

Astroparticle tests of dark matter theories

Pat Scott

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Slides at: tinyurl.com/patsscott

The astroparticle dark matter degustation menu:

- Direct detection
- Indirect detection
 - γ rays
 - charged cosmic rays
 - CMB
 - neutrinos
 - X-rays
 - radio
- Cosmological abundance / relic density
- Big Bang Nucleosynthesis (BBN)
- Dark matter in stars
- Gravitational probes
 - N-body simulation
 - substructure
- Complementarity

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The astroparticle dark matter degustation menu:

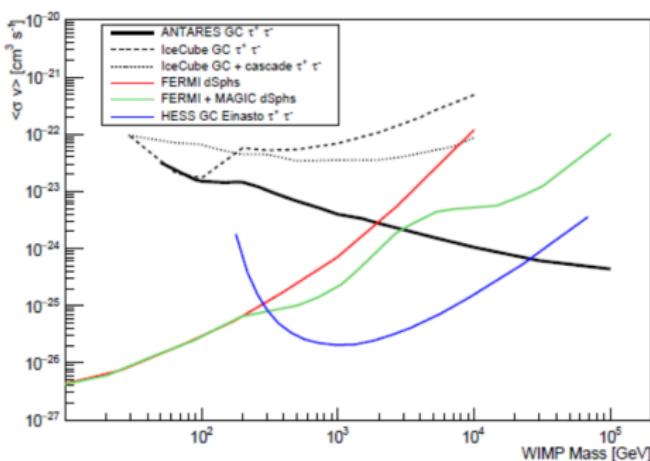
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Annihilation in the Galactic Centre

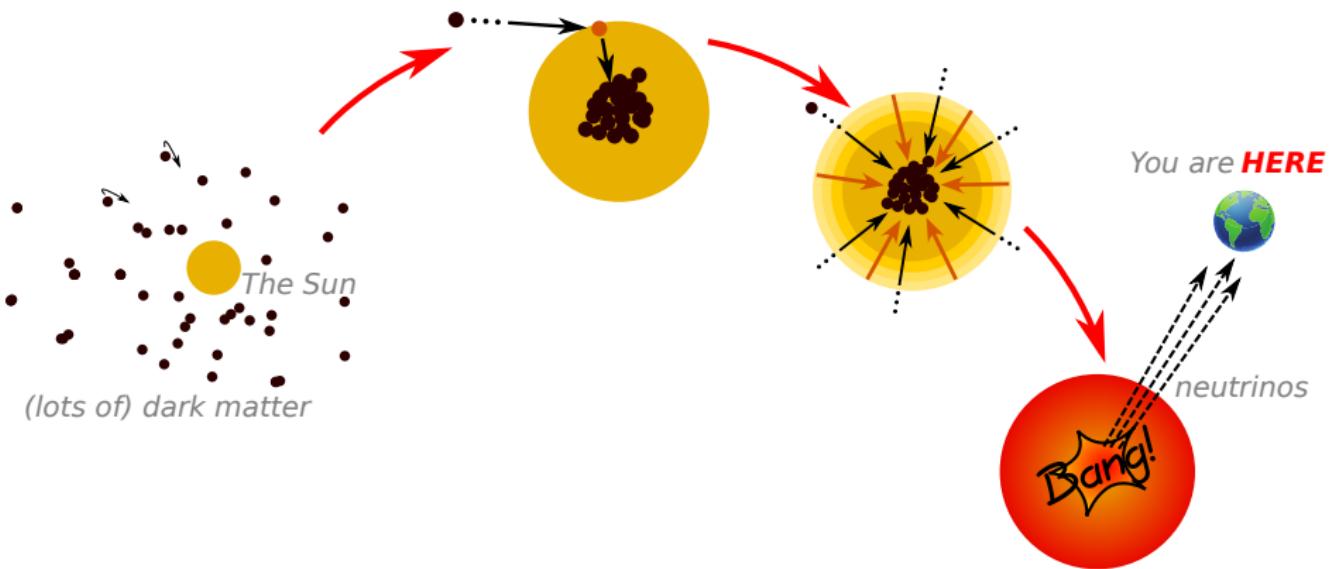


Annarita Margiotta (Mon parallel)

- ANTARES has leading sensitivity for GC search at high mass
- due to better location + angular resolution than IceCube

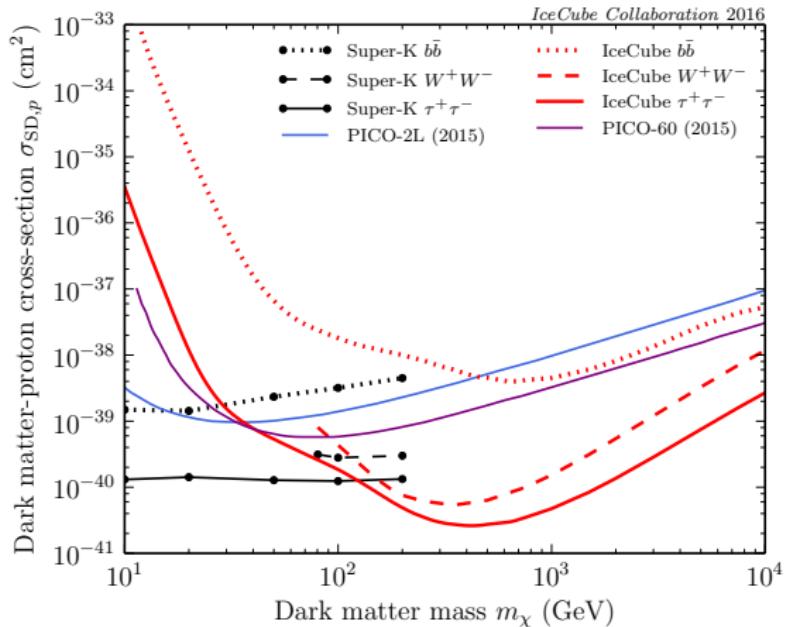
Dark matter in the Sun

Indirect detection



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79-string IceCube re-analysis (latest published limits)



Available at
nulike.hepforge.org

IceCube Collab. (contacts: PS + M. Danninger) arXiv:1601.00653, JCAP 2016

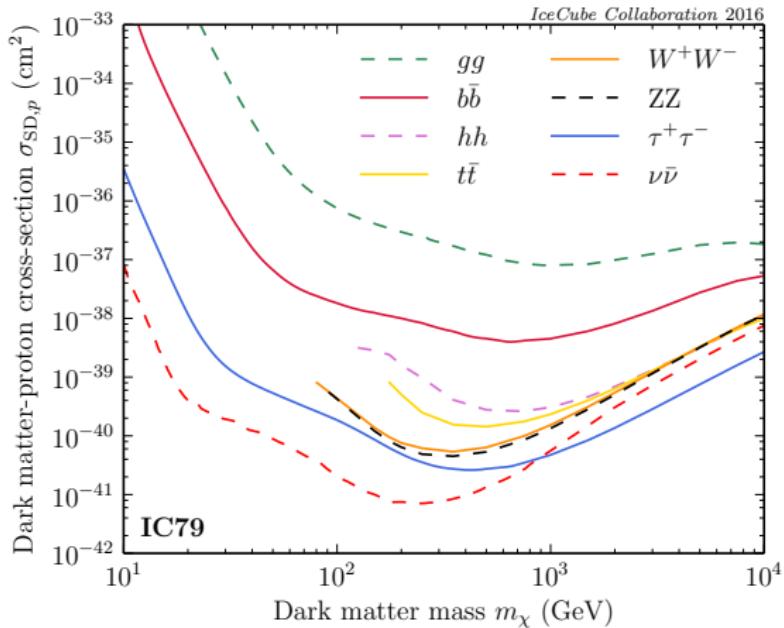
nulike: model-independent unbinned limit calculator for generic BSM models

Data + detector response release:

icecube.wisc.edu/science/data/ic79-solar-wimp

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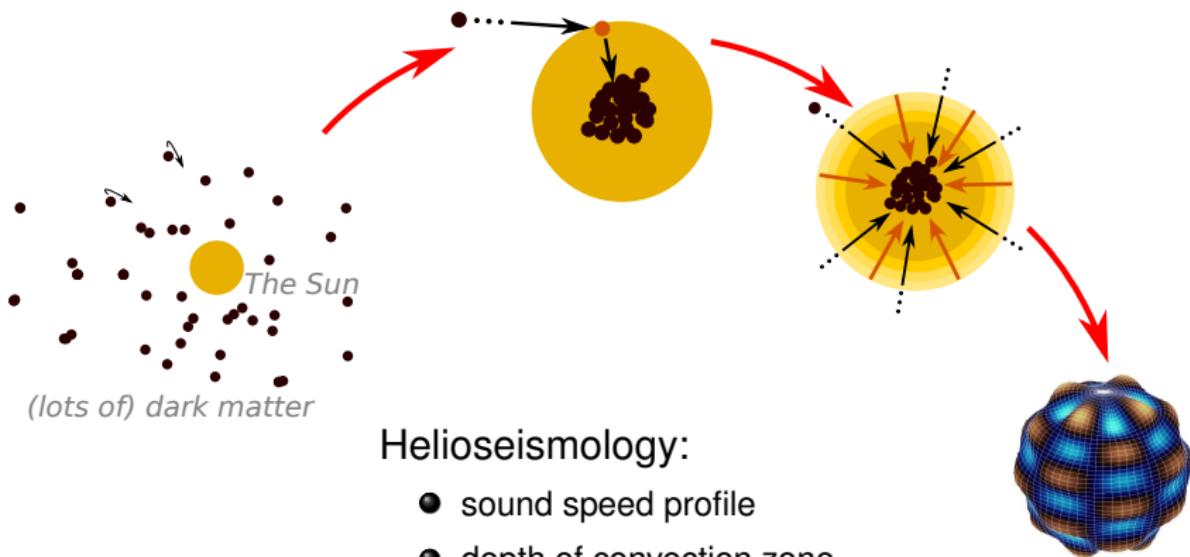
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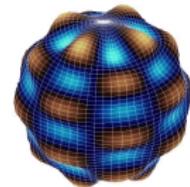
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Heat conduction

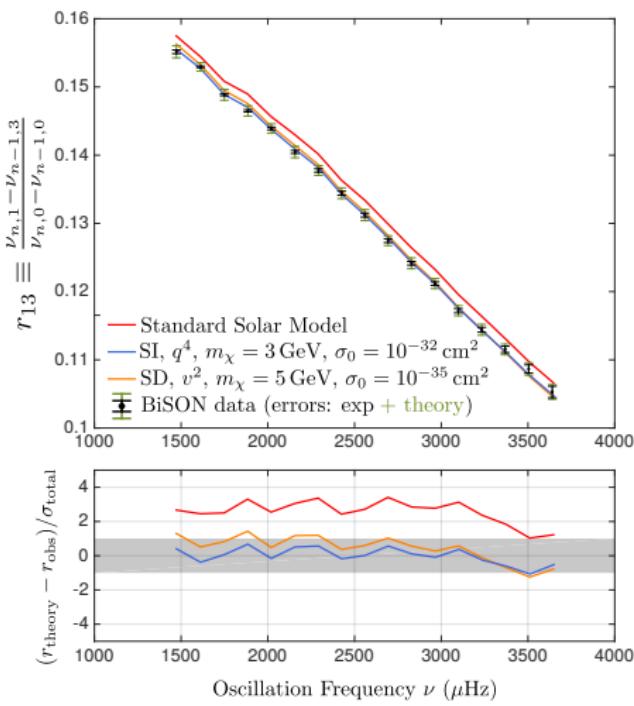


Helioseismology:

- sound speed profile
- depth of convection zone
- frequency separations
- solar neutrinos
- solar abundances



Dark matter and the solar abundance problem



Vincent & PS, *JCAP* (2014) arXiv:1311.2074

Vincent, PS & Serenelli, *PRL* (2015) arXiv:1411.6626

Vincent, Serenelli & PS *JCAP* (2015) arXiv:1504.04378

Vincent, PS & Serenelli, *JCAP* (2016) arXiv:1605.06502

Geytenbeek et al., arXiv:1610.06737

Solar photospheric abundances factor of ~ 2 less than inferred from helioseismology

(Asplund, Grevesse, Sauval & PS, 'AGSS09')

Many solutions attempted

None really successful.

➡ DM conduction?

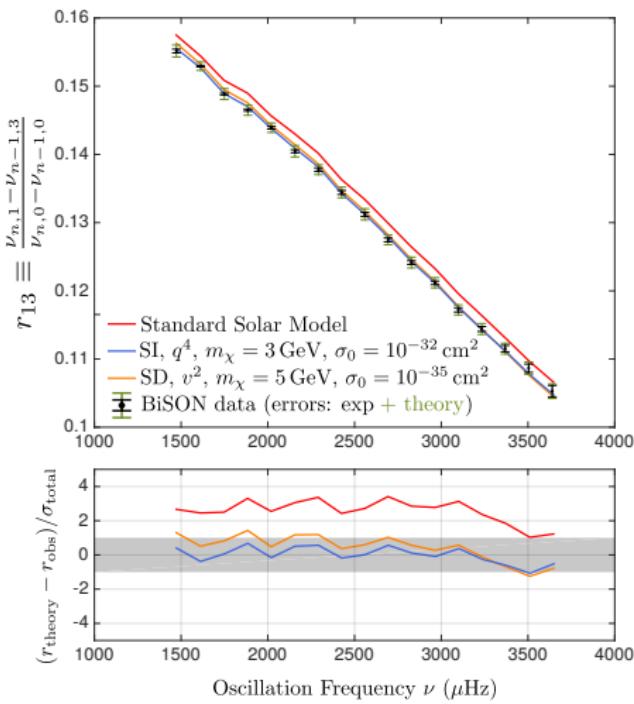
... spin-(in)dependent (SI/SD) interactions no good, but

$\sigma \propto q^n$, $\sigma \propto v^n$ can give serious improvements

$$\chi^2_{\text{red}} = 7.3 \rightarrow 2.3$$

(direct detection bound OK)

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Evaporation is an issue at low masses

Only recently calculated for these models

→ Giogio Busoni's talk
(Tues parallel)

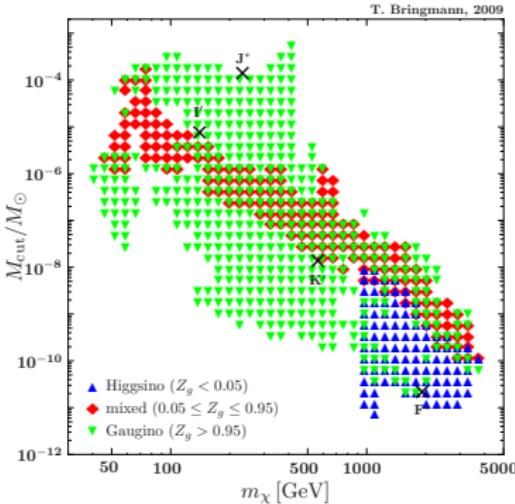
These limits apply to *asymmetric* models of DM
⇒ ~ no annihilation

Compact stars also give strong limits, especially for *bosonic* asymmetric DM
⇒ collapse to black holes (see Petraki & Volkas *IJMPA* 2013, Zurek *Phys. Rept.* 2013)

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Kinetic decoupling and small-scale structure

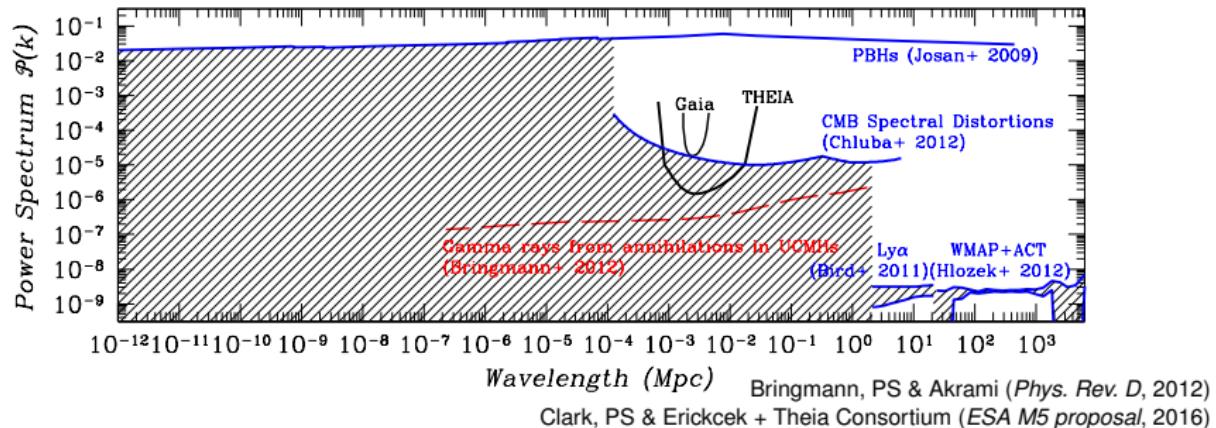
- Particle production and abundance is **chemical freeze-out**
- Particle velocities and final DM temperature are determined by **kinetic freeze-out**
- Kinetic decoupling temperature → kinetic decoupling scale → minimum DM halo mass
- Impacts boost factors for indirect detection ($\Phi \propto \rho^2$)
- Kinetic decoupling is very very model-dependent → subhalo cutoff tells us about the model



Curvature perturbation limits from substructure

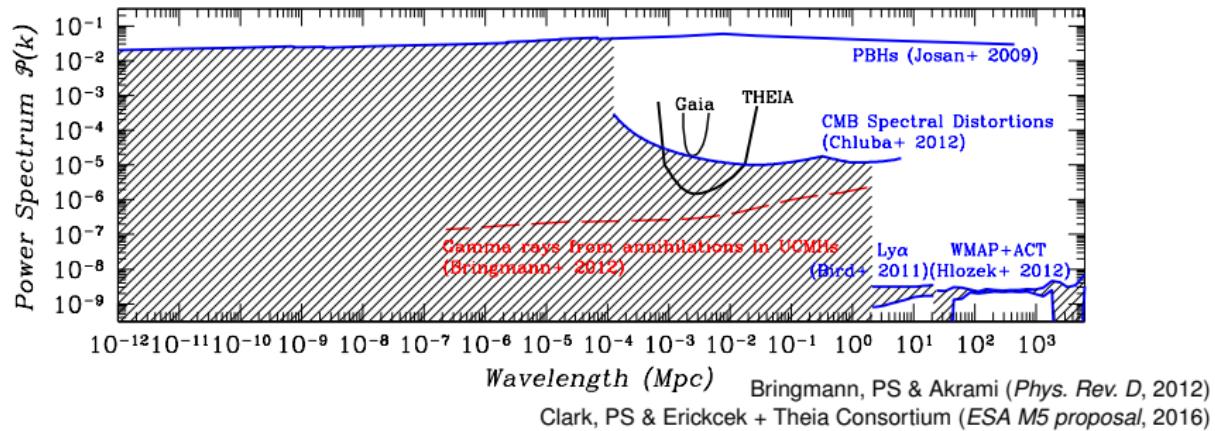
Limits on primordial spectrum $\mathcal{P}(k)$ from densest substructure \sim 5 orders better than from PBHs

⇒ strong limits on inflationary models (Aslanyan et al. *PRL* 2016)



Curvature perturbation limits from substructure

Limits on primordial spectrum $\mathcal{P}(k)$ from densest substructure ~ 5 orders better than from PBHs
⇒ strong limits on inflationary models (Aslanyan et al. *PRL* 2016)



Limits also possible from pulsar timing
⇒ interesting for SKA (Clark, Lewis, PS, *MNRAS* 2015a,b)

Impacts interpretation of *Fermi* Galactic Centre gamma-ray excess, AMS \bar{p} → Hamish Clark, Martin Stref (Mon parallels)
as well as results of N-body sims → Nick Iwanus (Mon parallel)

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ege

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ege

Global fits for dark matter and new physics

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS
LHCb
Belle-II
Fermi-LAT
CTA
HESS
IceCube
XENON/DARWIN
Theory

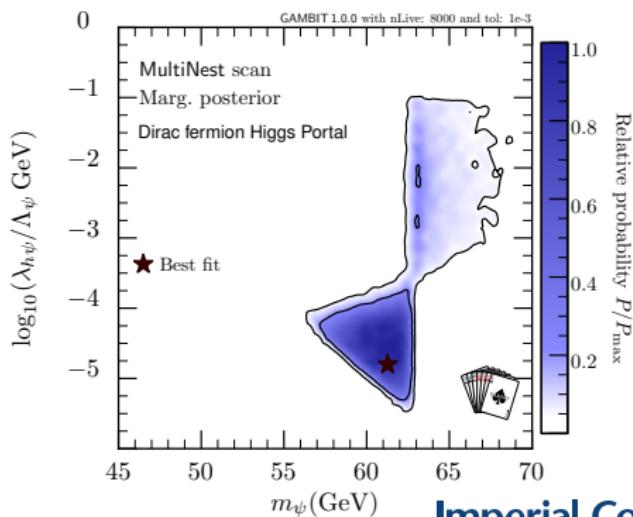
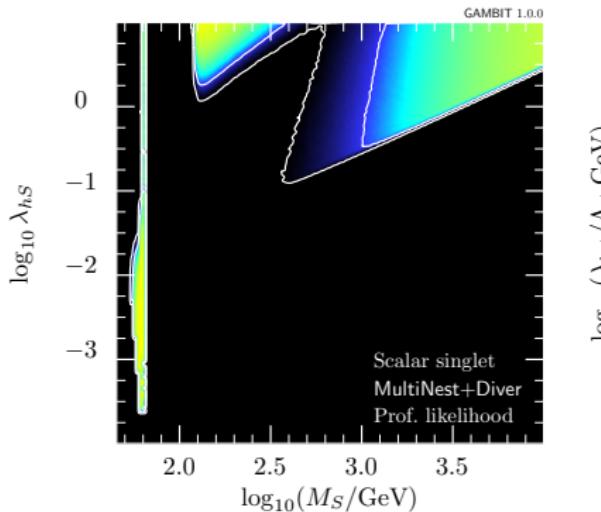
A. Buckley, P. Jackson, C. Rogan, M. White,
M. Chrzaszcz, N. Serra
F. Bernlochner, P. Jackson
J. Conrad, J. Edsjö, G. Martinez, P. Scott
C. Balázs, T. Bringmann, J. Conrad, M. White
J. Conrad
J. Edsjö, P. Scott
J. Conrad, R. Trotta
P. Athron, C. Balázs, T. Bringmann,
J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, A. Fowlie,
J. Harz, S. Hoof, F. Kahlhoefer, A. Krislock,
A. Kvellestad, M. Pato, F.N. Mahmoudi, J. McKay,
A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger,
M. White, S. Wild



31 Members, 9 Experiments, 4 major theory codes, 11 **Imperial College London**

GAMBIT in a nutshell

- You tell GAMBIT what you want to calculate
- It delivers, by automagically identifying and stitching together all necessary model, observable, likelihood and external calculations
- Public release + 9 papers in Jan/Feb (MSSM + Higgs portal DM version)
- More info: SlfA seminar @2pm today



James McKay, Ankit Beniwal (Tues DM parallel)

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Summary: the menu again

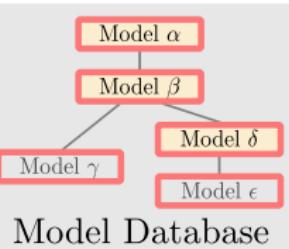
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- Dark matter in stars → [Busoni]
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 - N-body simulation → [Iwanus, Gamaldi]
 - substructure → [Clarke, Iwanus]
- Complementarity → [McKay, Beniwal, SIfa@2pm]

Backup slides

Functional overview of GAMBIT

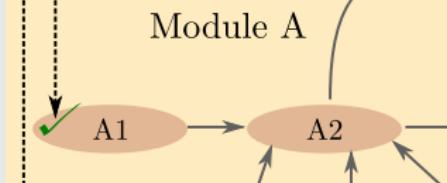
YAML file

User requests scan
of model δ using
1. capability of A2
2. capability of B1



Physics Modules

Module functions
(Feed upwards and horizontally only)



Core

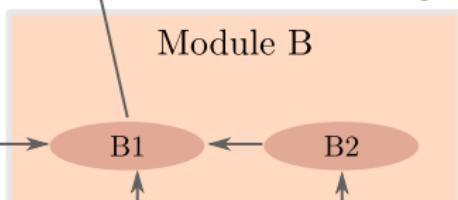
Core runs
1. A1
2. A2
3. B2
4. B1

Printers

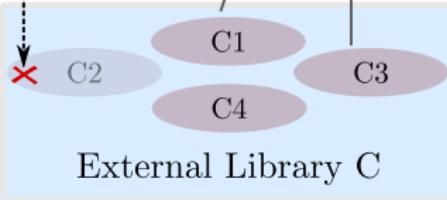
ScannerBit



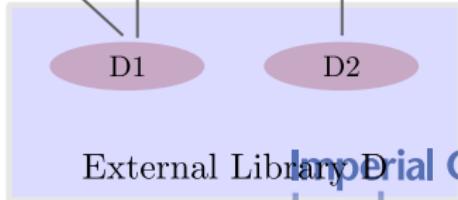
Module B



Backend functions
and variables
(Feed upwards only)



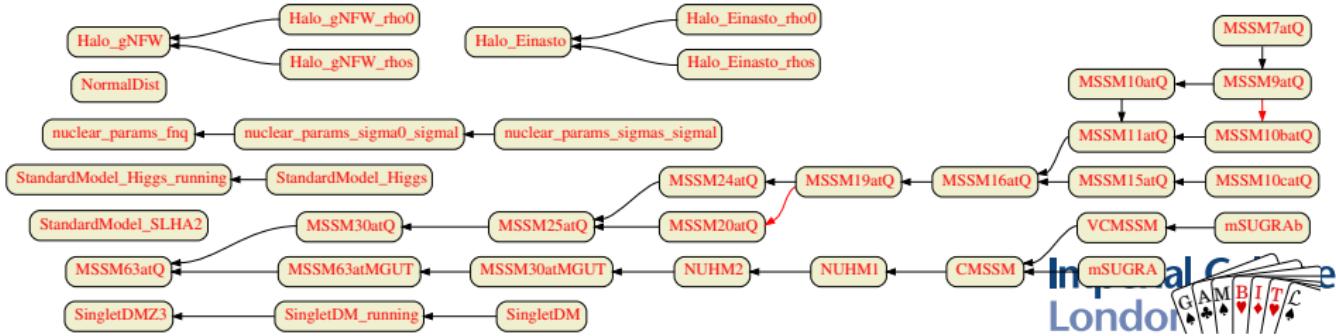
Backends



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Hierarchical Model Database

- Models are defined by their parameters and relations to each other
- Models can inherit from **parent models**
- Points in child models can be **automatically translated** to ancestor models
- **Friend models** also allowed (cross-family translation)
- Model dependence of every function/observable is tracked
⇒ **maximum safety, maximum reuse**



- Module functions can require specific functions from **backends**
- Backends are external code libraries (DarkSUSY, FeynHiggs, etc) that include different functions
- GAMBIT automates and abstracts the interfaces to backends → backend functions are tagged according to **what they calculate**
- → with appropriate module design, **different backends and their functions can be used interchangeably**
- GAMBIT dynamically adapts to use whichever backends are actually present on a user's system (+ provides details of what it decided to do of course)

Backends: mix and match

BACKENDS	VERSION	PATH TO LIB	STATUS	#FUNC	#TYPES	#CTORS
DDCalc0	0.0	Backends/installed/DDCalc/0.0/libDDCalc0.so	OK	62	0	0
DarkSUSY	5.1.1	Backends/installed/DarkSUSY/5.1.1/lib/libdarksusy.so	OK	68	0	0
FastSim	1.0	Backends/installed/fastsim/1.0/lib/libfastsim.so	absent/broken	1	0	0
FeynHiggs	2.11	Backends/installed/FeynHiggs/2.11.2/lib/libFH.so	OK	14	0	0
HiggsBounds	4.2.1	Backends/installed/HiggsBounds/4.2.1/lib/libhiggsbounds.so	OK	10	0	0
HiggsSignals	1.4	Backends/installed/HiggsSignals/1.4.0/lib/libhigssignals.so	OK	11	0	0
LibFarrayTest	1.0	Backends/examples/libFarrayTest.so	OK	9	0	0
LibFirst	1.0	Backends/examples/libfirst.so	OK	8	0	0
	1.1	Backends/examples/libfirst.so	OK	15	0	0
LibFortran	1.0	Backends/examples/libfortran.so	OK	6	0	0
MicrOmegas	3.5.5	Backends/installed/micromegas/3.5.5/MSSM/MSSM/libmicromegas.so	OK	15	0	0
MicrOmegasSingletDM	3.5.5	Backends/installed/micromegas/3.5.5/SingletDM/SingletDM/libmicromegas.so	OK	13	0	0
Pythia	8.186	Backends/installed/Pythia/8.186/lib/libpythia8.so	absent/broken	0	27	105
	8.209	Backends/installed/Pythia/8.209/lib/libpythia8.so	OK	0	28	107
SUSYPOPE	0.2	no path in config/backend_locations.yaml	absent/broken	3	0	0
SUSY_HIT	1.5	Backends/installed/SUSY-HIT/1.5/libsusyhit.so	OK	55	0	0
SuperIso	3.4	Backends/installed/SuperIso/3.4/libsuperiso.so	OK	32	0	0
gamLike	1.0.0	Backends/installed/gamLike/1.0.0/lib/gamLike.so	OK	3	0	0
nulike	1.0.0	Backends/installed/nulike/1.0.0/lib/libnulike.so	OK	4	0	0

Gambit diagnostic backend line 1 (press h for help or q to quit) ▶



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DDCalc0	0.0	Backends/installed/DDCalc/0.0/libDDCalc0.so	OK	62	0	0
DarkSUSY	5.1.1	Backends/installed/DarkSUSY/5.1.1/lib/libdarksusy.so	OK	68	0	0
FastSim	1.0	Backends/installed/fastsim/1.0/lib/libfastsim.so	absent/broken	1	0	0
FeynHiggs	2.11	Backends/installed/FeynHiggs/2.11.2/lib/libFH.so	OK	14	0	0
HiggsBounds	4.2.1	Backends/installed/HiggsBounds/4.2.1/lib/libhiggsbounds.so	OK	10	0	0
HiggsSignals	1.4	Backends/installed/HiggsSignals/1.4.0/lib/libhigssignals.so	OK	11	0	0
LibFarrayTest	1.0	Backends/examples/libFarrayTest.so	OK	9	0	0
LibFirst	1.0	Backends/examples/libfirst.so	OK	8	0	0
	1.1	Backends/examples/libfirst.so	OK	15	0	0
LibFortran	1.0	Backends/examples/libfortran.so	OK	6	0	0
MicrOmegas	3.5.5	Backends/installed/micromegas/3.5.5/MSSM/MSSM/libmicromegas.so	OK	15	0	0
MicrOmegasSingletDM	3.5.5	Backends/installed/micromegas/3.5.5/SingletDM/SingletDM/libmicromegas.so	OK	13	0	0
Pythia	8.186	Backends/installed/Pythia/8.186/lib/libpythia8.so	absent/broken	0	27	105
	8.209	Backends/installed/Pythia/8.209/lib/libpythia8.so	OK	0	28	107
SUSYPOPE	0.2	no path in config/backend_locations.yaml	absent/broken	3	0	0
SUSY_HIT	1.5	Backends/installed/SUSY-HIT/1.5/libsusyhit.so	OK	55	0	0
SuperIso	3.4	Backends/installed/SuperIso/3.4/libsuperiso.so	OK	32	0	0
gamLike	1.0.0	Backends/installed/gamLike/1.0.0/lib/gamLike.so	OK	3	0	0
nulike	1.0.0	Backends/installed/nulike/1.0.0/lib/libnulike.so	OK	4	0	0

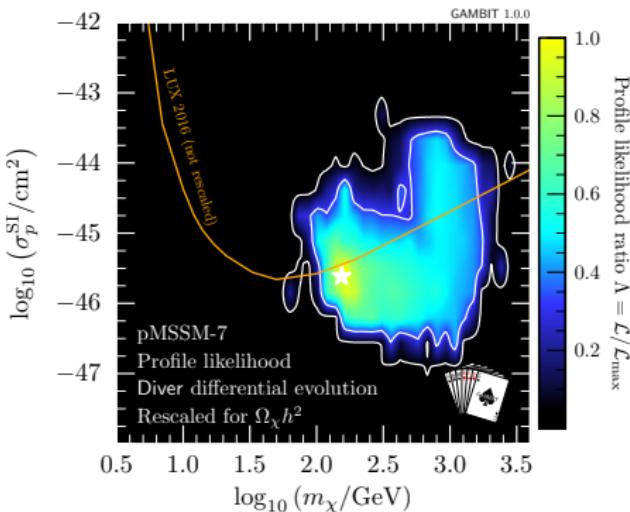
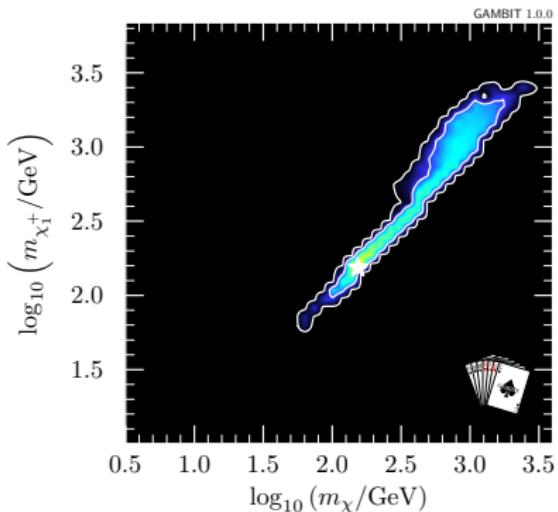
Gambit diagnostic backend line 1 (press h for help or q to quit) ▶





- Module functions and backend functions get arranged into a **dependency tree**
- Starting with requested observables and likelihoods, GAMBIT fills each dependency and backend requirement
- Obeys **rules** at each step: allowed models, allowed backends, constraints from input file, etc
 - → tree constitutes a directed acyclic graph
 - → GAMBIT uses graph-theoretic methods to ‘solve’ the graph to determine function evaluation order

Results: Weak-scale MSSM (MSSM-7; preliminary)



- $m_{\tilde{f}}, M_2, A_u, A_d, m_{Hu}, m_{Hd}, \tan \beta + 5$ nuisances
- Mostly χ^\pm co-annihilation & H/A^0 funnel
- Includes LUX 2016, Panda-X + direct simulation of all relevant LHC Run 1 limits. Run 2 coming soon. **Imperial College London**