Dark Matter in Particle Physics

10/29/2016
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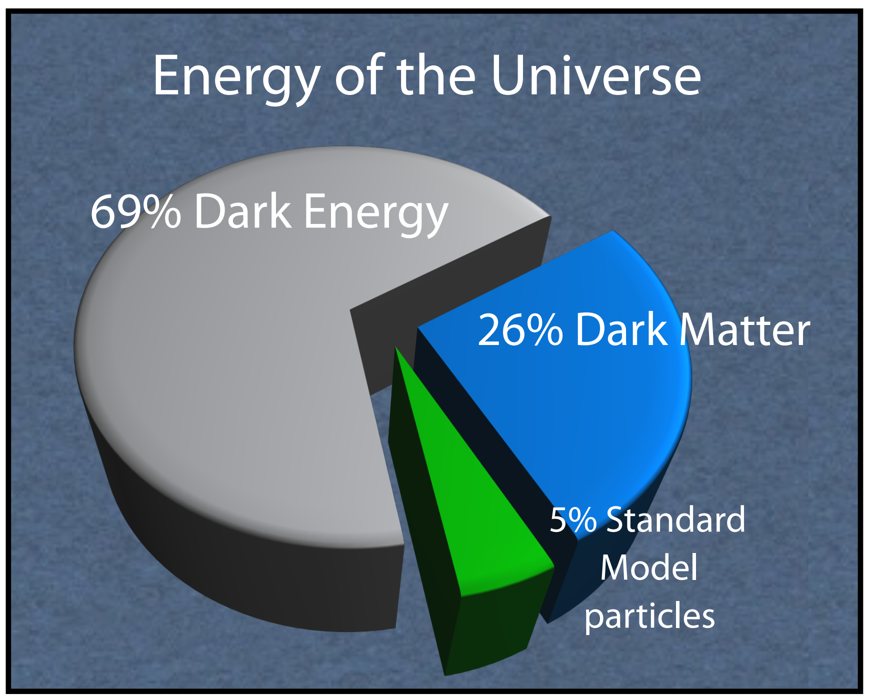
The Standard Model of Cosmology

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$

$$H^2 \equiv \left(\frac{\dot{a}}{a} \right)^2 = \frac{1}{3M_{\rm PL}^2} (\rho_{\rm rad} + \rho_{DM} + \rho_b + \rho_\Lambda) - \frac{k}{a^2}$$

$$(M_{\rm PL} = (8\pi G)^{-1/2} \simeq 2.4 \times 10^{18} {\rm GeV})$$

Cosmological Parameters (PLANCK 2015 Results : CMB + LSS)



$H_0 = 67.74 \pm 0.46$ km/s/Mpc

$\Omega_{DM} h^2 = 0.1188 \pm 0.0010$

$\Omega_B h^2 = 0.02230 \pm 0.00023$

$\Omega_\Lambda = 0.6911 \pm 0.0062$ (→ Accelerating !)

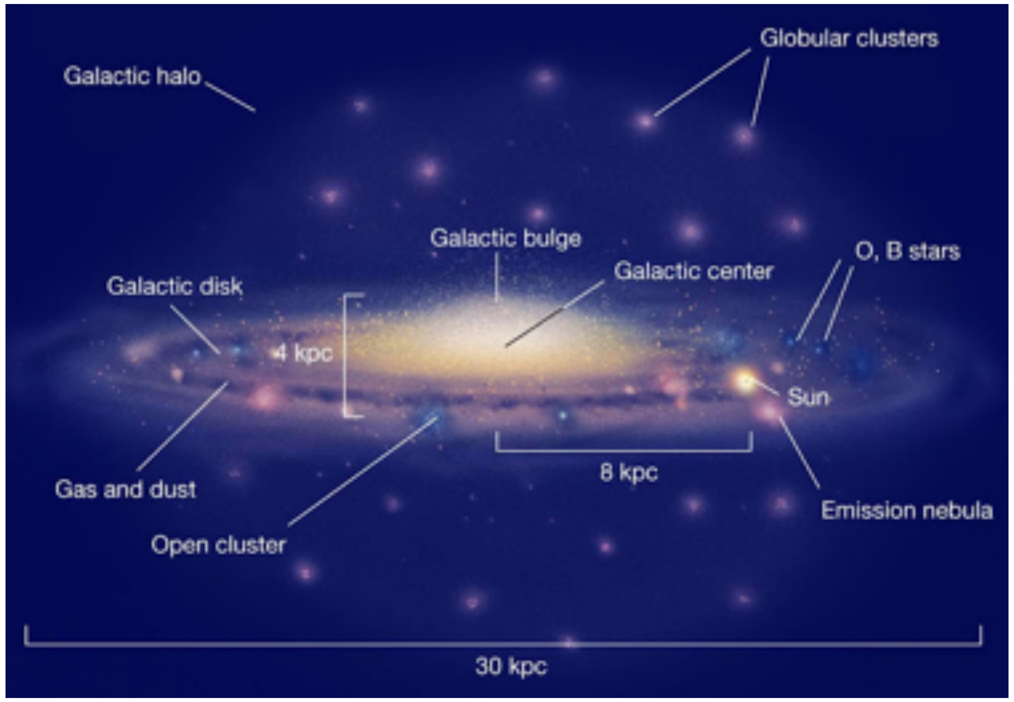
$\Omega_K = 0.0008 \pm 0.0040$ (→ FLAT !)

$(\Omega_X = \rho_X / 3 M_{PL}^2 H_0^2)$

[$\Omega_X = 1 \leftrightarrow \rho_X = 4.7 \times 10^{-6}$ GeV/cm^3 ~ $10^{11} M_\odot$/Mpc^3 (critical density)]

gas emission :
CO line (115GHz -> 3mm)
HI line 21cm

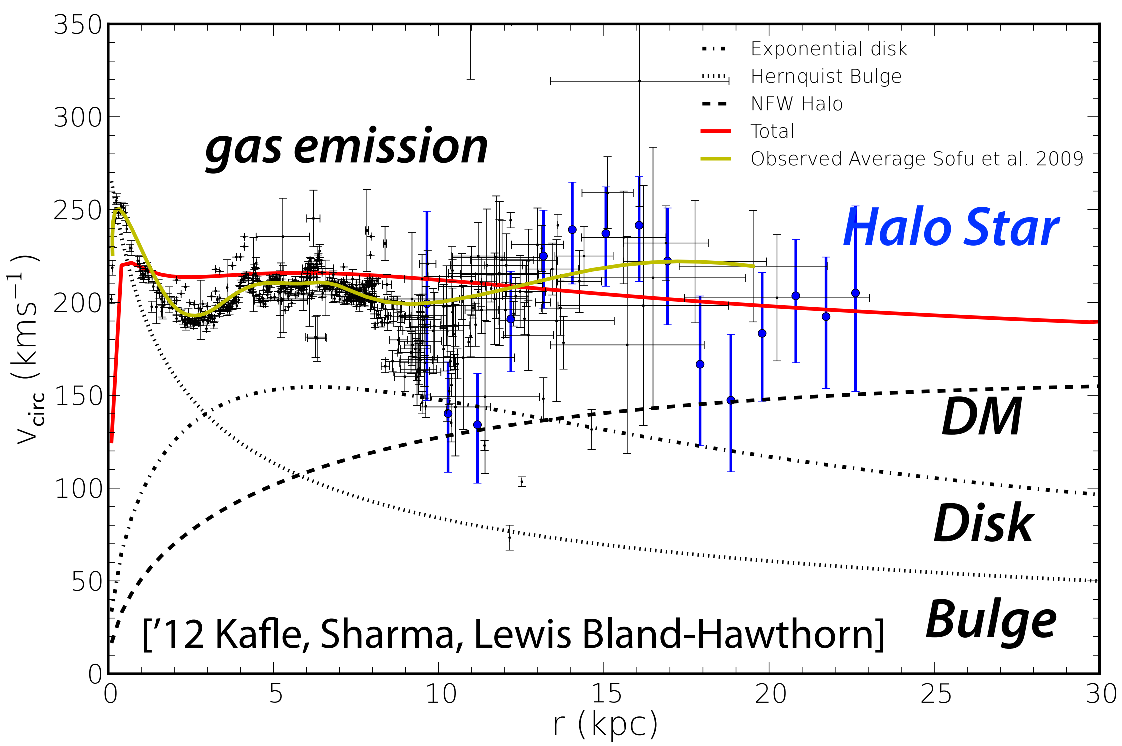
Galaxy Rotation Curve (ex : Milky Way Galaxy)



[Credit: Pearson Education Inc]

- Visible Entries of Milky Way

> ***Thin Disk ~ 6.5 x10^{10} $M_\odot$***
>
> ***Bulge ~ 1.8 x 10^{10} $M_\odot$***
>
> ***Halo ~ 10^9 $M_\odot$***



- Milky Way Rotation Curve

If no DM → $v \propto r^{-1/2}$ though v_{obs} ~ ***const…***

Galaxies are surrounded by the Dark Halo !

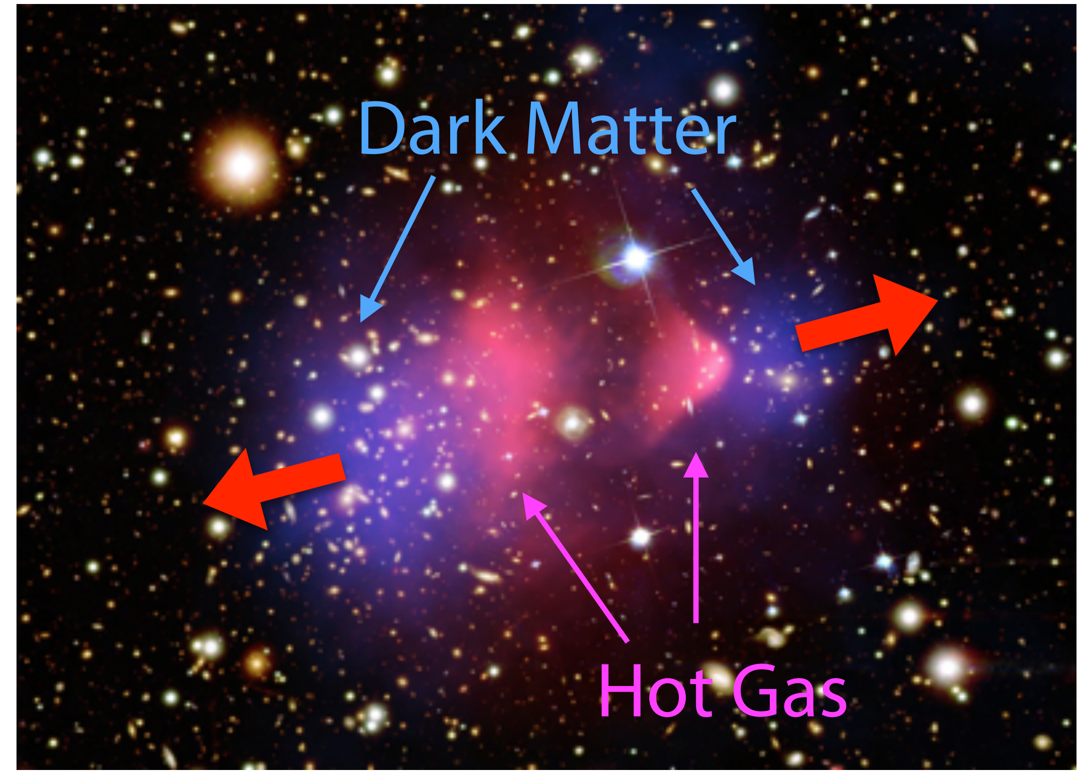
> ***ρ_{DM} (at SUN) ~ 0.4 GeV/cm^3***
>
> ***$M_{DM\ Halo}$ (R<300kpc) ~ 10^{12} $M_\odot$***

Galaxy accumulated matter in a few ***Mpc***
Density is enhanced by about 10^6.

(Estimation of DM density in outer galaxies is lots easier.)

Bullet Cluster (galaxy cluster 1E 0657-56)

Optical



Blue : Gravitational Lensing (HST)
Pink : X-Ray (Chandra)

- Very rough constraints on the dark matter cross section :

DM density : $10^{16}\,M_\odot/Mpc^3$ at the core ($R < 100kpc$) of the galaxy cluster ***(see e.g. ['12 Newman, Treu, Ellis, Sand])***

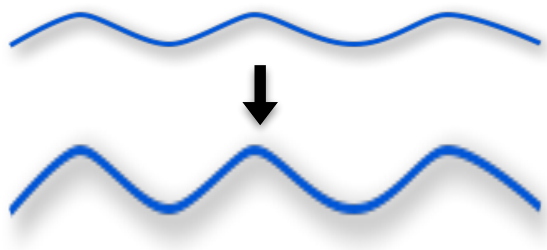
$v \sim 4500 km/s$ is estimated from the shock wave front of the hot gas.

Mean free pass : $(\sigma v\, n_{DM})^{-1} > O(100)\ kpc$

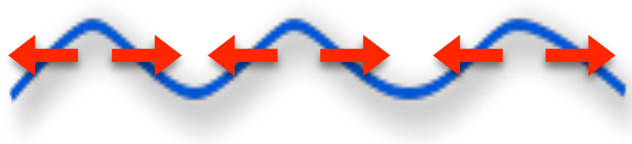
$\rightarrow \sigma/m < 10^{-24}\,cm^2 / GeV \sim 1\ barn/GeV$

(cf. $\sigma_{hadron}/GeV \sim 0.1\ barn/GeV$)

Structure Formation



Structures (galaxies, galaxy clusters …) are formed from initial small density fluctuation.



Before recombination, baryon is tied to photon and the density fluctuation cannot grow due to high pressure.

- Baryon fluctuation grows only after recombination, but there is not enough time to form e.g. galaxy cluster…

$$\delta(\text{galaxy cluster}) \sim 10^3 \times 4(\Delta T/T)_{CMB} \ll 1$$

$$(\Delta T/T)_{CMB} \sim 10^{-5}$$

- The density fluctuation of "pressure free" dark matter starts growing before the recombination time !

→ *We need Cold Dark Matter !*

Known Properties of Dark Matter

- DM makes up ***27%*** of total energy and ***85%*** of matter

  → ***non-trivial (thermal history etc.)***

- Neutral (does not couple to photon)

  → ***charge assignment (model building)***

- Cold (slow not to erase the structure)

  → ***heavy or small velocity dispersion***

- Stable / very long lived (lifetime >> $\boldsymbol{10^{17}}$ sec)

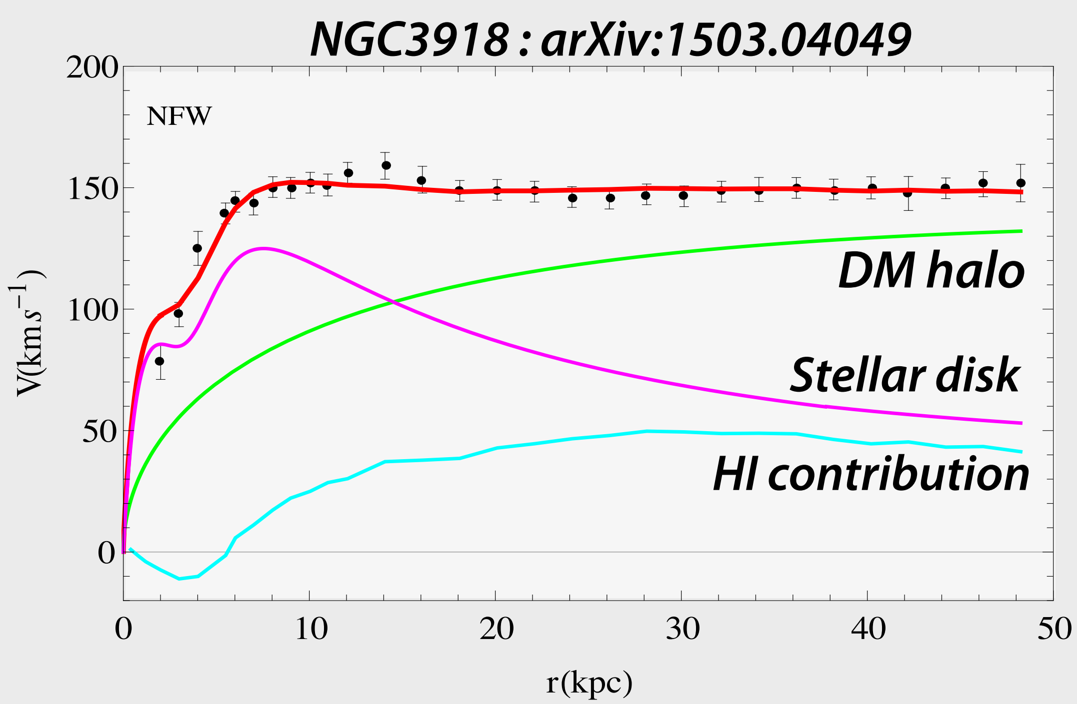
  → ***by (accidental) symmetry***

→ ***New Particle not in the Standard Model !***

✔ *How well do we know about the mass of dark matter ?*

✔ So far, we only managed to restrict its mass between
10^{-31} GeV and 10^{57} GeV,

de Broglie length of dark matter in ***NGC3198*** :



$\lambda_{DM} \sim 2\pi/M_{DM}v \sim 40kpc\,(10^{-31}GeV/m_{DM})$
$(v \sim 200km/s$ @ $R \sim 10kpc)$

[If we use consider dwarf galaxies with size ***O(100)pc*** with $v < 10km/s$, we might put severer constraint $m_{DM} > 10^{-28}GeV$]

[If dark matter is fermion, Trimaine-Gunn bound (dwarf Spheroidal)

$$M_{DM} > 2keV$$

$$\rho_{DM} = M_{DM}^4/8\pi^3 \int^{vmax} dv\, v^2 f(v) < M_{DM}^4/8\pi^3 \int^{vmax} dv\, v^2$$]

[CAUTION : THIS IS A BACK-OF-THE-ENVELOPE CALCULATION]

✓ *How well do we know about the mass of dark matter ?*

- So far, we only managed to restrict its mass between 10^{-31}*GeV* and 10^{57}*GeV*,

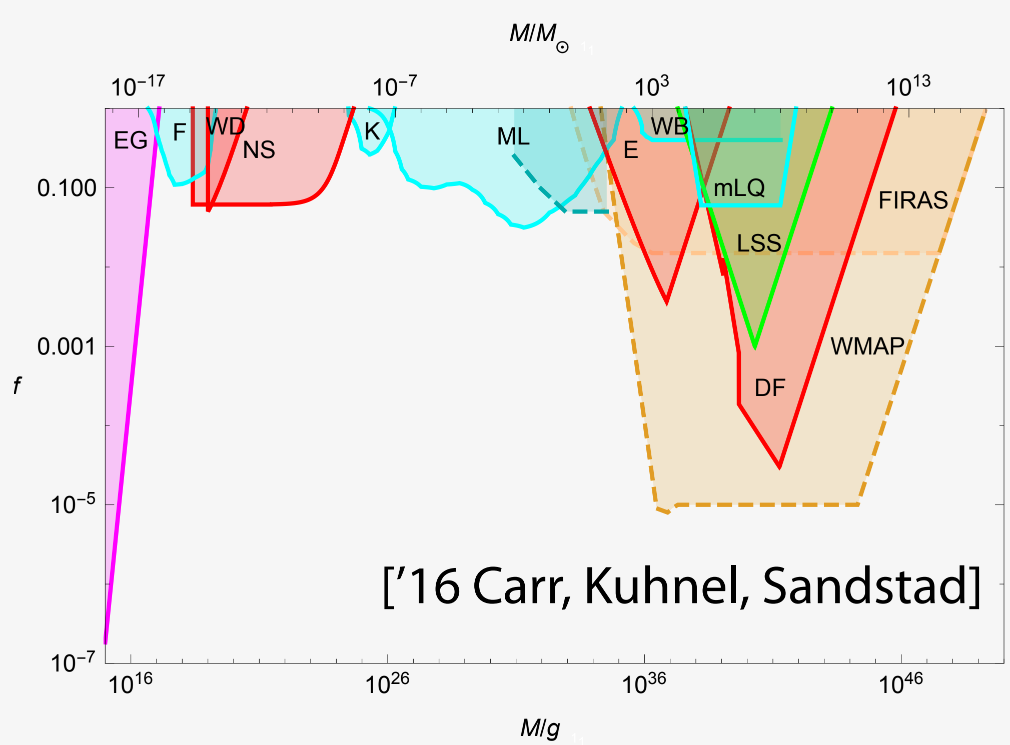
Mass of Milky Way :

$$M_{300kpc} = 0.9 \pm 0.3 \times 10^{12}\, M_\odot \text{ (arxiv:1002.4565)} \rightarrow M_{DM} << M_{300kpc}$$

$$(M_\odot = 1.989 \times 10^{33} g = 1.111 \times 10^{57} GeV)$$

Particle DM with mass $M >> M_{PL}$ = Black hole

(Schwarzschild radius = $2GM_{DM}$ > Compton Length M_{DM}^{-1})



→ Gas accretion onto DMs distorts CMB !

→ MACHO searches also put constraints.

$$M_{DM} < 10^{-7} - O(1)\, M_\odot$$

[Neutron star capture ? arXiv:1301.4984]

[Continuous spectrum ?
arXiv:1501.07565 Clesse, Garcıa-Bellido
arXiv:1605.04974 Kawasaki, Mukaida, Yanagida]

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✓ *Candidates in Particle Physics ?*

Top down approach : DM candidates in Big pictures

- ✓ Supersymmetry (Neutralino, Gravitino, Q-ball)
- ✓ Extra Dimension (KK-Graviton)
- ✓ Composite Higgs Models
- ✓ Strong CP problem (axion)

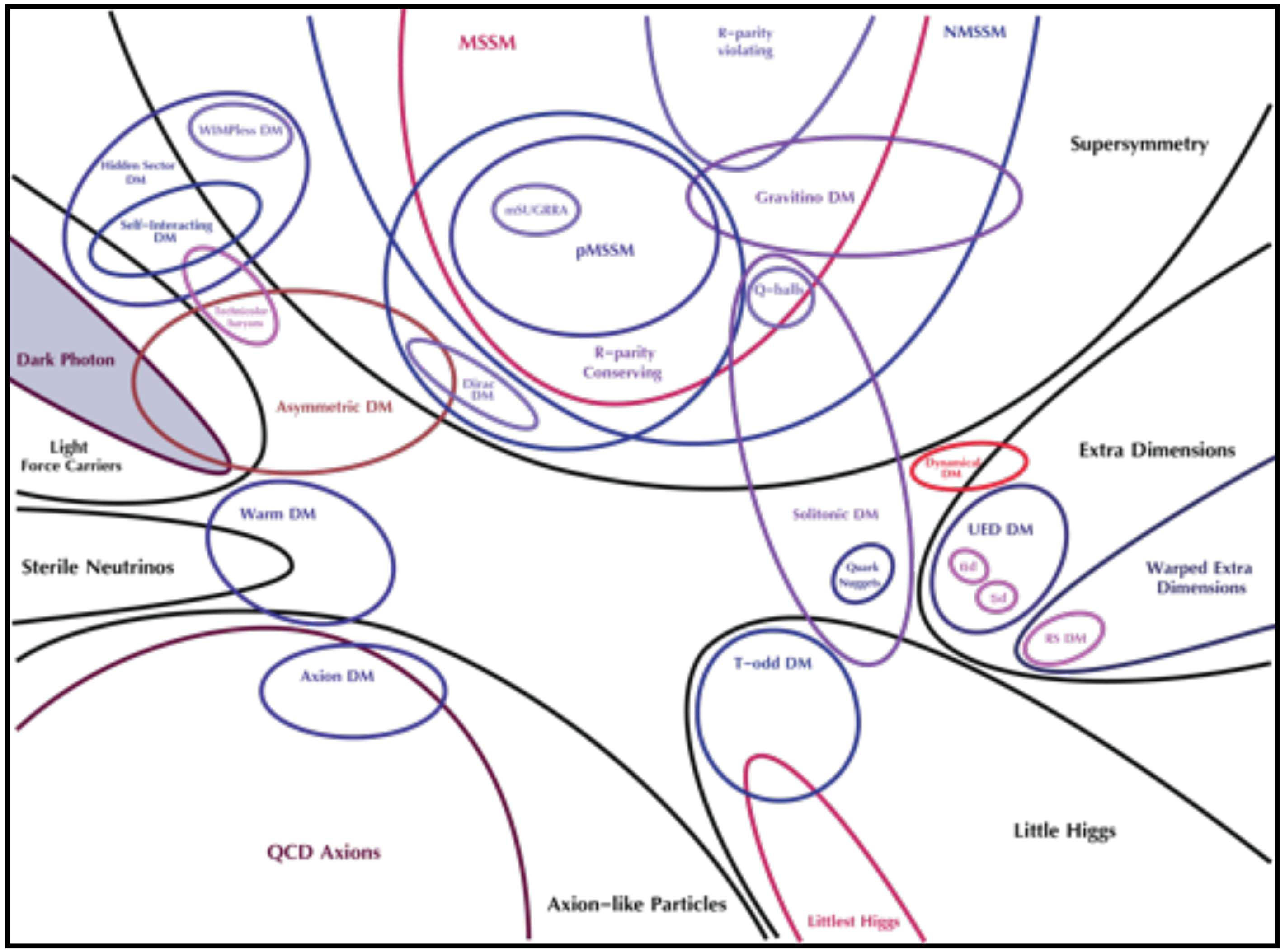
…

Bottom up approach : DM model building

- ✓ Minimal models of Dark Matter
  (We extend SM as minimal as possible.)
- ✓ Dark Matter with intriguing properties
  (cf. very heavy/light DM, multi component DM,
  self interacting DM, Primordial Black Hole …)
- ✓ Dark Matter models to explain "signals"
  (cf. direct detection, cosmic ray, galaxy structure …)

✓ *Candidates in Particle Physics ?*

We have lots of candidates…



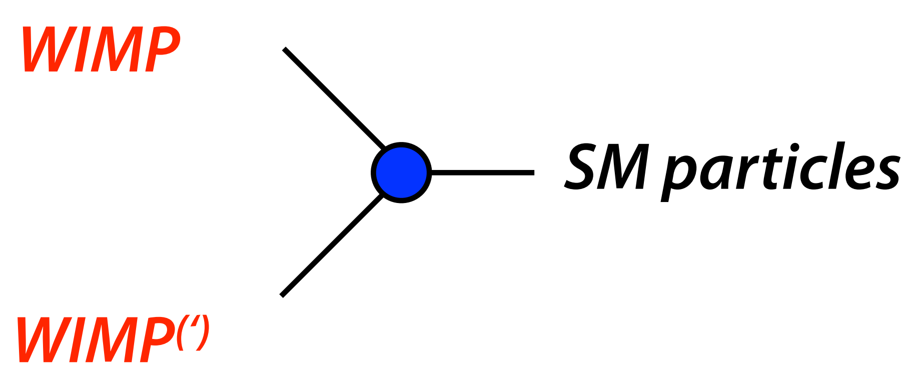
[Credit: Tim M. P. Tait]

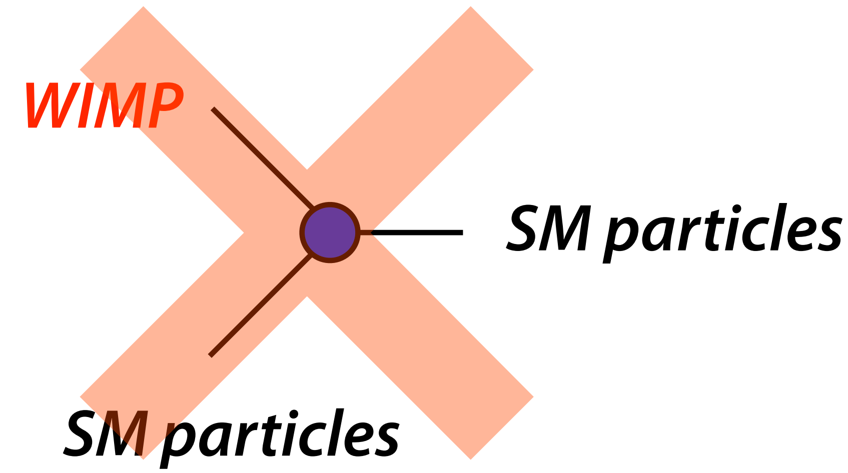
Theorists keep building new DM models until the DM is discovered.

WIMP

Weakly Interacting Massive Particle (WIMP)

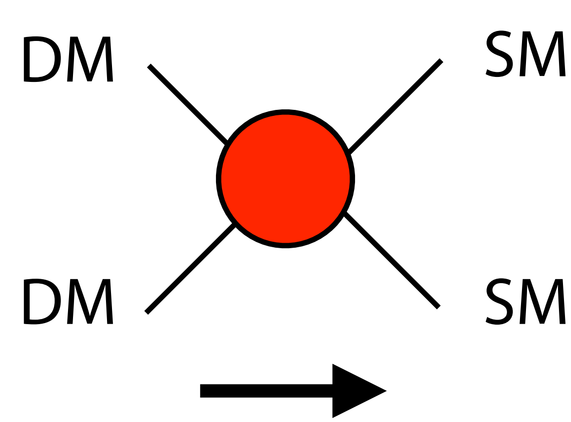
Among various candidates, the so called WIMP models are the most popular !





In variant models, we may replace SM particles with some light new particles.

- Dark Matter density is determined by the annihilation process and it does not depend on the initial condition !



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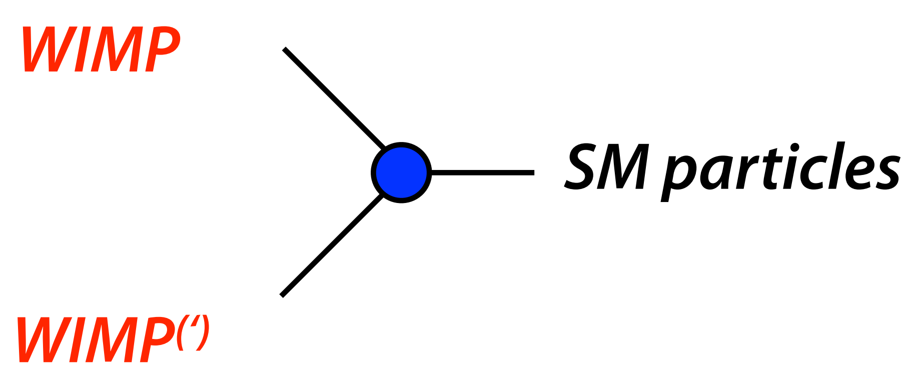

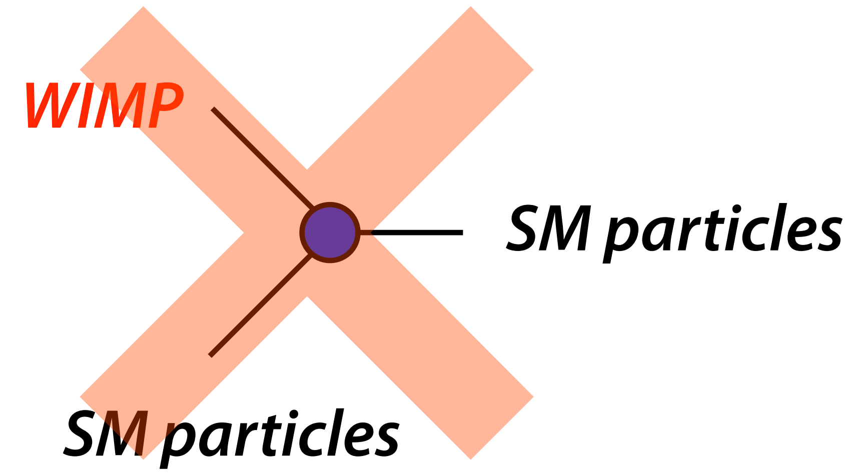

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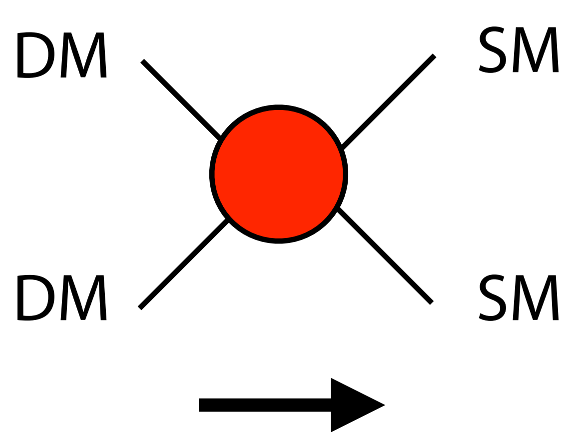
- Dark Matter can be detected by looking for remnants of its annihilation in the present universe !



Indirect detection via cosmic ray searches !

Weakly Interacting Massive Particle (WIMP)

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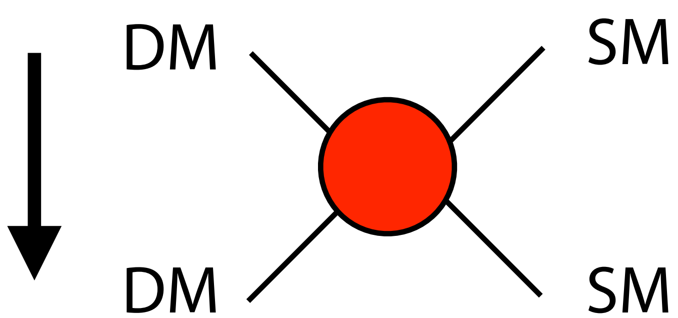

Direct detection via DM scattering !

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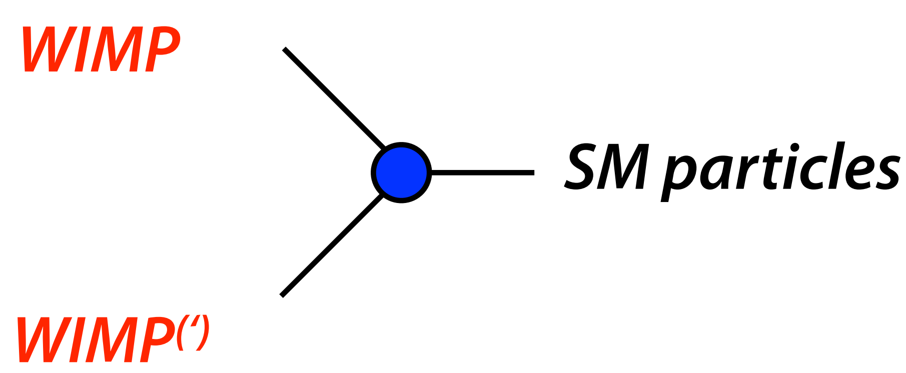
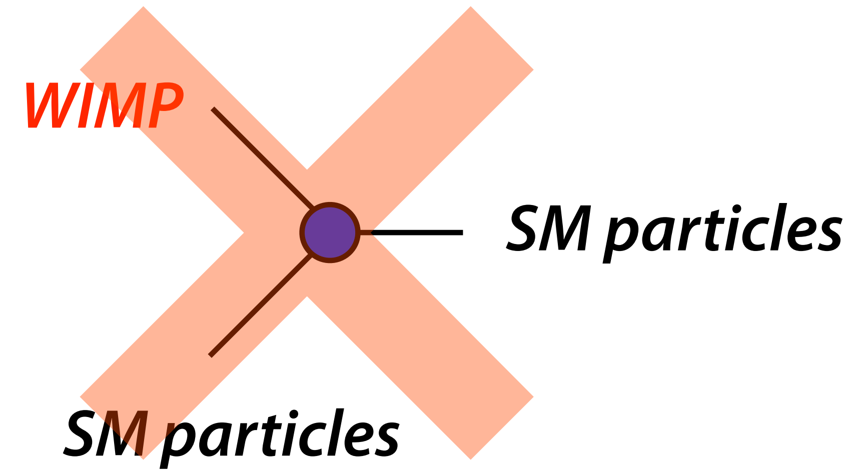
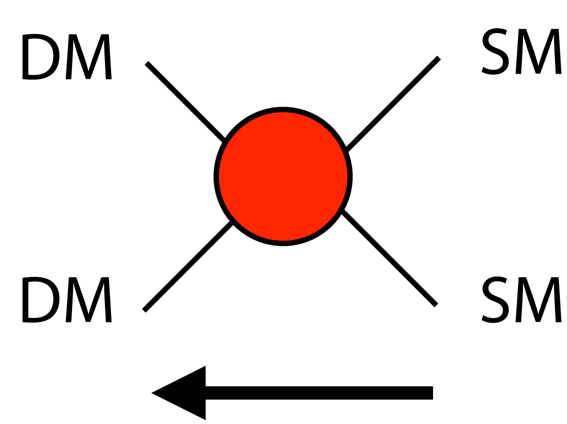




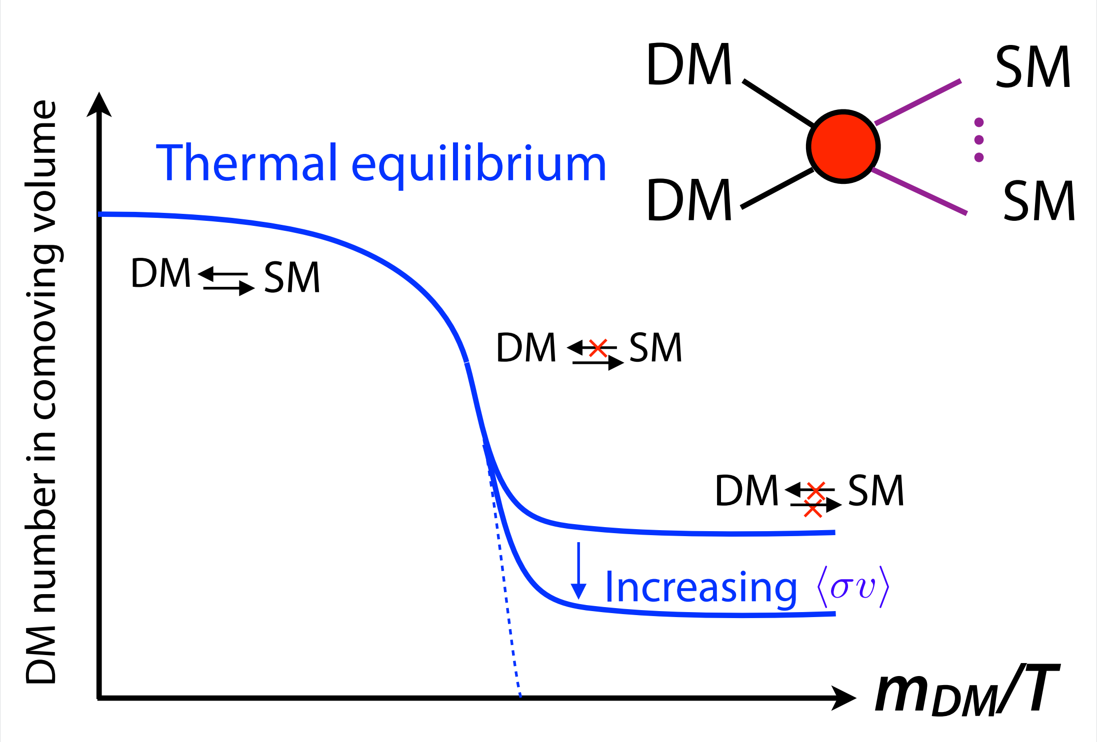
In variant models, we may replace SM particles with some light new particles.

Dark Matter can be produced at collider experiments !



Missing Energy searches at colliders experiments.

✔ *WIMP abundance*



- DM is in thermal equilibrium for $T > m_{DM}$.
- For $n_{DM} < T$, DM is no more created
- DM is still annihilating for $m_{DM} < T$ for a while...
- DM is also diluted by the cosmic expansion
- DM cannot find each other and stop annihilating at some point
- DM number in comoving volume is frozen

Boltzmann Equation :

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle \sigma v \rangle (n_{\rm DM}^2 - n_{\rm eq}^2) \qquad n_{eq} \propto e^{-m_{DM}/T}$$

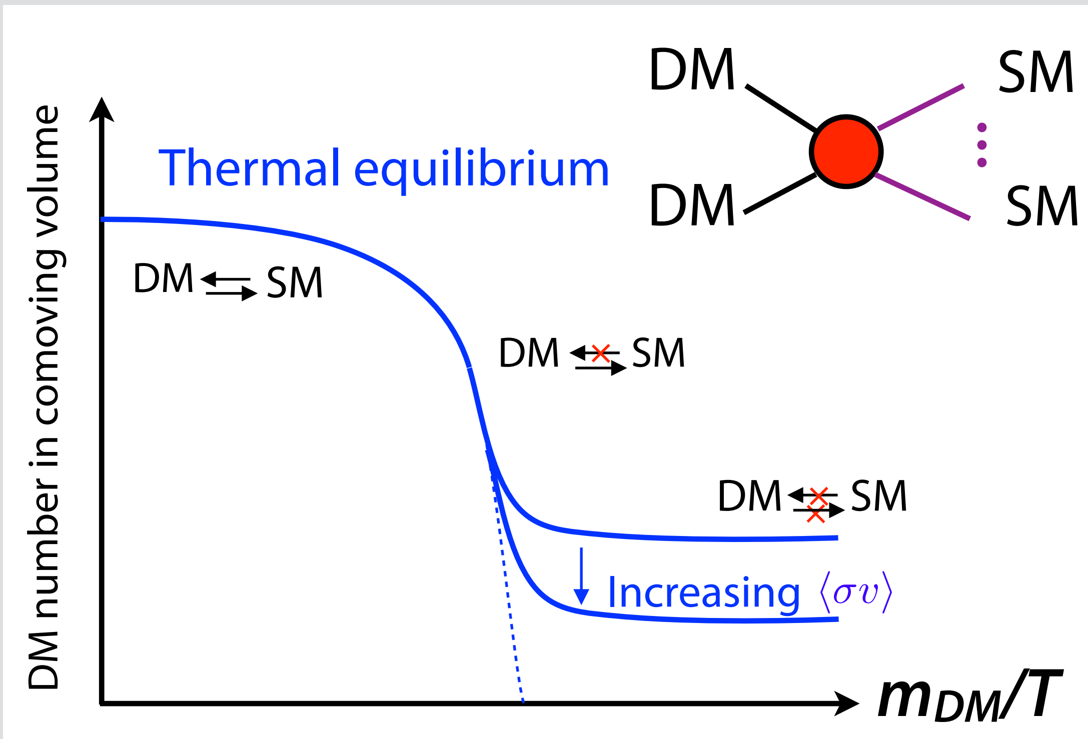
✔ Number density (per comoving) is fixed when :

DM cannot be produced from thermal bath : $T_F \sim m_{DM}/20$

DM cannot find its partner for annihilation any more : $(\langle\sigma v\rangle n_{DM}) < H$

$$n_{DM} \sim 1/(\langle\sigma v\rangle H) \text{ at } T_F$$

✓ *WIMP abundance*



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$$\rho_{DM}(\mathrm{now}) = m_{DM}\, n_{DM}(\mathrm{now}) = m_{DM}\, T_0^3\, (n_{DM}(\mathrm{now})/T_0^3)$$

$$= m_{DM}\, T_0^3\, (n_{DM}(T_F)/T_F^3)$$

DM abundance (for s-wave annihilation)

$$\Omega_{DM} h^2 \simeq 0.1 \times \left(\frac{10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

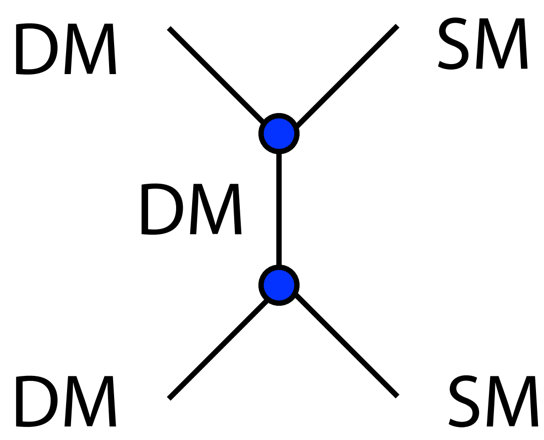
✓ Abundance depends on the DM mass through $\langle\sigma v\rangle$.

WIMP Miracle !

DM abundance (for s-wave annihilation)

$$\Omega_{DM}h^2 \simeq 0.1 \times \left(\frac{10^{-9}\,\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)$$

- Typical Annihilation Cross section :



$$\langle\sigma v\rangle \sim \frac{\pi\,\alpha^2}{m_{DM}^2}$$

- Observed Dark Matter Density can be explained for

$m_{DM} \sim$ ***O(100)GeV - O(1) TeV*** and $\alpha \sim 10^{-2}$

This corresponds to physics beyond the Standard Model !

→ WIMP is interrelated to Big Picture of the BSM !

Mass Range of WIMP

Lower Limit on WIMP mass

Dark matter freezes-out from the thermal bath at around

$$T_F \sim M_{DM}/O(10)$$

for $\langle \sigma v \rangle \sim 10^{-9} GeV^{-2}$.

Freeze-out should complete before the neutrino decoupling and BBN

$$M_{DM} >> O(10) MeV$$

- If $m_{DM} < O(1) MeV$, H is larger for a given T, and (n/p) becomes larger
  → ^4He abundance is increased compared with Hydrogen abundance.

- If freeze-out after the neutrino decoupling at $T \sim 1 MeV$, the DM annihilation increases or decreases effective number of the neutrino depending on the branching ratio.

Mass Range of WIMP

Upper Limit on WIMP mass

The heavier the DM is, the larger couplings are required.

$$\langle\sigma v\rangle \sim \frac{\pi\alpha^2}{m_{DM}^2} \sim 10^{-9}\mathrm{GeV}^{-2}$$

→ Unitarity Limit on WIMP mass (1990 Griest & Kamionkowski)

Each partial wave cross section is limited from above

$$\sigma_\ell v_{\rm rel} \leq \frac{16\pi(2\ell+1)}{s\, v_{\rm rel}}$$

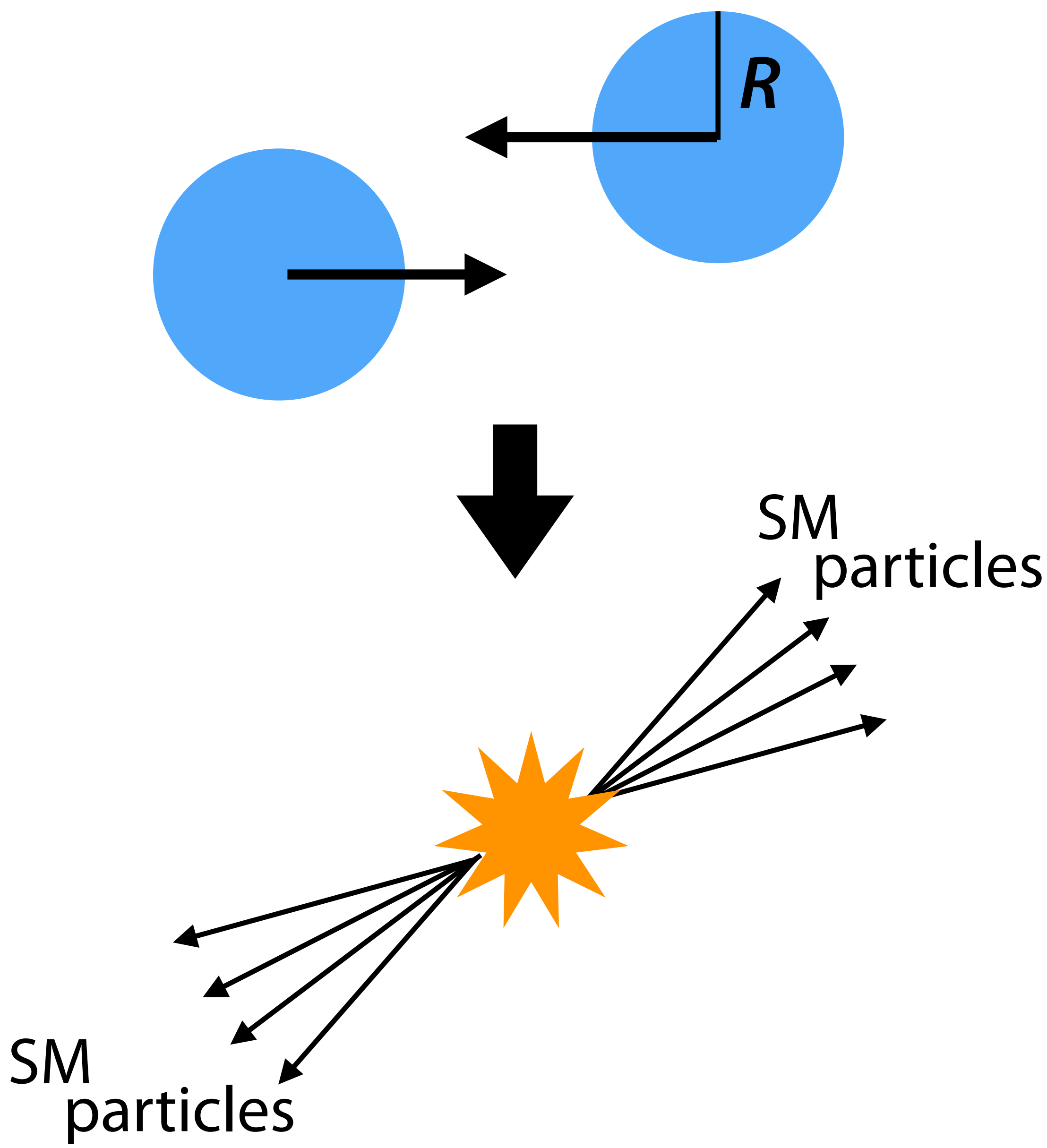
(spineless case for simplicity)

→ $M_{DM} < 300$ TeV

WIMP mass range : $O(10)\mathrm{MeV} < M_{WIMP} < 300\mathrm{TeV}$

Thermal WIMP beyond the unitarity limit ?

- What if dark matter annihilates as ***extended objets*** with geometric cross sections, $\sigma \sim \pi R^2$? (1990 Griest & Kamionkowski)



$L_{MAX} \sim M_{DM}\, v\, R$

$$\sum_{\ell=0}^{L_{\rm MAX}} \sigma_\ell < \sum_{\ell=0}^{L_{\rm MAX}} \frac{4\pi(2\ell+1)}{M_{DM}^2 v^2}$$

$$\sim \frac{4\pi L_{\rm MAX}^2}{M_{DM}^2 v^2} = 4\pi R^2$$

consistent with unitarity limit !

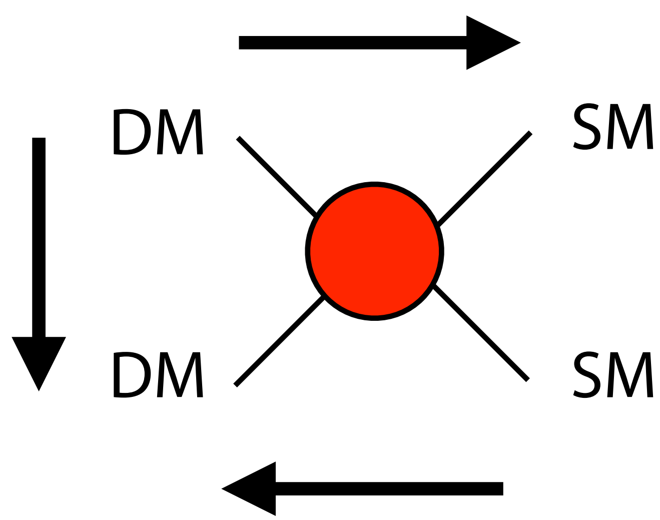
For $R >> 1/(M_{DM}\, v)$, we may have thermal relic dark matter much heavier than ***O(100)TeV !***

Model Building is tough…

see e.g. Harigaya, MI, Kaneta, Nakano, Suzuki JHEP 1608 (2016) 151

✓ *WIMP SUMMARY*

- ✓ Dark Matter density is determined by the annihilation process and it does not depend on the initial condition !
- ✓ Dark Matter can be detected by looking for remnants of its annihilation in the present universe !
- ✓ Dark Matter can be detected by looking for DM scattering onto target materials !
- ✓ Dark Matter can be produced at collider experiments !
- ✓ WIMP is often related to Big Picture !
- ✓ WIMP mass range is rather limited (***O(10)MeV** < M_{WIMP} < **300TeV***)



WIMP detection

Direct WIMP Detection

Look for recoil of DM-nucleus scattering : ***DM + A → DM + A***

Event Rate : $$\frac{dN}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM}} \frac{\sigma_A(q)}{2\mu_A^2} \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} d^3v \frac{f_\oplus(v)}{v}$$

$$v_{\rm min} = \sqrt{\frac{m_A E_R}{2\mu_A^2}} \qquad q = \sqrt{2 m_A E_R}$$

Spin Independent Interaction (A² enhancement !)

$$\mathcal{L}_{\rm int} \propto {\rm DM}^2 \times \bar{\psi}_n \psi_n \longrightarrow \sigma_A = \frac{\mu_A^2}{\mu_n} A^2 F_A(q)^2 \sigma_n$$

Spin dependent Interaction

$$\mathcal{L}_{\rm int} \propto ({\rm DM}^2)_\mu \times \bar{\psi}_n \gamma_5 \gamma^\mu \psi_n \longrightarrow \sigma_A = \frac{\mu_A^2}{\mu_n} \frac{J_A + 1}{J_A} S_n^{A\,2} \sigma_n$$

(A : atomic number, Ψ_n : nucleon, F_A, S^A form factors, J_A spin of nucleus)

Direct WIMP Detection

Standard Halo Model ***(detection rate is model dependent)***

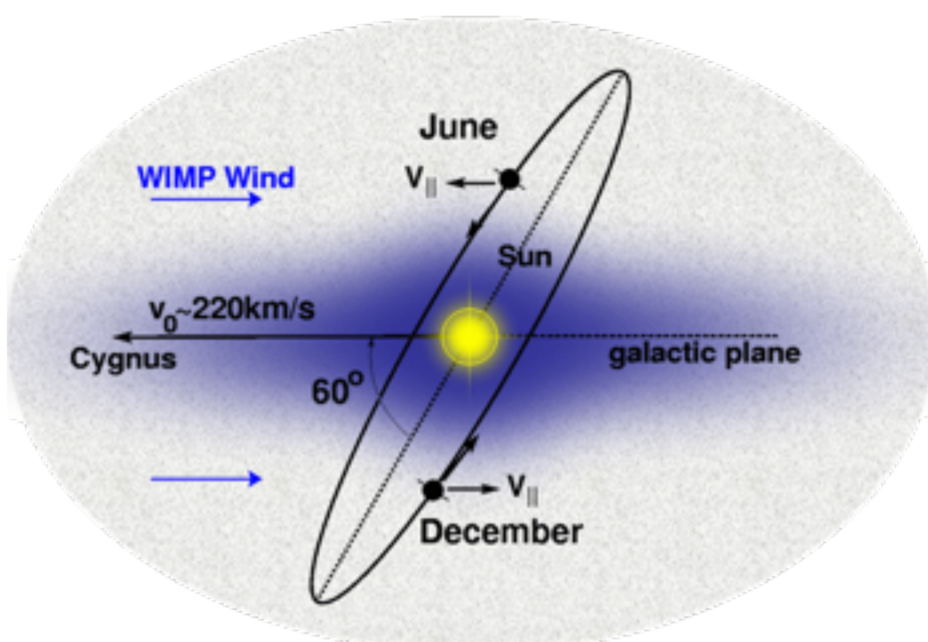
$$f_{\oplus}(\vec{v}) = f_{\rm gal}(\vec{v} + \vec{v}_{\odot} + \vec{v}_{\oplus}(t))$$

$$f_{\rm gal}(\vec{v}) = [\exp(-v^2/\sigma_v^2) - \exp(-v_{\rm esc}^2/\sigma_v^2)] \times \theta(v_{\rm esc} - v)$$

$(\sigma_v = 220 km/s, v_{esc} = 650 km/s)$

solar velocity : ***(0, 220 , 0) + (10 , 13 , 7) km/s***

earth velocity : ***30 km/s***

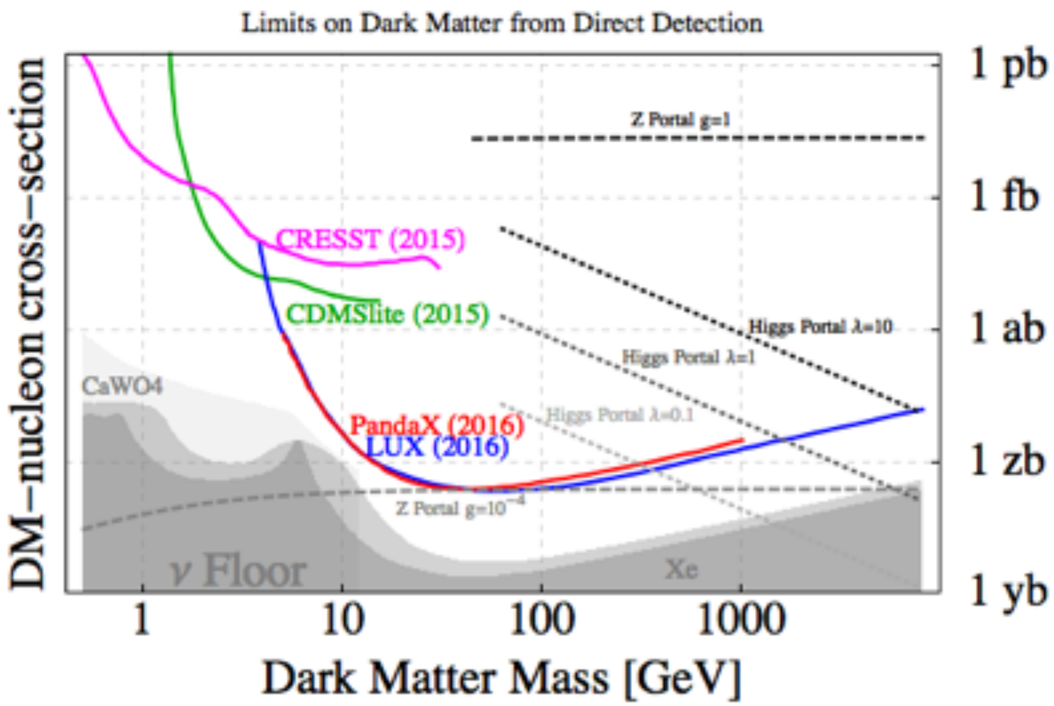


Annual modulation is O(1)% effect !

https://www.hep.shef.ac.uk/research/dm/intro.php

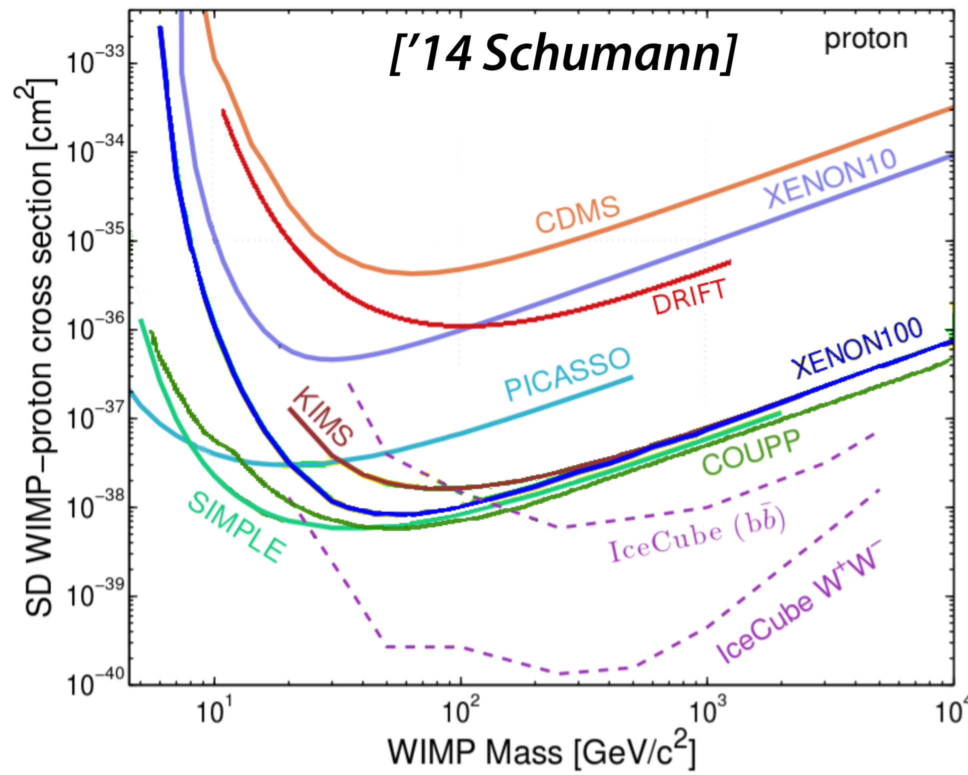
✔ Constraints

Spin Independent (zb = 10^{-45}cm^2)



http://resonaances.blogspot.jp/2016/09/weekend-plot-update-on-wimps.html

Spin dependent



✔ Examples (nucleon - Majorana Dark Matter : χ)

$$\mathcal{L}_{\rm int} = \frac{c_{h\chi\chi}}{2}\, h(\chi\chi + \chi^\dagger\chi^\dagger) \;\rightarrow\; \mathcal{L}_{\rm int} \propto {\rm DM}^2 \times \bar{\psi}_n\psi_n \;\rightarrow\; \sigma_{\rm SI} = 8\times 10^{-45}\ {\rm cm}^2 \left(\frac{c_{h\chi\chi}}{0.1}\right)^2$$

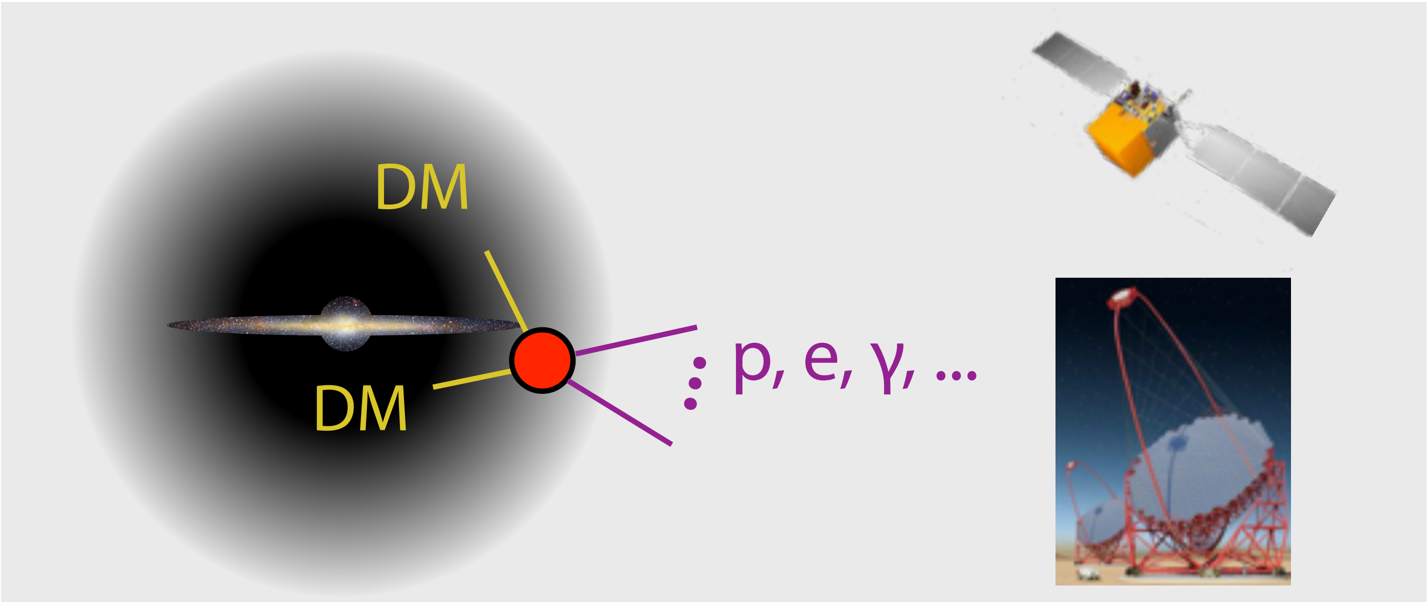
$$\mathcal{L}_{\rm int} = c_{Z\chi\chi}\,\chi^\dagger\bar{\sigma}^\mu\chi Z_\mu \;\rightarrow\; \mathcal{L}_{\rm int} \propto ({\rm DM}^2)_\mu \times \bar{\psi}_n\gamma_5\gamma^\mu\psi_n \;\rightarrow\; \sigma_{\rm SD} = 3\times 10^{-39}\ {\rm cm}^2 \left(\frac{c_{Z\chi\chi}}{0.1}\right)^2$$

✔ Examples (neutron - Dirac Dark Matter : χ)

$$\mathcal{L}_{\rm int} = c^D_{Z\chi\chi}\bar{\chi}\gamma^\mu\chi Z_\mu \;\rightarrow\; \mathcal{L}_{\rm int} \propto ({\rm DM}^2)_\mu \times \bar{\psi}_n\gamma^\mu\psi_n \;\rightarrow\; \sigma_{\rm SI} = 6.8\times 10^{-41}{\rm cm}^2 \left(\frac{c^D_{Z\chi\chi}}{0.1}\right)^2$$

Indirect WIMP Detection (see more arXiv:1511.08787)

Look for the flux of the annihilation products : DM + DM → SM particles



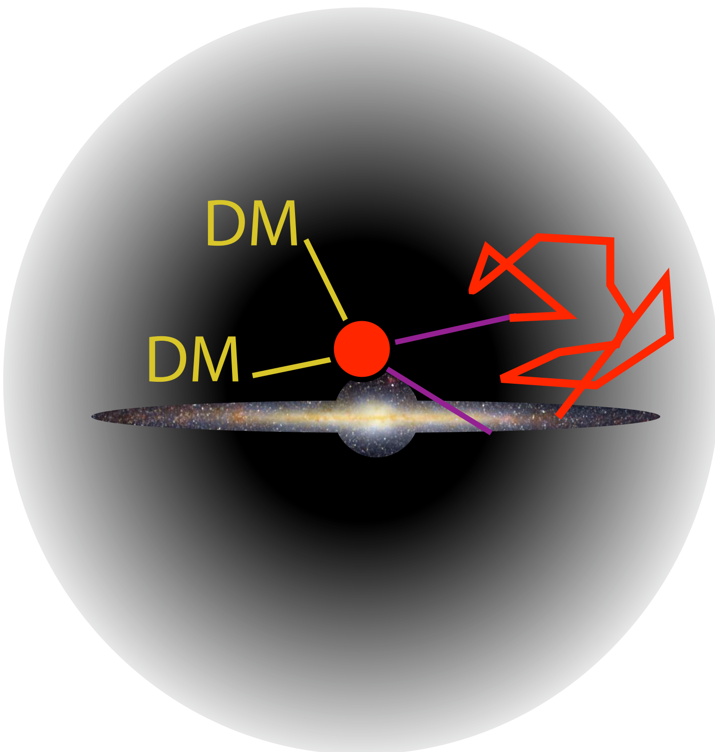
- Cosmic Ray charged particle (proton, electron, etc...)

  They change their direction during the propagation.

- Gamma ray, neutrino fluxes : coming straight from the source.

  Many independent targets (Galactic Center, Cluster, etc...)

Indirect WIMP Detection *(see e.g. ['15 Elor, Rodd, Slatyer, Xue])*



Cosmic Ray charged particle (proton, electron, etc...)

Flux : $\psi(E) \sim Q(E) \times Min[\, t_{diff}, t_{loss}\,]$

t_{diff} = (time scale of diffusion)
$\sim 10^{17} sec \times (E/GeV)^{-\delta}$

t_{loss} = Energy loss rate $\sim E^{-1}$

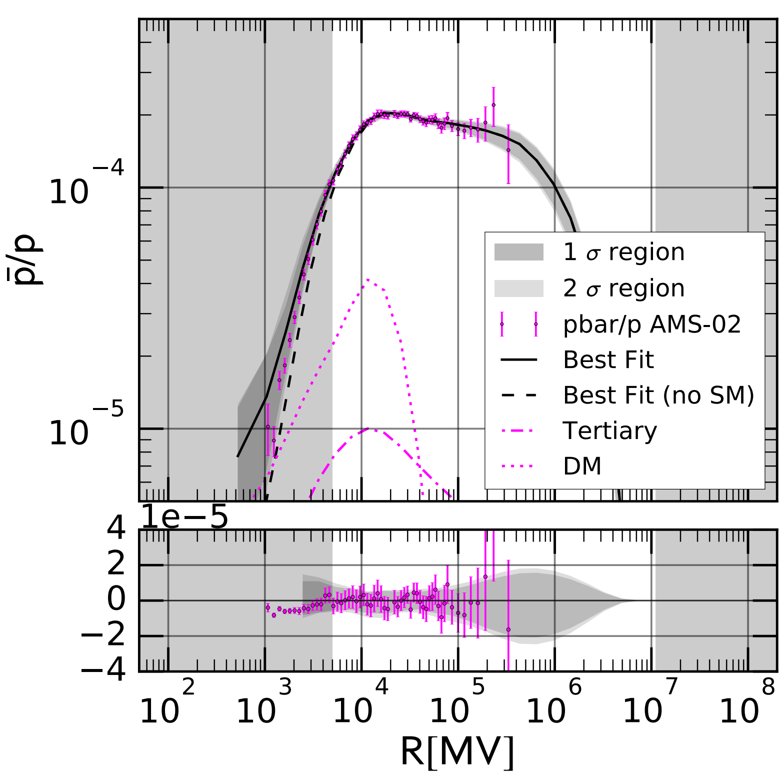
DM annihilation : $Q_x(E) = (\rho_{DM}/m_{DM})^2 <\sigma v> dN_x/dE$

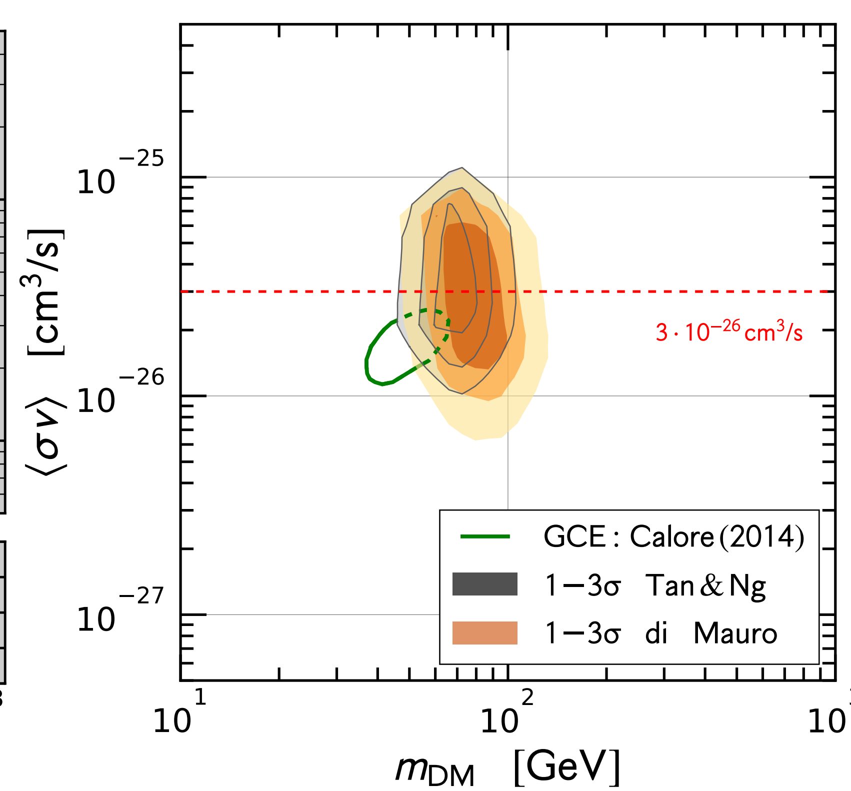
Pros : less sensitive to DM profile in the Milky Way

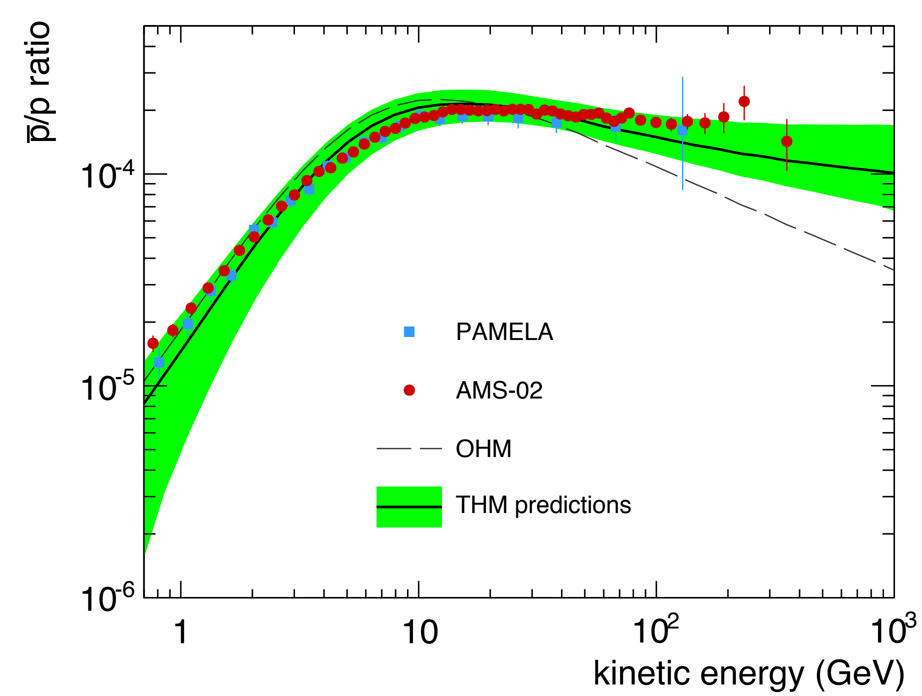
Cons : background/propagation uncertainties

4.5σ detection of DM ? [arXiv: 1610.03071, 1610.03840]

[arXiv: 1610.06182]







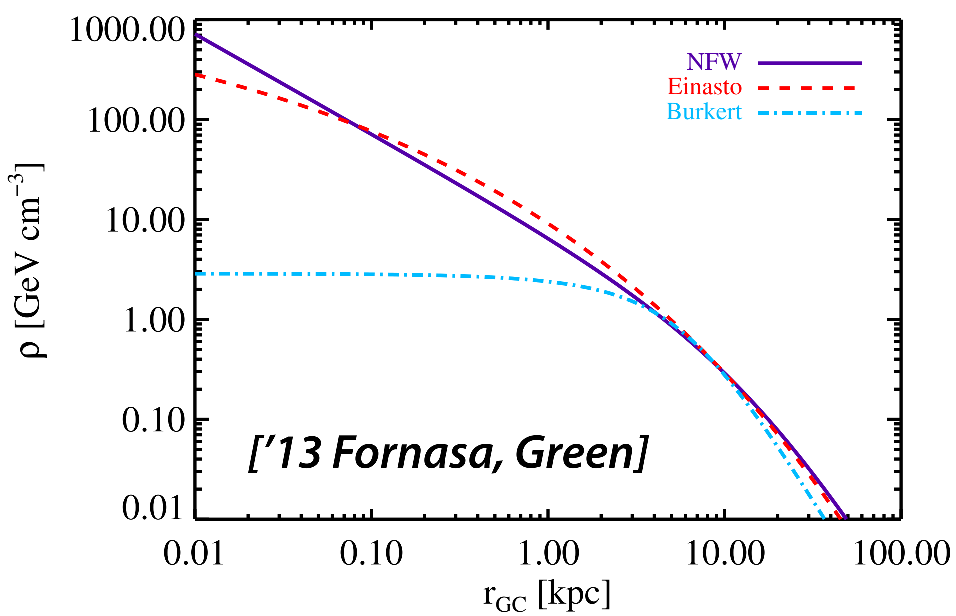
Uncertainties are underestimated !

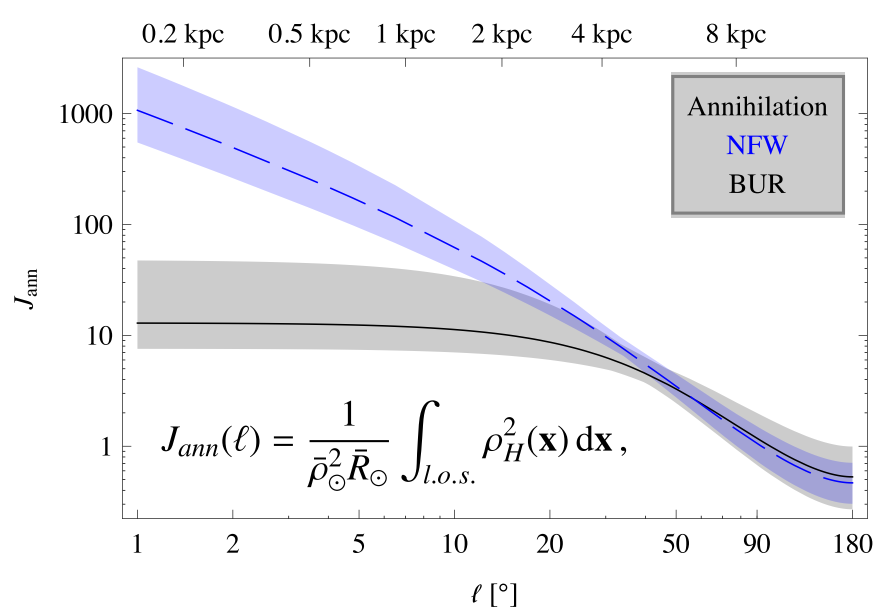
Indirect WIMP Detection (see more arXiv:1511.08787)

Gamma Ray Detection (many independent targets)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2{m_\chi}^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s}\rho^2_{\rm DM}(l,\Omega)\,dl\,d\Omega$$

J-factor : DM profile





['13 Nesti, Salucci]

Galactic Center should be the prime target !

However, the DM profile at the core of the Milky Way has not been understood…

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

(r_s ~ 20kpc)

$$\rho_{\rm Burk}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left(1+\frac{r^2}{r_s^2}\right)}$$

(r_s ~ 6kpc)

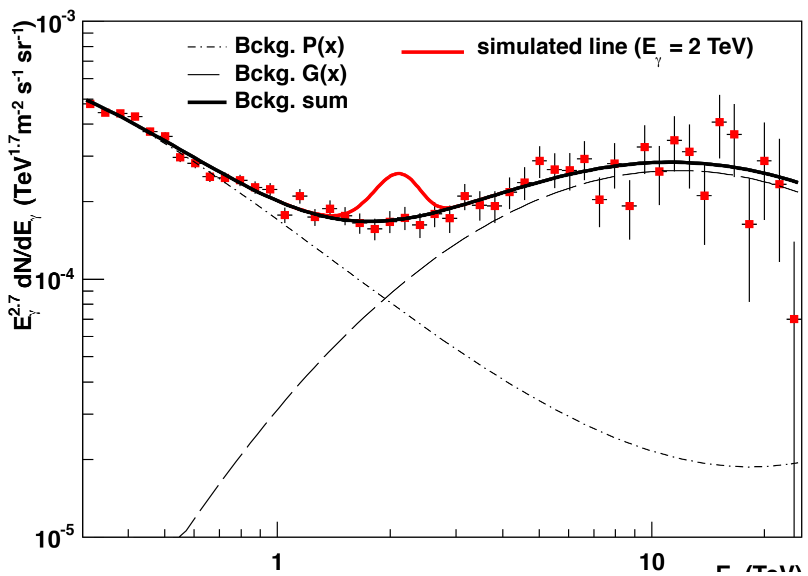
✔ *Indirect WIMP Detection (see more arXiv:1511.08787)*

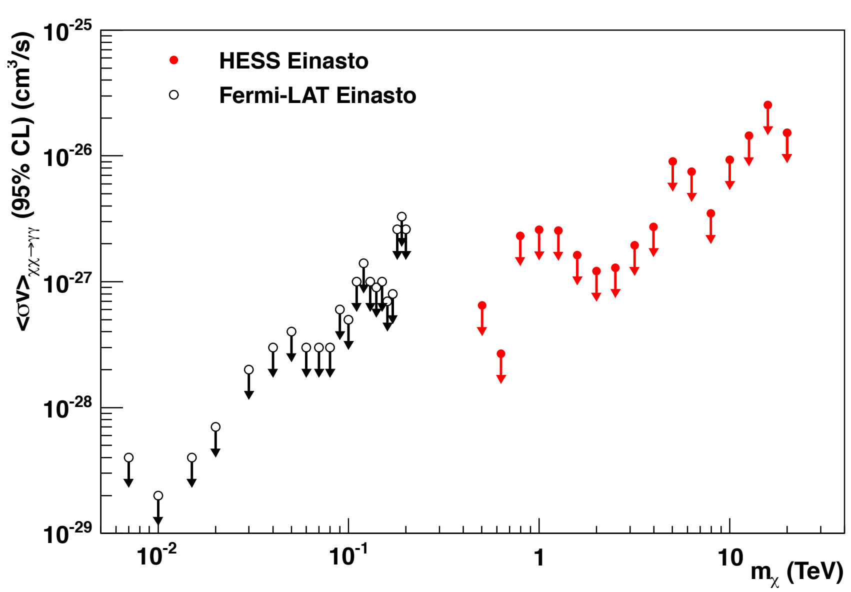
Gamma Ray Detection (many independent targets)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi}\frac{\langle \sigma v \rangle}{2{m_\chi}^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s}\rho^2_{\rm DM}(l,\Omega)\,dl\,d\Omega$$

J-factor : DM profile

['13 H.E.S.S.]





✔ *Gamma Ray Line Search From Galactic Center*

Galactic Center should be the prime target !

Lots of background gamma ray !

→ search for line spectrum !

H.E.S.S. $\theta < 1°$ ($|b| > 0.3°$)

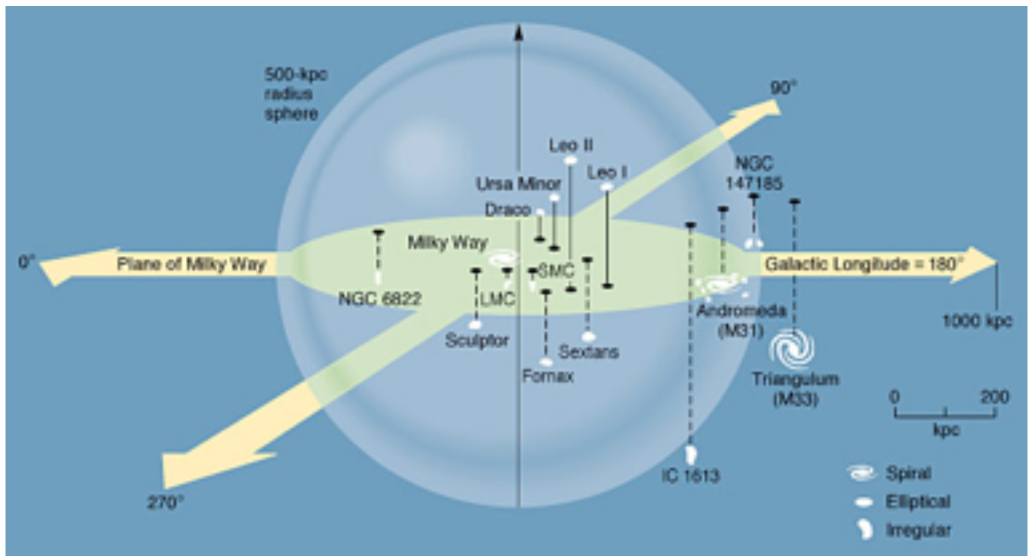
O(100) profile uncertainty

FERMI-LAT 20° x 20°($|b| > 10°$)

O(10) profile uncertainty

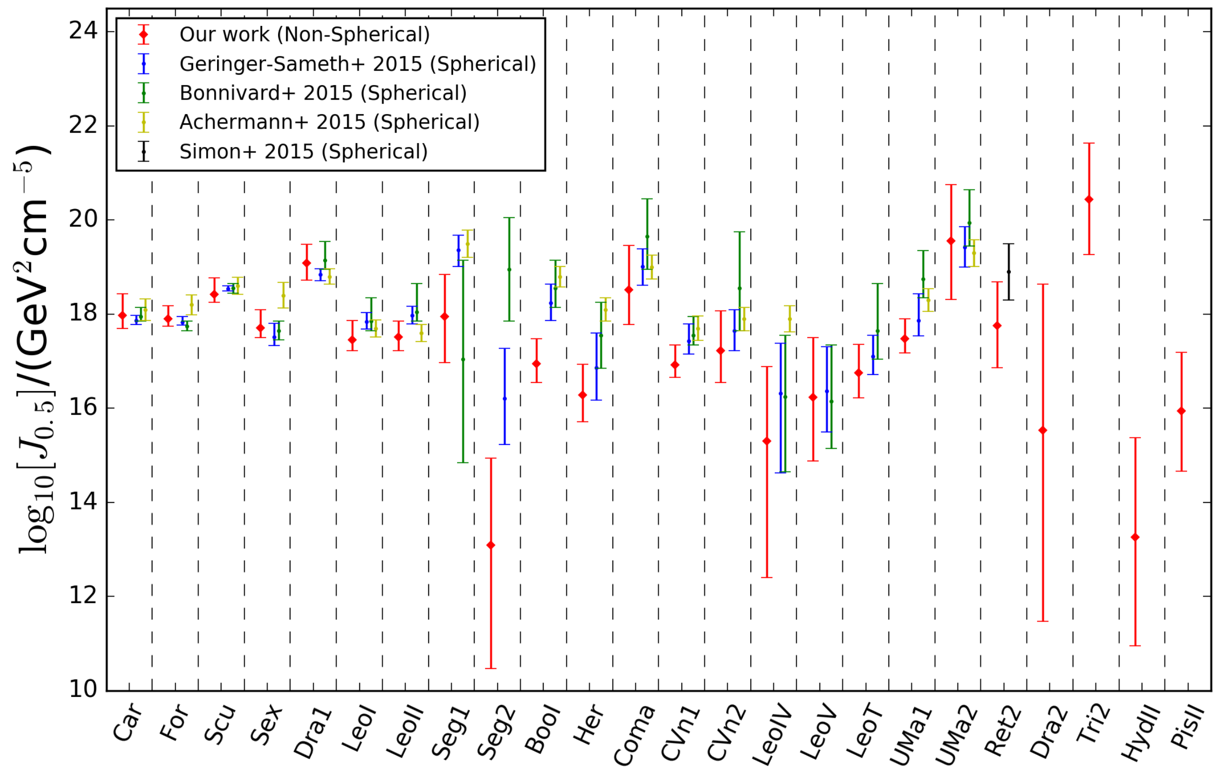
✓ Indirect WIMP Detection (see more arXiv:1511.08787)

✓ Dwarf Spheroidal Galaxies !



http://astronomy.nmsu.edu/tharriso/ast110/class24.html

['16 Hayashi, Ishikawa, Matsumoto, MI, Ishigaki, Sugai]



Object	N_{sample}	RA(J2000) [hh:mm:ss]	DEC(J2000) [dd:mm:ss]	M_V	$D_\odot$ [kpc]	b_* [pc]	q' (axial ratio)	Ref.[a]
Classical dwarfs								
Carina	776	06:41:36.7	−50:57:58	-9.1 ± 0.5	106 ± 6	250 ± 39	0.67 ± 0.05	1,6
Fornax	2523	02:39:59.3	−34:26:57	-13.4 ± 0.3	147 ± 12	710 ± 77	0.70 ± 0.01	1,6
Sculptor	1360	01:00:09.4	−33:42:33	-11.1 ± 0.5	86 ± 6	283 ± 45	0.68 ± 0.03	1,6
Sextans	445	10:13:03.0	−01:36:53	-9.3 ± 0.5	86 ± 4	695 ± 44	0.65 ± 0.05	1,6
Draco	468	17:20:12.4	+57:54:55	-8.8 ± 0.3	76 ± 6	221 ± 19	0.69 ± 0.02	1,7
Leo I	328	10:08:28.1	+12:18:23	-12.0 ± 0.3	254 ± 15	251 ± 27	0.79 ± 0.03	1,8
Leo II	200	11:13:28.8	+22:09:06	-9.8 ± 0.3	233 ± 14	176 ± 42	0.87 ± 0.05	1,9
Ultra faint dwarfs								
Segue 1	73	10:07:04.0	+16:04:55	-1.5 ± 0.8	32 ± 6	29^{+8}_{-5}	0.53 ± 0.10	1,10
Segue 2	24	02:19:16.0	+20:10:31	-2.5 ± 0.3	35 ± 2	35 ± 3	0.85 ± 0.13	1,11
Boötes I	37	14:00:06.0	+14:30:00	-6.3 ± 0.2	66 ± 2	242 ± 21	0.61 ± 0.06	1,12
Hercules	18	16:31:02.0	+12:47:30	-6.6 ± 0.4	132 ± 12	330^{+75}_{-52}	0.32 ± 0.08	1,13
Coma Berenices	59	12:26:59.0	+23:54:15	-3.7 ± 0.6	44 ± 4	64 ± 7	0.62 ± 0.14	1,14
Canes Venatici I	214	13:28:03.5	+33:33:21	-7.9 ± 0.5	224^{+22}_{-20}	554 ± 63	0.61 ± 0.03	1,14
Canes Venatici II	25	12:57:10.0	+34:19:15	-4.8 ± 0.6	151^{+15}_{-13}	132 ± 16	0.48 ± 0.11	1,14
Leo IV	18	11:32:57.0	−00:32:00	-5.1 ± 0.6	158^{+15}_{-14}	152 ± 17	0.51 ± 0.11	1,14
Leo V	5	11:31:09.6	+02:13:12	-5.2 ± 0.4	178 ± 10	135 ± 32	0.50 ± 0.15	1,15
Leo T	19	09:34:53.4	+17:03:05	-7.1 ± 0.3	417^{+20}_{-19}	170 ± 15	~ 1.00	1,14
Ursa Major I	39	10:34:52.8	+51:55:12	-5.6 ± 0.6	106^{+9}_{-8}	308 ± 32	0.20 ± 0.04	1,14
Ursa Major II	20	08:51:30.0	+63:07:48	-3.8 ± 0.6	32^{+5}_{-4}	127 ± 21	0.37 ± 0.05	1,14
Reticulum II	25	03:35:42.1	−54:02:57	-2.7 ± 0.1	32 ± 3	32^{+2}_{-1}	0.41 ± 0.03	2,16
Draco II	9	15:52:47.6	+64:33:55	-2.9 ± 0.8	20 ± 3	19^{+8}_{-6}	$0.76^{+0.27}_{-0.24}$	3,17
Triangulum II	13	02:13:17.4	+36:10:42	-1.8 ± 0.5	30 ± 2	34^{+9}_{-8}	$0.79^{+0.17}_{-0.21}$	4,18
Hydra II	13	12:21:42.1	−31:59:07	-4.8 ± 0.3	134 ± 10	68 ± 11	$0.99^{+0.01}_{-0.19}$	5,19
Pisces II	7	22:58:31.0	+05:57:09	-5.0 ± 0.5	~ 180	~ 60	0.60 ± 0.10	1,19

DM profile can be estimated from motions of stars.

We observe gamma ray flux from entire dwarf galaxies .

→ less sensitive to the structure of the core region!

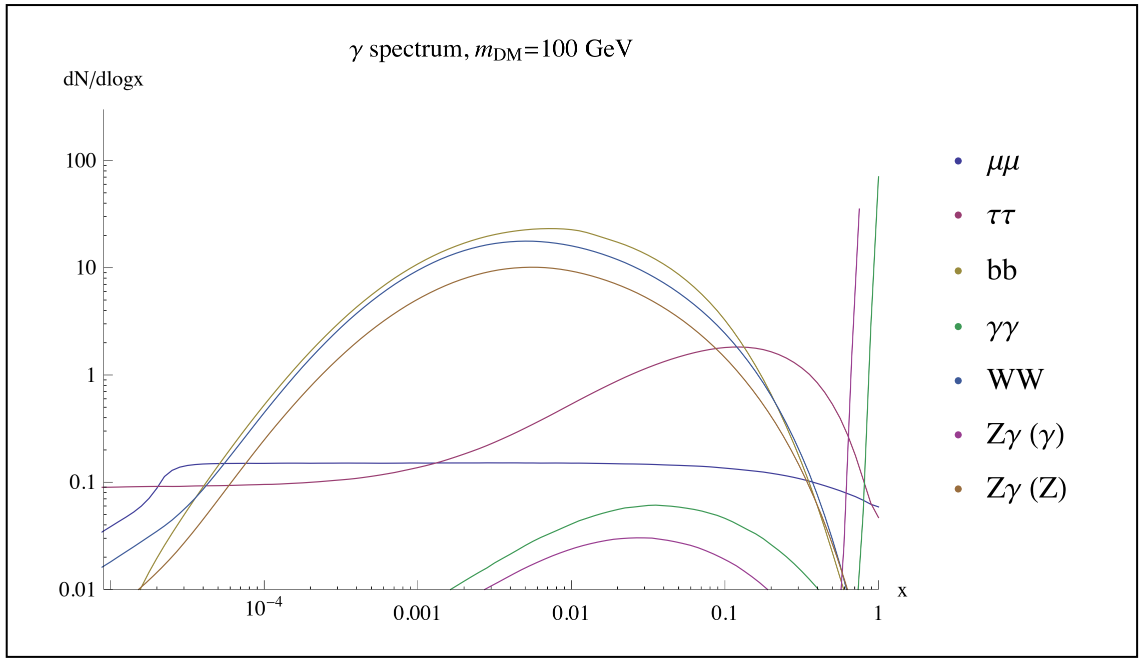
Less active, and hence, less background gamma ray.

Indirect WIMP Detection (see more arXiv:1511.08787)

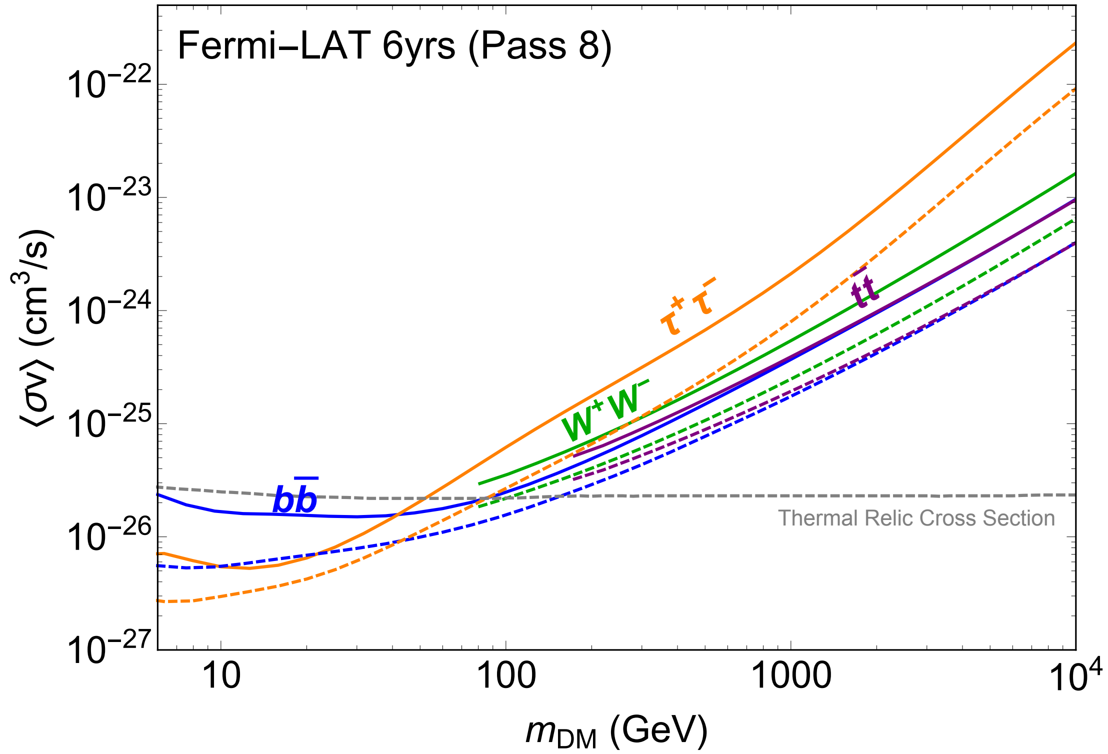
Constraints on continuous spectrum from dwarf Spheroidal Galaxy

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2{m_\chi}^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s}\rho^2_{\mathrm{DM}}(l,\Omega)dld\Omega$$

['15 Carpenter, Colburn, Goodman]



['16 Hayashi, Ishikawa, Matsumoto, MI, Ishigaki, Sugai]



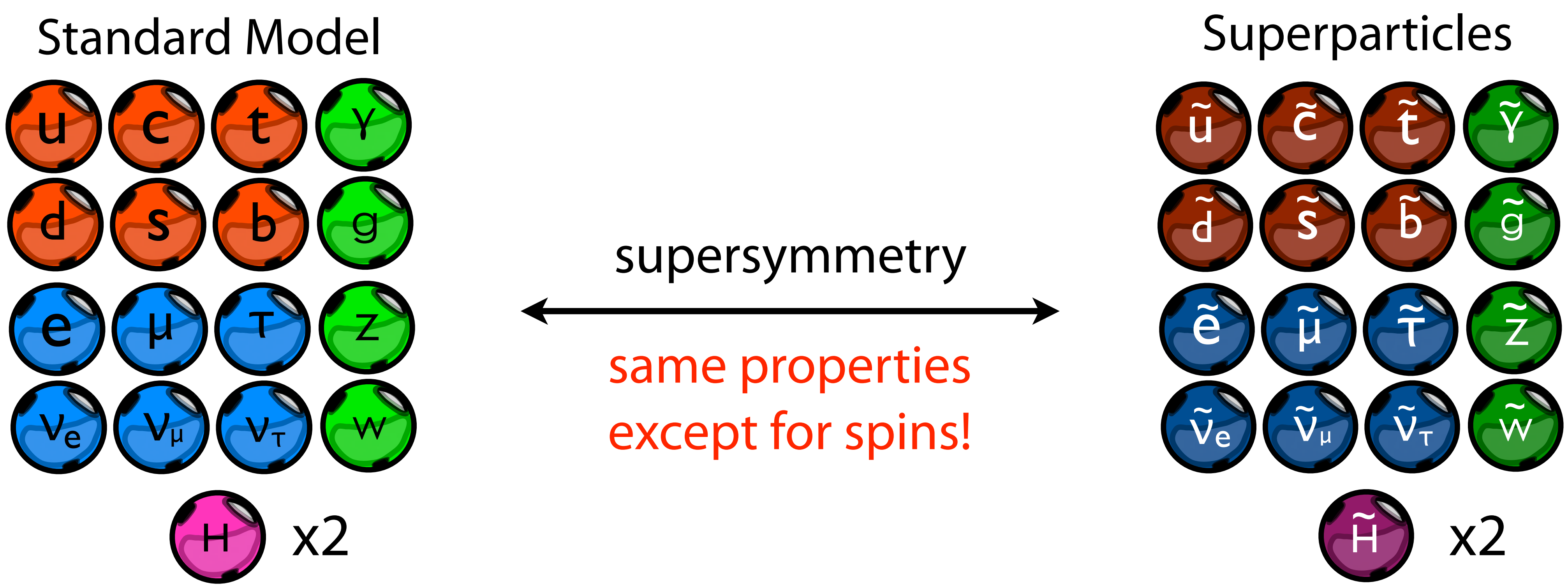
WIMP cross section has been excluded for m_{DM} < 100GeV annihilating into bb!

WIMP examples

WIMP example

Supersymmetric Standard Model

- We just enlarge spacetime symmetry to supersymmetry !



Advantage : Higgs Mass protection from quantum fluctuation !

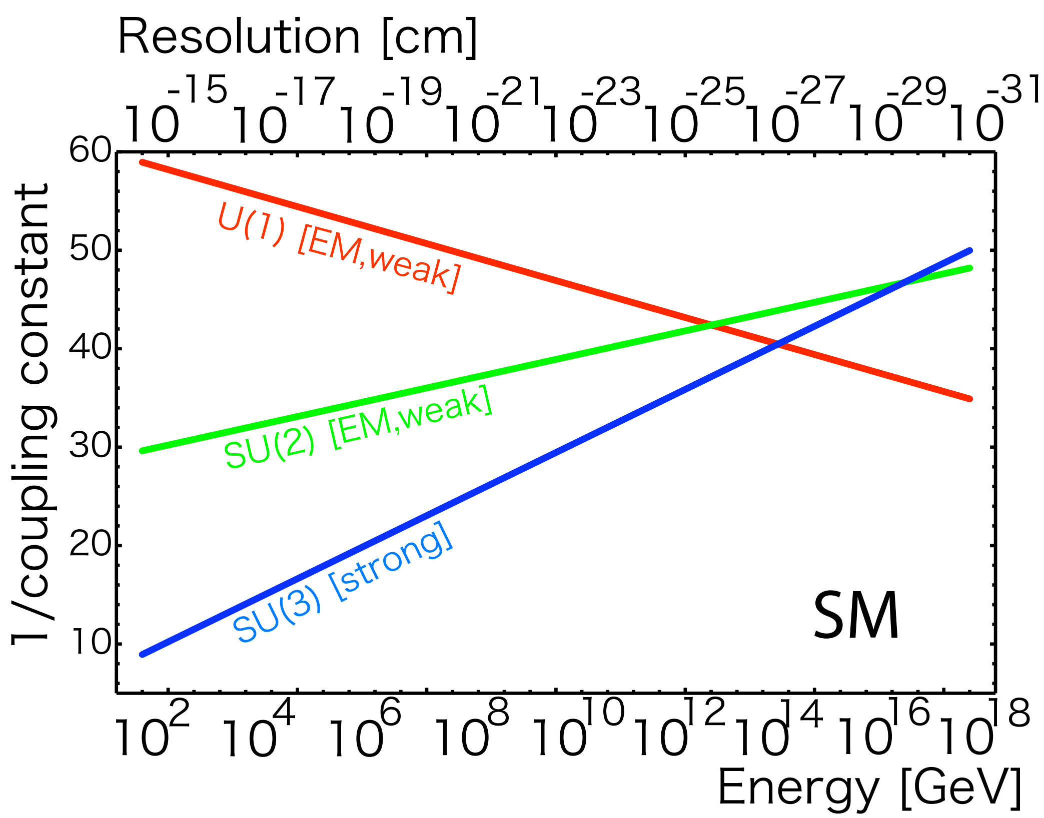
(Supersymmetry is eventually broken spontaneously
→ Superparticles are heavier than the Standard Model particles)

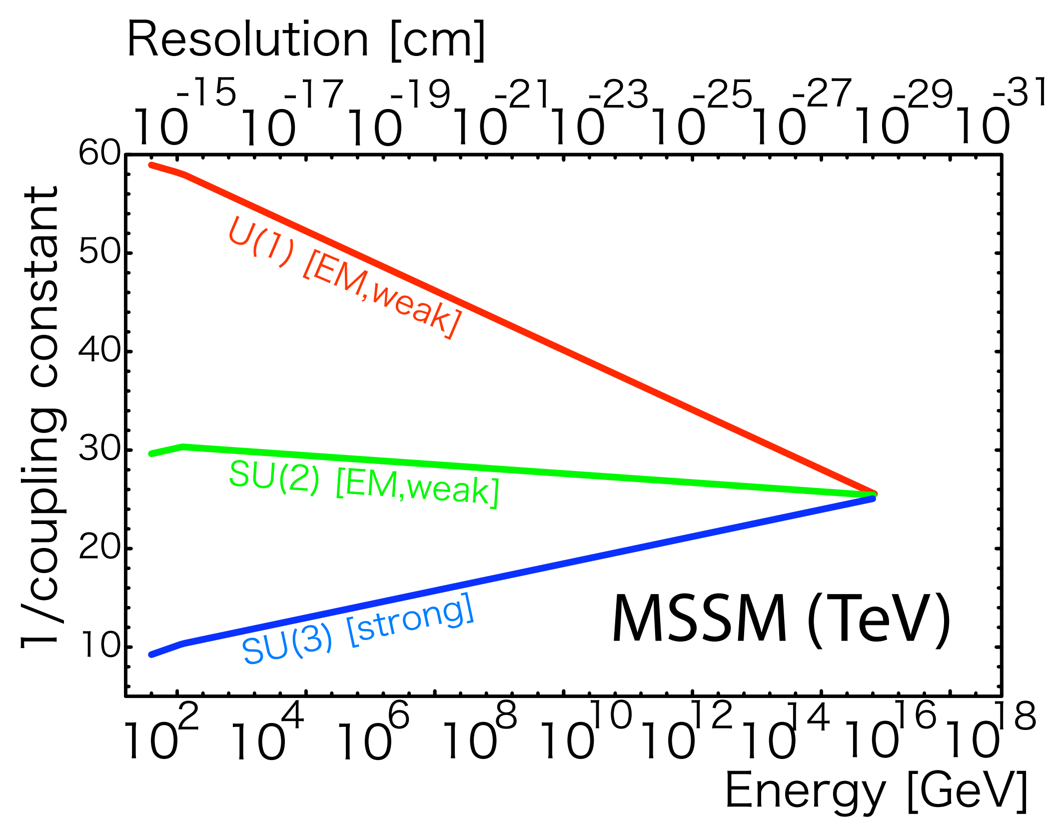
WIMP example

Supersymmetric Standard Model

Big Bonus !

Just by introducing the superpartners at around ***TeV***, the gauge coupling unification become more precise!





Supersymmetric standard model is perfectly consistent with GUT !

✓ *WIMP example*

Supersymmetric Standard Model

✓ Dark Matter Candidates = Superpartners of neutral particles.

Photon, Z-boson, Higgs boson → Neutralino (Bino, Neutral Wino, Higgsino)

Neutrino → Sneutrino

Graviton → Gravitino

How about the stability?

The lightest supersymmetric particle (LSP) can be stable !

The Neutralino LSP DM is most successful !

The neutralino LSP is the lightest mixed state of Bino, Neutral Wino, Higgsino.

The DM properties (abundance etc) depend on the compositions.

The composition depends on model parameters.

(Sneutrino DM has been excluded by direct detection experiments : $c_{Z\chi\chi}^{D} \sim 1$)

(Gravitino DM is possible but it is not WIMP (too weak interaction).)

WIMP example

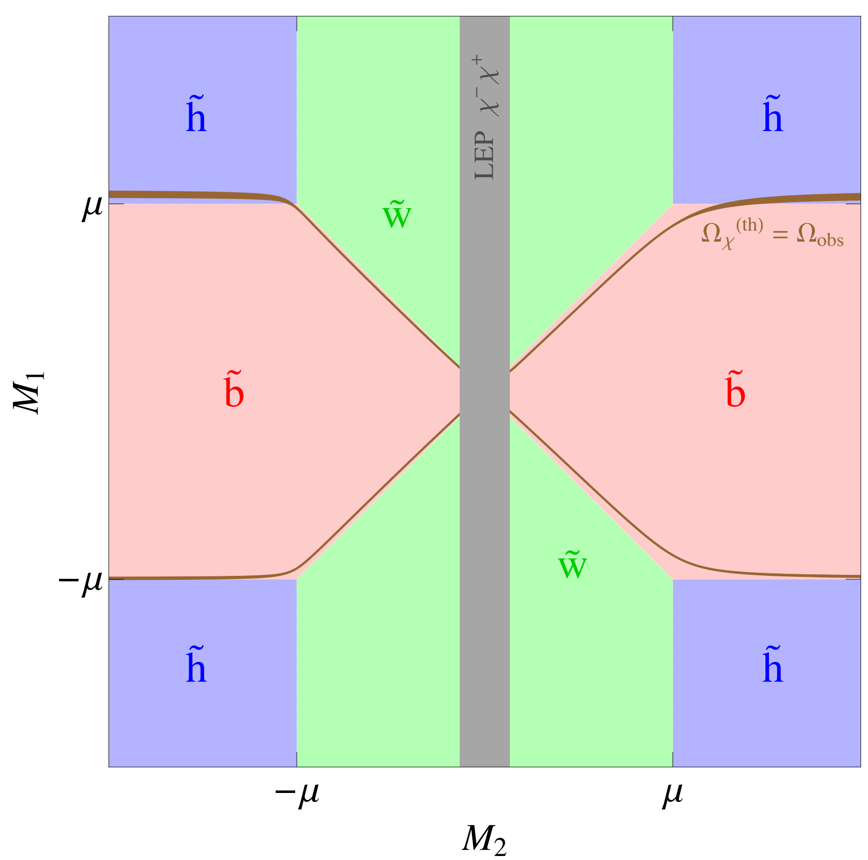
Neutralino mixing mass

$$M_\chi = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v\cos\beta & \frac{1}{2}g'v\sin\beta \\ 0 & M_2 & \frac{1}{2}gv\cos\beta & -\frac{1}{2}gv\sin\beta \\ -\frac{1}{2}g'v\cos\beta & \frac{1}{2}gv\cos\beta & 0 & -\mu \\ \frac{1}{2}g'v\sin\beta & -\frac{1}{2}g'v\cos\beta & -\mu & 0. \end{pmatrix} \begin{matrix} \textit{bino} \\ \textit{wino} \\ \textit{Higgino1} \\ \textit{Higgino2} \end{matrix}$$

→ *lightest Neutralino is DM !*

Main component of the LSP

bino / wino / Higgsino DM



['12 Cheung, Hall, Pinner, Ruderman]

Pure Bino LSP : too small cross section to be WIMP

Pure Wino LSP : WIMP cross section at M_{wino} ~ 3TeV

Pure Higgsino LSP : WIMP cross section at $M_{Higgsino}$ ~ 1TeV

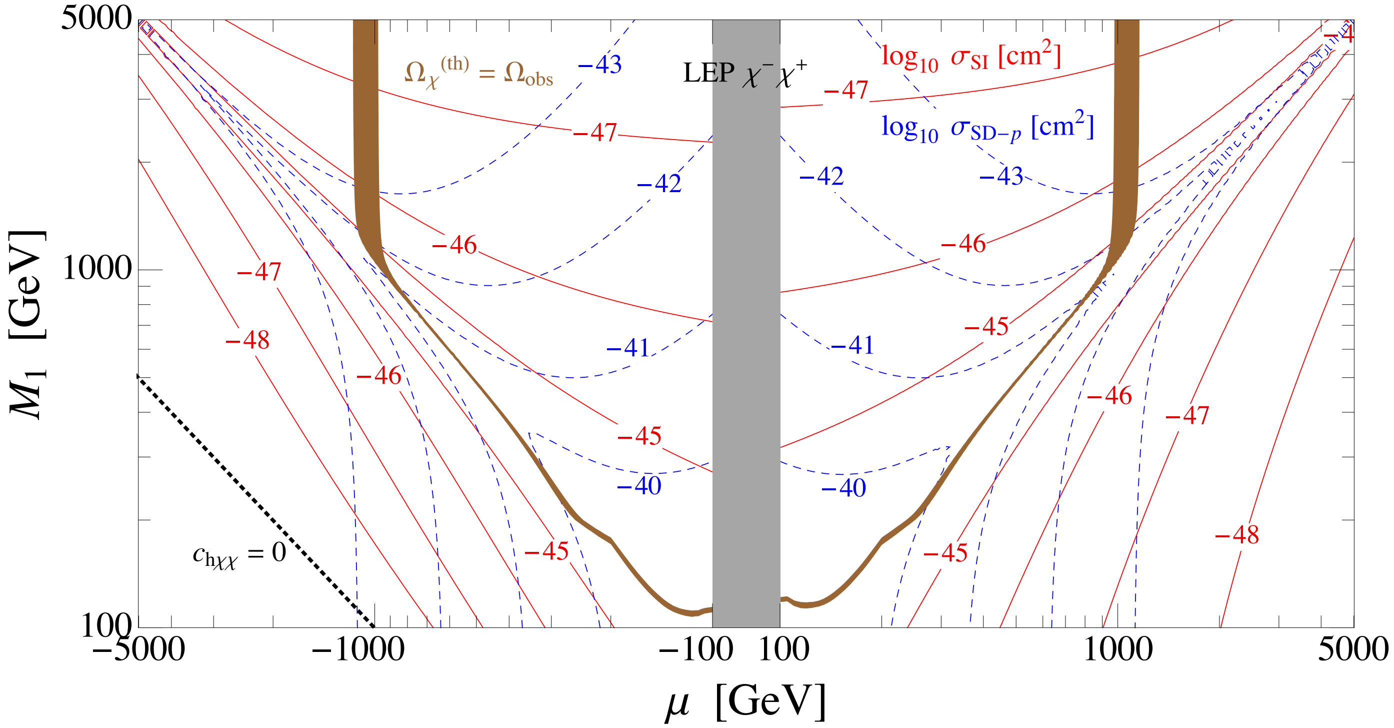
For WIMP with M_χ < TeV, we need appropriate mixing !

→ $C_{h\chi\chi}$ and $C_{Z\chi\chi}$ tend to be unsuppressed.

→ Direct detection cross sections are rather unsuppressed.

✔ *WIMP example*

['12 Cheung, Hall, Pinner, Ruderman]



On the brown lines, the dark matter abundance is consistent with observation !

✔ Direct detection searches give complemental information to the LHC searches and the indirect searches (***<σv> ~ 10^{-9}GeV^{-2}***).

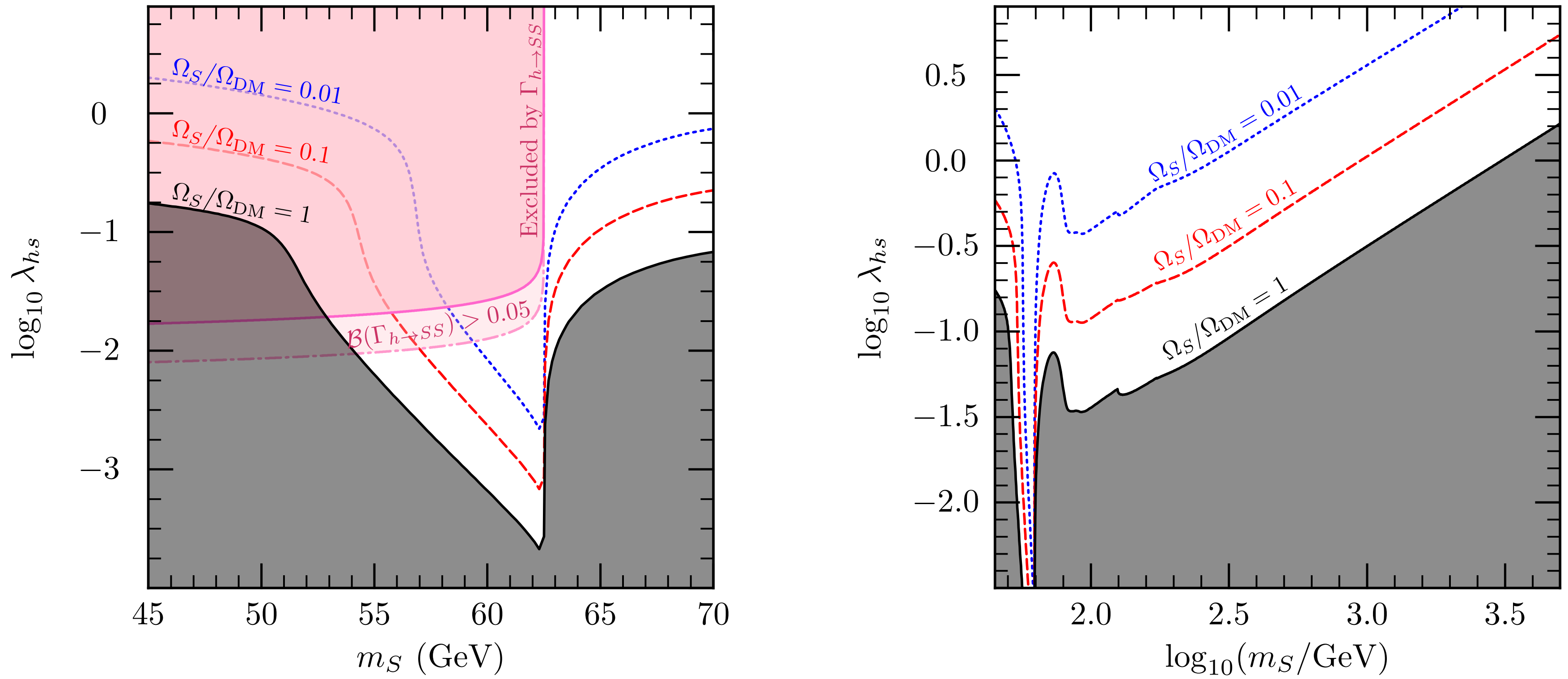
WIMP example

singlet scalar dark matter

Just add a stable scalar singlet S

$$V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hs} S^2 |H|^2 \ .$$

Abundance is explained by S+S→h+h annihilation !



[e.g. '13 Cline, Scott, Kainulainen, Wenigner]

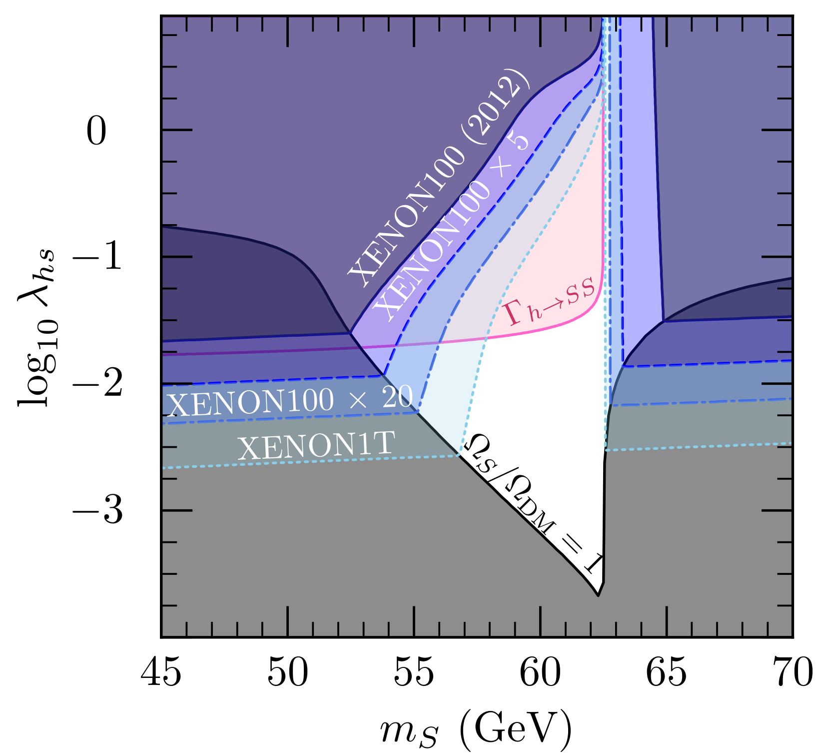
WIMP example

singlet scalar dark matter

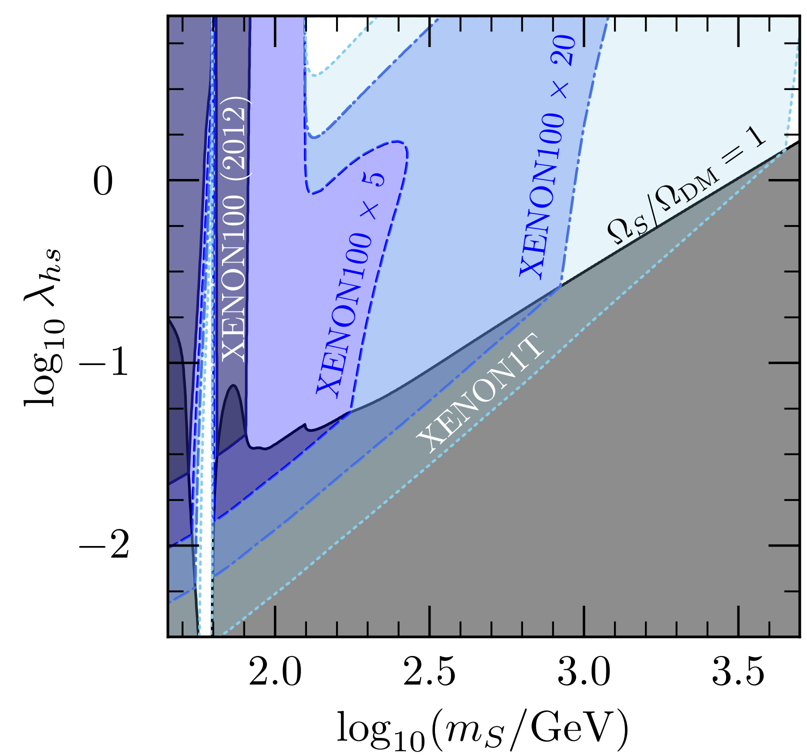
Just add a stable scalar singlet S

$$V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hs} S^2 |H|^2 \; .$$

Constrained by the direct detection experiments ($C_{h\chi\chi} \sim \lambda_{hs} v_H / m_S$)



LUX ~ XENON100 x 5



[e.g. '13 Cline, Scott, Kainulainen, Wenigner]

✔ *WIMP example*

✔ *Minimal Dark Matter ['05 Cirelli, Fornengo, Strumia]*

Just add SU(2) triplet fermion (← same charges with W&Z boson !)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\tilde{\chi}}^0 \left(i\partial\!\!\!/ - M_2\right)\tilde{\chi}^0 + \bar{\tilde{\chi}}^- \left(i\partial\!\!\!/ - M_2\right)\tilde{\chi}^-$$
$$-g\left(\bar{\tilde{\chi}}^0 W\!\!\!\!/^{\dagger}\tilde{\chi}^- + h.c.\right) + g\bar{\tilde{\chi}}^-\left(c_W Z\!\!\!/ + s_W A\!\!\!/\right)\tilde{\chi}^-$$

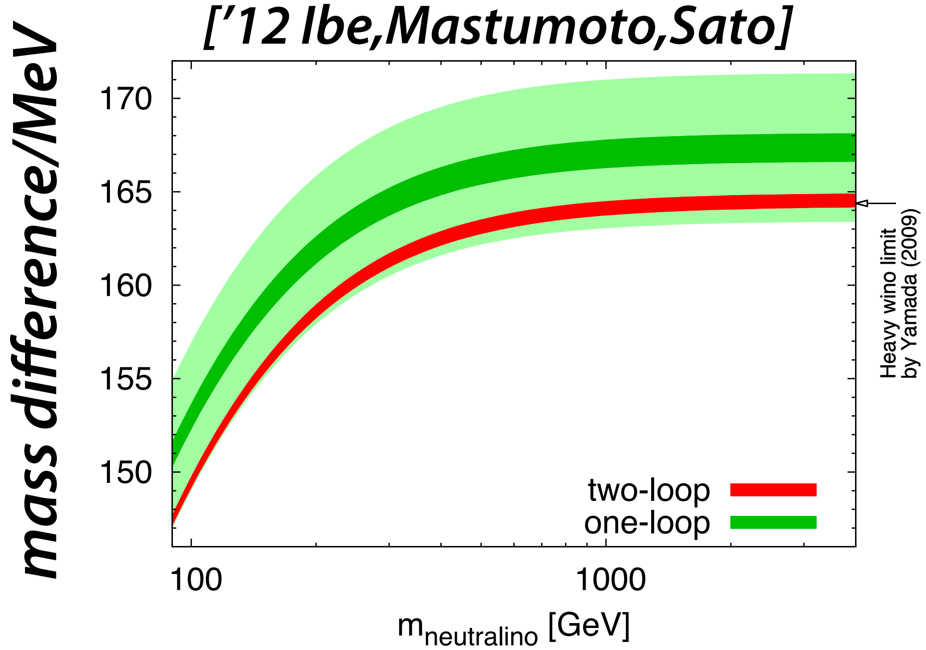
All the interactions are determined by gauge interactions.

Free parameter = Mass !

(This is nothing but the PURE WINO LSP in supersymmetry)

Triplet fermion = Charged component + Neutral component

['12 Ibe,Mastumoto,Sato]



Decay mode : $\chi^{\pm} \rightarrow \chi^0 + \pi^{\pm}$: $\tau_{wino} = O(10^{-10})$ *sec.*

Disappearing track search at LHC

$m_{triplet} > 270\,\text{GeV}$ ($8\,\text{TeV}\,\&\,20\,\text{fb}^{-1}$)

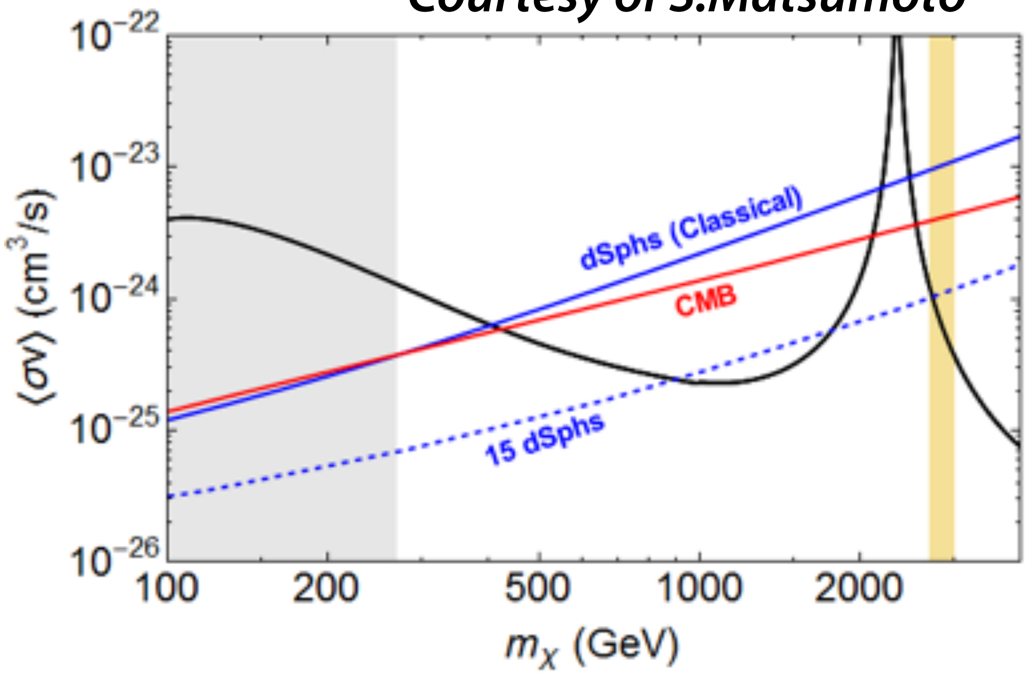
[arXiv:1310.3675]

WIMP example

<u>Minimal Dark Matter *['05 Cirelli, Fornengo, Strumia]*</u>

Indirect search by gamma-ray from dwarf Spheroidal galaxies are promising !

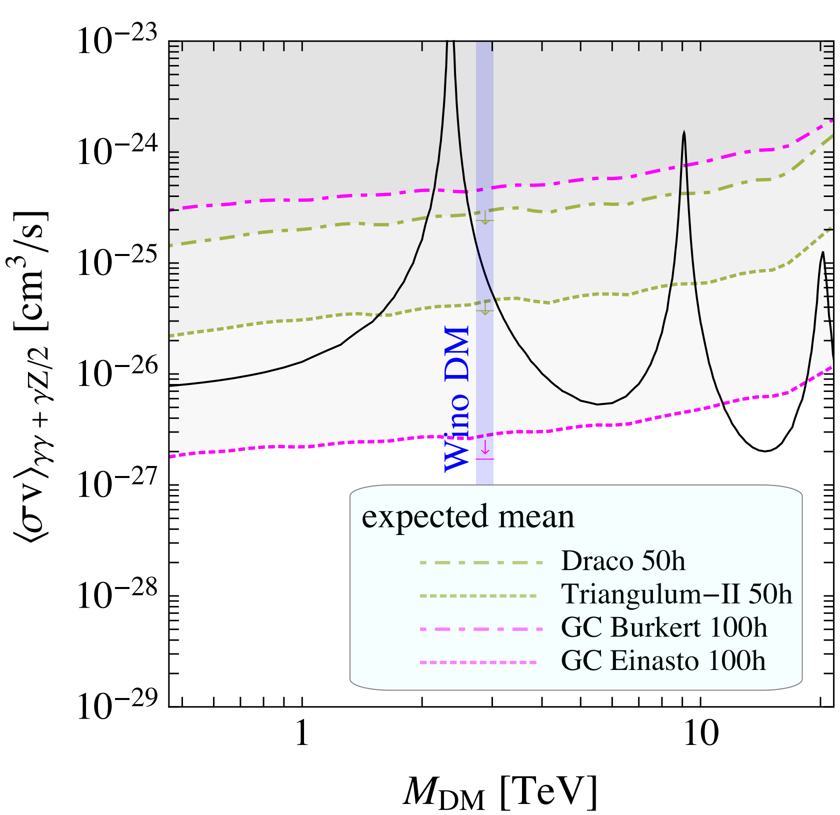
Courtesy of S.Matsumoto



Fermi-LAT 6 years data excluded the triplet dark matter in

$m_{triplet}$ < 400 GeV (classical dSphs)

[For recent J-factor estimation '16 Hayashi, Ichikawa, Matsumoto, MI, Ishigaki, Sugai]



Future prospect at CTA

Dwarf looks better target than the galactic center by taking the DM profile of the galactic center into account!

['16 Lefranca, Moulina, Panci, Sala, Silk]

Hotter Dark Matter

Hotter Dark Matter

In the WIMP scenario, the DM decouples from thermal bath at $T < m_{DM}$

If the DM couples to thermal bath more weakly, it can decouple at $T >> m_{DM}$

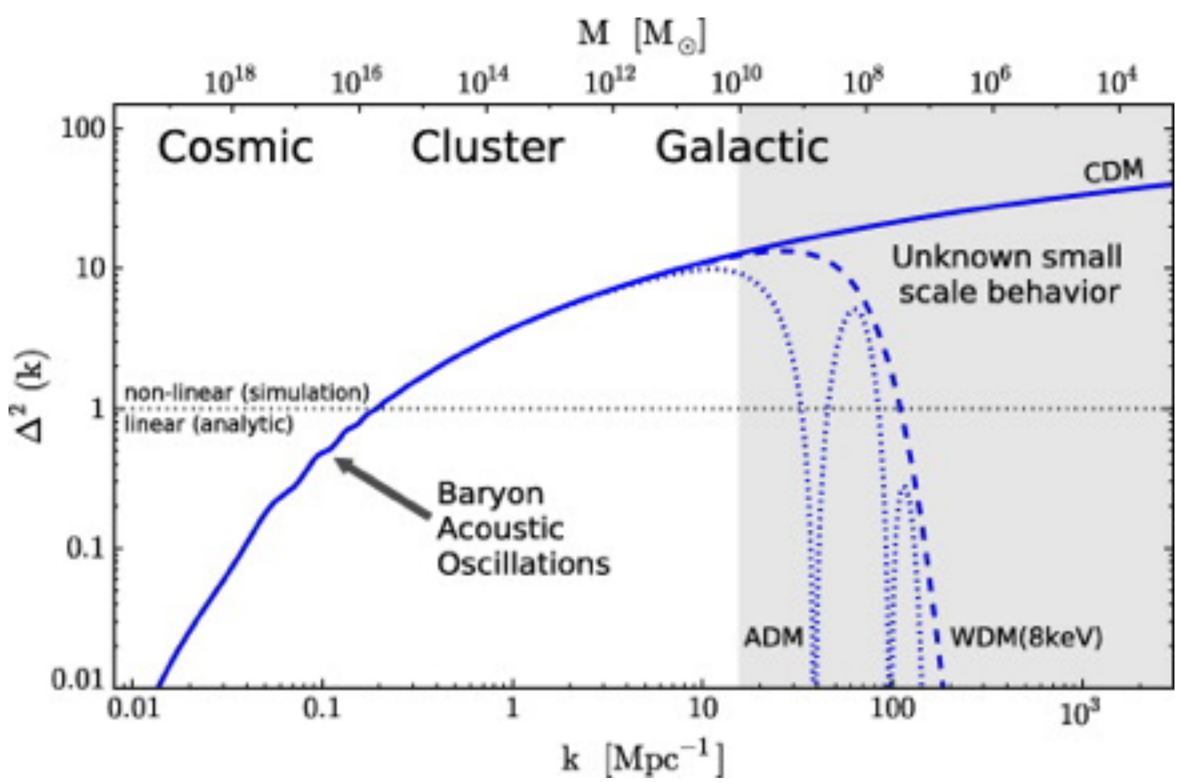
→ ***HOT RELIC***

- Neutrino (decouple at $T \sim 1 MeV$)

$$\Omega_\nu h^2 \simeq \left(\frac{\sum m_\nu}{90\mathrm{eV}} \right)$$

- Light Gravitino at $T_D >> m_{3/2}$

$$\Omega_{3/2} h^2 \simeq \left(\frac{10.75}{g_S(T_D)} \right) \left(\frac{m_{3/2}}{90\mathrm{eV}} \right)$$



[Credit: Michael Kuhlen, Mark Vogelsberger, and Raul Angulo]

Hot Relic has a velocity $v \sim T/m$ at $T < m$.

Erases structure smaller than

$L_{fs} < 80$ *Mpc (10eV/m)*

→ ***HOT DARK MATTER (INCONSISTENT !)***

✓ *Warm dark matter*

If we can ***dilute*** the dark matter appropriately,

$$\Omega_{3/2}h^2 \simeq \left(\frac{100}{\Delta}\right)\left(\frac{10.75}{g_S(T_D)}\right)\left(\frac{m_{3/2}}{10\mathrm{keV}}\right)$$

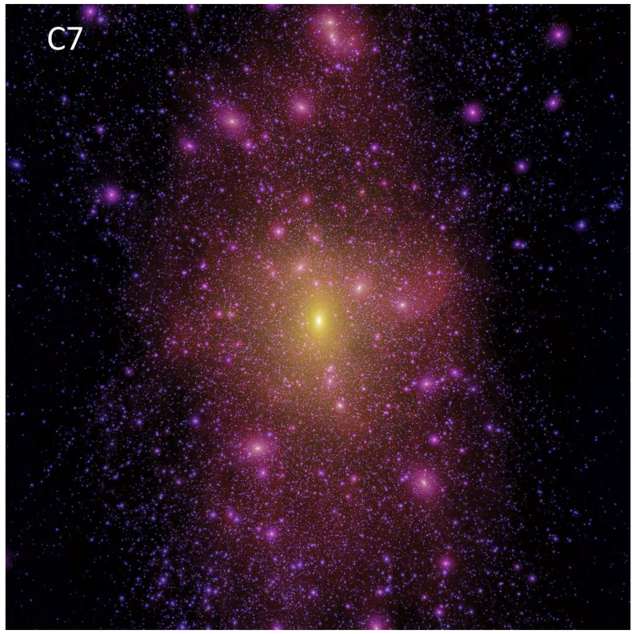
gravitino can be warm dark matter

L_{fs} < 0.1 Mpc (10keV/m)

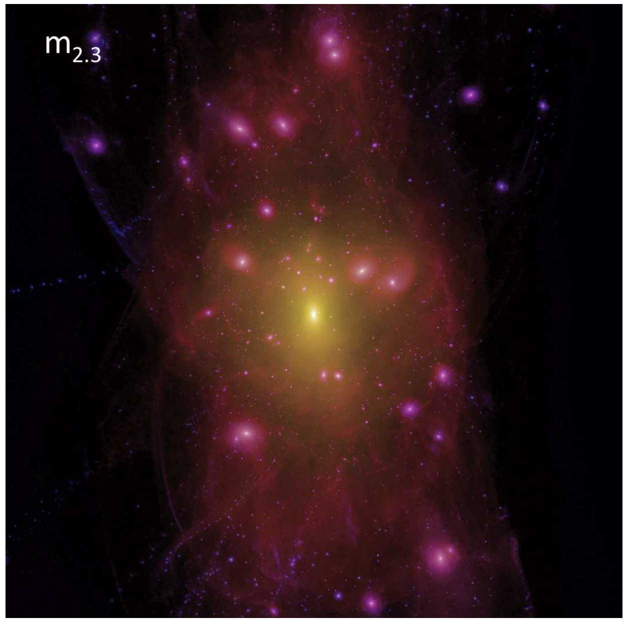
✓ The "missing satellites" problem

The Milky Way has only about 25 satellites.
CDM simulation predicts a very large number of subhalos.

CDM



WDM(2.3keV)



['13 Lovell, Frenk,Eke, Jenkins, Gao, Theuns]

The number of satellite galaxies is too small for ***m_{DM} < 2.2 keV***.

CDM + ***Baryon*** simulation are important !

✓ *Warm dark matter*

If we can ***dilute*** the dark matter appropriately,

$$\Omega_{3/2}h^2 \simeq \left(\frac{100}{\Delta}\right)\left(\frac{10.75}{g_S(T_D)}\right)\left(\frac{m_{3/2}}{10\mathrm{keV}}\right)$$

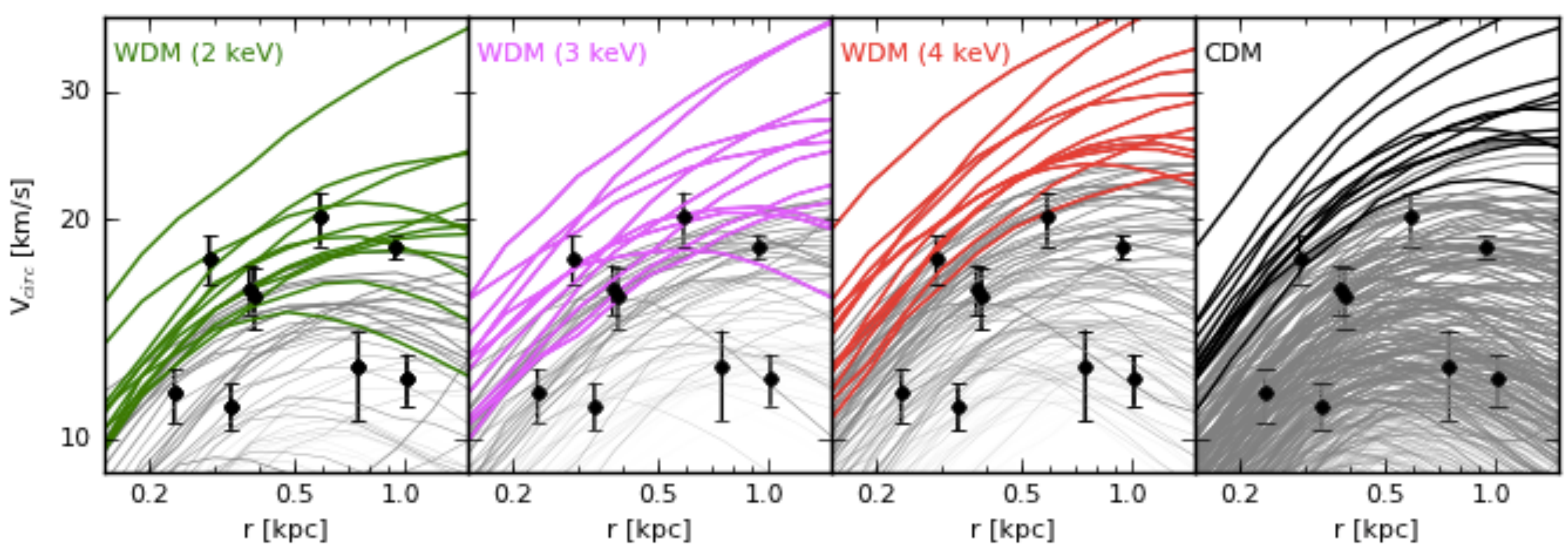
gravitino can be warm dark matter

L_{fs} < 0.1 Mpc (10keV/m)

Too Big to Fail problem

The Milky Way has only 3 satellites with V_{MAX} > 30km/s

CDM simulation predicts 10 subhalos with V_{MAX} > 30km/s



['14 Schneider1, Anderhalden, Maccio, Diemand]

m_{DM} ~ 2 keV looks good

Consistency with constraints from Lyman-α forests ?

Warm dark matter

If we can *dilute* the dark matter appropriately,

$$\Omega_{3/2}h^2 \simeq \left(\frac{100}{\Delta}\right)\left(\frac{10.75}{g_S(T_D)}\right)\left(\frac{m_{3/2}}{10\mathrm{keV}}\right)$$

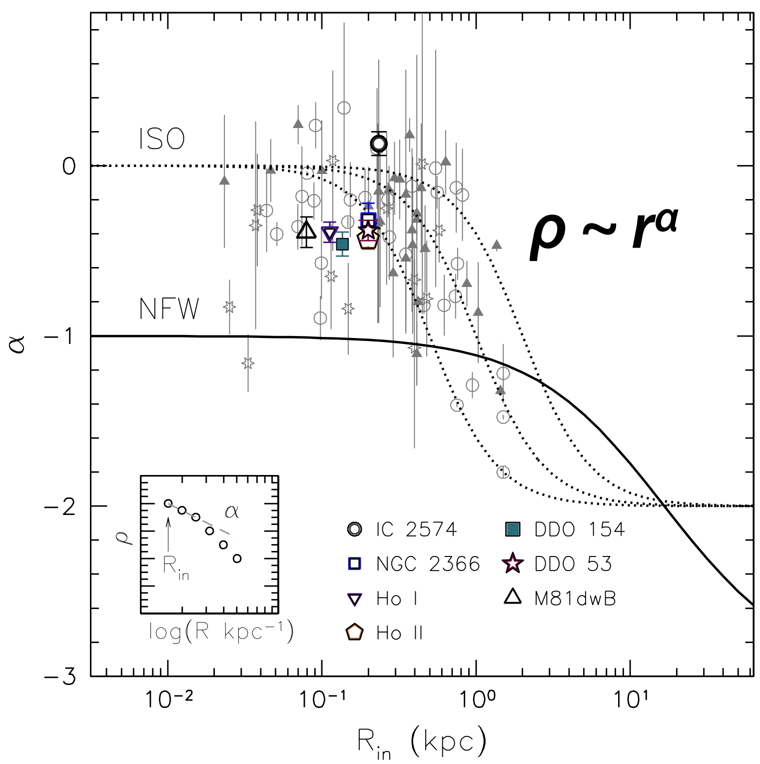
gravitino can be ***warm dark matter***

L_{fs} < 0.1 Mpc (10keV/m)

Core-Cusp Problem

Kinematical data show that the dwarf satellites seem to have cores

CDM simulation predicts cuspy density profile (NFW)



['11 Oh, de Blok1 , Brinks, Walter, Kennicutt]

Warm Dark Matter cannot solve this problem…

['13 Lovell, Frenk,Eke, Jenkins, Gao, Theuns]

CDM + Baryon simulation are important !

Self Interacting Dark Matter

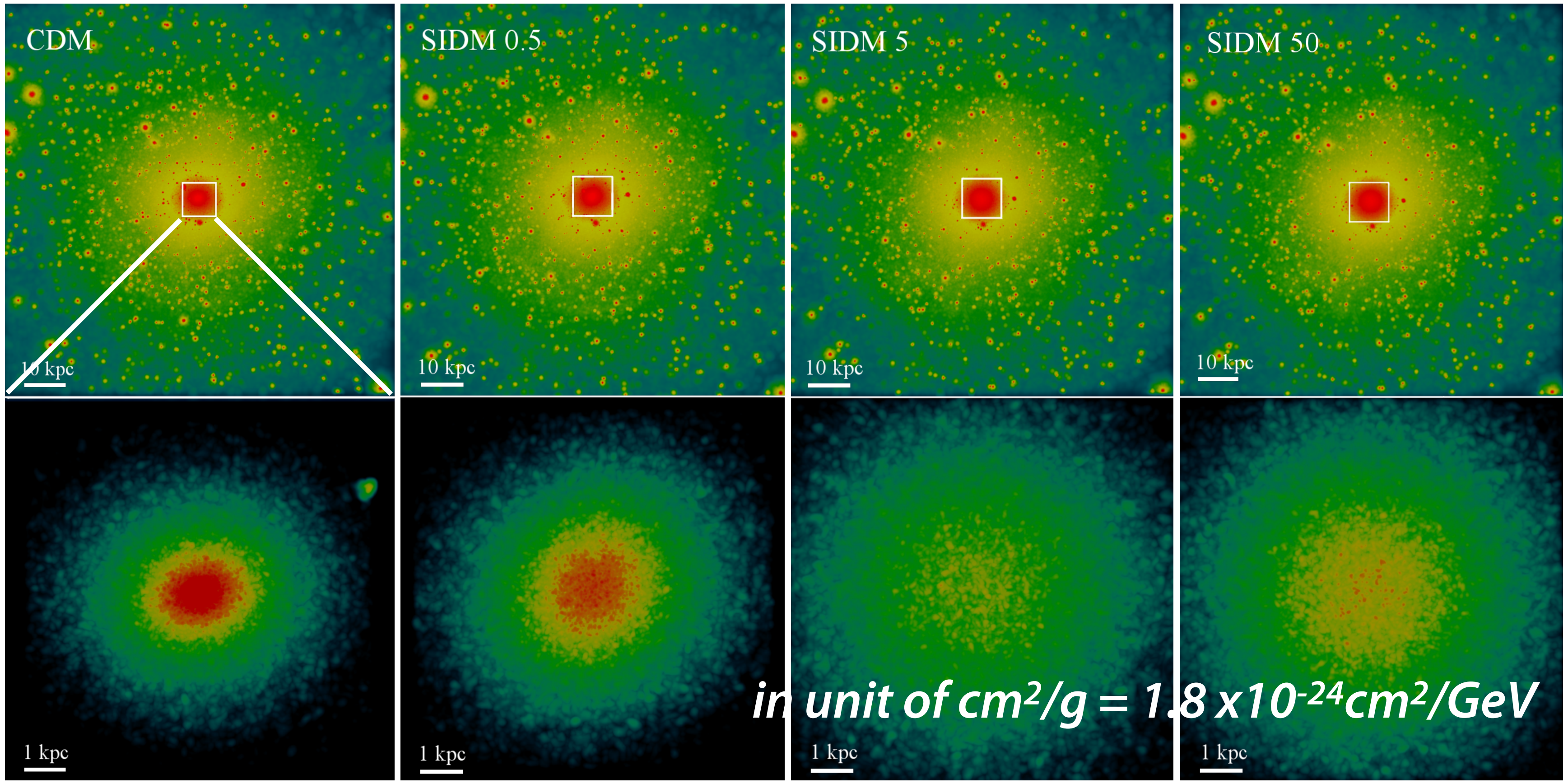
Self interacting dark matter

DM with strong (but short-range) interaction with ***σ/m ~ 10⁻²⁴ cm² / GeV***
→ ***Self-interacting dark matter***

- Model often involves new strong dynamics (like QCD) at ***O(100)MeV - O(1)GeV*** → rich phenomenology !

[e.g. '14 Boddy, Feng, Kaplinghat, Tait,
'14 Hochberg, Kuflik, Murayama, Volansky Wacker]

Core-Cusp problem can be solved for $\sigma/m \sim 10^{-24}\,cm^2/GeV$!

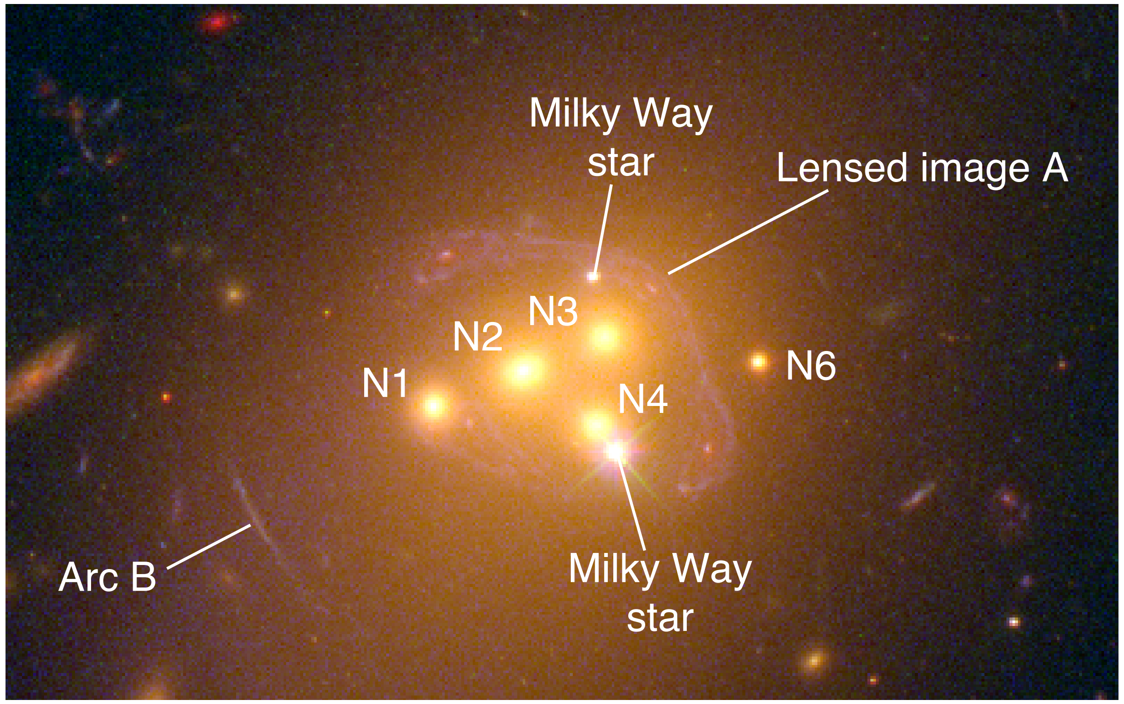


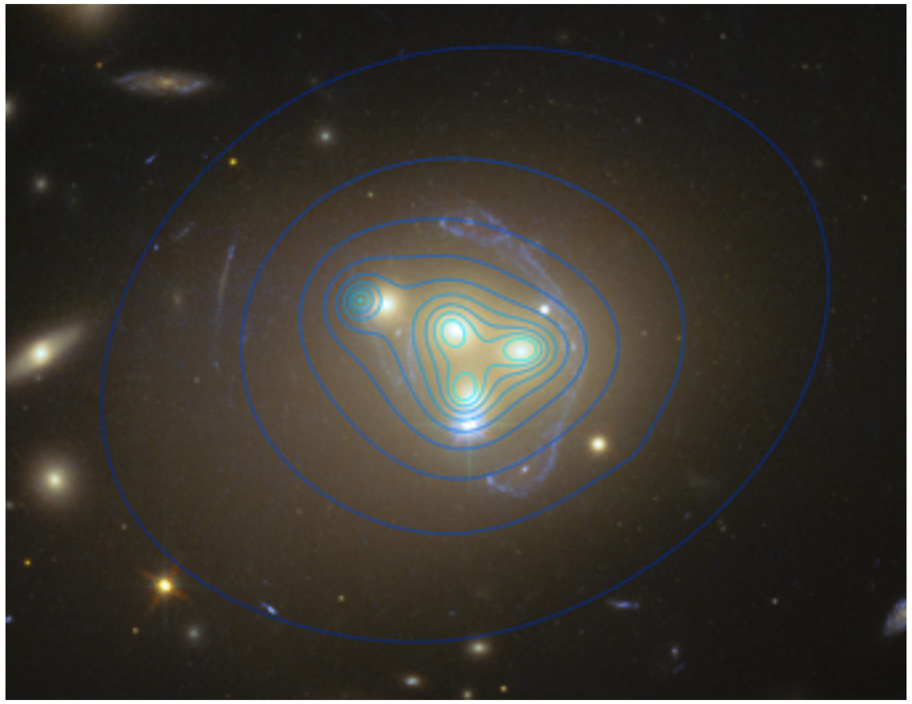
['14 Elbert, Bullock, Garrison-Kimmel, Rocha, Onorbe, Pter]

Self interacting dark matter

Evidence of Self-interacting Dark Matter ??

Dark matter behavior in Abel 3827 [15 Massey et.al.]





Four galaxies have dark matter offset from the visible galaxies.

Dark matter implying lag due to friction with $\sigma/m \sim 1.5 cm^2/g$.

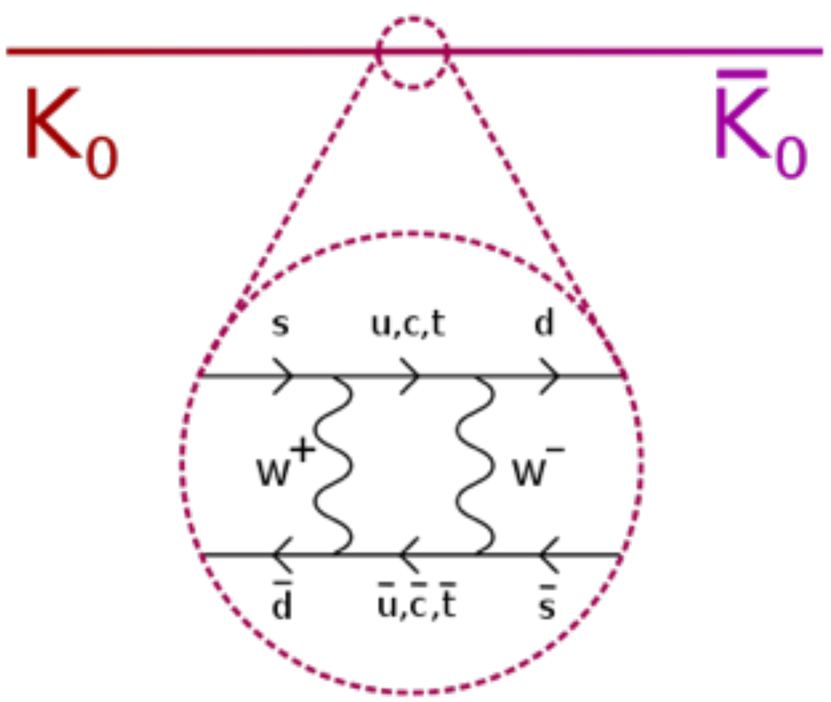
['15 Kahlhoefer, Schmidt-Hoberg, Kummer, Sarkar]

Axion

Strong CP problem

Experimentally, ***QCD*** is known to preserve ***CP*** symmetry very well.

- ✓ Hadron spectrum respects ***CP*** symmetry very well.
- ✓ ***CP*** violating transitions in the SM are caused by ***CP*** violation in the weak interaction (i.e. by the CKM phase).



Picture from : https://en.wikipedia.org/wiki/Kaon

Strong CP problem

This feature is not automatically guaranteed in ***QCD*** .

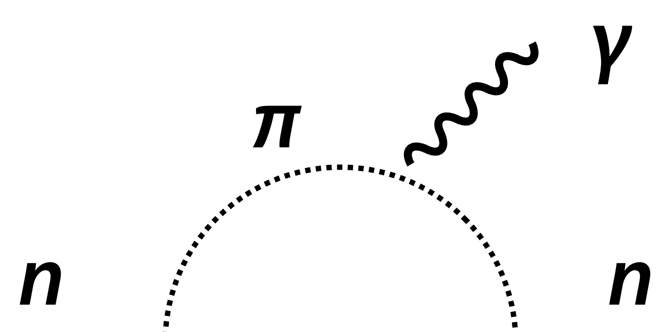
- ***QCD*** has its own ***CP***-violating parameter : $\boldsymbol{\theta}$

$$S_{\rm QCD} = \int d^4x \left(-\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu} + \frac{i\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_{i=1}^{N_f} \bar{q}_i (D - M) q_i \right)$$

- $\boldsymbol{\theta}$ - term violates the ***P*** and ***CP*** symmetries

$$\int d^4x\, G_{\mu\nu}\tilde{G}^{\mu\nu} \to -\int d^4x\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- The $\boldsymbol{\theta}$ - term is highly constrained experimentally!



$d_n/e \sim 10^{-15}\,\theta$ ['79 Crewther]

Null observation of the ***neutron EDM*** :

$d_n/e < 2.9 \times 10^{-26}$ **@ 90%CL**

[hep-ex/0602020]

$\to \theta < 10^{-11}$

Why so small ? = Strong CP Problem

✔ ***Axion Solution*** *['77 Peccei-Quinn, '78 Weinberg, '78 Wilczek]*

Axion : pseudo scalar field ***a***

Arrange models so that the axion couples to gluons via

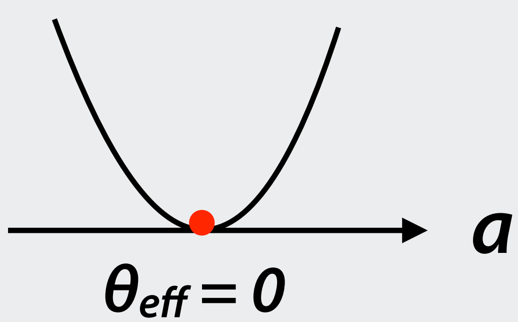
$$\mathcal{L}_{\rm eff} = \frac{g_s^2}{32\pi^2}\left(\theta - \frac{6a}{f_a}\right) G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

(f_a : free parameter)

(cf. π_0 , η' in QCD have similar coupling)

QCD strong dynamics leads to "potential of the axion"

In terms of the axion, the PQ mechanism can be interpreted as a dynamical tuning of the θ angle.



$$\mathcal{L} = \frac{1}{2} m_a^2 f_a^2 (a/f_a - \theta/6)^2 \longrightarrow \langle a/f_a \rangle = \theta/6$$

$$\theta_{\rm eff} = \theta - 6\langle a/f_a \rangle = 0$$

Strong CP problem can be solved !

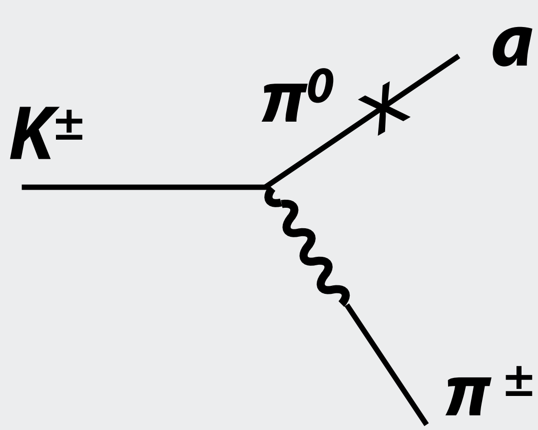
Axion Solution

Axion mass

$$m_a \sim \frac{f_\pi m_\pi}{f_a}$$

$f_\pi = 93MeV, m_\pi = 135MeV$

f_a is constrained by meson decay into axion.



$Br(K^\pm \to \pi^\pm + a \text{ (invisible)})$

$= O(f_\pi^2 / f_a^2) \times Br(K^\pm \to \pi^\pm + \pi^0)$

$< 5 \times 10^{-11}$ [E787 hep-ex/0403034]

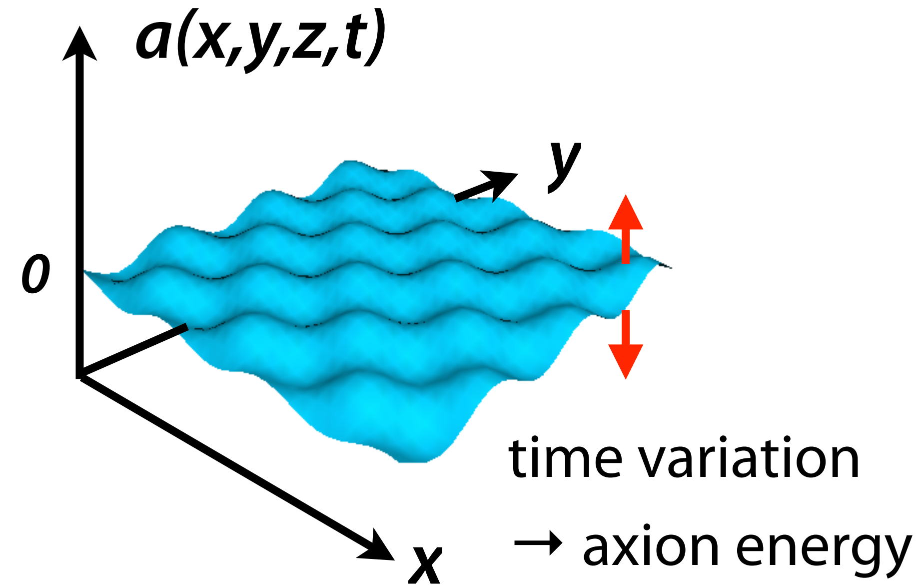
$f_a > O(1)TeV$

$f_a > O(1)TeV \to$ axion mass $< O(10)keV$

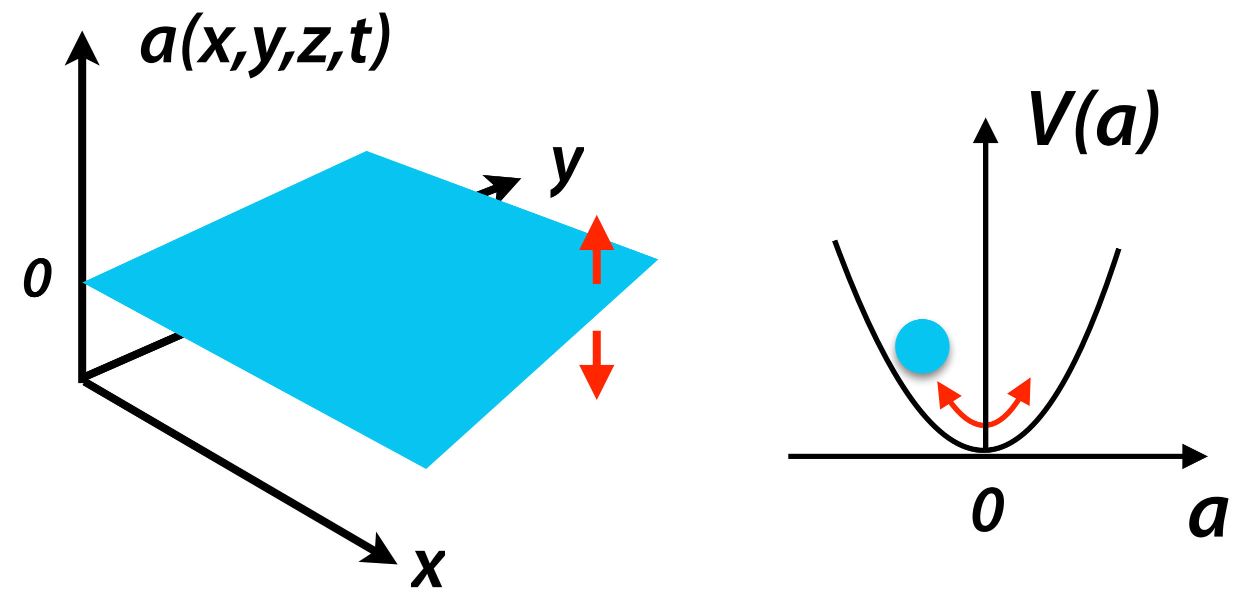
Astrophysical constraints (such as SN cooling) become important

current lower limit : $f_a > 10^9$ GeV

✔ ***Axion Dark Matter = Coherent oscillation of axion field***



spacial fluctuation
→ axion momentum



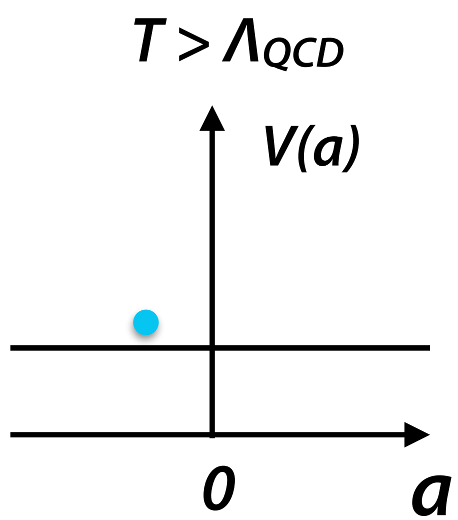
coherent oscillation
→ axion energy with v = 0

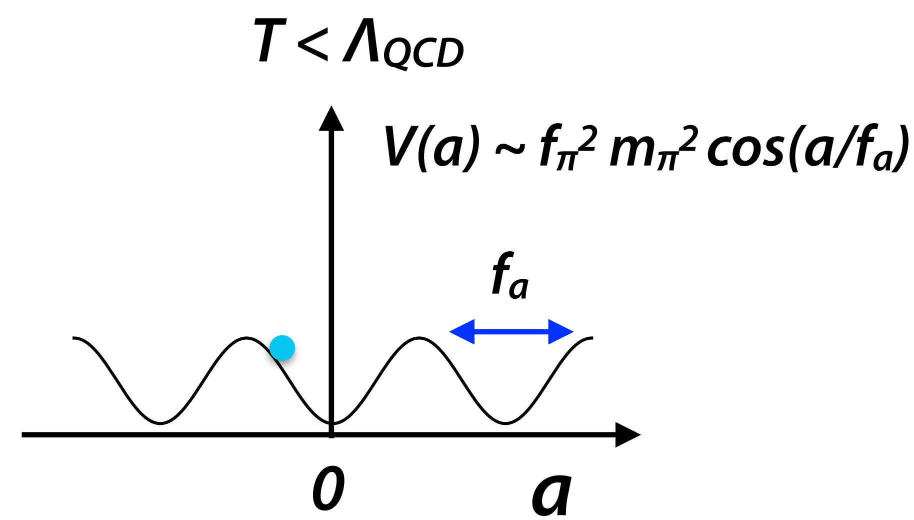
Axion energy density is given by the amplitude of the oscillation !

$$\rho_a = m_a^2 |a_0|^2$$

Axion Dark Matter = Coherent oscillation of axion field

Axion starts oscillation when $T < \Lambda_{QCD} = O(100)$MeV.





Typically, the initial amplitude : $a_0 = O(f_a)$.

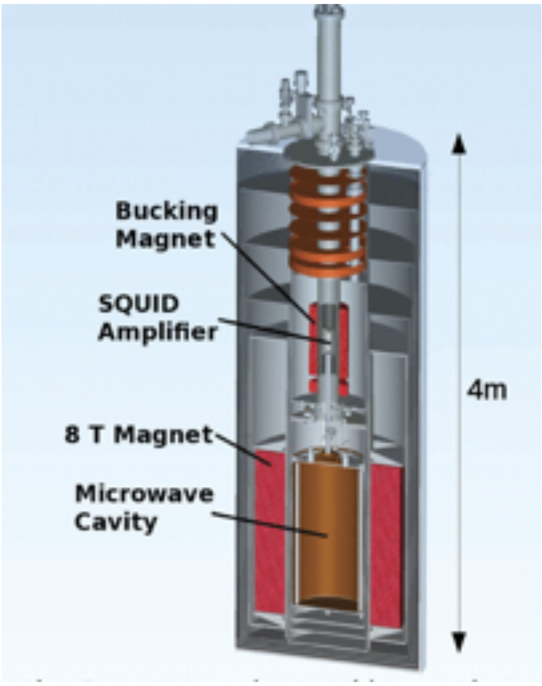
$$\Omega_a h^2 \simeq 0.2 \times \left(\frac{a_0}{f_a}\right)^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{QCD}}{400\,\mathrm{MeV}}\right)$$ ['86 Turner]

Dark Matter Density can be explained for

$f_a \sim 10^{12}$ GeV ($m_a \sim 10\,\mu$eV)

(For a larger f_a, we need $a_0/f_a \ll 1$)

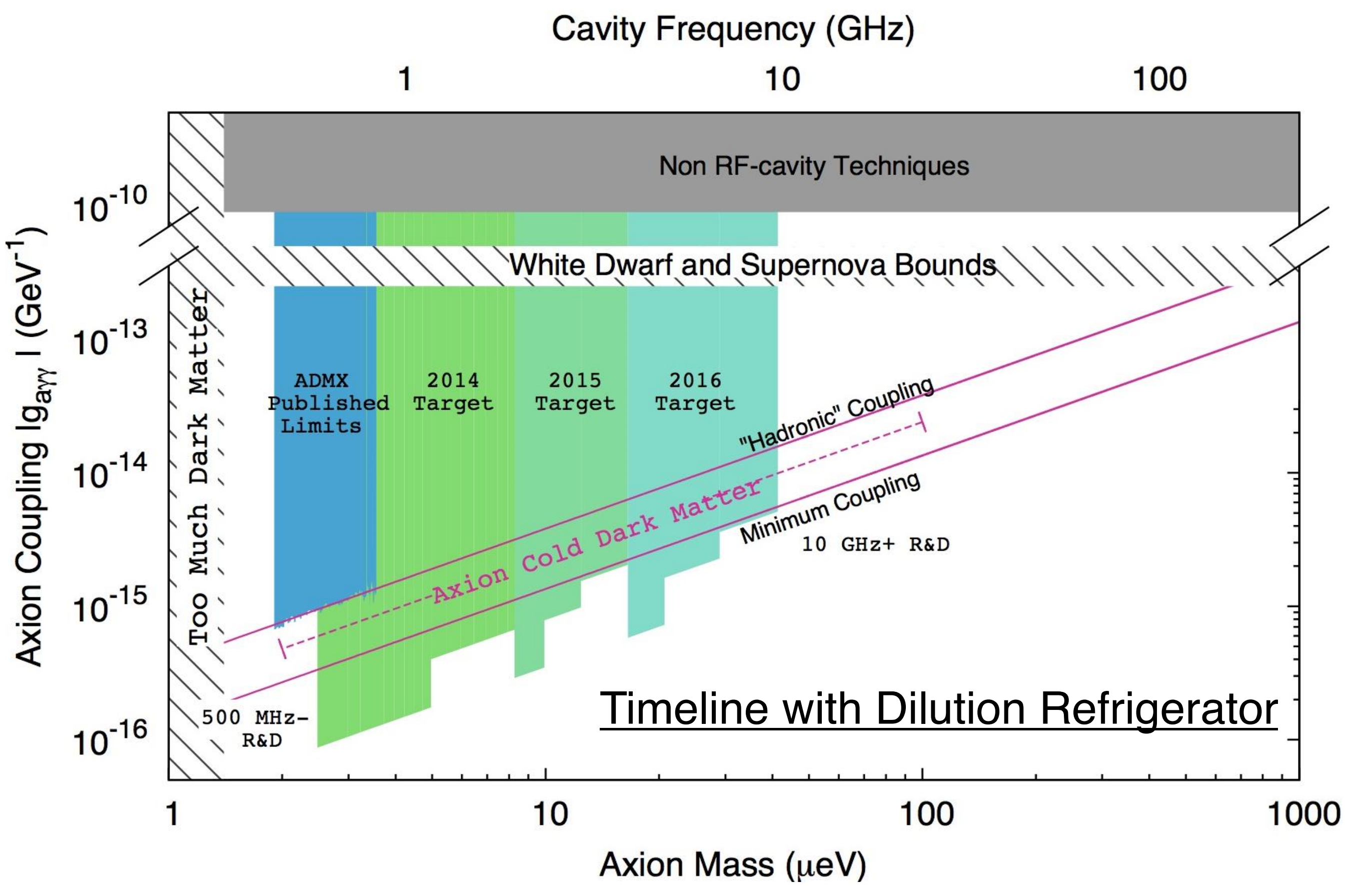
Axion Dark Matter Search (ADMX)

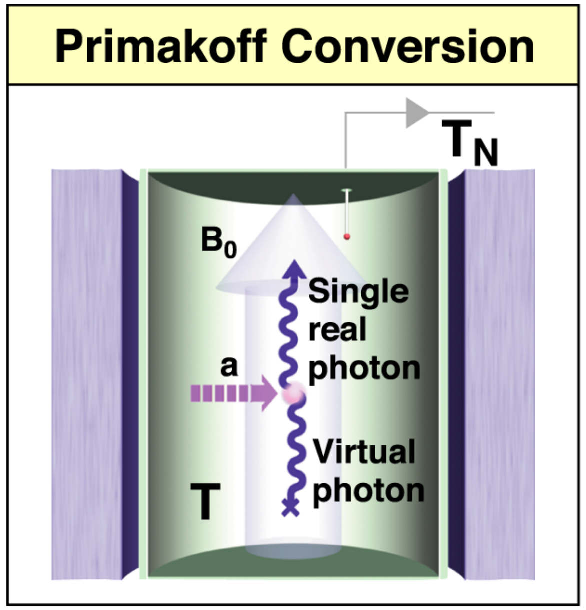


Use axion-photon coupling

$$\mathcal{L} \sim \frac{ig^2}{32\pi^2}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} \propto a\,\mathrm{E}\cdot\mathrm{B}$$

Large portion of parameter space will be tested in near future !

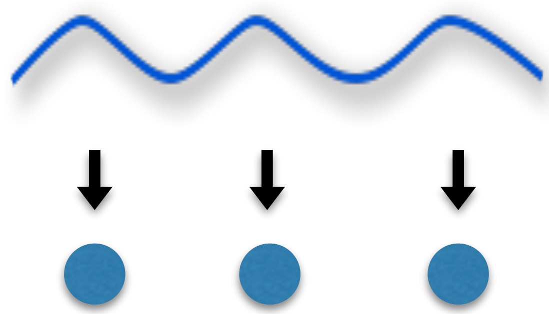




Primordial Black Hole

✓ ***Primordial Black Hole***

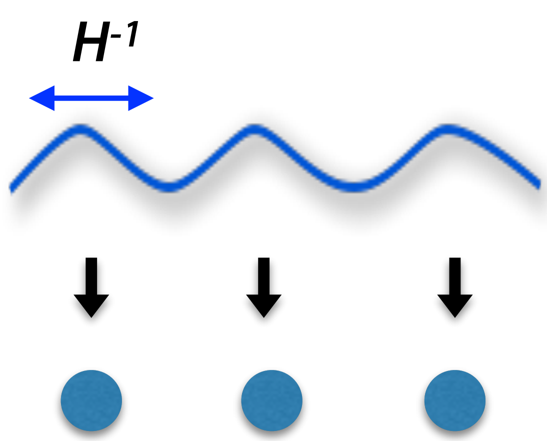
The density fluctuations of $\delta = (\rho - \rho_{average})/\rho_{average} = O(1)$ collapse.



$\delta = O(1)$

Collapsed objects

If $\delta = O(1)$ for the fluctuation with a spacial size $\sim H^{-1}$



$\delta = O(1)$

Collapsed objects : Mass $\sim 4\pi/3\, \rho\, H^{-3}$

Schwarzschild Radius of : G Mass $\sim H^{-1}$ *> Object Size !*

$\delta = O(1)$ of a spacial size $\sim H^{-1}$ → Black Hole

✓ *Primordial Black Hole*

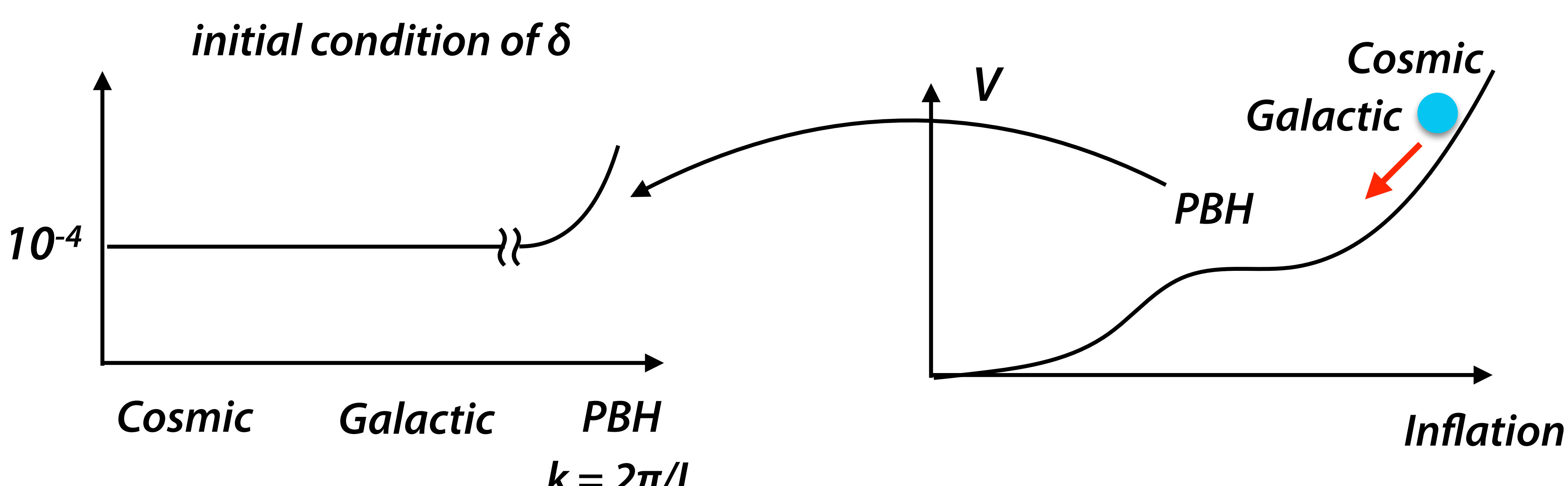
At large scales, the fluctuations are

$$\delta(\mathrm{CMB,\ galaxy\ cluster}) \sim 4(\Delta T/T)_{CMB} \sim 10^{-4}$$

at H^{-1} *~ CMB, galaxy cluster sizes…*

We prepare large fluctuation at very small structure scale !

$$\delta(\mathrm{PBH}) \sim 1 \quad \text{at } H^{-1} \ll \text{CMB, galaxy cluster sizes}$$



In inflation theory, large fluctuation is achieved for flat potential !

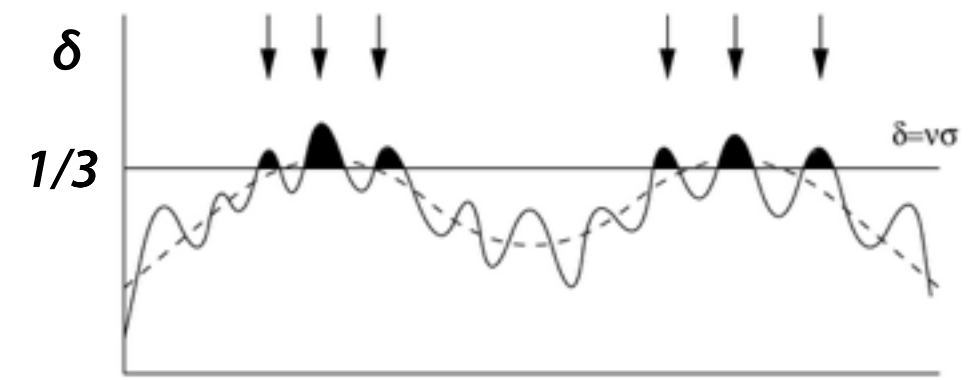
Primordial Black Hole

- Mass of the PBH formed at $H \sim T^2/M_{PL}$

$$M_{BH} \sim 4\pi/3\, \rho\, H^{-3}$$

$$\sim 0.066 M_{\odot} \left(\frac{\mathrm{GeV}}{T}\right)^2$$

- Energy fraction at the formation



https://ned.ipac.caltech.edu/level5/Sept03/Peacock/Peacock6_2.html

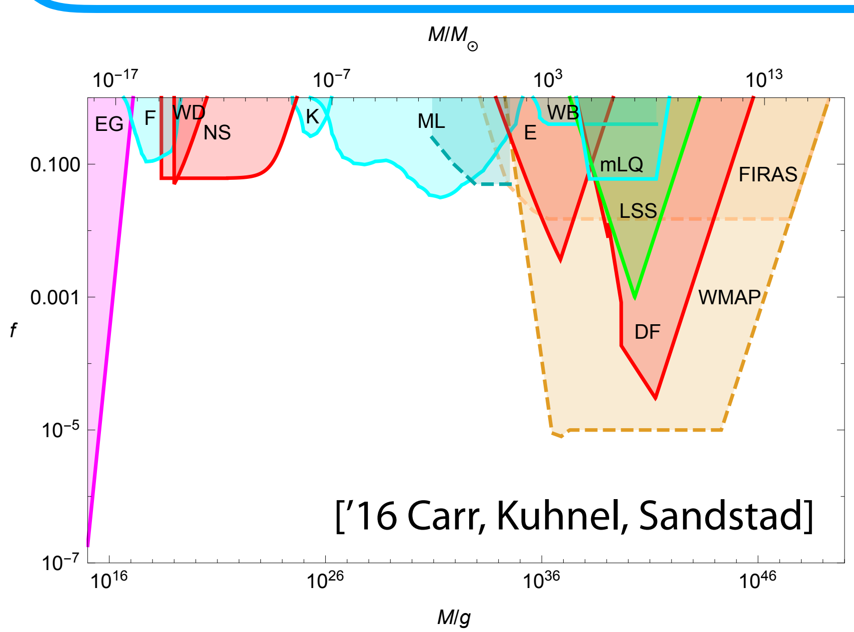
Energy fraction at the formation

$$\beta_*(M_*) = \int_{1/3}^{1} \frac{d\delta}{\sqrt{2\pi}\bar{\delta}(M_*)} \exp\left(-\frac{\delta^2}{2\bar{\delta}^2(M_*)}\right) \simeq \bar{\delta}(M_*) \exp\left(-\frac{1}{18\bar{\delta}^2(M_*)}\right),$$

Abundance

$$\Omega_{BH} h^2 \simeq 5.6 \times 10^7 \beta_*$$

→ ***δ(M) ~ 0.05***

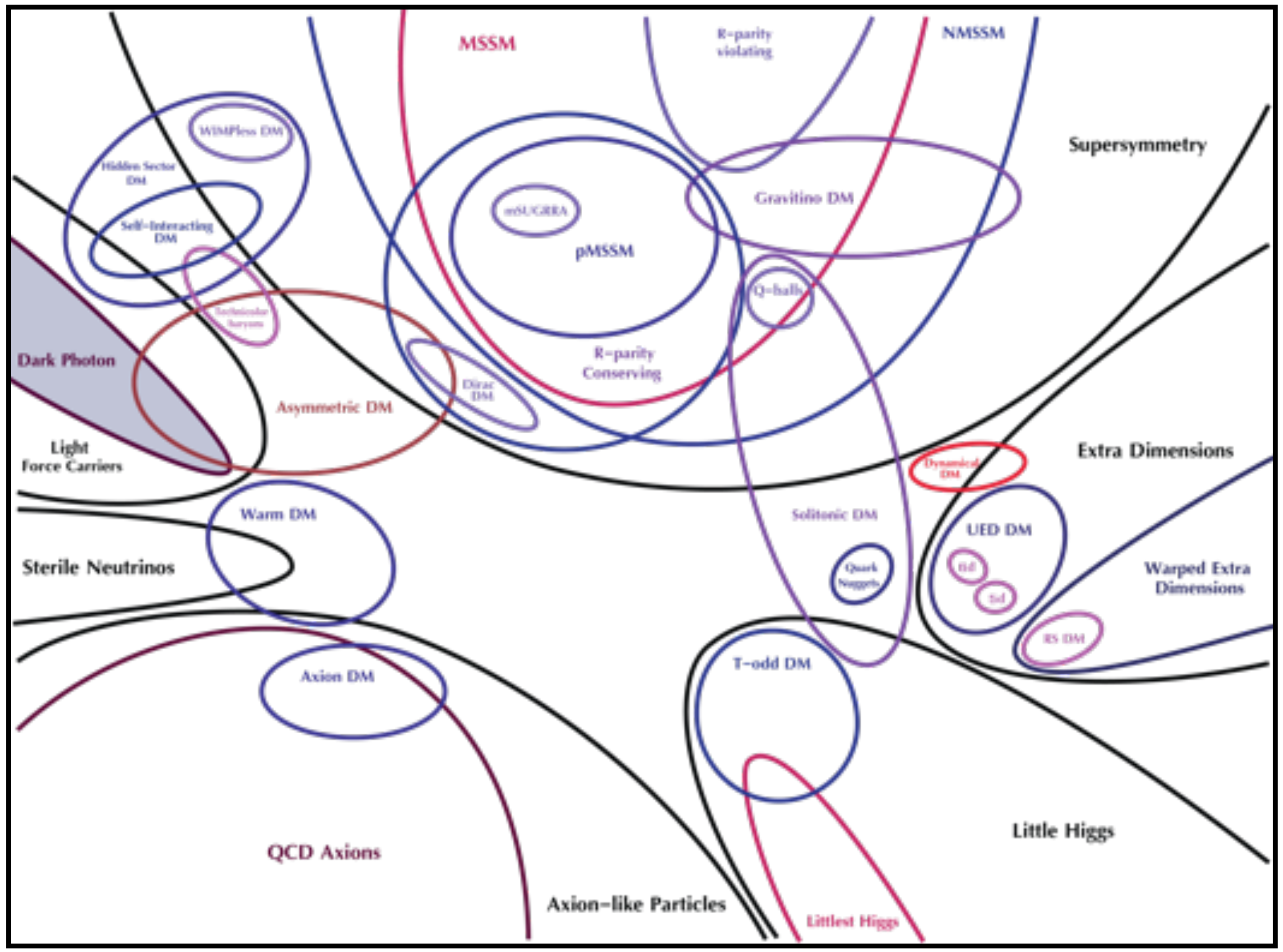


PBH dark matter can be tested by

- Gravitational Wave
- Gravitational Lensing

Summary ?

We have lots of candidates…



[Credit: Tim M. P. Tait]

Theorists keep building new DM models until the DM is discovered.

Please Find Dark Matter !!!

Back up

✔ *WIMP example*

- Suppression from purity.

χ-χ-Higgs interactions originate from $h^\dagger \tilde{h} \tilde{b}$ $h^\dagger \tilde{h} \tilde{w}$

→ SI cross sections are suppressed for pure Higgsino/Gaugino neutralino.

χ-χ-Z boson interactions originate from $\bar{\tilde{H}}_1 \gamma_5 \gamma_\mu Z^\mu \tilde{H}_2 + h.c.$

$(\tilde{H}_{1,2} = (\tilde{H}_u^{0(\mathrm{Majorana})} \pm \tilde{H}_d^{0(\mathrm{Majorana})})/\sqrt{2})$

→ SD cross sections are also suppressed for pure Higgsino/Gaugino neutralino.

Bino/Higgsino DM

$$c_{h\chi\chi}, c_{Z\chi\chi} \propto \theta \qquad \theta = \frac{(\sin\beta \pm \cos\beta)\sin\theta_W}{\sqrt{2}} \left(\frac{M_Z}{\Delta M}\right),$$

Bino/Wino DM

$$c_{h\chi\chi}, c_{Z\chi\chi} \propto \theta \qquad \theta = \frac{\sin 2\beta \sin 2\theta_W}{2} \left(\frac{M_Z^2}{\mu(M_2 - M_1)}\right)$$