Review of
Direction-Sensitive Direct Dark Matter Search

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Physics in LHC and the Early Universe

Contents

Dark Matter Direct detection

Physics

Experiments

科研費 KAKENHI

Direction-Sensitive WIMP-search NEWAGE

Algebra of LHC

2×5σ =

The Nobel Prize in Physics 2013

François Englert, Peter Higgs

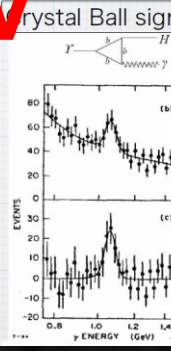
Hanagaki-san's slide

="crystal ball" + 30yrs!

History of Higgs Search

8GeV

- 1980's
  - Crystal Ball at Doris
    - $\Upsilon \to H\gamma$
  - CESR etc.
    - $\Upsilon \to H\gamma$, $\pi \to e\nu$ H(→ee), B→KH(→$\mu\mu$, $\pi\pi$, KK)
  - m_H > 8 or 9 GeV



Algebra of DM search

×15 difference

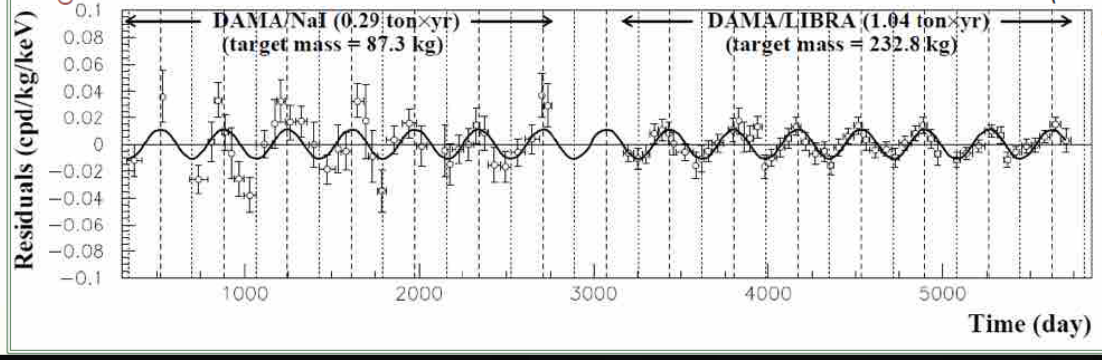
over 9σ (by 14yrs of measurement) < discovery

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate of scintillation events *vs* time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648



continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86 9.2σ C.L.

50GeV

Absence of modulation: NI

χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the param

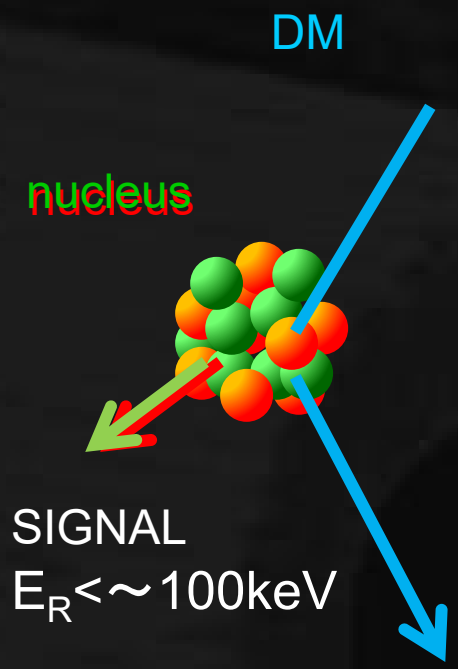
A = (0.0112 ± 0.0012)

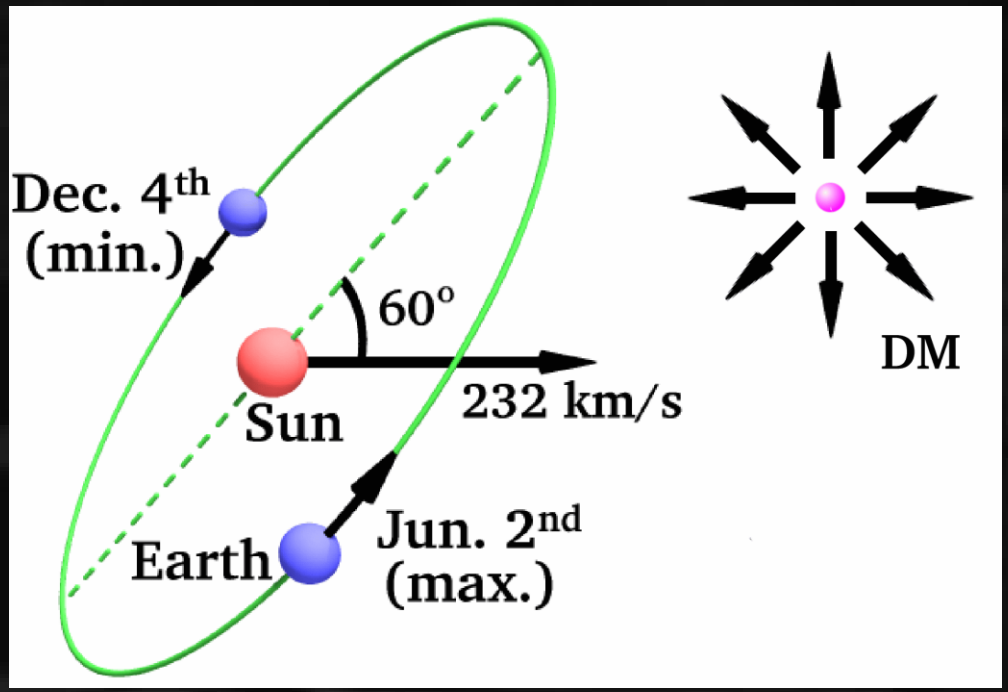
t_0 = (144±7) d - T = (

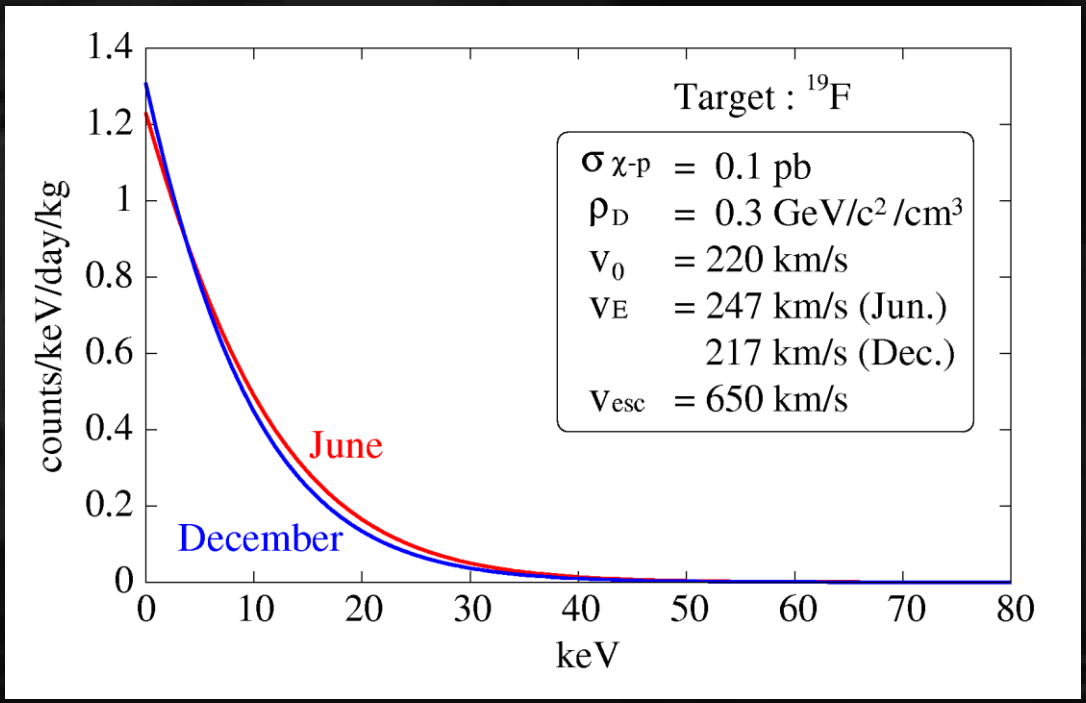
Direction Sensitive

×15=7??GeV

DM direct detection





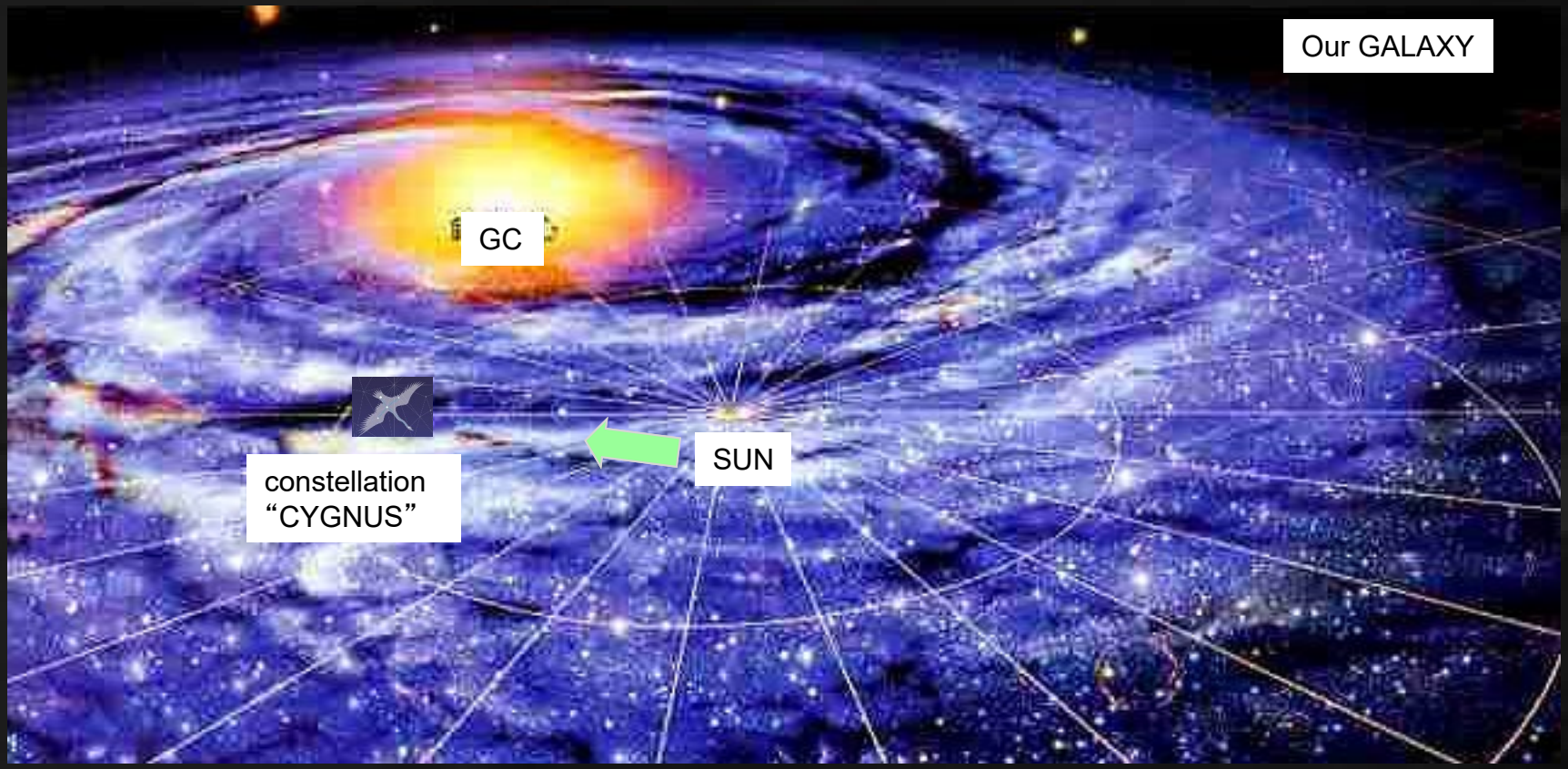


expected direct DM signals

- ① observed * events
- ② energy spectrum
- ③ seasonal modulation
- ④ material dependence
- ⑤ direction-sensitive

Physics cases

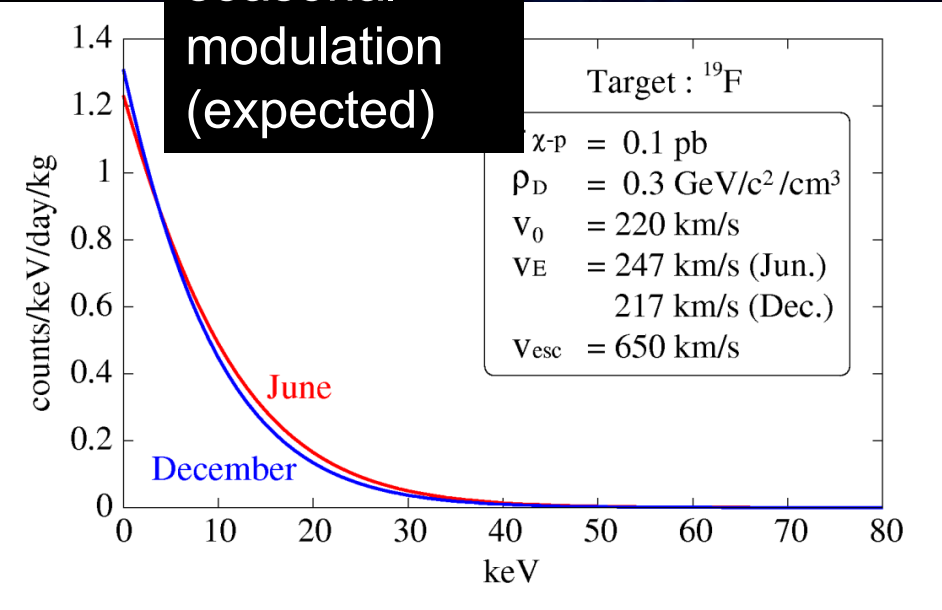
Direction-Sensitive Dark Matter Search concept “CYGNUS”



WIMP-WIND from “CYGNUS”

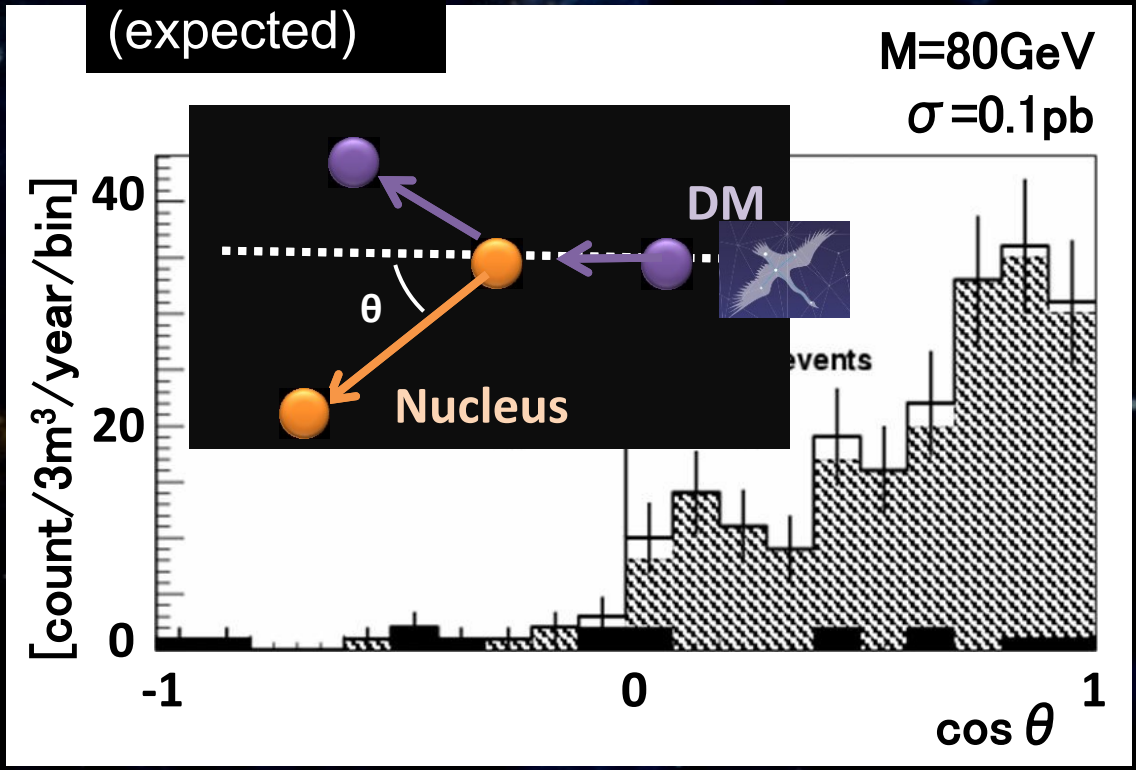
“CYGNUS” concept

seasonal modulation (expected)



directionality (expected)

Physics Letters B 578 (2004) 241–246

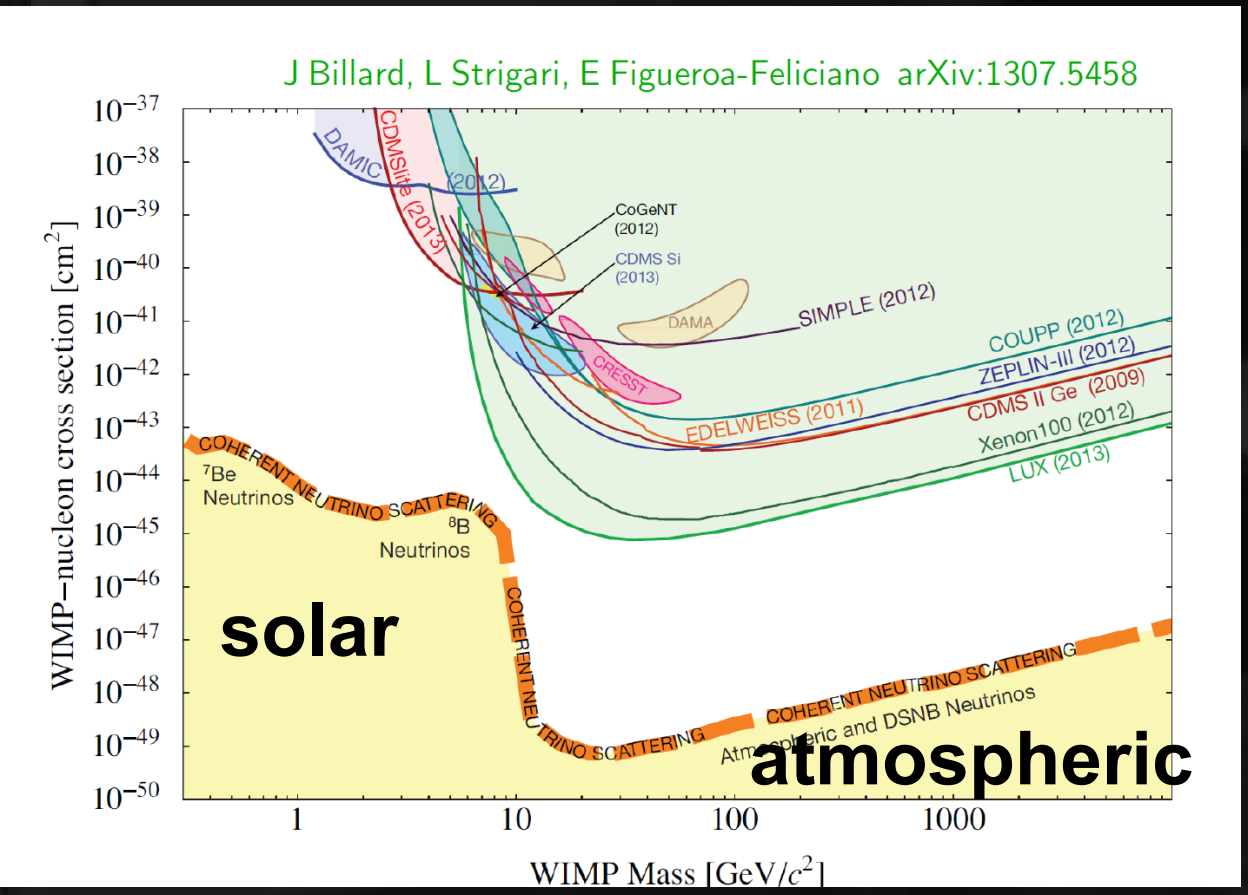


Clear Discovery

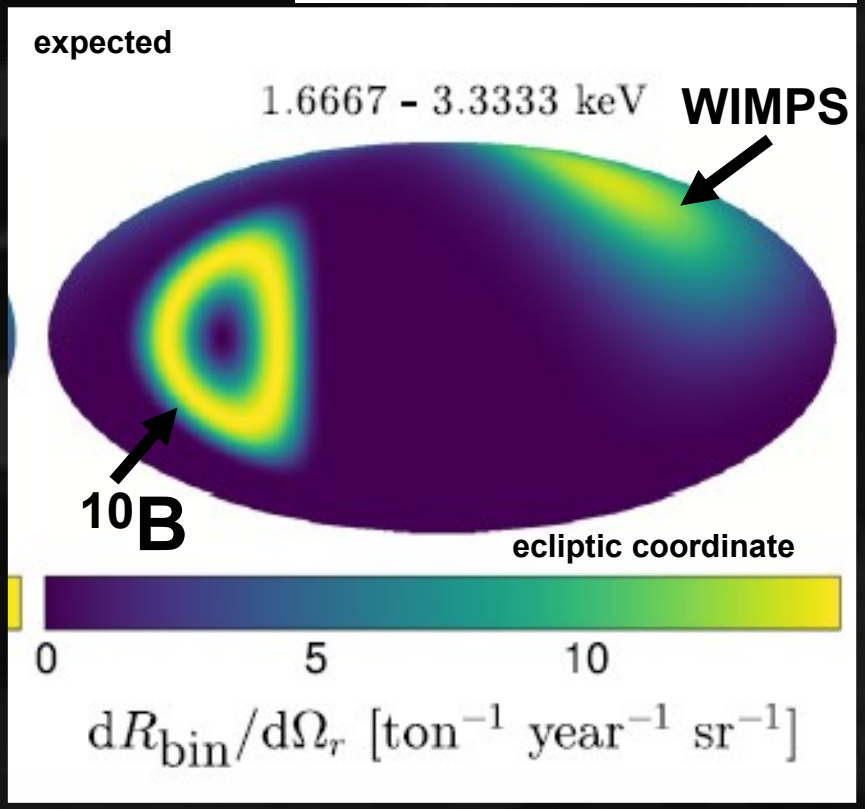
+ study the nature of DM after discovery

“CYGNUS” physics towards discovery

- **Potential to search beyond the “neutrino floor”†**



F. Mayet et al. / Physics Reports 627 (2016) 1–49

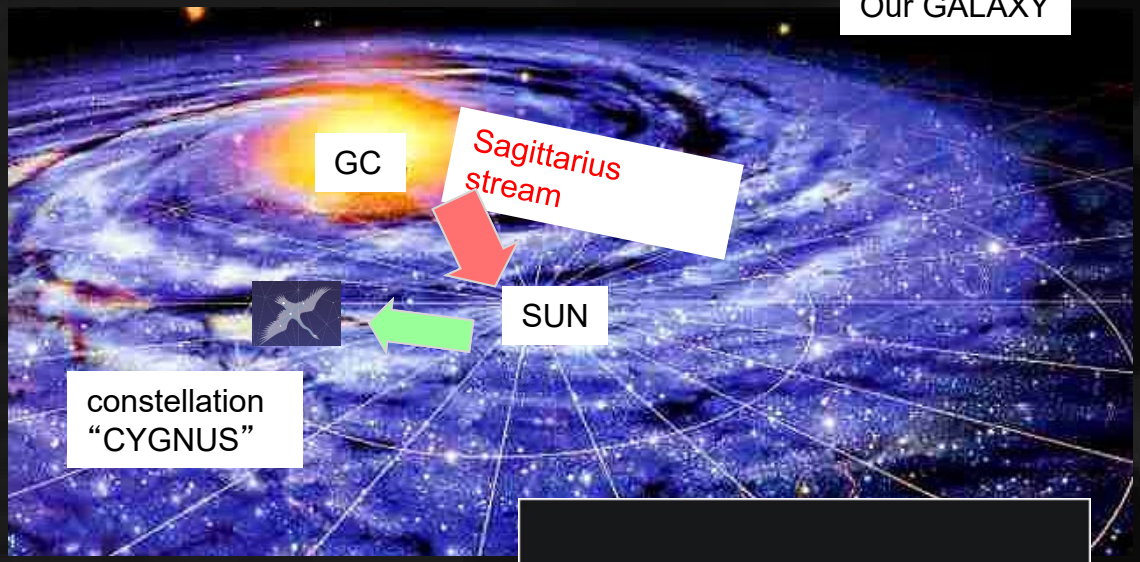


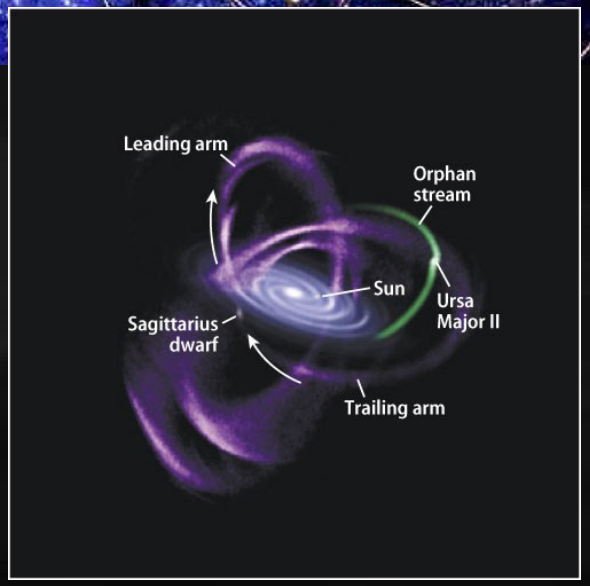
- **clearly distinguishable**

† neutrino-nucleus coherent scattering

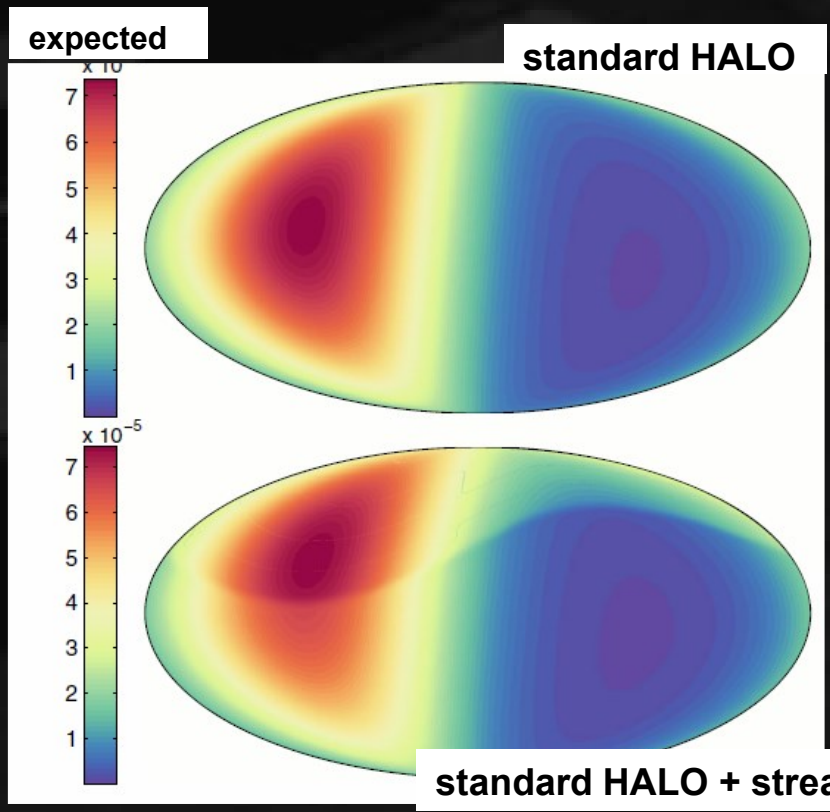
“CYGNUS” physics after discovery

- **Test the DM motion**
  - **ex. Sagittarius stream**





PHYSICAL REVIEW D **90,** 123511 (2014)



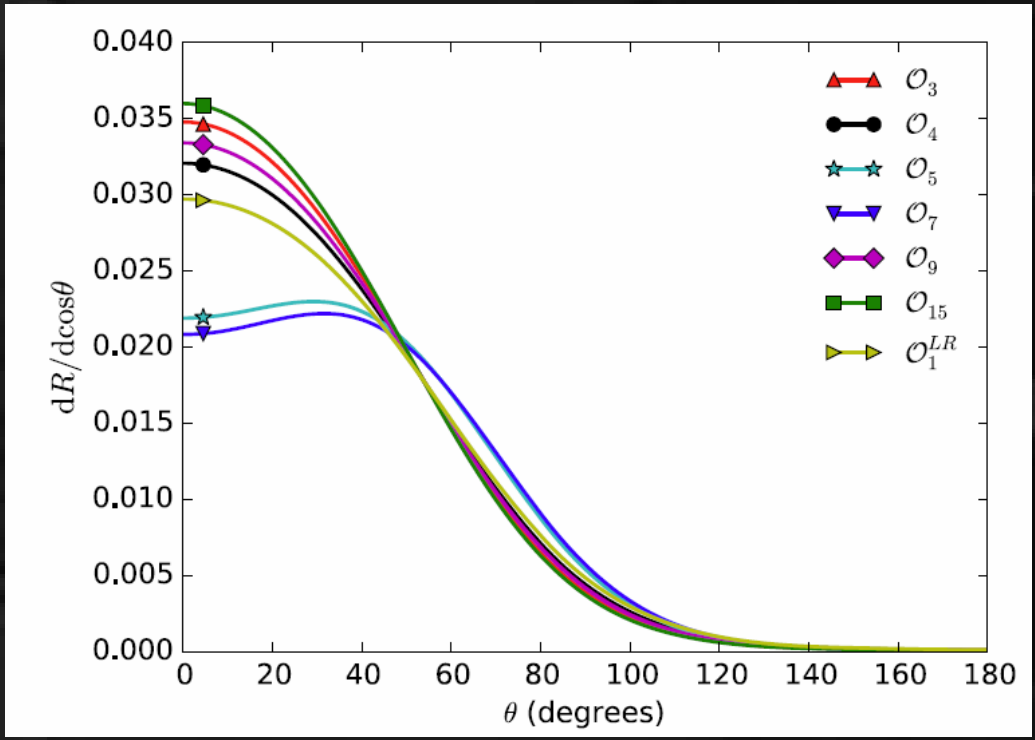
galactic coordinate

- **streams, halo model…**

“CYGNUS” physics after discovery

- **Test the interaction by scattering angle ①**

PHYSICAL REVIEW D **92,** 023513 (2015)



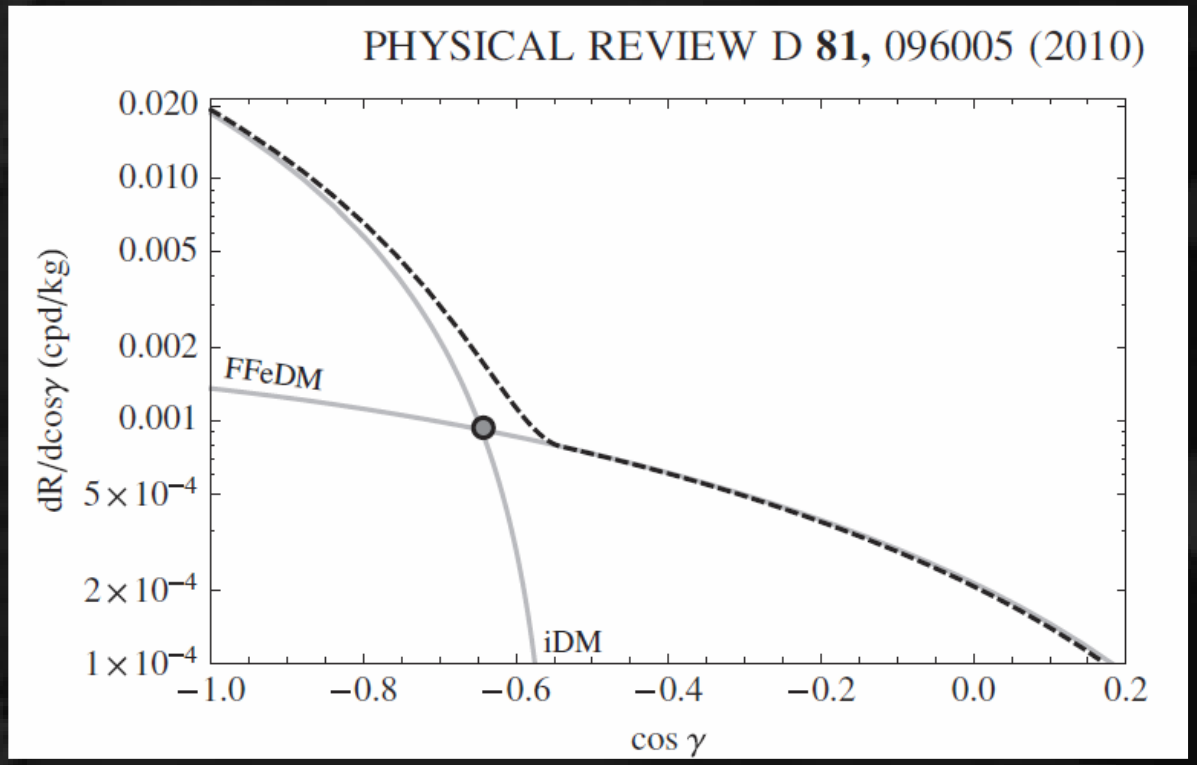
SI SD

$$\text{Proportional to} \begin{cases} 1 & : \mathcal{O}_1, \mathcal{O}_4, \\ v_\perp^2 & : \mathcal{O}_7, \mathcal{O}_8, \\ q^2 & : \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_{11}, \mathcal{O}_{12}, \\ v_\perp^2 q^2 & : \mathcal{O}_5, \mathcal{O}_{13}, \mathcal{O}_{14}, \\ q^4 & : \mathcal{O}_3, \mathcal{O}_6, \\ q^4(q^2 + v_\perp^2) & : \mathcal{O}_{15}, \\ q^{-4} & : \mathcal{O}_1^{\mathrm{LR}}. \end{cases}$$

- **some operators are distinguishable**

“CYGNUS” physics after discovery

- **Test the interaction by scattering angle ②**



- **iDM (inelastic scatterings dark matter) and normal darkmatter (FFeDM (**form factor elastic dark matter**)) show different angular DISTRIBUTION**

Experimental Status

Experimental concept

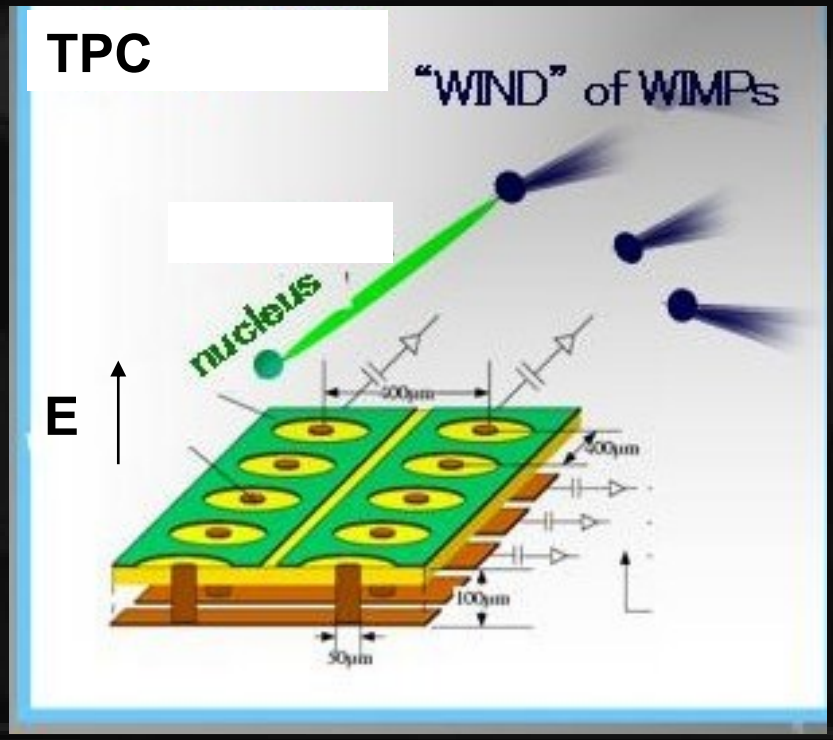
Recoil nuclear track detection < 100keV

challenge: short track

a few mm in low pressure gas
a few 100 nm in solid

Most typical “CYNGUS”: low pressure gas TPC

2D readout + timing
→ 3D tracking



DRIFT: pioneer of "CYGNUS" concept

- early 2000s ~
  - large TPC
  - low BG study

ELSEVIER Nuclear Instruments and Methods in Physics Research A 463 (2001) 142–148
RESEARCH Section A
www.elsevier.nl/locate/nima

Measurement of carbon disulfide anion diffusion in a TPC

Tohru Ohnuki[a,*], Daniel P. Snowden-Ifft[a], C. Jeff Martoff[b]

[a] Department of Physics, Occidental College, 1600 Campus Road, Los Angeles, CA 90041-3314, USA
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Received 15 May 2000; received in revised form 13 November 2000; accepted 14 November 2000

R Nuclear Instruments and Methods in Physics Research A 498 (2003) 155–164
RESEARC Section A
www.elsevier.com/lo

Neutron recoils in the DRIFT detector

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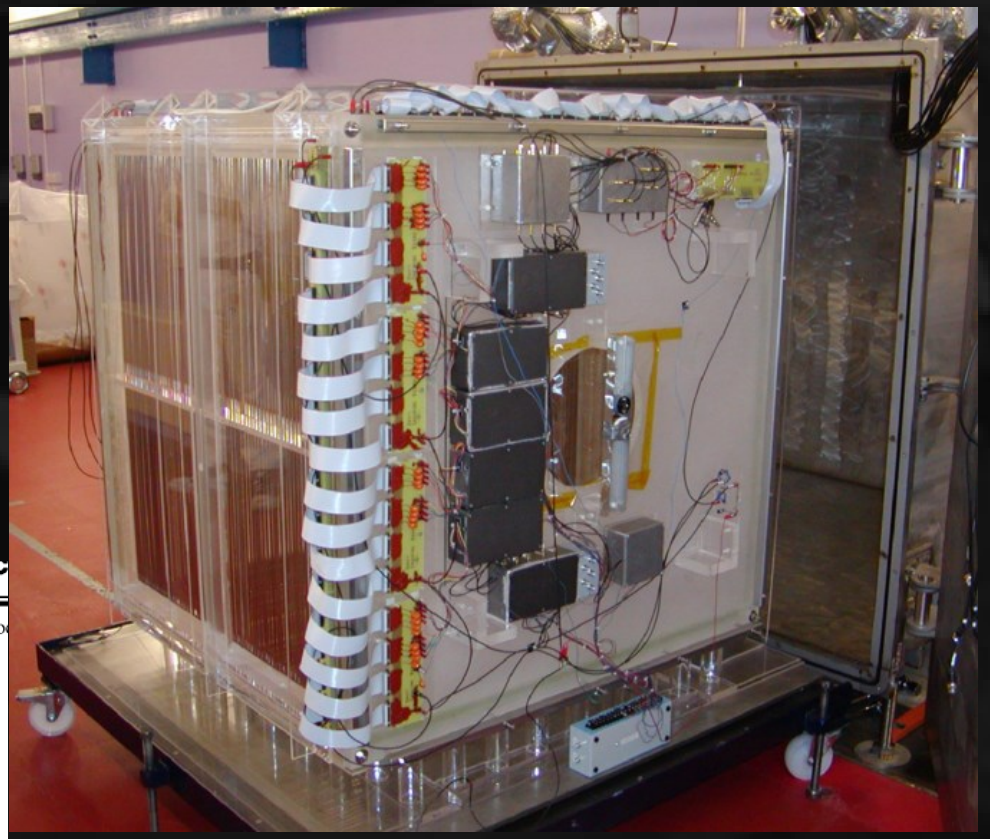
[b] Barton Hall, Temple University, 1900 N. 13th St., Philadelphia, PA 19122-6082, USA

Received 5 July 2002; received in revised form 11 October 2002; accepted 27 November 2002



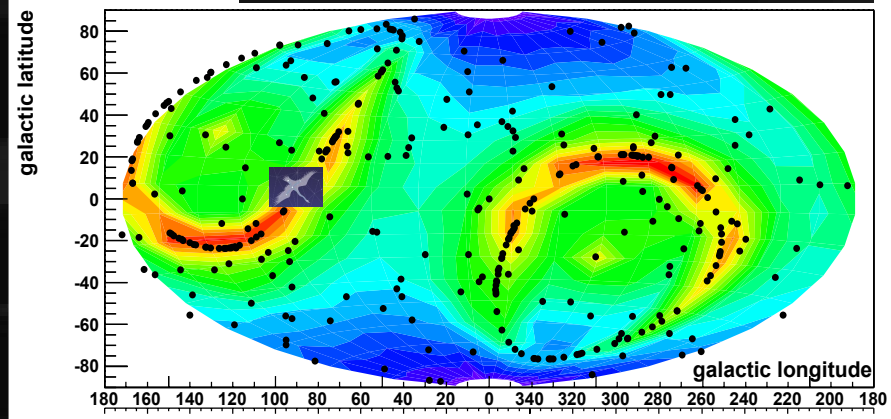
- 2mm pitch multi-wire proportional chamber
- not very direction-sensitive

NEWAGE: always direction-sensitive

New general WIMP search with an Advanced Gaseous tracker Experiment

- μ-PIC(MPGD) based TPC
  - 3-D tracks SKYMAP
- CF_4 gas for SD search

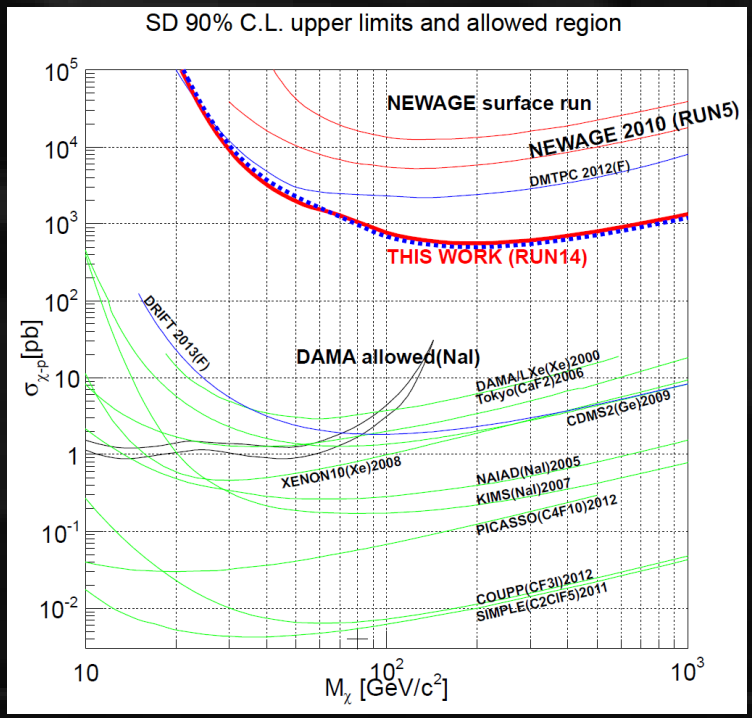
SKYMAP (measured DATA)



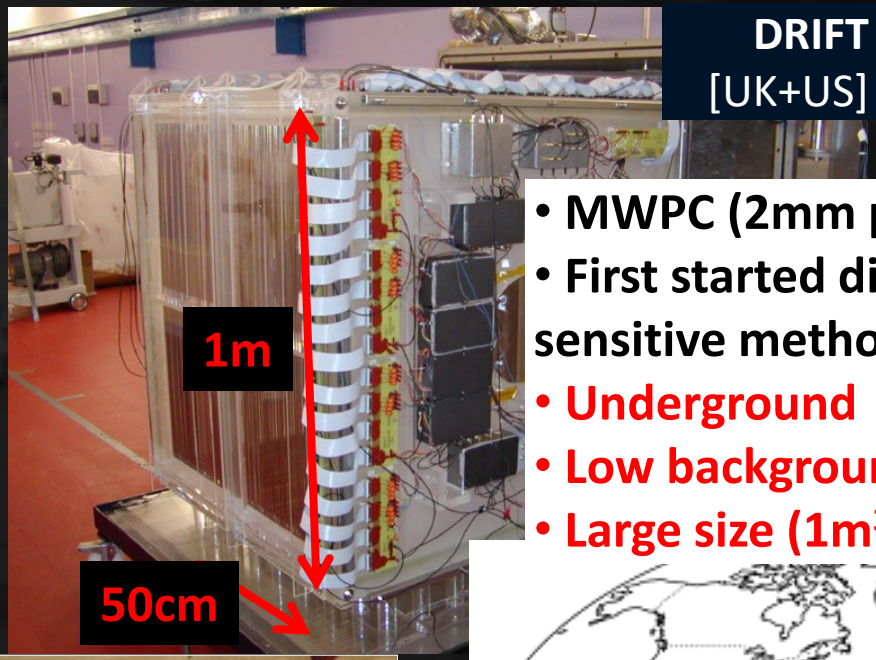
- **Proposal** PLB 578 (2004) 241
- **First direction-sensitive limits**

  PLB654 (2007) 58
- **Underground results**

  PLB686 (2010) 11, PTEP (2015) 043F01s
- **Phase for "low BG detector"**

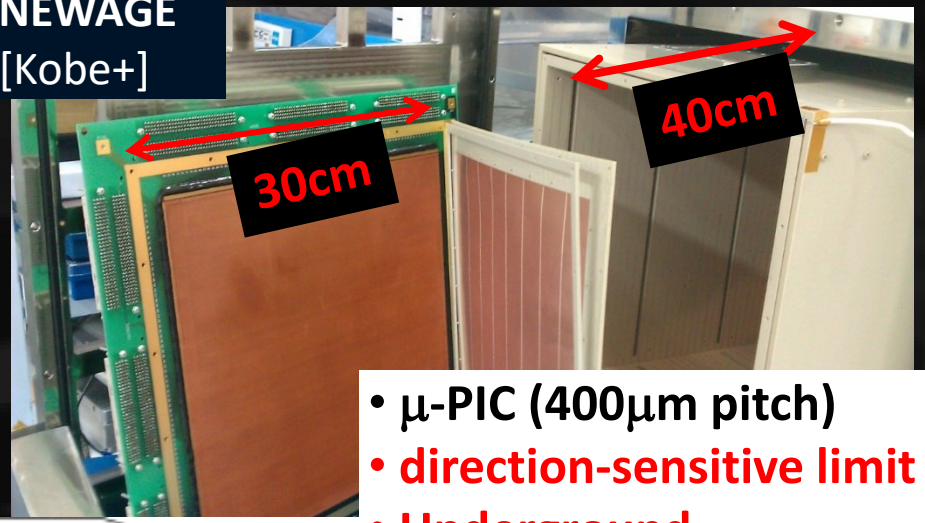


Cygnus, gas TPCs



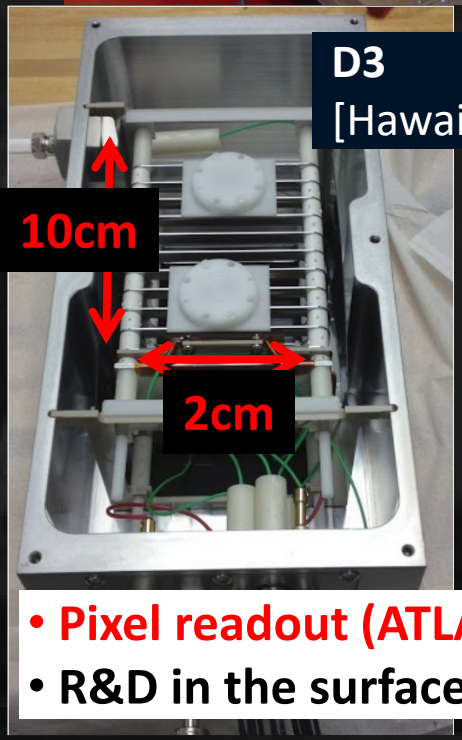
DRIFT
[UK+US]

- MWPC (2mm pitch)
- First started direction-sensitive method
- Underground
- Low background
- Large size ($1m^3$)



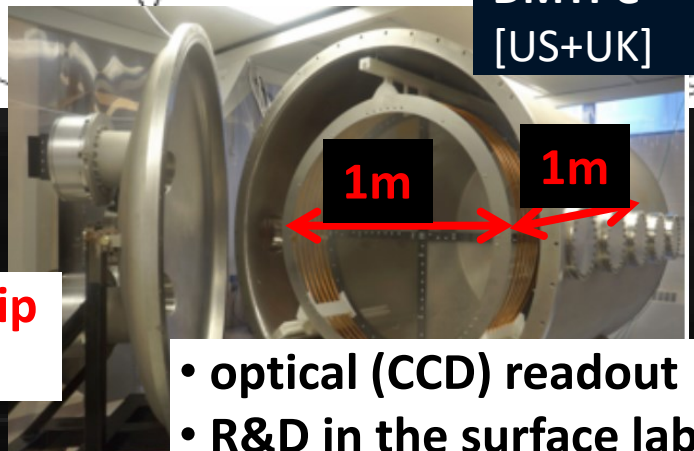
NEWAGE
[Kobe+]

- μ-PIC (400μm pitch)
- direction-sensitive limit
- Underground



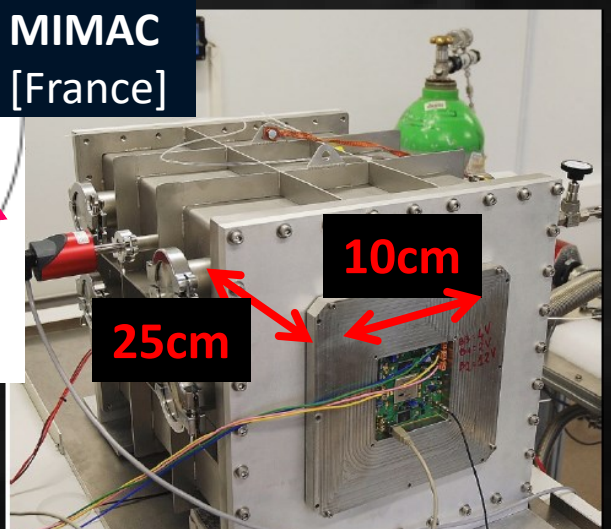
D3
[Hawaii]

- Pixel readout (ATLAS FE-I4) chip
- R&D in the surface lab



DMTPC
[US+UK]

- optical (CCD) readout
- R&D in the surface lab



MIMAC
[France]

- Micromegas (~400μm pitch)
- quenching factor measurement

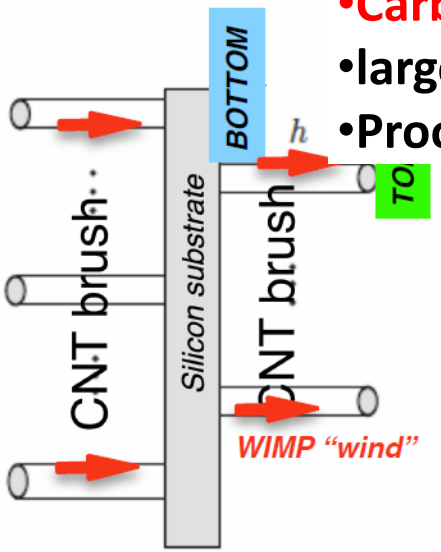
Cygnus, others

Gianluca Cavoto INFN Roma
IDM 2016
18th 22nd July 2016
The University of Sheffield

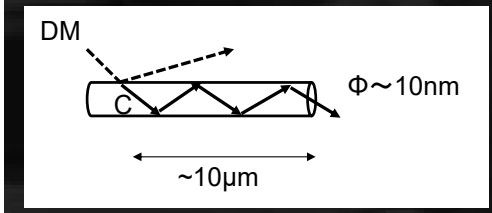
NEWSdm
[Japan+Italy]

- emulsion (20~50nm crystal)
- good position resolution
- large mass
- No time resolution

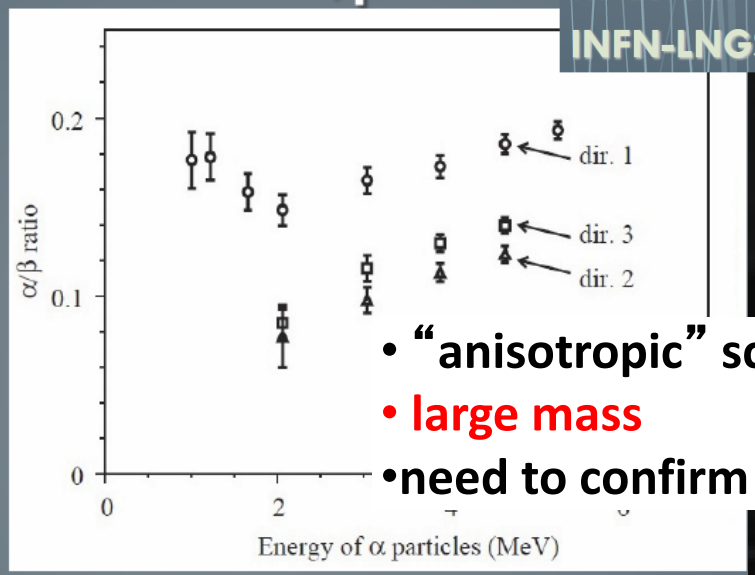
DeCANT
[Italy]



- Carbon nano tube
- large mass
- Proof of concept is ongoing



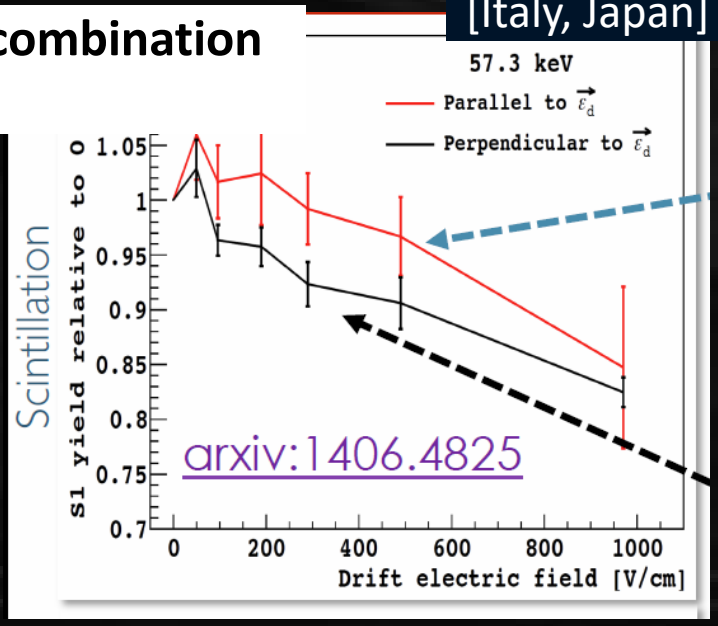
$ZnWO_4$
[Italy, Japan]



- "anisotropic" scintillator
- large mass
- need to confirm in low energy

Liq Ar
[Italy, Japan]

- columnar recombination
- large mass



SUMMARY

- Direction sensitive dark-matter search
  - Discovery and further investigation
  - Many small size R&Ds are actively ongoing

EFT operators

PHYSICAL REVIEW D **92,** 023513 (2015)

$$\mathcal{O}_1 = 1$$
$$\mathcal{O}_3 = i\vec{S}_n \cdot \left(\frac{\vec{q}}{m_n} \times \vec{v}^{\perp}\right)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_n$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_n} \times \vec{v}^{\perp}\right)$$
$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_n \cdot \vec{q})$$
$$\mathcal{O}_7 = \vec{S}_n \cdot \vec{v}^{\perp}$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_n \times \vec{q})$$
$$\mathcal{O}_{10} = i\vec{S}_n \cdot \vec{q}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_n \times \vec{v}^{\perp})$$
$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^{\perp})\left(\vec{S}_n \cdot \frac{\vec{q}}{m_n}\right)$$
$$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_n}\right)(\vec{S}_n \cdot \vec{v}^{\perp})$$
$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_n}\right)\left((\vec{S}_n \times \vec{v}^{\perp}) \cdot \frac{\vec{q}}{m_n}\right). \qquad \text{(A2)}$$

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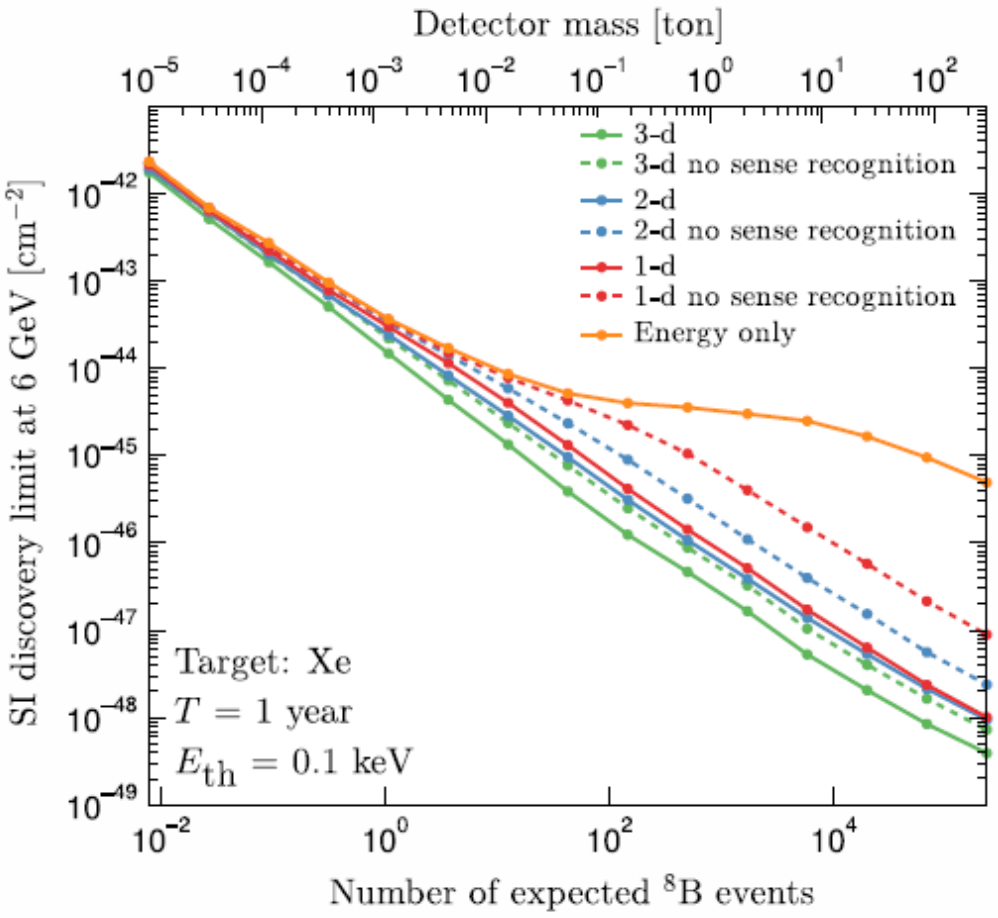

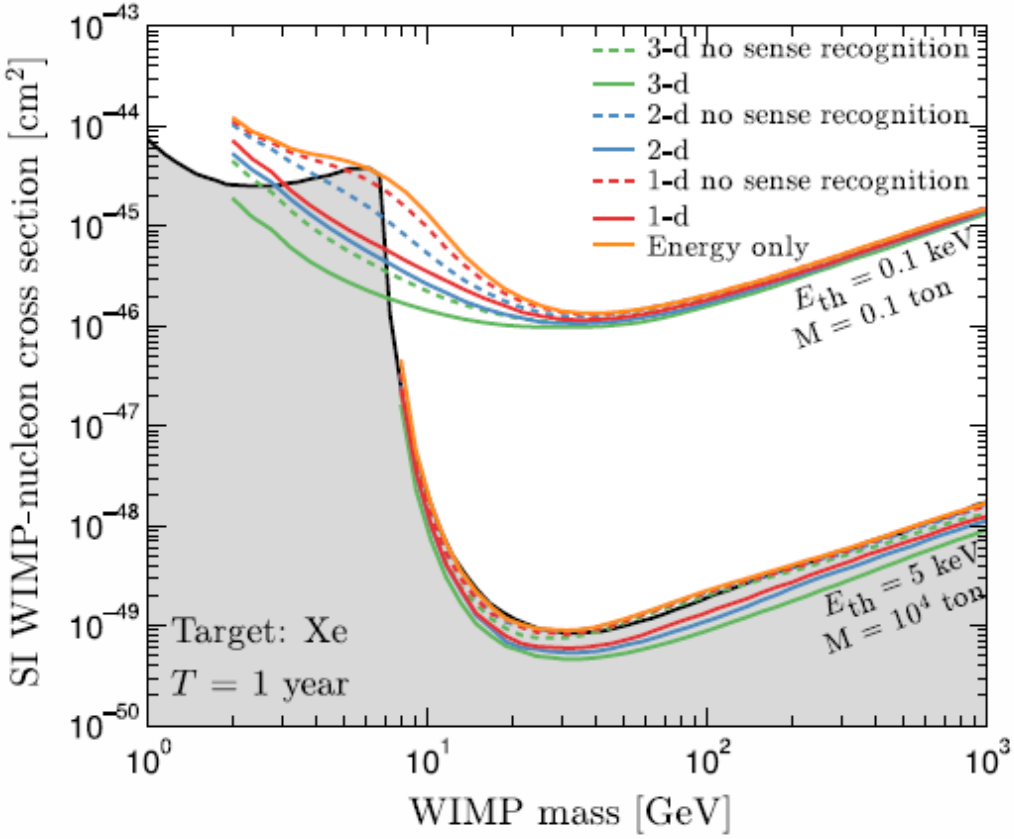

Physics Letters B 578 (2004) 241–246