



MadDM

Dark Matter Phenomenology
in the MG5_aMC@NLO framework

Gopolang (Gopi) Mohlabeng

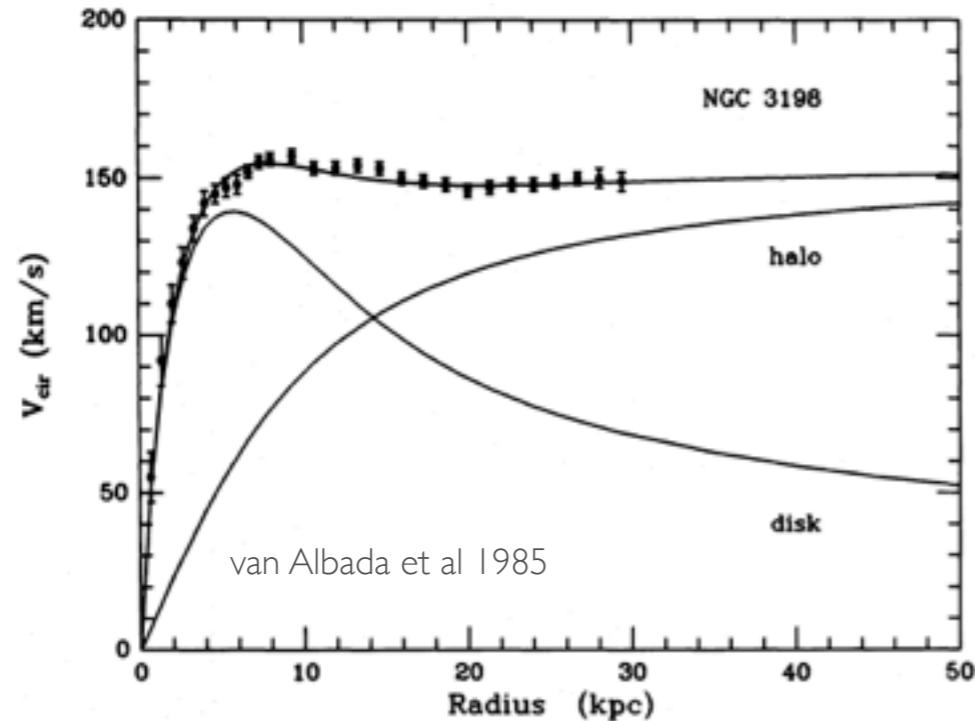
Tutorial

Quick Recap

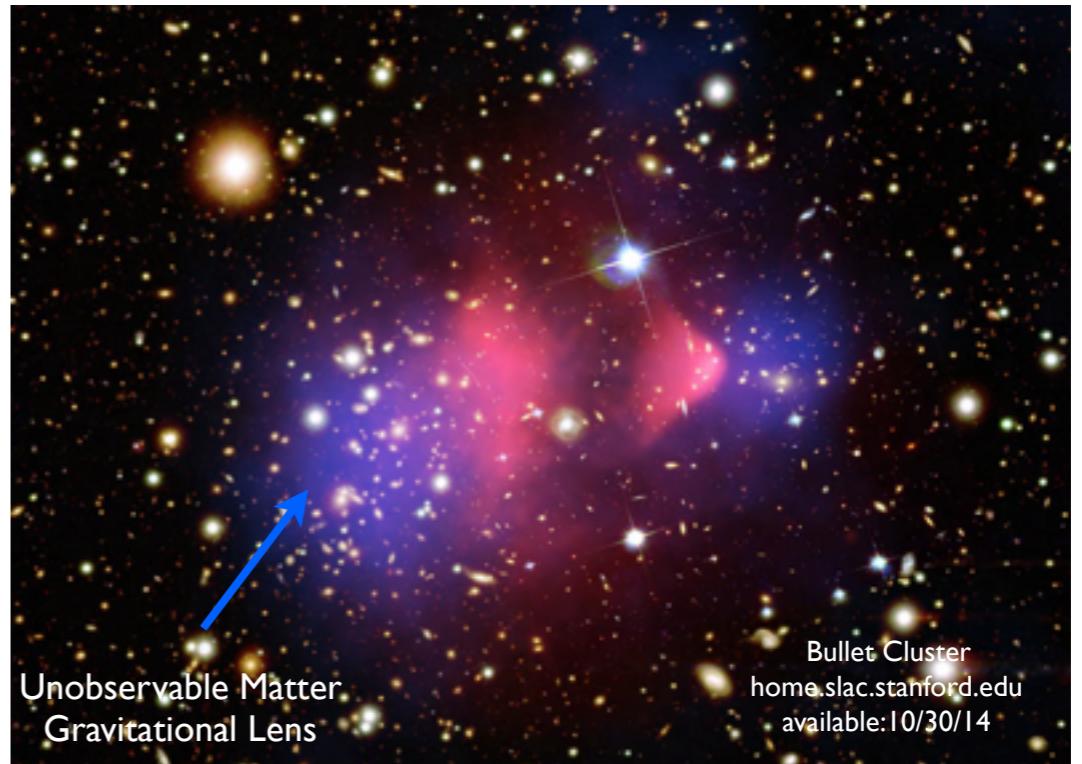
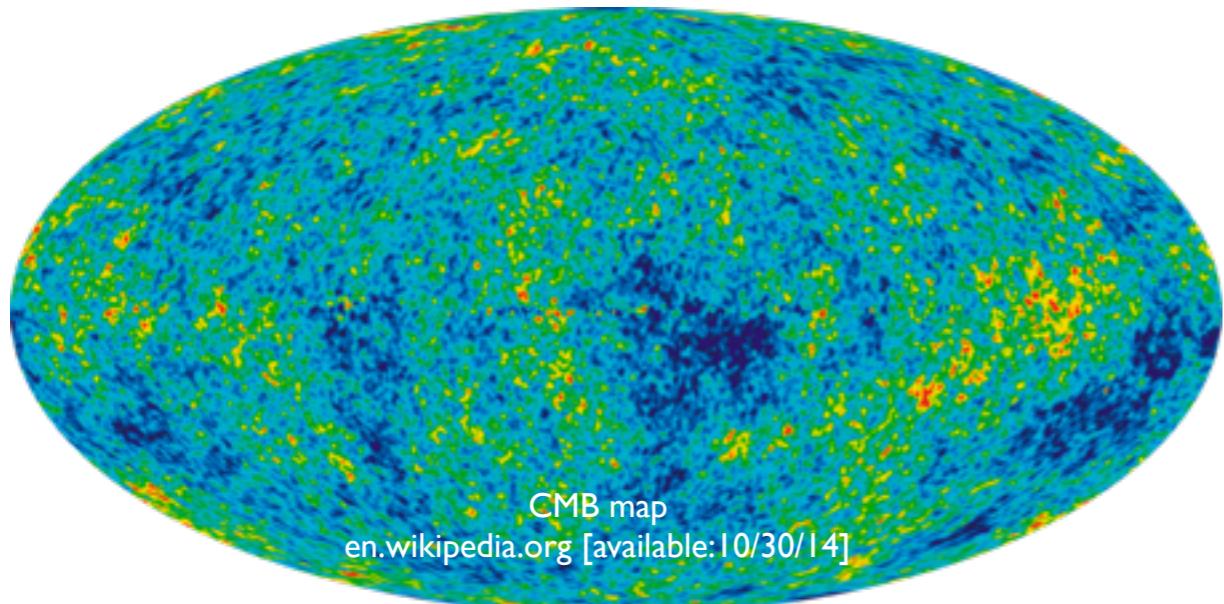
The (Inconvenient) Truth about DM

We have many hints DM exist, **but no direct evidence!**

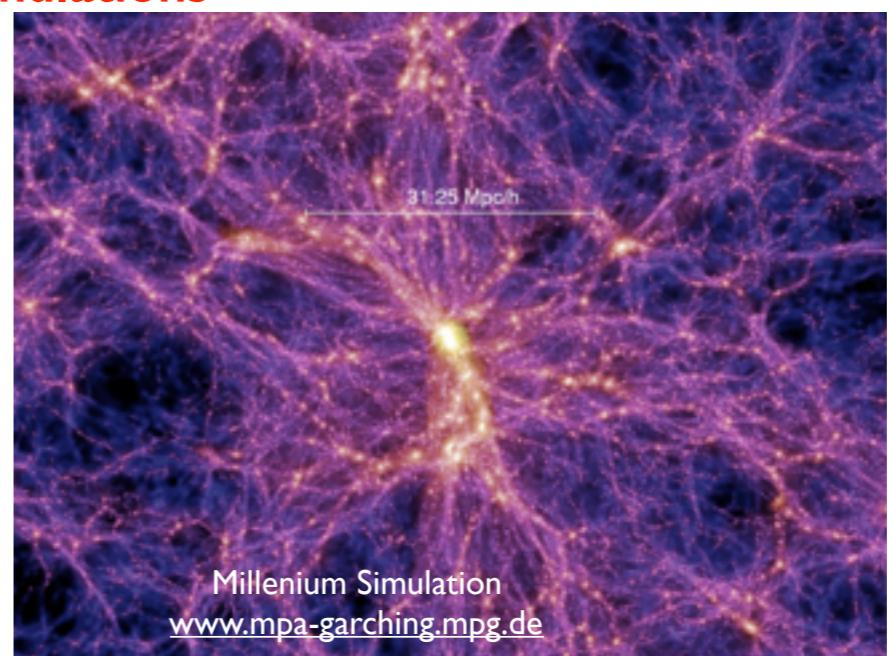
Rotational velocities of spiral galaxies



Velocity dispersions, CMB maps, N-body simulations



Gravitational Lensing



The (Inconvenient) Truth about DM

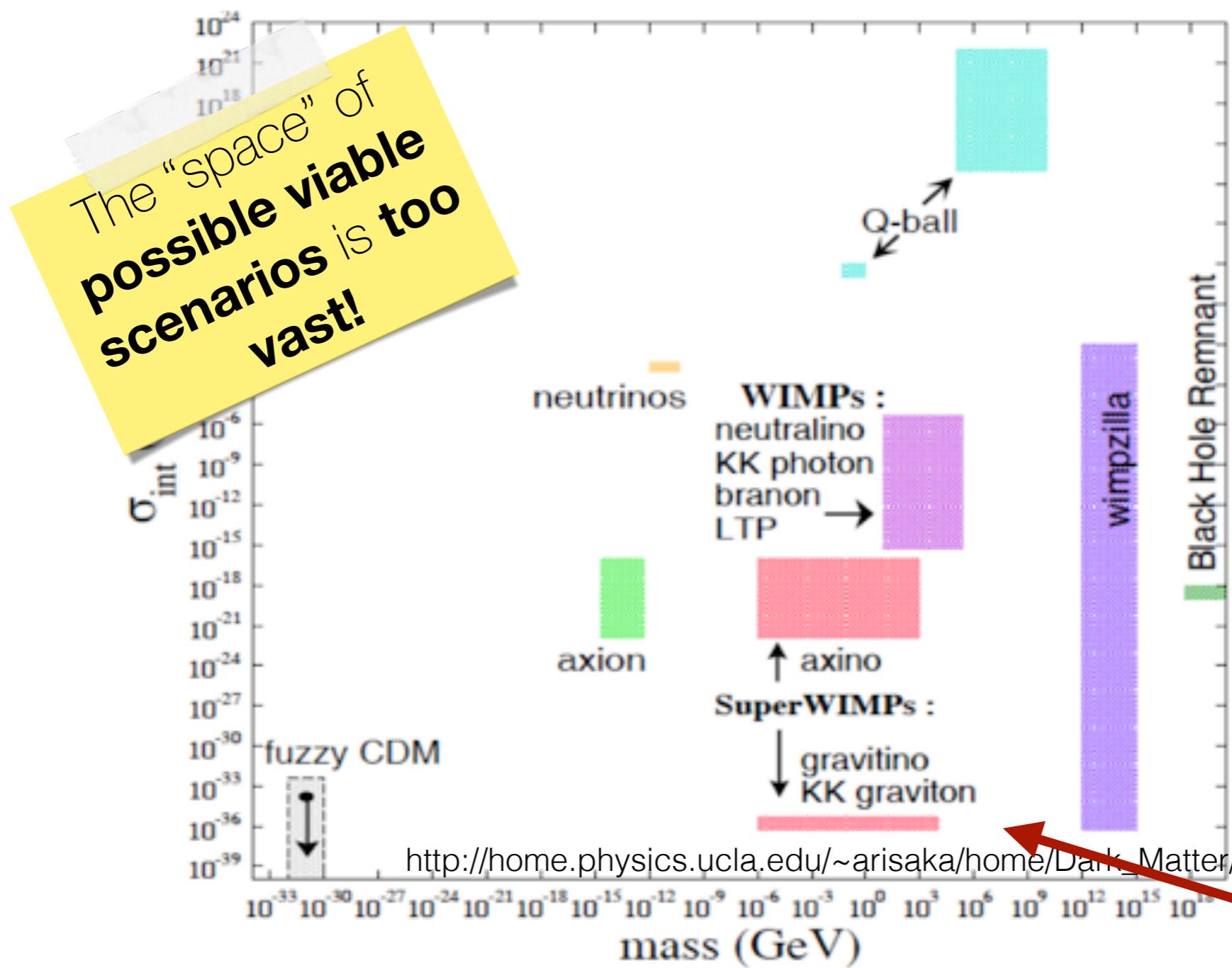
If particle DM exists, **what do we know about it?**

Dark Matter:

1. Mass = ???
2. Spin = ???
3. Decays = ???
4. Interactions = **Gravity**, ???
5. Elementary = ???
6.

DM could in principle only interact gravitationally...

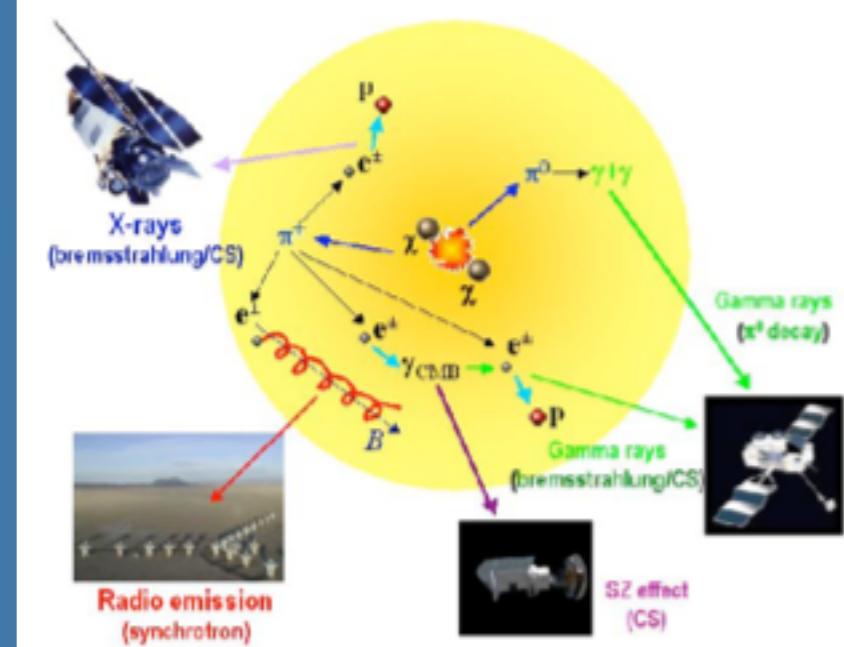
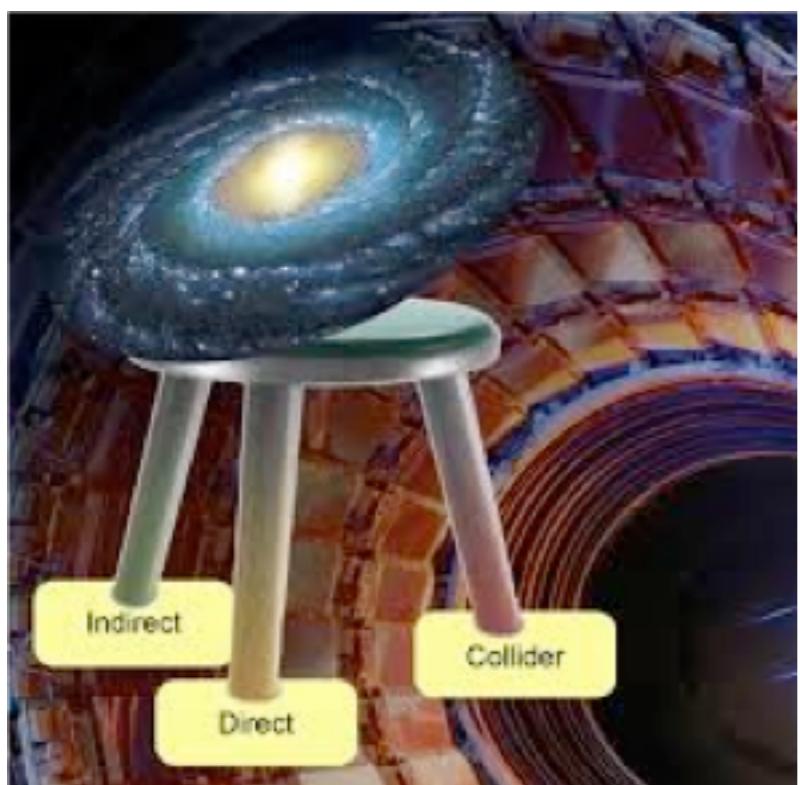
- We have no sense of where new physics is **hiding**



DM models
alone span many
orders of magnitude
in energy scales

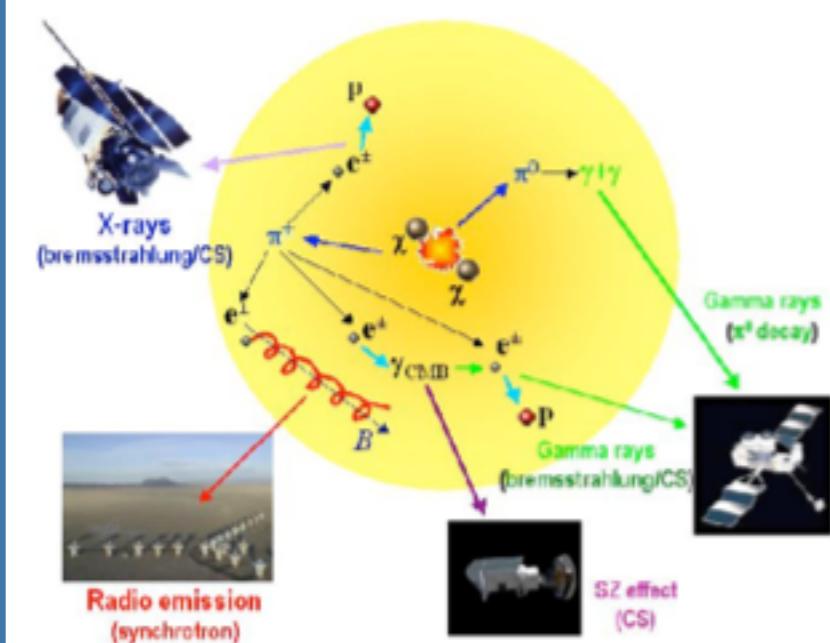
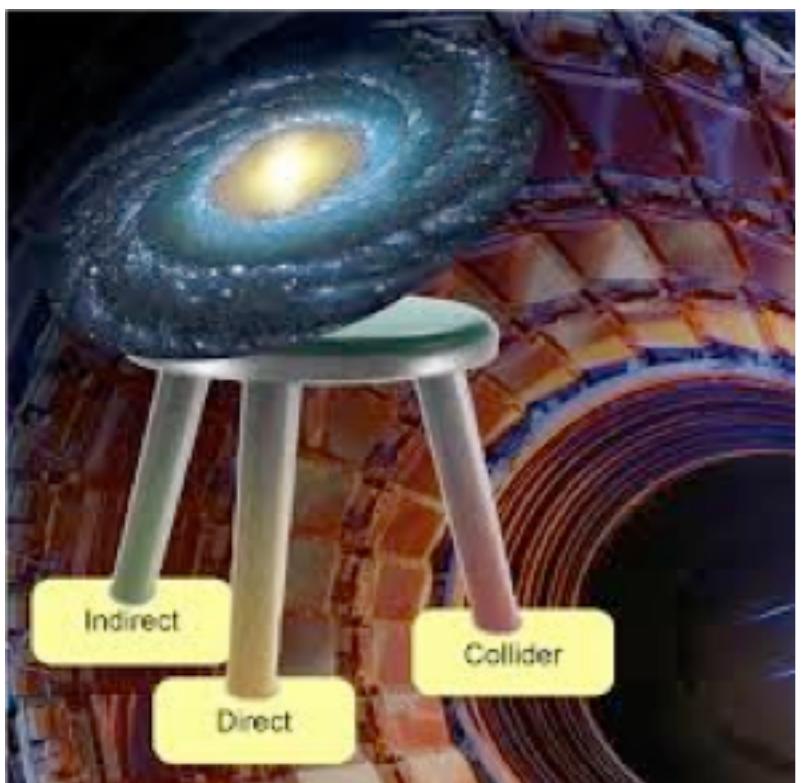
However, assuming DM has other interactions...
...we can devise methods for its detection

- Astrophysics and Cosmology: $\rightarrow \chi\chi \rightarrow \text{all}$
- Direct Detection: $\rightarrow p/n \chi \rightarrow p/n \chi$
- Indirect Detection: $\rightarrow \chi\chi \rightarrow e^+e^-, p\bar{p}, \gamma\gamma$
- Colliders: $\rightarrow pp \rightarrow \chi\chi + j$

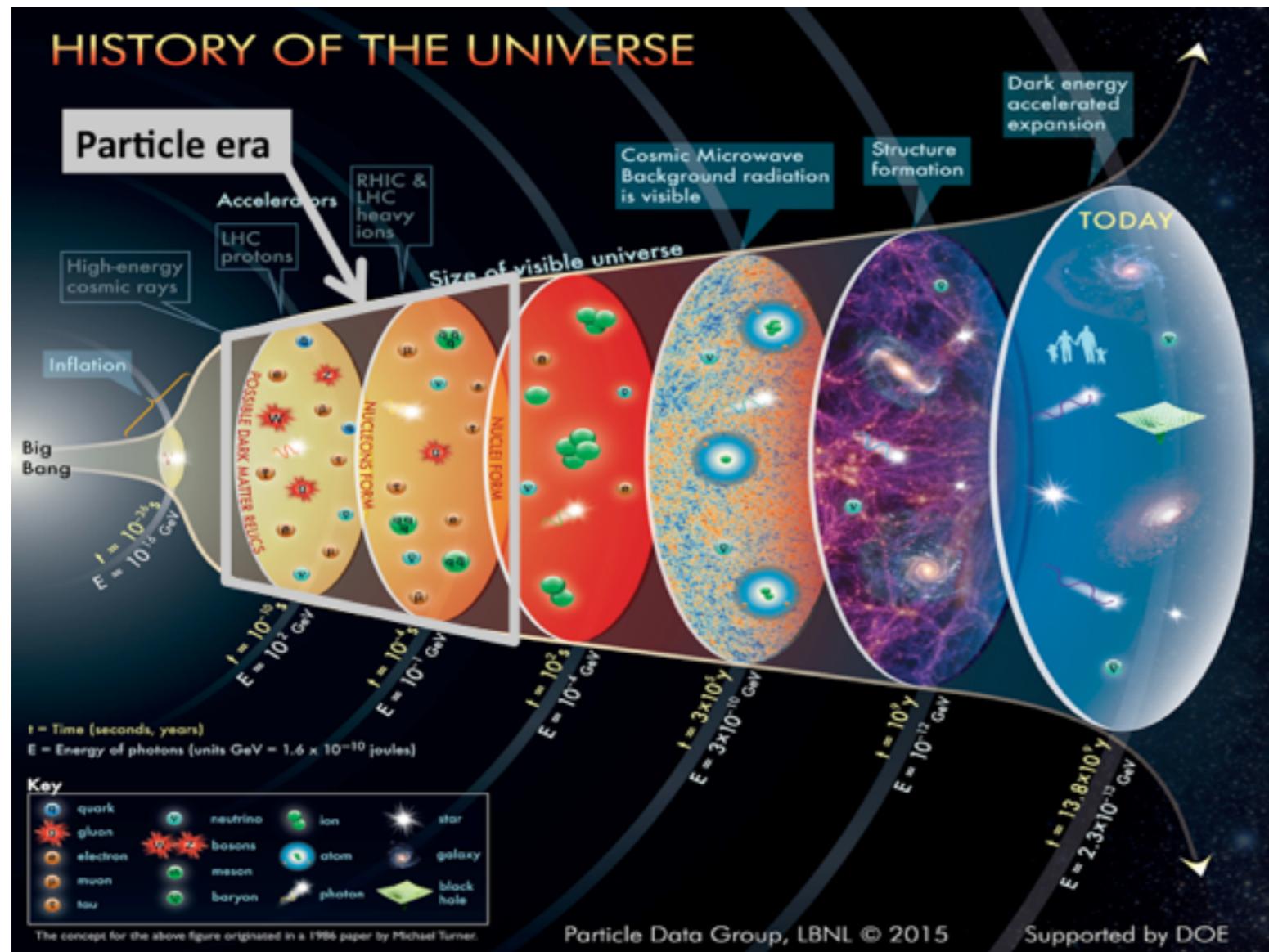


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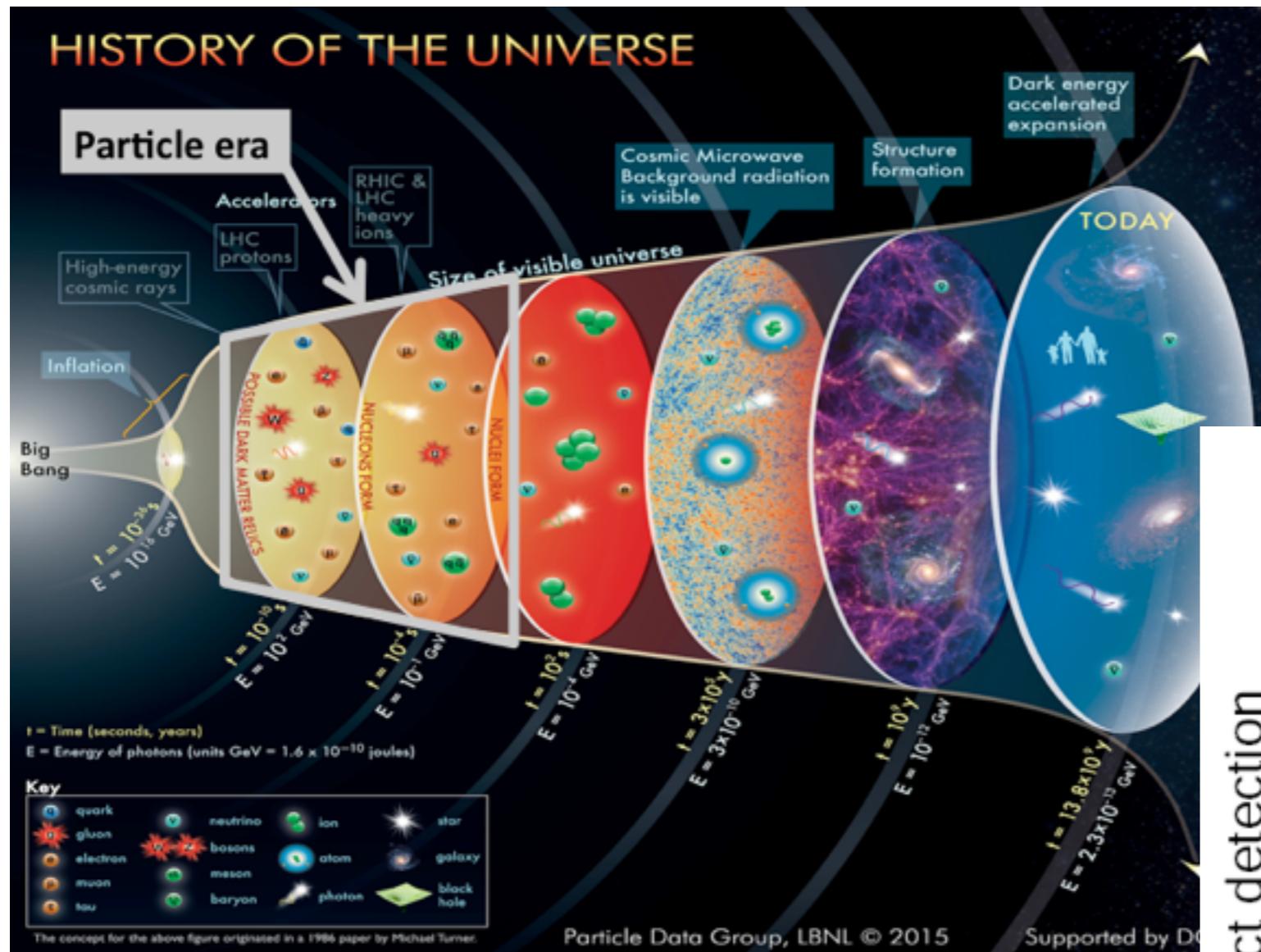
What is Relic Abundance?



- Dark Matter particles annihilate into SM and vice-versa
- Plasma is in Thermal Equilibrium

- Universe started with a **BANG!!!!**
- Immediately after that it started rapidly expanding (Inflation)
- Then expansion started slowing down
- At this point everything is in a hot plasma at very high Temperature.
- Particles are being annihilated and created at will.

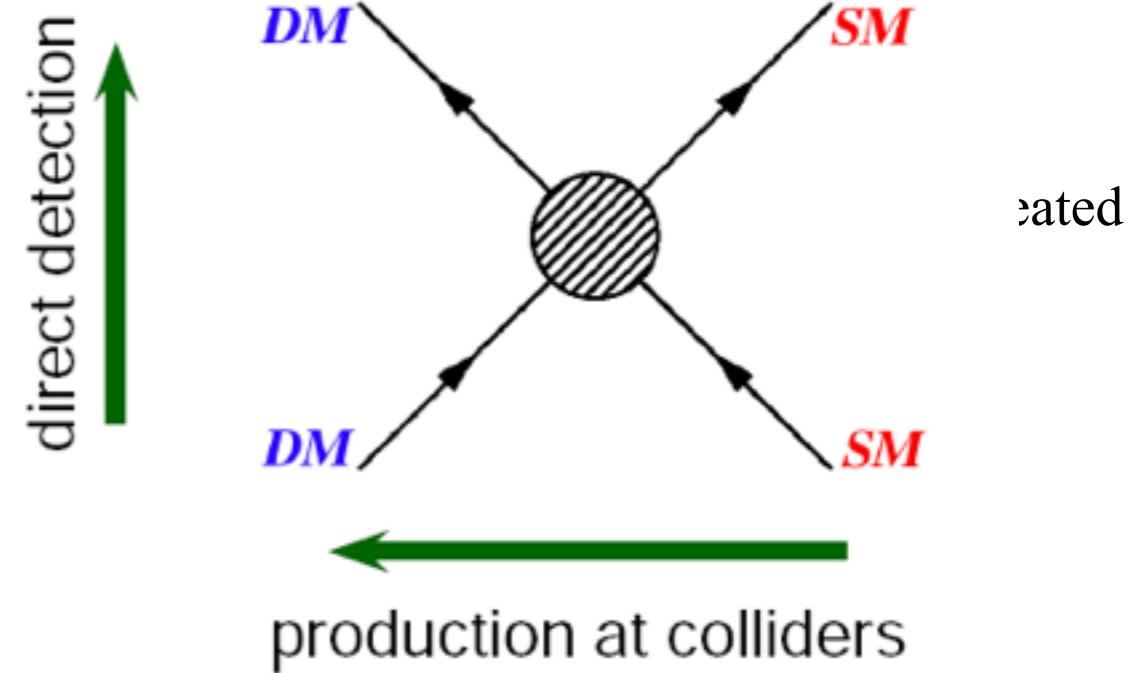
Relic Abundance



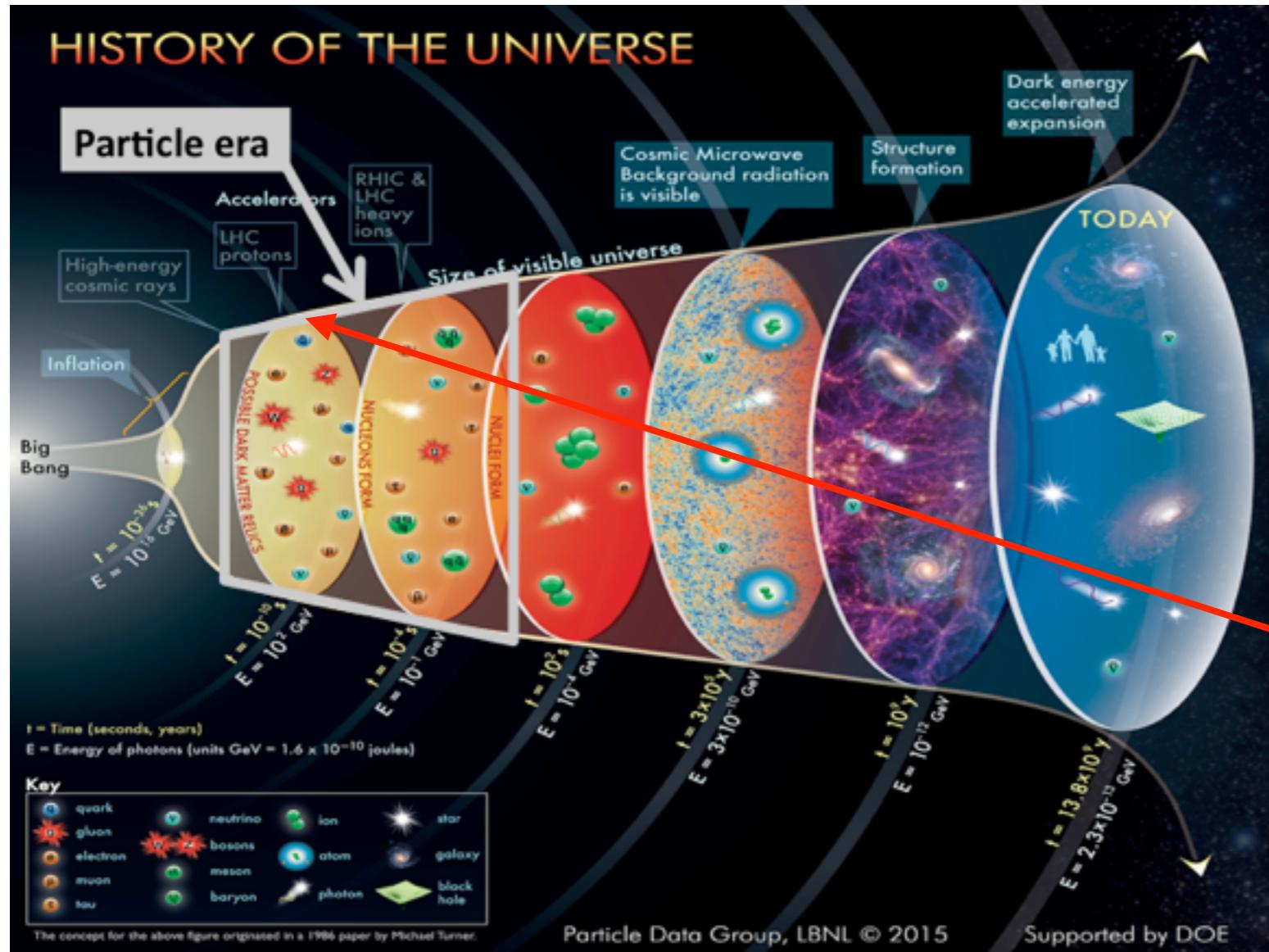
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thermal freeze-out (early Univ.)
indirect detection (now)

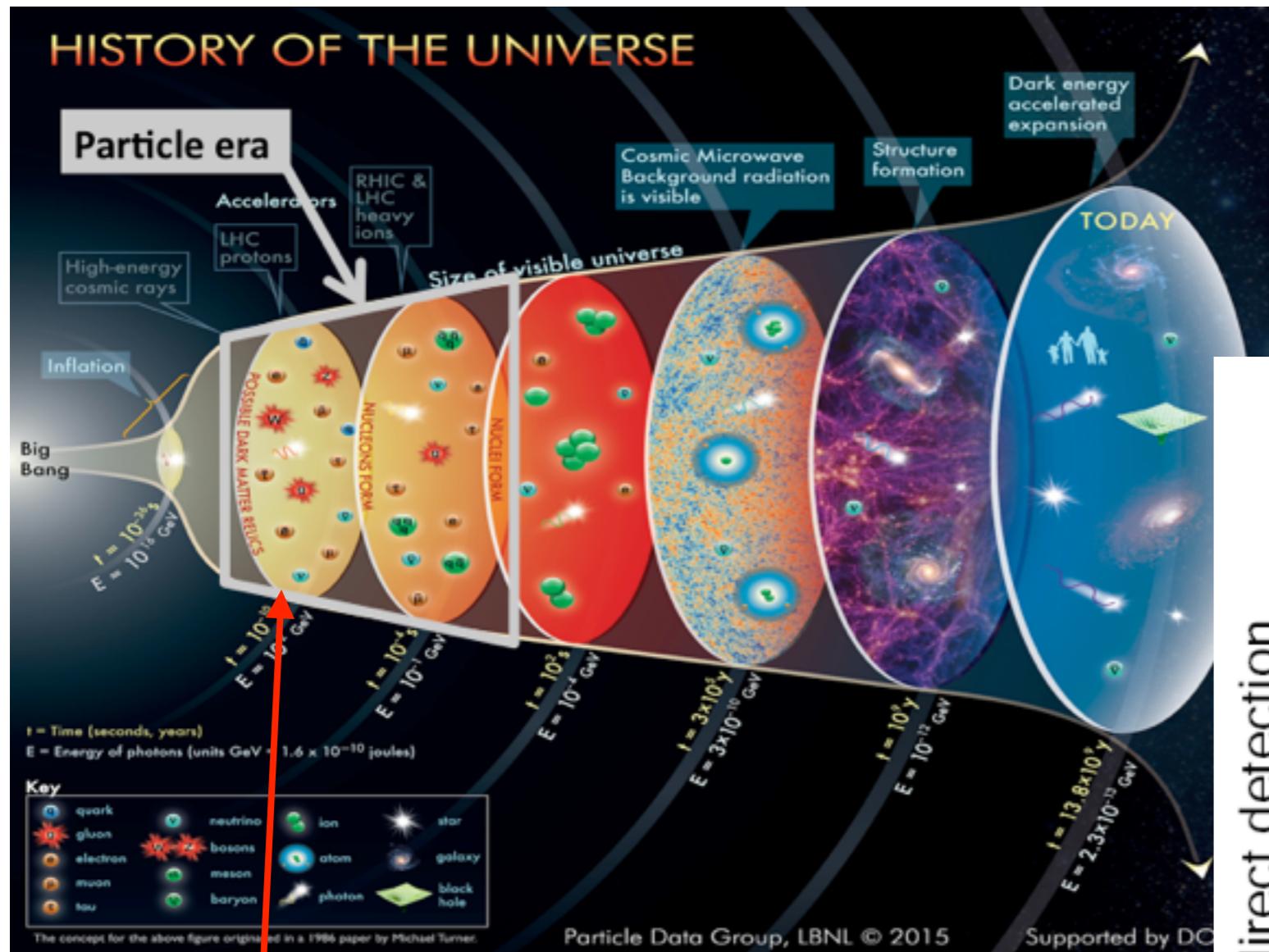


Relic Abundance



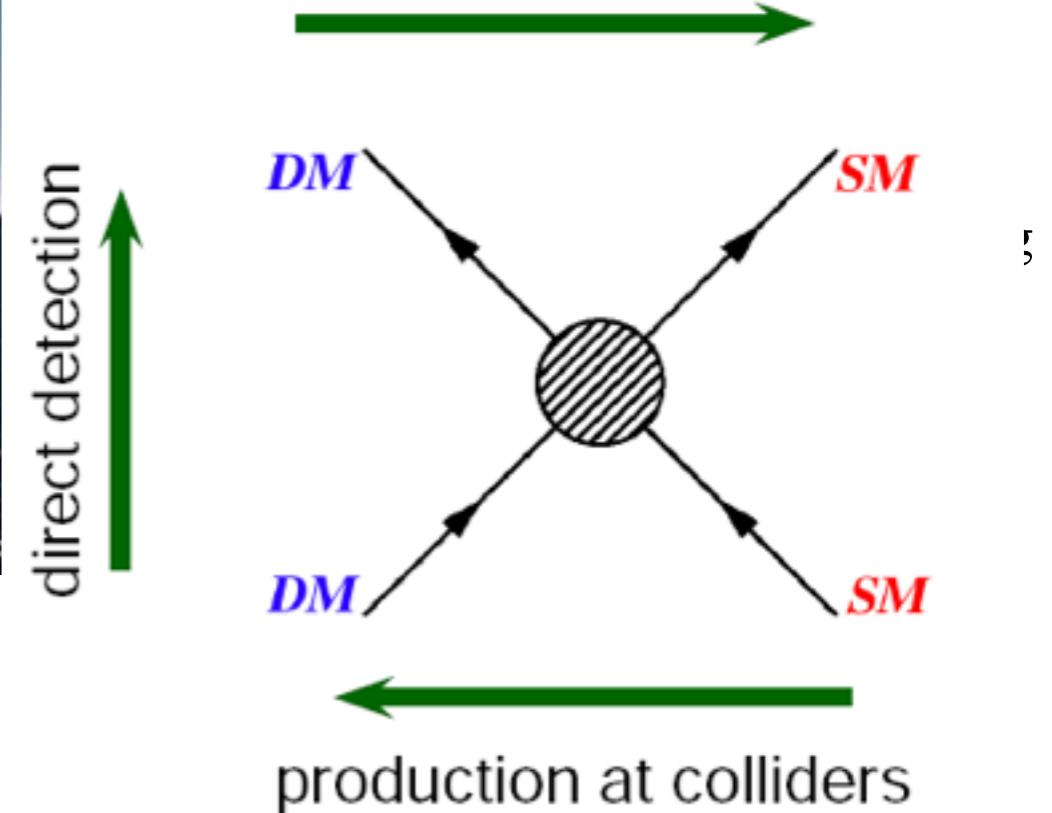
- Universe Continues to expand and plasma gets colder.
- SM can no longer annihilate to DM
- Only DM can annihilate to SM
- Universe keeps expanding and cooling

Relic Abundance

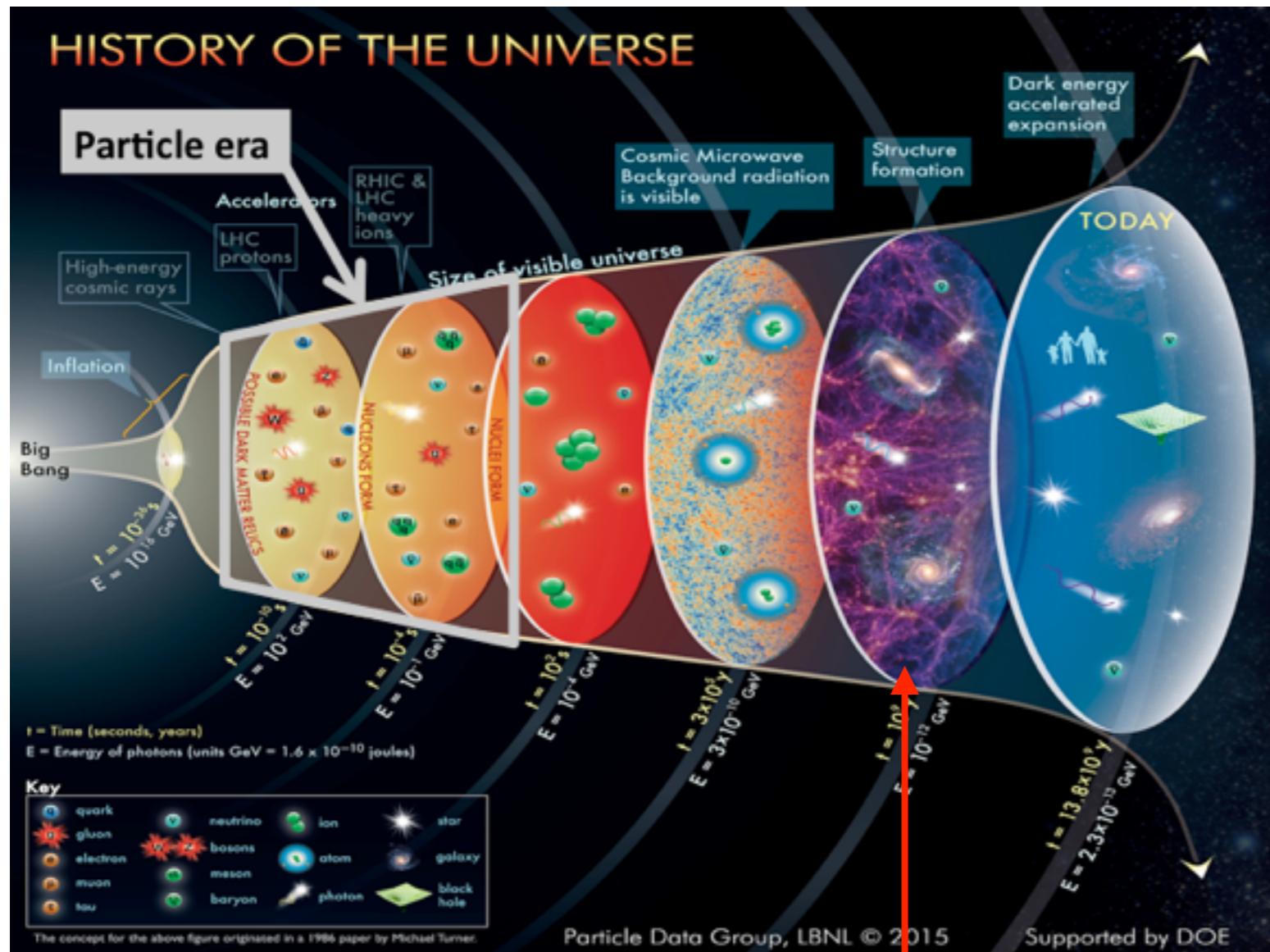


- DM particles can no longer find each other to annihilate (Thermal Freeze - out)
- Relic Abundance tells us amount of DM left in Universe after Freeze-out

- Universe Continues to expand and plasma gets colder.
- SM can no longer annihilate to DM thermal freeze-out (early Univ.) indirect detection (now)



Relic Abundance



- Universe Continues to expand and plasma gets colder.
- SM can no longer annihilate to DM
- Only DM can annihilate to SM
- Universe keeps expanding and cooling

- DM particles can no longer find each other to annihilate (**Freeze - out**)
- These frozen out particles will clump to form halos and structure.

How do we calculate Relic Abundance?

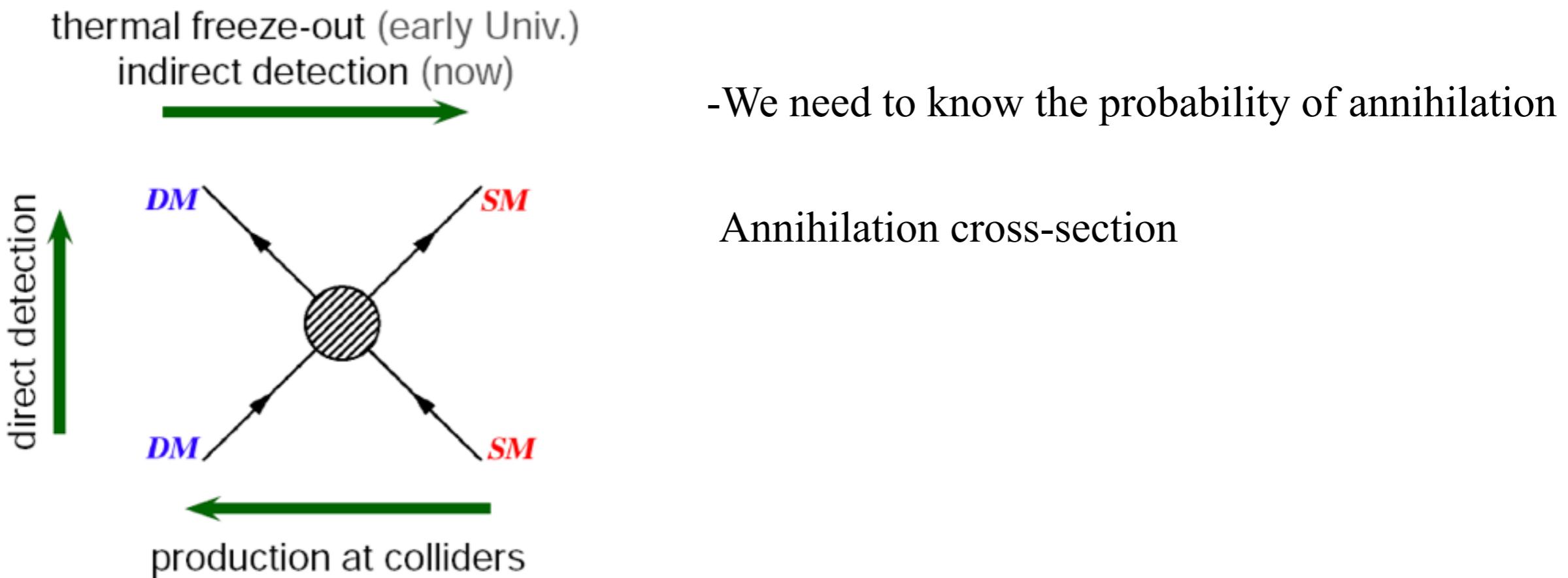
- For any given dark matter model, we want to find the parameters that give the right relic abundance.
- But where do we start? What is the first quantity we need to know?

Hint: what gives the probability of DM interacting with the SM?

How do we calculate Relic Abundance?

- For any given dark matter model, we want to find the parameters that give the right relic abundance.
- But where do we start? What is the first quantity we need to know?

Hint: what gives the probability of DM interacting with the SM?



Calculating Relic Abundance?

Annihilation cross-section must be thermally averaged - average over the velocities over all the DM particles in the thermal plasma

Thermally averaged annihilation cross-section

$$\langle \sigma_a v \rangle$$

Particle physics model gives you this. It contains information about masses and couplings

- Because we have large number of DM particles traveling at different velocities, to find their number densities, we need to solve the Boltzmann Eqn

$$\frac{dn}{dt} + 3Hn = - \langle \sigma_a v \rangle (n^2 - (n^{eq})^2)$$

rate of expansion of Universe

number density of DM during thermal equilibrium

n gives the amount of DM that froze out as a function of time and is scales by annihilation cross-section.

calculating Relic Abundance?

By convention define comoving number density $Y \equiv \frac{n}{s}$

$$\frac{dY}{dx} = -\frac{s}{Hx^2} <\sigma_a v> (Y^2 - (Y^{eq})^2) \quad x \equiv \frac{m}{T}$$

Temperature of the universe

Solving this gives us number density as function of Temperature

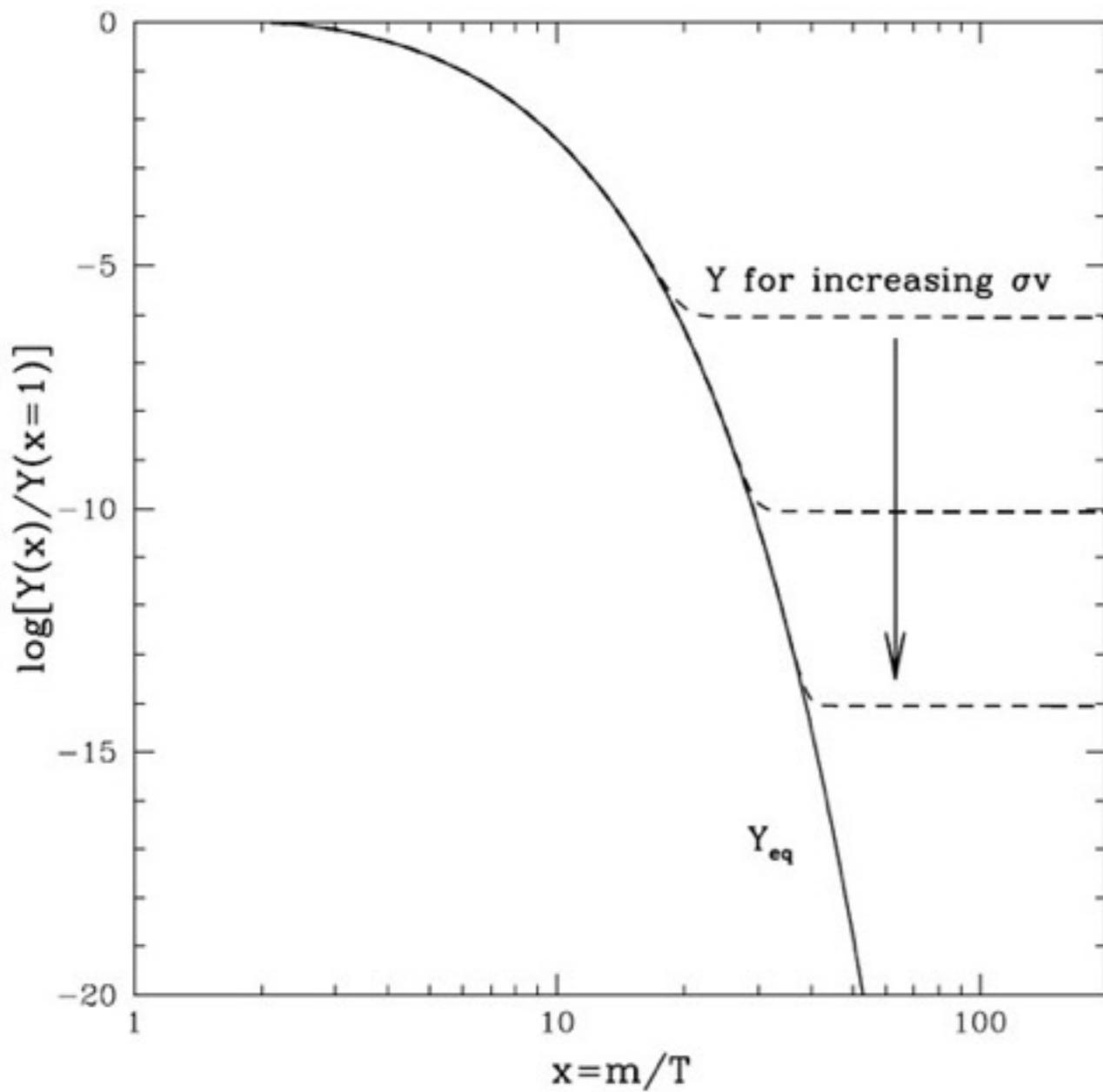
So we will know exactly at what Temp DM froze out

Calculating Relic Abundance?

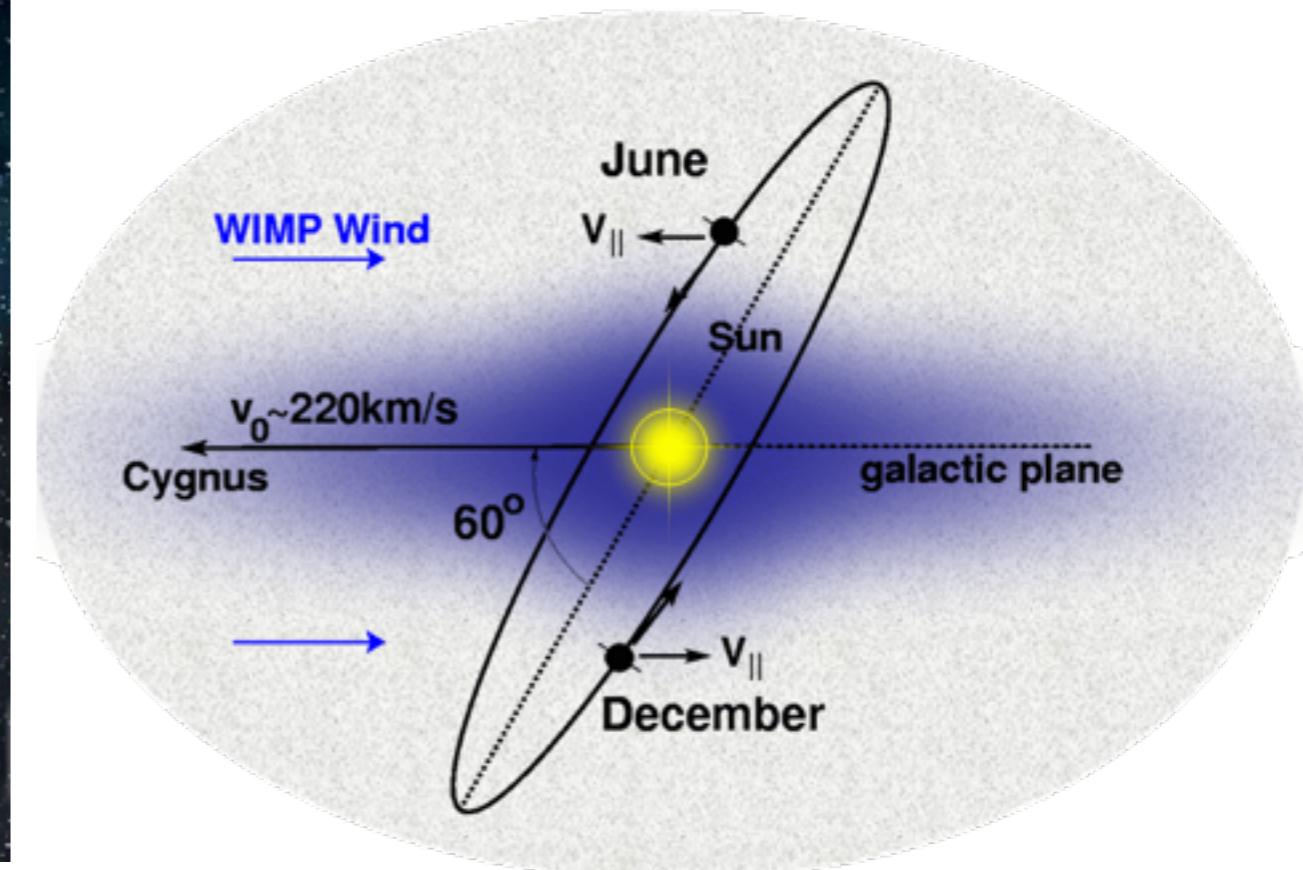
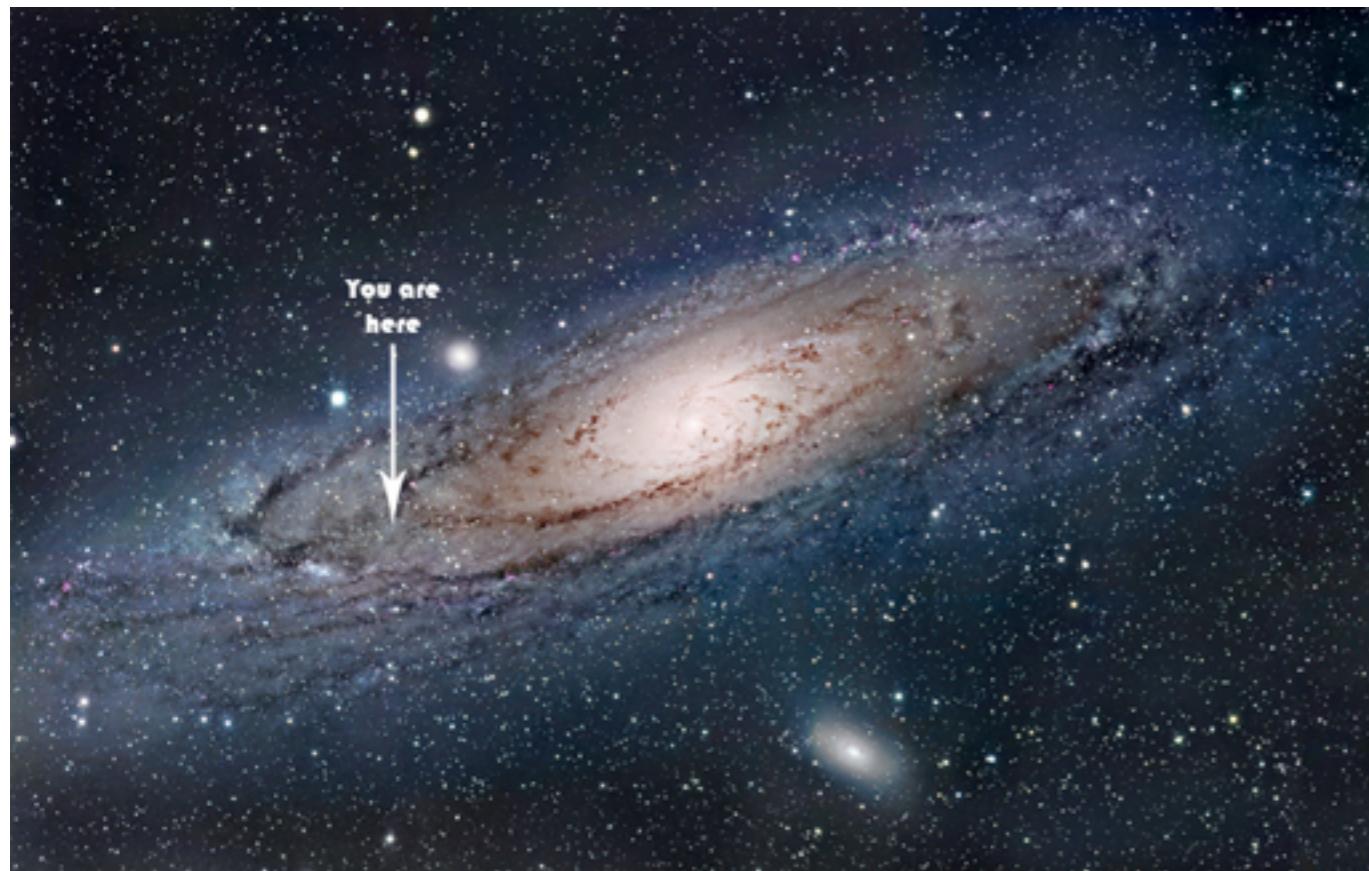
After solving Boltzmann-Eqn, get the value of Y

Relic Abundance defined as:

$$\Omega h^2 = \frac{ms_0 Y^\infty}{\rho_{crit}}$$



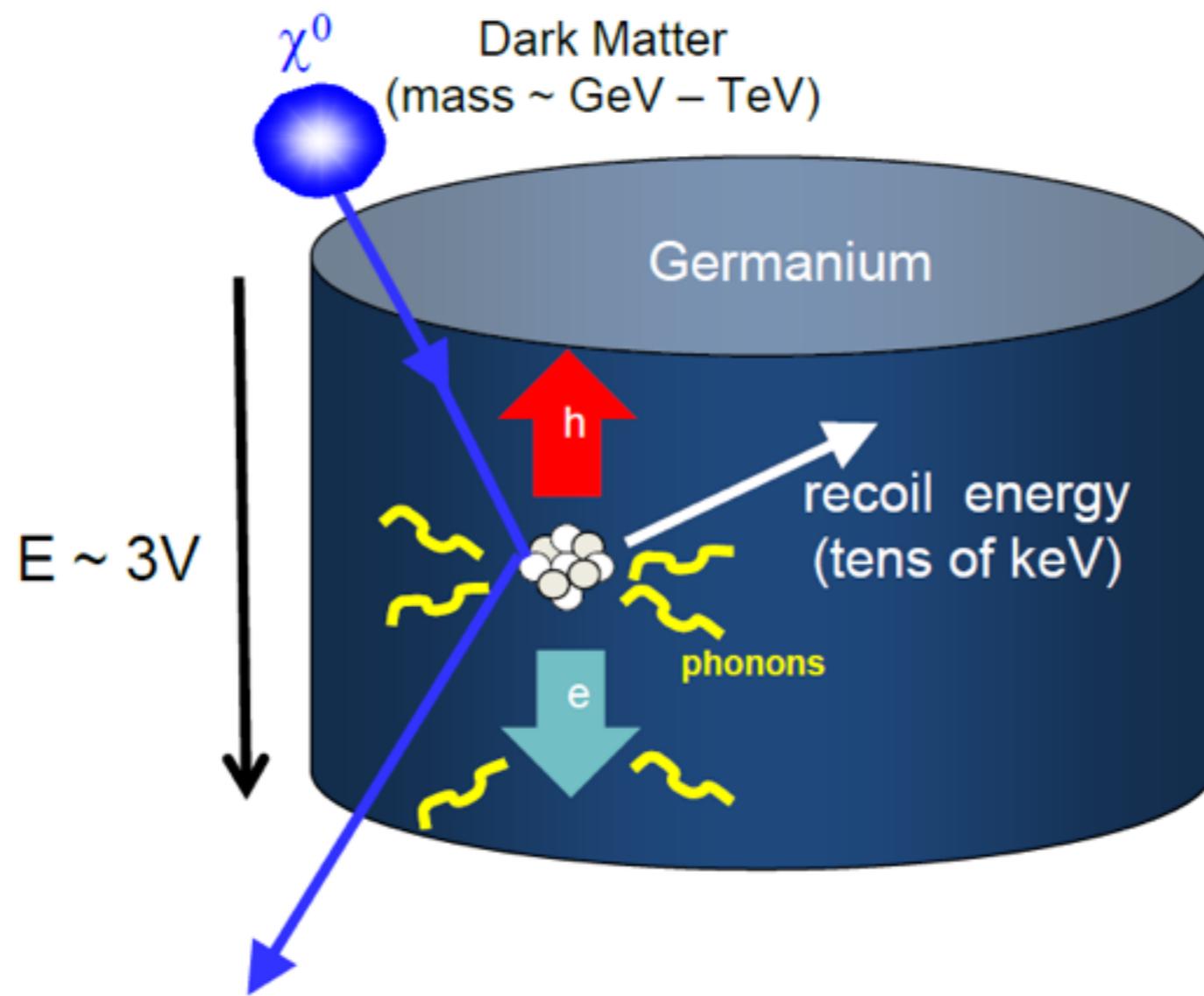
What about Direct Detection?



As sun moves around galactic plane Earth gets hit by DM wind

What about Direct Detection?

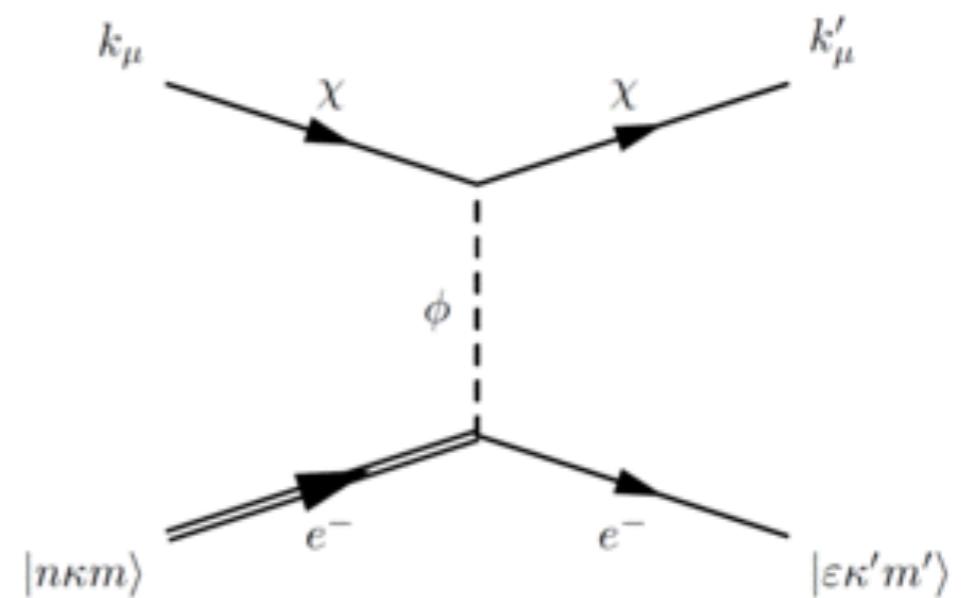
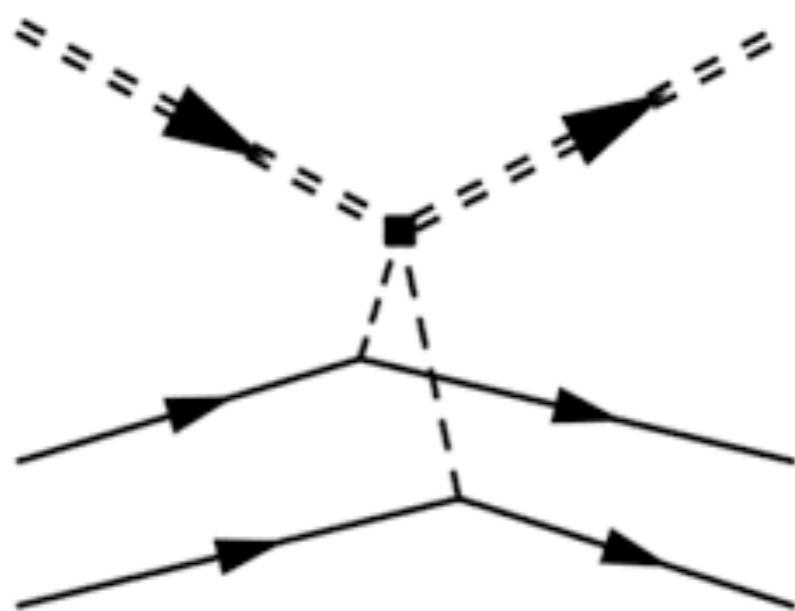
Put a detector deep in the Earth and wait for DM to interact



We calculate the Direct Detection Cross-section

Probability for DM particle to scatter off SM particle in the Detector

- DM would interact with Nucleus, but microscopically it actually interacts with nucleons
- Protons and Neutrons $\sigma_{\chi-p}$ & $\sigma_{\chi-n}$
- DM can also scatter off electrons $\sigma_{\chi-e}$



We calculate the Direct Detection Cross-section

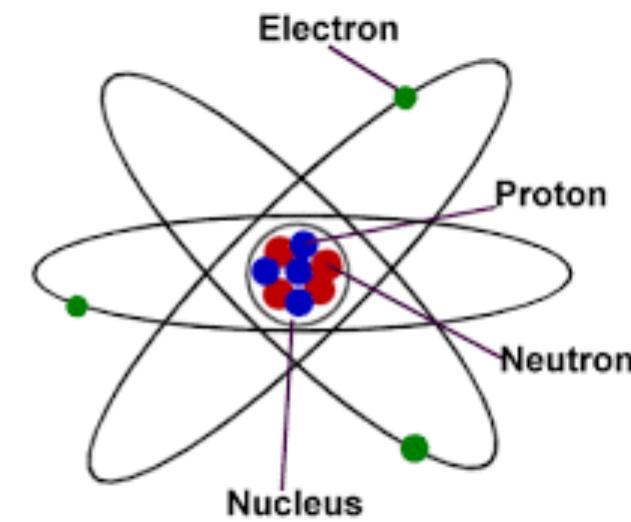
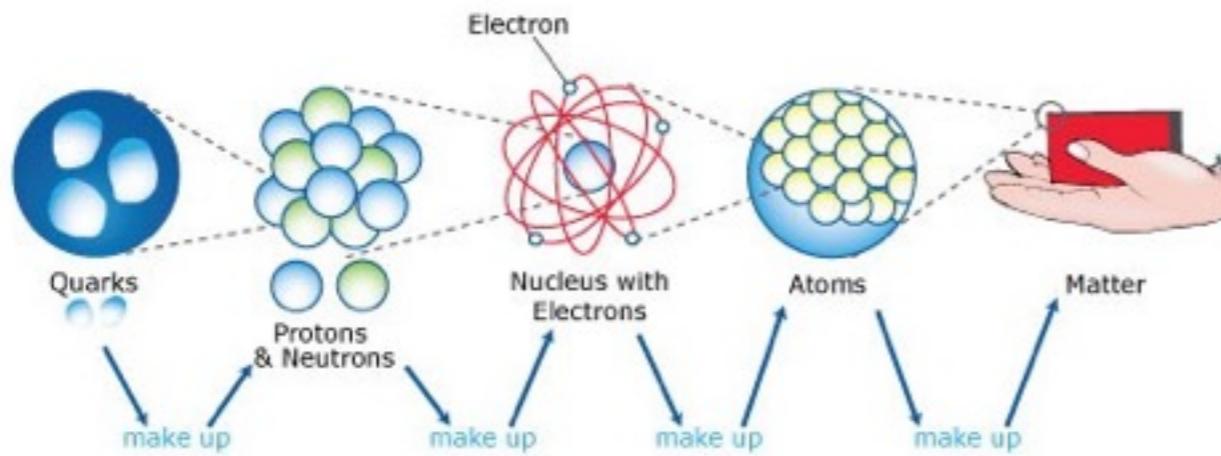
These cross-sections are Calculated using Quantum Field Theory methods

$$\sigma_{\chi-SM} \sim |M|^2$$

This is where the model information comes in

Can be translated into the Dark Matter - Nucleus cross-section

Nucleus is what we find in the detector, but nucleons are more elementary

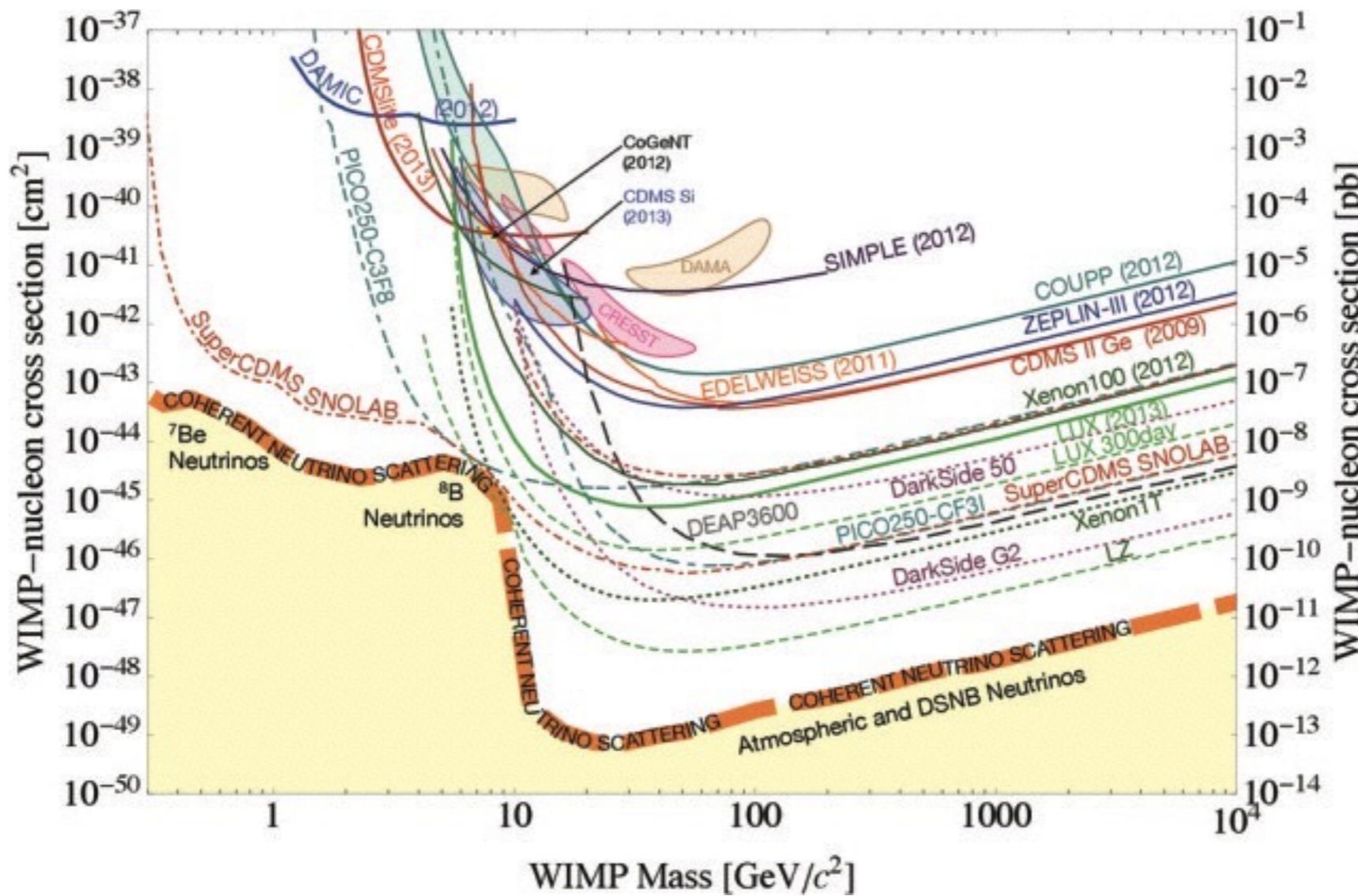


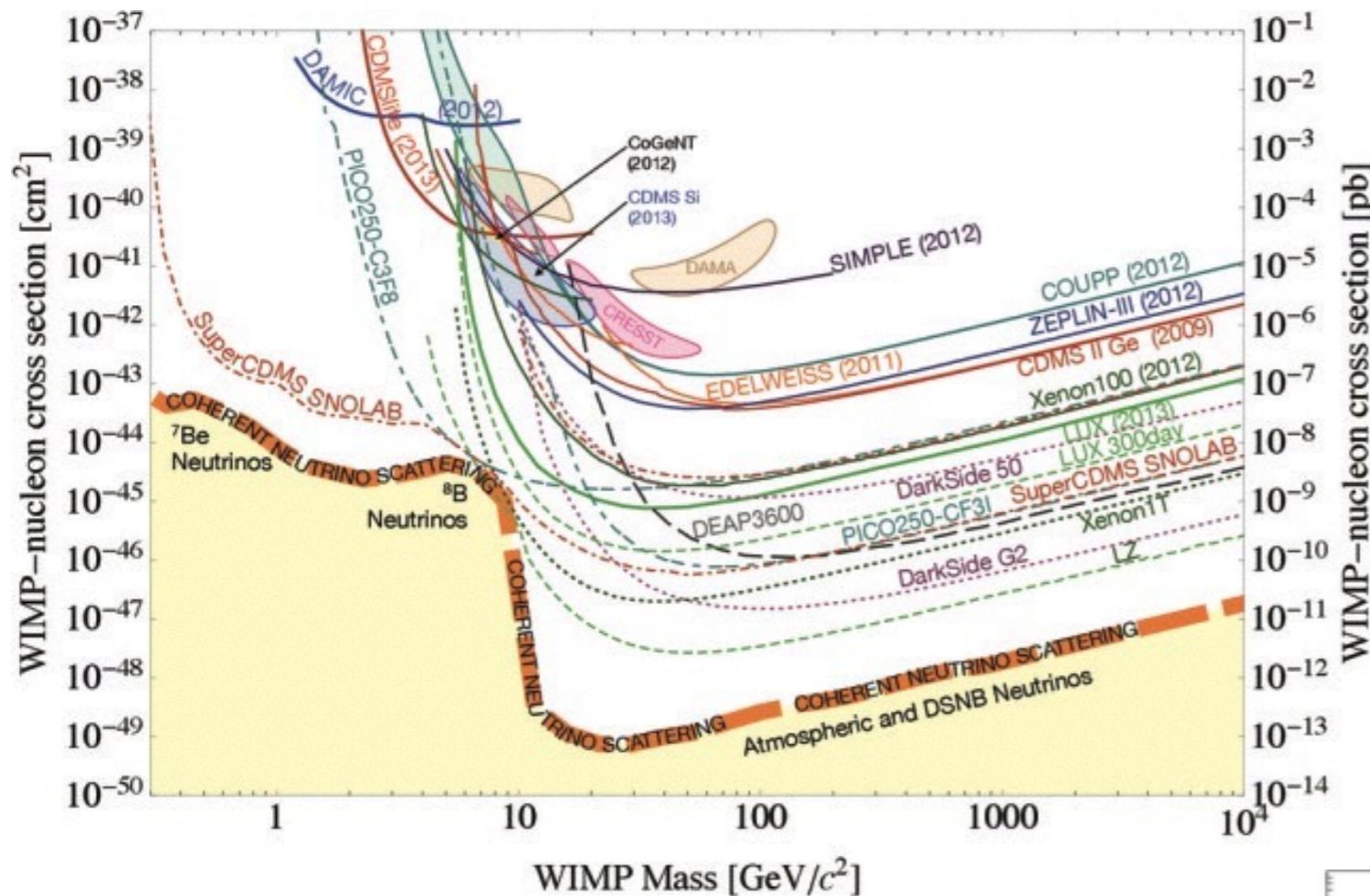
We calculate the Direct Detection Cross-section

$\sigma_{\chi-p}$ & $\sigma_{\chi-n}$ Can be translated to the dark matter nucleus cross-section

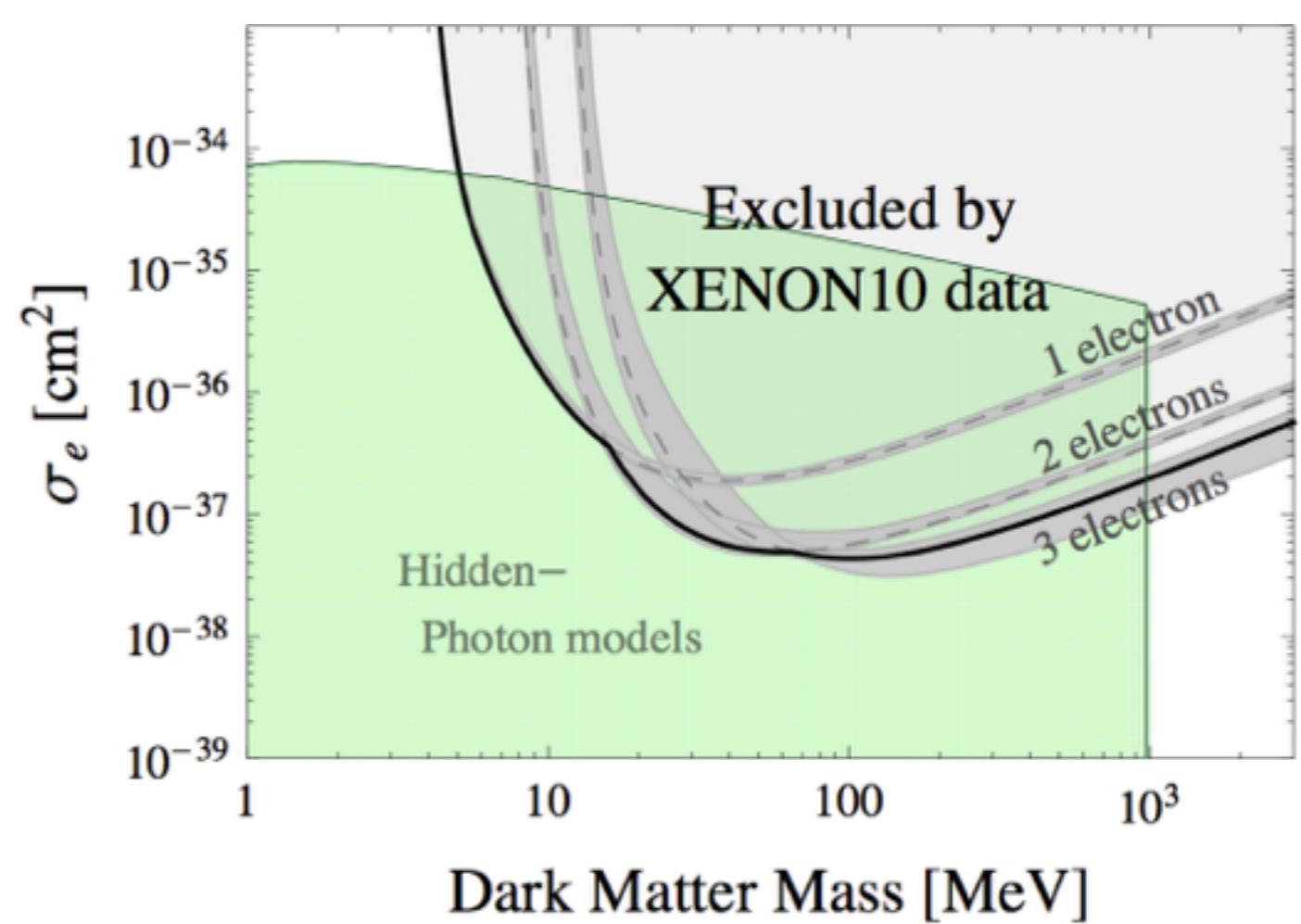
$$\sigma_{\chi-N} = \frac{4}{\pi} \mu_A^2 [Z f_p + (A - Z) f_n]^2$$

$$f_n = \frac{\pi}{4\mu_n^2} \sigma_{\chi-n} \quad f_p = \frac{\pi}{4\mu_p^2} \sigma_{\chi-p}$$





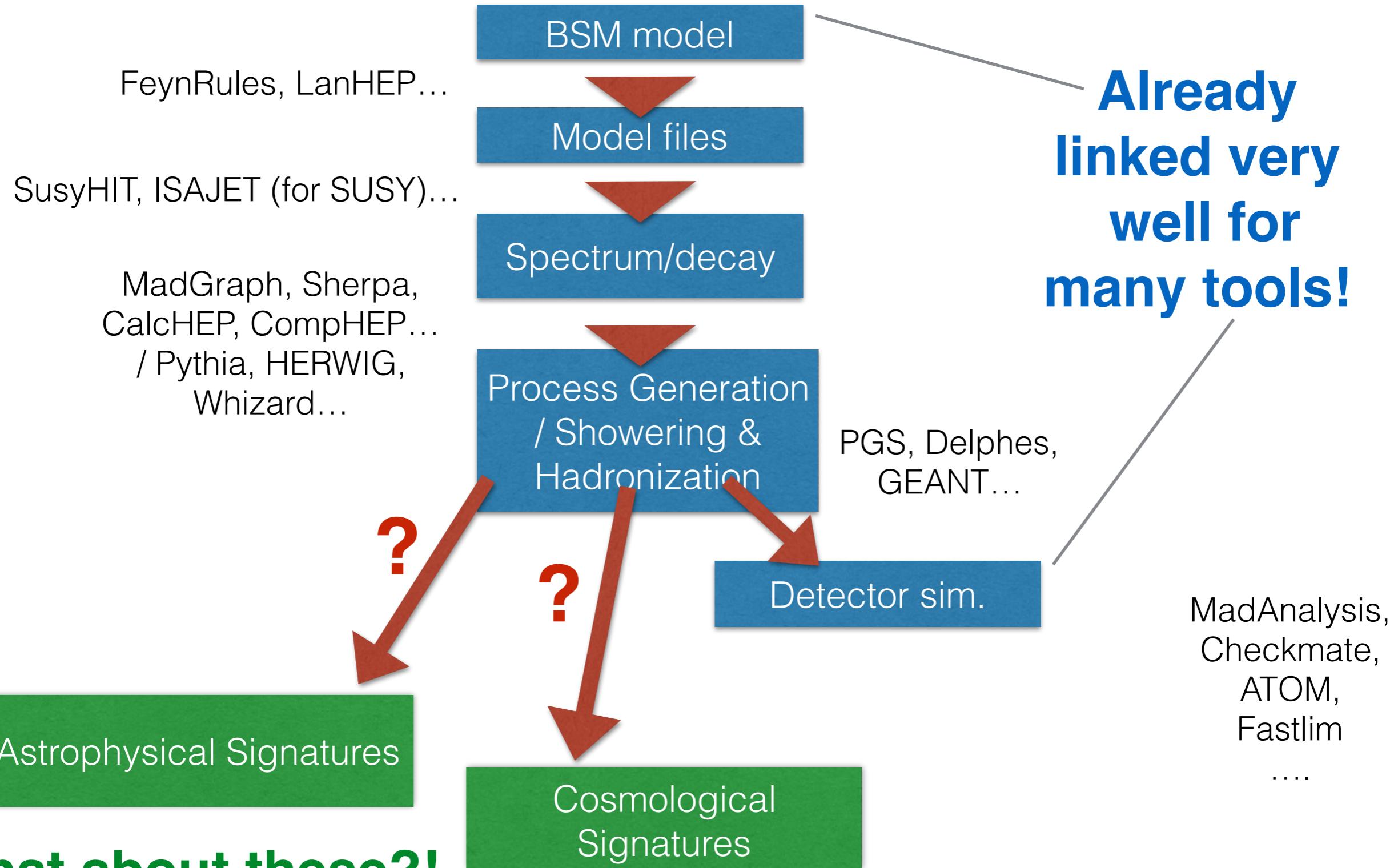
dark matter electron
limits



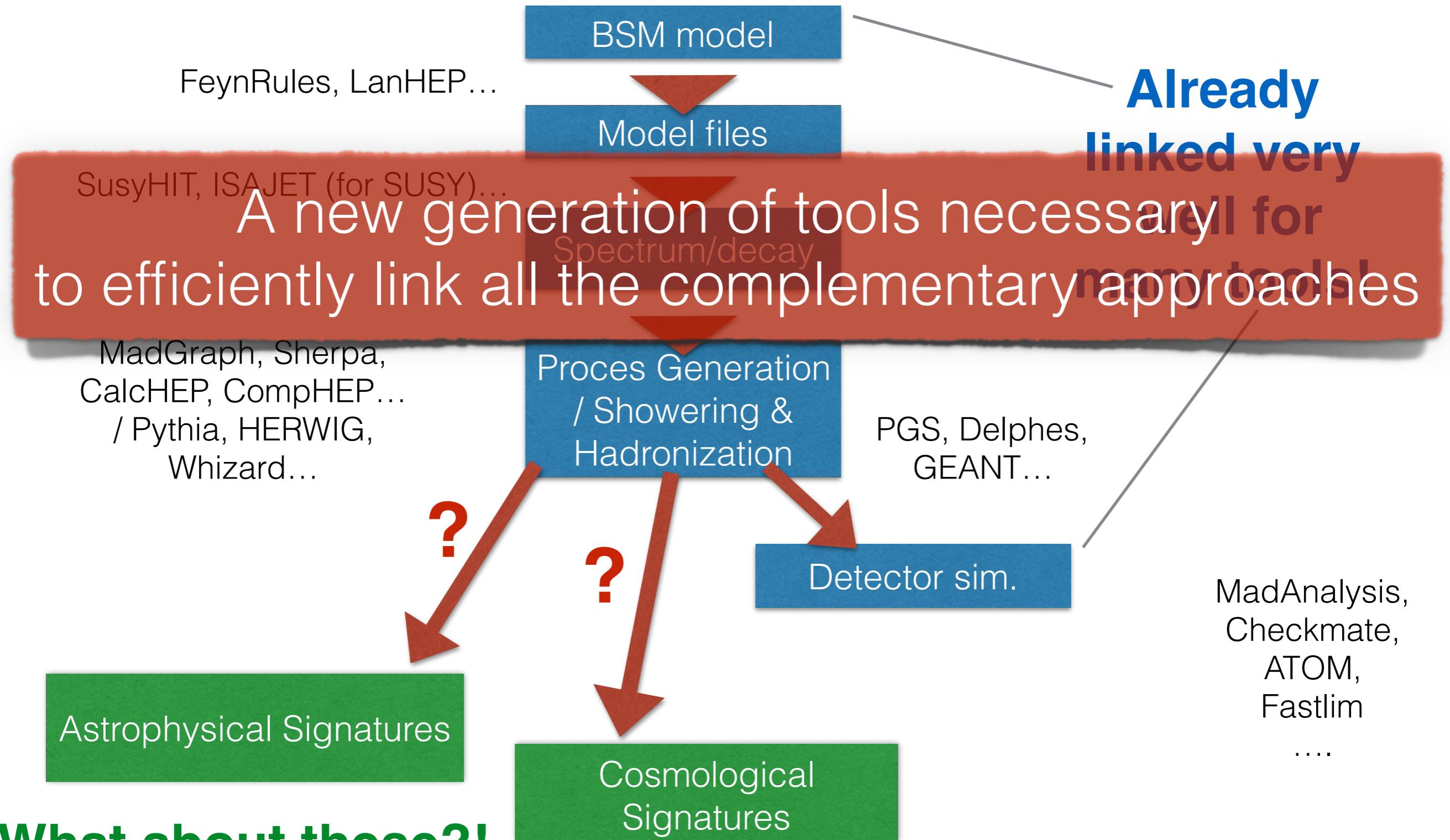
dark matter nucleus cross-section
limits

Where do simulation tools come in here?

BSM tools in LHC era



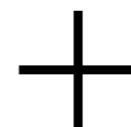
BSM tools in LHC era



Comprehensive DM studies

Collider Signals

- w/ missing energy
- w/o missing energy

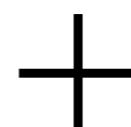


Cosmological Signals

- DM relic density
- Baryon asymmetry
- ...

Astro-physical Signals

- cosmic ray fluxes
- direct detection
- ...



Complex Parameter Spaces

- Scans over N parameters

= Comprehensive DM study

MadDM aims to be a tool for **easy and efficient comprehensive DM studies!**



MadDM emerged as an effort to link:

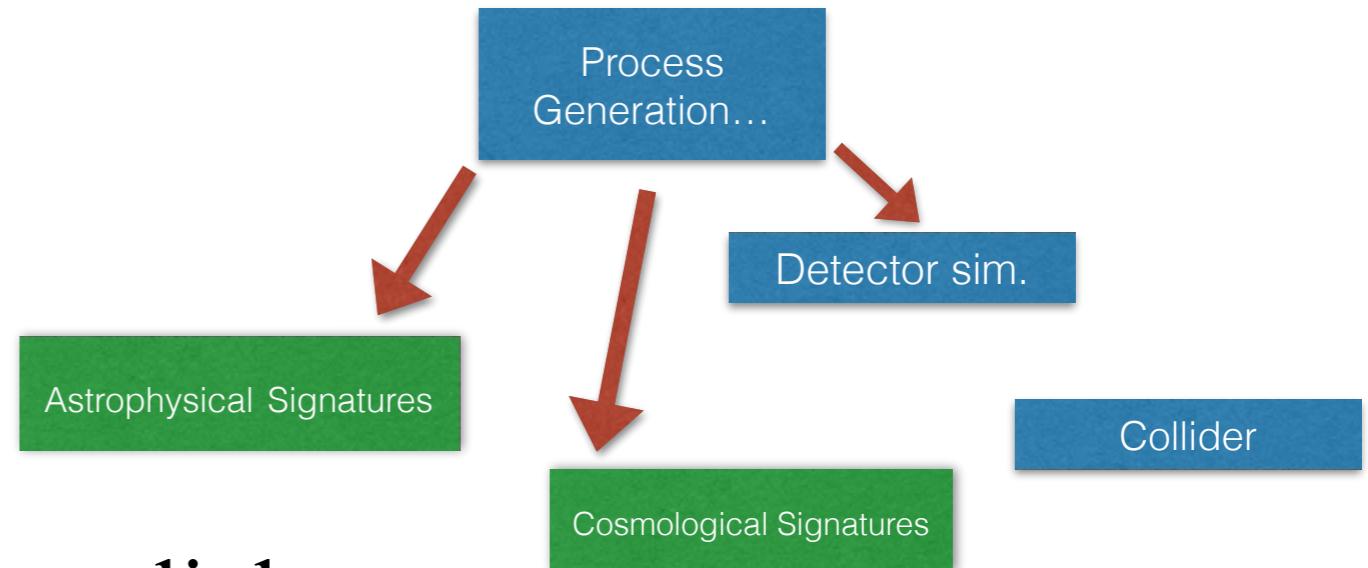
- DM collider searches, with
- early cosmology signatures (relic density) and
- direct/indirect detection.

Goal is to allow both **Experimentalists** and **Theorists** to calculate signatures of DM models at all interfaces with click of a button.

User friendly architecture of **MadGraph5_aMC@NLO** provides ideal framework for MadDM development.



MadDM



MadDM emerged as an effort to link:

- DM **collider searches**, with
- early **cosmology signatures** (relic density) and
- direct/indirect **detection**.

Version 1.0 of MadDM focused on calculations of **DM relic density** (in a generic UFO model).

Version 2.0 of MadDM extended the functionality to **DM direct and directional detection**.

Version 3.0 DM Indirect detection.



MadDM

Today we will use MadDM to calculate:

1. Relic Abundance of DM

2. Direct Detection Cross-Section

We will compare these to the experimental values

Lets start the Tutorial

Please turn on your Computer and go to the virtual machine

Lets start the Tutorial

Please turn on your Computer and go to the virtual machine

Once that is up, please go to firefox and download a model from here:

Feynrules model database: <http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage>

Click on **Simple Extensions of the SM**

Click on **Simplified DM models** and scroll all the way down

click on the: **DMsimp_s_spin0_MD.zip** : The model files for spin0 mediators.

Or

just copy the link below in your browser and scroll down

<http://feynrules.irmp.ucl.ac.be/wiki/DMsimp>

- Download the model file **DMsimp_s_spin0_MD.zip** model file and unzip it
 - Copy the **unzipped** file into the following folder:

madgraph >> MG5_aMC_2_6_2

- Then go to the **models** folder

Copy the unzipped **DMsimp_s_spin0_MD** folder here

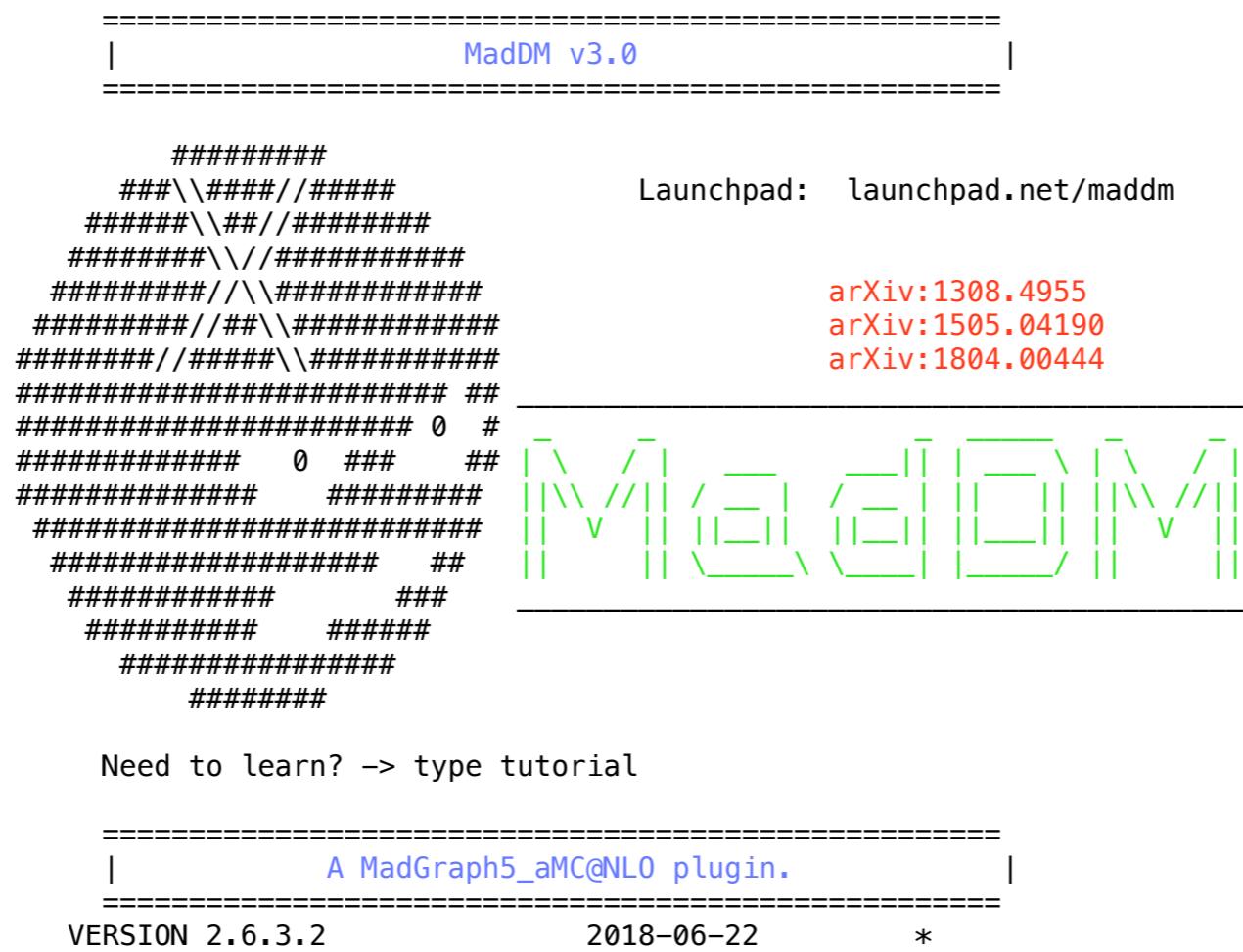
Now you are ready for DM calculations

Click on the Terminal App

```
type: cd madgraph/MG5_aMC_2_6_2
```

Now you are in the MG5_aMC_2_6_2 folder

Now type: ./bin/maddm.py



```
MadDM > import model DMsimp_s_spin0_L0
MadDM > define darkmatter xd
MadDM > generate relic_density
MadDM > add direct_detection
MadDM > output My_maddm_run
MadDM > launch My_maddm_run
```

The following switches determine which programs are run:

Description	values	other options
1. Compute the Relic Density	relic = ON	OFF
2. Compute direct(ional) detection	direct = directional	direct OFF
3. Compute indirect detection/flux	indirect = OFF	Please install module
4. Run Multinest scan	nestscan = OFF	Please install module

You can also edit the various input card:

- * Enter the name/number to open the editor
- * Enter a path to a file to replace the card
- * Enter **set NAME value** to change any parameter to the requested value

5. Edit the model parameters	[param]
6. Edit the MadDM options	[maddm]

[60s to answer]

```
MadDM > 2
```

MadDM > 2

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=====	=====	=====
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6. Edit the MadDM options	[maddm]	

MadDM > 0

A standard output:

```
INFO: Start computing relic,direct
maddm_card missed argument print_sigmas. Takes default: False
INFO: compilation done
INFO: MadDM Results
INFO:
***** Relic Density
OMEGA IS 86870.714448
INFO: Relic Density      = 8.69e+04      EXCLUDED
INFO: x_f                = 5.00e+00
INFO: sigmav(xf)         = 1.35e-15
INFO: xsi                = 1.00e+00
INFO:
***** Direct detection [cm^2]:
INFO: SigmaN_SI_p        All DM = 1.07e-46    ALLOWED    Xenon1ton ul   = 2.07e-45
INFO: SigmaN_SI_n        All DM = 1.09e-46    ALLOWED    Xenon1ton ul   = 2.07e-45
INFO: SigmaN_SD_p        All DM = 1.63e-61    ALLOWED    Pico60 ul     = 8.73e-41
INFO: SigmaN_SD_n        All DM = 7.80e-61    ALLOWED    Lux2017 ul    = 2.58e-40
```

So what does this mean?

```
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maddm_card missed argument print_sigmas. Takes default: False
INFO: compilation done
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```

So the dark matter mass here is 100 GeV

MadDM gives relic abundance of **86870**

The value we want from experiment is:

So what does this mean?

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OMEGA IS 86870.714448  
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INFO: SigmaN_SD_n         All DM = 7.80e-61      ALLOWED  
Xenon1ton ul            = 2.07e-45  
Xenon1ton ul            = 2.07e-45  
Pico60 ul               = 8.73e-41  
Lux2017 ul              = 2.58e-40
```

So the dark matter mass here is 10 GeV

MadDM gives relic abundance of **86870**

The value we want from experiment is: **0.12**

Direct Detection Cross-section?

Direct Detection

```
INFO: Start computing relic,direct
maddm_card missed argument print_sigmas. Takes default: False
INFO: compilation done
INFO: MadDM Results
INFO:
***** Relic Density
OMEGA IS 86870.714448
INFO: Relic Density      = 8.69e+04      EXCLUDED
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INFO: SigmaN_SI_p       All DM = 1.07e-46    ALLOWED    Xenon1ton ul   = 2.07e-45
INFO: SigmaN_SI_n       All DM = 1.09e-46    ALLOWED    Xenon1ton ul   = 2.07e-45
INFO: SigmaN_SD_p        All DM = 1.63e-61    ALLOWED    Pico60 ul     = 8.73e-41
INFO: SigmaN_SD_n        All DM = 7.80e-61    ALLOWED    Lux2017 ul    = 2.58e-40
```

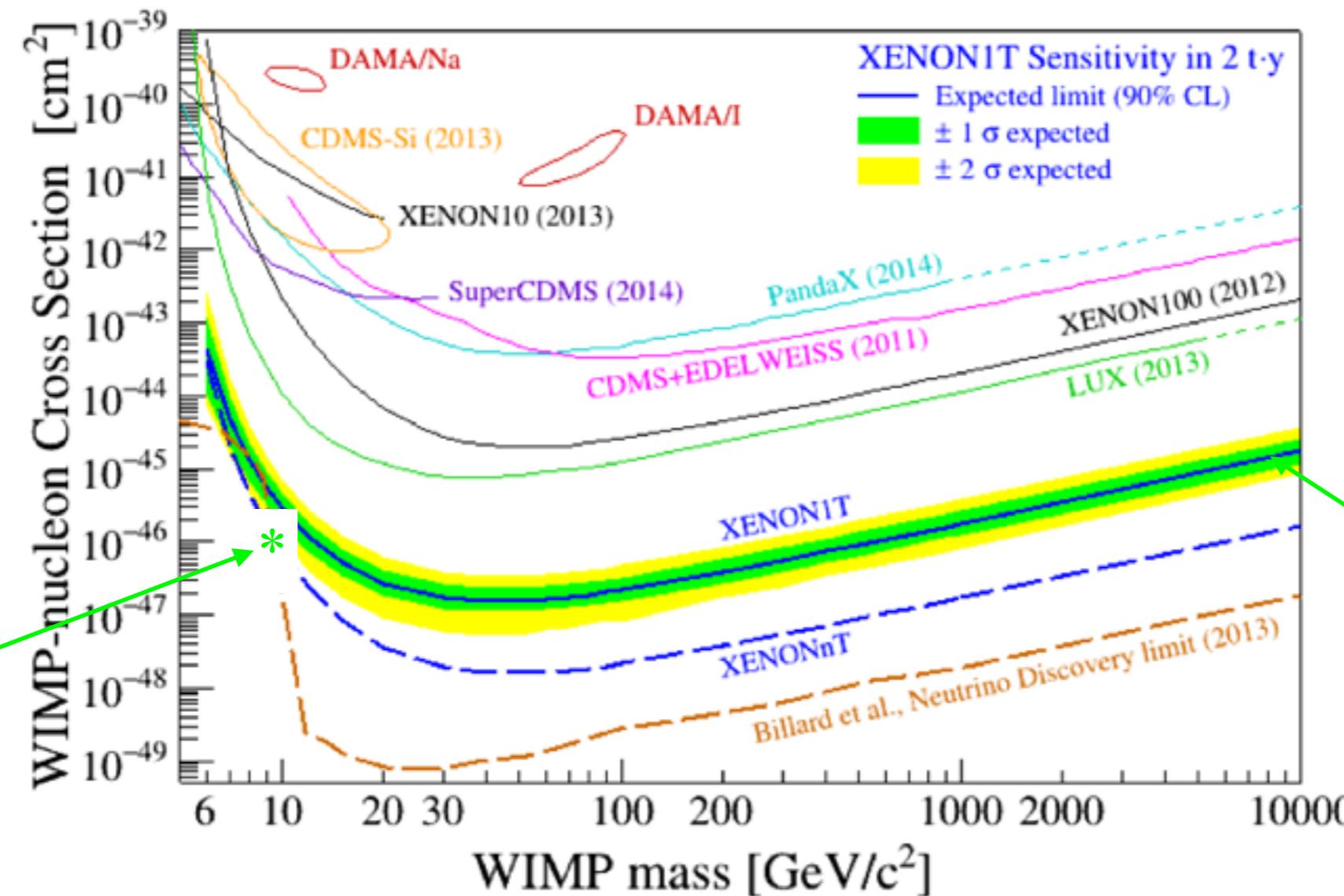
Focus on this line

Direct Detection

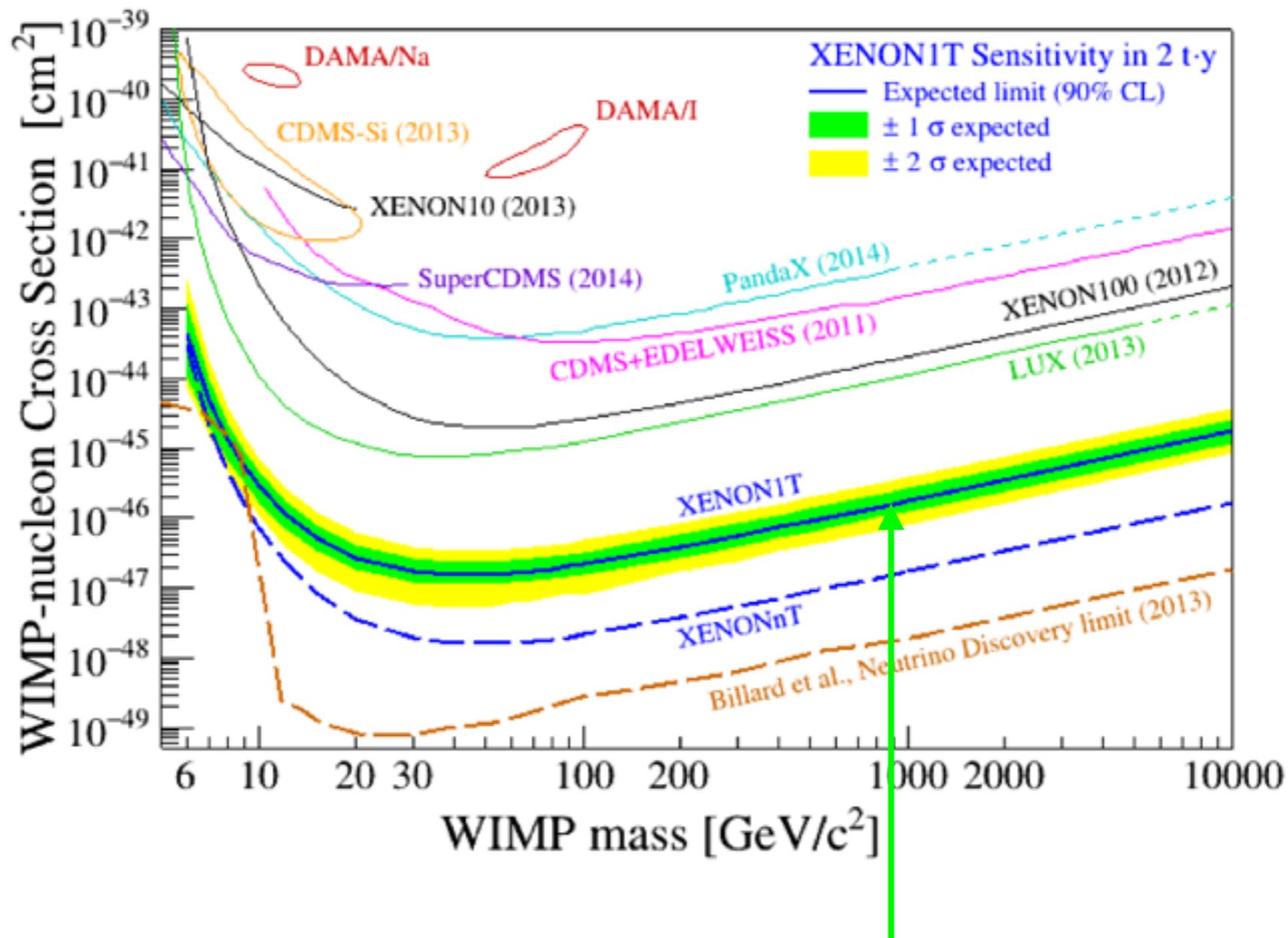
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INFO: SigmaN_SD_n       All DM = 7.80e-61 ALLOWED   Lux2017 ul   = 2.58e-40

```



Direct Detection



You can find this line by typing:

MadDM > Exit

You will be in the MG5_aMC_2_6_2 directory

Type: cd PLUGIN/maddm/ExpData

here you will find **Xenont1T_data_2017.dat** which contains the data for that line

One more thing

MadDM > launch My_maddm_run

The following switches determine which programs are run:

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2. Compute direct(ional) detection	direct = direct	OFF directional
3. Compute indirect detection/flux	indirect = OFF	Please install module
4. Run Multinest scan	nestscan = OFF	Please install module

You can also edit the various input card:

- * Enter the name/number to open the editor
- * Enter a path to a file to replace the card
- * Enter **set NAME value** to change any parameter to the requested value

/=====	/=====
5. Edit the model parameters [param]	
6. Edit the MadDM options [maddm]	

In order to change the mass of the particle:

MadDM > 5

Scroll down to the mass information

looks like this

```
#####
## INFORMATION FOR MASS
#####
Block mass
 1 5.040000e-03 # MD
 2 2.550000e-03 # MU
 3 1.010000e-01 # MS
 4 1.270000e+00 # MC
 5 4.700000e+00 # MB
 6 1.720000e+02 # MT
11 5.110000e-04 # Me
13 1.056600e-01 # MMU
15 1.777000e+00 # MTA
23 9.118760e+01 # MZ
25 1.250000e+02 # MH
51 1.000000e+01 # MXc
52 1.000000e+01 # MXd
54 1.000000e+03 # MY0
5000001 1.000000e+01 # MXr
999000006 7.000000e+01 # sdmm
999000008 7.000000e+01 # vdmm
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
12 0.000000 # ve : 0.0
14 0.000000 # vm : 0.0
```

← Focus on this line

looks like this

Type i

```
#####
## INFORMATION FOR MASS
#####
Block mass
 1 5.040000e-03 # MD
 2 2.550000e-03 # MU
 3 1.010000e-01 # MS
 4 1.270000e+00 # MC
 5 4.700000e+00 # MB
 6 1.720000e+02 # MT
11 5.110000e-04 # Me
13 1.056600e-01 # MMU
15 1.777000e+00 # MTA
23 9.118760e+01 # MZ
25 1.250000e+02 # MH
51 1.000000e+01 # MXc
52 2.000000e+02 # MXd
54 5.000000e+02 # MY0
5000001 1.000000e+01 # MXr
999000006 7.000000e+01 # sdmm
999000008 7.000000e+01 # vdmm
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
12 0.000000 # ve : 0.0
14 0.000000 # vm : 0.0
```

Focus on this line

Type **esc** then **:wq**

Now we get

```
INFO: Start computing relic,direct
maddm_card missed argument print_sigmas. Takes default: False
INFO: compilation done
INFO: MadDM Results
INFO: Define xsi = Relic density/Planck measurement for thermal scenarios.
INFO: Rescaling theory prediction for xsi(direct det.) and xsi^2(indirect det.) for thermal scenarios.

INFO:
***** Relic Density
OMEGA IS 0.0486860496279
INFO: Relic Density      = 4.87e-02      ALLOWED
INFO: x_f                = 2.30e+01
INFO: sigmav(xf)         = 1.01e-08
INFO: xsi                = 4.06e-01
INFO:
***** Direct detection [cm^2]:
INFO: SigmaN_SI_p        Thermal = 8.27e-46      EXCLUDED      All DM = 2.04e-45      EXCLUDED      Xenon1ton ul      = 2.60e-46
INFO: SigmaN_SI_n        Thermal = 8.38e-46      EXCLUDED      All DM = 2.06e-45      EXCLUDED      Xenon1ton ul      = 2.60e-46
INFO: SigmaN_SD_p         Thermal = 4.74e-61      ALLOWED       All DM = 1.17e-60      ALLOWED       Pico60 ul        = 9.13e-41
INFO: SigmaN_SD_n         Thermal = 7.19e-62      ALLOWED       All DM = 1.77e-61      ALLOWED       Lux2017 ul        = 5.24e-41
```

Now I leave you to compare with the experiment

Some References

If you want to learn about DM look at some of these references and reproduce some of the equations

1. Particle Dark Matter Evidence, Candidates & Constraints, D. Hooper & G. Bertone,
<https://arxiv.org/pdf/hep-ph/0404175.pdf>
2. MadDM v1.0, M. Backovic, K. Kong & M. McCaskey,
<https://arxiv.org/pdf/1308.4955.pdf>
3. Direct Detection of Dark Matter with MadDM v2.0, M. Backovic, K. Kong & A. Martini, O. Mattelaer & G. Mohlabeng, <https://arxiv.org/pdf/1505.04190.pdf>
4. MadDM v3.0: A comprehensive tool for Dark Matter studies,
<https://arxiv.org/pdf/1804.00044.pdf>

If you have any questions send me an email: gmohlabeng@bnl.gov



Thank you!