Messages from the sky
:Matter, Dark matter and others:
Lecture #2

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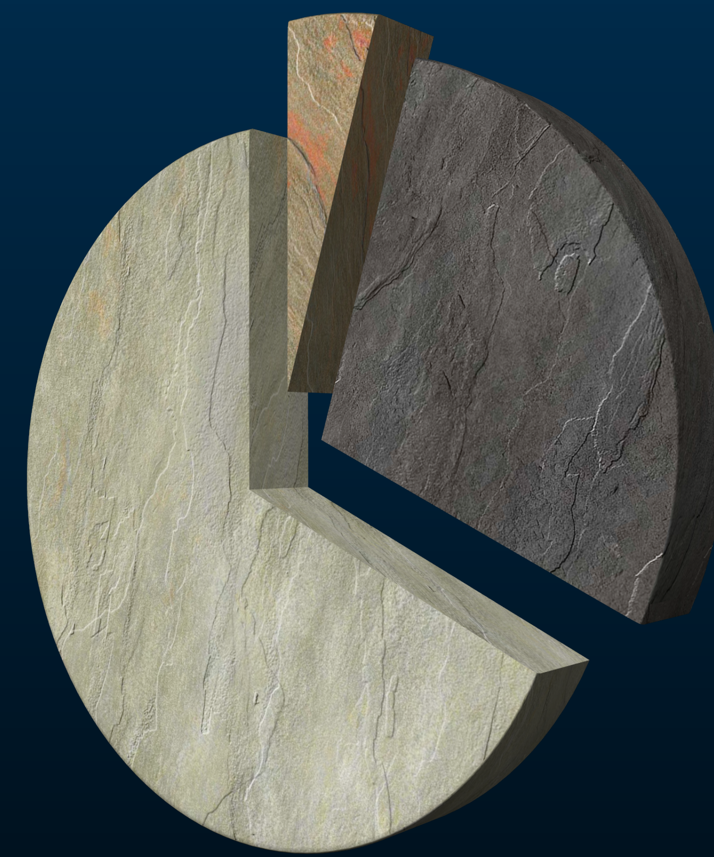
The 9th Asian Winter School
on strings, Particles and Cosmology
Busan, Jan 18-27, 2015

Summary of Lecture 1

- SM is in good shape
- **Evidences** for BSM
  - ✓ **DM**
  - ✓ DE
  - ✓ neutrino masses
  - ✓ inflation
  - ✓ Baryon asymmetry in nature



- Bayron (4.9%)
- Dark matter (26.6%)
- Dark energy (68.5%)

Planck 2014 (prelim)

How does a BSM sector appear?

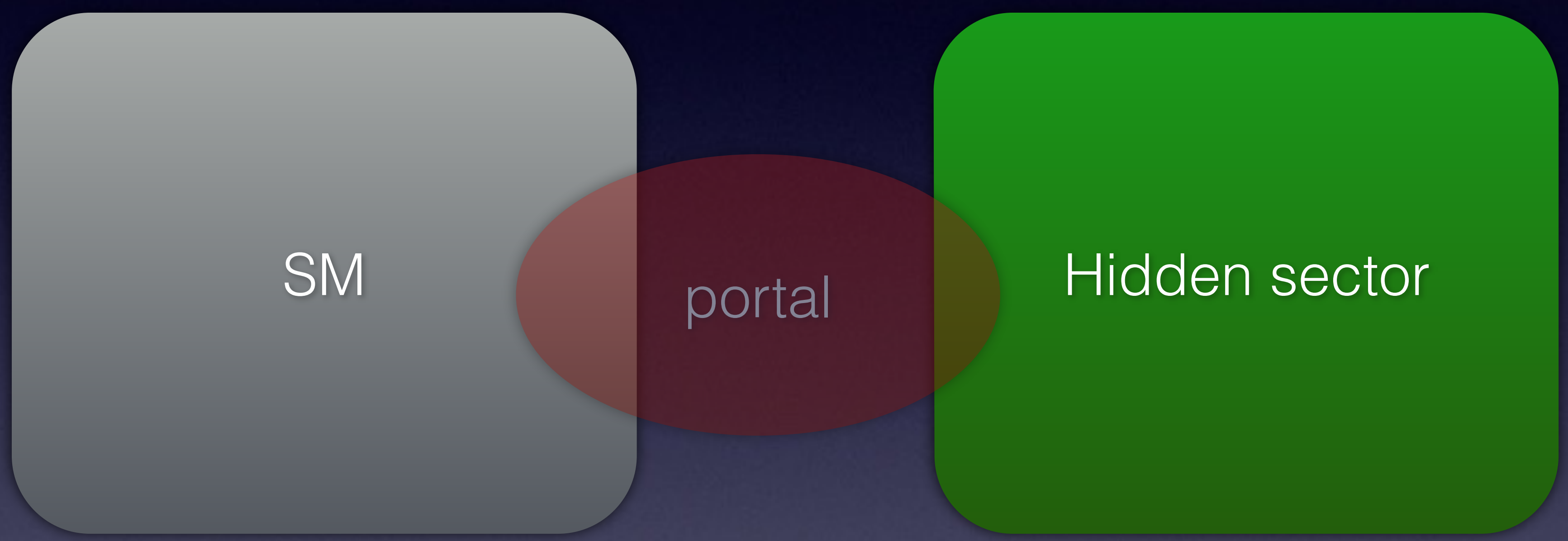
SM is embedded in a bigger structure

A particle in the other part may play the role of DM.

A hidden sector exists

BSM is completely separate from SM
The hidden sector is only seen by G (DM?)

Hidden sector with a ‘portal’



The hidden sector has (weak, non-G) interaction with the SM sector through a portal

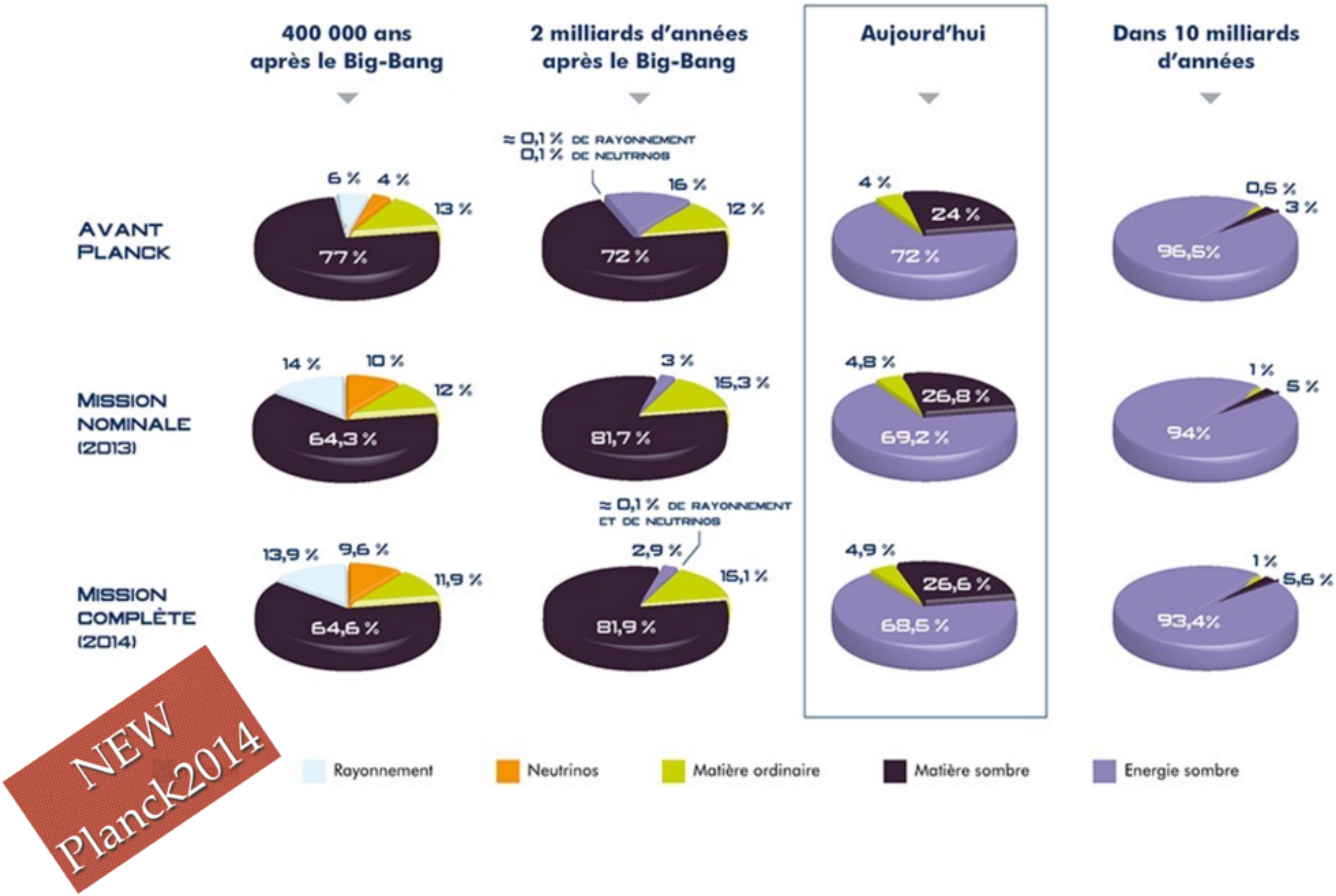
(e.g.) $$-\frac{\sin\epsilon}{2}F_{\mu\nu}H^{\mu\nu}-\sigma|H|^2\phi^2-\lambda\bar{\ell}_L H N$$

BSM

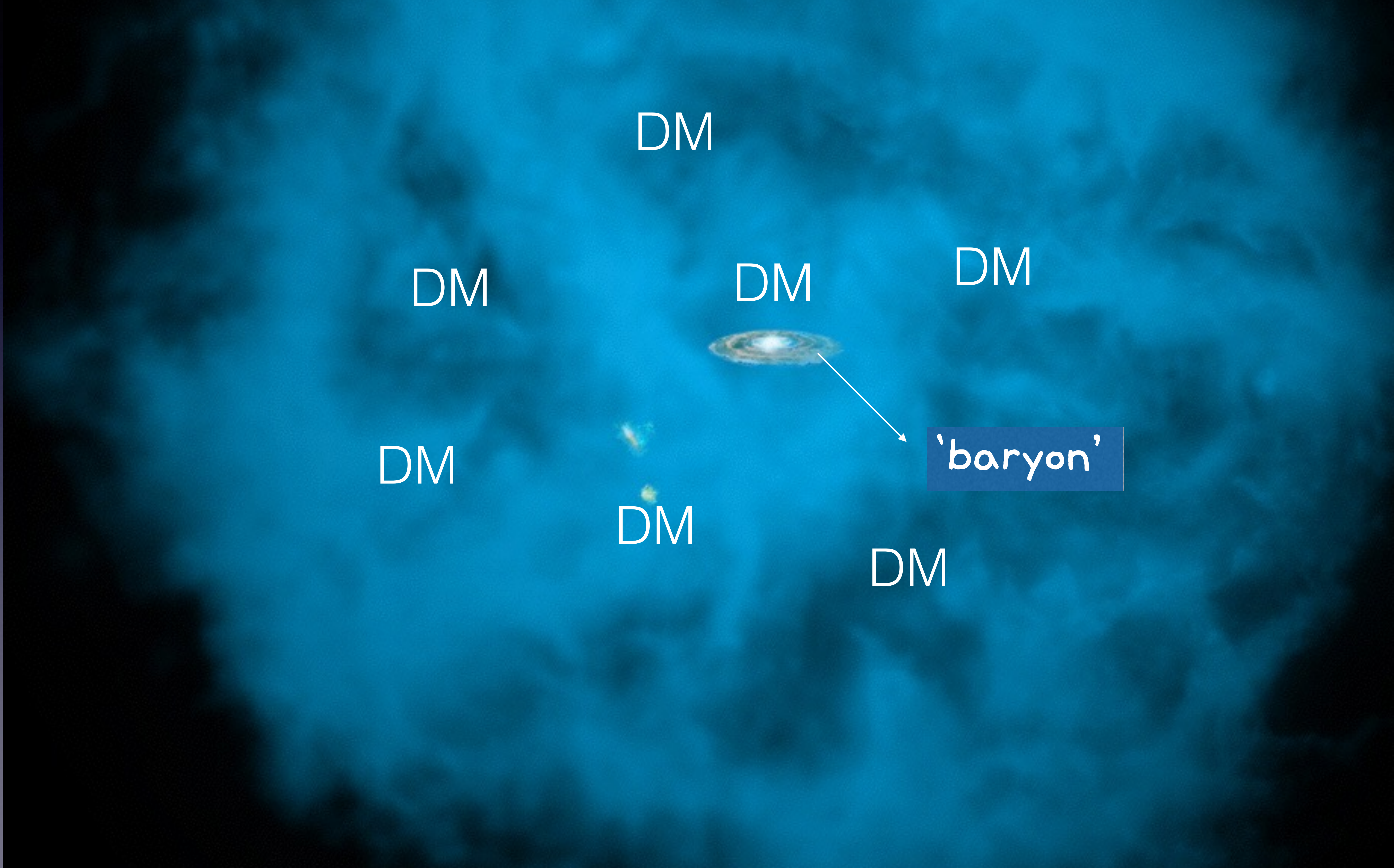
- It seems that many (probably not all) BSM extension include dark matter
- Thus, by studying dark matter, you may learn about how the BSM sector appears in a bigger perspectives (e.g. string theory)

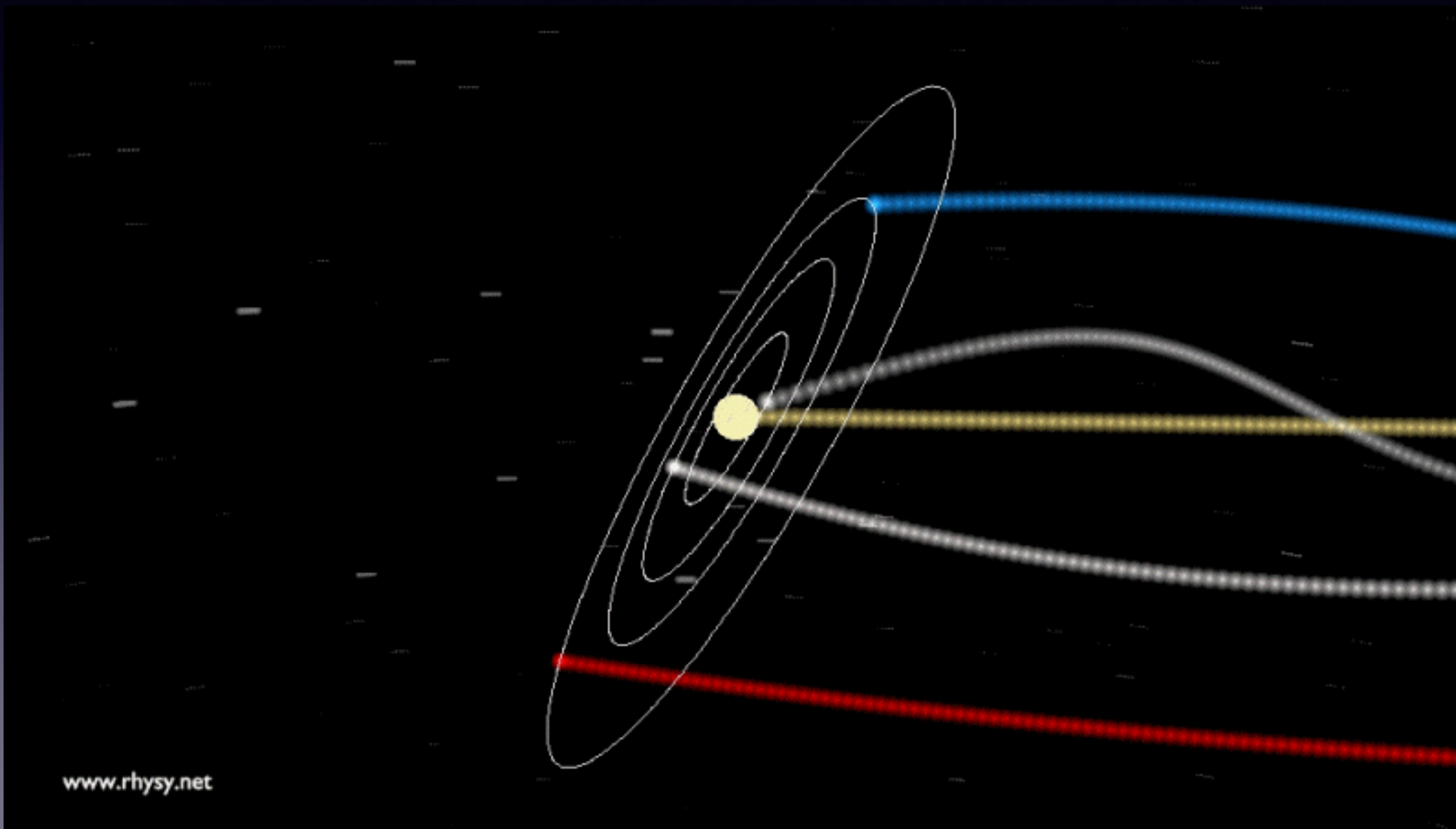
Lecture 2

- Basics of standard cosmology
- Dark matter


400 000 ans
après le Big-Bang
2 milliards d'années
après le Big-Bang
Aujourd'hui
Dans 10 milliards
d'années
AVANT
PLANCK
6 %
4 %
13 %
77 %
≈ 0,1 % DE RAYONNEMENT
0,1 % DE NEUTRINOS
16 %
12 %
72 %
4 %
24 %
72 %
0,5 %
3 %
96,5%
MISSION
NOMINALE
(2013)
14 %
10 %
12 %
64,3 %
3 %
15,3 %
81,7 %
4,8 %
26,8 %
69,2 %
1 %
5 %
94%
MISSION
COMPLÈTE
(2014)
≈ 0,1 % DE RAYONNEMENT
ET DE NEUTRINOS
13,9 %
9,6 %
11,9 %
64,6 %
2,9 %
15,1 %
81,9 %
4,9 %
26,6 %
68,5 %
1 %
5,6 %
93,4%
NEW
Planck2014
Rayonnement
Neutrinos
Matière ordinaire
Matière sombre
Energie sombre

Modern view of Galaxy




www.rhysy.net

$$\rho_{DM} = 0.3 - 0.4\text{GeV}/\text{cm}^3$$

$$v = 240\text{km}/\text{s}$$

$$j = n_{DM}v = \frac{0.3}{\text{cm}^3}\frac{240km}{\text{s}} \cdot \frac{\text{GeV}}{M_{DM}}$$

$$\approx 7.2 \times 10^7/\text{cm}^2$$

Properties of DM particle

- Stable (or very long lived >>age of Univ.)
- Non-luminous (not seen by light)
- Cold (warm) to explain Galaxy formation
- the right density
- If WIMP M<80 TeV typically GeV-TeV (can be heavier if non-thermal)

Neutrino

(Heavy) Neutrino is the only candidate in the SM
but way too small..

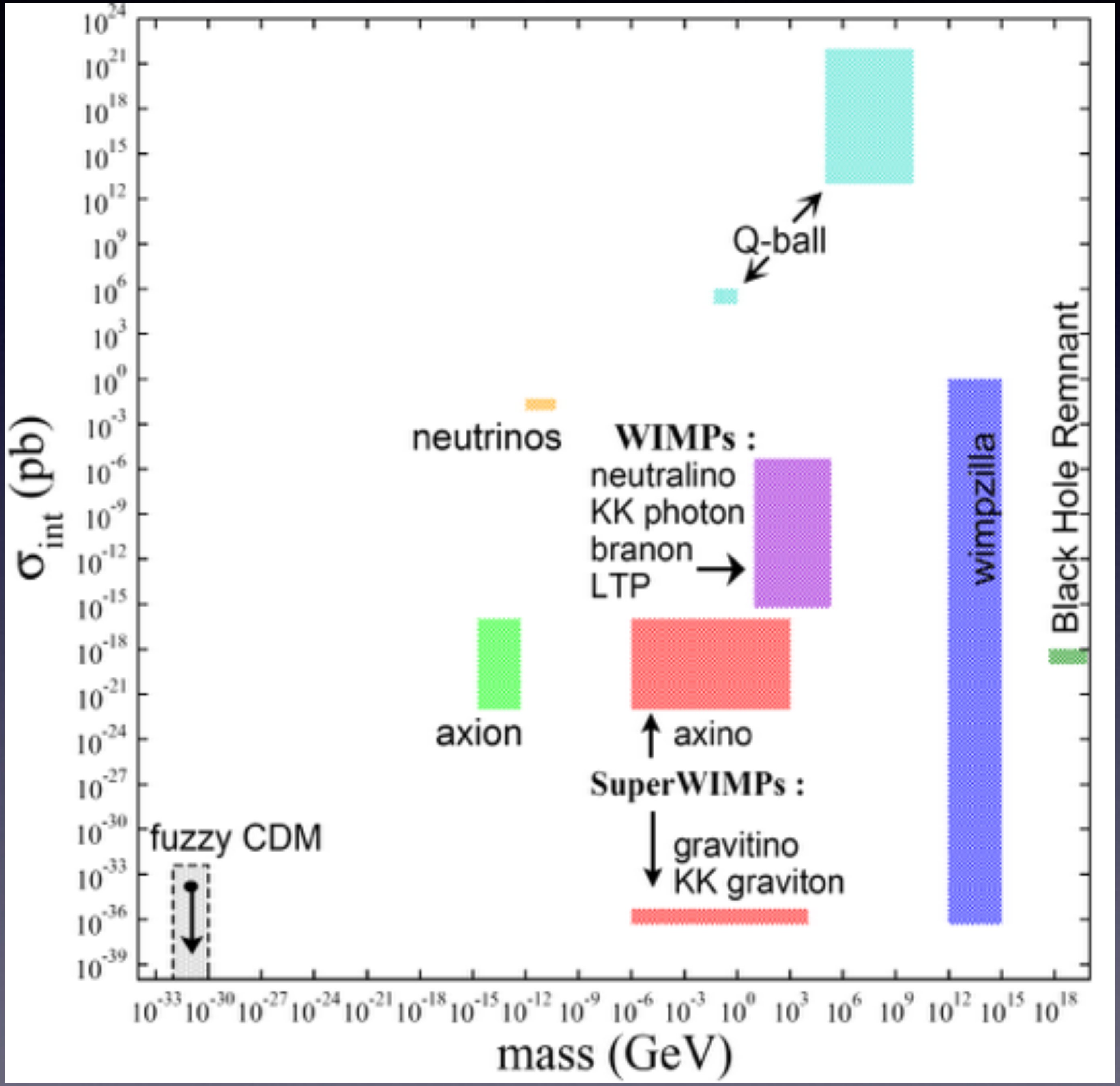
$$\Omega_\nu h^2 \simeq \frac{\sum_i m_{\nu_i}}{90\text{eV}} \lesssim 0.01$$

$$\sum_i m_{\nu_i} \lesssim 0.1 \text{ eV}$$

Planck 2013

DARK MATTER CANDIDATES

- There are many
- Masses and interaction strengths span many, many orders of magnitude,
- **WIMP is the most popular candidate due to WIMP-miracle.**

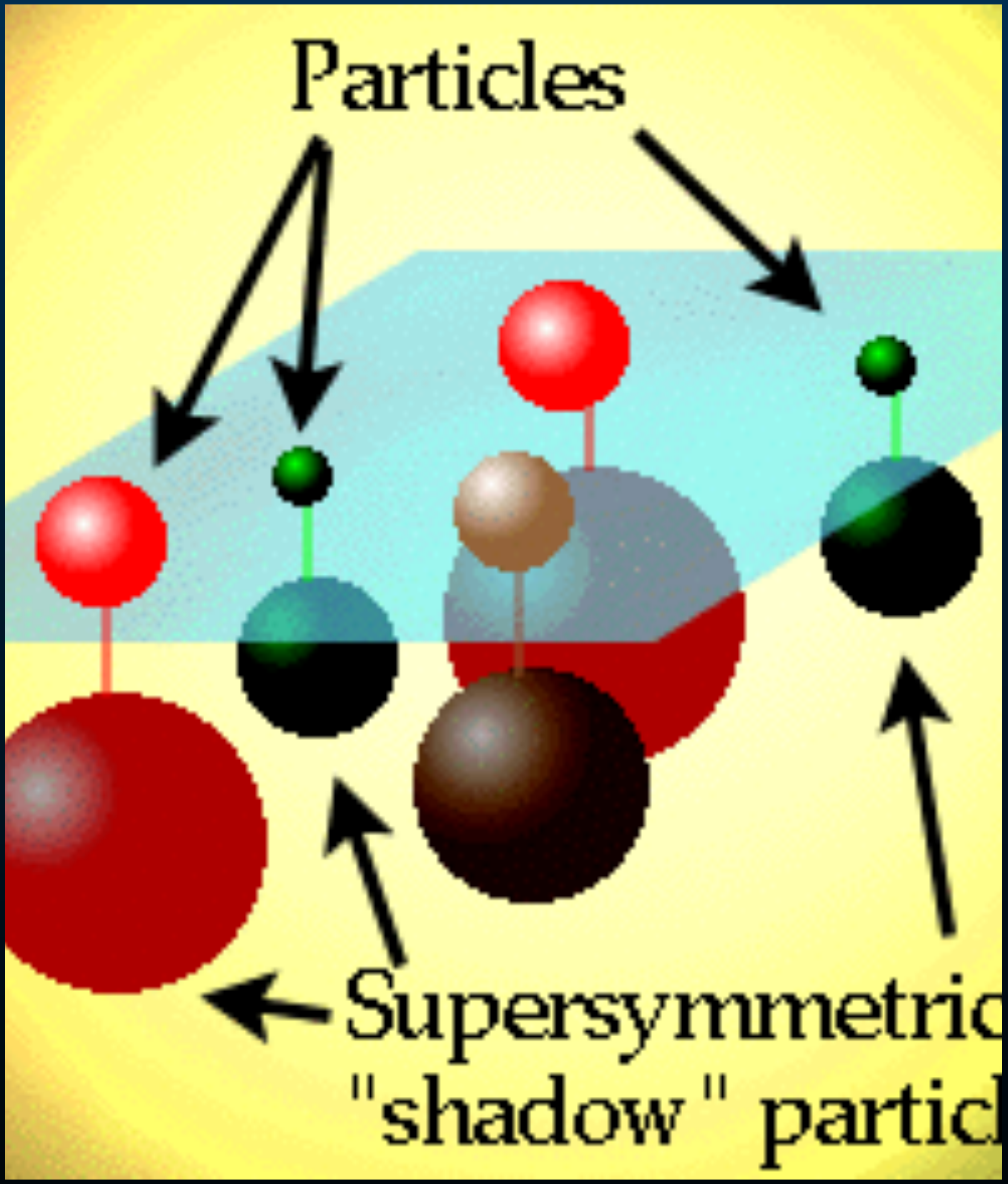


WIMP model building

- Stable : symmetry (Z_2, new gauge symmetry …), kinematically stable)
- Non-luminous : electrically neutral or milli-charged, weakly interacting
- Massive ~ GeV-TeV by certain mechanisms other than the Higgs mechanism (??)
- WIMP miracle almost always guarantees the right relic abundance

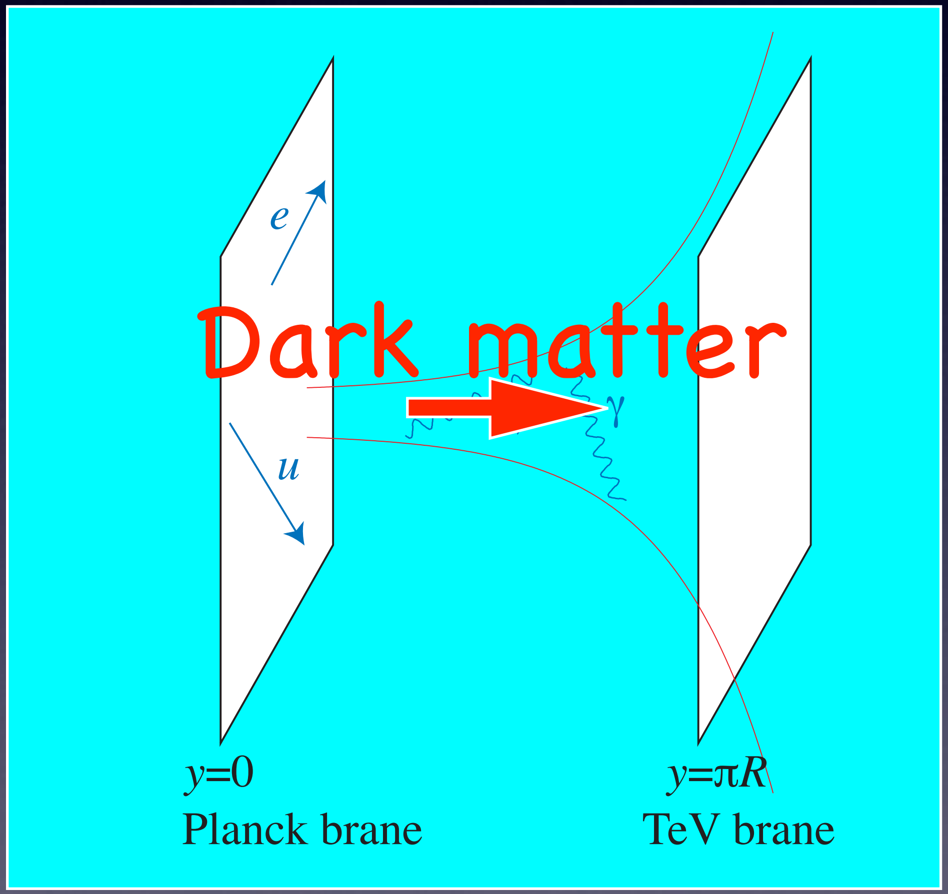
ex) SUSY Dark Matter

- Mass =SUSY breaking scale, TeV scale is preferred for hierarchy problem
- Stability = R-parity, necessary for proton longevity
- Neutralino = (wino, bino, higgsinoX2), obtained by RG running from a unification scale where all susy particles are assumed to have the same masses



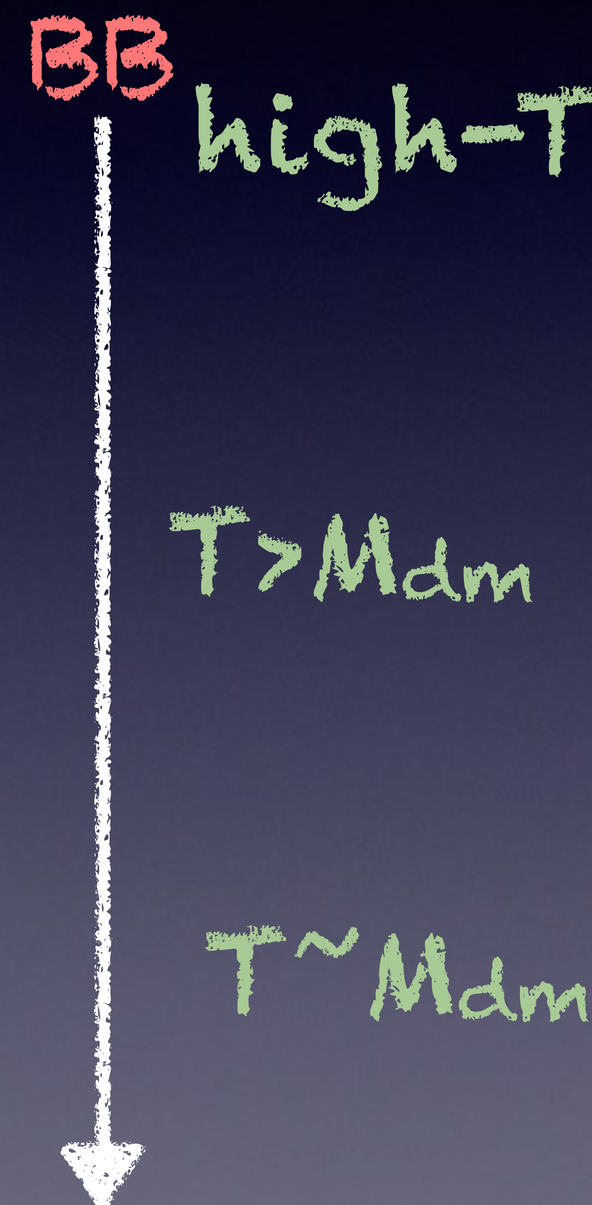
(ex) KK Dark Matter

- Mass = Quantized momentum to compact extra dimension, preferably TeV scale for hierarchy problem
- Stable due to Kaluza-Klein parity, built in by geometry construction
- KK-photon~TeV fits the right relic density



A standard history of DM in BB theory

- DM was produced with other particles (quarks, leptons, gauge bosons)
- stayed in thermal equilibrium (i.e. production rate = annihilation rate)
- Universe cools down T<Mdm, no more production only annihilation



BB

production &
thermal equilibrium

$$\chi\chi \leftrightharpoons e\bar{e}, \gamma\gamma \ldots$$

T>Mdm

T~Mdm

only annihilation

$$\chi\chi \to e\bar{e}, \gamma\gamma \ldots$$

T<M

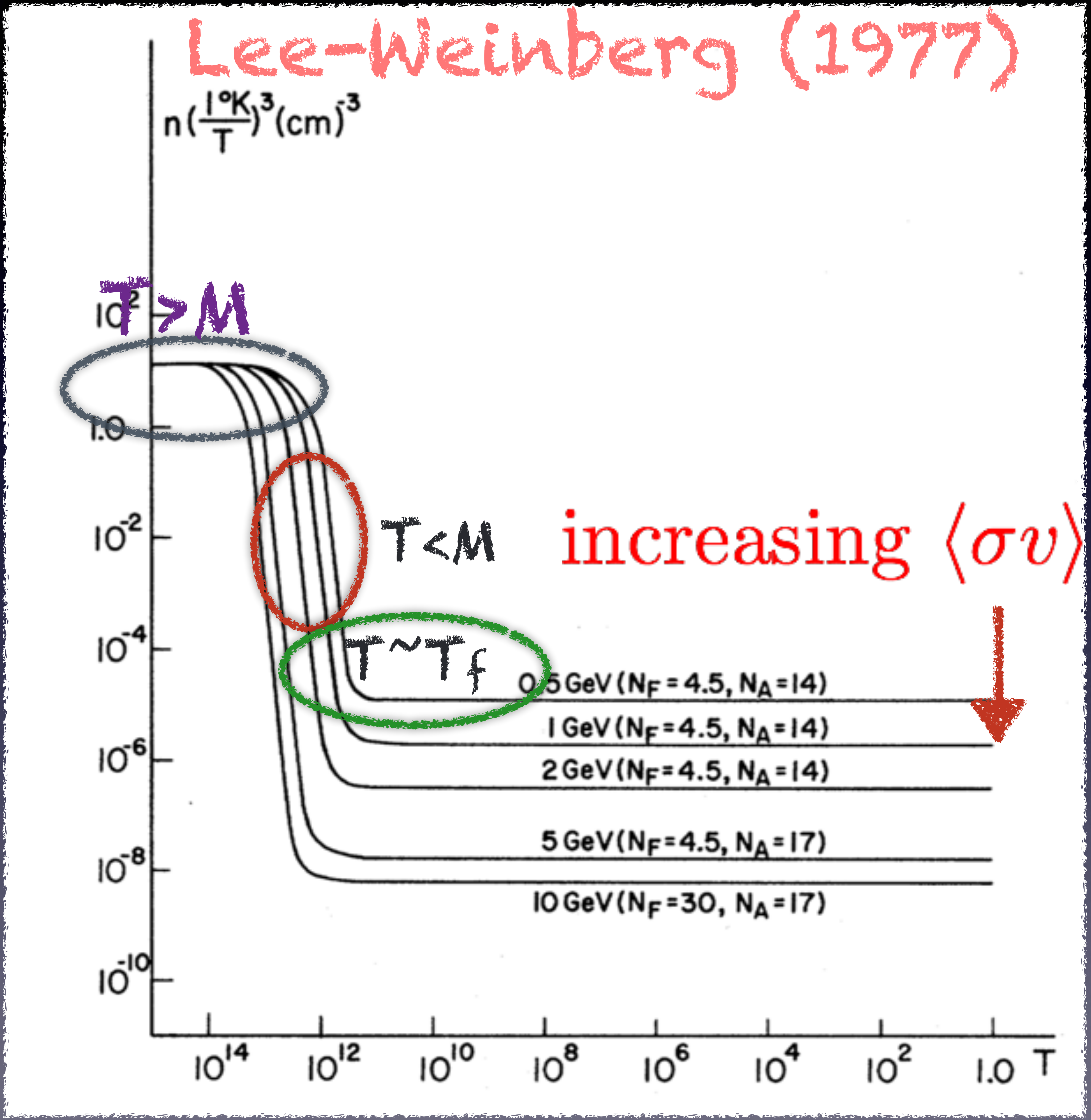
no more annihilation
due to expansion

T=T$_f$ $\Gamma_A \sim H$

Freeze-out

$$Y = n_\chi / s$$

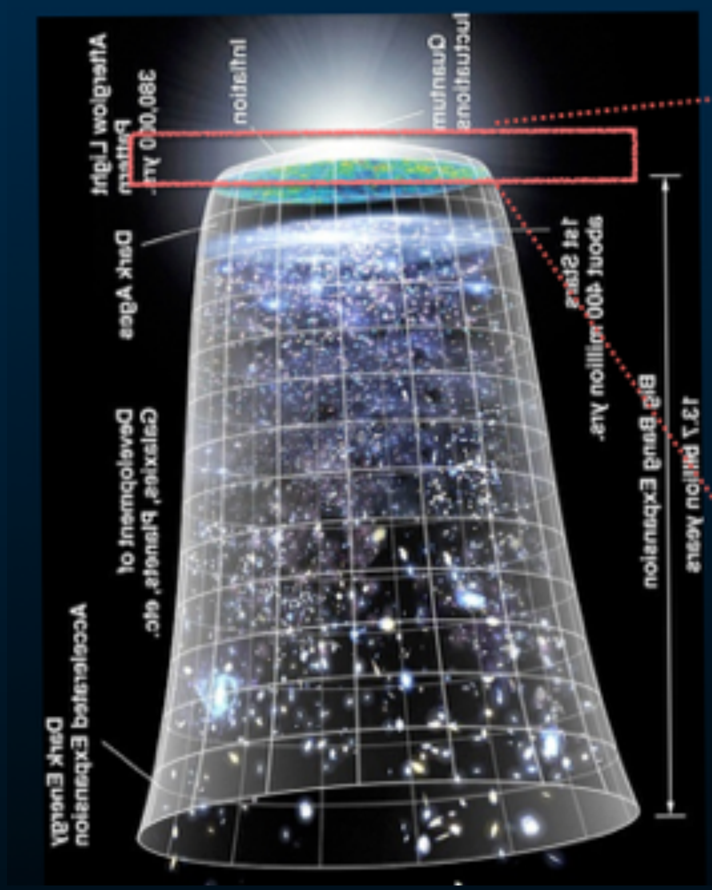
now



Lee-Weinberg (1977)
$n(\frac{1°K}{T})^3 (cm)^{-3}$
T>M
T<M
increasing $\langle \sigma v \rangle$
T~T$_f$
0.5 GeV (N_F=4.5, N_A=14)
1 GeV (N_F=4.5, N_A=14)
2 GeV (N_F=4.5, N_A=14)
5 GeV (N_F=4.5, N_A=17)
10 GeV (N_F=30, N_A=17)
10^2
1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{14}
10^{12}
10^{10}
10^8
10^6
10^4
10^2
1.0
T

WIMP miracle

Lee-Weinberg (1977)



Big Bang

high T

- 10^{-23}sec production

T> mass

- Thermal equilibrium(production rate = expansion rate)

T< mass

- freeze out

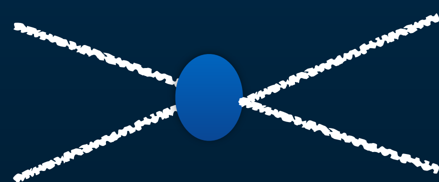
$$\Omega_\chi h^2 \approx \frac{0.1\text{pb}\cdot c}{\langle \sigma_A v\rangle}$$

$$\therefore \langle \sigma \frac{v}{c} \rangle \simeq 1\text{pb}$$

Typical weak interaction!

WIMP<100 TeV

unitarity



$$\sigma = const \cdot \frac{g^2}{m_\chi^2} < const \cdot \frac{4\pi}{m_\chi^2}$$

$$\Omega h^2 = \frac{0.1\text{pb} \cdot c}{\langle \sigma v \rangle} \lesssim 0.11 \quad \Rightarrow 1 \text{ pb} < \sigma \lesssim \frac{4\pi}{m_\chi^2}$$

$$m_\chi \lesssim \sqrt{\frac{4\pi}{\text{pb}}} \simeq 80\text{TeV}$$

so, typically GeV - 10 TeV is the most interesting range

WIMP micracle: some details

Consider **W**eakly **I**nteracting **M**assive **P**articles:

$$X + \bar{X} \leftrightarrow \ell + \bar{\ell}$$

$\uparrow$

strongly interacting particles
(e.g. charged leptons)

$$n_\ell \approx n_\ell^{\rm eq}$$

Assume: no initial asymmetry, i.e. $n_X = n_{\bar{X}}$.

The Boltzmann equation for $N_X \equiv n_X/s$ can then be written as

$$\frac{dN_X}{dt} = -s\langle\sigma v\rangle\left[N_X^2 - (N_X^{\rm eq})^2\right] \qquad (\star)$$

Q. What if 2-〉3 dominate?
see Hochberg etal
Phys.Rev.Lett. 113 (2014) 171301
'SIMPlest miracle'

$$\dot{n}_\pi + 3Hn_\pi \;=\; -(n_\pi^3 - n_\pi^2 n_\pi^{\rm eq})\langle\sigma v^2\rangle_{3\to 2}$$

Defining $x \equiv M_X/T$ and using $H = H(M_X)/x^2$ (RD), we can write ($\star$) as

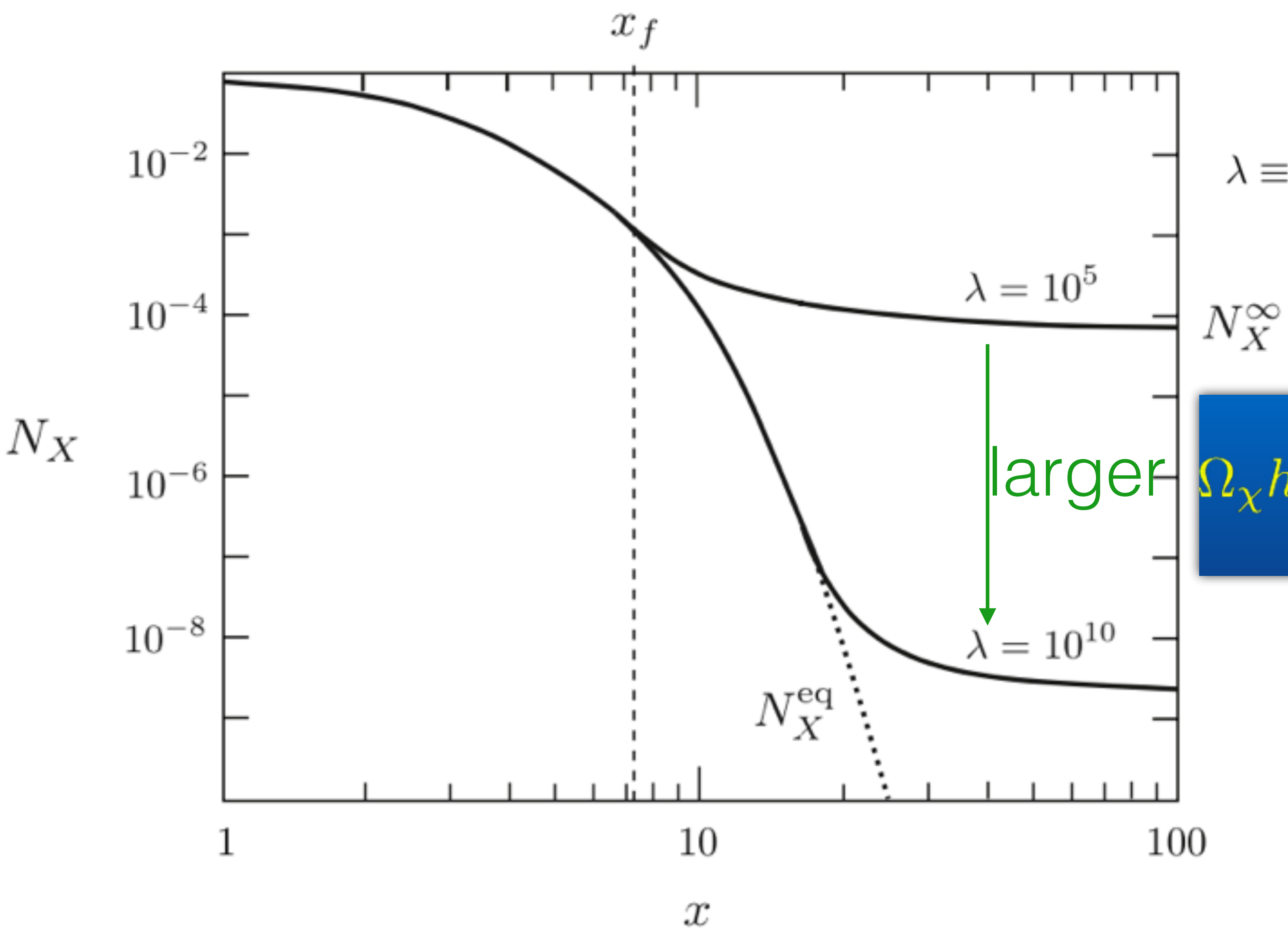
$$\boxed{\frac{dN_X}{dx} = -\frac{\lambda}{x^2}\left[N_X^2 - (N_X^{\rm eq})^2\right]}$$

RICCATI EQUATION

where $\quad \lambda \equiv \frac{2\pi^2}{45} g_{\star S} \frac{M_X^3 \langle \sigma v \rangle}{H(M_X)} \sim \frac{\text{particle physics}}{\text{cosmology}}$.

Find the solution for $\lambda \approx const.$

Numerical Solution



$$\lambda \equiv \frac{2\pi^2}{45} g_{\star S} \frac{M_X^3 \langle \sigma v \rangle}{H(M_X)}$$

$$\Omega_\chi h^2 \approx \frac{0.1\text{pb} \cdot c}{\langle \sigma_A v \rangle}$$

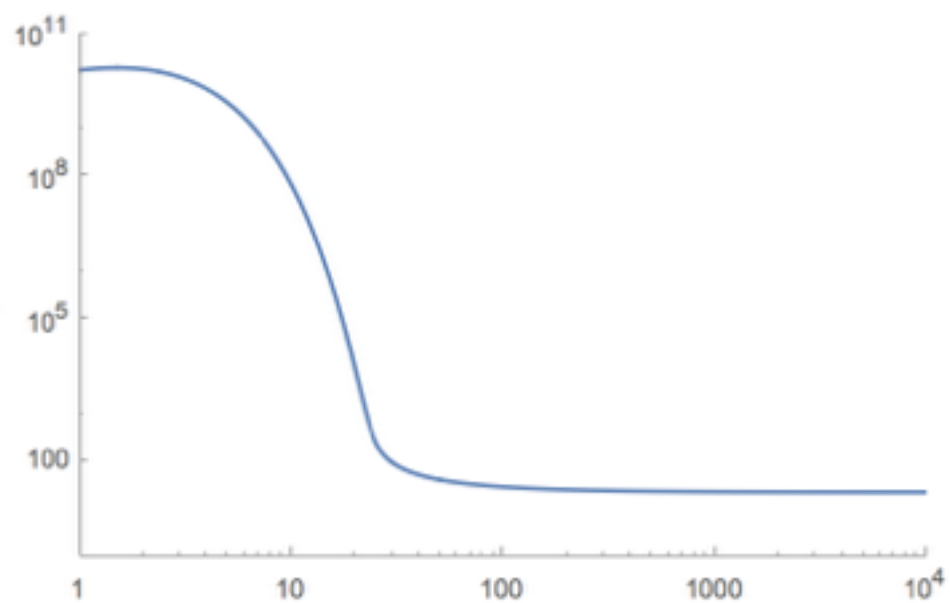
Even I can do it!

boltzmann.nb

Boltzmann Equation

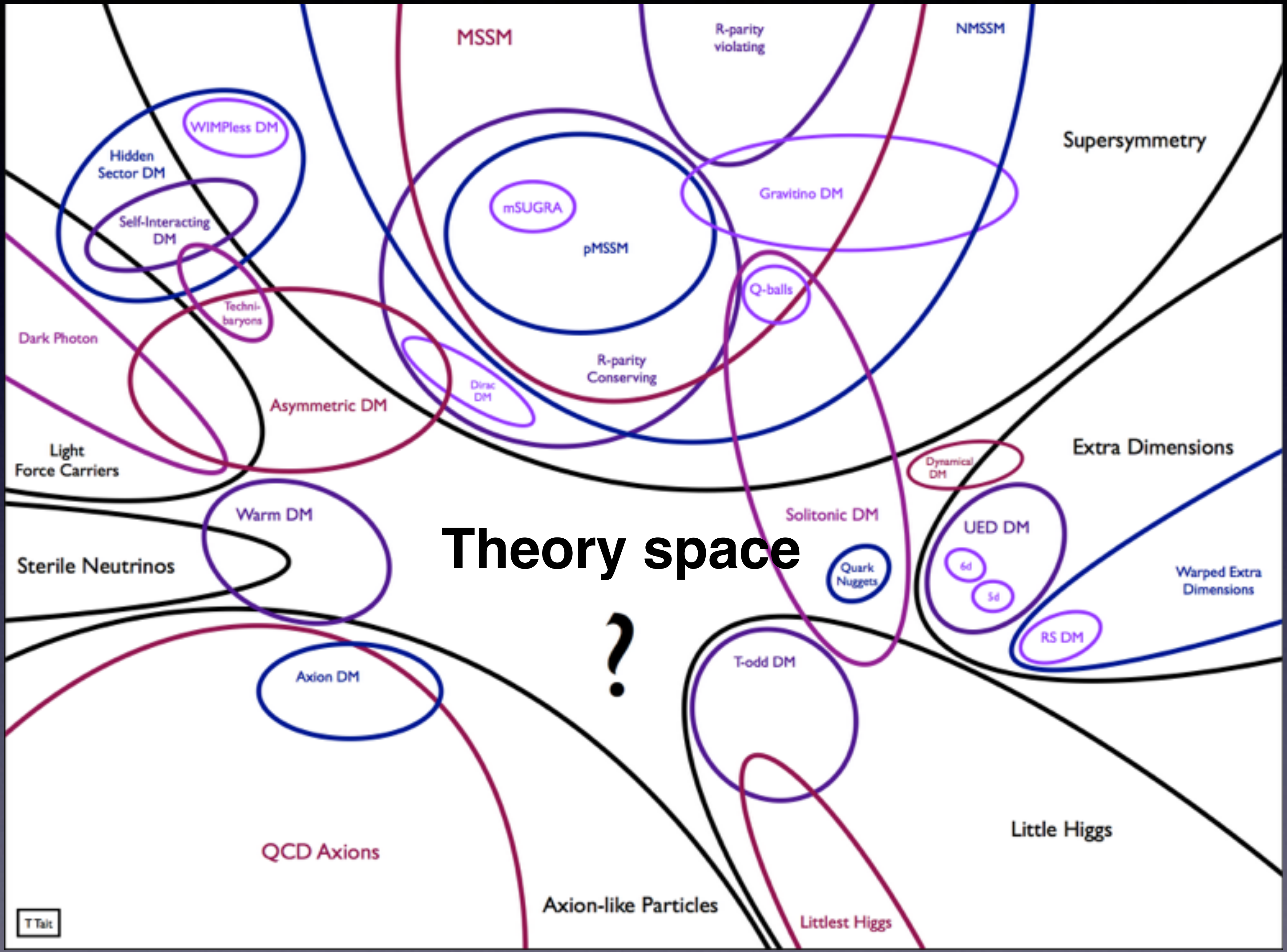
```
In[1]:= MyAssumptions = {m → 1000, g → 100, σ → 10^-10, Subscript[M, Pl] → 2.44 × 10^18};
solution1 =
  NDSolve[
   {D[y[x], x] == -(1/x^2) (y[x]^2 - (0.192 Subscript[M, Pl] m σ x^(3/2) E^-x)^2),
    y[1] == 0.192 Subscript[M, Pl] m σ 1^(3/2) E^-1} /. MyAssumptions, y, {x, 1, 50}];
bc = Evaluate[y[50] /. solution1];

In[4]:= solution2 =
  NDSolve[
   {D[y[x], x] == -(1/x^2) (y[x]^2 - (0.192 Subscript[M, Pl] m σ x^(3/2) E^-x)^2),
    y[50] == bc} /. MyAssumptions, y, {x, 50, 10000}];

In[13]:= LogLogPlot[Evaluate[y[x] /. solution1], {x, 1, 50},
  PlotRange → {{1, 10000}, {1, 10^11}}];
LogLogPlot[Evaluate[y[x] /. solution2], {x, 50, 10000},
  PlotRange → {{1, 10000}, {1, 10^11}}];
Show[%, %%]
```

Out[15]=

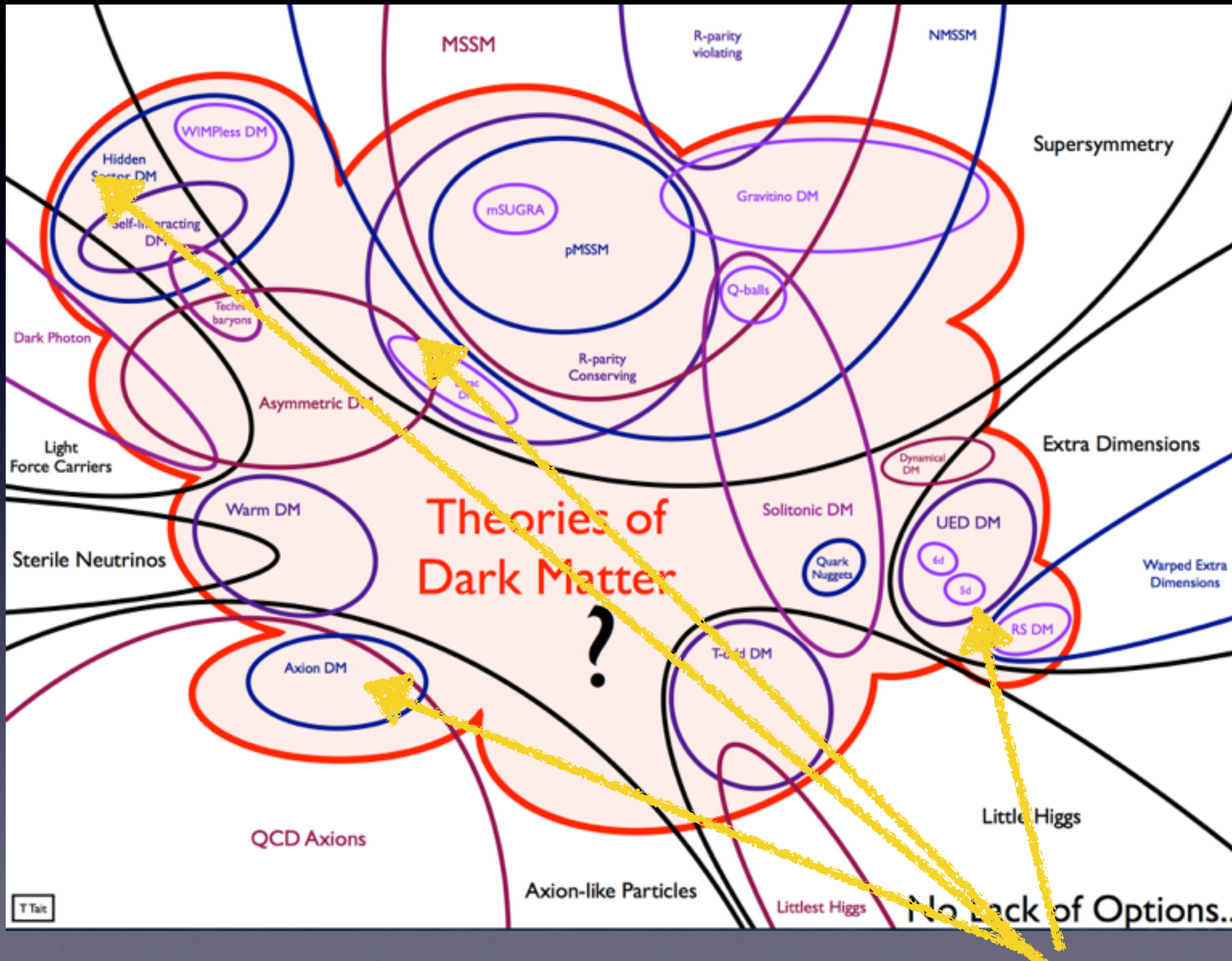


100% ▸

But…don't forget the huge theory space



There are many candidates in the market

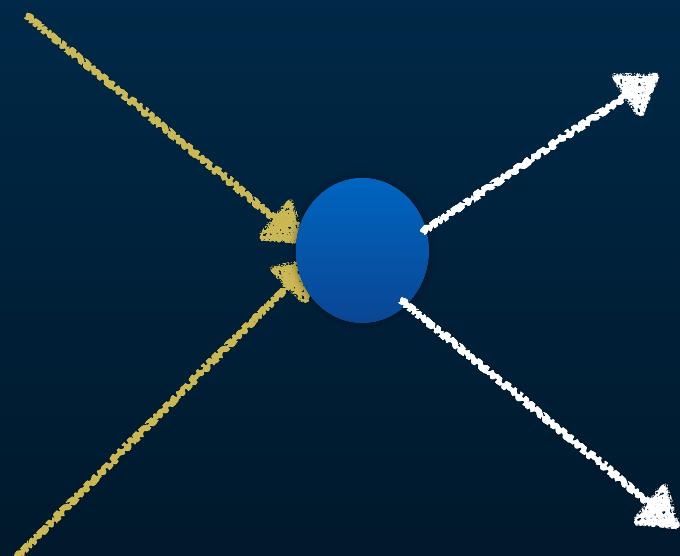


This is mine!

Search strategies for WIMP

- Direct detection of DM+SM scattering (~underground experiments)
- Indirect detection of WIMP signals from pair annihilation in Galaxy or in the Sun
- Collider search for `missing energy’

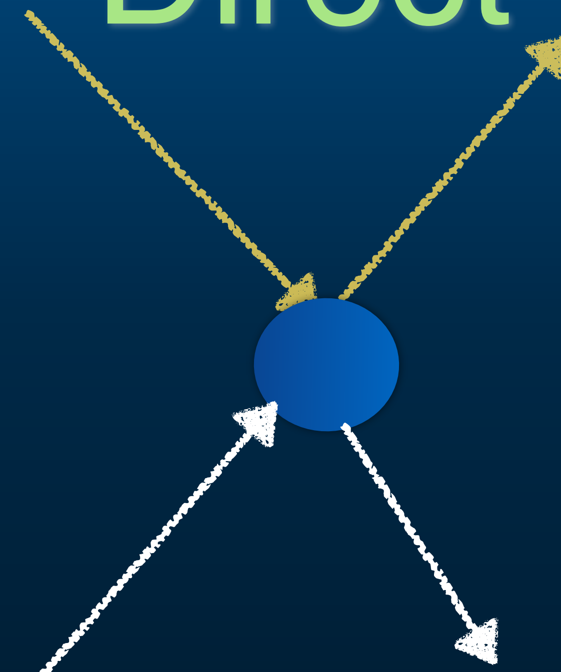
“WIMP”
we know how
to find them



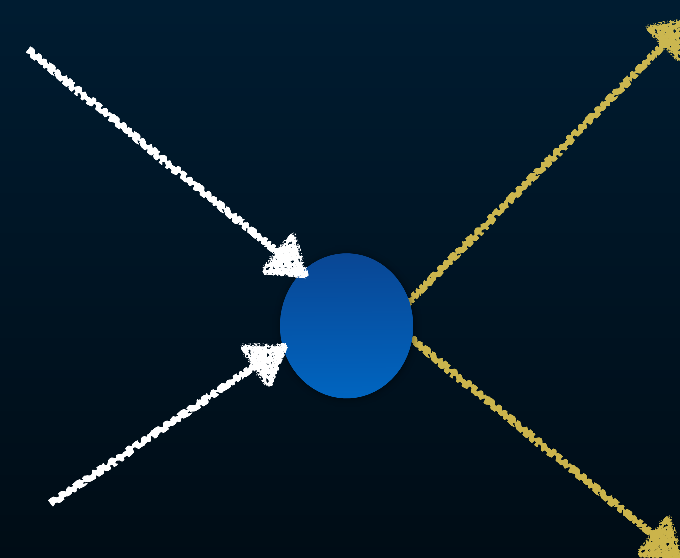
dm+dm -> q +q

“indirect”

“Direct”



dm+ q -> dm+q

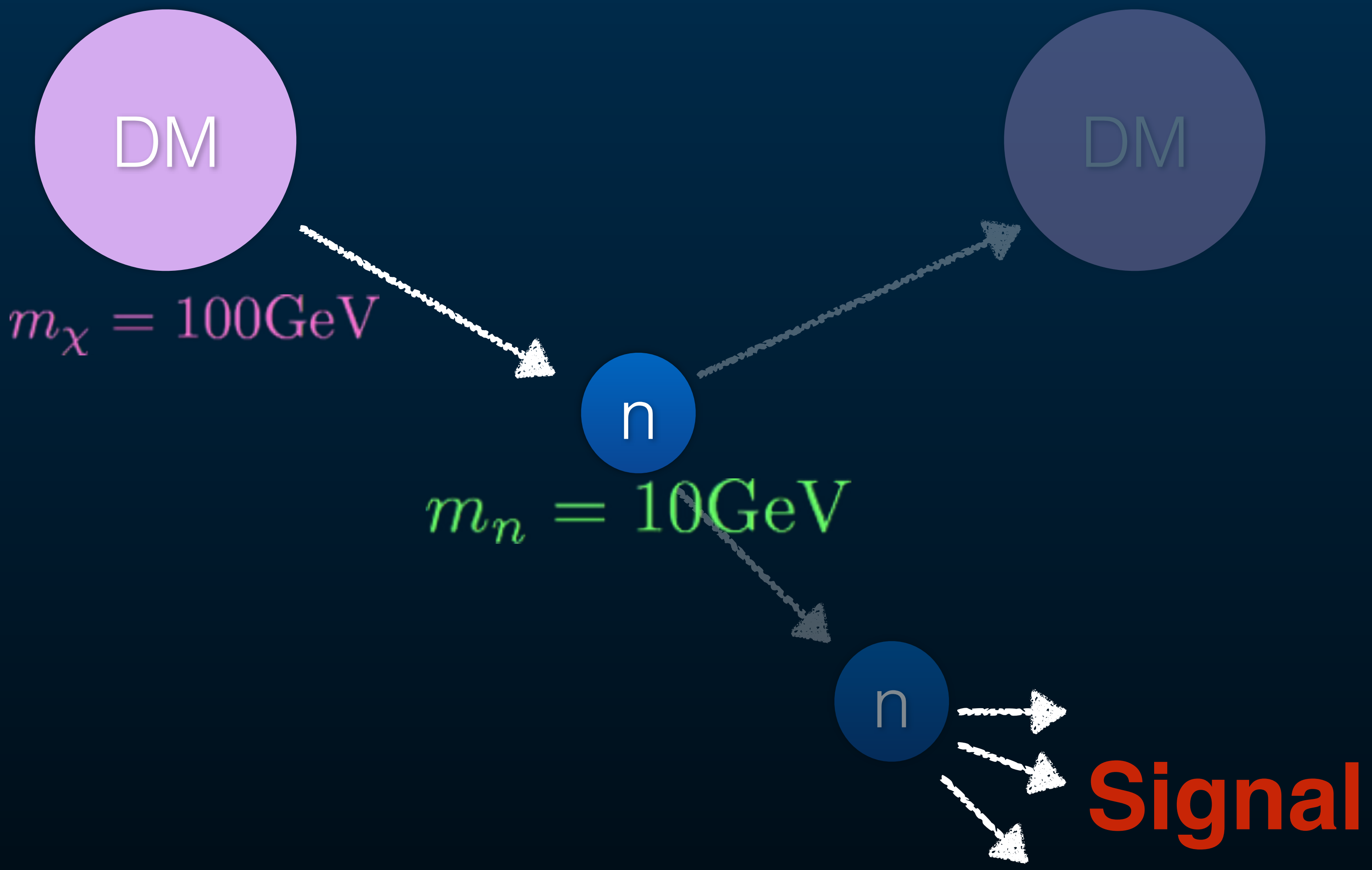


q+q -> dm +dm

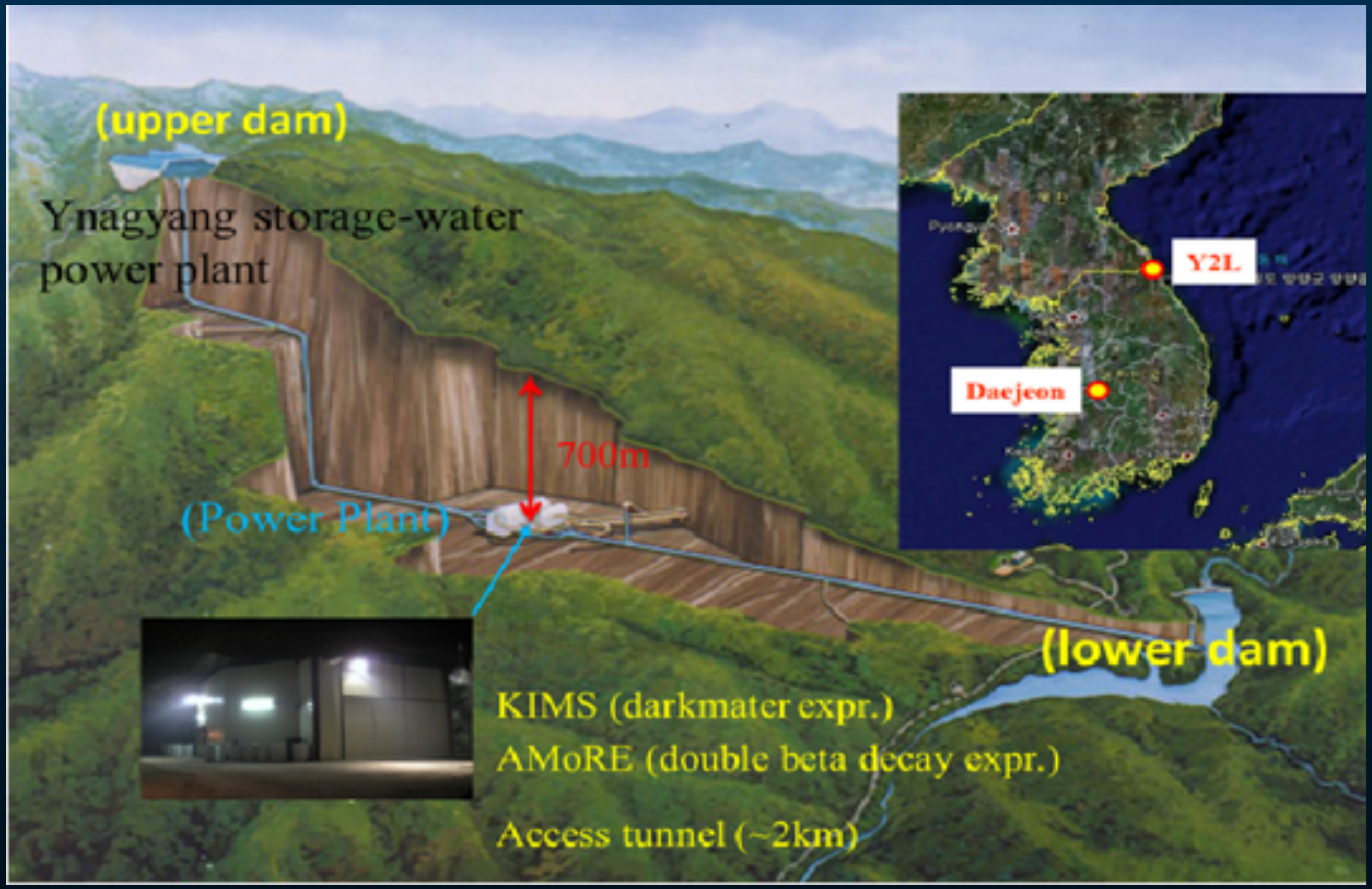
“Collider”

Direct detection

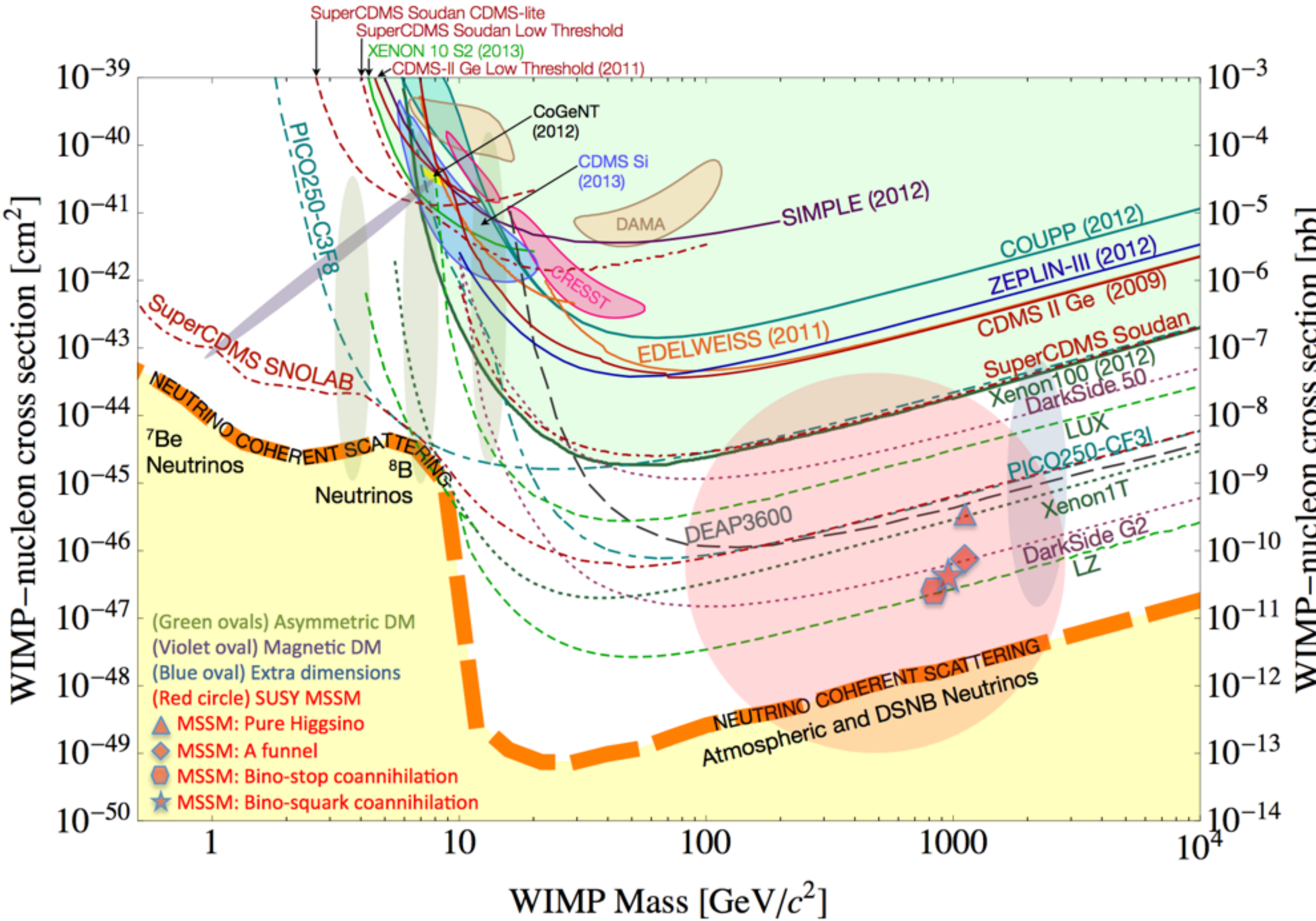
- WIMP are all around us! (rotation curve, density~0.3-0.4 GeV/cm^3)
- velocity~240 km/sec (depending on season, why?)
- WIMP can interact with the SM particles (weakly though)
- WIMP-Nucleon recoil energy~1-100keV


DM
DM
$m_\chi = 100\text{GeV}$
n
$m_n = 10\text{GeV}$
n
Signal

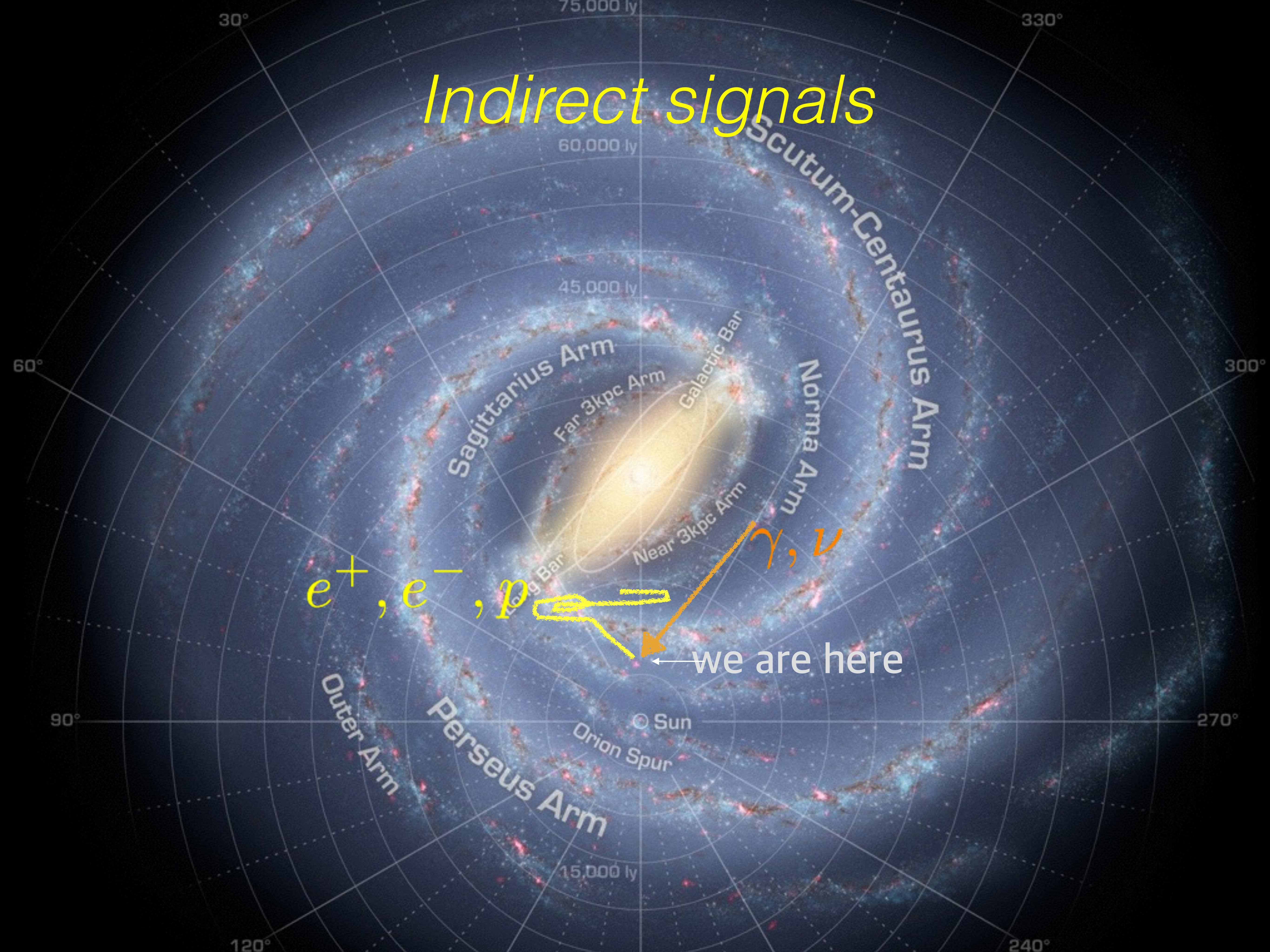
Center for Underground Research in KOREA



Current WIMP Cross-section Limits



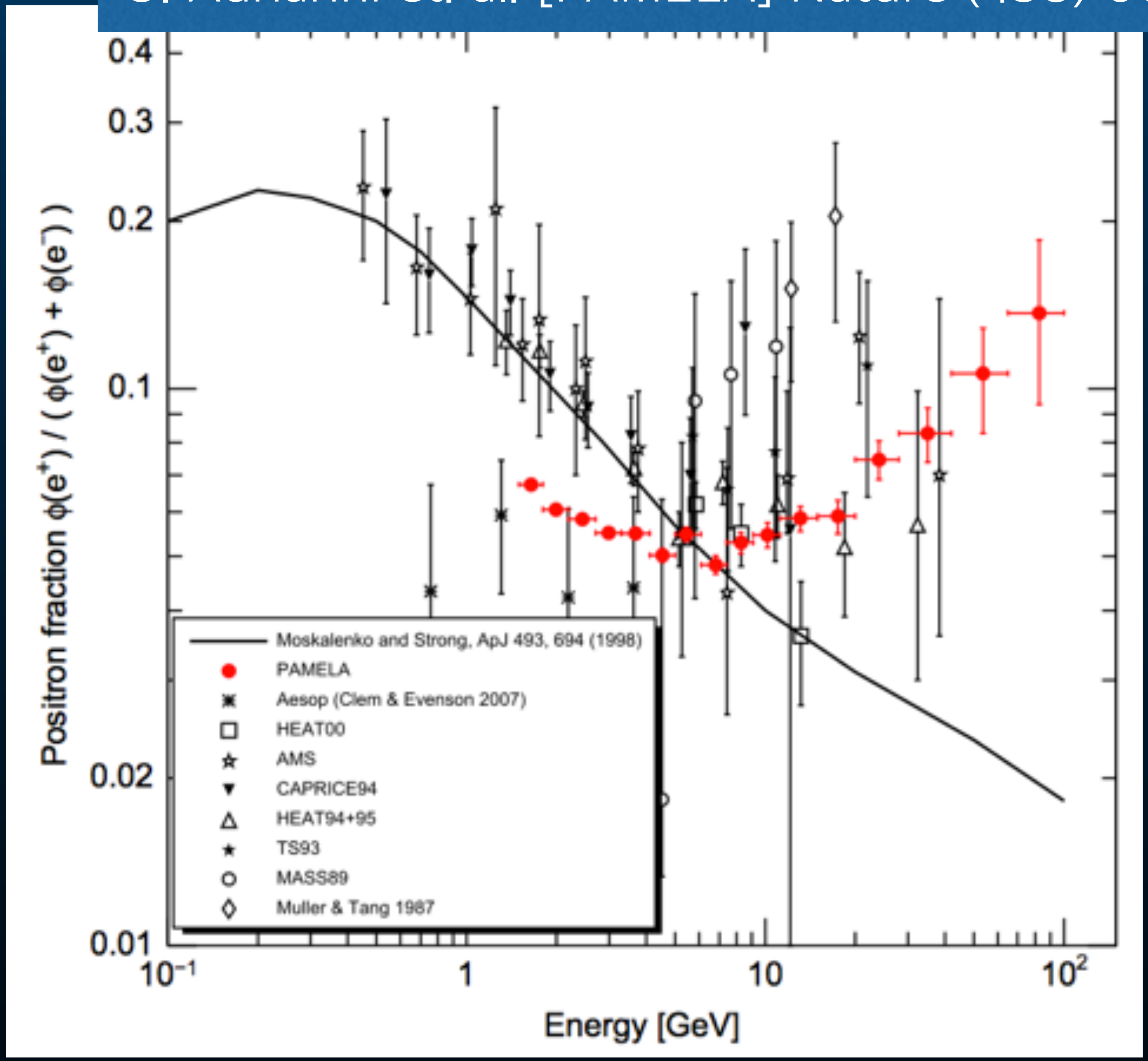
Indirect signals



Indeed, the beginning of 21st century is full of surprises in cosmic-ray physics

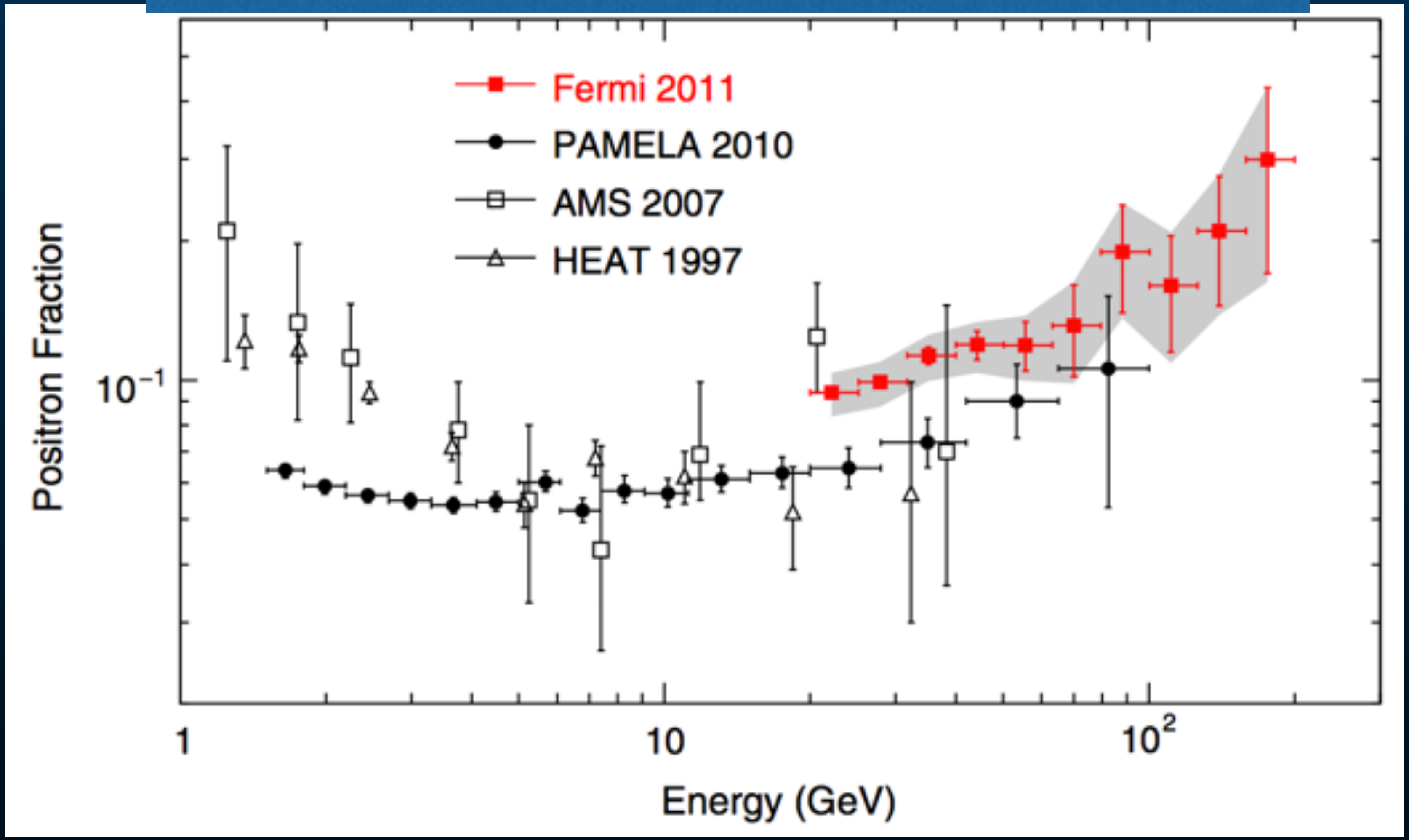
Pamela e+/(e−+E+)

O. Adriarini et. al. [PAMELA] Nature (458) 607, (2009)



confirmed by Fermi-LAT

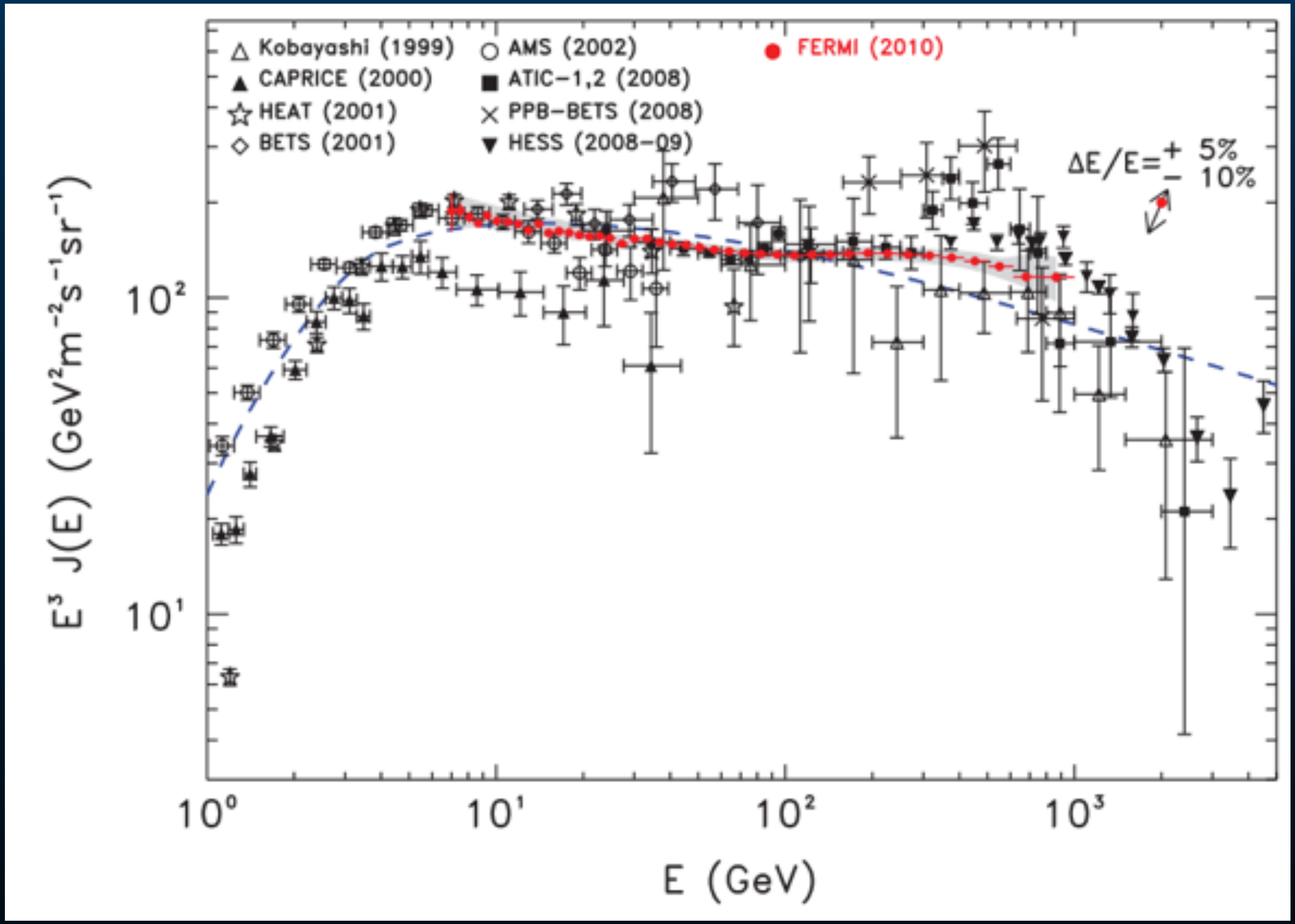
M. Ackermann [Fermi-LAT] PRL 108, 011103 (2012)



AMS-II coming soon!

Fermi-LAT 'electron'

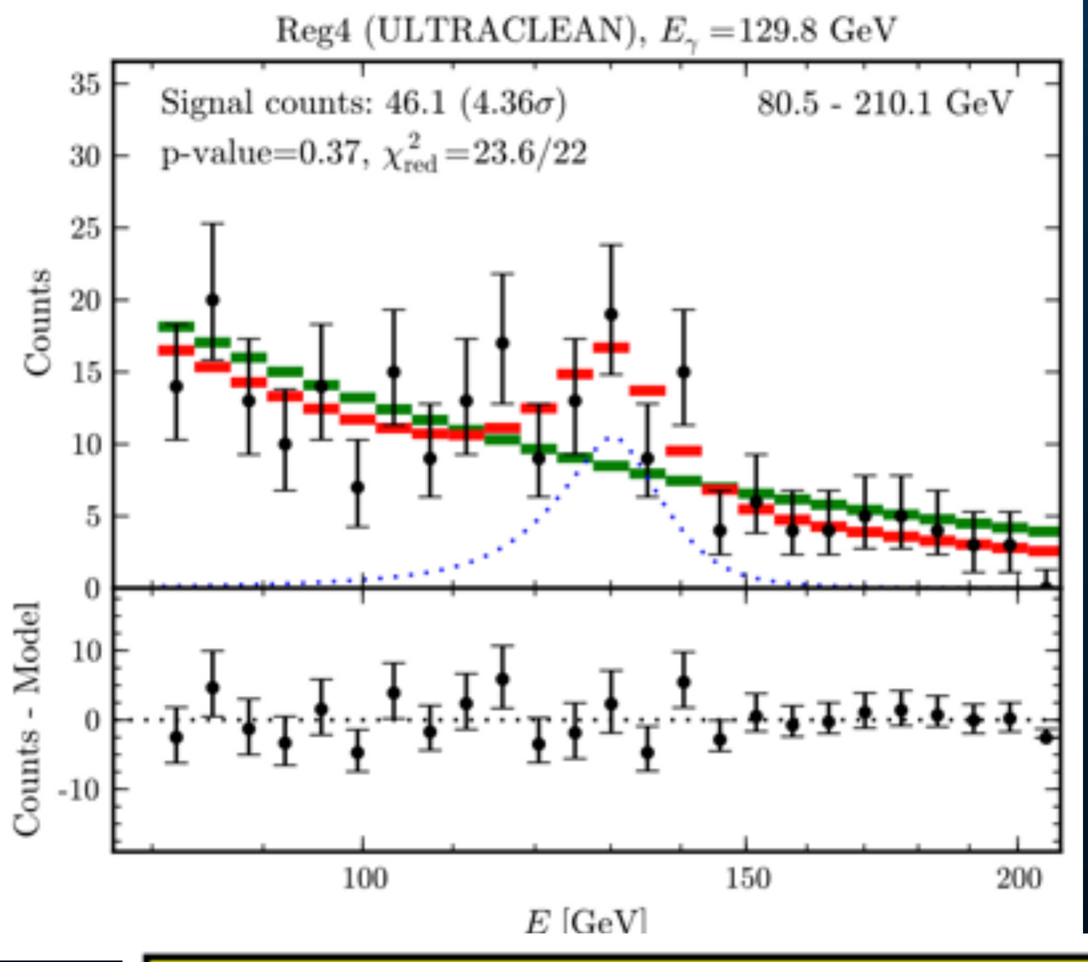
A. A. Abdo et. al [Fermi-LAT collaboration] PRL (2009)
M. Ackermann et. al. [Fermi-LAT collaboration] PRD (2010)

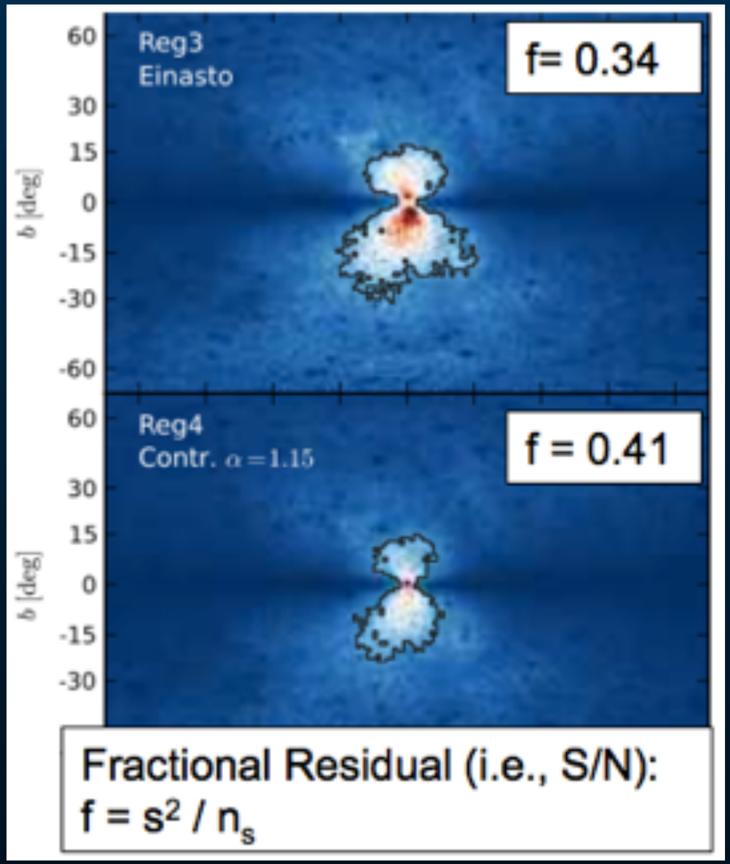


[SCP & Shu 2009]
[Kong, Rizzo, SCP 2010,2011]

Fermi-LAT
130 GeV gamma-ray line

Bringmann et. al. 2012
Weniger 2012
Park & SCP 2012



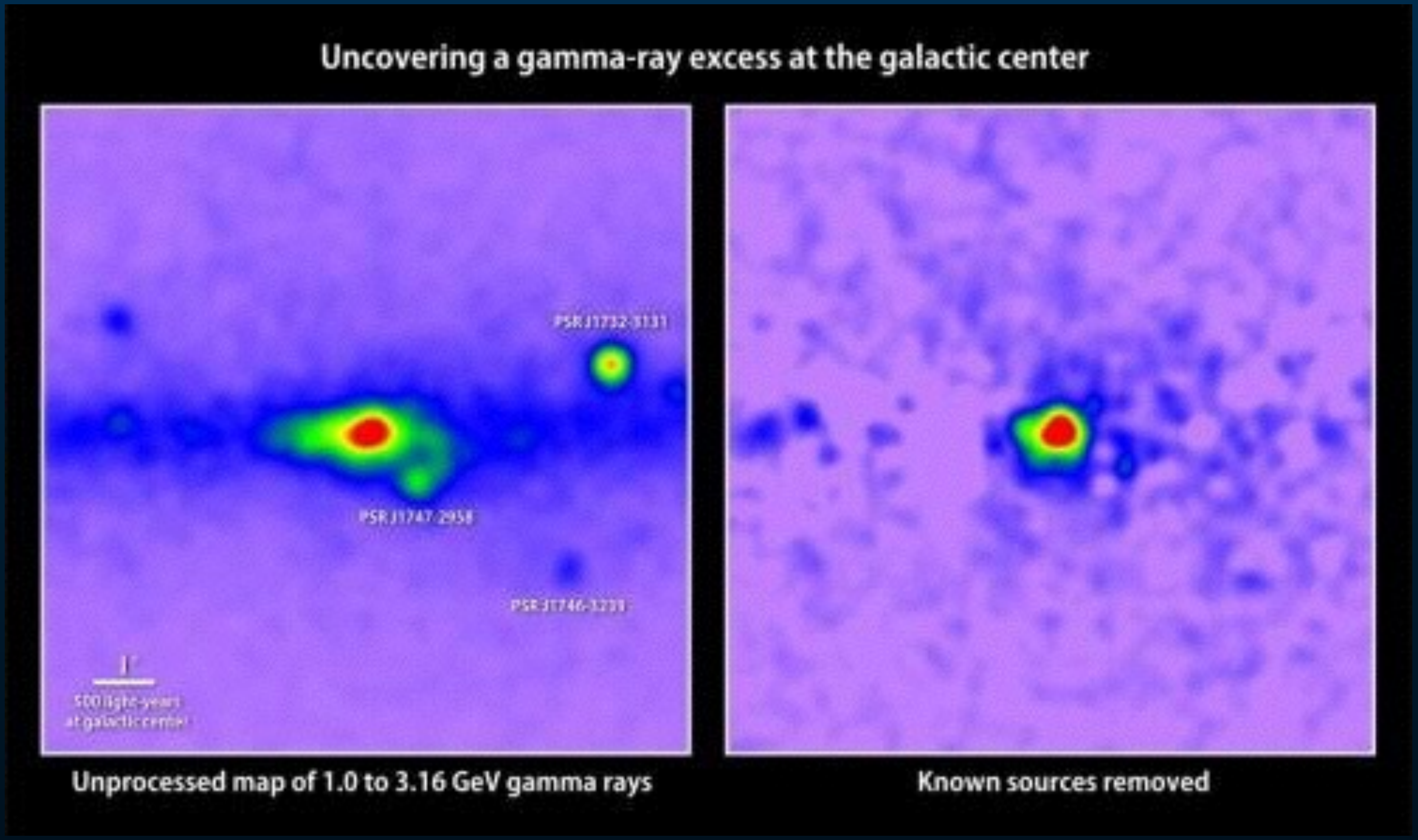


Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC).

- Signal is particularly strong in 2 out of 5 test regions, shown above.
- Over 4σ, with S/N > 30%, up to ~60% in optimized regions of interest (ROI).
- Some indication of double line (111 &130 GeV).

Fermi-LAT gamma-ray excess "GeV"

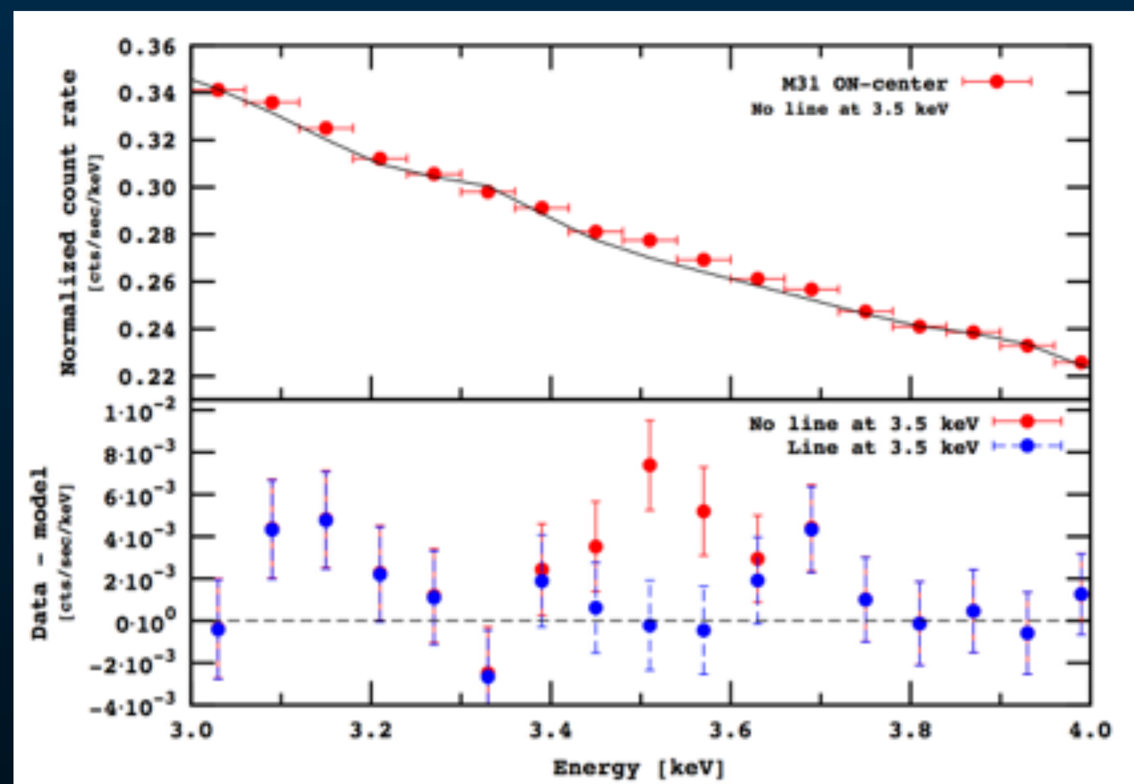
Hooper, Linden 2014



Hot topic of the season

3.5 keV 'line' from galactic cluster

Boyarsky etal. 1402.4119



from keV DM?

axino~ Park, Kong, SCP Phys.Lett. B (2014)

axion ~ Lee, SCP, Park Eur.Phys.J. C74 (2014) 9, 3062

If non-thermal?

DM can be heavier! >100 TeV

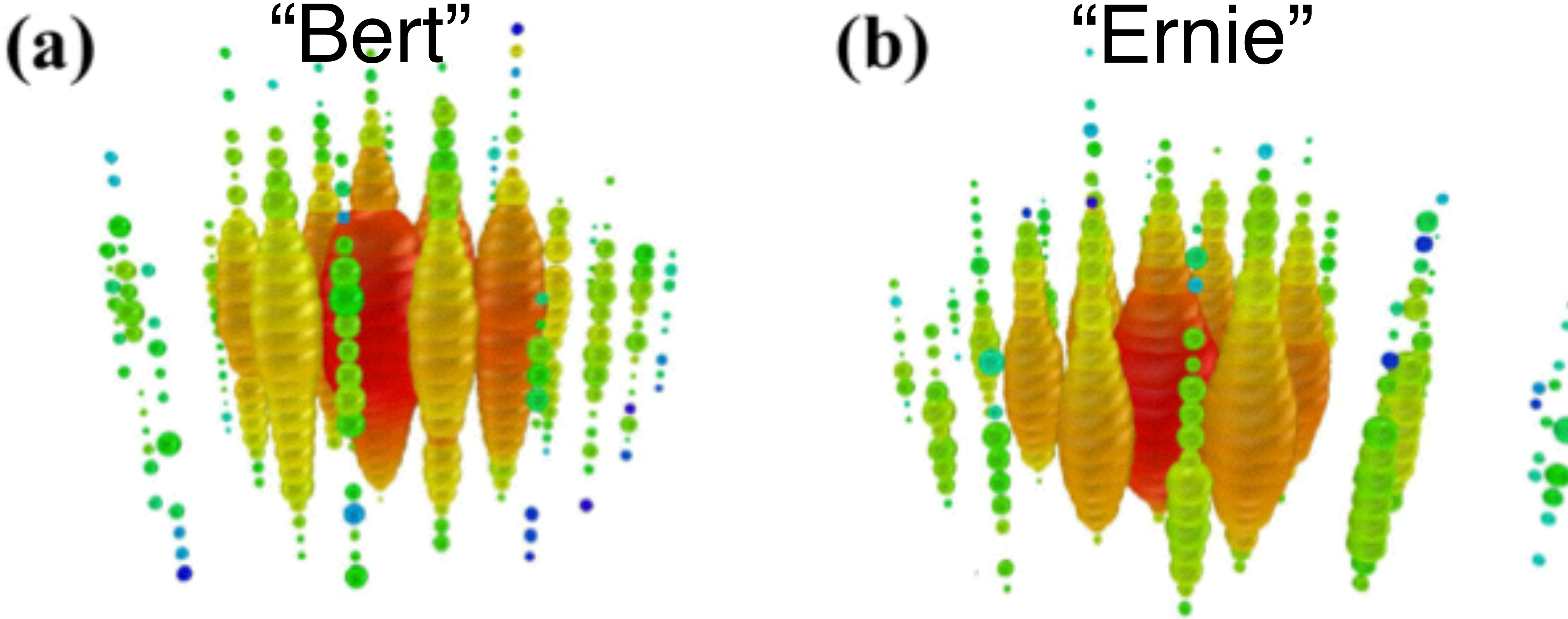
NEW !

Two PeV neutrinos observed by IceCube

in 615.9 days

[Aartsen et. al. (IceCube) Phys.Rev.Lett. 111 (2013) 021103]

"Bert" "Ernie"

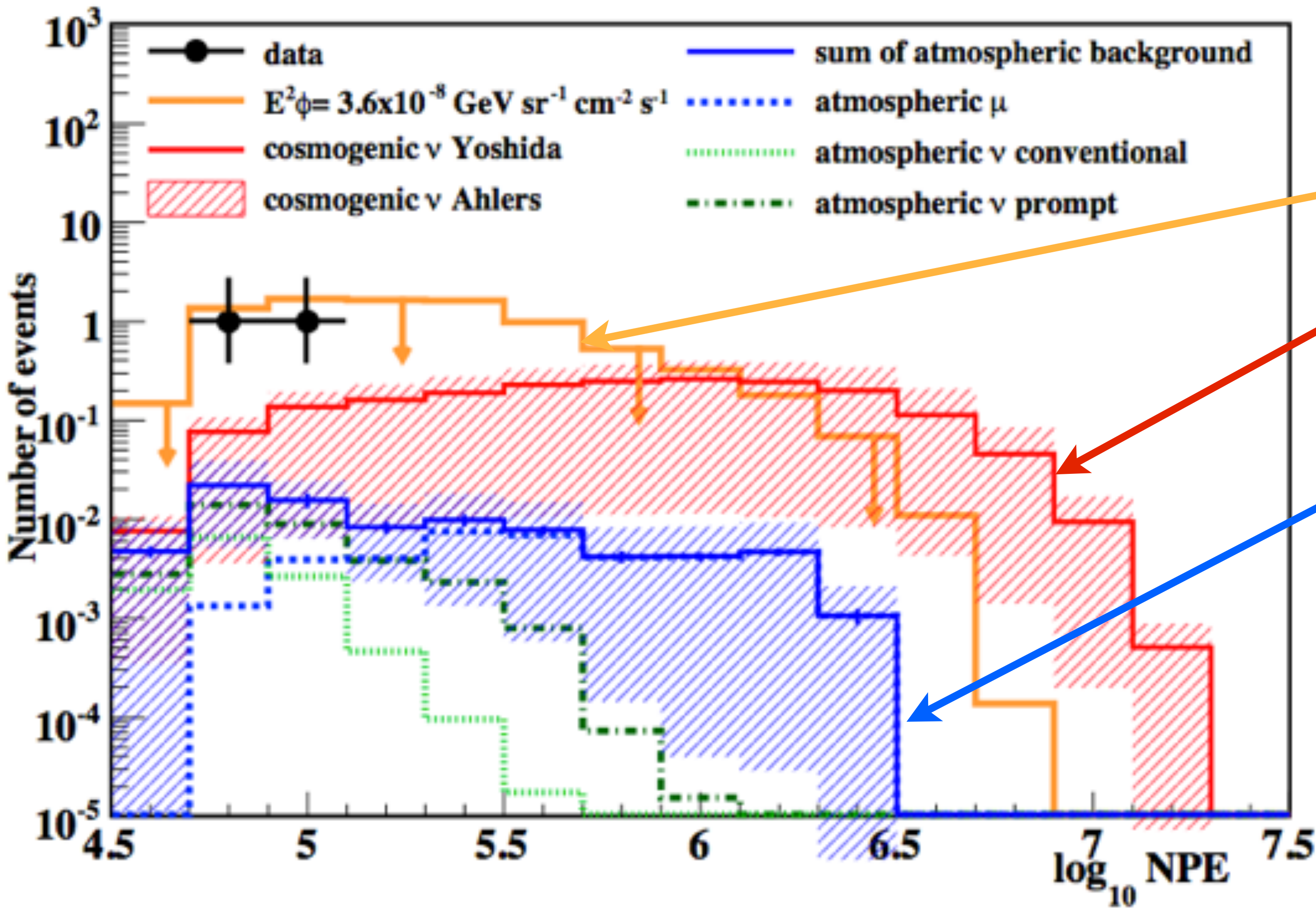


$1.04 \pm 0.16\mathrm{PeV}$ $1.14 \pm 0.17\mathrm{PeV}$

~consistent with fully contained simulated particle showers induced by neutral-current $\nu_{e,\mu,\tau}$ or charged-current ν_e interactions within the IceCube detector.

The observational result looks odd ..

**Expected: $0.082 \pm 0.0024^{+0.041}_{-0.057}$



~E^{-2} ??

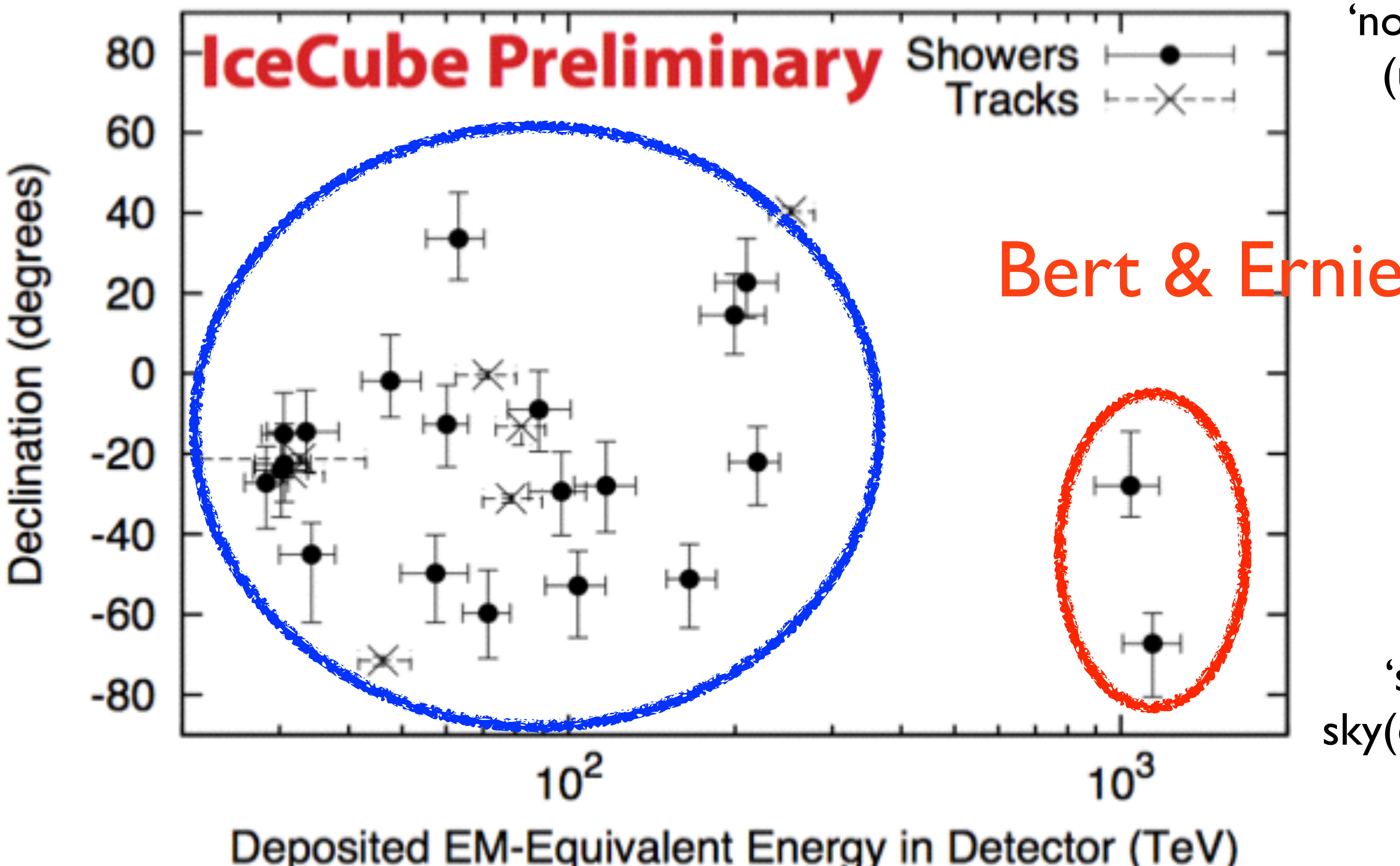
-Too low in energy for GZK

-Too high in energy for atmospheric nu.

upshot:

These events cannot be understood by known sources!

In addition,
26 more neutrinos observed in 1TeV-250TeV window,
(cf) background is 10.6+-4.5

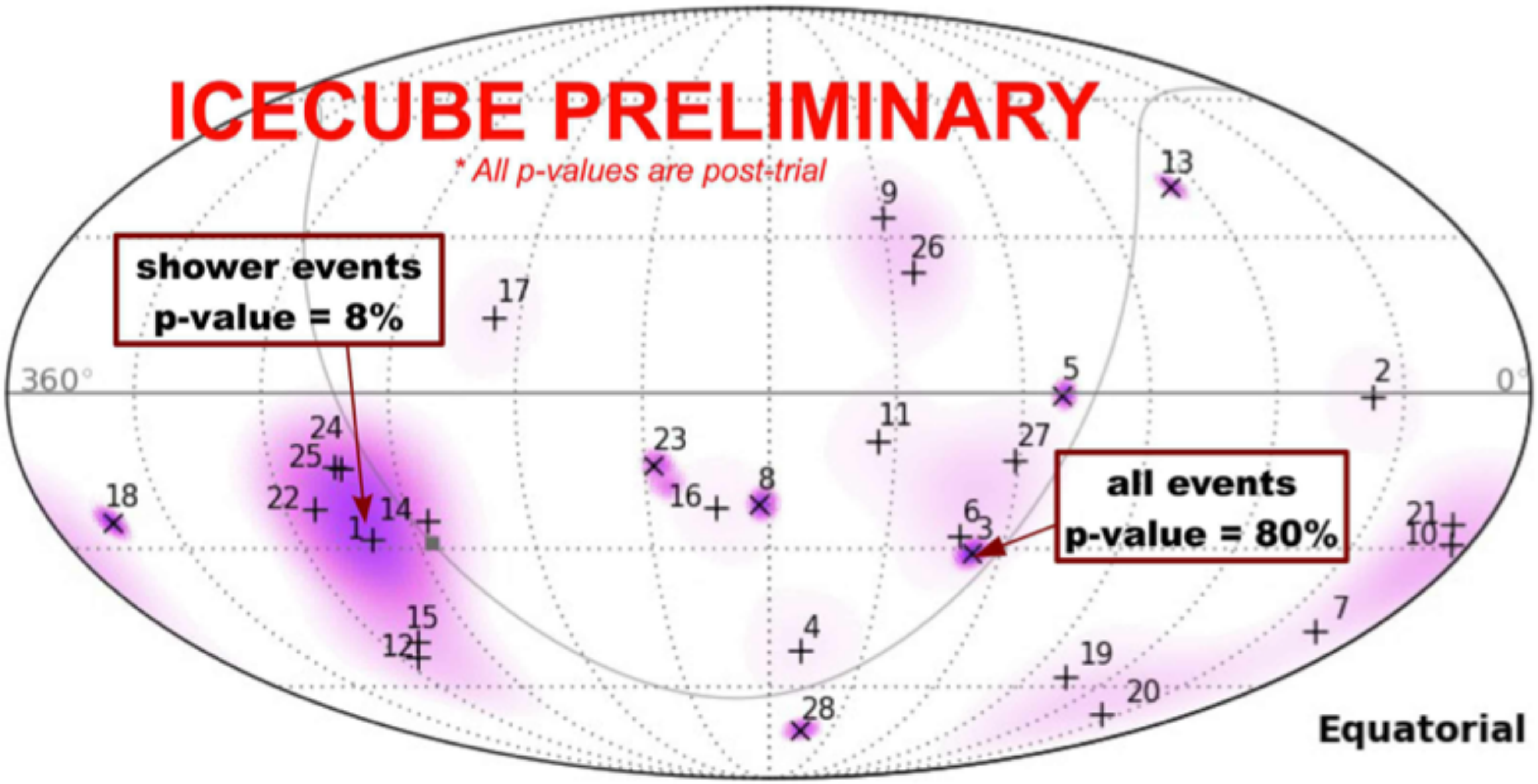


'northern sky (upgoing)'

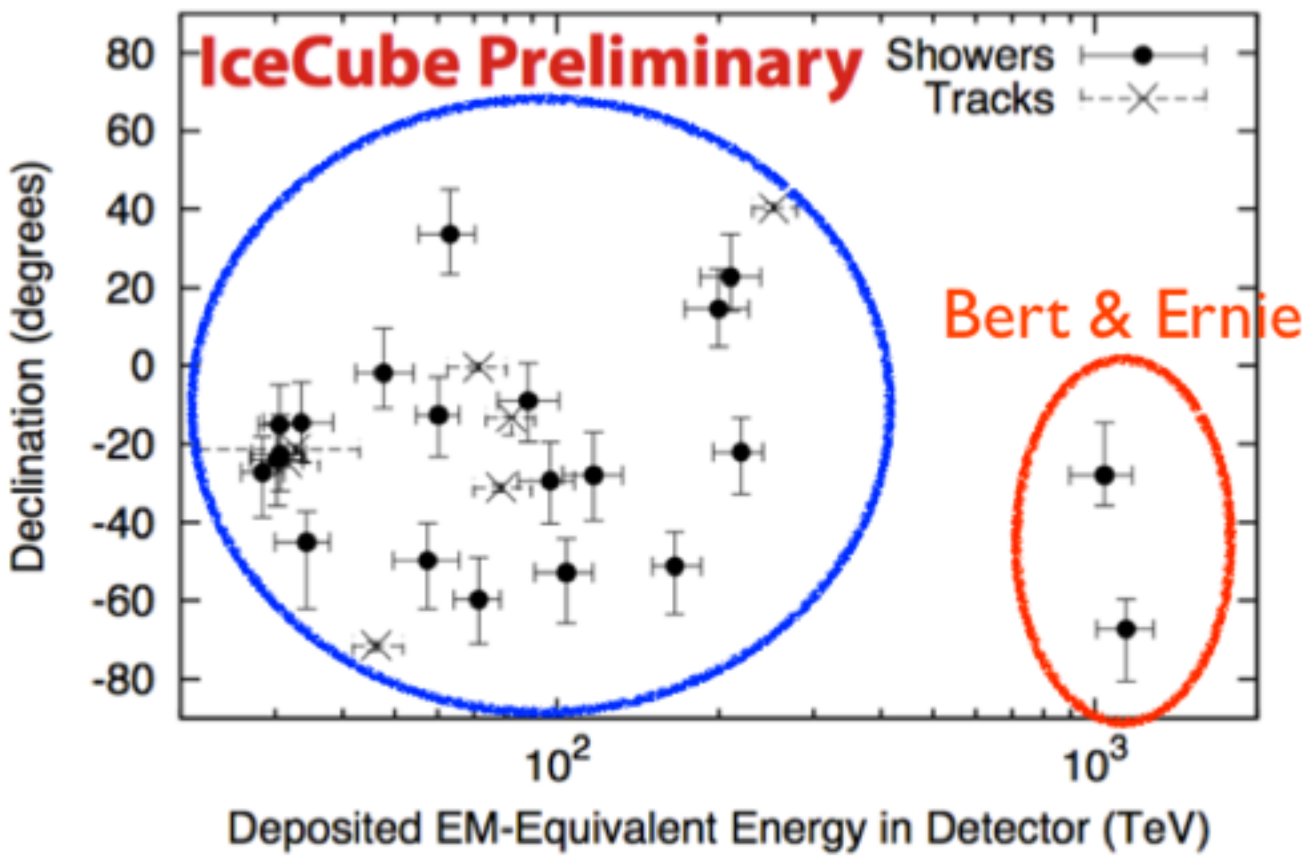
'southern sky(downgoing)'

-talk by N. Whitehorn at IPA2013

Skymap: No Significant Clustering ~not from a local source



Closer look at the DATA



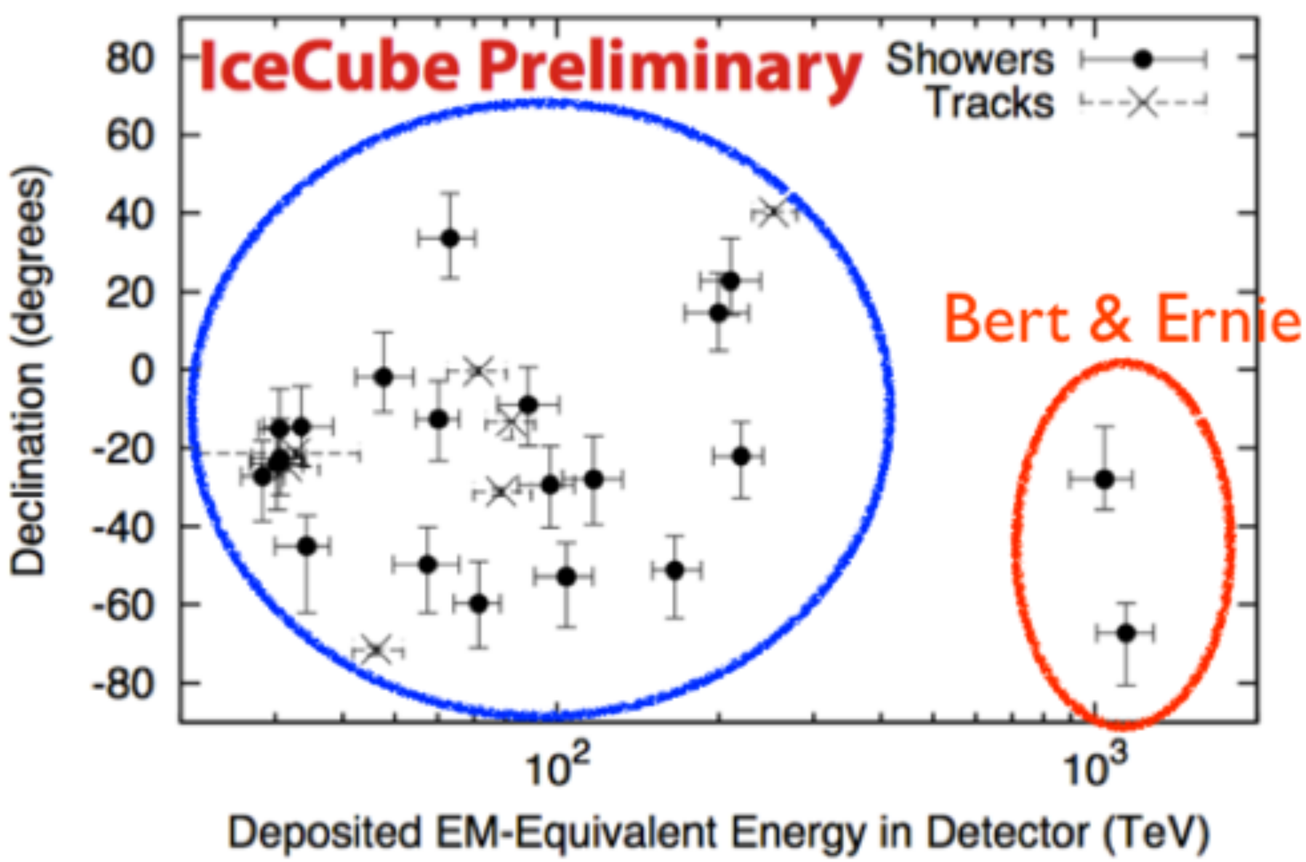
Properties of observed neutrinos

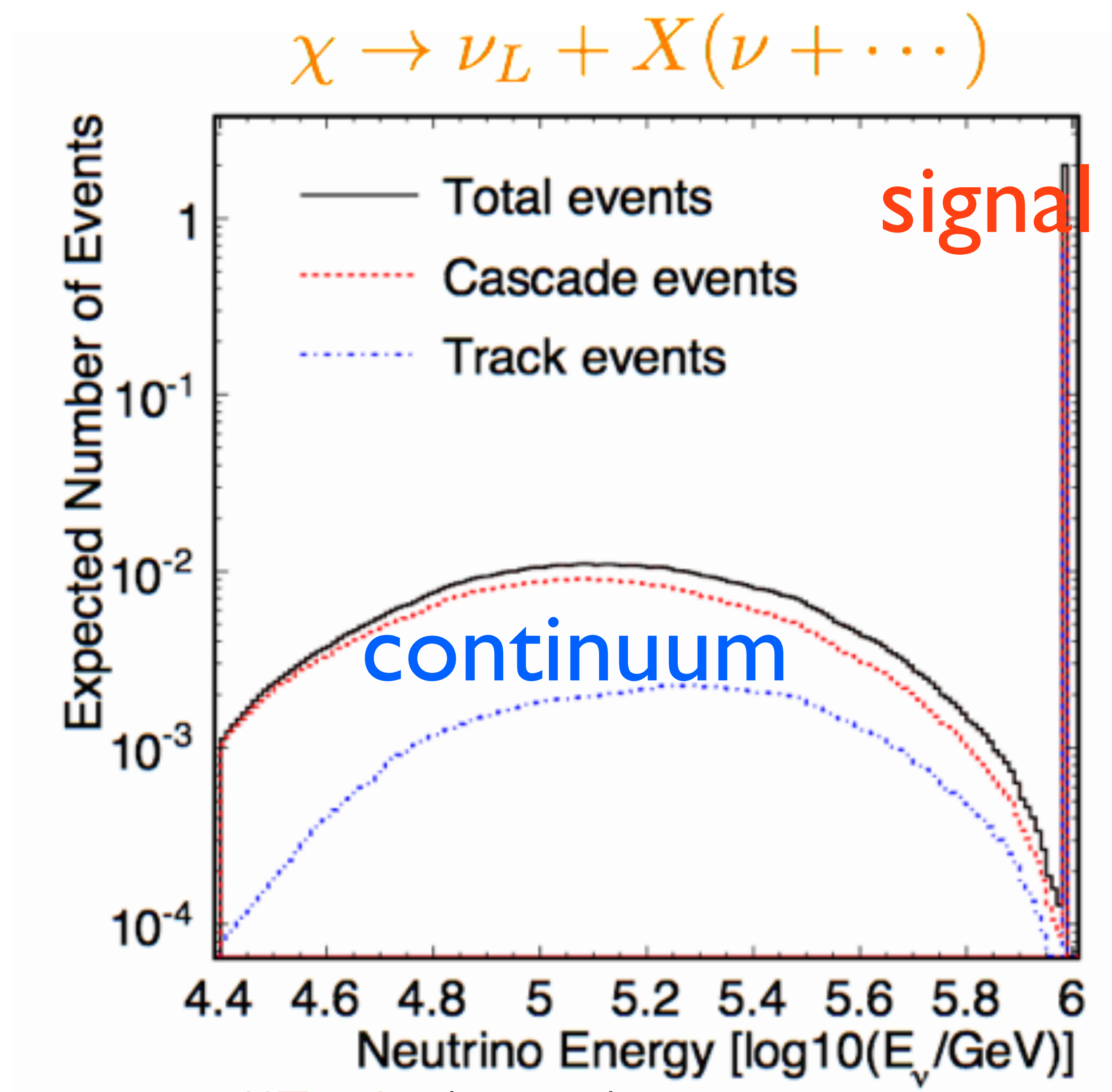
- "Continuous" in 1-250 TeV
- "Peak" at ~1 PeV
- Consistent with isotropic distribution
- 1:1:1 neutrino flavor

$$P(\nu_e \leftrightarrow \nu_e) = 0.56\,,$$
$$P(\nu_e \leftrightarrow \nu_\mu) = P(\nu_e \leftrightarrow \nu_\tau) = 0.22\,,$$
$$P(\nu_\mu \leftrightarrow \nu_\mu) = P(\nu_\mu \leftrightarrow \nu_\tau) = P(\nu_\tau \leftrightarrow \nu_\tau) = 0.39\,.$$

understandable since after a long enough propagation, neutrino flavor info. would disappear

The “continuum+peak” may imply particle DM!





**Tracks (nu_mu)
**Cascades (nu_e+nu_tau)

Ann vs Decay

[Kohri, SCP, Rott (2013)]

Annilating $\chi\chi \to \nu_L + X(\to \nu + \cdots)$

-less than one event/100 years with PeV DMs

-centered (50% within 25°)

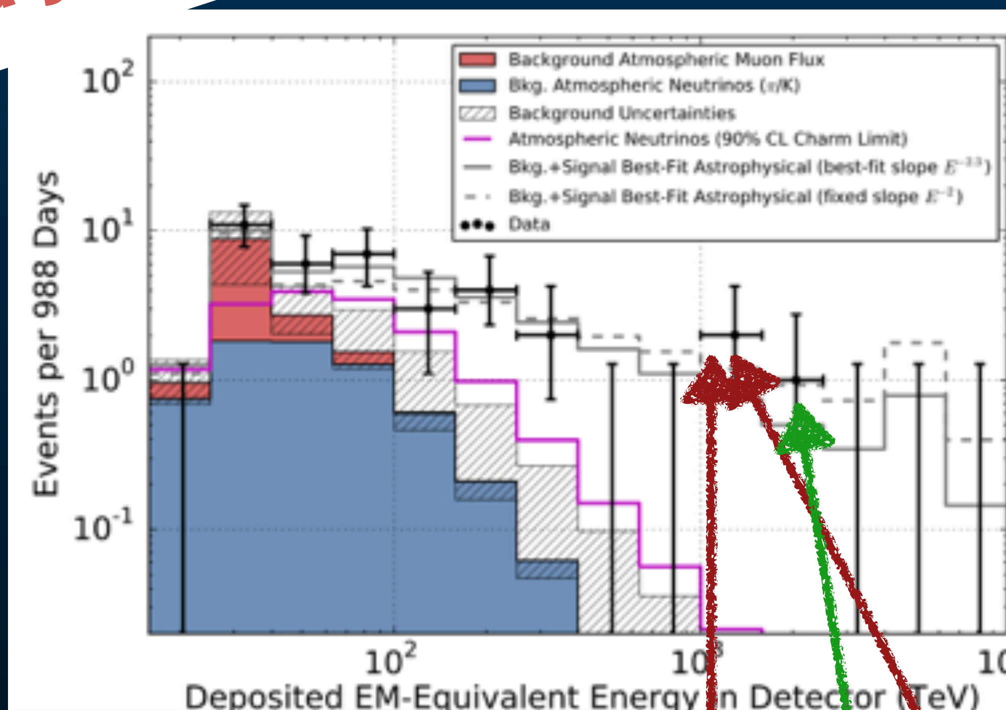
Decaying (preferred)

$\tau_\chi \sim 10^{28-29}\mathrm{sec}$ would fit the "peak"

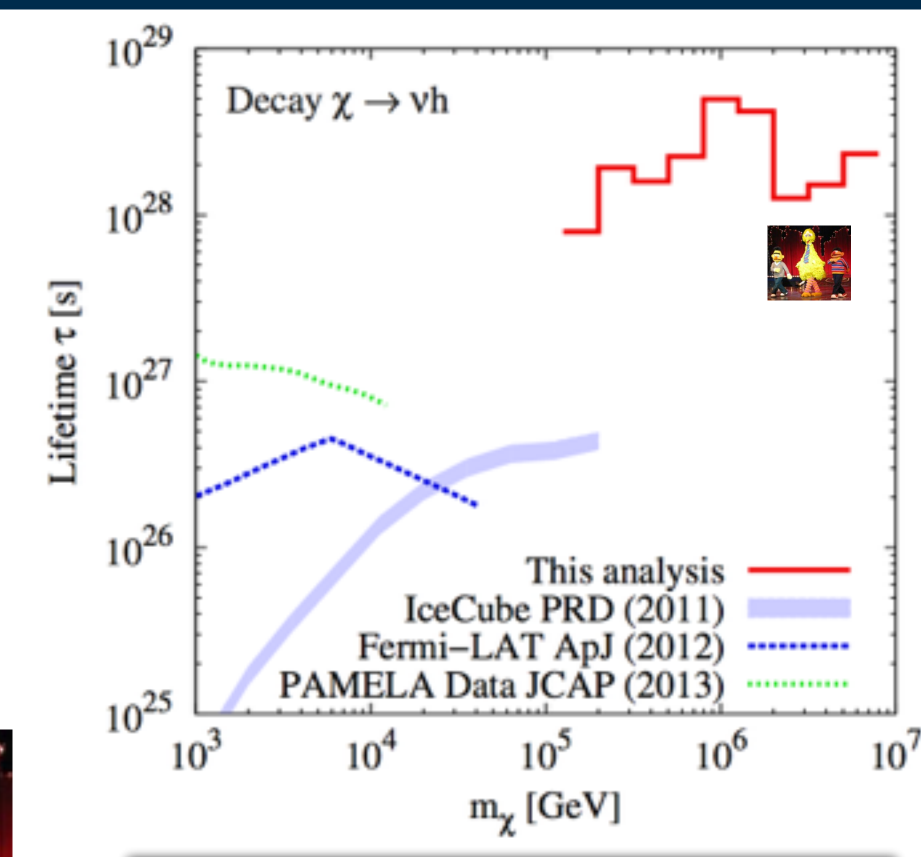
-broadly distributed (50% within 65°)

News from South pole 3rd year

IceCube PeV neutrinos



IceCube 3yr arXiv:1405.530

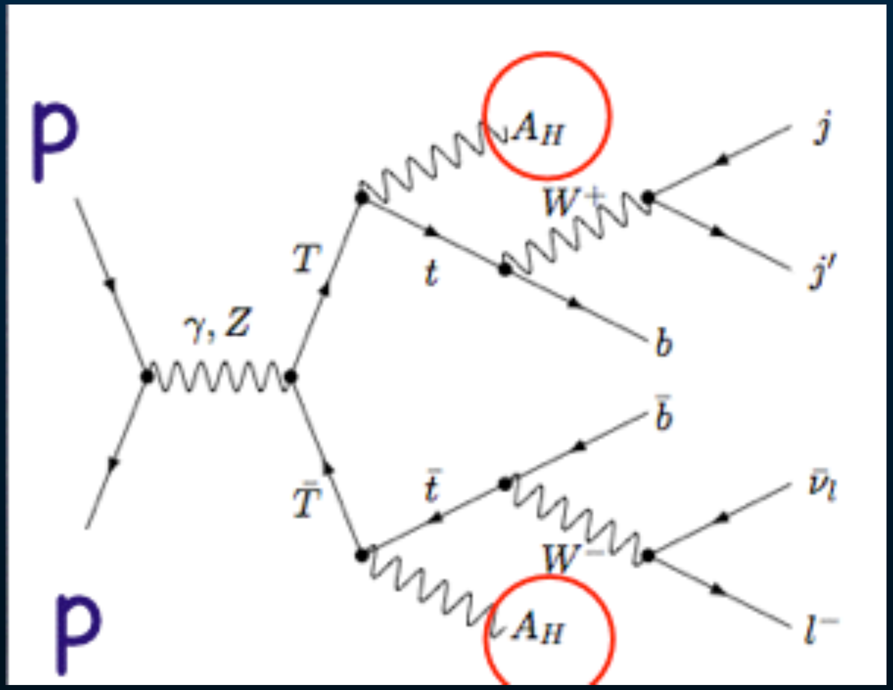


Rott, Kohri, SCP;1408.4864
to appear in PRL

Collider search for DM

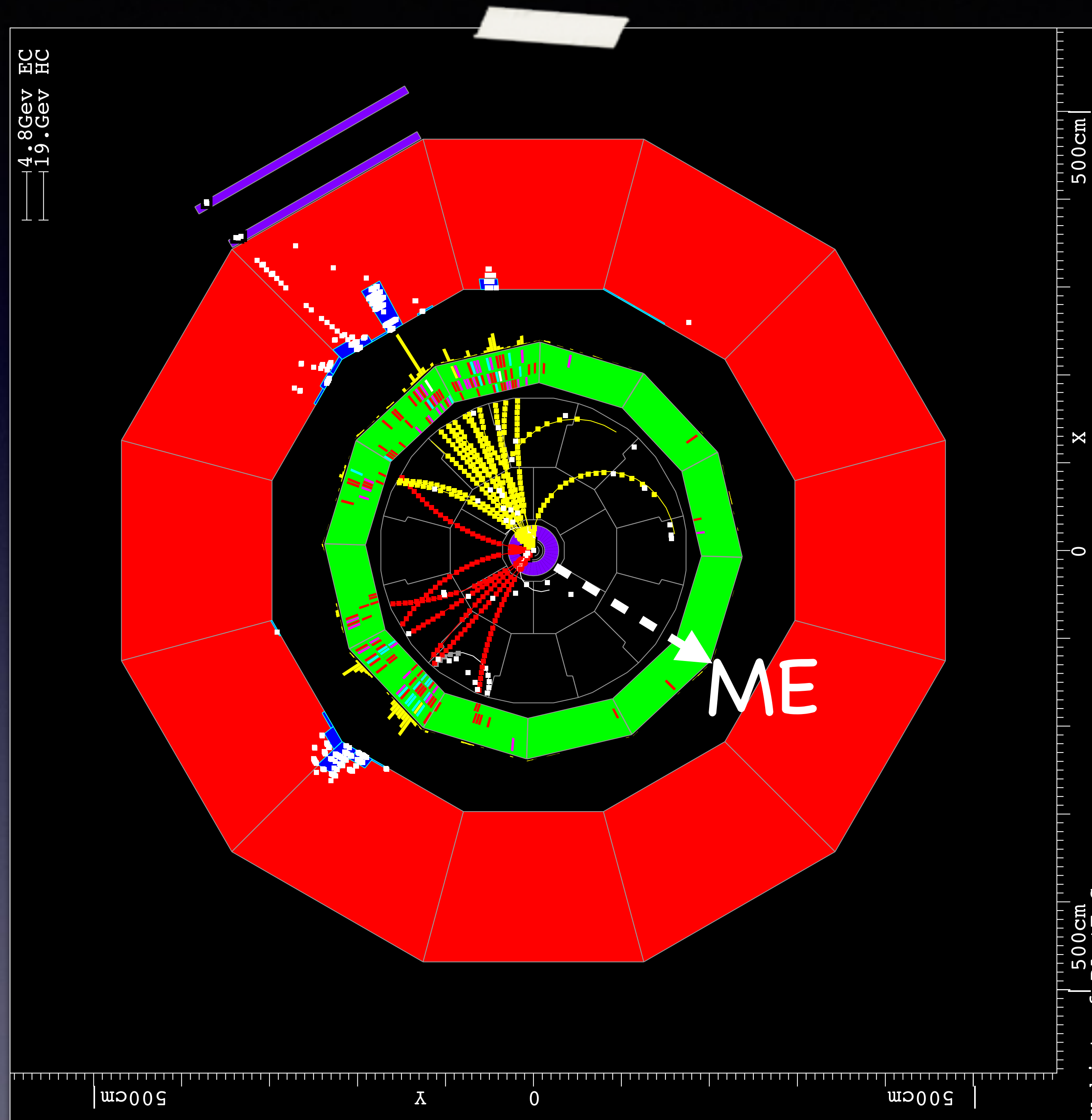
- Production of heavy new particle may be seen at the LHC
- DM can be the final state of heavy particle decay: q’-> q+ dm
- DM cannot be directly detected so that they are regarded as Missing Energy

Collider physics for DM



Kong, Park 2007

DM particles ``seen" as missing energy signals!


ME
4.8Gev EC
19.Gev HC
500cm
X
0
Y
500cm
YX hist.of BA.+E.C.

Summary of Lecture 2

- FWR metric is obtained from cosmological principle (isotropy and homogeneity). Friedman eq. governs actual expansion rates.

- WIMP searches based on direct, indirect and collider techniques are going on. (many hints but not definite yet)

- Heavier regime is started to get covered by new experiments, e.g., IceCube.

arXiv:1006.1901

Compact hyperbolic extra dimension: a M–theory solution and its implications for the LHC

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Abstract: We study M–theory solutions involving compact hyperbolic spaces. The combination of a gap *à la* Randall–Sundrum and the topology of an internal Riemann surface allows a geometrical solution to the hierarchy problem that does not require light Kaluza–Klein modes. We comment on the consequences of such a compactification for LHC physics.