Crash course on tools for Dark Matter research

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Dark Matter Days 2017 – CIFFU BUAP

Motivation

Research on Dark Matter
could be hard without
a good set tools

disclaimer: I don't know who is this guy

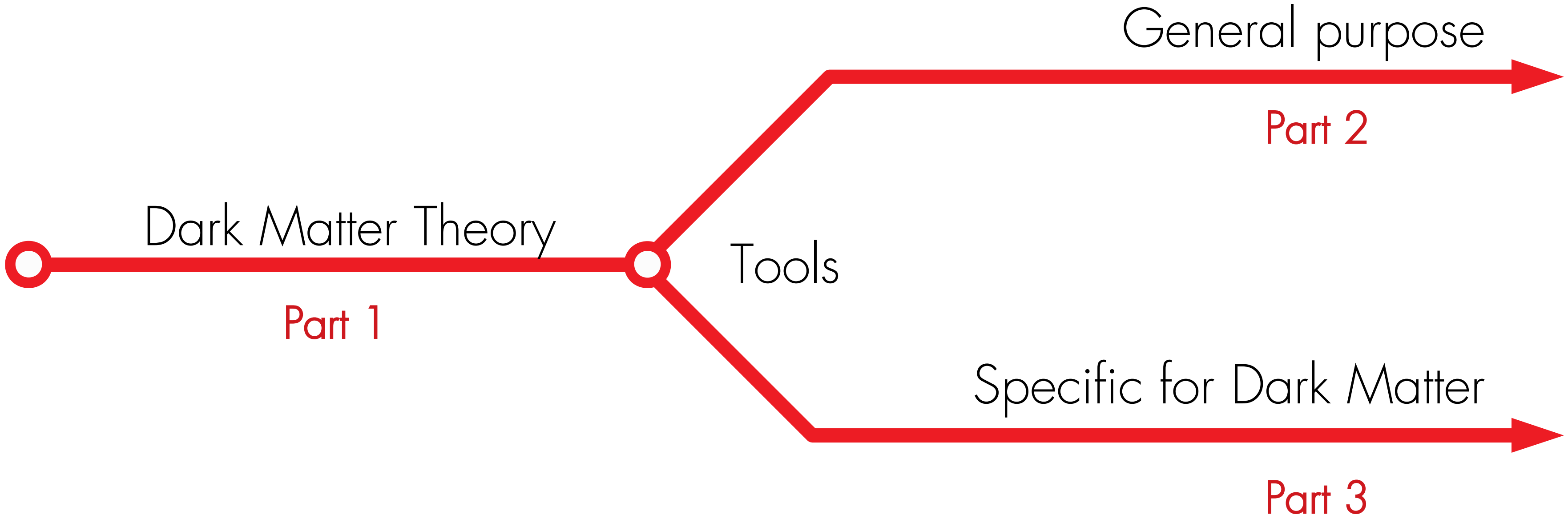
Motivation

We hope for a unique tool to solve all our problems (in physics)

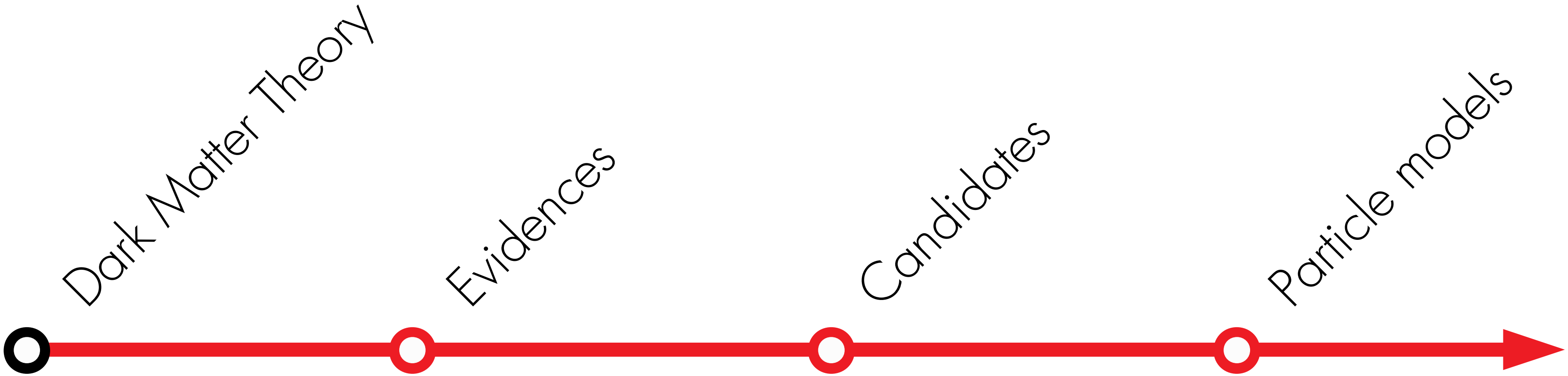
Motivation

… but most of the tools are made by physicists to solve their own problems

Course plan


General purpose
Part 2
Dark Matter Theory
Tools
Part 1
Specific for Dark Matter
Part 3

Today's plan



Dark Matter: Evidences

A little of history

1933: Fritz Zwicky postulated dark matter in order to explain Coma cluster dynamics as a bound system

http://youtu.be/C8ZOgKlsqEA

A little of history

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

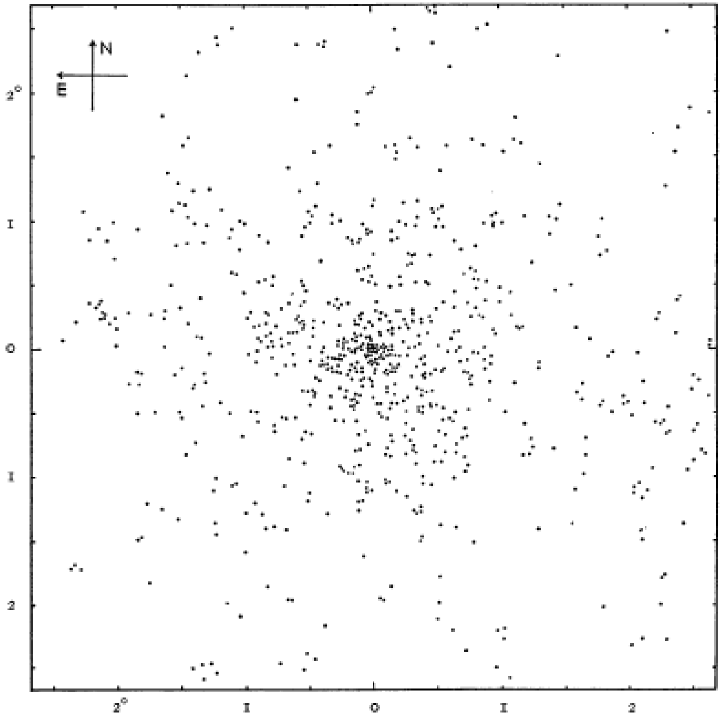
Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

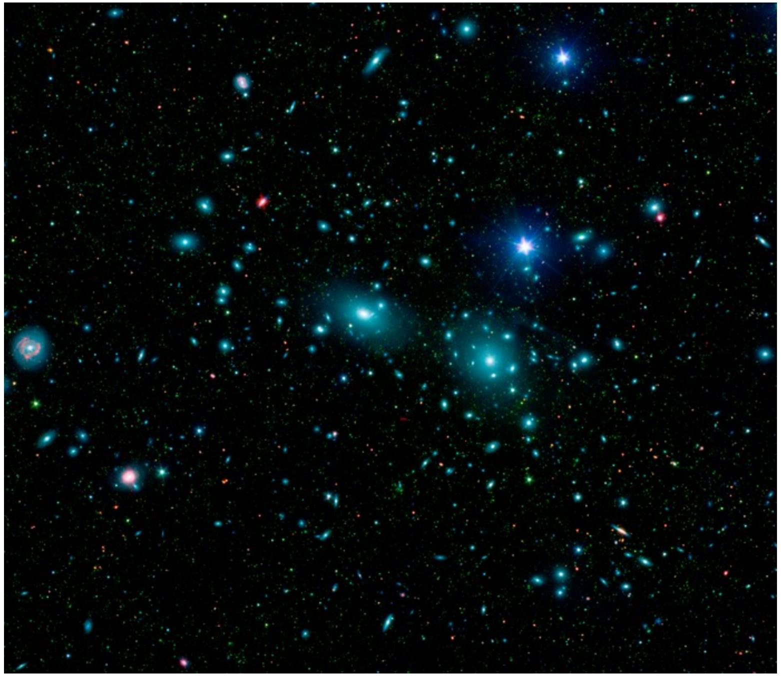
As a first step toward the realization of the proposed program, the Coma cluster of

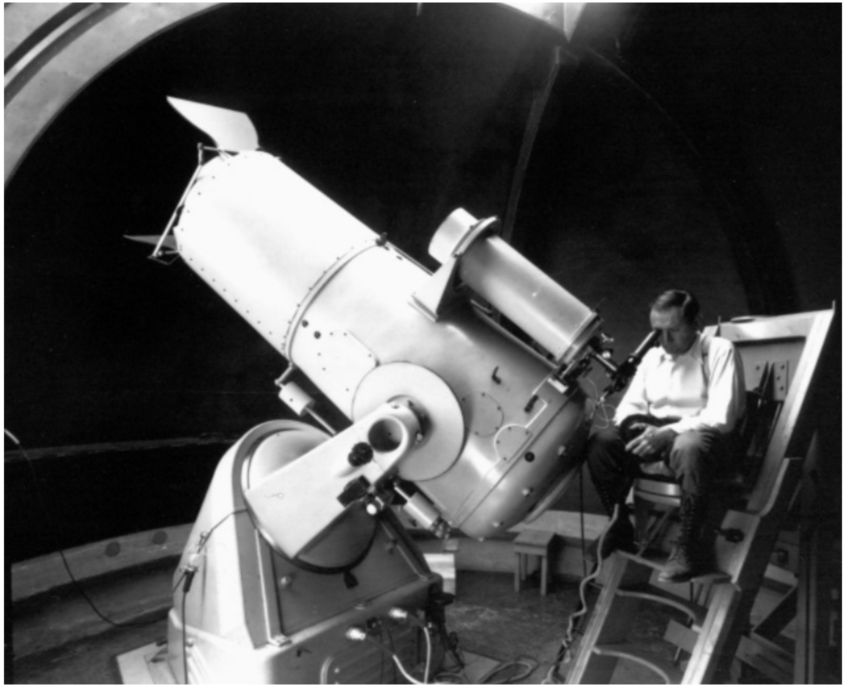
III. THE VIRIAL THEOREM APPLIED TO CLUSTERS OF NEBULAE

If the total masses of clusters of nebulae were known, the average masses of cluster nebulae could immediately be determined from counts of nebulae in these clusters, provided internebular material is of the same density inside and outside of clusters.



A little of history





Coma Galaxy Cluster

Virial Theorem

Fritz Zwicky

Dark Matter

Virial theorem

It relates global quantities of a system in equilibrium

$$\langle T \rangle = -\frac{1}{2} \sum_{k=1}^{N} \langle \vec{F}_k \cdot \vec{r}_k \rangle$$

For gravitationally bounded objects:

$$\langle T \rangle = -\frac{1}{2} \langle V_{\rm total} \rangle \longrightarrow M_{\rm total} \simeq \frac{2 R_{\rm total} \bar{v}^2}{G}$$

A little of history

60's – 70's Vera Rubin studied rotation curves of many galaxies

Doppler effect and redshift

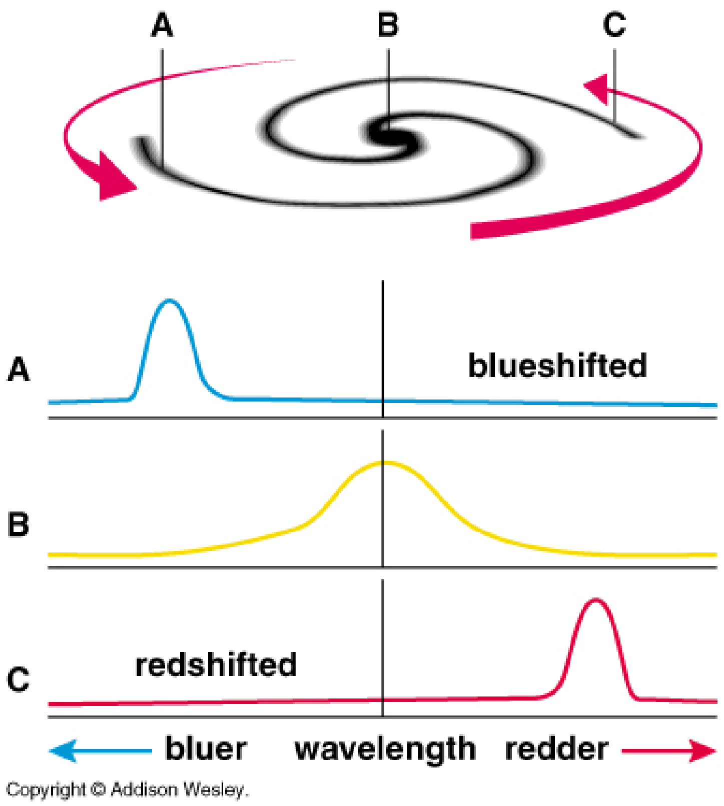
Observed redshift $\longrightarrow$ $$z = \frac{\lambda_{\mathrm{obs}} - \lambda_{\mathrm{emit}}}{\lambda_{\mathrm{emit}}}$$

$$1 + z = \frac{1 + v\cos\theta/c}{\sqrt{1 + v^2/c^2}}$$ $\longrightarrow$ Estimation of the velocity

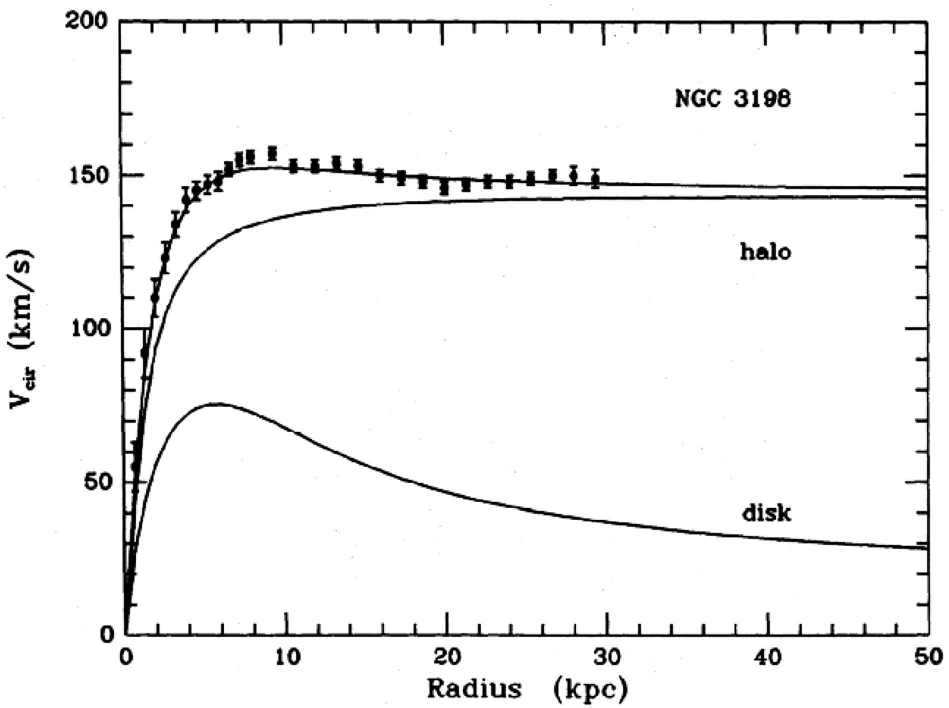
z>0 object going away

z<0 object getting closer

A little of history

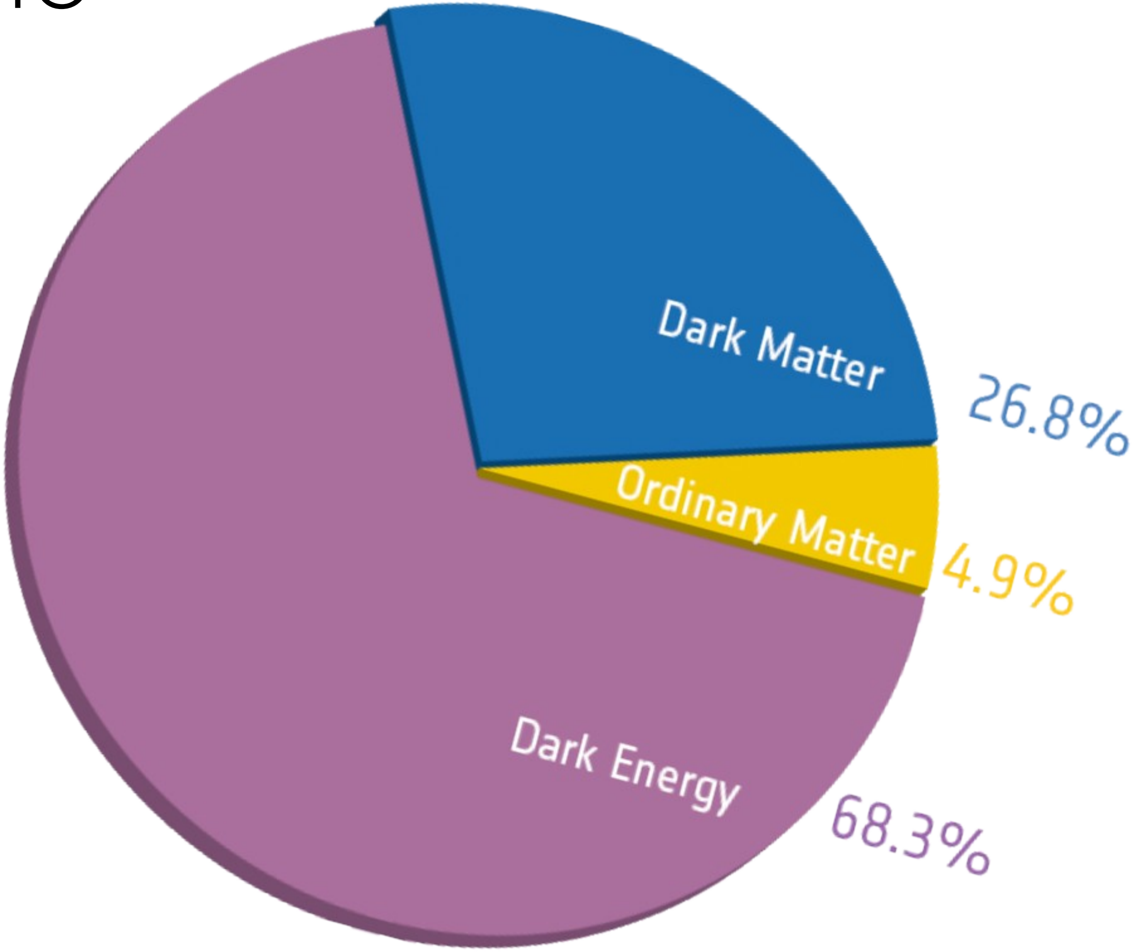


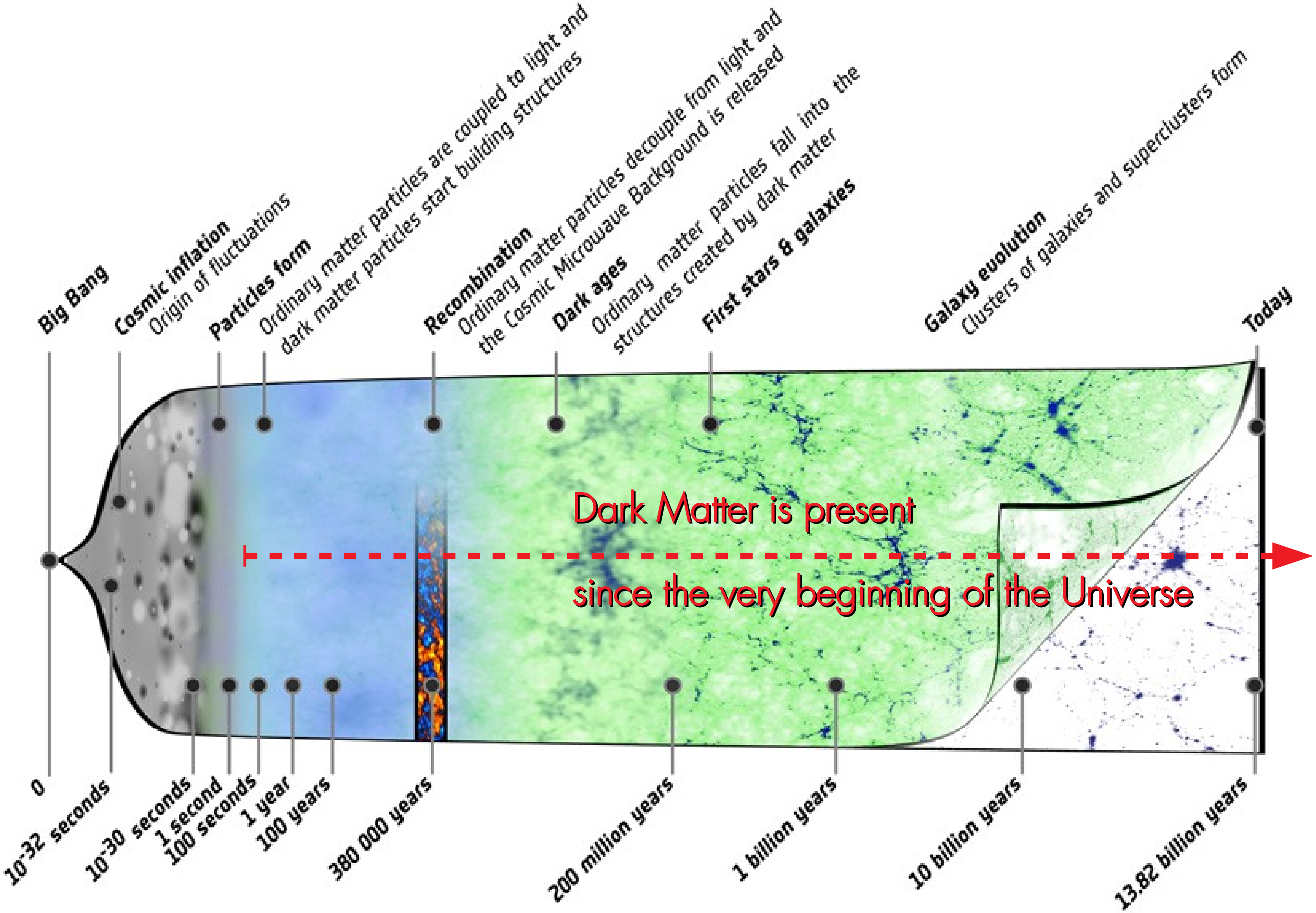
60's – 70's Vera Rubin studied rotation curves of many galaxies



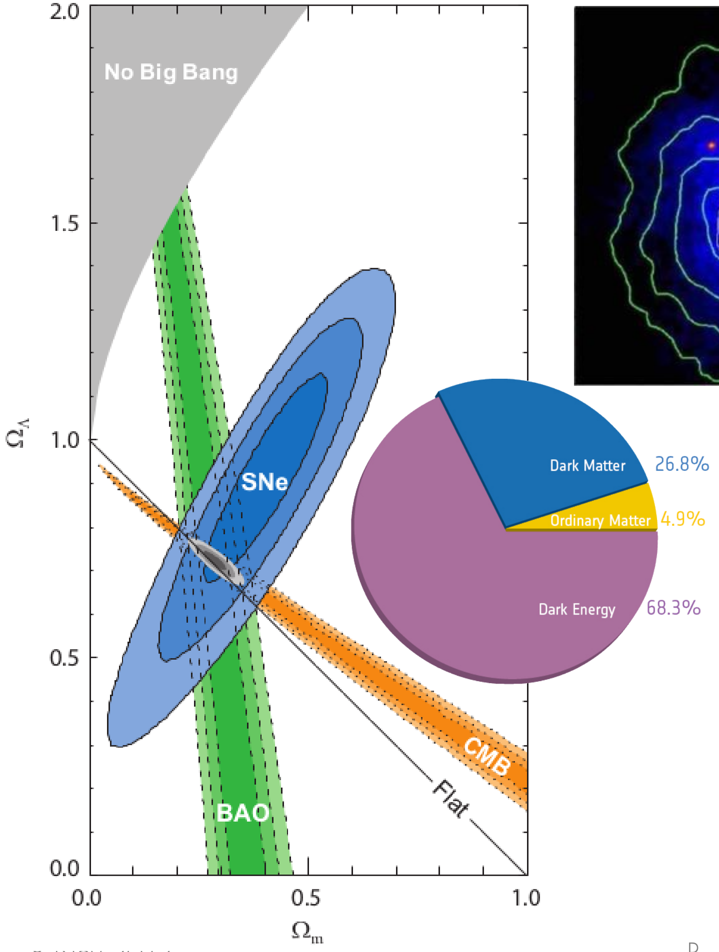

(short story)
Dark Matter is everywhere!

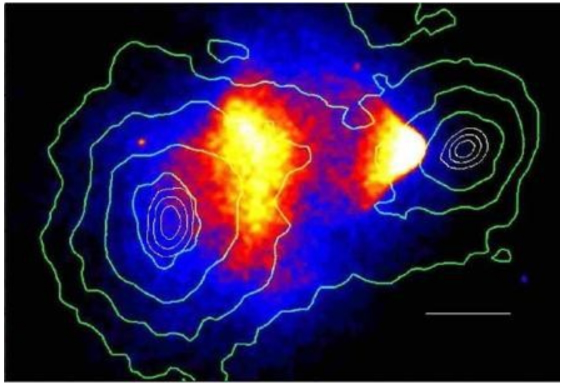
Cosmic pie

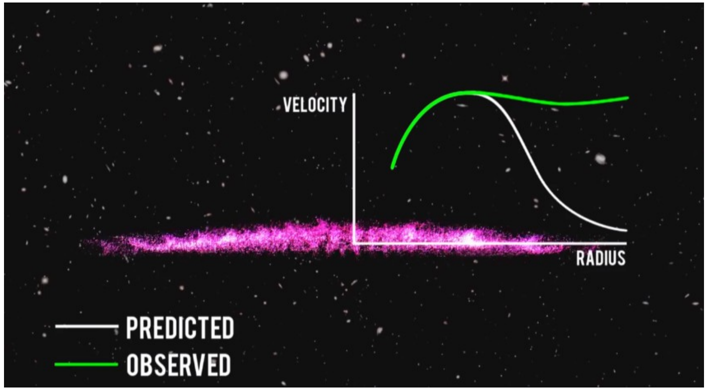



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Dark Matter is present
since the very beginning of the Universe
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Dark Matter







Observations support Dark Matter

- Dynamics of clusters and galaxies
- Structure formation
- CMB anisotropies
- Baryon Acoustic Oscillation

$$\Omega_{DM} h^2 = 0.1196 \pm 0.0031$$

Galactic scales

Rotation curve
Weak lensing
Velocity dispersion of satellite galaxies
Velocity dispersion of dSphs

Galaxy cluster scales

Velocity dispersion of individual galaxies
Strong and weak lensing
Peculiar velocity flows
X-ray emission

Cosmological scales

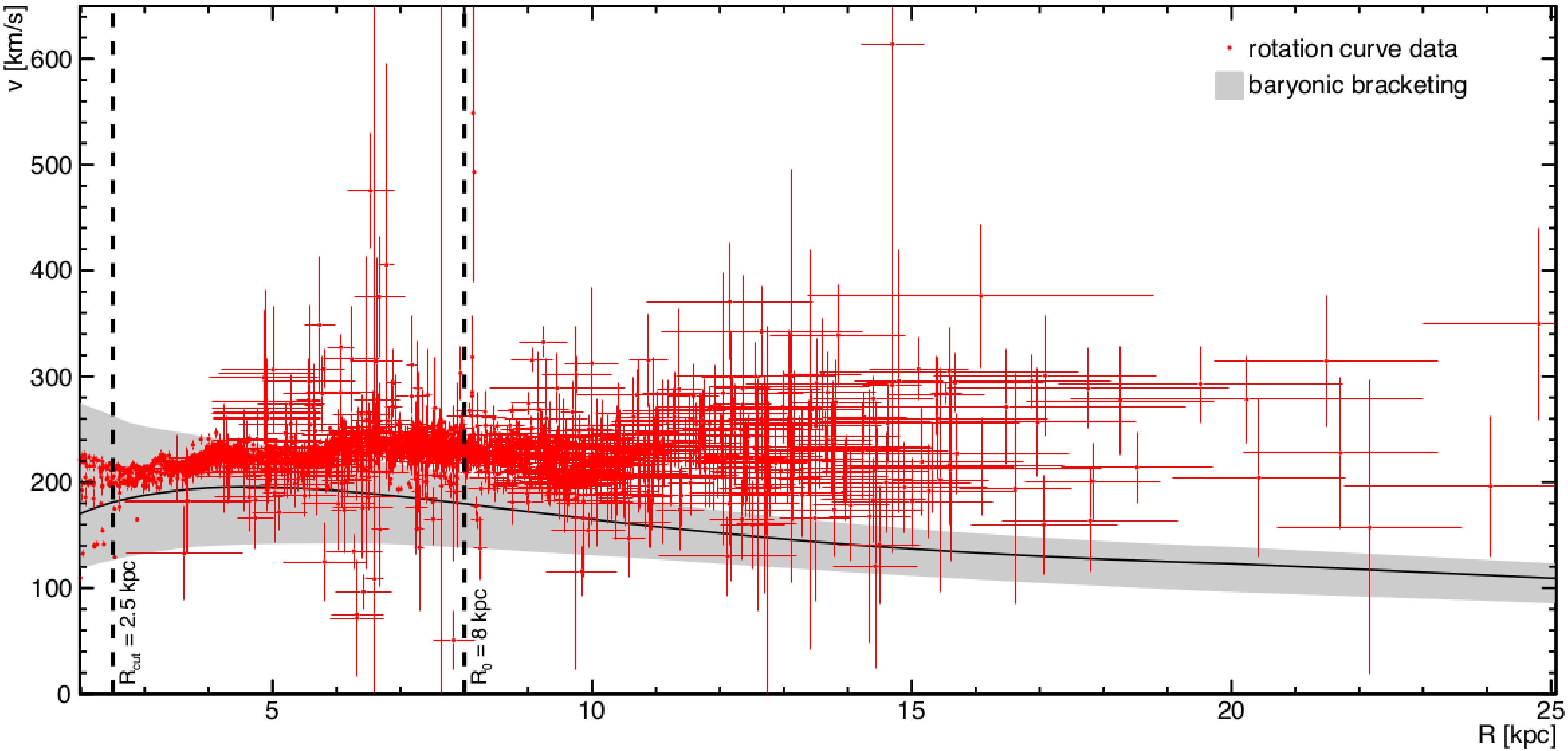
CMB anisotropies
Growth of structure
LSS distribution
BAOs
SZ effect

smaller
kpc

larger
Gpc

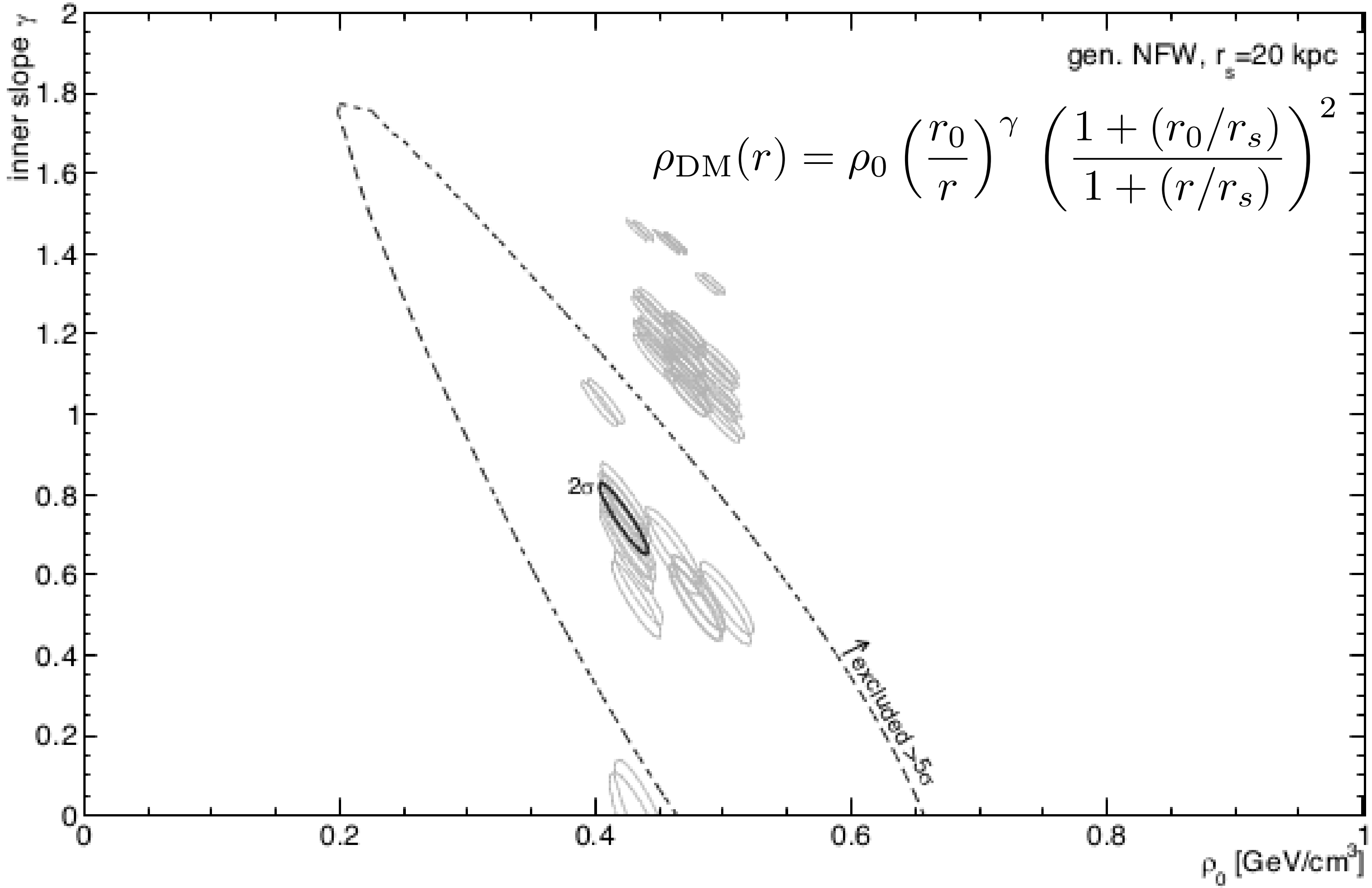
Galactic scales

M. Pato et al JCAP 1512 (2015)



Galactic scale

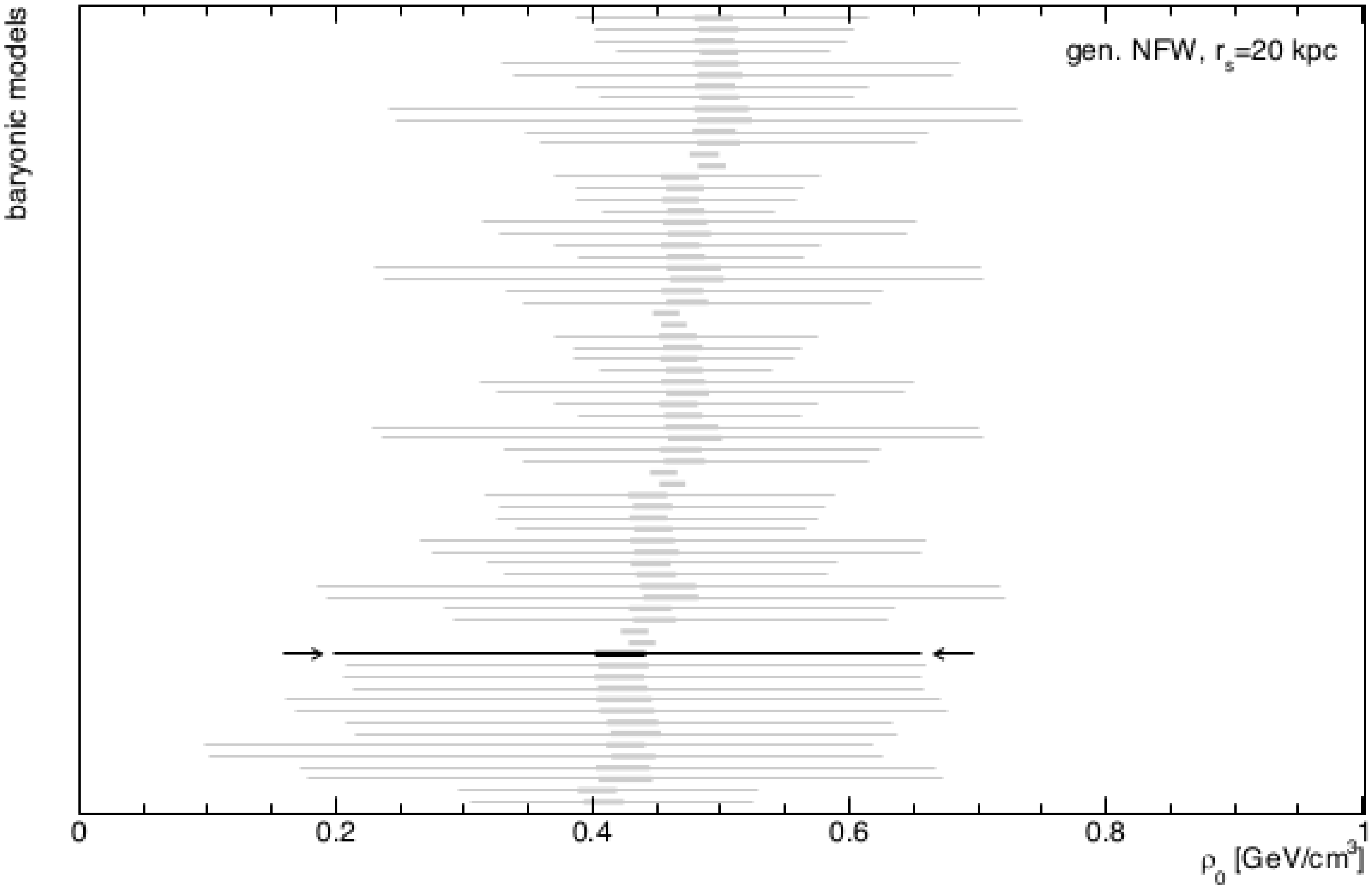
M. Pato et al JCAP 1512 (2015)



$$\rho_{\rm DM}(r) = \rho_0 \left(\frac{r_0}{r}\right)^{\gamma} \left(\frac{1+(r_0/r_s)}{1+(r/r_s)}\right)^2$$

Galactic scale

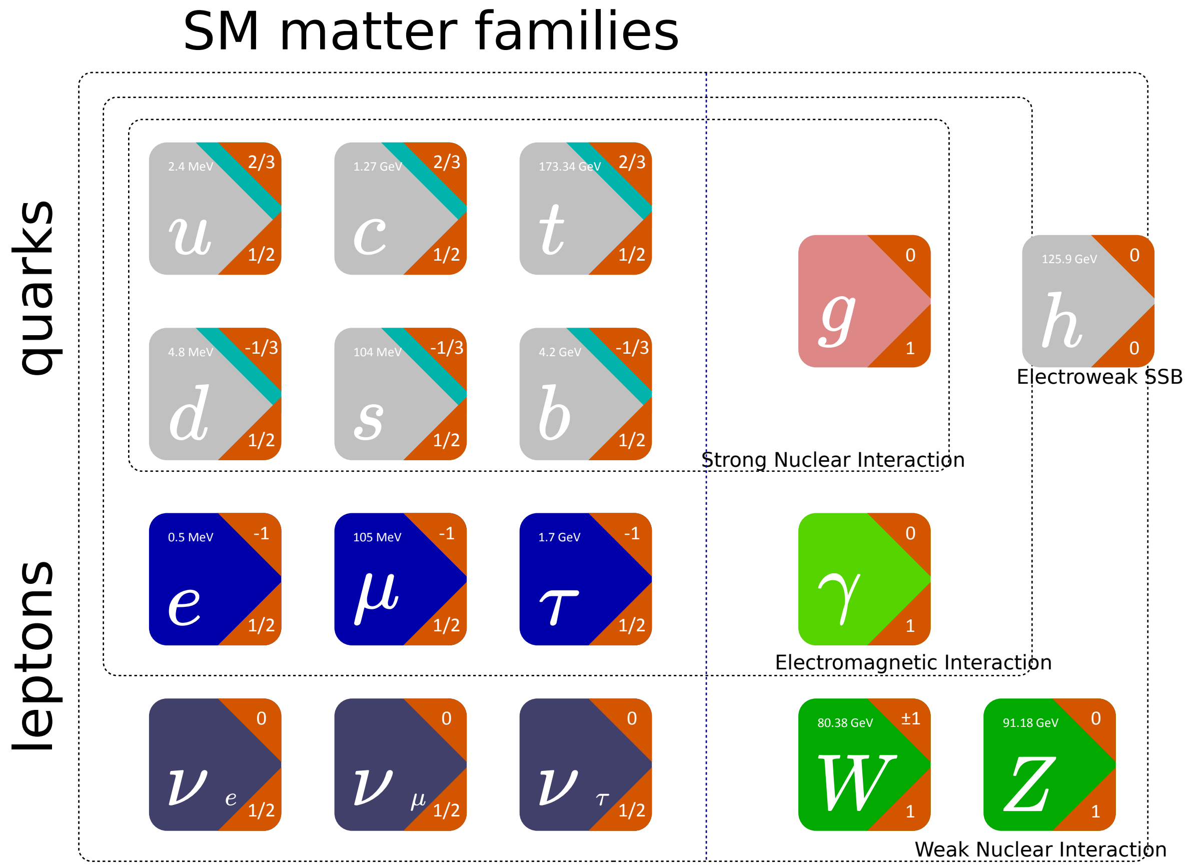
M. Pato et al JCAP 1512 (2015)



a small sample of

Dark Matter Candidates

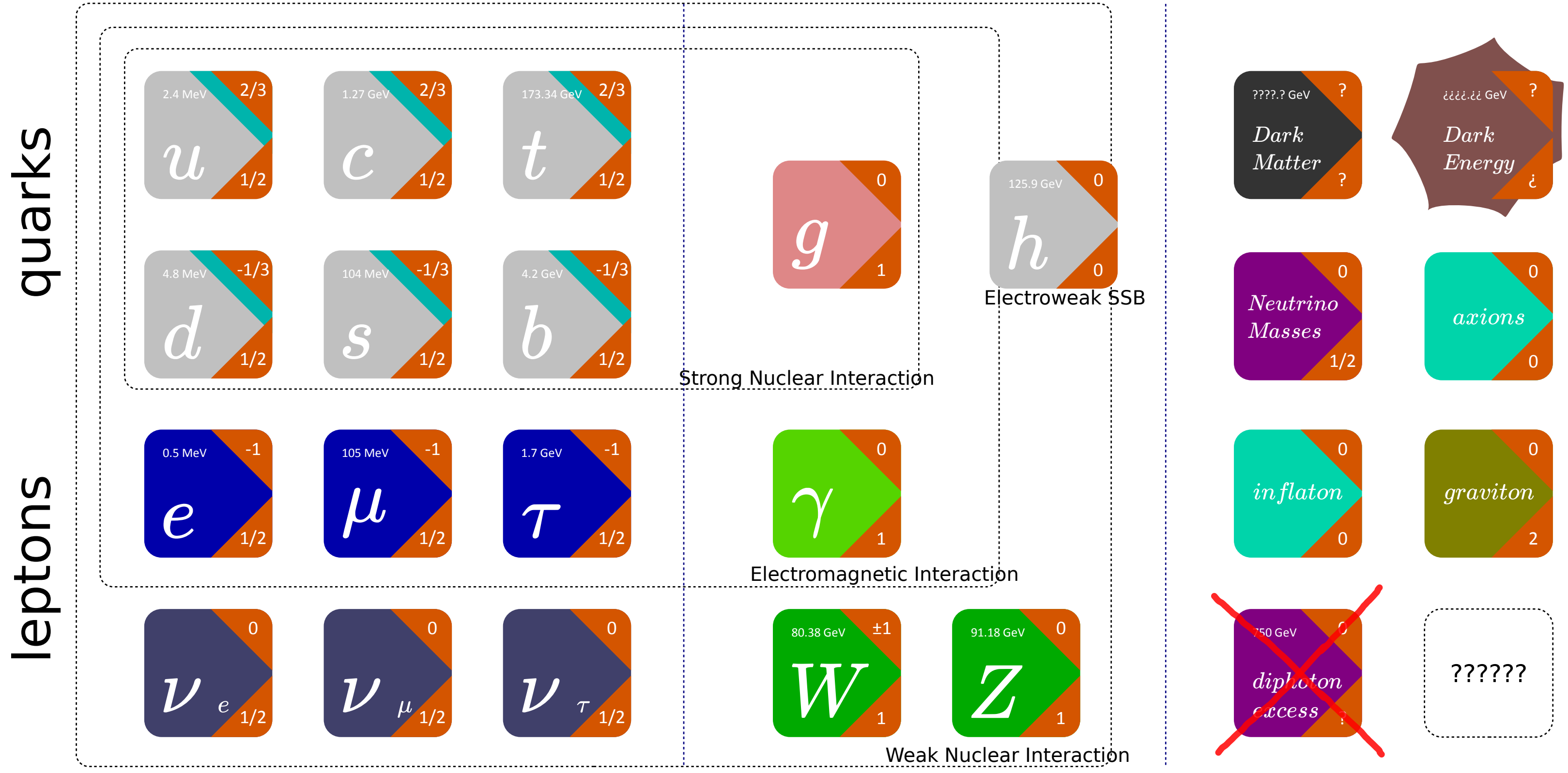
The Standard Model (so far)



The Standard Model (so far)

SM matter families

Beyond SM



Dark Matter particle properties

Massive

Non baryonic

Electrically neutral

Stable

Dark Matter particle properties

Massive

Non baryonic

Electrically neutral

Stable

Dark Matter particle properties

Massive (*)

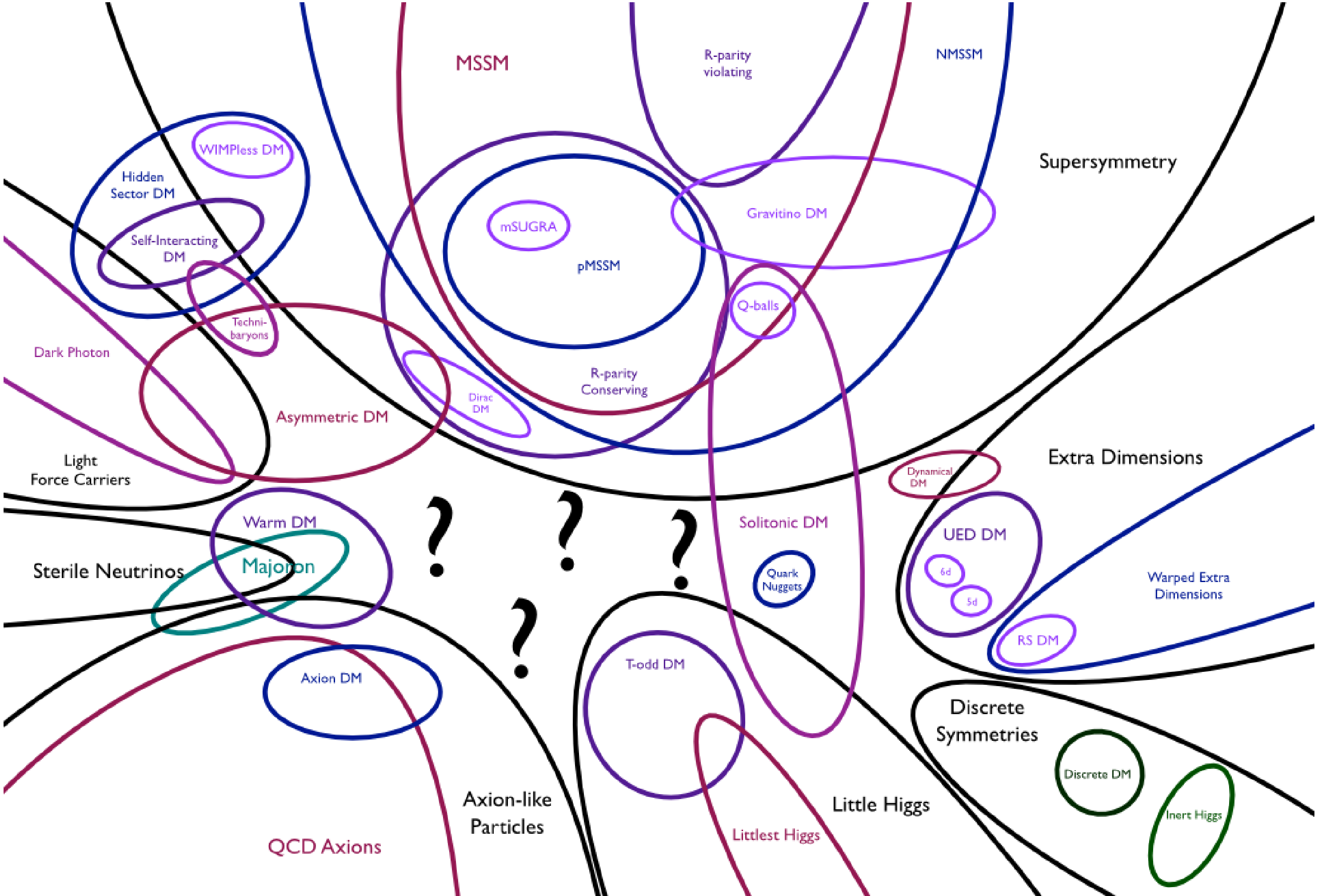
Non baryonic

Electrically neutral (**)

Stable (***)

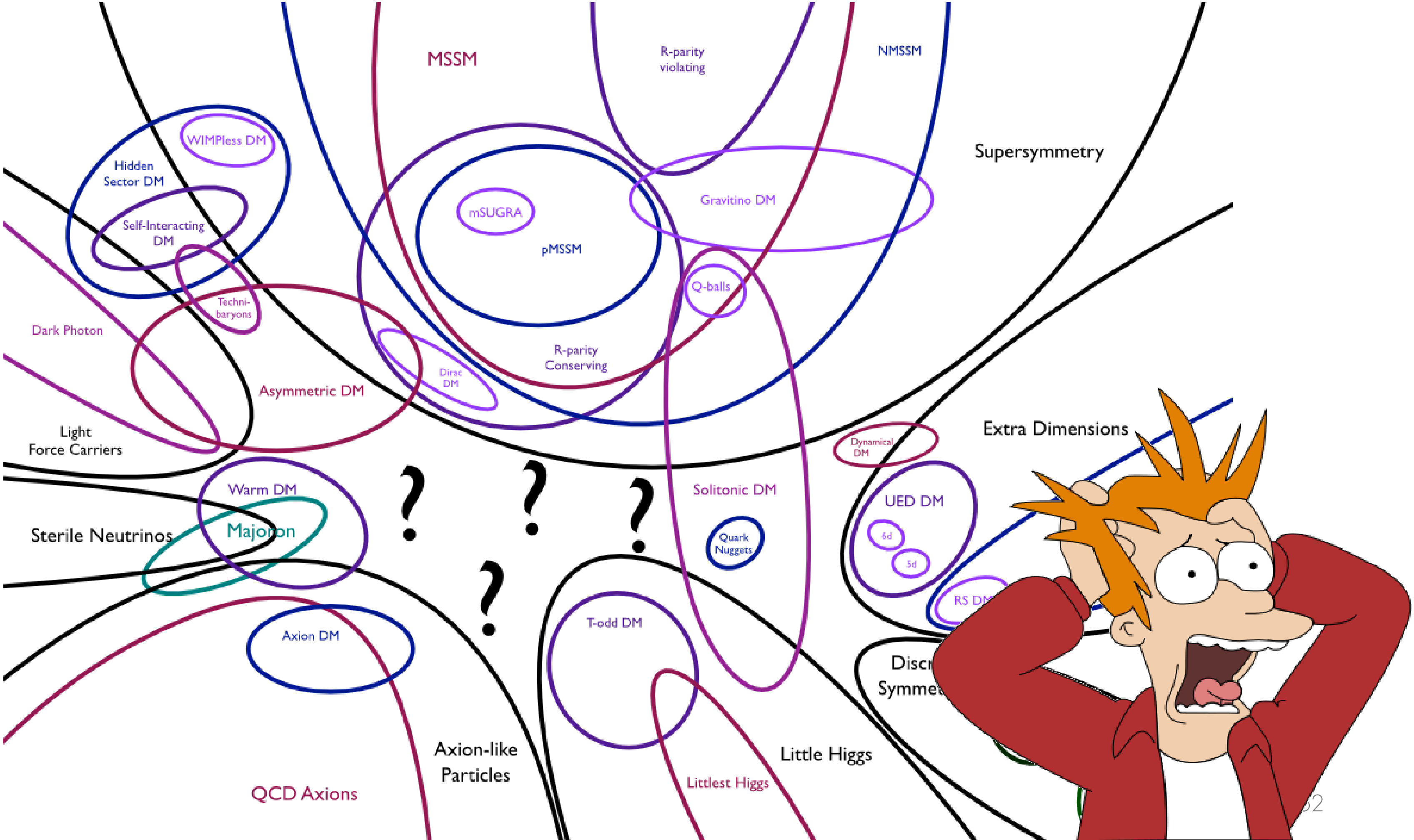
(*) Its mass can go from 10^{-22} eV to 10^{9} GeV
(**) Except Milicharged DM or CHAMPs
(***) DM lifetime larger than 10^{27} seconds (Universe = 10^{17} seconds)

Some candidates



Adapted from 1401.6085

Some candidates



Adapted from 1401.6085


ν_s
Sterile Neutrinos

Sterile neutrinos

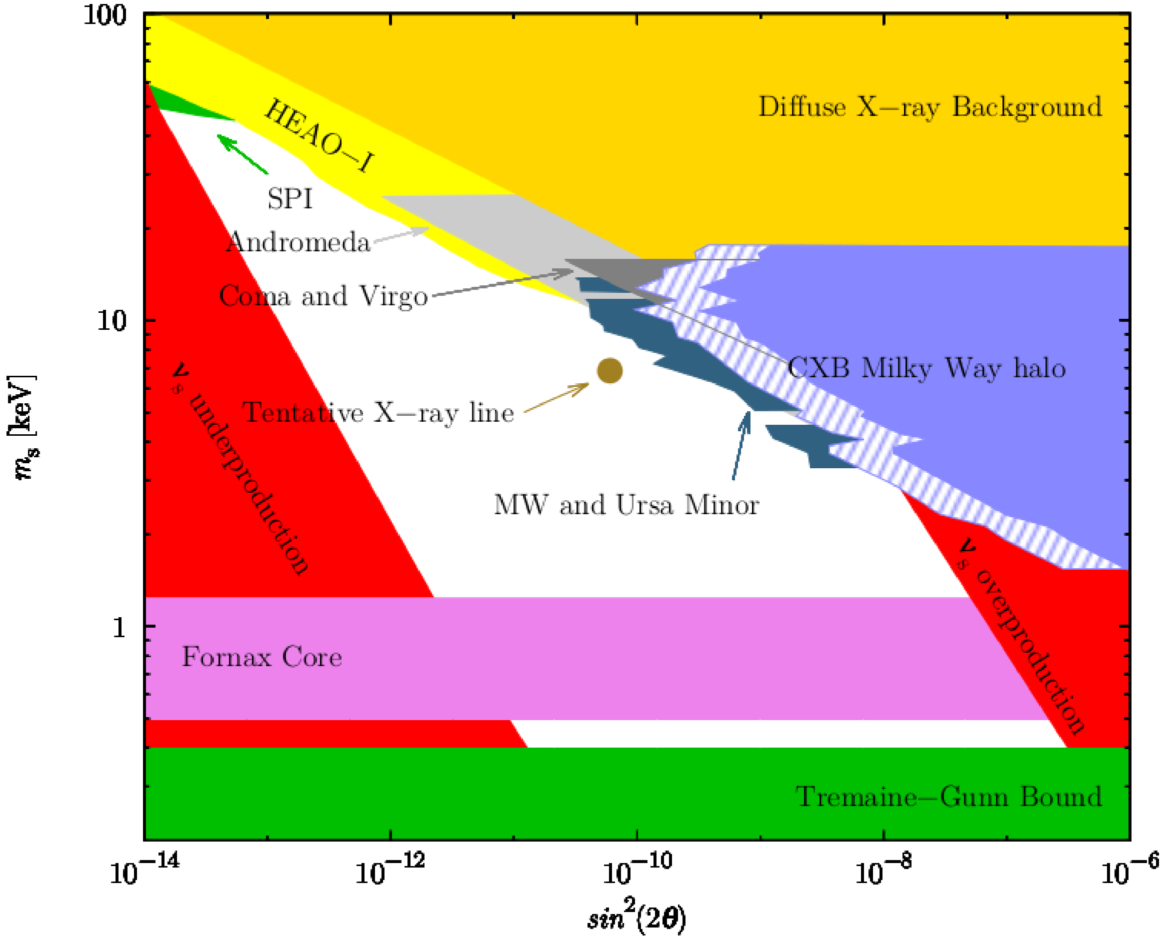
If right-handed neutrinos are part of the SM.
They are natural SM gauge singlets

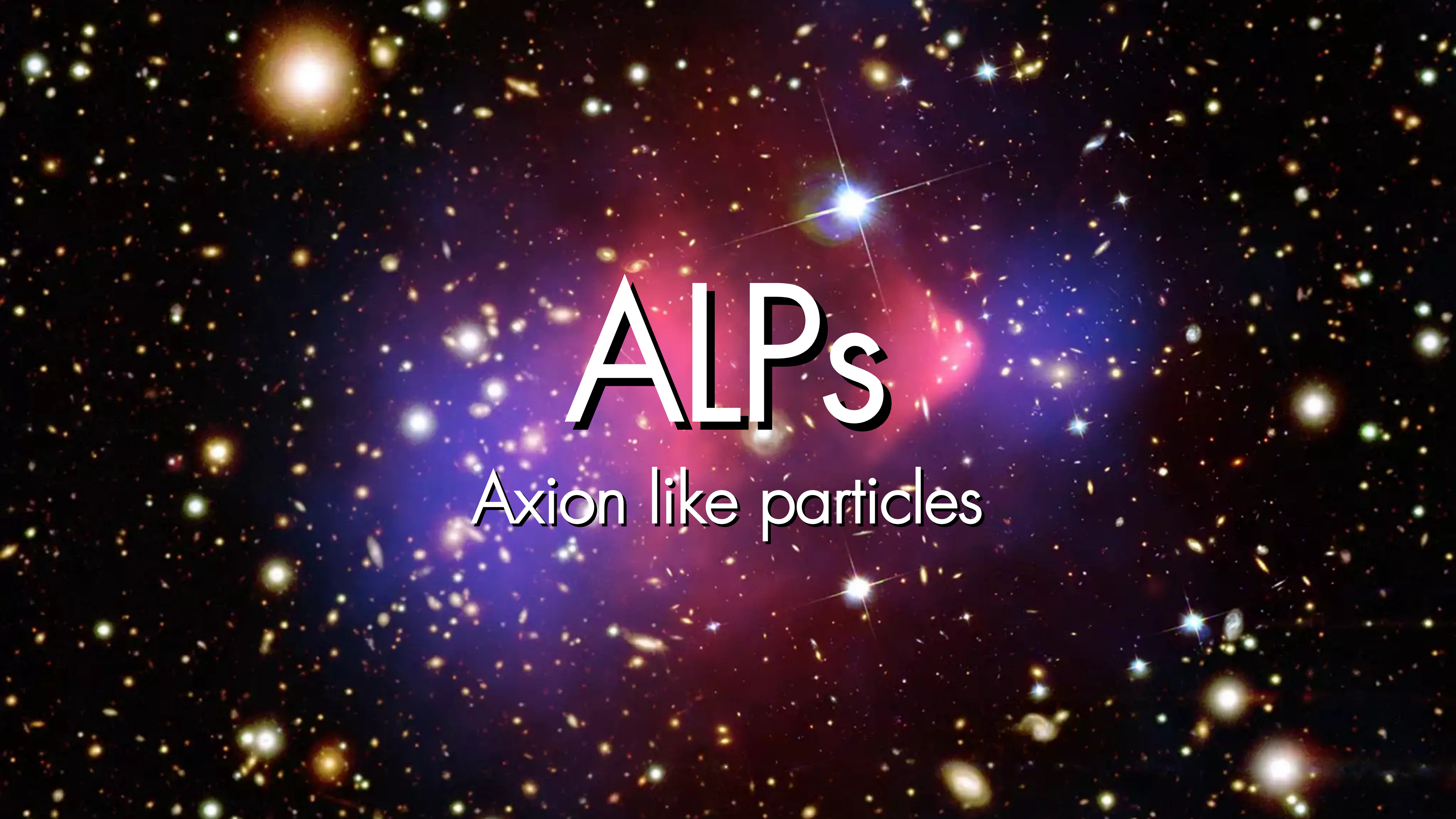
$$\mathcal{L}_2 = Y_2 \bar{L} H \nu_R \qquad\qquad \mathcal{L}_R = \frac{1}{2} M_R \, {\nu_R}^T \nu_R + \text{h.c.}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

Neutrino masses can be generated via the seesaw mechanism

Sterile neutrinos



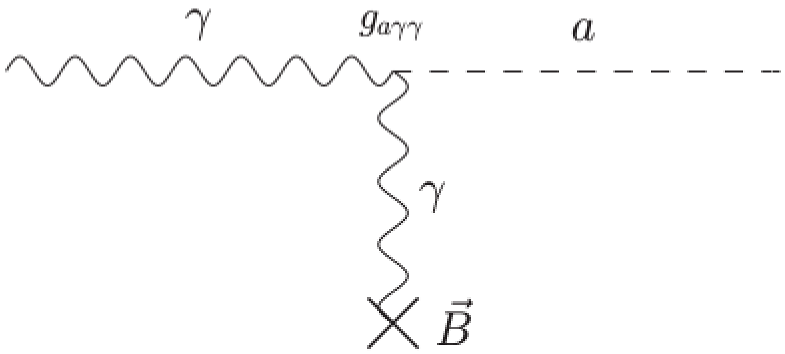

ALPs
Axion like particles

Axion Like Particles

Pseudo-Goldstone bosons.

$$\mathcal{L} = -\frac{1}{4} g_\phi \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

It main feature is the coupling to photons



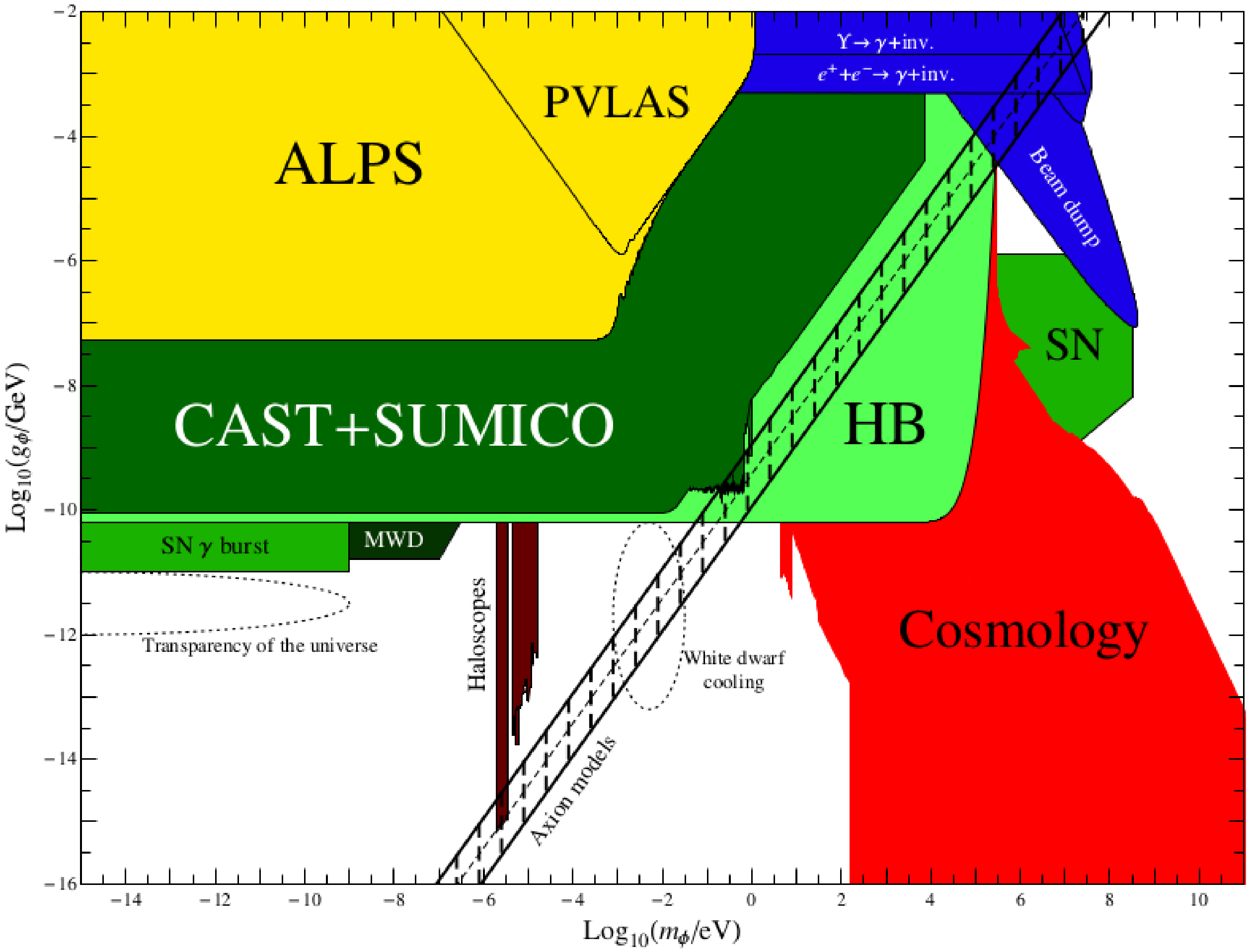
Primakoff effect

Searches involves photon emission line

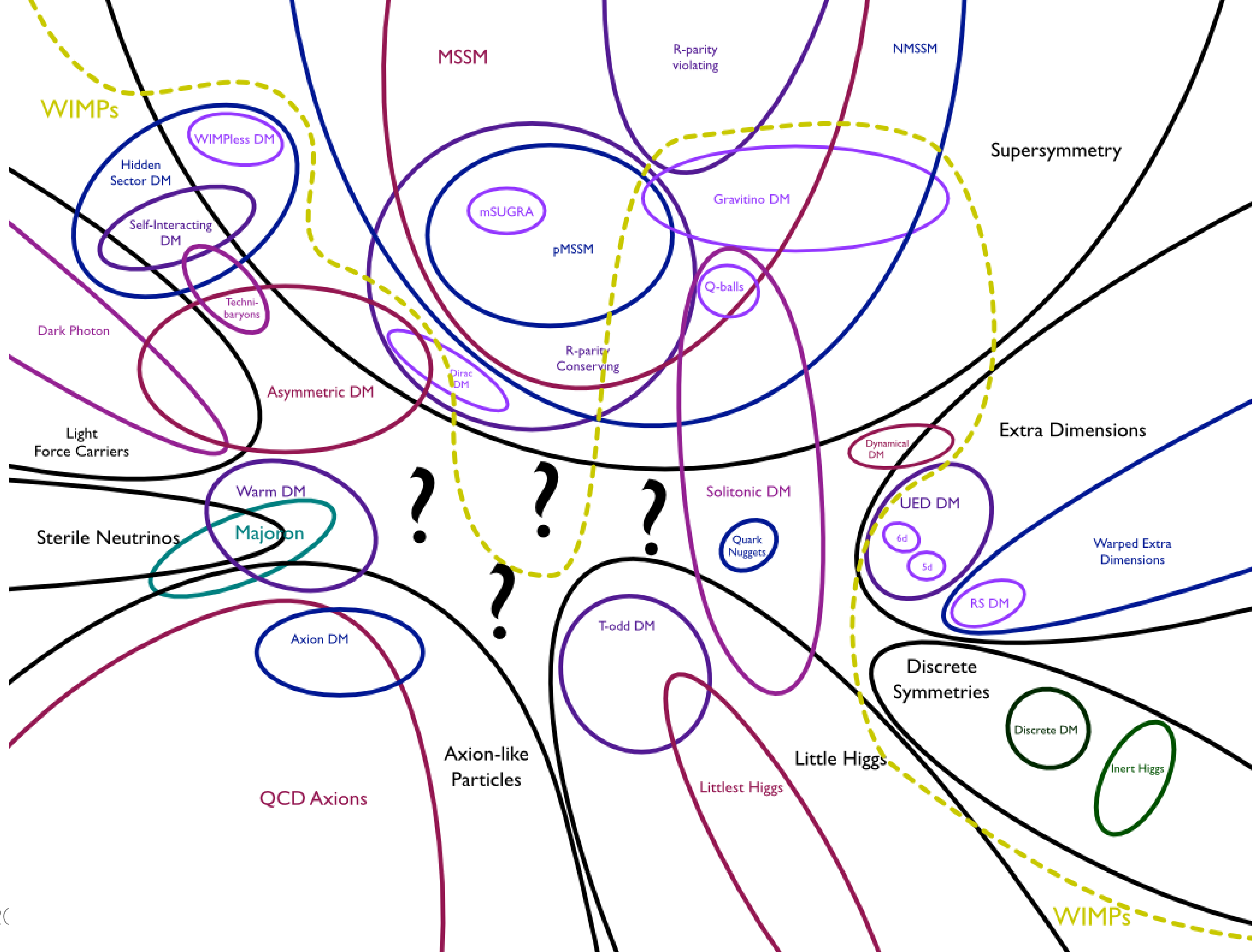
Attenuation due to photon-axion conversion

See: 1210.3196

Axion Like Particles

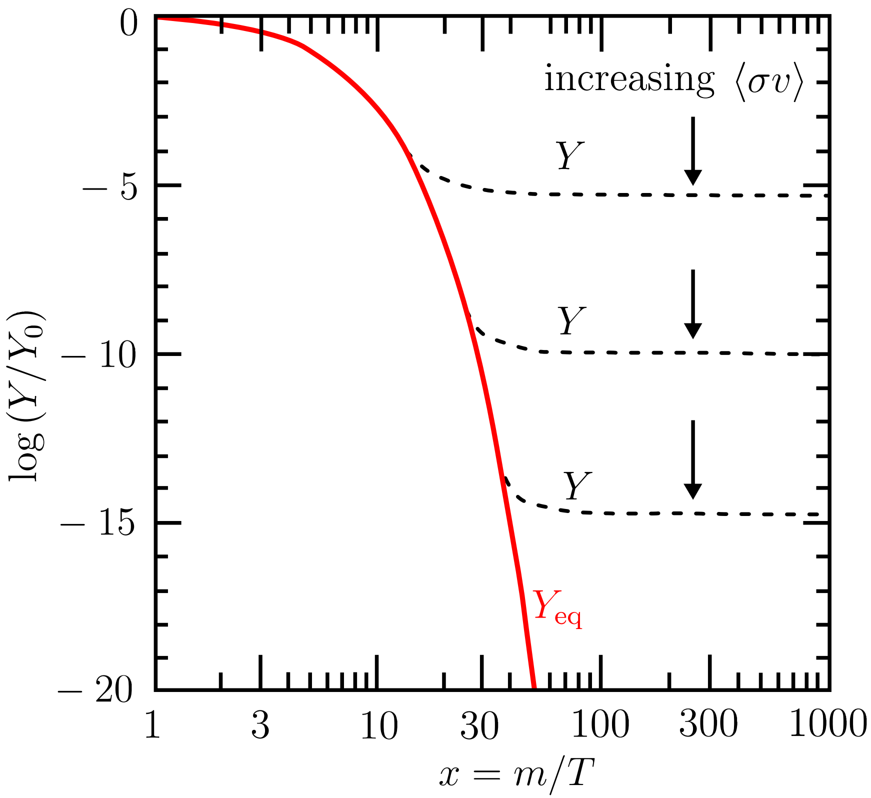



WIMPs
Weakly Interactive Massive Particles



WIMPs
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Majoron
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Discrete Symmetries
Discrete DM
Inert Higgs
Axion-like Particles
Little Higgs
Littlest Higgs
QCD Axions
WIMPs
?
?
?
?

WIMPs



Big Bang Thermal relic

Correct relic abundance for

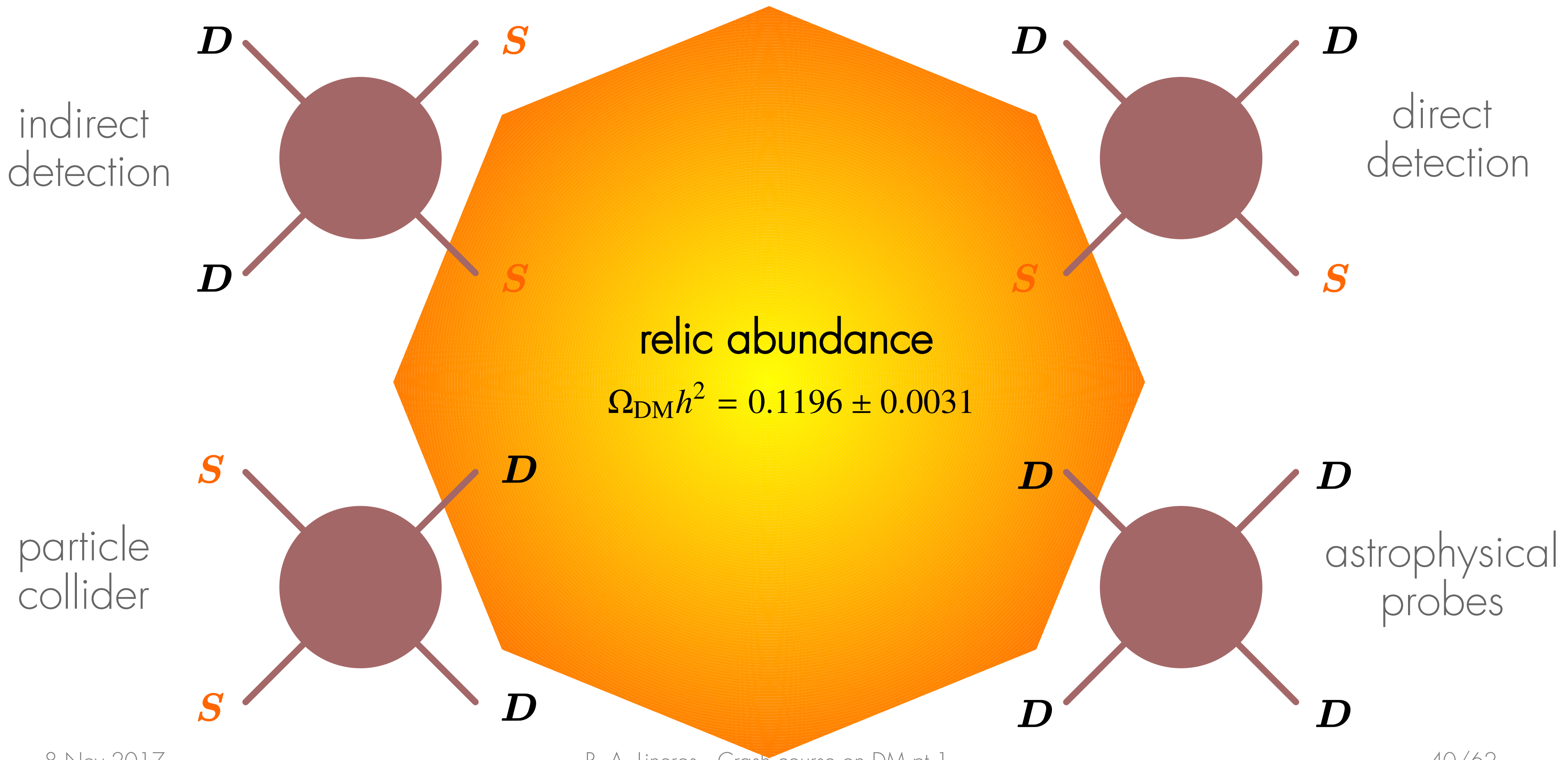
<σv> ~ 1 pb · c

Mass in GeV-TeV range

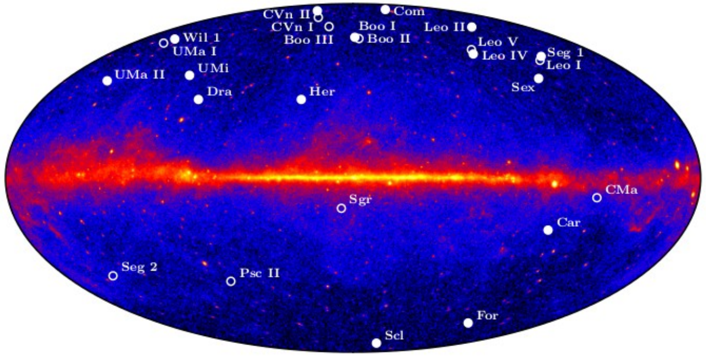
For WIMPs:

$$\Omega_{\mathrm{DM}} h^2 \simeq 0.1 \, \frac{3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle_{\mathrm{f.o.}}} \qquad T_{\mathrm{DM}}^{\mathrm{f.o.}} \simeq \frac{1}{20} m_{\mathrm{DM}}$$

Dark Matter Searches



Dark Matter Searches



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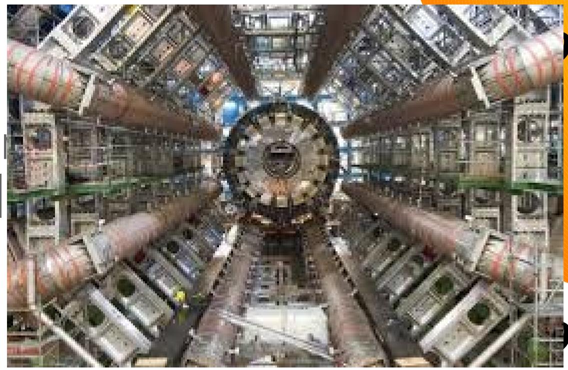
relic abundance

$$\Omega_{\rm DM}h^2 = 0.1196 \pm 0.0031$$

pa
col



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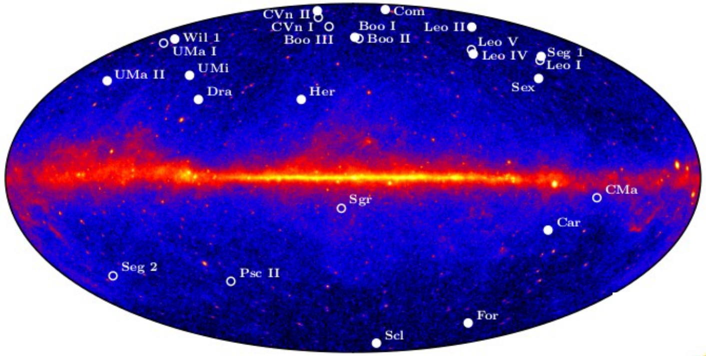
Dark Matter Searches



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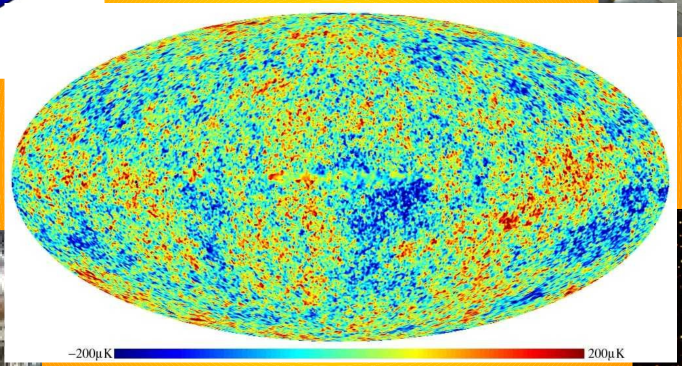

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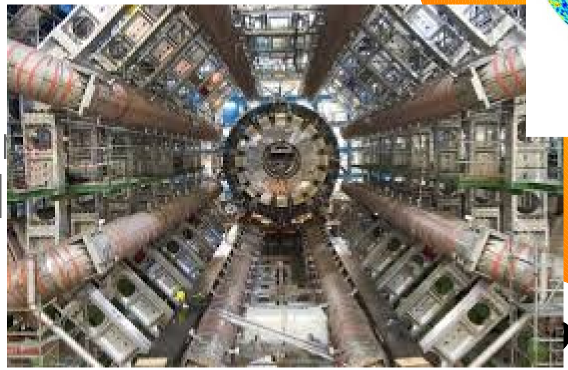

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Some extra details:

Búsqueda de Materia Oscura con astropartículas 1/4

https://youtu.be/DHc8Z2b1W5M

Búsqueda de Materia Oscura con astropartículas 2/4

https://youtu.be/Gpi4vlQM348

Búsqueda de Materia Oscura con astropartículas 3/4

https://youtu.be/Mxt33mN7sgU

Búsqueda de Materia Oscura con astropartículas 4/4

https://youtu.be/y-dpl_FulQY

Particle models with WIMP DM

Inert singlet DM model

The simplest DM model.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi}{2}\phi^2 - \frac{\lambda_\phi}{4}\phi^4 - \frac{\lambda_{\phi h}}{2}\phi^2 H^\dagger H + \mathcal{L}_{SM}$$

Features:

DM is a real scalar charged with a Z_2 symmetry
The interaction with the SM is via Higgs particle

The relevant parameter are mass and coupling to the Higgs

Inert singlet DM model

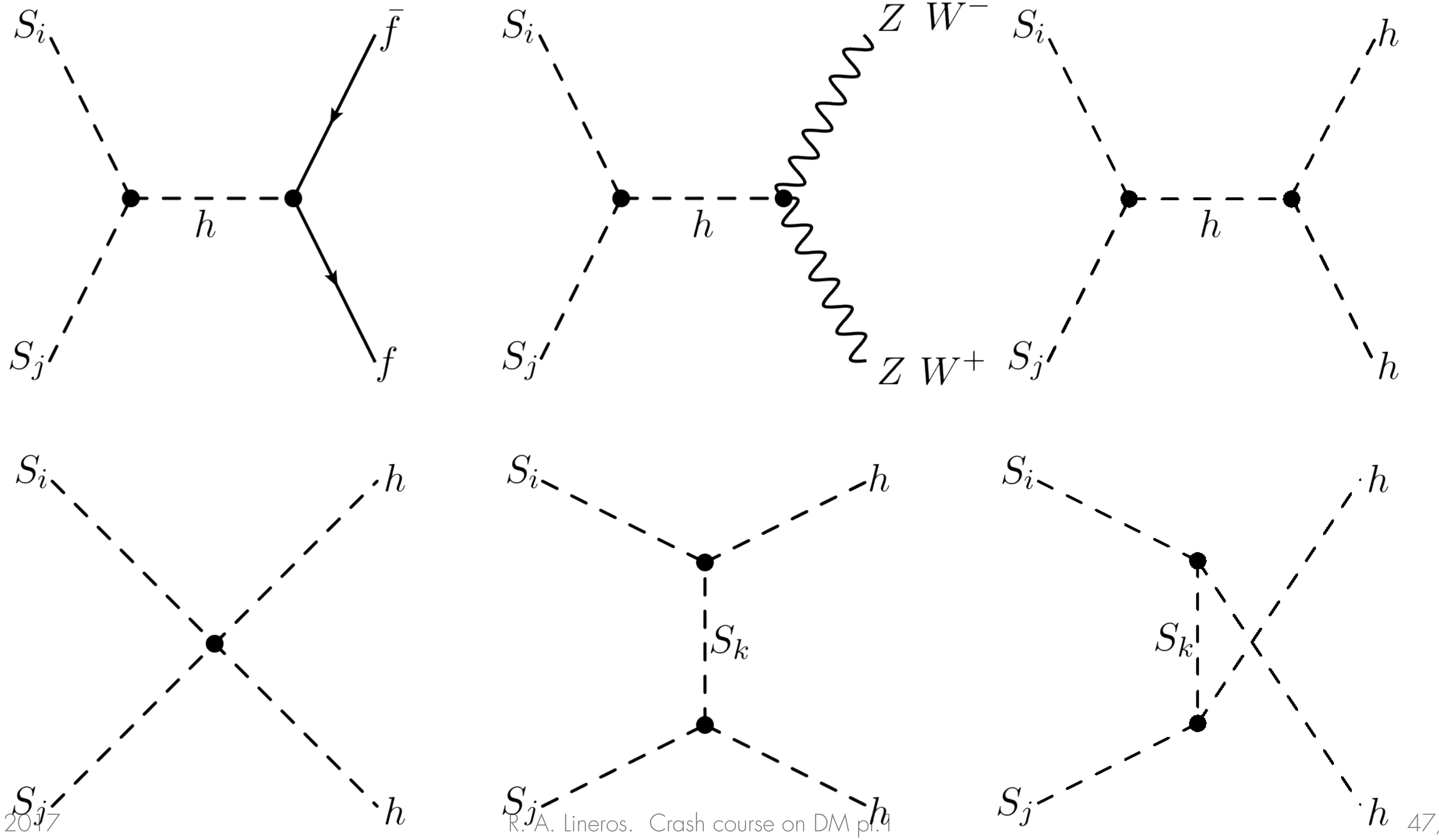
The simplest DM model.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{m_\phi}{2}\phi^2 - \frac{\lambda_\phi}{4}\phi^4 - \frac{\lambda_{\phi h}}{2}\phi^2 H^\dagger H + \mathcal{L}_{SM}$$

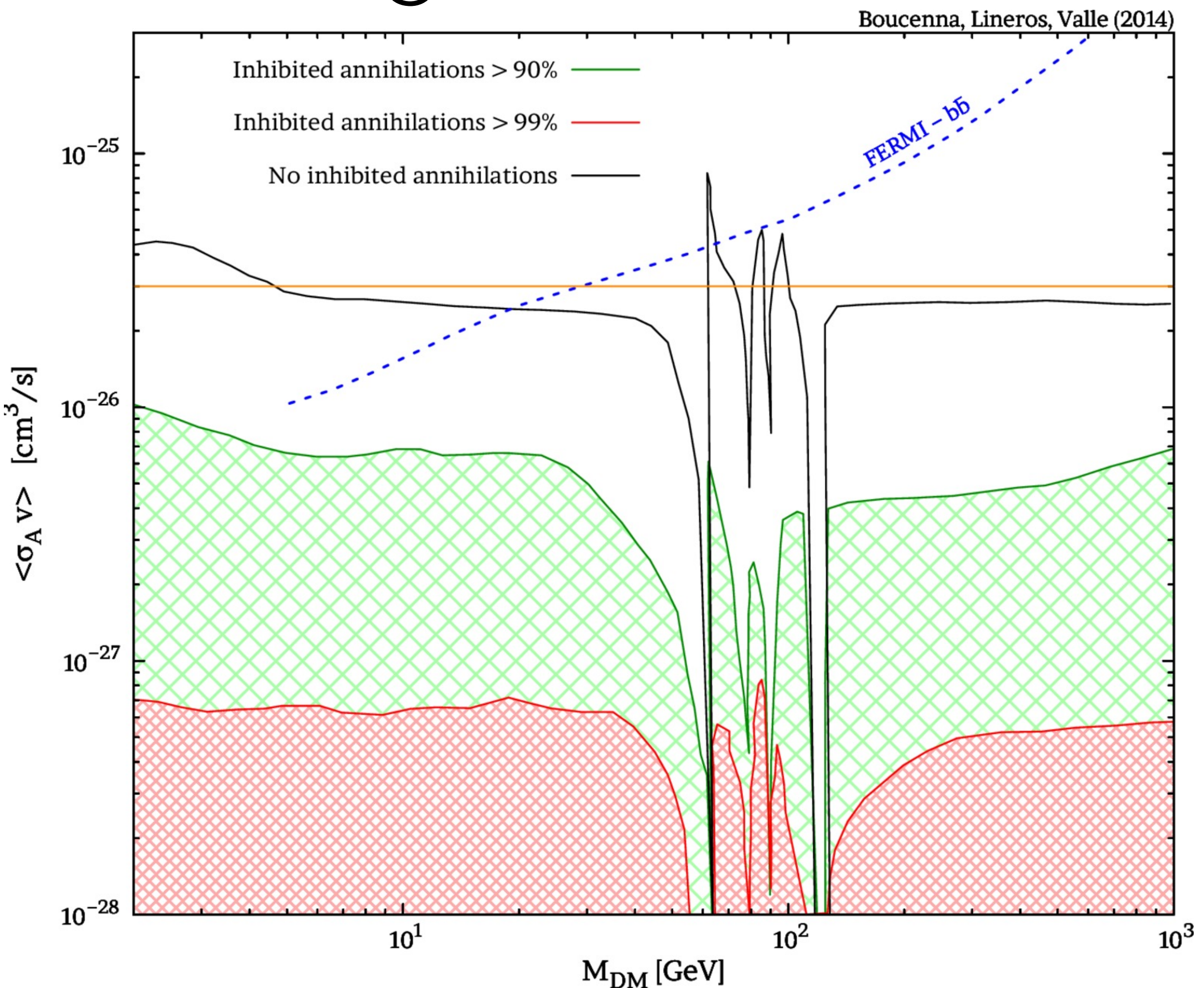
Small exercise:

Draw diagrams relevant for the relic abundance

Inert singlet DM model



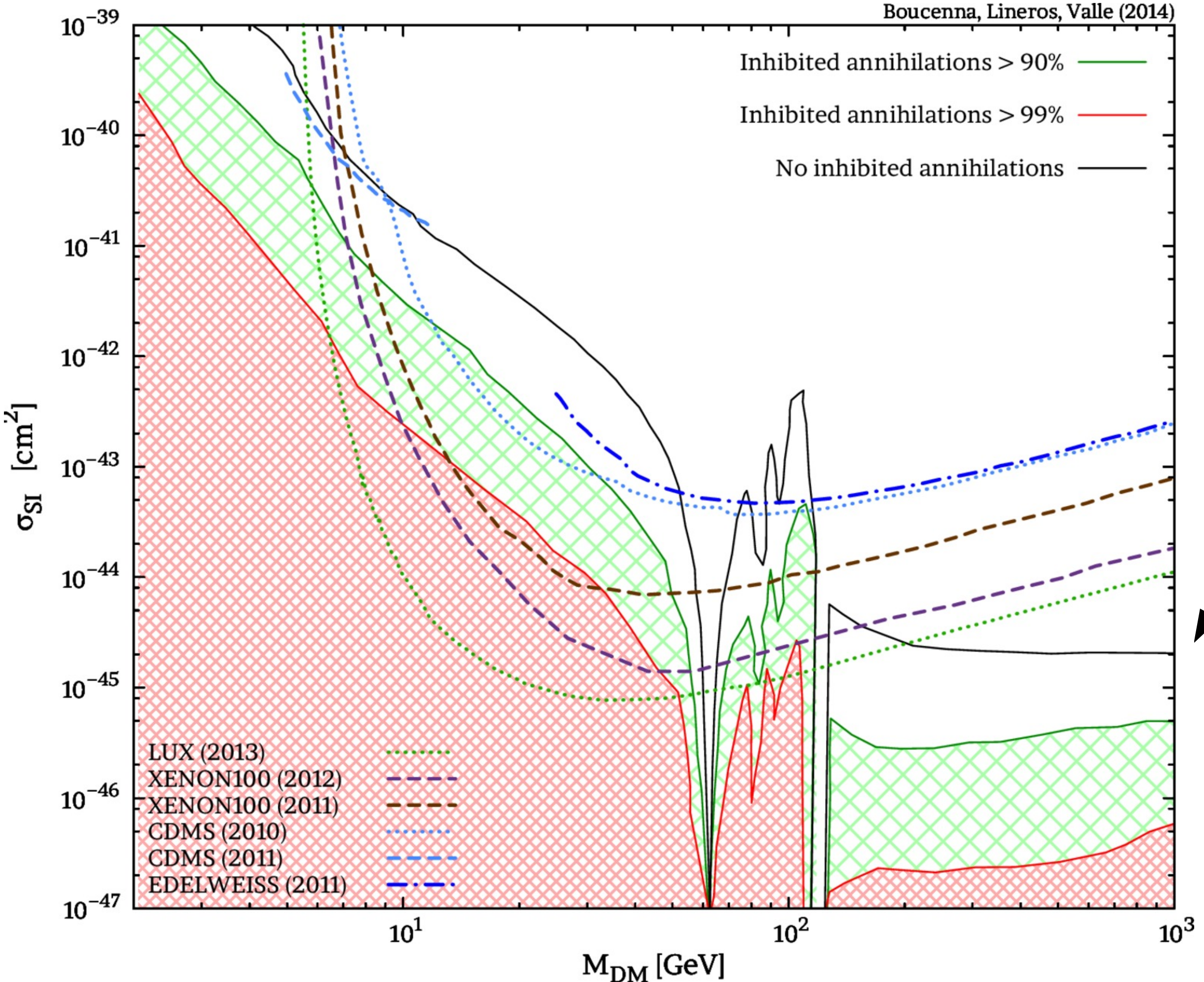
Inert singlet DM model



Solution is the black line

Tight relation among mass and higgs coupling

Inert singlet DM model



Solution is the black line

Tight relation among mass and higgs coupling

Fermion singlet DM model

Dark Matter is a majorana fermion connected to the SM via a scalar singlet

$$\mathcal{L} = \frac{1}{2}\overline{\psi}\left(i\gamma_\mu\partial_\mu - m_\psi\right)\psi + \omega\phi\overline{\psi}\psi + \frac{1}{2}\left(\partial_\mu\phi\right)^2 - \frac{m_\phi^2}{2}\phi^2$$
$$- \frac{\lambda_1}{3}\phi^3 - \frac{\lambda_2}{4}\phi^4 - \frac{\lambda_3}{2}\phi H^\dagger H - \frac{\lambda_4}{2}\phi^2 H^\dagger H + \mathcal{L}_{SM}$$

The model contains:
2 extra particles and 7 parameters

More freedom to reproduce DM observables

Small exercise:

Draw diagrams relevant for the relic abundance

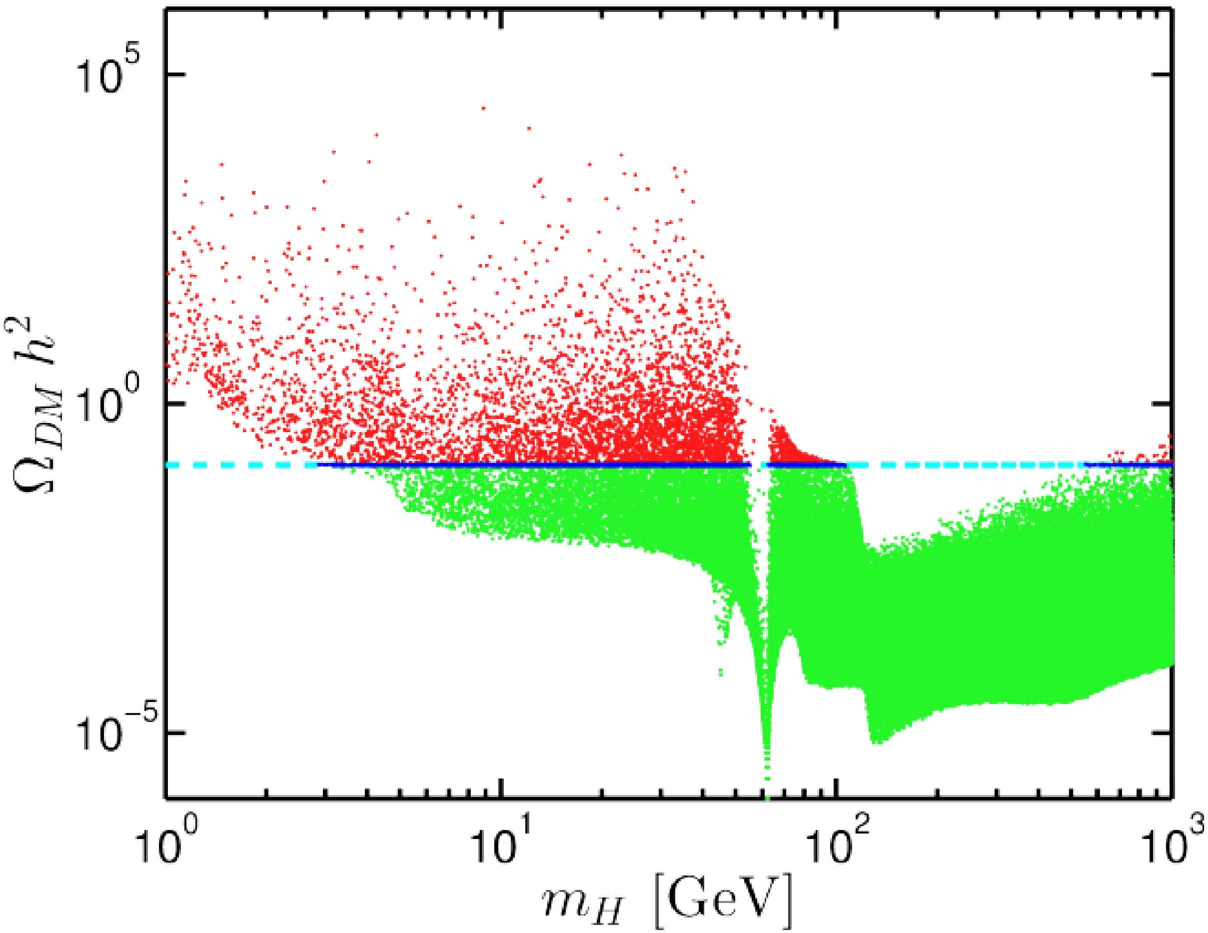
Inert Higgs DM model

DM is part of a SU(2) scalar doublet (copy of Higgs) but charged with a Z_2 symmetry

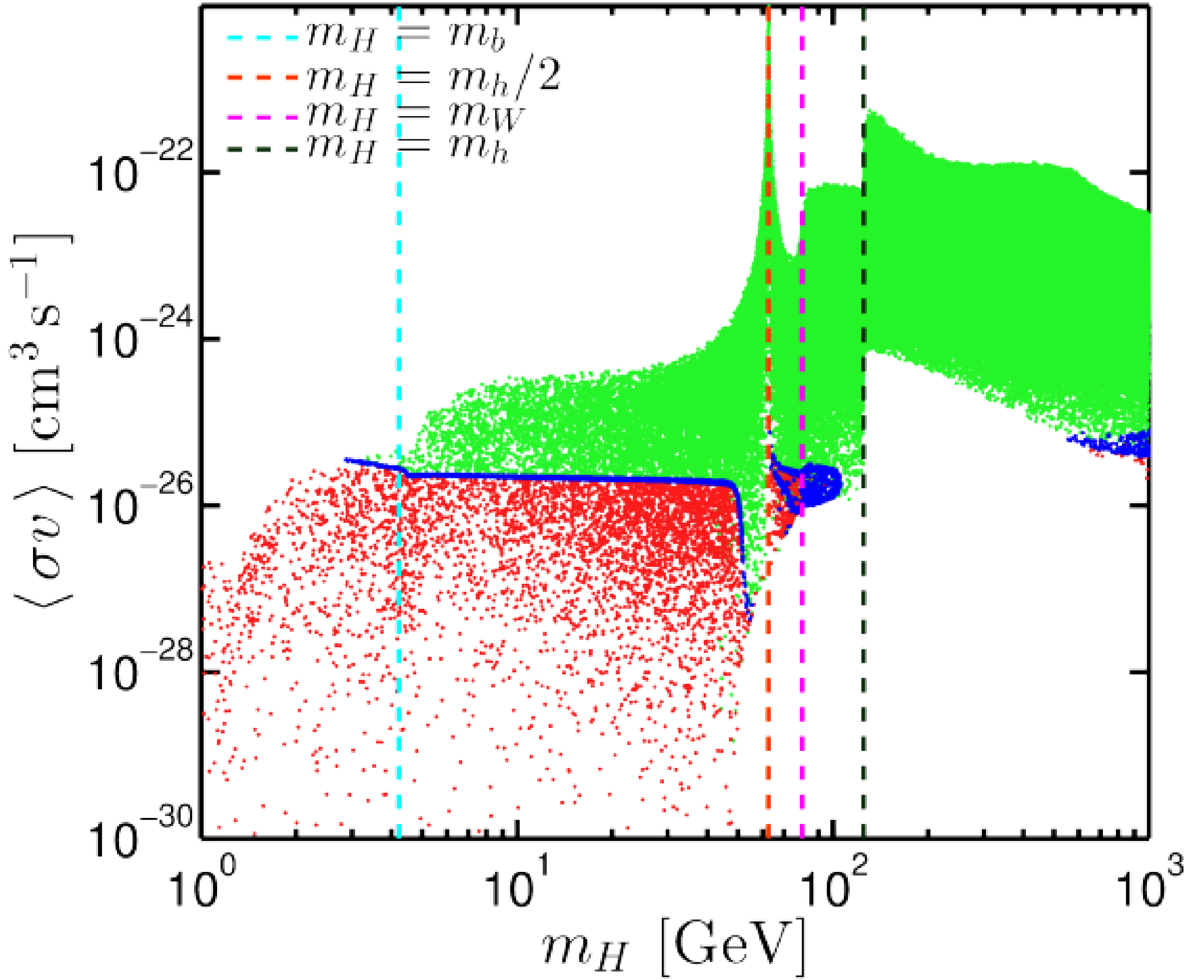
$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 \\ + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right],$$

$$H_1 = \left(\begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{array} \right) \quad , \quad H_2 = \left(\begin{array}{c} H^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{array} \right)$$

Inert Higgs DM model



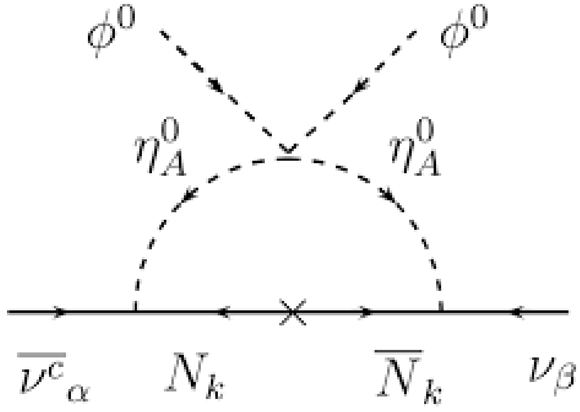
Inert Higgs DM model



Scotogenic DM model (Ma, 2006... and many other papers)

Model provides a mechanism where neutrino acquire mass via loop.

Inside the loop DM particles run.



$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik} h_{jk} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right],$$

Scotogenic DM model

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2} M_i \overline{N_i} N_i^{\mathcal{C}} + h_{ij} \overline{N_i}\, \widetilde{\eta}^\dagger\, \ell^j + \text{h.c.}$$

$$\begin{aligned} V = {} & m_H^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(\phi^\dagger \phi\right)^2 \\ & + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(\phi^\dagger \phi\right) \left(\eta^\dagger \eta\right) \\ & + \lambda_4 \left(\phi^\dagger \eta\right) \left(\eta^\dagger \phi\right) + \left[\frac{\lambda_5}{2} \left(\eta^\dagger \phi\right)^2 + \text{h.c.} \right] \end{aligned}$$

Singlet-Triplet Scotogenic DM

DM is mix between a singlet fermion and a SU(2) triplet

	Standard Model			Fermions		Scalars	
	L	e	ϕ	Σ	N	η	Ω
$SU(2)_L$	2	1	2	3	1	2	3
Y	-1	-2	1	0	0	1	0
Z_2	$+$	$+$	$+$	$-$	$-$	$-$	$+$

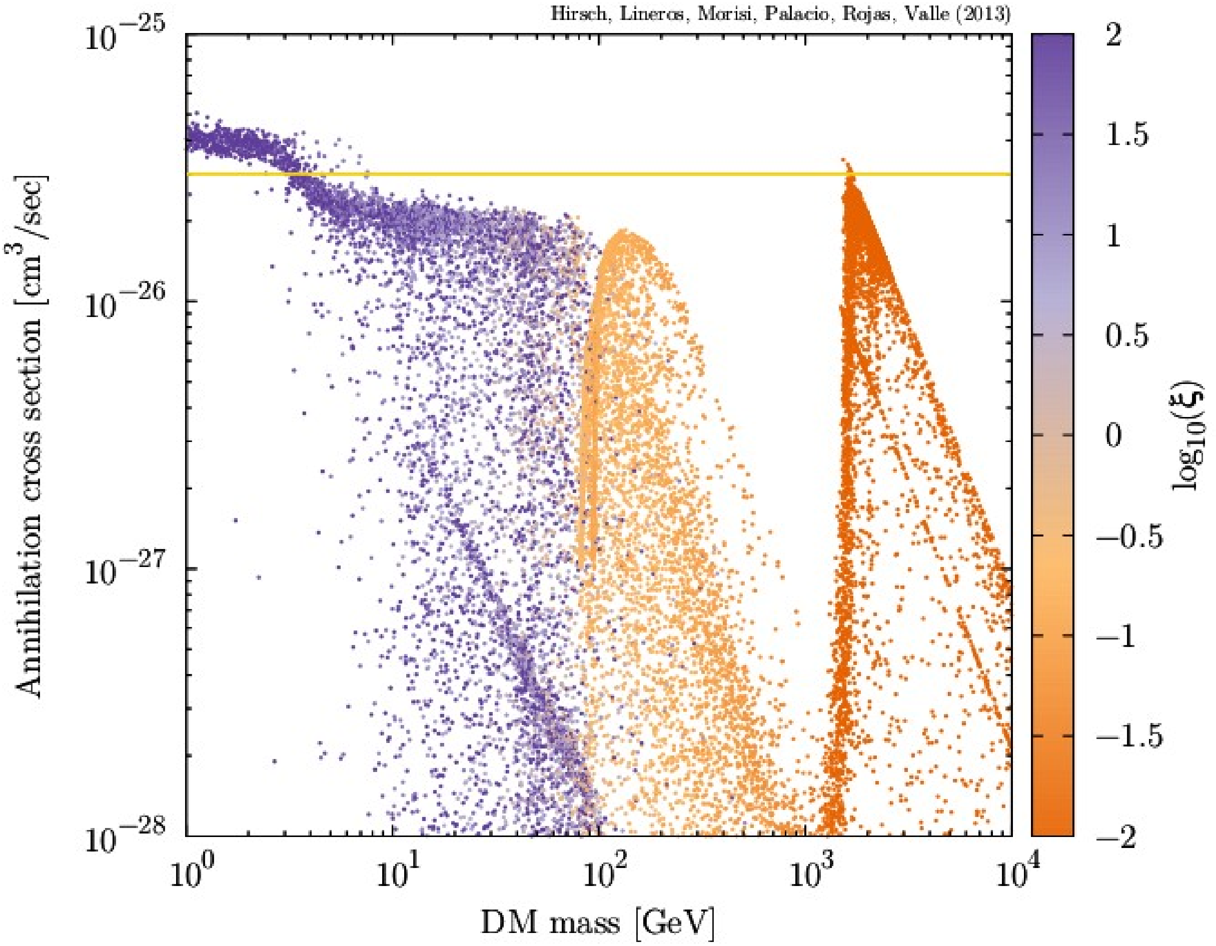
Singlet-Triplet Scotogenic DM

$$\mathcal{L} \supset -Y_{\alpha\beta}\,\overline{L}_\alpha e_\beta \phi - Y_{\Sigma_\alpha}\overline{L}_\alpha C \Sigma^\dagger \tilde{\eta} - \frac{1}{4} M_\Sigma \mathrm{Tr}\left[\overline{\Sigma}^c \Sigma\right] +$$

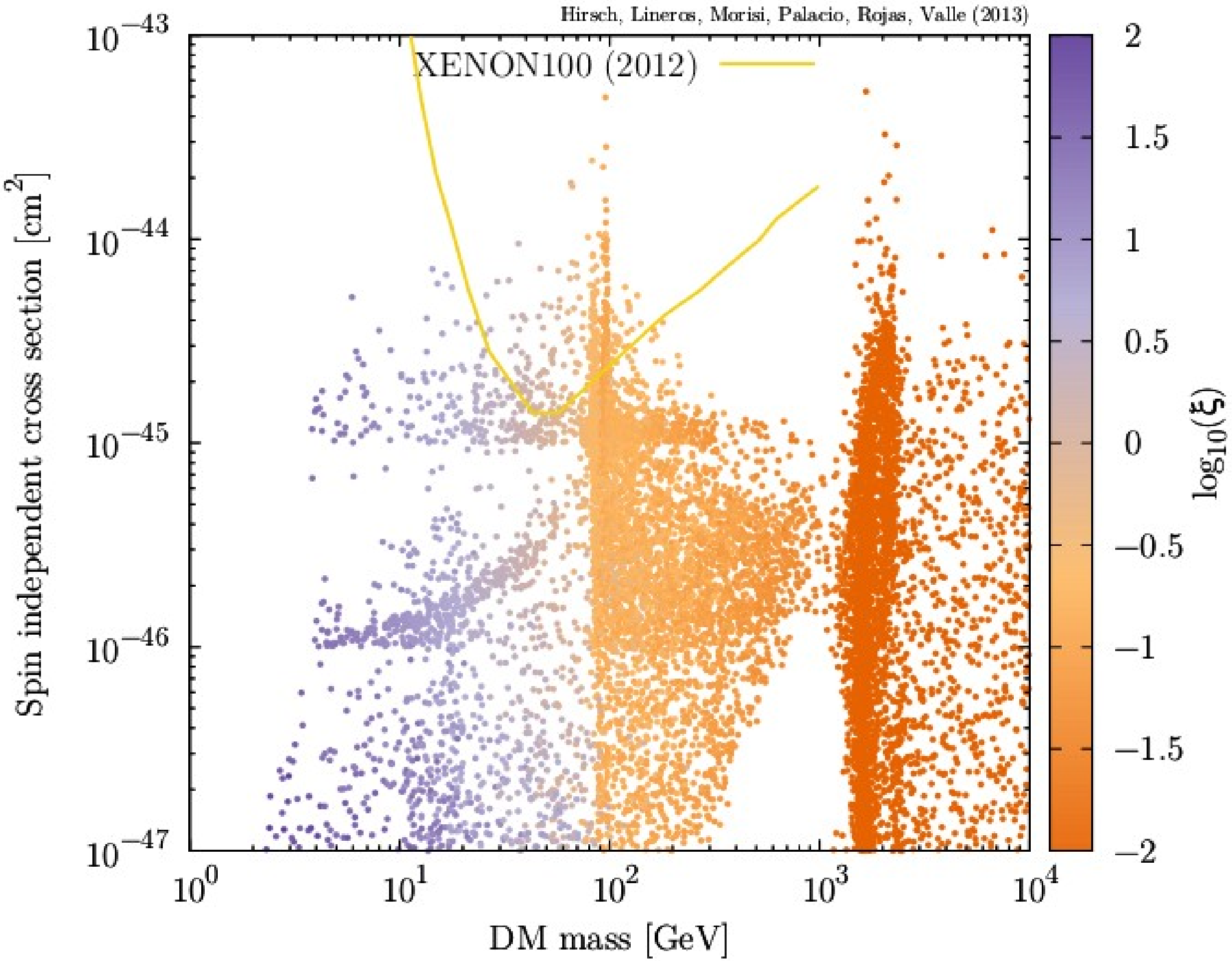
$$-Y_\Omega \mathrm{Tr}\left[\overline{\Sigma}\Omega\right] N - Y_{N_\alpha}\overline{L}_\alpha \tilde{\eta} N - \frac{1}{2} M_N \overline{N}^c N + h.c.$$

$$\begin{aligned} V_{\rm scal} = & -m_1^2 \phi^\dagger\phi + m_2^2 \eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) \\ & + \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2 + h.c. - \frac{M_\Omega^2}{4} Tr\left(\Omega^\dagger\Omega\right) + \left(\mu_1\phi^\dagger\Omega\phi + h.c.\right) \\ & + \lambda_1^\Omega \phi^\dagger\phi\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_2^\Omega\left(Tr(\Omega^\dagger\Omega)\right)^2 + \lambda_3^\Omega Tr(\left(\Omega^\dagger\Omega\right)^2) + \lambda_4^\Omega\left(\phi^\dagger\Omega\right)\left(\Omega^\dagger\phi\right) \\ & + \left(\mu_2\eta^\dagger\Omega\eta + h.c.\right) + \lambda_1^\eta \eta^\dagger\eta\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_4^\eta\left(\eta^\dagger\Omega\right)\left(\Omega^\dagger\eta\right)\;, \end{aligned}$$

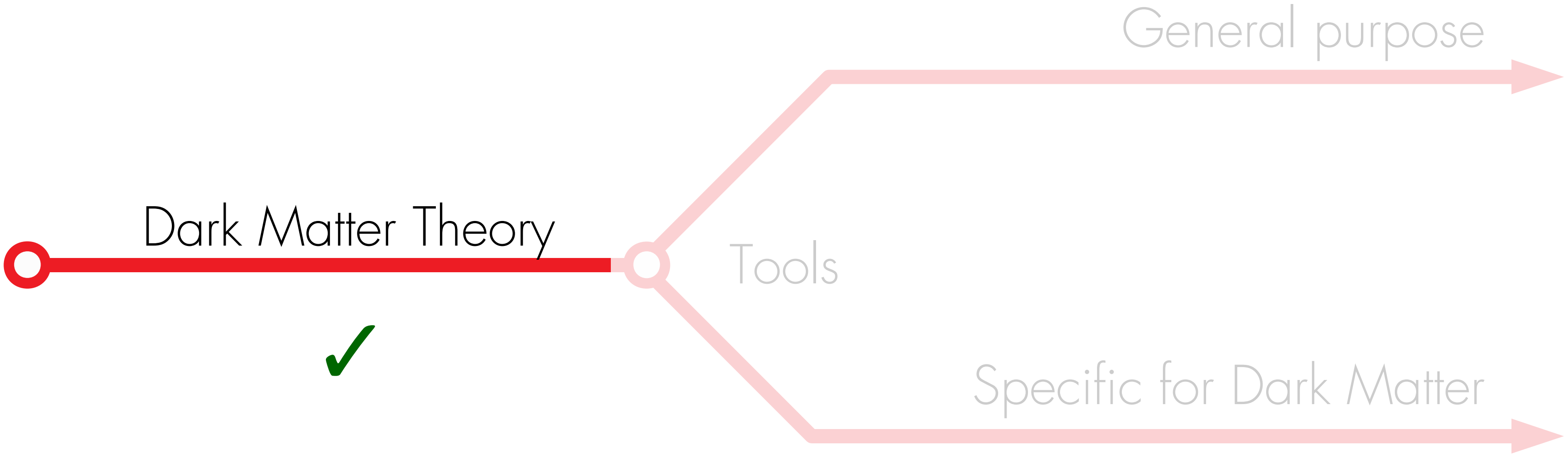
Singlet-Triplet Scotogenic DM



Singlet-Triplet Scotogenic DM



Course plan


General purpose
Dark Matter Theory
Tools
✓
Specific for Dark Matter

Tomorrow!

codes!

Thanks