Aspects of Dark Matter phenomenology

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Seminar University of Irvine, Particle Theory Group, 4th of October 2013

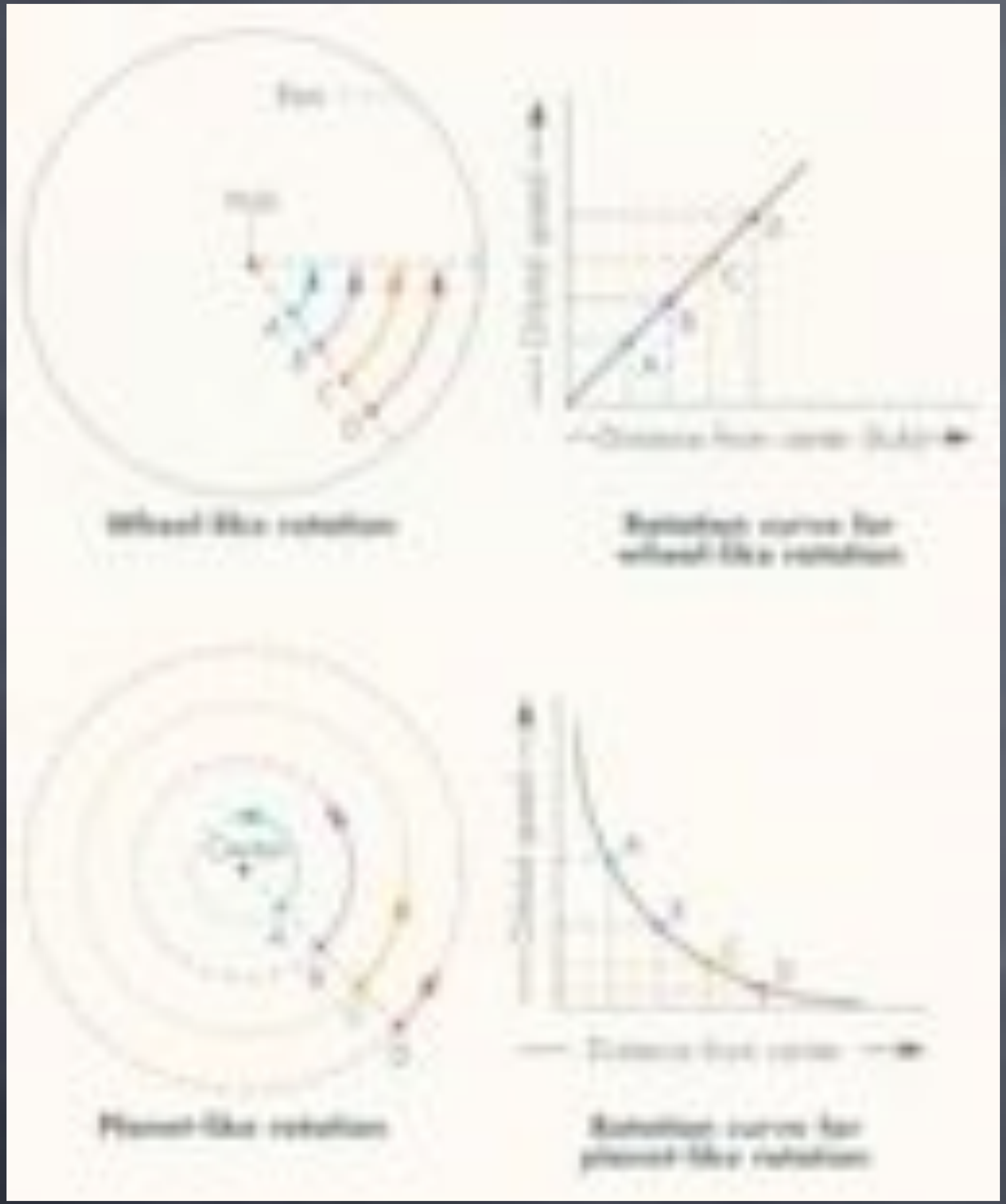
Outline

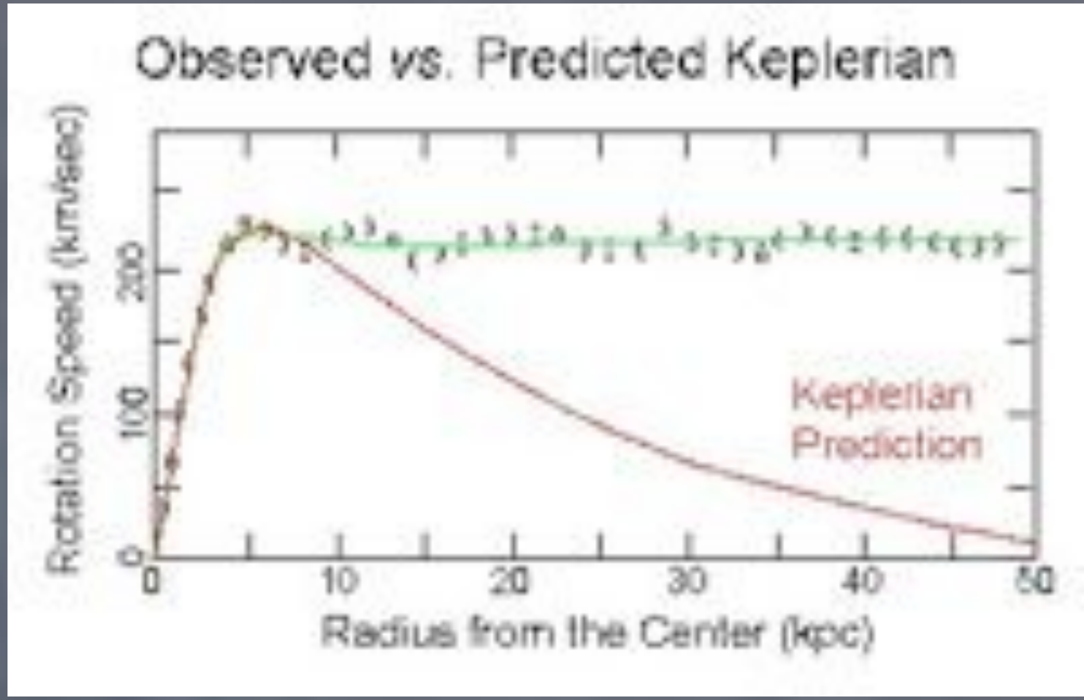
- Dark matter evidences
- A little thermal history of the Universe in 3 acts
- Boltzman equation from insi(ght)de
- A specific example : Extra U(1) [hidden photon, Z', Zdark..]
- Astrophysical signals, exemple of synchrotron emission
- Conclusion an perspective

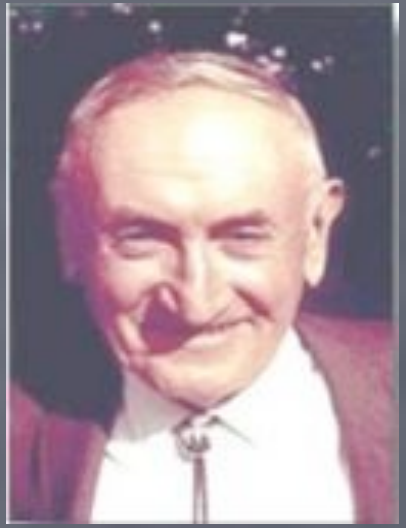
Astroparticle

- 3 different scales : particle (pb), Astro (light years), Cosmo (Hubble time)
- 3 different philosophies/visions of physics
- Accelerators are made by physicists for physicists whereas Universe was made by ? for ?
- LHC provides 600 millions collisions per seconds whereas we just have 1 Universe : we cannot reproduce the experiment to increase the luminosity!!!
- LHC provides his own background, whereas in the Universe, you have no idea of the background as you always measure Signal+Background.

Dark matter evidence : Galactic scale



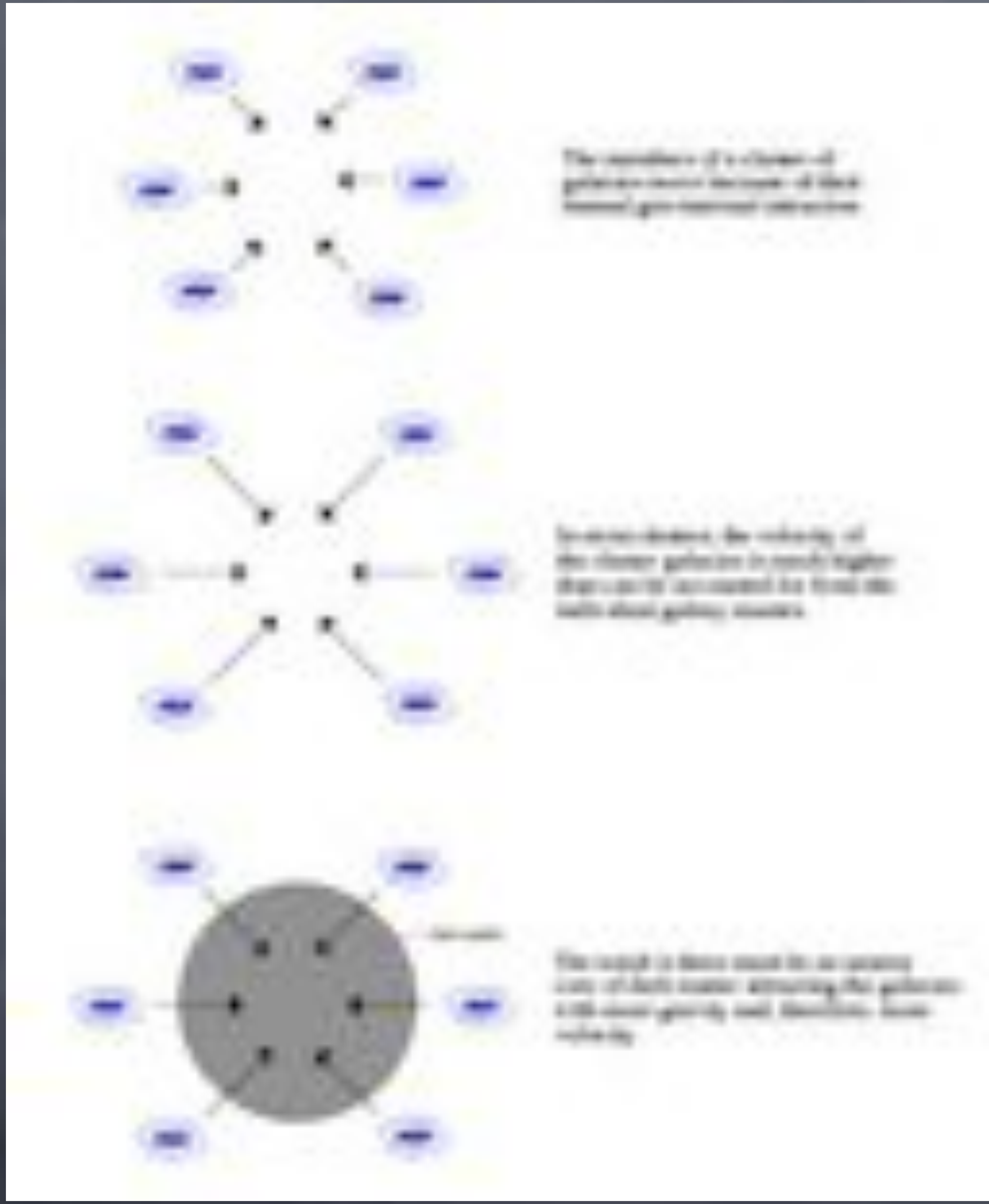


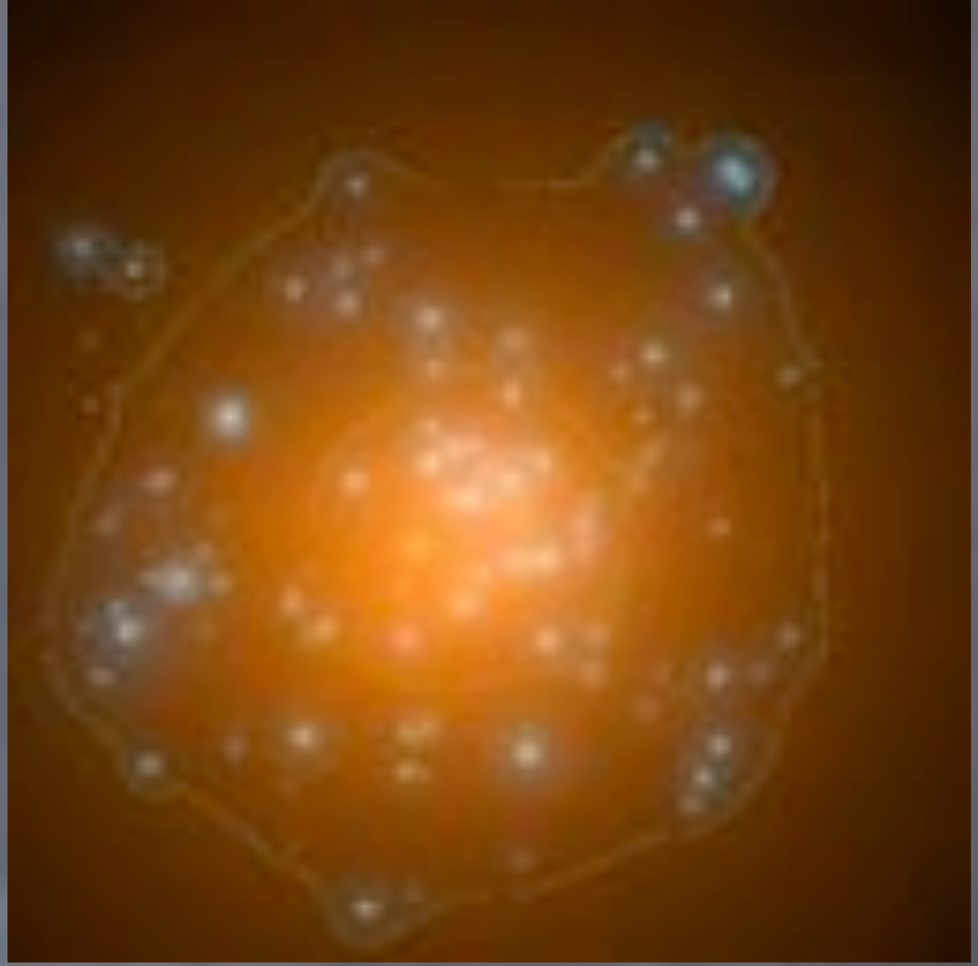


$$\rho_{DM} \propto \frac{1}{r^2} \rightarrow M_{gal} = Volume * \rho \propto r \rightarrow v \sim cte$$

$$\frac{GmM_{gal}}{r} = mv^2 \rightarrow v \propto \frac{1}{\sqrt{r}}$$

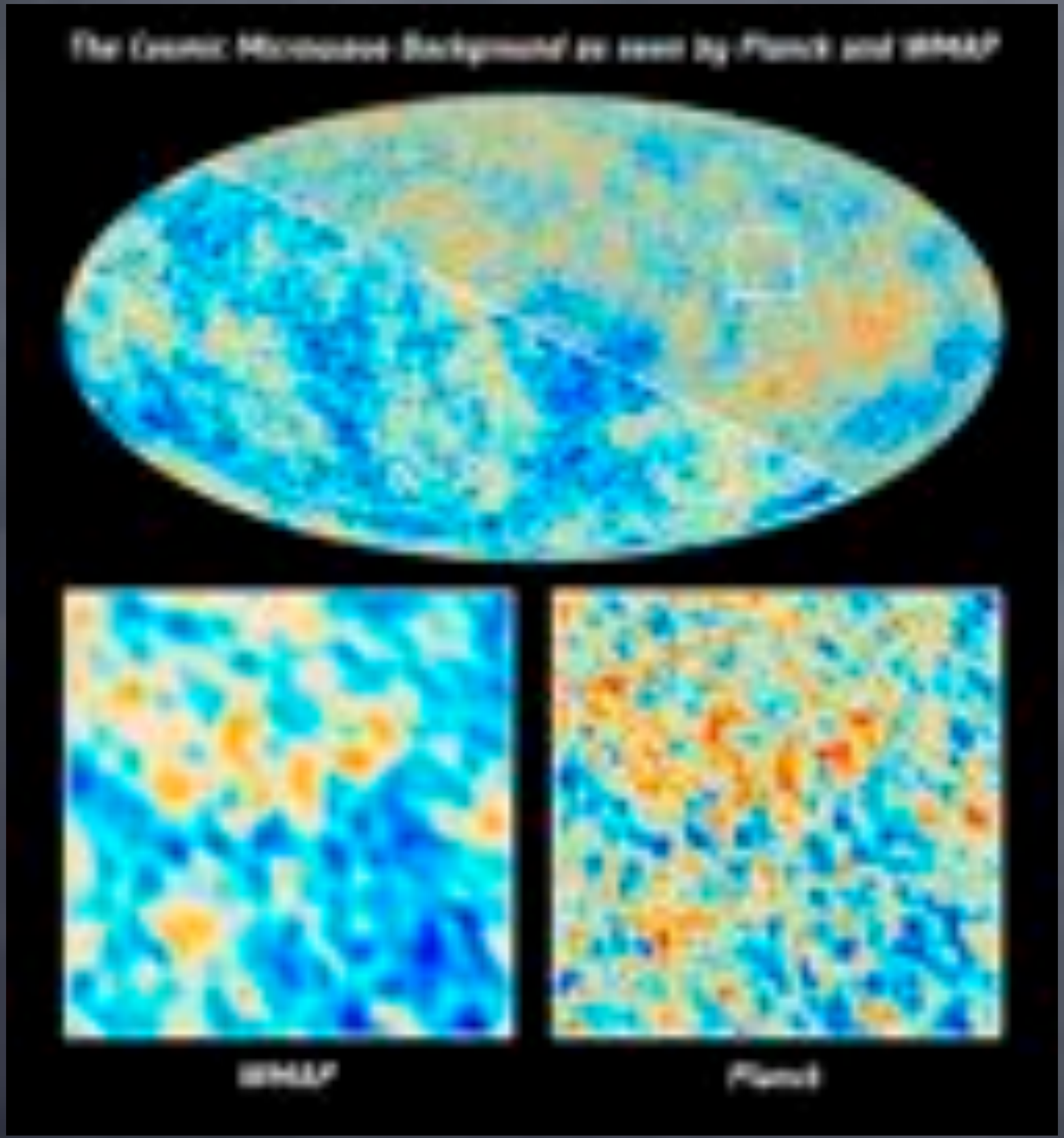
Cluster of Galaxy scale

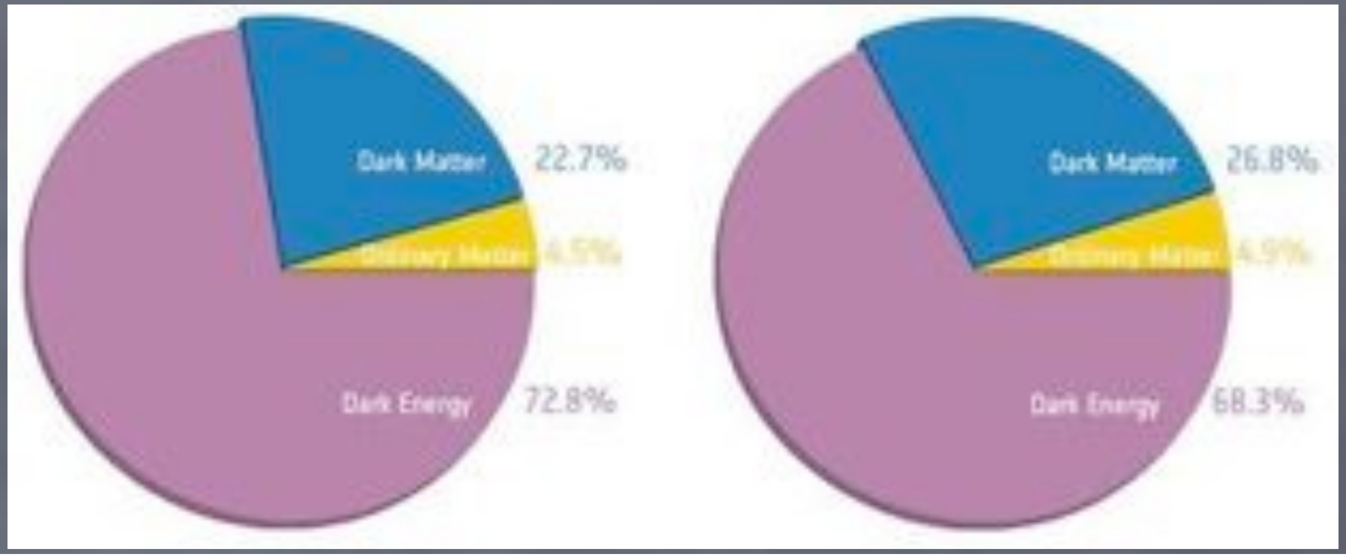


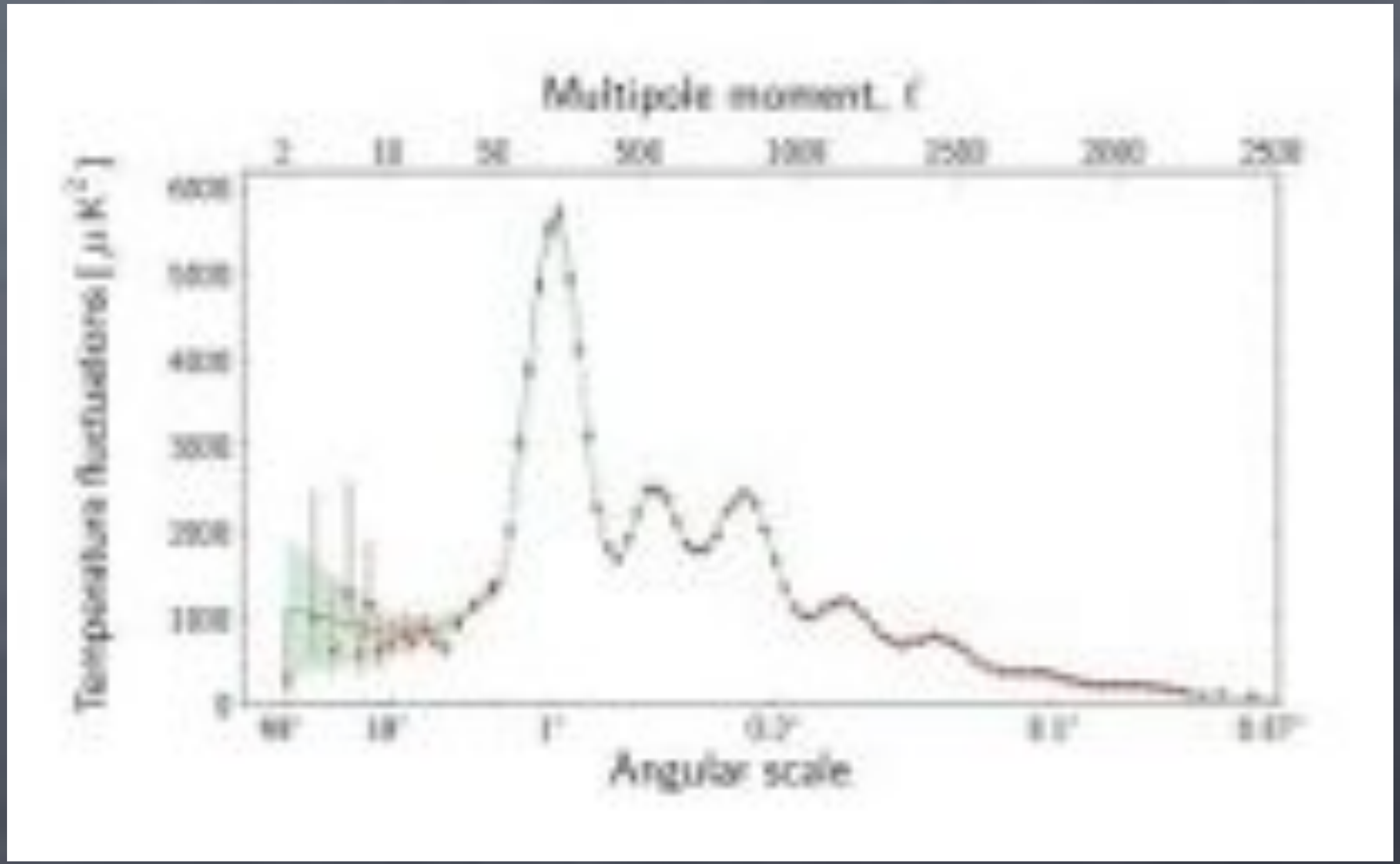


Cosmological scale (PLANCK results March 19th)

Cosmic Microwave Background (CMB)







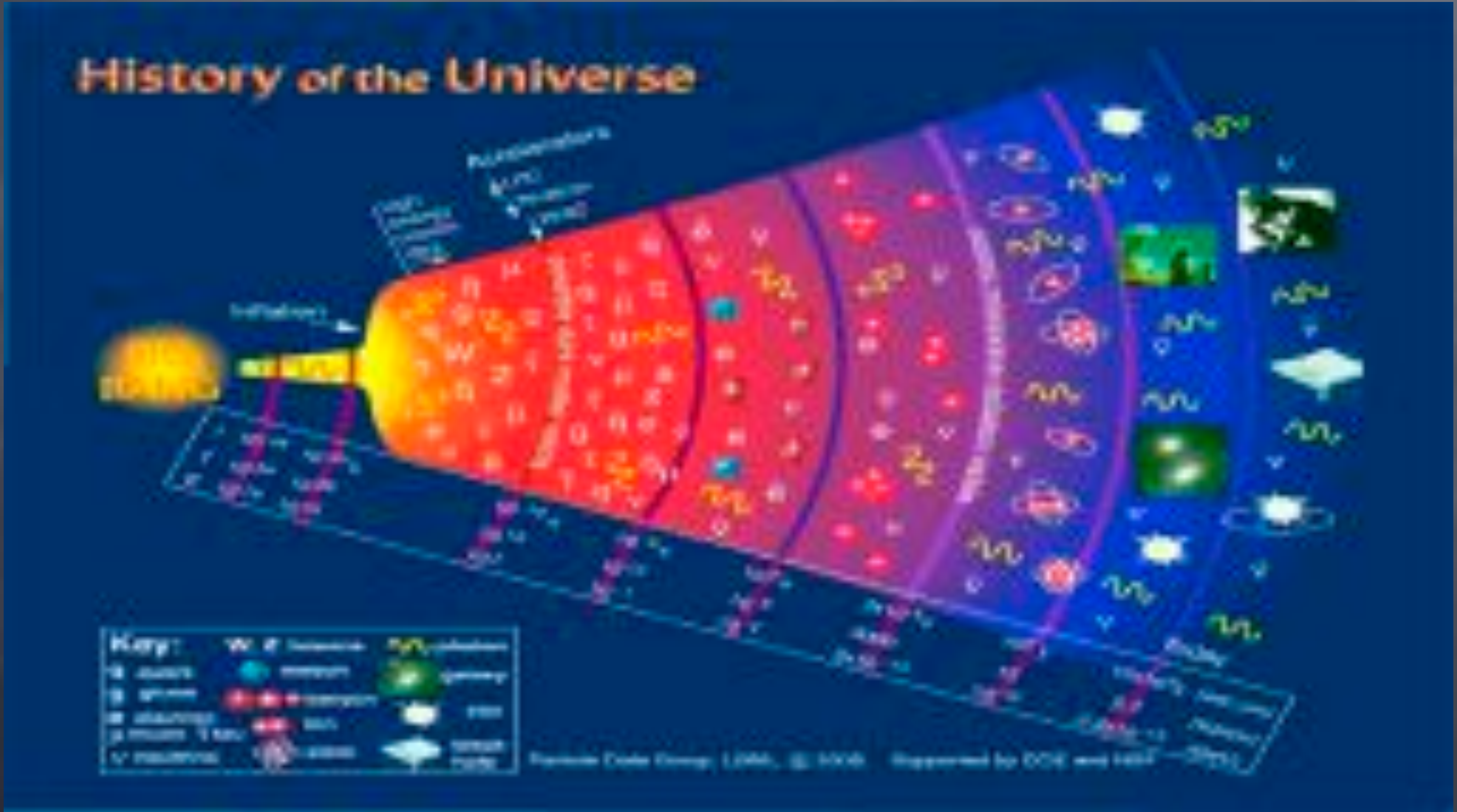
Dark Matter candidates

Neutralino
Gravitino
KK modes
ν_R
Hidden fermonic sector
Dark U(1)
Sterile neutrino
Phantom dark matter
Higgs doublet
Mirror dark matter
Stable extra gauge boson..

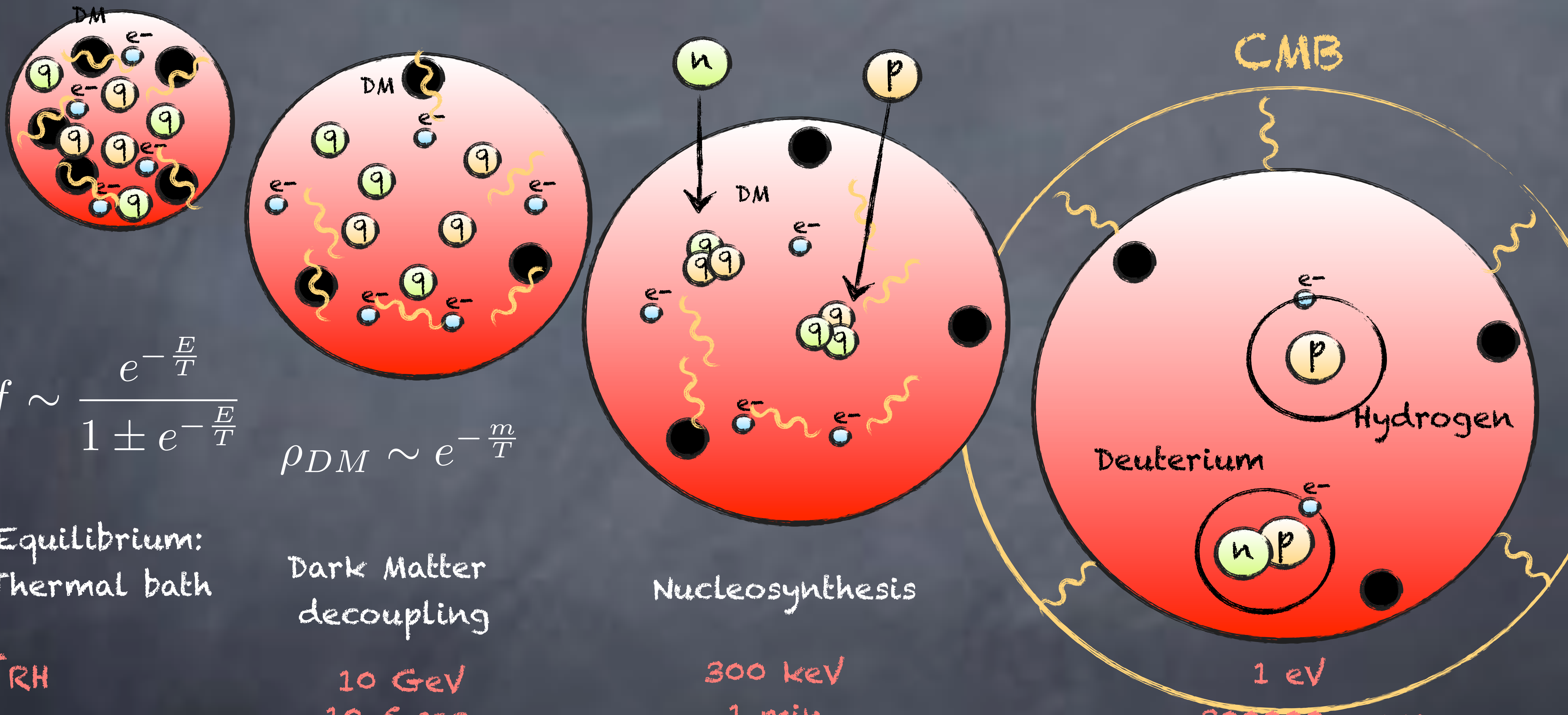
Mass/coupling classification

- Weakly coupling (neutralino, sterile neutrino..)
- Planck induced coupling (gravitino)
- Intermediate («feeble») coupling (FIMP, SO(10) theories)
- Dark coupling (Extra U(1), dark photons)

A little thermal history of the Universe (I)



A little thermal history of the Universe (II)



$$f \sim \frac{e^{-\frac{E}{T}}}{1 \pm e^{-\frac{E}{T}}}$$

$$\rho_{DM} \sim e^{-\frac{m}{T}}$$

Equilibrium:
Thermal bath

Dark Matter
decoupling

Nucleosynthesis

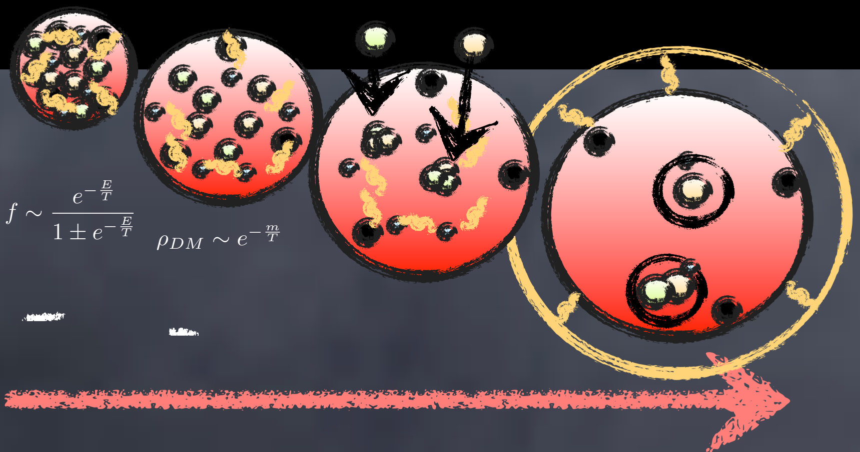
T_{RH}
time

10 GeV
10-5 sec

300 keV
1 min

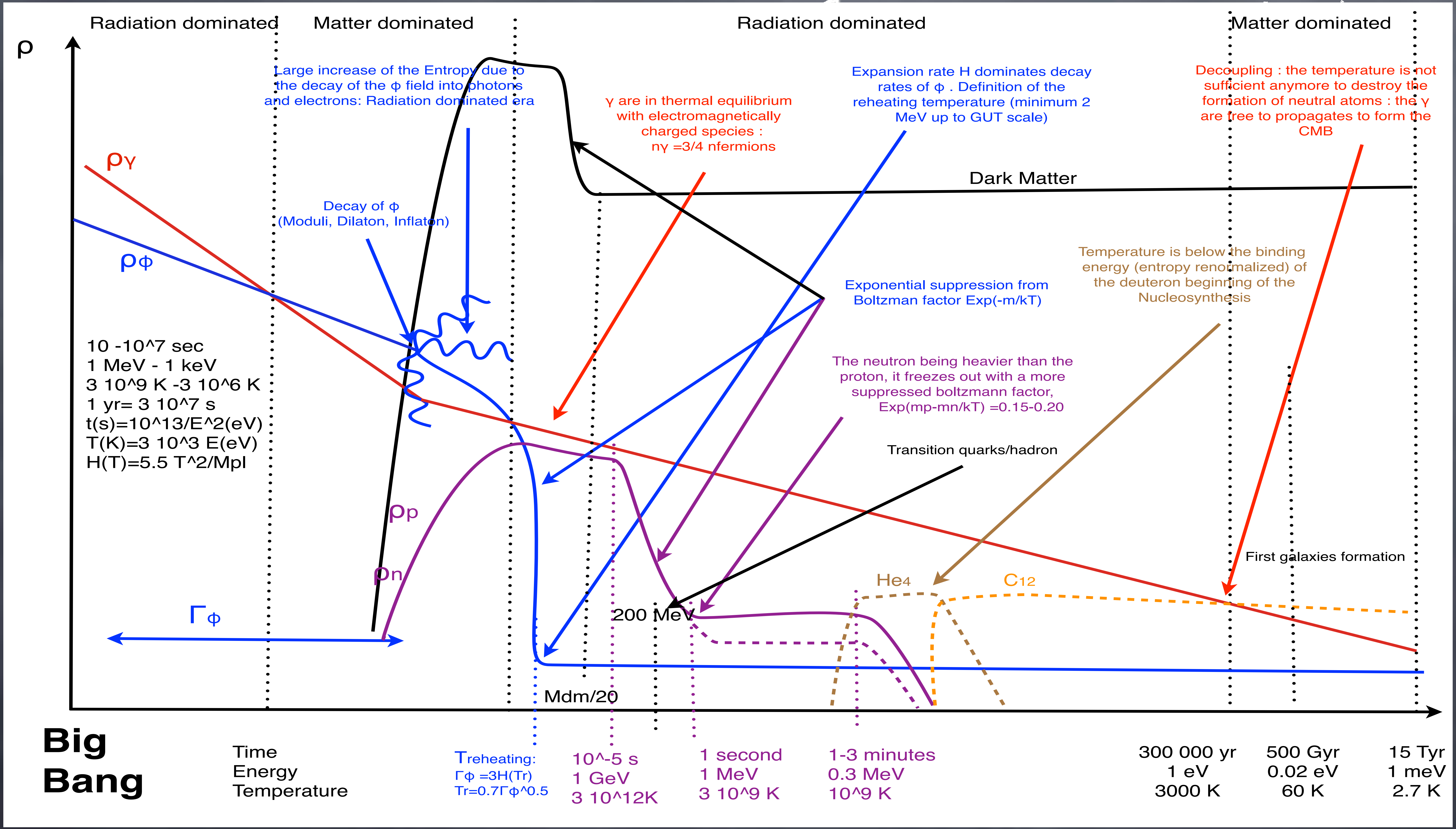
1 eV
300000 years

A little thermal history of the Universe (II)

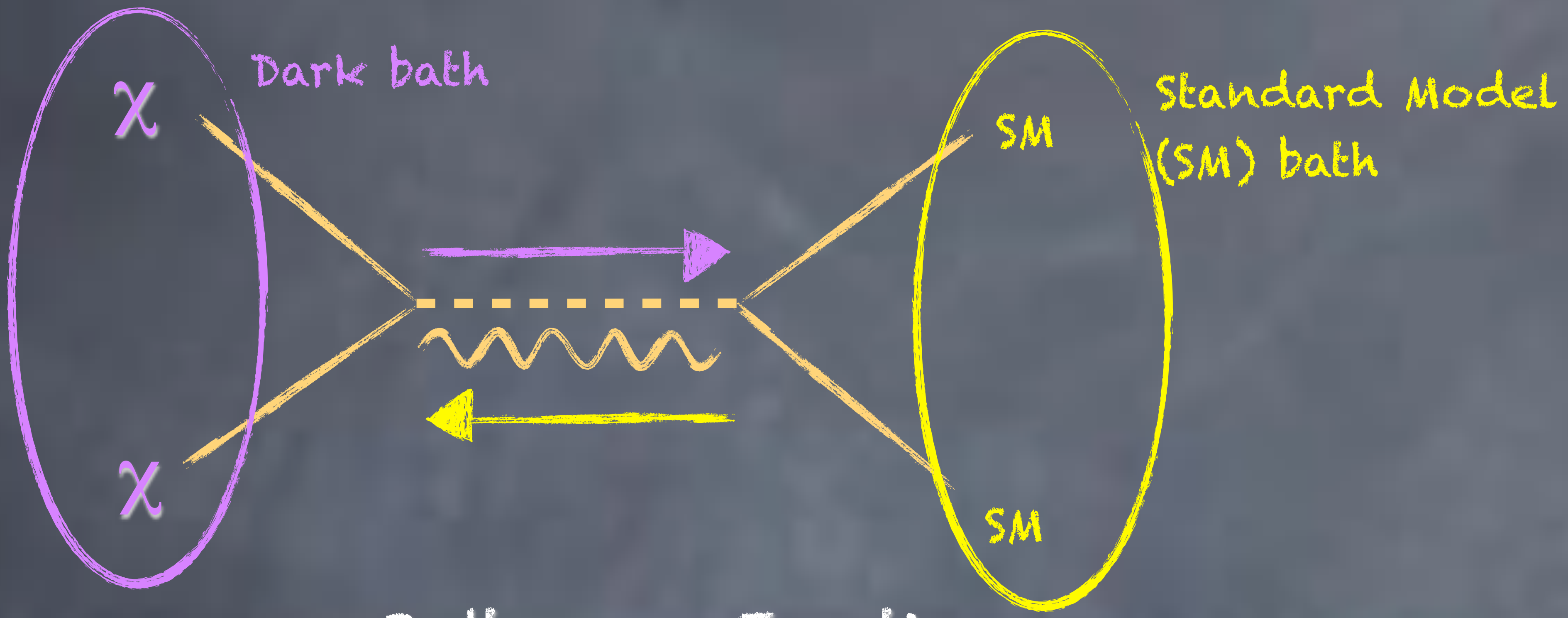


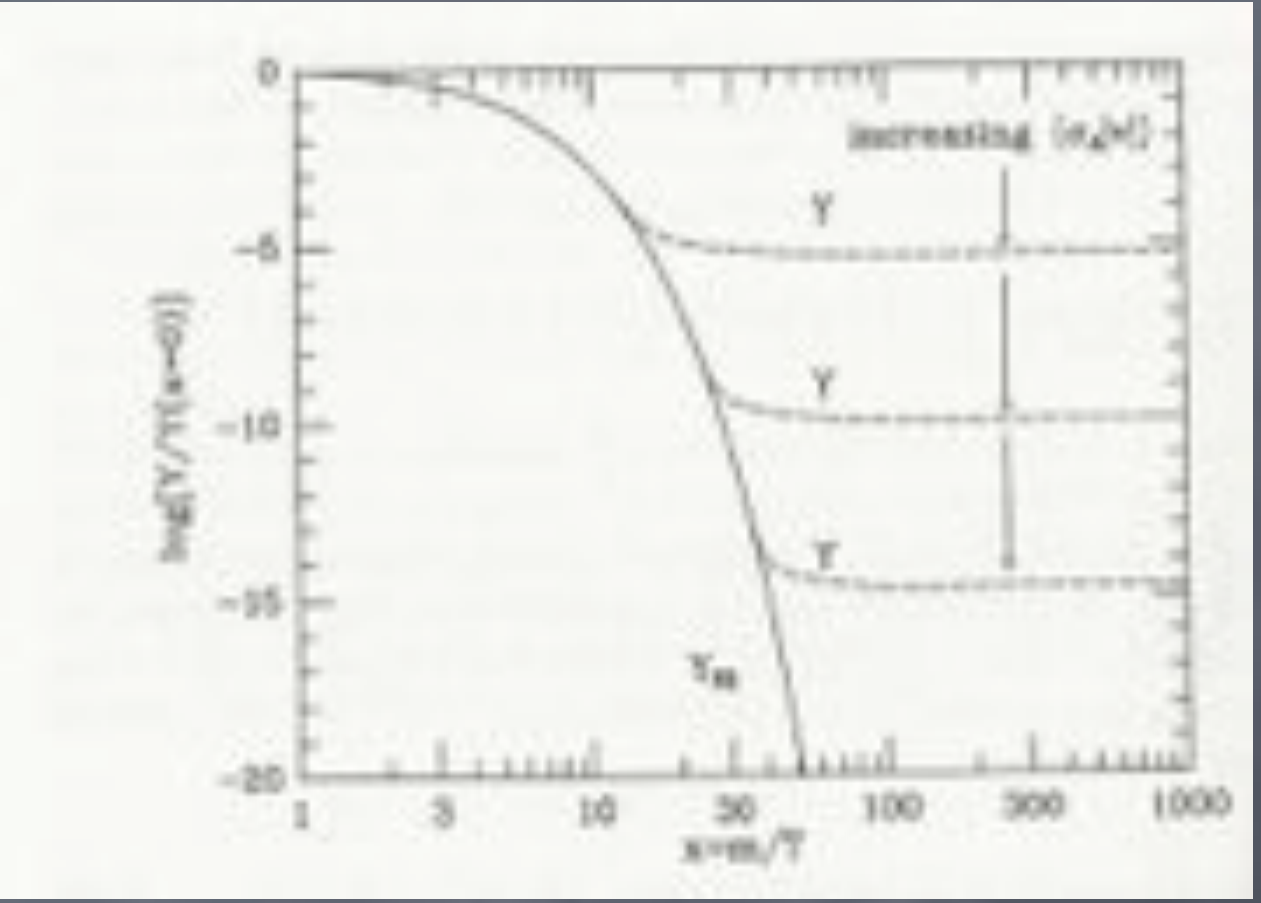
$f \sim \frac{e^{-\frac{E}{T}}}{1 \pm e^{-\frac{E}{T}}}$

$\rho_{DM} \sim e^{-\frac{m}{T}}$


Radiation dominated
Matter dominated
Radiation dominated
Matter dominated
ρ
Large increase of the Entropy due to the decay of the ϕ field into photons and electrons: Radiation dominated era
γ are in thermal equilibrium with electromagnetically charged species : nγ =3/4 nfermions
Expansion rate H dominates decay rates of ϕ . Definition of the reheating temperature (minimum 2 MeV up to GUT scale)
Decoupling : the temperature is not sufficient anymore to destroy the formation of neutral atoms : the γ are free to propagates to form the CMB
ργ
Dark Matter
Decay of ϕ (Moduli, Dilaton, Inflaton)
ρϕ
Temperature is below the binding energy (entropy renormalized) of the deuteron beginning of the Nucleosynthesis
Exponential suppression from Boltzman factor Exp(-m/kT)
10 -10^7 sec
1 MeV - 1 keV
3 10^9 K -3 10^6 K
1 yr= 3 10^7 s
t(s)=10^13/E^2(eV)
T(K)=3 10^3 E(eV)
H(T)=5.5 T^2/Mpl
The neutron being heavier than the proton, it freezes out with a more suppressed boltzmann factor, Exp(mp-mn/kT) =0.15-0.20
Transition quarks/hadron
ρp
ρn
First galaxies formation
He4
C12
Γϕ
200 MeV
Mdm/20
Big Bang
Time
Energy
Temperature
Treheating:
Γϕ =3H(Tr)
Tr=0.7Γϕ^0.5
10^-5 s
1 GeV
3 10^12K
1 second
1 MeV
3 10^9 K
1-3 minutes
0.3 MeV
10^9 K
300 000 yr
1 eV
3000 K
500 Gyr
0.02 eV
60 K
15 Tyr
1 meV
2.7 K

A little thermal history of the Universe (III)





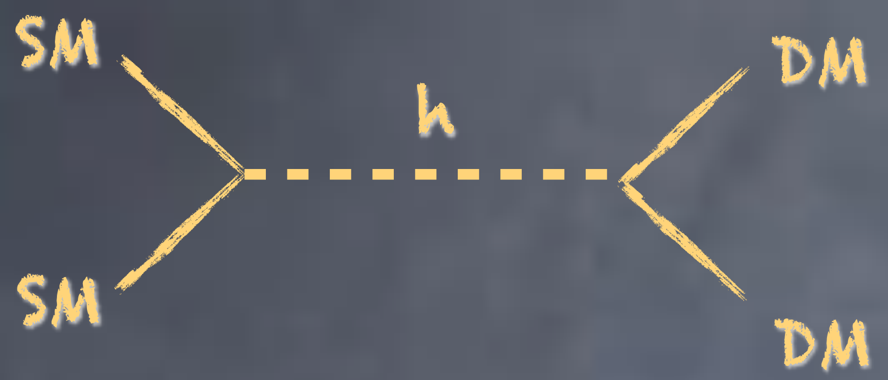
Boltzmann Equation
for a density of dark particle n :

$$\frac{dn}{dt} = -3\,H\,n - \langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right] \qquad (H = \dot{R} / R)$$

$$\Omega h^2 \sim \frac{3.10^{-27}\,cm^3\,s^{-1}}{\langle \sigma v \rangle} \sim 0.1 \;\Rightarrow\; \langle \sigma v \rangle \sim 3.10^{-26}\,cm^3\,s^{-1}$$

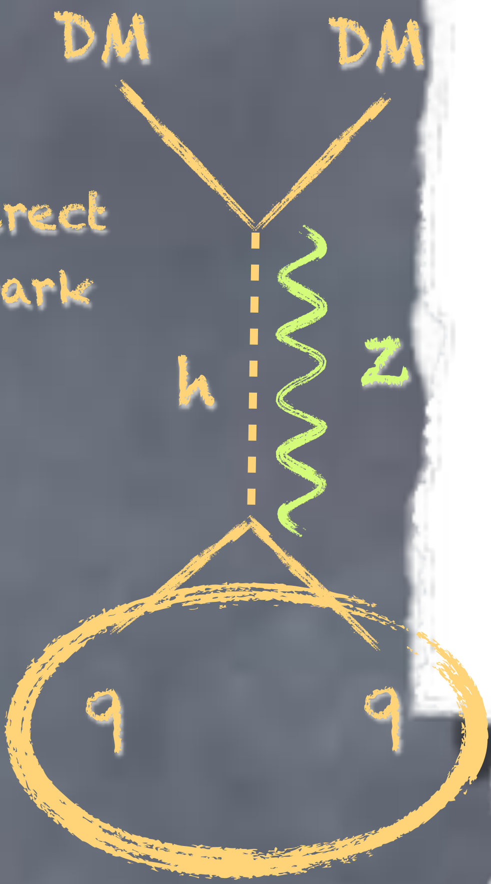
Important assumption: the dark matter was in thermal equilibrium in the Standard Model bath (plasma) since the early history of the Universe.

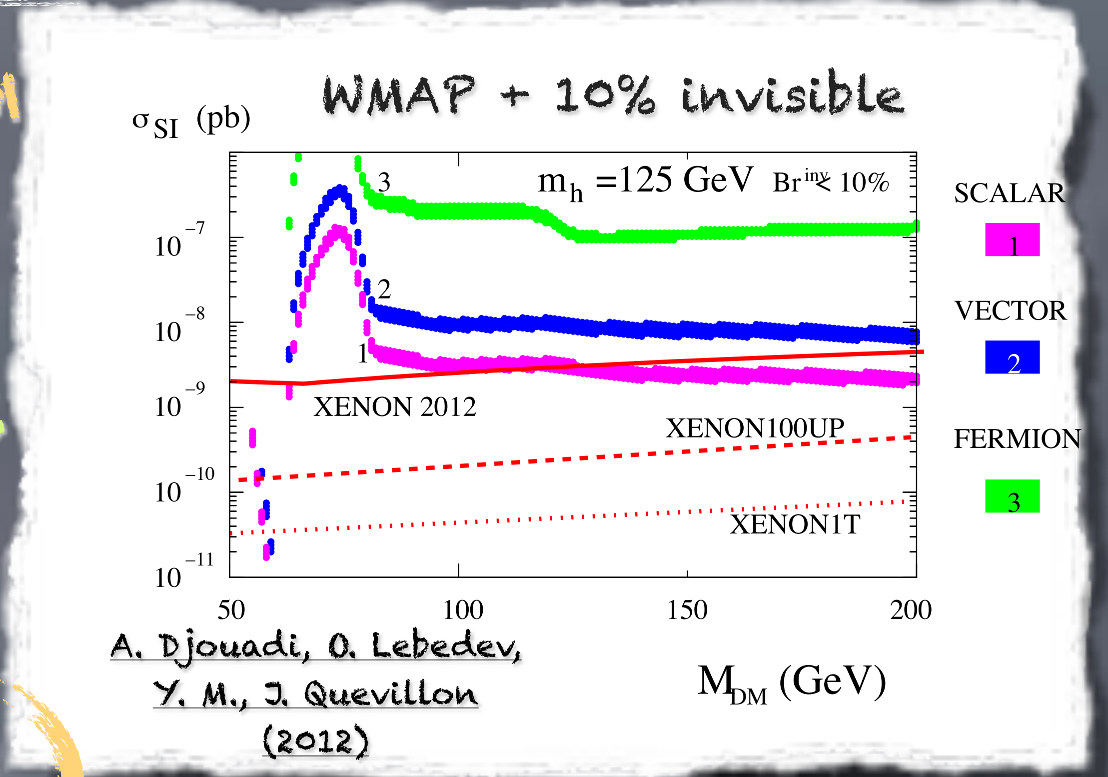
What is the mediator(s)?

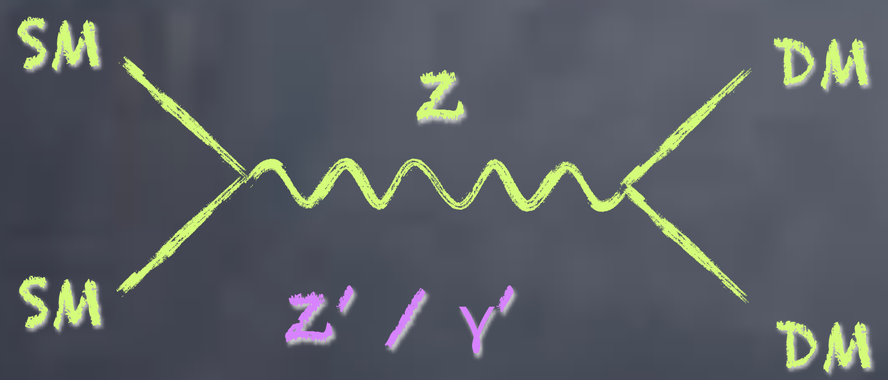


Higgs portal
darkons
phantom DM

Excluded by direct
detection of Dark
Matter



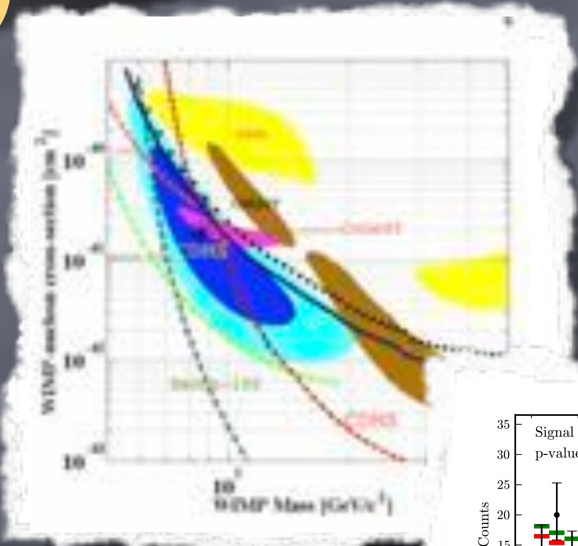


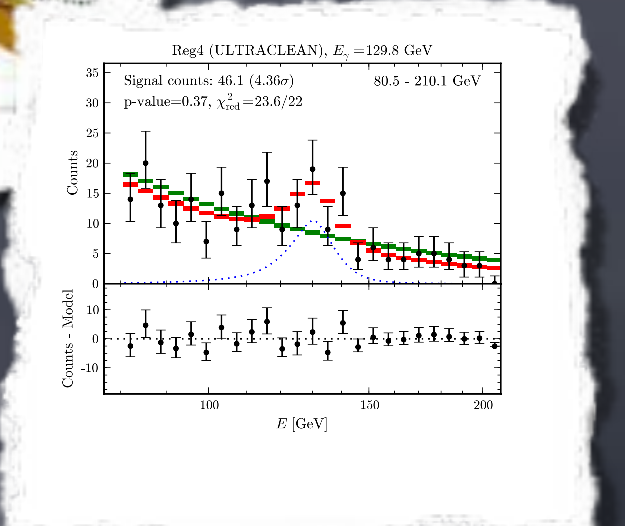


Z portal
(sneutrino dark
matter)

Excluded by direct
detection of Dark
Matter

Falk, Olive, Srednicki
(1994)



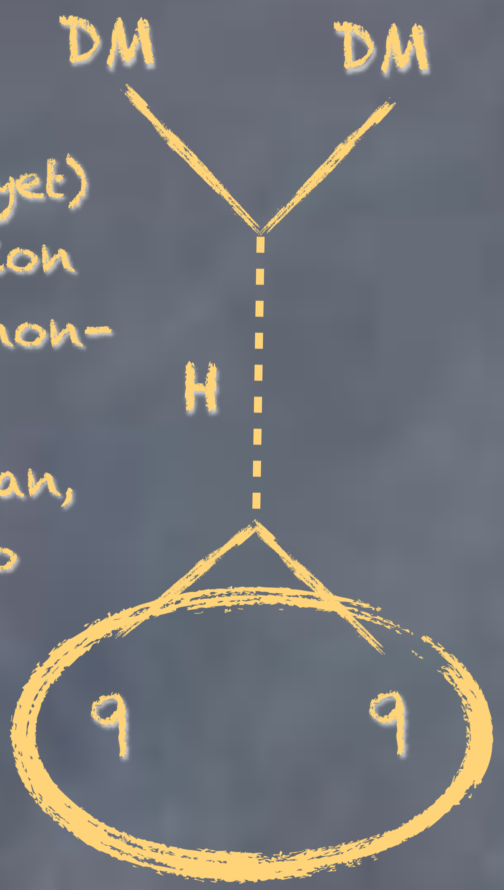


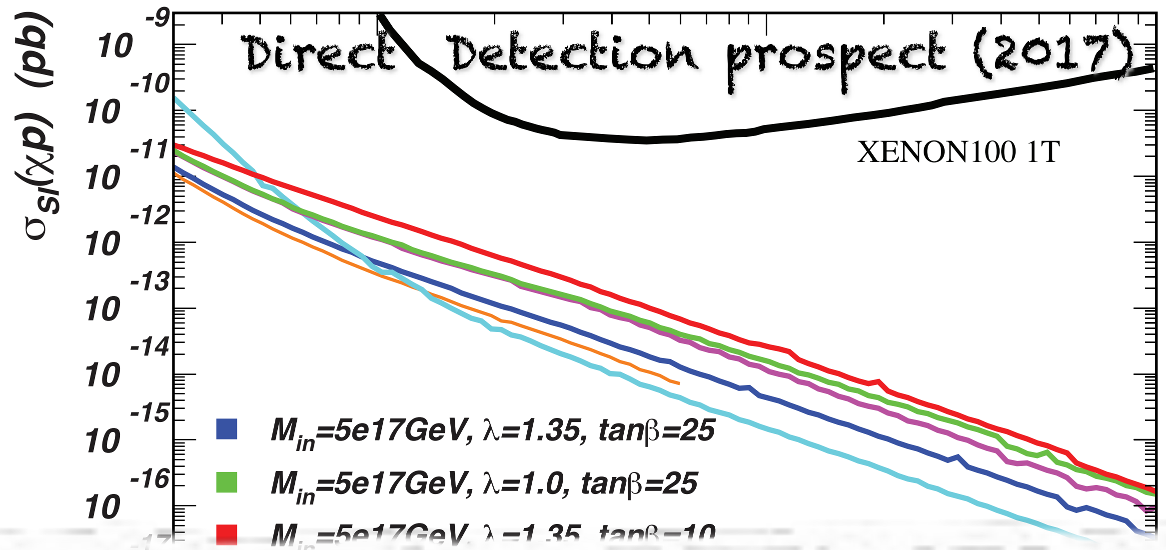
Z' portal
Hidden photon
(mirror dark
matter)

Not excluded
Can explain excess observed by
CRESST/CoGENT/DAMA
or FERMI monochormatic line

What is the (s)mediator ?

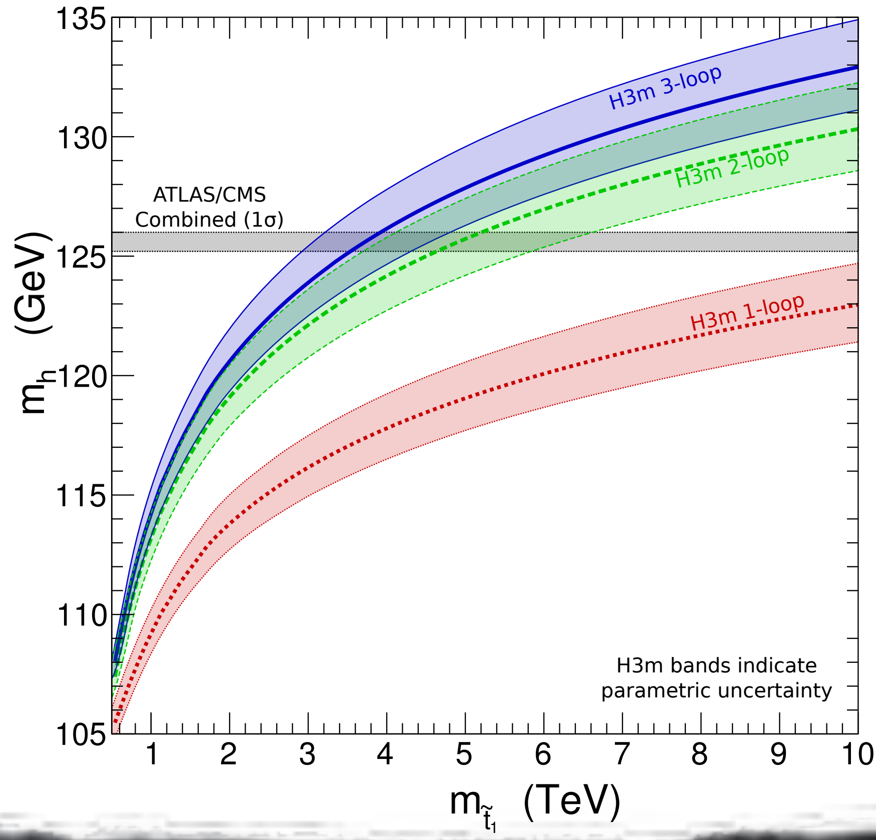
Neutralino
in (N)MSSM
No exclusions (yet)
Possible detection
+ possibility of non-SUSY scalar
Cotta, Rajaraman, Tait, Wijangco
1305.6609

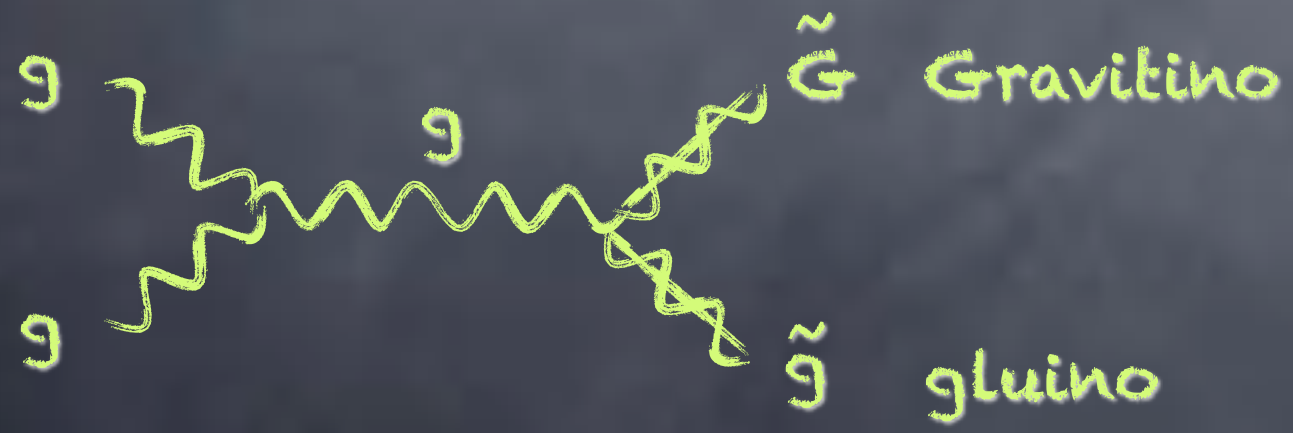




BUT in coherent Supergravity scenario, difficult to observe due to Higgs mass :
mh = Mz + Log(Mst/Mt) => heavy scalar sector => Heavy Higgses

Feng, Kant, Profumo, Sanford
3 loops Higgs
1306.2318



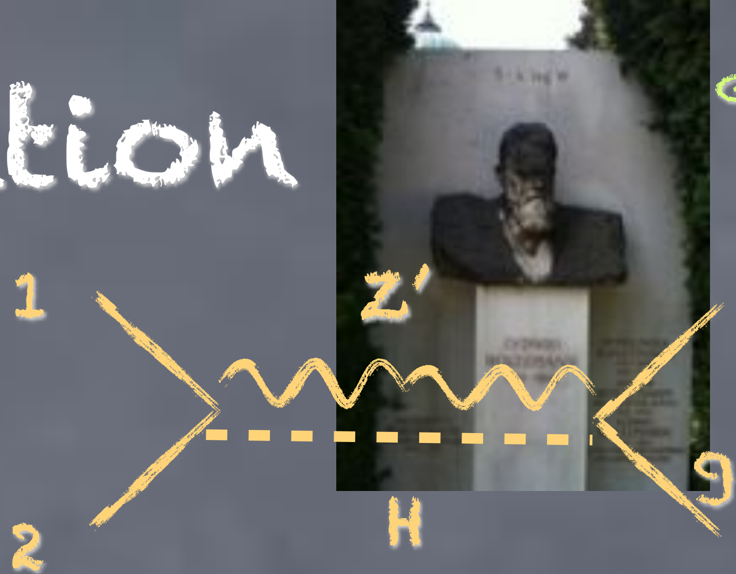


Gravitino dark matter
No detection hopes

Insights on the Boltzman equation

M. Blenow,
G. Hernandez,
Y. Mambrini,
B. Zaldivar
2013

$$\frac{dn}{dT} = 3\frac{n}{T} - \frac{\langle \sigma v \rangle}{HT}(n_{eq}^2 - n^2) \qquad \frac{dY}{dT} = T^2 \frac{\langle \sigma v \rangle}{H(T)}(Y^2 - Y_{eq}^2); \quad Y = \frac{n}{s}; \quad H(T) \simeq \frac{T^2}{M_{Pl}}$$



$$\langle \sigma v \rangle = \int_{T_{RH}}^{T} \Pi_i \; d^3\tilde{p}_i |\mathcal{M}|^2 e^{-\frac{E_1}{T}} e^{-\frac{E_2}{T}}$$

Z'=H=M

Two possibilities

Dark matter is not produced by inflaton decay at reheating time TRH

- MM < TRH

$$|\mathcal{M}|^2 \propto g_D^2$$

$$\Rightarrow \frac{dY}{dT} \propto g_D^2 \frac{M_{Pl}}{T^2}$$

$$\Rightarrow Y(T) \propto g_D^2 \frac{M_{Pl}}{T}$$

$$g_D \simeq g_{EW} \; : \; \text{WIMP}$$

$$g_D \simeq 10^{-10} \; : \; \text{FIMP}$$

- MM > TRH

$$|\mathcal{M}|^2 \propto g_D^2 \left(\frac{T^2}{M_M^2}\right)^2$$

$$\Rightarrow \frac{dY}{dT} \propto g_D^2 \frac{M_{Pl} T^2}{M_M^4}$$

$$\Rightarrow Y(T) \propto g_D^2 \frac{M_{Pl}}{M_M^4} \; T_{RH}^3$$

Non Equilibrium Thermal (NETDM) :
SO(10), Intermediate scale

- gD ~ T/MPl

Planck/gravitational induced coupling

$$\langle \sigma v \rangle \propto \frac{1}{M_{Pl}^2}$$

$$\Rightarrow \frac{dY}{dT} \propto \frac{1}{M_{Pl}}$$

$$\Rightarrow Y(T) \propto \frac{T_{RH} - T}{M_{Pl}}$$

$$\simeq \frac{T_{RH}}{M_{Pl}}$$

Gravitino DM prob. :TRH~10^8 GeV

Dark matter is produced in equilibrium with the SM species at TRH

- gD ~ gEW

Standard freeze out (FO) scenario. <σv> ~ 10^-9 The dark matter decouples when n is Boltzman suppressed :

n(T) <σv> << H(T)

WIMP
(neutralino, Higgs portal..)

Insig

$$\frac{dn}{dT} = 3\frac{n}{T} - \frac{\langle\sigma v\rangle}{HT}$$

Two poss

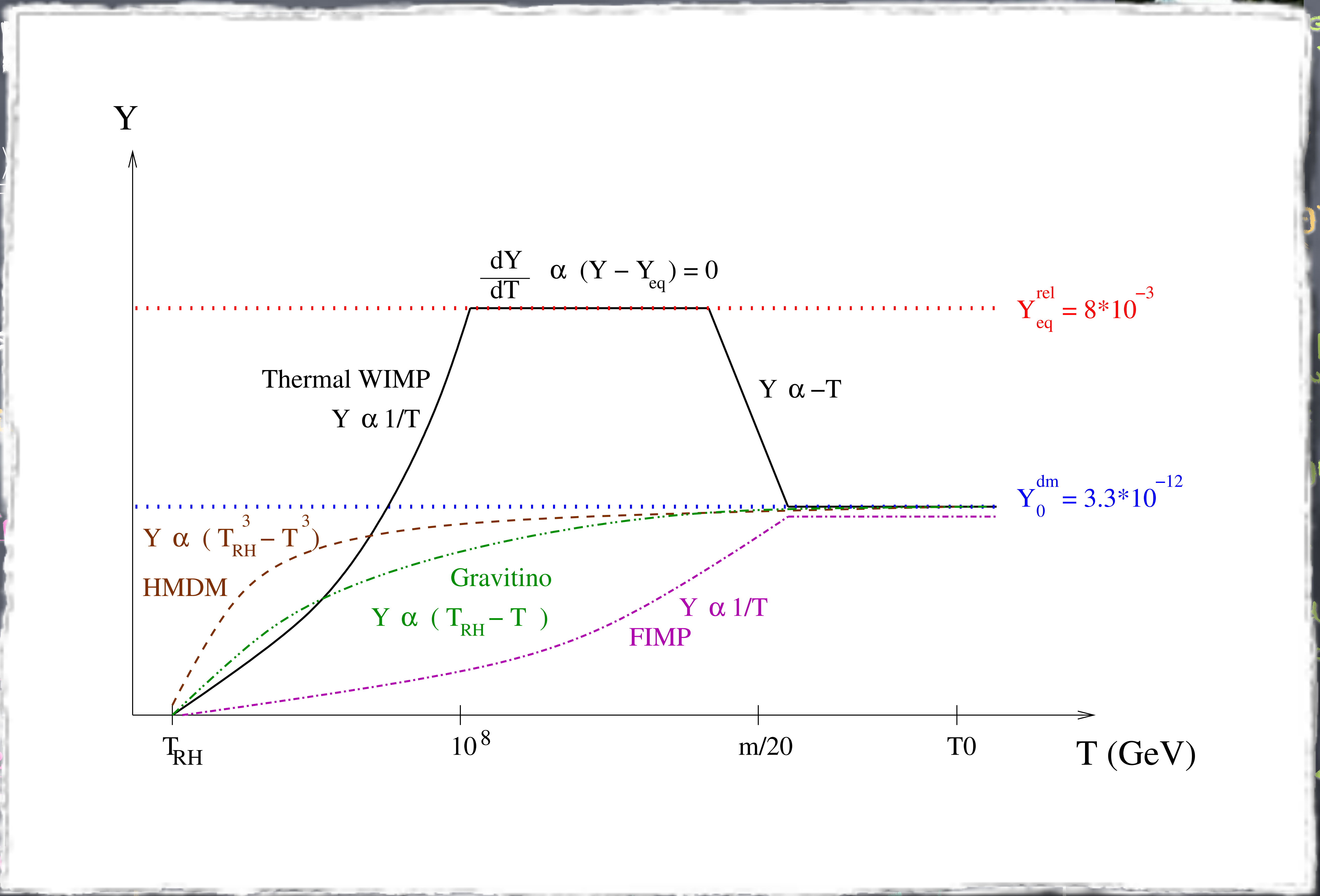
Dark matter i

- $M_M < T$

$|\mathcal{M}|^2$

$\Rightarrow \frac{dY}{dT} \propto g_I^2$

$\Rightarrow Y(T) \propto g_I^2$



$g_D \simeq g_{EW}$:

$g_D \simeq 10^{-10}$: FIMP SO(10), Intermediate scale

M. Blenow, G. Hernandez, Y. Mambrini, B. Zaldivar 2013

DM

DM

produced with the SM TRH

EW

out (FO) 10^-9 The decouples oltzman

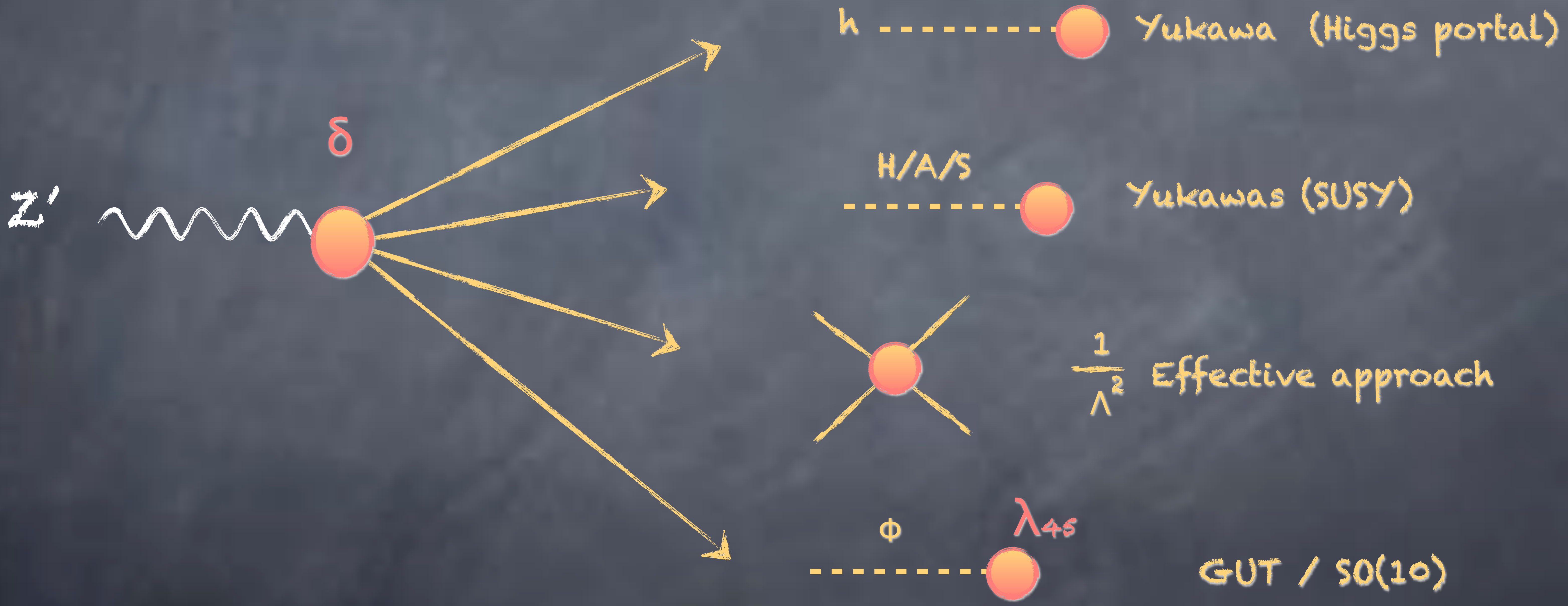
< H(T)

GeV

(neutralino, Higgs portal..)

A concrete example

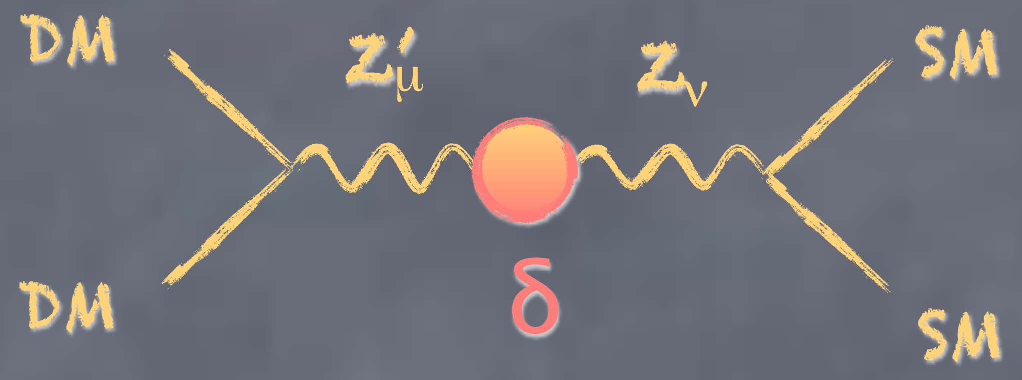
In all what follows I will take Z′ as a mediator for illustration but..



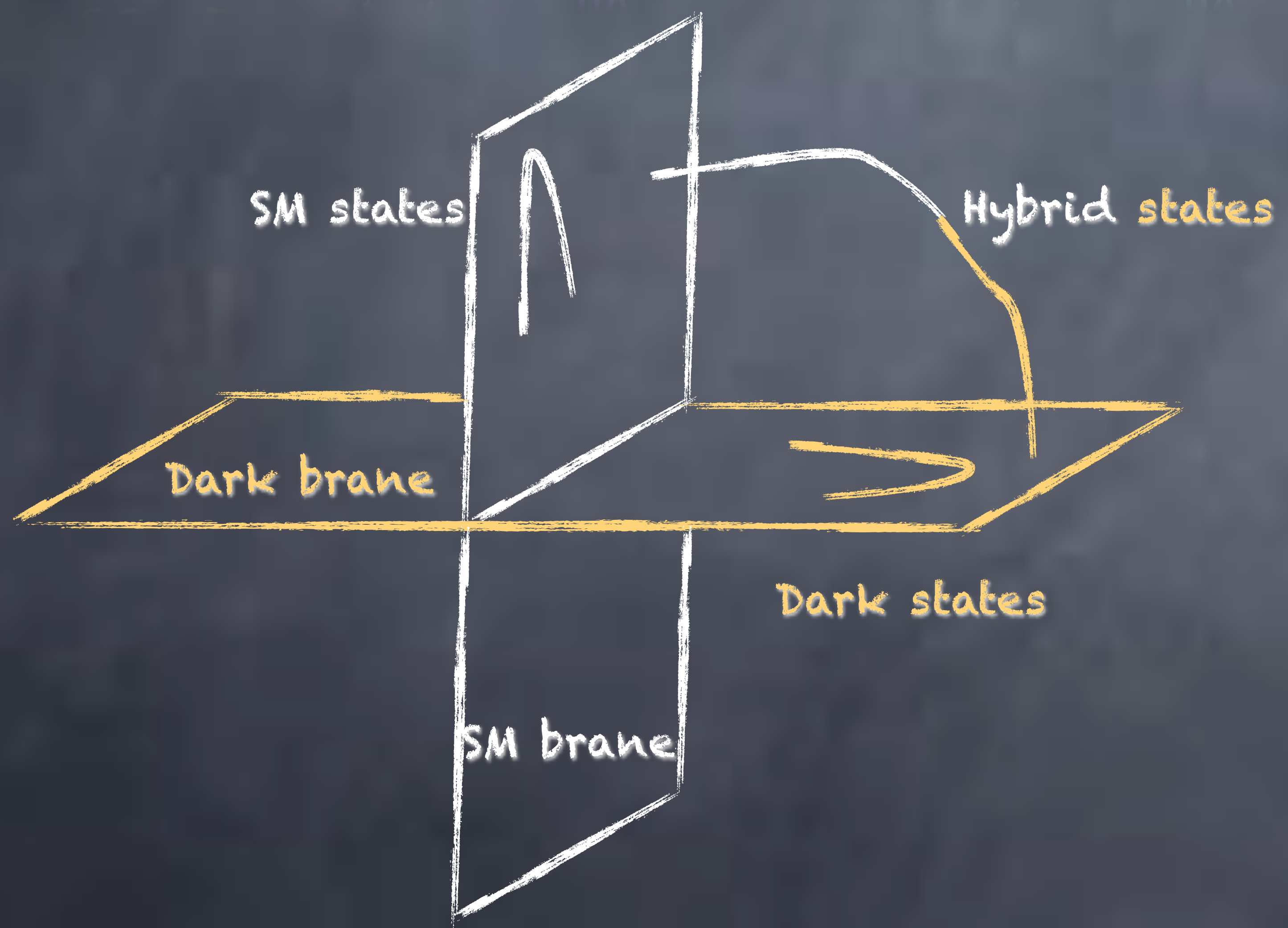
A concrete exemple : Extra U(1)

$SU(3)*SU(2)*U(1)*U_D(1)$

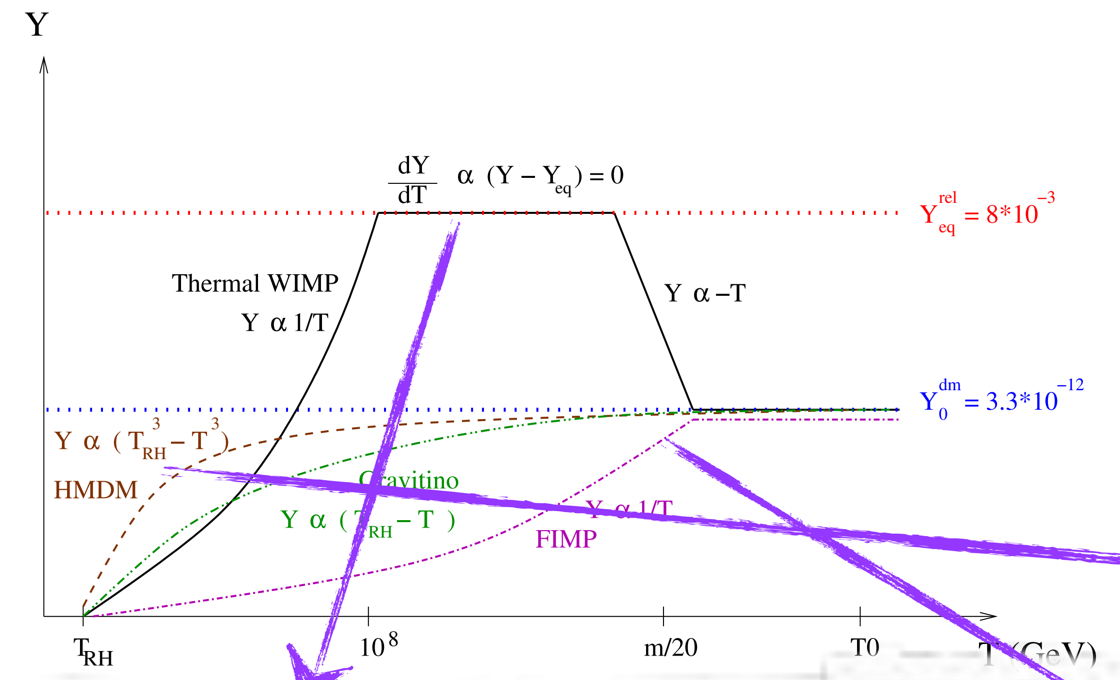
$g_\mu \quad W_\mu \quad Y_\mu \quad X_\mu$

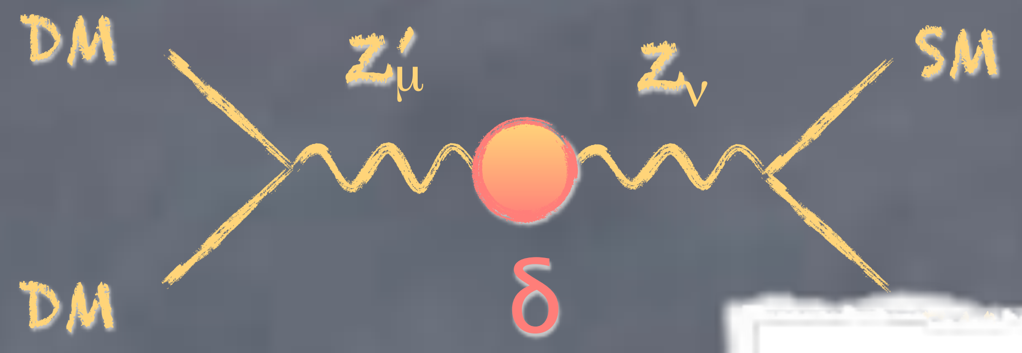


$$\mathcal{L}' = -1/4\, F^{Y}_{\mu\nu} F^{Y\mu\nu} - 1/4\, F^{X}_{\mu\nu} F^{X\mu\nu} + \delta/2\, F^{Y}_{\mu\nu} F^{X\mu\nu}$$

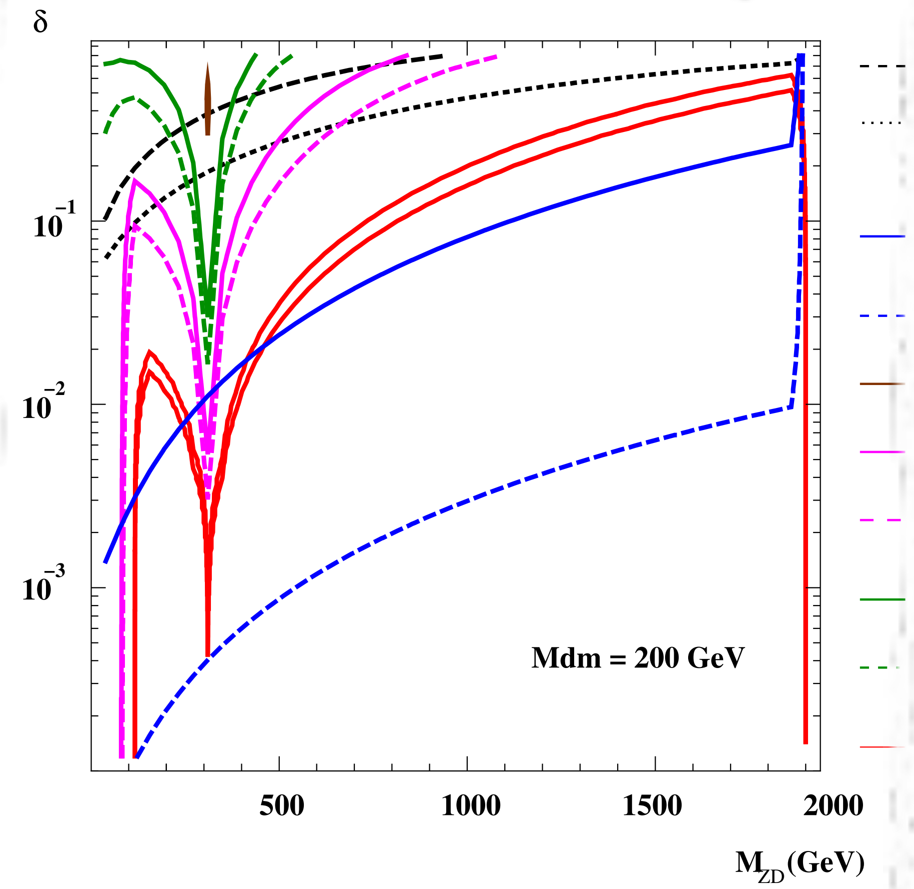


exemple : Extra U(1)



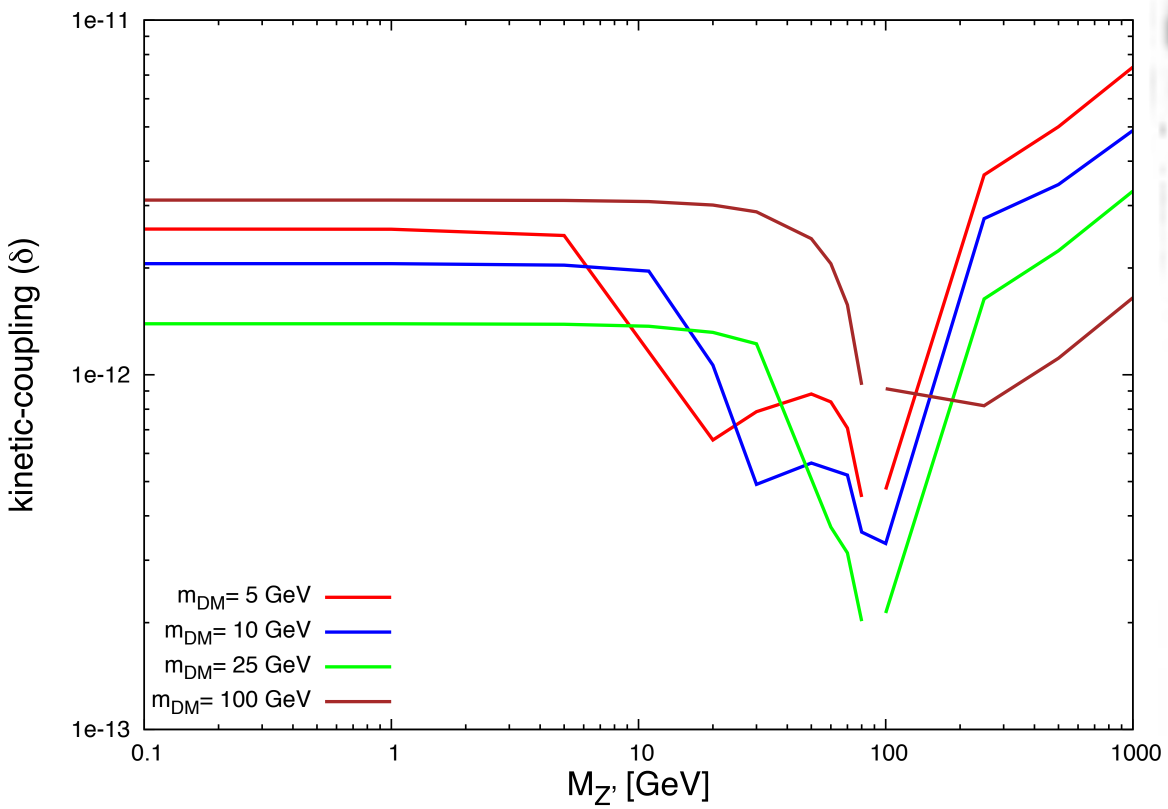


Mz' < TRH, δ ~gEW



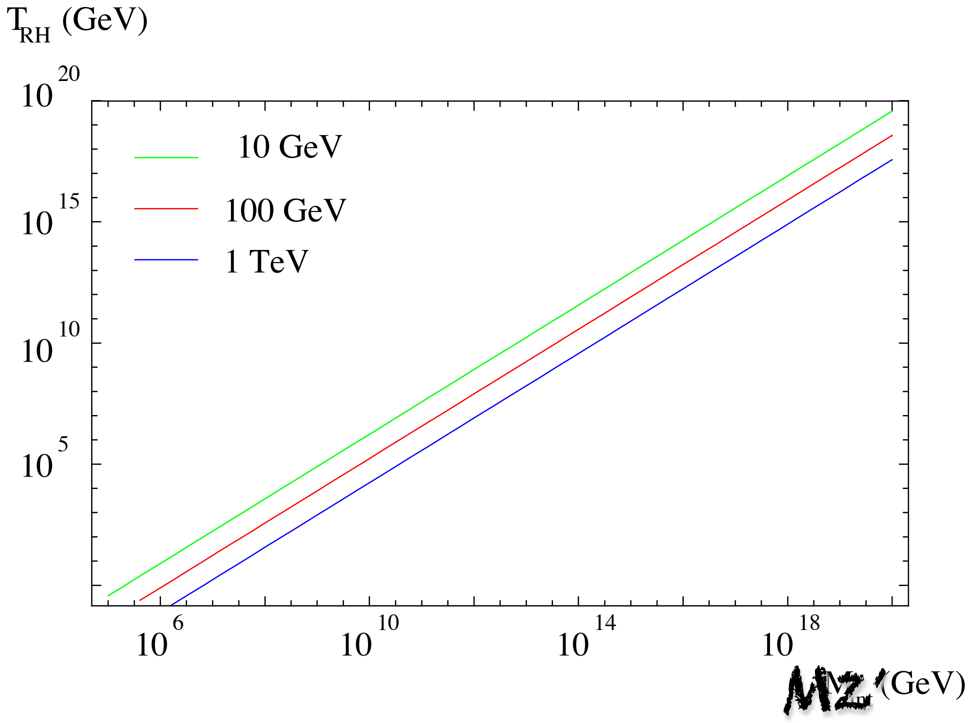
Y. M. (2011)

Mz' < TRH, δ ~ 10^{-11}



X. Chu, Y. M., J. Quevillon, B. Zaldivar (2013)

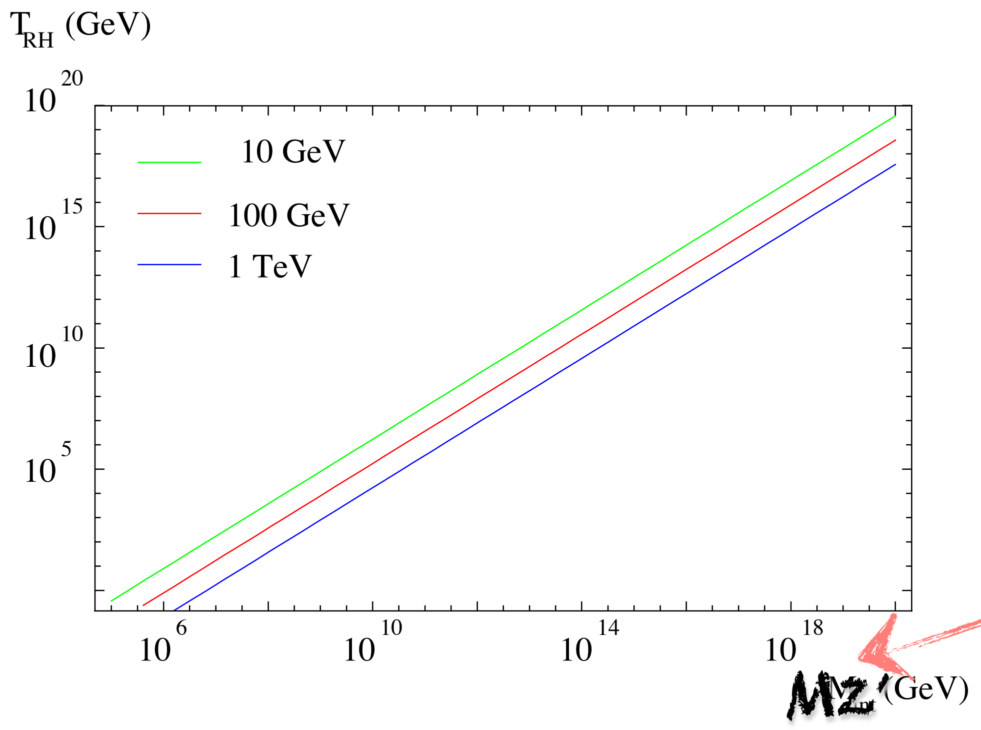
Mz' > TRH, δ ~ gEW



Y. M., K. Olive., J. Quevillon, B. Zaldivar (2013)

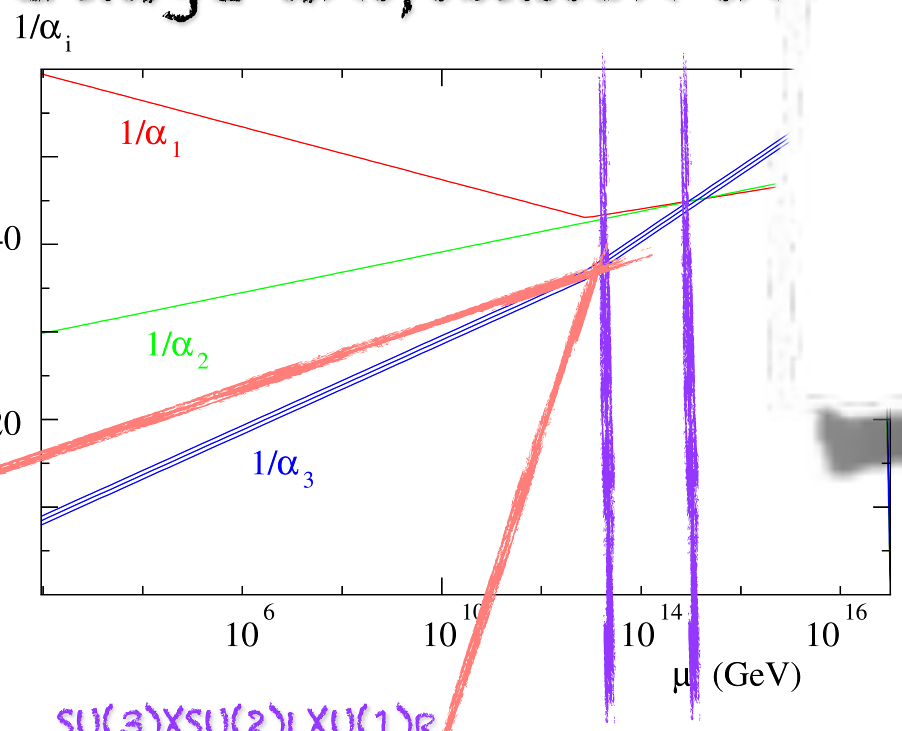
Ultra-Violet realization

Mz' > TRH, δ ~ gEW



Y. M., K. Olive., J. Quevillon, B. Zaldivar (2013)

Gauge unification in



Mz' => TRH from WMAP/PLANCK

TABLE I. Possible breaking schemes of SO(10).

	$SO(10) \to \mathcal{G}\times$ [Higgs]	M_{int}(GeV)	T_{RH}(GeV)
A	$4 \times 2_L \times 1_R$ [**16**]	$10^{12.9}$	3×10^9
A	$4 \times 2_L \times 1_R$ [**126**]	$10^{11.8}$	1×10^8
B	$4 \times 2_L \times 2_R$ [**16**]	$10^{14.4}$	3×10^{11}
B	$4 \times 2_L \times 2_R$ [**126**]	$10^{13.8}$	5×10^{10}
C	$3_C \times 2_L \times 2_R \times 1_{B-L}$ [**16**]	$10^{10.6}$	3×10^6
C	$3_C \times 2_L \times 2_R \times 1_{B-L}$ [**126**]	$10^{8.6}$	6×10^3

Unification condition =>
Reheating temperature

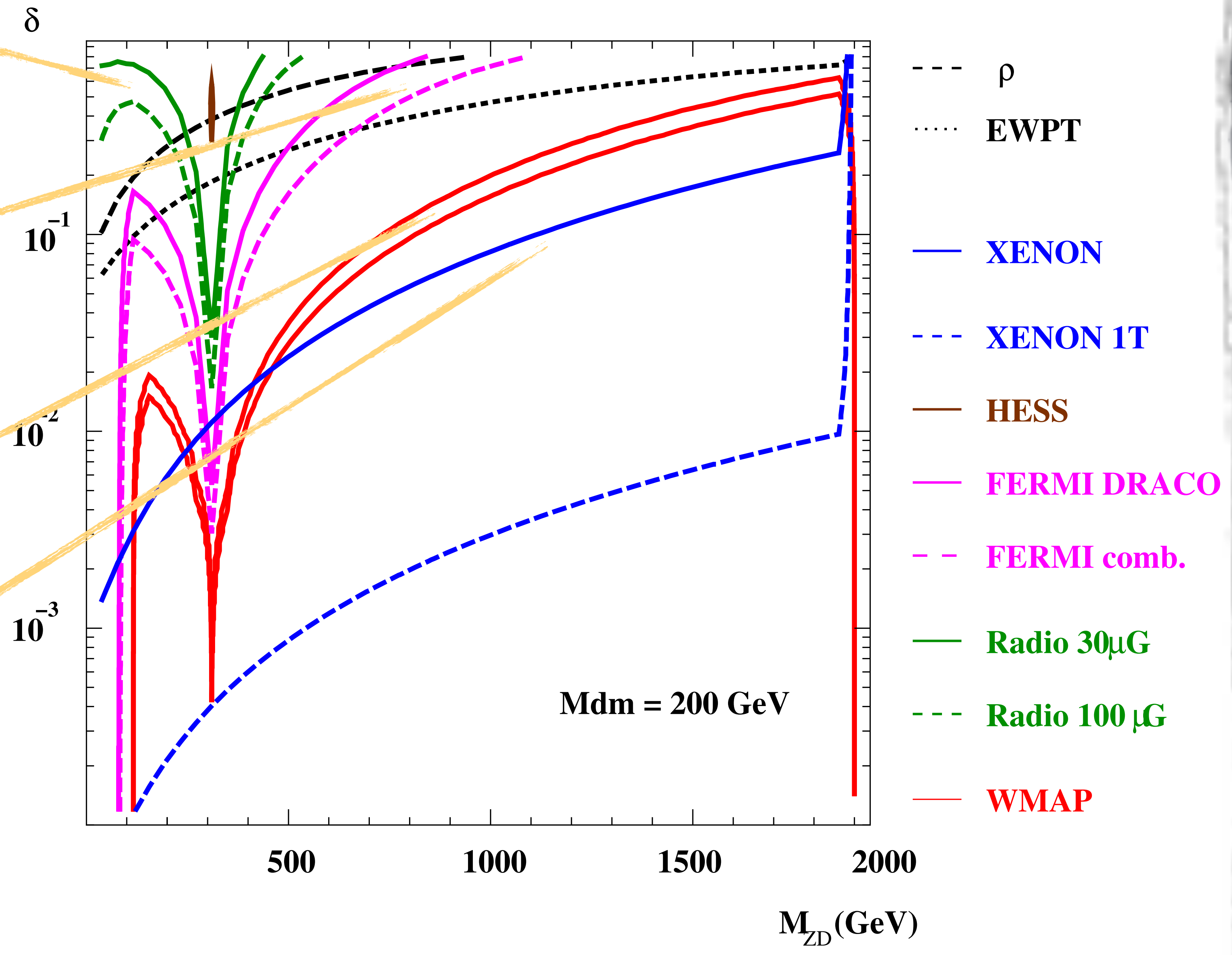
Astro-phenomenological study

Synchrotron radiation

Photon indirect detection

Relic abundance

Direct detection



1104.4799

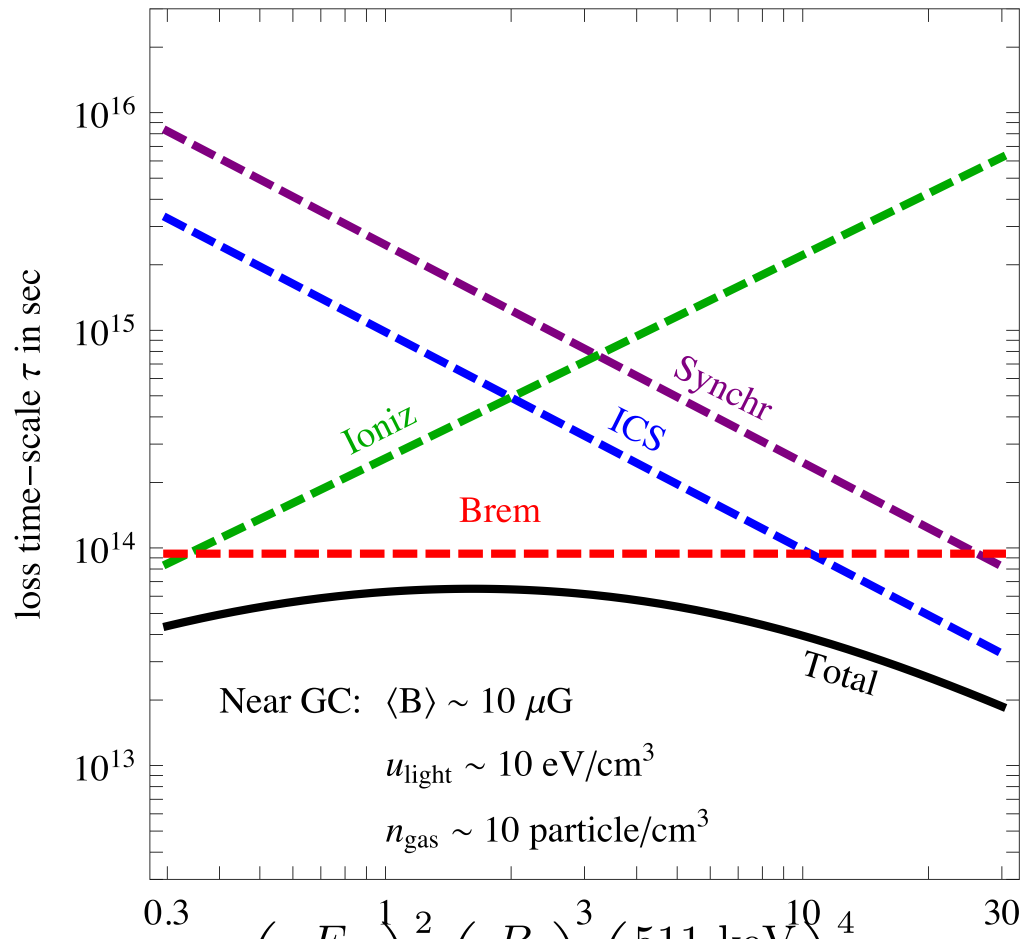
Energy losses processes

Charged particles moving in the interstellar medium lose energy from different processes

$$\langle P\rangle = \langle P\rangle_{synch} + \langle P\rangle_{IC} + \langle P\rangle_{Coul} + \langle P\rangle_{I} + \langle P\rangle_{brem}$$

$$= \frac{4}{3}\sigma_T c U_B + \frac{4}{3}\sigma_T c U_{rad} - 2\pi r_0^2 m_e c^3 Z n \frac{1}{\beta}\left[\ln\left(\frac{E m_e c^2}{4\pi r_0 \hbar^2 c^2 n Z}\right) - \frac{3}{4}\right]$$

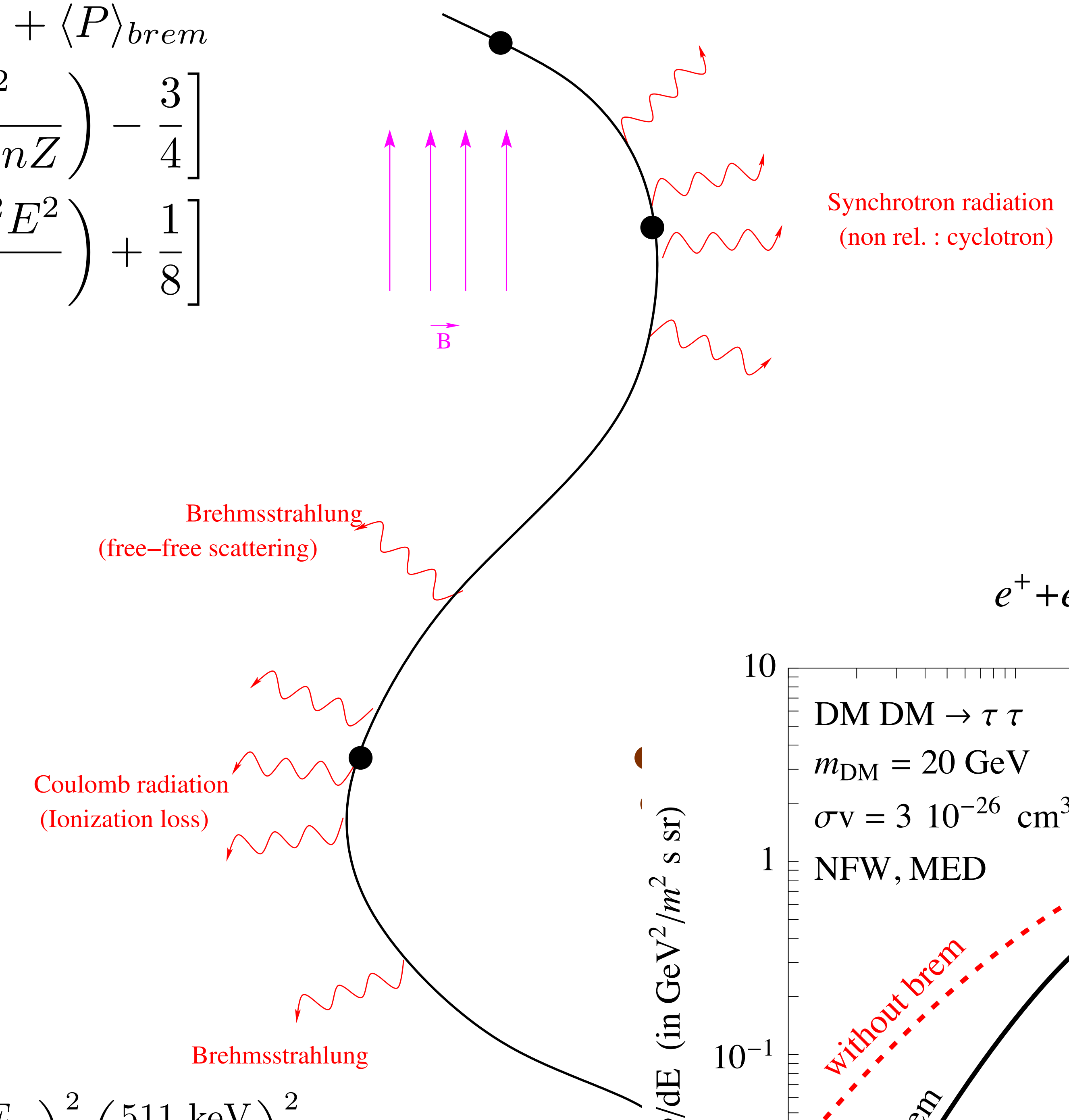
$$-2\pi r_0^2 m_e c^3 \frac{1}{\beta}\sum_{s=H,He} Z_s n_s \left[\ln\left(\frac{(\gamma-1)\beta^2 E^2}{2 I_s^2}\right) + \frac{1}{8}\right]$$

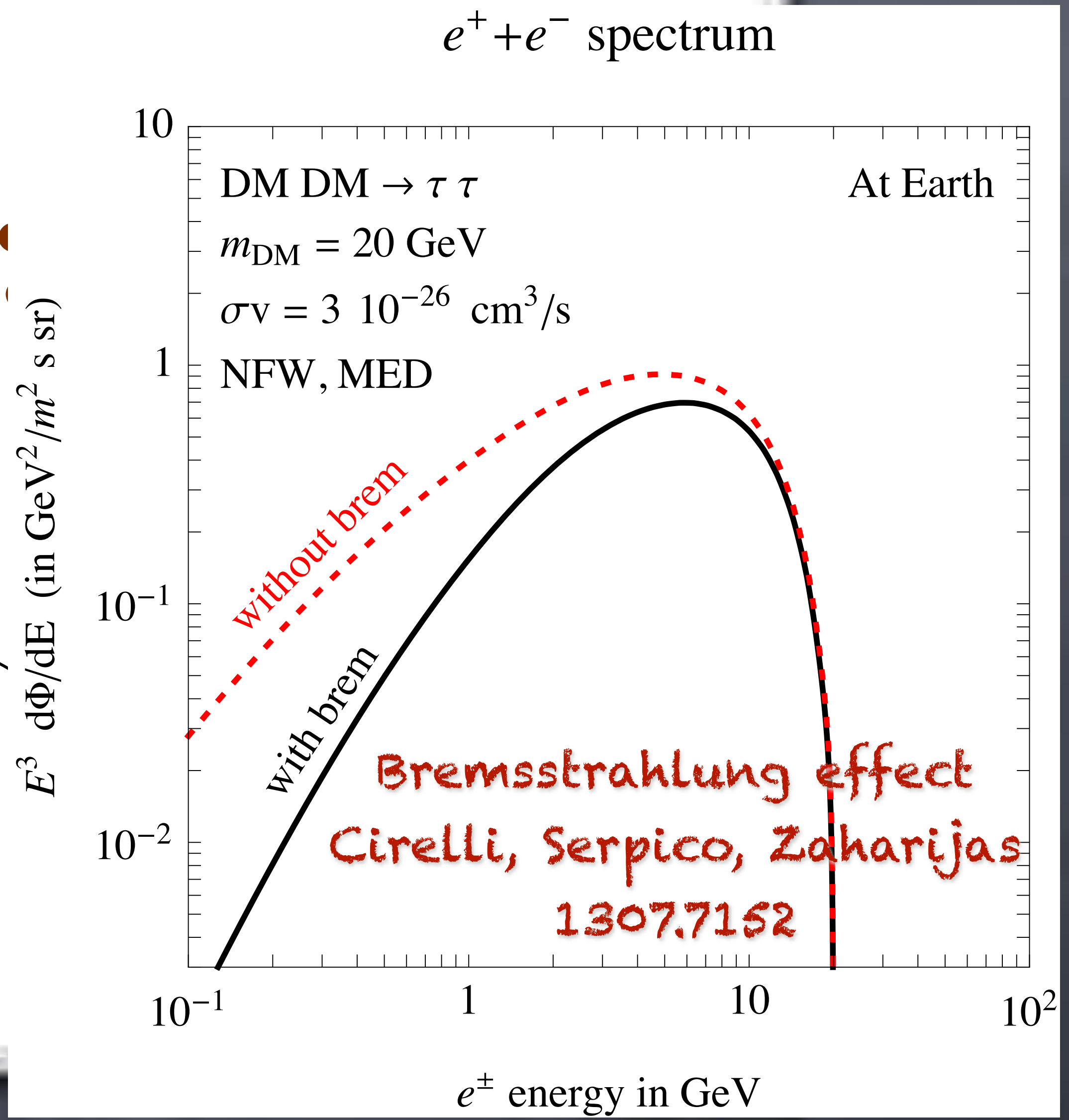


$$= 2.51\times10^{-18}\left(\frac{E}{\text{GeV}}\right)^2\left(\frac{B}{\mu\text{G}}\right)^2\left(\frac{511\ \text{keV}}{m}\right)^4 + 2.56\times10^{-17}\left(\frac{E}{\text{GeV}}\right)^2\left(\frac{511\ \text{keV}}{m}\right)^2$$

$$+5.5\times10^{-16}\left(\frac{Zn}{1\ \text{cm}^{-3}}\right)\left(\frac{1}{\beta}\right)\left[1+\frac{1}{74}\ln\left(\frac{E/m_e c^2}{Zn/(1\ \text{cm}^{-3})}\right)\right]$$

$$+7.4\times10^{-18}\left(\frac{1}{\beta}\right)\sum_{s=H,He}\left(\frac{Z_s n_s}{1\ \text{cm}^{-3}}\right)\left[\ln\left(\frac{(\gamma-1)\beta^2E^2}{2I_s^2}\right)+\frac{1}{8}\right]\ \text{GeV s}^{-1}$$

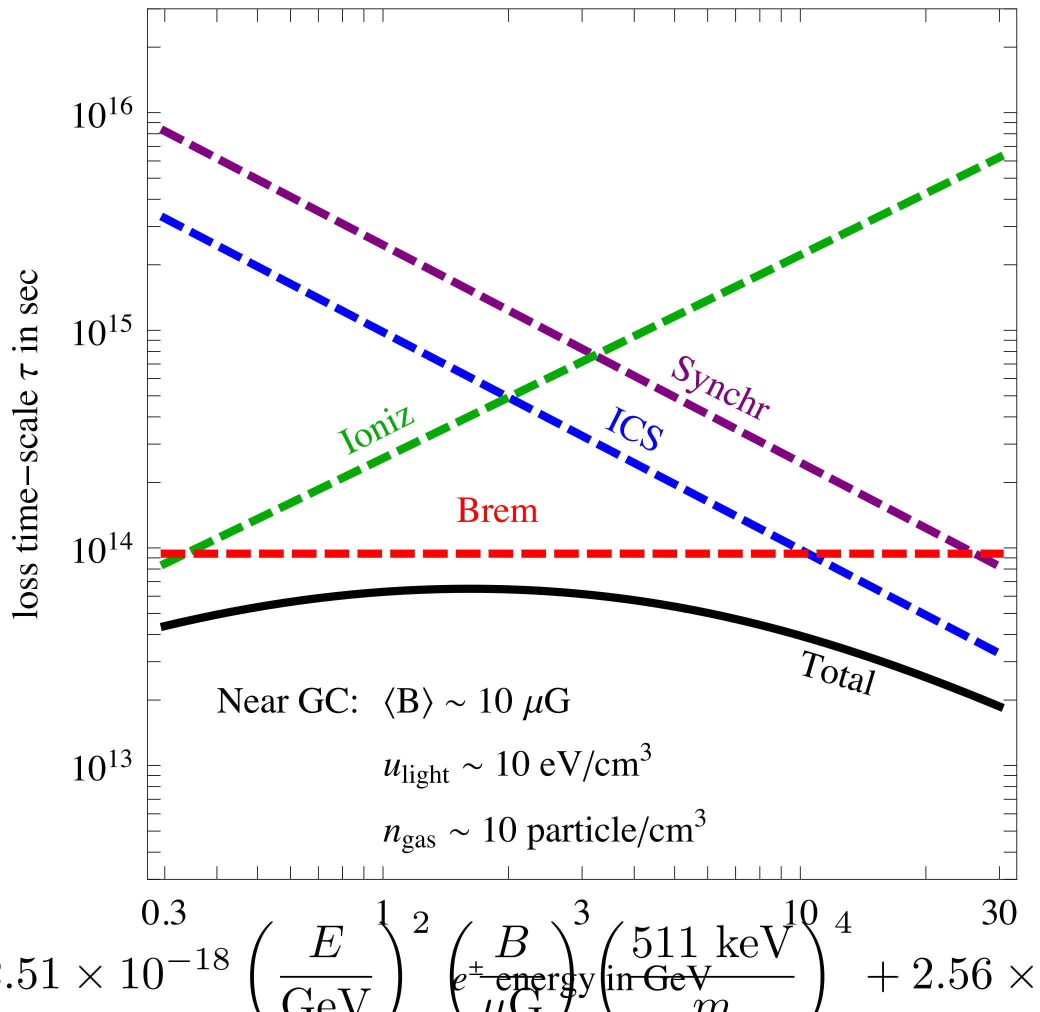




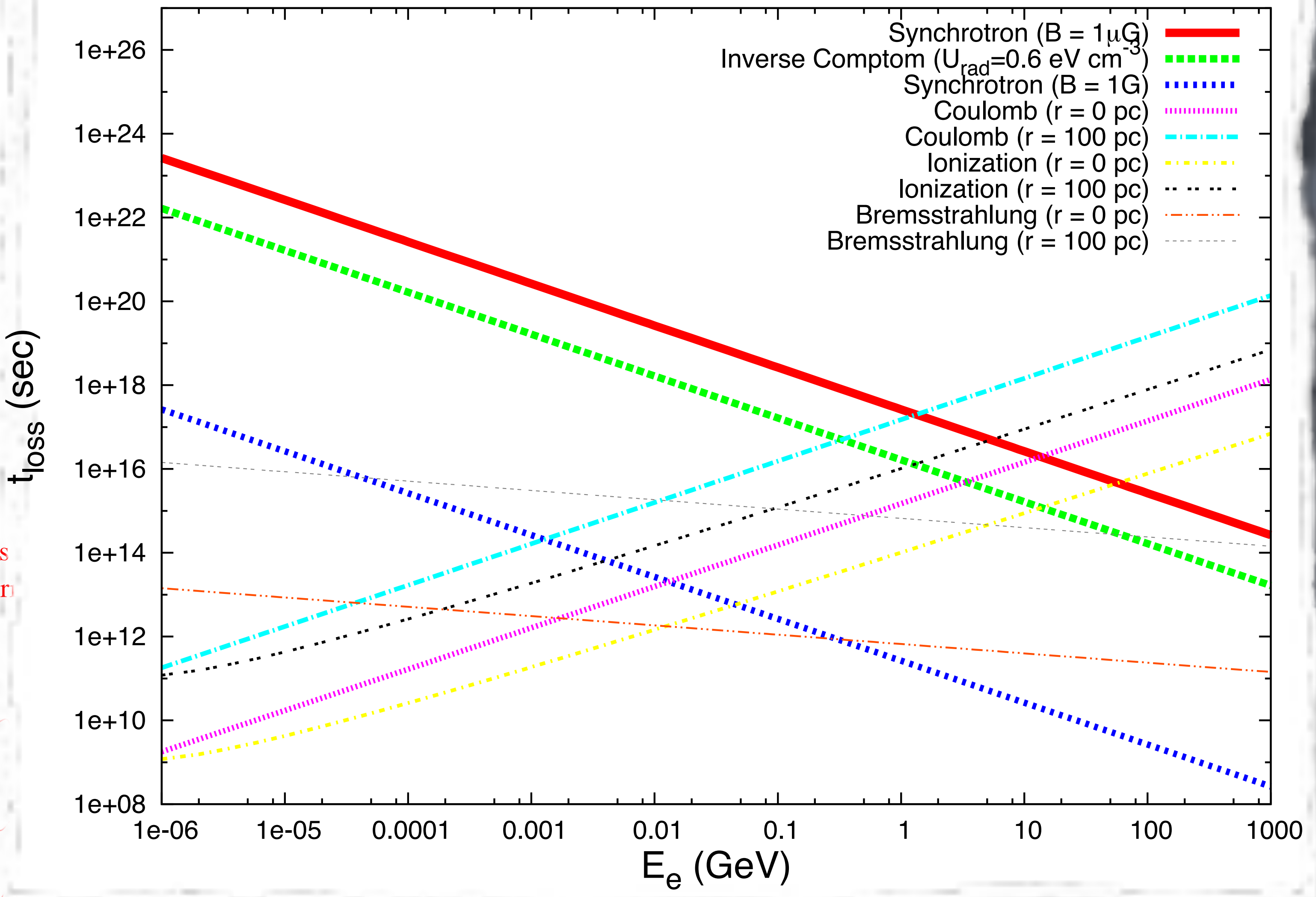
$$\langle P\rangle = \langle P\rangle_{synch} + \langle P\rangle_{IC} + \langle P\rangle_{Coul} + \langle P\rangle_{I} + \langle P\rangle_{brem}$$

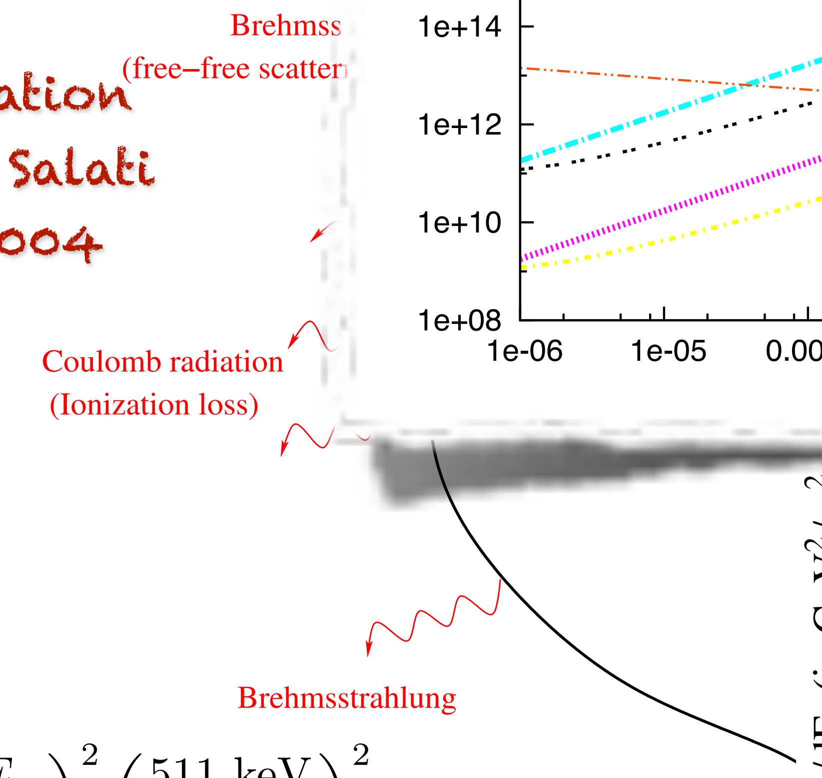
$$= \frac{4}{3}\sigma_T c U_B + \frac{4}{3}\sigma_T c U_{rad} - 2\pi r_0^2 m_e c^3 Z n \frac{1}{\beta}\left[\ln\left(\frac{E m_e c^2}{4\pi r_0 \hbar^2 c^2 n Z}\right) - \frac{3}{4}\right]$$

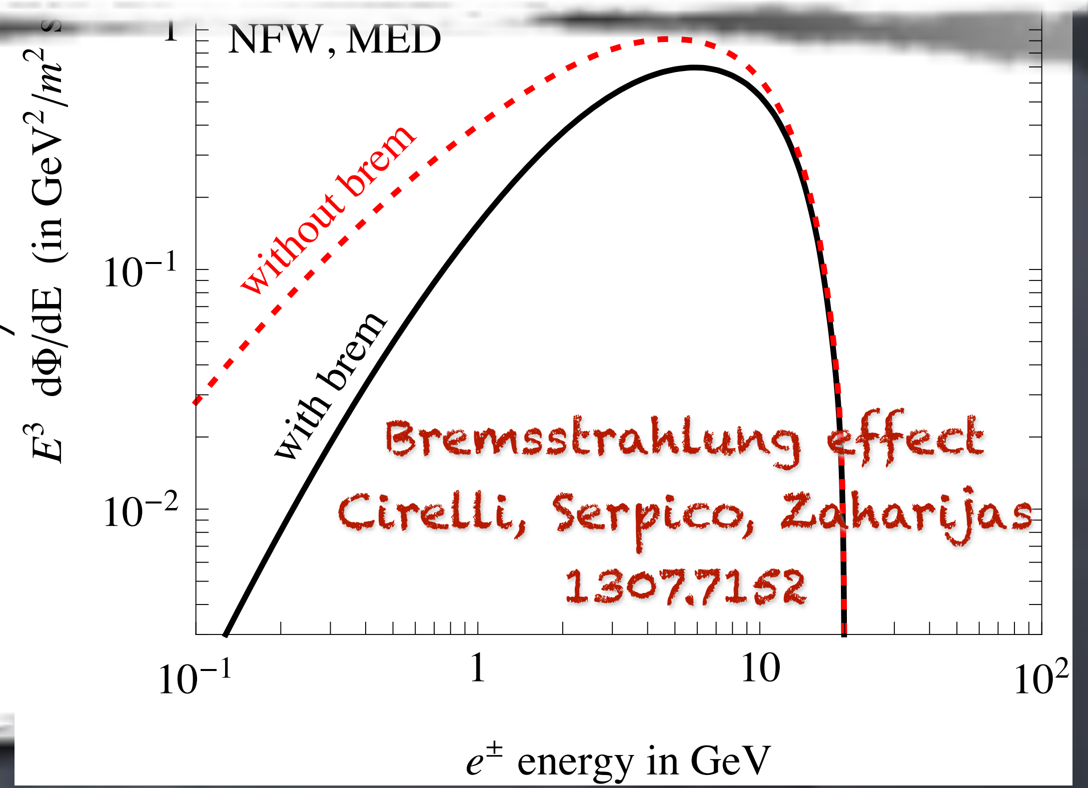
$$-2\pi r_0^2 m_e c^3 \frac{1}{\beta} \sum_{s=H,He} Z_s n_s \left[\ln\left(\frac{(\gamma-1)\beta^2 E^2}{2 I_s^2}\right) + \frac{1}{8}\right]$$



Propagation
Lavalle, Salati
1205.1004







Bremsstrahlung effect
Cirelli, Serpico, Zaharijas
1307.7152

$$= 2.51\times10^{-18}\left(\frac{E}{\mathrm{GeV}}\right)^2\left(\frac{B}{\mu G}\right)\left(\frac{511\ \mathrm{keV}}{m}\right)^4 + 2.56\times10^{-17}\left(\frac{E}{\mathrm{GeV}}\right)^2\left(\frac{511\ \mathrm{keV}}{m}\right)^2$$

$$+5.5\times10^{-16}\left(\frac{Zn}{1\ \mathrm{cm}^{-3}}\right)\left(\frac{1}{\beta}\right)\left[1+\frac{1}{74}\ln\left(\frac{E/m_e c^2}{Zn/(1\ \mathrm{cm}^{-3})}\right)\right]$$

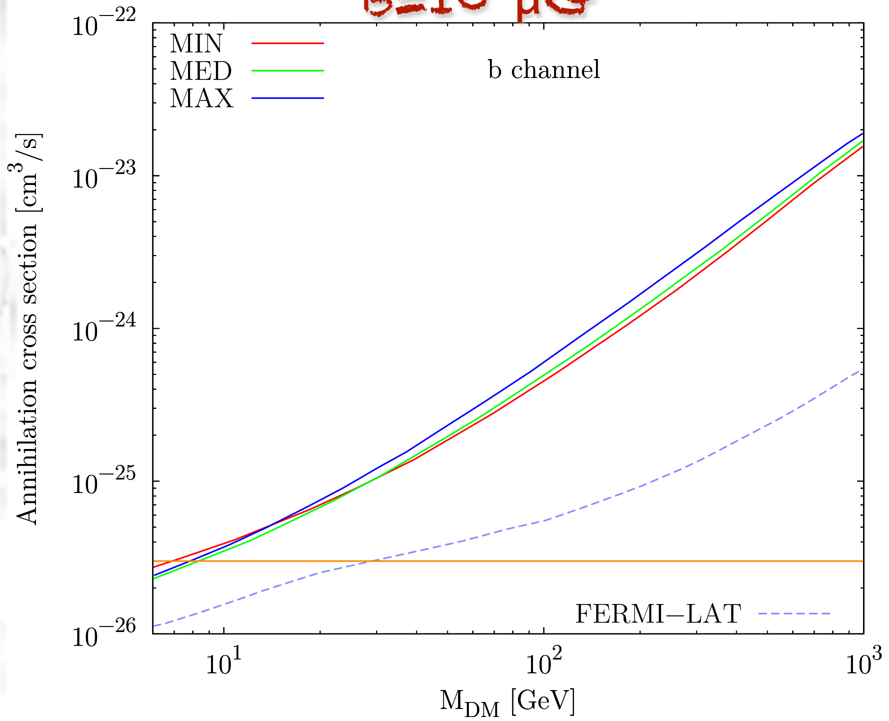
$$+7.4\times10^{-18}\left(\frac{1}{\beta}\right)\sum_{s=H,He}\left(\frac{Z_s n_s}{1\ \mathrm{cm}^{-3}}\right)\left[\ln\left(\frac{(\gamma-1)\beta^2E^2}{2I_s^2}\right)+\frac{1}{8}\right]\ \mathrm{GeV\ s^{-1}}$$

Synchrotron emission and effective approach

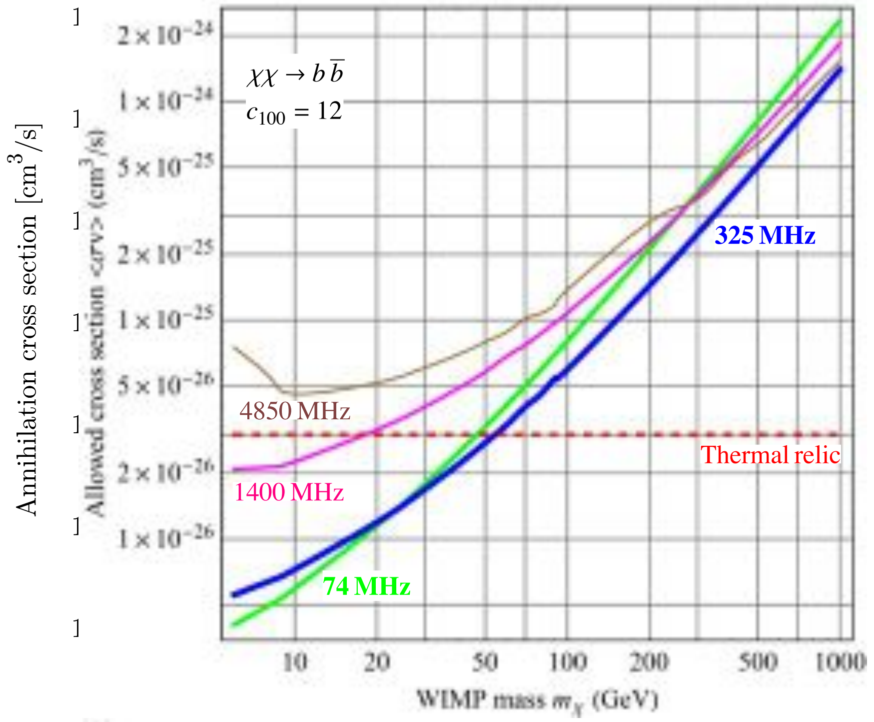
To restrict the annihilation cross section for a given DM mass and final state

It seems that nearby galaxies are even more restrictive

Synchrotron Galactic Center
Lineros
1309.4630
B=10 μG



Synchrotron M31
Egorov, Pierpaoli
1304.0517



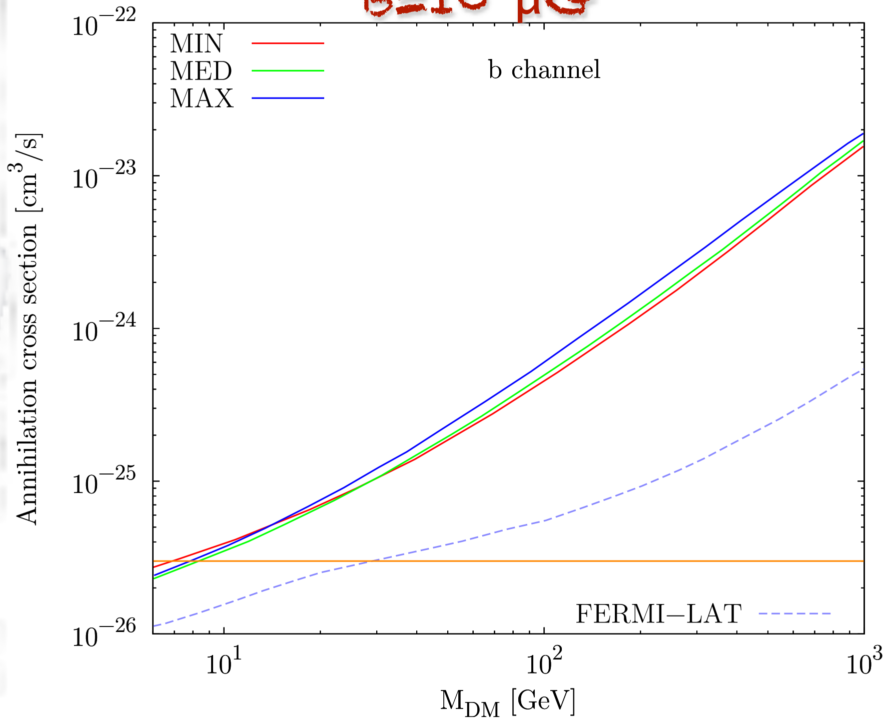
Synchrotron emission and effective approach

To restrict the annihilation cross section for a given DM mass and final state

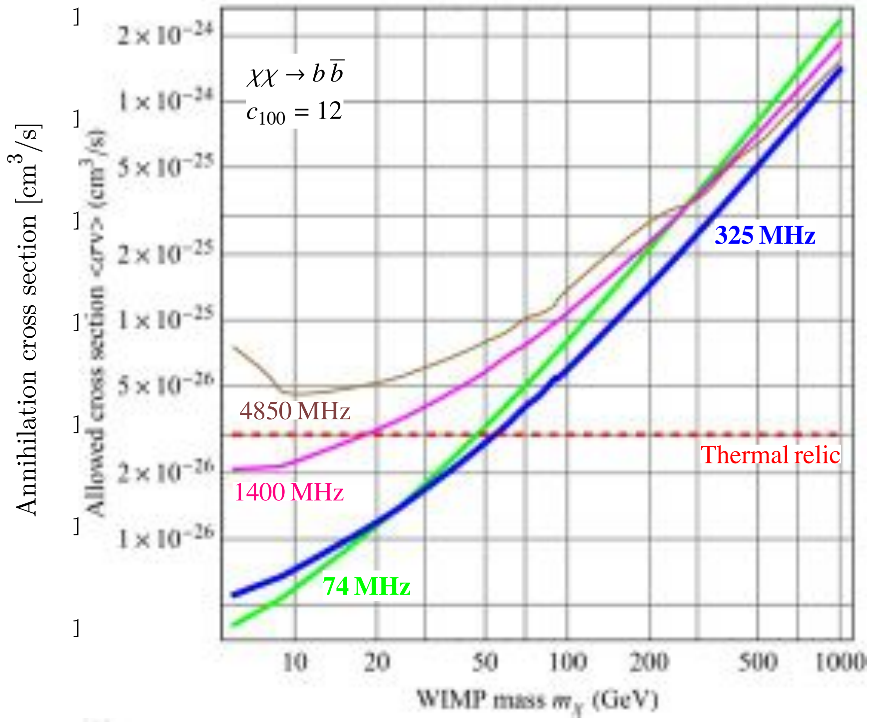
It seems that nearby galaxies are even more restrictive

We can in the first step look at effective couplings

Synchrotron Galactic Center
Lineros
1309.4630
B=10 μG



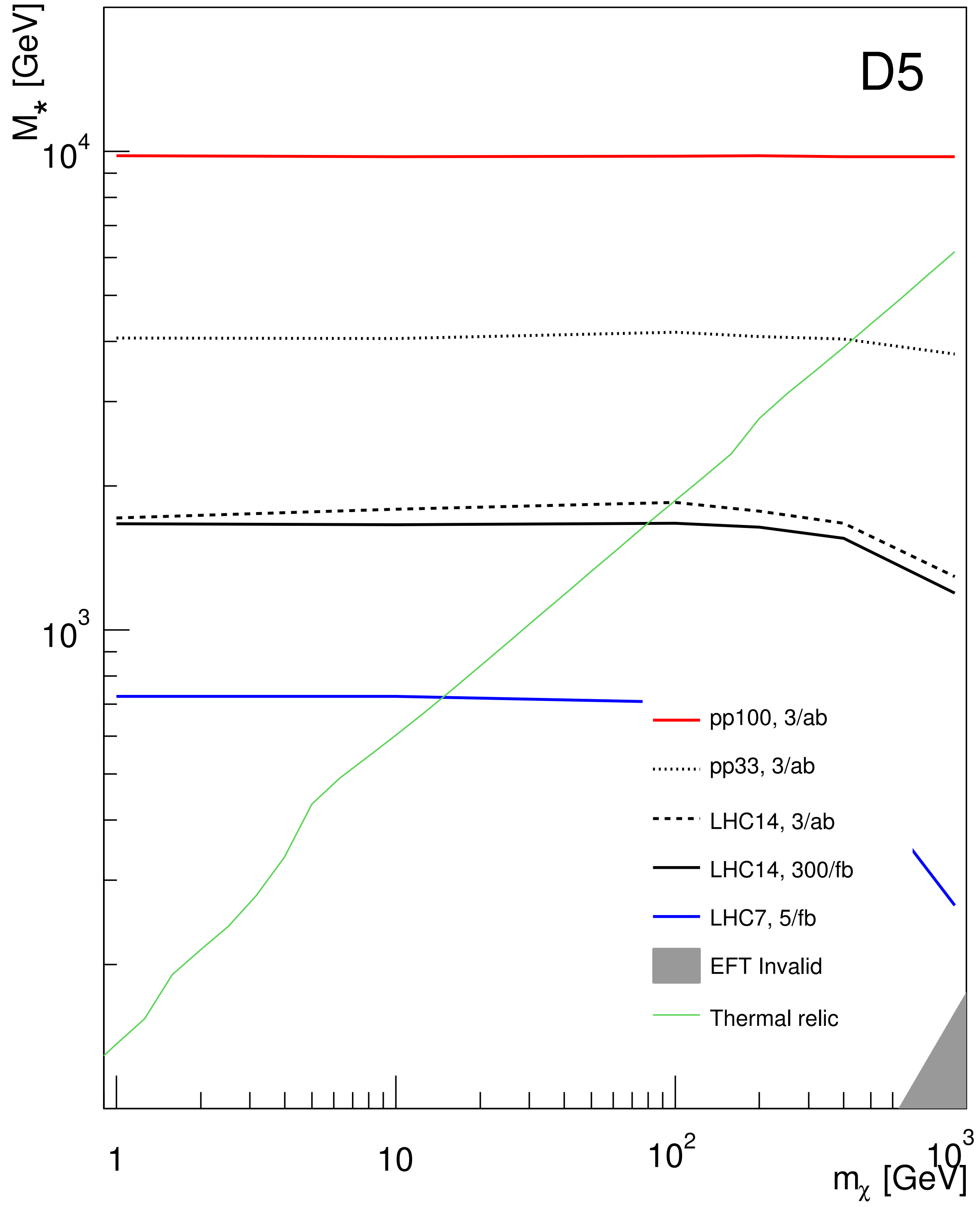
Synchrotron M31
Egorov, Pierpaoli
1304.0517



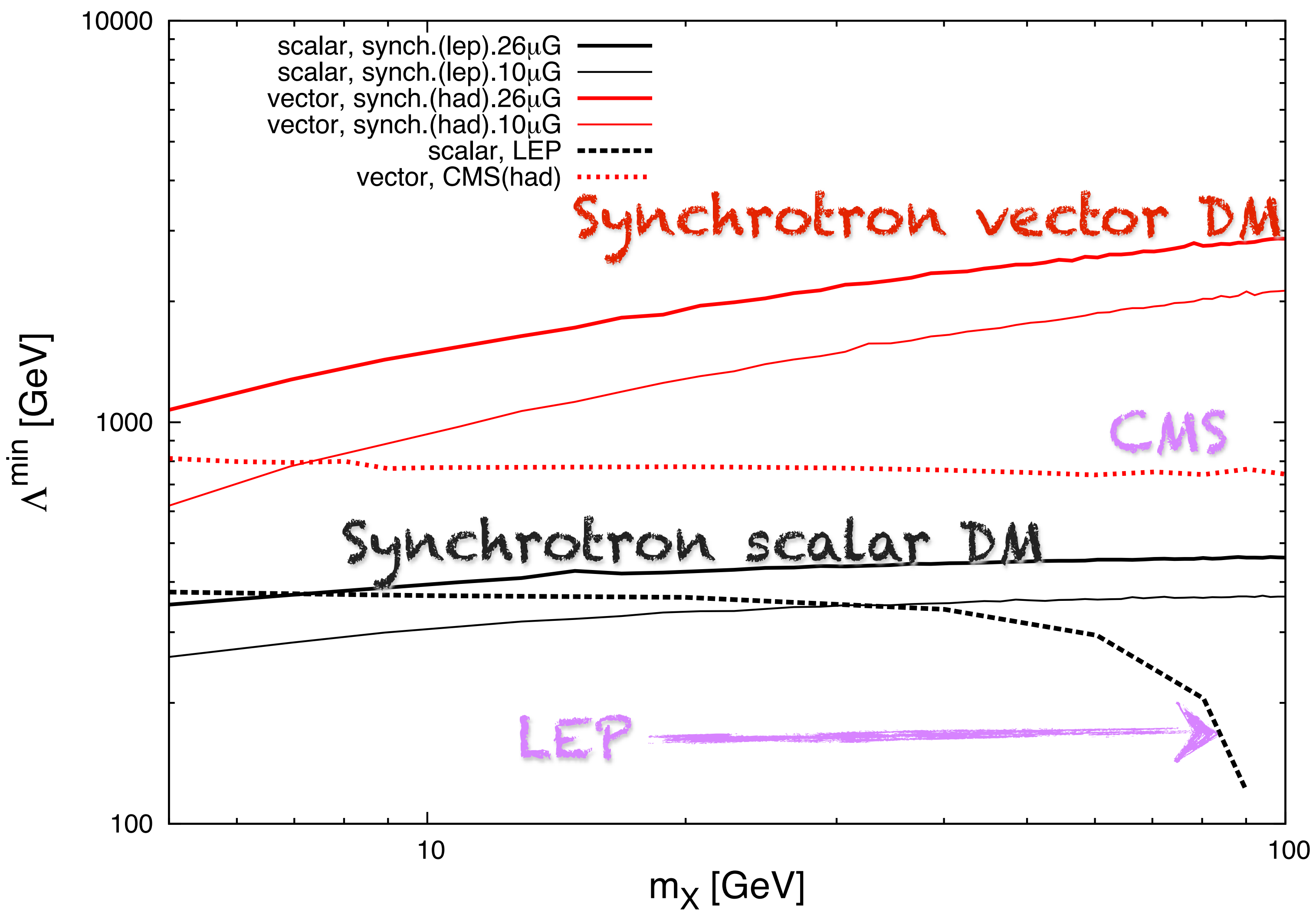
Zhou, Berge, Wang, Whiteson, Tait

LHC prospect

1307.5327



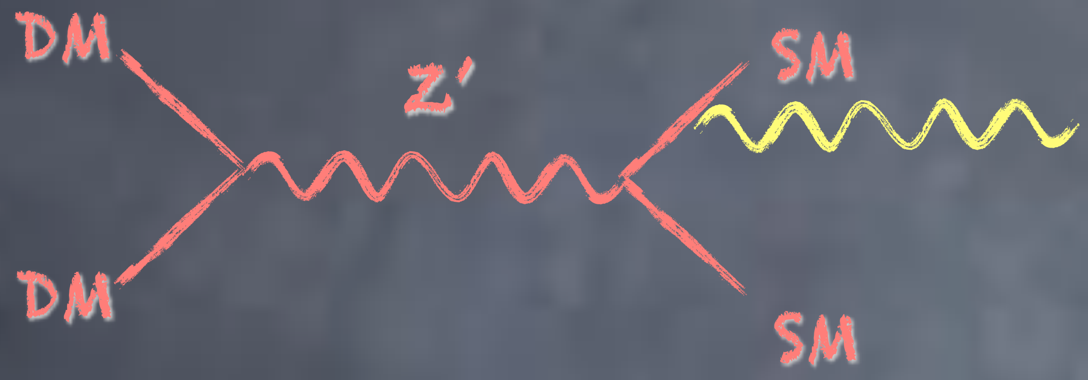
$$\mathcal{L}_{eff} = \frac{1}{\Lambda^{(2)}}\bar{\chi}\chi\bar{b}b$$

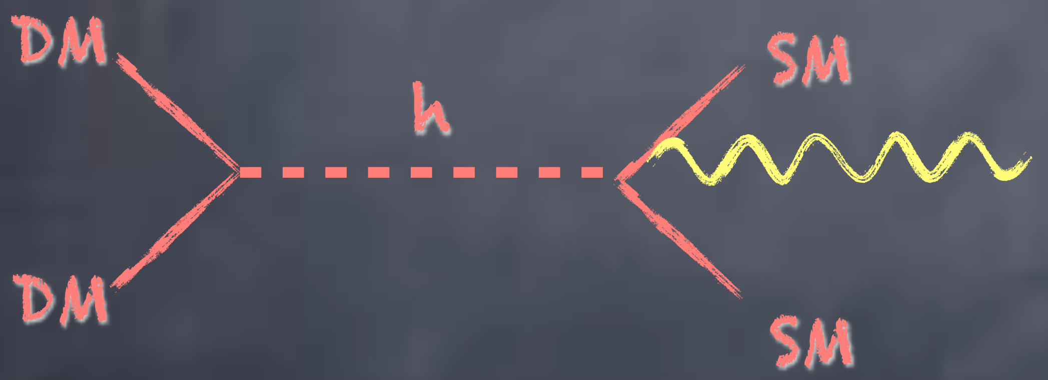


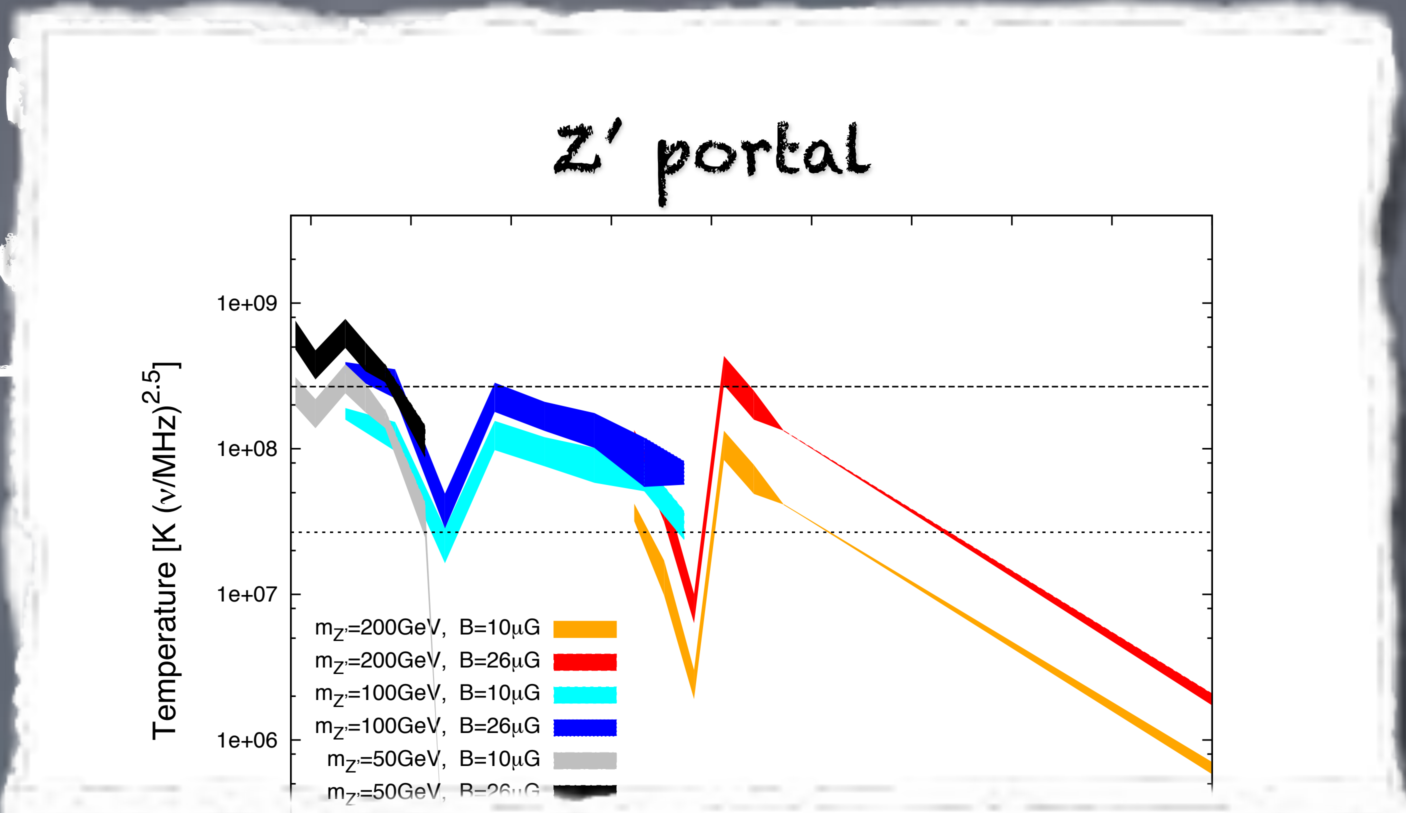
Mambrini, Tytgat, Zaharijas, Zaldivar

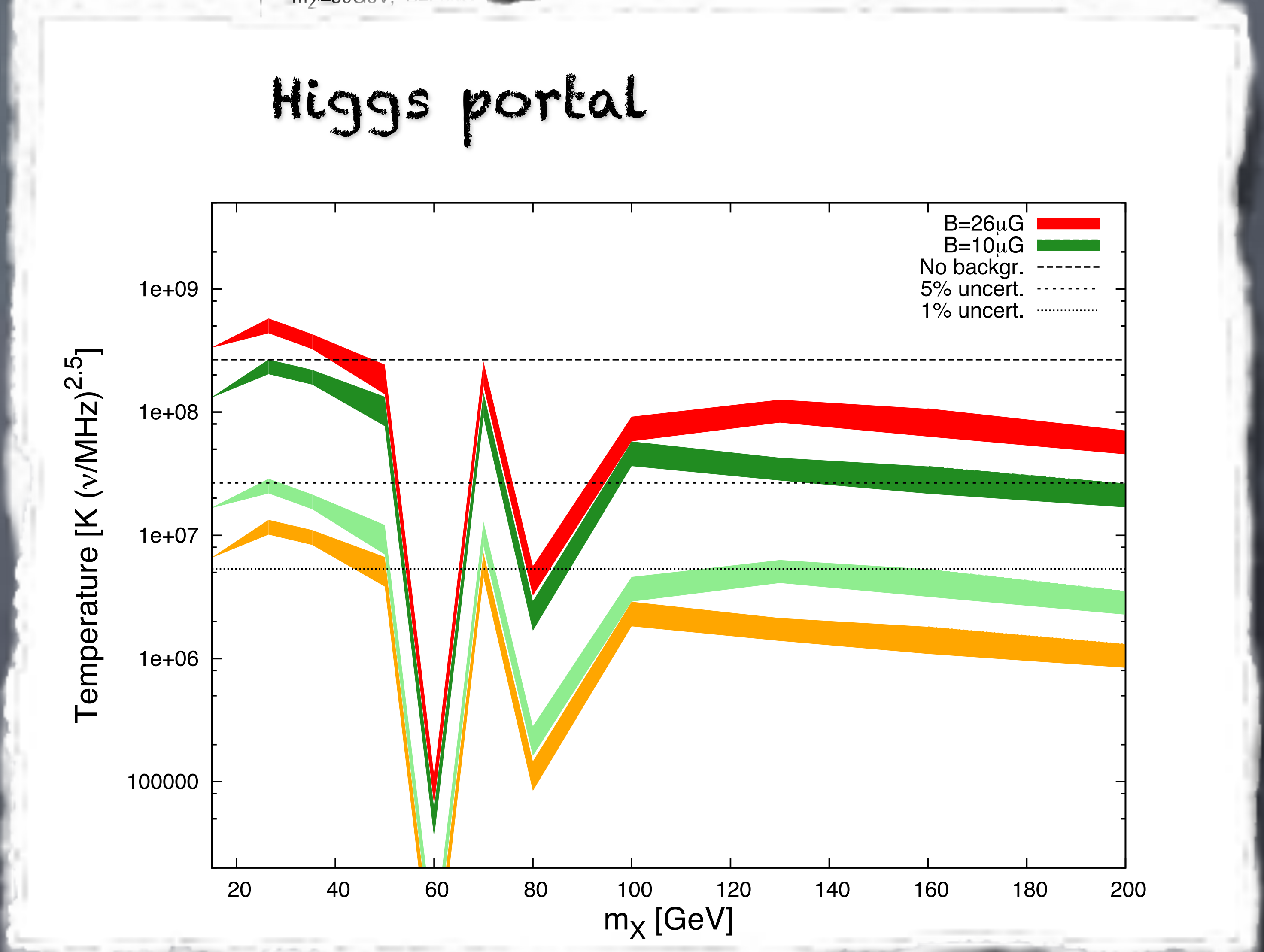
1206.2352

Synchrotron emissi
Z′ cas







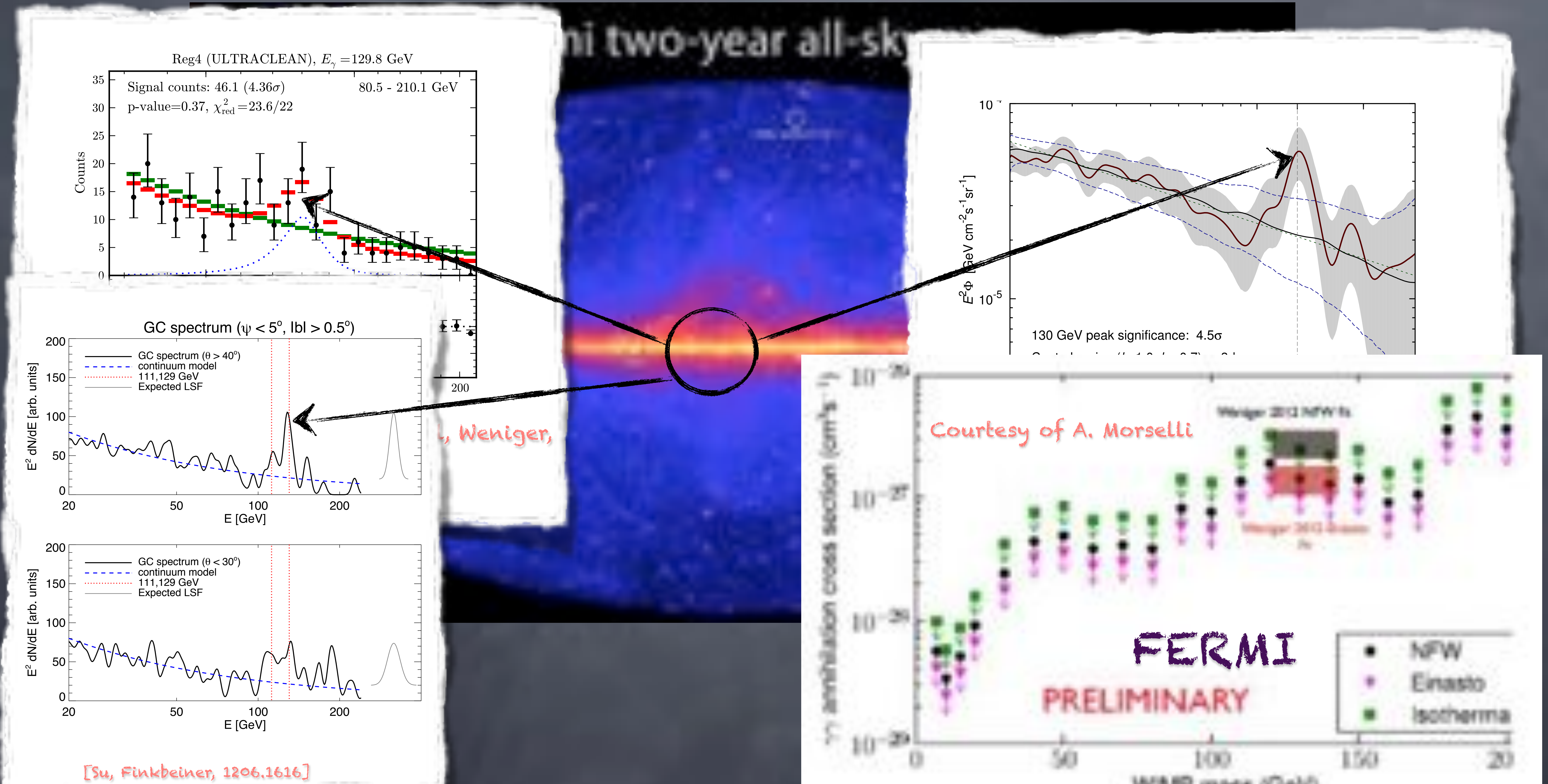


Prospective - Conclusion

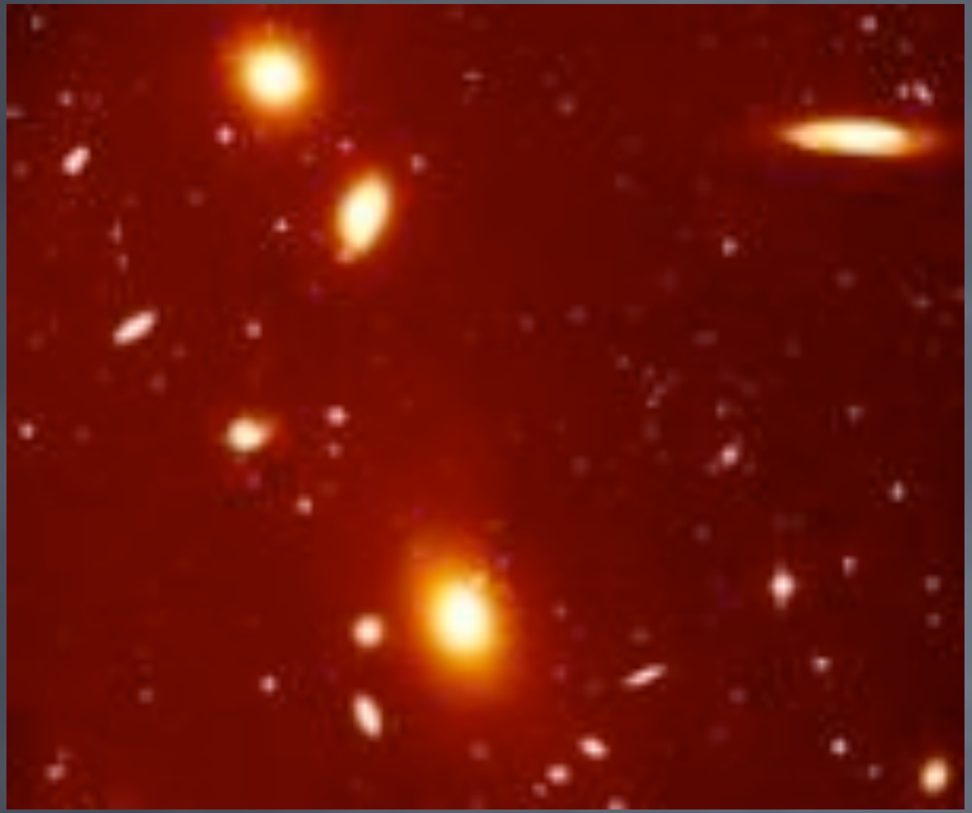
- A lot of extensions to the classical thermal history of the Universe
- Synchrotron radiation interesting detecting mode
- Heavy states (> T_{RH}) as natural as WIMP scenario
- Promising next years...

Observation of a line : Galactic Center

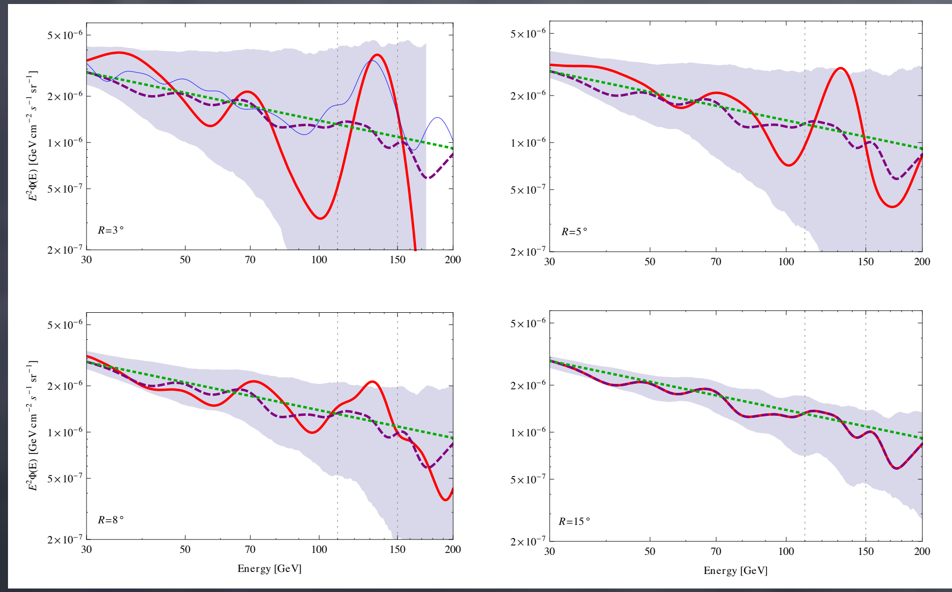
Observation of a line : Galactic Center



Other parts of the sky?

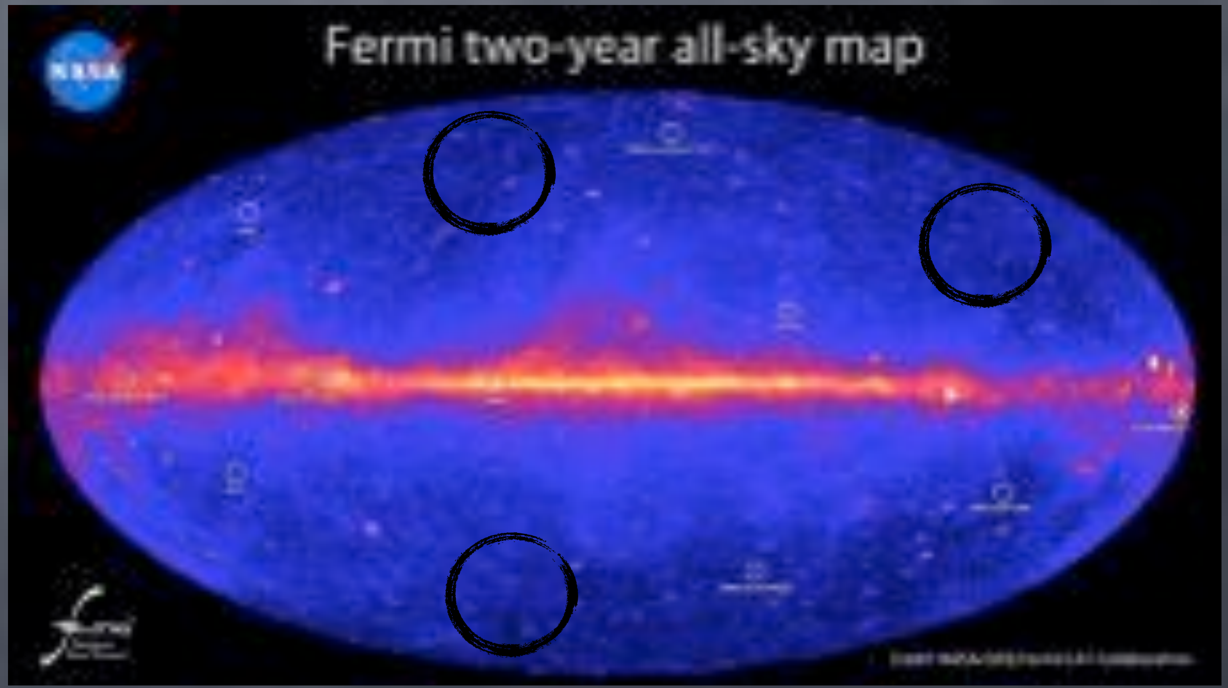


Clusters of Galaxies



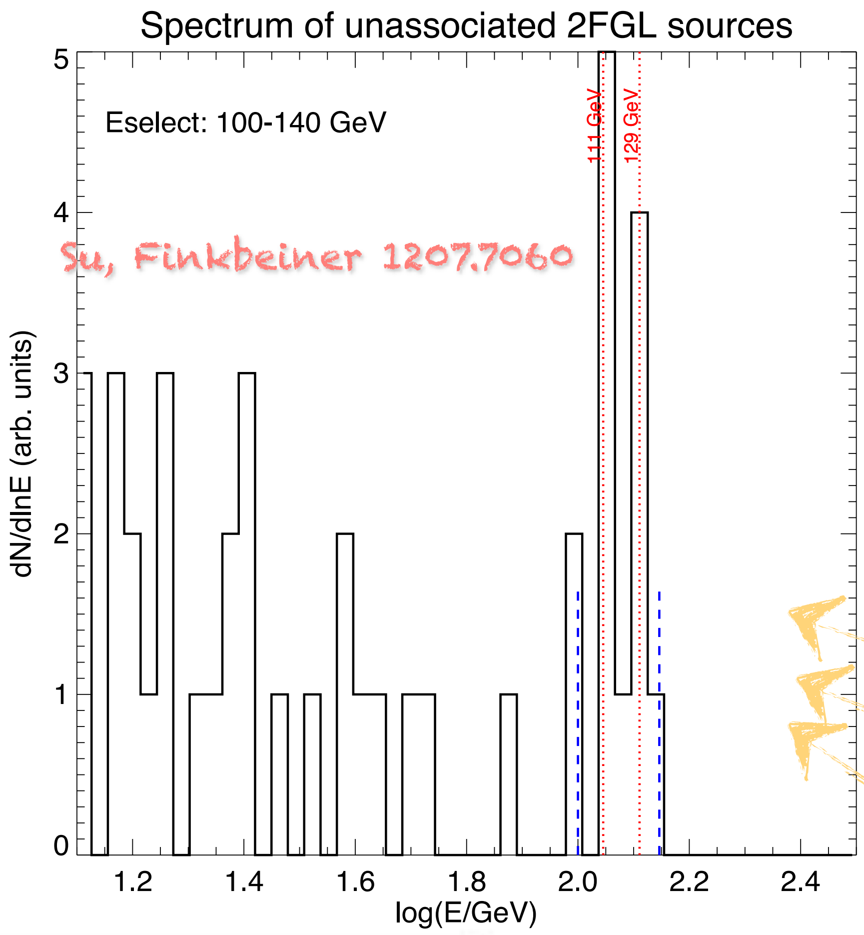
Hektor, Raidal, Tempel 1207.4466

Dwarf, AGN, H clouds, earth limb : no



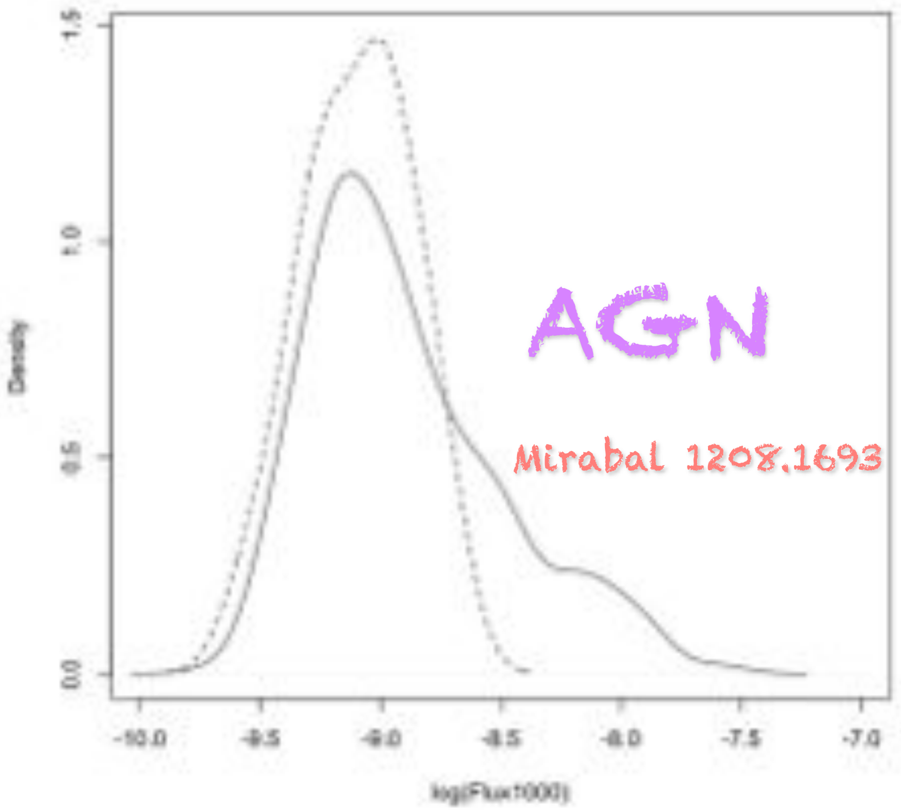
Unassiocated sources?

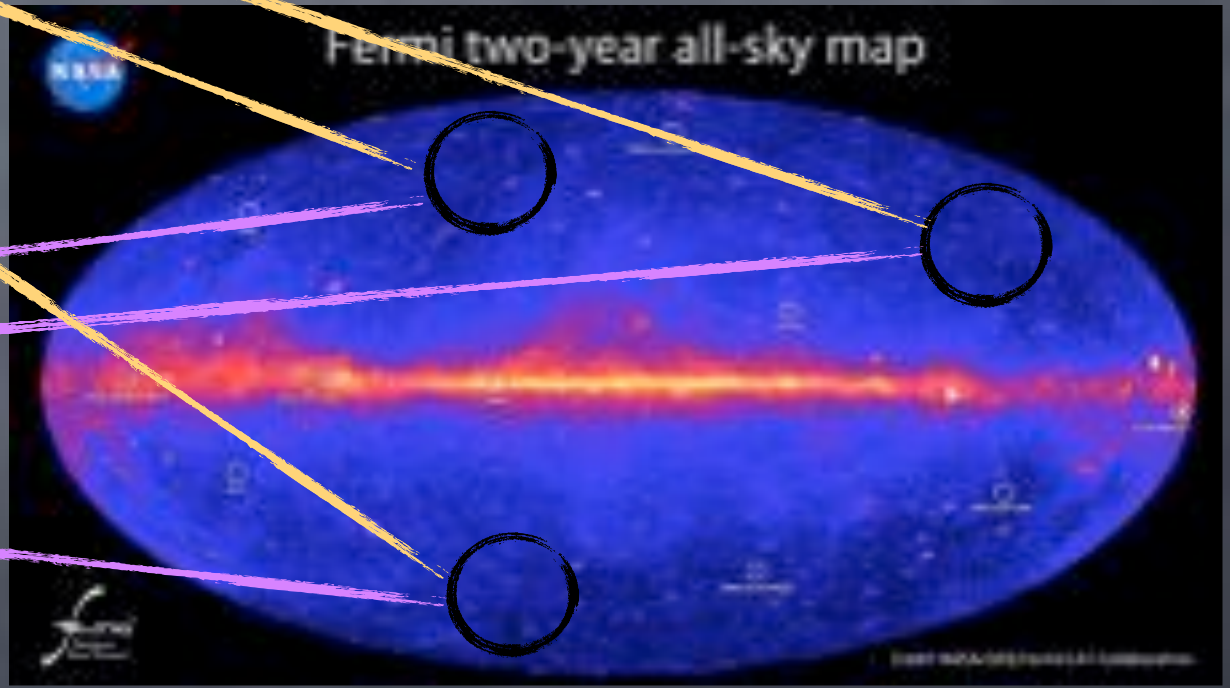
Other parts of the sky?



f, AGN, H clouds, earth limb : no

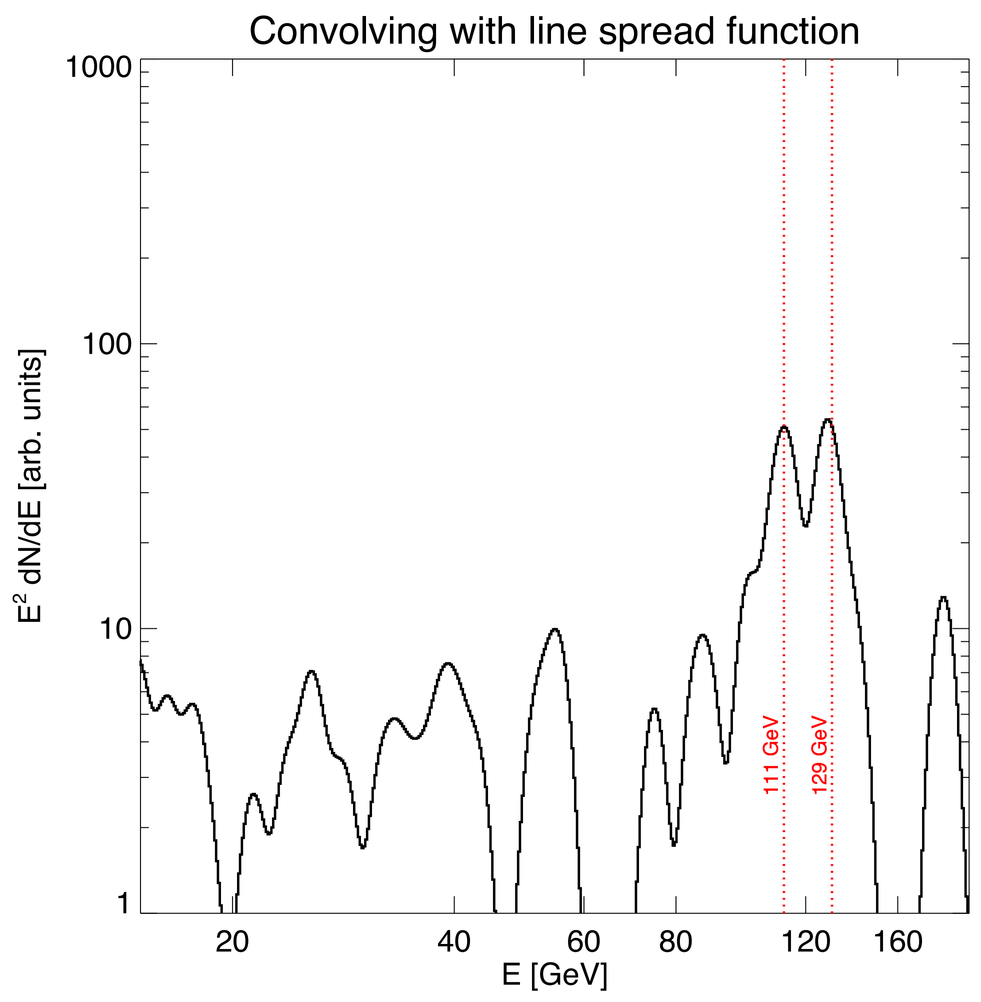
NO



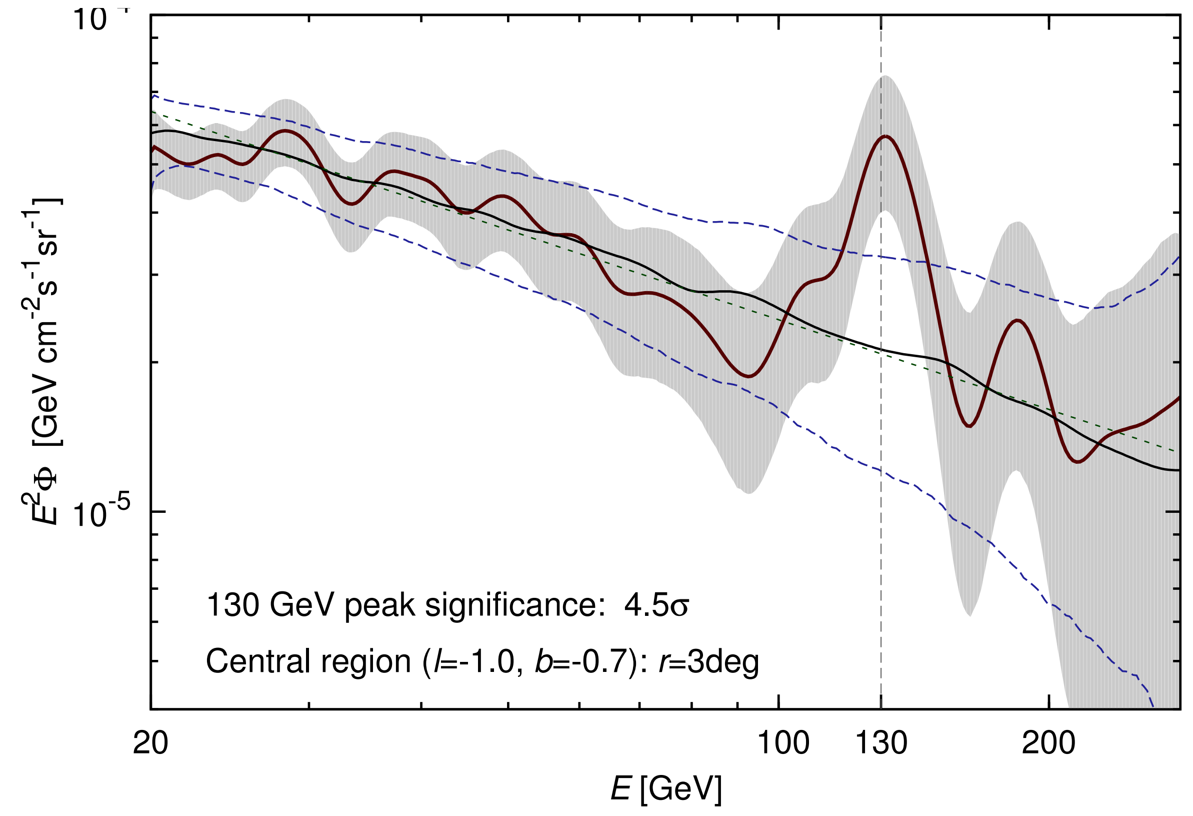


Unassiocated sources?

One line or 2 lines?



Su Finkbeiner 1206.1616

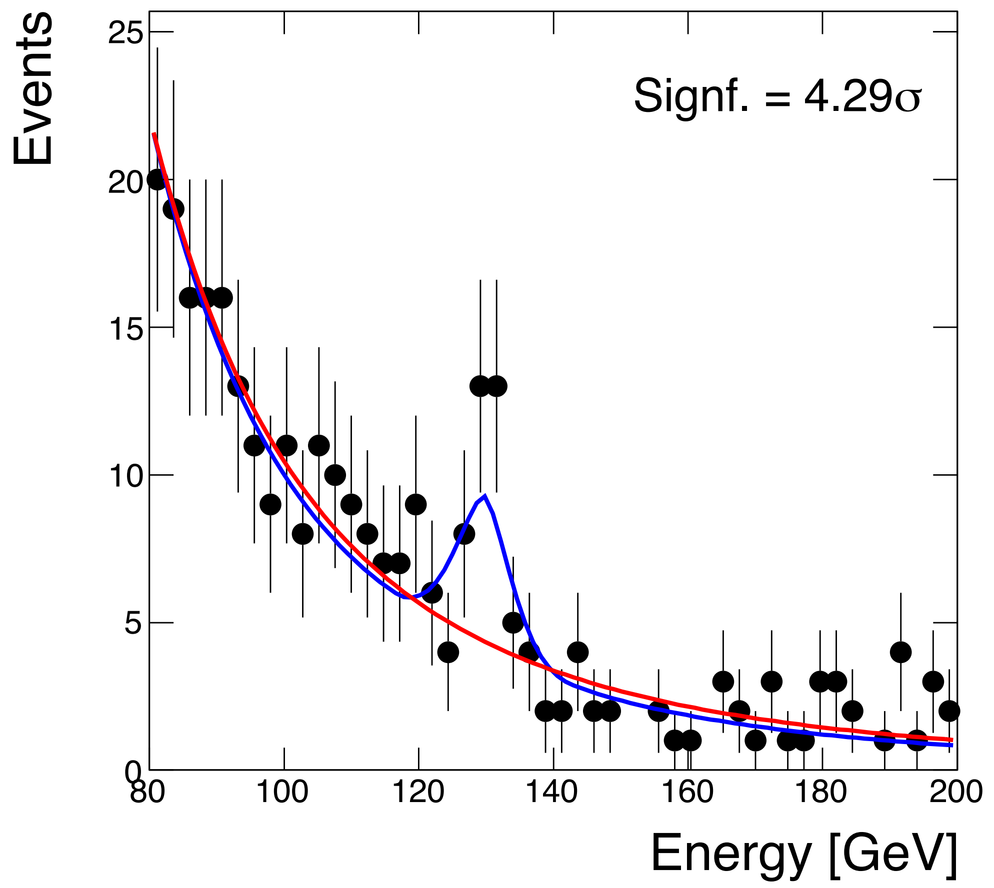


[Tempel, Hektor, Raidal, 1205.1045]

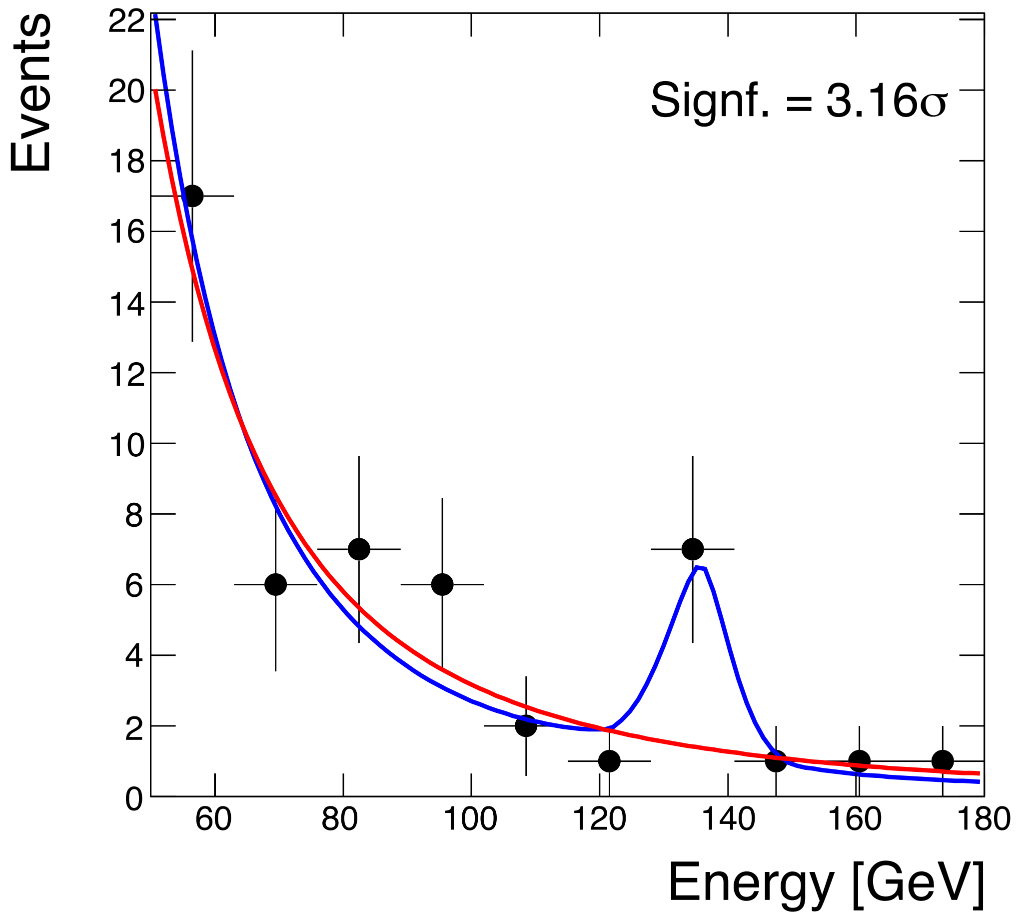
FERMI resolution ΔE/E = 10% not sufficient to distinguish 1 or 2 lines.

(Oda, 1207.1537)

Other lines in the sky?



Earth limb Finkbeiner, Su , Weniger
1209.4562
«no significant 130 GeV in the Earth limb sample»



[Whiteson, 1302.0427]

Earth Limb + sun still in question. Efficiency of FERMI around 135 GeV?

Several models appeared quickly in the market

Ibarra, Lopez Gehler, Pato : «Dark matter constraints from box-shaped gamma-ray features», 1205.0007; Dudas, Mambrini, Pokorski, Romagnoni: «Extra U(1) as a natural source of a monochromatic gamma ray line», 1205.1520; Cline : «130 GeV dark matter and the Fermi gamma-ray line», 1205.2688; Choi, Seto : «A Dirac right-handed sneutrino dark matter and its signature in the gamma-ray lines», 1205.3276; Kyae, Park, «130 GeV Gamma-Ray Line from Dark Matter decay», 1205.4151; Min Lee, Park, Park : «Fermi Gamma-Ray Line at 130 GeV from Axion-Mediated Dark Matter», 1205.4675; Ajaraman, Tait, Whiteson : «Two Lines or Not Two Lines? That is the Question of Gamma Ray Spectra, 1205.4723; Buckley, Hooper : «Implications of a 130 GeV Gamma-Ray Line for Dark Matter», 1205.6811; Chu, Hambye, Scarna, Tytgat: «What if Dark Matter Gamma-Ray Lines come with Gluon Lines», 1206.2279; Das, Ellwanger, Mitropoulos : «A 130 GeV photon line from dark matter annihilation in the NMSSM», 1206.2639; Kang, Li, Li, Liu : «Brightening the (130 GeV) Gamma-Ray Line», 1206.2863; Feng, Yuan, Fan : «Tentative wiggle in the cosmic ray electron/positron spectrum at 100 GeV : a dark matter annihilation signal in accordance with the 130 GeV gamma-ray line?», 1206.4758; Cohen, Lisanti, Slatyer, Wacker : «Illuminating the 130 GeV Gamma Line with Continuum Photons», 1207.0800; Cholis, Tavakoli, Ullio : «Searching for the continuum photons correlated to the 130 GeV gamma-ray line;, 1207.1468; Frandsen, Haish, Kahlhoefer, Mertsch, Schmidt-Hoberg : «Loop-induced dark matter direct detection signal from gamma-ray lines», 1207.3971; Park, Park : «Radiatively decaying scalar dark matter throigh U(1) mixings and the Fermi 130 GeV gamma-ray line», 1207.4981; Bergstrom, Bertone, Conrad, Farnier, Weniger : «Investigating Gamma-Ray Lines from Dark Matter with Future Observatories», 1207.6773; Tulin, Yu, Zurek : «Three Exceptions for Thermal Dark Matter with Enhanced Annihilation to Gamma-Gamma», 1208.0009; Hooper, Linden : «Are Lines From Unassociated Gamma-Ray Sources Evidence For Dark Matter Annihilation?», 1208.0828; Cline, Moore, Frey : «Composite magnetic dark matter and the 130 GeV line», 1208.2685; Bai, Shelton : «Gamma Lines without a Continuum : Thermal Models for the Fermi-LAT 130 GeV Gamma Line», 1208.4100; Laha, Ng, Dasgupta, Horiuchi : «Galactic Center Radio constraints on Gamma-Ray Lines from Dark Matter Annihilation», 1208.5488; Bergrstrom, «The 130 Fingerprint of Right-handed Neutrino dark matter», 1208.6082; Wang, Han : «130 GeV gamma-ray line and enhacement of h -> gamma gamma in the Higgs triplet model plus a scalar dark matter», 1209.0376; Weiner, Yavin : «UV Completion of Magnetic Inelastic Dark Matter and RayDM for the Fermi Line(s)», 1209.1093; Mambrini : «Don't tell me you are really reading all these references!!», 130218xx; Fan, Reece :»A Simple Recipe for the 111 and 128 GeV Lines», 1209.1097; Baek, Ko, Senaha : «Can Zee-Babu model implemented with scalar dark matter explain both Fermi/LAT 130 GeV gamma-ray excess and neutrino physics?», 1209.1685; Shakya : «A 130 GeV Gamma Ray Signal from Supersymmetry», 1209.2427; Rao, Whiteson : «Where are the Fermi Lines Coming From?», 1210.4934; Schmidt-Hoberg, Staub, Wolfgang Winkler, «Enhanced diphoton rates at FERMI and the LHC», 1211.2835; Fazran, Rezaei Akbarieh, «natural explanation for 130 GeV photon line in vector boson dark matter model», 1211.4685; Gorbukov, Tyniakov, «On the offset of the DM cusp and the interpretation of the 130 GeV line as a DM signal», 1212.0488; Kopp, Neil, Primulando, Zupan : «From gamma ray line signals of dark matter to the LHC», 1301.1683; Jackson, Servant, Shaughnessy, Tait, Taoso : «gamma--ray lines and One Loop Continuum from s-channel Dark Matter Annihilation, 1302.1802;

A monochromatic smoking gun signal

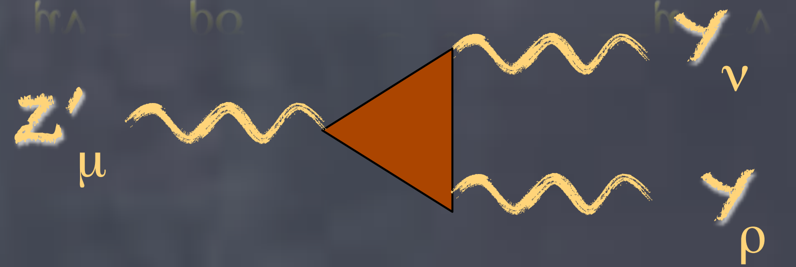
Kumar,Wells 08
Anastopoulos, Bianchi, Dudas, Kiritsis 06
Antoniadis, Boyarsky, Espahbodi, Ruchayskiy Wells, 09
Dudas, YM, Pokorski, Romagnoni 09 + 12
YM 09

Ψ	U(1)	U'(1)
Ψ_{SM}	X_{SM}	0
Ψ_i	X_i	X'_i
Ψ_h	0	X'_h

$$\mathcal{L} \xrightarrow{U'(1)} \mathcal{L} + \lambda\, \varepsilon^{\mu\nu\rho\sigma} F^Y_{\mu\nu} F^Y_{\rho\sigma} + \mathcal{L}'$$

$$\mathcal{L} = F^{Y\mu\nu} F^Y_{\mu\nu} - (d_\mu a - M_X X_\mu)^2 - i\, \bar{\Psi}_h \gamma^\mu D_\mu \Psi_h$$

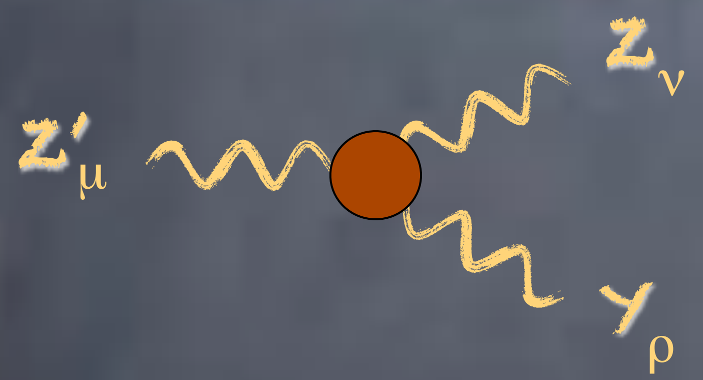
$$\mathcal{L}' = B\, a\, \varepsilon^{\mu\nu\rho\sigma} F^Y_{\mu\nu} F^Y_{\rho\sigma} + C\, \varepsilon^{\mu\nu\rho\sigma} X_\mu Y_\nu F^Y_{\rho\sigma}$$

$\delta \mathcal{L}' = -\,\delta\,($  $)$

Other approaches motivating CS-like couplings

Gauge invariant 6d operators

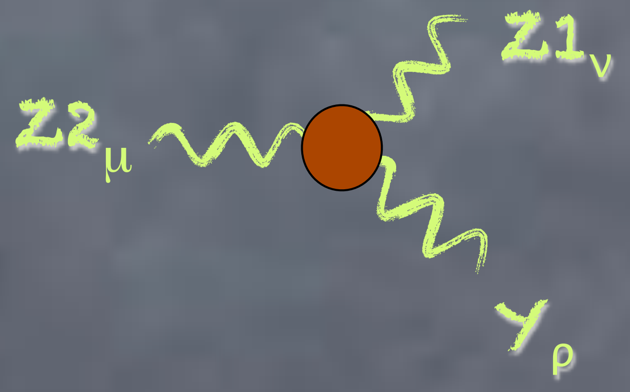
$$\frac{i}{M^2}\epsilon^{\mu\nu\rho\sigma}(\partial_\mu\theta_X - g_X Z'_\mu)H^+\mathcal{D}_\nu H F^Y_{\rho\sigma}$$

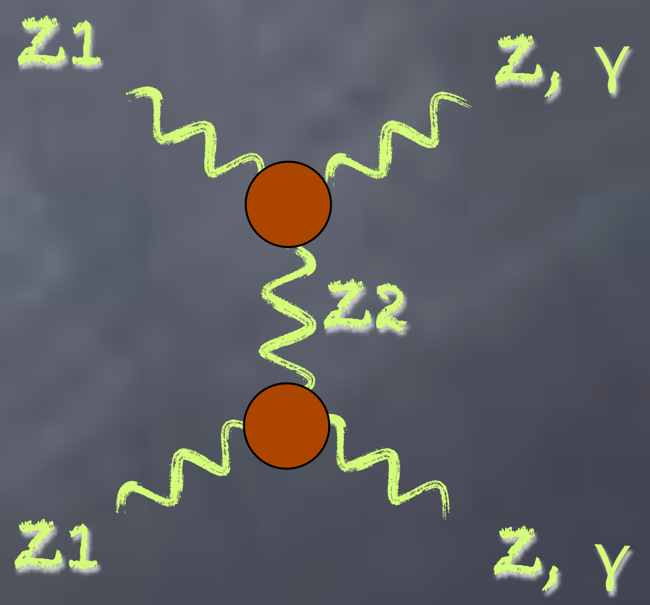


Antoniadis, Boyarsky, Espahbodi, Ruchayskiy, Wells, 2009
Dudas, Mambrini, Pokorski, Romagnoni, 2009

With 2 extra U's(1) : 4d operators

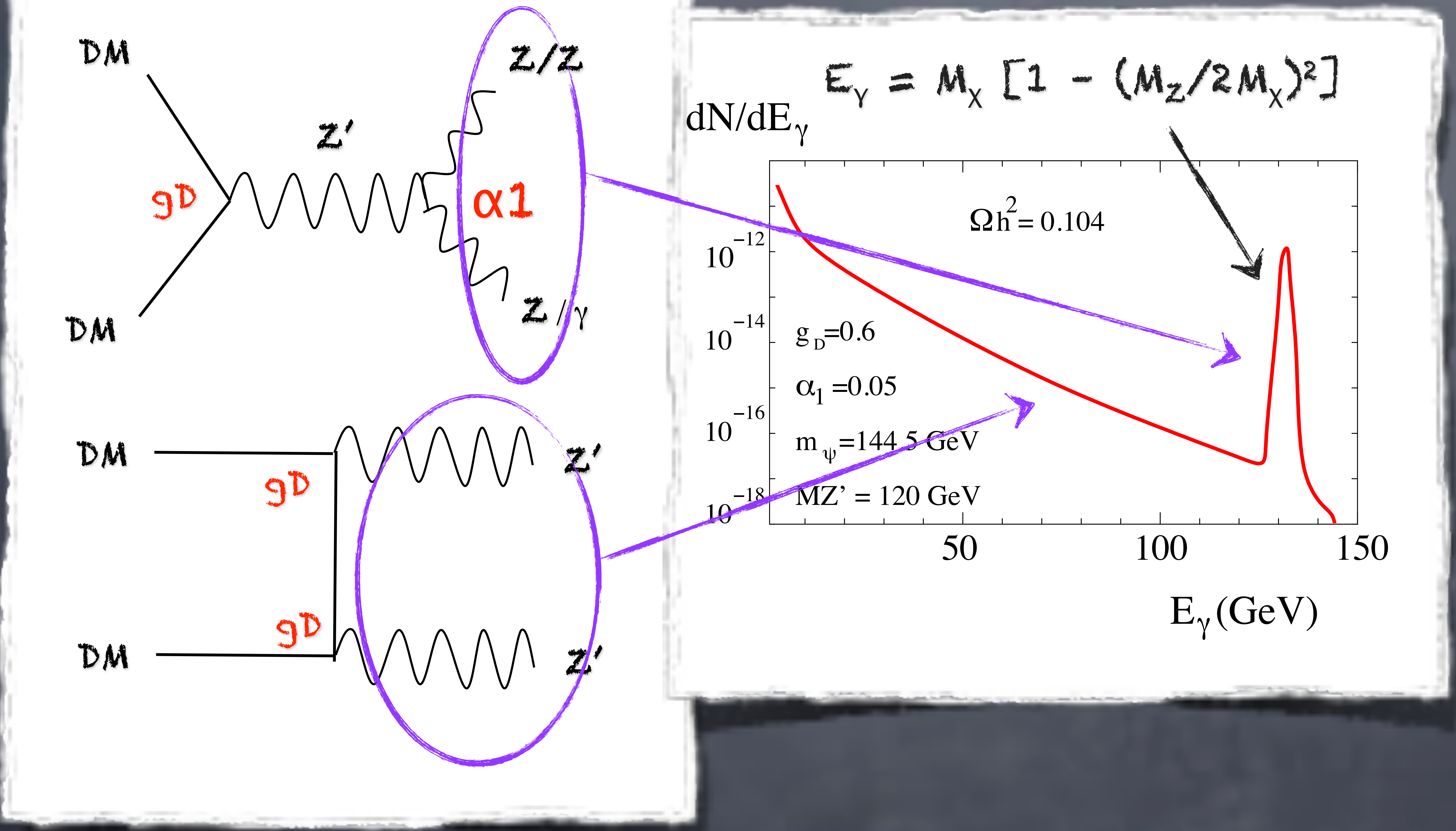
$$\epsilon^{\mu\nu\rho\sigma}(\partial_\mu\theta_1 - g_1 Z^1_\mu)(\partial_\mu\theta_2 - g_2 Z^2_\mu)F^Y_{\rho\sigma}$$



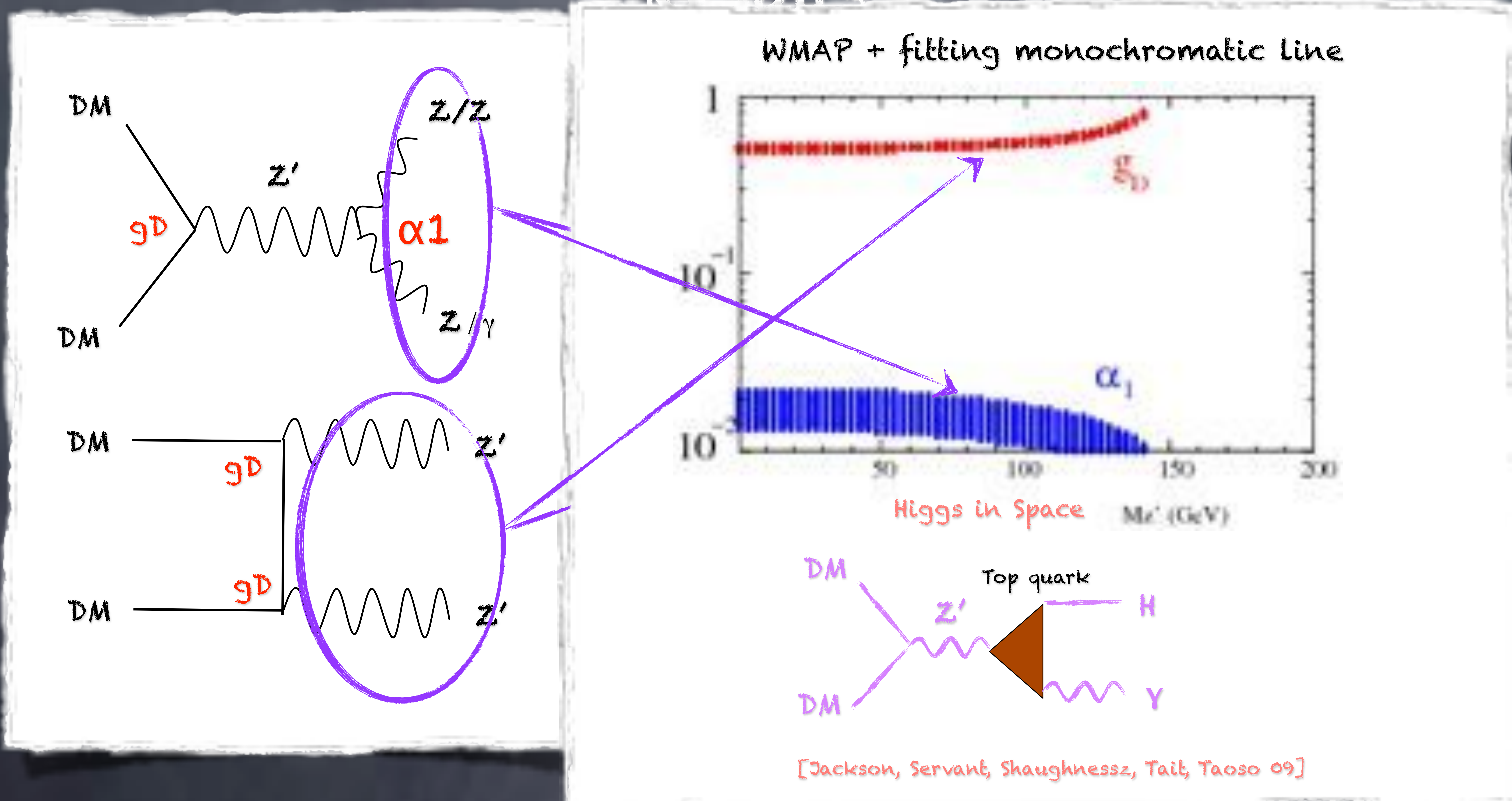


Farzan, Akbarieh, 2012
Domingo Lebedev, Mambrini, 2013

Results


DM
DM
gD
Z'
α1
Z/Z
Z /γ
DM
DM
gD
gD
Z'
Z'
Eγ = MX [1 - (MZ/2MX)²]
dN/dEγ
Ωh² = 0.104
gD=0.6
α1 =0.05
mψ=144.5 GeV
MZ' = 120 GeV
10⁻¹²
10⁻¹⁴
10⁻¹⁶
10⁻¹⁸
50
100
150
Eγ (GeV)

Results


WMAP + fitting monochromatic line
DM
DM
Z'
gD
Z/Z
Z /γ
α1
DM
DM
gD
gD
Z'
Z'
1
10^{-1}
10^{-2}
g_D
α_1
50
100
150
200
Mz' (GeV)
Higgs in Space
DM
DM
Z'
Top quark
H
γ
[Jackson, Servant, Shaughnessz, Tait, Taoso 09]

Prospective - Conclusion

- A lot of extensions to the classical thermal history of the Universe
- Monochromatic line still to be tested
- Supersymmetry? Extra forces? Sterile neutrino?
- Heavy states (> T_{RH}) as natural as WIMP scenario
- Promising next years...