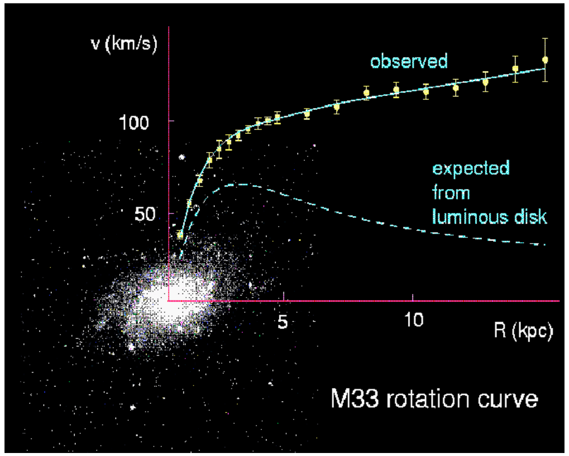
Dark matter tools:
an overview

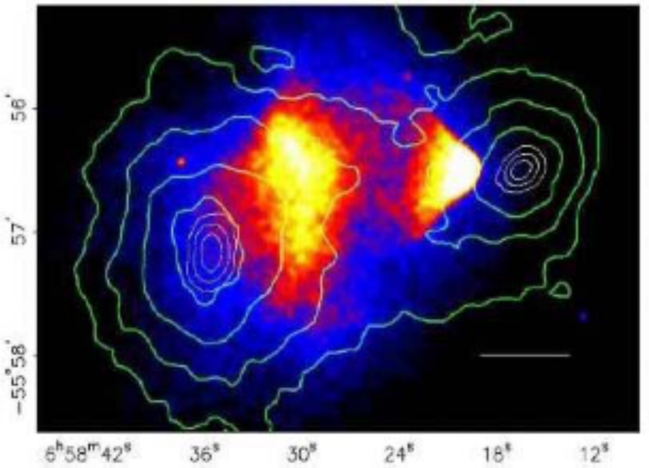
G. Bélanger
LAPTh - Annecy

Particle physics and cosmology Tools, Corfu, Sep 9-14, 2017

Evidence for dark matter

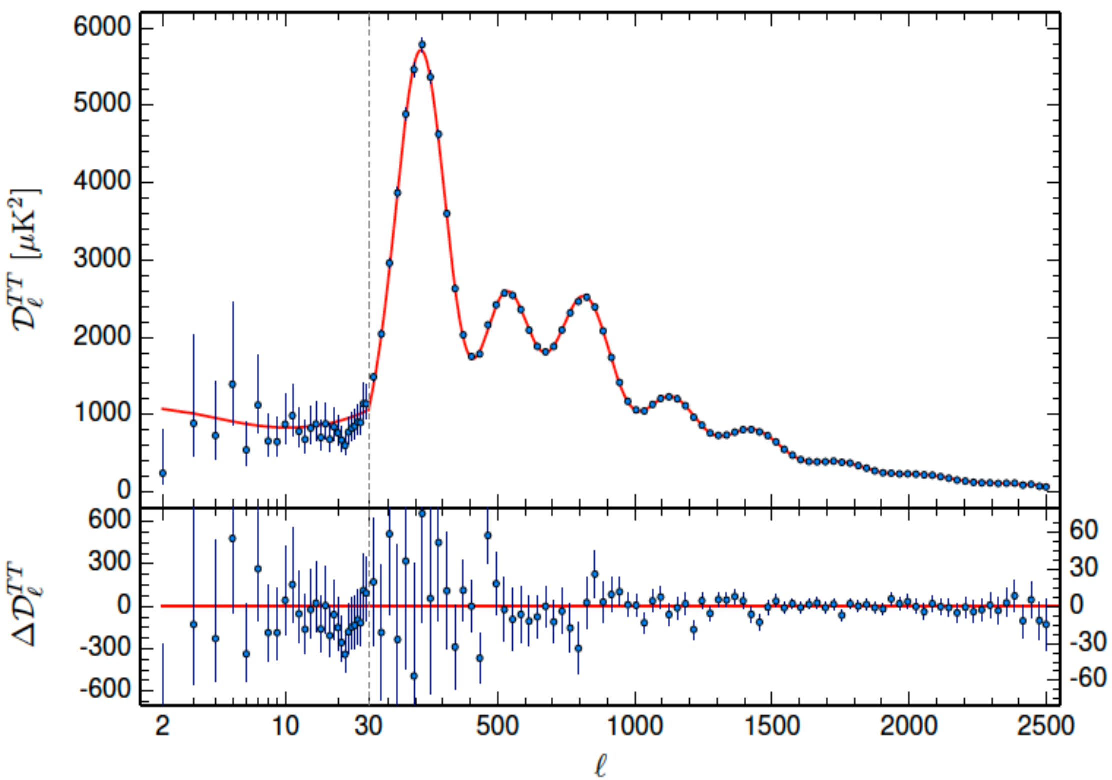
- Evidence from different scales : galaxies (rotation curves), galaxy clusters (M/L, lensing, Xray), CMB
- All point to large dark matter component – also in agreement with light element abundance
- Structure formation: DM is mostly cold (non-relativistic), no electromagnetic interactions

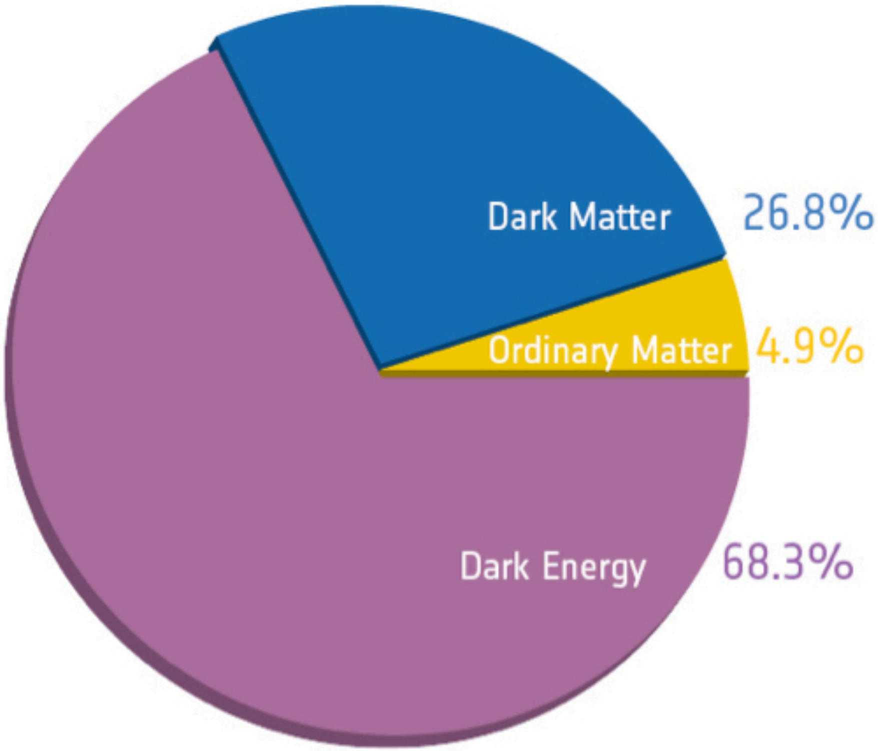




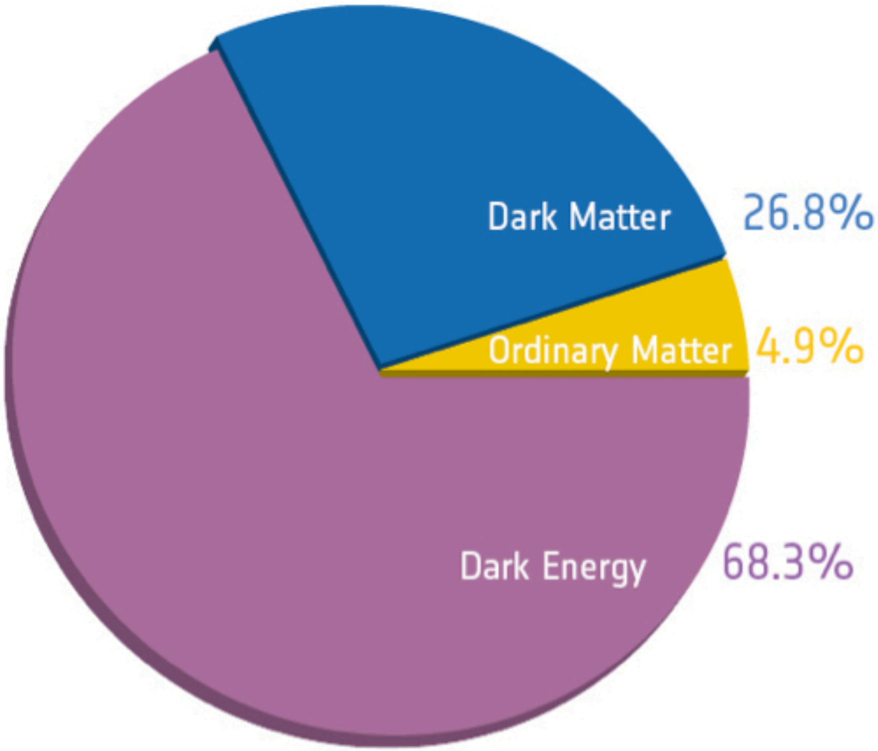
What do we know about dark matter?

- Within ΛCDM model – precisely know its relic density
- $\Omega_{cdm}\, h^2 = 0.1193 +/- 0.0014$ (PLANCK – 1502.01589)





Universe is made of 27% cold dark matter.
Can it be a new particle?



Universe is made of 27% cold dark matter.
Can it be a new particle?

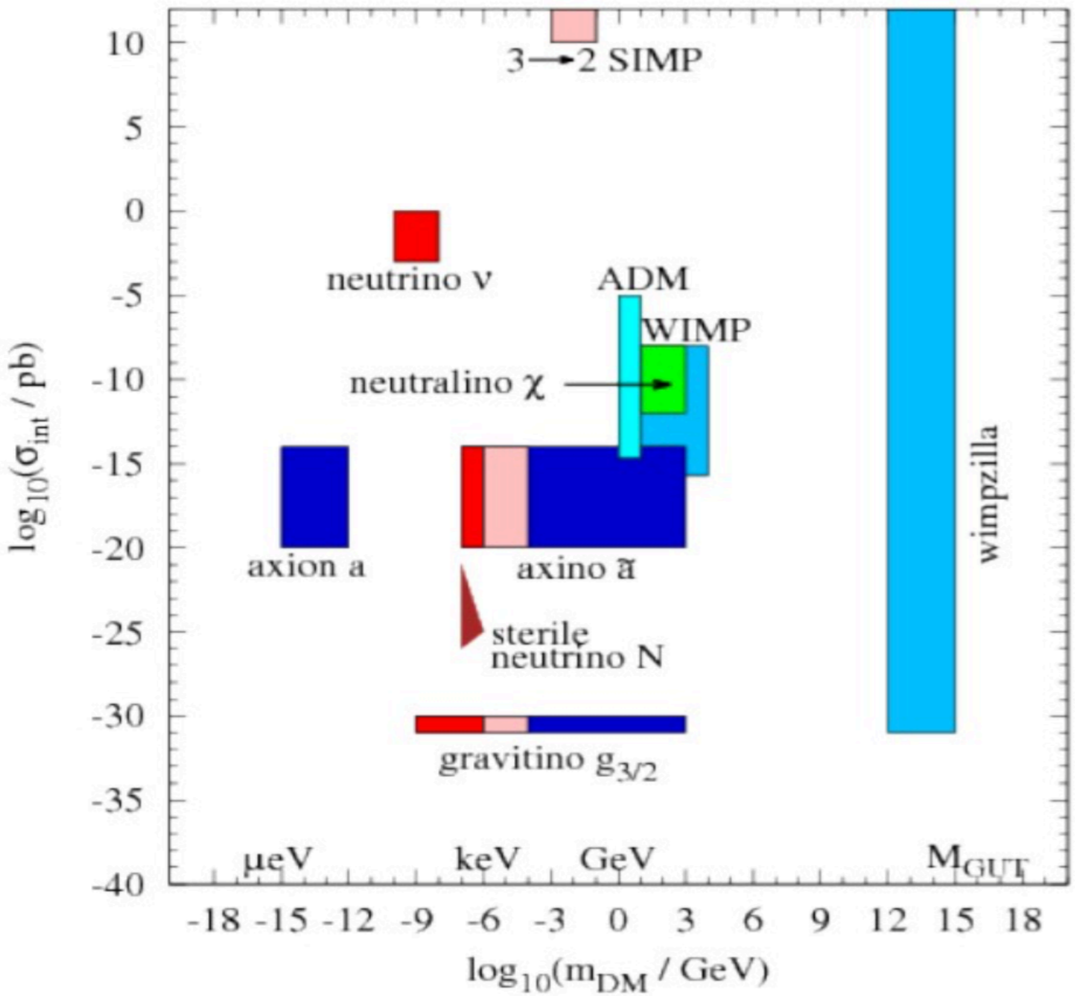
Early studies on cosmological constraints on new particles :

P. Binetruy, G. Girardi, P. Salati, Nucl.Phys.B237 (1984) 285
P. Binetruy, G. Girardi, P. Salati, Phys. Lett. 134B (1984) 174

Dark matter

- Dark matter cannot be baryons nor neutrinos (too hot) – prime candidate since the 80's – new weakly interacting particle (WIMP)
- At the time – supersymmetry was favourite extension of the SM, with R-parity introduced to avoid rapid proton decay the lightest supersymmetric particle (LSP) is stable and a natural DM candidate (neutralino)
- Nowadays much larger range of dark matter candidates – more extensions of the SM (extra dimensions, extended scalar sector, little Higgs, composite…)
- Only requirement for WIMP is new neutral particle + discrete symmetry + weak interactions
- Explaining dark matter is one of the main motivation for physics beyond the standard model

A wide variety of DM candidates
wide range of interactions/mass scales



WIMPs

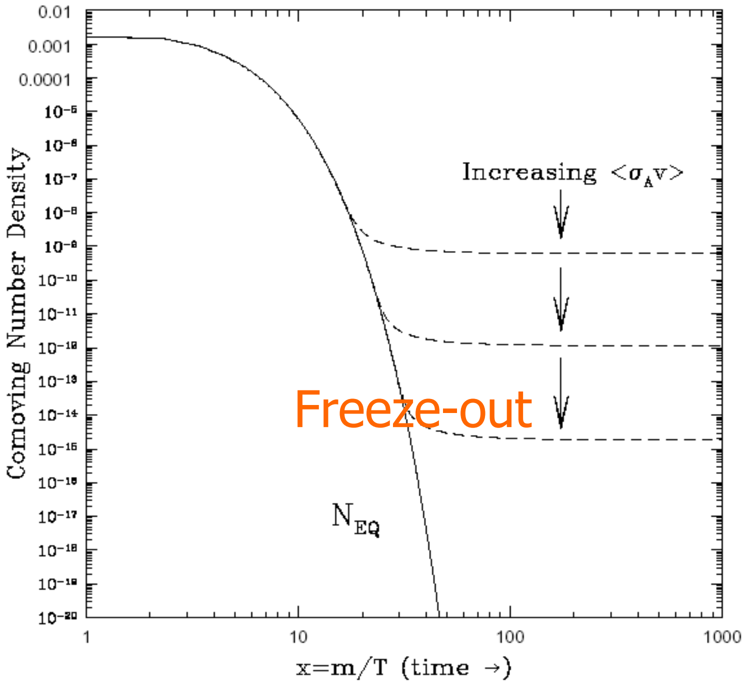
FIMPs

SIMPs

Asymmetric

WIMPs

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature
- LSP decouples from SM particles, density depends only on expansion rate of the universe



$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

WIMPs- relic density

- Write equation in terms of abundance

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p < \sigma v > (Y(T)^2 - Y_{eq}(T)^2)$$

- Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and proper treatment of poles and thresholds
  - Gondolo, Gelmini, NPB 360 (1991)145

$$\Omega h^2 \equiv \frac{\rho_\chi}{\rho_c} = \frac{m_\chi \, Y_\infty \, s_\infty}{1.05 \times 10^{-5} \ \mathrm{GeV}^2 \ \mathrm{cm}^{-3}},$$

- Weakly interacting particles have roughly annihilation cross section to obtain $\Omega h^2 \sim 0.1$

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \quad .$$

Coannihilation

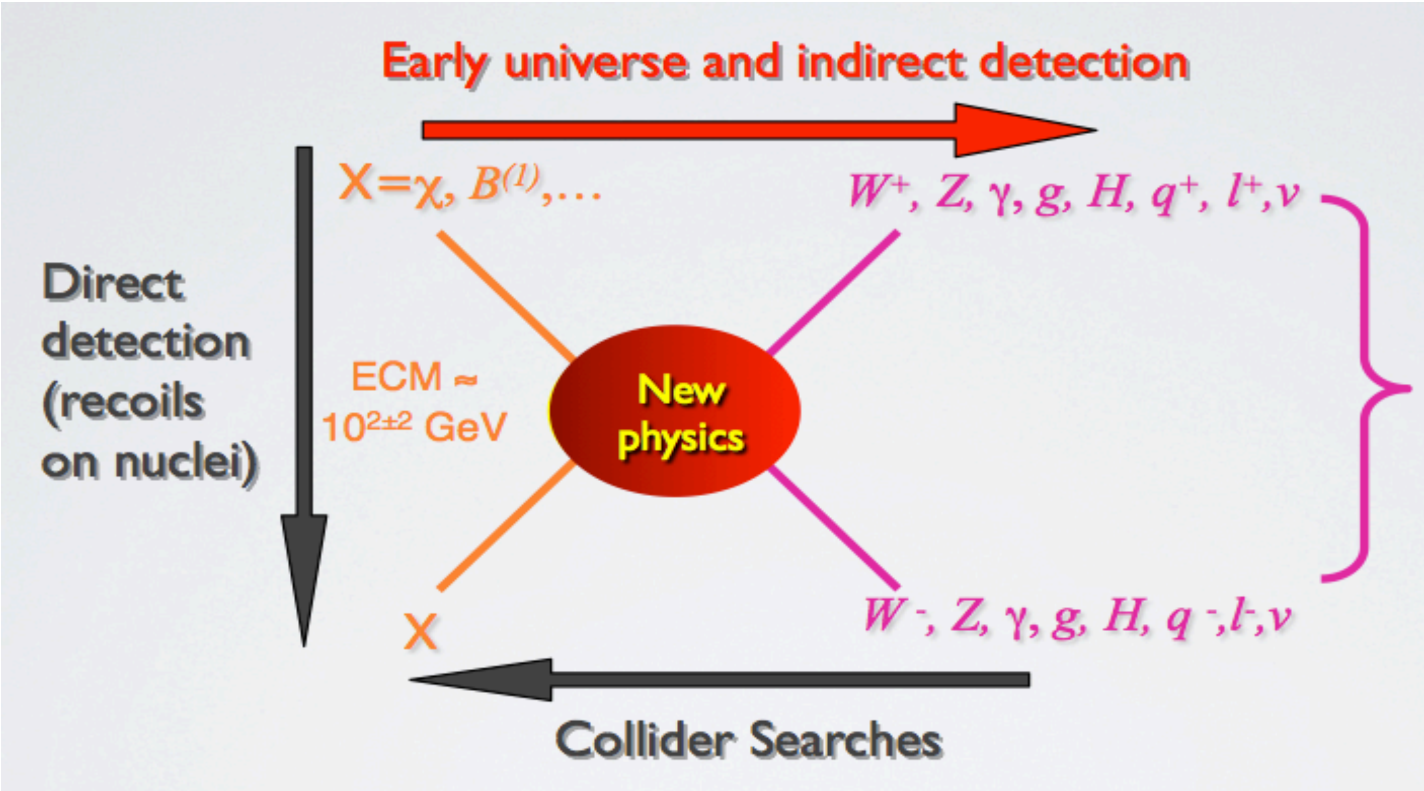
- If M(NLSP)~M(LSP) then $\chi + X \rightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP
- Relic density depends on all processes involving LSP/NLSP → SM
- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes - Edsjo, Gondolo PRD56(1997) 1879

Exp(- ΔM)/T

$$< \sigma v >= \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T\left(\sum_i g_i m_i^2 K_2(m_i/T)\right)^2}$$

- Important processes are those involving particles close in mass to LSP, for example up to 3000 processes can contribute in MSSM
- *Need for codes for precise relic density computation*

Probing the nature of dark matter



• *In the WIMP paradigm, Comprehensive* tools *for dark matter studies : precise calculation of*

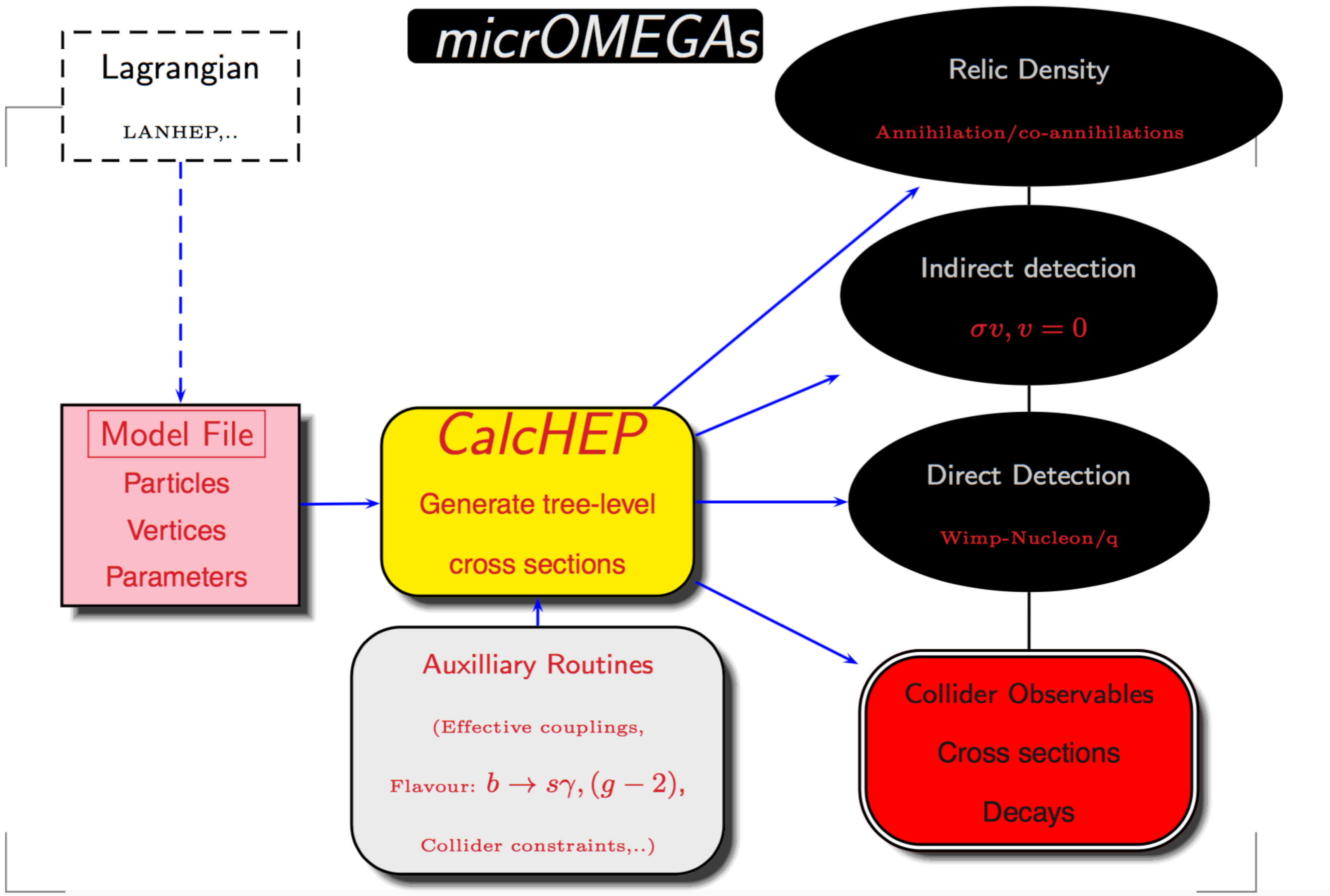
relic density, direct detection, indirect detection, cross section at colliders and decays

Public DM tools

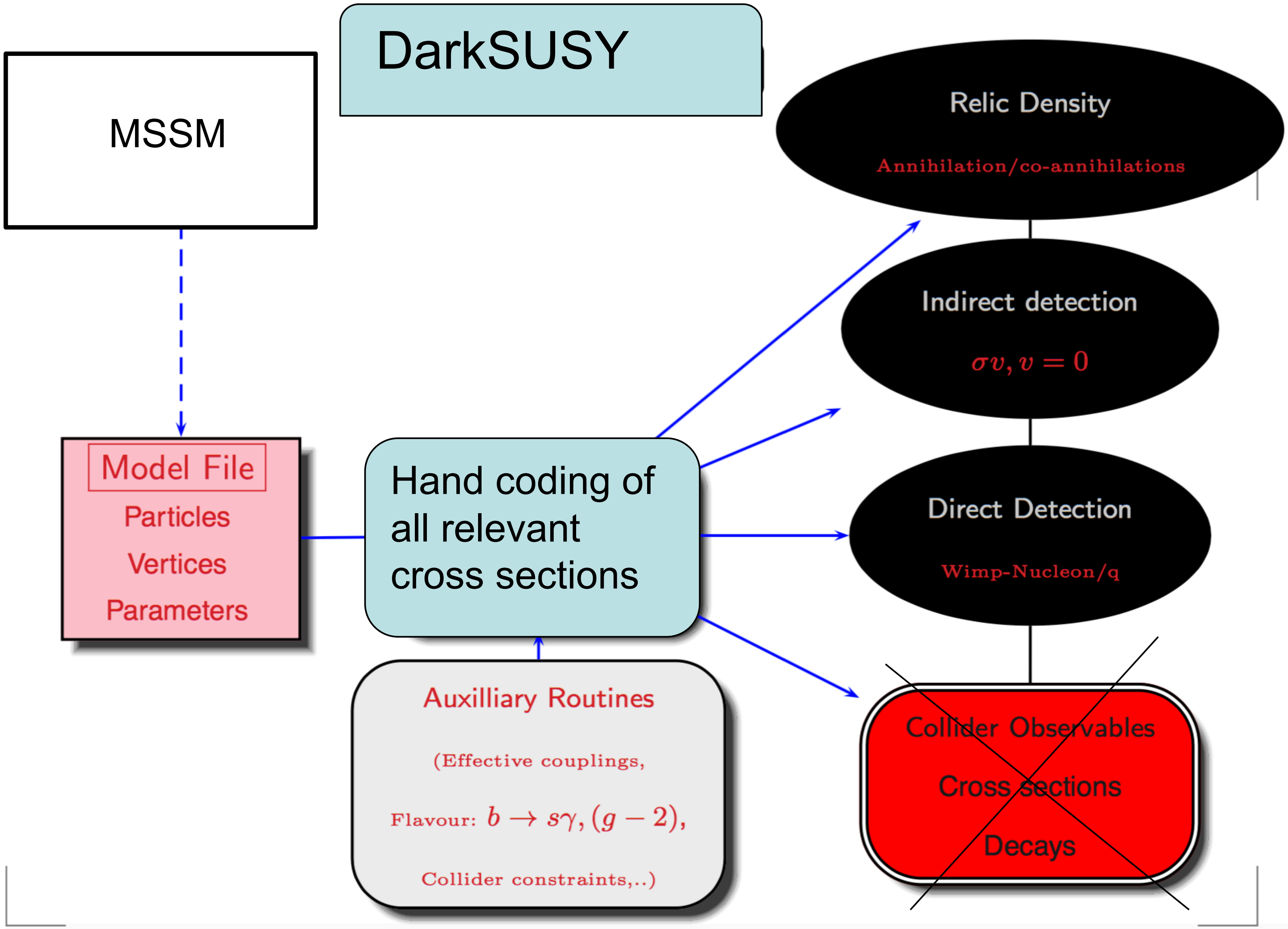
- Neutdriver - neutralino in supersymmetry
  - Jungman, Griest, Kamionkowski (1995) – not maintained
- micrOMEGAs
  - GB, Boudjema, Pukhov, Semenov (2001)
- DarkSUSY
  - Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz (2000—2004)
- IsaRed and IsaRes in IsaTools
  - Baer, Balazs, Belyaev (2002)
- SuperISORelic
  - Arbey, Mahmoudi (2009)
- MadDM
  - Backovic, Kong, McCaskey (2013)
- And many private codes: K. Olive, M. Drees, L. Roszkowski…

Philosophy

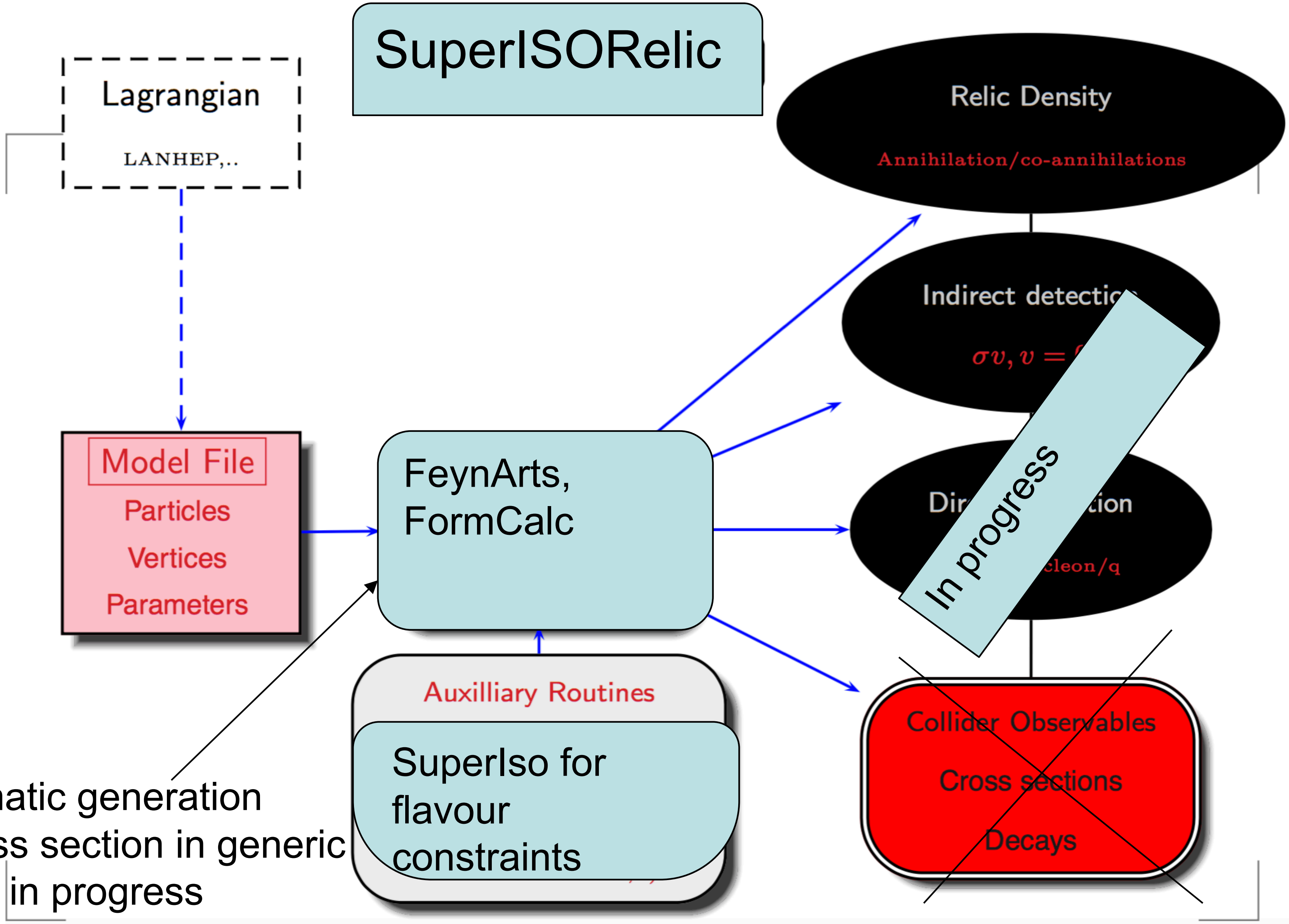
- Modularity and flexibility
  - Possibility to exchange modules, user might want to improve one module
- Models are often complex with huge parameter space
  - Speed of execution
- Ready made, stand-alone package for the non-expert
  - User friendly
- We do not know what DM is made of
  - Possibility to include different DM candidates (only 2)
- Several groups are developing specialized codes
  - Link them


micrOMEGAs
Lagrangian
LANHEP,..
Model File
Particles
Vertices
Parameters
CalcHEP
Generate tree-level
cross sections
Auxilliary Routines
(Effective couplings,
Flavour: $b \to s\gamma, (g-2)$,
Collider constraints,..)
Relic Density
Annihilation/co-annihilations
Indirect detection
$\sigma v, v = 0$
Direct Detection
Wimp-Nucleon/q
Collider Observables
Cross sections
Decays

C code

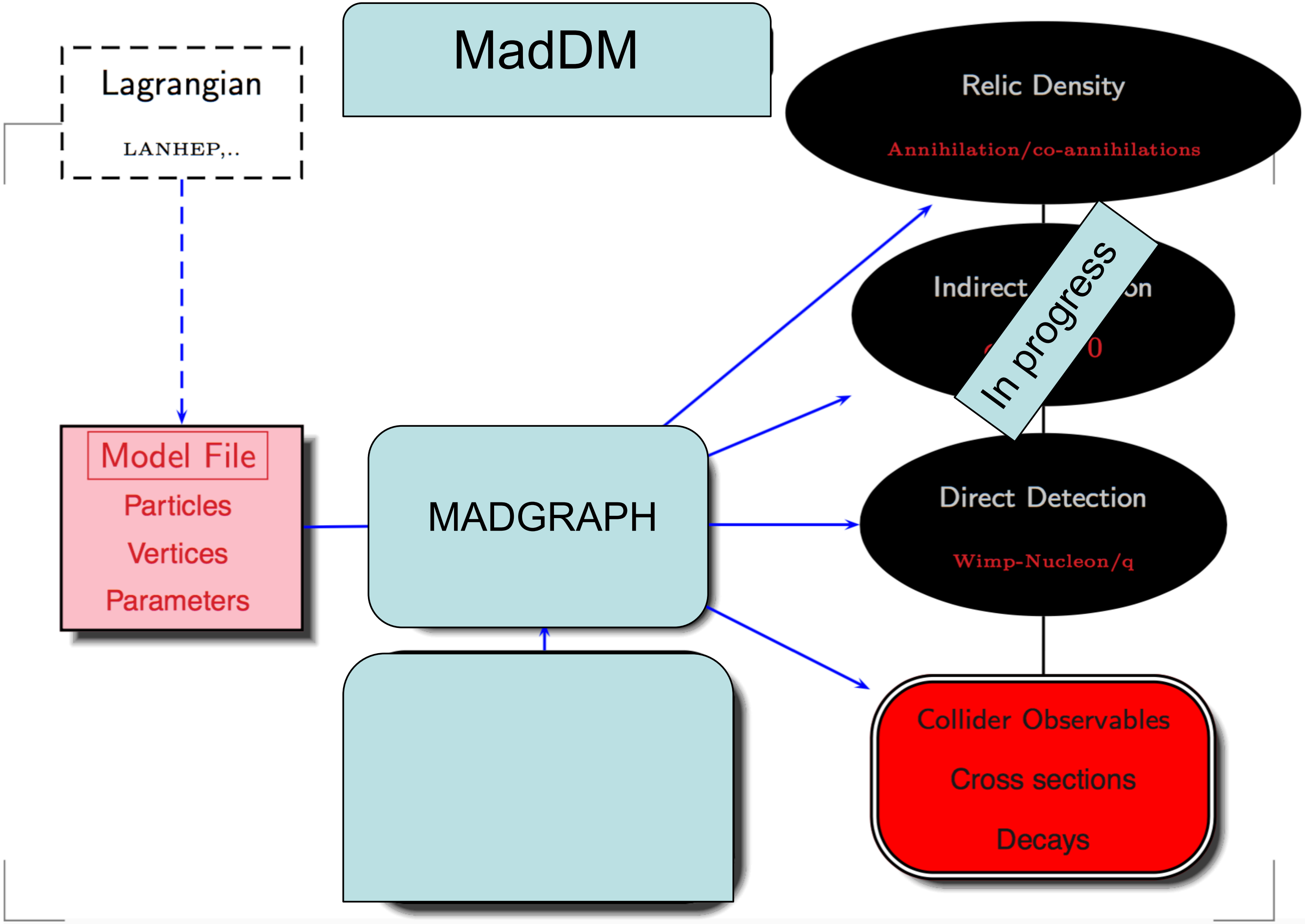


Fortran code



Automatic generation
of cross section in generic
Model in progress

C code



Fortran and python
(for Madgraph interface)

Dark matter models

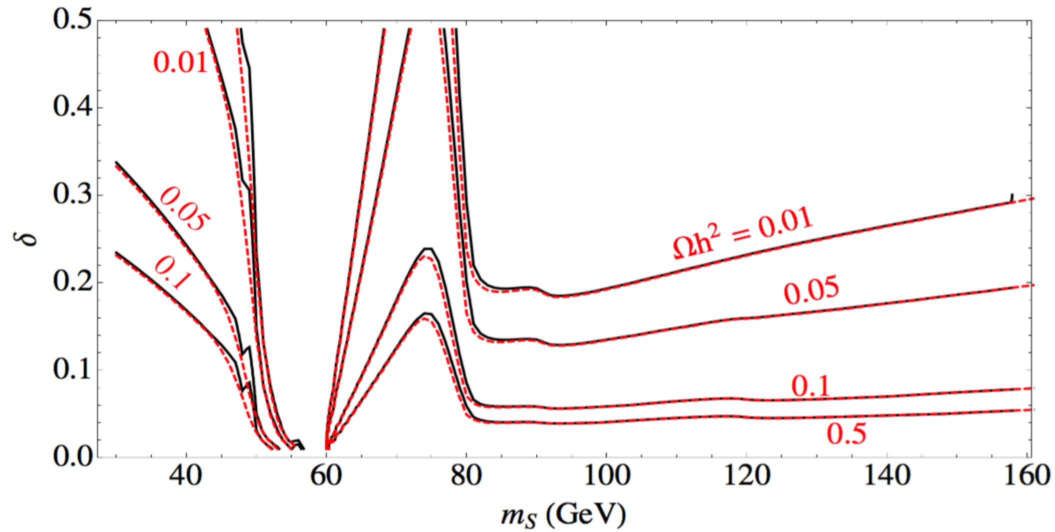
- MSSM : included in all codes,
  - Both high scale models (CMSSM, NUHM…) as well as electroweak scale input (pMSSM)
  - Spectrum calculators (Suspect, Isajet, Softsusy, Spheno) – important radiative corrections to masses
  - Interface made easy with Susy Les Houches Accord (SLHA)
  - Various model specific constraints (b->s γ (NLO) , $(g-2)_{\mu}$, $B_s \to \mu\mu$, $\Delta\rho$,LEP, Higgs)
- NMSSM (in micrOMEGAs, SuperISO, MadDM) – SLHA2
  - relies on NMSSMTools (NMSPEC and NMHDECAY) for spectrum calculation, indirect constraints (B physics, g-2, Higgs collider constraints) - Ellwanger, Gunion, Hugonie
- Host of other models available and user implementation of generic model possible (micrOMEGAs and MadDM)

Relic density tool

- Define model files (automatically or by hand) as well as routines/tools to compute Spectrum
- After the model is implemented and checked
  - Definition of LSP
  - Computes all annihilation and coannihilation cross-sections
  - Complete tree-level matrix elements for all 2-2 subprocesses
  - Checks for presence of resonances
  - Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and improved accuracy near poles and thresholds
    - Gondolo, Gelmini, NPB 360 (1991)145
    - coannihilation : Edsjo, Gondolo PRD56 (1997) 1879
- Includes only relevant channels - criteria based on mass difference with LSP
- Some codes calculate the relic density for any LSP (even charged)
  - Relevant when LSP is very weakly coupled, NLSP freeze—out then decay to DM

Reliability of results

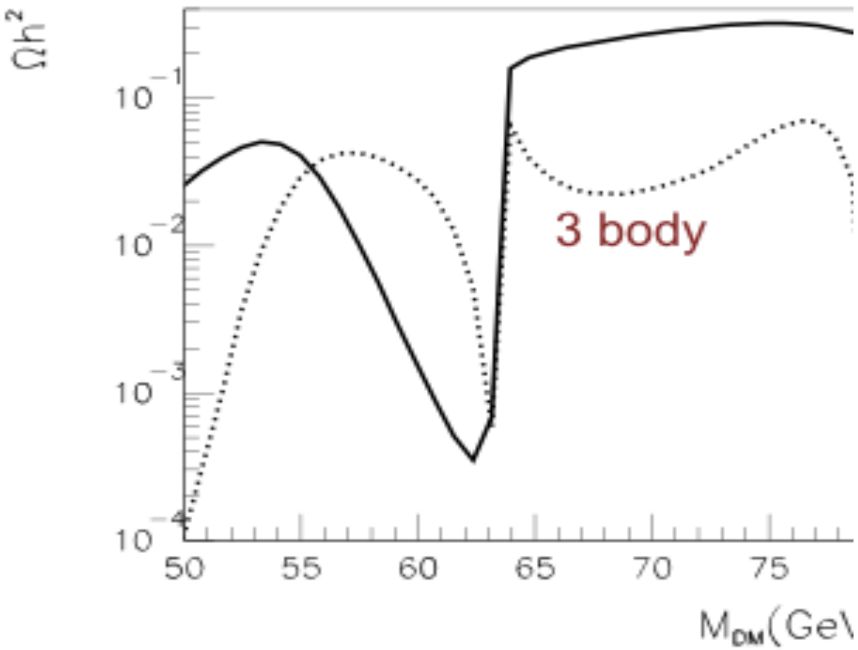
- Extensive comparisons between DarkSUSY/micrOMEGAs, SuperISO/micrOMEGAs, MadDM/micrOMEGAs – generally results are in good agreement – few percent
- MadDM/micrOMEGAs – Backovic et al 1308.0955
  - Real singlet model : % level except near Higgs resonance
  - MSSM : 5% level except near Higgs resonance when large Δm_b corrections (25%)



Higher-order effects

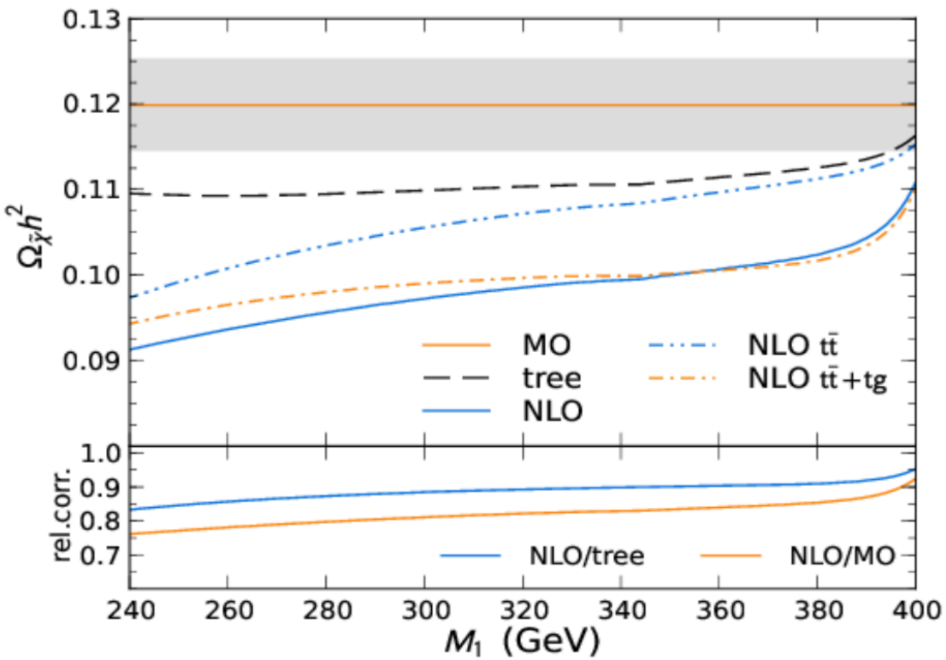
- Is it enough to include only 2-2 tree-level annihilation?
  - Photon radiation (aka internal bremsstrahlung) can be relevant
  - Annihilation into 3-body final state can be as large as 2-body, eg when annihilation into W pairs kinematically suppressed - C. Yaguna, arXiv: 1003.2730

- MSSM : bino/higgsino LSP, μ=150GeV, $M_2=2M_1$
- Dominant channels WW,Zh

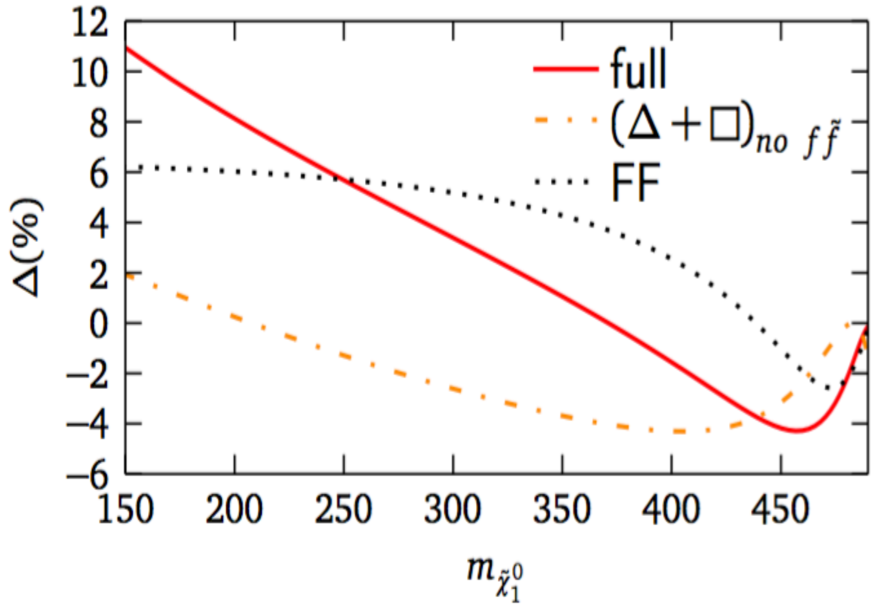


Higher-order effects

- What about NLO corrections? (example in MSSM)
  - Corrections to masses/couplings, Higgs width through spectrum calculator
  - QCD corrections can be large– worked out for example in DM@NLO and fed into DS or micrΩ (left) – in principle accessible in MadDM through Madgraph@NLO
  - Electroweak corrections – can also be large - some cases treated with SloopS – then fed into micrOMEGAs



Harz et al, 1609.04998

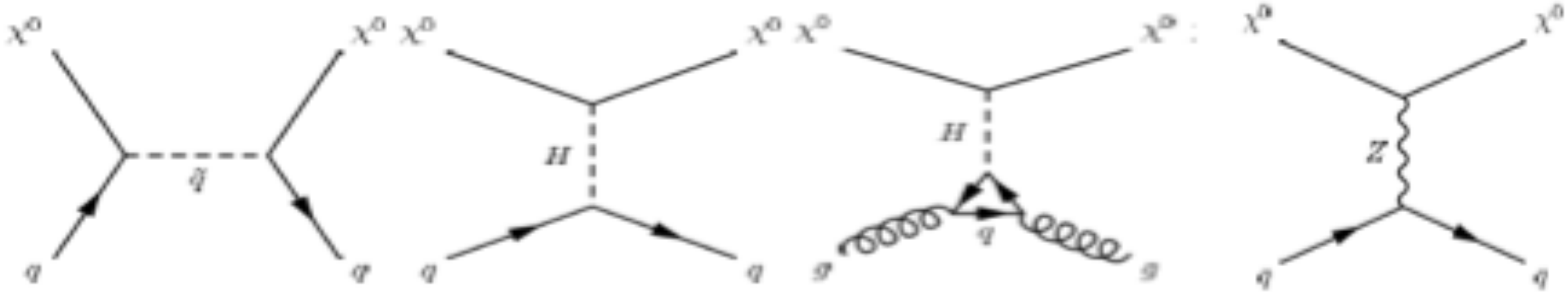


Corrections to ZZ in MSSM, Boudjema et al, 1403.7459

Direct detection

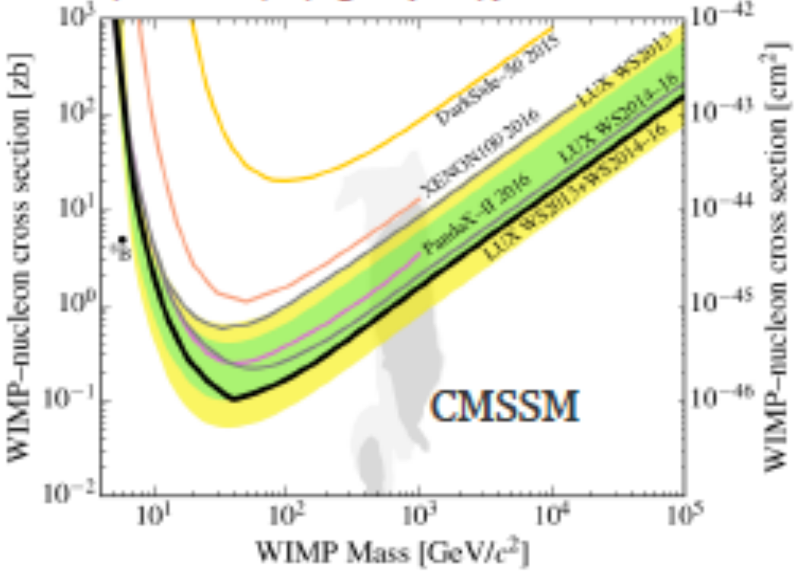
Direct detection

- Elastic scattering of WIMPs off nuclei in a large detector
- Measure nuclear recoil energy, E_R
- Would give best evidence that WIMPs form DM
- Two types of scattering
  - Coherent scattering on A nucleons in nucleus, for spin independent interactions (dominant for heavy nuclei
  - Spin dependent interactions – only on one unpaired nucleon (important for light nuclei)

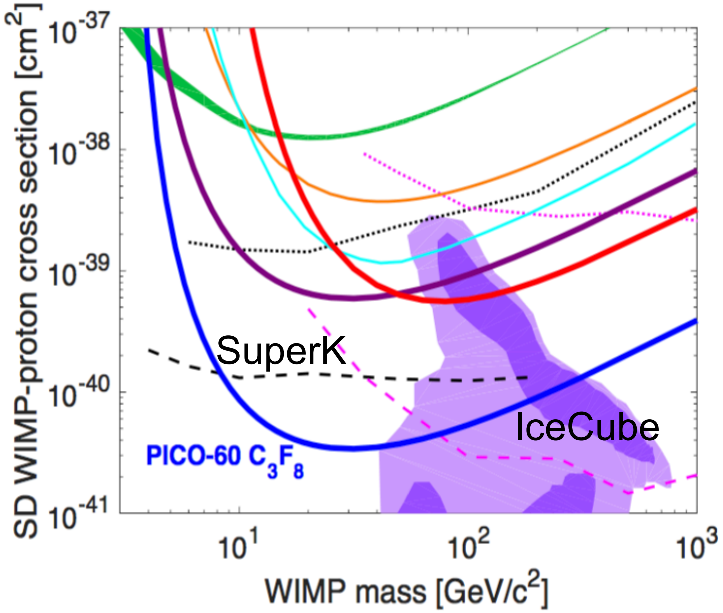


Limits DM searches

LUX, PRL 118, 021303 (2017)
PANDA-X, PRL 118, 071301 (2017)



Pico, 1702.07666



Sensitive enough to probe DM models
Ongoing – Xenon1T
m<10GeV more challenging

SD detector now probe parameter
Space of MSSM
SuperK – IceCube assume
DM annihilation channel (tau)

WIMP- Nucleon amplitude

- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude *at small momentum ~100MeV*,
- Generic form for a fermion

$$\mathcal{L}_F = \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + i\kappa_1 \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \gamma_5 \psi_N + i\kappa_2 \bar{\psi}_\chi \gamma_5 \psi_\chi \bar{\psi}_N \psi_N + \kappa_3 \bar{\psi}_\chi \gamma_5 \psi_\chi \bar{\psi}_N \gamma_5 \psi_N$$
$$+ \kappa_4 \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N + \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N$$

- For Majorana fermion only 2 operators survive at small q^2
- First need to compute the WIMP quark amplitudes
  - Compute symbolically from Feynman diagrams+ Fierz (DS)
  - Automatic approach -works for all models-micrOMEGAs &MadDM
- Effective Lagrangian for WIMP-quark scattering has same generic form as WIMP nucleon

WIMP quark effective Lagrangian

- Implement effective Lagrangian including operators relevant for specific DM spin

$$\hat{\mathcal{L}}_{eff}(x) = \sum_{q,s} \lambda_{q,s}\hat{O}_{q,s}(x) + \xi_{q,s}\hat{O}'_{q,s}(x)$$

- Add it to input model to get the interference term between L_{inp} and L_{eff} -> allow to single out SD or SI contribution

	WIMP Spin	Even operators	Odd operators
SI	0 1/2 1	$2M_\chi\phi_\chi\phi^*_\chi\overline{\psi}_q\psi_q$ $\overline{\psi}_\chi\psi_\chi\overline{\psi}_q\psi_q$ $2M_\chi A_{\chi,\mu}A^\mu_\chi\overline{\psi}_q\psi_q$	$i(\partial_\mu\phi_\chi\phi^*_\chi - \phi_\chi\partial_\mu\phi^*_\chi)\overline{\psi}_q\gamma^\mu\psi_q$ $\overline{\psi}_\chi\gamma_\mu\psi_\chi\overline{\psi}_q\gamma^\mu\psi_q$ $+i\lambda_{q,o}(A^{*\alpha}_\chi\partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha\partial_\mu A^*_{\chi\alpha})\overline{\psi}_q\gamma_\mu\psi_q$
SD	1/2 1	$\overline{\psi}_\chi\gamma_\mu\gamma_5\psi_\chi\overline{\psi}_q\gamma_\mu\gamma_5\psi_q$ $\sqrt{6}(\partial_\alpha A^*_{\chi,\beta}A_{\chi\nu} - A^*_{\chi\beta}\partial_\alpha A_{\chi\nu})$ $\epsilon^{\alpha\beta\nu\mu}\overline{\psi}_q\gamma_5\gamma_\mu\psi_q$	$-\frac{1}{2}\overline{\psi}_\chi\sigma_{\mu\nu}\psi_\chi\overline{\psi}_q\sigma^{\mu\nu}\psi_q$ $i\frac{\sqrt{3}}{2}(A_{\chi\mu}A^*_{\chi\nu} - A^*_{\chi\mu}A_{\chi\nu})\overline{\psi}_q\sigma^{\mu\nu}\psi_q$

WIMP-quark to WIMP-nucleon

- Include coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Extracted from experiments – or from lattice calculations
  - Source of theoretical uncertainties
- Example , scalar coefficients, contribution of q to nucleon mass

$$\langle N | m_q \bar{\psi}_q \psi_q | N \rangle = f_q^N M_N \qquad \lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}$$

$$f_Q^N = \frac{2}{27}\left(1 - \sum_{q \le 3} f_q^N\right)$$

- Can be defined by user
- Different coefficients can lead to large corrections in cross section
  - Bottino et al hep-ph/0010203, Ellis et al hep-ph/0502001

Output

Can be directly compared to limits

- Amplitudes (protons and neutrons)
- SI and SD cross sections on protons and neutrons
- Rates (SI and SD) for specific nuclei

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n (A-Z)\right)^2 I(E)$$

Nuclear form factors

Particle physics + quark content in nucleon

DM velocity distribution

$$I(E) = \int_{v_{min}(E)}^{\infty} \frac{f(v)}{v} dv$$

$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

- Modularity and flexibility: can change velocity distribution, nuclear form factors...

Beyond the basics

- Larger set of effective operators could be probed
- Not included in any of the tools described
- New tool : DirectDM : mathematica code that provide the link between EFT and effective operators for DM-nucleon within a specific model. Bishara et al 1708.02678

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi \left(\vec{S}_N \cdot \vec{v}_\perp\right), \qquad \mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp\right) \mathbb{1}_N\,,$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right), \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right),$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right),$$

- Directional detection (included only in MadDM)
  - If DM discovered, directional detection can be used to extract information on halo property
  - Multi-ton detector will become sensitive to neutrino background – directional detection useful to distinguish from DM

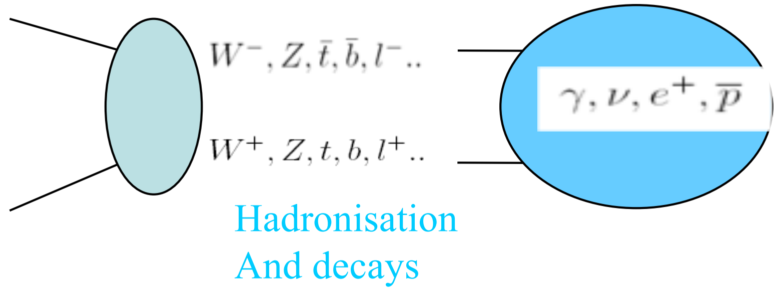
Indirect detection

micrOMEGAs, DarkSUSY
MadDM and SuperISO (in progress)

Indirect detection

- Annihilation of pairs of DM particles into SM : decay products observed

- Searches for DM in 4 channels
  - Antiprotons (Pamela,AMS)
  - Positrons/electrons from galactic halo/center (Pamela, AMS, Fermi..)
  - Photons from galactic halo/center (Egret, Fermi, Hess..)
  - Neutrinos from Sun (IceCube)



v=0.001c

from pythia

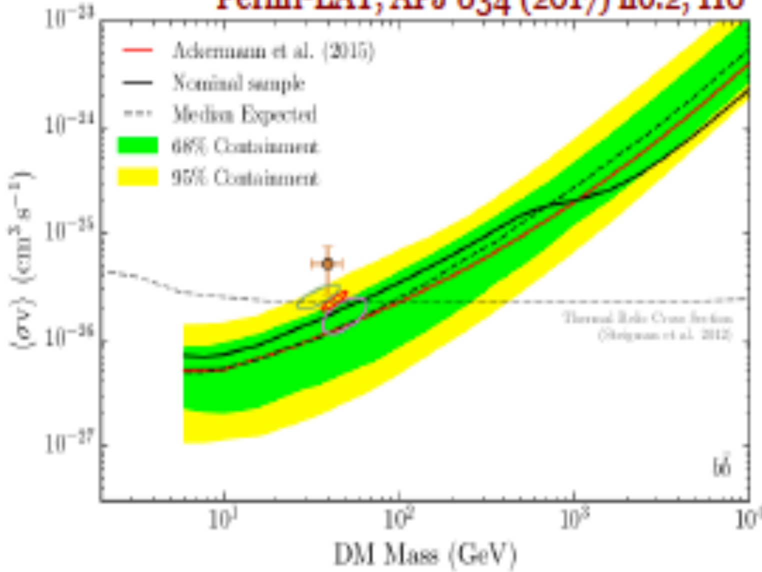
$$Q(x,\mathrm{E}) = \frac{<\sigma v>}{2}\left(\frac{\rho(\mathbf{x})}{m_\chi}\right)^2 \frac{dN}{dE}$$

Limits DM searches - photons

Continuum

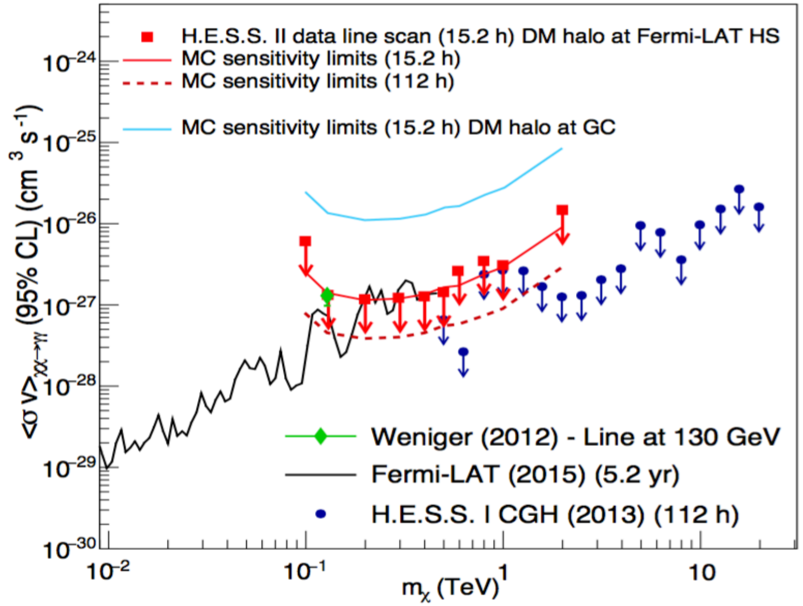
Fermi-LAT limit from dSPhs

Fermi-LAT, APJ 834 (2017) no.2, 110



Gamma rays from Dwarfs – robust limits
Probe generic annihilation cross section
for DM below ~70GeV
Results given for many annihilation channels – simple to recast the limit for specific model with several annihilation channels

Gamma-ray line
HESS, 1609.08091



Cross section can be directly compared with output of code

Photons

- Flux calculation

$$\Phi_{\gamma,\nu} = \frac{1}{8\pi} \frac{<\sigma_{ann} v>}{m_\chi^2} \sum_{f.s.} \left(\frac{dN_{\gamma,\nu}}{dE} \right)_{f.s.} \int_{l.o.s.} \rho_s^2$$

- Photon production
  - In decay of SM particles + R-even new particles
  - dN/dE : basic channels ff, VV, VH, HH and polarization of gauge bosons
  - For particles of unknown mass (Z',H) compute 1->2 decay recursively until only basic channels
  - Annihilation into 3 body ($\chi\chi \to e^+e^-\gamma$) – can have strong impact on spectrum
- Integral over line of sight depends strongly on the galactic DM distribution – especially in Galactic center
  - NFW, isothermal, Einasto

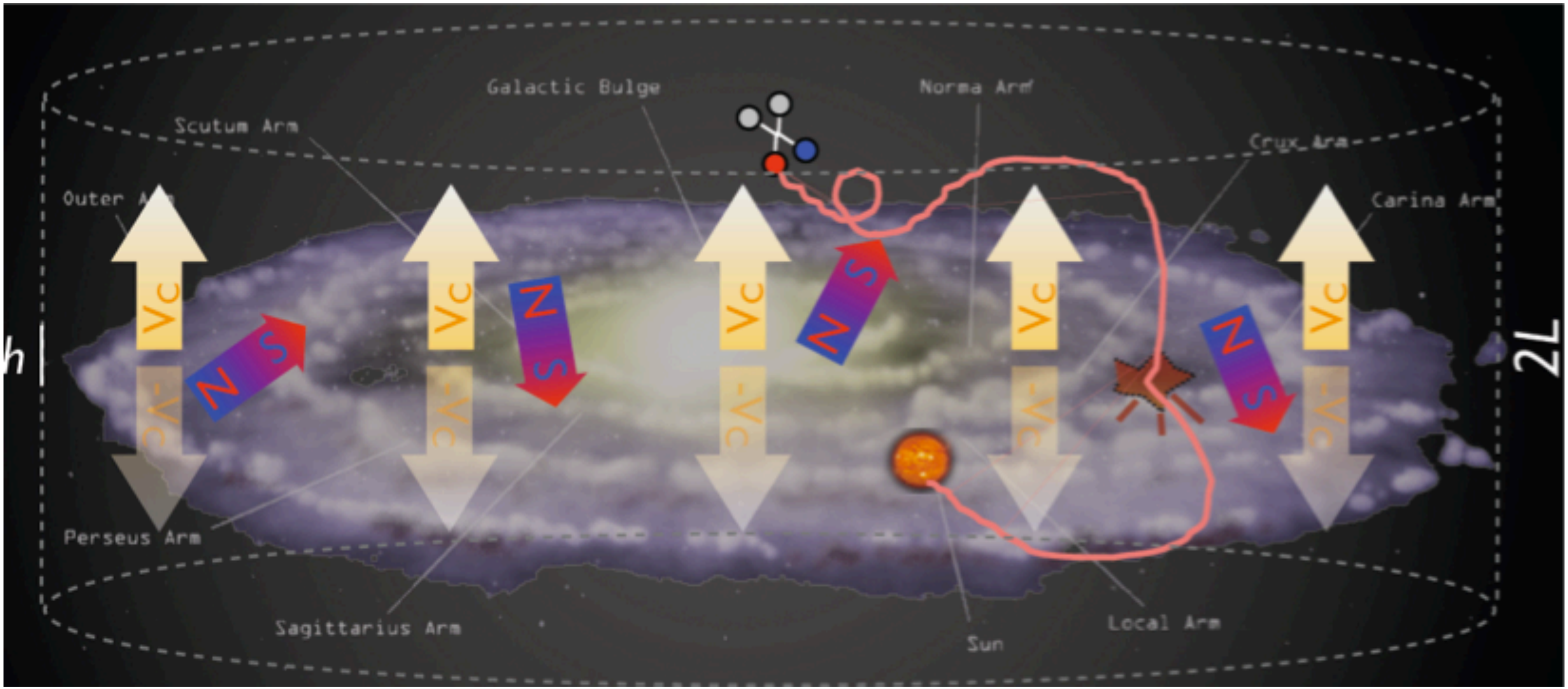
Monochromatic gamma-rays

- Monochromatic gamma rays ($\gamma\gamma$,γZ) and (γh) are loop-induced BUT lead to very distinctive signal

- In micrOMEGAs available for MSSM and NMSSM - in generic models only have the Higgs contribution (through $h\gamma\gamma$ effective vertices)
  - Computed with SloopS, a code for computation of one-loop processes in the SM,MSSM and some extensions
    - F. Boudjema, A. Semenov, D. Temes, hep-ph/0507127
    - G. Chalons, A. Semenov, arXiv:1110.2064
- Included in DarkSusy for MSSM
- No difficulty to include in MadDM for any model provided with NLO model files

Antiprotons and positrons from DM annihilation in halo

M. Cirelli, Pascos2009



$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E) \nabla N] - \frac{\partial}{\partial E}[b(E) N] = q(\mathbf{x}, E)$$

diffusion Energy losses Source

Propagation of cosmic rays

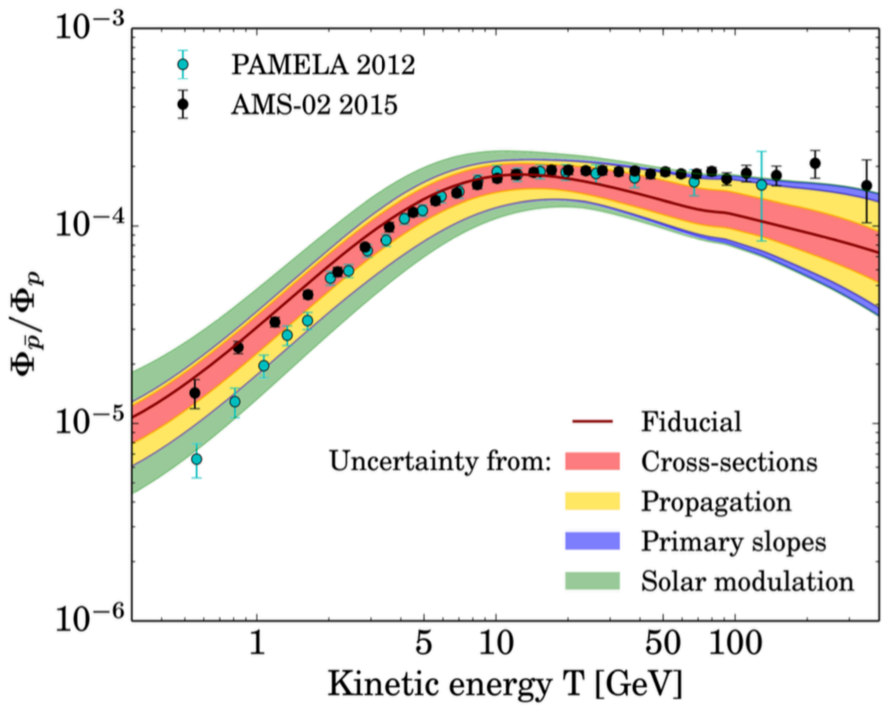
- *For Charged particle spectrum detected different than spectrum at the source*

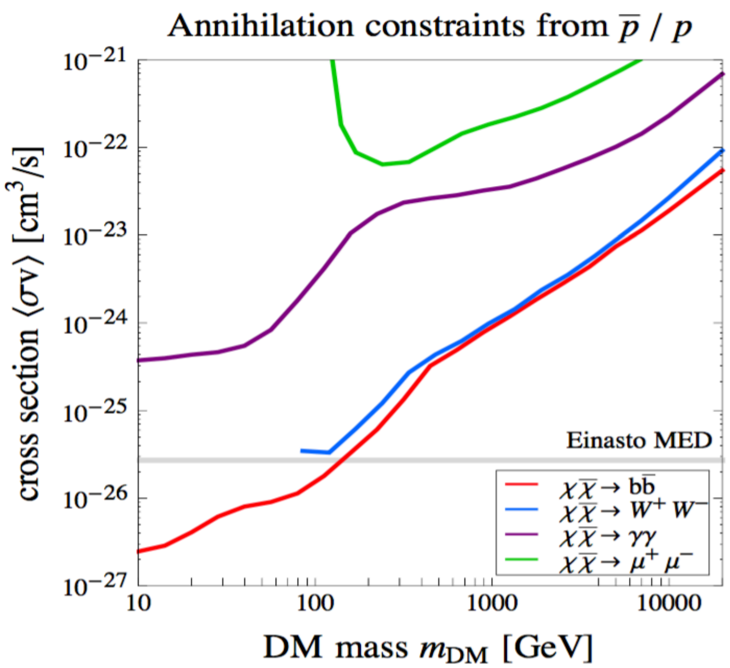
$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E) \nabla N] - \frac{\partial}{\partial E} [b(E) N] = q(\mathbf{x}, E)$$

- Charged cosmic rays deflected by irregularities in galactic magnetic field
  - For strong magnetic turbulence effect similar to space diffusion
- Energy losses due to interactions with interstellar medium
- Convection driven by galactic wind and reacceleration due to interstellar shock wave
- For positron, antiproton : solution propagation equations based on
  - Lavalle, Pochon, Salati, Taillet, astro-ph/0603796 (micrOMEGAs)
  - Semi-empirical diffusion equation in a 2d model with cylindrical symmetry and free escape boundary conditions (DarkSUSY)

Comparison with data

- *Large uncertainties on the secondary antiproton spectrum*
- *Constraints on DM from AMS02 for given annihilation channel and propagation model – can be directly compared with output of DS/micro*





Giesen et al, 1504.04276

Neutrinos from DM capture in Sun

- DM particles captured by Sun/Earth, concentrate in center and annihilate into SM, lead to neutrino flux, can be observed at Earth (SuperKamiokande, IceCube)
- Shape of neutrino flux depends on DM annihilation channel
- Capture rate determined by cross section for DM scattering on nuclei --related to DD

$$\dot{N}_\chi = C_\chi - A_{\chi\chi} N_\chi^2 - A_{\chi\bar{\chi}} N_\chi N_{\bar{\chi}} - E N_\chi \,,$$
$$\dot{N}_{\bar{\chi}} = C_{\bar{\chi}} - A_{\chi\bar{\chi}} N_\chi N_{\bar{\chi}} - A_{\chi\bar{\chi}} N_{\bar{\chi}}^2 - E N_{\bar{\chi}} \,,$$

- When capture/annihilation is large, equilibrium is reached and annih. rate determined by capture rate

$$\frac{d\phi_\nu}{dE_\nu} = \frac{1}{4\pi d^2}\left(\Gamma_{\chi\chi} Br_{\nu\nu} \frac{dN_{\nu\nu}}{dE} + \Gamma_{\chi\bar{\chi}} \sum_f Br_{f\bar{f}} \frac{dN_f}{dE}\right)$$

- Solve equation for number density numerically and obtain ν flux at Earth

$$\frac{d\phi_\nu}{dE_\nu} = \frac{1}{4\pi d^2}\left(\Gamma_{\chi\chi} Br_{\nu\nu}\frac{dN_{\nu\nu}}{dE} + \Gamma_{\chi\bar{\chi}}\sum_f Br_{f\bar{f}}\frac{dN_f}{dE}\right)$$

- Neutrino spectrum originating from different SM decays and including oscillation available in
  - PPPC4DM, M. Cirelli et al, 1012.4515
- Neutrinos that reach the Earth interact with rock below or water/ice in detector -> muon flux
- Both neutrino flux and muon flux are computed (micrOMEGAs and DarkSUSY) – see J. Edsjo's talk

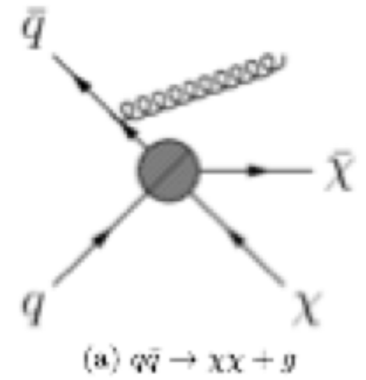
Dark Matter at colliders

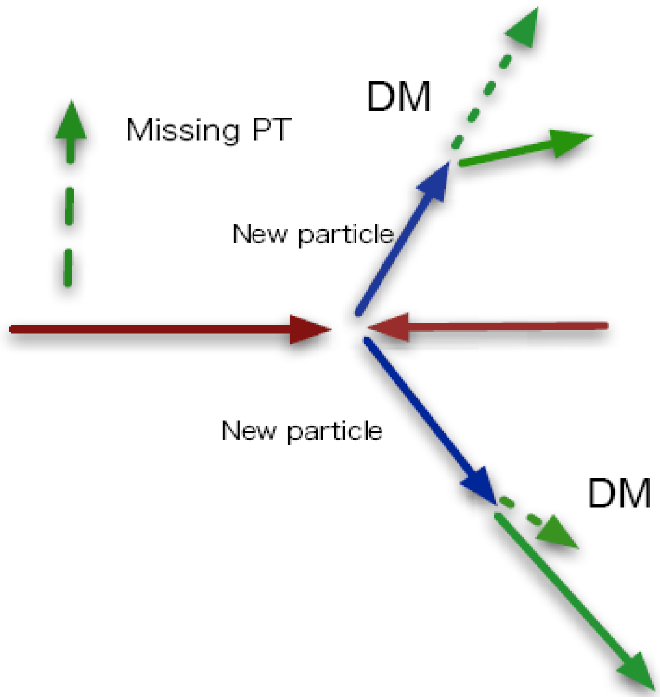
Collider physics

- Higgs sector put strong constraints on BSM: Higgs mass, Higgs signal strengths and searches for new Higgses
  - easy to interface to codes that fit HiggsSignal strengths (Lilith or HiggsSignals)
  - One issue : must provide loop-induced Higgs partial widths (two-photons and two-gluons) - known in MSSM
  - Generic formulae for contributions of new fermions/scalar/vector in the loop – A. Djouadi, Phys. Rep. 459 (2008)
    - implemented in micrOMEGAs together with tool to extract vertices automatically from the model file
  - Also simple interface to code that provides limits from Higgs searches-HiggsBounds

DM production at LHC

- DM direct production : missing energy (need additional particle to trigger) – monojet, monophoton, mono-X
- DM in Higgs decays
- Production of coloured particles: DM in decay chain (MET+..)
- Charged tracks and displaced vertices (for quasi stable NLDSP –next-lightest dark sector particle)
- Production of mediator (in standard channels)





DM at LHC

- Many searches for new particles at LHC – several tools for reinterpretation – Checkmate, Smodels, MadAnalysis5, Fastlim …
- 3 approaches for DM tools : 1) leave it to specialists (eg fitting codes), 2) interfaces, 3) specific routines
  - micrOMEGAs: interface to SmodelS for simplified models results
    - fast and efficient for scan of parameter space but so far cannot exploit full LHC results in all channels
    - specific routines for Z' searches and monojet
  - MadDM : interface to MadAnalysis5
  - DarkSUSY – no development beyond LEP limits and Higgs sector but included in Gambit
  - SuperISORelic – no development, to be included in GamBit, also private code for extensive checks of LHC limits

Generalisation of relic density calculation

–WIMPs : Discrete symmetries other than Z_2
–Asymmetric dark matter
–Feebly interacting particles and non-thermal production
–Beyond LCDM : Different universe expansion

Other discrete symmetries

- Discrete remnant of some broken gauge group, eg Z_N
- Impact for dark matter: new processes
  - semi-annihilation : processes involving different number of "odd particles" $\chi\chi \to \chi^*$ SM,
  - T. Hambye, 0811.0172, T. Hambye, M. Tytgat, 0907.1007
  - Modification of Boltzmann equation

$$\frac{dn}{dt} = -v\sigma^{xx^*\to XX}\left(n^2 - \bar{n}^2\right) - \frac{1}{2}v\sigma^{xx\to x^*X}\left(n^2 - n\,\bar{n}\right) - 3Hn.$$

  - More than one WIMP-DM candidate : Assisted freeze-out/DM conversion : interaction between particles from different dark sectors
  - Two coupled Boltzmann equations
  - Solved numerically in micrOMEGAs4, MadDM

Asymmetric DM

- Motivation : baryon-antibaryon and DM asymmetry related
- The case where DM is not self-conjugate (e.g. Dirac fermion, complex scalar)
- $Y^+(Y^-)$: abundance of DM particle(anti-)

$$\frac{dY^{\pm}}{ds} = \frac{2 < \sigma v >}{3H}\left(Y^+Y^- - Y^+_{eq}Y^-_{eq}\right)$$

- $\Delta Y = Y^+ - Y^-$ is constant
- Define $Y = 2(Y^+Y^-)^{1/2}$

$$\frac{dY}{ds} = \frac{< \sigma v >}{3H}\left(Y^2 - Y^2_{eq}\right)\sqrt{1 + \left(\frac{\Delta Y}{Y}\right)^2}$$

- Similar to equation for self-conjugate - solve num.

$$\Omega h^2 = \frac{8\pi}{3H^2_{100}}\frac{m_\chi}{M_{\rm Planck}}\frac{\sqrt{Y_0^2 + \Delta Y^2}}{s_0}$$

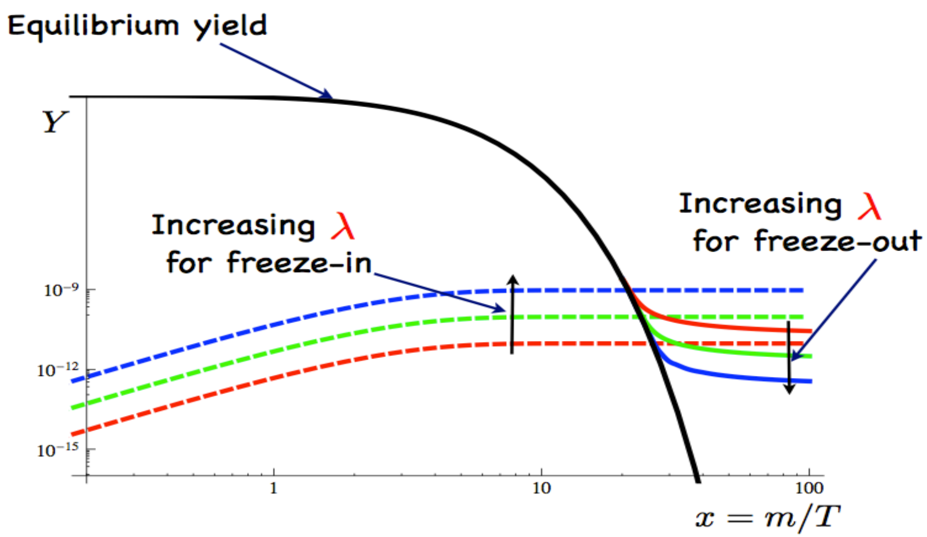
- Note asymmetry always increase relic abundance

FIMPS (Feebly interacting MP)

- Freeze-in (Hall et al 0911.1120): in early Universe, DM so feebly interacting that decoupled from plasma
- Assume that after inflation abundance DM very small, interactions are very weak but lead to production of DM
- T~M, DM 'freezes-in' - yield increase with interaction strength

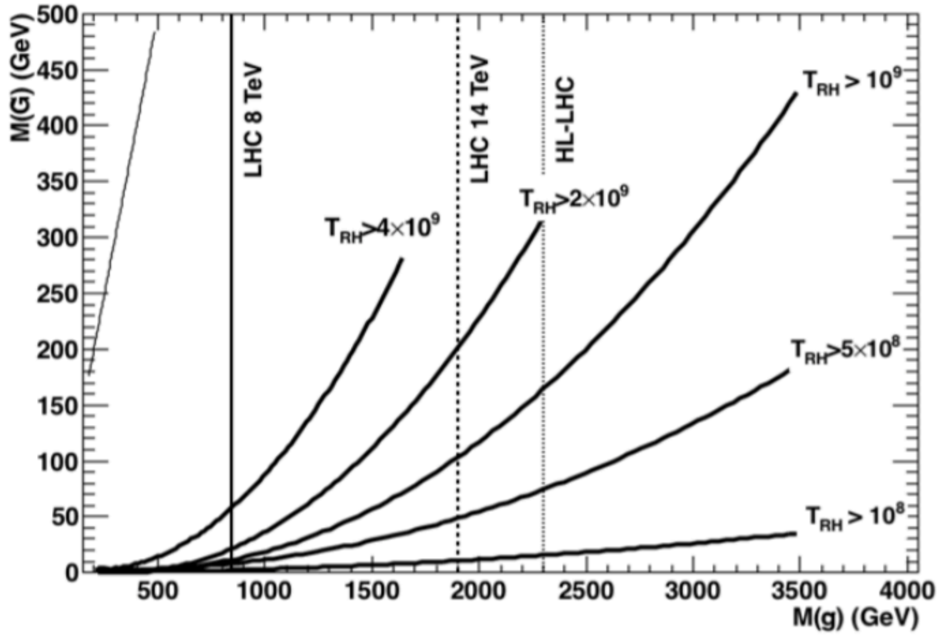
$$\dot{n}_\chi + 3Hn_\chi = \langle \sigma v \rangle_{X\bar{X}\to\chi\bar{\chi}}(T) n_{eq}^2(T) + n_{eq}(T)\Gamma_{Y\to\chi\chi}(T)$$

- Production by annihilation or decay
- Can lead to Long-lived particles



The case of gravitino

- Gravitinos : alternative DM candidate in SUSY (also RH-sneutrino)
- Despite very weak interactions – can be produced from gaugino scattering - included in SuperISO
- Can also be produced from decay of NLSP – relic density related to that of NLSP - all codes
- LHC can put constraints on reheating temperature
  – Arbey et al, 1505.04595



Beyond ΛCDM

- Modify parameters of cosmological model (expansion rate, entropy content, non-thermal DM production, effective numbers of ν) – in SuperISO

$$H^2 = \frac{8\pi G}{3}(\rho_{rad} + \rho_D) \ .$$

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

$$\frac{ds}{dt} = -3Hs + \Sigma_D$$

- Impact DM relic density, can match relic density with almost any susy model
  - Gelmini,Gondolo, hep-ph/0602230; Arbey, Mahmoudi, 0906.0368
- Can affect light element abundance, codes to compute light element abundance:
  - PArthENoPE, O. Pisanti et al, 0705.0290
  - AlterBBN, A. Arbey, 1106.1363
- In general : constraints from cosmology on DM – not considered in DM tools so far

Conclusion

- *To understand the nature of* dark matter *clearly need information and cross checks from cosmology, direct and indirect detection as well as from collider physics*
- *Several tools are available for this purpose – just waiting for a confirmed signal!!*