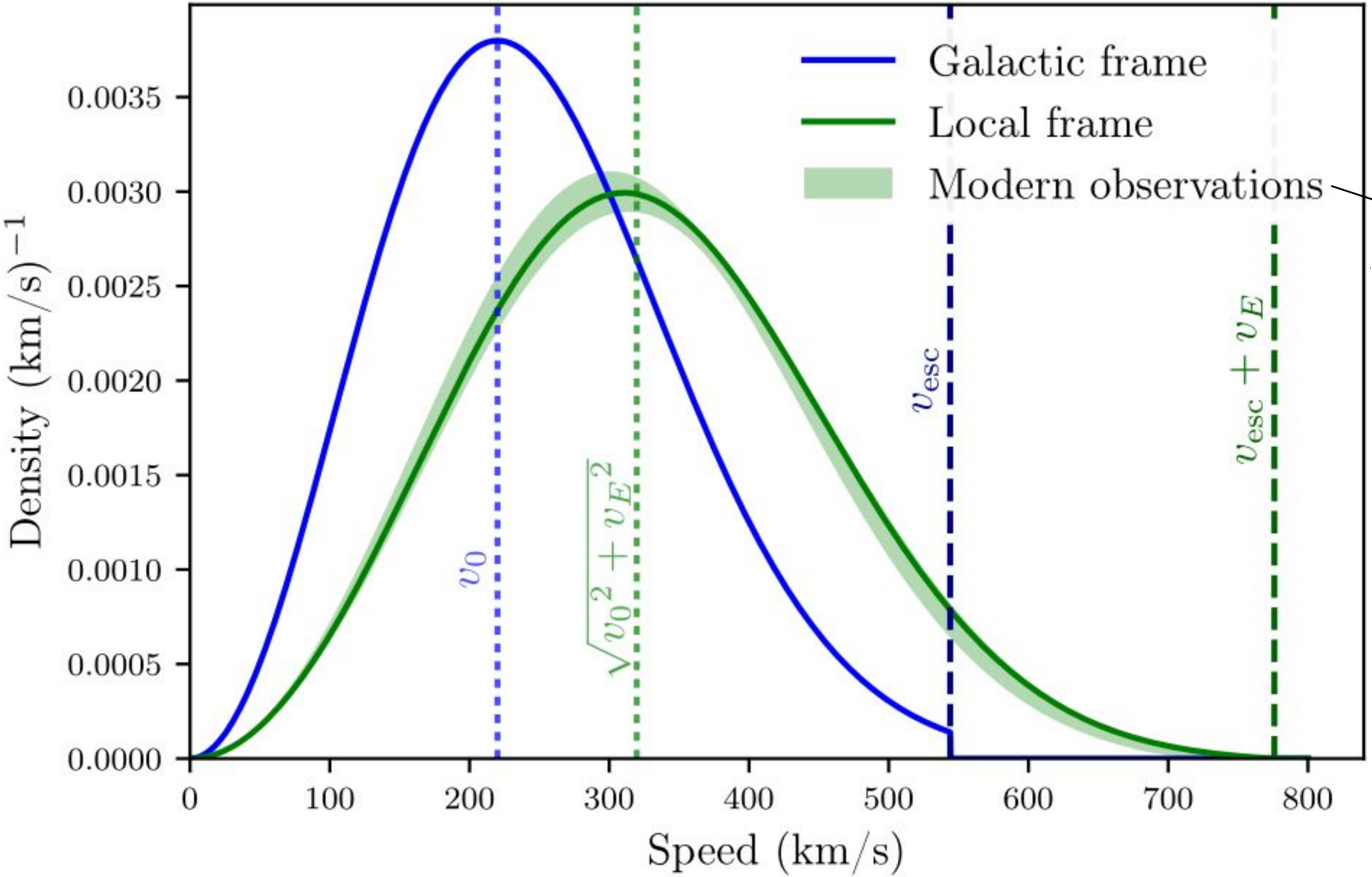
Direct dark matter detection & machine learning

Jelle Aalbers
11 April 2019

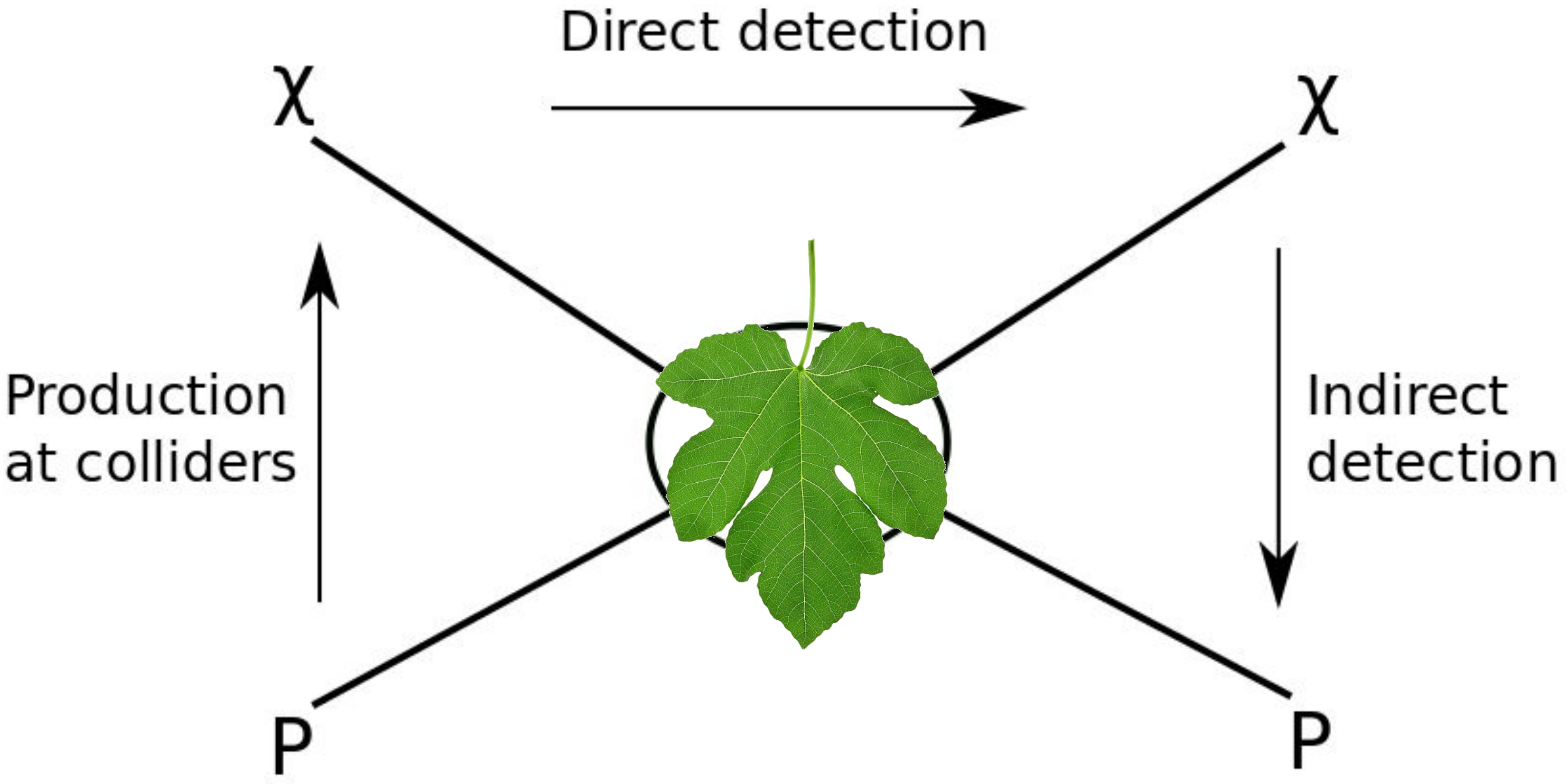
Oskar Klein centre

Stockholm University

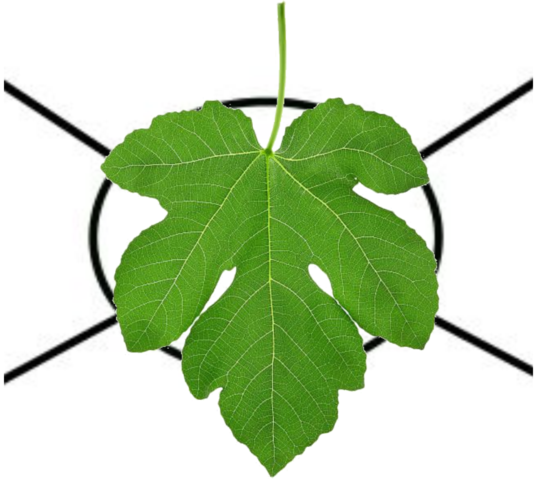
Part 1: Introduction to direct detection



… of the *parameters* of the halo model. Constraining the halo itself with observations is another issue entirely!

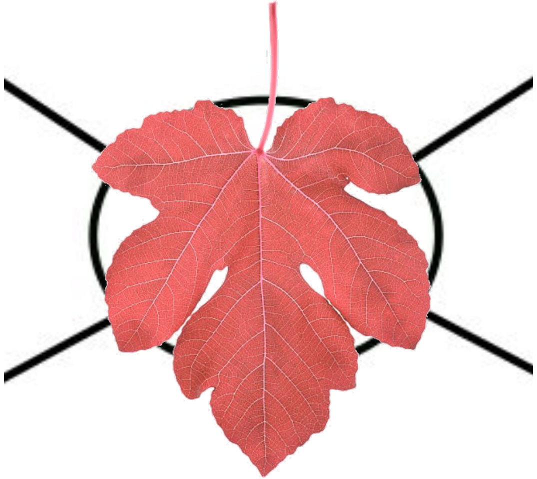


Direct detection
χ
χ
Production
at colliders
Indirect
detection
P
P



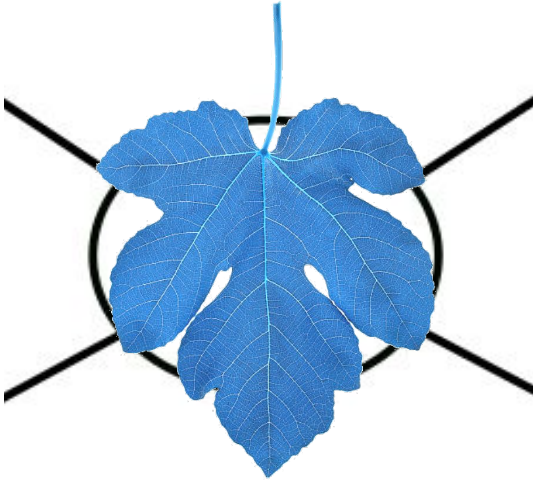
Spin-**I**ndependent

Normal, dominant
A^2 enhancement



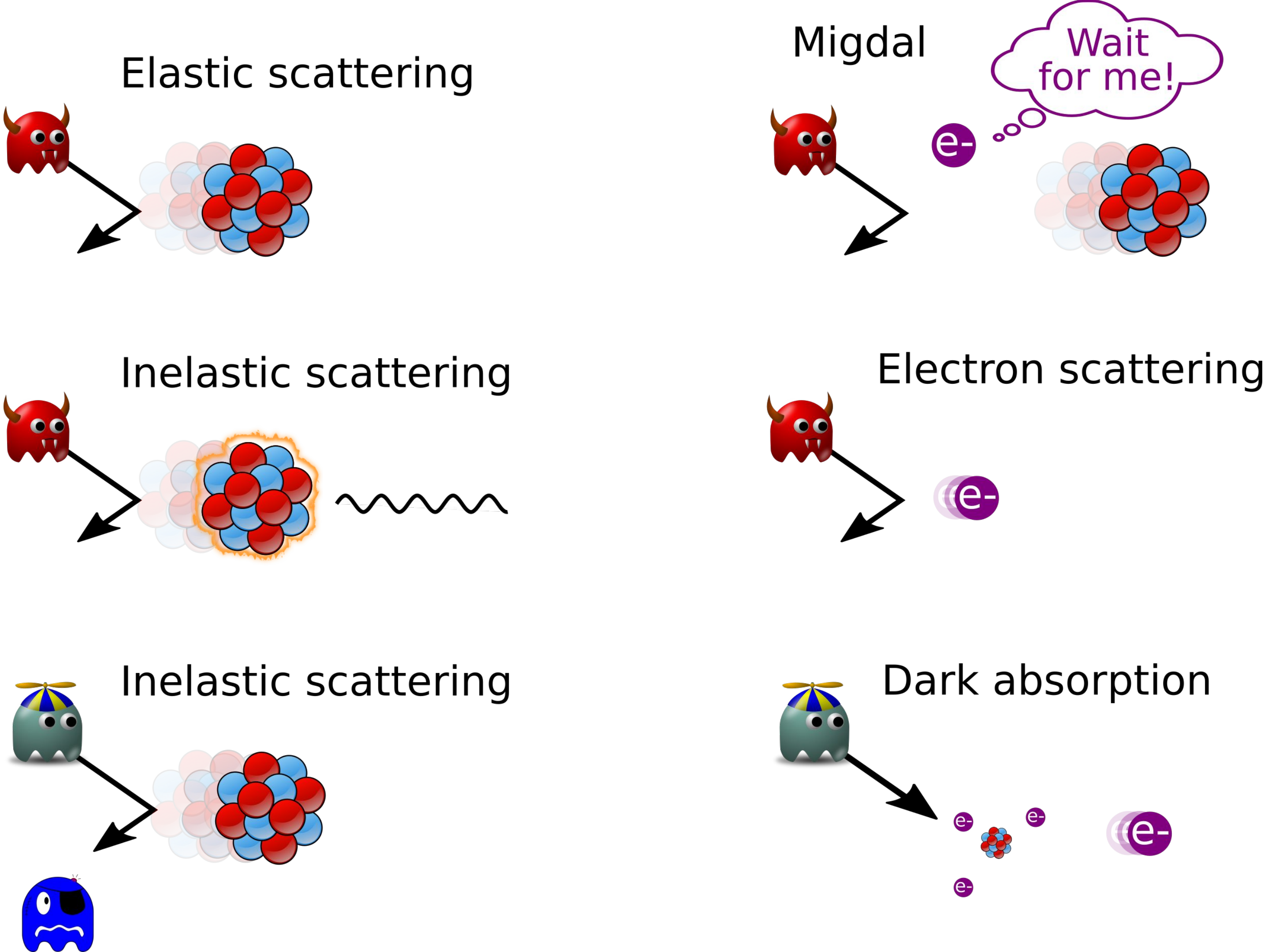
Spin-**D**ependent

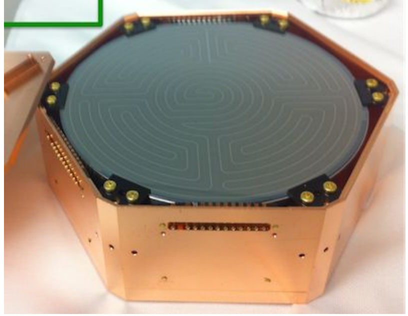
Smaller but
measurable



q^2 suppressed

Forget about
direct detection


Elastic scattering
Migdal
Wait for me!
e-
Inelastic scattering
Electron scattering
e-
Inelastic scattering
Dark absorption
e-
e-
e-
e-

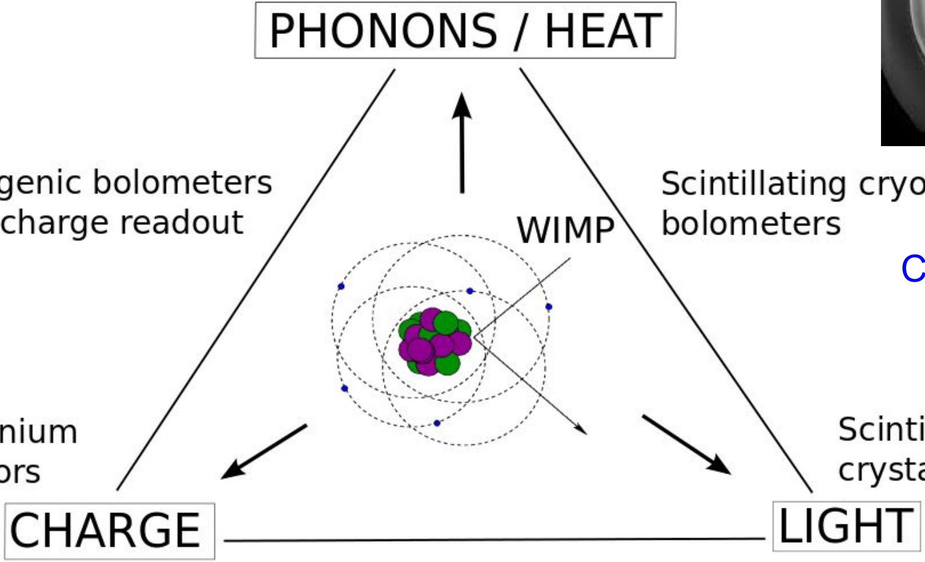


SuperCDMS
EDELWEISS

Cryogenic bolometers

Superheated liquids

PICO



Cryogenic bolometers with charge readout

Scintillating cryogenic bolometers

CRESST

CoGeNT

DAMIC
SENSEI

CCDs

Germanium detectors

Scintillating crystals

DAMA/LIBRA
COSINE, SABRE

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

XMASS, DEAP

Xenon: XENON, LUX/LZ, PandaX
Argon: DarkSide, ArDM, WArP

Requirements for a DM detector

1. Emit detectable light (photons), charge (electrons) or heat

2. Large mass

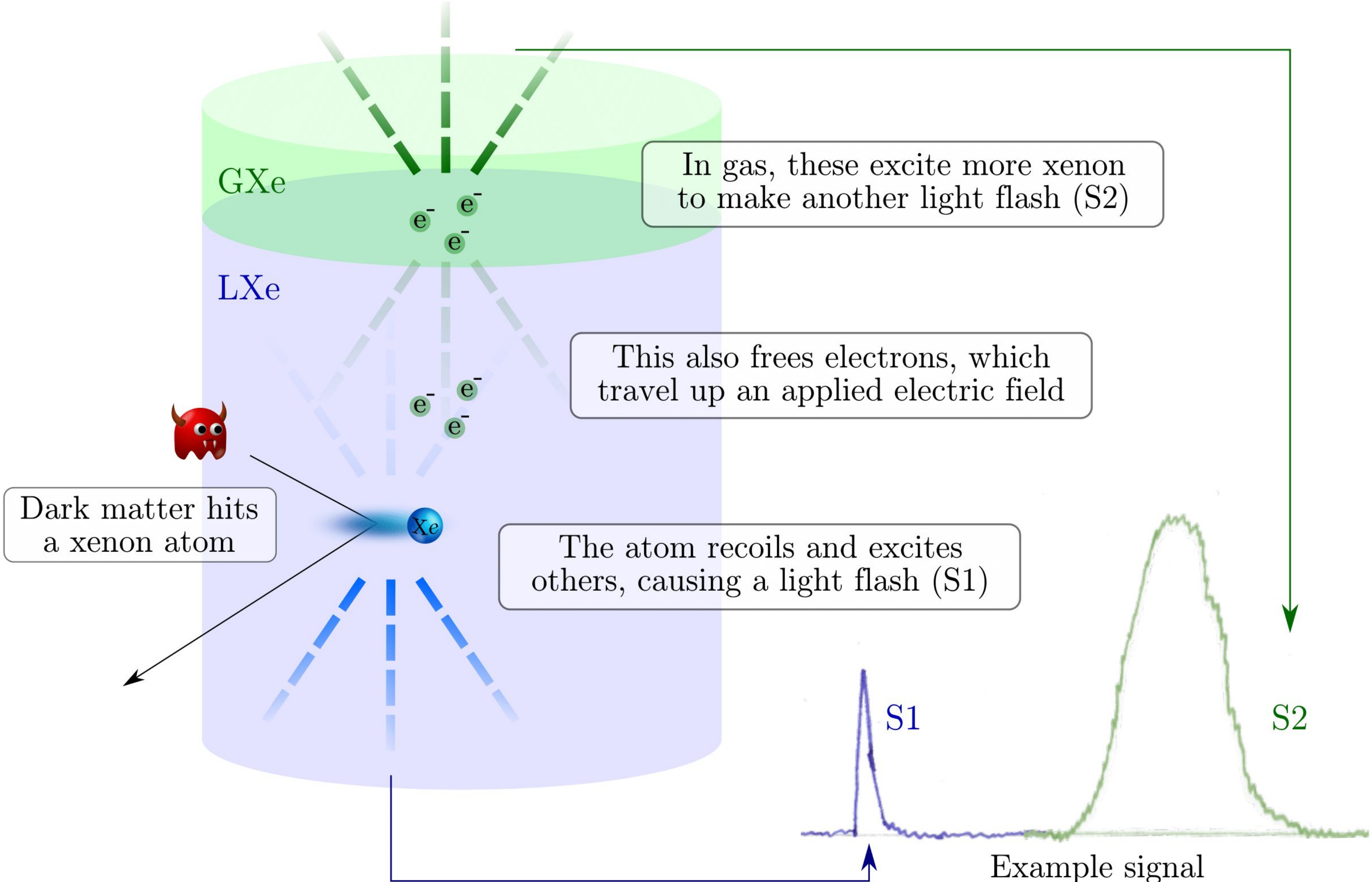
3. High atomic number

4. Low-radioactivity

5. Deep underground

Future: directional sensitivity

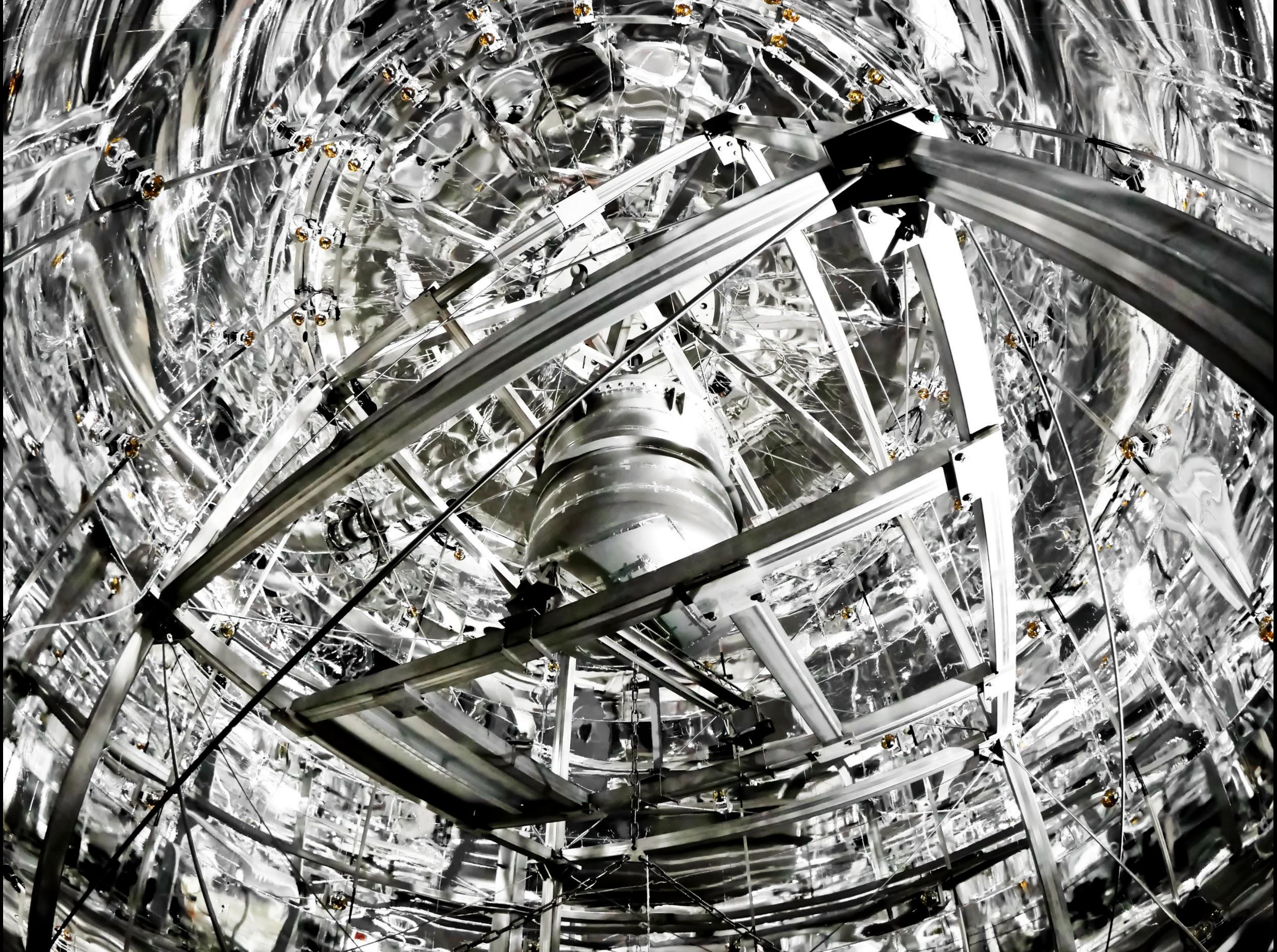
	He	Ne	Ar	Kr	**Xe**
Nucleons	4	20	40	84	**131**
Rate x	16	400	1 600	7 056	**17 161**



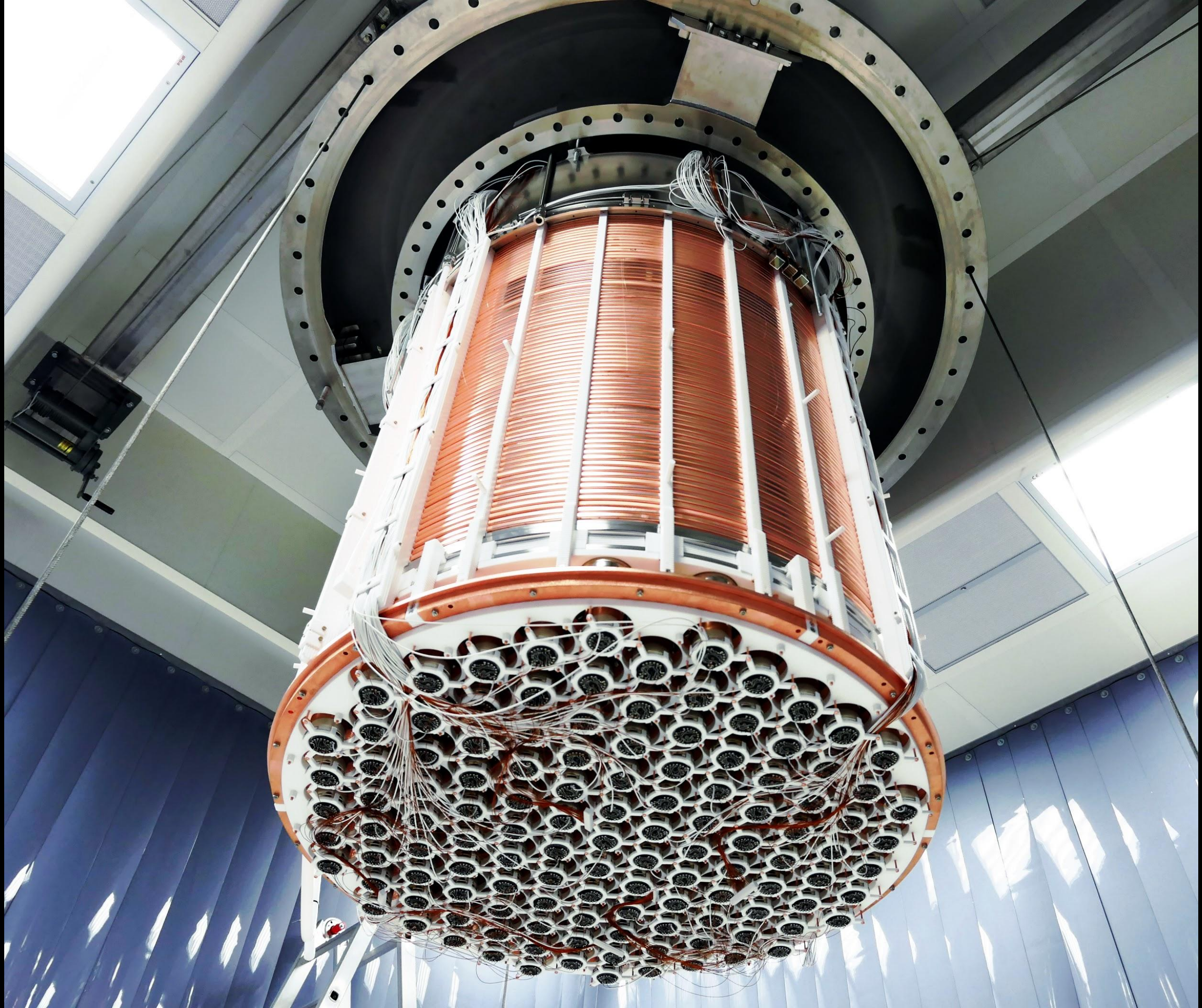
GXe
LXe
In gas, these excite more xenon to make another light flash (S2)
This also frees electrons, which travel up an applied electric field
Dark matter hits a xenon atom
Xe
The atom recoils and excites others, causing a light flash (S1)
S1
S2
Example signal

XENON collaboration

Image: S. Breur



XENON collaboration



XENON collaboration

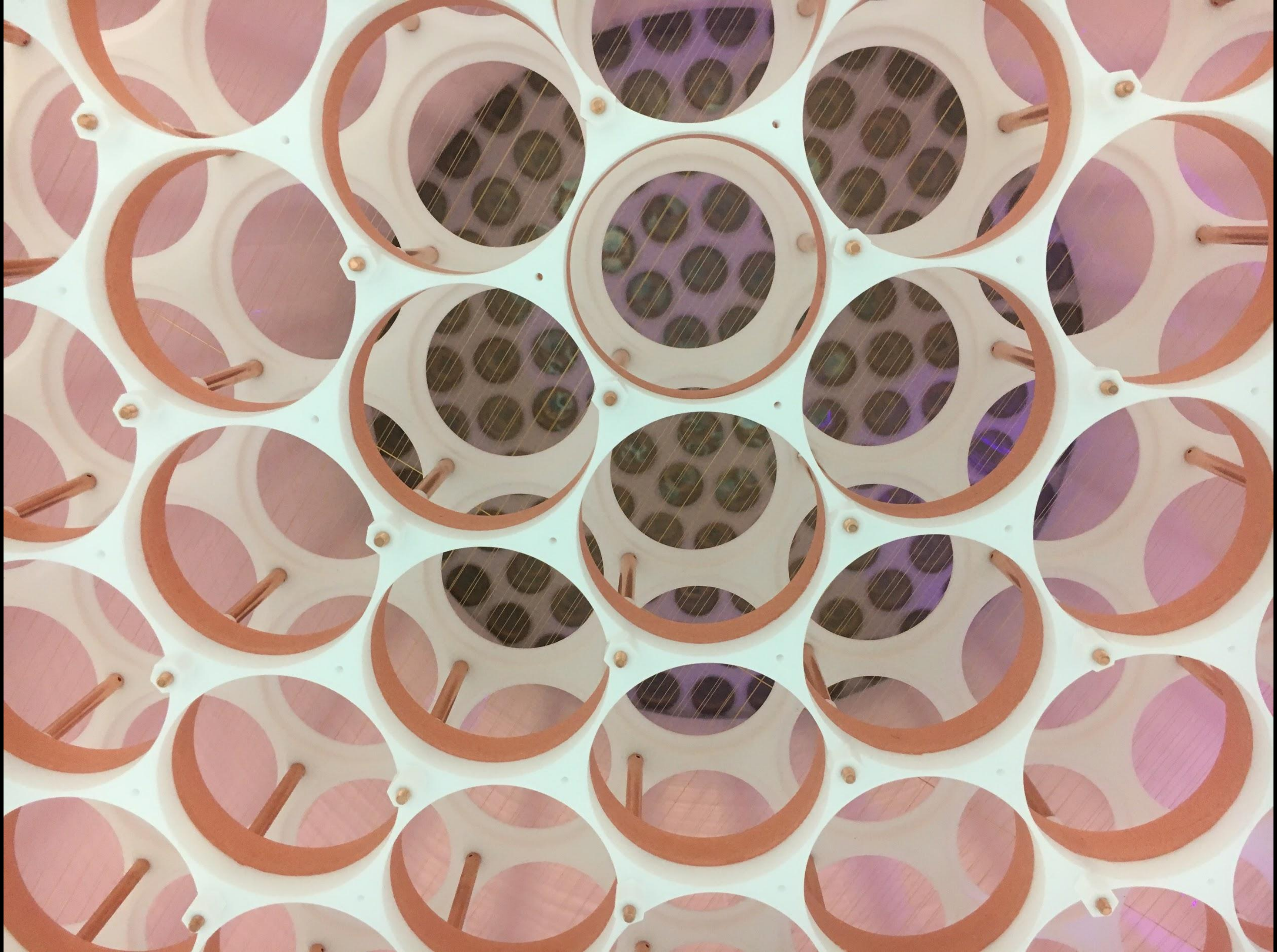
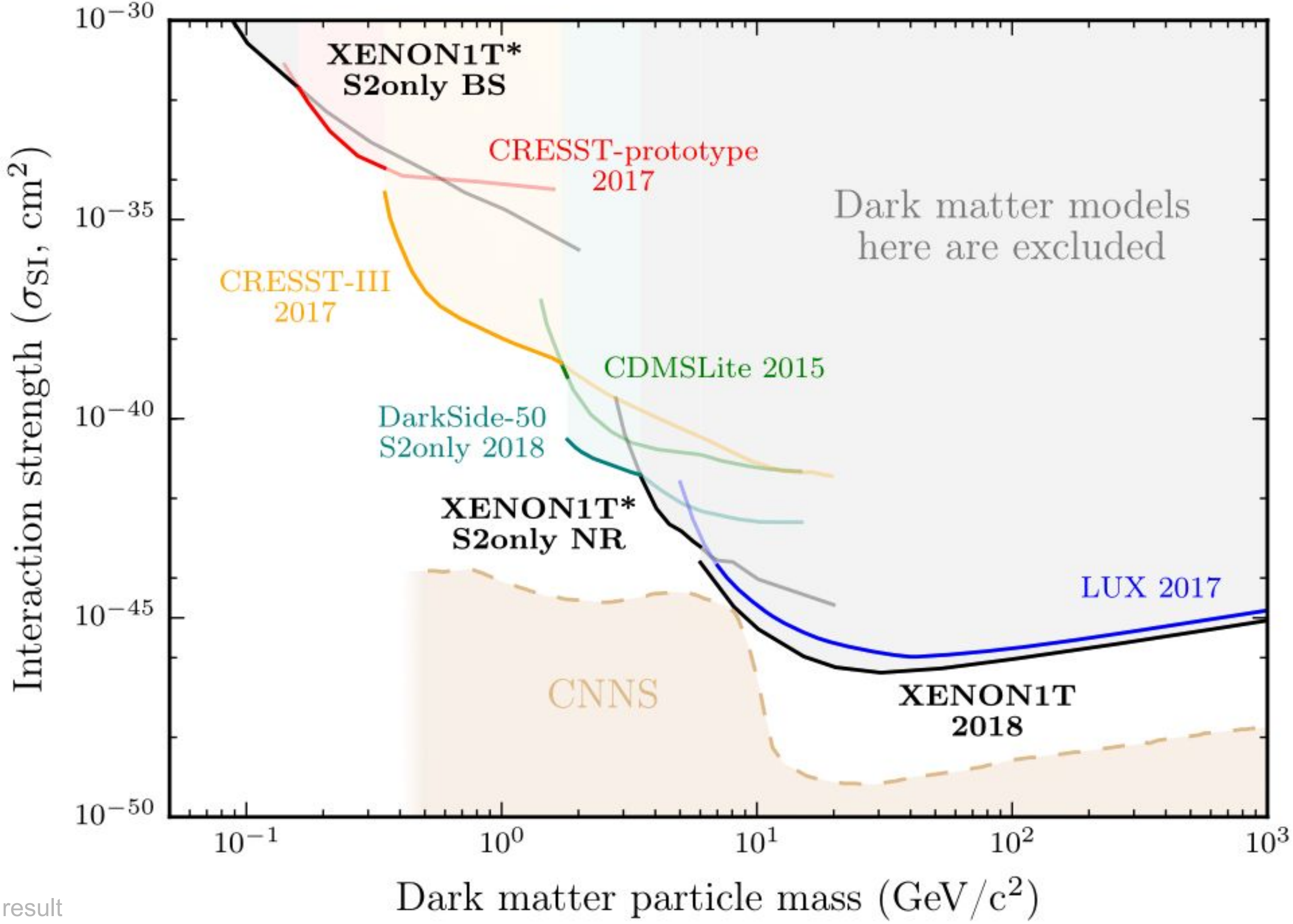
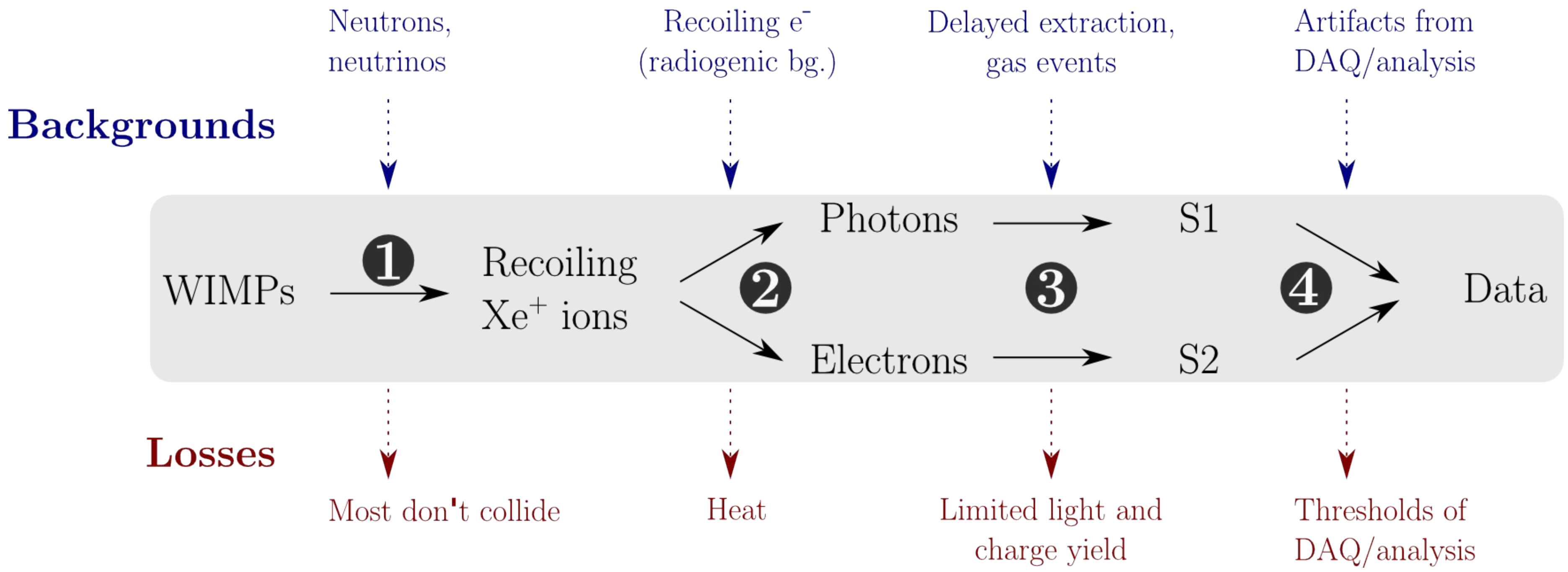


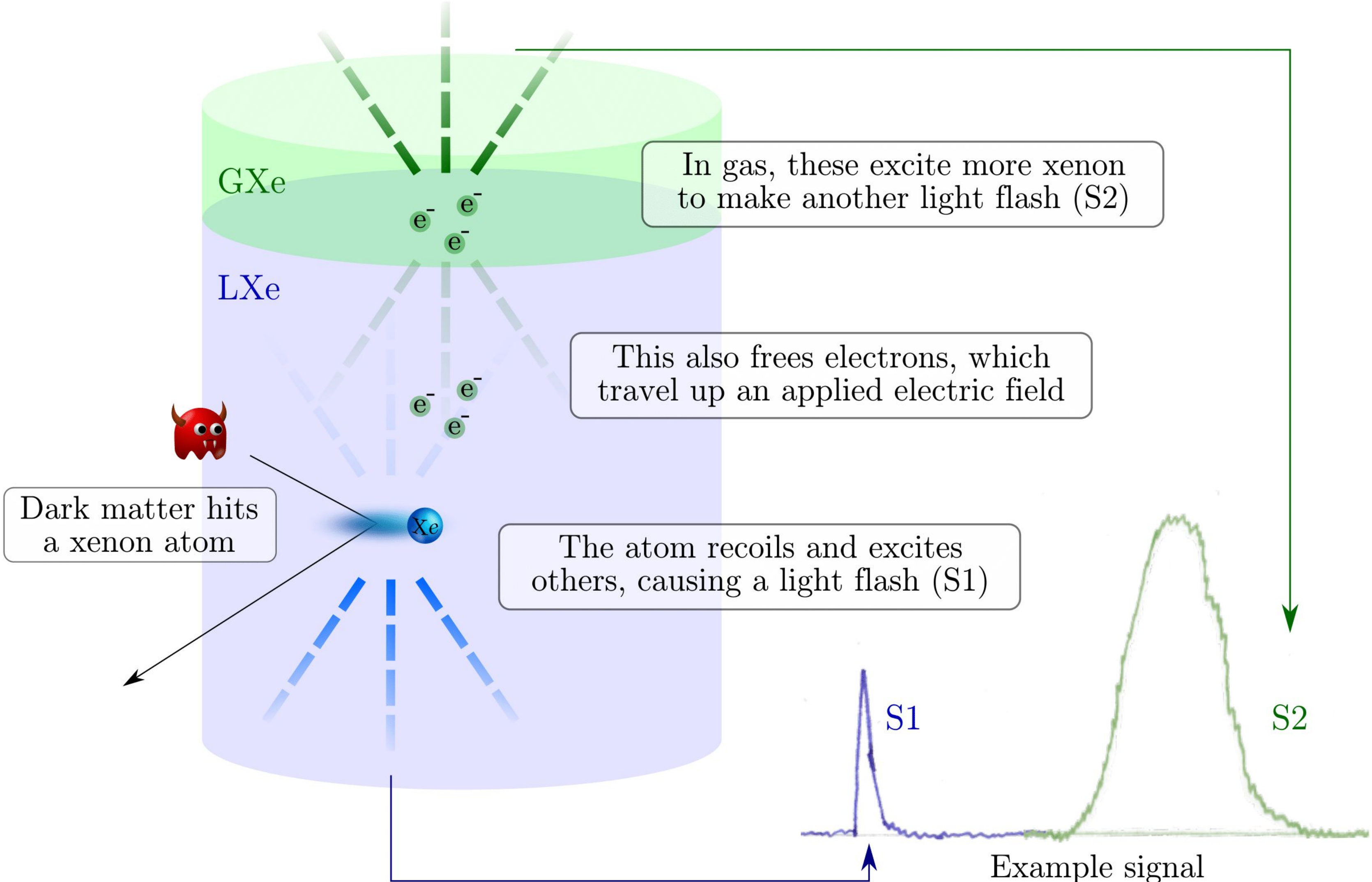
Image:
L. Grandi



*: proof-of-concept result
from my PhD thesis (UvA 2018)

Part 2: XENON1T data analysis


Backgrounds
Neutrons,
neutrinos
Recoiling e⁻
(radiogenic bg.)
Delayed extraction,
gas events
Artifacts from
DAQ/analysis
WIMPs
1
Recoiling
Xe+ ions
2
Photons
Electrons
3
S1
S2
4
Data
Losses
Most don't collide
Heat
Limited light and
charge yield
Thresholds of
DAQ/analysis



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Xe
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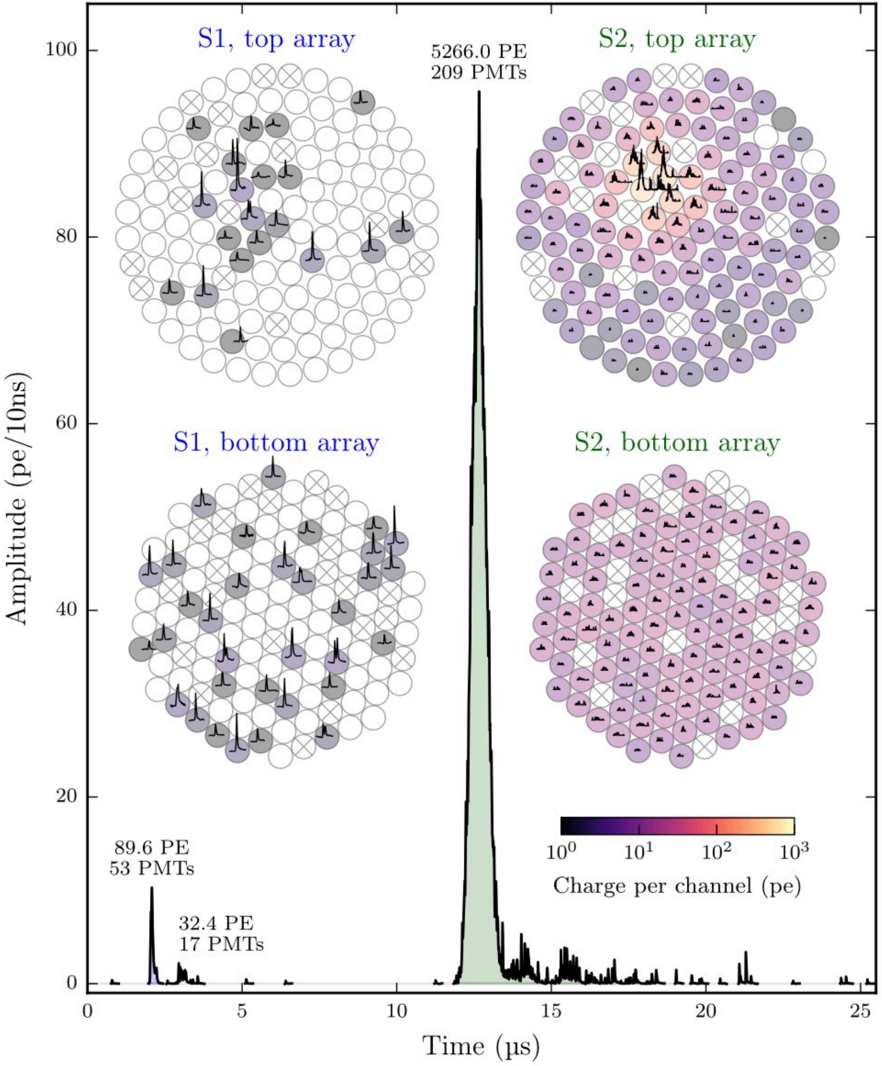
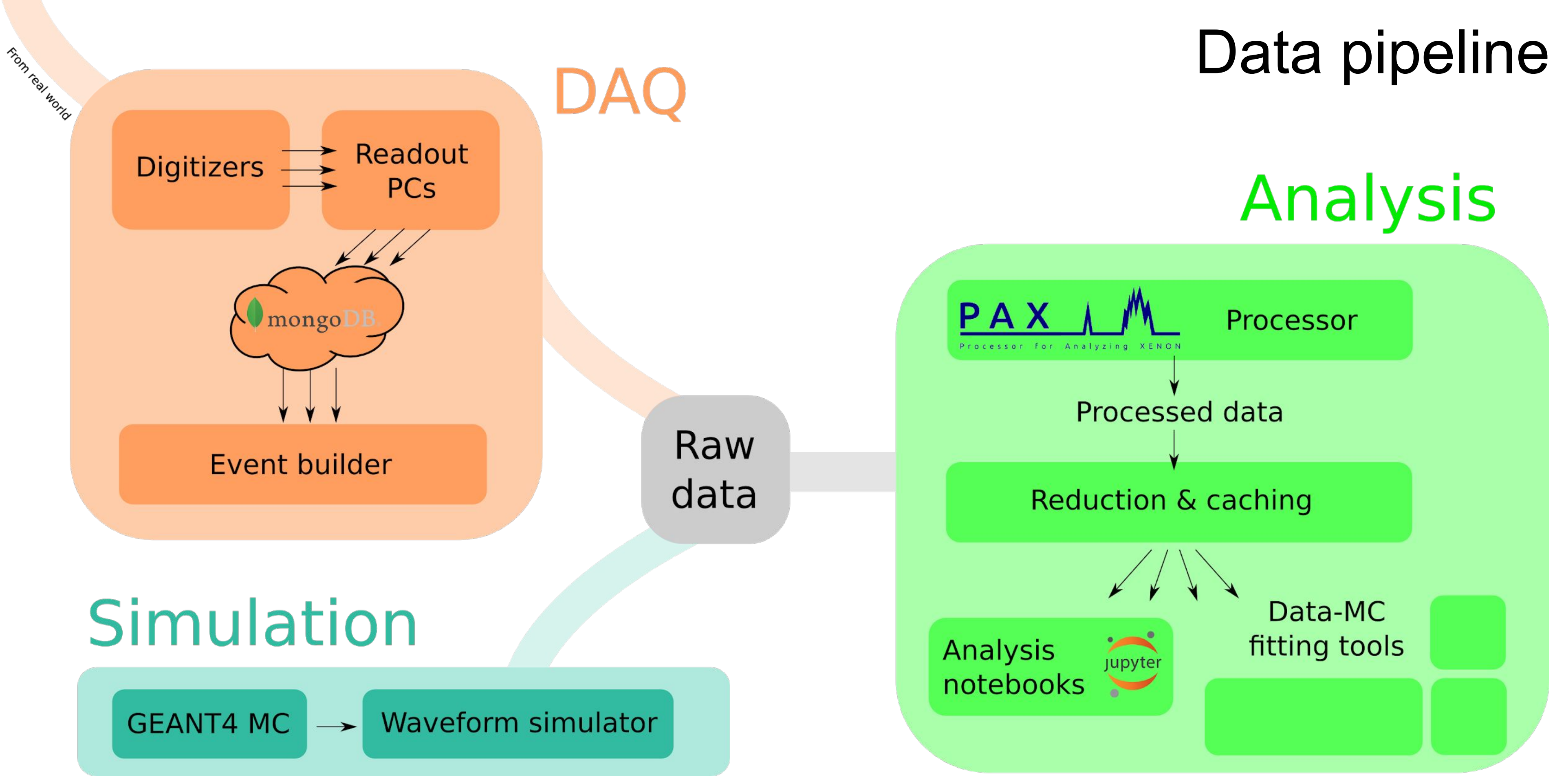
S1
S2
Example signal



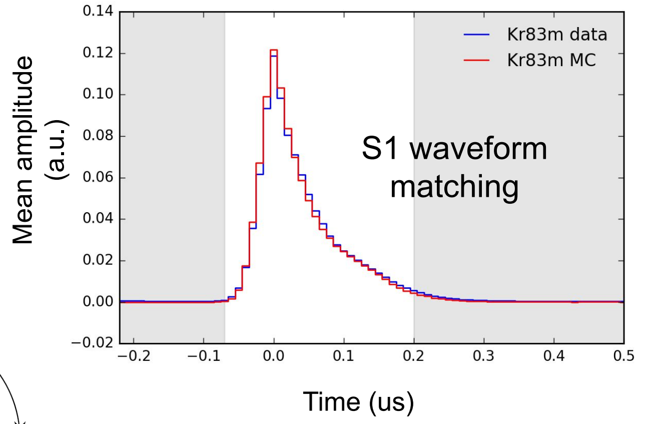
S1, top array
5266.0 PE
209 PMTs
S2, top array
S1, bottom array
S2, bottom array
89.6 PE
53 PMTs
32.4 PE
17 PMTs
Amplitude (pe/10ns)
Time (µs)
Charge per channel (pe)

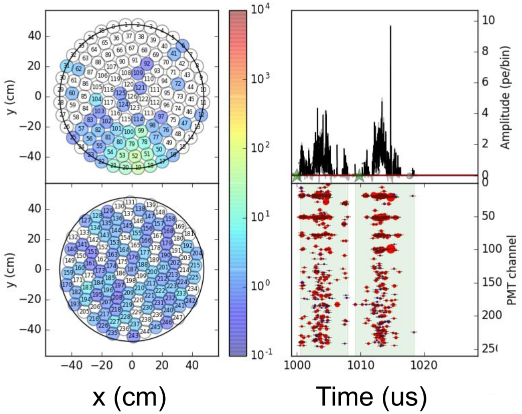
Data pipeline



[https://github.com/XENON1T]

Processor & simulator calibration



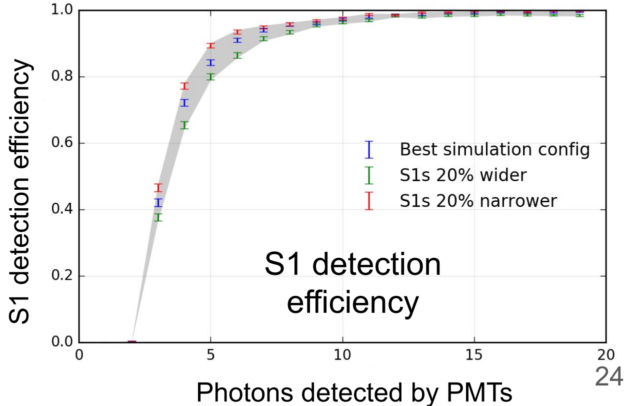


Measure simulator / data agreement

Improve simulator

Measure performance on simulated data

Improve processor



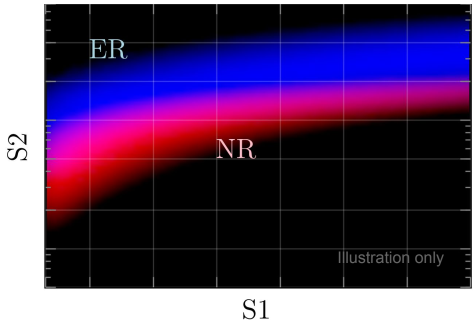
Keeping the cycle virtuous:

- Humans examine processed events
- Simulator contains (mostly) physical models
- Simulator injects statistical variation, processor must be generic

Processor and simulator: [https://github.com/XENON1T/pax]

Backgrounds

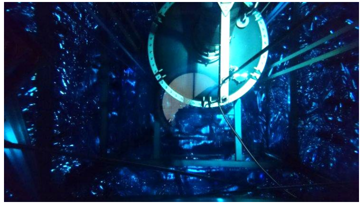
	Extrinsic	Intrinsic
Electronic recoil	Radiogenic γ, β	^{222}Rn progeny (β) ^{85}Kr (β) ν-electron scattering ^{136}Xe ββ
Nuclear recoil	Radiogenic neutrons Cosmogenic (μ-induced) n	Coherent ν-nucleus sc.



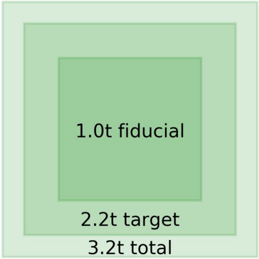
S1/S2 discrimination

^{85}Kr distillation
[arxiv:1612.04284]

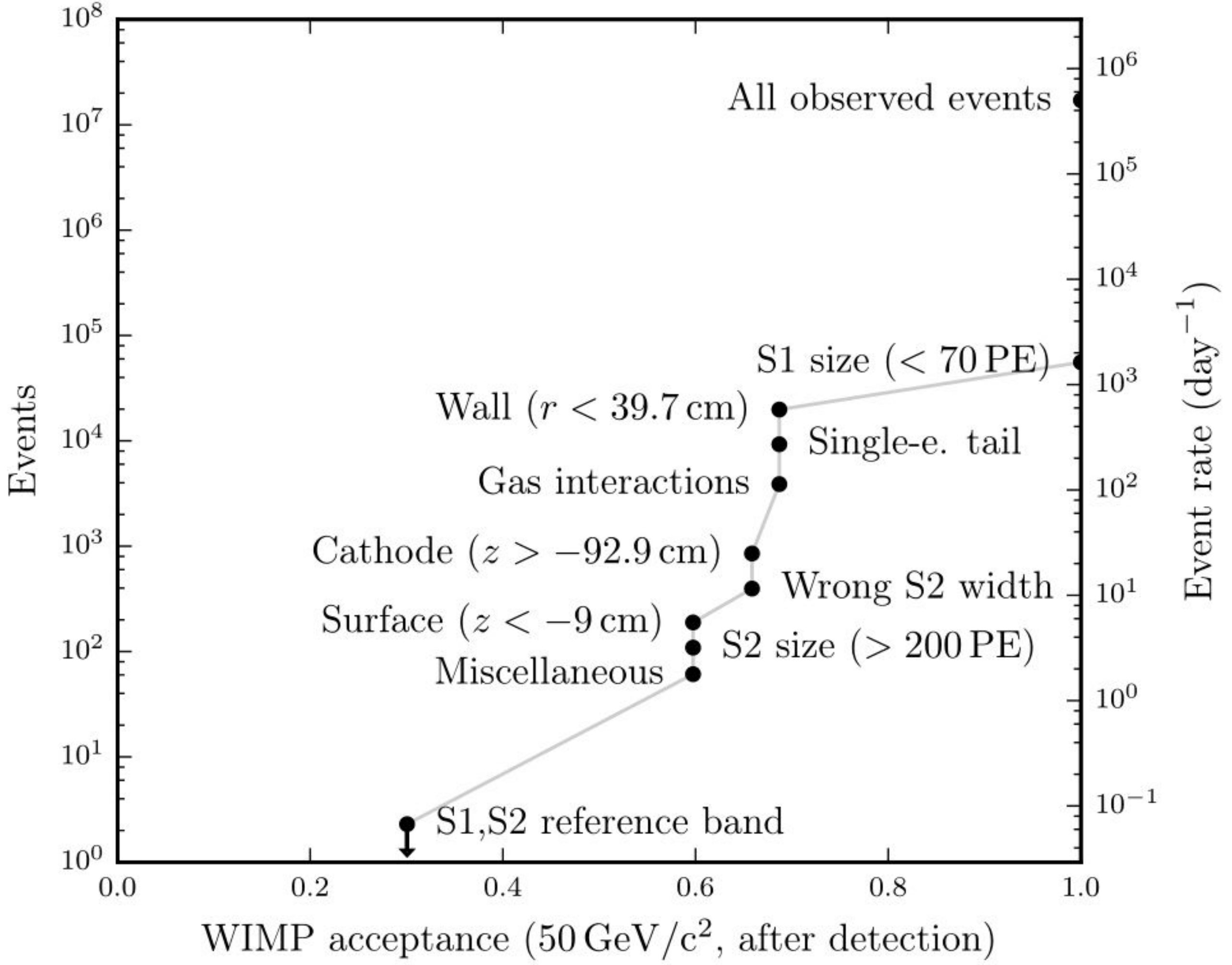
Gran Sasso mountain
3.6 km water eq.



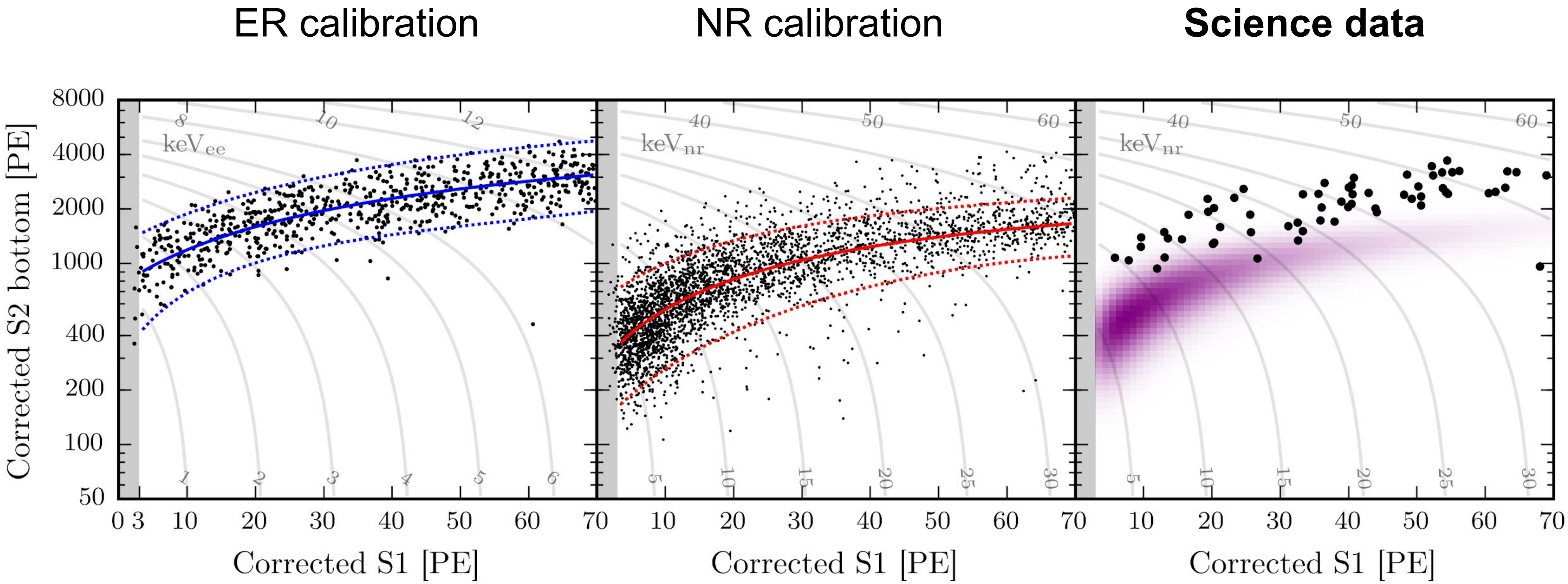
Instrumented water shield
10m high, 10m diam.
[https://arxiv.org/abs/1406.2374]



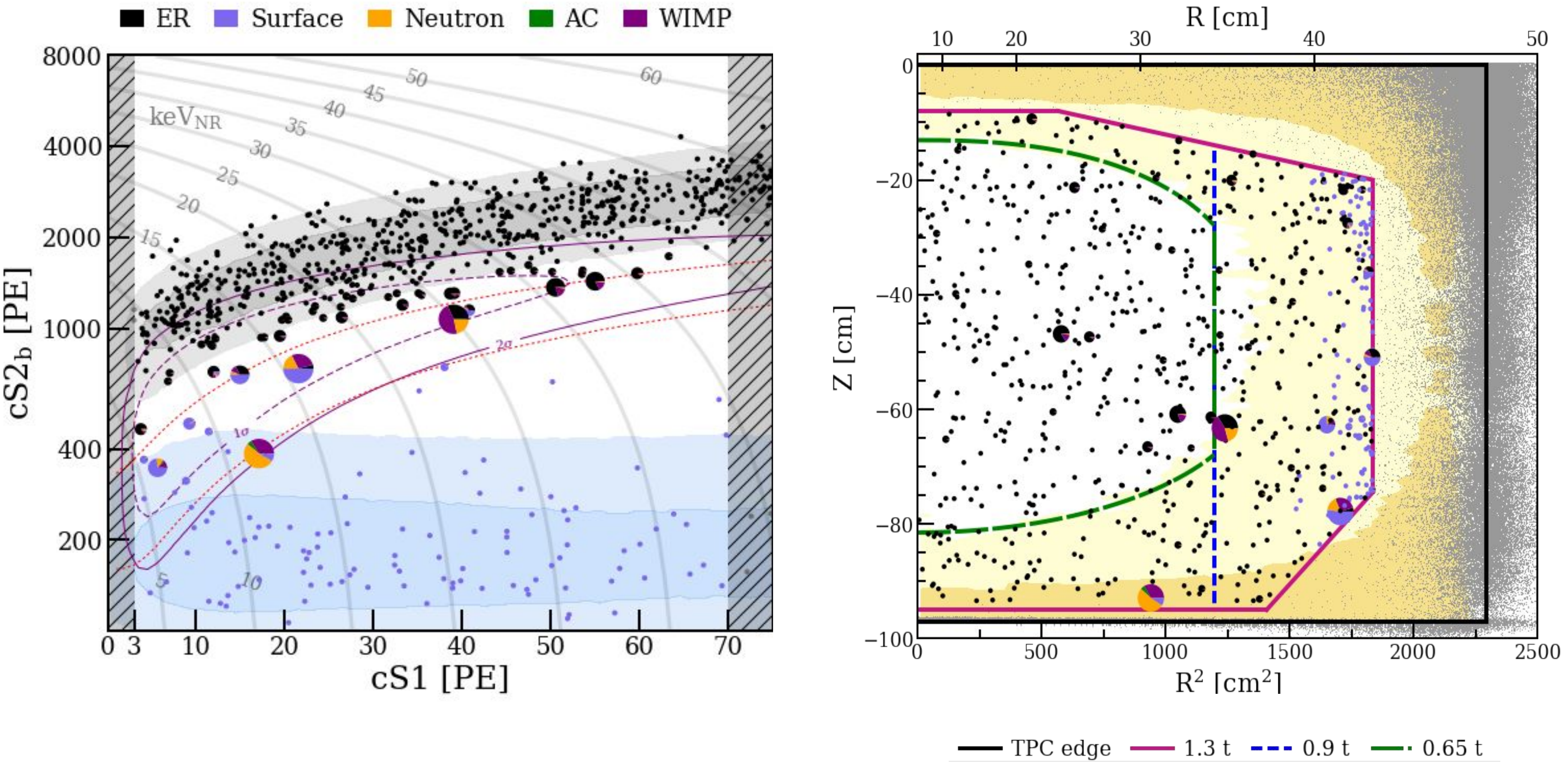
LXe self-shielding



All observed events
S1 size (< 70 PE)
Wall ($r < 39.7\,\mathrm{cm}$)
Single-e. tail
Gas interactions
Cathode ($z > -92.9\,\mathrm{cm}$)
Wrong S2 width
Surface ($z < -9\,\mathrm{cm}$)
S2 size (> 200 PE)
Miscellaneous
S1,S2 reference band
Events
Event rate (day^{-1})
WIMP acceptance ($50\,\mathrm{GeV/c^2}$, after detection)
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6
0.0 0.2 0.4 0.6 0.8 1.0



This data is from XENON1T’s first science run; we since took a longer run, but the principle is the same.



ER
Surface
Neutron
AC
WIMP
keV$_{NR}$
cS2$_b$ [PE]
cS1 [PE]
R [cm]
Z [cm]
R^2 [cm^2]
TPC edge
1.3 t
0.9 t
0.65 t

PHYSTAT-DM

Stockholm 2019

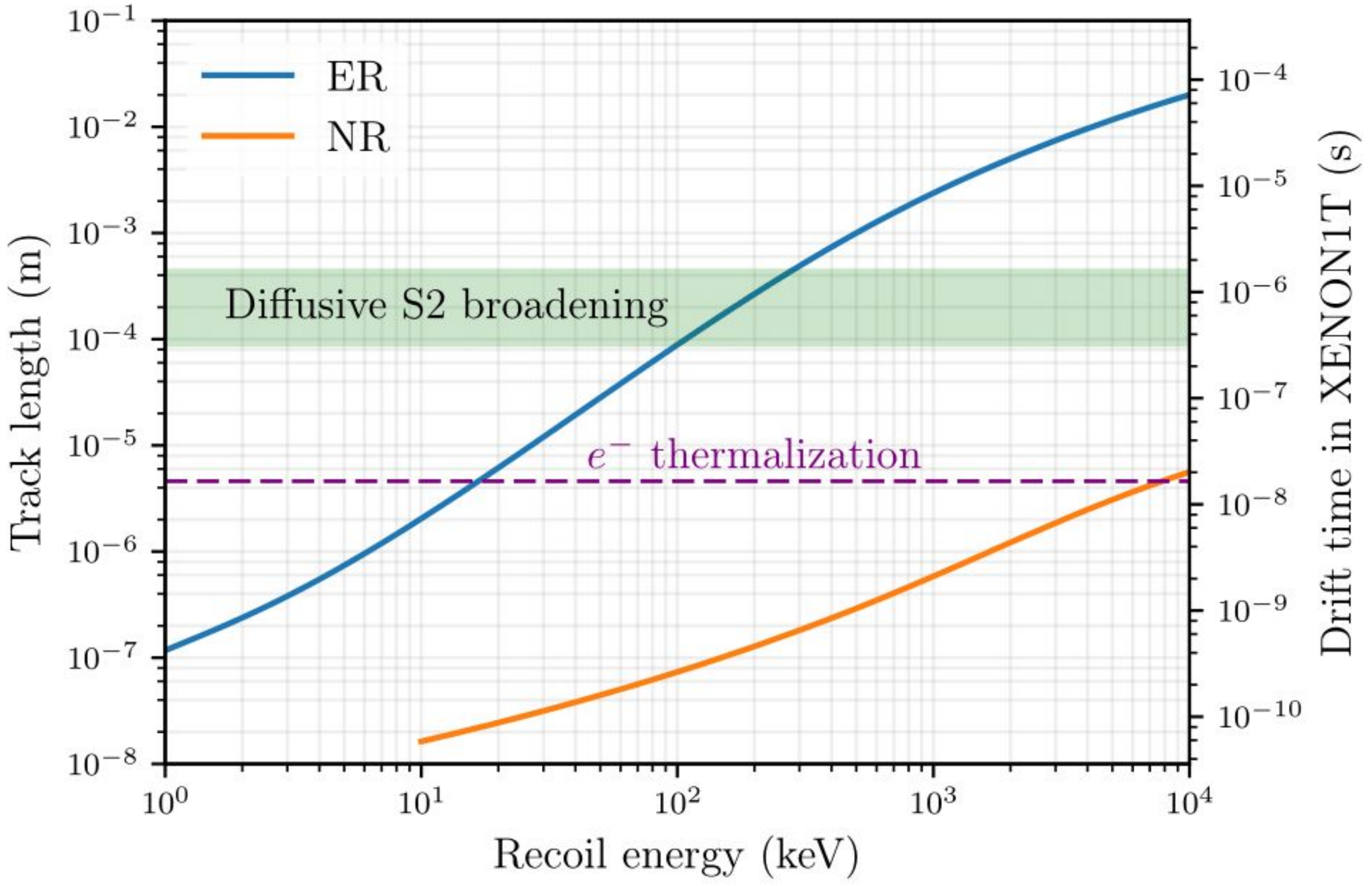
Want to hear more or discuss about statistical issues in direct detection?

Stockholm

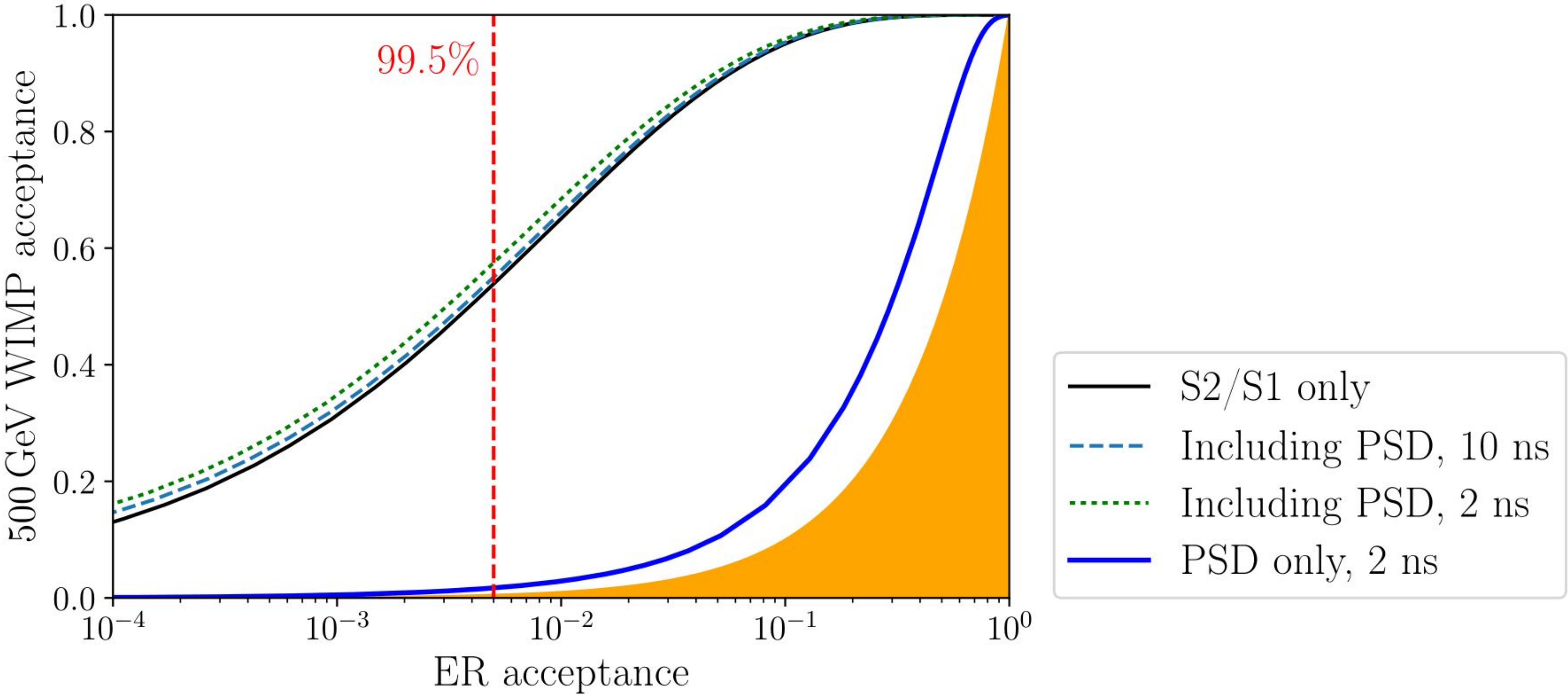
31 July - 2 August 2019

Open for abstracts now

https://indico.cern.ch/event/769726/



ER
NR
Diffusive S2 broadening
e^- thermalization
Track length (m)
Drift time in XENON1T (s)
Recoil energy (keV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^0
10^1
10^2
10^3
10^4



Hogenbirk, E. *et al.* JINST 13 (2018) no.05, P05016 arXiv:1803.07935

Part 3: Machine learning

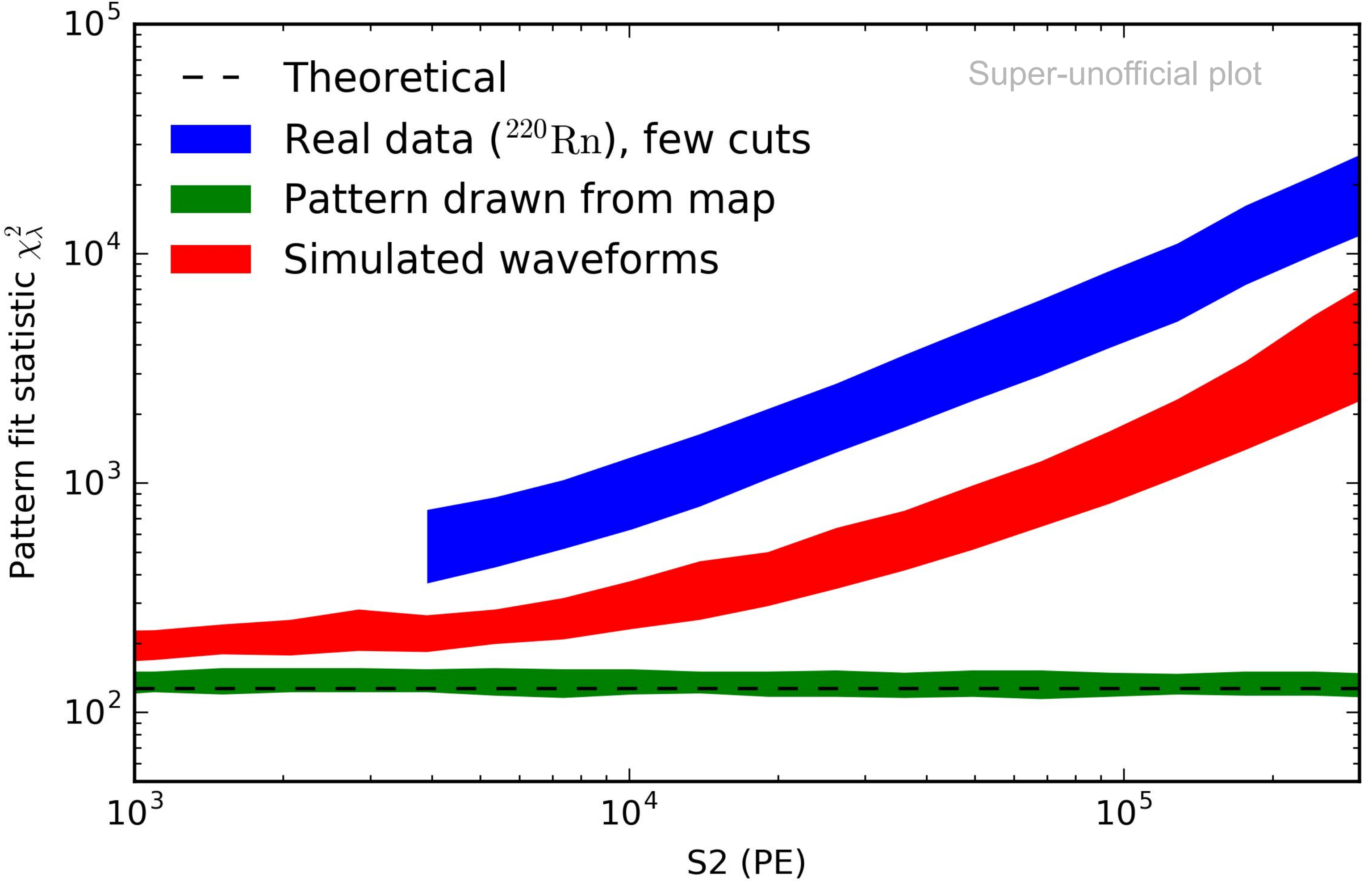
Position reconstruction

Can you beat the machine?
https://pelssers.github.io/reconstruct/

Legend:

TPF: TopPatternFit, likelihood maximizer
NN: Neural net (old-style, few-layer, fully-connected)
RWM: Iterated weighted mean over shrinking set
MP: Maximum PMT
WM: Weighted mean

Javascript game
by Bart Pelssers

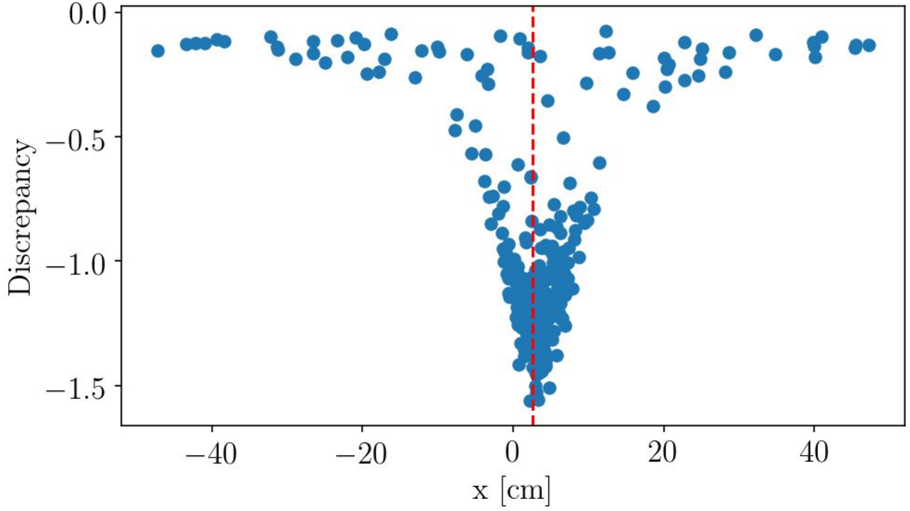


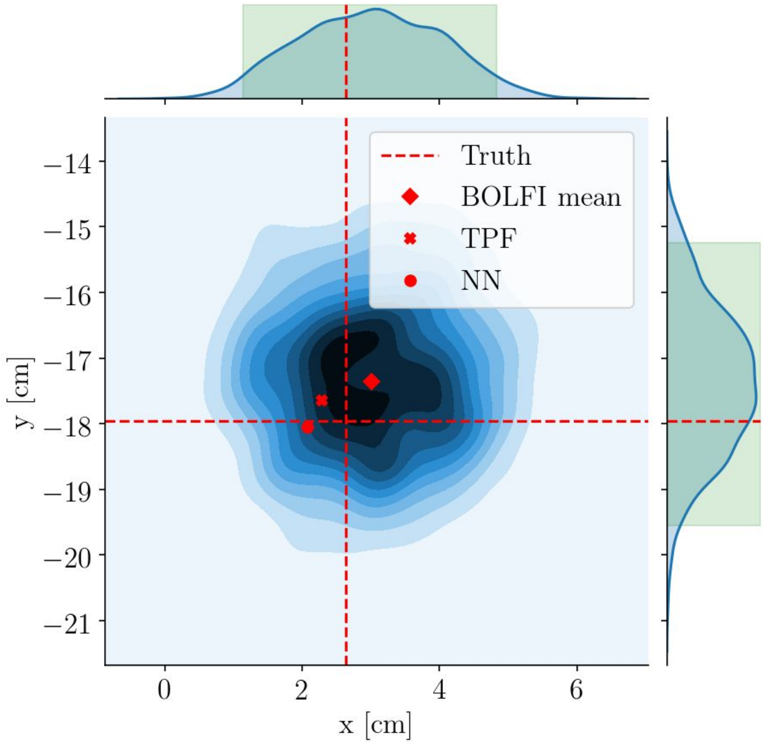
Theoretical
Real data ($^{220}\mathrm{Rn}$), few cuts
Pattern drawn from map
Simulated waveforms
Super-unofficial plot
Pattern fit statistic χ^2_λ
S2 (PE)
10^2
10^3
10^4
10^5

Reconstruction using BOLFI

Work by Bart Pelssers and Umberto Simola
JINST 14 (2019) / arXiv:1810.09930

Basic idea:
Sample position from prior/posterior
Run simulator
Measure goodness of fit (summary stat.)
Update posterior
Repeat





~15% improvement over likelihood fitter
(because the likelihood is incomplete)

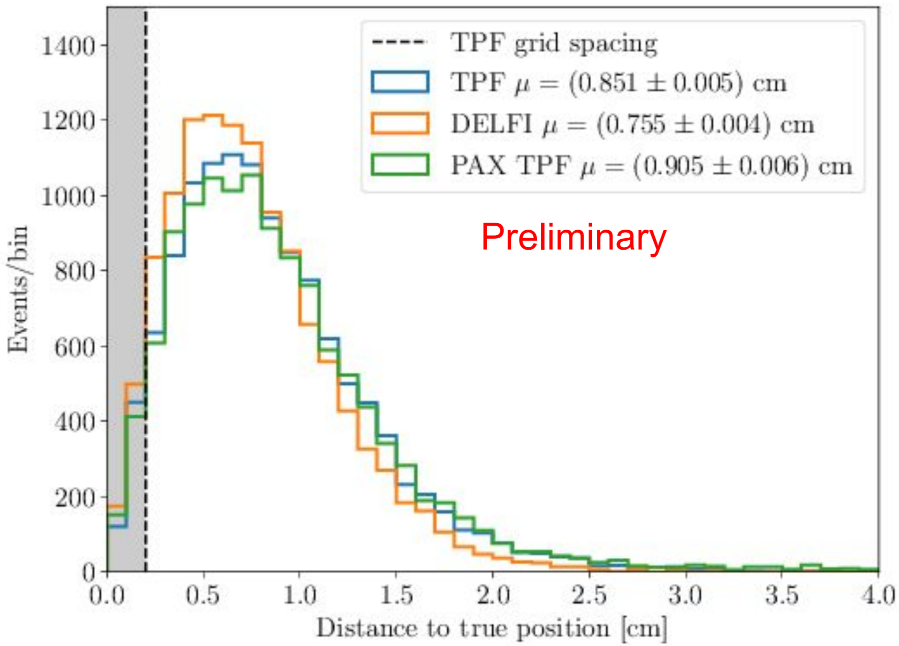
Work by Bart Pelssers and Justin Alsing
Using Pydelfi: arxiv:1903.00007

Density Estimation Likelihood Free Inference

Emulate simulator with deep neural net

Pydelfi learns sampling distribution p(data | parameters)

Comparable to BOLFI in accuracy but much faster.



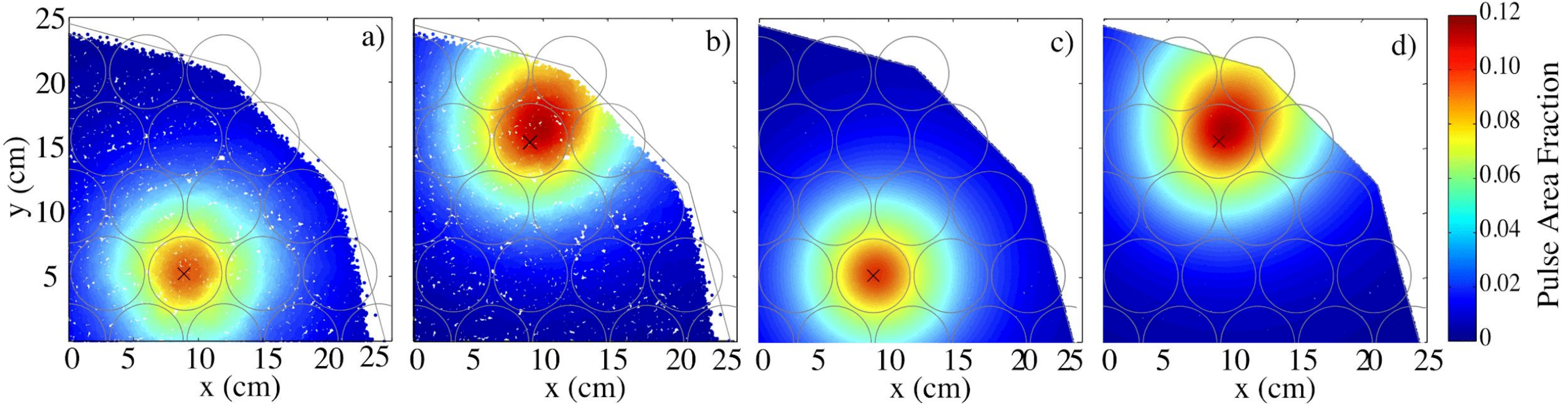
Learning light maps: fitting

Work from the LUX collaboration
JINST 13 (2018), [arXiv:1710.02752](https://arxiv.org/abs/1710.02752)

Reconstruct positions
Fit light maps
Repeat

$$\eta\left(\rho\right) = \frac{A}{\left(1+\gamma^2\rho^2\right)^{\frac{3}{2}}} + m\rho + b$$

$$\begin{aligned}
\varepsilon_g\left(\rho, r\right) &= \left[\varkappa_g \exp\left(\frac{r}{\xi_g}\right) + \alpha_g(r)\right] \exp\left(-\frac{\rho}{\zeta_g + \beta_g(r)}\right) \\
\alpha_g\left(r\right) &= k_{g,1} \exp\left[-\frac{\left(r - k_{g,2}\right)^2}{2\left(k_{g,3}\right)^2}\right] + k_{g,4}r + k_{g,5} \\
\beta_g\left(r\right) &= k_{g,6} \exp\left[-\frac{\left(W_c - r\right)^2}{2\left(k_{g,7}\right)^2}\right],
\end{aligned}$$



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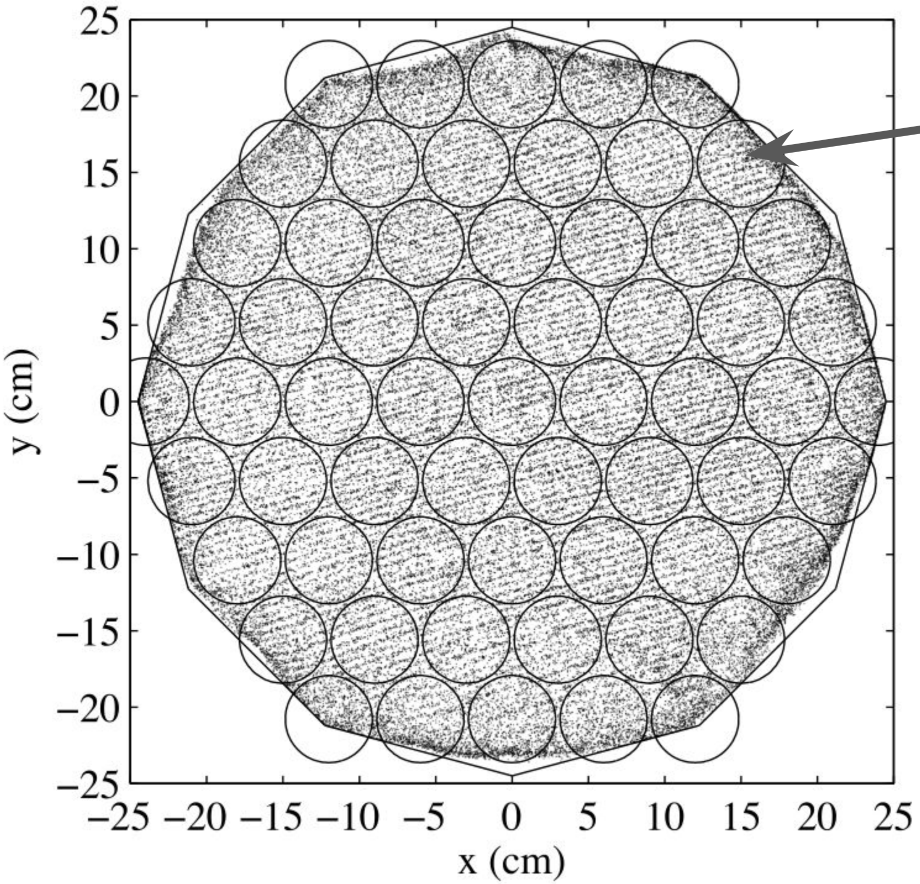


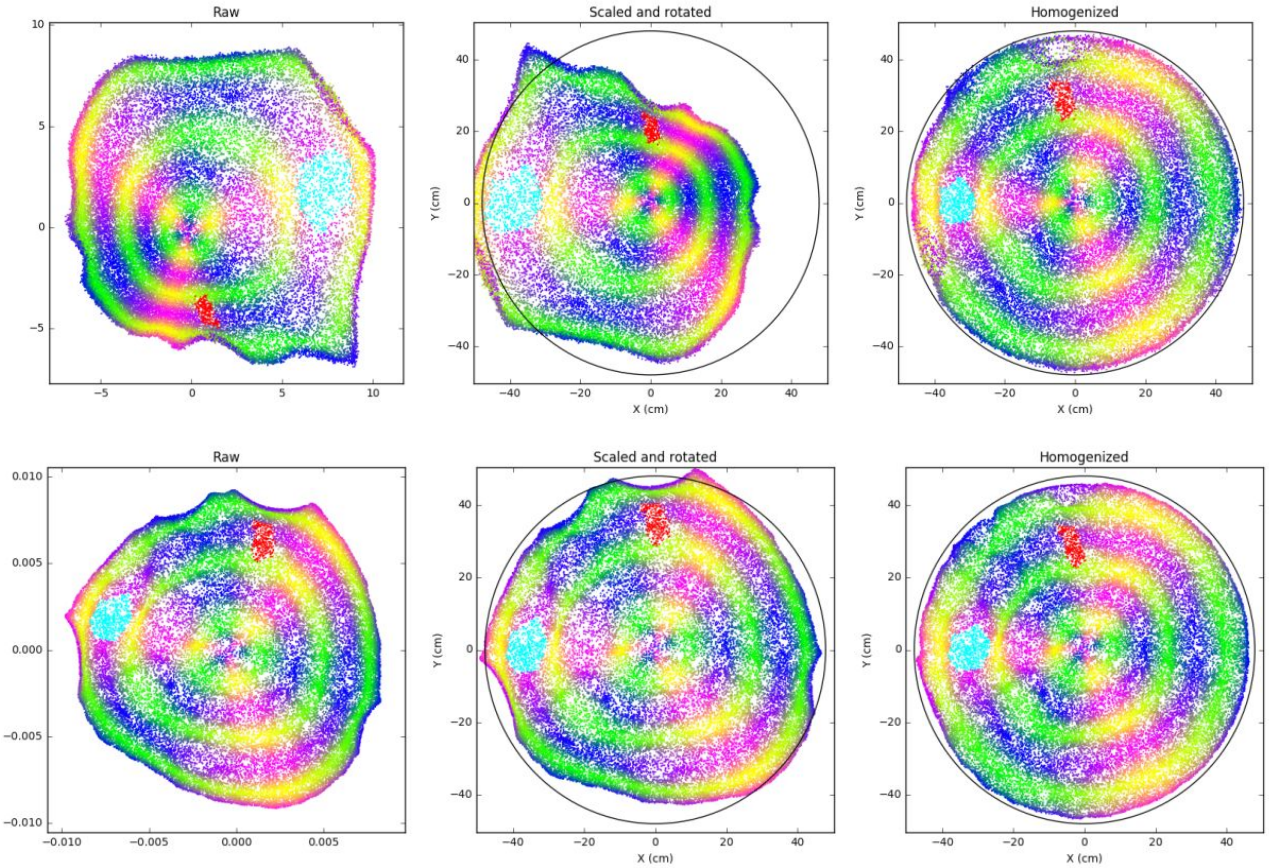
5mm
wires!

Learning light maps: embedding

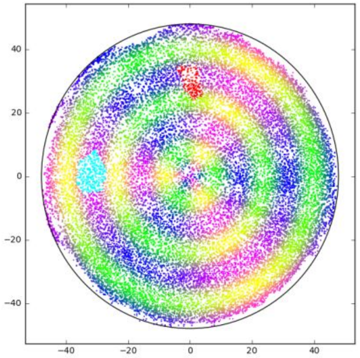
Work in progress
Jelle Aalbers, Chris Tunnell

PCA

LLE



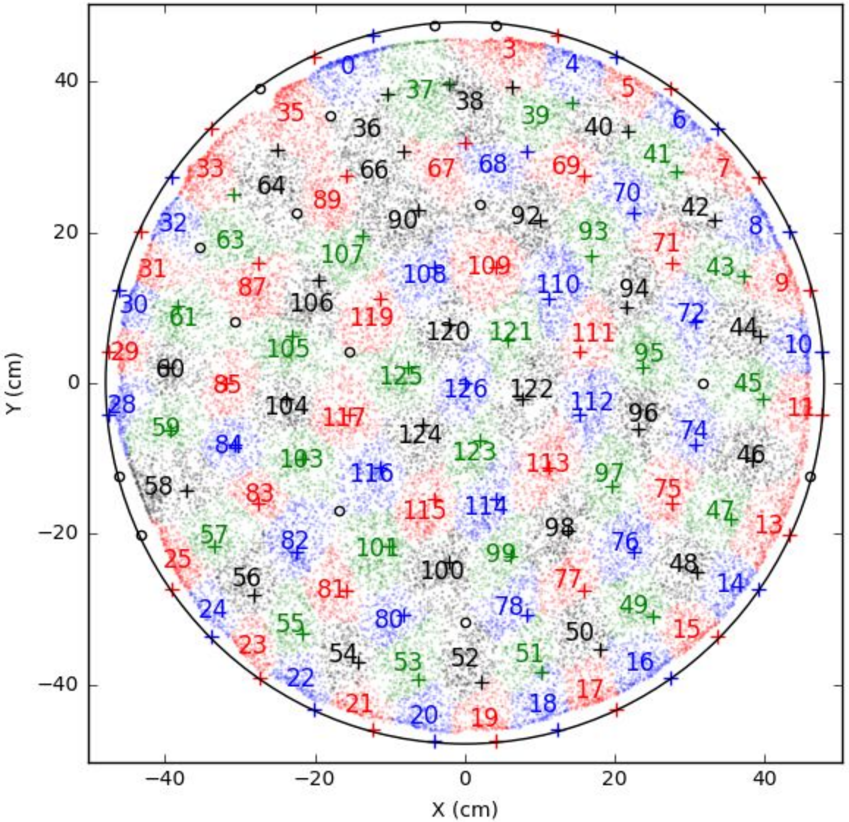
Colors: TPF positions



NOT truth values!!

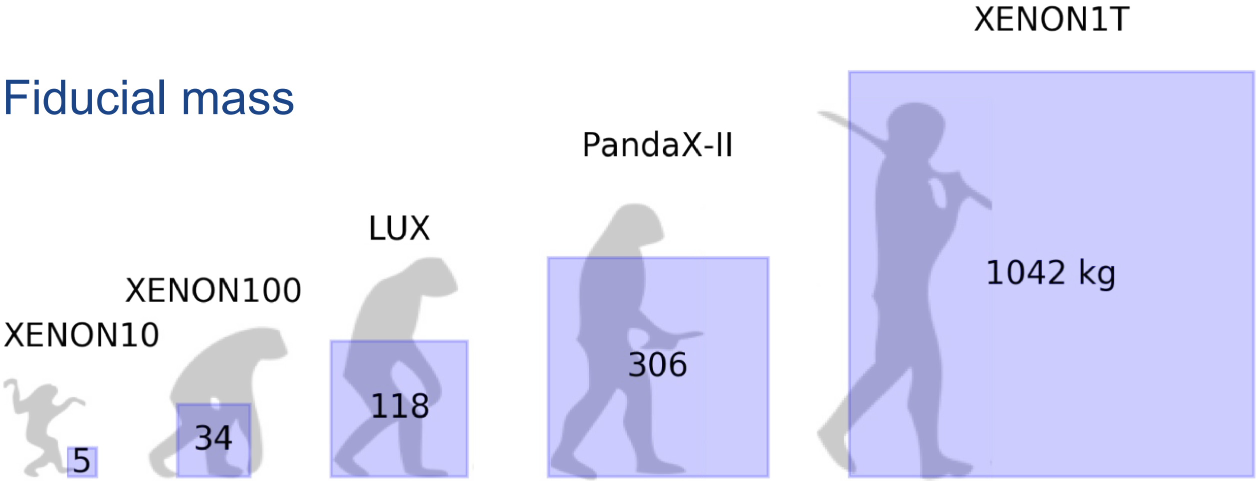
Learning light maps: embedding

Work in progress
Jelle Aalbers, Chris Tunnell



No cables are swapped!

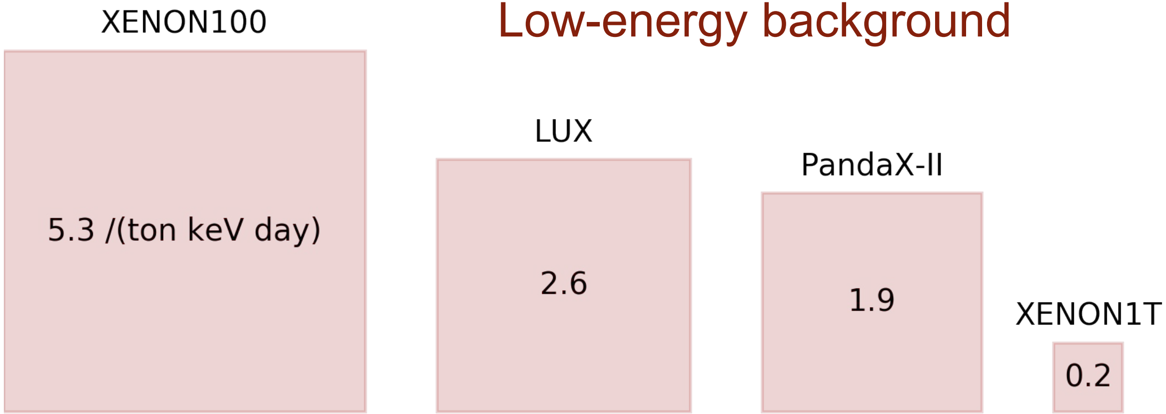
Fiducial mass



XENONnT, LZ

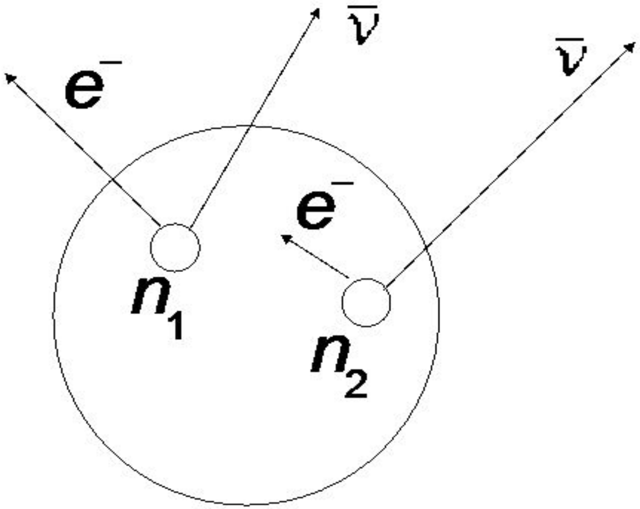
Several tonnes

Low-energy background

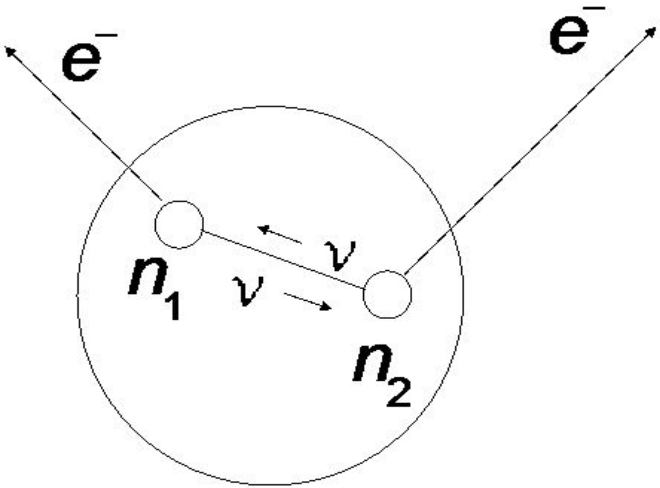


Fine print: Most experiments have different runs, often each with different fiducial volumes and background levels. LUX has a position-dependent likelihood, so there is more than one relevant background level in their fiducial volume(s). On this slide keV should be read as keV electronic recoil equivalent (keVee). XENON10's fiducial low-energy ER background was 600 events/(ton keV day). The "march of progress" is a misleading caricature of the rich and branching evolution of the great apes. Any resemblance between the ape-men and scientists working in the field is purely accidental.

Rare radioactive decays $t_{1/2} = 10^{21} - 10^{22}$ years!



2νββ

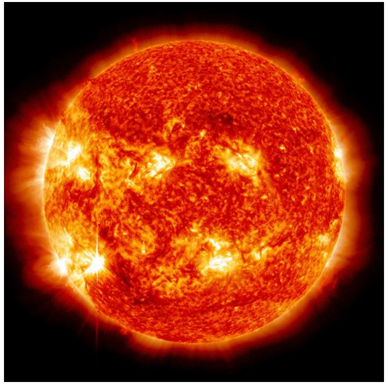


0νββ

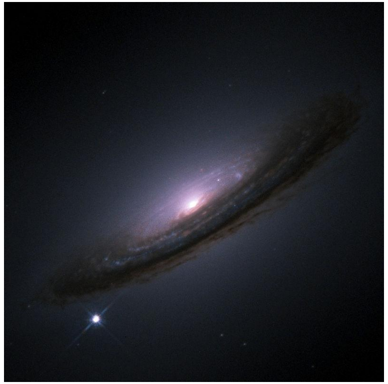
Double beta decay

Neutrinoless
double beta decay

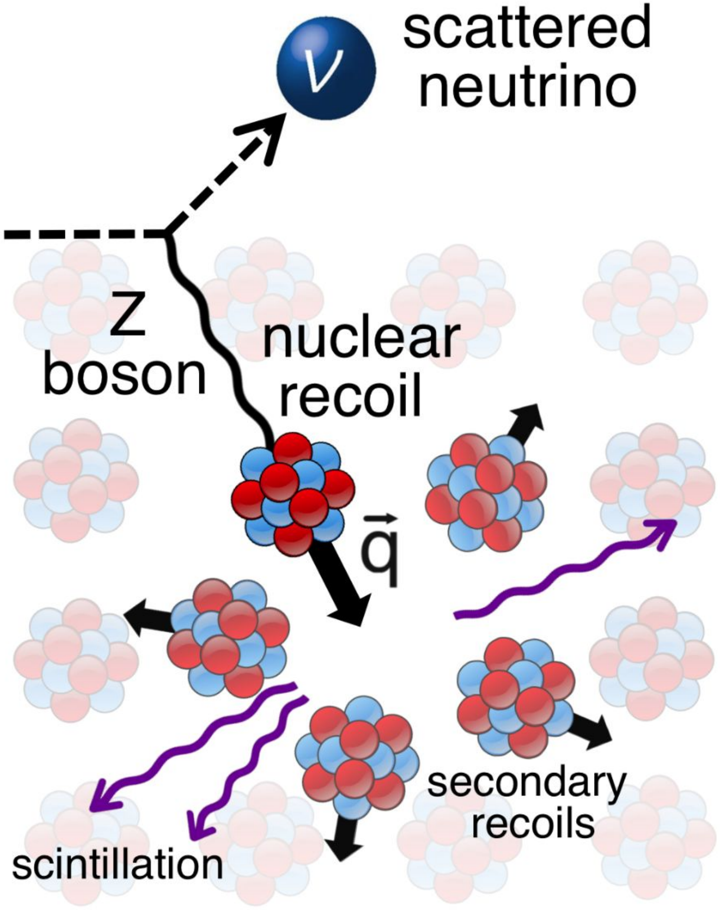
Elastic neutrino-nucleus scattering

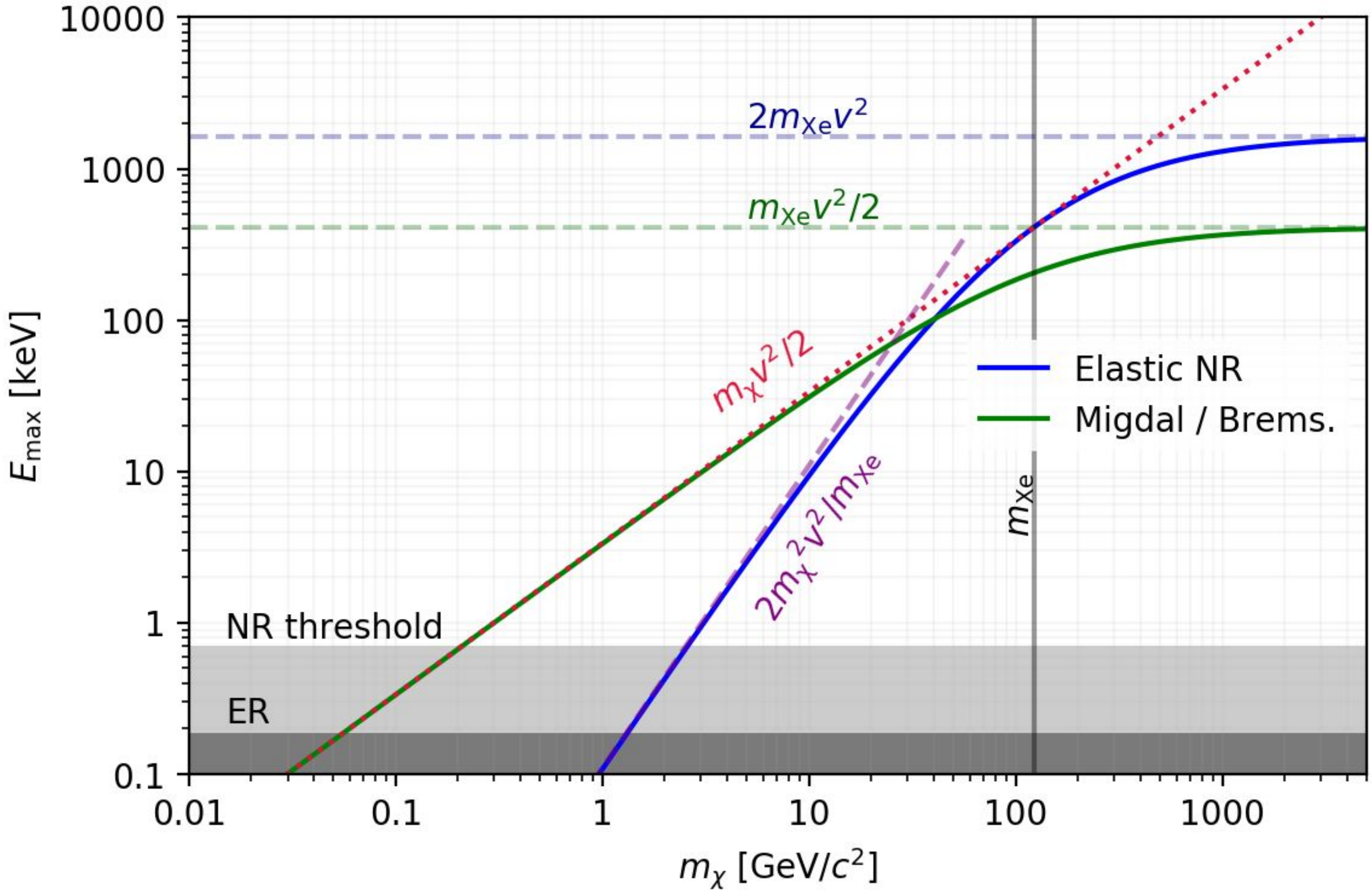


Solar neutrinos
^{8}B

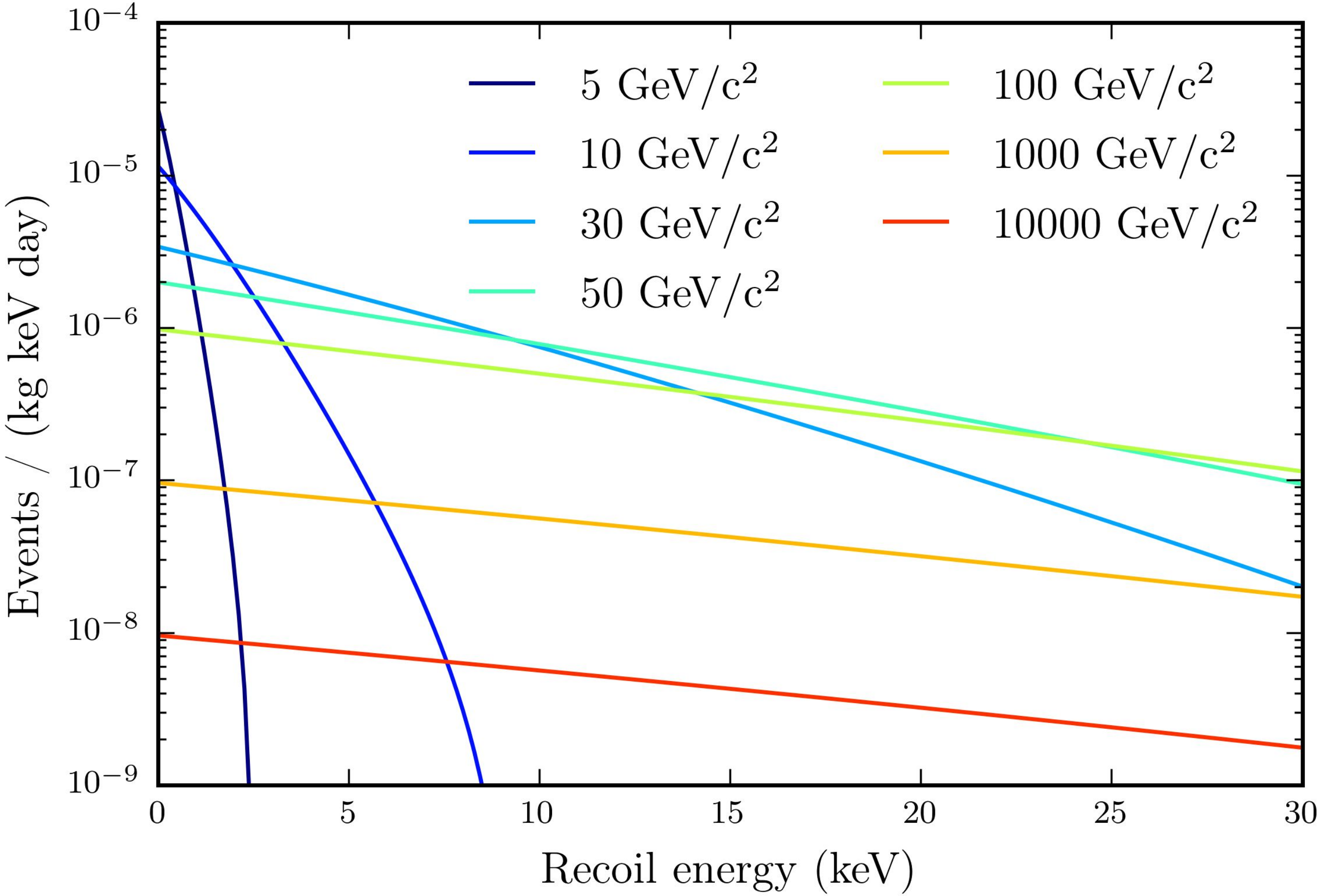


Galactic supernovae

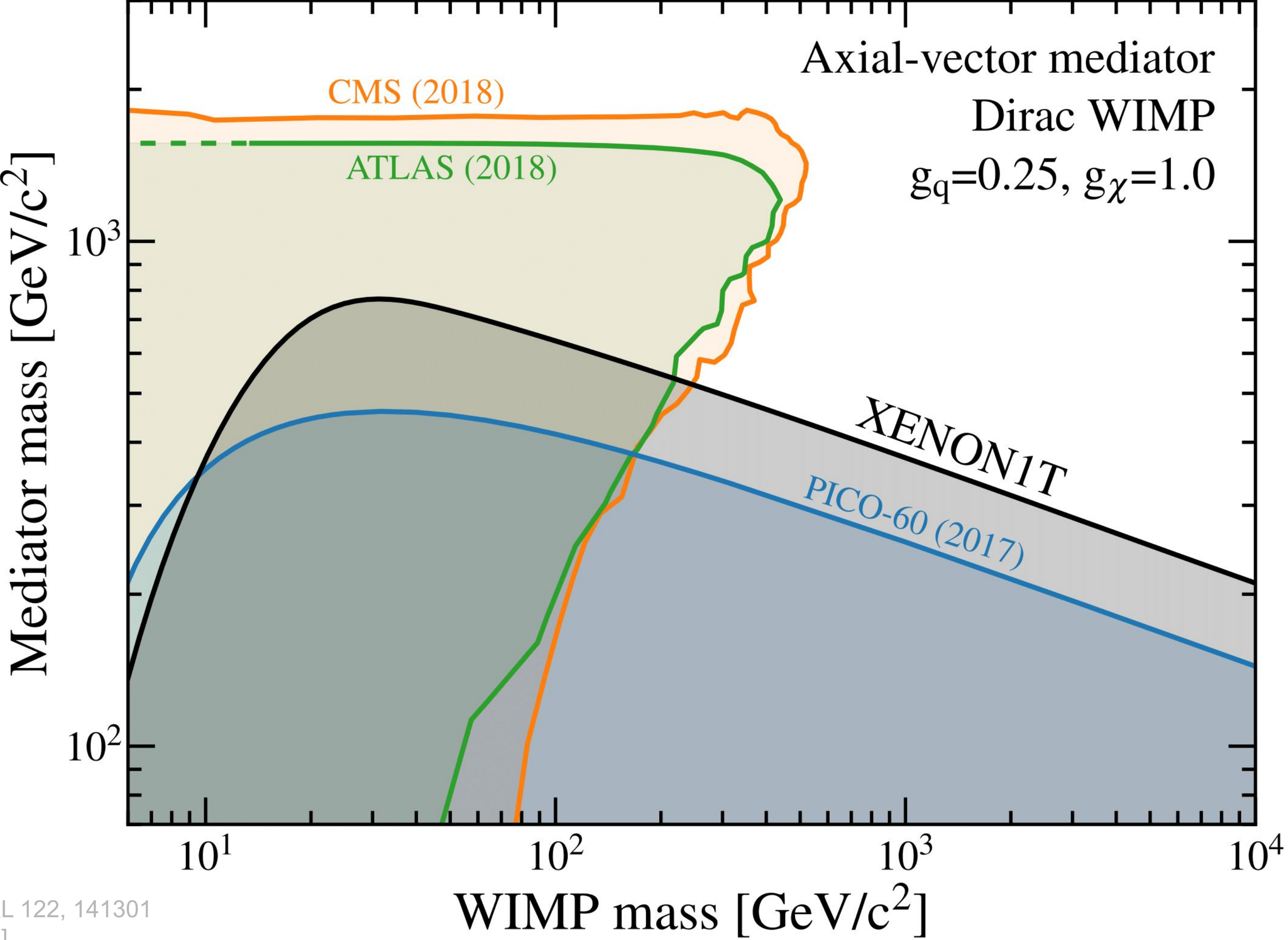




10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
$E_{\max}$ [keV]
m_χ [GeV/c^2]
$2m_{\mathrm{Xe}}v^2$
$m_{\mathrm{Xe}}v^2/2$
$m_\chi v^2/2$
$2m_\chi{}^2v^2/m_{\mathrm{Xe}}$
m_{Xe}
Elastic NR
Migdal / Brems.
NR threshold
ER

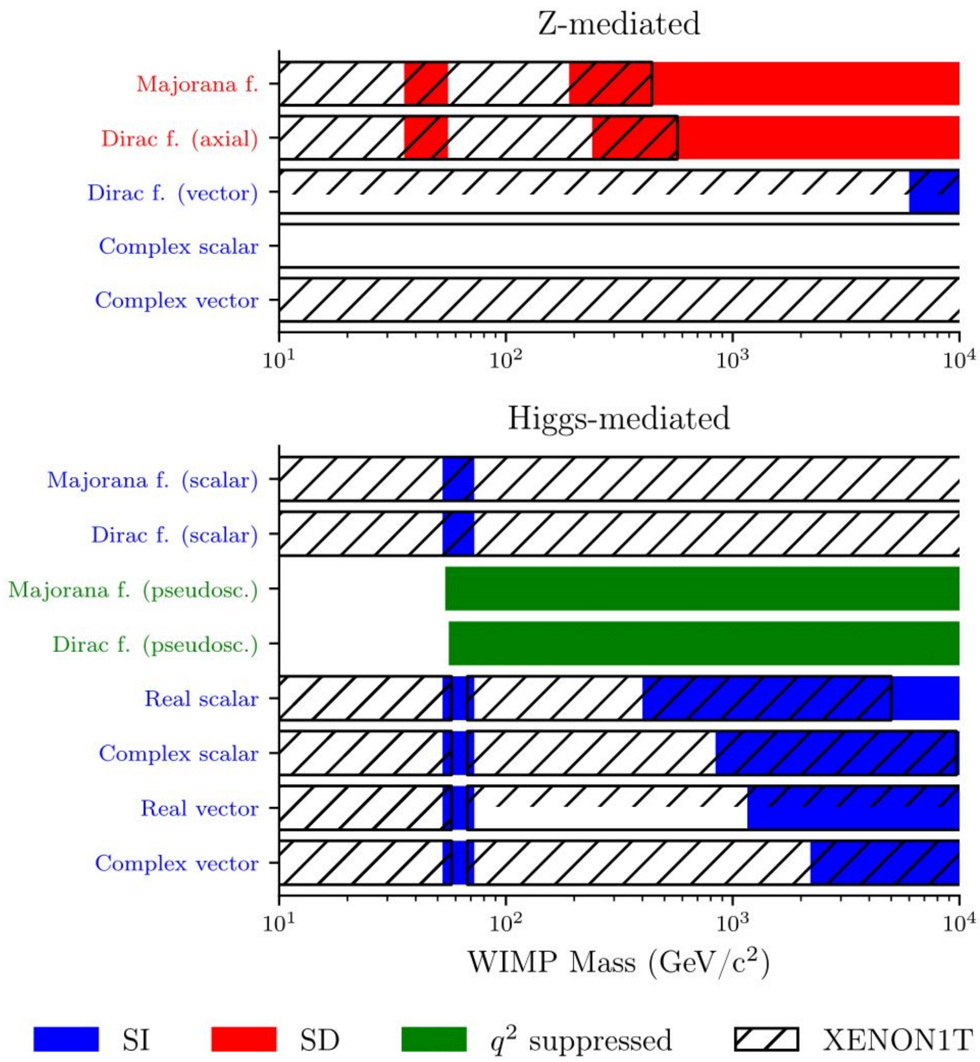


10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Events / (kg keV day)
0
5
10
15
20
25
30
Recoil energy (keV)
5 GeV/c^2
10 GeV/c^2
30 GeV/c^2
50 GeV/c^2
100 GeV/c^2
1000 GeV/c^2
10000 GeV/c^2



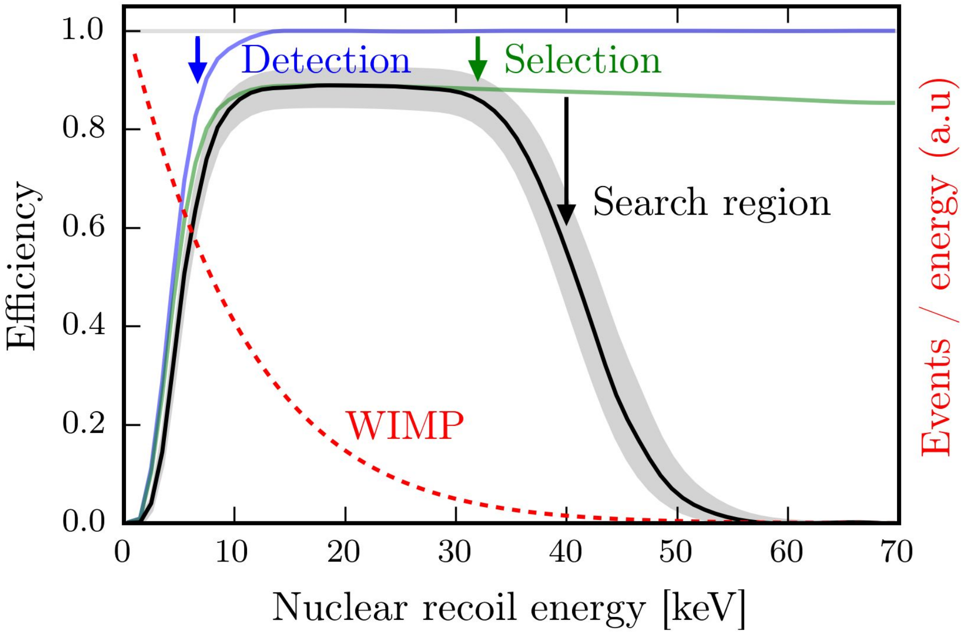
E. Aprile et. al. PRL 122, 141301
[arXiv 1902.03234]

(Fine print: these are only the simplest thermal-relic WIMP models)



Data from M. Escudero *et al.* JCAP 2016.12 pp. 029–029 .[arXiv:1609.09079]

Signal efficiency



Dominant signal loss is from 3 PMT S1 coincidence requirement
Example WIMP spectrum shown here is for m = 50 GeV