
Exp evidence: bullet cluster

colliding clusters

Exp evidence: supernovae

Supernovae





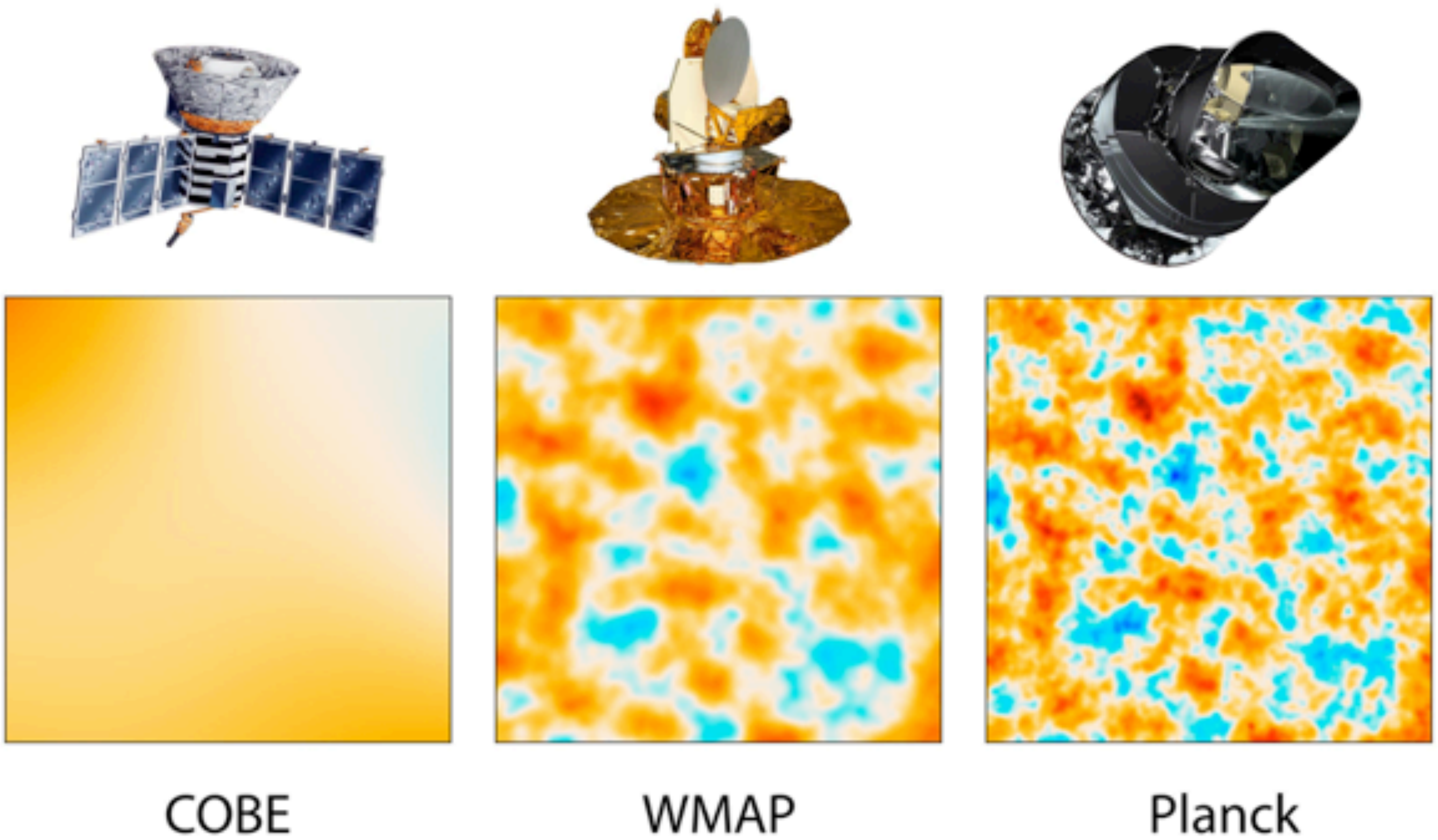
Constrain acceleration of expansion: Ω_m-Ω_Λ

attractive matter vs. repulsive dark energy

Exp evidence: CMB

Cosmic Microwave Background

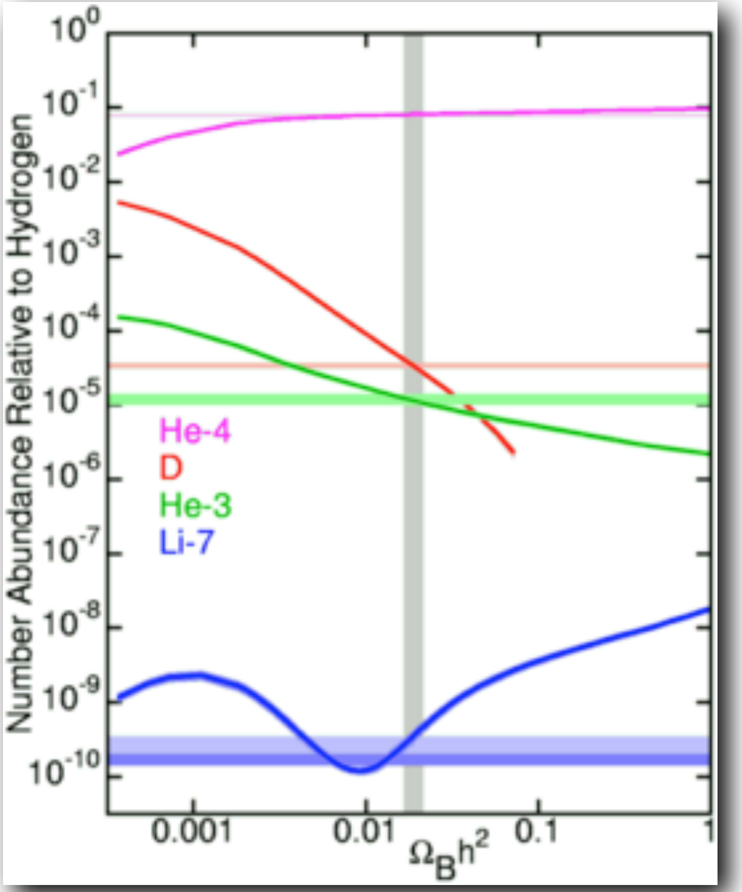
Constrain geometry of the Universe: $\Omega_\Lambda+\Omega_m$ total energy density



Exp evidence: BBN

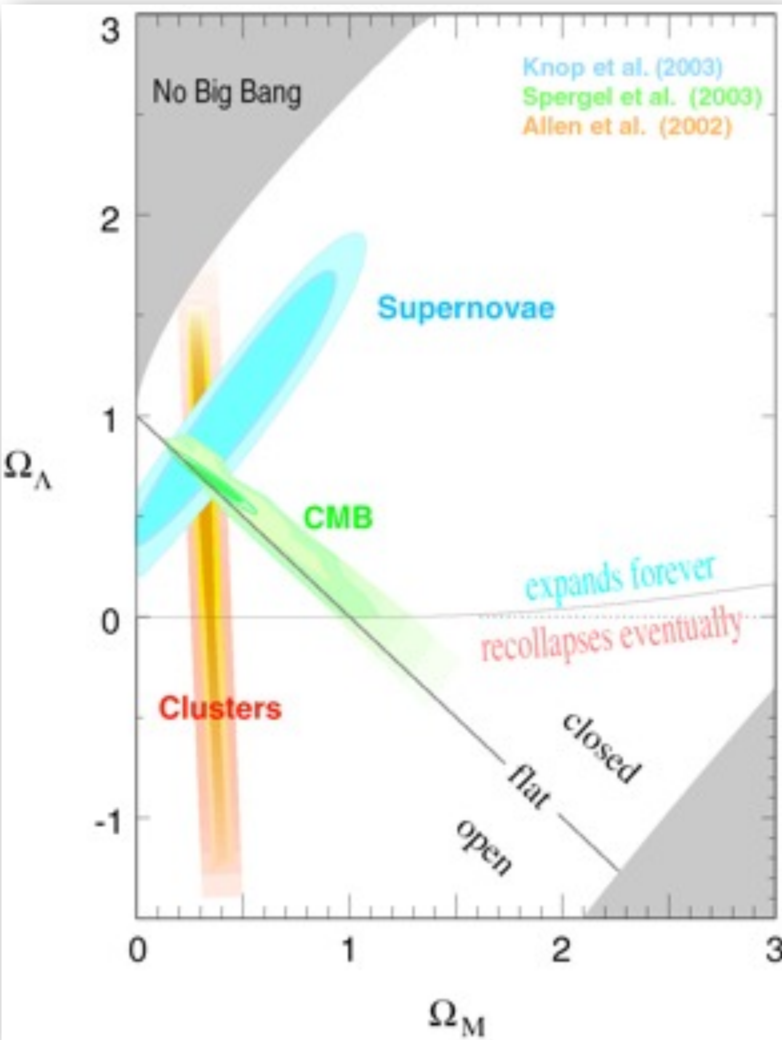
Big Bang Nucleosynthesis

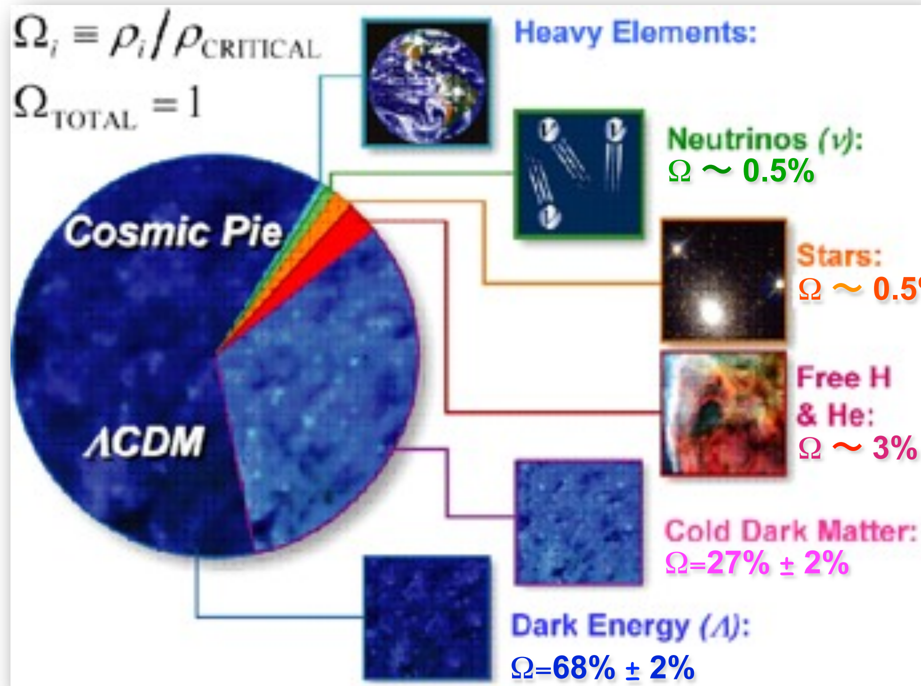
Constrain the density in baryon: Ω_B



Edward Wright (2012)

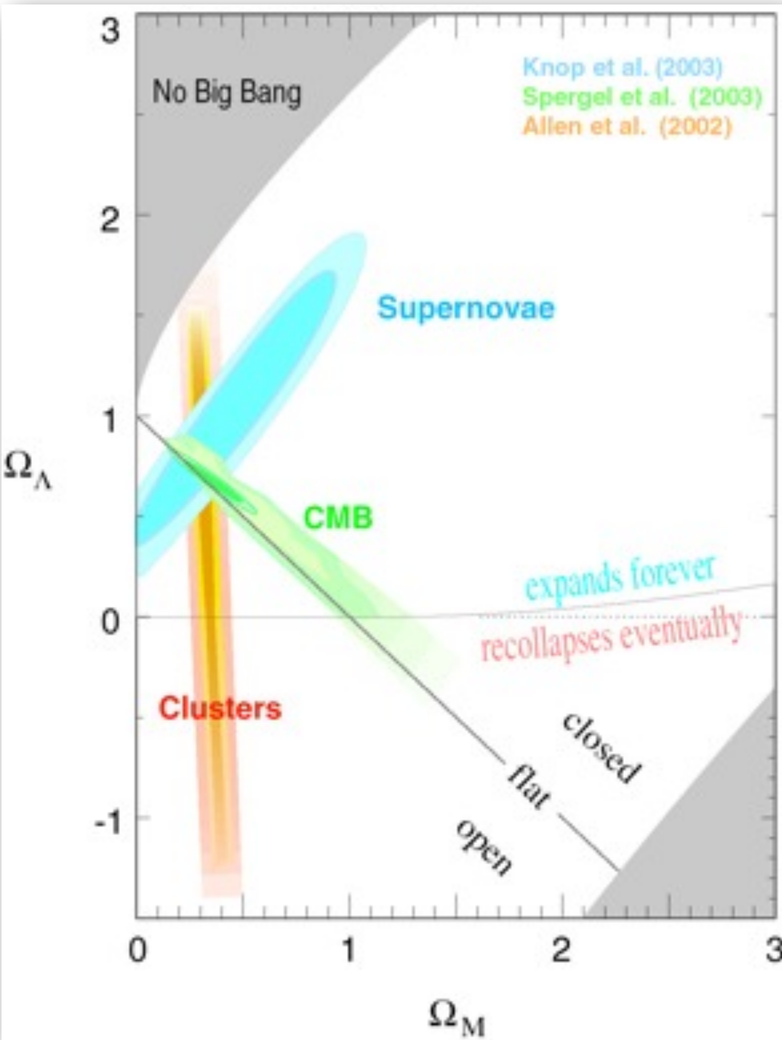
Synthesis

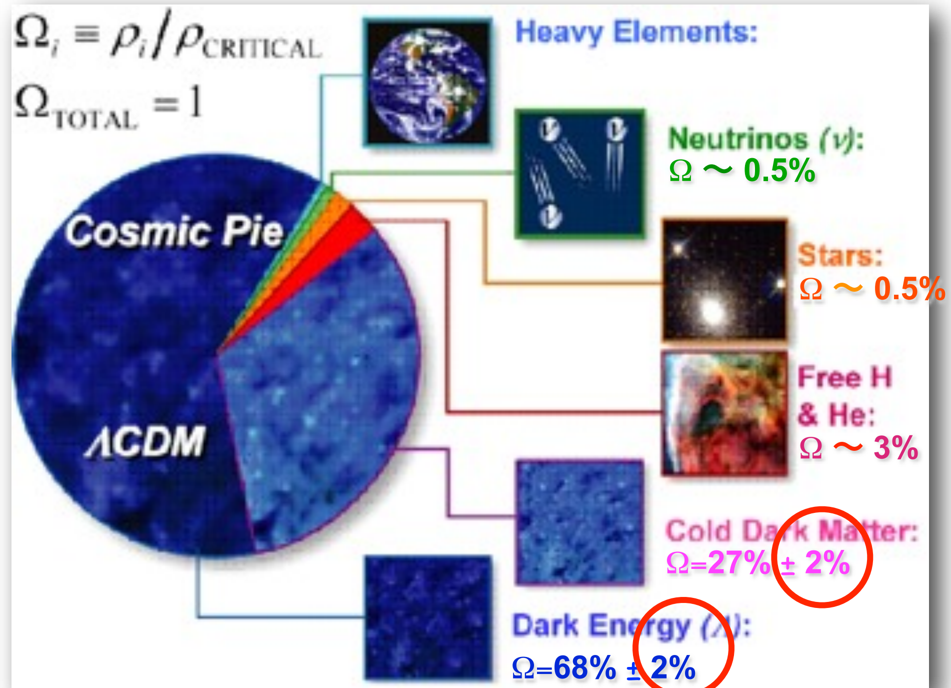




- Remarkable agreement
- Remarkable precision (<10%)

Synthesis





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We know how much, but no idea what it is.

Dark matter	Dark energy
No known particles contribute	All known particles contribute
Probably tied to $m_{weak} \sim 100$ GeV	Probably tied to $m_{Planck} \sim 10^{19}$ GeV
Several compelling solutions	No compelling solutions

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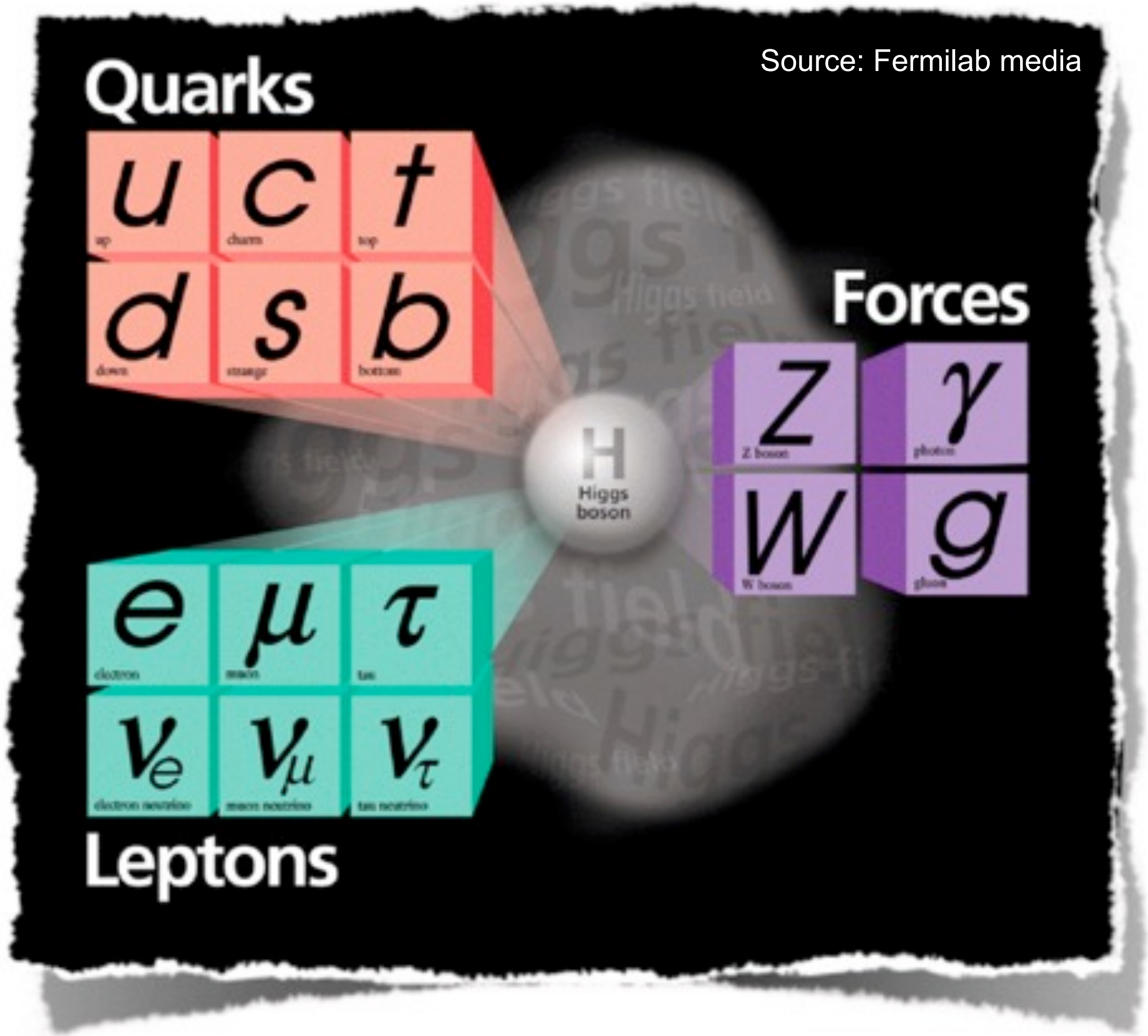
Candidates

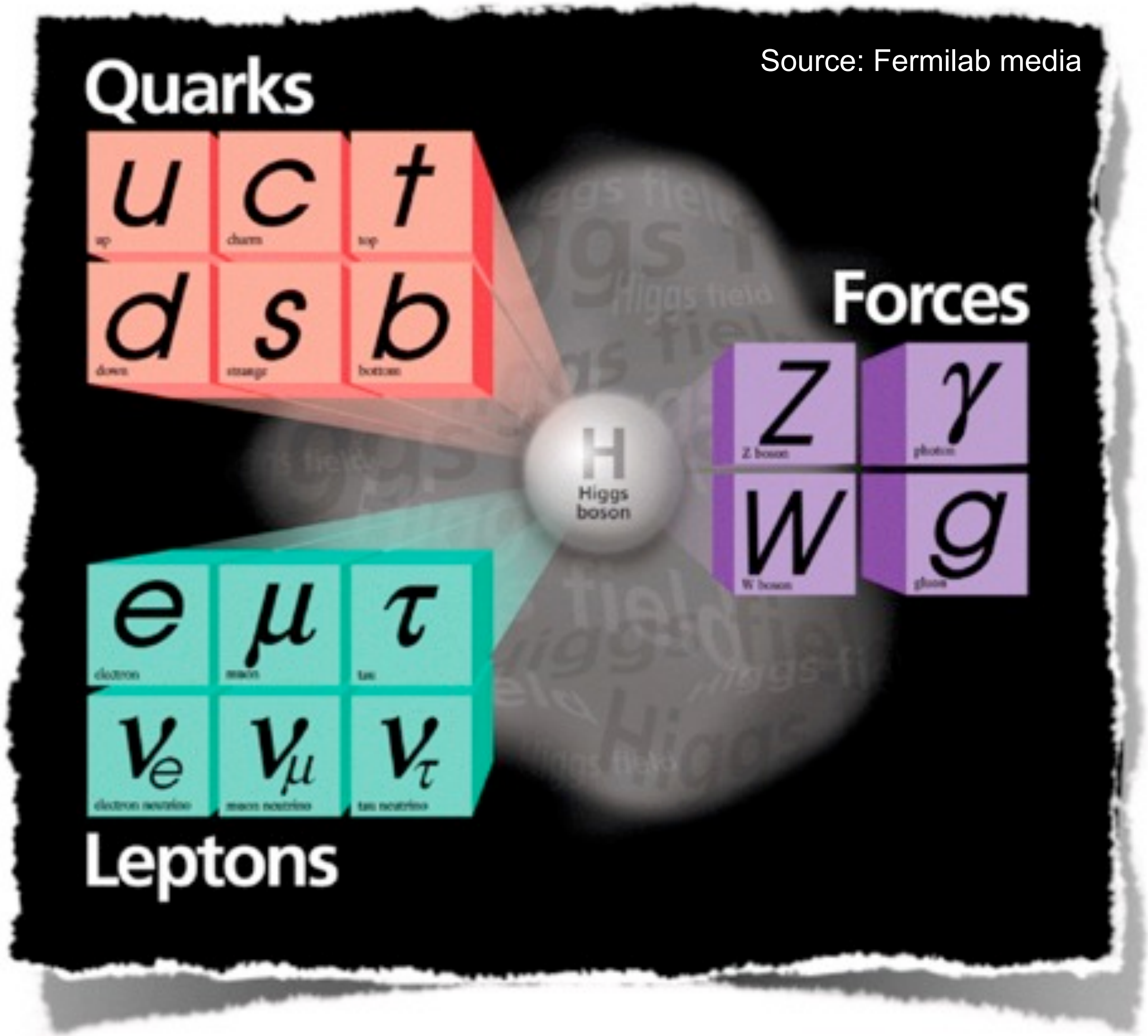
Dark matter



CDM requirements

- Stable
- Non-baryonic
- Neutral
- Cold (massive)
- Correct density
- Gravitational interacting

Dark matter



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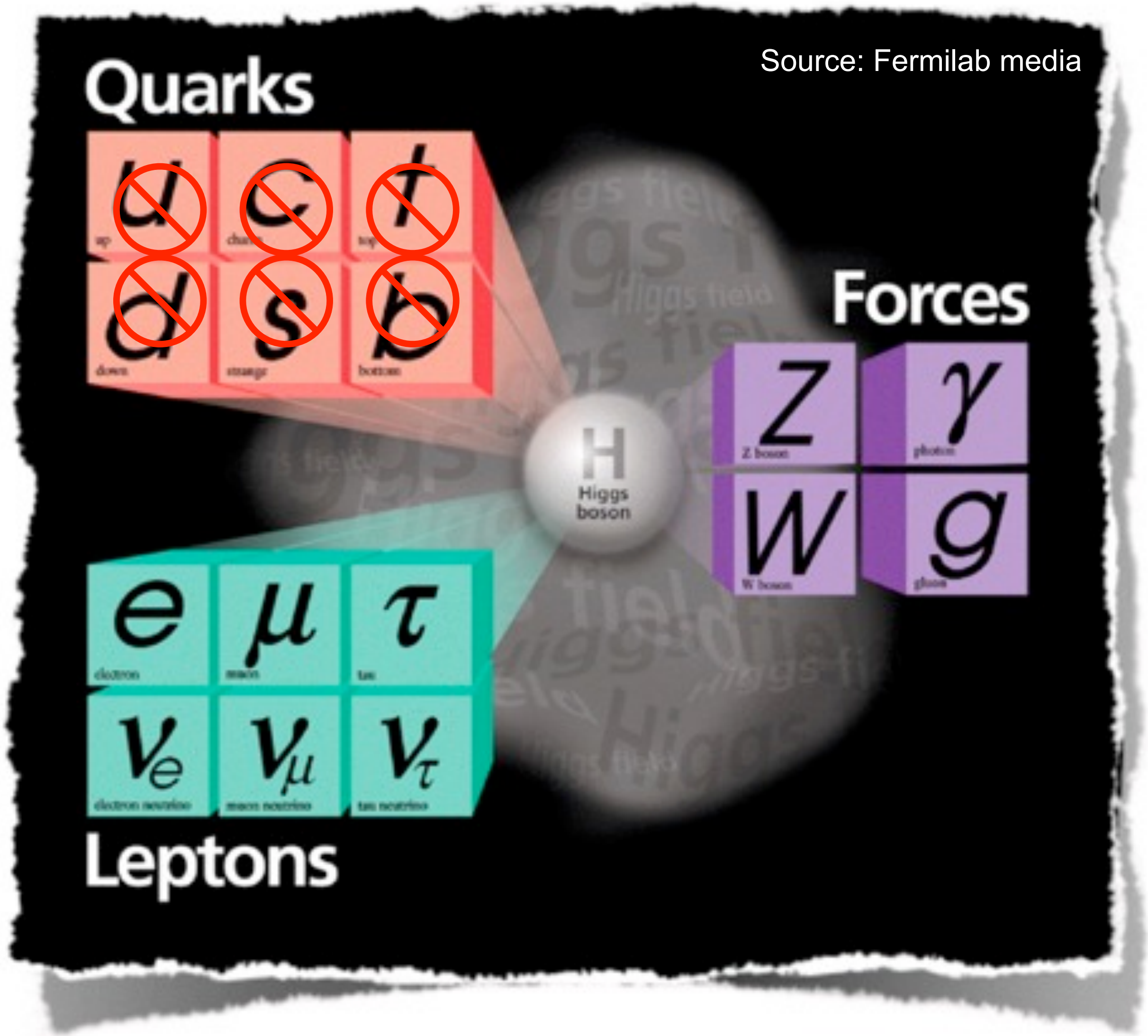

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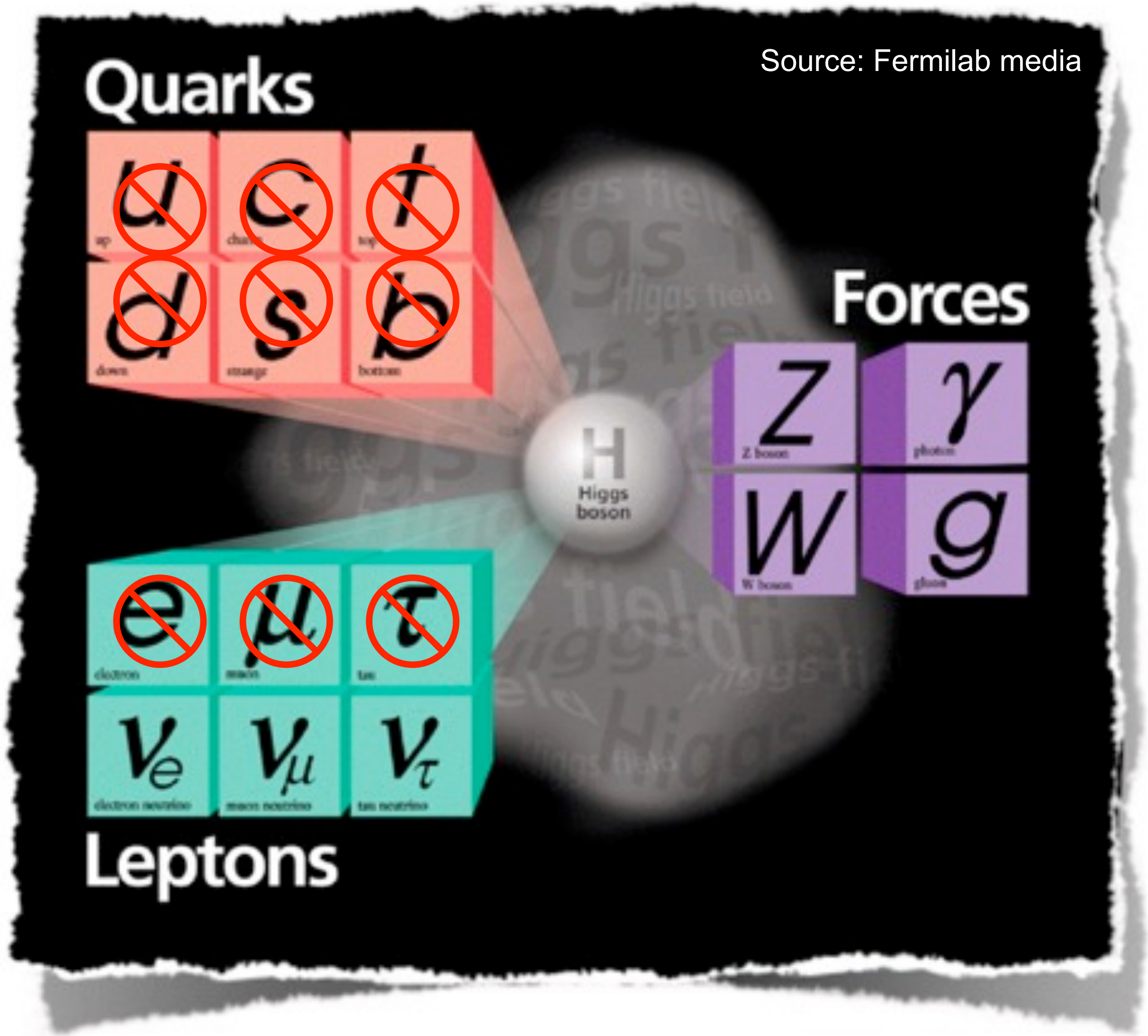

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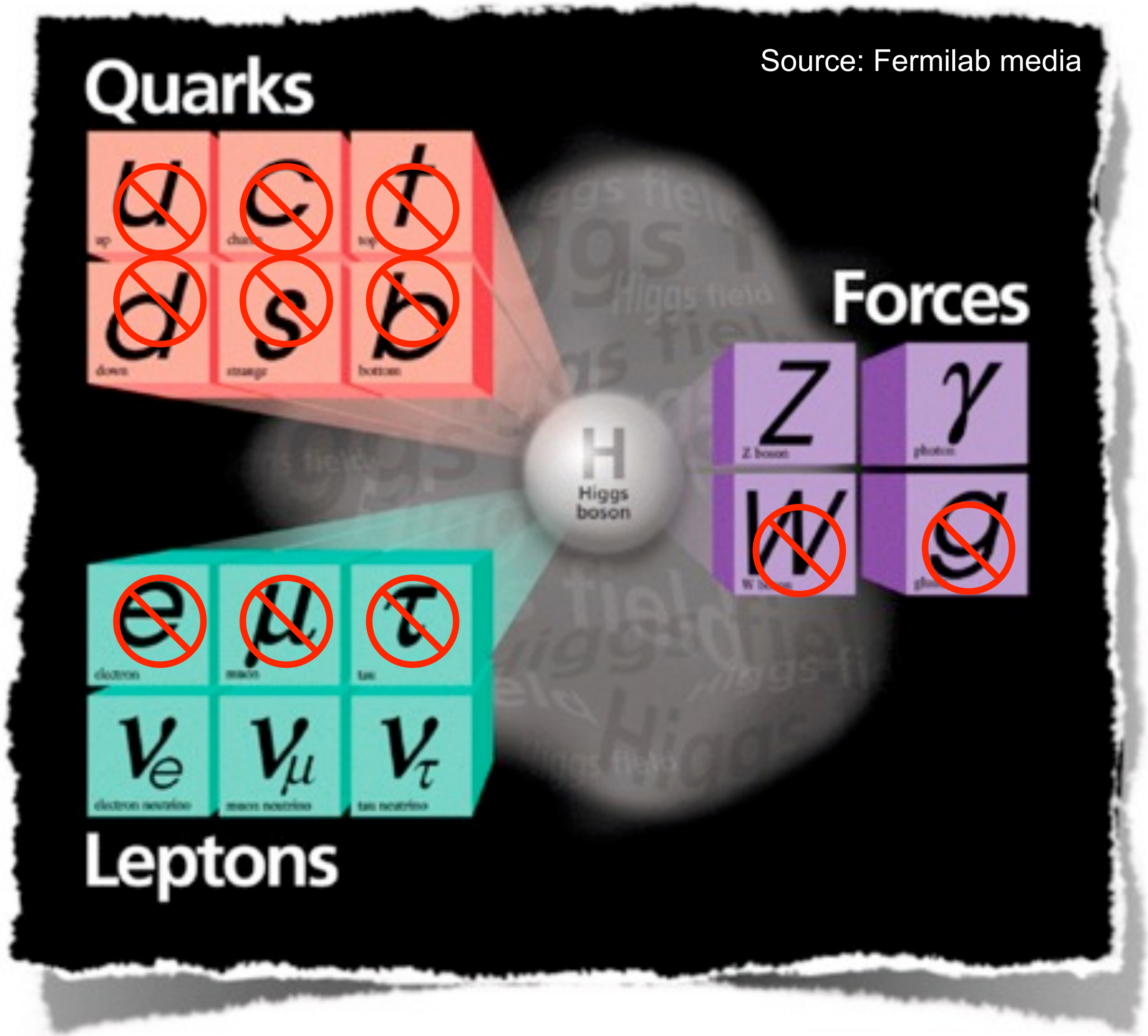

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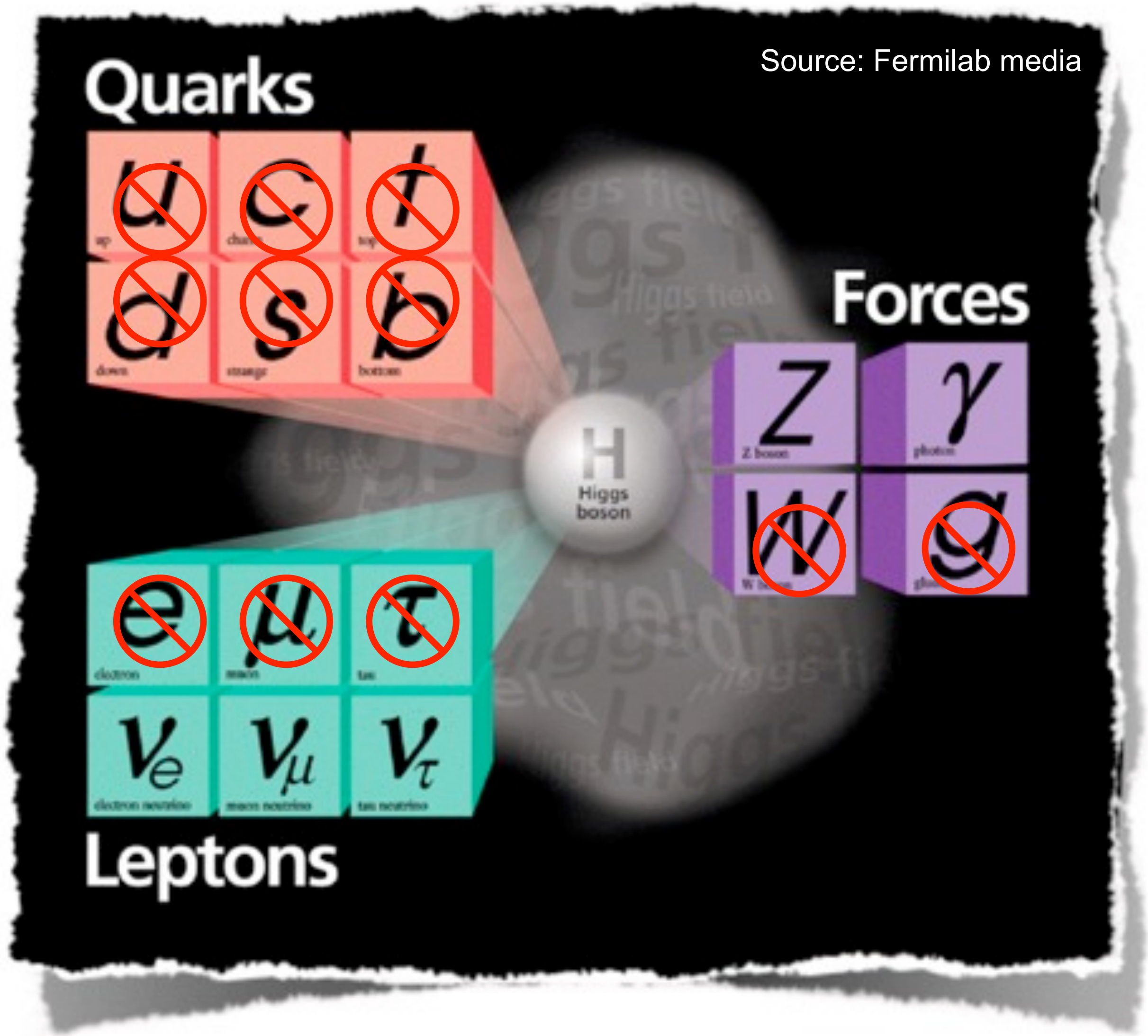

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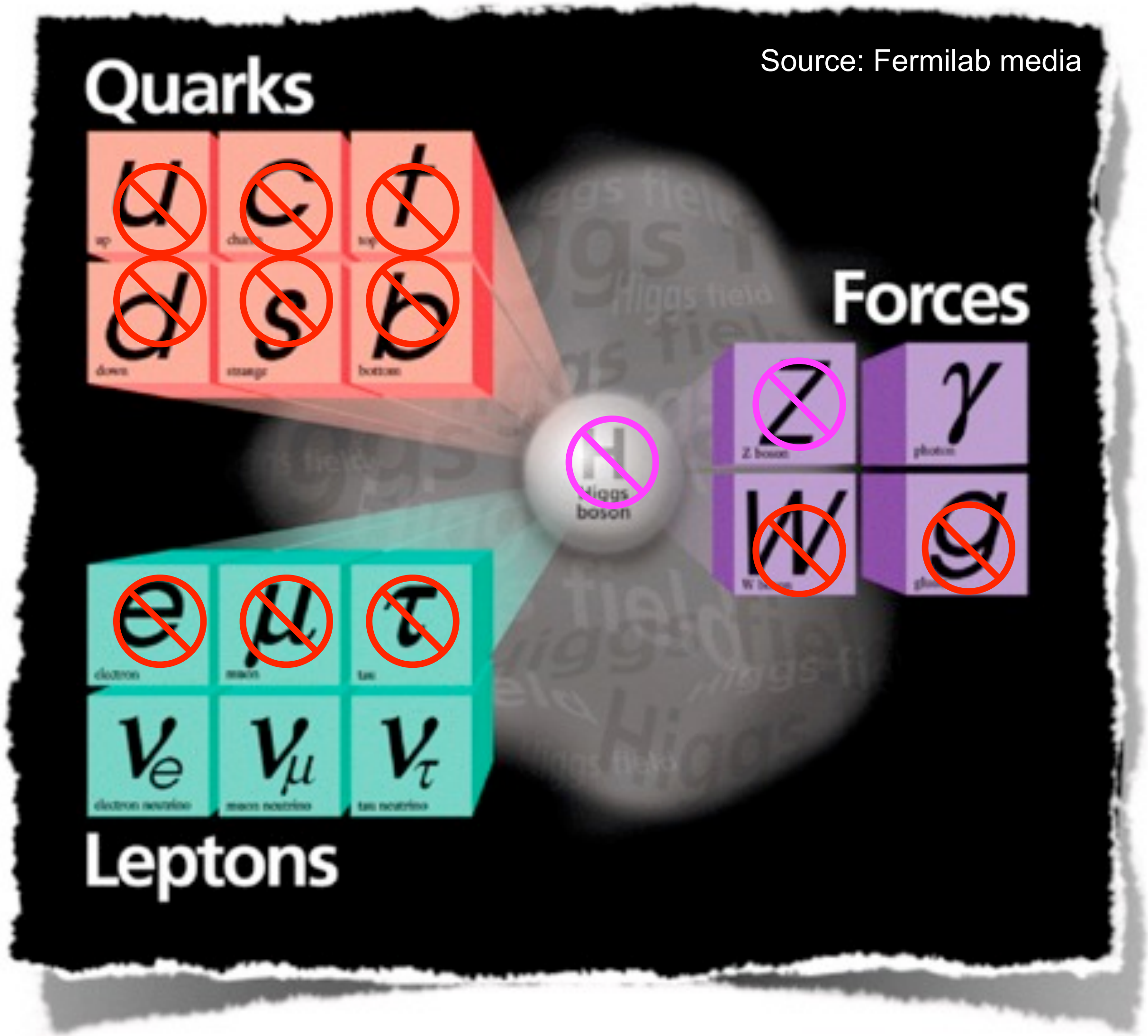

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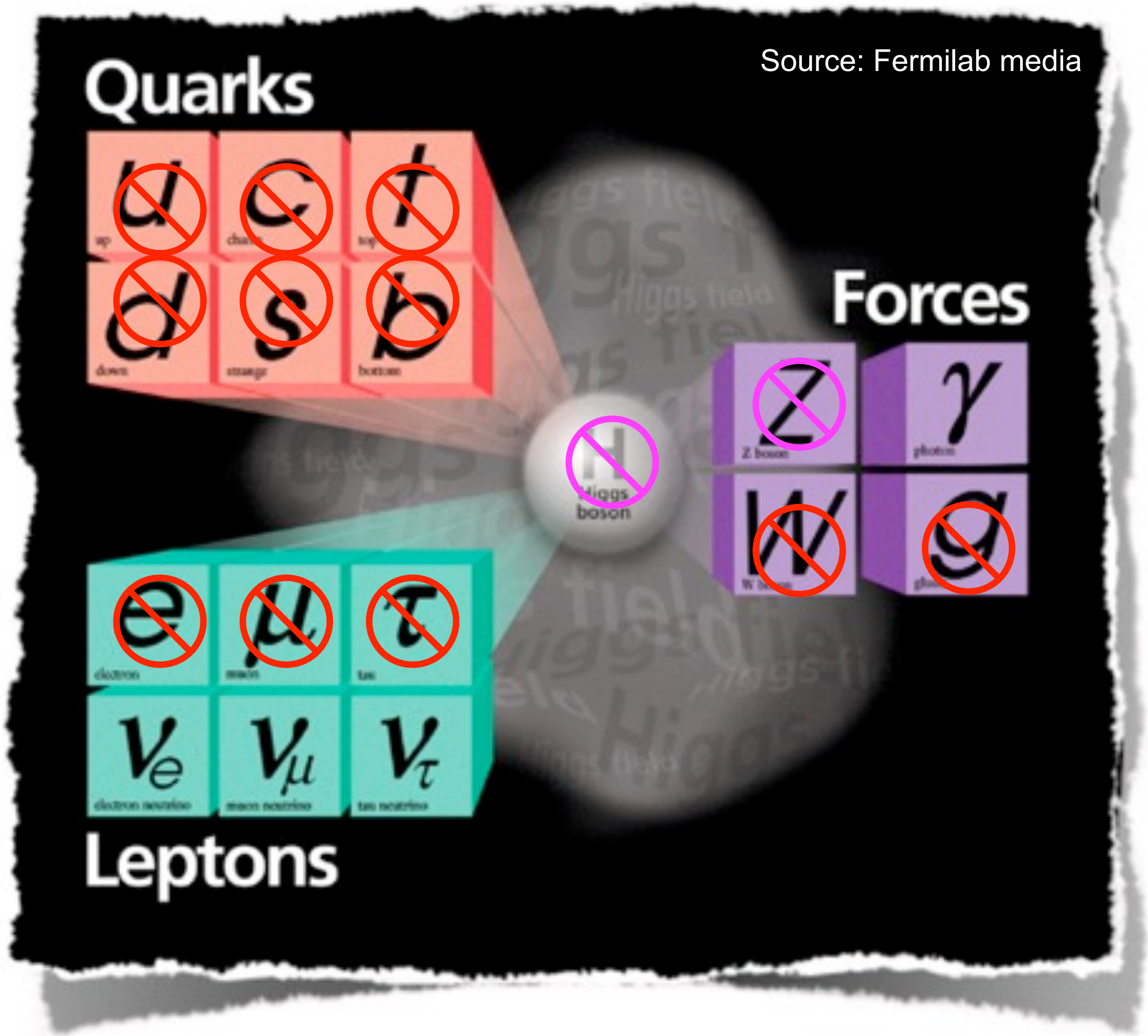

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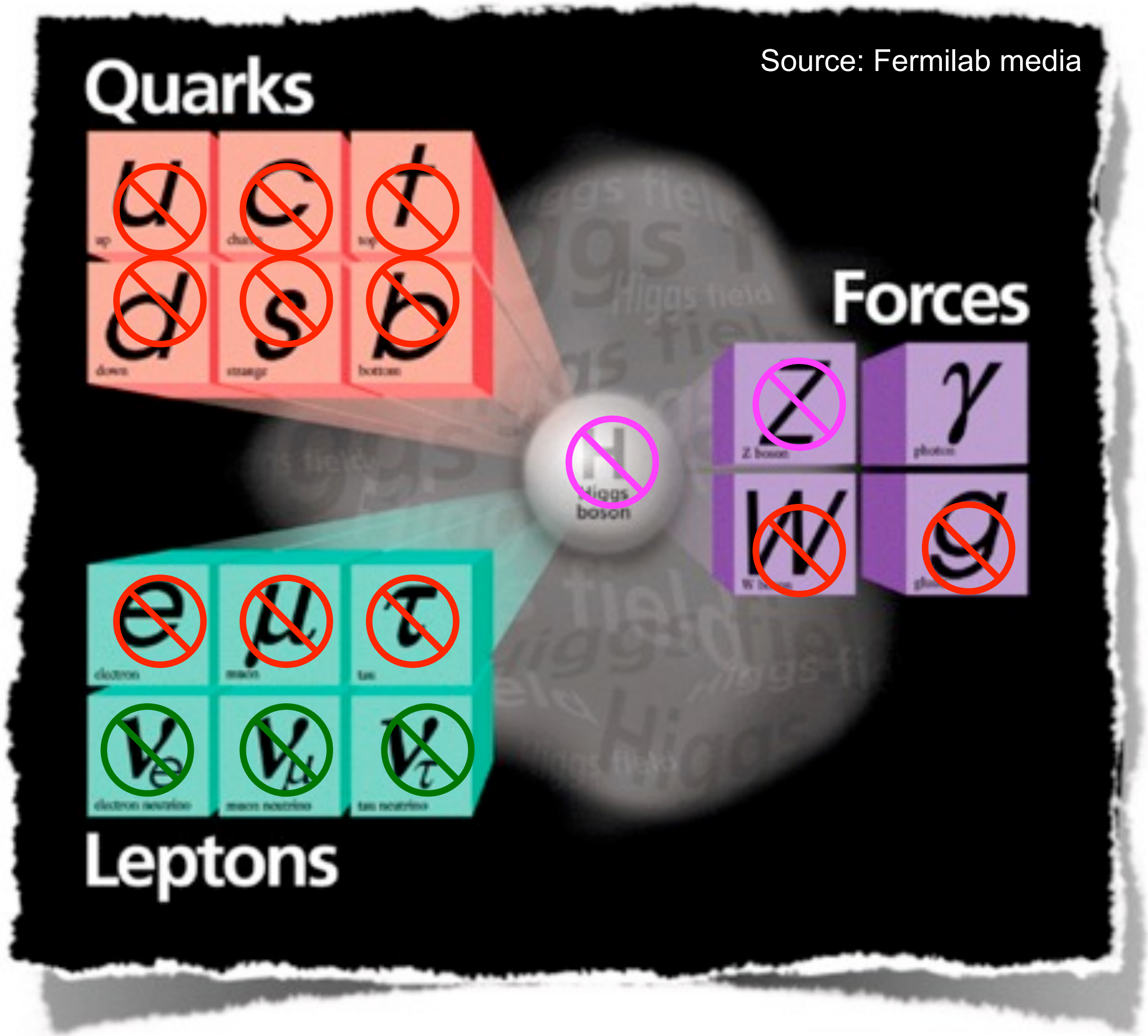

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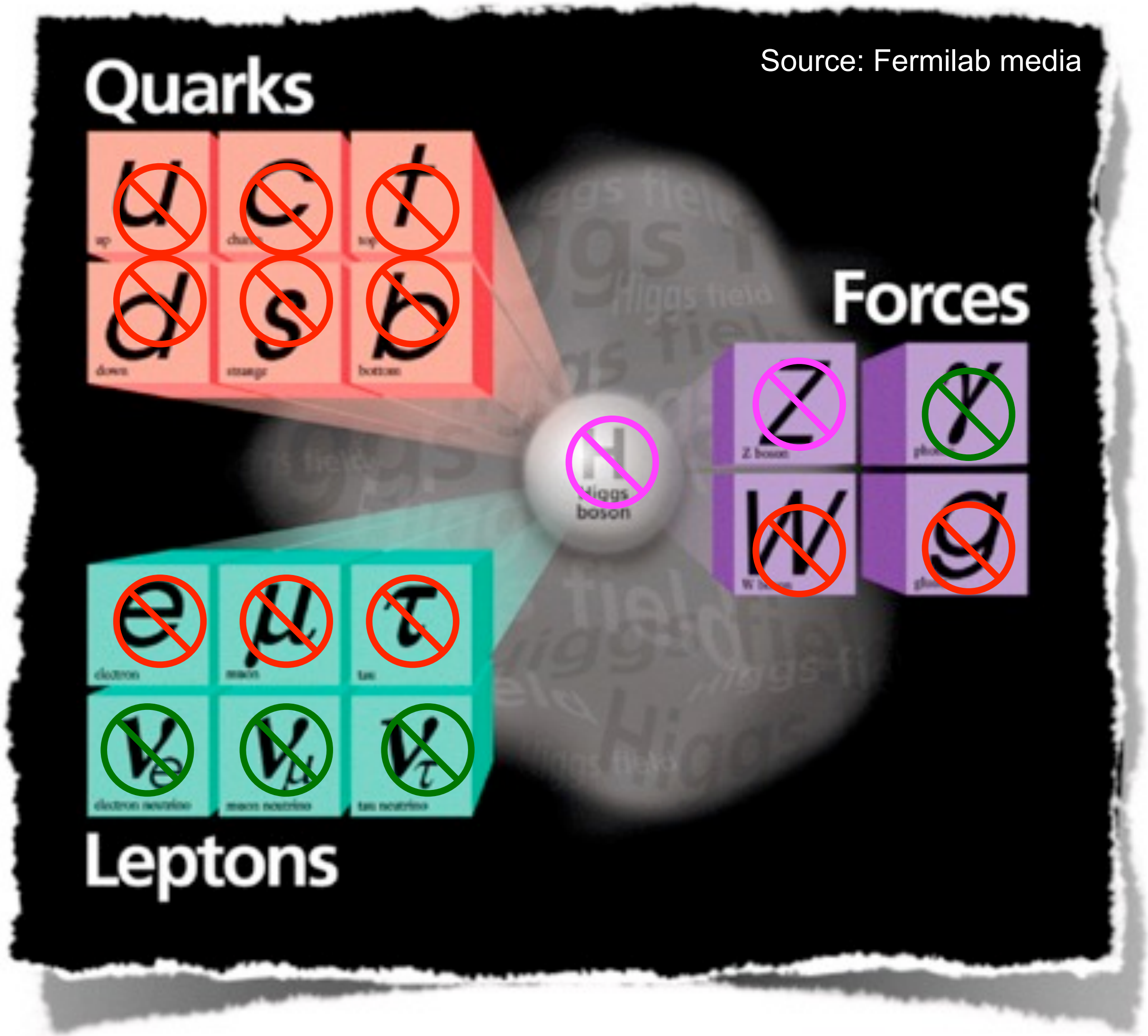

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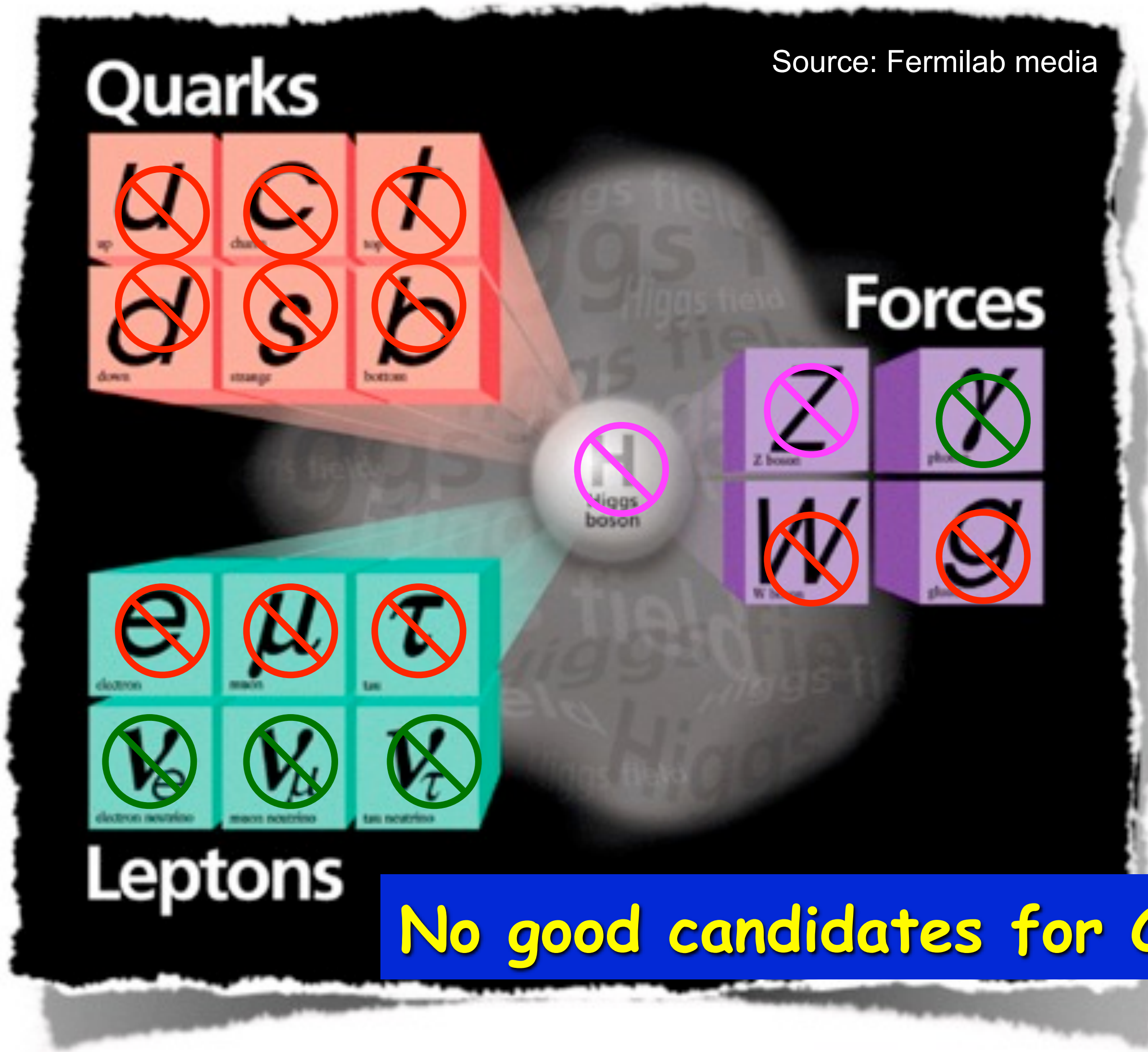

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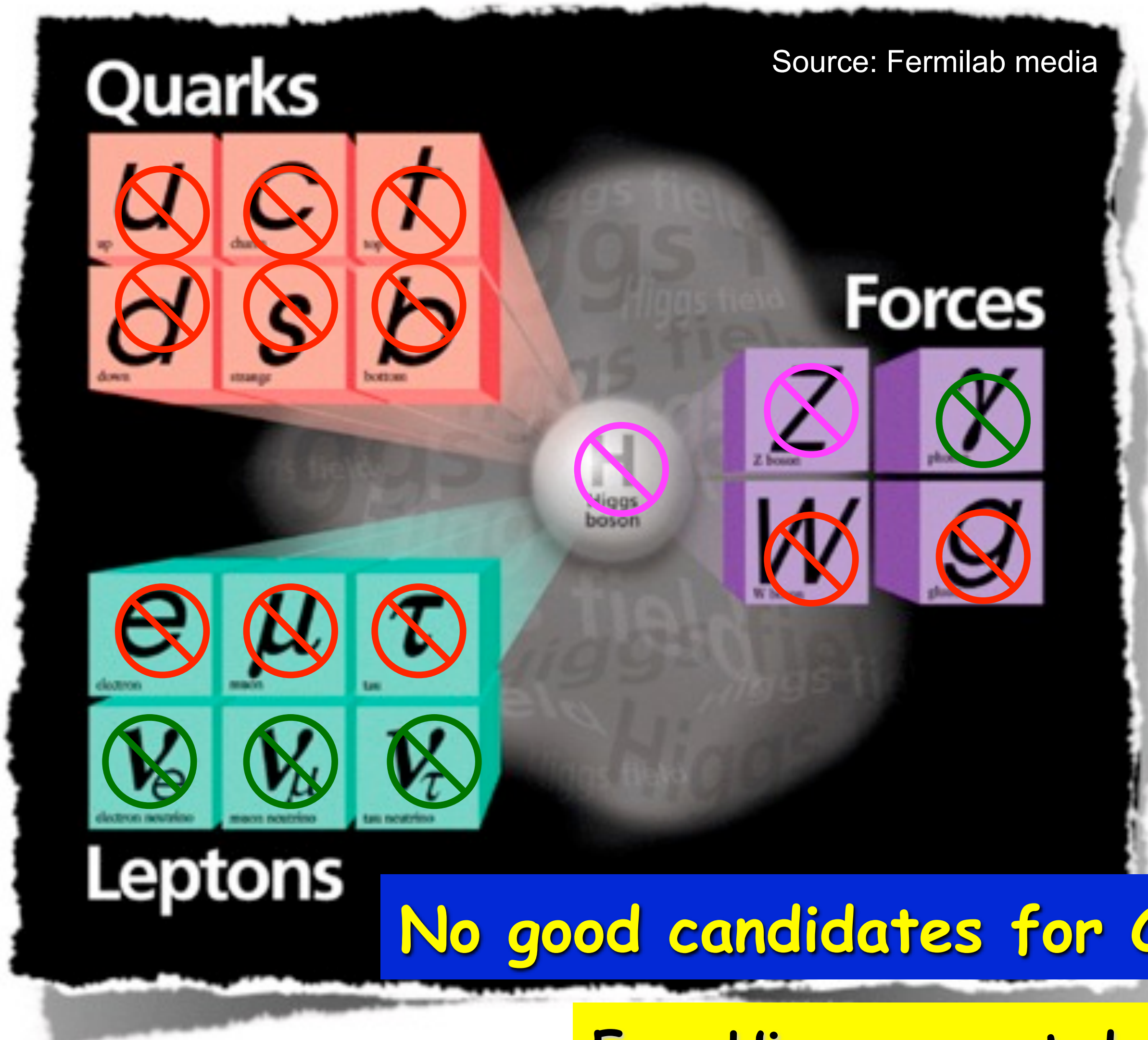
No good candidates for CDM in SM

Dark matter



CDM requirements

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- Non-baryonic
- Neutral
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- Correct density
- Gravitational interacting

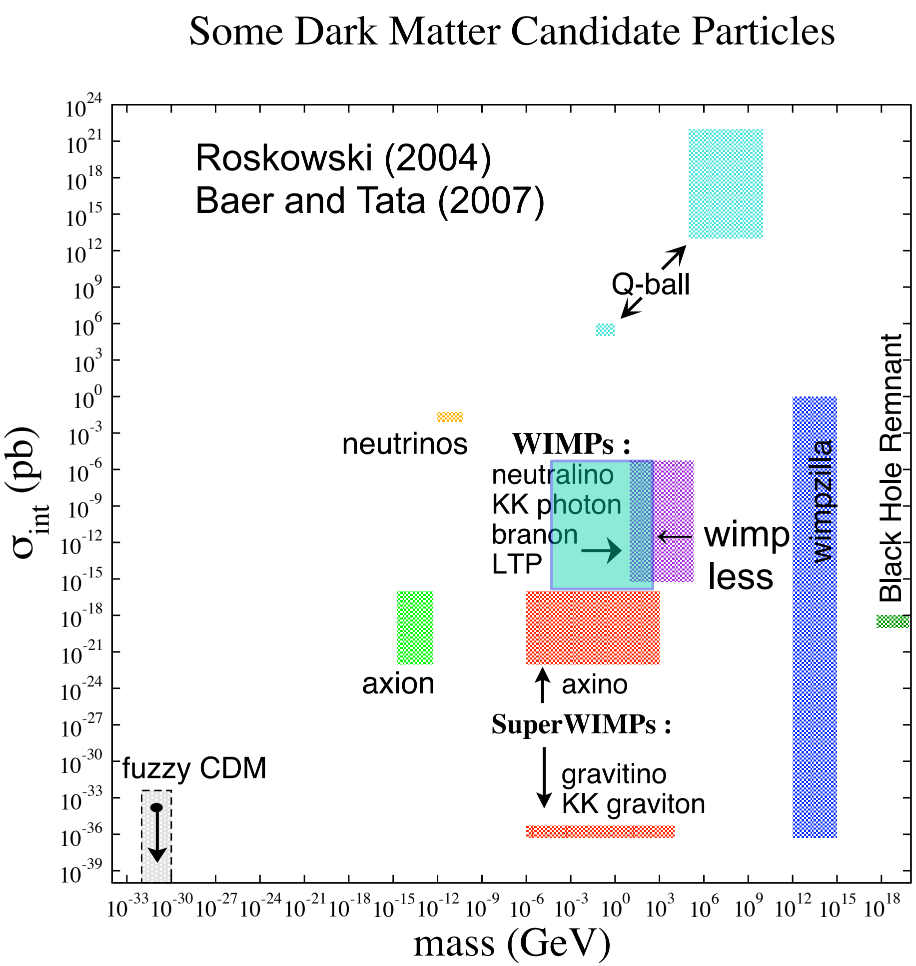
No good candidates for CDM in SM

Even Higgs can not do it !

Zoo of dark matter

DM provide precise, unambiguous evidence for new physics

mass and interaction strengths span many, many orders of magnitude



Zoo of dark matter

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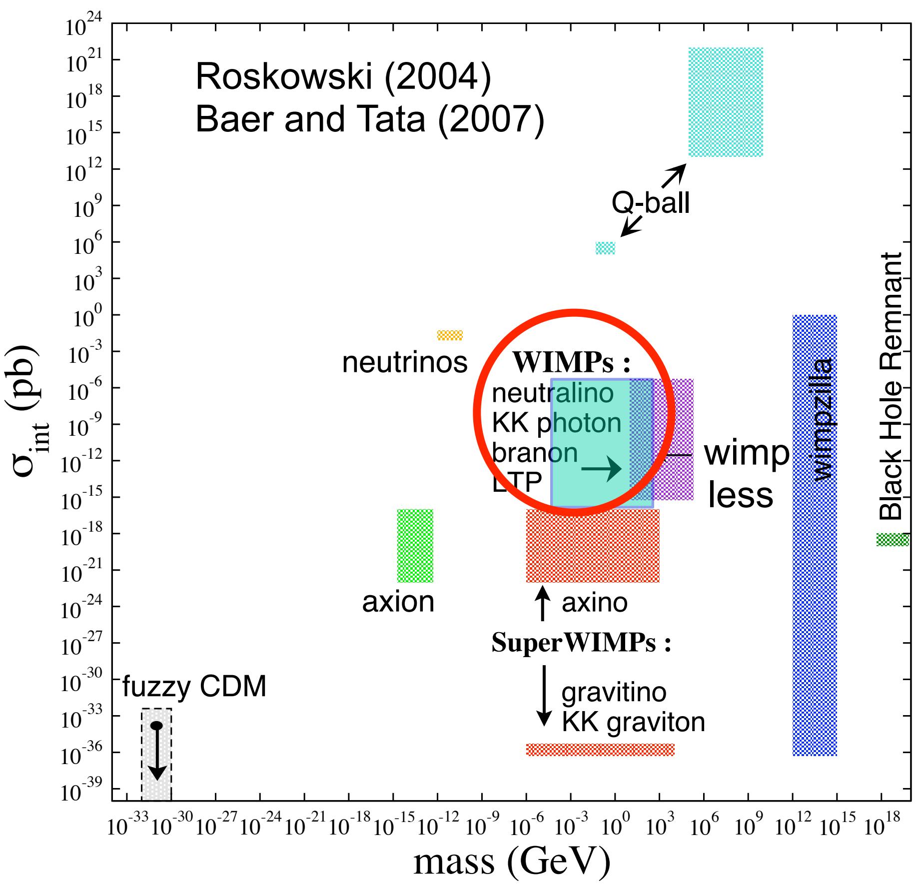
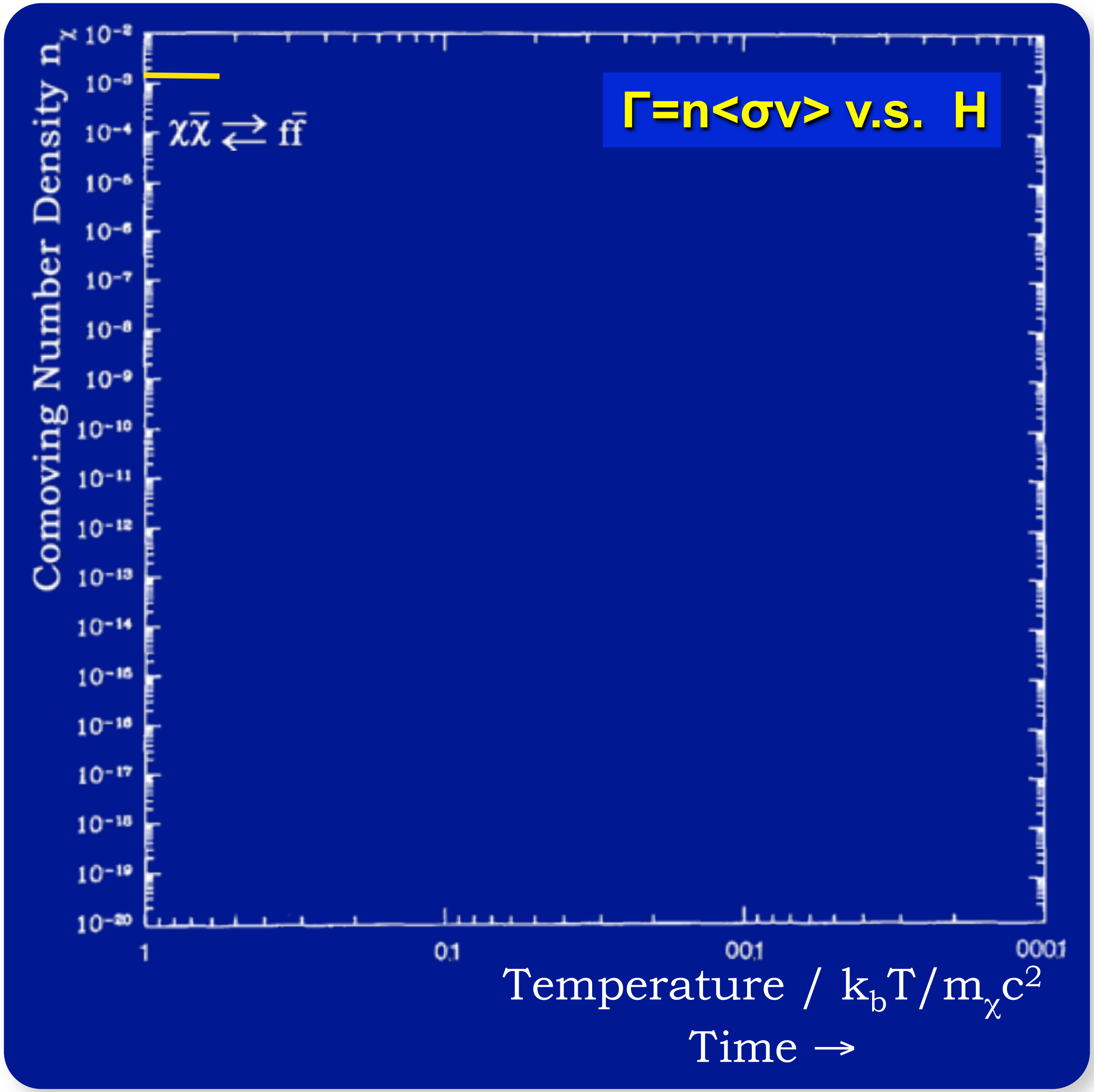
Some Dark Matter Candidate Particles

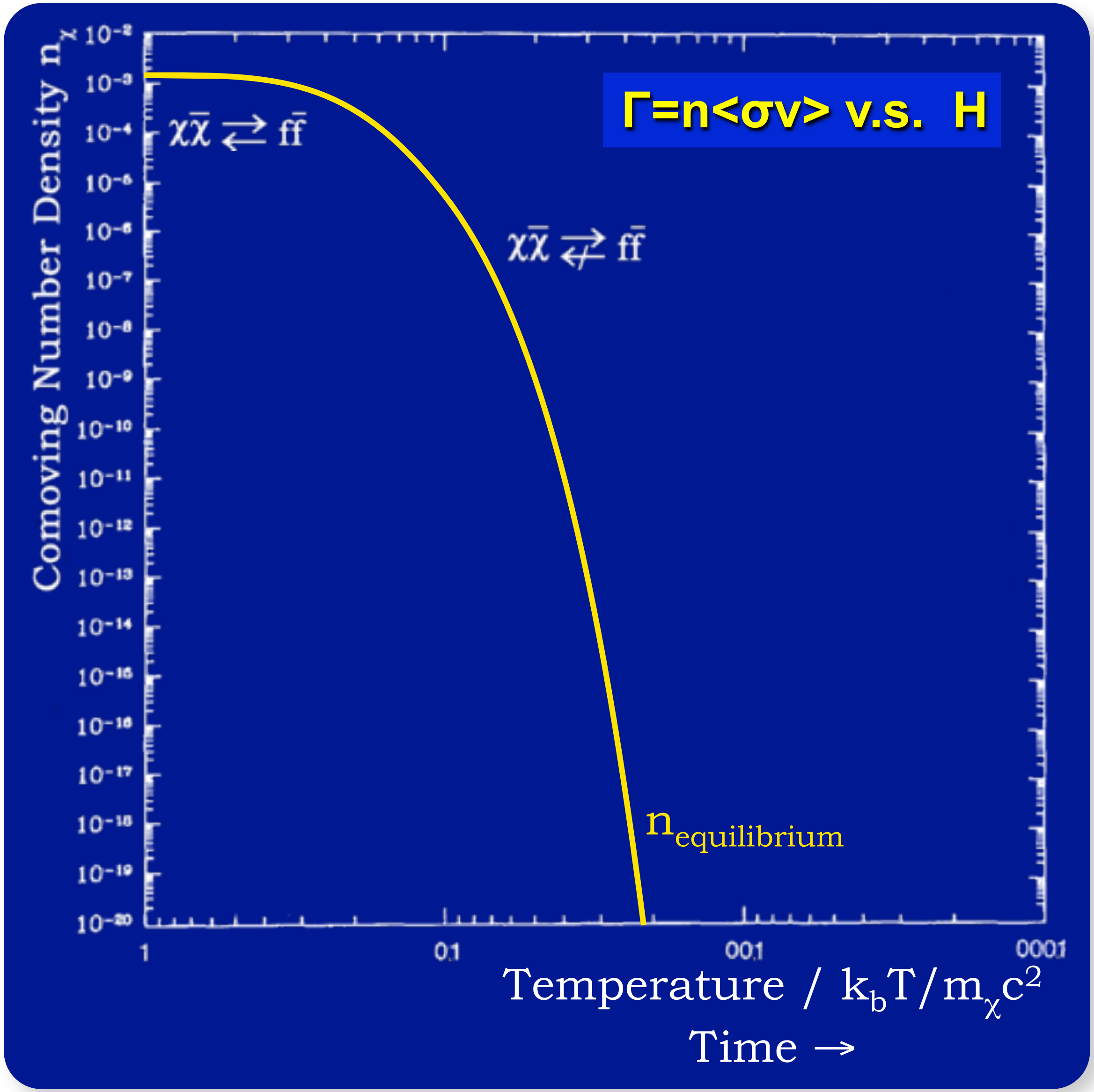


WIMP



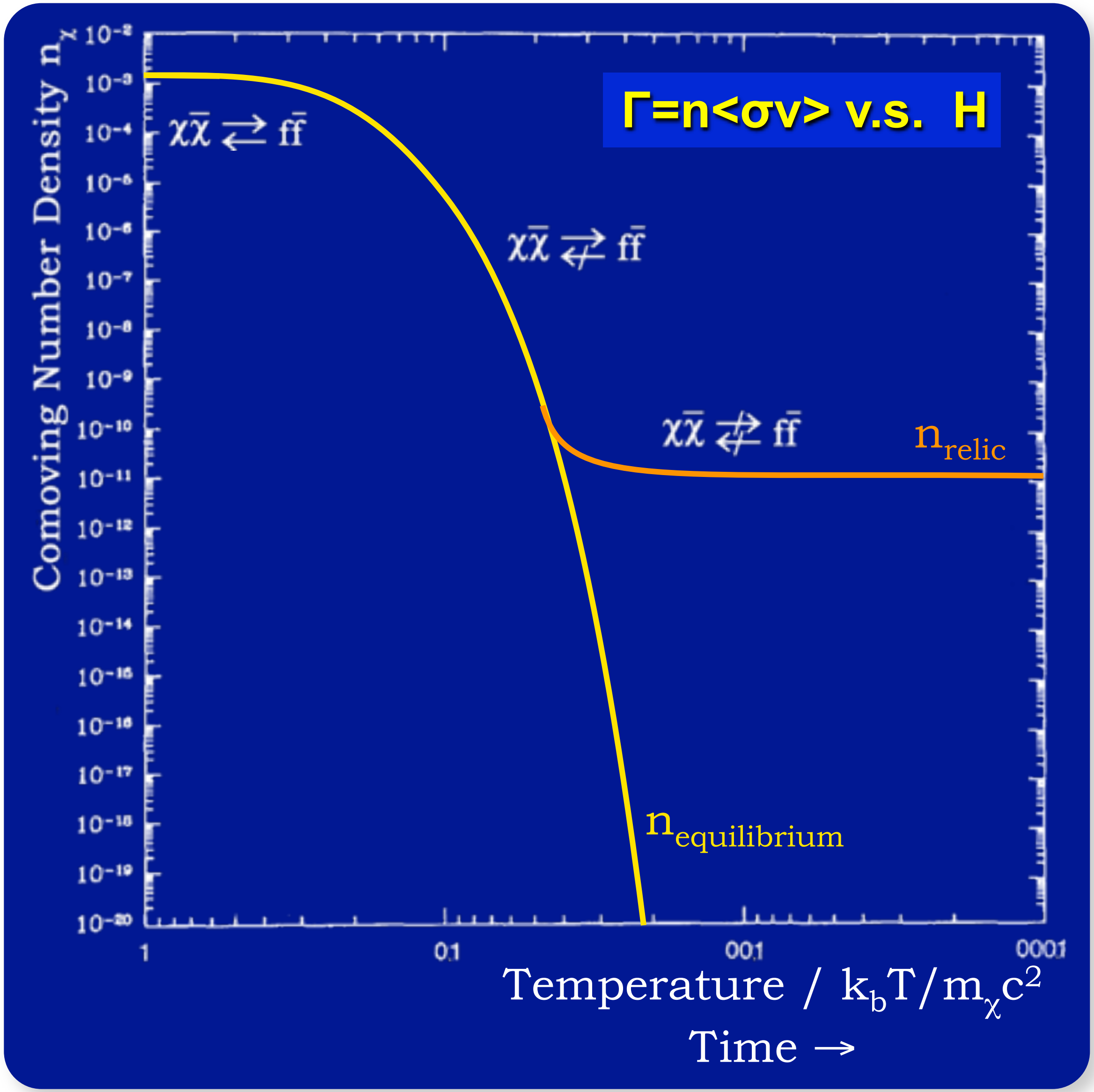
Comoving Number Density n_χ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
Γ=n<σv> v.s. H
1
0.1
0.01
0.001
Temperature / $k_b T/m_\chi c^2$
Time →

WIMP



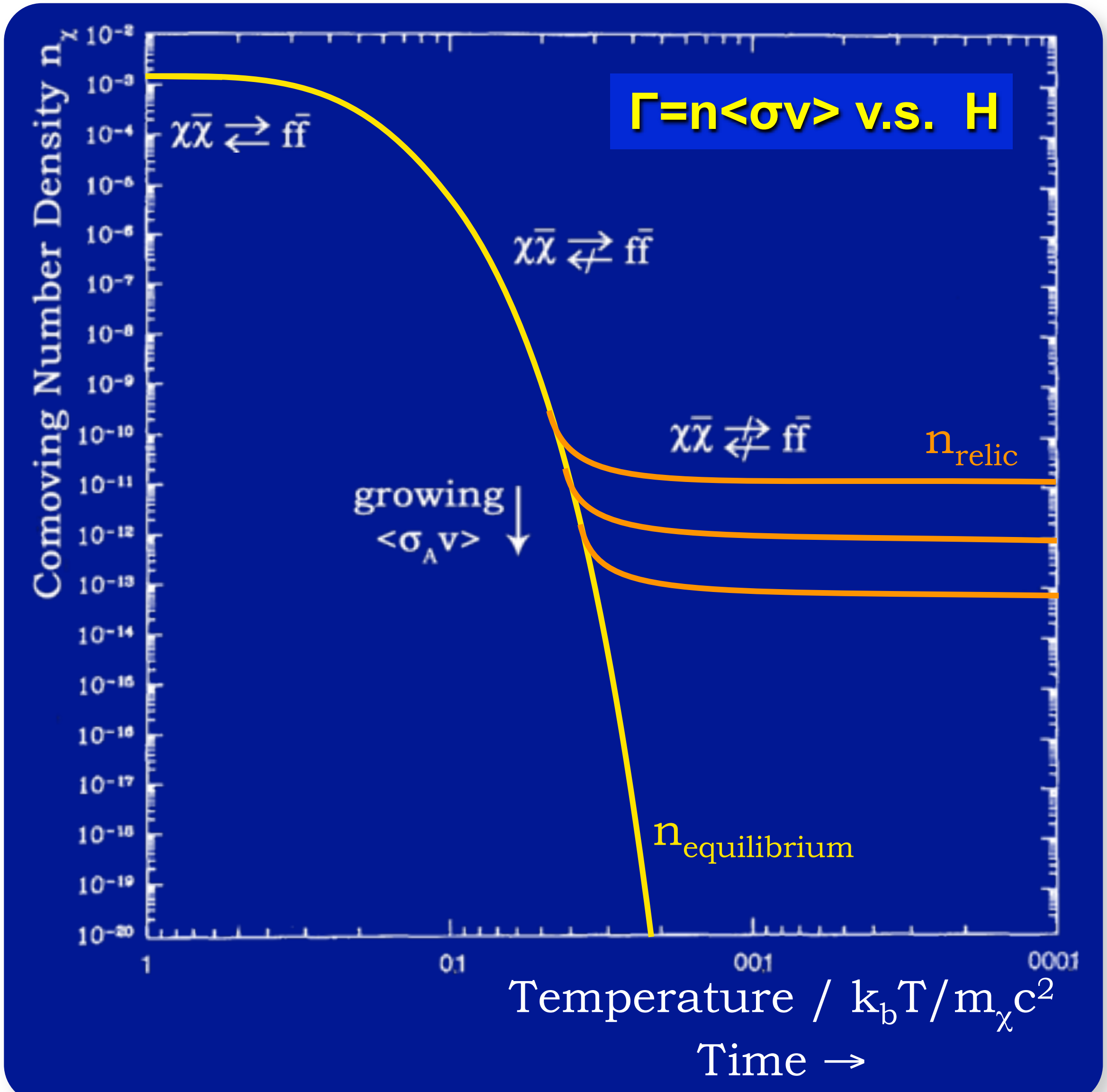
Γ=n<σv> v.s. H
Comoving Number Density n_χ
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
$n_{equilibrium}$
1
0.1
0.01
0.001
Temperature / $k_bT/m_\chi c^2$
Time →

WIMP



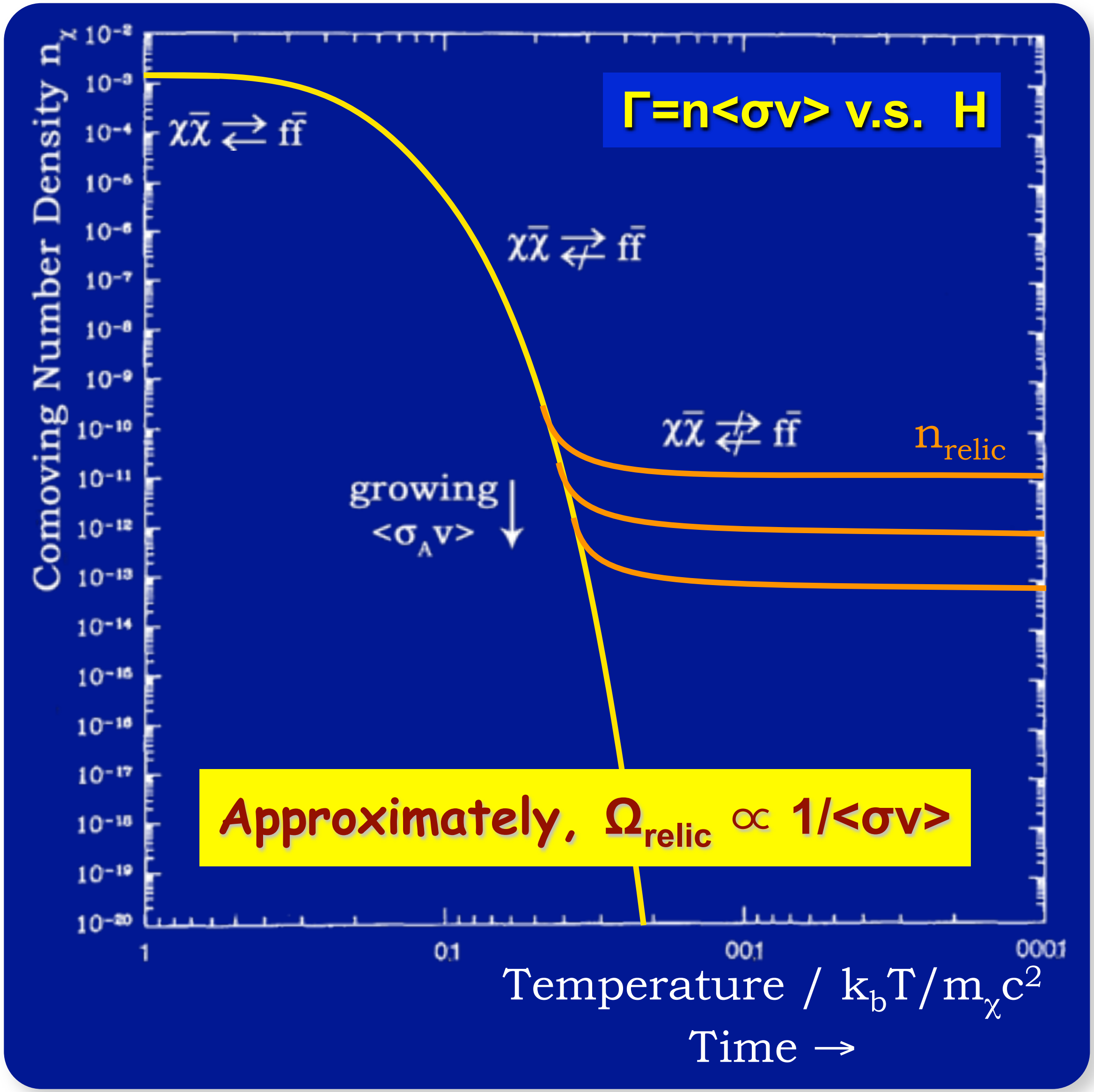
Comoving Number Density n_χ
$\Gamma = n\langle\sigma v\rangle$ v.s. H
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
n_{relic}
$n_{equilibrium}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
1
0.1
0.01
0.001
Temperature / $k_bT/m_\chi c^2$
Time →

WIMP



Comoving Number Density n_χ
Γ=n<σv> v.s. H
$\chi\bar{\chi} \rightleftarrows f\bar{f}$
n_{relic}
growing $\langle\sigma_A v\rangle$
$n_{equilibrium}$
Temperature / $k_bT/m_\chi c^2$
Time →

WIMP


Comoving Number Density n_χ
10^{-2}
10^{-3}
10^{-4}
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10^{-6}
10^{-7}
10^{-8}
10^{-9}
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$\chi\bar{\chi} \rightleftarrows f\bar{f}$
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n_{relic}
growing $\langle\sigma_A v\rangle$
Approximately, $\Omega_{relic} \propto 1/\langle\sigma v\rangle$
Temperature / $k_b T/m_\chi c^2$
Time →

WIMP

Weak Interacting Massive Particle

WIMP

- $m_{WIMP} \sim m_{weak}$
- g_{weak}^2

$$\Omega h^2 \sim \frac{2.6 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_{weak}^2} 0.1 \sim 10^{-9} \mathrm{GeV}^{-2}$$

$\Rightarrow \Omega h^2 \sim 0.3$

naturally around the observed value

WIMP

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WIMP

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- g_{weak}^2

connect to new physics @ TeV?

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naturally around the observed value

Dark matter and new physics

◉ In many BSM theories, DM is easier to explain than no DM

Dark Matter: new stable particle

- there are usually many new weak scale particles
- constraints (proton decay, large EW corrections)

↕

discrete symmetry

↕

stability

↕

good dark matter candidate

Dark matter and new physics

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$\updownarrow$

discrete symmetry

$\updownarrow$

stability

$\updownarrow$

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discrete symmetry — R-parity: SM particle + super-partner −

↕

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stability — lightest supersymmetric particle (LSP) stable
LSP $\not\Rightarrow$ SM particle, LSP $\not\Rightarrow$ super particle

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↕

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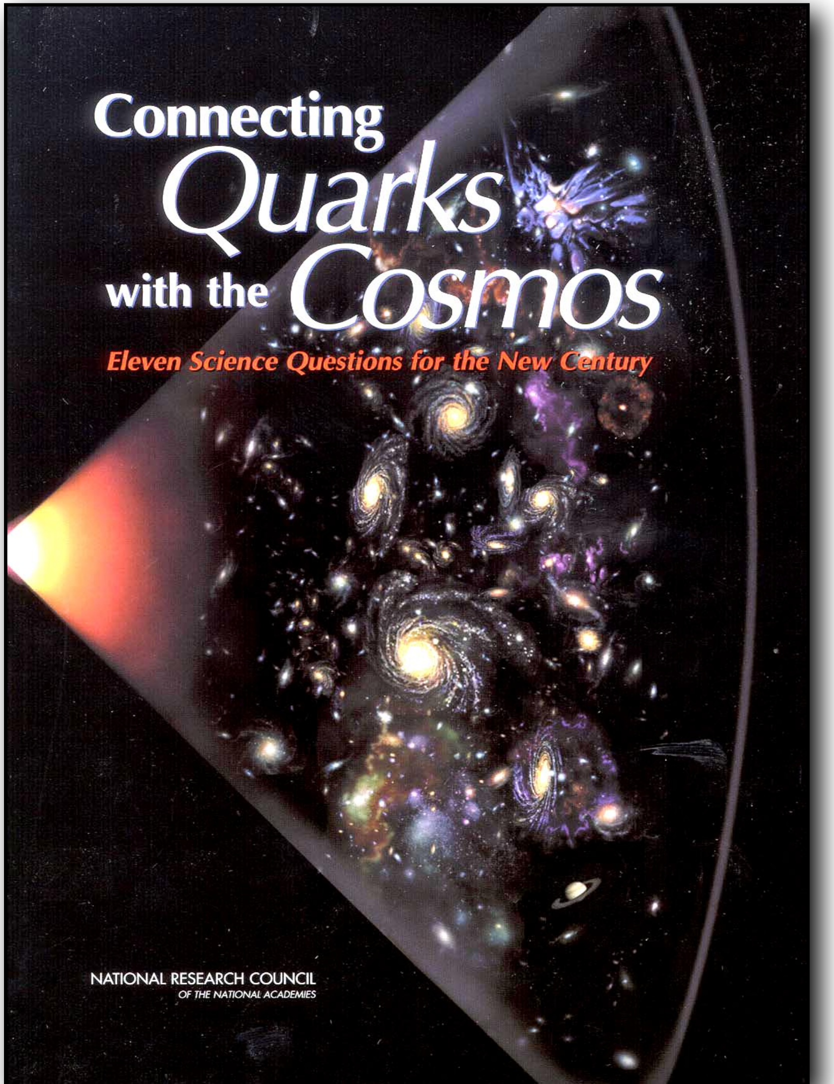
LSP $\not\Rightarrow$ SM particle, LSP $\not\Rightarrow$ super particle

↕

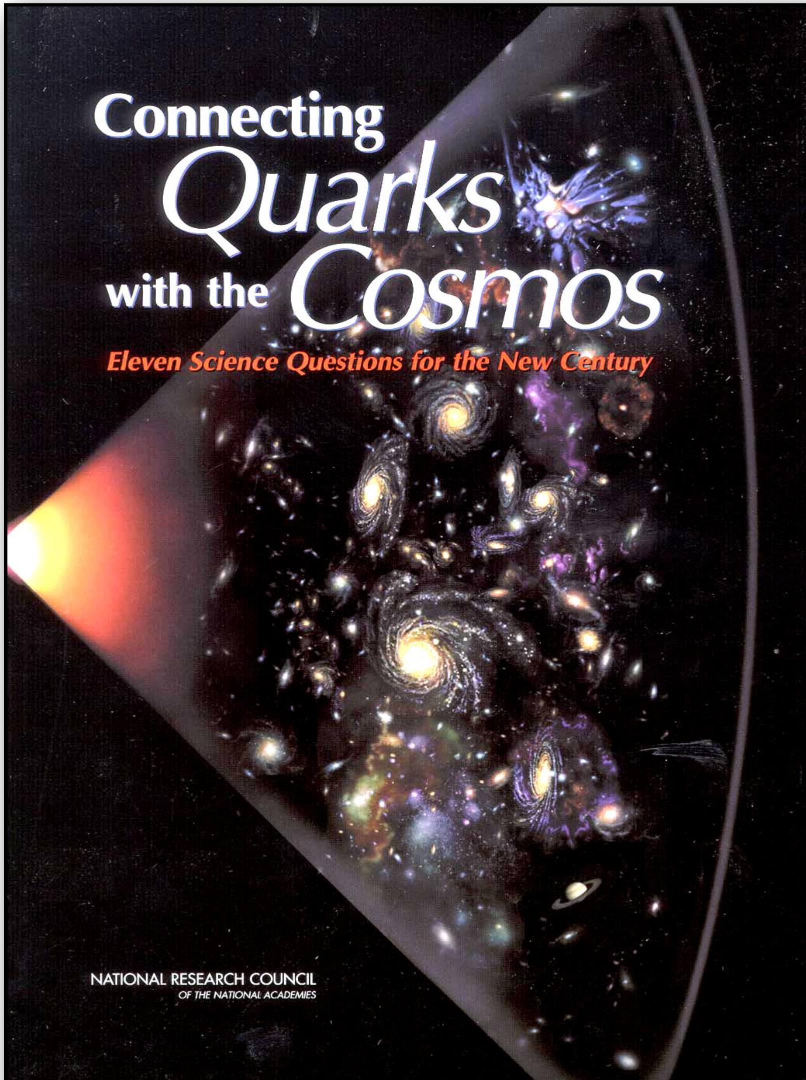
good dark matter candidate — LSP Dark Matter

LSP, LKP, LZP,...
lightest parity-odd particle

S. Su


Connecting Quarks with the Cosmos
Eleven Science Questions for the New Century
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

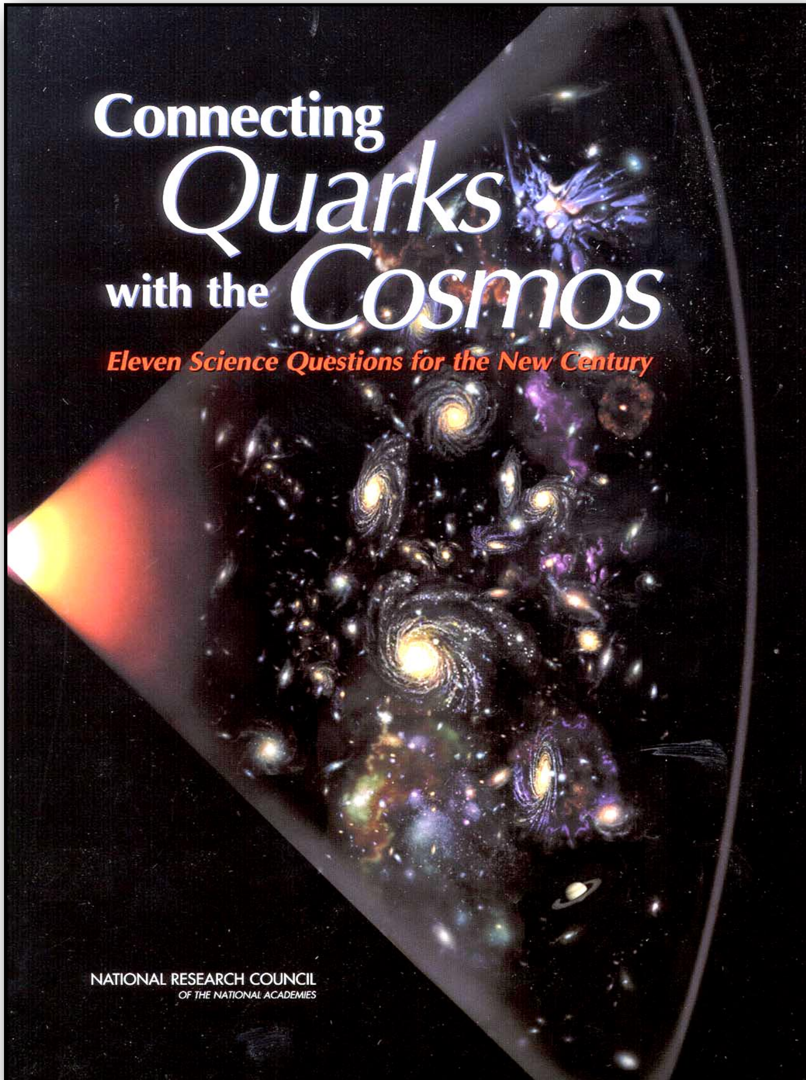
S. Su



Ouroburos

drawing by Theodores Pelecanos (1478)

S. Su



咬尾龙

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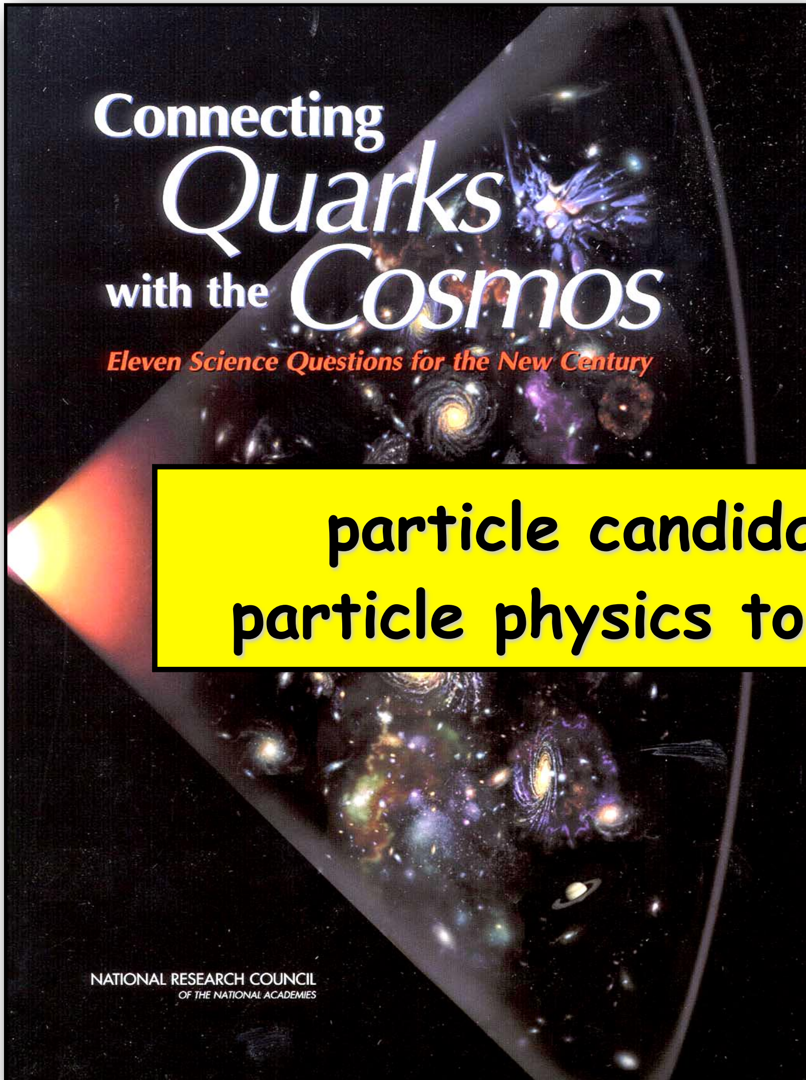

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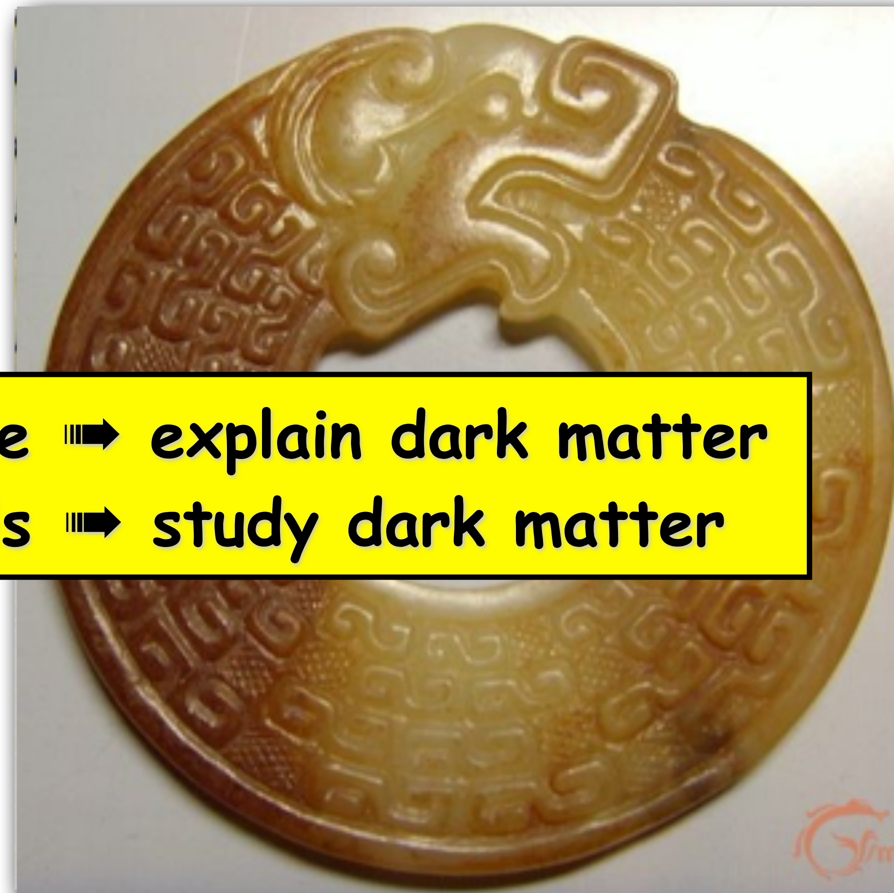


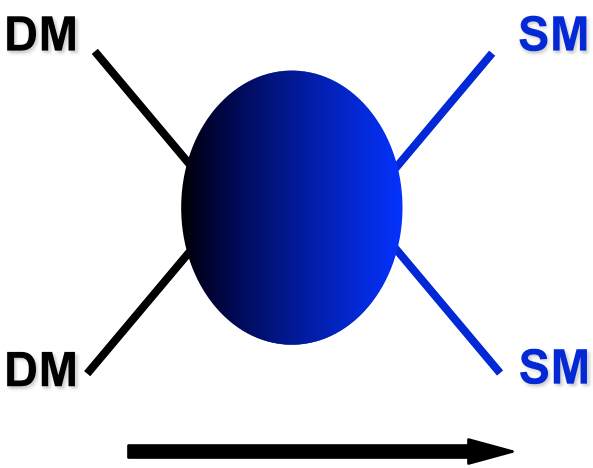
particle candidate ➠ explain dark matter

particle physics tools ➠ study dark matter

drawing by Theodores Pelecanos (1478)

Detection

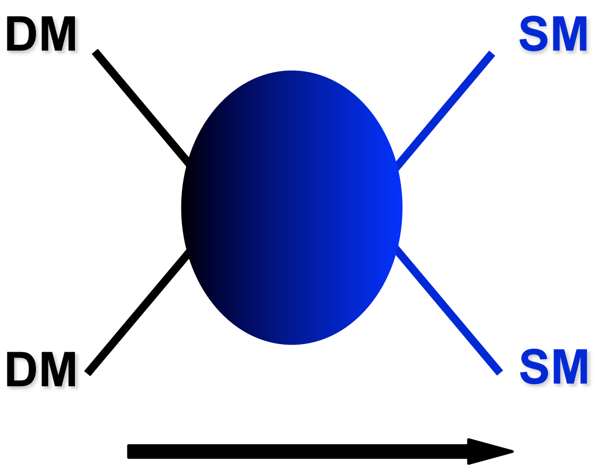
Dark matter detection



DM annihilation

Efficient annihilation then

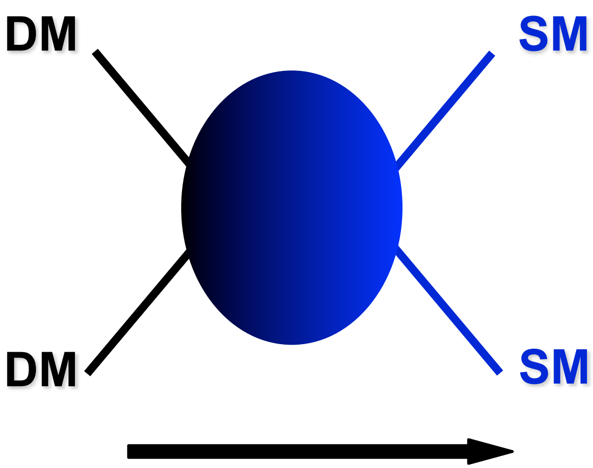
Dark matter detection



Indirect DM detection

AMS2, PAMELA, Fermi-LAT,...

Dark matter detection



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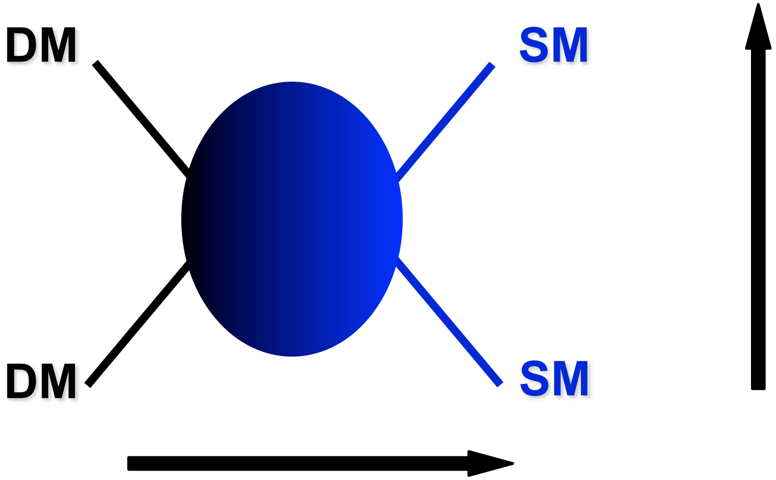

direct DM detection

CDMS, CoGeNT, CRESST, DAMA, XENON,LUX...

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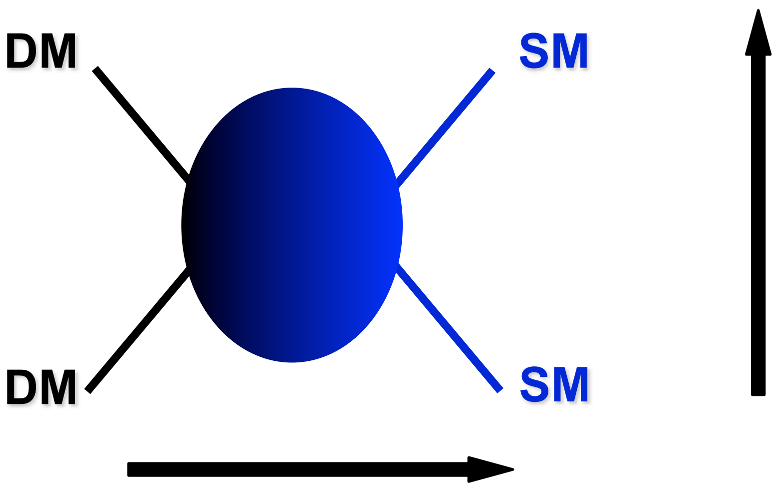
Efficient annihilation now

Dark matter detection



direct DM detection

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Efficient scattering now

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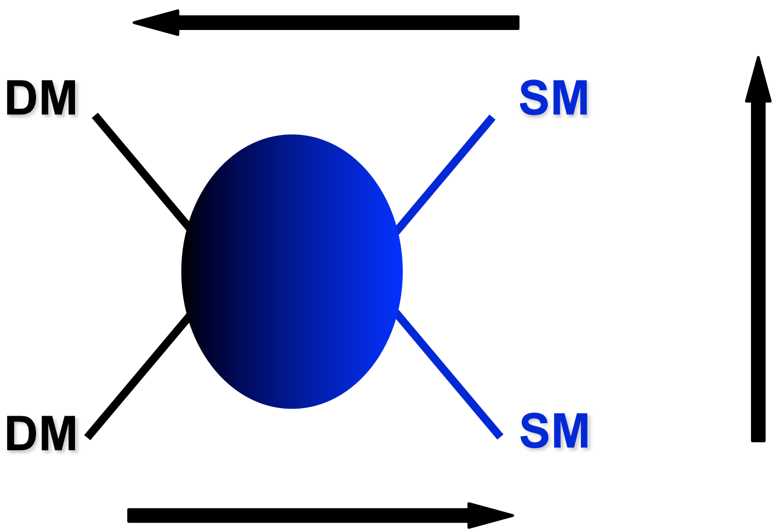
Efficient annihilation now

Dark matter detection

Collider Searches

LEP, Tevatron, LHC



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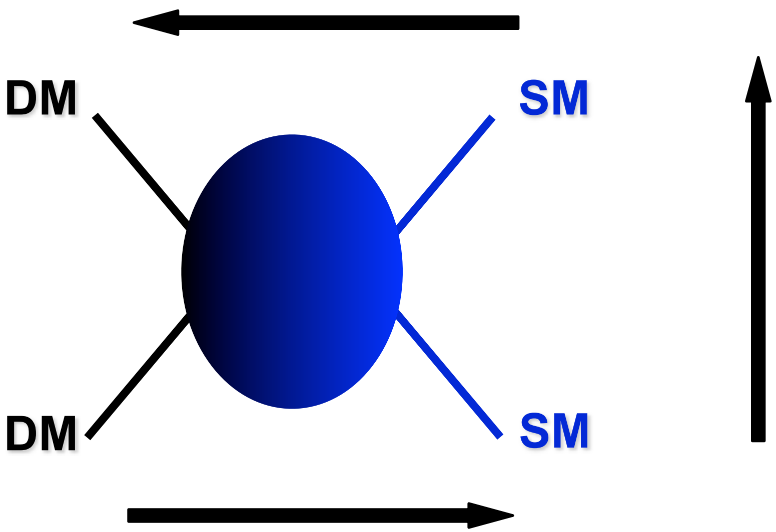

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Efficient scattering now

Indirect DM detection

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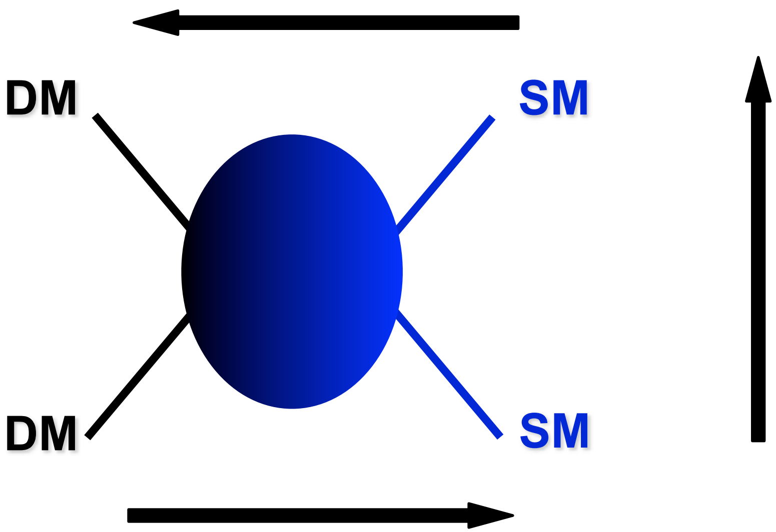
Efficient annihilation now

Caveat: might not be the same channel !

Dark matter detection

Collider Searches

LEP, Tevatron, LHC



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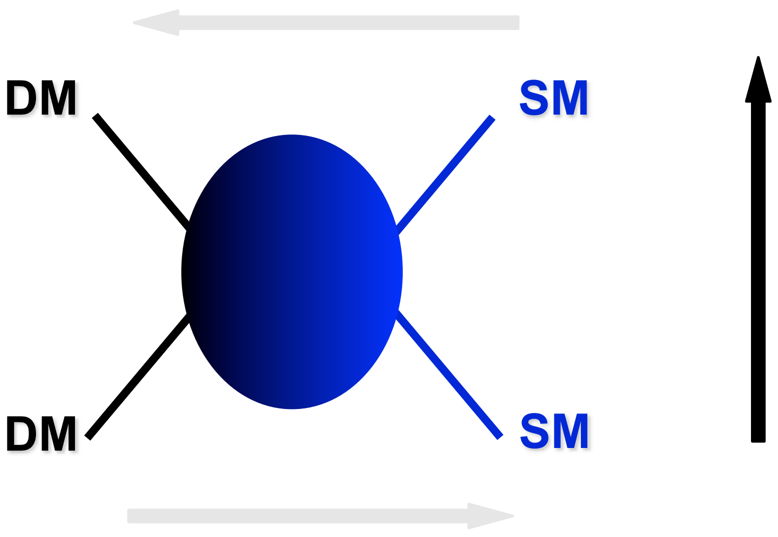

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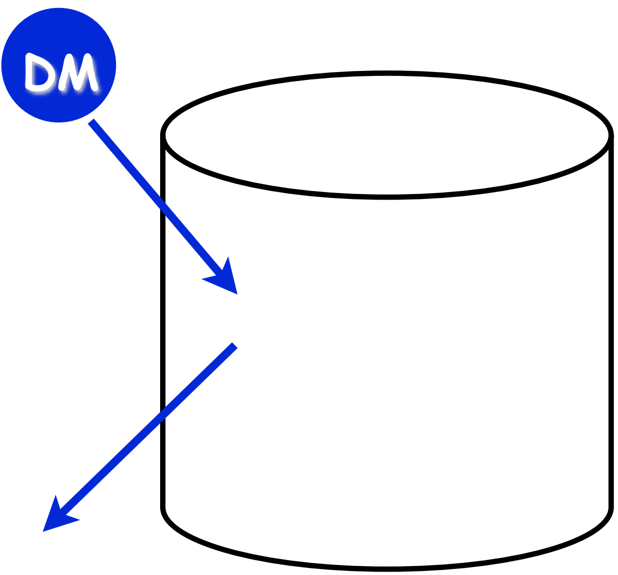
Direct detection

- Scatter from a Nuclei in a Terrestrial particle detector
- Measure nuclear recoil energy

rate: $R \approx \sum_i N_i n_X \langle \sigma_{iX} \rangle$



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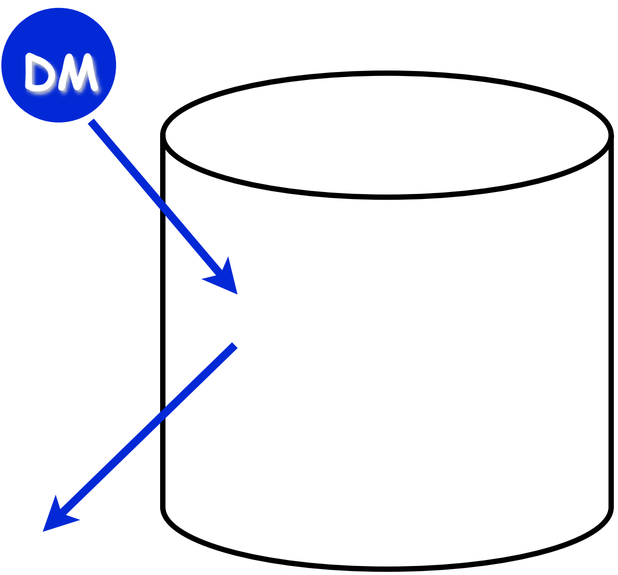
Number of target nuclei in detector



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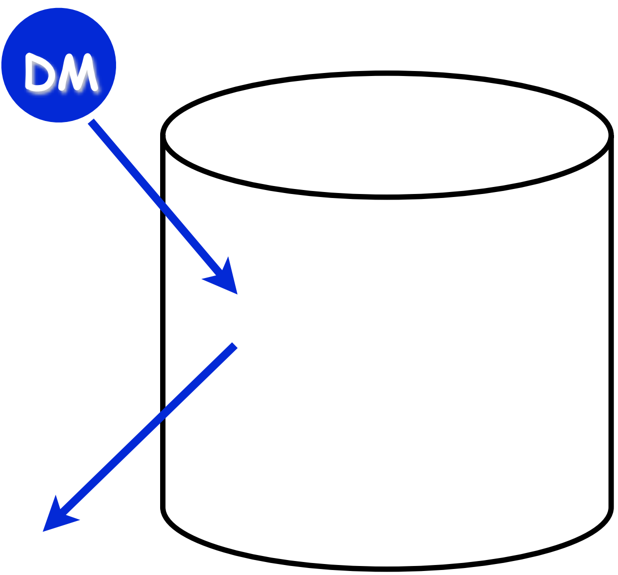
Local WIMP density (astro physics)



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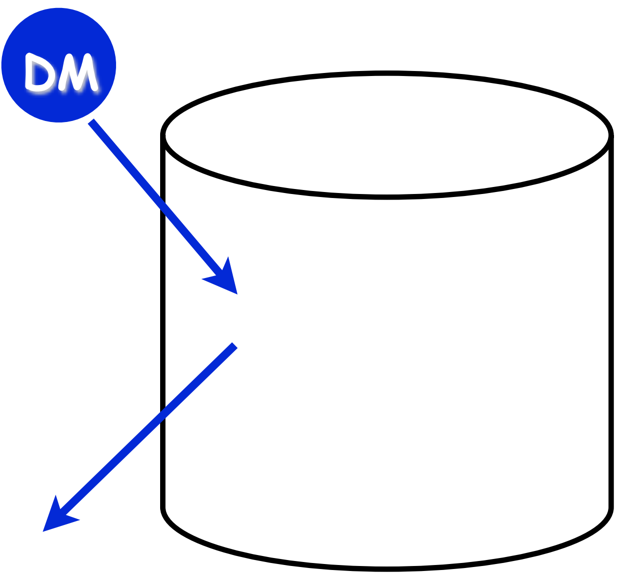

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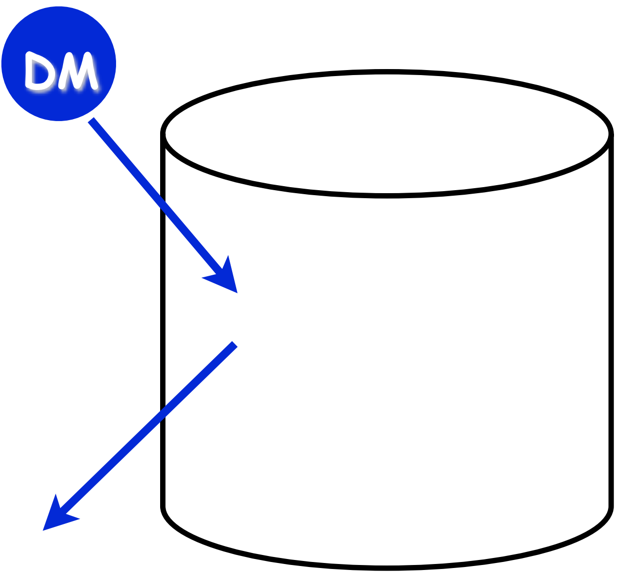
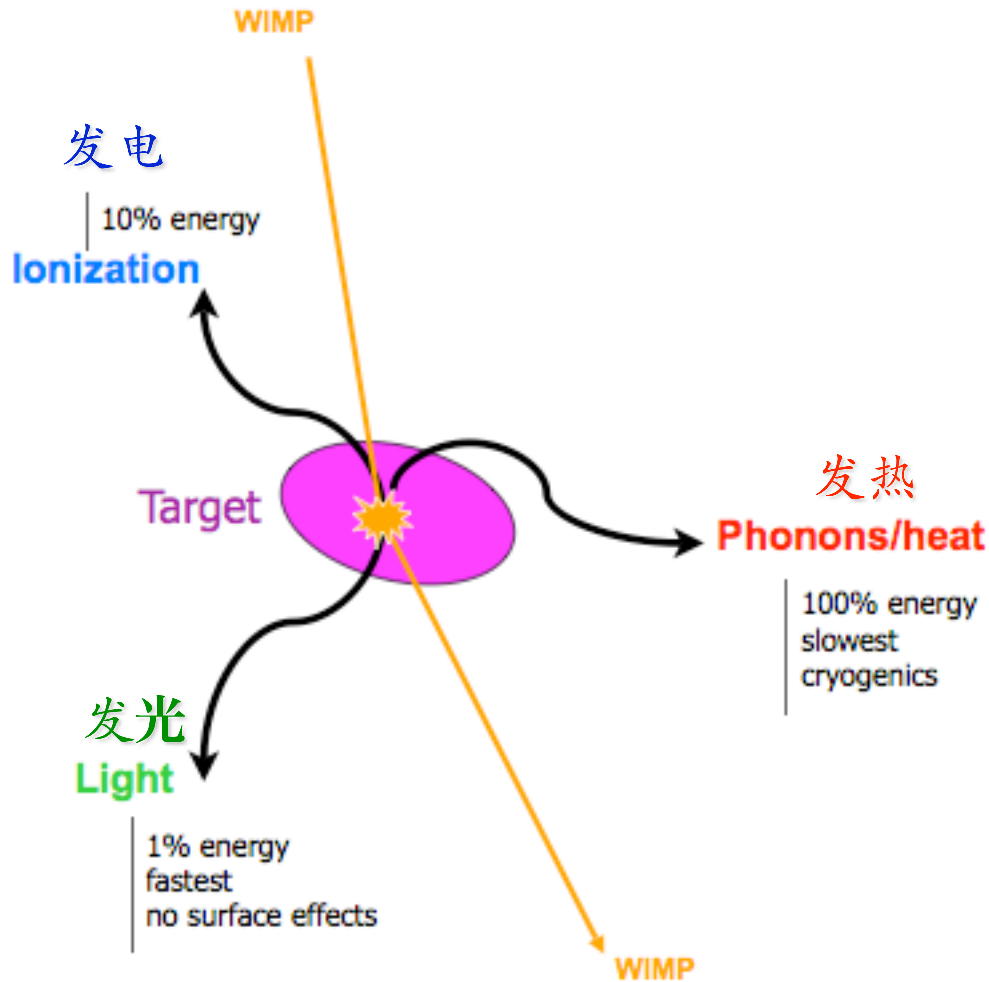


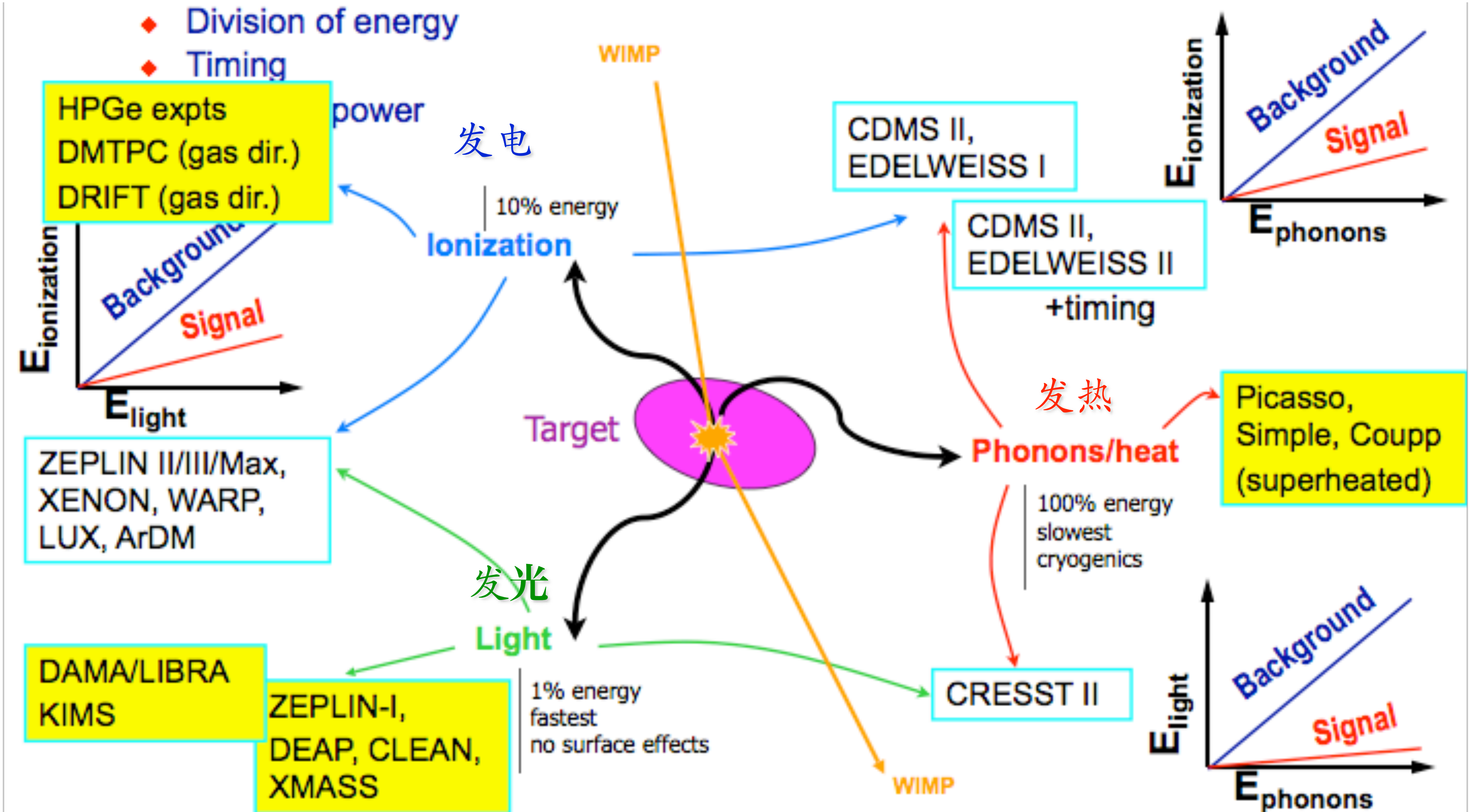
<E> ~ 30 KeV rate < 0.01/kg/day

Direct detection experiments



from Dan Akerib’s talk at CERCA DM workshop

Direct detection experiments



S. Su

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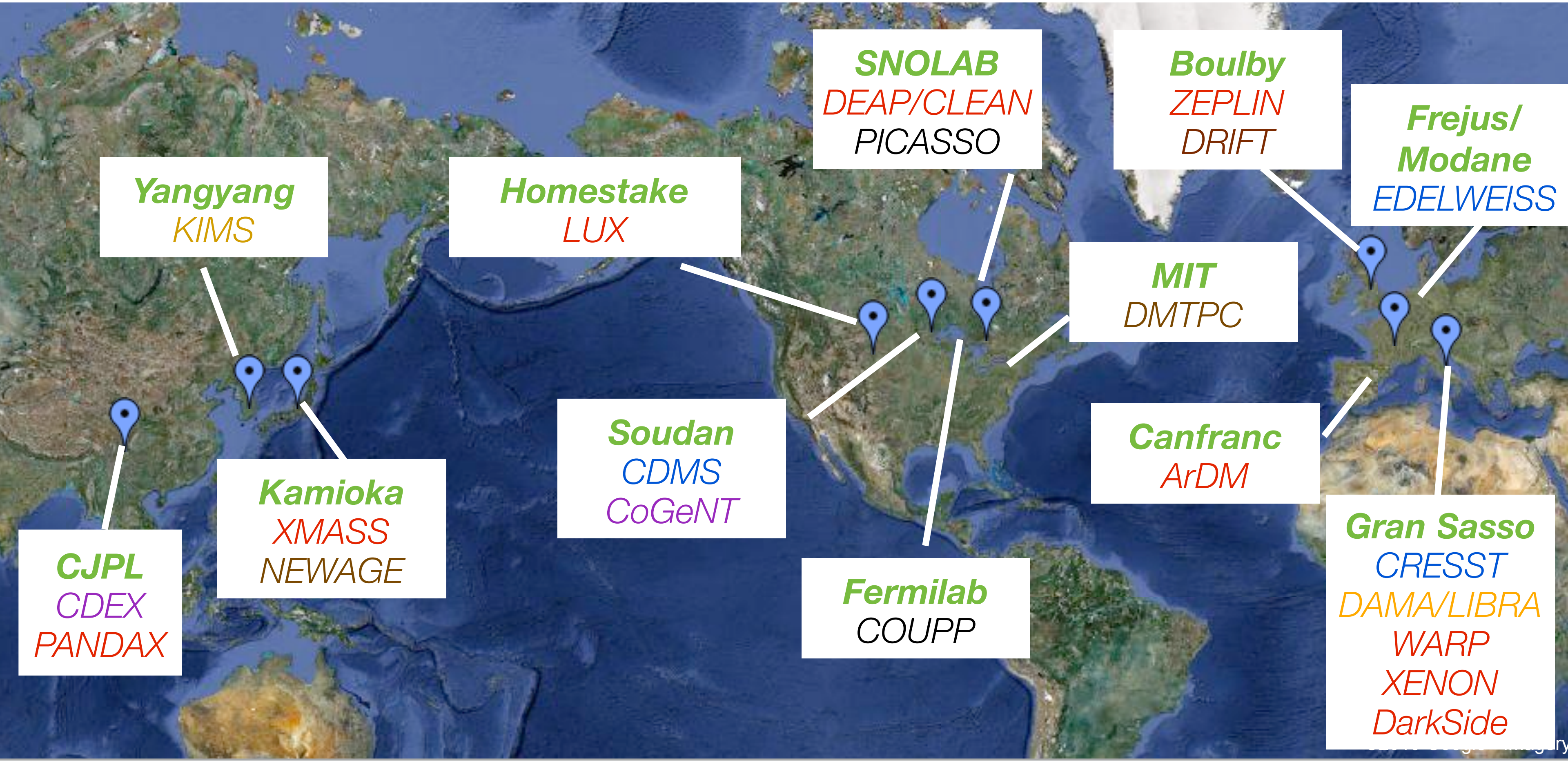
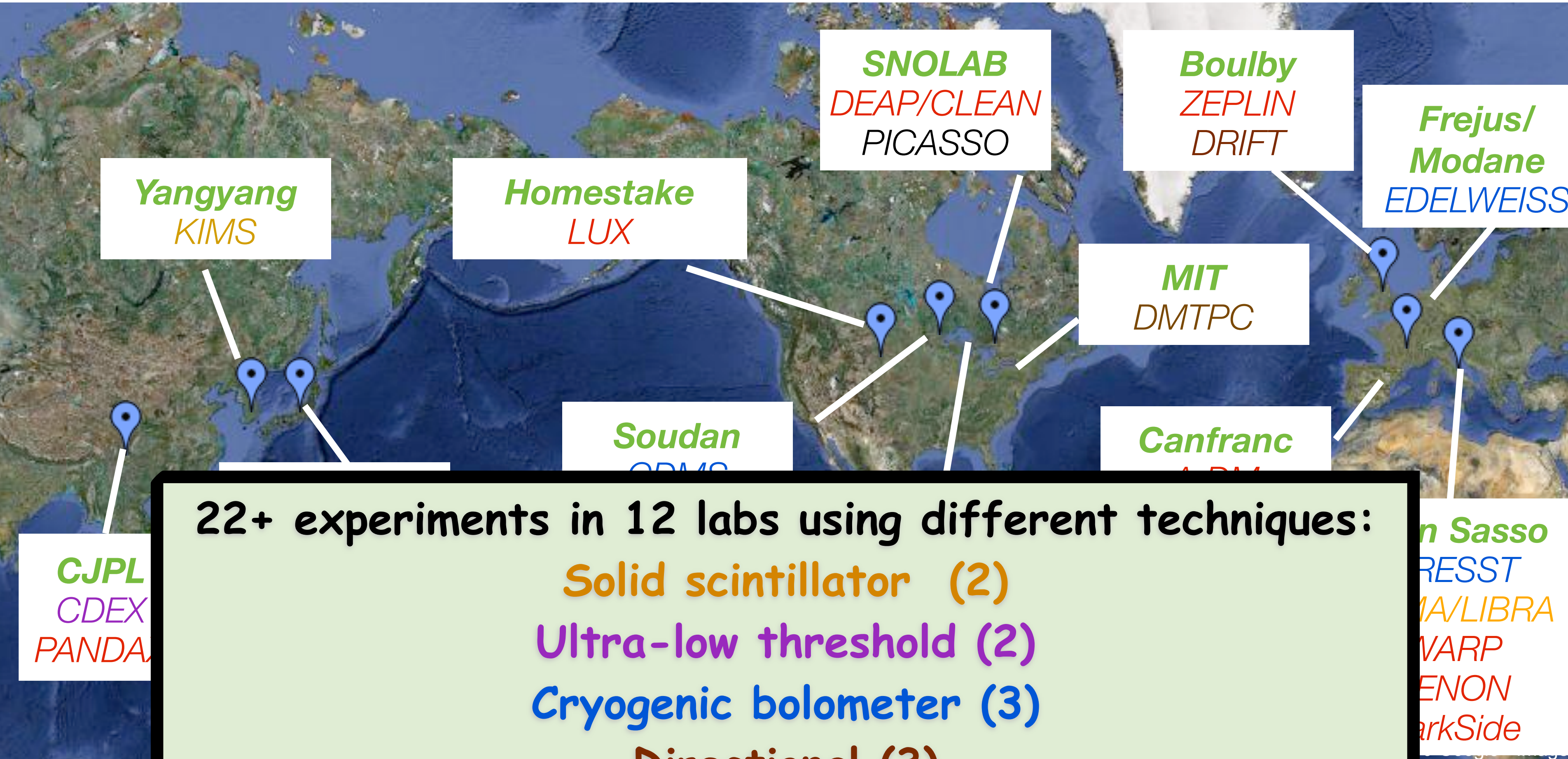
Direct detection experiments



Direct detection experiments



22+ experiments in 12 labs using different techniques:

Solid scintillator (2)

Ultra-low threshold (2)

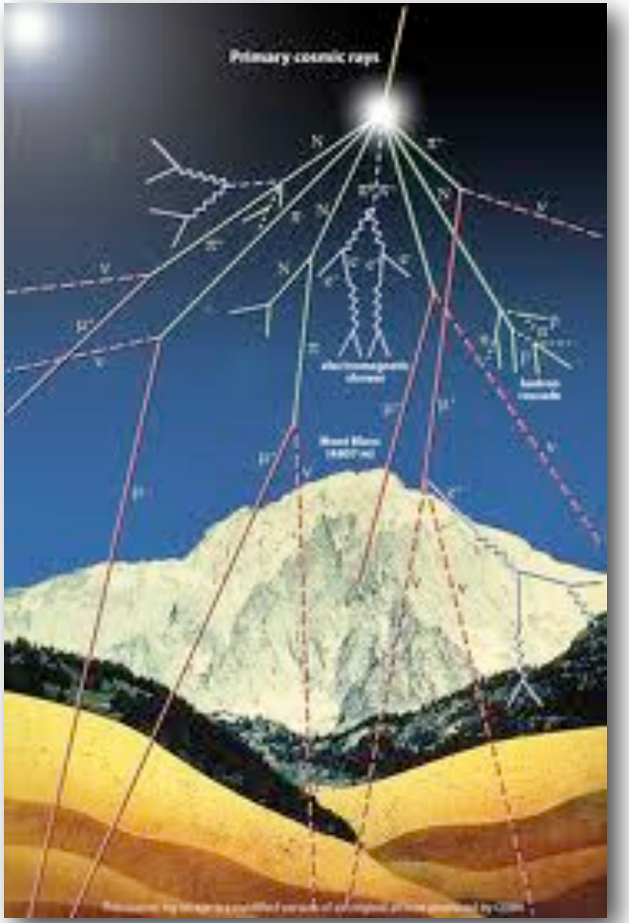
Cryogenic bolometer (3)

Directional (3)

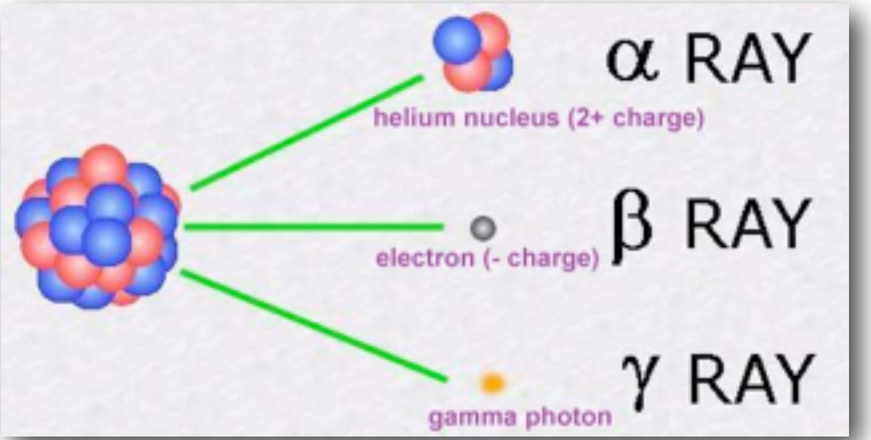
Superheated bubble chamber (3)

Noble Liquids - LXe (5), LAr (4)

Main challenge: backgrounds



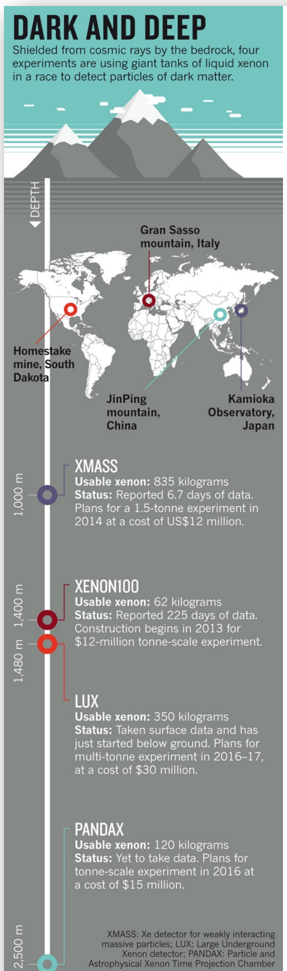
cosmic ray

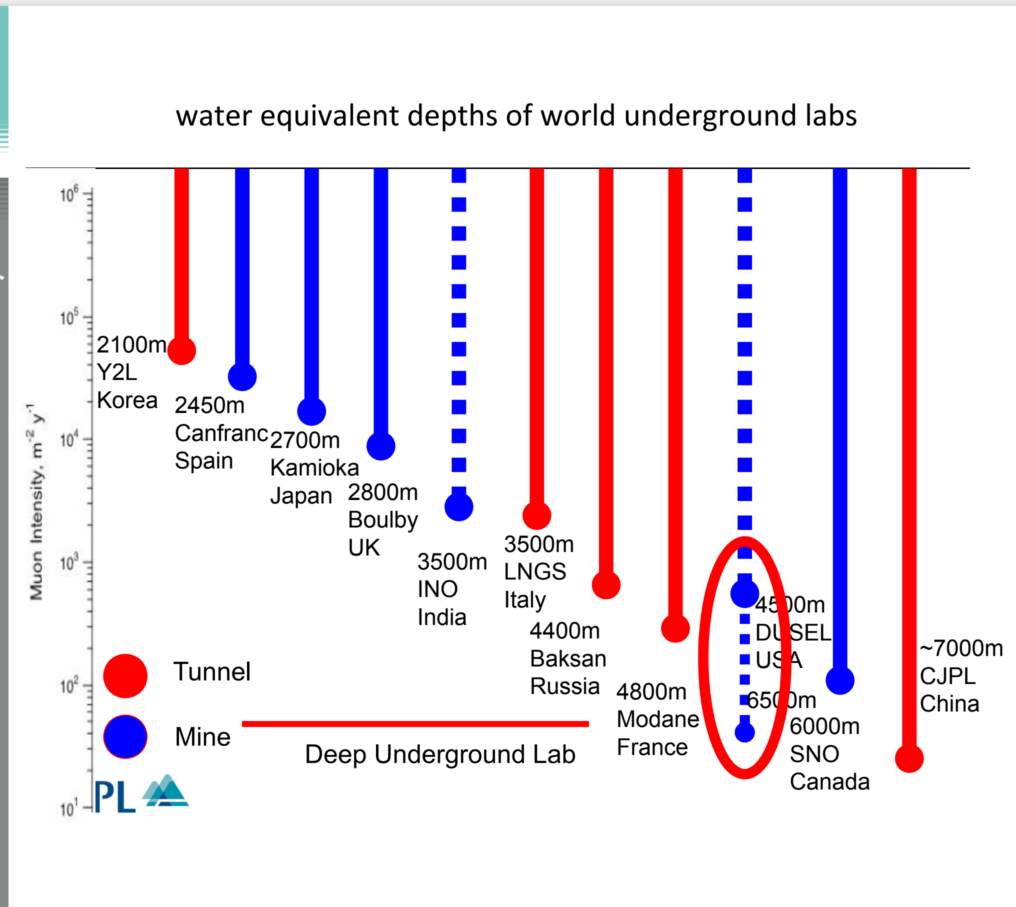


radioactivity

Direct detection in China

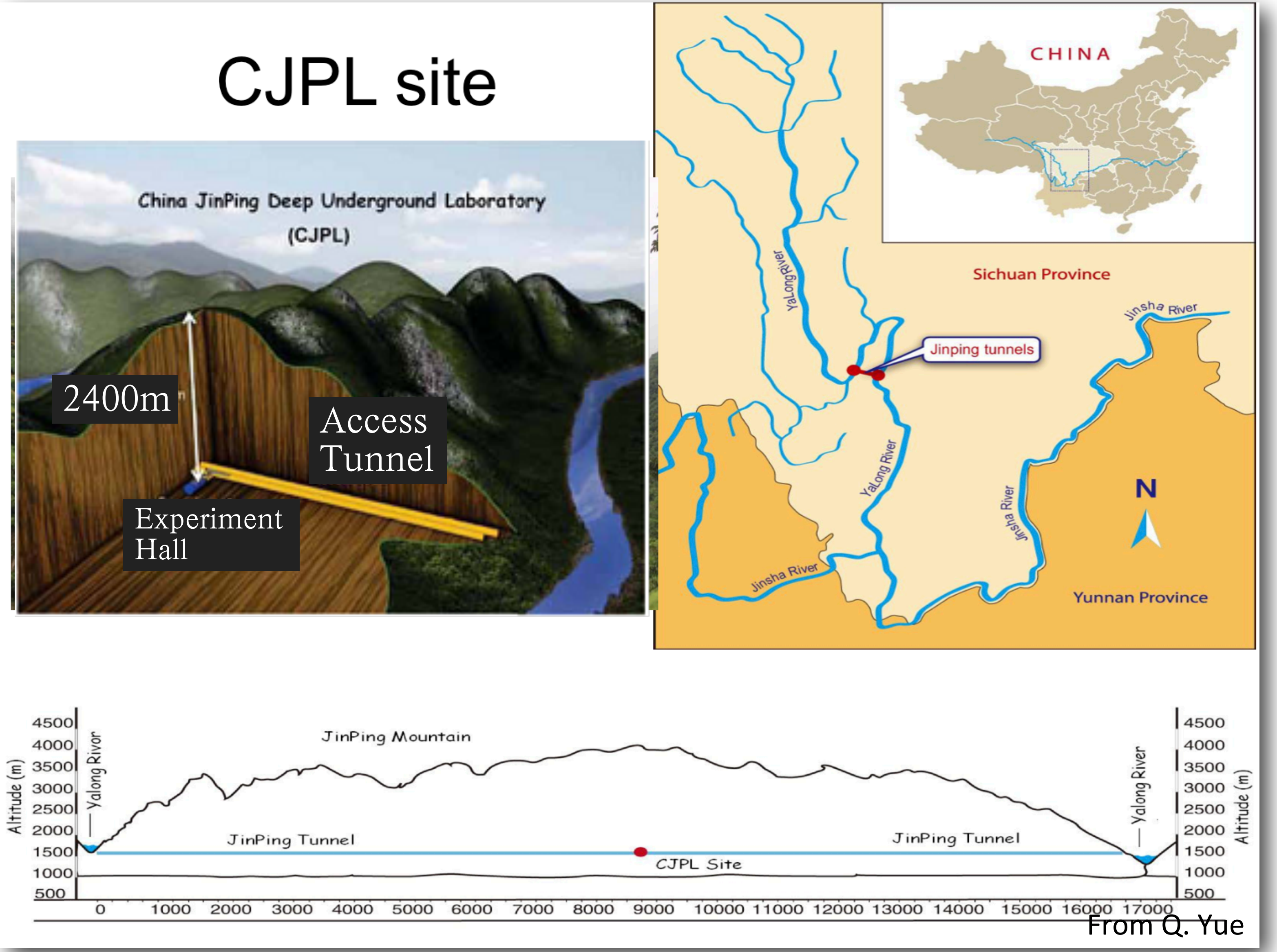
Dark matter experiments are located deep underground to be shielded from cosmic ray background.





Nature (2013)

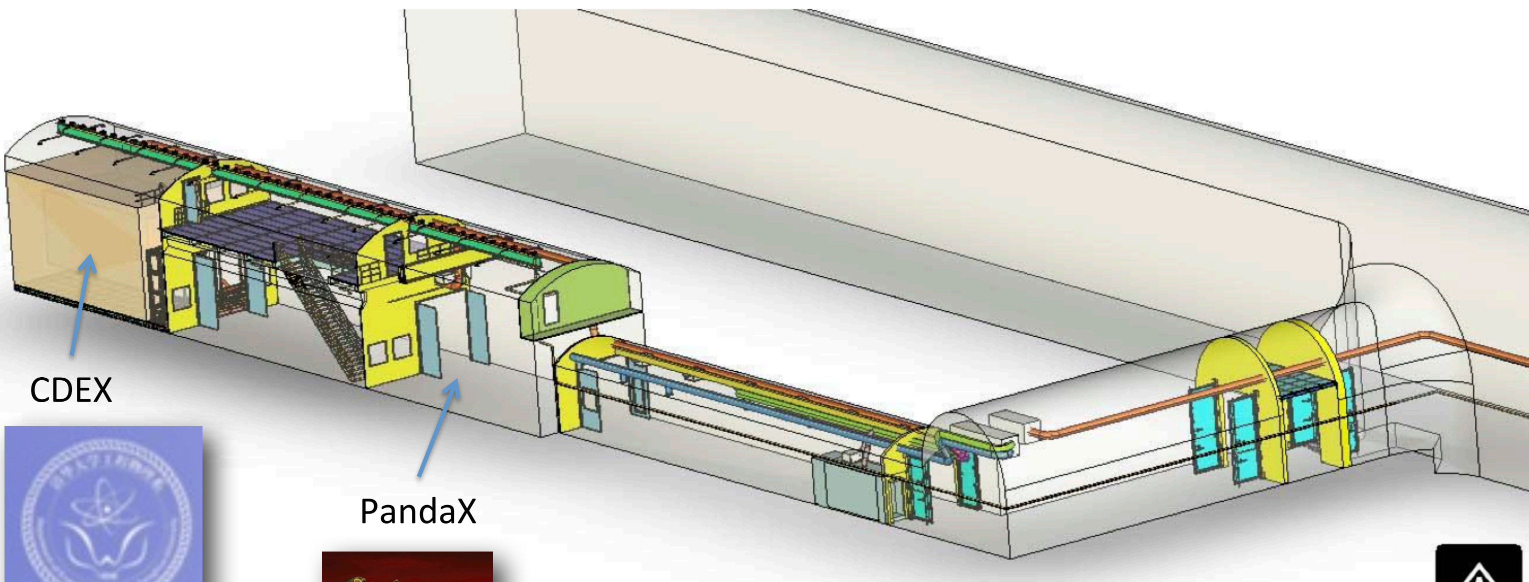
Direct detection in China



From Q. Yue

Direct detection in China

CJPL recent status(~4000m^3)



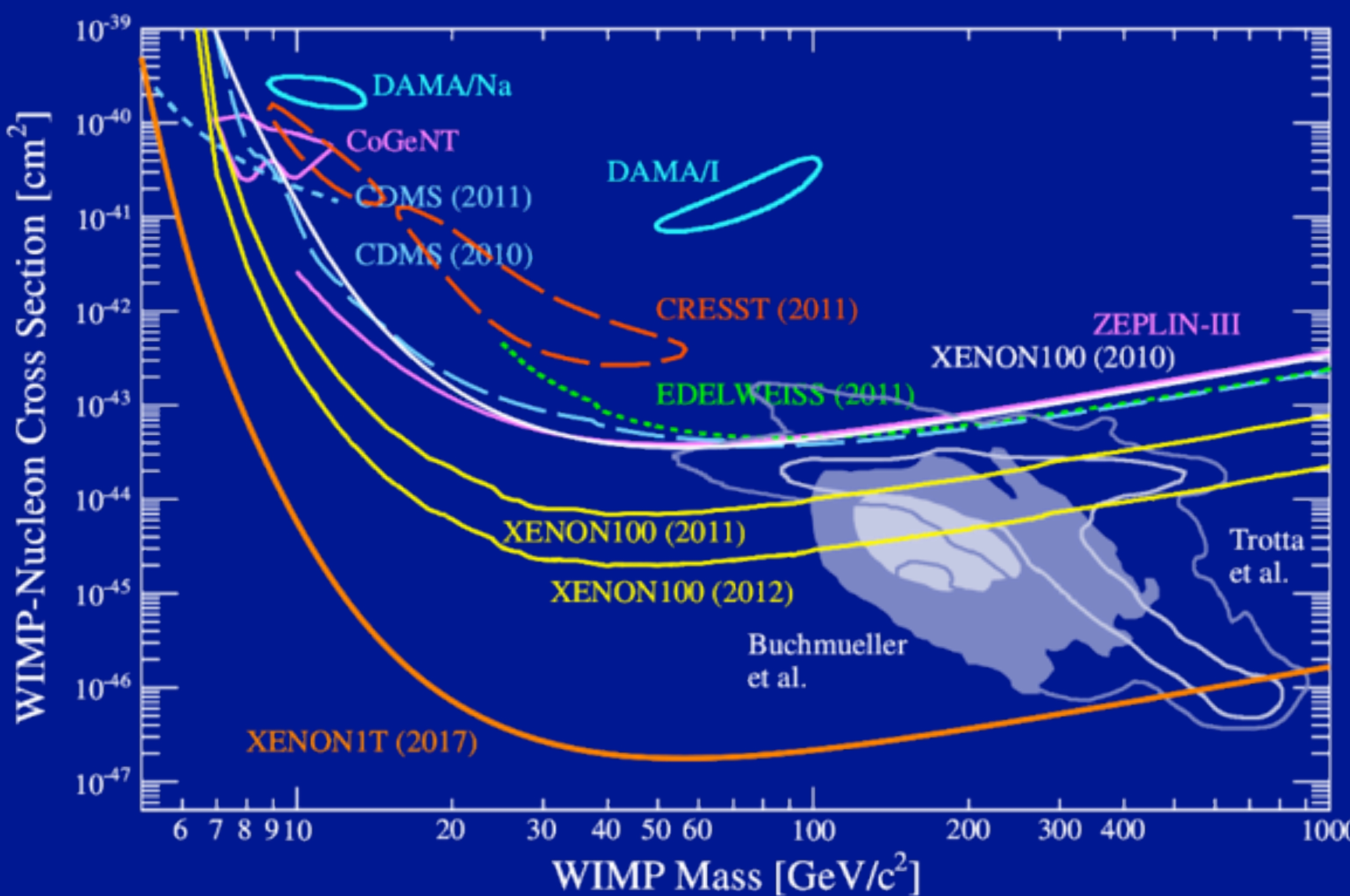
CDEX

PandaX

Li jing
岳骞

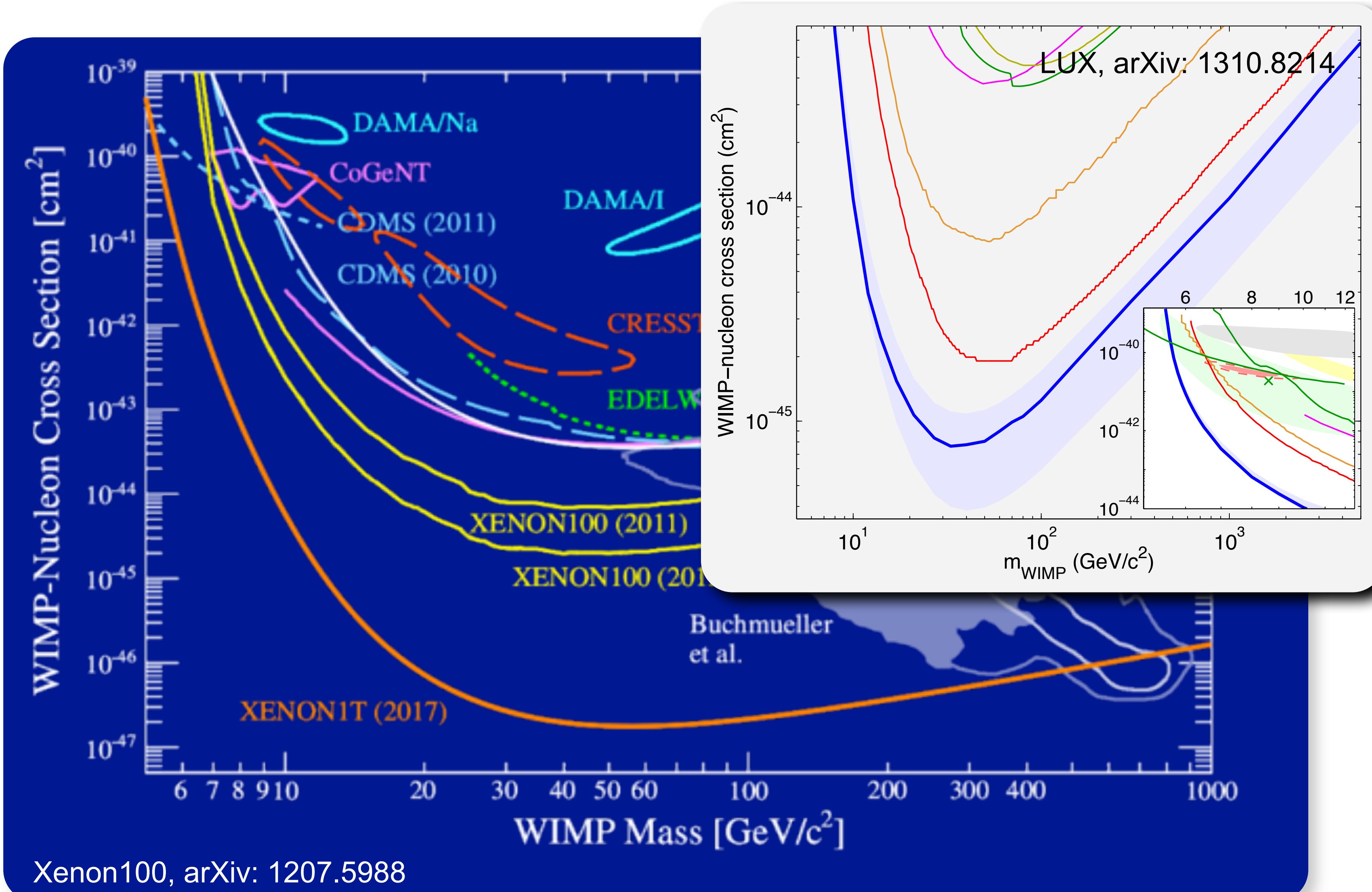
From Q. Yue

Direct detection

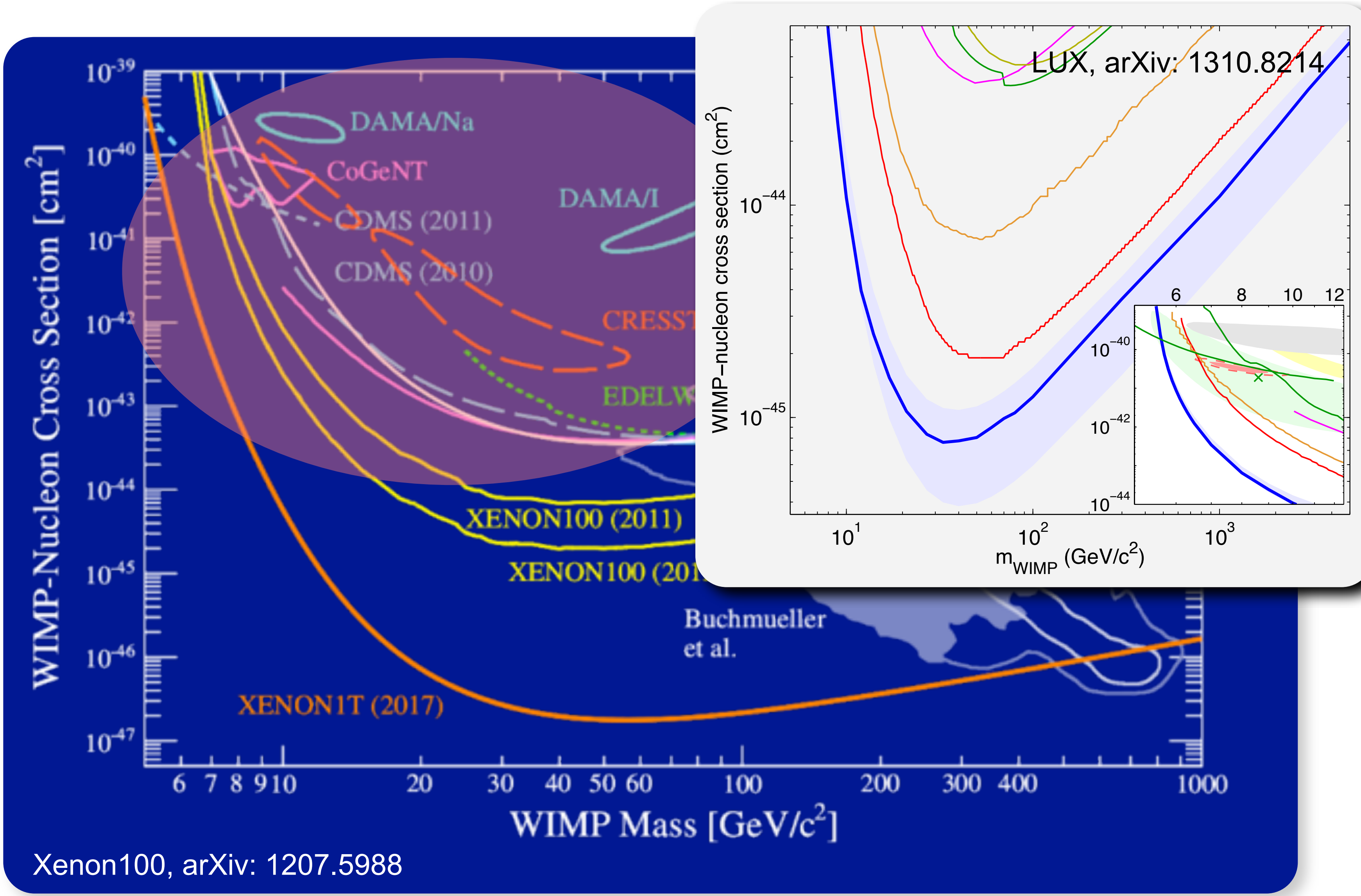


Xenon100, arXiv: 1207.5988

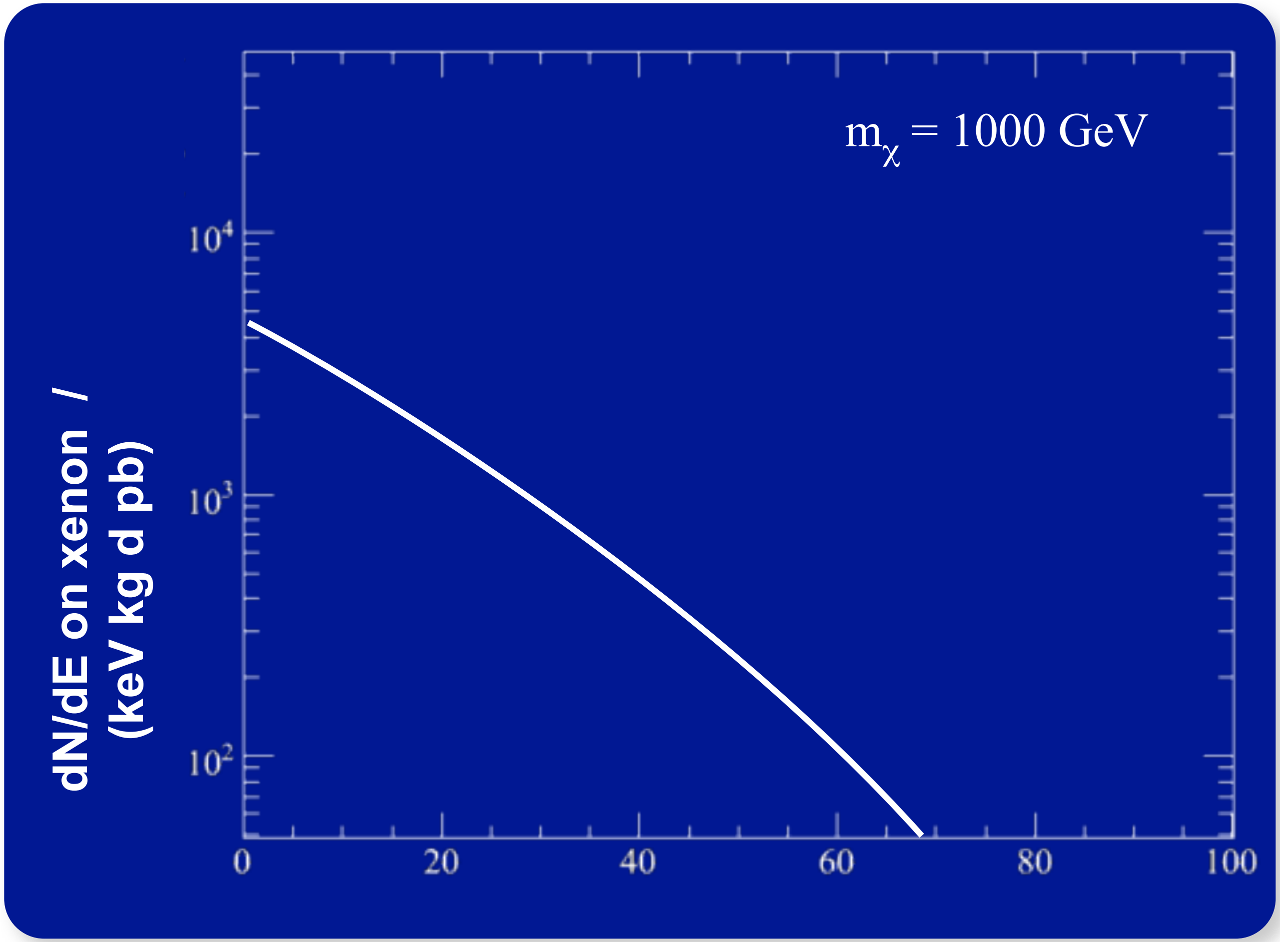
Direct detection



Direct detection



Expected WIMP spectrum



Low threshold, challenging signal!

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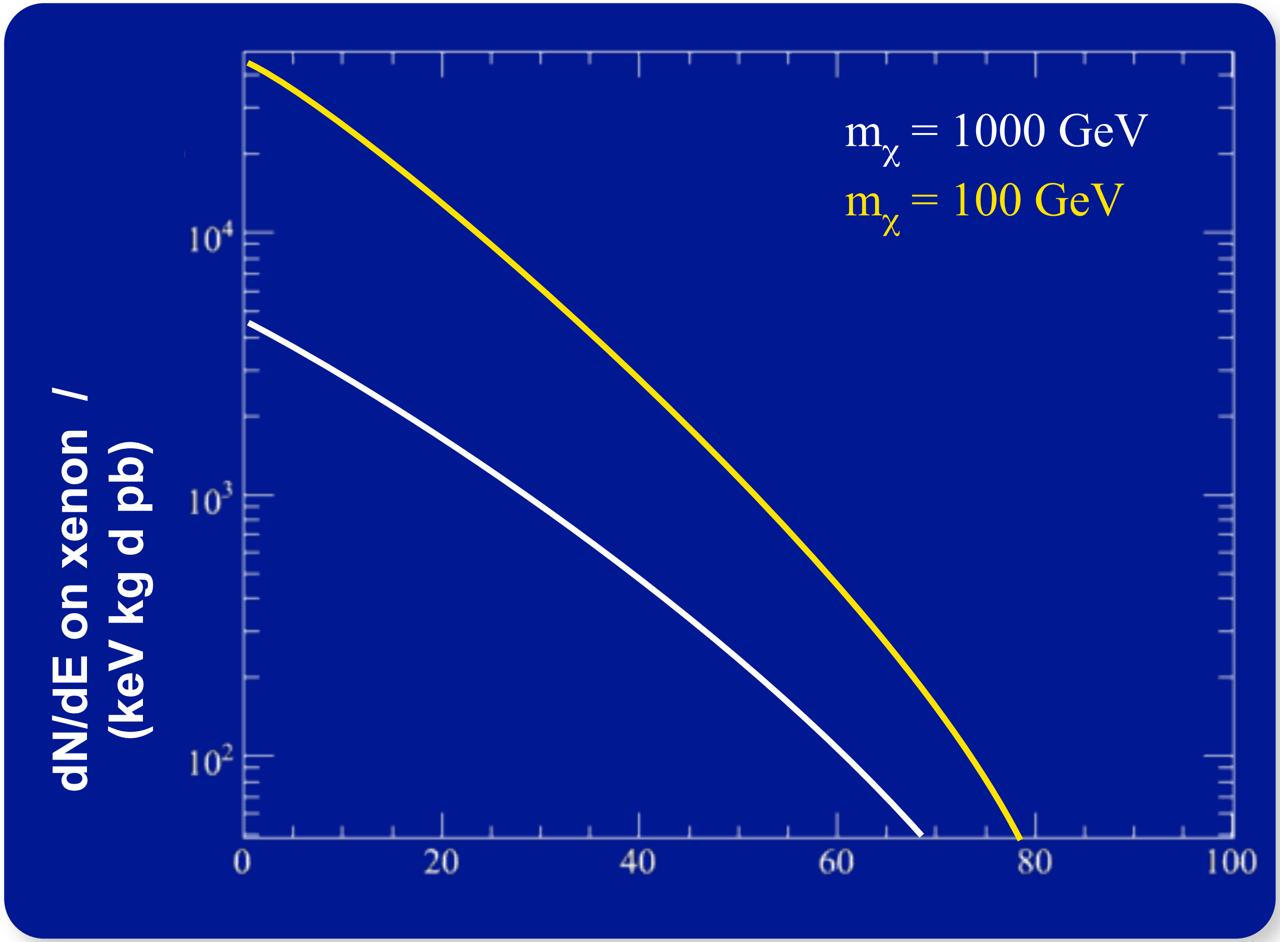

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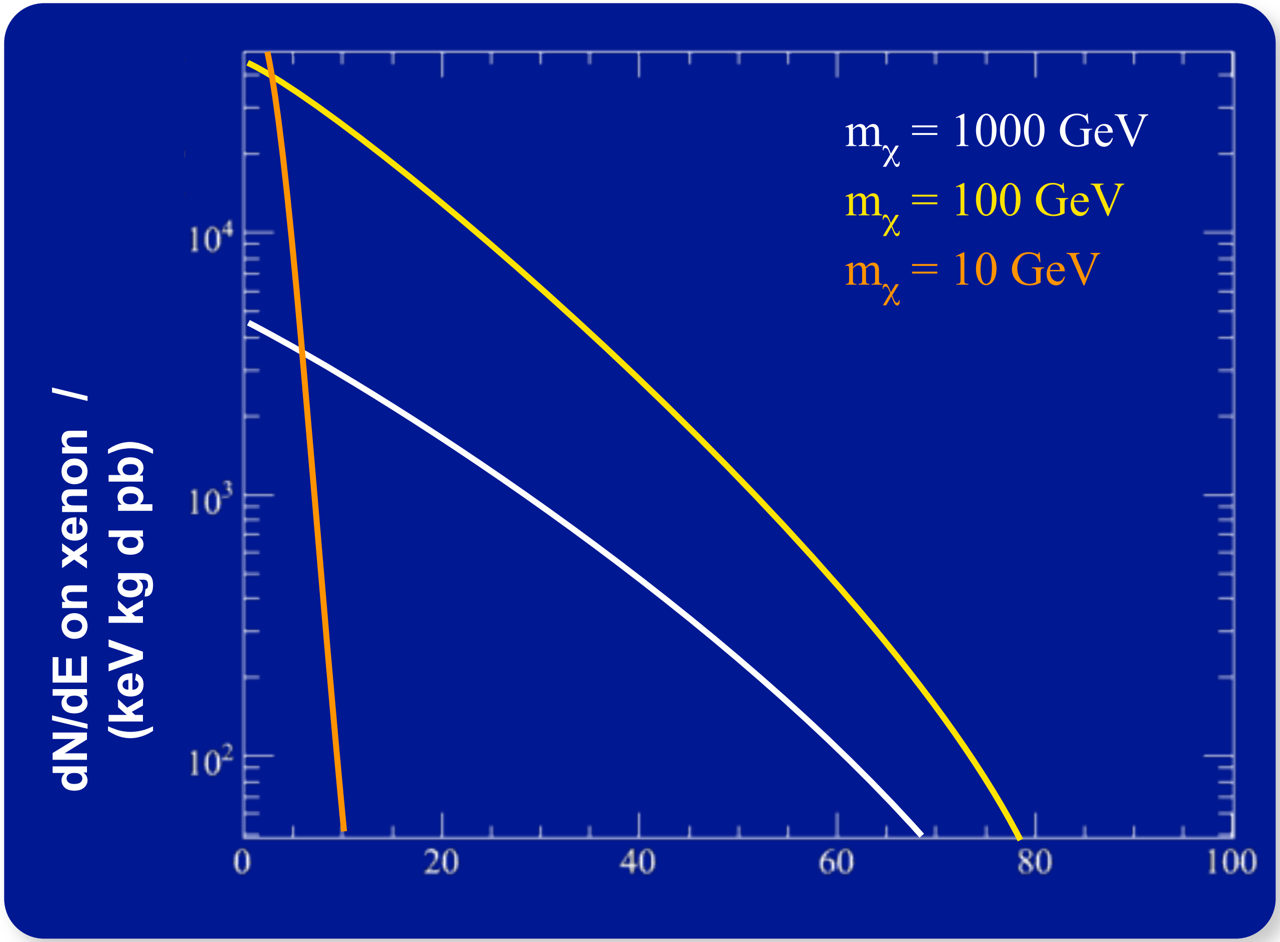


Low threshold, challenging signal!

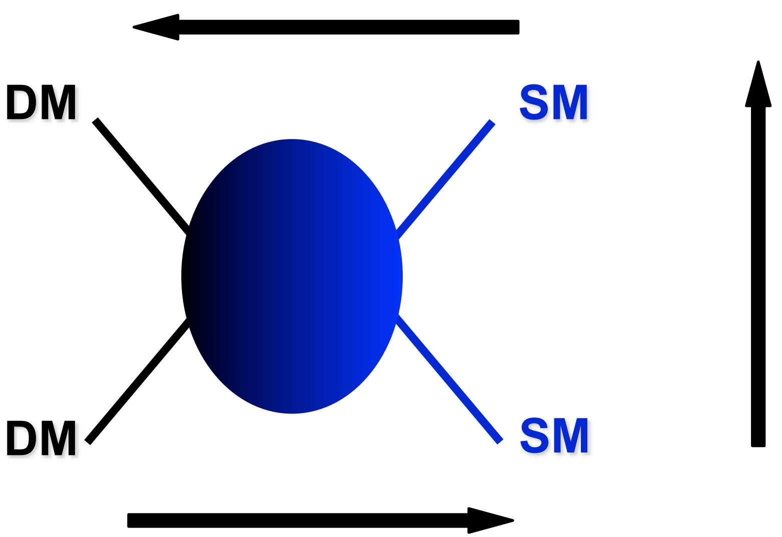
Direct detection: summary

- ◉ A lot of new detection techniques have been developed for direct dark matter detection.
- ◉ So far, there are no convincing results for a positive dark matter detection.
- ◉ Light DM signals observed in several dark matter experiments don't fit together. They are in conflict with null result experiments.
- ◉ Are the observed signals from unknown background? Or standard scattering model needs to be modified?
- ◉ Experiments with low BG and large detectors are coming online to continue the hunting of dark matter.

Dark matter detection

Collider Searches

LEP, Tevatron, LHC



direct DM detection

CDMS, CoGeNT, COUPP, CRESST, DAMA, XENON,...

Indirect DM detection

AMS2, PAMELA, Fermi-LAT,...

Dark matter detection

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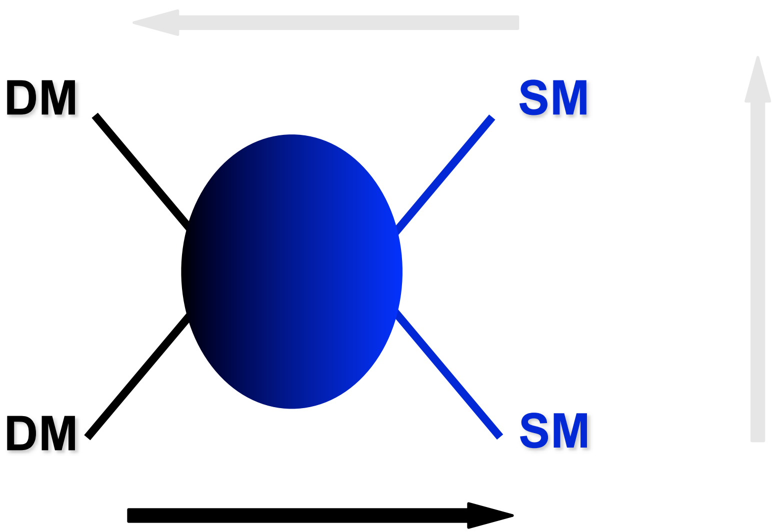

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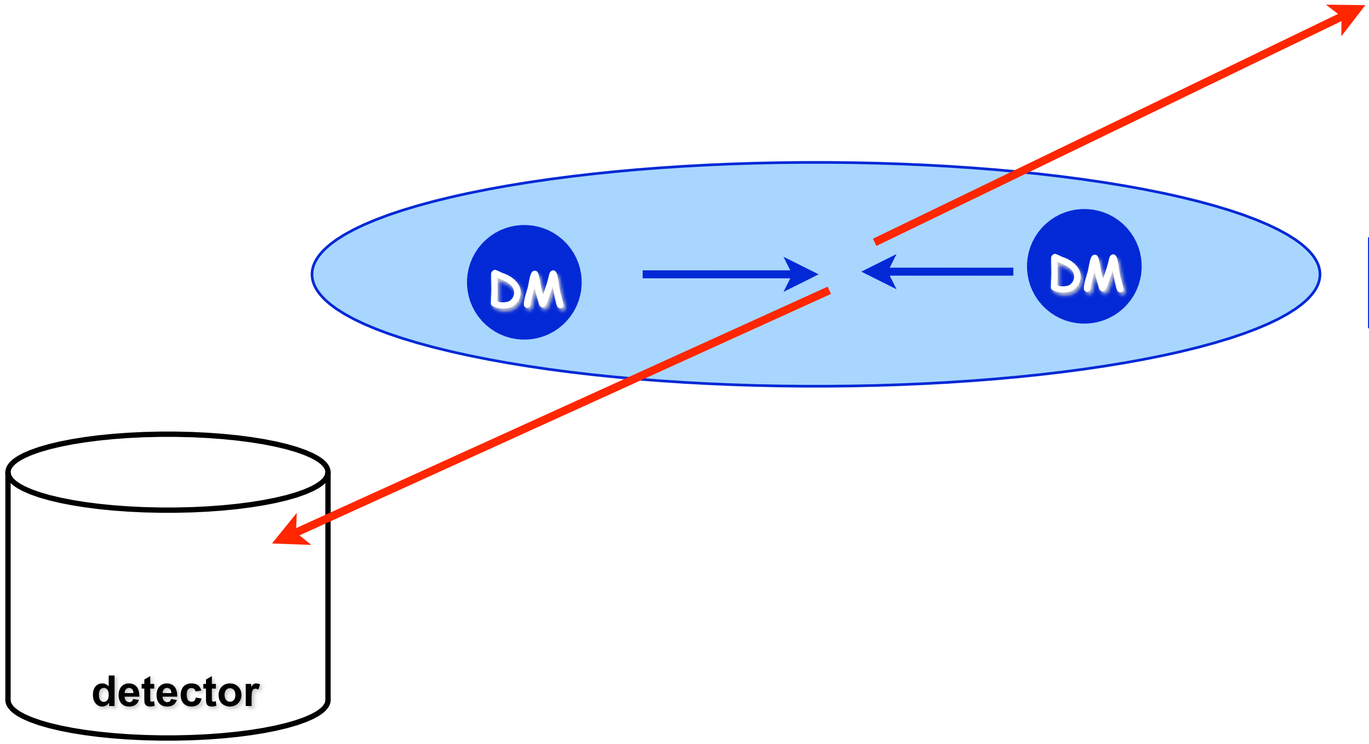
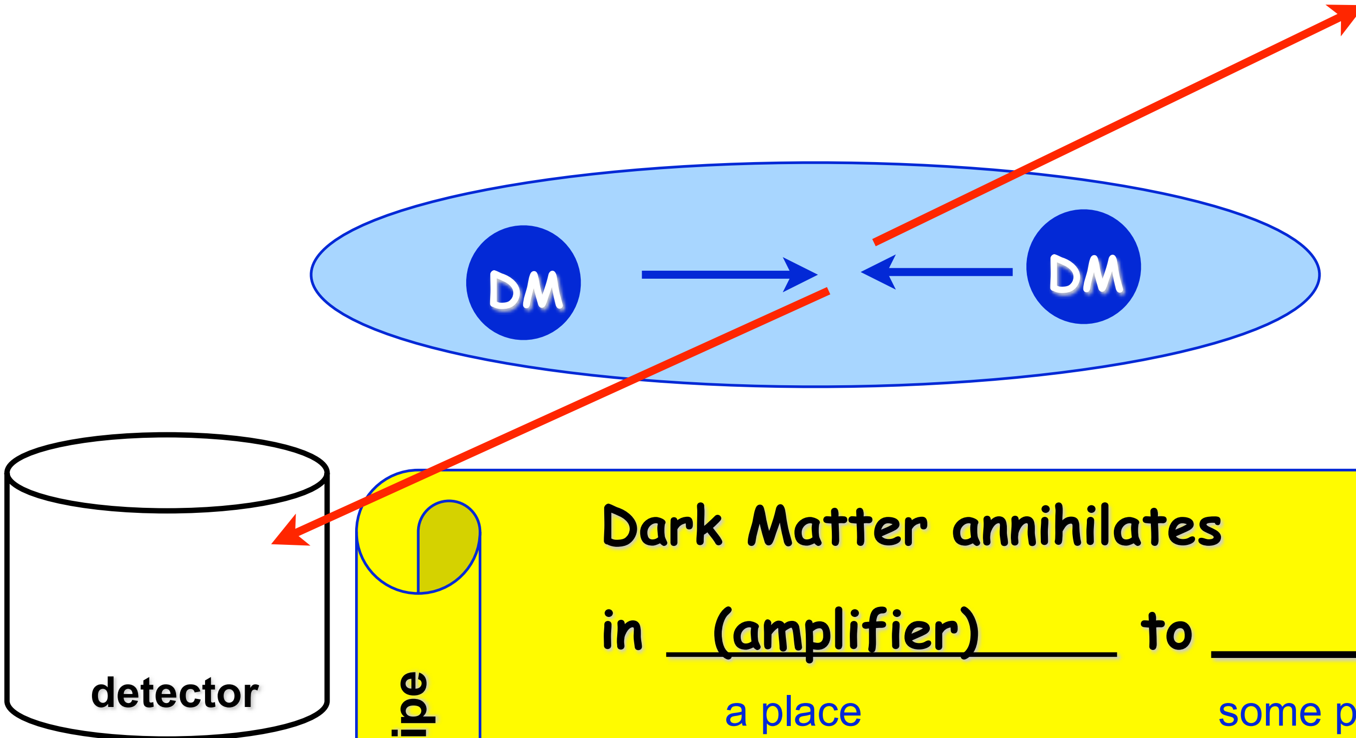


$\Gamma_A \propto n_{DM}^2$

Indirect detection



$\Gamma_A \propto n_{DM}^2$

recipe

Dark Matter annihilates

in ___(amplifier)___ to ________________,

a place some particles

which are detected by ____________.

an experiment

recipe

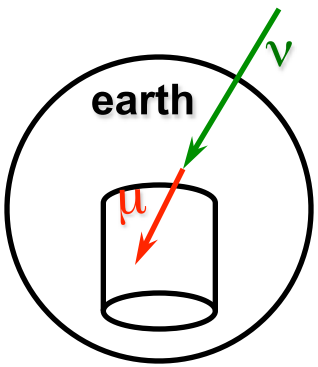
Dark Matter annihilates

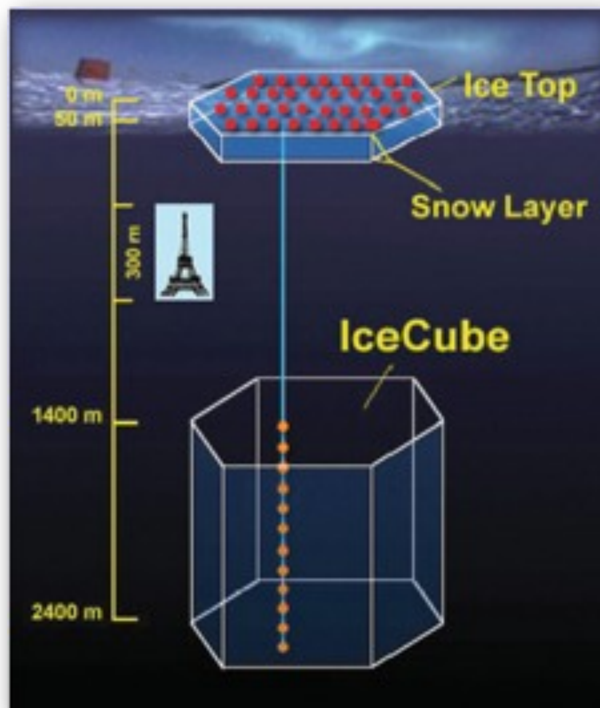
in <u>center of the sun</u> to <u>neutrinos</u>,

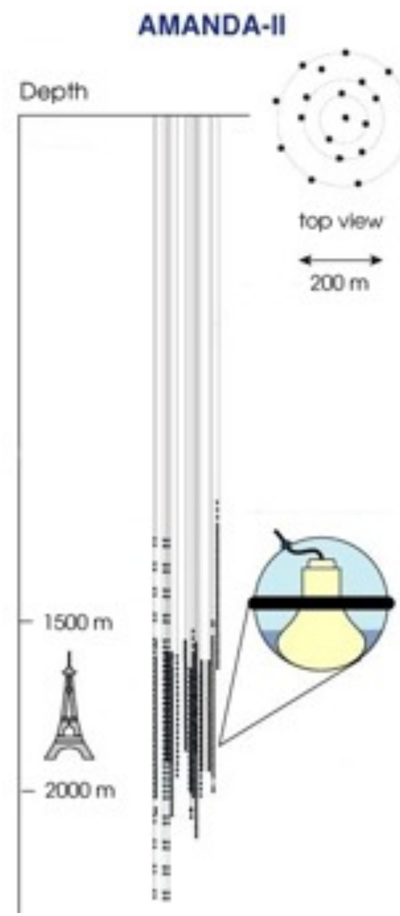
a place — some particles

which are detected by <u>AMANDA, ICECUBE.</u>

an experiment







Dark matter density in the sun, capture rate

S. Su

recipe

Dark Matter annihilates

in <u>galactic center</u> to <u>photons</u>,

a place — some particles

which are detected by <u>FERMI, HESS.</u>

an experiment

Dark matter density in the center of the galaxy

S. Su

recipe

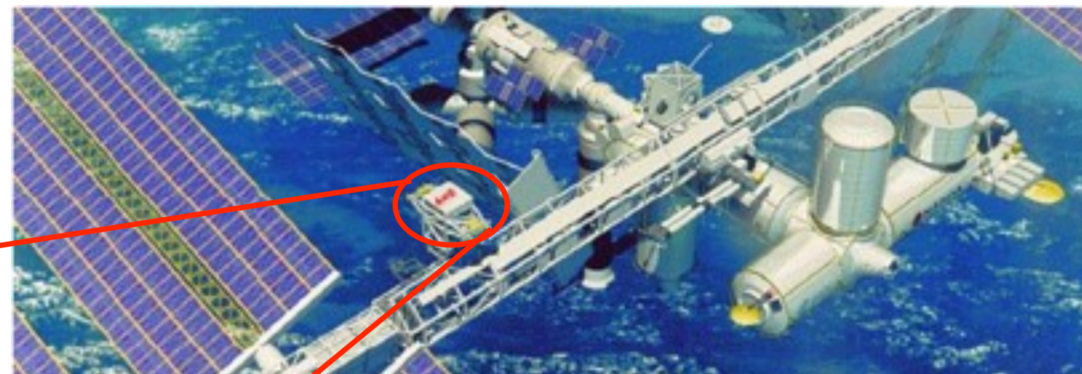
Dark Matter annihilates

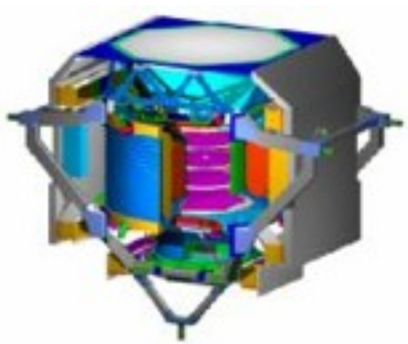
in __the halo__ to __positions__,

a place — some particles

which are detected by __AMS, FERMI, PAMELA.__

an experiment



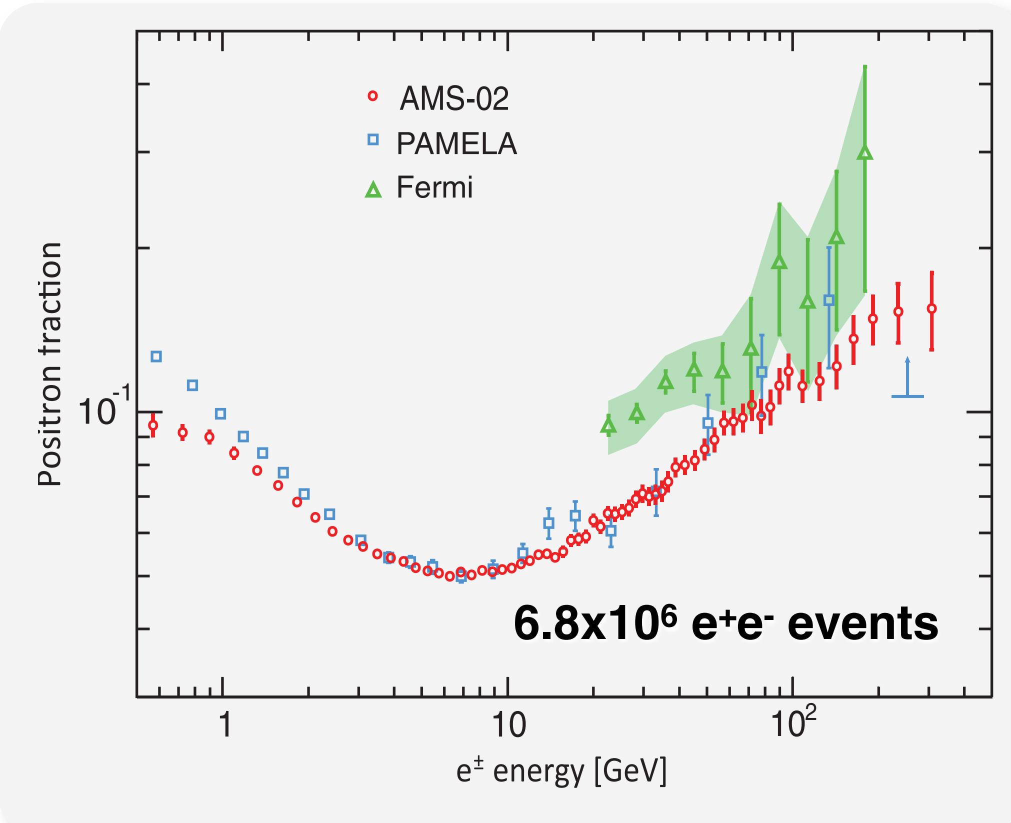


AMS

Dark matter density profile in the halo

AMS

AMS, PRL110, 141102 (2013)



- increased spectrum for e^+
- flat spectrum for e^- (above BG)
- anti-p consistent with BG

background?

particle physics: dark matter

astrophysics: pulsars ...

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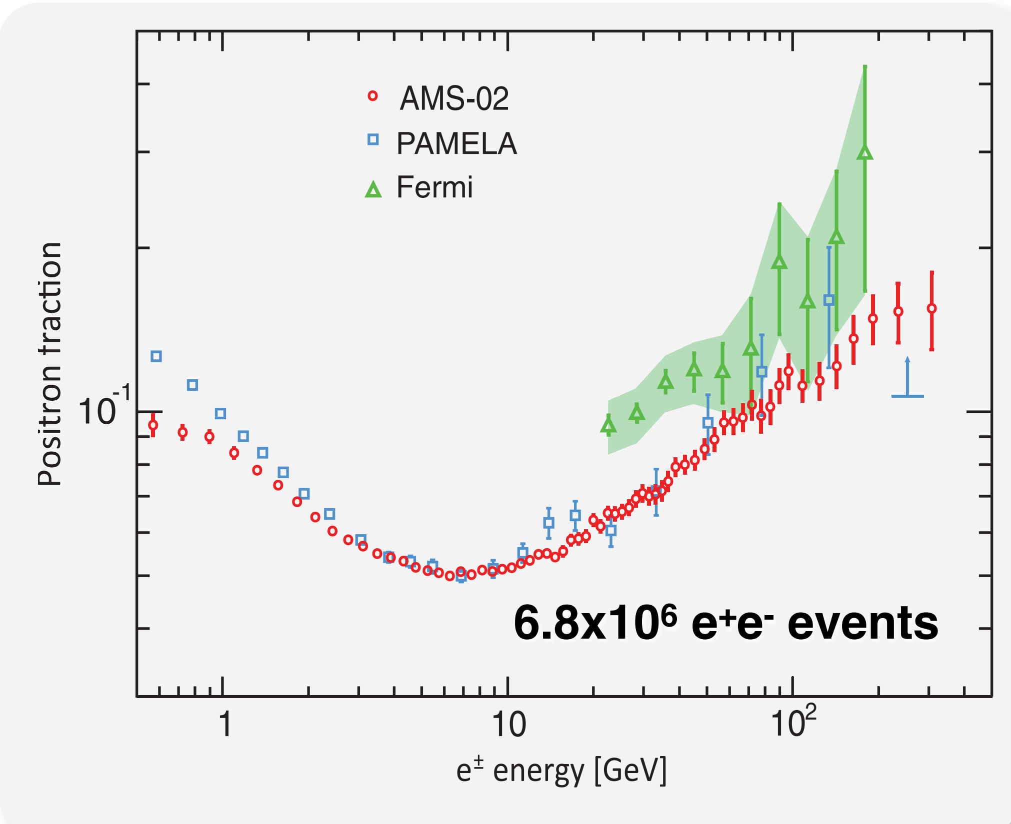

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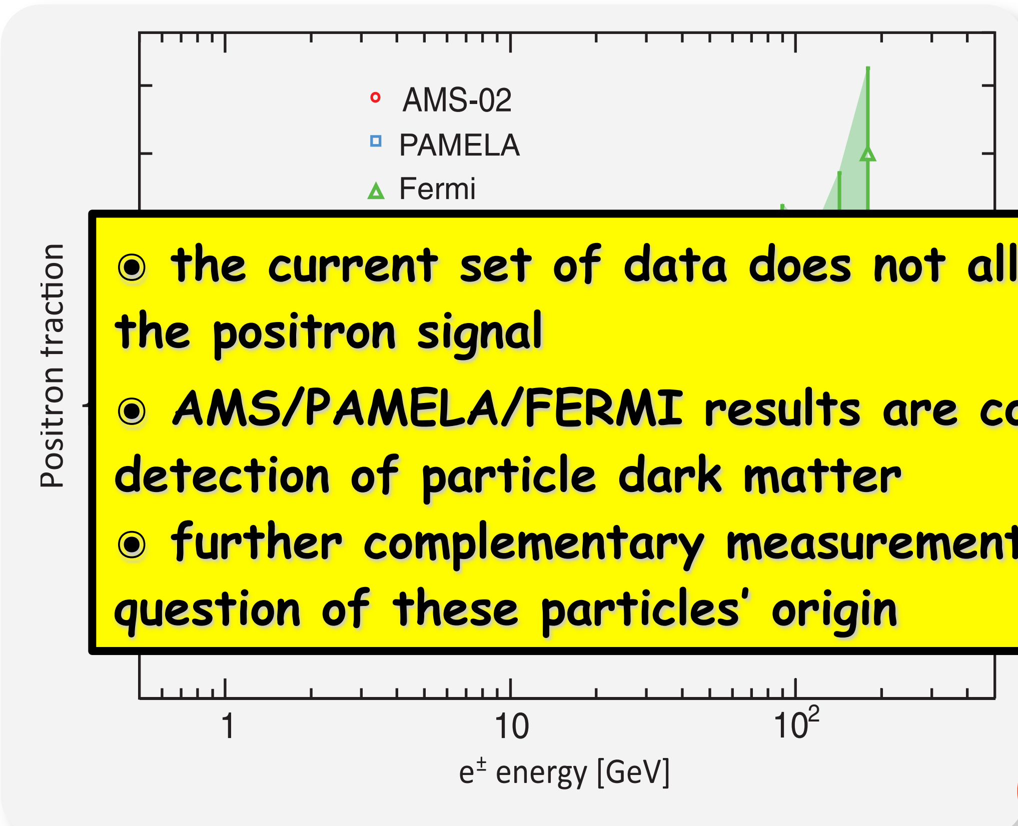


- increased spectrum for e^+
- flat spectrum for e^- (above BG)

- the current set of data does not allow us to identify the origin of the positron signal
- AMS/PAMELA/FERMI results are consistent with being the first detection of particle dark matter
- further complementary measurements are required to answer the question of these particles' origin

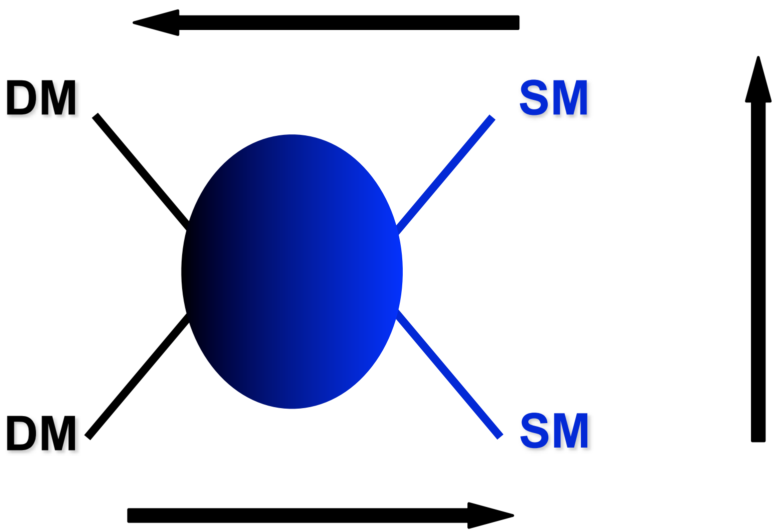
particle physics: dark matter

astrophysics: pulsars ...

Dark matter detection

Collider Searches

LEP, Tevatron, LHC



direct DM detection

CDMS, CoGeNT, COUPP, CRESST, DAMA, XENON,...

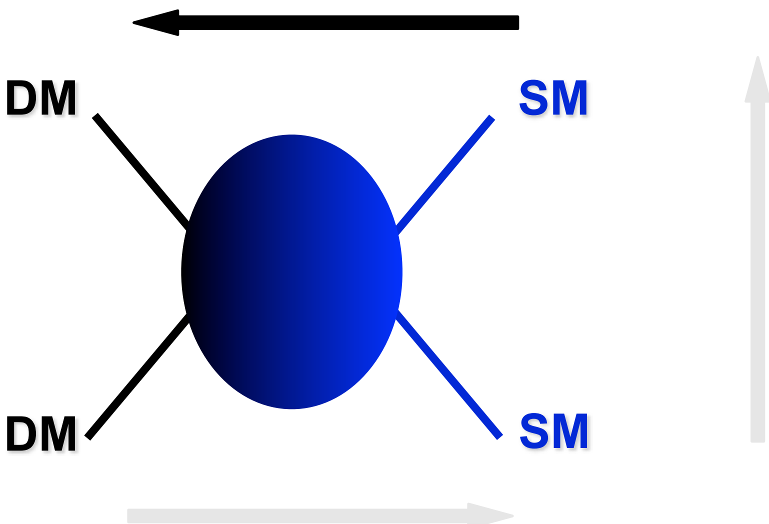
Indirect DM detection

AMS2, PAMELA, Fermi-LAT,...

Dark matter detection

Collider Searches

LEP, Tevatron, LHC



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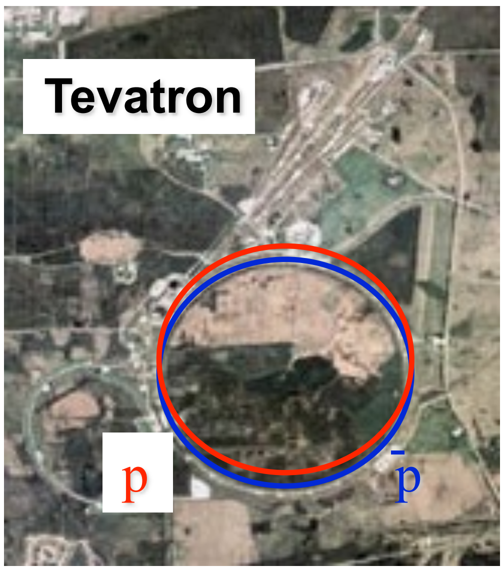
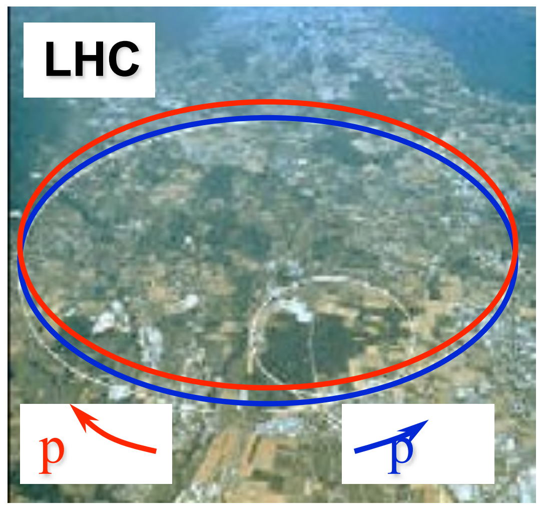
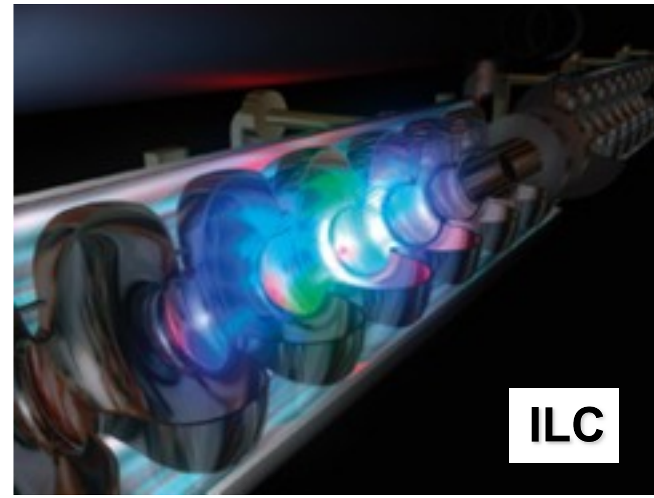
Collider study of dark matter







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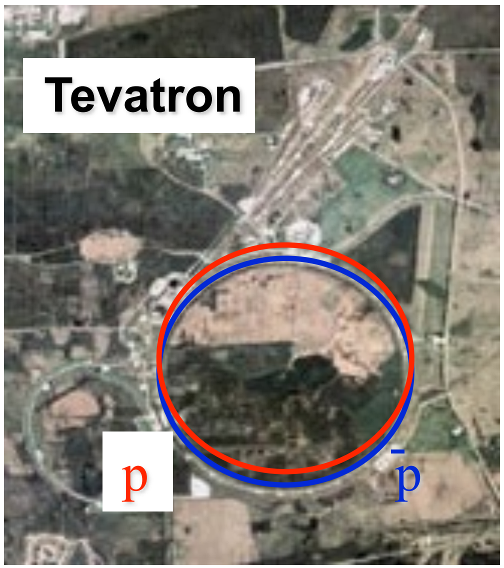
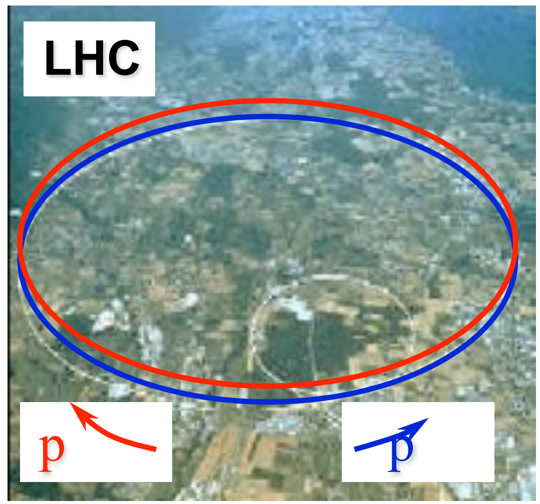
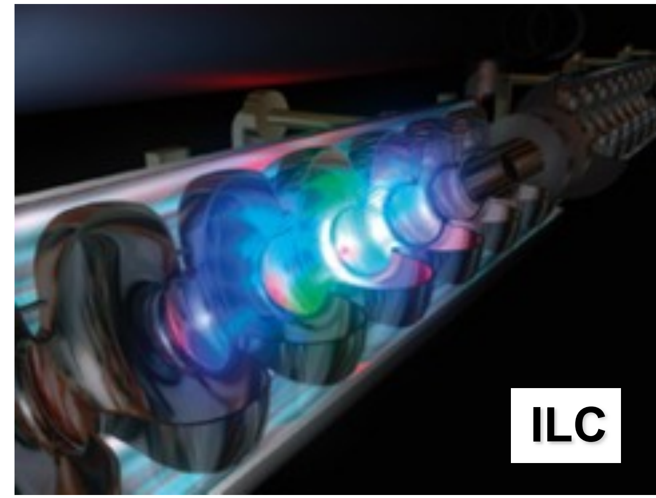
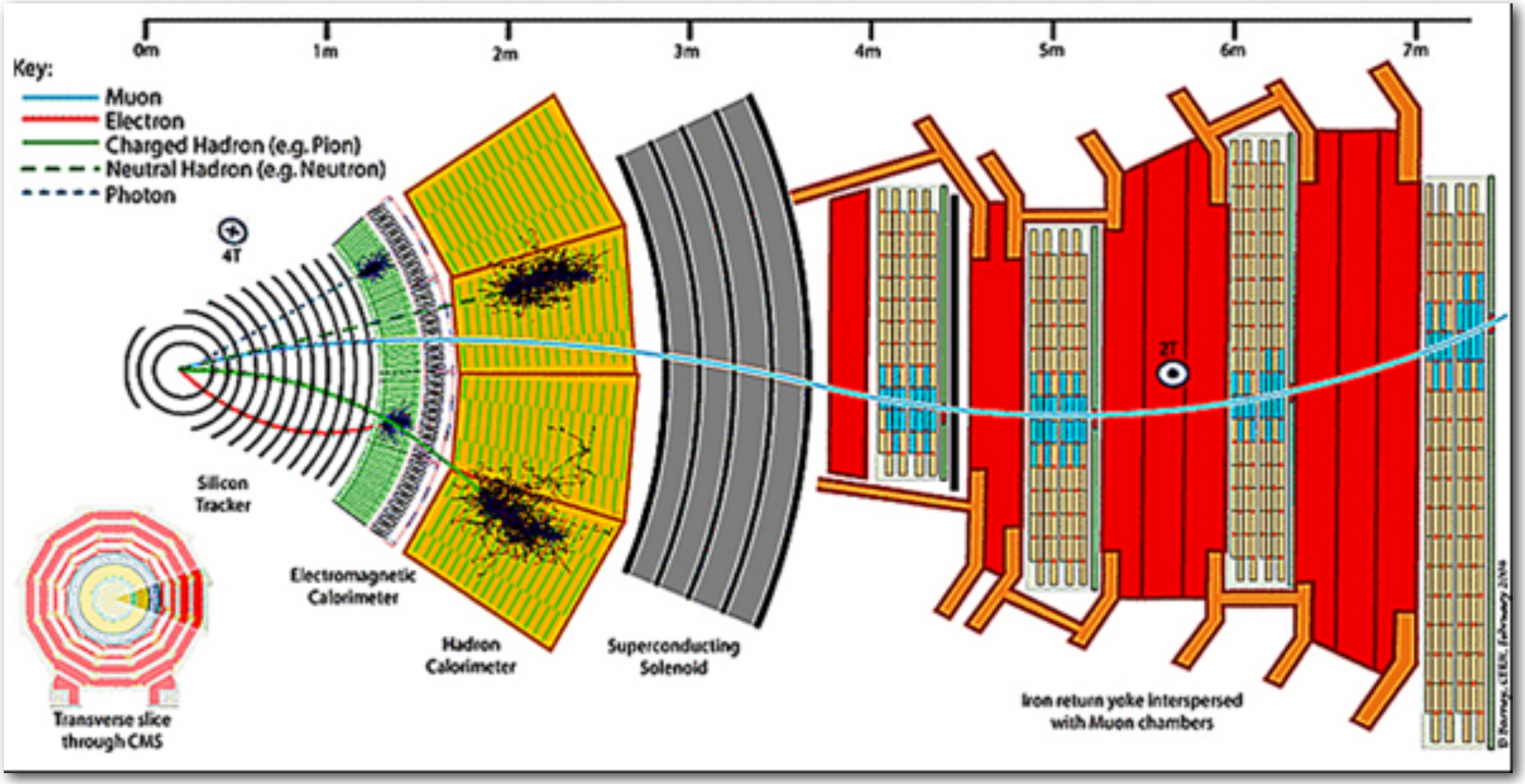






- How to observe DM signals?
- How to distinguish DM scenarios?
- How to determine DM properties?

Can we see DM at collider?



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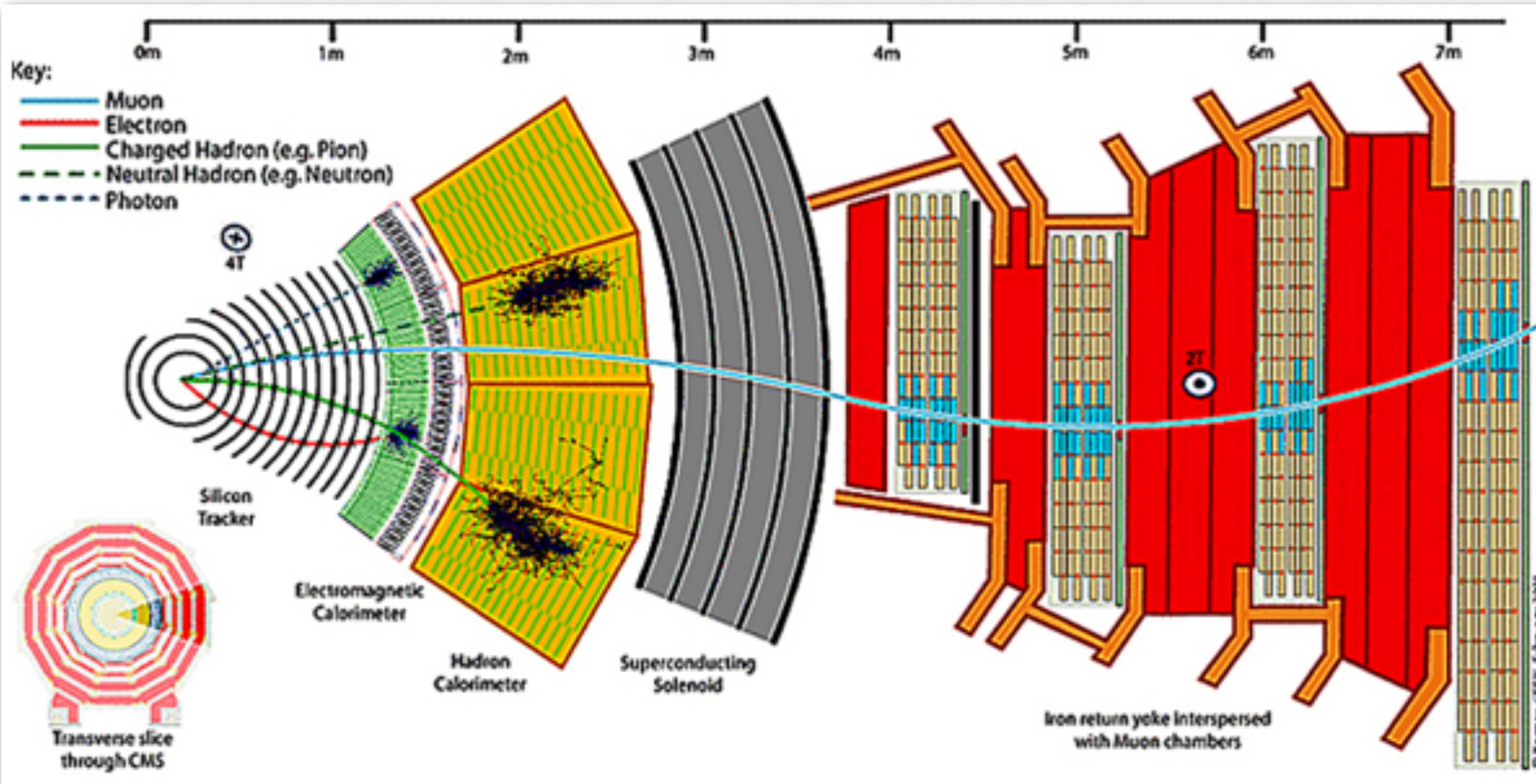

- DM Does not interact with detector, can not be observed directly

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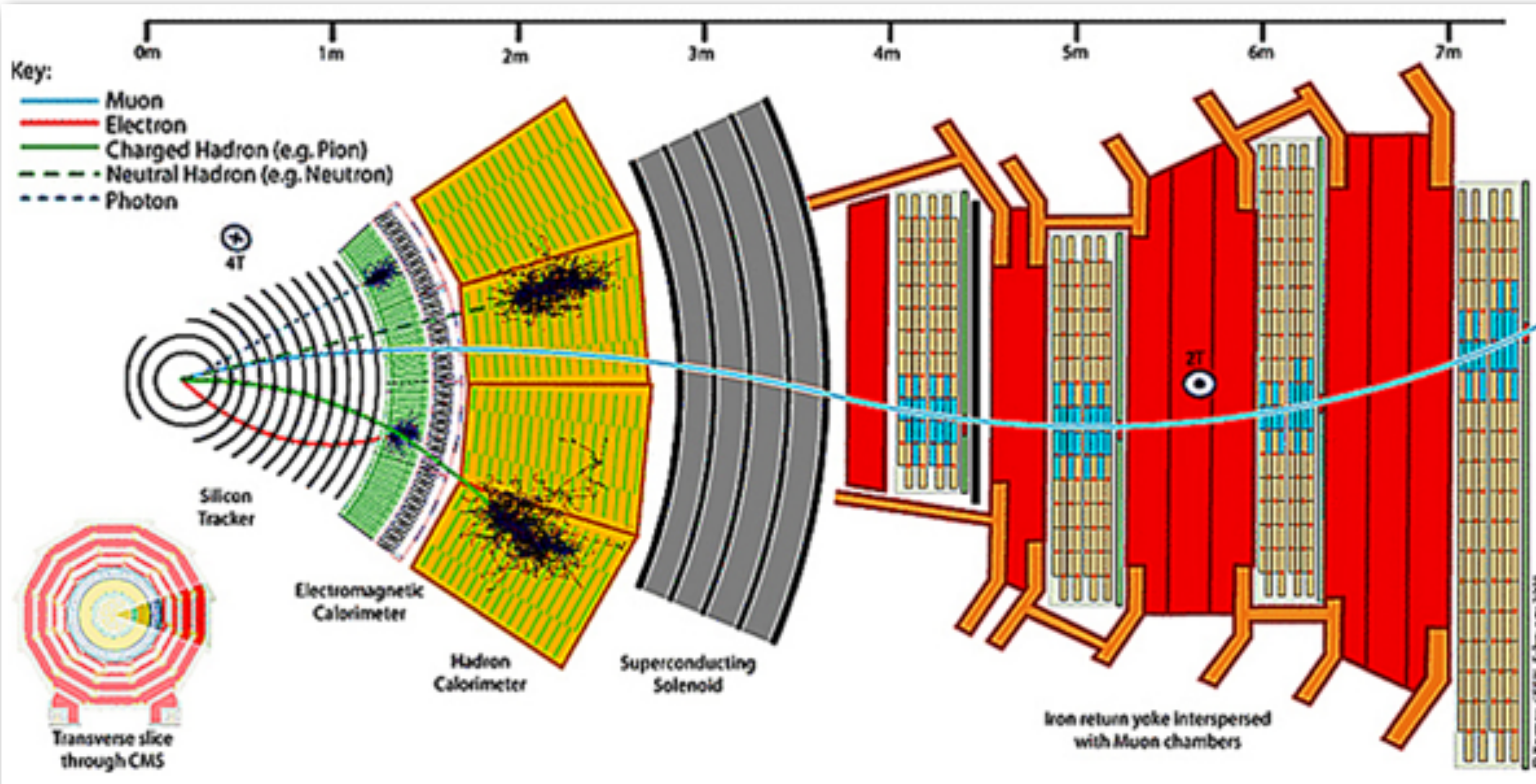


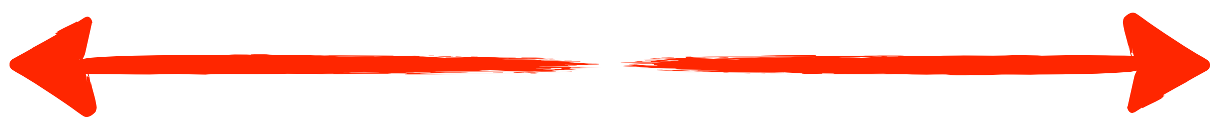
- DM Does not interact with detector, can not be observed directly

dark at collider as well

Missing E_T

Momentum conservation

$$\sum \vec{p} = 0$$



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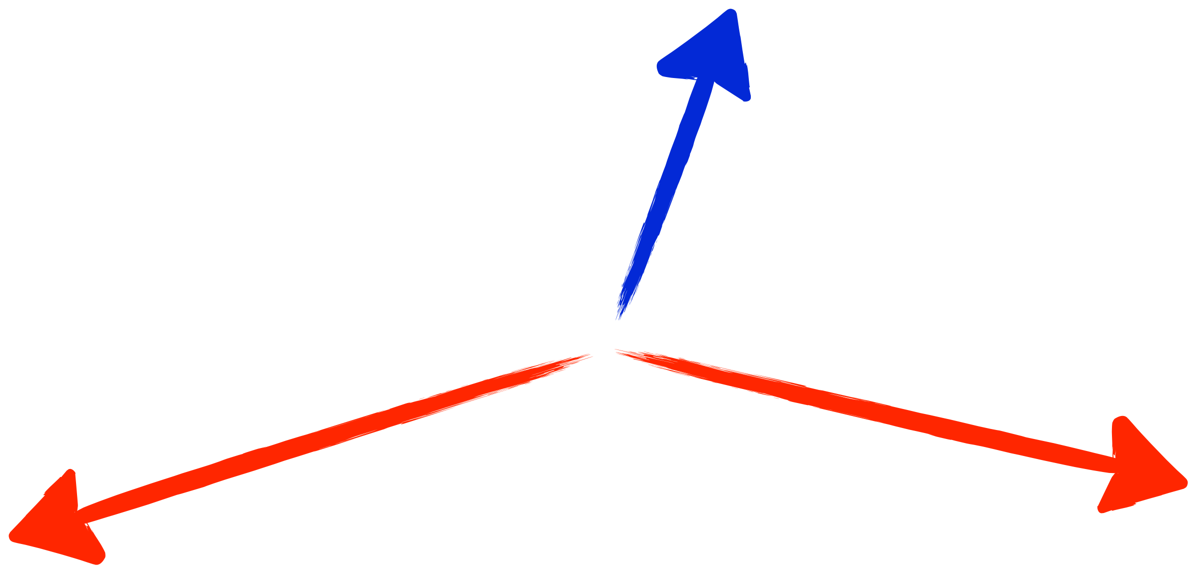

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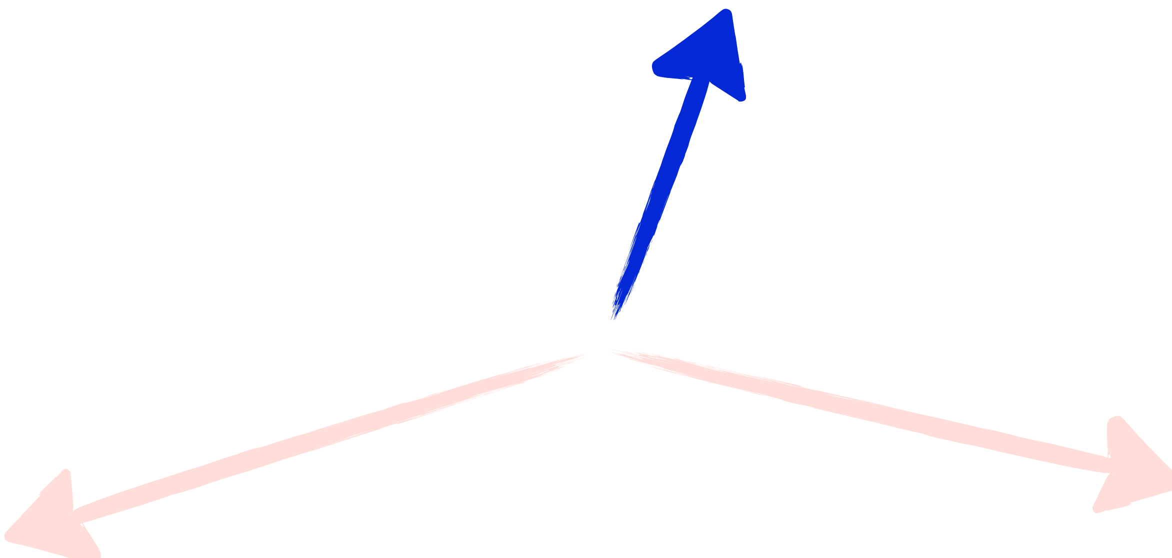

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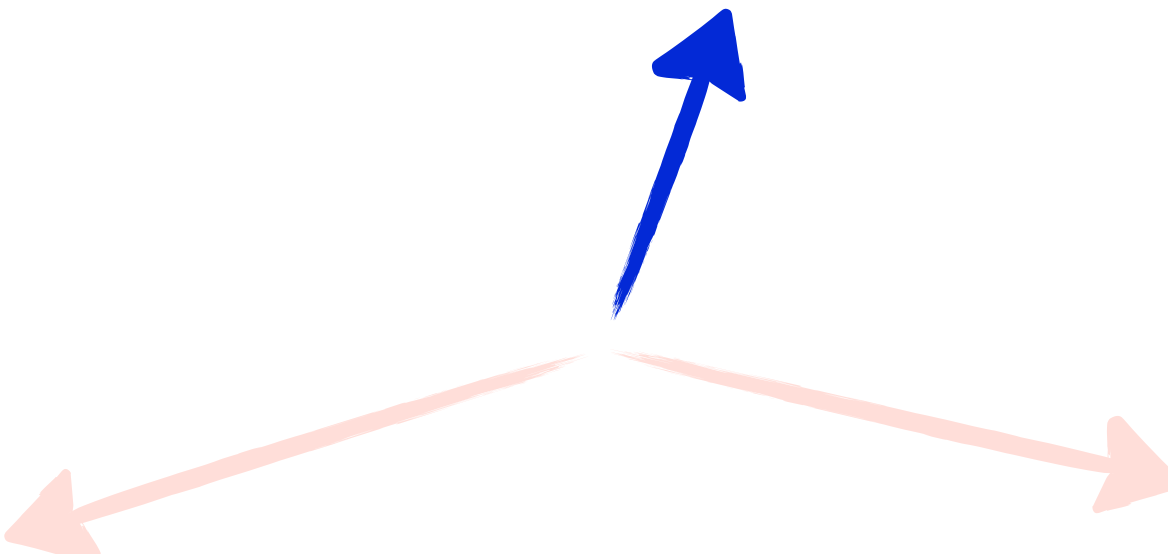


Hadron collider: $\sum \vec{p}_T = 0$

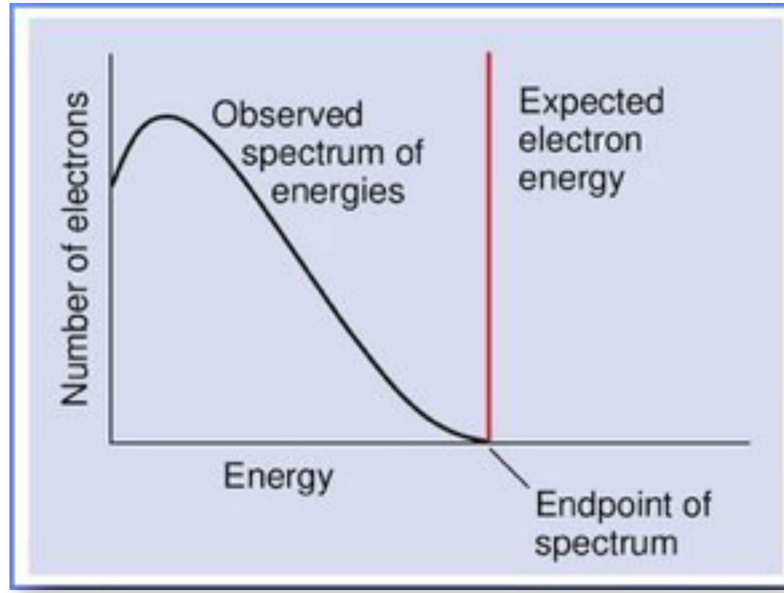
$\boxed{\textbf{DM: Missing } E_T \textbf{ signature}}$

We have see this before…

Neutrinos $n^0 \rightarrow p^+ e^- \bar{\nu}_e$

energy momentum conservation

- Pauli (1930), named "neutron"
  Chadwick (1932)
- Fermi (1933, 1934),
  "Neutrino": little neutral one



Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

$$\mathcal{L} = G_F \; \bar{\psi}_p \gamma^\mu \psi_n \; \bar{\psi}_e \gamma_\mu \psi_{\nu_e}$$

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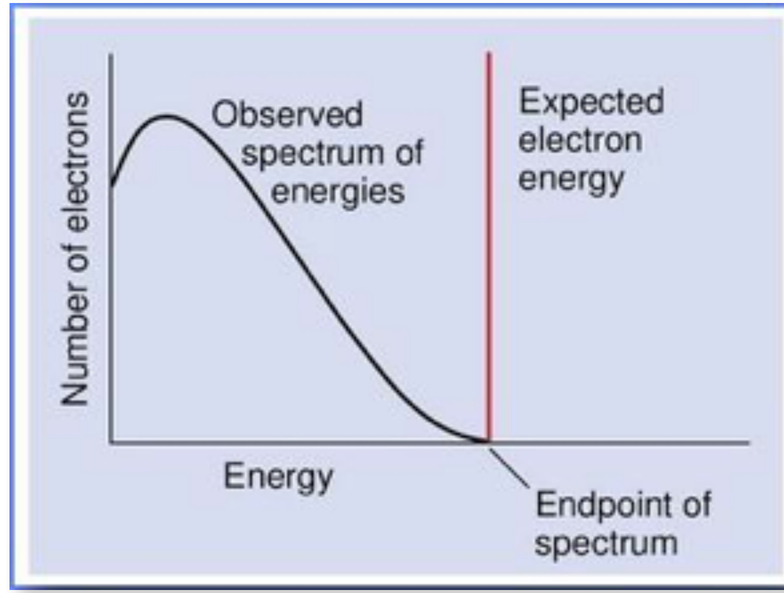

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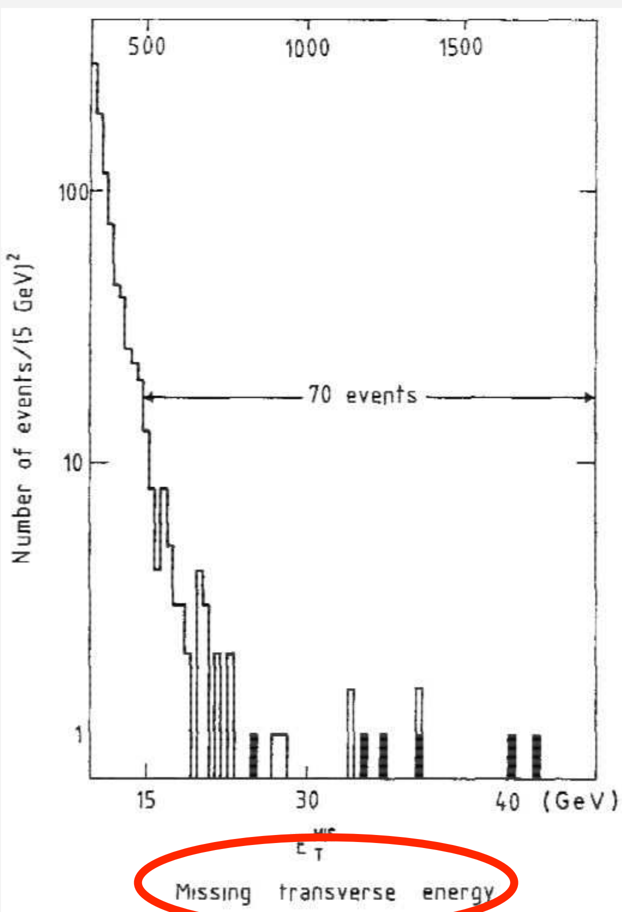
Nature: too remote from reality
Fermi: switch to experimental phyics

the 1st "dark matter" !

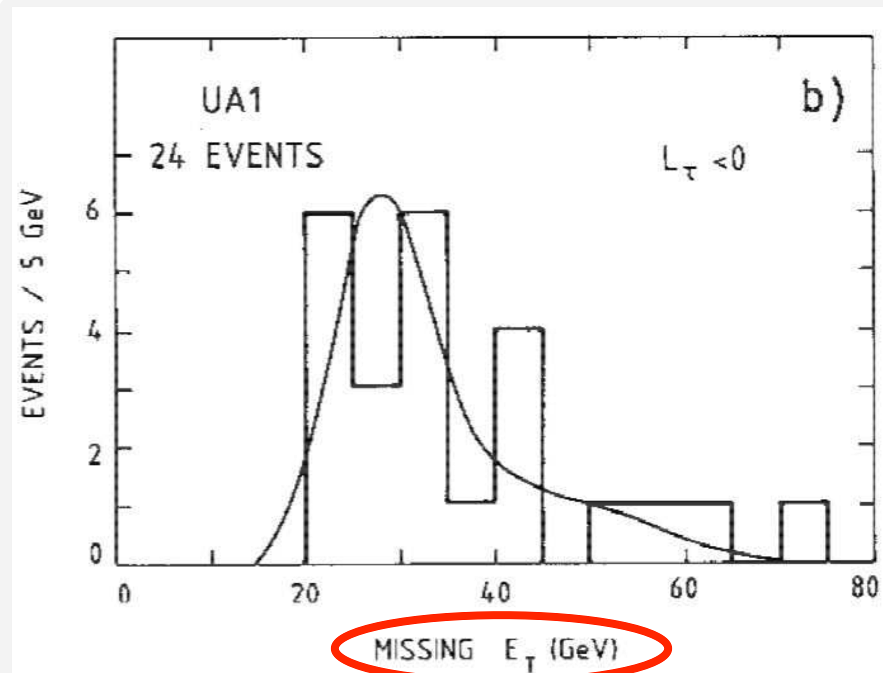
Neutrino: 1st example for missing energy

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland



◉ Discovery of W→ l ν_l (UA1/UA2, 1983)



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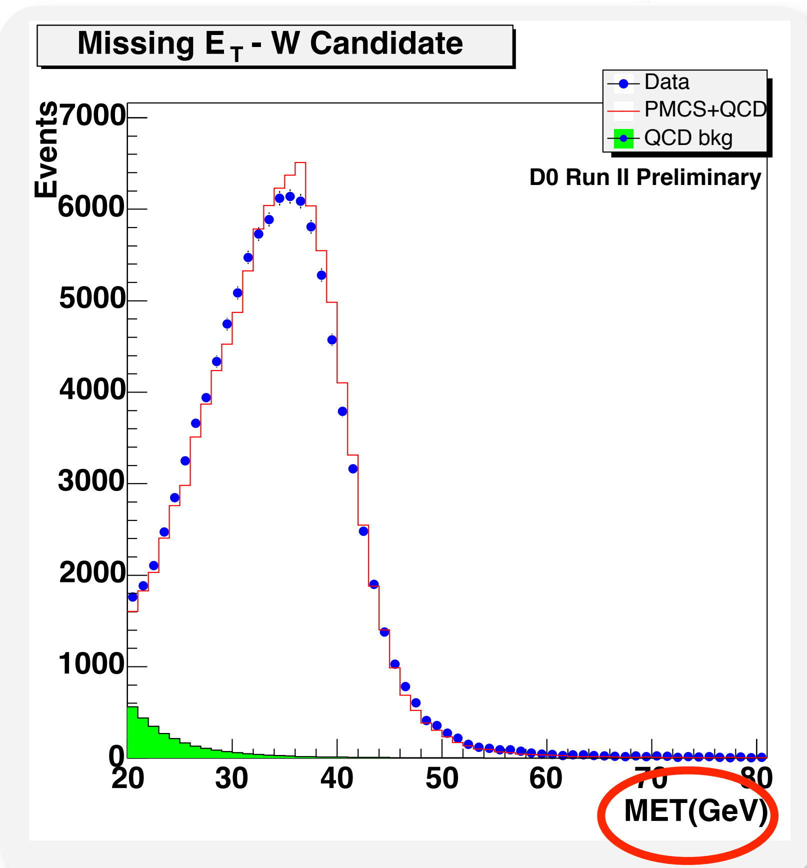

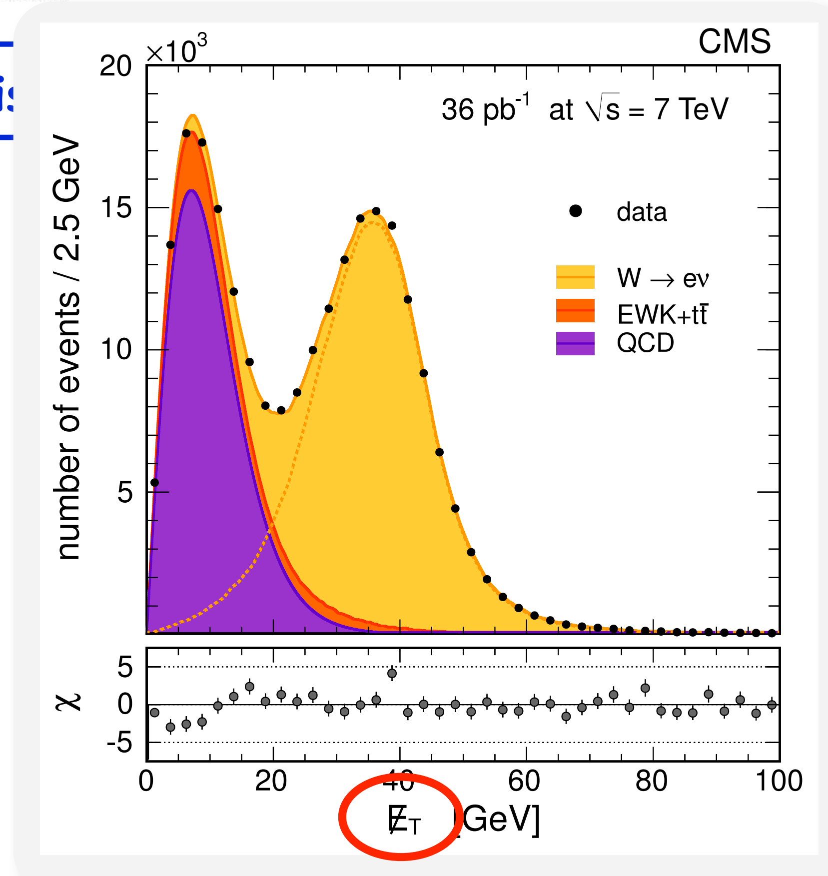

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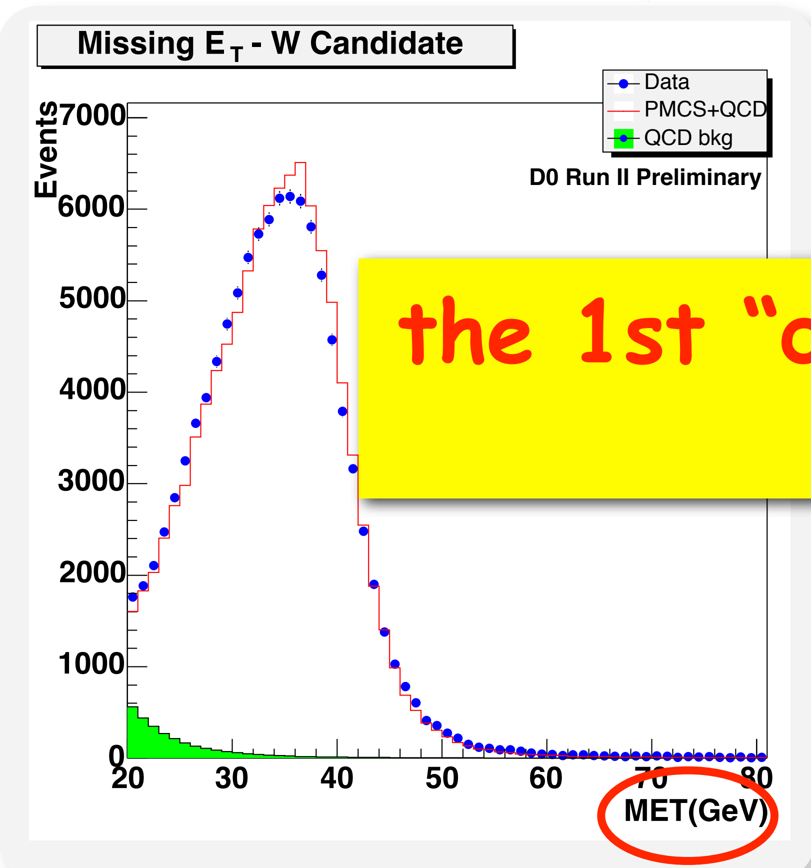

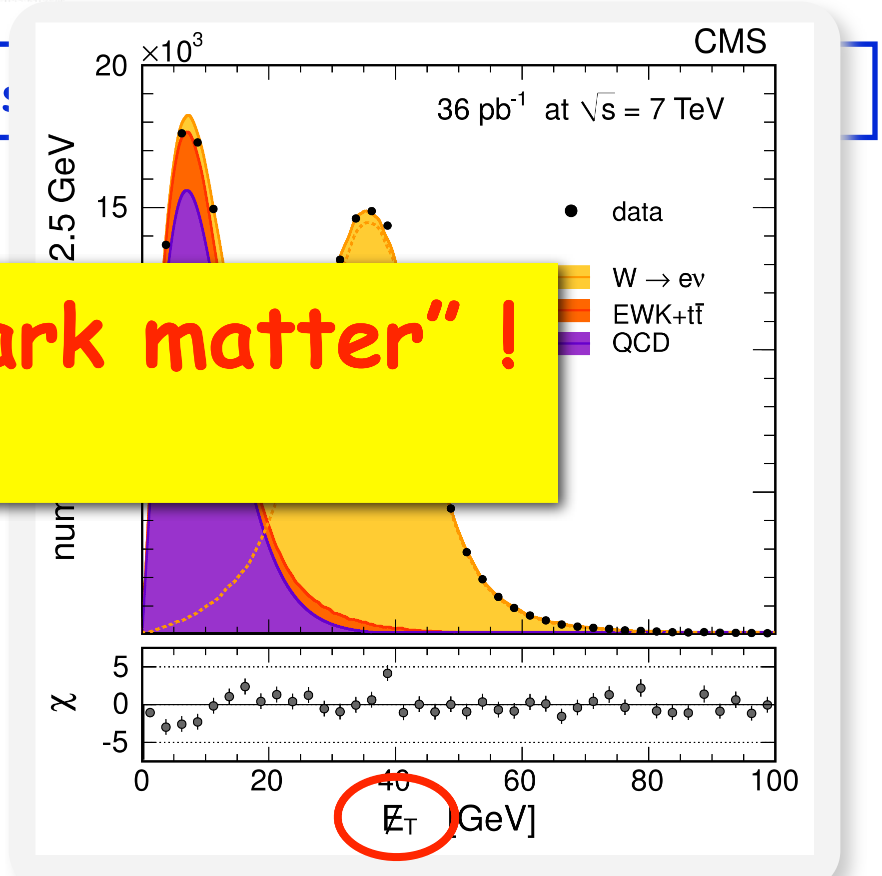

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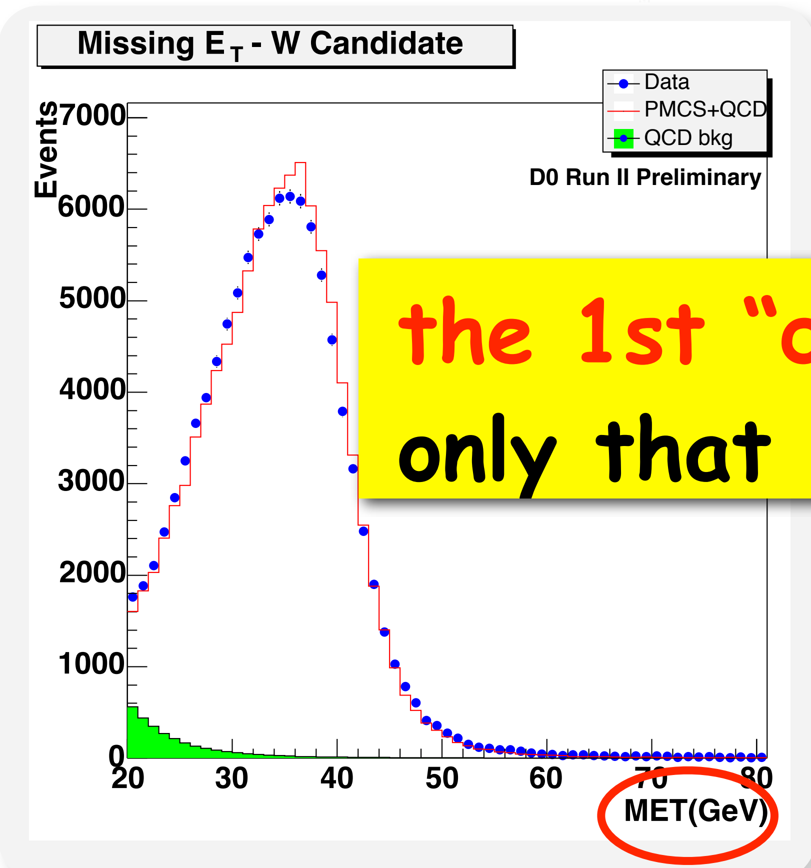
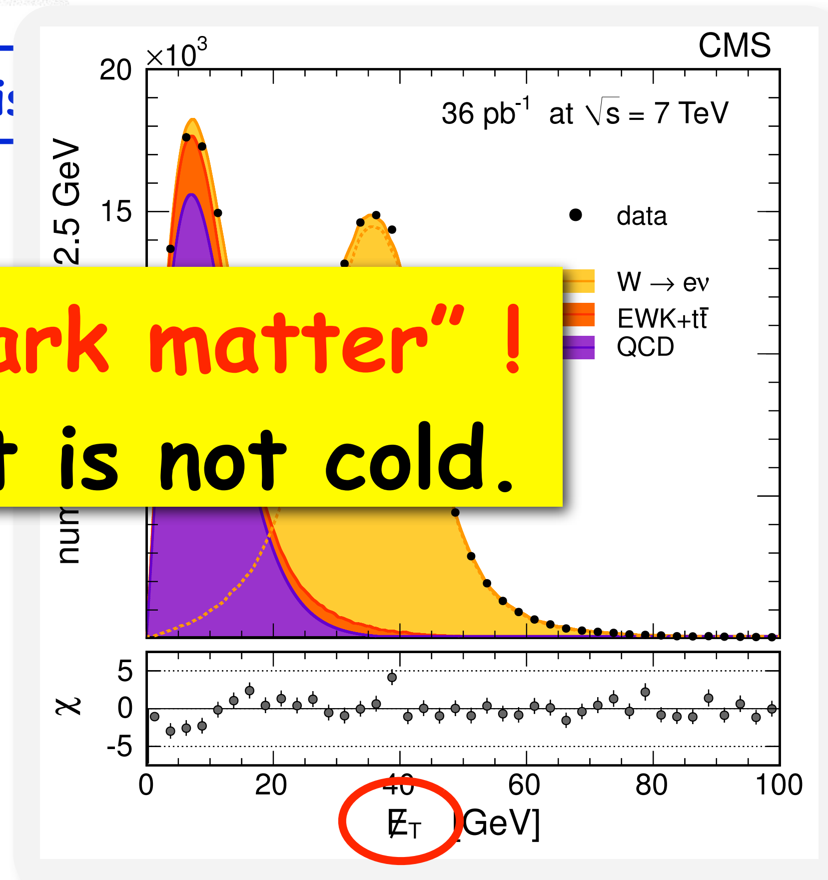
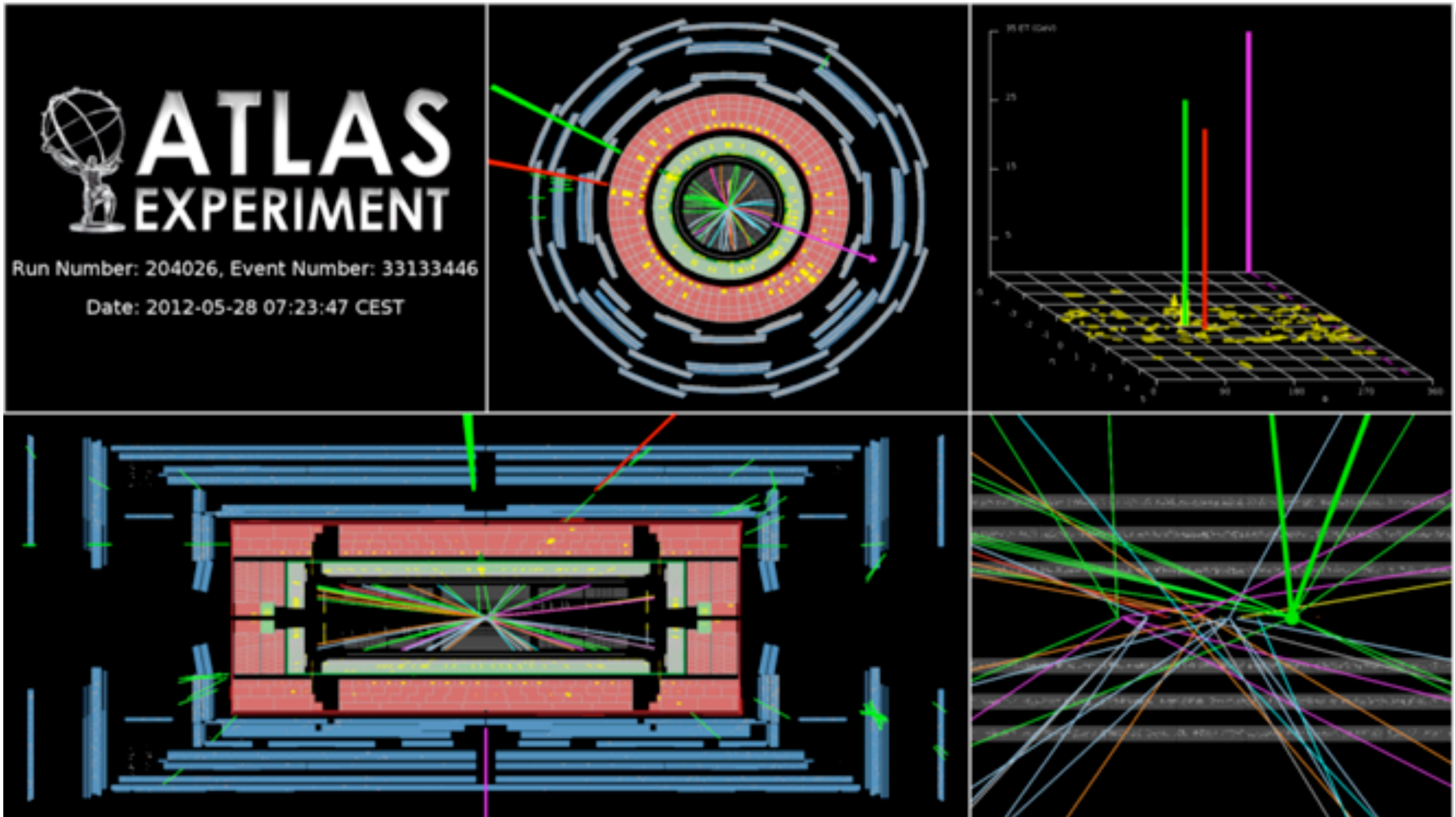




the 1st "dark matter" !

only that it is not cold.

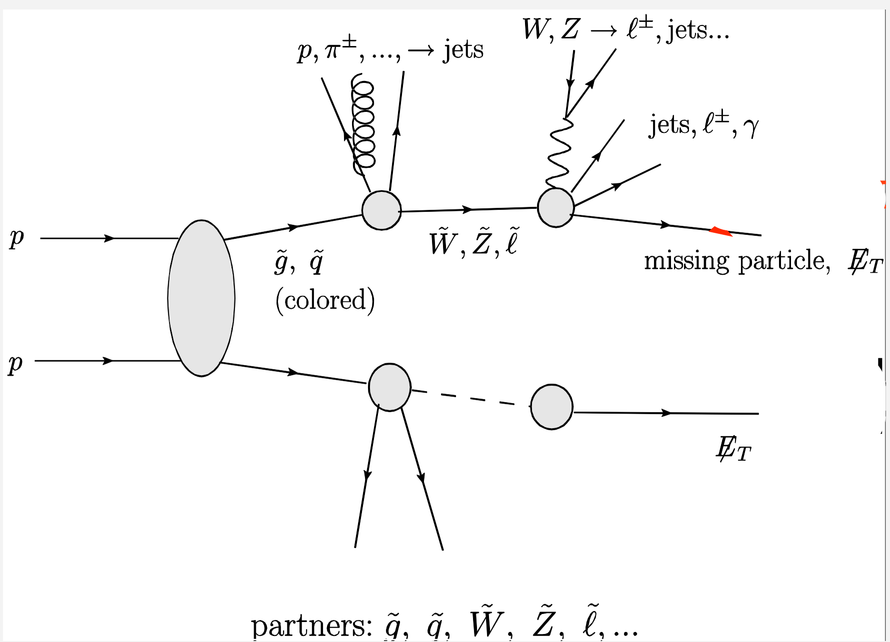
MET used everywhere...



Higgs $\rightarrow WW \rightarrow e\nu_e\ \mu\nu_\mu$

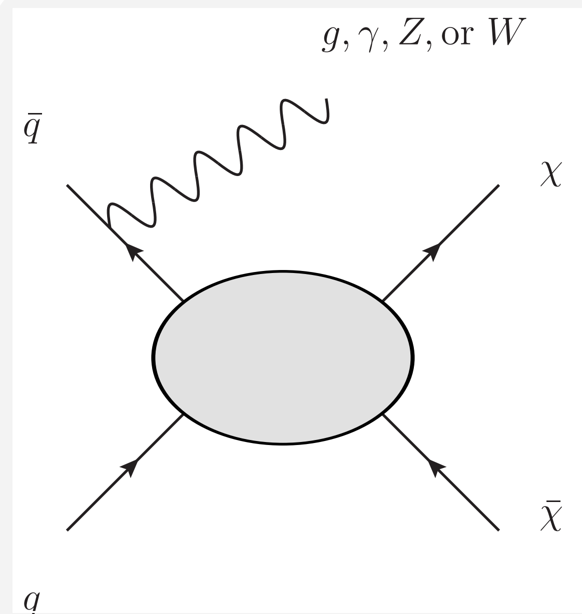
How to observe dark matter signal?

- Last particle in the cascade decay chain of parent particle



- direct (pair) production (with jet/photon/...)

effective operator approach



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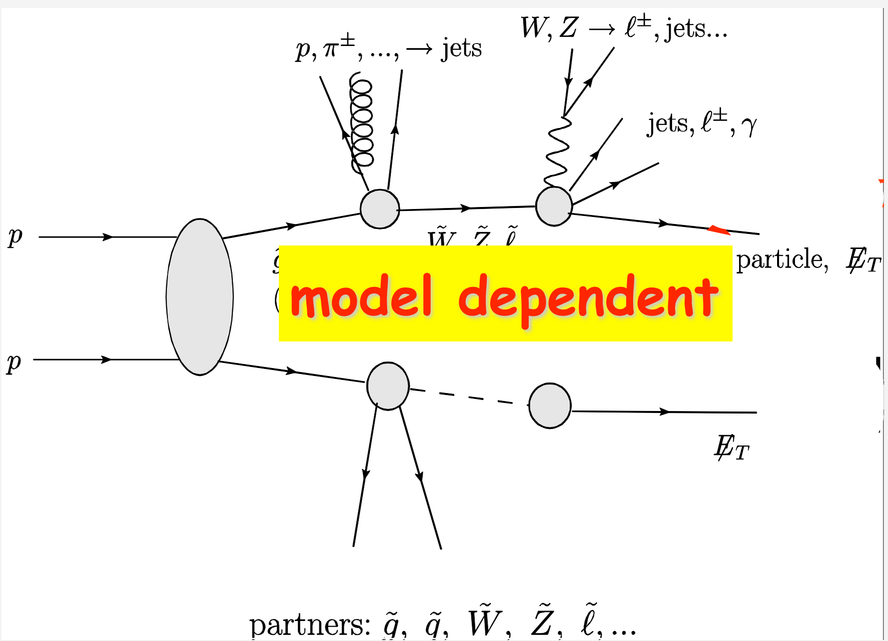

model dependent

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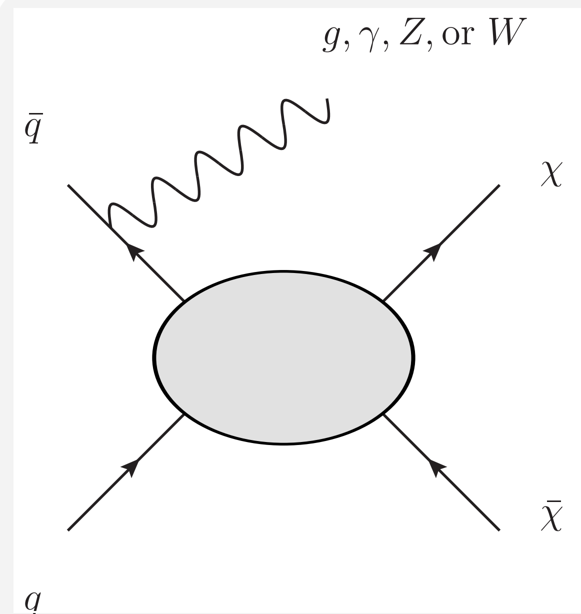

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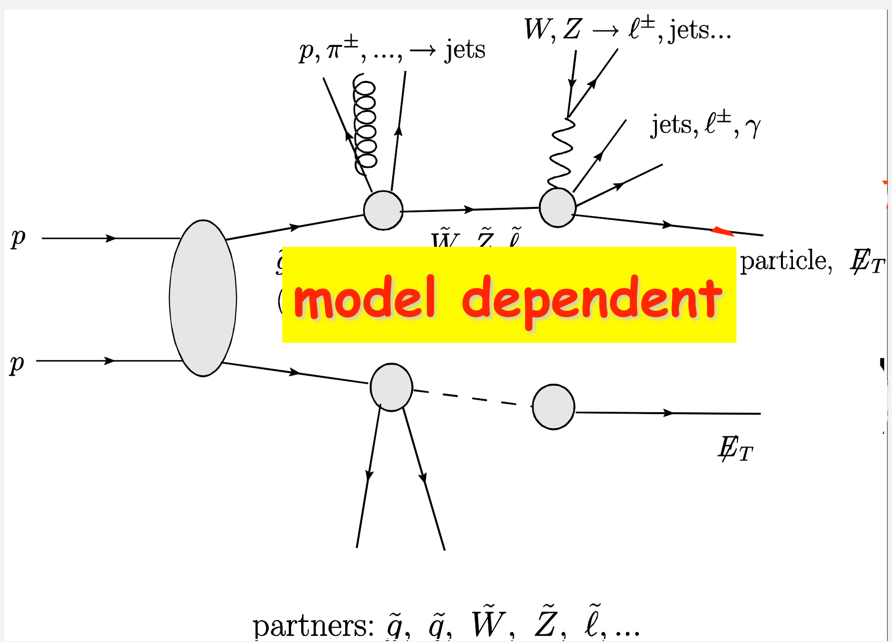

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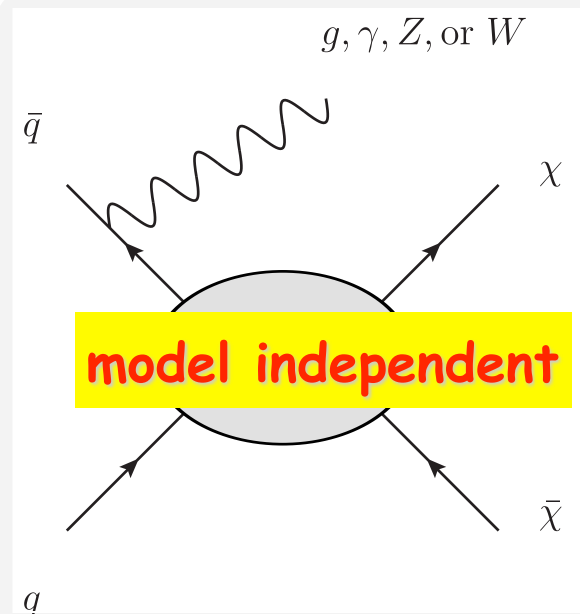

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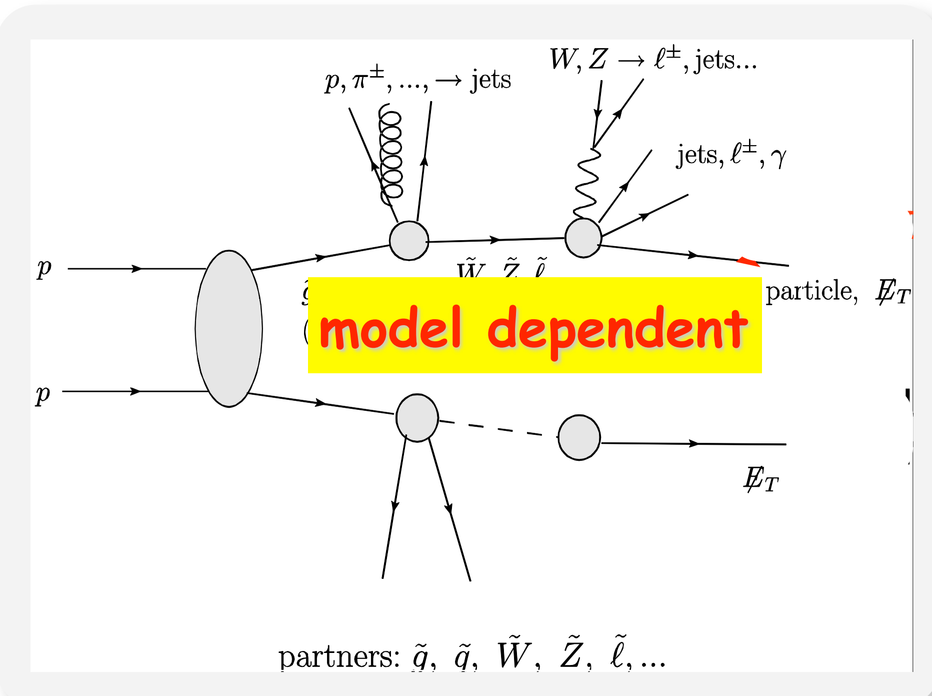

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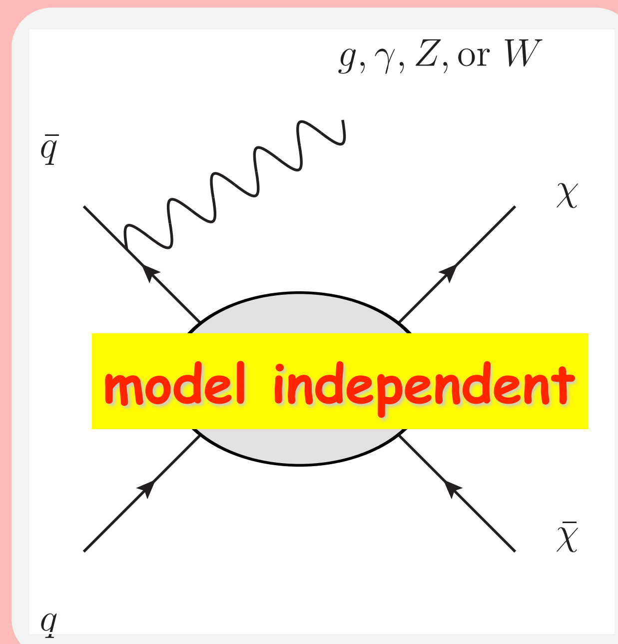
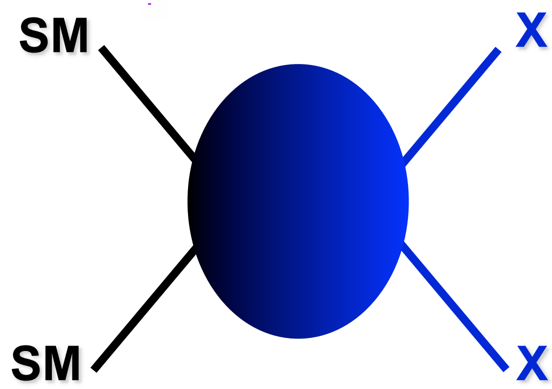


Comparison with direct detection

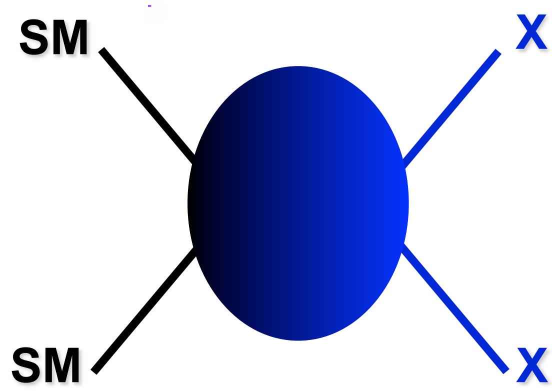
effective operator approach



$$\frac{1}{\Lambda^2}\bar{\chi}\Gamma^{\chi}\chi\bar{q}\Gamma^{q}q$$

Comparison with direct detection

effective operator approach



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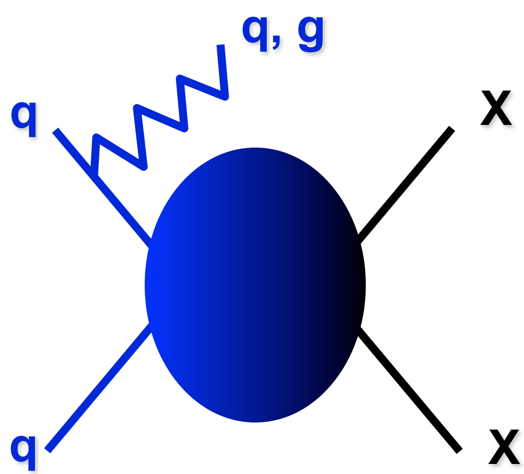
Collider Searches



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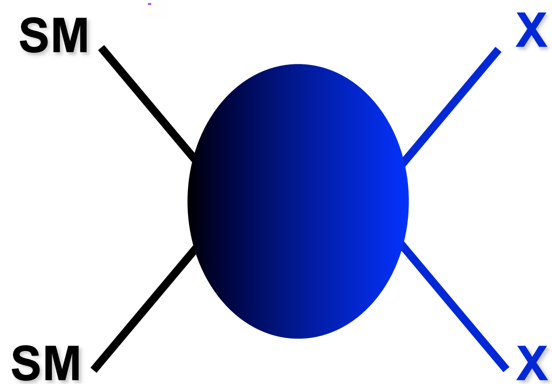

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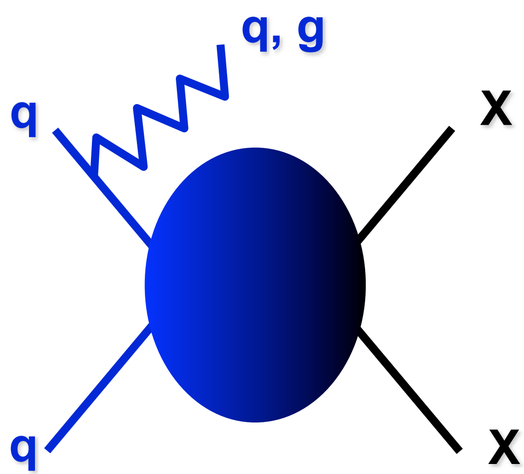
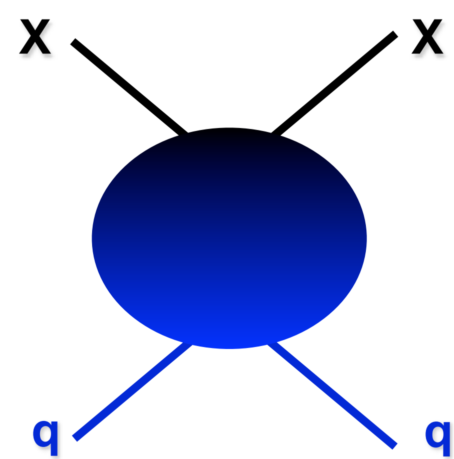


direct DM detection



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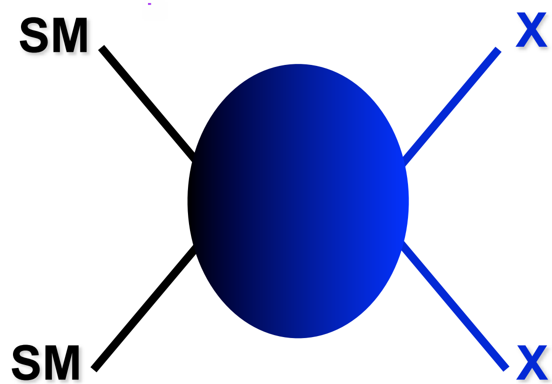

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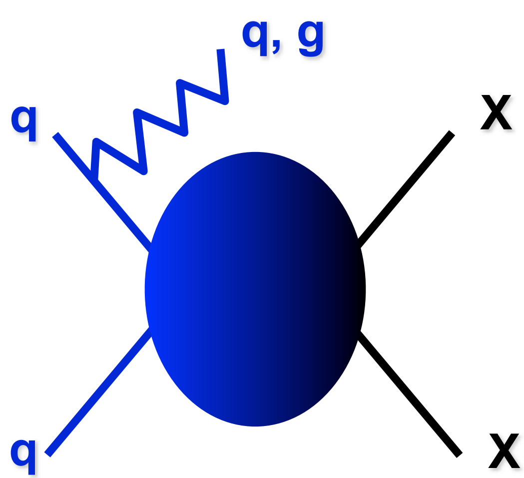
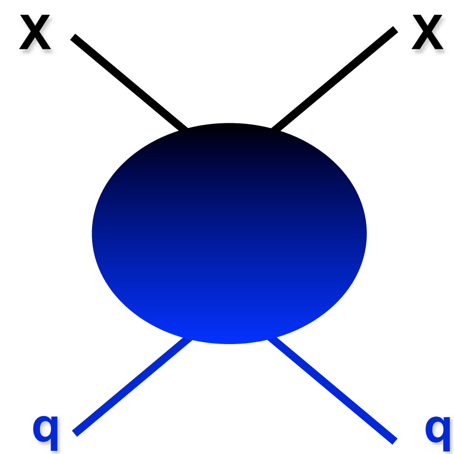


$$\frac{\sigma_{1j}}{\sigma_{DD}} \sim \alpha_s \frac{p_T^2}{\mu^2} \sim \mathcal{O}(1000)$$



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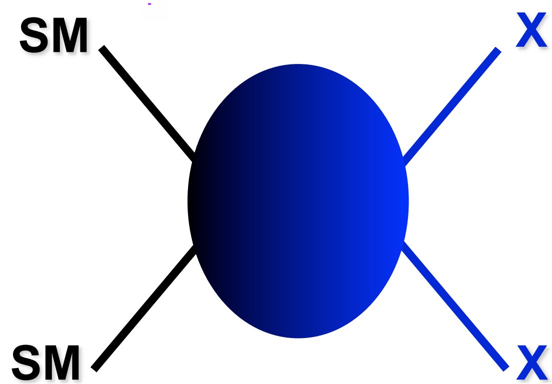

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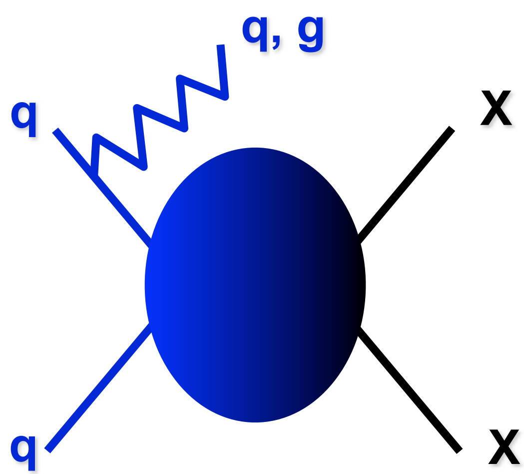

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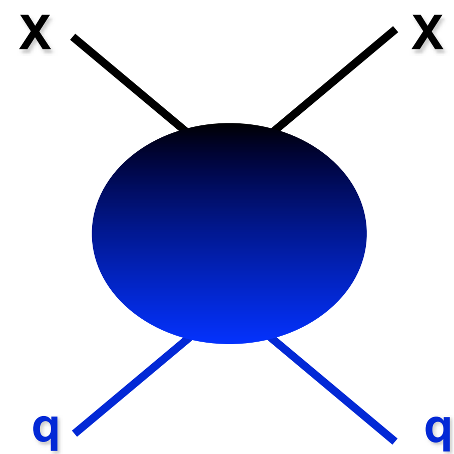
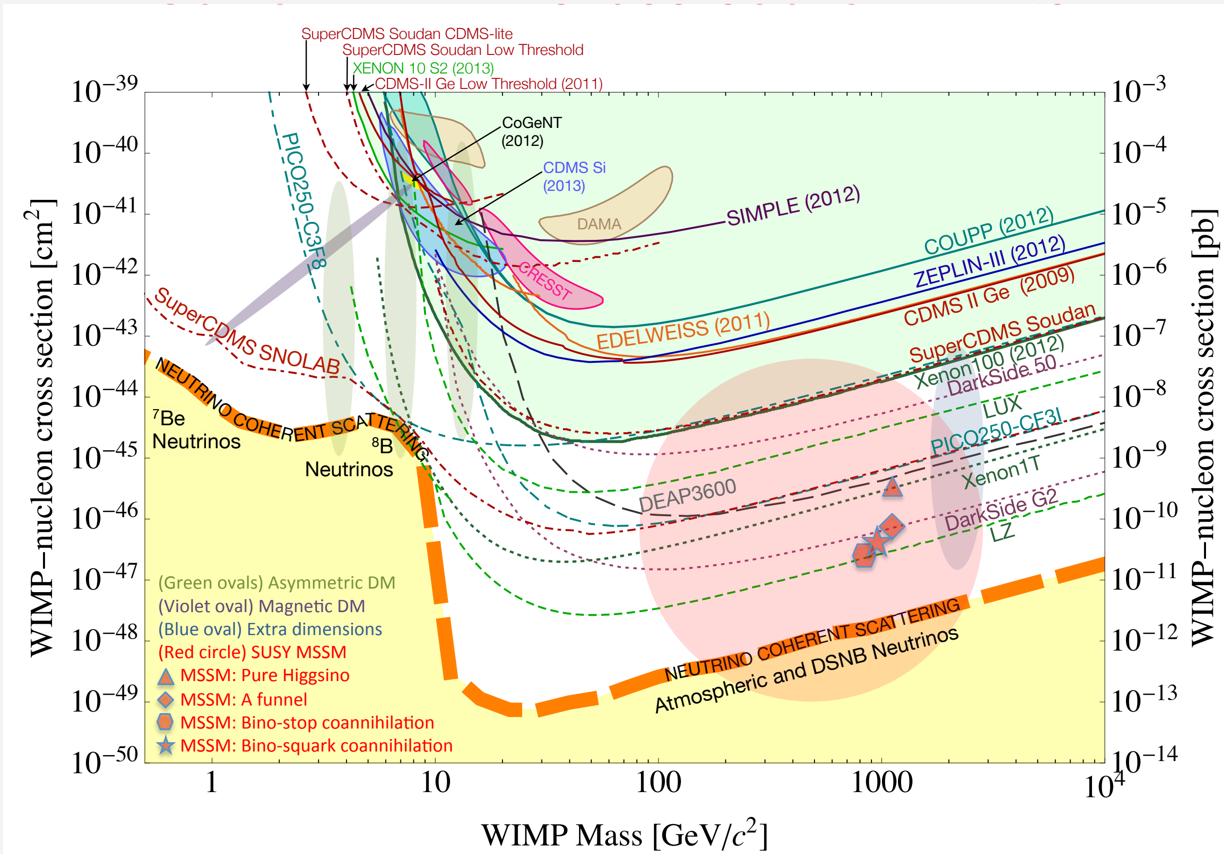


complementary between collider searches and DM direct detection.

Direct detection versus collider reach

LUX collaboration, 2013



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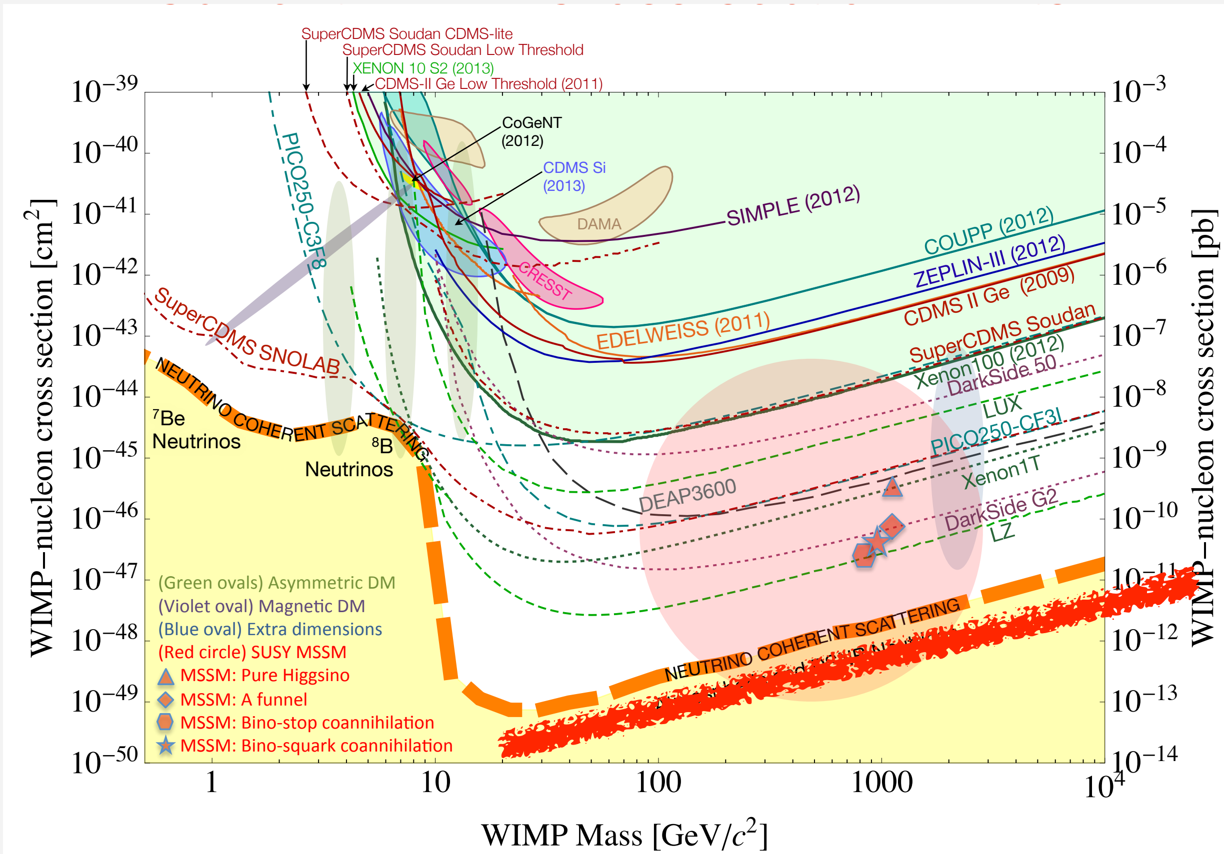

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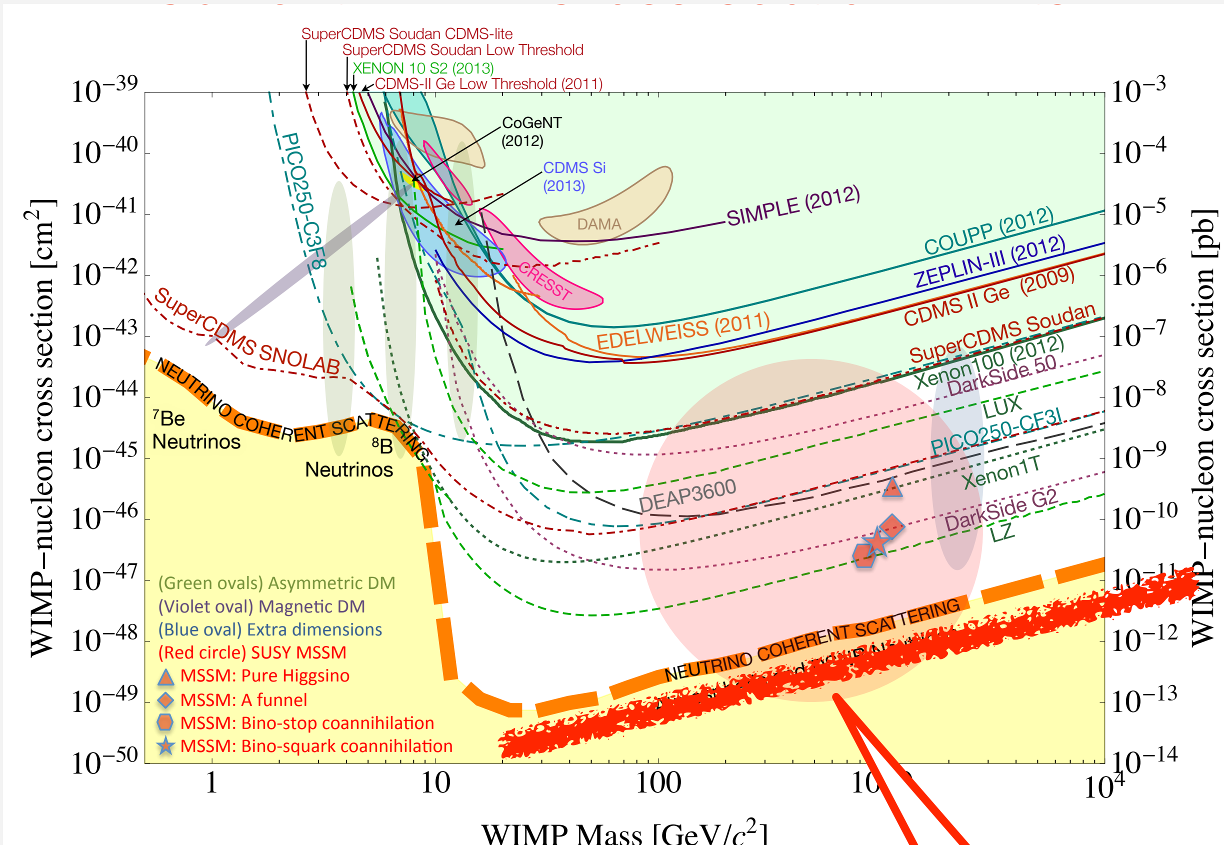
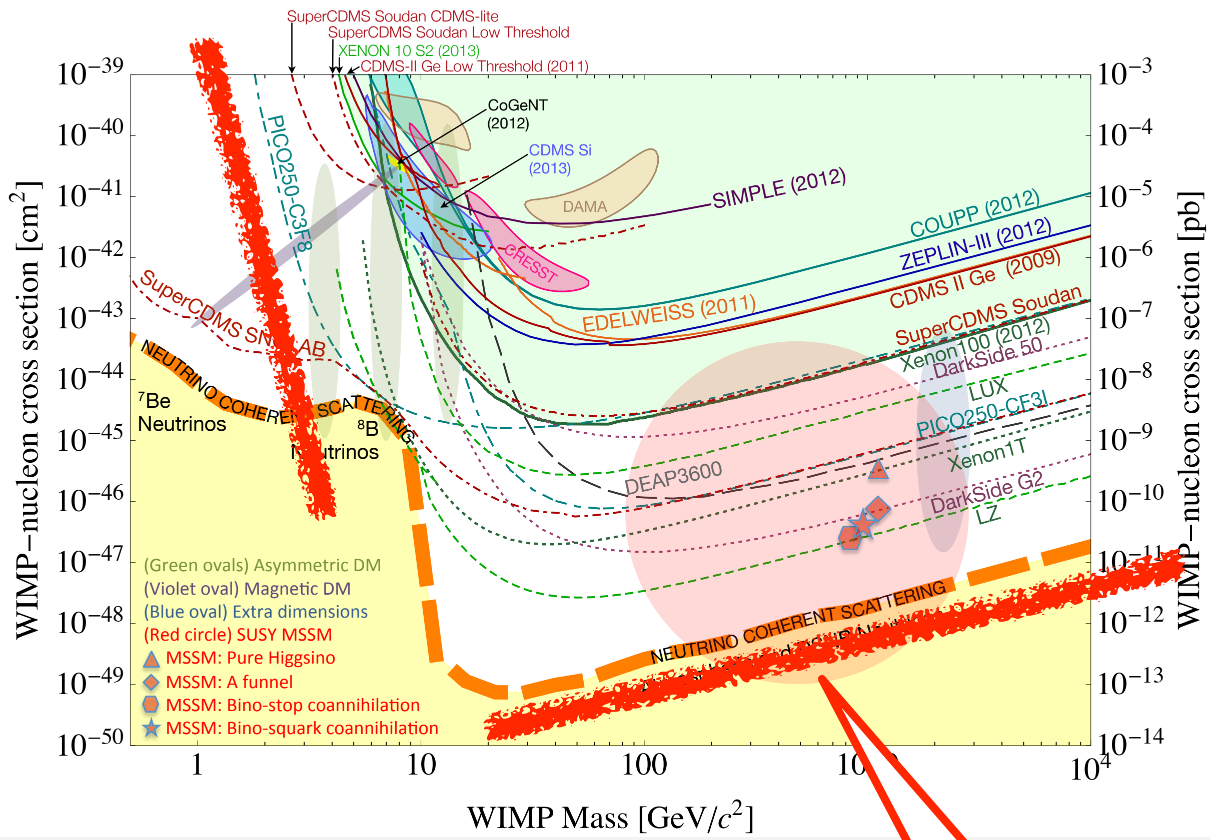


O(100) GeV DM, typical DM range

S. Su

Direct detection versus collider reach

LUX collaboration, 2013

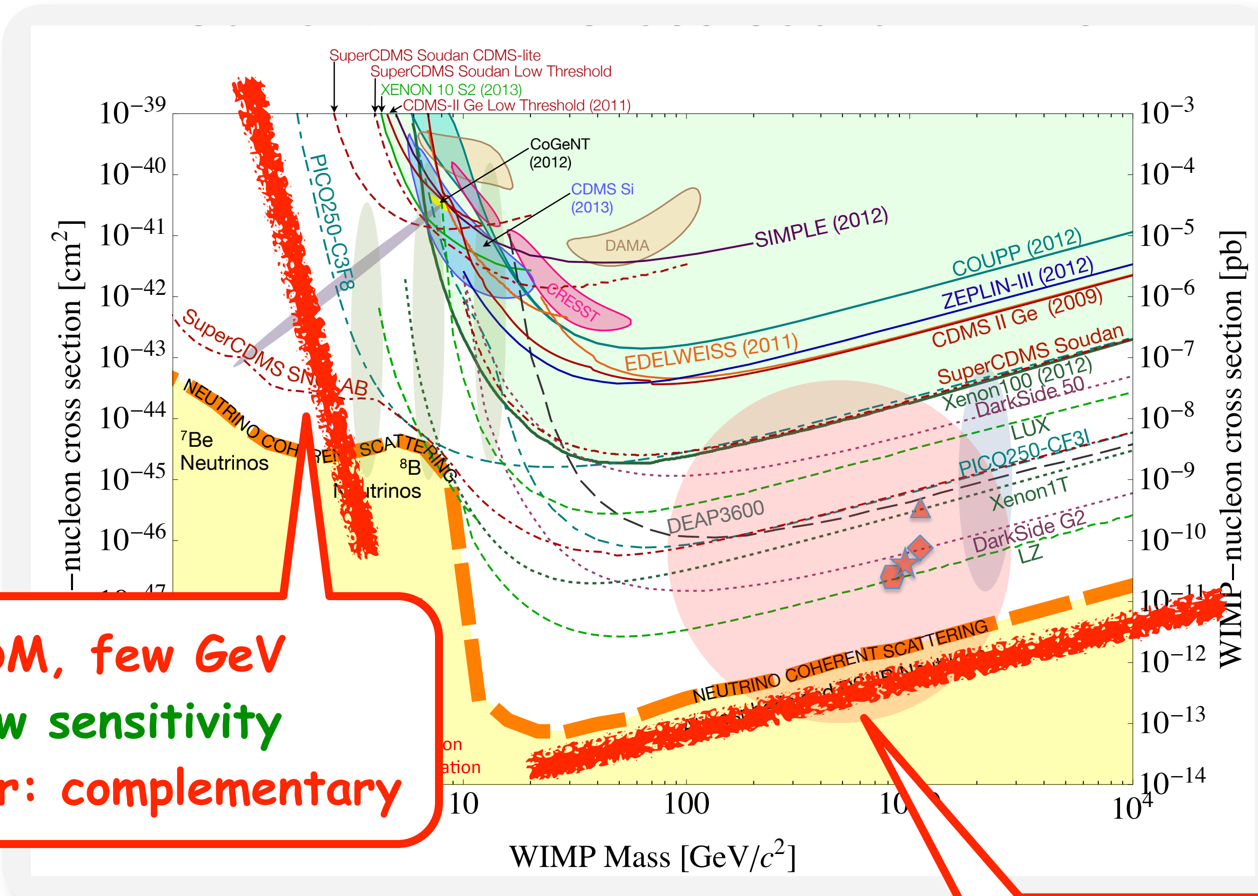


O(100) GeV DM, typical DM range

S. Su

Direct detection versus collider reach

LUX collaboration, 2013



light DM, few GeV

DD: low sensitivity

Collider: complementary

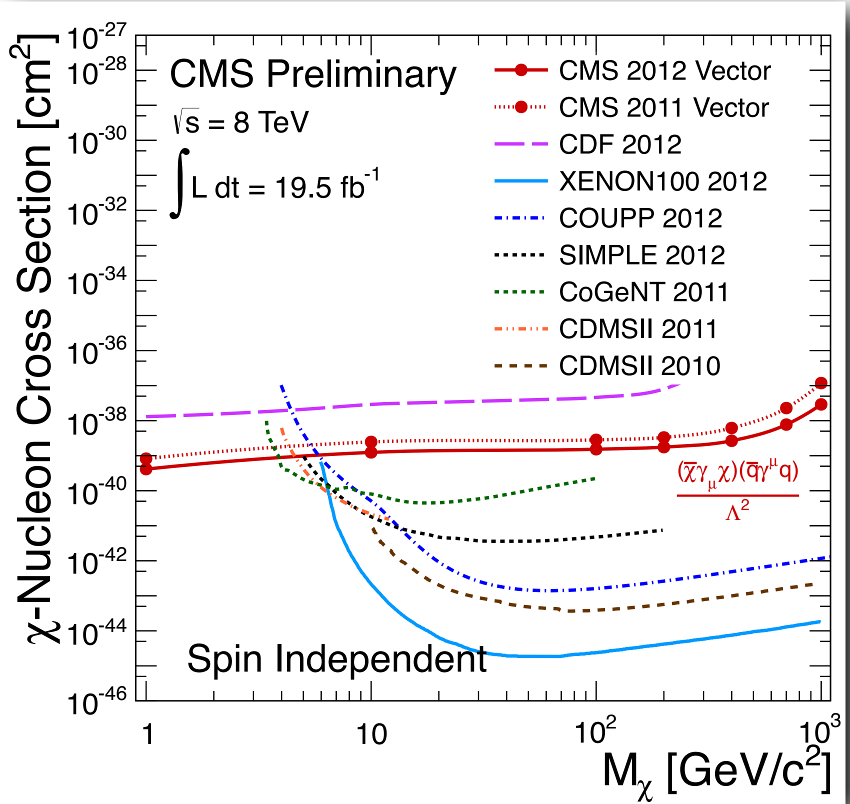
O(100) GeV DM,

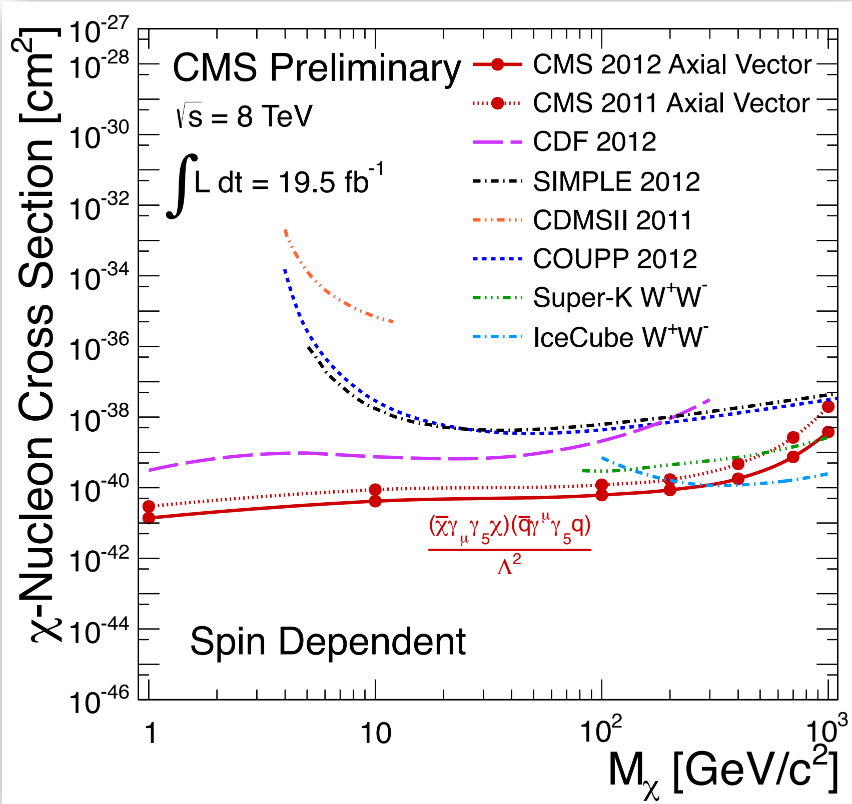
typical DM range

S. Su

CMS, monojet + MET

CMS, EXO-12-048





CMS, monojet + MET

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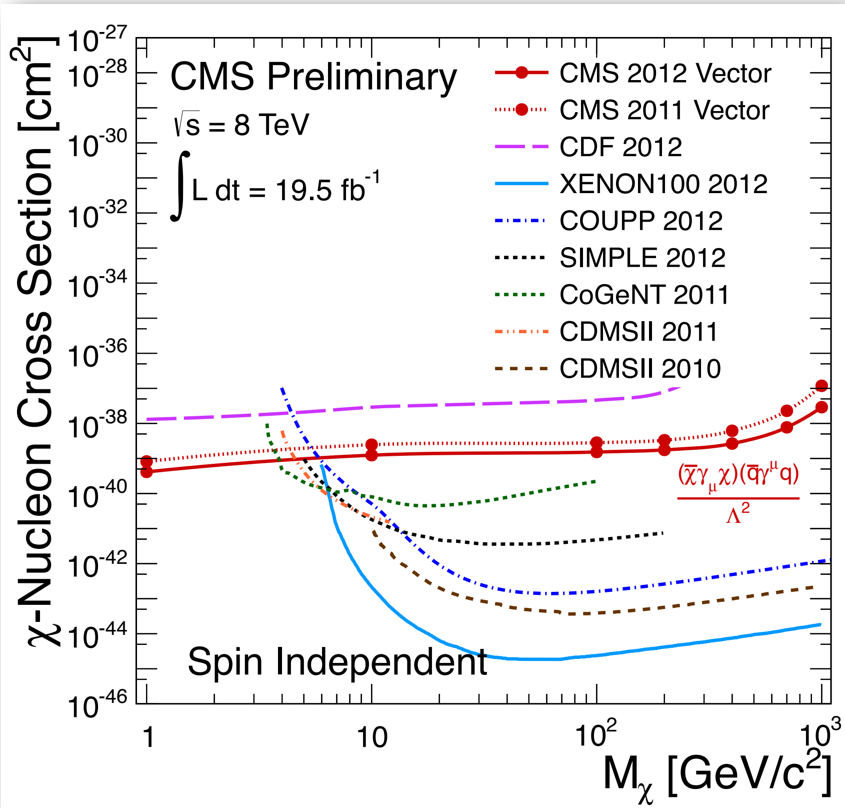
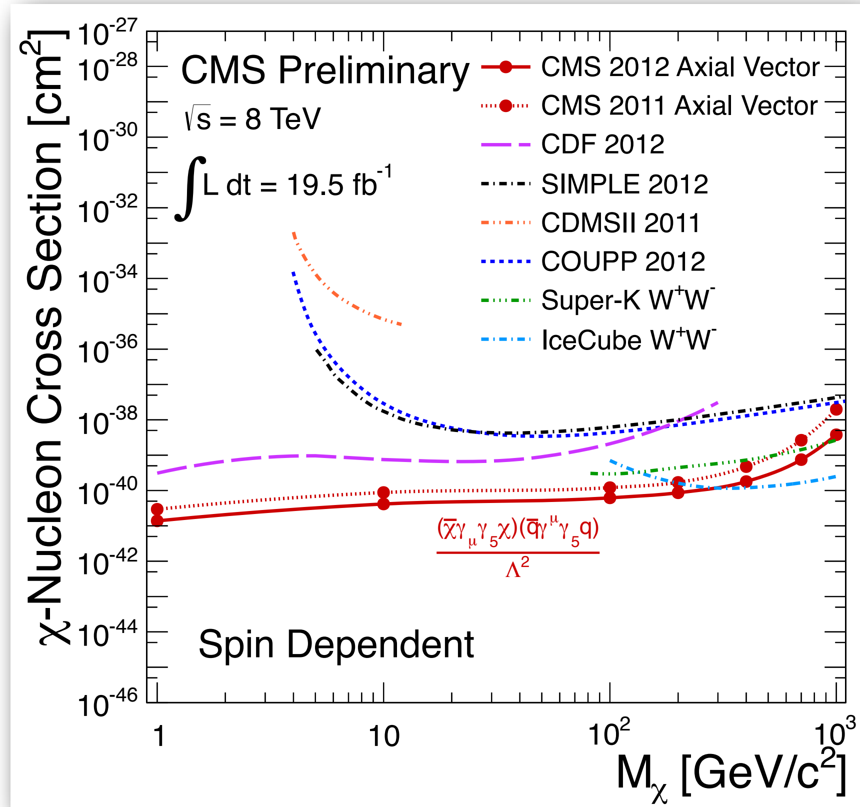
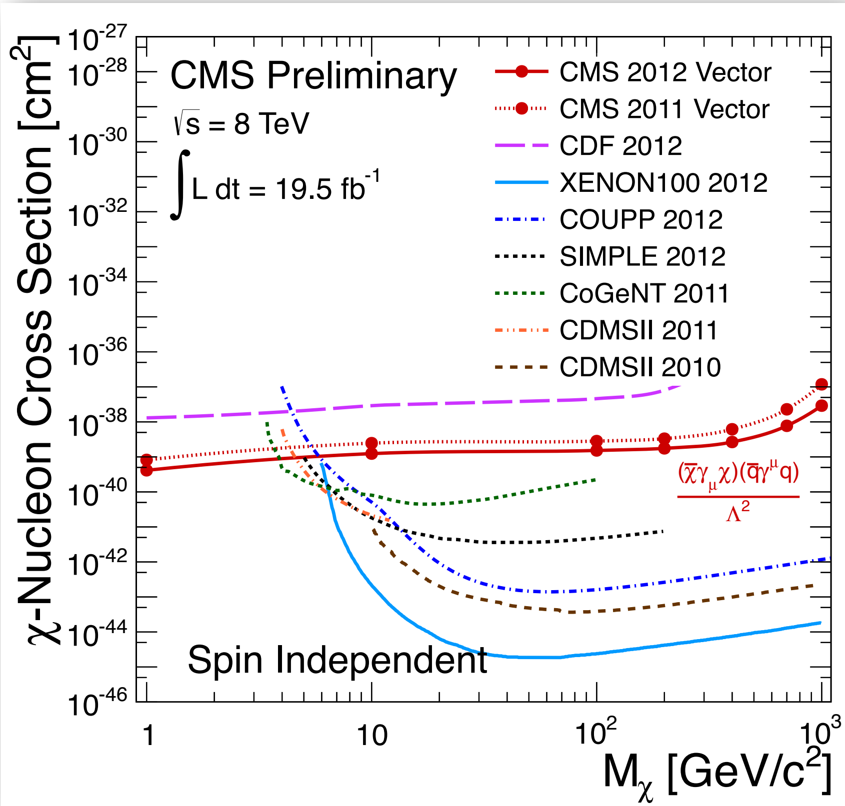


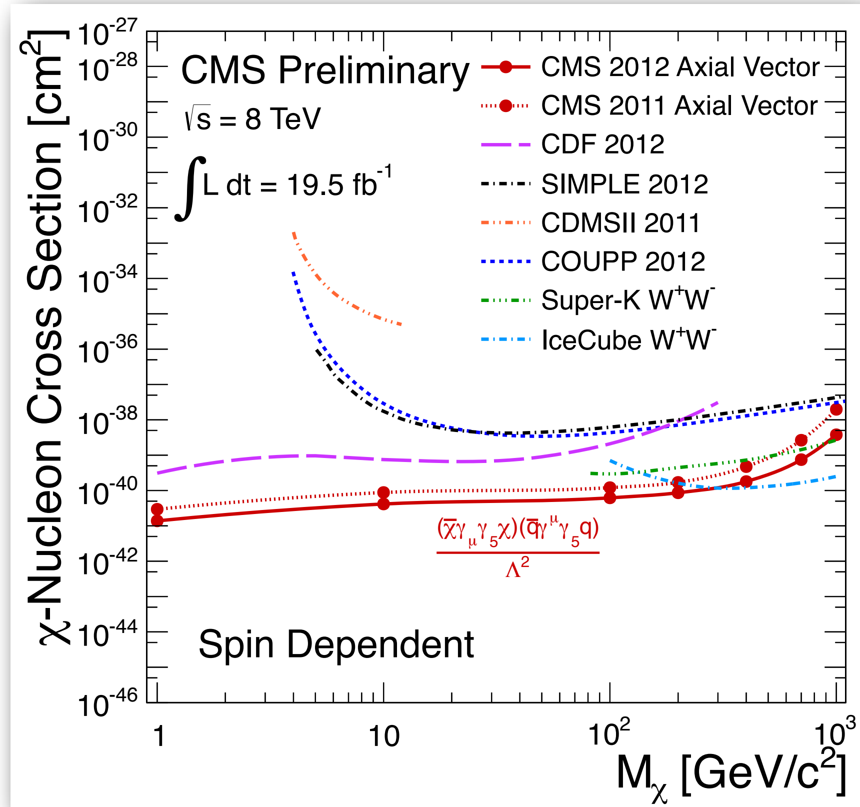


Collider better: small m_χ region, spin-dependent

CMS, monojet + MET

CMS, EXO-12-048





Collider better: small m_X region, spin-dependent

monojet, monophoton, monoZ, mono-b,...

Synergy

Synergy

Collider Inputs

Weak-scale Parameters

DM Annihilation DM-N Interaction

Synergy

Collider Inputs

Weak-scale Parameters

DM Annihilation DM-N Interaction

Relic Density Indirect Detection Direct Detection

Astrophysical and Cosmological Inputs

Synergy

parts per mille agreement for Ω_χ → discovery of dark matter

Collider Inputs

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Astrophysical and Cosmological Inputs

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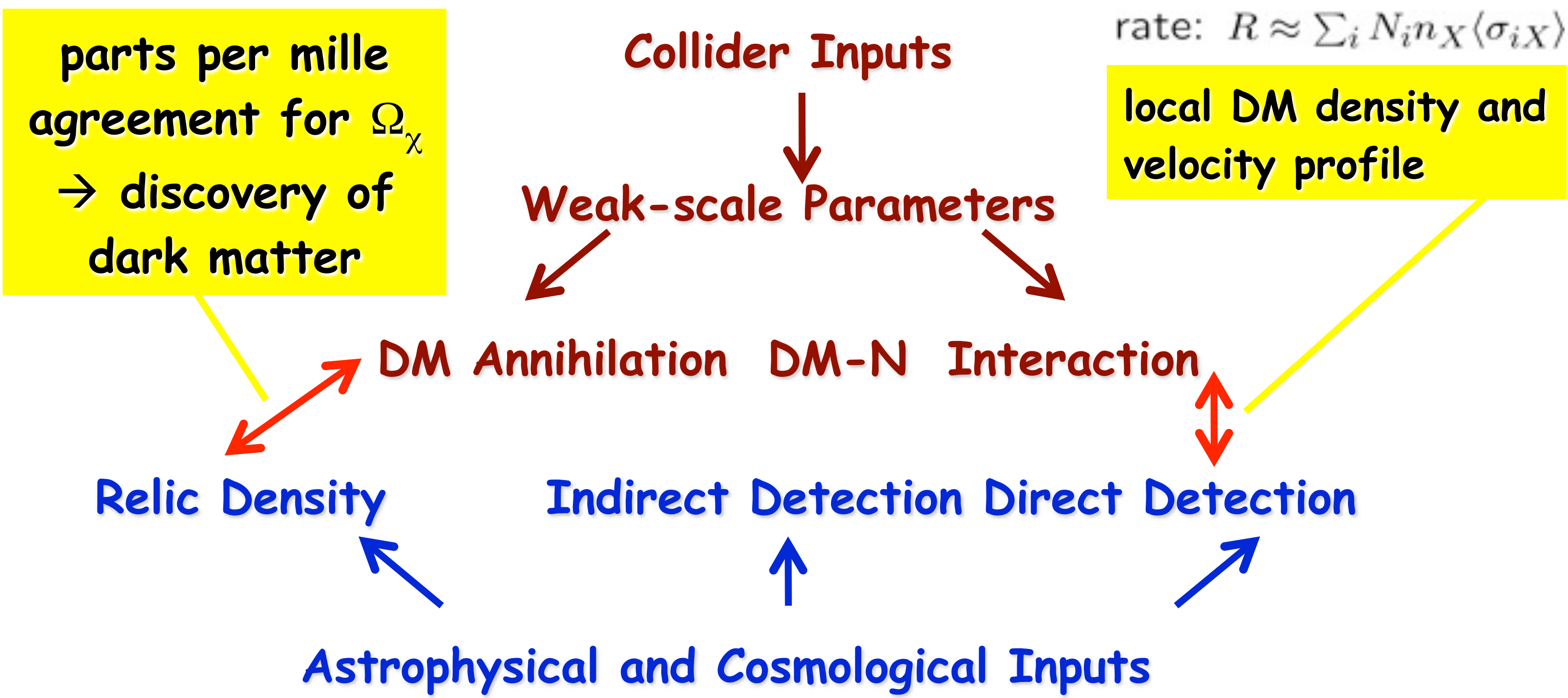
parts per mille agreement for Ω_χ → discovery of dark matter
Collider Inputs
rate: $R \approx \sum_i N_i n_X \langle \sigma_{iX} \rangle$
local DM density and velocity profile
Weak-scale Parameters
DM Annihilation
DM-N Interaction
Relic Density
Indirect Detection
Direct Detection
Astrophysical and Cosmological Inputs

Synergy

parts per mille agreement for Ω_χ
→ discovery of dark matter

Collider Inputs

↓

Weak-scale Parameters

rate: $R \approx \sum_i N_i n_X \langle \sigma_{iX} \rangle$

local DM density and velocity profile

DM Annihilation

DM-N Interaction

Relic Density

Indirect Detection

Direct Detection

Astrophysical and Cosmological Inputs

eliminate particle physics uncertainty
do real astrophysics

$$\frac{d\Phi}{dE_\gamma} = \int d^3r \frac{c}{|r|^2} n^2(r) \frac{d\sigma}{dE_\gamma}$$

Conclusion

- The existence of dark matter provides unambiguous evidence for new physics beyond the SM.
- Many new physics models naturally have a DM candidate: WIMP.
- DM direct detection.
  - no convincing evidence
  - light DM region: controversial.
- DM indirect detection
  - neutrinos, photos, positrons
  - PAMELA/FERMI/AMS: e+ signal
- DM at colliders
  - model independent: monojet, mono-xxx
  - model dependent searches
- Interplay between particle physics, astrophysics and cosmology

The Coming decade is going to be very exciting in particle physics, astrophysics, and cosmology

Stay tuned ...

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Stay tuned ...

谢谢！