WIMP or non-WIMP?
Thermal DM or non-thermal DM?
The questions to ask
BEFORE global analysis.

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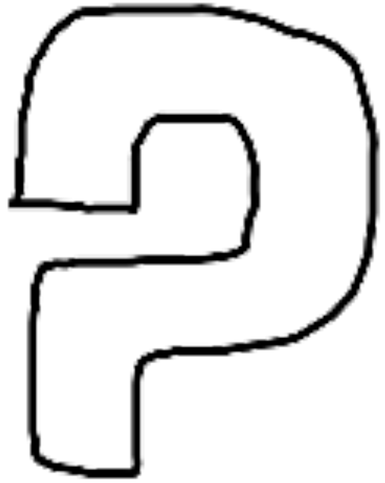
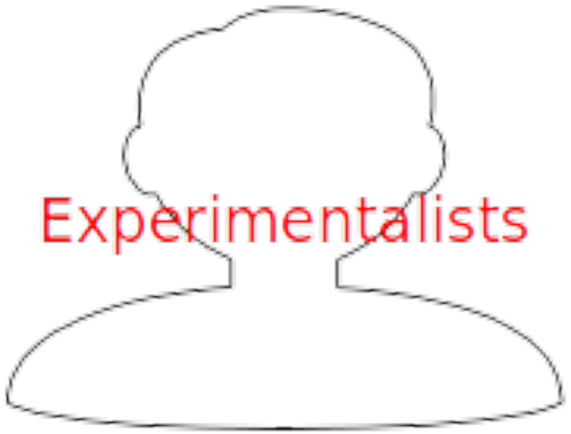
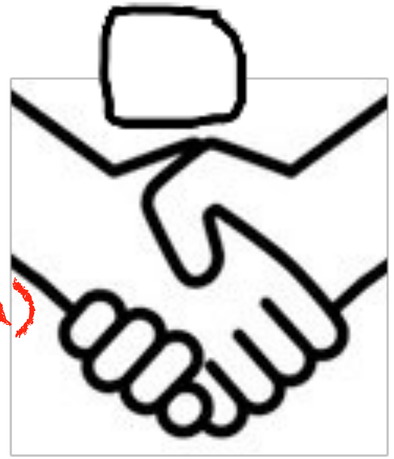
DM-Stat: Statistical Challenges in the Search for Dark Matter





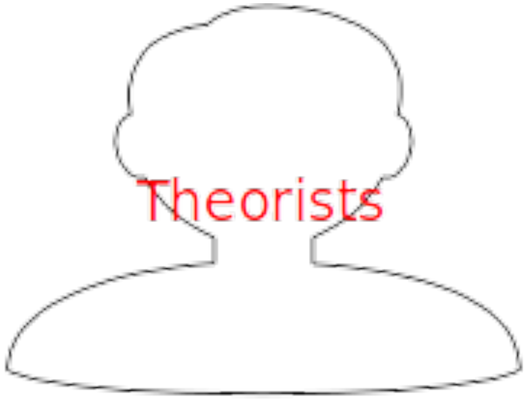
Priority:

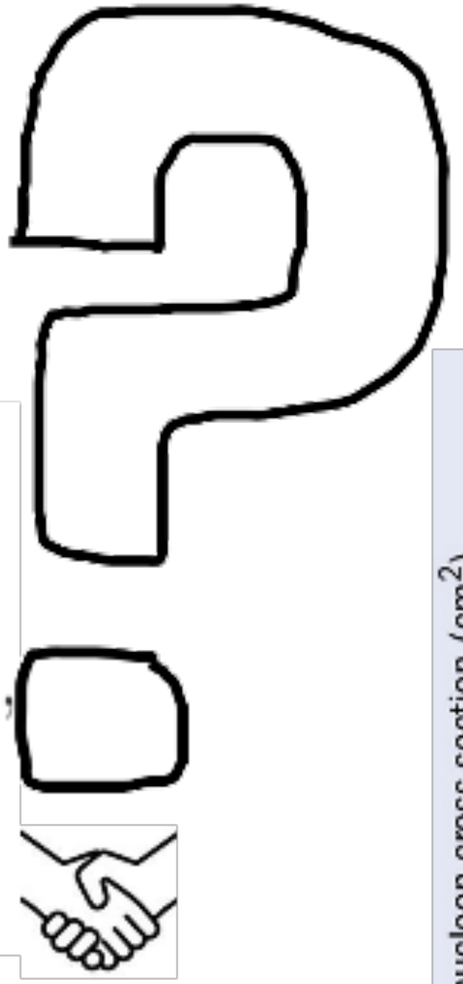
1. Known physics
2. Unknown physics (motivation)
3. Publication
4. Statistics



Priority:

1. Hardware
2. Software
3. Statistics=Known physics
4. Publication
5. Unknown physics

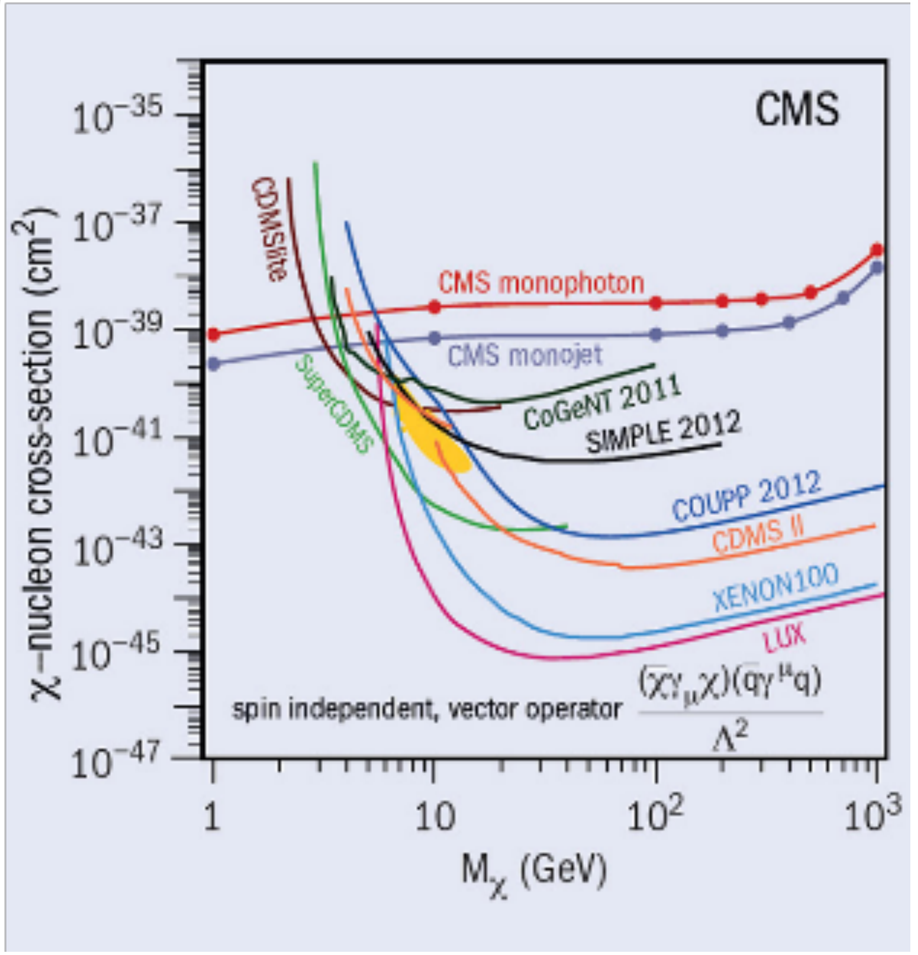


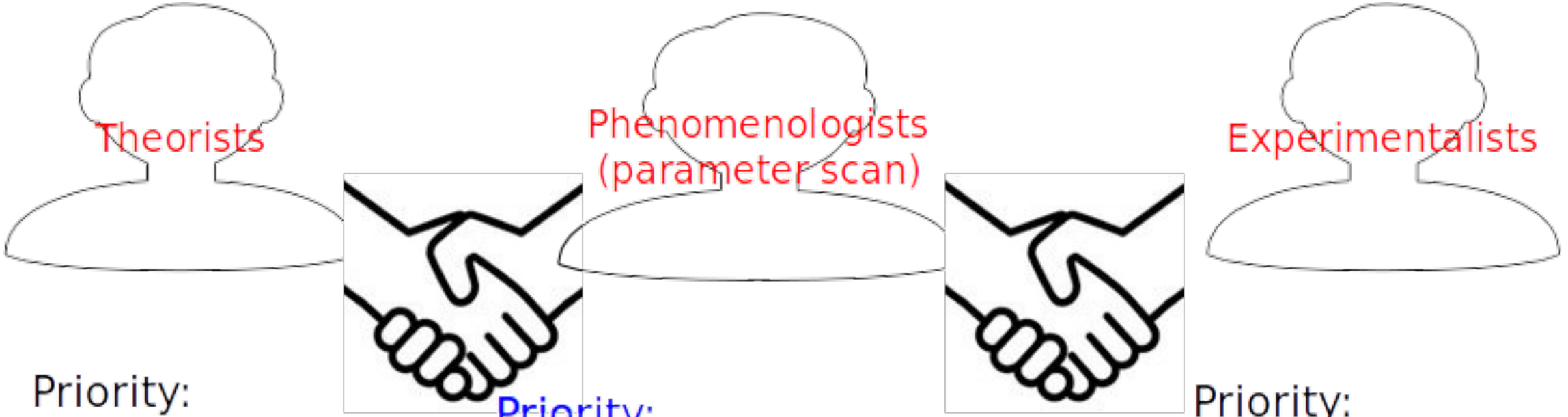


$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \,,$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \text{h.c.}\,.$$





Priority:

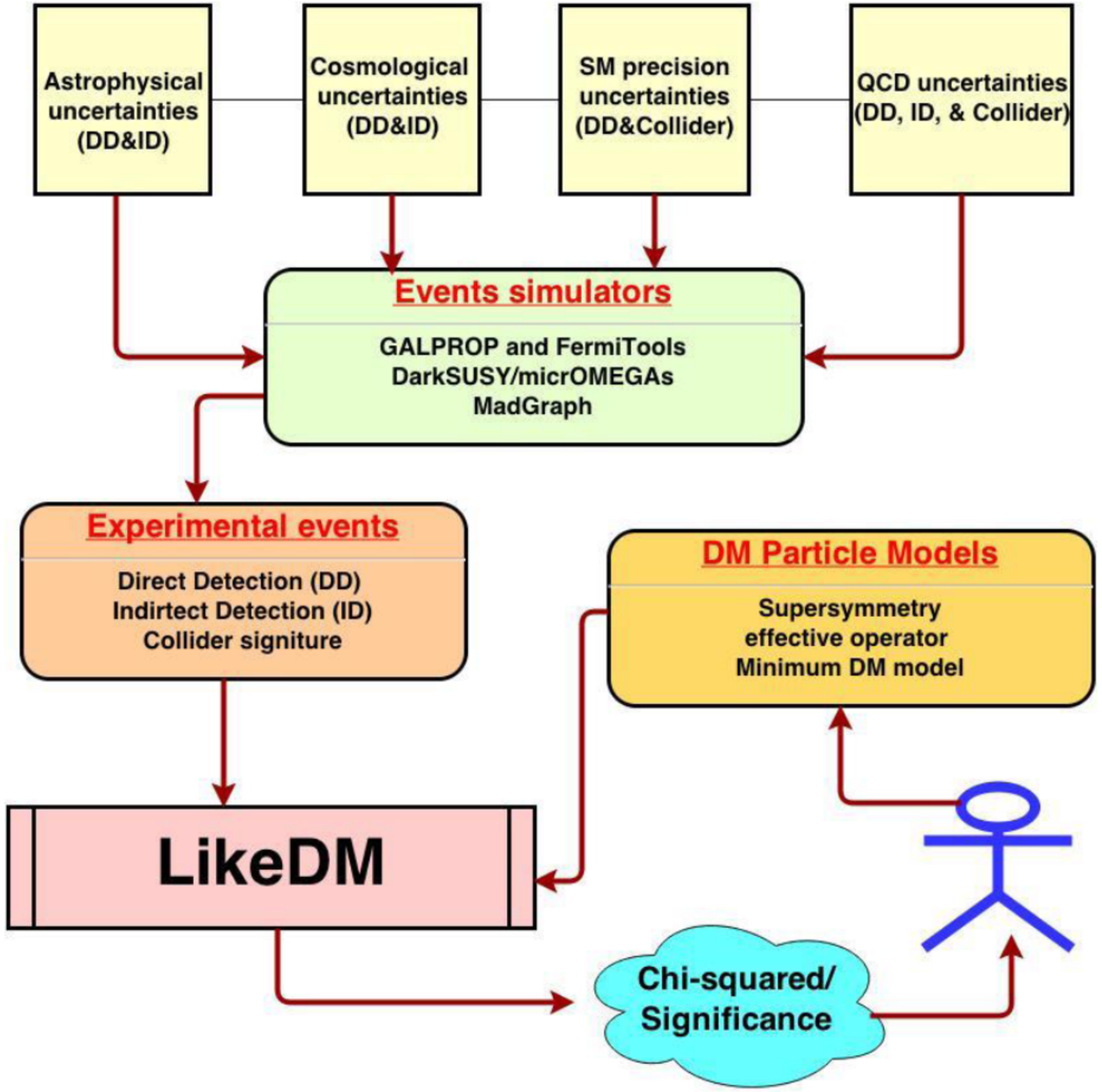
1. Known physics
2. Unknown physics
3. Publication
4. Statistics

Priority:

1. Known physics
2. Unknown physics
3. Statistics=Software=Hardware
4. Publication

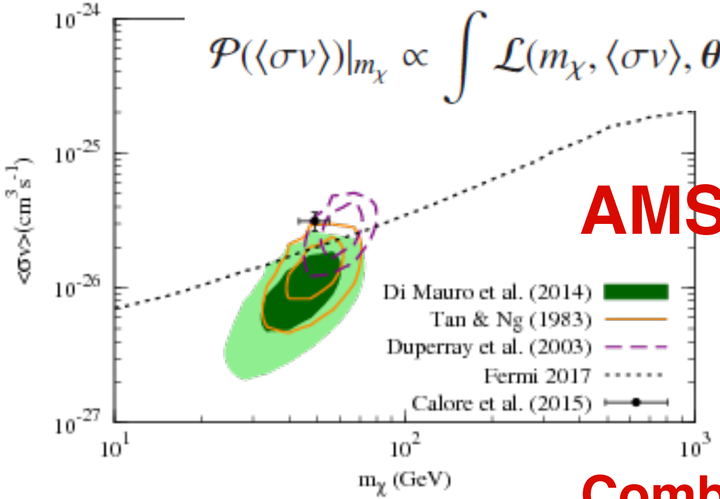
Priority:

1. Hardware
2. Software
3. Statistics=Known physics
4. Publication
5. Unknown physics



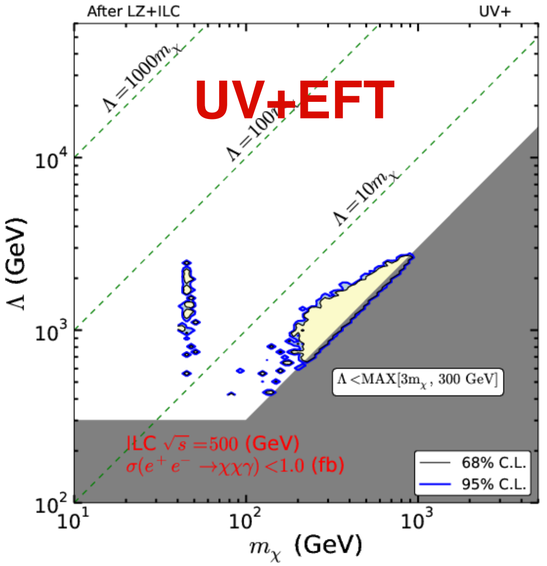
【Purpose】 Fast, conservative, but model independent likelihood!

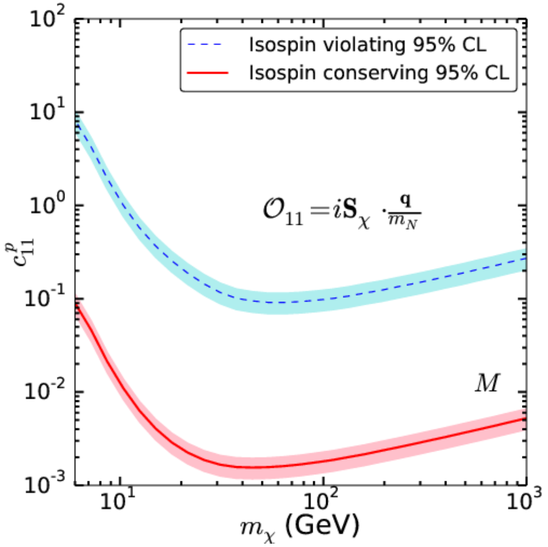
$$\mathcal{P}(\langle\sigma v\rangle)|_{m_\chi} \propto \int \mathcal{L}(m_\chi, \langle\sigma v\rangle, \theta_{\rm bkg}, \kappa)\, p(\theta_{\rm bkg})\, p(\kappa)\, {\rm d}\theta_{\rm bkg}\, {\rm d}\kappa,$$

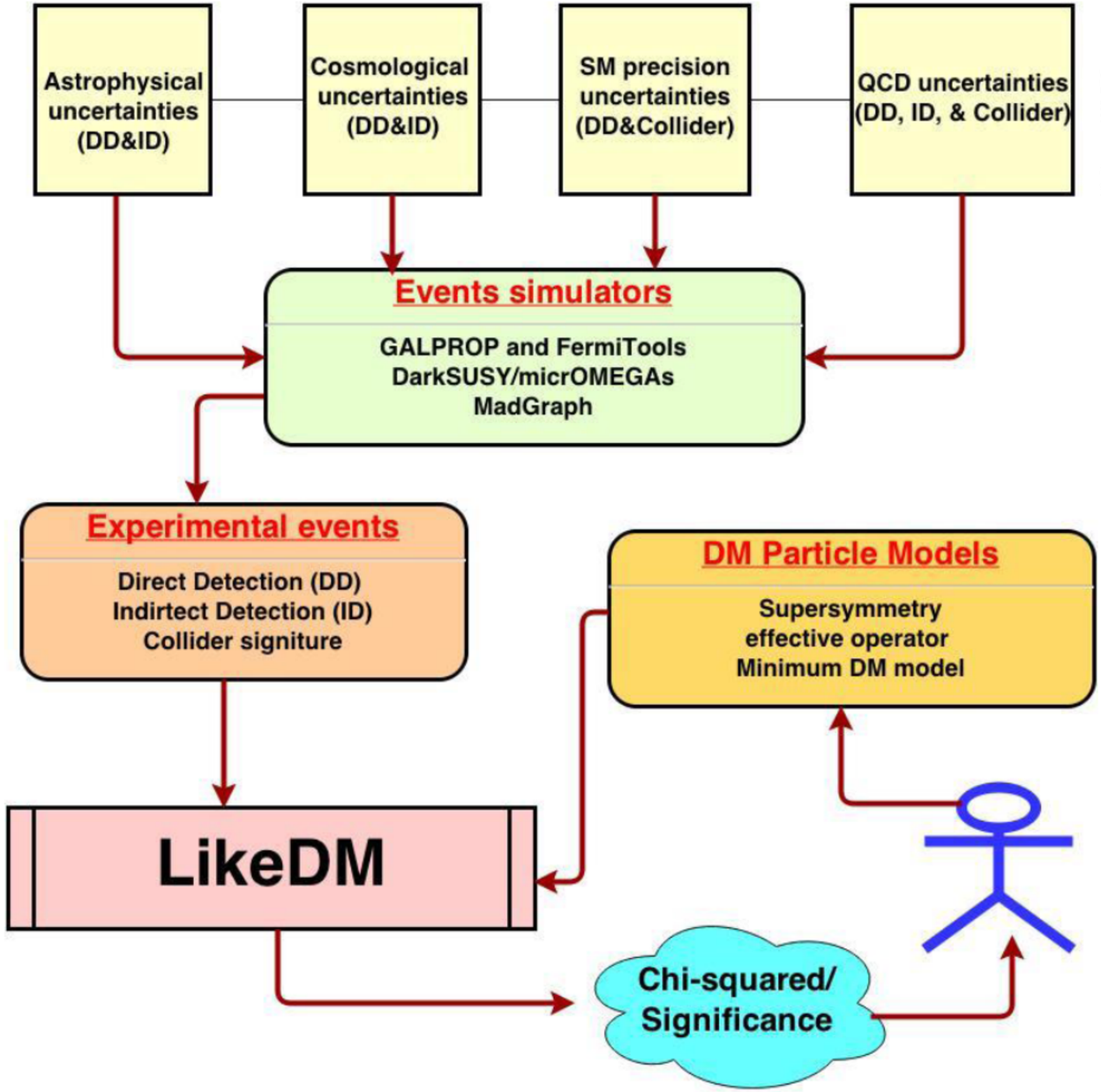


AMS02 antiproton

Combined DD likelihood







【Purpose】 Fast, conservative, but model independent likelihood!

【Future plan】

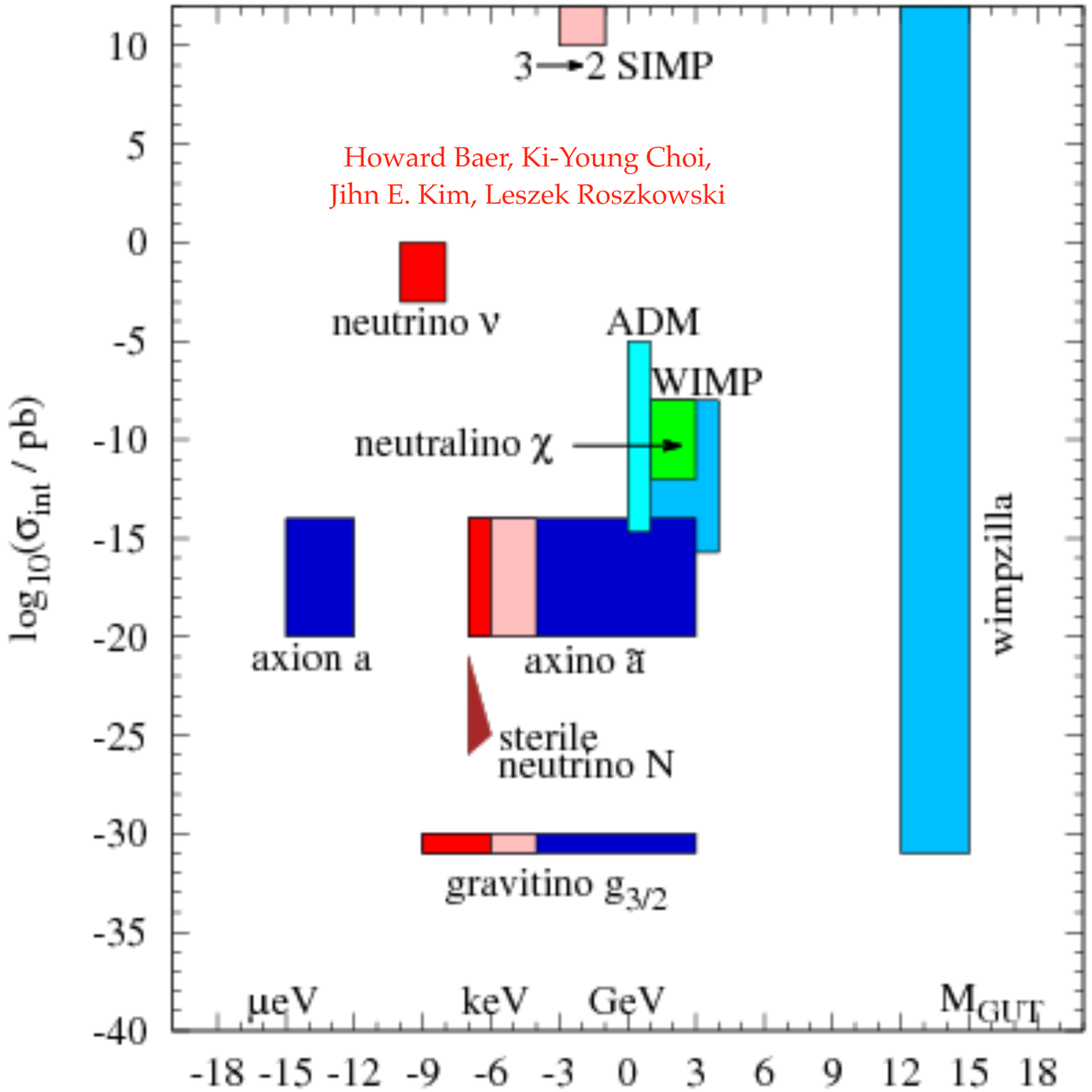
What can we improve with machine learning?

[1] Fast -> Even fast

[2] Conservative -> optimistic

[3] Model independent -> Model dependent (?)

There are so many DM models located at different mass scales.

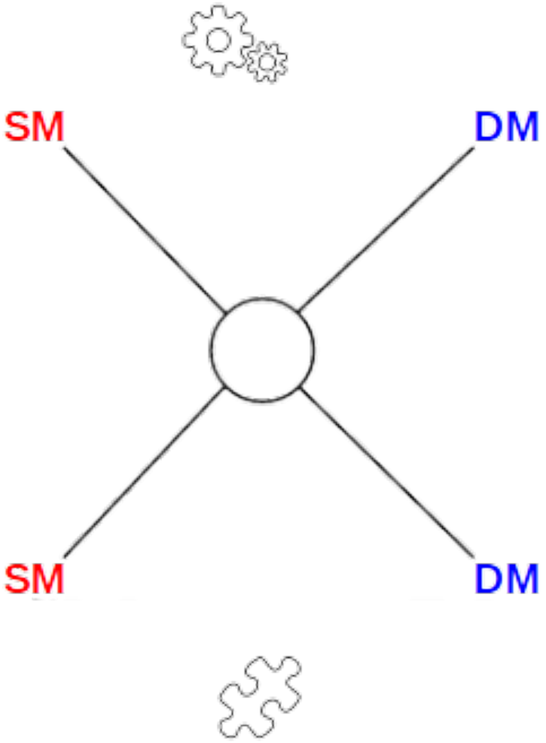


A few particle dark matter theories:

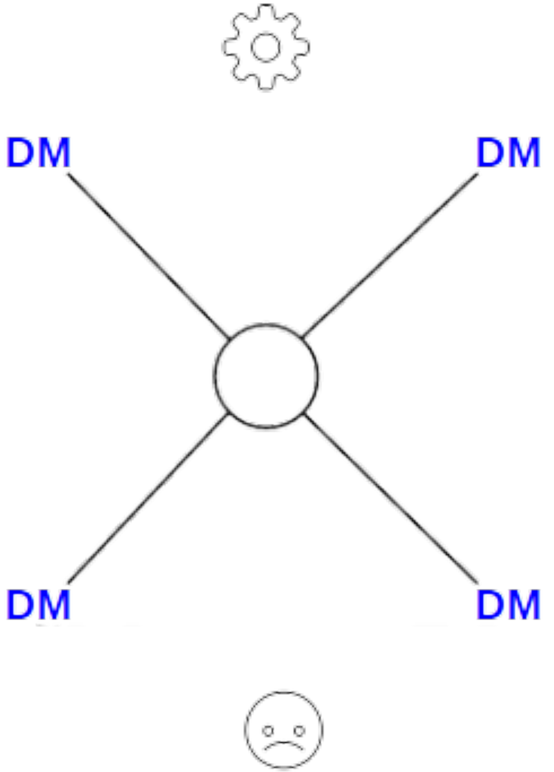
- axion
- sterile neutrino
- SUSY DM
  - neutralino in MSSM
  - Bino/Wino/Higgsino/Photino
  - sneutrino
  - gravitino
  - decaying gravitino
  - gravitino with large messenger mass
  - split SUSY DM
  - bound states for Sommerfeld enhancement
  - bino in E_6SSMwith massless inert singlets
  - neutralino from axion decay
  - NMSSM DM
  - mixed axion/neutralino
  - invisible photino
  - etc., etc. etc.
- Kaluza-Klein DM
- leptophilic DM
- leptophilic from non-abelian discrete symmetry
- asymmetric DM
- scalar singlet DM
- superGUT unified
- mirror DM
- non-thermal from decay of moduli
- resonance with momentum dependence
- helicity modification due to QED corrections
- dipole moment interacting DM
- dark instanton
- bosonic gas DM
- anti-baryonic
- ultra-light bosonic DM
- invisible photino
- T13 flavor symmetry decaying DM
- hydrodynamic vacuum DM
- dilatation anomaly DM
- bulk viscous unified DM
- ELKO field DM
- two singlet DM
- cosmic braneworld ultra-light DM
- superheavy quark clusters
- luxino
- non-canonical kinetic term DM
- branes filled with scalar fields
- real gauge singlet
- Higgs portal
- number theory DM
- asymmetric sneutrino
- modified Ricci model DM
- vacuum solitons
- complex singlet scalar
- D4 x Z2 flavor group DM
- non-minimal KK DM
- axion portal cascade
- light (MeV mass) DM
- two singlet DM
- self-interacting DM
- isospin violating DM
- inert Higgs
- skyrmion in littlest Higgs model
- techni-dilaton DM
- type-II seesaw mSUGRA DM
- vector DM
- goldsini
- WIMPless DM
- inert triplet DM
- vacuum solitons
- BEC from U(1) symmetry breaking
- eXciting DM (XDM)
- inelastic DM (iDM)
- flavor SU(3)Q triplet/singlet
- isospin violating
- axion-like repulsive DM
- D6 flavor symmetry
- warped Radion
- G2-MSSM
- gauged right-handed neutrino
- integration constant Horava DM
- tensor-four-scalar
- scalarons in R2 gravity
- secluded DM
- etc., etc., etc., etc., etc.

Taken from Griest (2014).

The strategy of DM hunting



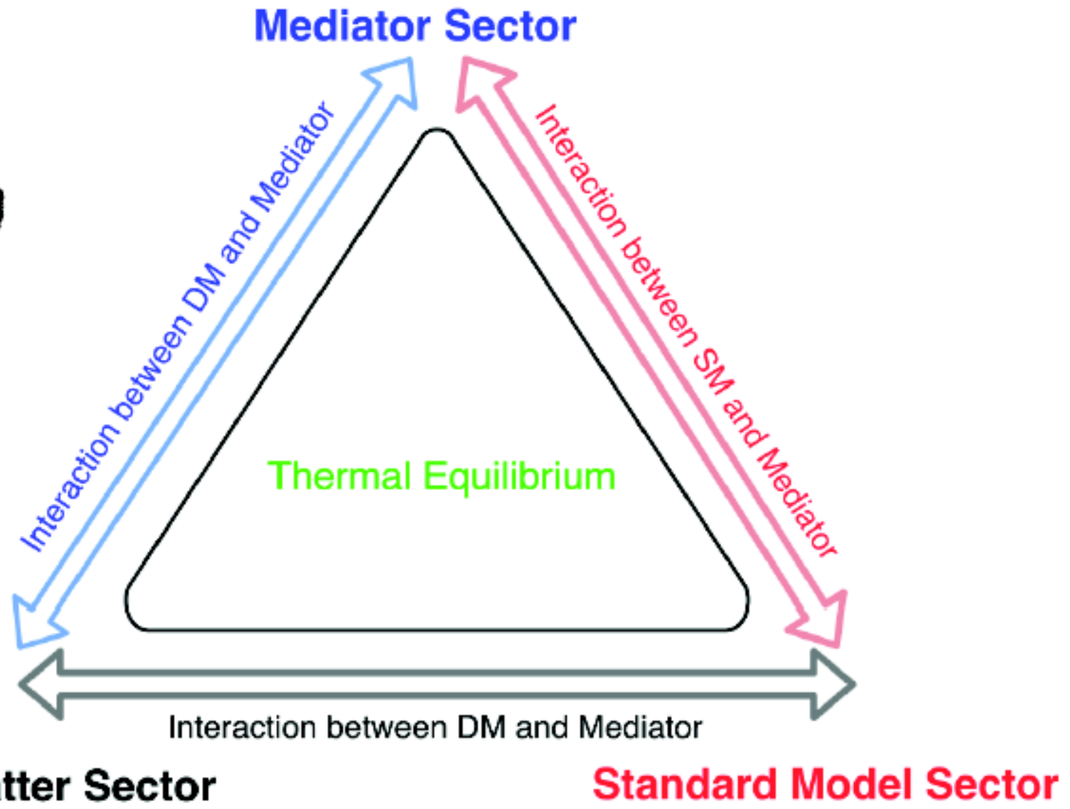
- SM SM > DM DM.
  Measurement of the missing energy at the colliders
- SM DM > SM DM.
  Measurement of the recoil energy of SM particles.
- DM DM > SM SM
  Measurement of the flux of cosmic ray.
- DM DM > DM DM.
  Astrophysical structure



- Dark Matter is EXPECTED to have weak interaction between SM and DM but it is not necessary to be.
- However, without weak interaction between DM and SM, method 1-3 are useless.
- WIMPs search in this era is very important but it is also time to be prepared for non-WIMP.

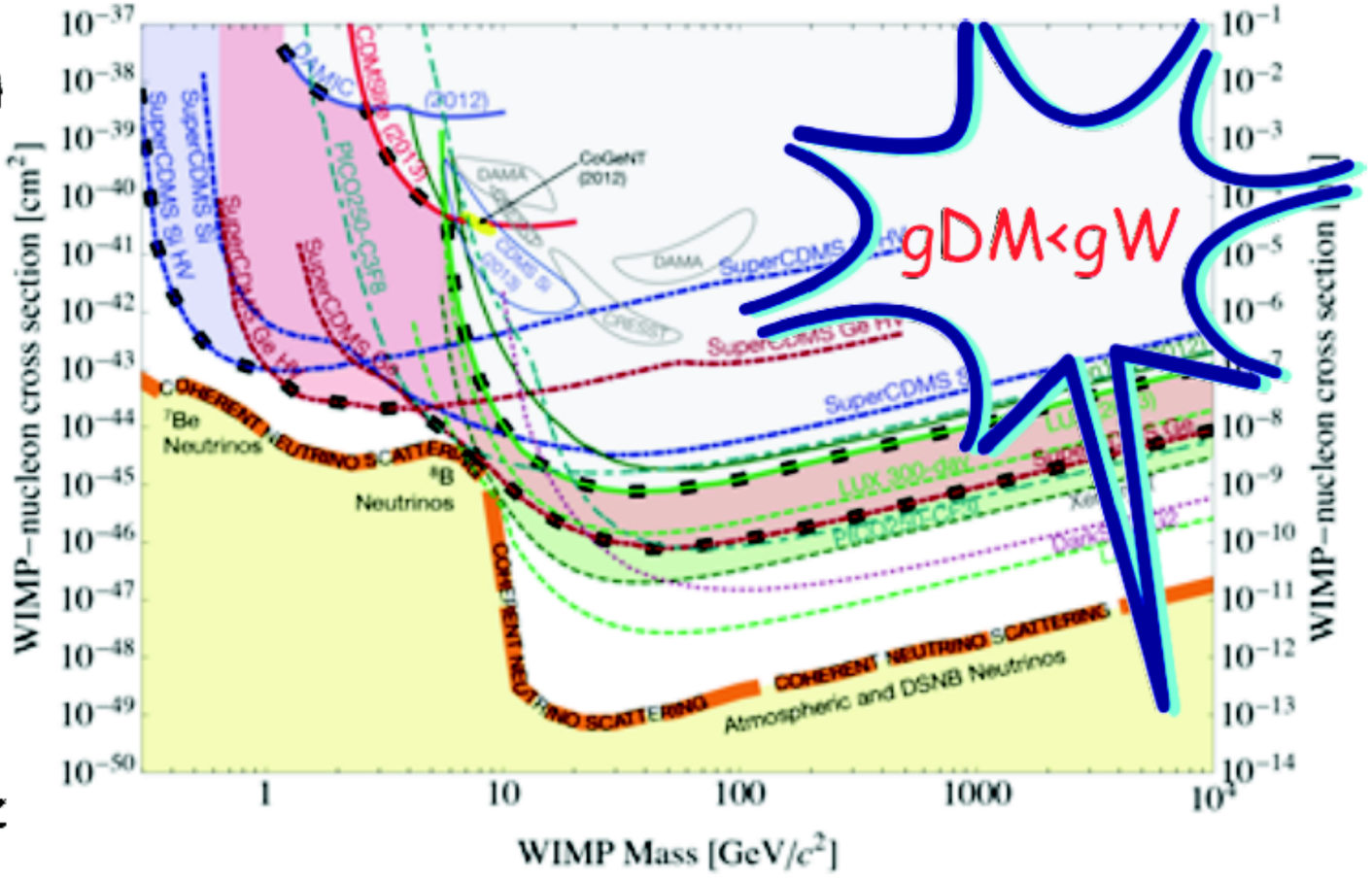
The belief of the WIMP "Miracle"

- Belief 1: DM cannot strongly couple to SM atoms, otherwise we should see it already.
- Belief 2: The early universe was at very high temperature and thermal equilibrium.
- If the DM has no interaction with SM particles, HOW does the momentum exchange or temperature transfer to maintain thermal equilibrium in the early universe?



The belief of the WIMP "Miracle"

- If the DM has weak coupling to interact with SM, the relic density requires the DM mass scale ~O(100 GeV)!
  --- Miracle claimed by Jonathan Feng
- The DM direct detection is approaching the corner.
- We can try to produce DM at the colliders.



Not WIMP?

- Strongly or super weakly interacting?
- DM could be detected already or still hidden.
- Non-WIMP is hard to be detected (in colliders and DD) without cosmological or astrophysical manners.
- Huge data from cosmology and astrophysics but totally unknown systematic uncertainties.

Is it thermal DM?

- Relic density likelihood gives the Map of DM search.
- If not thermal DM, what is the assumptions? Could we just go to next to minimum setup or next-to-next minimum?
- Based on such assumptions, can one find other powerful likelihoods like relic density?
- How to modify DM likelihoods?

Challenges

Experimental side:

- Too weak couplings.
- Larger exposure, Higher/Lower energy.
- Model complexity and popularity.
- Background systematics.
- Required knowledge more than DM.

Theoretical side:

- Motivations.
- Too many scenarios (relic).
- EFT almost gone.
- Model independent approach.
- Cross-field study of particle and astrophysical theory.

Global fitting:

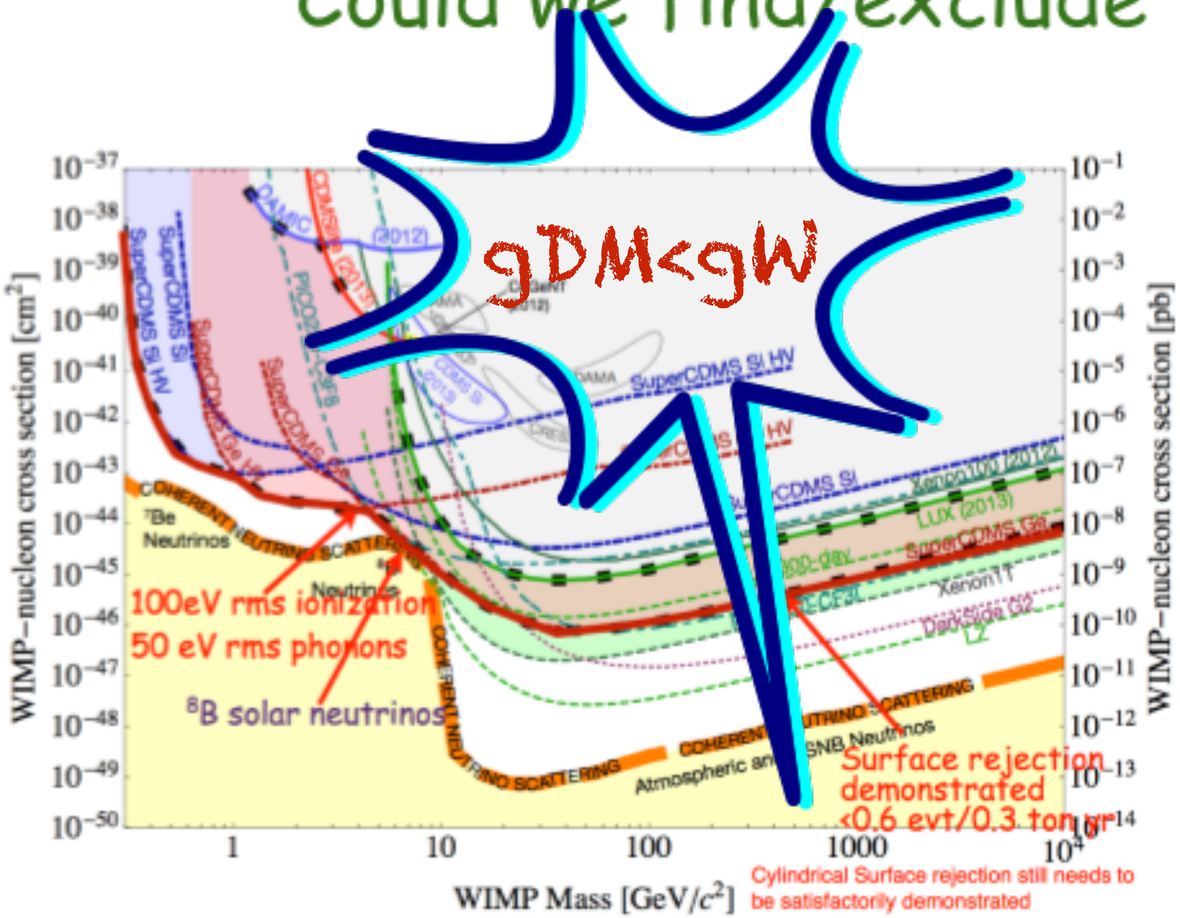
- Precision and conservative estimation.
- Fast likelihood computation.
- Model comparison (statistics).
- Fair adjoin analysis (weight?).
- Machine learning seems to be tricky to be used.

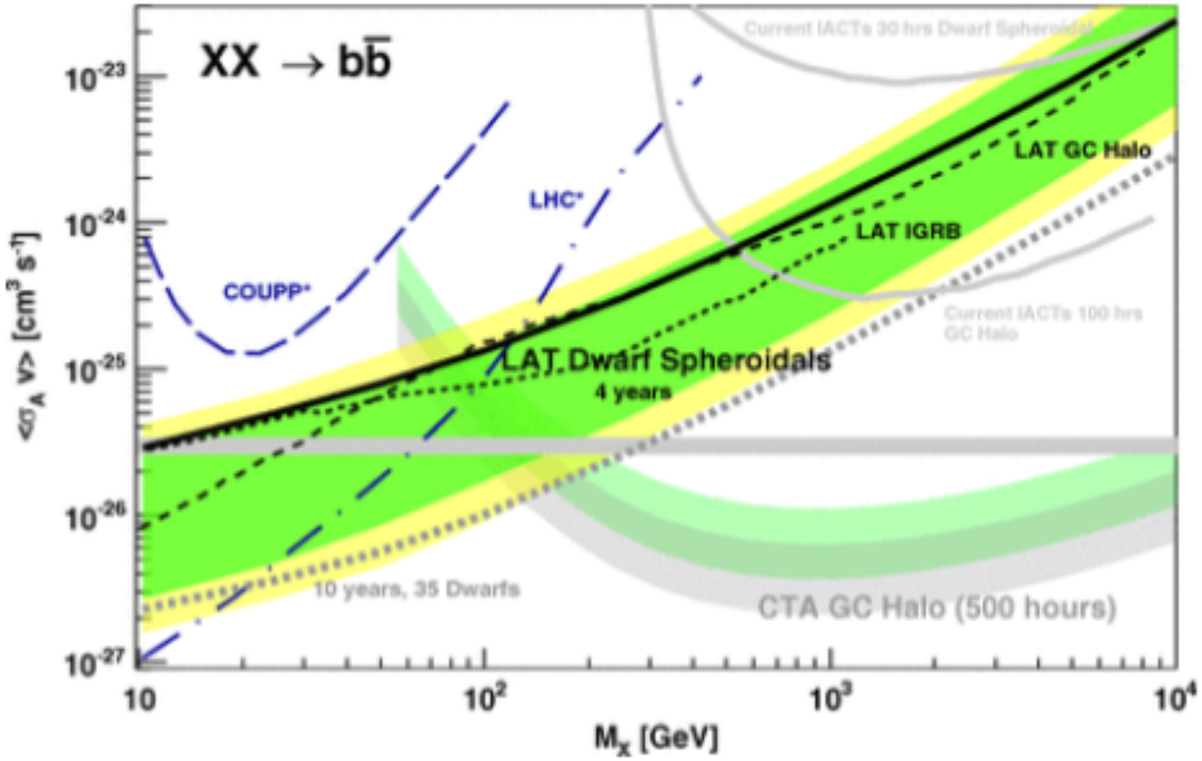
What is the next well-motivated DM scenario we should focus on?

Thank you!

Summary

Could we find/exclude WIMP DM in 20 years?

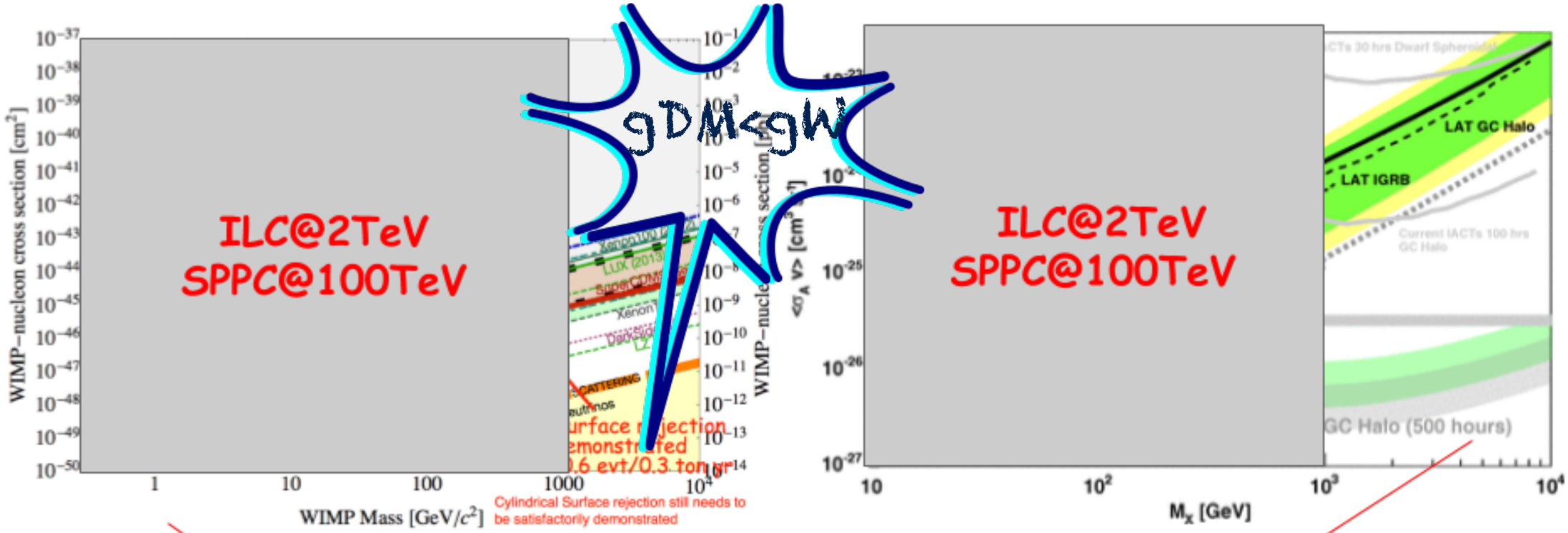




The most popular model is WIMPs but
it seems to be killed soon.
The DM underground detector plays unexpectedly well!

Summary

Could we find/exclude WIMP DM in 20~30 years?



Too low coupling -> WIMPless
Non-thermal relic density scenario

Too low coupling
Too heavy mass
-> Composite DM

Huo, Matsumoto, Tsai, Yanagida,
Published in JHEP 1609 (2016) 162