HAP Dark Matter meeting, Münster, 20 Feb 2013

Dark SUSY

The DS team:
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Predicting dark matter relic densities, direct and indirect detection rates (not only) in supersymmetric models

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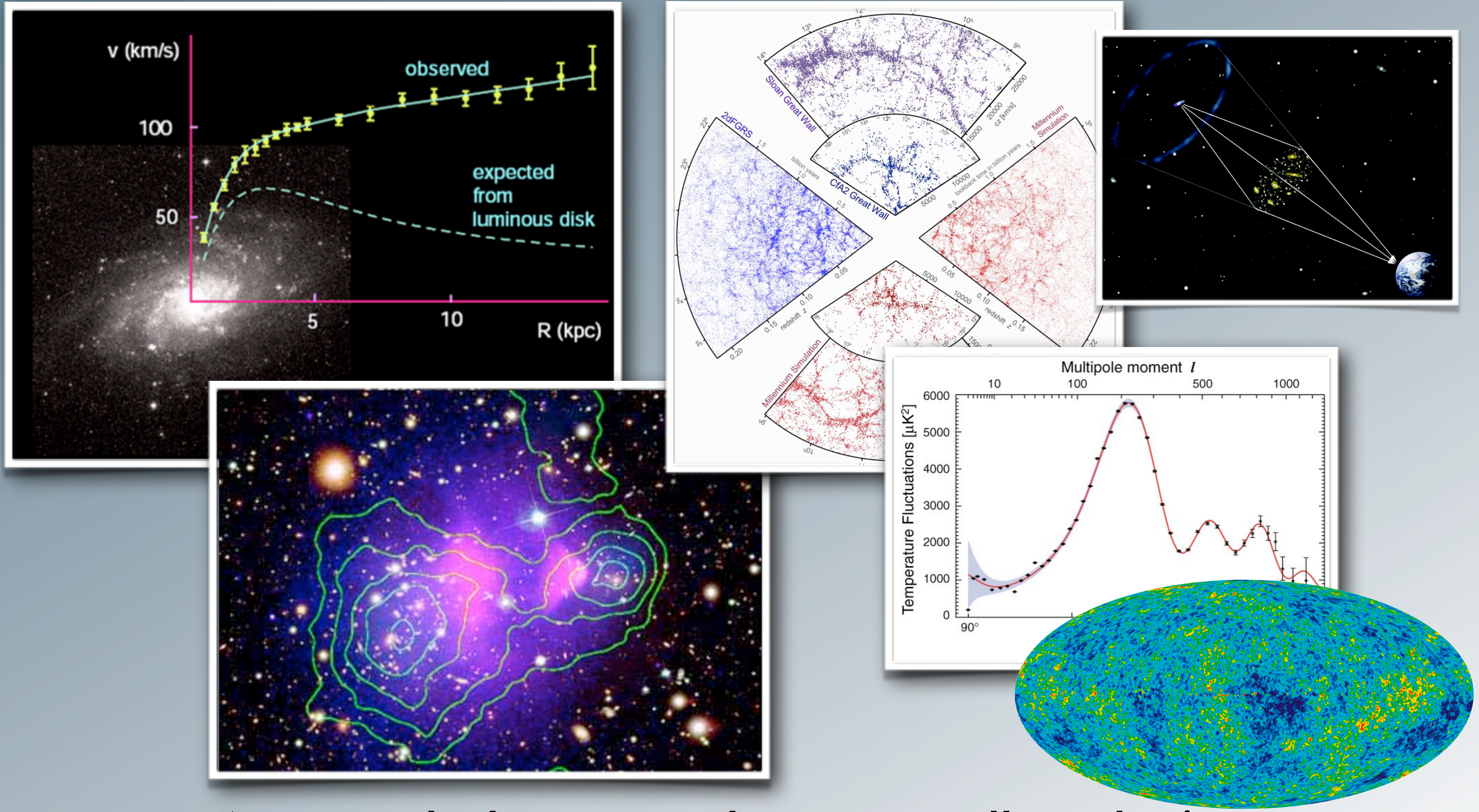
Deutsche Forschungsgemeinschaft DFG

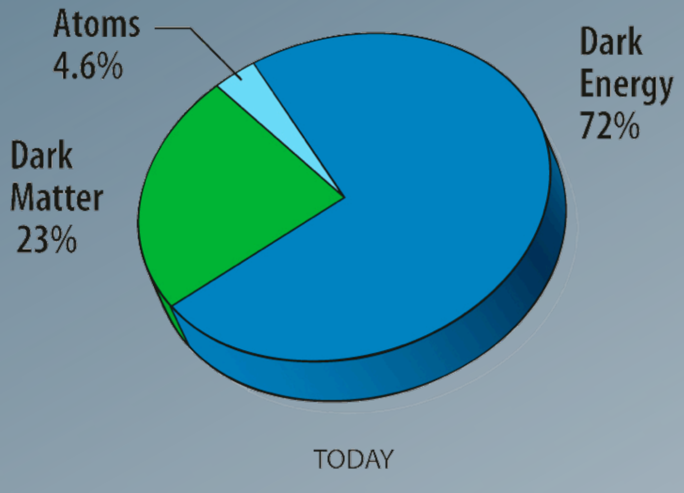
Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time

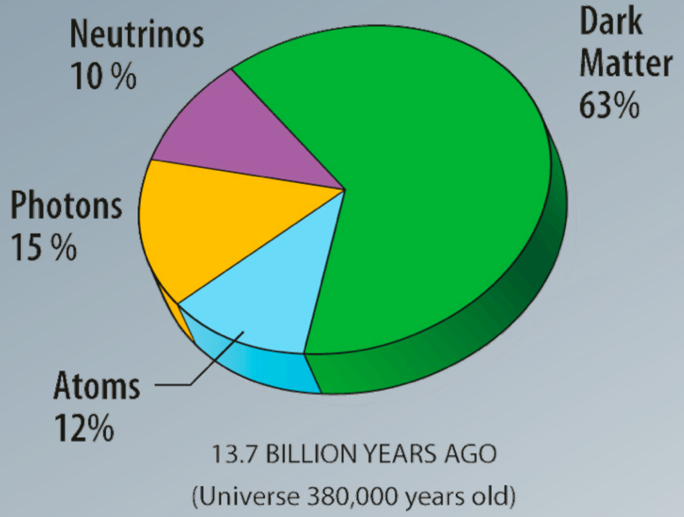
Dark matter all around



➡ *overwhelming evidence on all scales!*

Dark matter

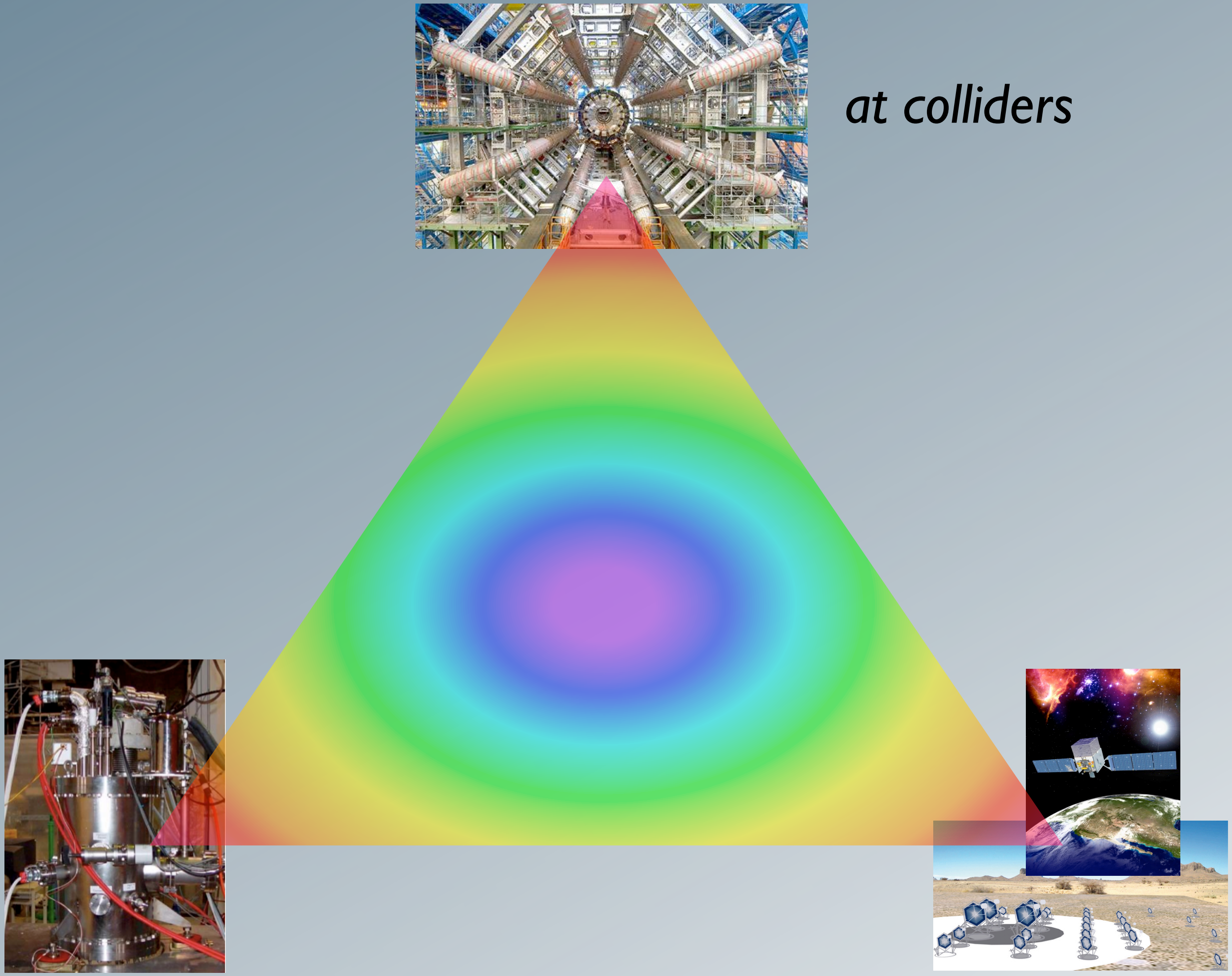




credit: WMAP

- *Existence* by now essentially impossible to challenge!
  - $\boxed{\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013}$ (WMAP)
  - electrically neutral (dark!)
  - non-baryonic (BBN)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - collisionless (bullet cluster)
- *WIMPS* are particularly good candidates:
  - ✓ well-motivated from particle physics [SUSY, EDs, little Higgs, ...]
  - ✓ thermal production "automatically" leads to the right relic abundance

Strategies for DM searches

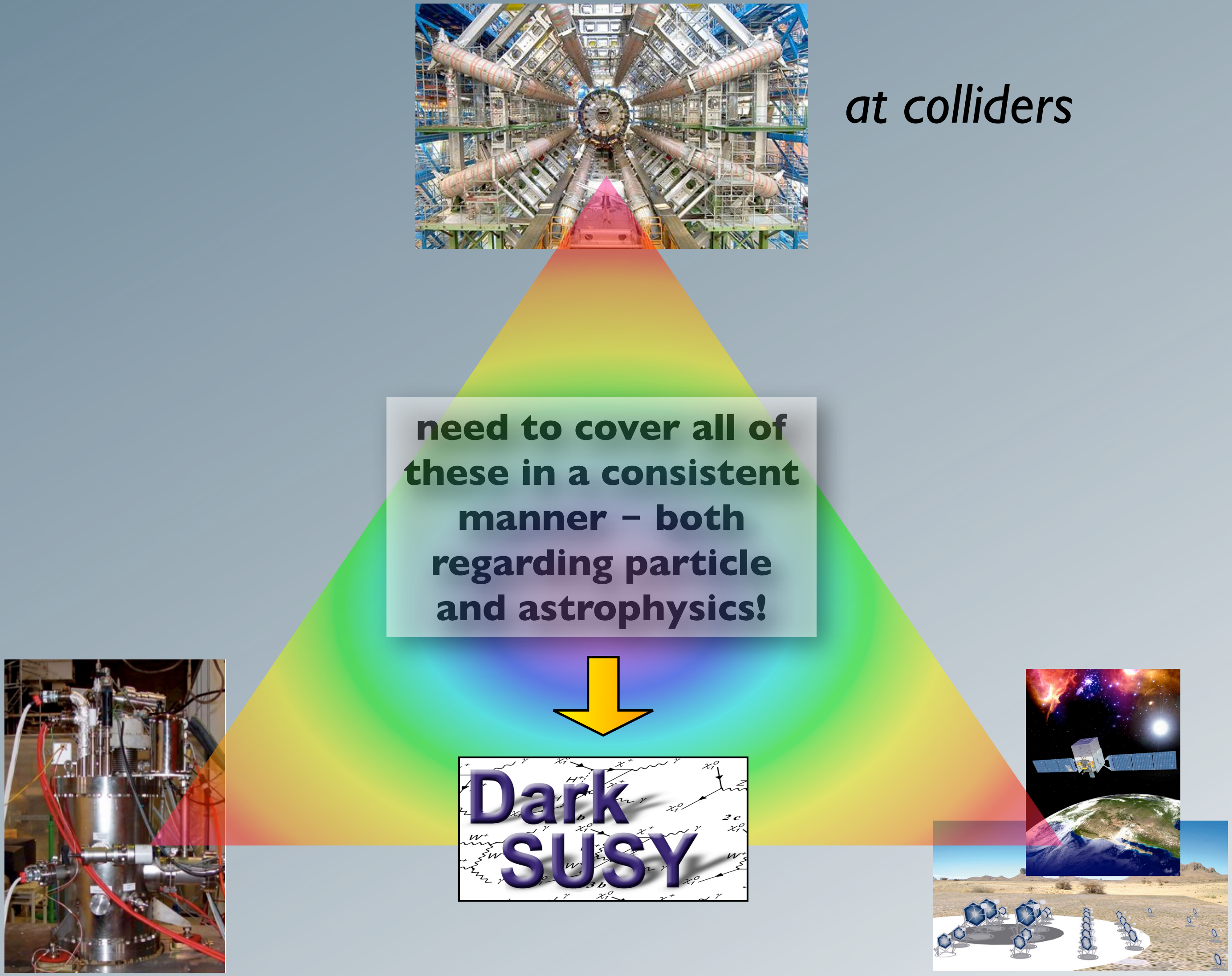


at colliders

directly

indirectly

Strategies for DM searches



at colliders

need to cover all of these in a consistent manner – both regarding particle and astrophysics!

directly

indirectly

disclaimer: impossible to cover everything in 40 minutes…!

Outline

- Introduction to and layout of DarkSUSY
- SUSY setup
- accelerator constraints
- Thermal decoupling: relic density and the smallest protohalos
- indirect detection
- direct detection
- Outlook: DS 6.0

NB:

Focus will be on neutralino DM, but most routines applicable to *any* WIMP!

General philosophy

- Library of subroutines and functions
- ‘Standard’ Fortran 77 – works on many platforms
- Modular structure (given f77 constraints…)
- Flexible
- Fast & accurate
- Version control (subversion) for precise version tagging

Getting started

1. http://www.darksusy.org

2. download

DarkSUSY Home Page

Welcome to DarkSUSY's home on the web!

DarkSUSY is a fortran package for supersymmetric dark matter calculations. It is written by Paolo Gondolo, Joakim Edsjö, Lars Bergström, Piero Ullio, Mia Schelke, Ted Baltz, Torsten Bringmann and Gintaras Duda. On these pages you will find information about DarkSUSY and you can also download the package.

If you use DarkSUSY, please refer to the following publication describing DarkSUSY:

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke and E.A. Baltz, JCAP 07 (2004) 008** [astro-ph/0406204]

Please also cite this web page as

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann and G. Duda, http://www.darksusy.org.**

Note. You should also refer to the original physics work on which DarkSUSY is based and which DarkSUSY uses. Most notably, DarkSUSY is interfaced (and uses) the following codes:

- FeynHiggs - for Higgs masses and widths
- HiggsBounds - for Higgs boson constraints from accelerators
- ISAJET/ISASUGRA -for mSUGRA/CMSSM RGE running
- SLHALIB - for reading/writing SLHA2 files

and can (for the experienced user) be configured to run with

- Galprop - for cosmic ray propagation (not used by default).

Internal pages (password restricted)

Current version *New!*

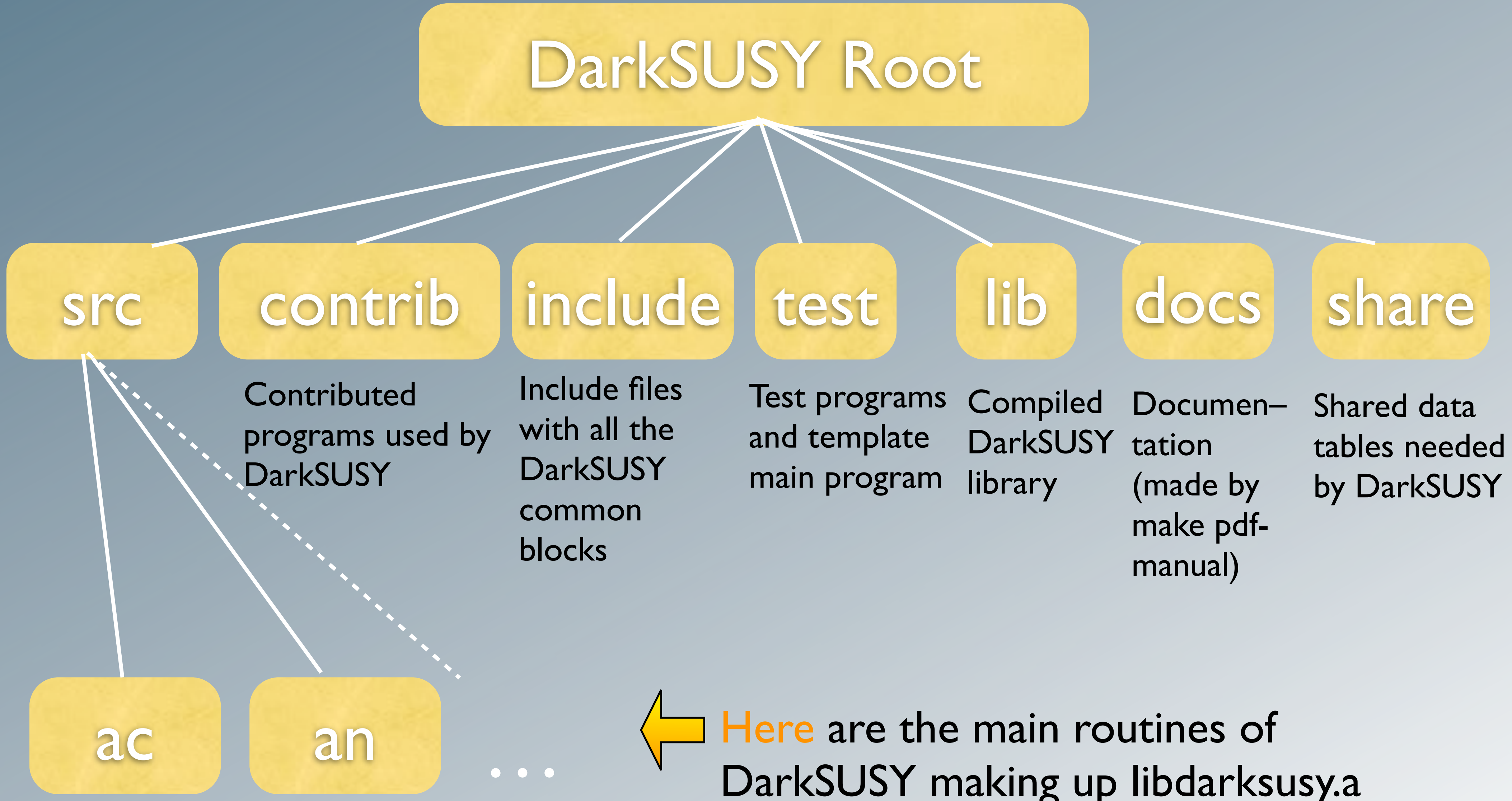
3. Install

- To compile and install DarkSUSY, just do

```
./configure [optional arguments]
make
```

- Works on most platforms and with most compilers (gfortran, ifort, ...)

Program layout



DarkSUSY Root

src

contrib

Contributed programs used by DarkSUSY

include

Include files with all the DarkSUSY common blocks

test

Test programs and template main program

lib

Compiled DarkSUSY library

docs

Documen–tation (made by make pdf-manual)

share

Shared data tables needed by DarkSUSY

ac

an

…

Here are the main routines of DarkSUSY making up libdarksusy.a

Manual

- A manual (not fully up to date yet & does not cover everything) is distributed with DarkSUSY. Create with

`make pdf-manual`	(default version)
`make pdf-manual-short`	(shorter version, without subroutine headers)

- Also see headers of various subroutines for instructions.

Happy running! :)

- Typical program layout – see /test for examples:

  call dsinit
  [make general settings]
  [determine your model parameters your way]
  call dsgive_model [or equivalent]
  call dssusy [or equivalent] – to set up DS for that model
  [calculate what you want]

  ⇨ Avoid by any means to modify the DS code itself – make your own private versions of routines if possible!

- Ask any of the authors if you need more help!

  (most relevant contact author given in routine headers)

SUSY setup

Model setup

We work in the framework of the minimal $N = 1$ supersymmetric extension of the standard model defined by, besides the particle content and gauge couplings required by supersymmetry, the superpotential

$$W = \epsilon_{ij} \left(-\hat{\mathbf{e}}_R^* \mathbf{Y}_E \hat{\mathbf{l}}_L^i \hat{H}_1^j - \hat{\mathbf{d}}_R^* \mathbf{Y}_D \hat{\mathbf{q}}_L^i \hat{H}_1^j + \hat{\mathbf{u}}_R^* \mathbf{Y}_U \hat{\mathbf{q}}_L^i \hat{H}_2^j - \mu \hat{H}_1^i \hat{H}_2^j \right) \qquad (2)$$

and the soft supersymmetry-breaking potential

$$\begin{aligned} V_{\text{soft}} \; = \; & \epsilon_{ij} \left(-\tilde{\mathbf{e}}_R^* \mathbf{A}_E \mathbf{Y}_E \tilde{\mathbf{l}}_L^i H_1^j - \tilde{\mathbf{d}}_R^* \mathbf{A}_D \mathbf{Y}_D \tilde{\mathbf{q}}_L^i H_1^j + \tilde{\mathbf{u}}_R^* \mathbf{A}_U \mathbf{Y}_U \tilde{\mathbf{q}}_L^i H_2^j - B \mu H_1^i H_2^j + \text{h.c.} \right) \\ & + H_1^{i*} m_1^2 H_1^i + H_2^{i*} m_2^2 H_2^i \\ & + \tilde{\mathbf{q}}_L^{i*} \mathbf{M}_Q^2 \tilde{\mathbf{q}}_L^i + \tilde{\mathbf{l}}_L^{i*} \mathbf{M}_L^2 \tilde{\mathbf{l}}_L^i + \tilde{\mathbf{u}}_R^* \mathbf{M}_U^2 \tilde{\mathbf{u}}_R + \tilde{\mathbf{d}}_R^* \mathbf{M}_D^2 \tilde{\mathbf{d}}_R + \tilde{\mathbf{e}}_R^* \mathbf{M}_E^2 \tilde{\mathbf{e}}_R \\ & + \frac{1}{2} M_1 \tilde{B} \tilde{B} + \frac{1}{2} M_2 \left(\tilde{W}^3 \tilde{W}^3 + 2 \tilde{W}^+ \tilde{W}^- \right) + \frac{1}{2} M_3 \tilde{g} \tilde{g} . \end{aligned} \qquad (3)$$

Here i and j are SU(2) indices ($\epsilon_{12} = +1$), $\mathbf{Y}$'s, $\mathbf{A}$'s and $\mathbf{M}$'s are 3×3 matrices in generation space, and the other boldface letter are vectors in generation space.

🟨 = 3x3 complex matrices 🟦 = complex parameters

Choosing parameters

- MSSM contains 124 free parameters
  (including complex phases, i.e. 105 new compared to SM)
- In DS all input params are currently real (MSSM-63), but many expressions are general enough to handle the full case (e.g. all vertices are already complex)
  ⇨ Generalization planned for future versions

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- General philosophy: try to be as general as possible when including new physics

  ⇨ Most expressions and setups are more general than typical use would indicate!

  (sometimes hard: code for rare decays e.g. relies on 3x3 sfermion mass matrices to be diagonal)

SUSY models

- Typical (but not necessary) simplifying assumptions:
  - take all parameters to be real $\rightsquigarrow$ effectively reduce CP violation
  - vanishing non-diagonal terms $\rightsquigarrow$ avoid FCNC & other rare processes
  - degeneracy of certain mass parameters
  - GUT conditions $\rightsquigarrow$ unification of coupling constants and scalar masses
  - ...
- Parameters usually specified at electroweak ('pMSSM-X') or GUT scale (e.g. 'mSUGRA/cMSSM')

⇨ Phenomenology depends crucially on these parameters

⇨ Often relations between masses (e.g. between chargino and neutralino)

SUSY models in DS

- Automatized setup routines available e.g. for

  MSSM-7: dsgive_model
  MSSM-25: dsgive_model25
  cMSSM: dsgive_model_isasugra

- Higgs sector with FeynHiggs

- SUSY Les Houches Accord 2 implemented (both read and write)

- mSUGRA interfaces: ISASUGRA and e.g. softsusy via SLHA2

Accelerator constraints

Constraints

- Direct accelerator searches
  - Squarks
  - Sleptons
  - Neutralinos
  - Charginos
  - Higgs bosons

from PDG

from HiggsBounds

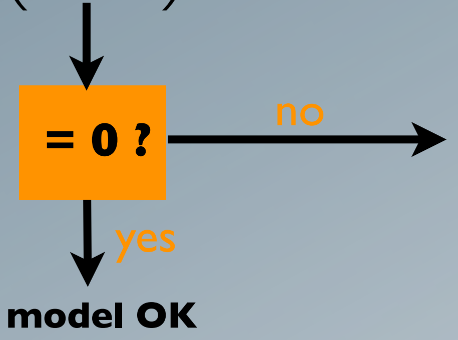
- Higher order corrections
  - Rare decays, $b \to s\gamma, \ldots$
  - Anomalous magnetic moment of the muon
  - Invisible width of Z boson

from literature or other tools (SuperIso, etc) via SLHA

General checks

- Accelerator constraints most easily check with

  call dsacbnd(excl)



From header of dsacbnd9.f:

```
c       bit set    dec.    oct.    reason
c       -------    ----    ----    ------
c             0       1       1    chargino mass
c             1       2       2    gluino mass
c             2       4       4    squark mass
c             3       8      10    slepton mass
c             4      16      20    invisible z width
c             5      32      40    higgs mass
c             6      64     100    neutralino mass
c             7     128     200    b -> s gamma
c             8     256     400    rho parameter
c             9     512    1000    (g-2)_mu
```

- This always points to the most recent version
  (though older versions of constraints are kept for backward compatibility)

- Unfortunately it takes some time for new constraints (or signals!) to make it into the code...

  e.g. LHC searches often presented for very concrete models
  ⇝ hard to interpret in more general setups!

Thermal decoupling

The WIMP "miracle"

- The number density of **W**eakly **I**nteracting **M**assive **P**articles in the early universe:

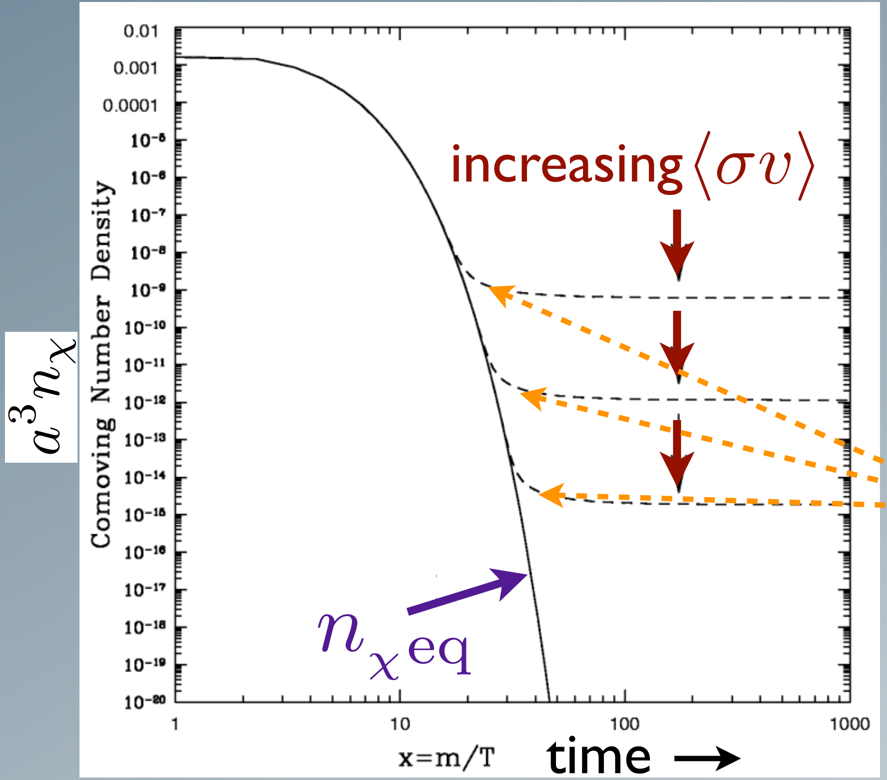


Fig.: Jungman, Kamionkowski & Griest, PR'96

$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)}$$

$\langle\sigma v\rangle :\ \chi\chi \to \mathrm{SM\ SM}$ **(thermal average)**

"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

for weak-scale interactions!

- **Relic density** (today): $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

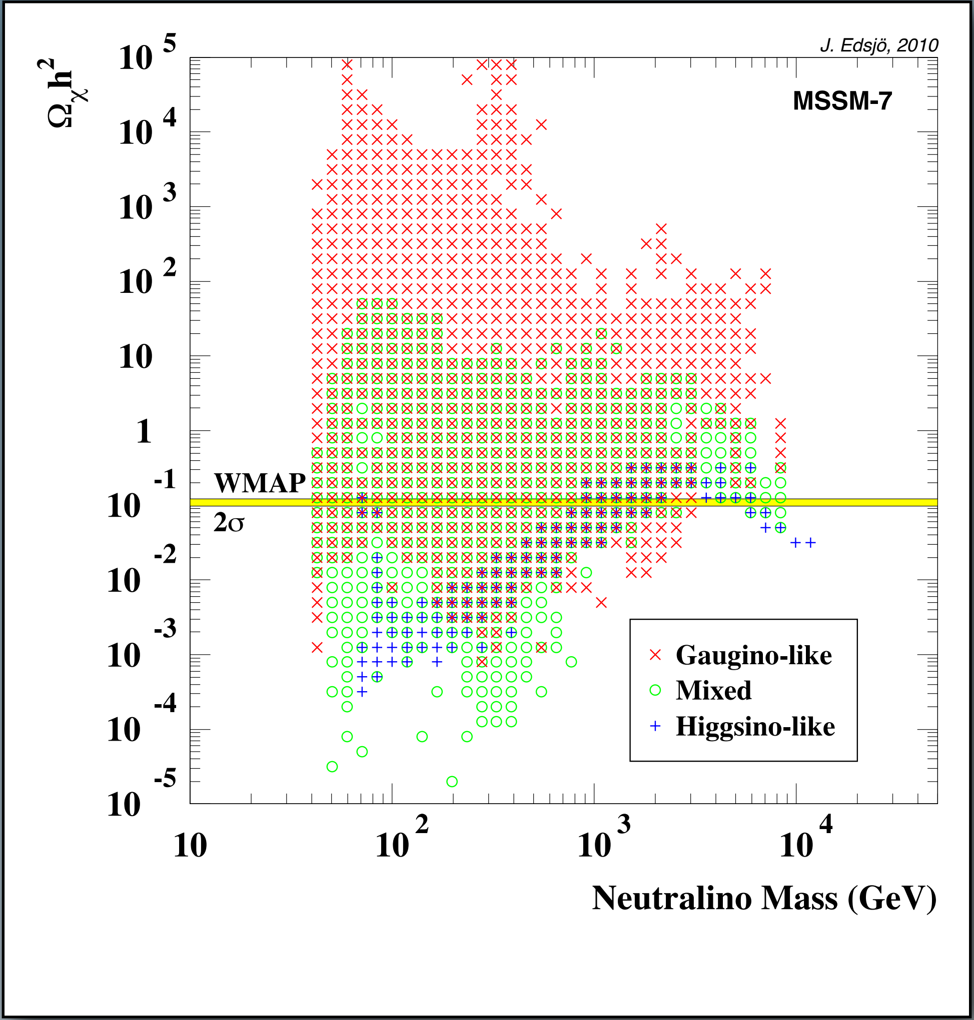
Relic density

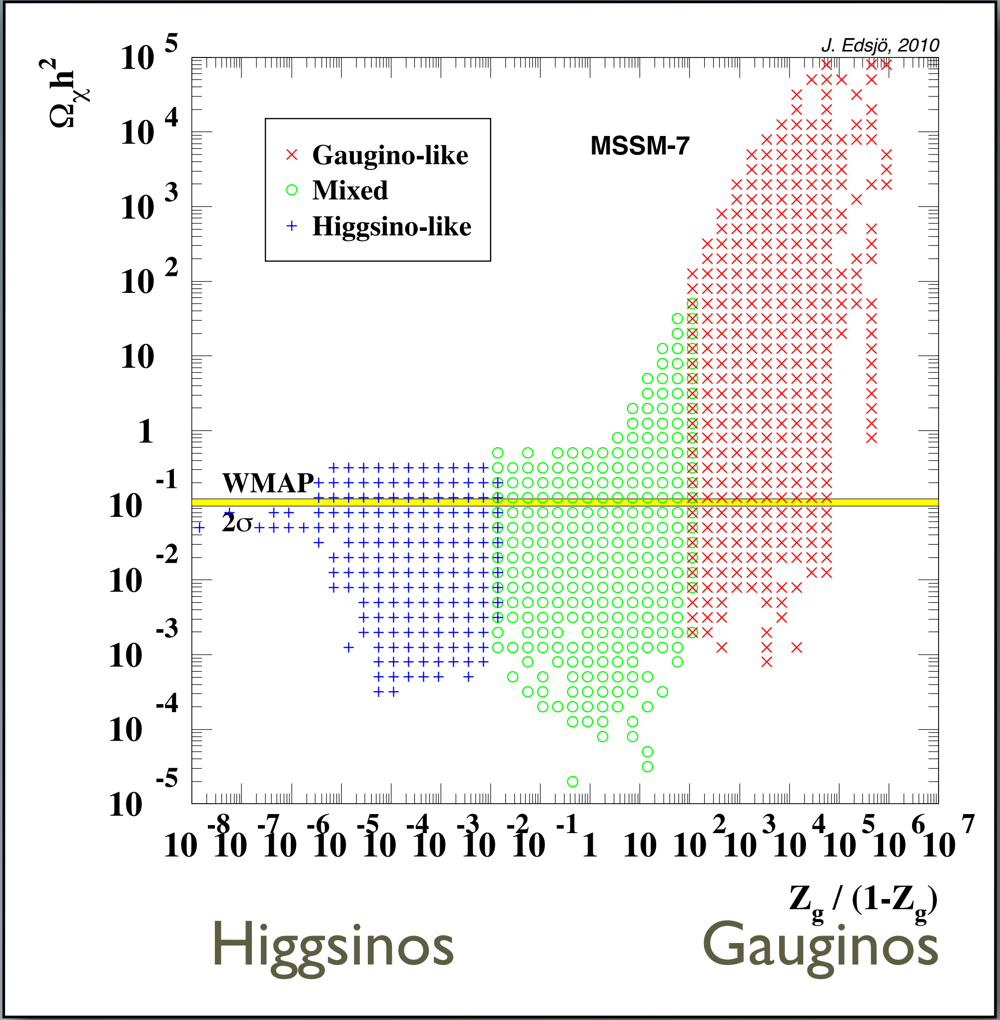
- An accurate approach requires to:
  - properly take into account thermal average <...>
  - include full annihilation cross section (all final states, resonances, thresholds)
  - include co-annihilations between all neutralinos, charginos & sfermions
  - ...
- We numerically solve the Boltzmann eqn, using in every step tabulated values for $W_{\text{eff}}(p)$:

$$\langle \sigma_{\text{eff}} v \rangle = \frac{\int_0^\infty dp_{\text{eff}} p_{\text{eff}}^2 W_{\text{eff}} K_1\left(\frac{\sqrt{s}}{T}\right)}{m_1^4 T \left[\sum_i \frac{g_i}{g_1} \frac{m_i^2}{m_1^2} K_2\left(\frac{m_i}{T}\right)\right]^2}$$

$$W_{\text{eff}} = \sum_{ij} \frac{p_{ij}}{p_{11}} \frac{g_i g_j}{g_1^2} W_{ij} \quad ; \quad W_{ij} = 4 E_1 E_2 \sigma_{ij} v_{ij}$$

Neutralino relic density





Neutralino is cosmologically interesting for large range of parameters!

RD for generic WIMPs

Call

dsrdens(wrate,npart,mgev,dof,nrs,rm,rw,nt,tm,oh2,tf,ierr,iwar)

where you have to supply

wrate - invariant effective annihilation rate (function)

npart - number of coannihilating particles

mgev - mass of these

dof - internal degrees of freedom of these

nrs - number of resonances

rm - mass of resonances

rw - width of resonances

nt - number of thresholds

tm - equivalent mass of thresholds

The routine then returns

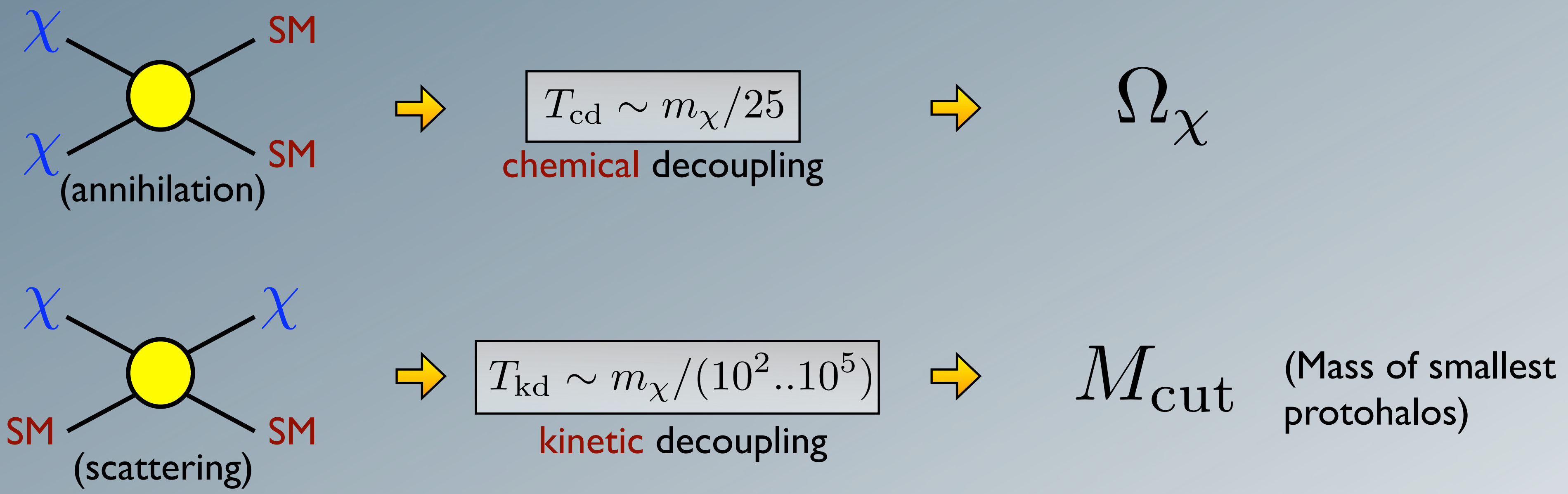
oh2 - omega h^2

tf - freeze-out temperature

NB: all this is taken care of for neutralinos in dsrdomega!

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:

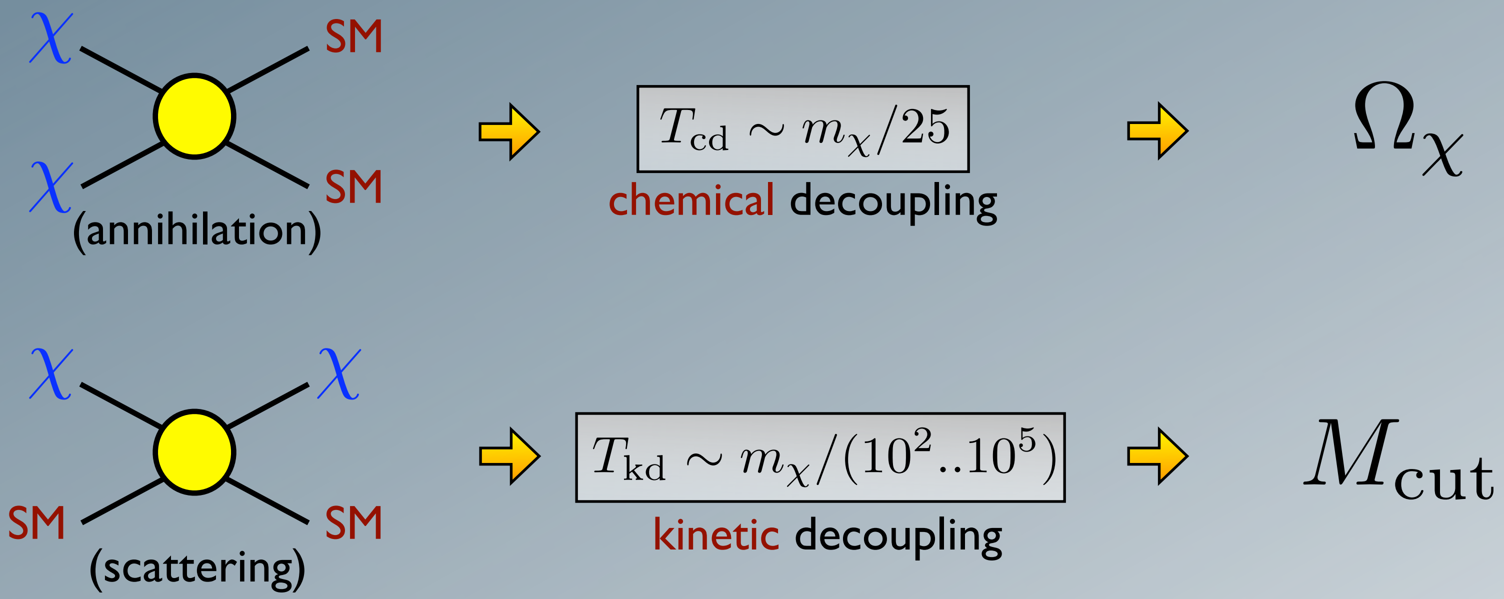


(annihilation) → $\boxed{T_{\rm cd} \sim m_\chi/25}$ chemical decoupling → Ω_χ

(scattering) → $\boxed{T_{\rm kd} \sim m_\chi/(10^2..10^5)}$ kinetic decoupling → $M_{\rm cut}$ (Mass of smallest protohalos)

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



$\boxed{T_{\rm cd} \sim m_\chi/25}$ → Ω_χ

chemical decoupling

$\boxed{T_{\rm kd} \sim m_\chi/(10^2..10^5)}$ → $M_{\rm cut}$ (Mass of smallest protohalos)

kinetic decoupling

- *no "typical"* $M_{\rm cut} \sim 10^{-6} M_\odot$*, but highly model-dependent*

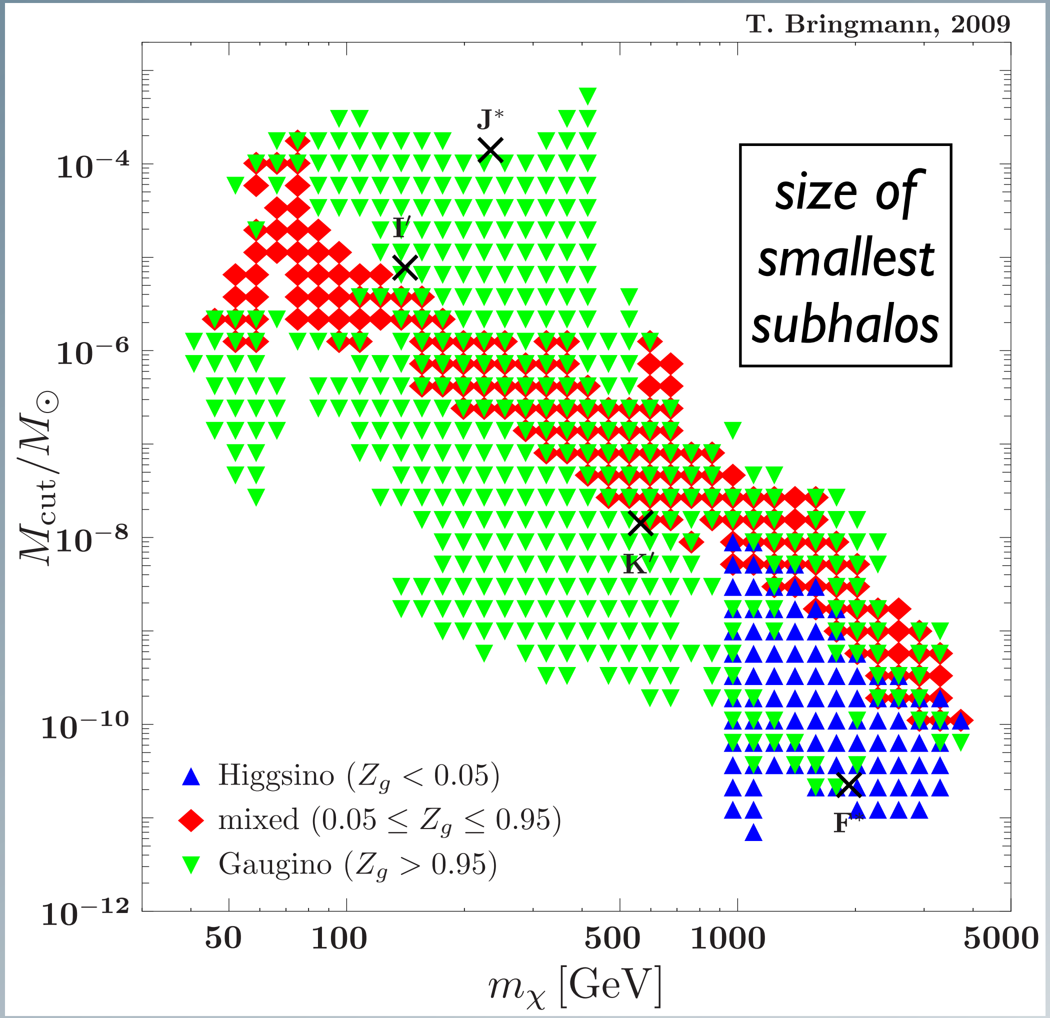
(Could be as large as scale of dwarf galaxies! ⇝ see: van den Aarssen, TB & Pfrommer, PRL '12)

- *another window into particle-physics nature of dark matter!?*

Kinetic decoupling

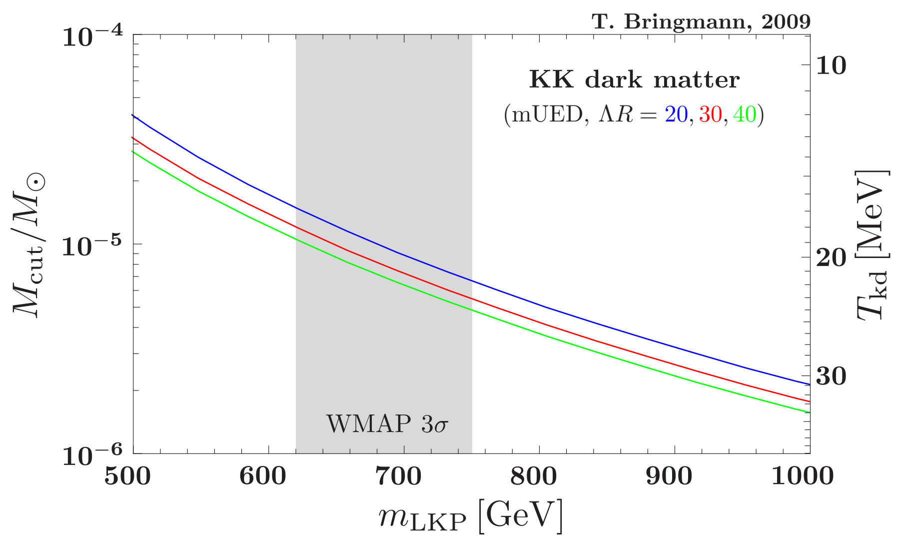
NEW in DS 5.1

- Fully included for neutralino...



size of smallest subhalos

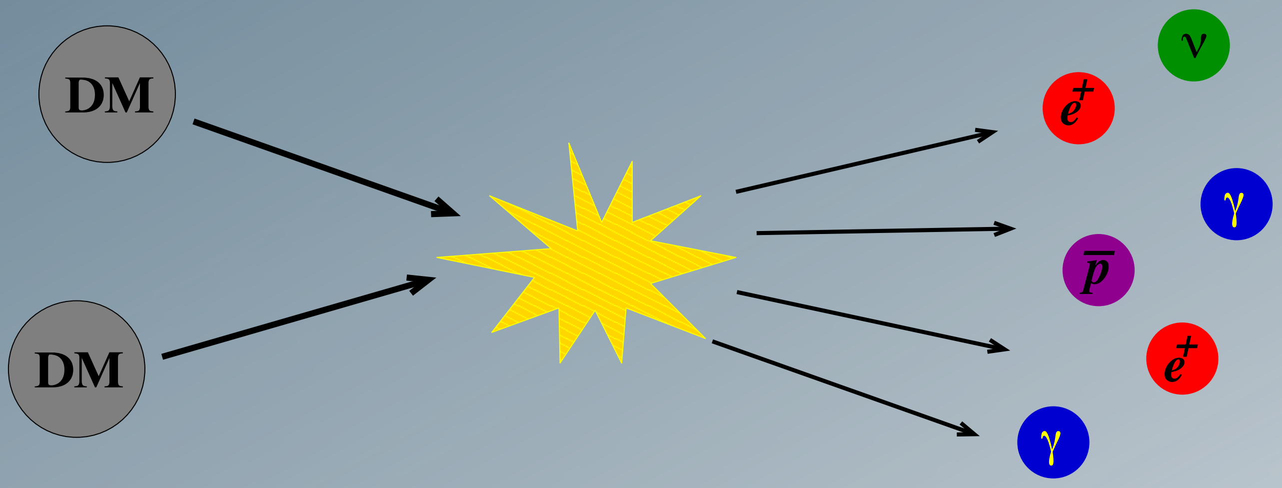
…as well as for KK DM!



TB, NJP '09

Indirect detection

Indirect DM searches



- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds

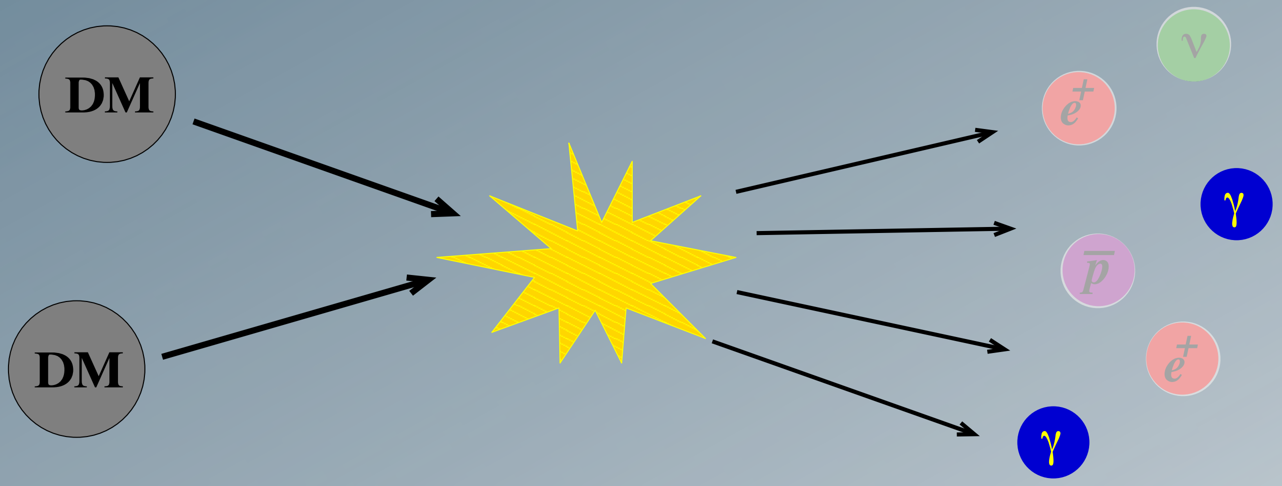
- The challenge: i) absolute rates

  $\rightsquigarrow$ regions of high DM density

  ii) discrimination against other sources

  $\rightsquigarrow$ low background; clear signatures

Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for ⇦ maybe most important!

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\boxed{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\mathrm{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r})\,\frac{\langle\sigma v\rangle_{\mathrm{ann}}}{8\pi m_\chi^2}\sum_f B_f\frac{dN_\gamma^f}{dE_\gamma}}$$

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astrophysics

for point-like sources:
$\simeq \left(D^2\Delta\psi\right)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector

D : distance to source

angular information

+ rather uncertain normalization

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for point-like sources:

$\simeq \left(D^2\Delta\psi\right)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector

D : distance to source

$\langle\sigma v\rangle_{\mathrm{ann}}$: total annihilation cross section

m_χ : WIMP mass $(50\,\mathrm{GeV}\lesssim m_\chi\lesssim 5\,\mathrm{TeV})$

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

⇩

angular information

+ rather uncertain normalization

⇩

high accuracy

spectral information

Halo profiles

- Any spherically symmetric profile possible. Presets:

  [call with dsmhset(‘name’)]
  - NFW, Einasto
  - Burkert, isothermal sphere
  - Moore, adiabatically contracted profiles
  - ...

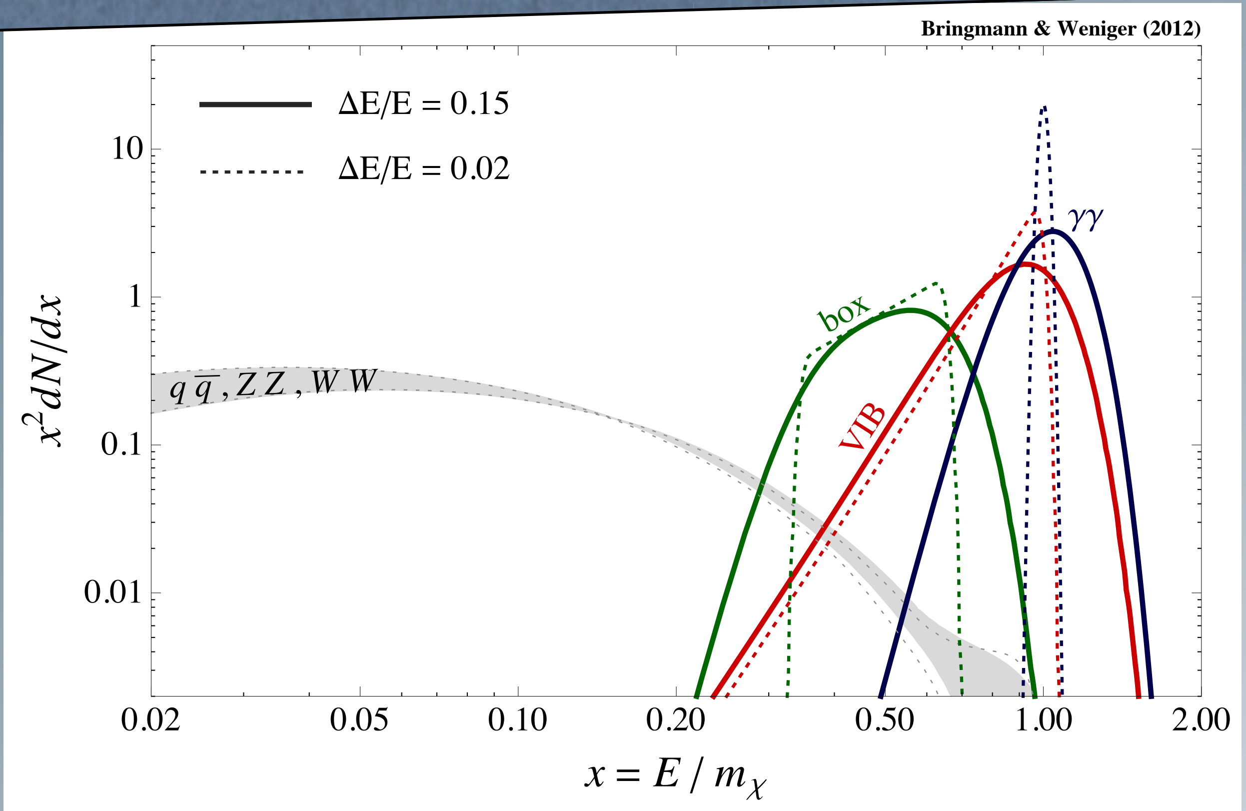
- Consistent velocity distribution is set up automatically

  [important for direct detection + neutrino rates!]

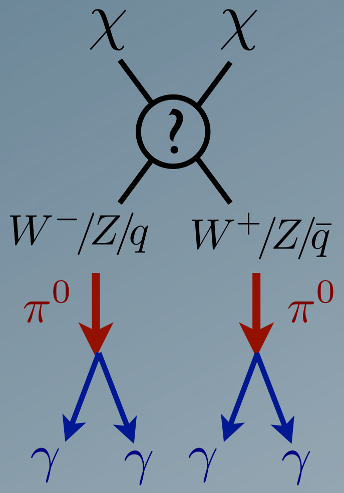
- ‘Boost factor’ of annihilation rate due to substructures

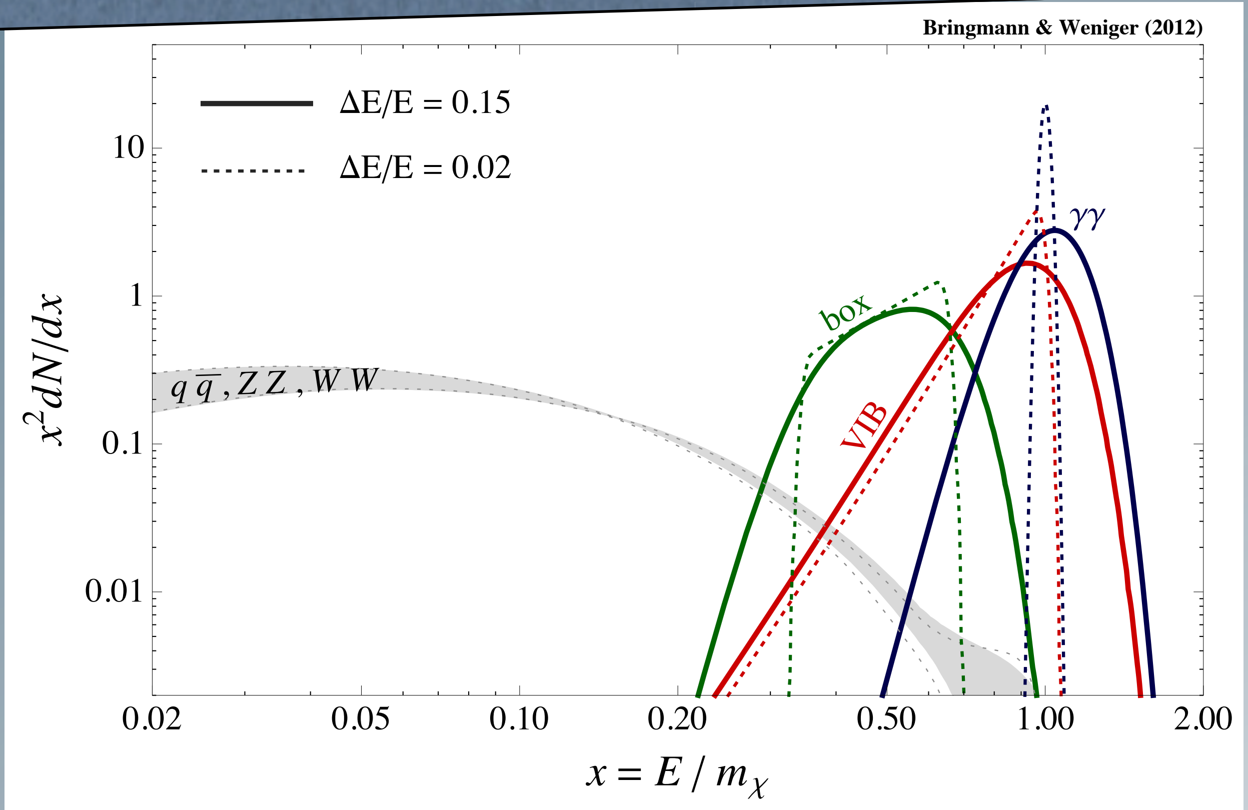
  [In principle ~log(M_{cut}), not yet implemented]

Annihilation spectra



Annihilation spectra

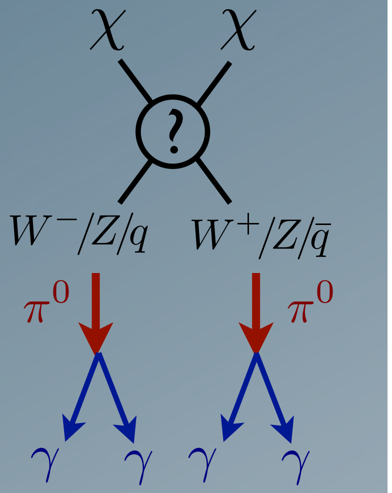


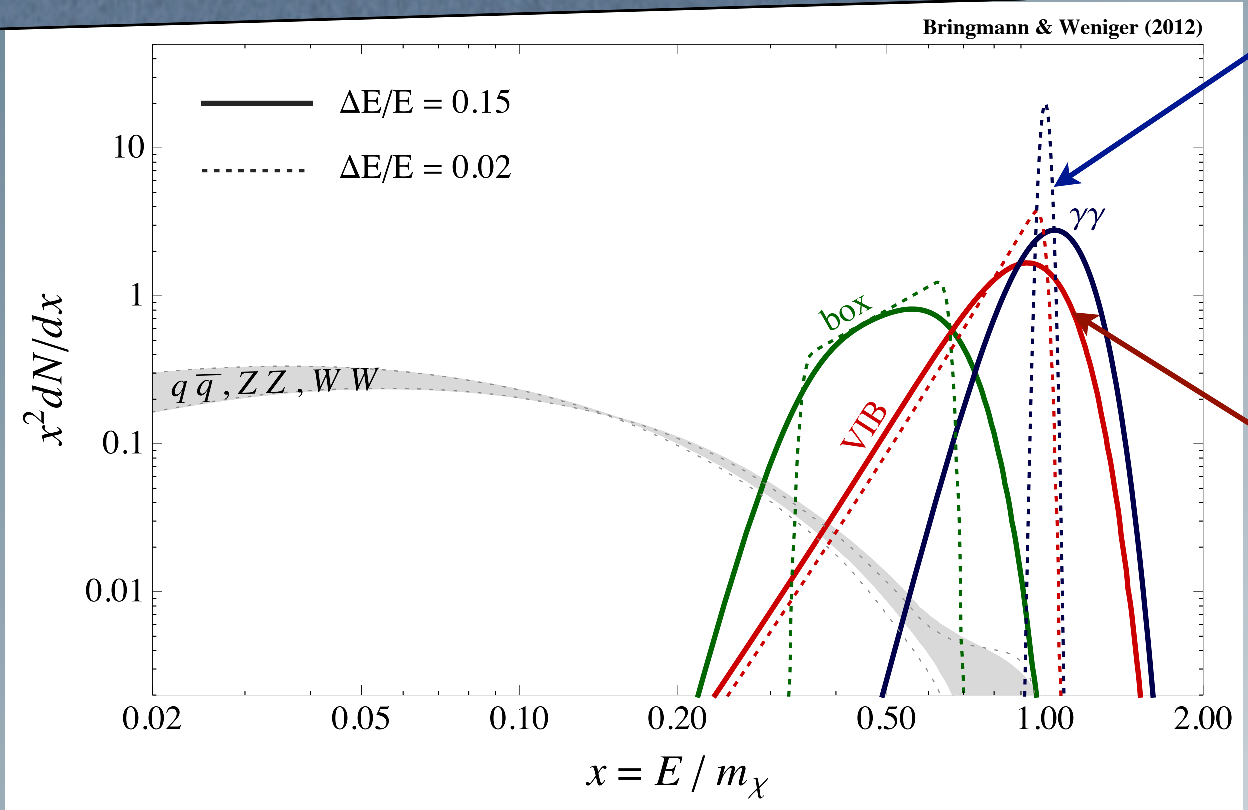

Bringmann & Weniger (2012)

- Secondary photons
  - *many* photons but
  - featureless & model-independent
  - difficult to distinguish from astro BG

→ *good constraining potential*

Annihilation spectra





Bringmann & Weniger (2012)

Monochromatic lines

$\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

$\mathcal{O}(\alpha_{\rm em}^2)$

(Virtual) Internal Bremsstrahlung

$\chi\chi \to \bar{f} f \gamma, W^+W^-\gamma$

$\mathcal{O}(\alpha_{\rm em})$

- Secondary photons
  - *many* photons but
  - featureless & model-independent
  - difficult to distinguish from astro BG

⇨ *good constraining potential*

- Primary photons
  - direct annihilation to photons
  - model-dependent 'smoking gun' spectral features near $E_\gamma = m_\chi$

⇨ *discovery potential*

IB and SUSY

- Neutralino annihilation helicity suppressed: $\langle\sigma v\rangle \propto \frac{m_\ell^2}{m_\chi^2}$

IB and SUSY

- Neutralino annihilation ~~helicity~~ suppressed: $\langle\sigma v\rangle \propto \xcancel{\frac{m_\ell^2}{m_\chi^2}} \; \frac{\alpha_{\rm em}}{\pi}$

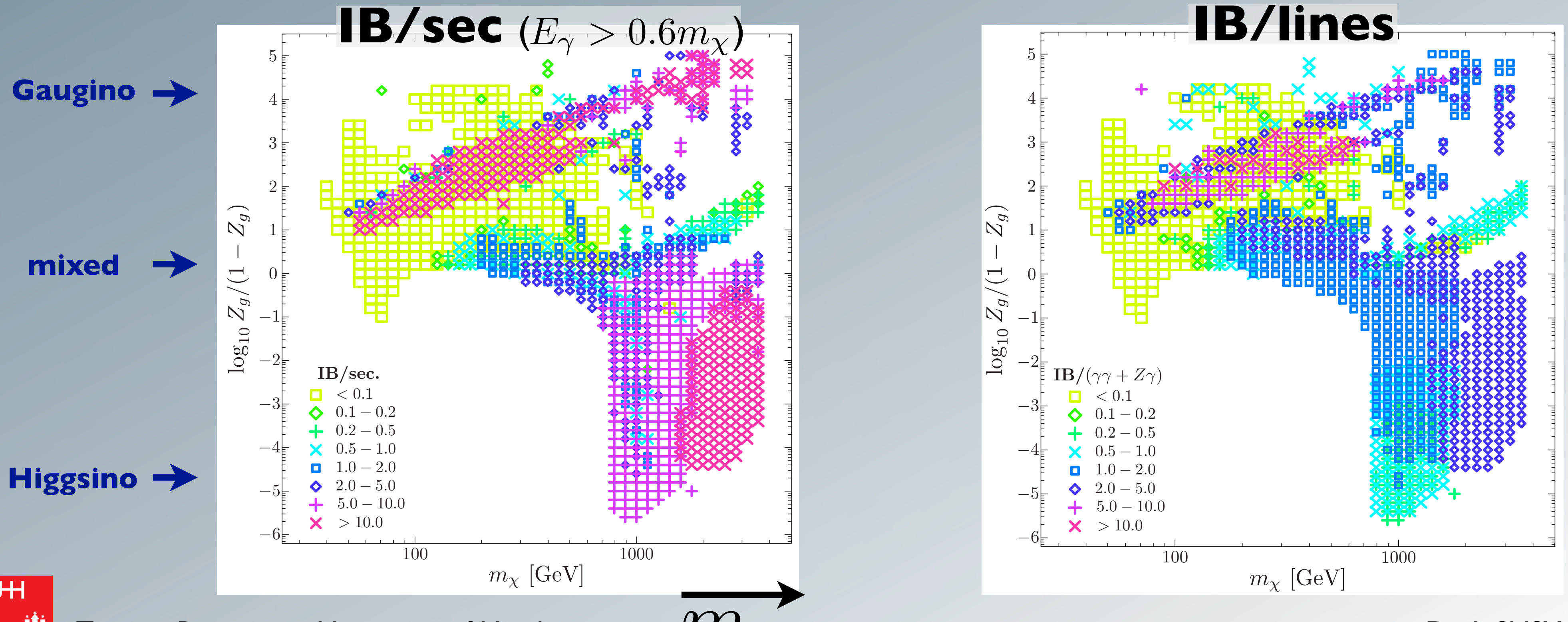
➡ $\langle\sigma v\rangle_{3-\rm body} \gg \langle\sigma v\rangle_{2-\rm body}$ *possible!*

IB and SUSY

- Neutralino annihilation ~~helicity~~ suppressed: $\langle\sigma v\rangle \propto \cancel{\frac{m_\ell^2}{m_\chi^2}}\ \frac{\alpha_{\rm em}}{\pi}$

  ➜ $\langle\sigma v\rangle_{3-\mathrm{body}} \gg \langle\sigma v\rangle_{2-\mathrm{body}}$ *possible!*

- Full implementation in DarkSUSY, scan cMSSM and MSSM-7: TB, Edsjö & Bergström, JHEP '08

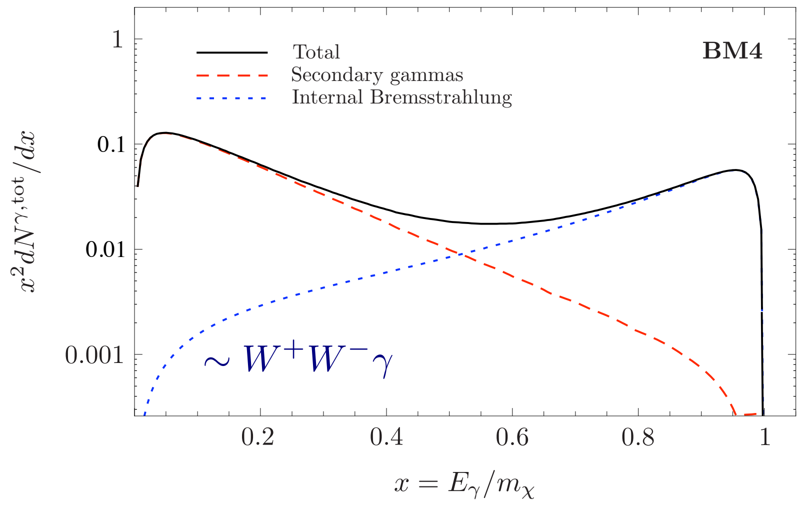


IB/sec ($E_\gamma > 0.6 m_\chi$)

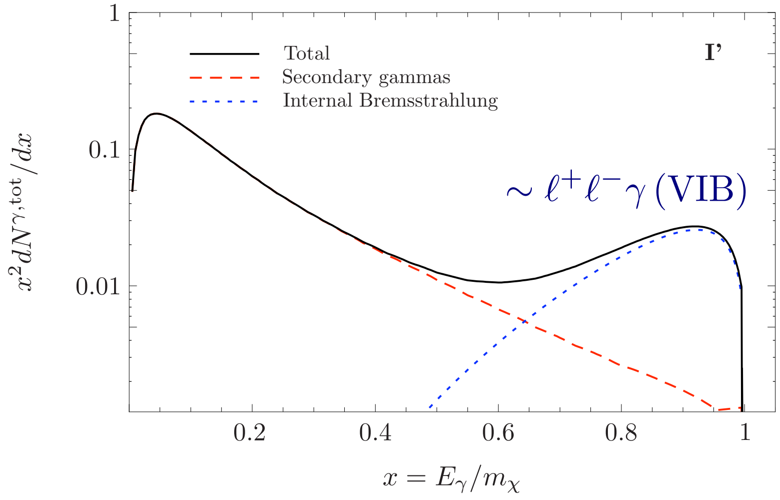
IB/lines

mSUGRA spectra

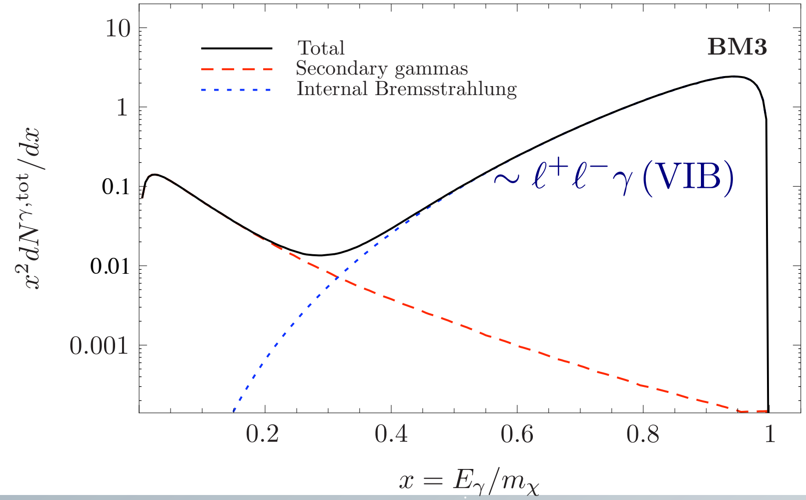
focus point region ($m_\chi = 1926$ GeV)



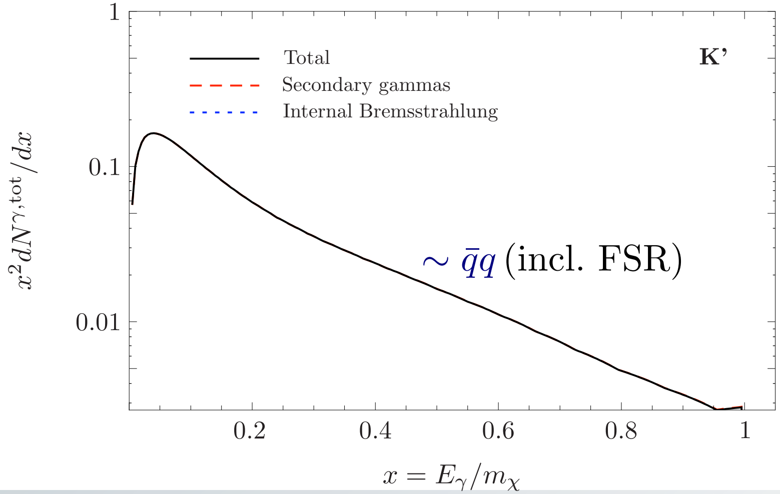
bulk region ($m_\chi = 141$ GeV)



coannihilation region ($m_\chi = 233$ GeV)



funnel region ($m_\chi = 565$ GeV)



(benchmarks taken from TB, Edsjö & Bergström, JHEP ’08 and Battaglia et al., EPJC ’03)

The 130 GeV ‘line’ at the GC

- Significance:

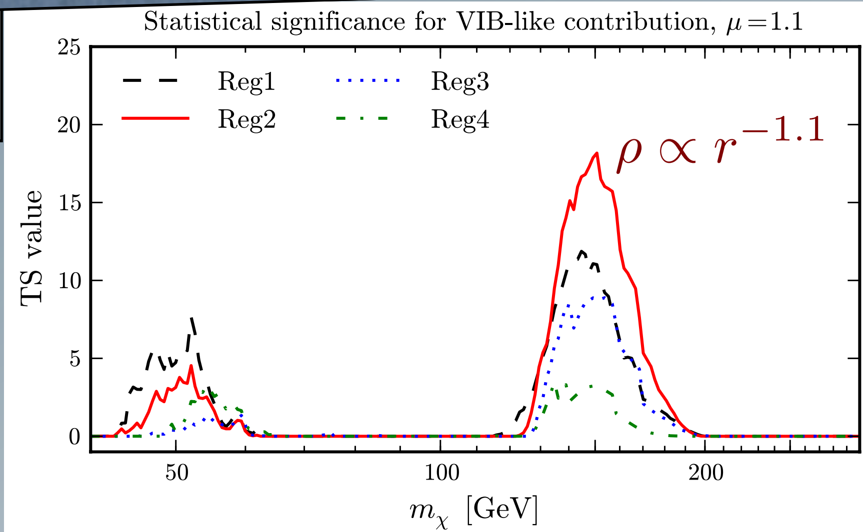
$$TS \equiv -2\ln\frac{\mathcal{L}_{\rm null}}{\mathcal{L}_{\rm DM}}$$

4.3σ **locally**

3.1σ **globally**

‘look-elsewhere effect’

[trial factors: m_χ & target regions]


Statistical significance for VIB-like contribution, $\mu=1.1$

TB, Huang, Ibarra, Vogl & Weniger, JCAP ’12

interpretation as annihilating DM:

signal	VIB	γH	γZ	$\gamma\gamma$
mass [GeV]	~150	~155	~145	~130

TB & Weniger, PDU ’12

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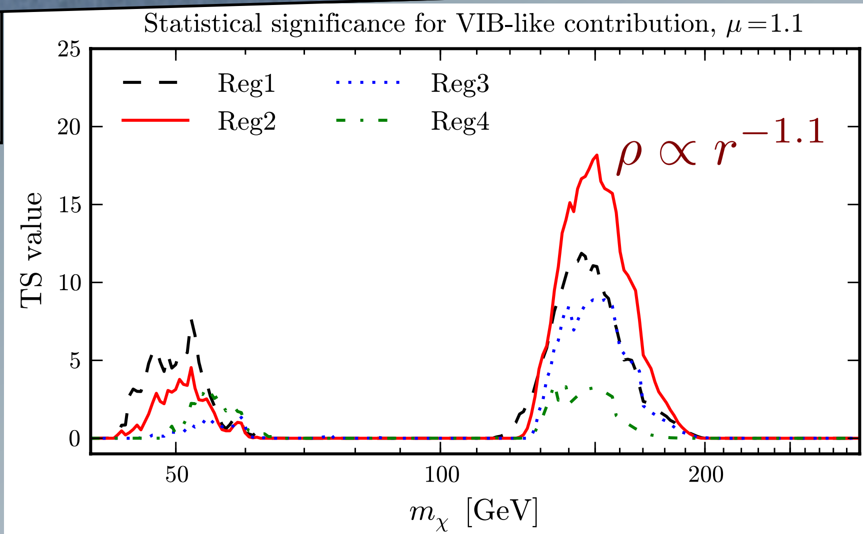

TB, Huang, Ibarra, Vogl & Weniger, JCAP ’12

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Weniger, JCAP ’12 --➔ focus on statistical analysis + line interpretation

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Su & Finkbeiner, 1206.1616 --➔ include spatial templates in analysis: >5σ global significance!

TB & Weniger, PDU ’12

●●●

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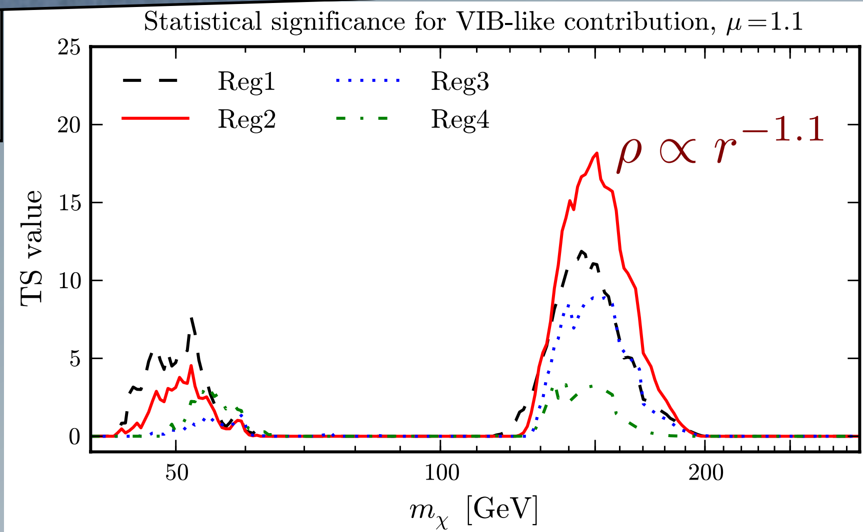

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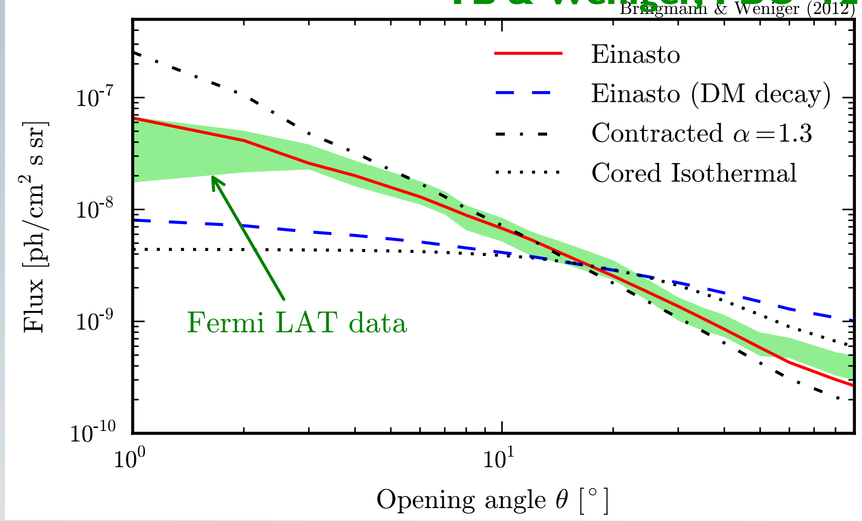
TB & Weniger, PDU ’12



- ‘Too good to be true’…

potential caveats:

?

- Signal rate ‘too large’ ?
- Signal off-set from the GC?
- Same signal in Earth limb!?

The 130 GeV 'line' at the GC

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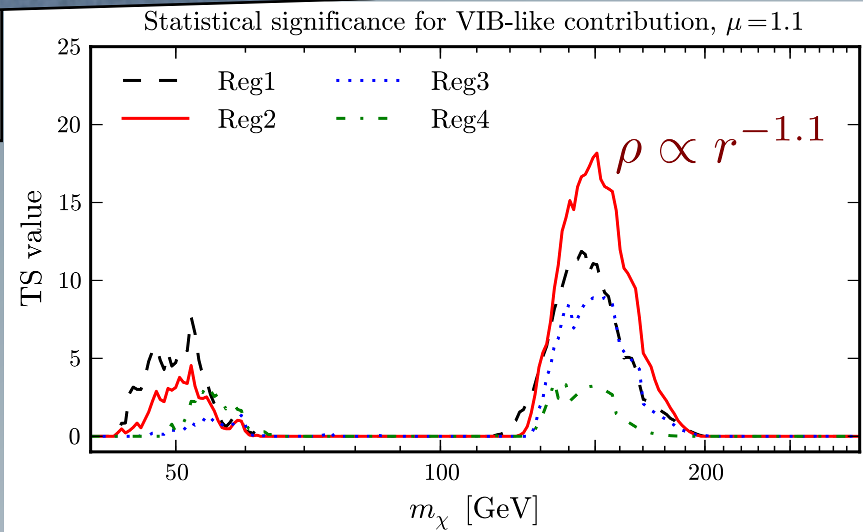

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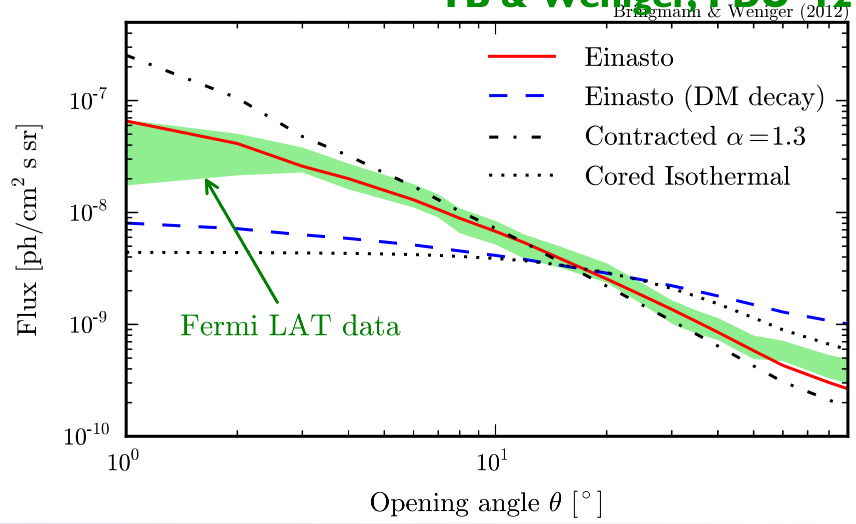
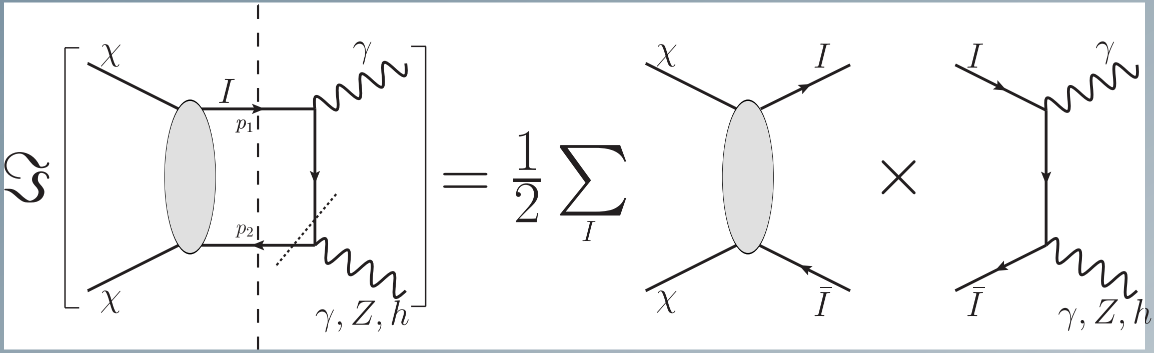
➔ *Stay tuned !!!*



DM model implications

- Need rather large annihilation rate
  - implies resonances and/or large couplings (see e.g. Buckley & Hooper, PRD '12)
  - *difficult* to achieve for *thermally* produced DM!
  - expect large secondary rates (optical theorem!)



Asano, TB, Sigl & Vollmann,
1211.6739

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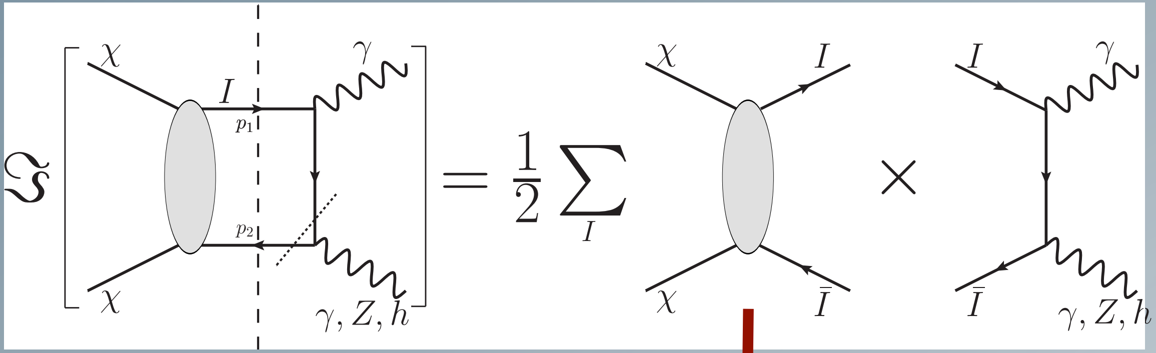

Asano, TB, Sigl & Vollmann, 1211.6739

Constraints from continuum γ-rays, antiprotons and radio!

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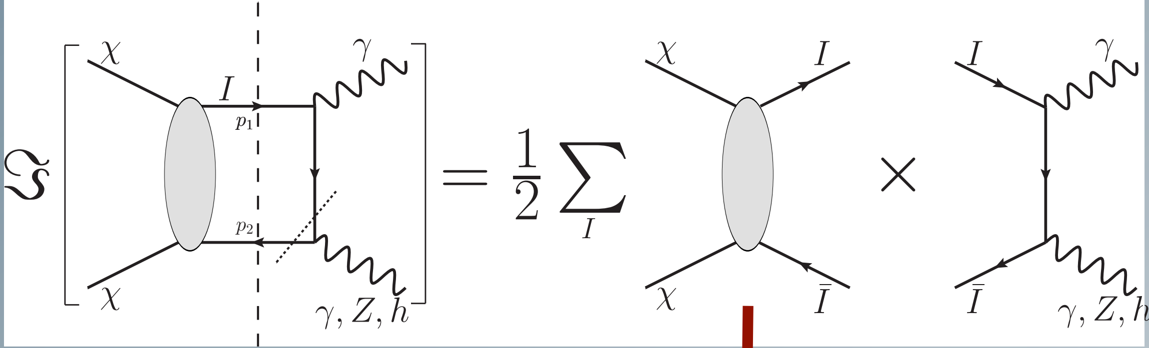

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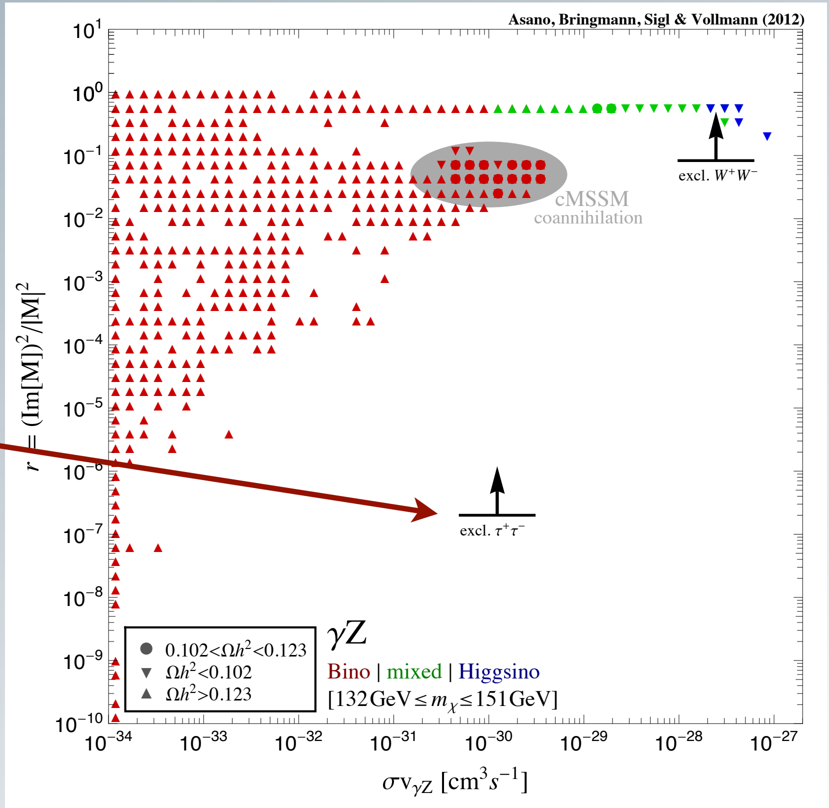
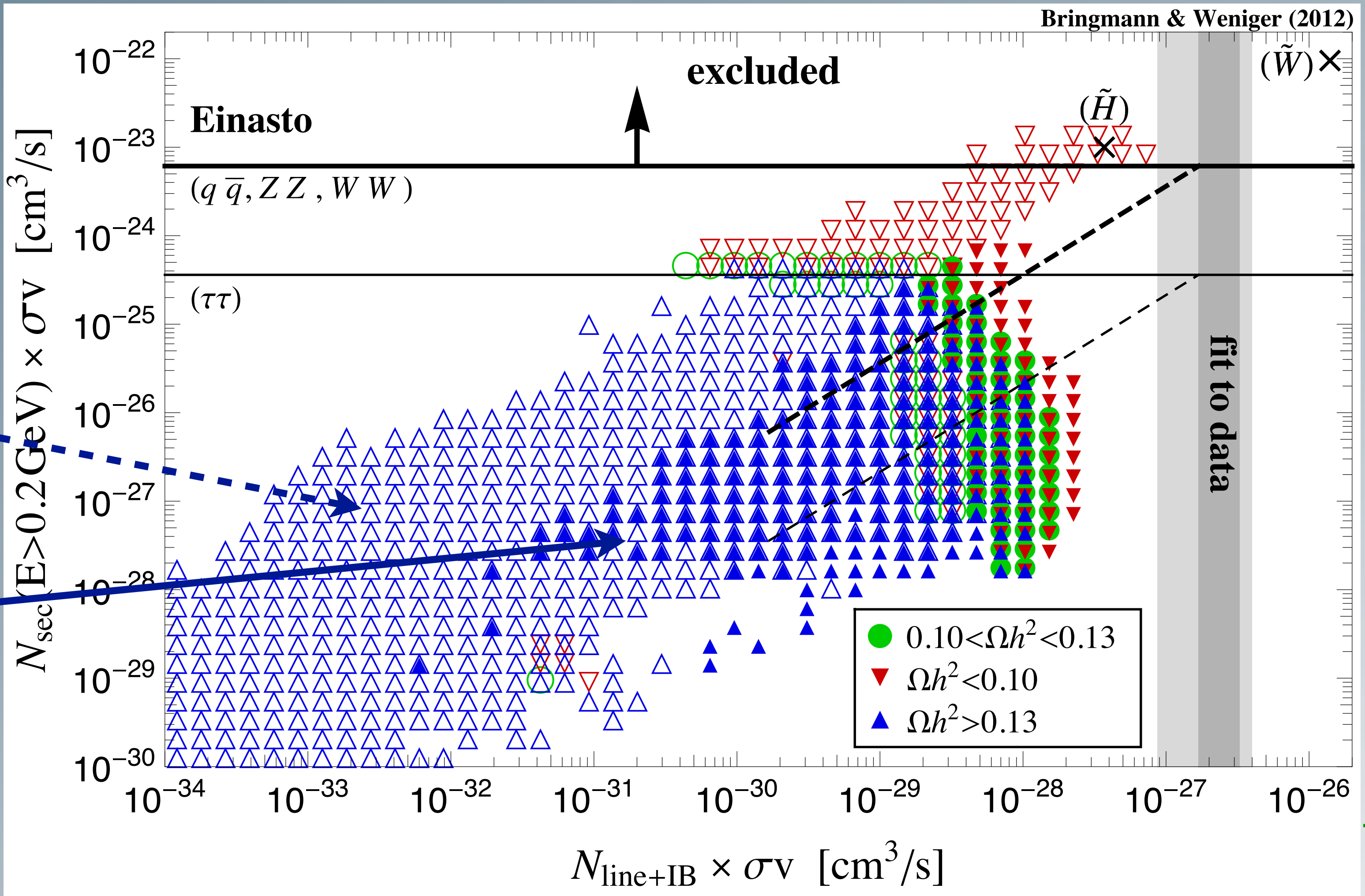


SM particles in loop essentially excluded as viable explanation!

Lines vs VIB

[cMSSM + MSSM-7; keep only models with correct mass and line-like spectra]



open symbols: line-dominated

filled symbols: VIB-dominated

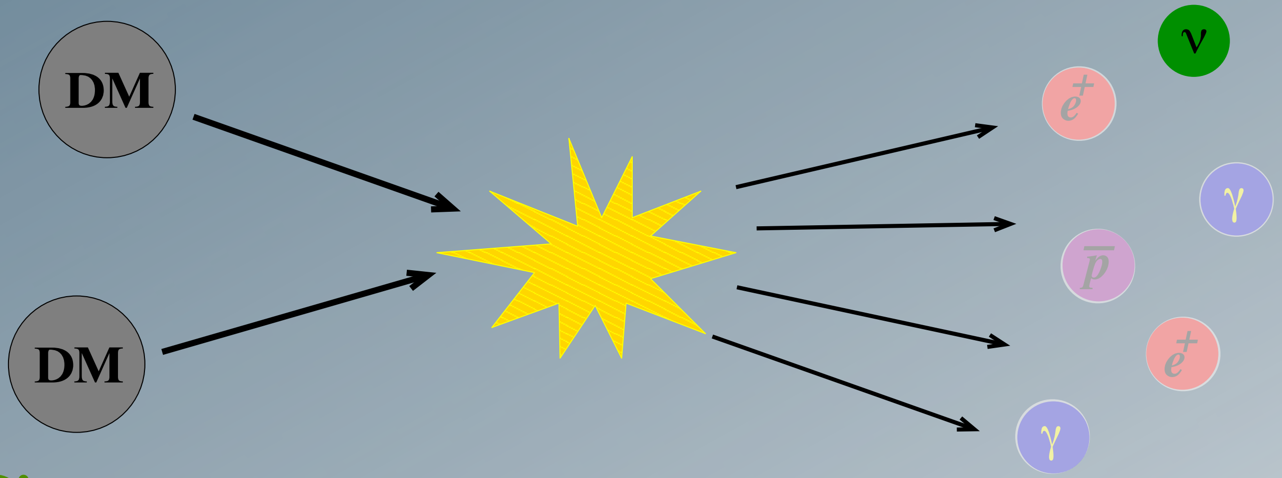
continuum gamma-ray constraints

TB & Weniger, PDU '12

➡ *VIB more likely explanation than lines?*

(see also Bergström, PRD '12, Shakya 1209.2427, ...)

Indirect DM searches



Neutrinos:

- Unperturbed propagation like for photons
- But signal significance (for the same target) usually considerably worse
- New feature: signals from the center of sun or earth!

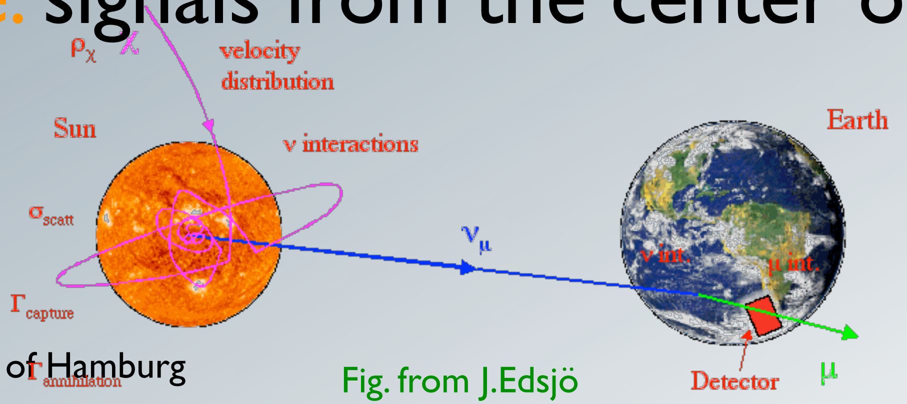


Fig. from J.Edsjö

Neutrino signals

$$\dot{N} = C - \underbrace{C_A N^2}_{2\Gamma_A} - C_E N$$

capture rate

evaporation rate

⇨

Annihilation rate:

$$\Gamma_A = \frac{1}{2} C \tanh^2 \frac{t}{\sqrt{C_A C}}$$

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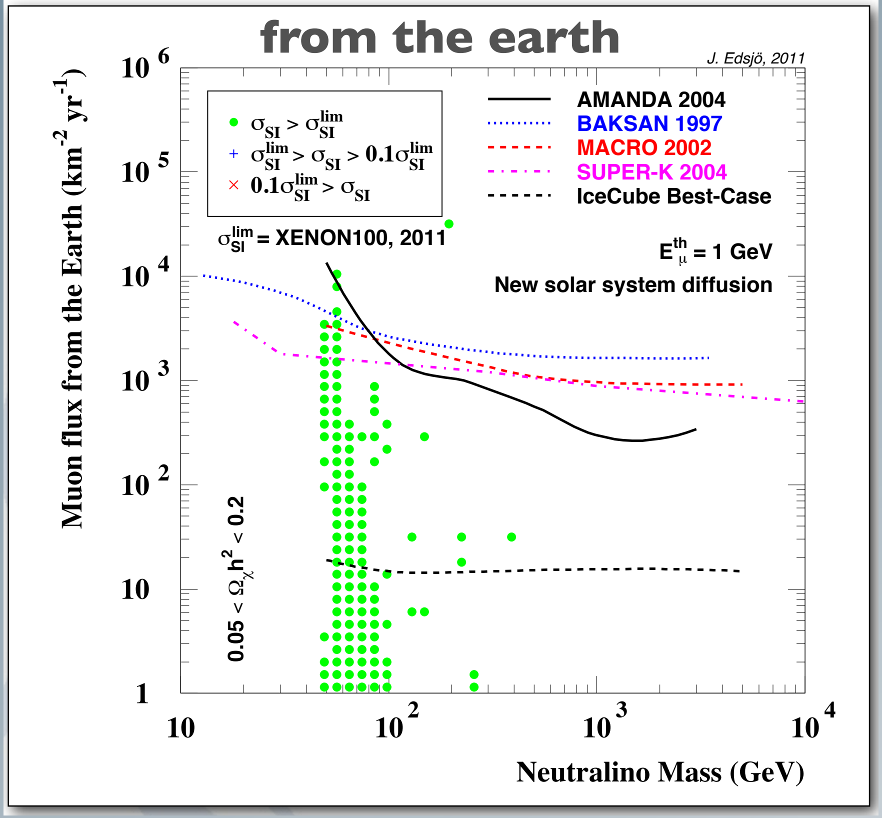
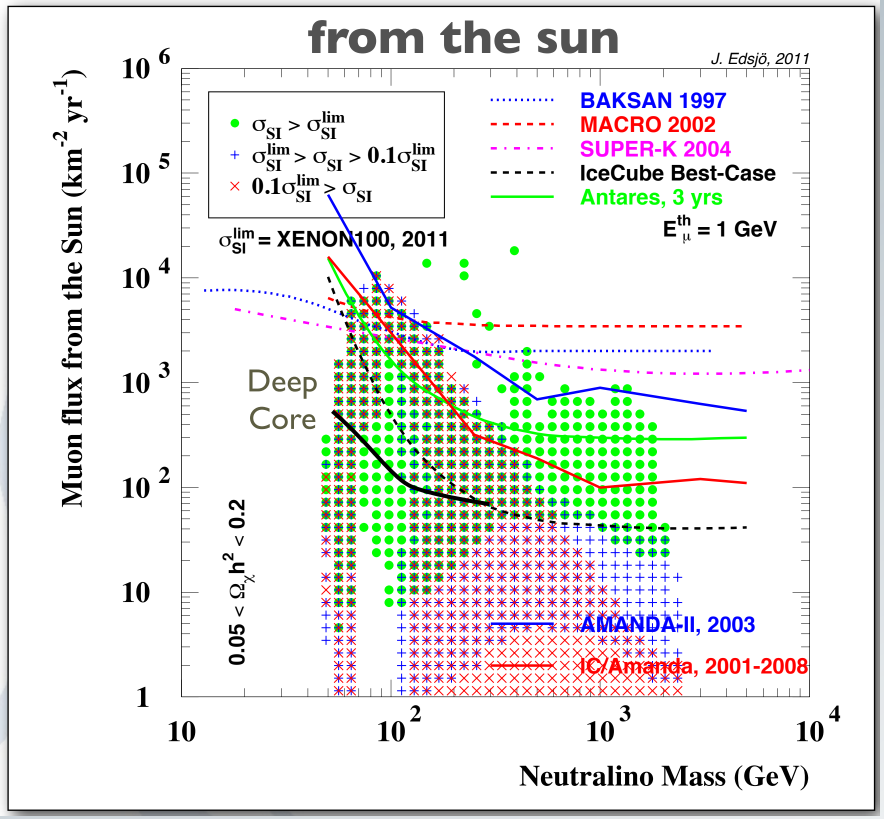


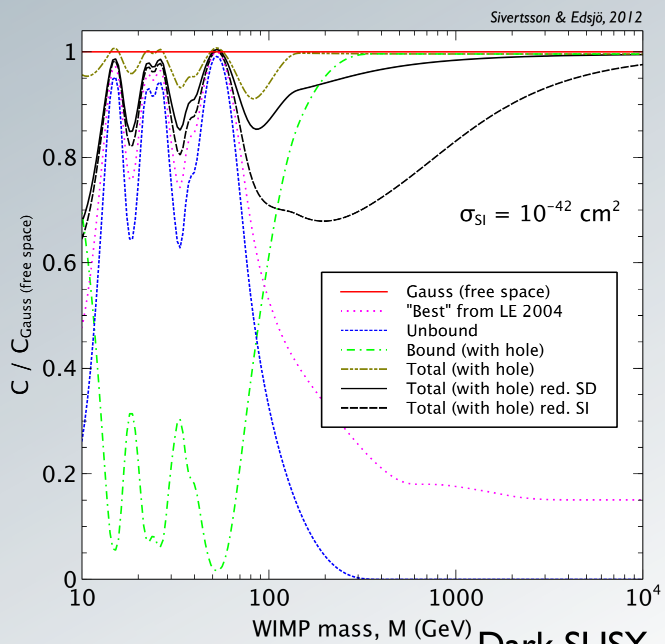
from the earth



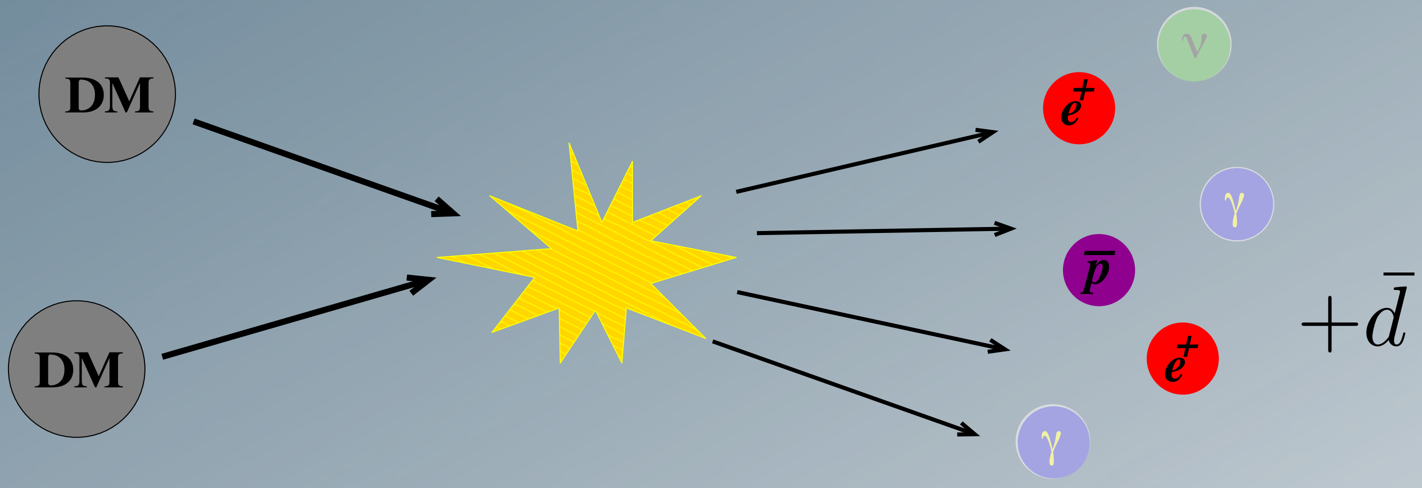
from the sun

ν's from Sun/Earth

- Rate of neutrino-induced muons in neutrino telescopes
- Neutrino scattering and absorption in Sun included
- Full numerical capture calculation with any velocity distribution
- Neutrino oscillations, all flavors and hadronic showers
- Simple dark disk models, effects of Jupiter included
- In the pipeline: fully implement solar system diffusion
  (though free-space approximation works quite well)


Sivertsson & Edsjö, 2012

Indirect DM searches



Charged cosmic rays:

- GCRs are confined by galactic magnetic fields
- After propagation, no directional information is left
- Also the spectral information tends to get washed out
- Equal amounts of matter and antimatter

  ⇨ focus on antimatter (low backgrounds!)

Propagation

- Little known about Galactic magnetic field distribution
- Random distribution of field inhomogeneities
  $\rightsquigarrow$propagation well described by diffusion equation

$$\boxed{\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla - v_c)\psi + \frac{\partial}{\partial p} b_{\mathrm{loss}}\psi - \frac{\partial}{\partial p} K \frac{\partial}{\partial p}\psi = q_{\mathrm{source}}}$$

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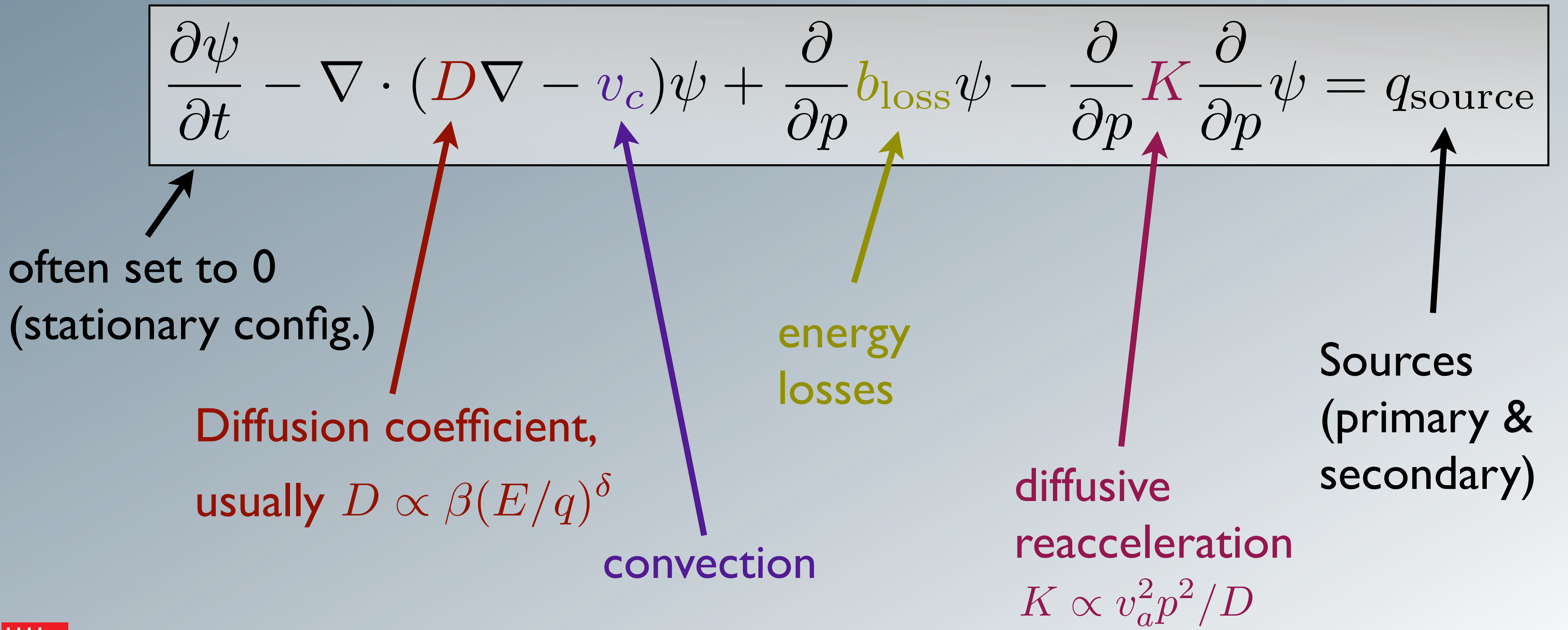

$$\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla - v_c)\psi + \frac{\partial}{\partial p} b_{\rm loss}\psi - \frac{\partial}{\partial p} K \frac{\partial}{\partial p}\psi = q_{\rm source}$$

often set to 0
(stationary config.)

Diffusion coefficient,
usually $D \propto \beta(E/q)^\delta$

convection

energy
losses

diffusive
reacceleration
$K \propto v_a^2 p^2 / D$

Sources
(primary &
secondary)

Analytical vs. numerical

How to solve the diffusion equation?

Analytical vs. numerical

How to solve the diffusion equation?

- Numerically
  - ⊕ 3D possible
  - ⊕ any magnetic field model
  - ⊕ realistic gas distribution, full energy losses
  - ⊖ computations time-consuming
  - ⊖ (“black box”)

e.g.

Strong, Moskalenko, …

DRAGON

Evoli, Gaggero, Grasso & Maccione

Analytical vs. numerical

How to solve the diffusion equation?

- Numerically
  - + 3D possible
  - + any magnetic field model
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  - − computations time-consuming
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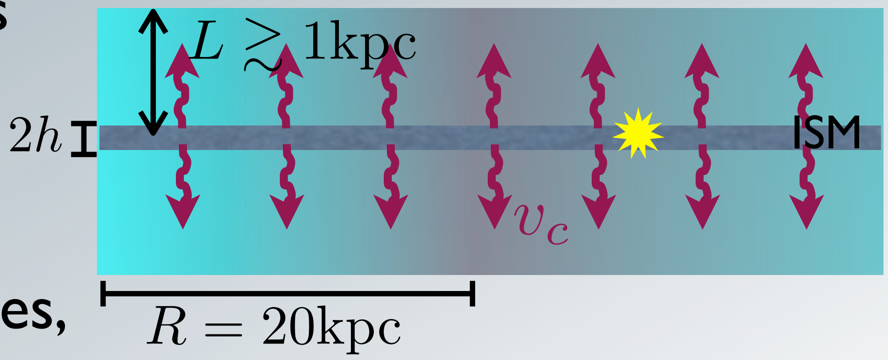
e.g. GALPROP

Strong, Moskalenko, …

DRAGON
Evoli, Gaggero, Grasso & Maccione

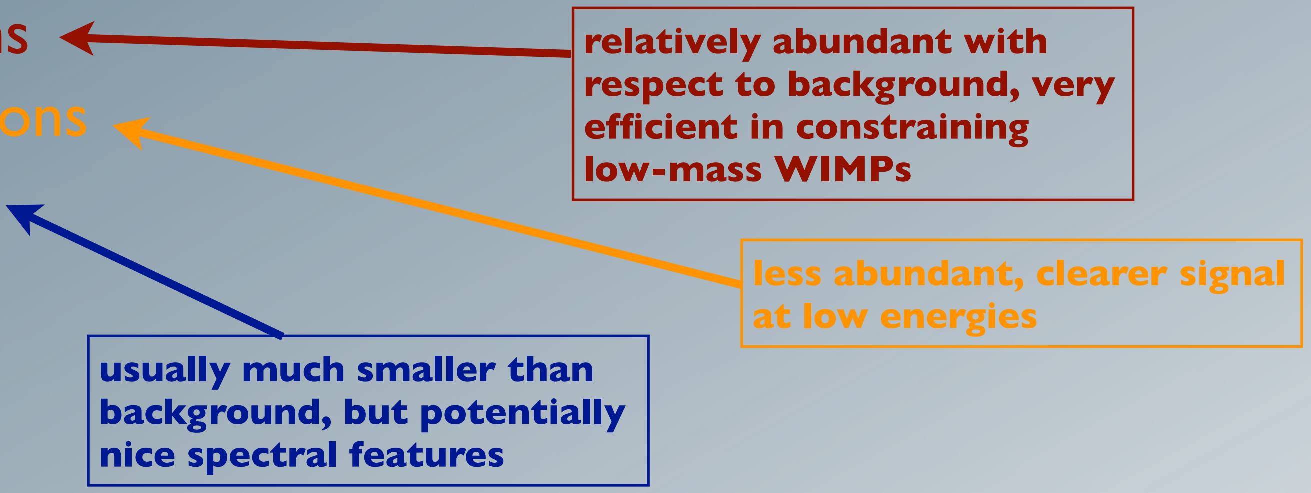
- (Semi-)analytically
  - + Physical insight from analytic solutions
  - + fast computations allow to sample full parameter space
  - − only 2D possible (axial symmetry)
  - − simplified gas distribution, energy losses, re-acceleration

e.g. Donato, Maurin, Salati, Taillet, ...



DS Routines

- Analytical expressions to calculate fluxes of
  - antiprotons
  - antideuterons
  - positrons



relatively abundant with respect to background, very efficient in constraining low-mass WIMPs

less abundant, clearer signal at low energies

usually much smaller than background, but potentially nice spectral features

- Interfaces to
  - Galprop **[for experts only]**
  - USINE **[available once USINE is public]**
  - DRAGON **[in preparation]**

SUSY DM and PAMELA

- Neutralino annihilation helicity suppressed:

$$\langle \sigma v \rangle \propto \frac{m_\ell^2}{m_\chi^2}$$

SUSY DM and PAMELA

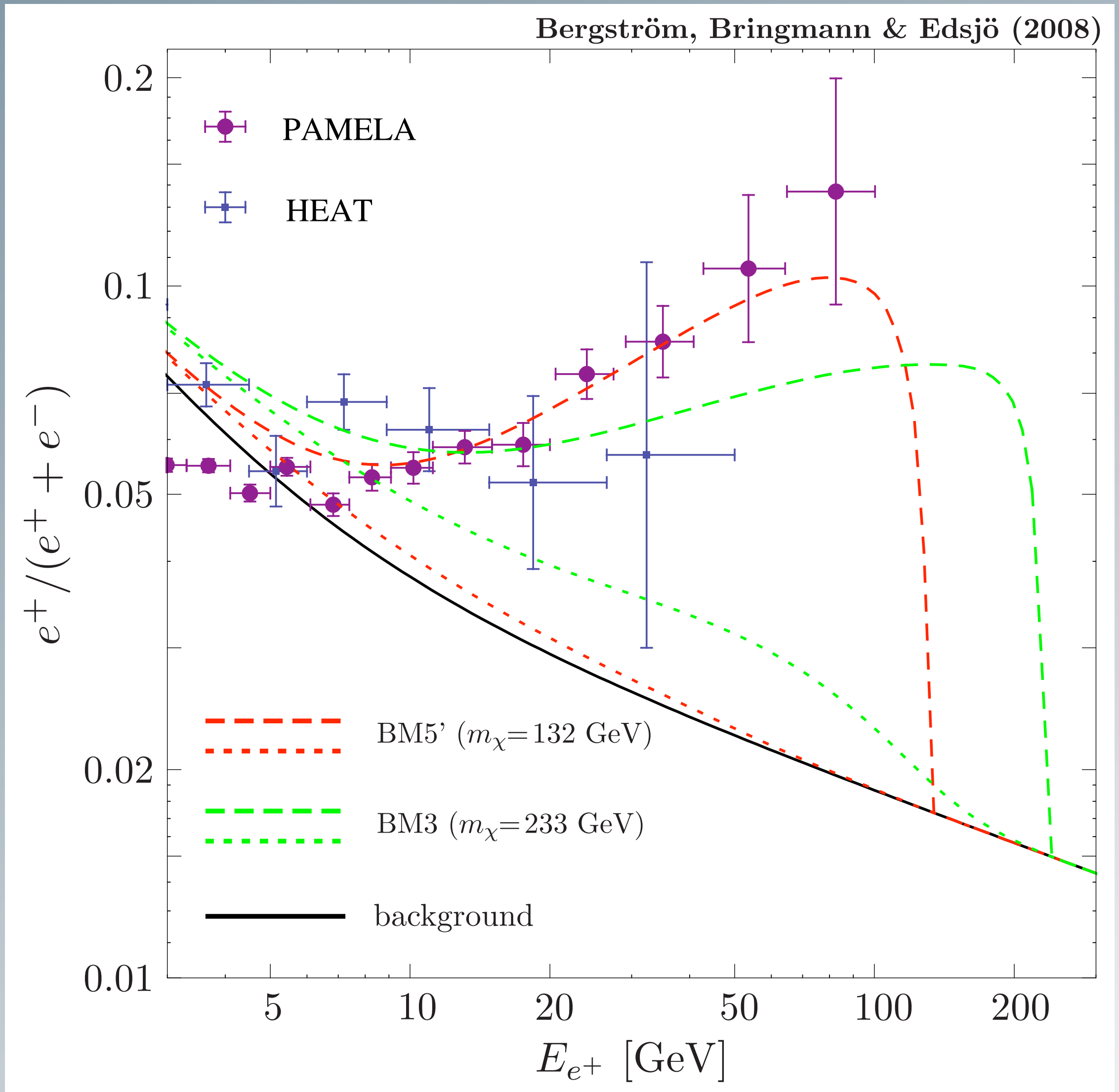
- Neutralino annihilation ~~helicity~~ suppressed:

$$\langle\sigma v\rangle \propto \cancel{\frac{m_\ell^2}{m_\chi^2}} \quad \frac{\alpha_{\rm em}}{\pi}$$

- Surprisingly hard spectra possible if $\chi\chi \rightarrow e^+e^-\gamma$ dominates!

  ➡ first attempt to connect PAMELA excess to DM

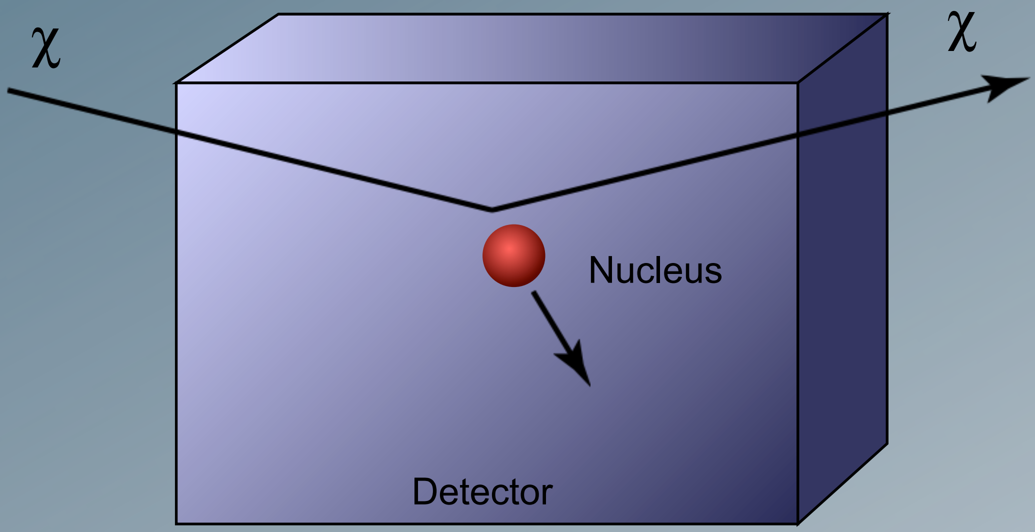
- ***but***: enormous boost factors needed w.r.t. thermal cross section...



Bergström, TB & Edsjö, PRD '08

Direct detection

General principles

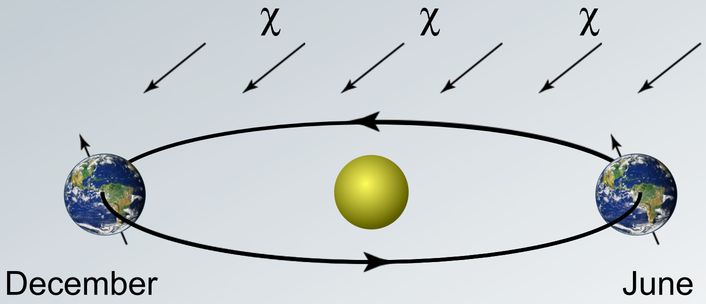


Goal:
measure
recoil energy
of nucleus

A) try to identify single events in ‘background-free’ environment

or

B) search for annual modulation of the signal



Even rates

Recoil rate:

$$\boxed{\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{2 m_\chi m_r^2} F^2(Q) \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v} dv}$$

with

$$\begin{aligned} Q &= \frac{|\mathbf{q}|^2}{2m_N} = \frac{m_r^2 v^2}{m_N}(1 - \cos\theta_{CM}) \\ v_{\rm min} &= \sqrt{\frac{Q m_N}{2 m_r^2}} \\ m_r &= \frac{m_\chi m_N}{m_\chi + m_N} \end{aligned}$$

main particle physics uncertainty
(+quark content of nucleon!)

$F(Q)$ – form factor

σ_0 – elastic scattering cross section

ρ_0 – local dark matter density ($\sim 0.3\ \mathrm{GeV/cm^3}$)

$f(v)$ – velocity distribution

main astrophysical uncertainty

Direct detection in DS

- Routines to calculate
  - spin-dependent scattering rates (couples to total spin of nucleus)
  - spin-independent scattering rates (coherent $\rightsquigarrow$ signal enhancement roughly $\propto A^2$)
  - differential as function of time
    $\rightsquigarrow$ can be used to calculate e.g. modulation signal

dsddneunuc

dsdddrde

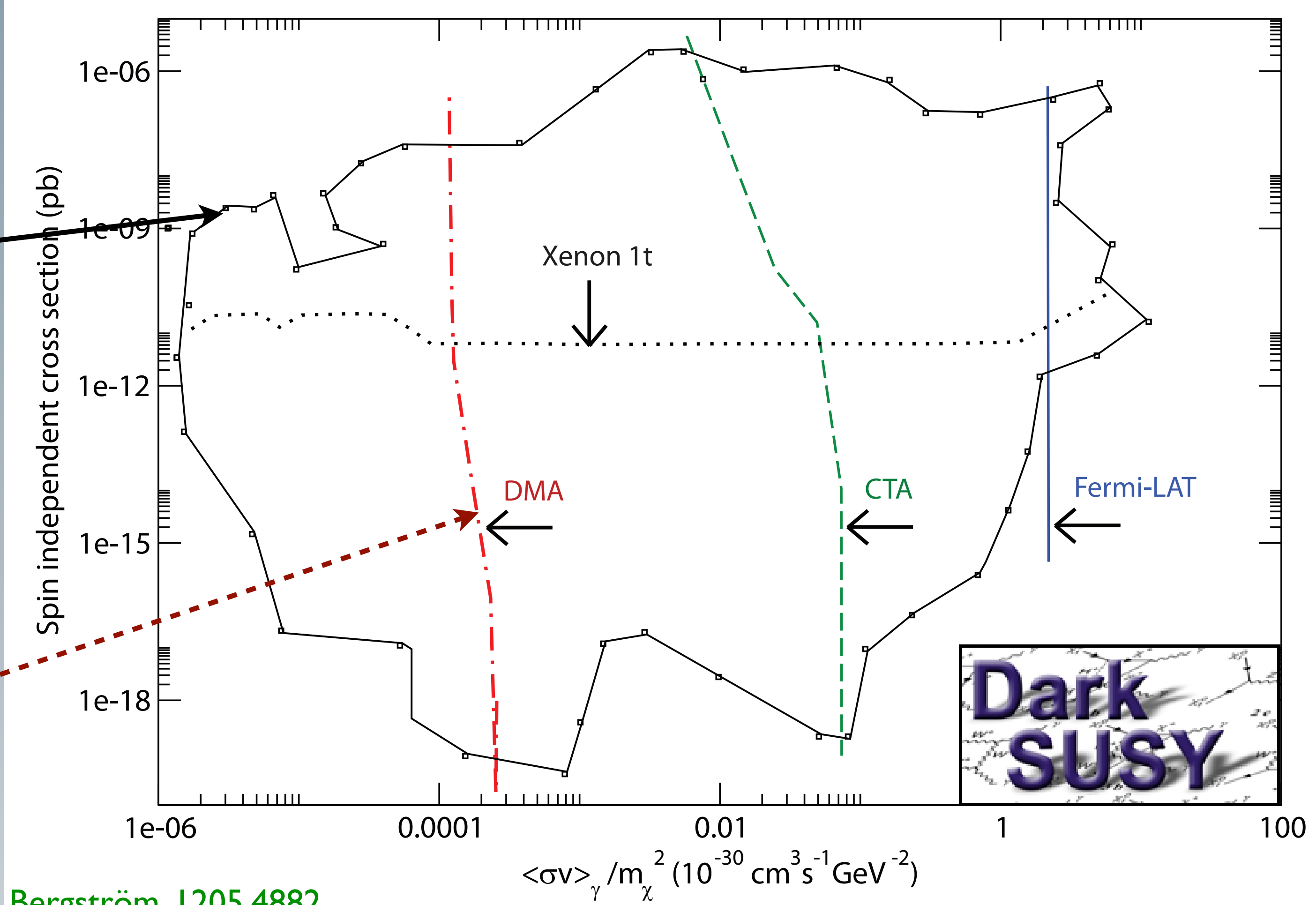
- Routines for different targets (nucleons/nuclei/compunds)
- Halo model and velocity profile can be chosen arbitrarily
- Various choices of form factors implemented

Direct vs. indirect searches

- Direct and indirect searches probe SUSY parameter space from an '**orthogonal**' direction Bergström, TB & Edsjö, PRD '11
  - remains true after most recent LHC bounds Bechtle *et al.*, JHEP '12

- MSSM scan
  - relic density, (pre-LHC) collider bounds OK
  - Galactic center (NFW, no boost)

- The "Dark Matter Array":
  - 10 x A_{eff}(CTA)
  - E > 10 GeV
  - *dedicated:* t_{obs} ~5000*h*



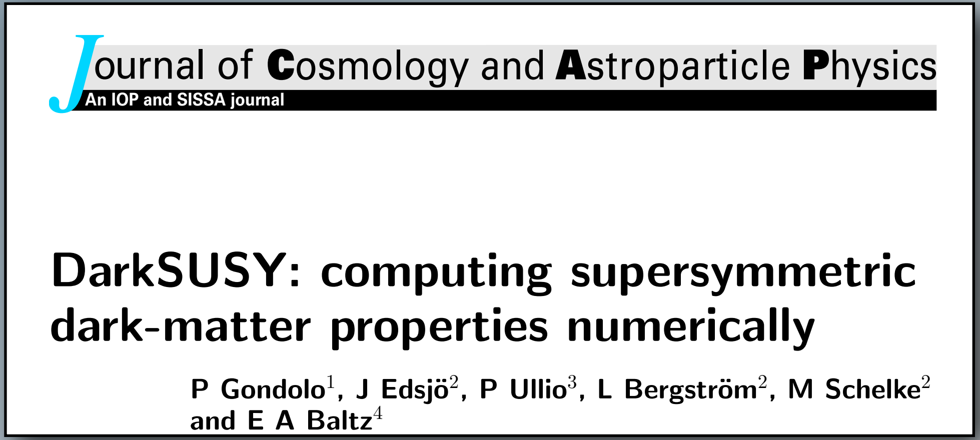
Bergström, 1205.4882

Reference + outlook

References

- Long paper (describing DS 4.1)

  JCAP **06** 004 (2004)
  [astro-ph/0406204]



Journal of **C**osmology and **A**stroparticle **P**hysics
An IOP and SISSA journal

DarkSUSY: computing supersymmetric dark-matter properties numerically

P Gondolo[1], J Edsjö[2], P Ullio[3], L Bergström[2], M Schelke[2] and E A Baltz[4]

- Current version (DS 5.1), cite as

  P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann and G. Duda, http://www.darksusy.org

NEW!

- ...but please remember to also cite relevant contributed code and implemented results from the literature when you use DarkSUSY!

DarkSUSY 6.0

Major update by the end of this year:

- restructuring of code (even more modular!)
- New refined halo annihilation and neutrino routines
- Better solar models
- Interface to USINE, DRAGON;
  improved CR propagation
- DLHA=Dark matter Les Houches Accord ?
- Going away from hard cuts to likelihoods when possible (already implemented for IceCube!)
- ...

Conclusions

Download DS @

http://www.darksusy.org

and get started…!

☺

Thanks for your attention!