2021年7月30日

総研大オンライン集中講義「計測と制御」

暗黒物質探索実験への応用

身内賢太朗

神戸大学　大学院理学研究科
物理学専攻　准教授

1　暗黒物質探索実験

2　ASIC、FPGAの使用

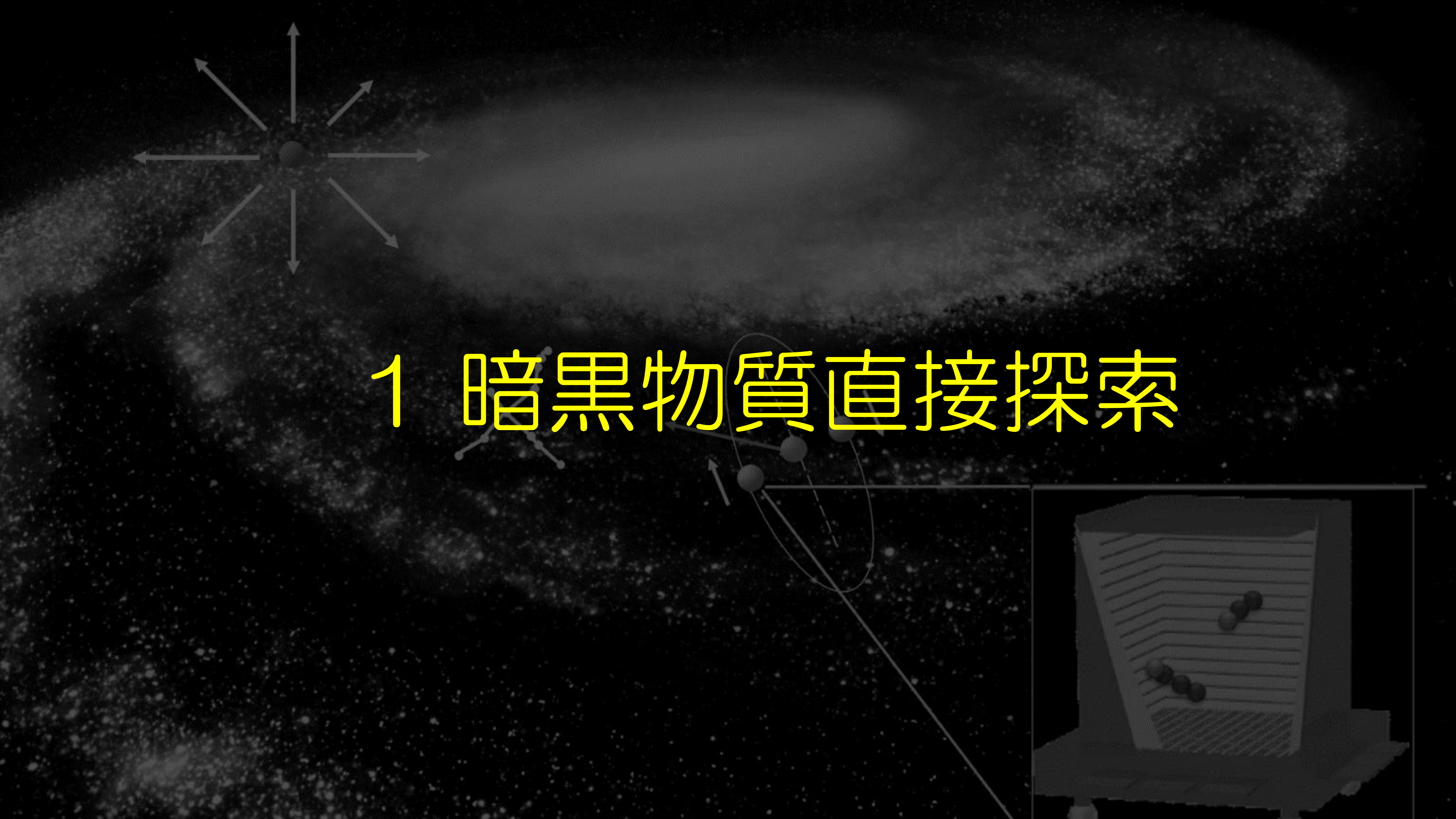
3　この先

- 自己紹介：身内賢太朗（みうち けんたろう）

- いまのところずっと　暗黒物質直接探索　⇄　見つからない
- そろそろ　見つけて　性質解明　と行きたい

- D論　　　　　東大物理　みのわ研　　　　LiFボロメータ
- PD〜助教　　　京大物理　宇宙線研究室　　ガスTPC
- 准教授　　　　神戸大　粒子物理研究室　　+=液体キセノン検出器

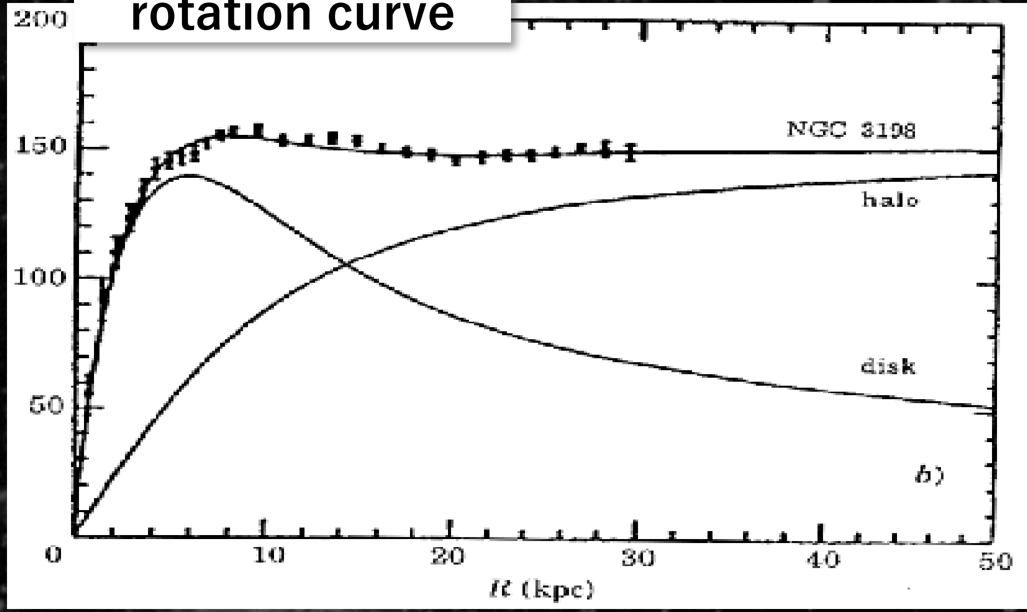
1 暗黒物質直接探索



- DM: seen in various scales in the universe
  - @ galaxy: rotation curves (1970~)
  - @ cluster of galaxies: collision of galaxy clusters (2007~)
  - @ universe: CMB and other observations (2002~)

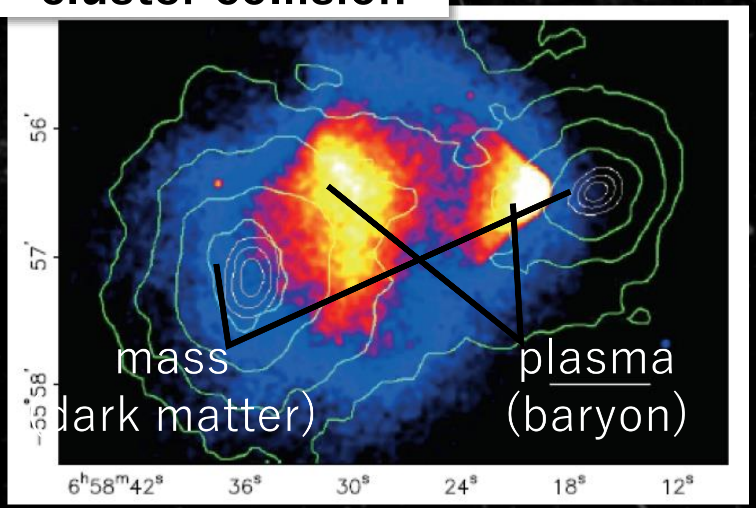
GR !

rotation curve



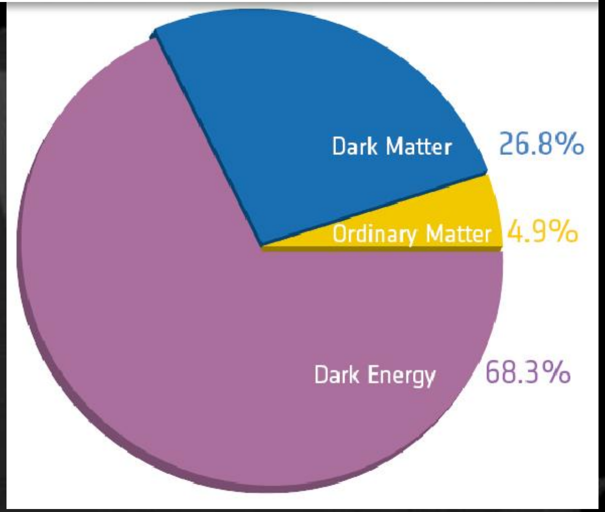
Annu. Rev. Astron. Astrophys. 29(1991)409

cluster collision



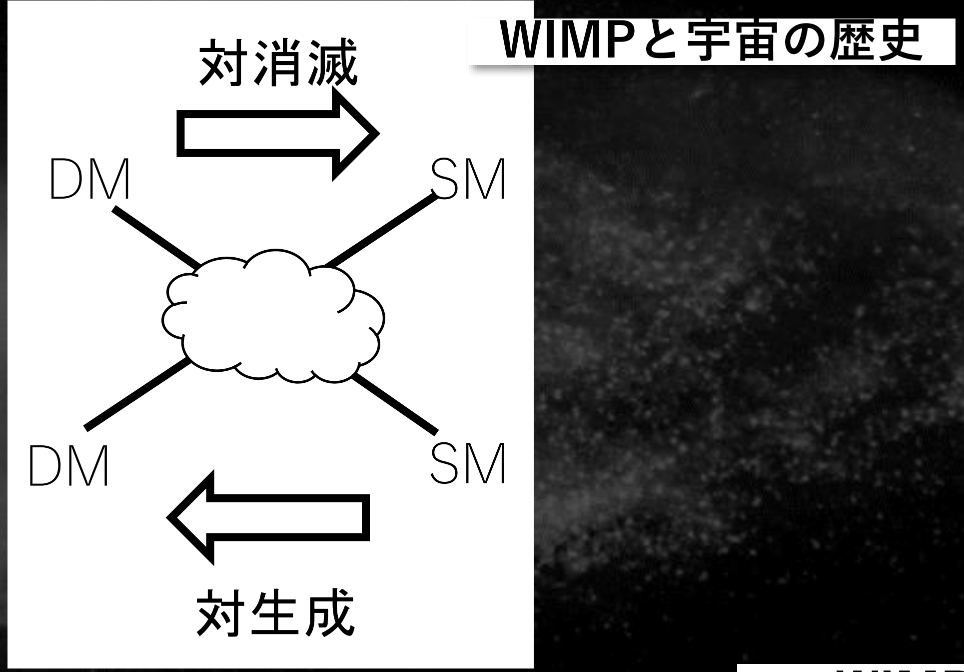
THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10

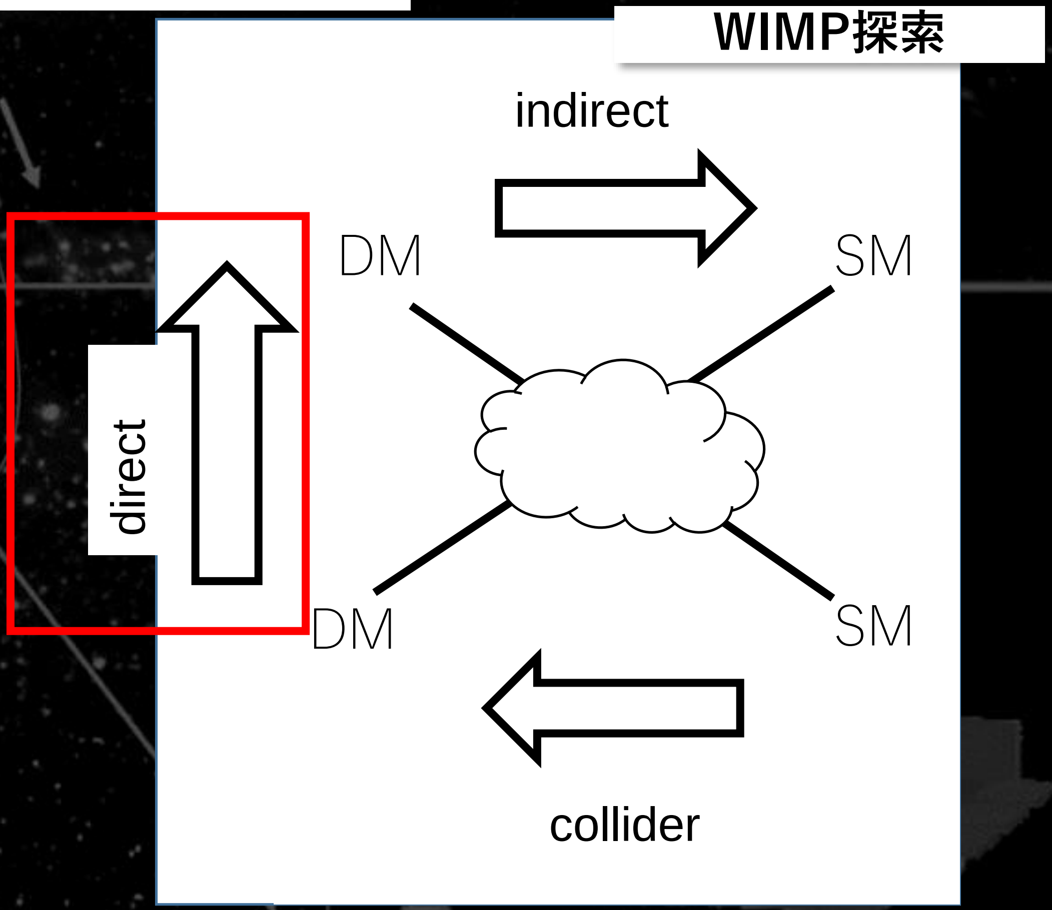
pie chart of the universe



Plank team

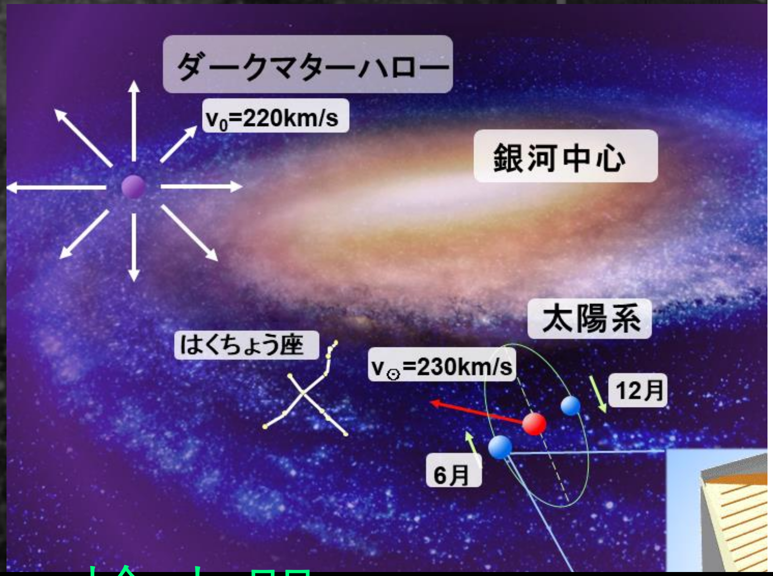
- 多くのDM候補
  - 一粒でn度おいしいものが「良い候補」
    - AXION (CP problem in QCD)
    - Primordial black hole (BHs are there)
    - WIMPs (Weakly Interacting Massive Particles)
  - WIMPs
    - Produced in the early universe
    - Annihilate
      rate ∝ cross section × velocity
    - Freeze out at some point
      abundance is fixed
    - σ～weak scale explains present abundance
      ⇒WIMP miracle！
  - WIMP探索 hunting
    - 直接探索
    - 間接探索
    - 加速器による探索



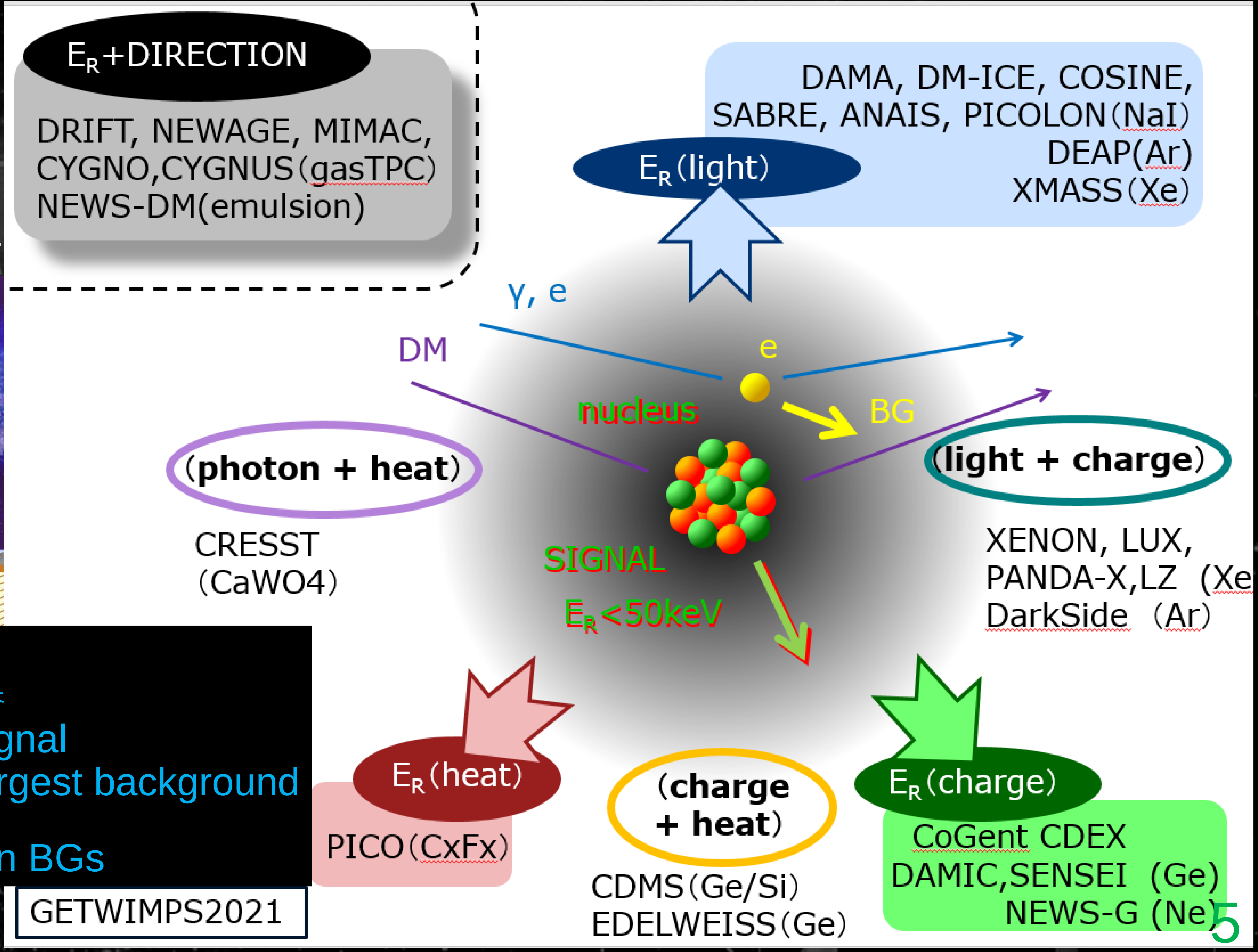


直接探索

詳細:
日本物理学会誌 第75巻
(2020年) 第2号　68-76頁
「宇宙のダークマター直接探索の現状」など。

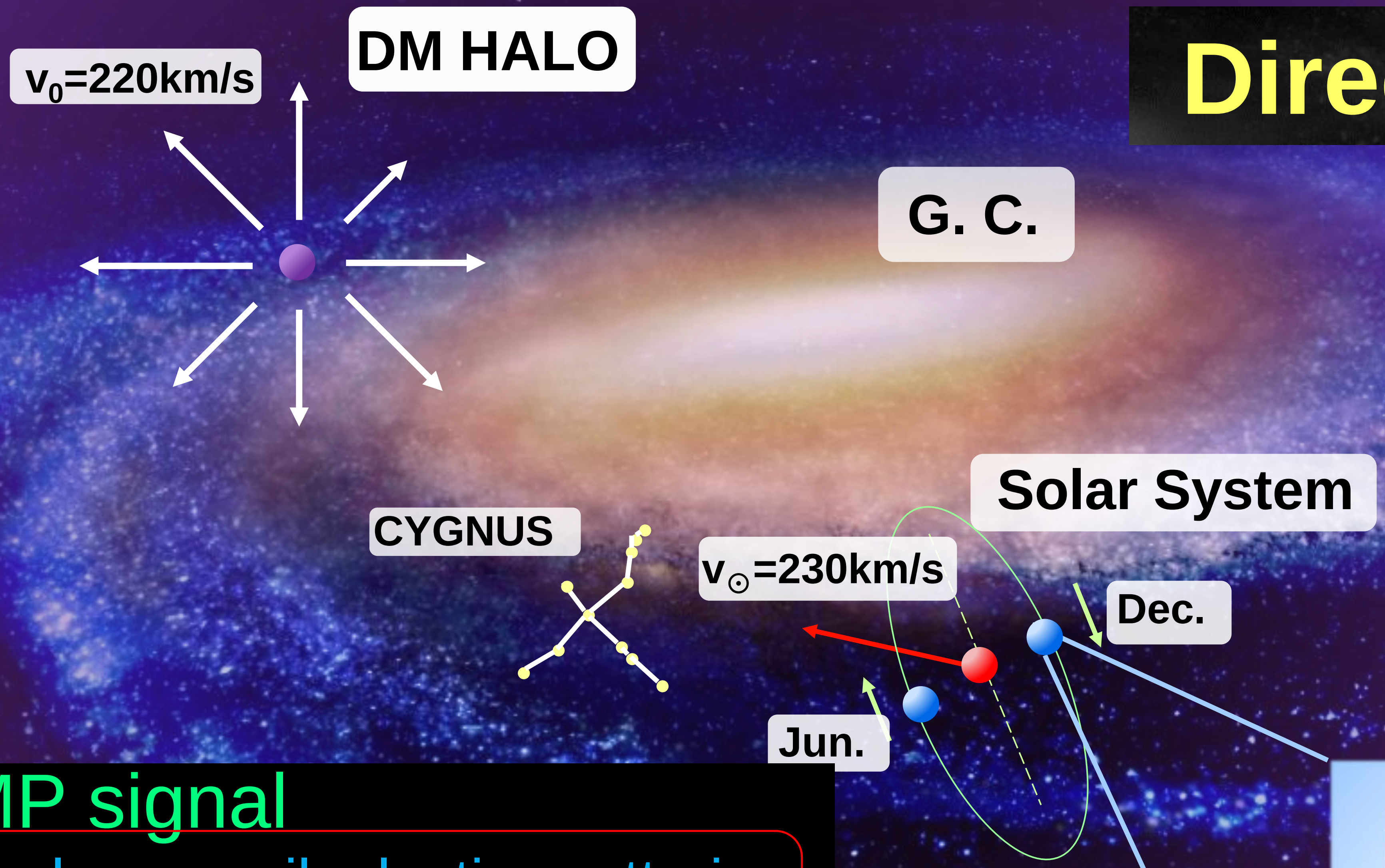


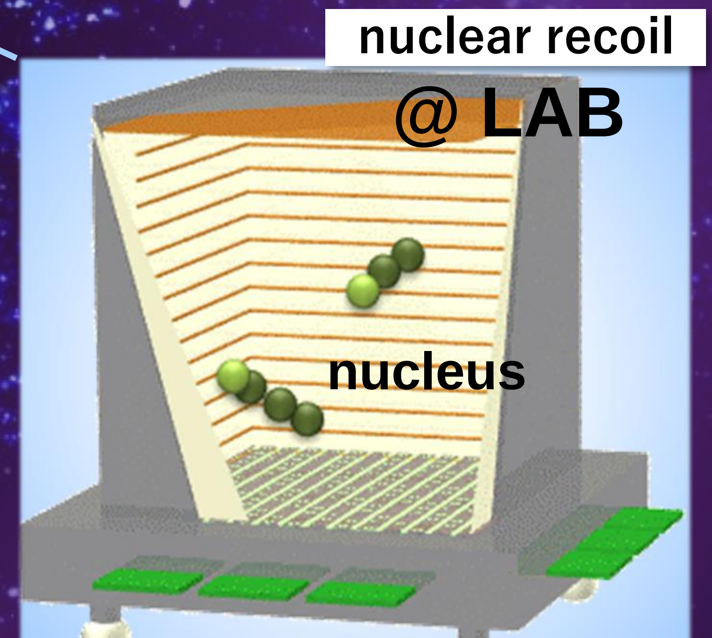
- 検出器
  - 通常の放射線検出器
  - 原子核反跳 (NR): signal
  - 電子反跳（ER）：largest background
  - more than two info
    ⇒　reject electron BGs



Kentaro Miuchi

Direct Detection



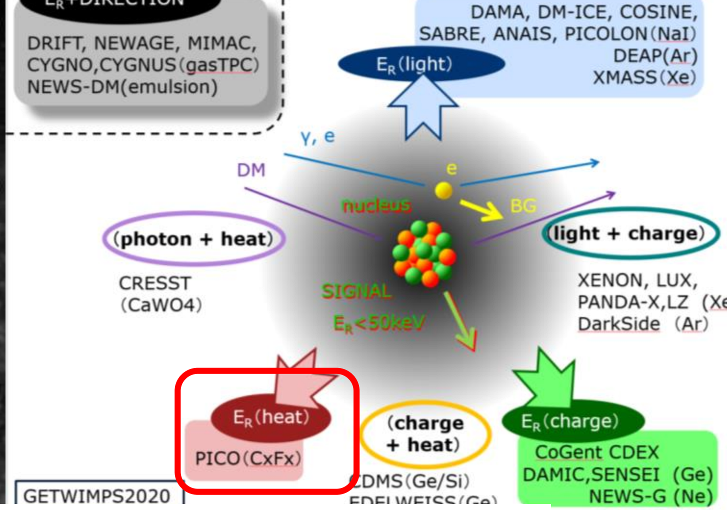


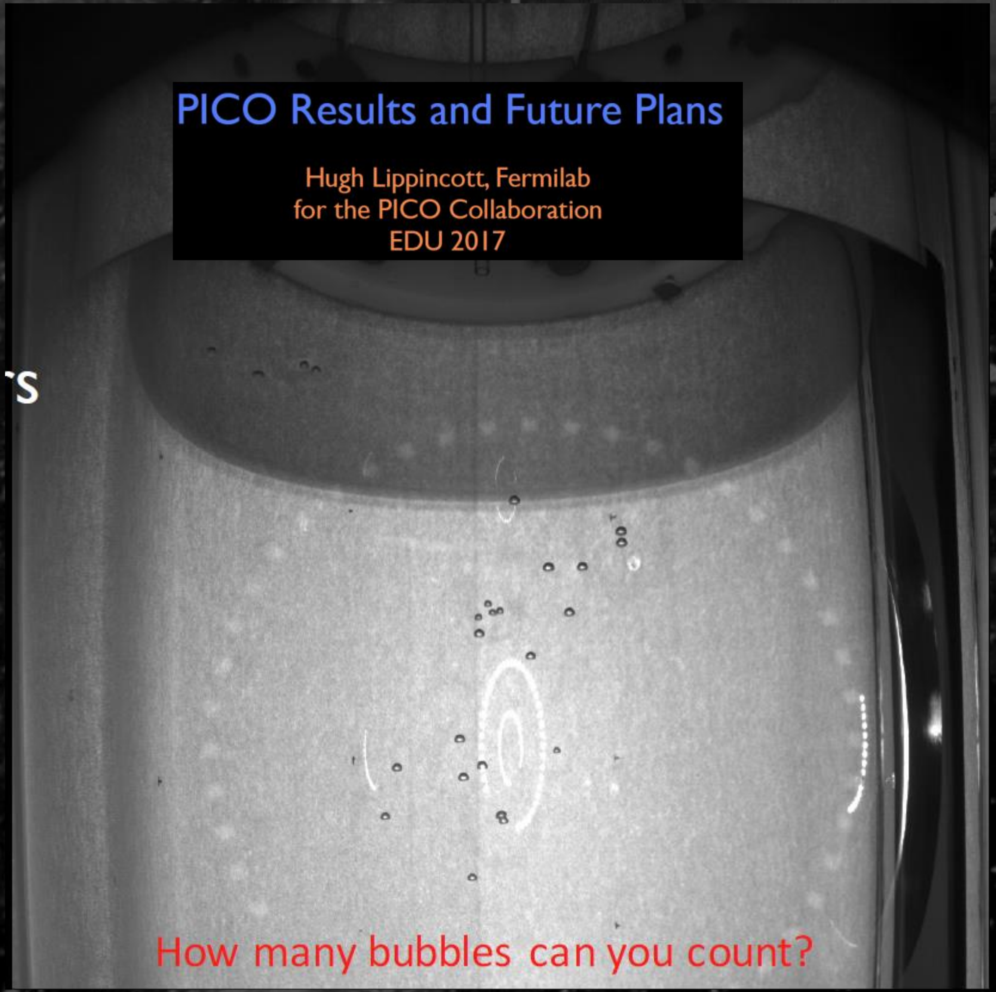
- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction

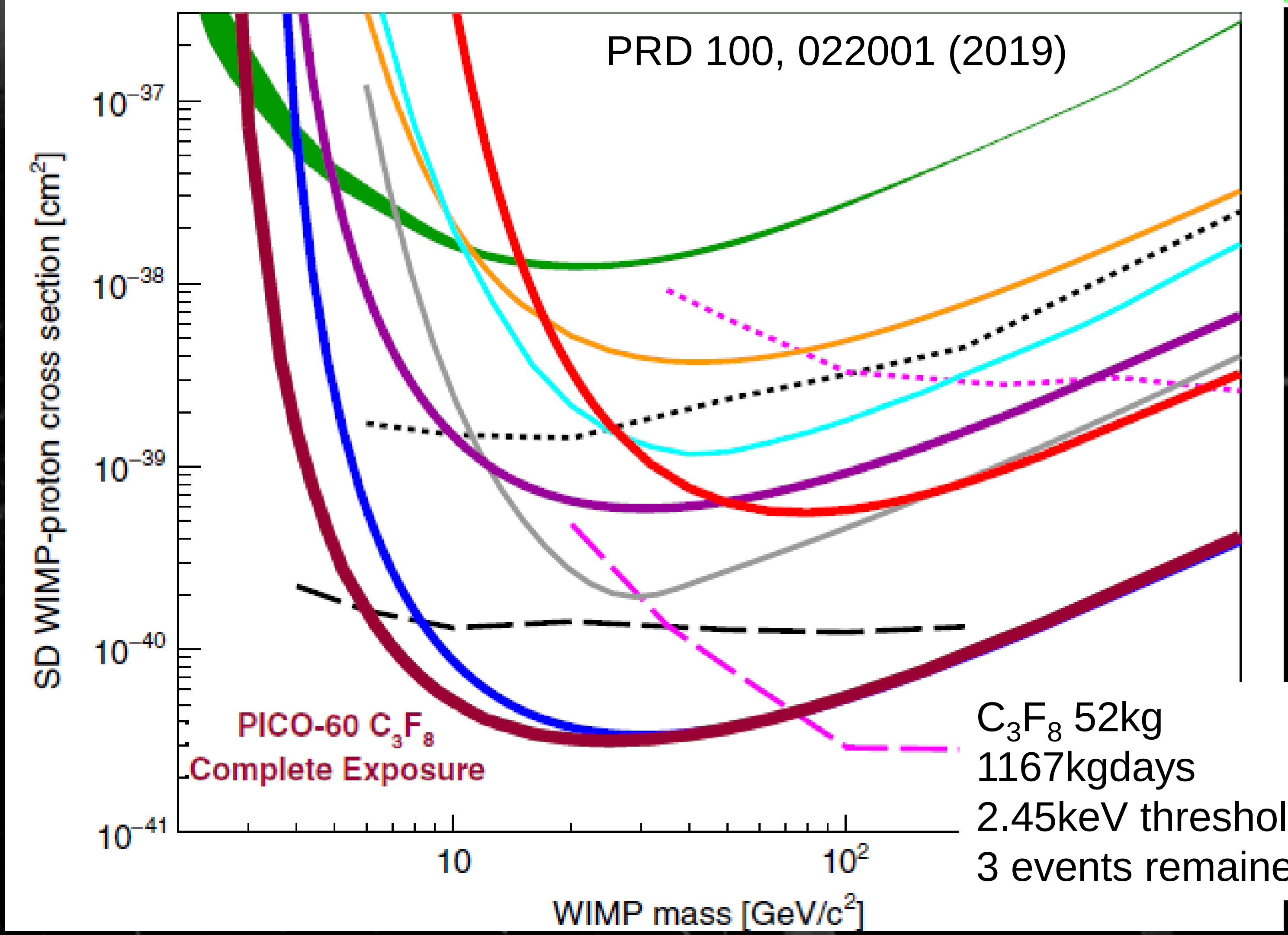
（エレキ的には）
結構ローテクでも頑張れる

- Bubble chamber
  - PICO
    - Superheated chamber
    - Threshold-type detector
    - Best SD sensitivity

音と写真



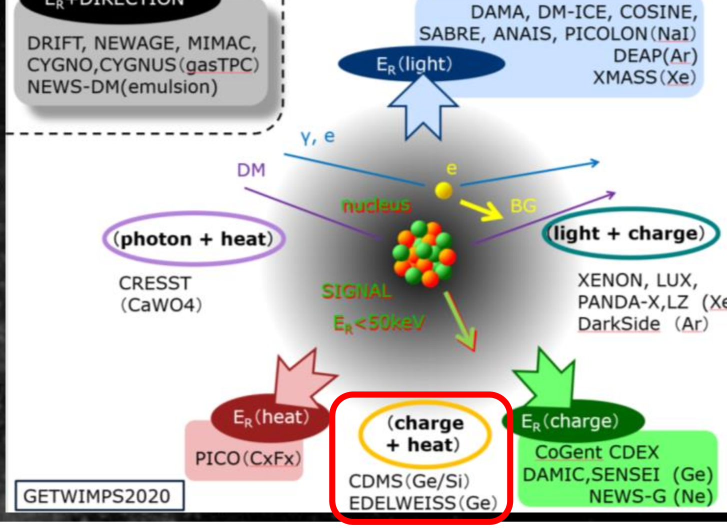




C_3F_8 52kg
1167kgdays
2.45keV threshold
3 events remained

- Bolometers
  - Low energy threshold ⇒ low mass DM

検出器3つ
⇒ TES+SQUID



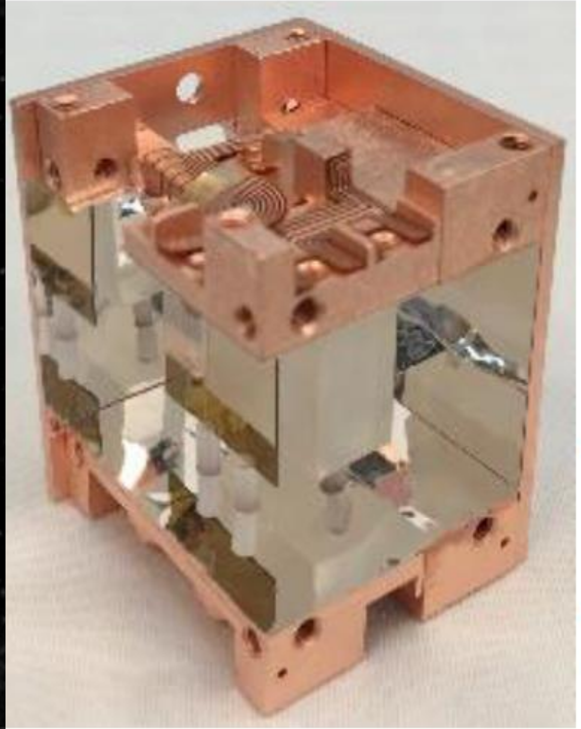
Latest results of CRESST-III's search for sub-GeV/c² dark matter

Holger Kluck
on behalf of the CRESST collaboration

16th International Conference on Topics in Astroparticle and Underground Physics (TAUP2019)

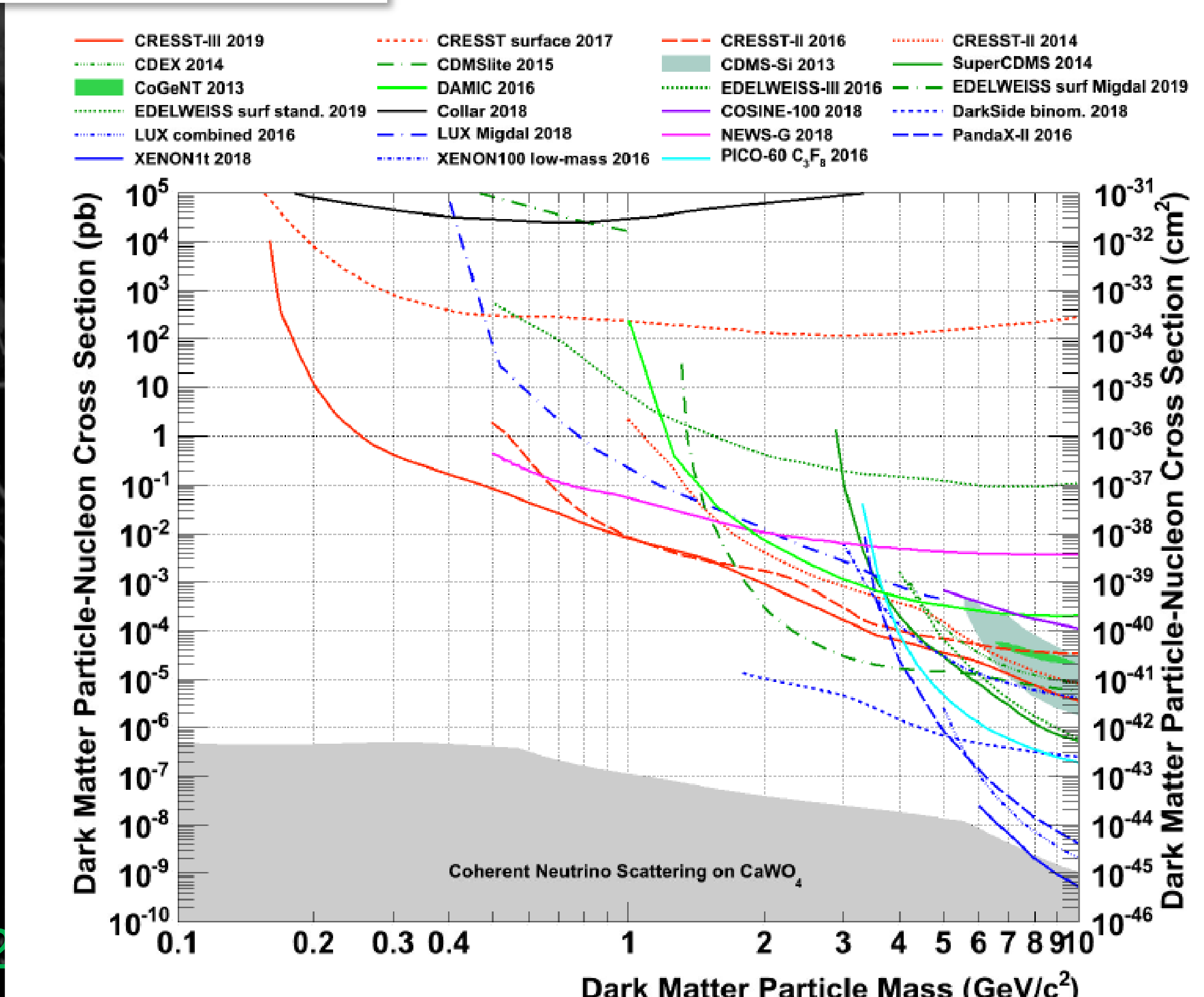
September 10, 2019

CRESST-III detector



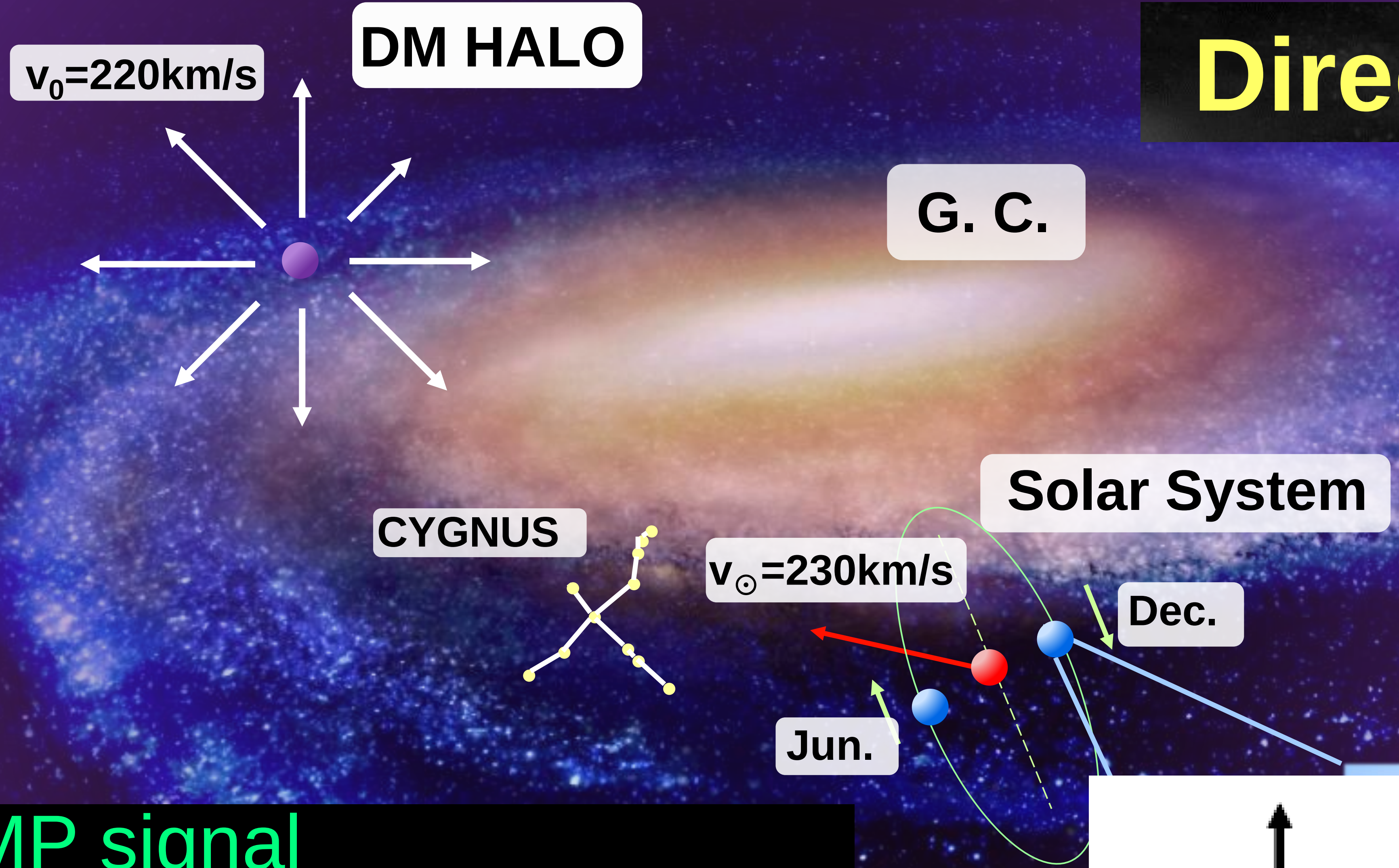
- May 2016:
  10 CRESST-III modules installed
- Jul 2016 – Feb 2018:
  data taking (80% blinded, 20% training set)
- Detector A
  → lowest nuclear recoil threshold so far: 30.1 eV
- Target crystal mass: 23.6g
- Gross exposure: 5.6 kg d
- [arXiv:1904.00498], accepted by Phys.Rev.D
  → this talk

CRESST-III result



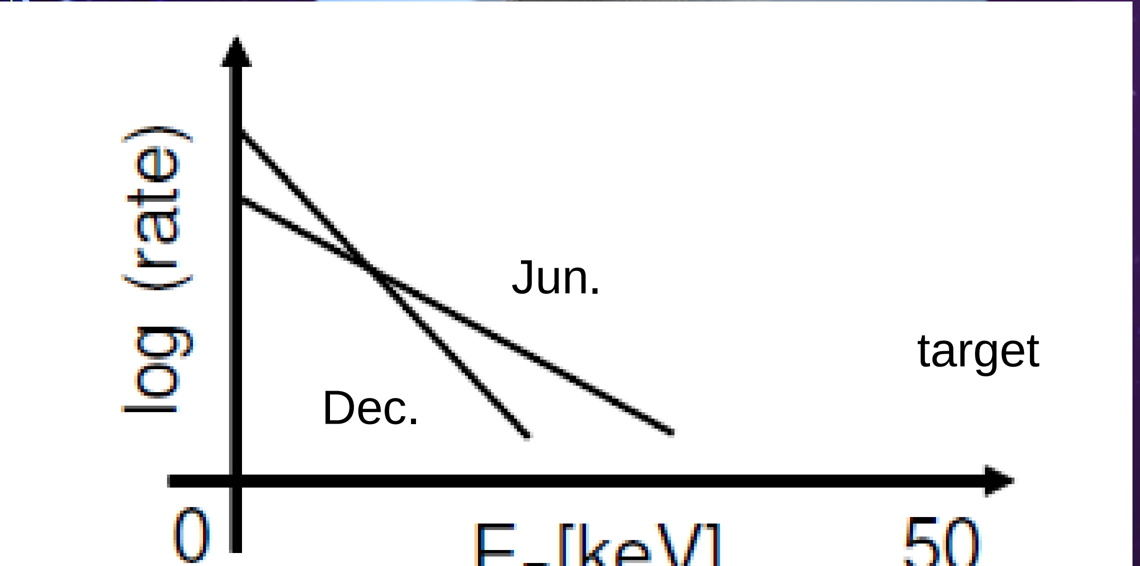
Kenta
Oct. 2

Direct Detection

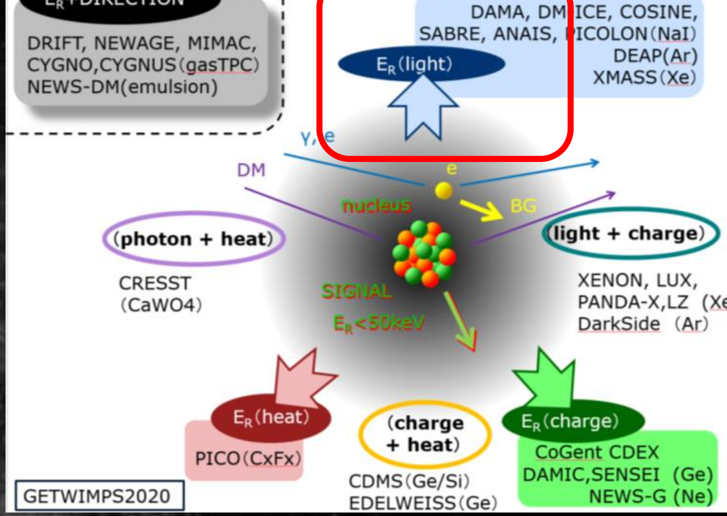


- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction

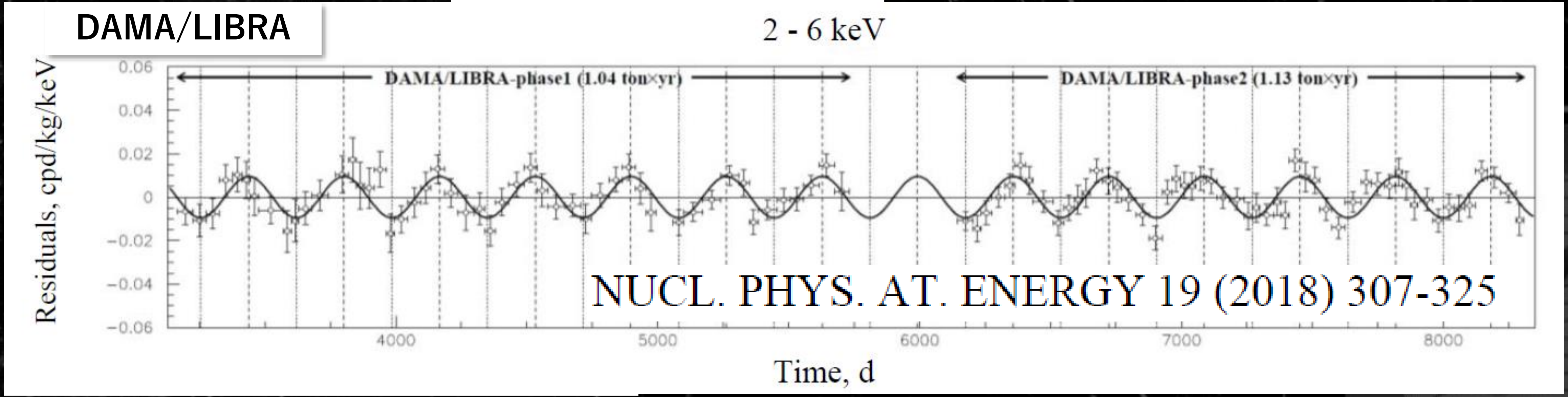
seasonal modulation



- DAMA　(NaI)
  - 25×10kg NaI scintillators　⇒ PMT 50本 ⇒ CAMAC charge ADC
  - Annual modulation were reported：1998〜
  - Latest 2.46 ton year　12.9 σ
  - SOMETHING is detected



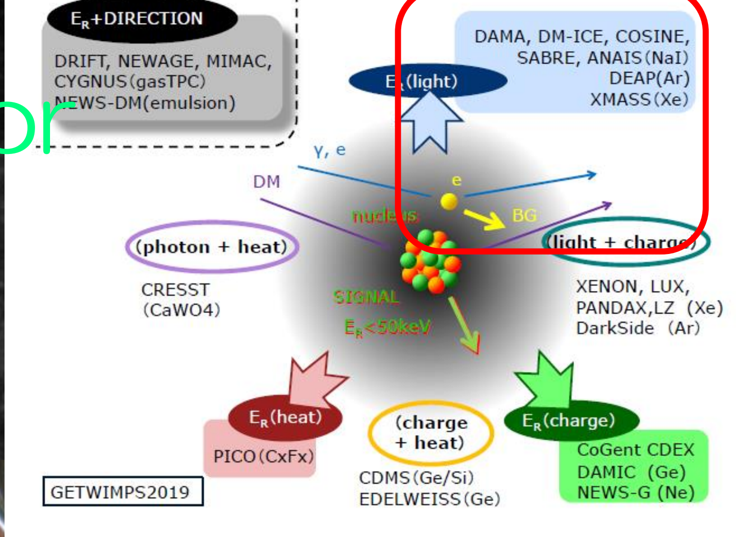
Eur. Phys. J. C (2008) 56: 333–355
DOI 10.1140/epjc/s10052-008-0662-y



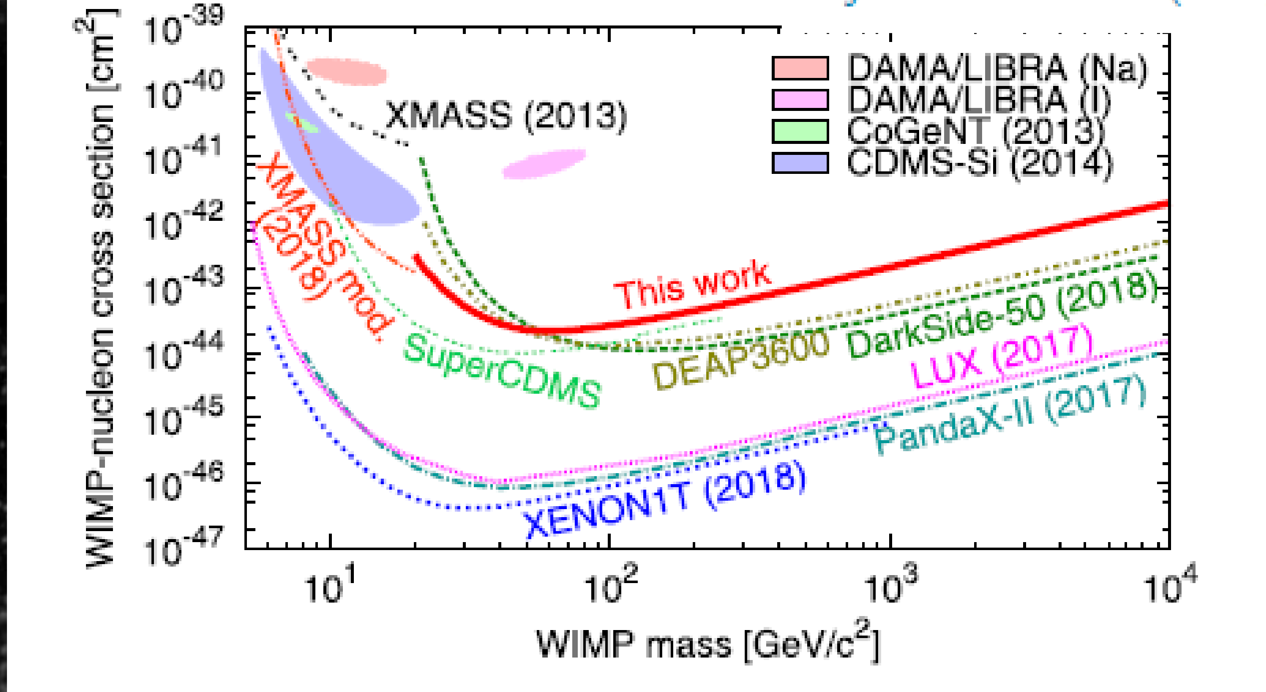
No BG explains this modulation
No natural DM model explains, either…

Kentaro Miuchi

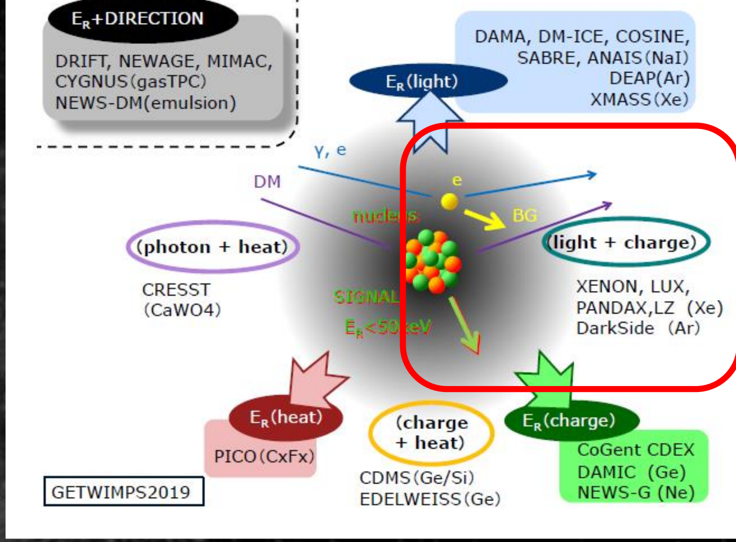
- Liq Xenon：1 phase (liquid-only) detector
  - XMASS
    Nuclear Instruments and Methods in Physics Research A 716 (2013) 78–85
    - Observation 2013 Nov.～2019 Mar.
    - 800kg liquid xenon
    - 642× PMTs ⇒ 500MHz FADC
  - One of the main results ”fiducial paper”
    - “self-shielding” of liquid xenon



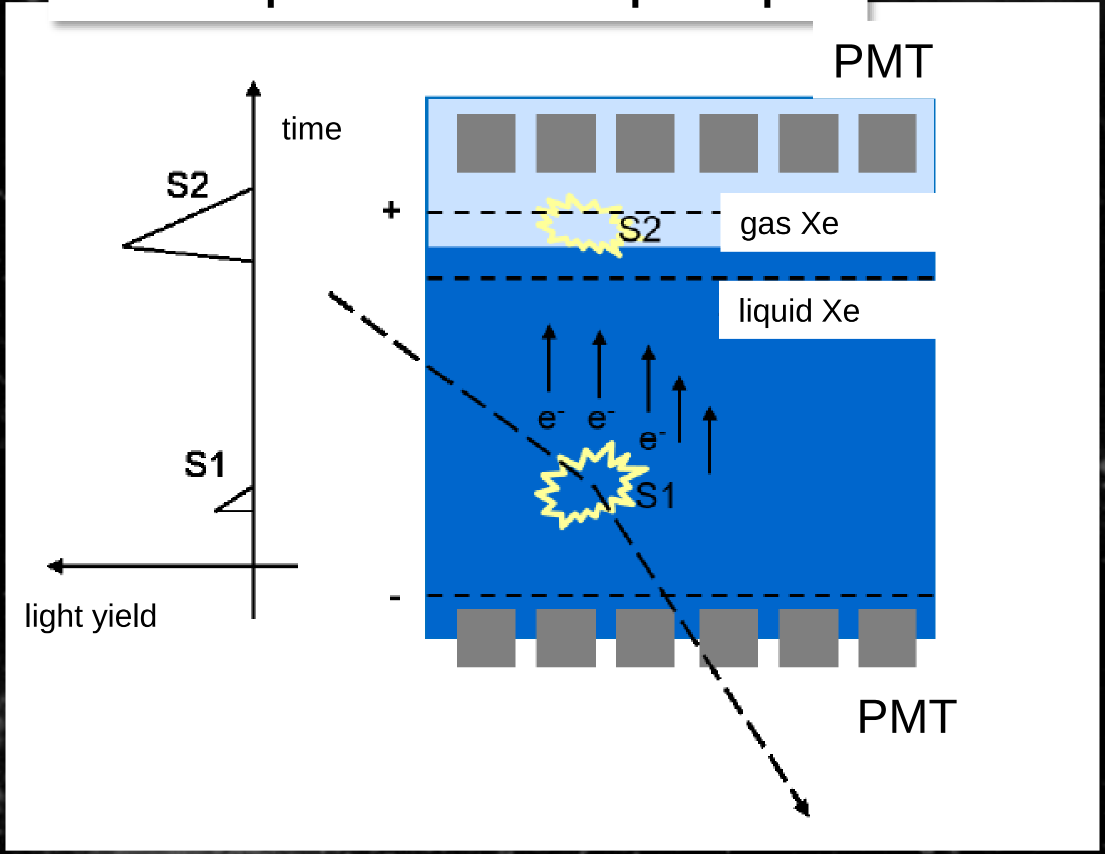
Physics Letters B 789 (2019) 45–53



- Liquid Xe：double-phase（liquid+gas）
  - ER事象を除去可能
  - XENONnT（コミッショニング中）
    - 5.9ton液体キセノン ⇒ 494PMTs
      ⇒ FADC（100MHz triggerless）

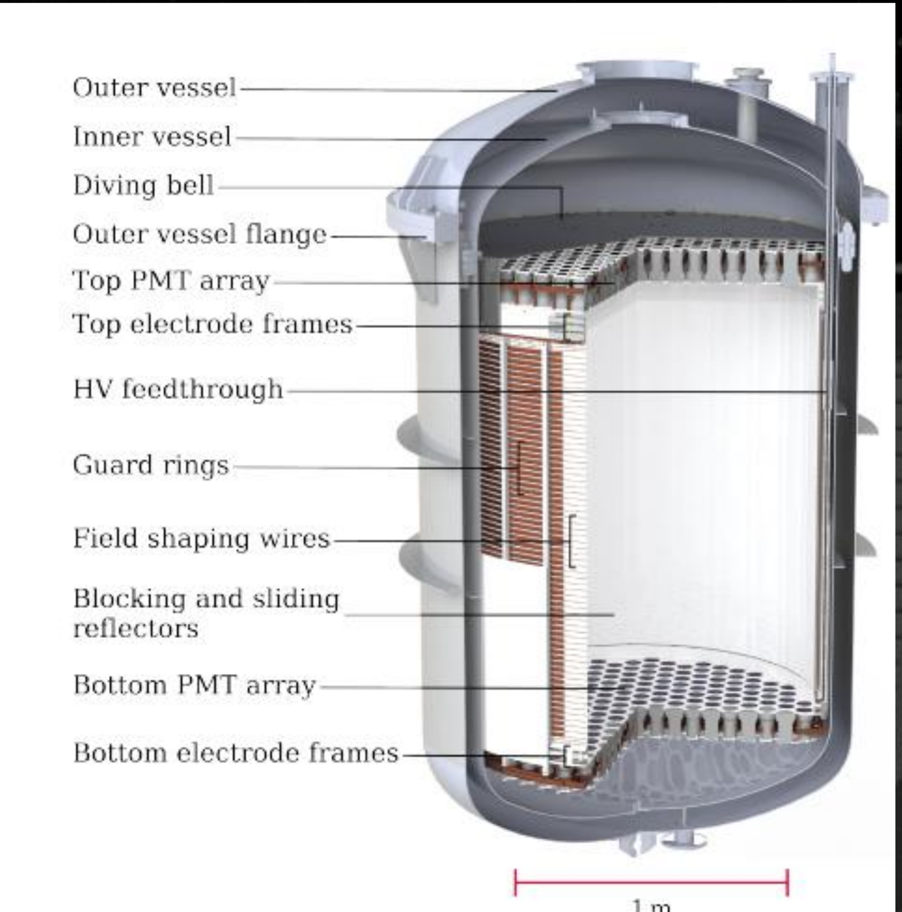


Double phase detector principle

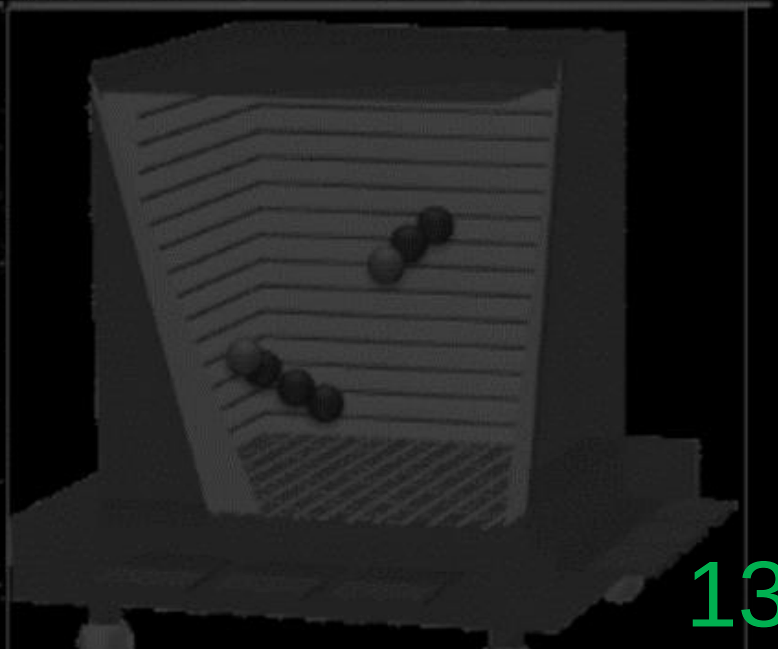


JCAP11(2020)031

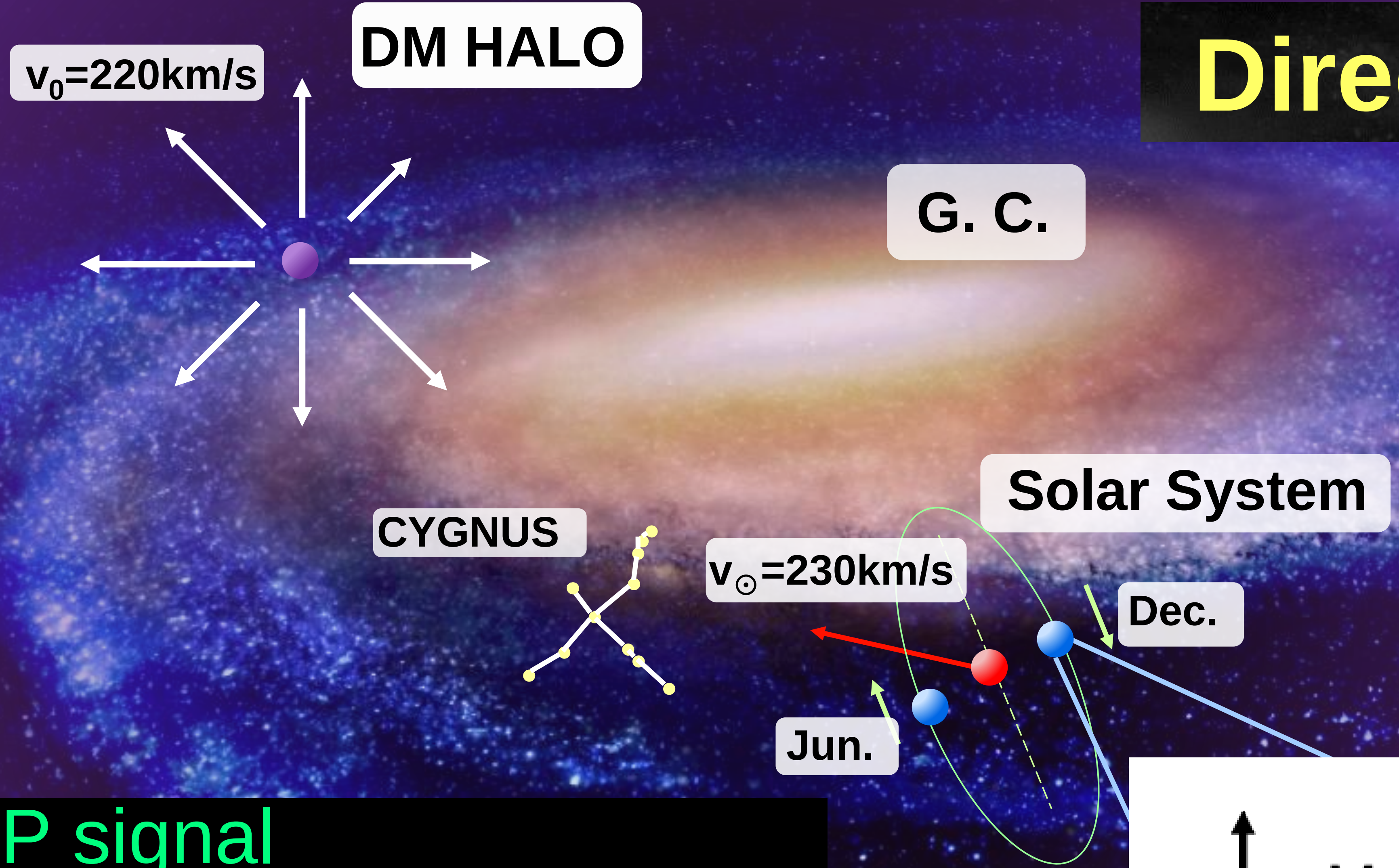
XENONnT detector



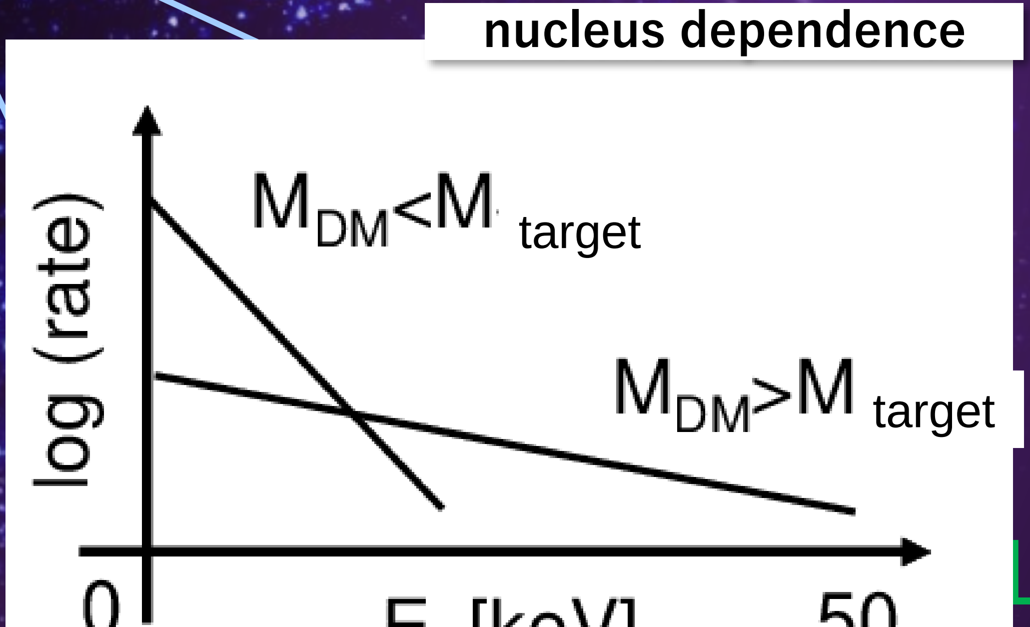
- NaI、XENONなどのシンチレータ
  - tonクラスの検出器 ⇒ 数百本のPMT（ゲイン～10^6）で読む
  - チャンネル数的にも、ゲイン的にも　力技（ADC16ch×n）で読めてしまう。
  - むしろ放射性バックグラウンド低減に力を入れてきた。
- シンチだとASICやFPGAの活躍場所ない？
  - そうでもない。



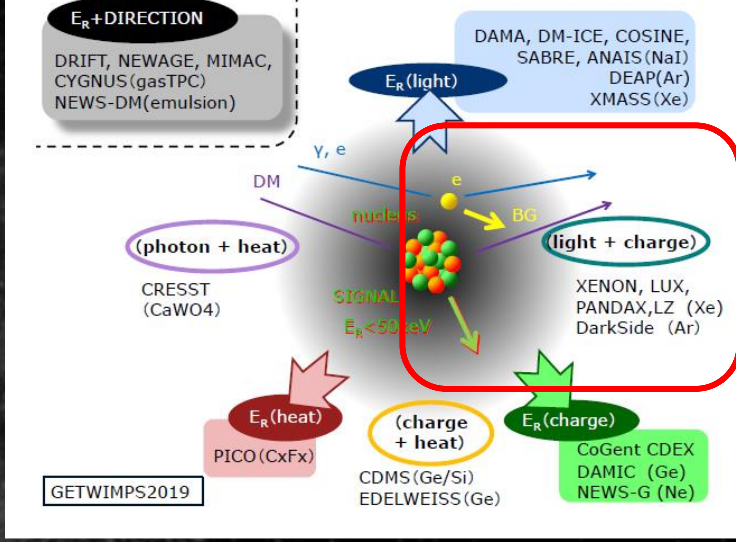
Direct Detection

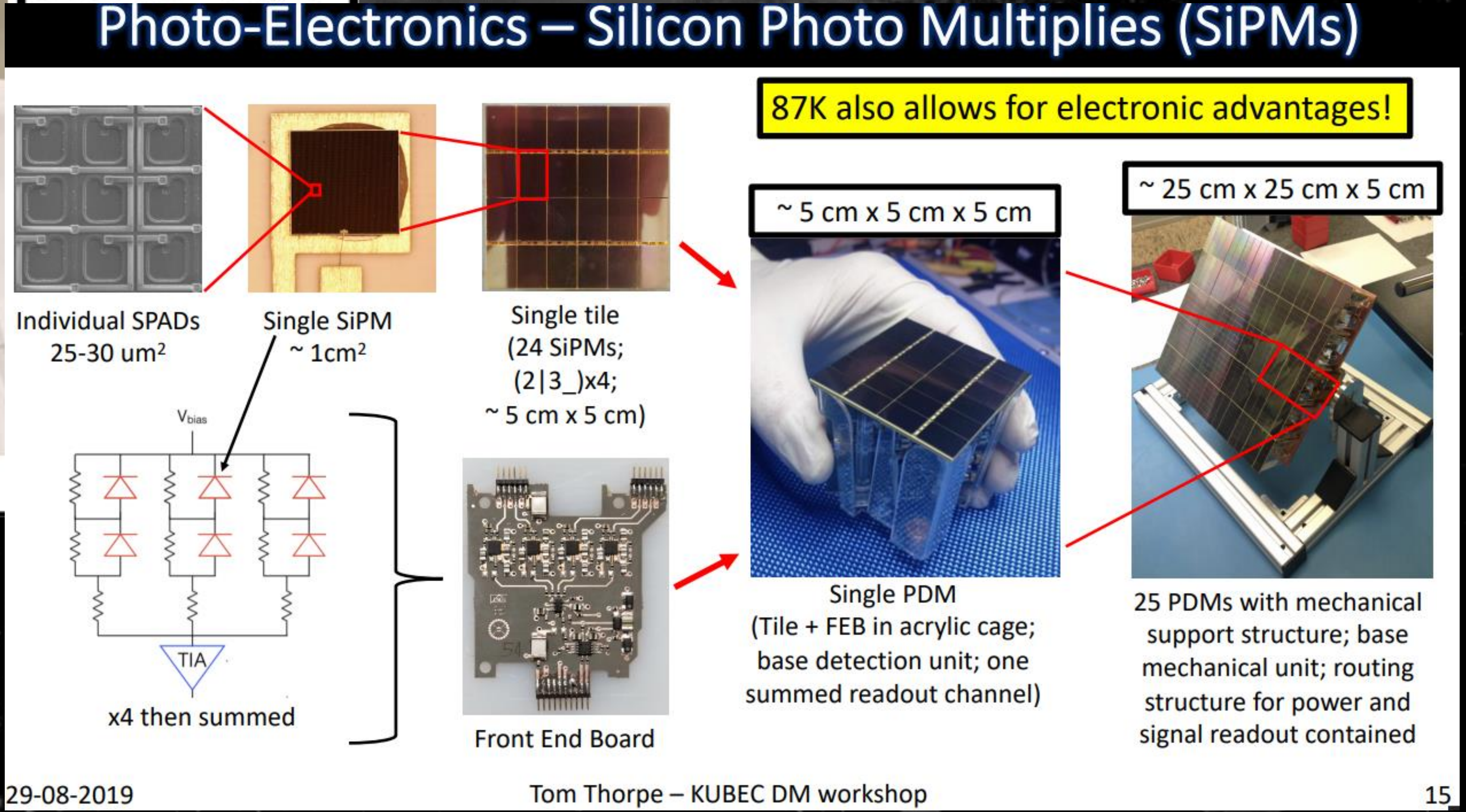


- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction



- Liquid Ar : double-phase (liquid+gas)
    - DARKSIDE 20k (R&D 中)
        - 50ton液体アルゴンキセノン ⇒ ~8000 PDMs





- SENSEI：skipper CCD
  - 汎用ではないけれど、エレキの勝利例

PRL **119,** 131802 (2017)

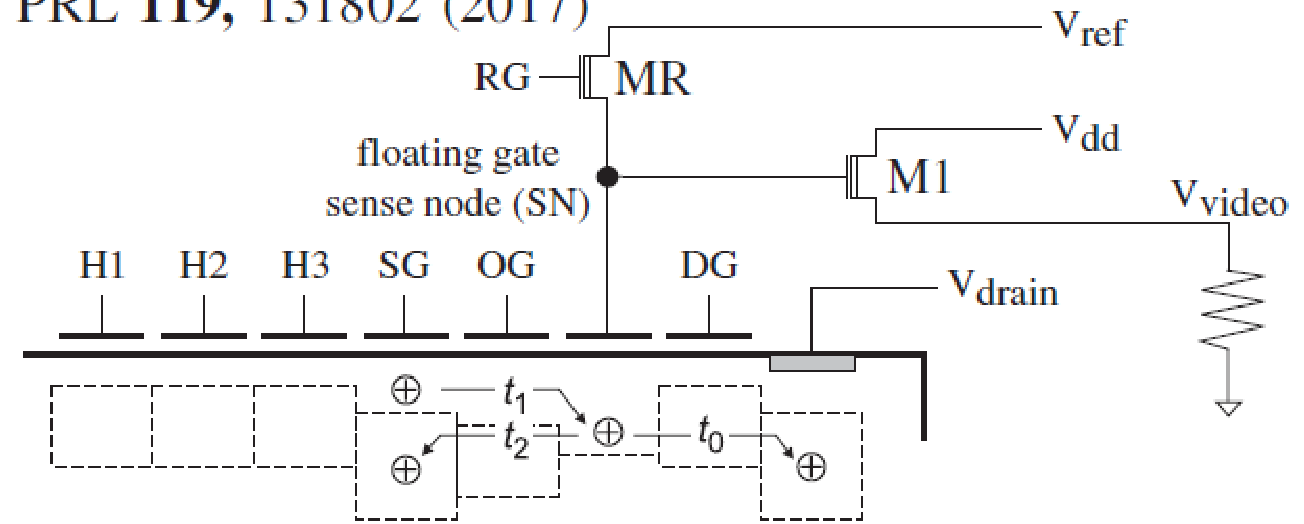
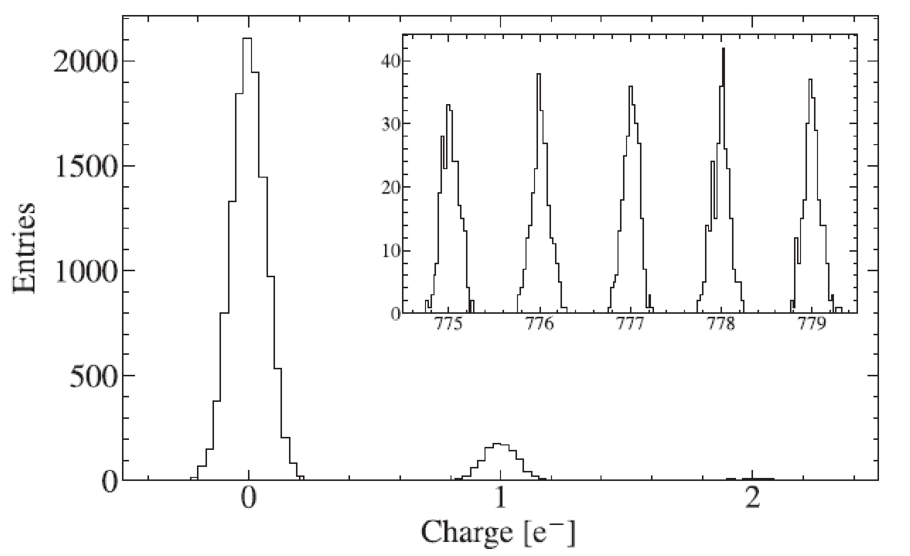
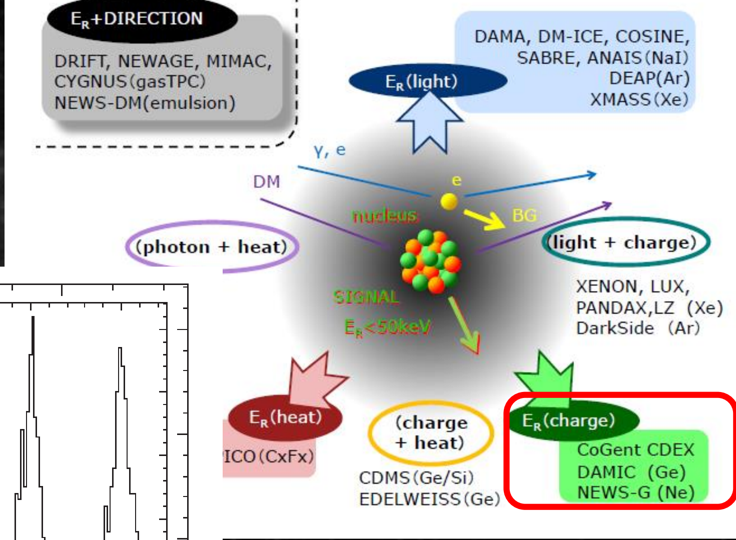
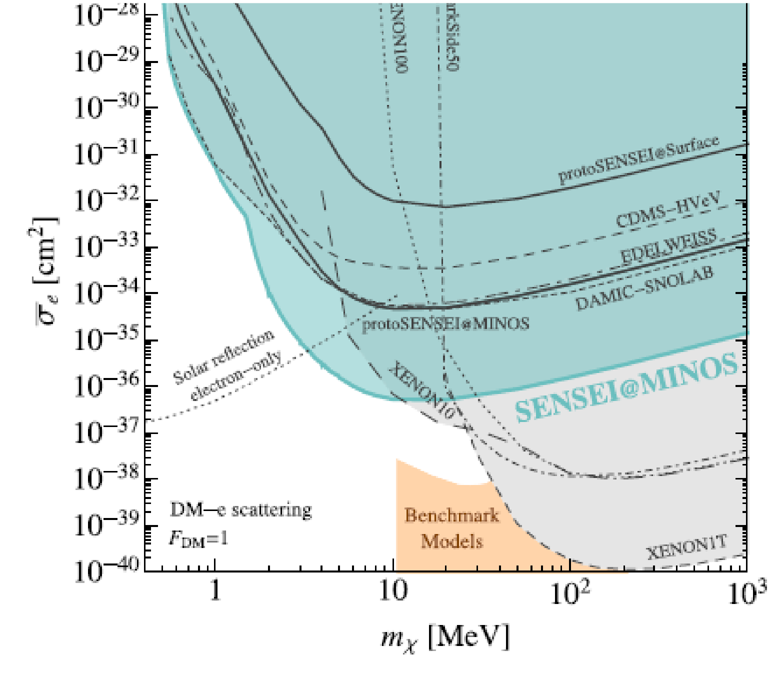


FIG. 2. Schematic of the Skipper CCD output stage. H1, H2, and H3 are the horizontal register clock phases. MR is a switch to reset the sense node to V_{ref}. M1 is a MOSFET in a source follower configuration. Because of its floating gate, the Skipper CCD readout performs a nondestructive measurement of the charge at the SN.

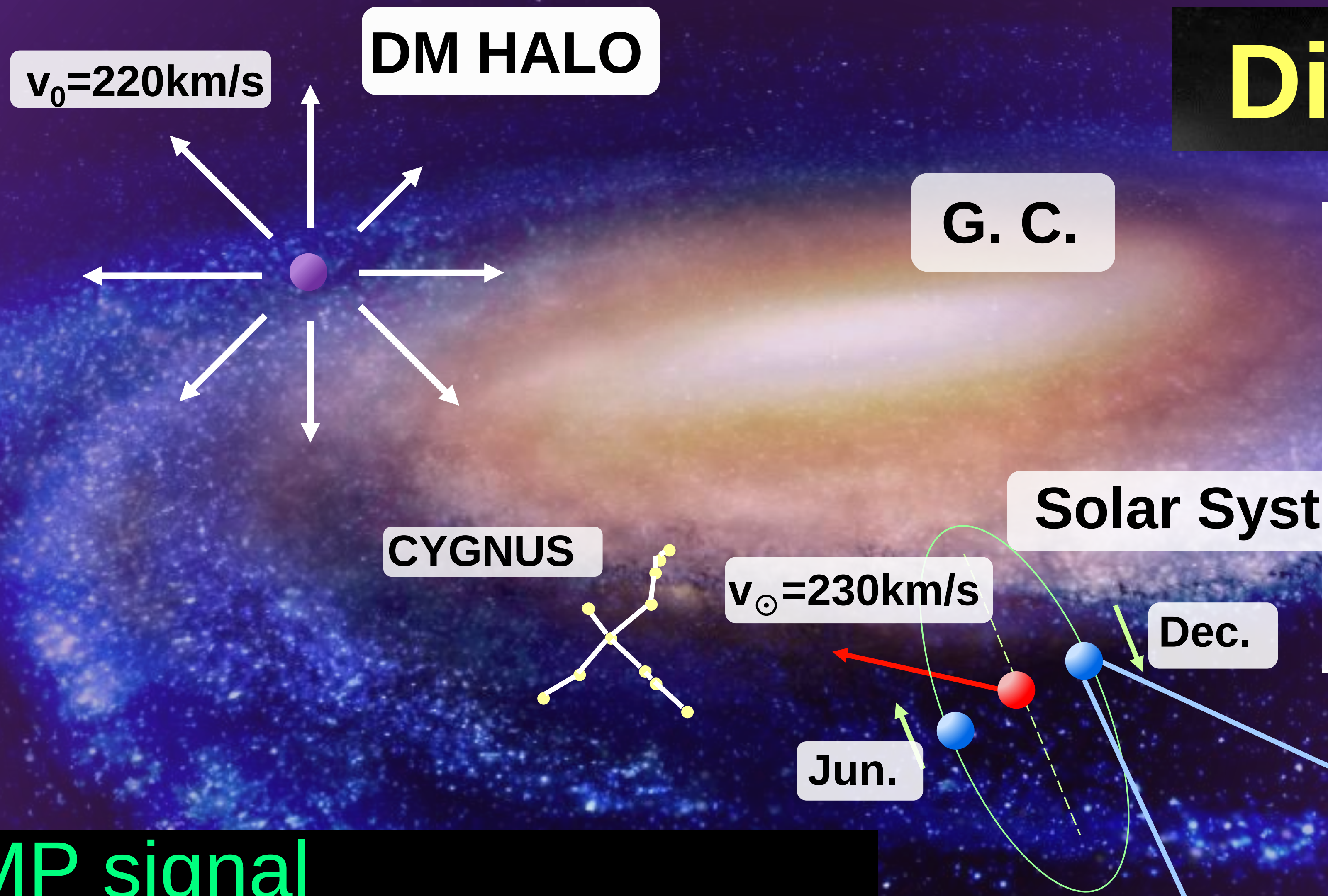


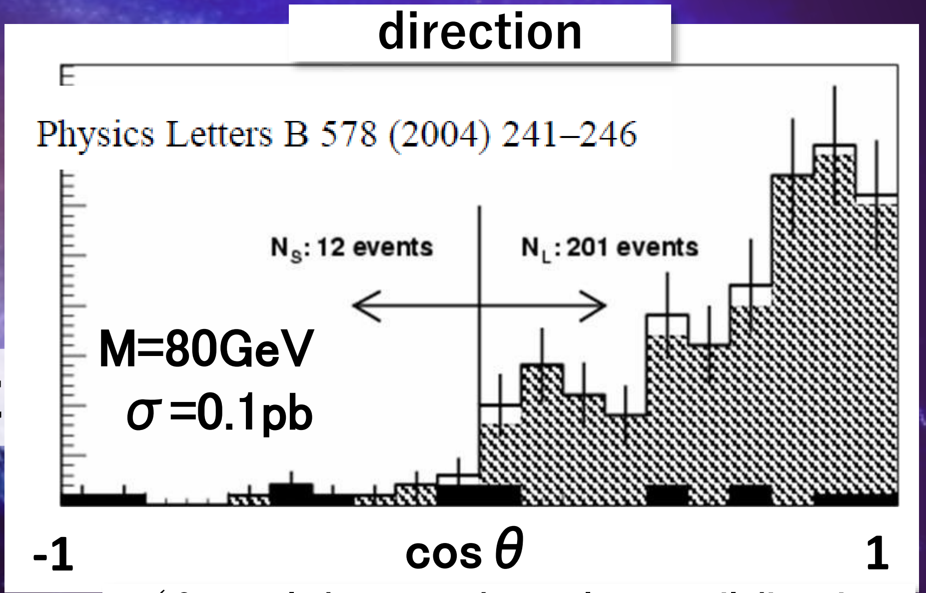


PHYSICAL REVIEW LETTERS **125,** 171802 (2020)

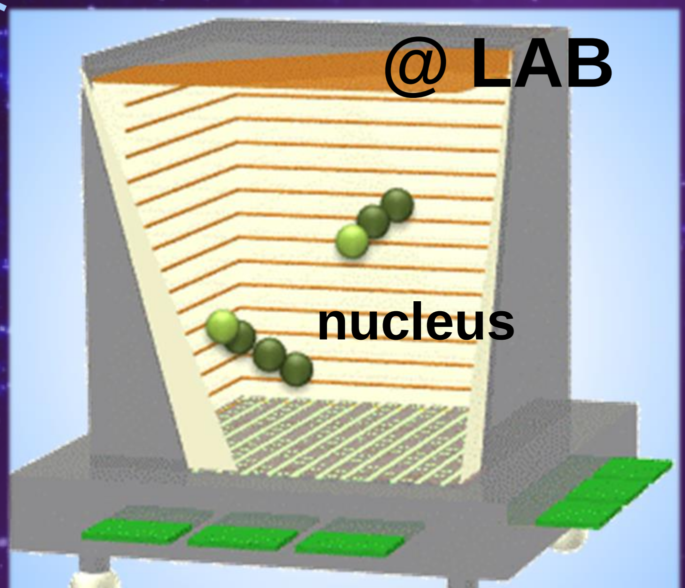


Direct Detection





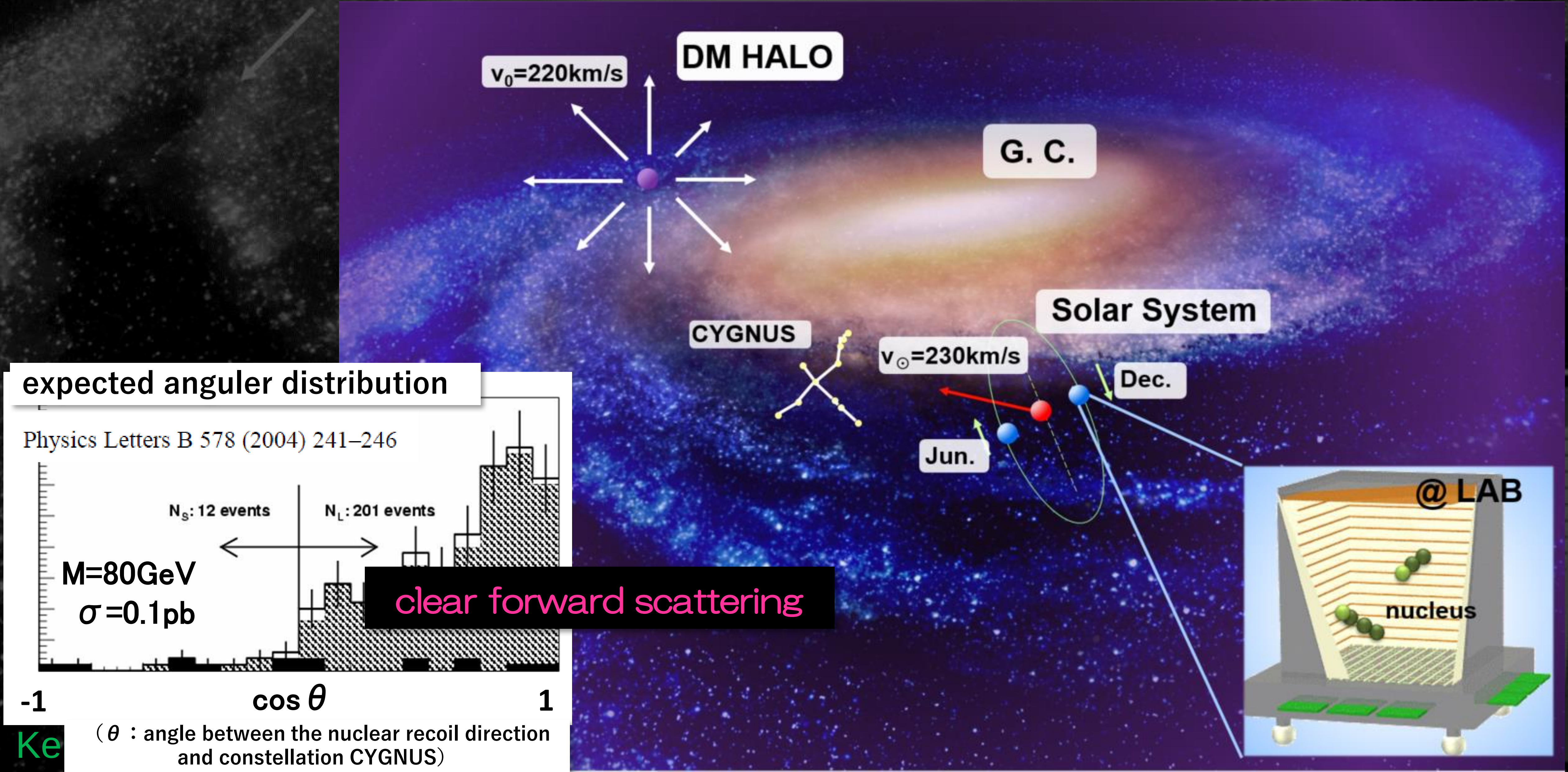
（θ：angle between the nuclear recoil direction and constellation CYGNUS）



- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction

２ ASIC、 FPGAの使用

- やりたいこと：方向に感度をもった暗黒物質探索
  - 低圧のガス中で数mmの原子核反跳飛跡を検出
  - 暗黒物質発見の確実な証拠&発見後の性質解明



Ke

• MPGD for DM

- 方向に感度を持つ探索提案　（1980年代）
- CCDイメージを使った原理実証（1990年代）

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 37, NUMBER 6 — 15 MARCH 1988

Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

PRL73(1994)1067

FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.

NIMA 263(1988)351

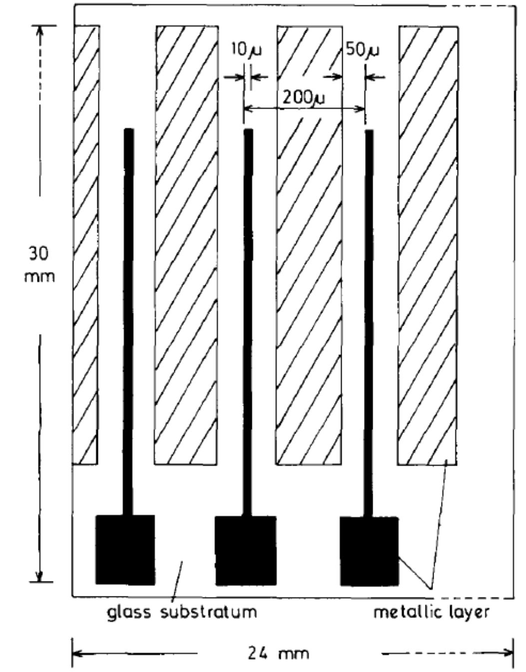
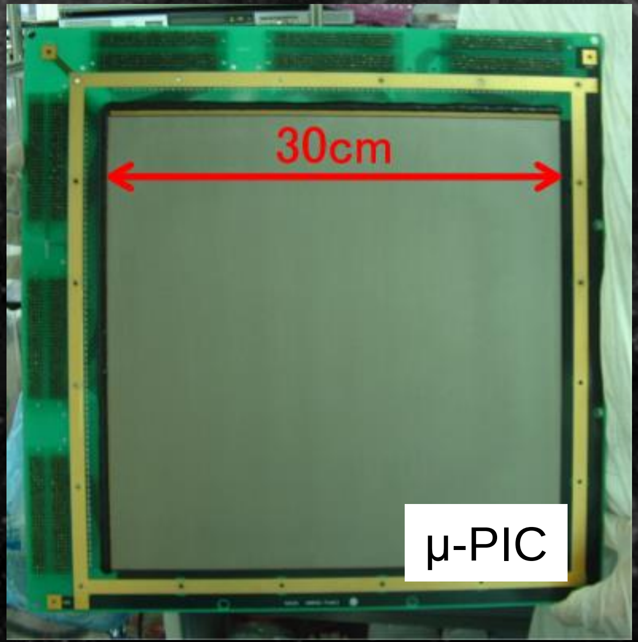
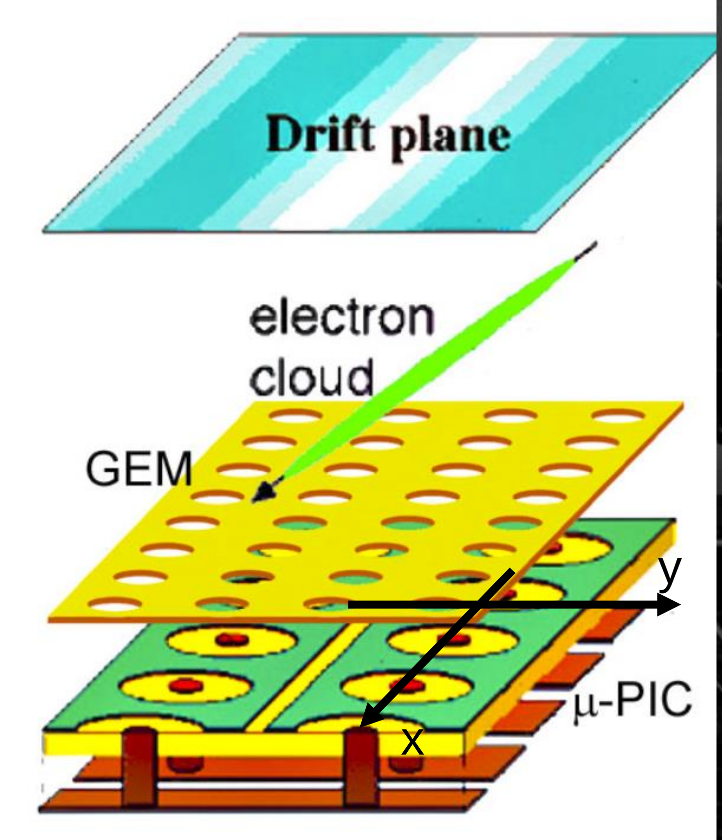


Fig. 1. Dimensions of the microstrip plate (MS-plate) used for the measurements. The chromium layer on the glass substrate is 300 nm in thickness.

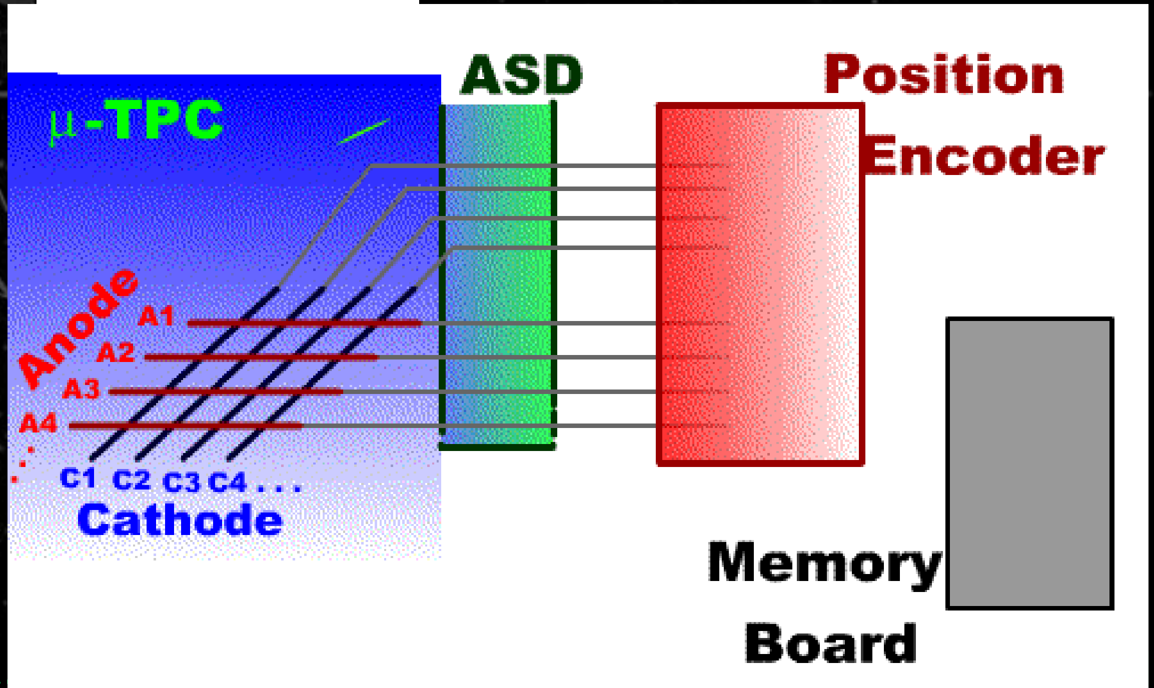
- マイクロパターンガス検出器（MPGD）の台頭（1990年代）

- ストリップ読み出しのガスTPC
  - 2次元イメージ（x y同時計測）
  - 時間情報で3次元め





TPCの原理



• MPGD：エレキマンの時代

- 5cm角　MSGC 500ch

T. Tanimori et al./Nucl. Instr. and Meth. in Phys. Res. A 381 (1996) 280–288

- LeCroy TRA-100 16ch/chip （アナログアンプ）
  ：性能自体は大きくは変わらない　（消費電力などで進化）
- 後段の処理系が大きく進化してきた。

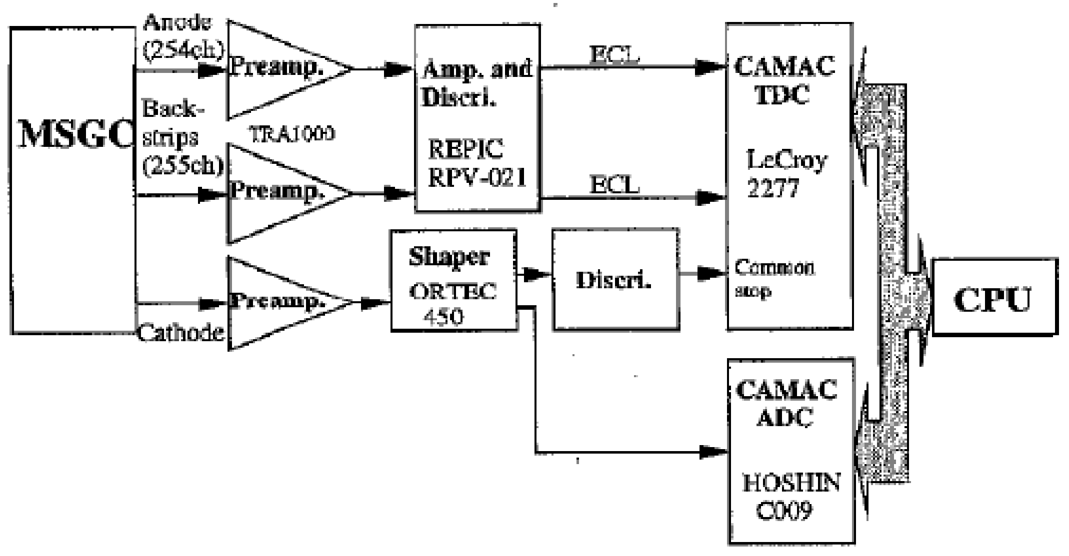
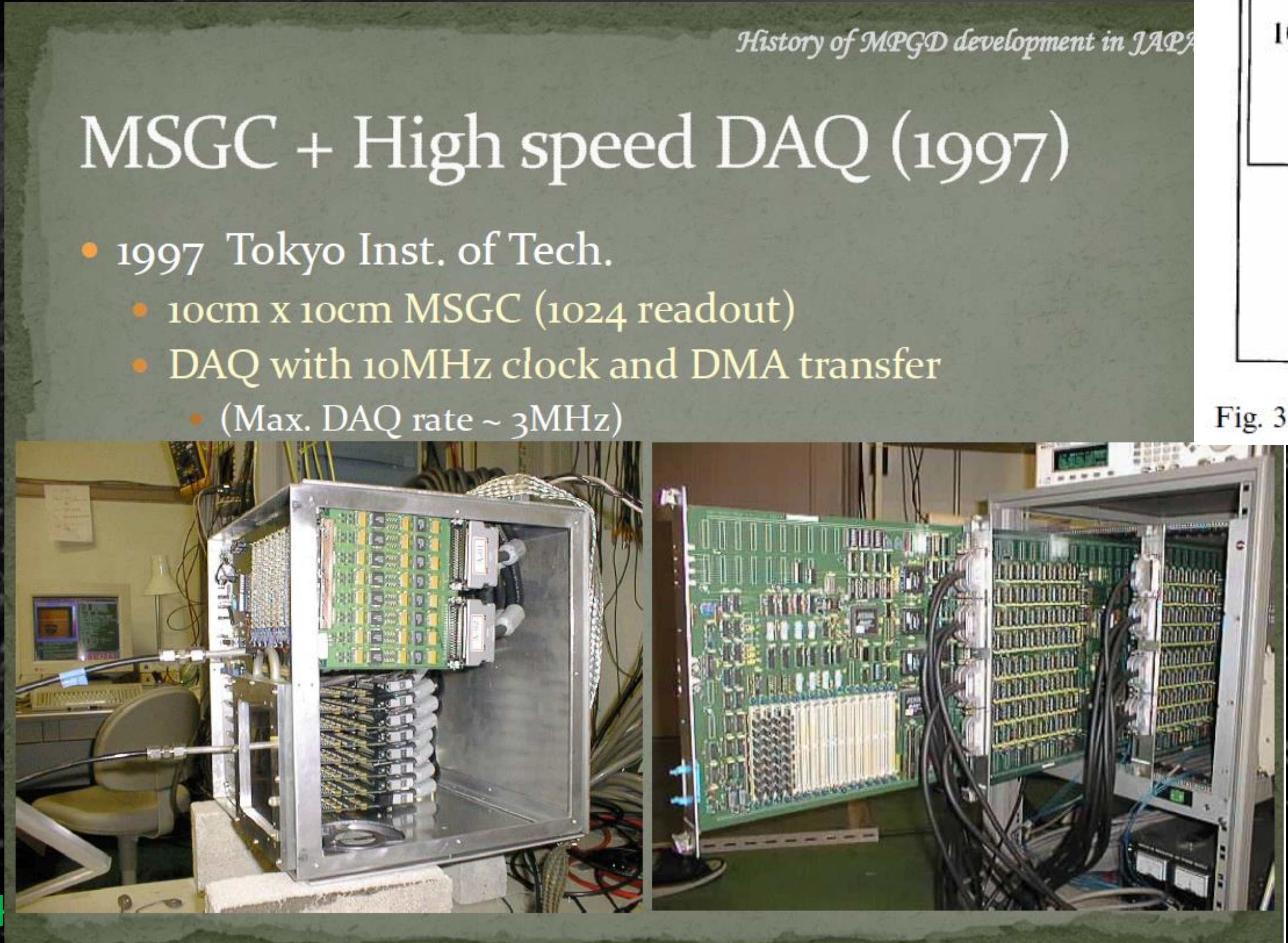


Fig. 9. Block diagram of the readout system.

Fig. 9. A charge integrated preamplifier with a time constant of 500 ns was designed using the LeCroy TRA100 monolithic amplifier chip. Each preamplifier card contains 16 amplifiers. As a main-amplifier and discriminator system, we used the system developed at KEK (National Laboratory for High Energy Physics in Japan) as a part of the drift-chamber readout system which includes a fast current amplifier and discriminator. The discriminated pulses were fed to CAMAC multi-hit TDCs. Fig. 10 shows the distribution of the timing difference between an anode pulse and

- 専用「encoder」
  - digital化して、なんやかんやするという原型



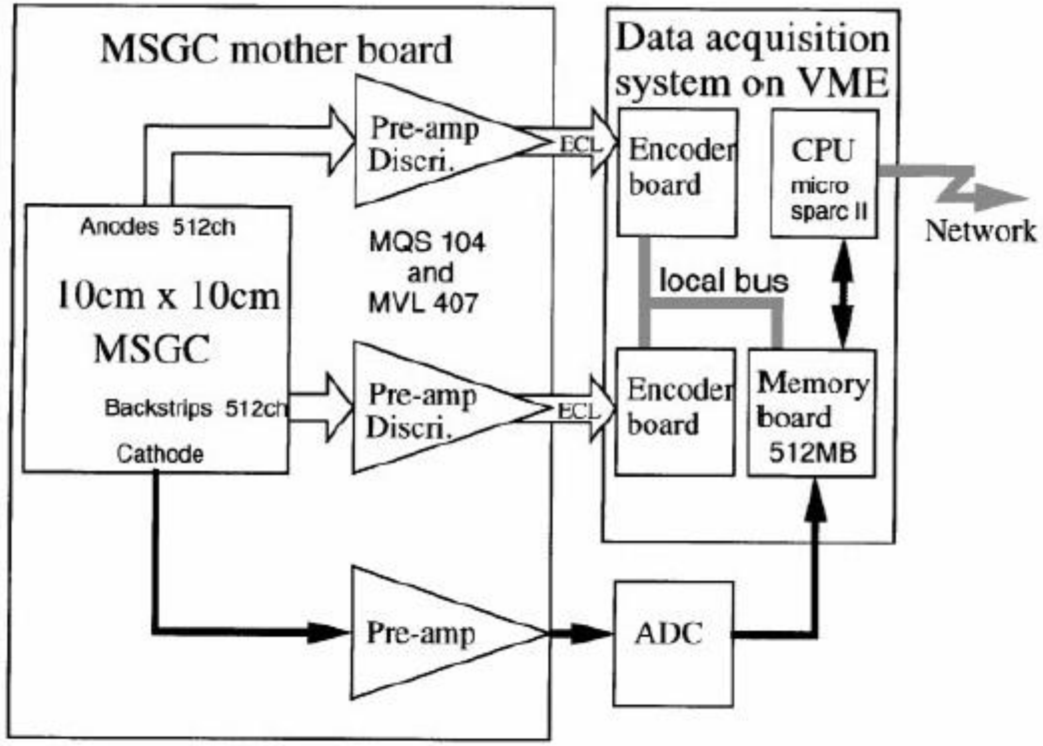
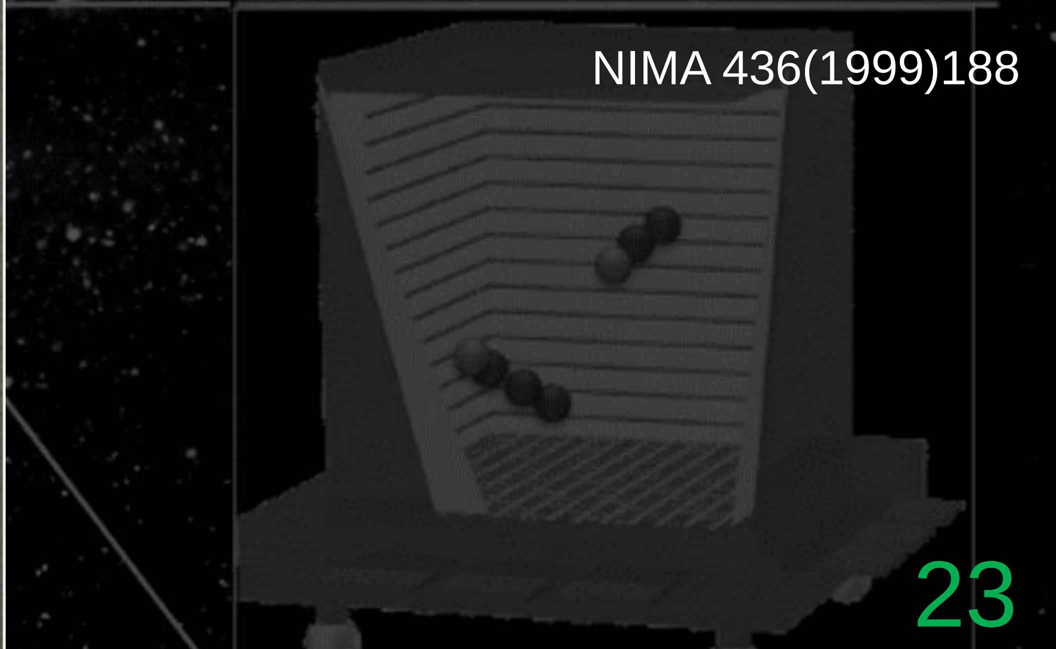


Fig. 3. Block diagram of the new synchronous readout system.

NIMA 436(1999)188



- MSGC/μ-PIC用 ASICの歴史
  - Lecroyチップ（TRA-1000）
    - アナログチップ 16ch/chip 500ns decay
  - ASDチップ (TCGチップ: CXA3183Q)
    - w/ discriminator 4ch/chip 16ns decay
    - bipolar 59mW/ch
  - ASDチップ(μ-PICチップ: CXA3653Q)
    - w/ discriminator 4ch/chip 80ns decay
    - bipolar 57mW/ch
  - CMOSチップ(Iwakiチップ：FE2009-bal)
    - w/ discriminator 16ch/chip
    - CMOS 18mW/ch
    - 6bit DAC for threshold adjustment

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 46, NO. 6, DECEMBER 1999

ASD IC for the Thin Gap Chambers in the LHC Atlas Experiment

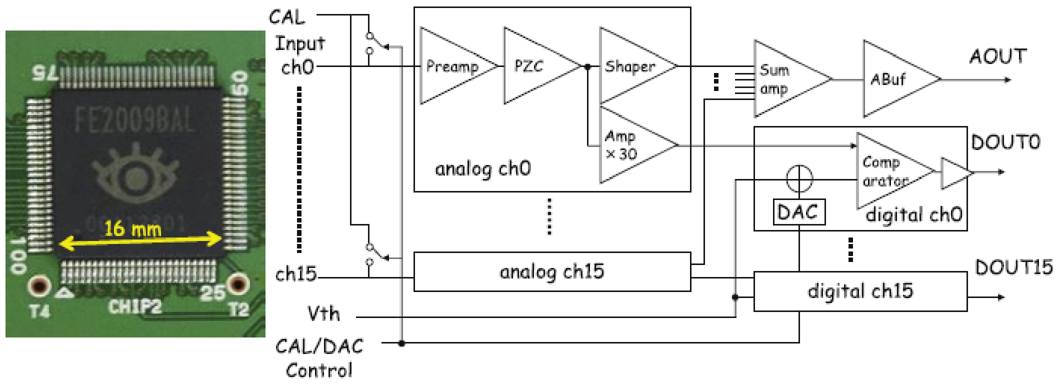
Osamu Sasaki[1] and Mitsuhiro Yoshida[2]

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 51, NO. 4, AUGUST 2004 1337

Development of an ASD IC for the Micro Pixel Chamber

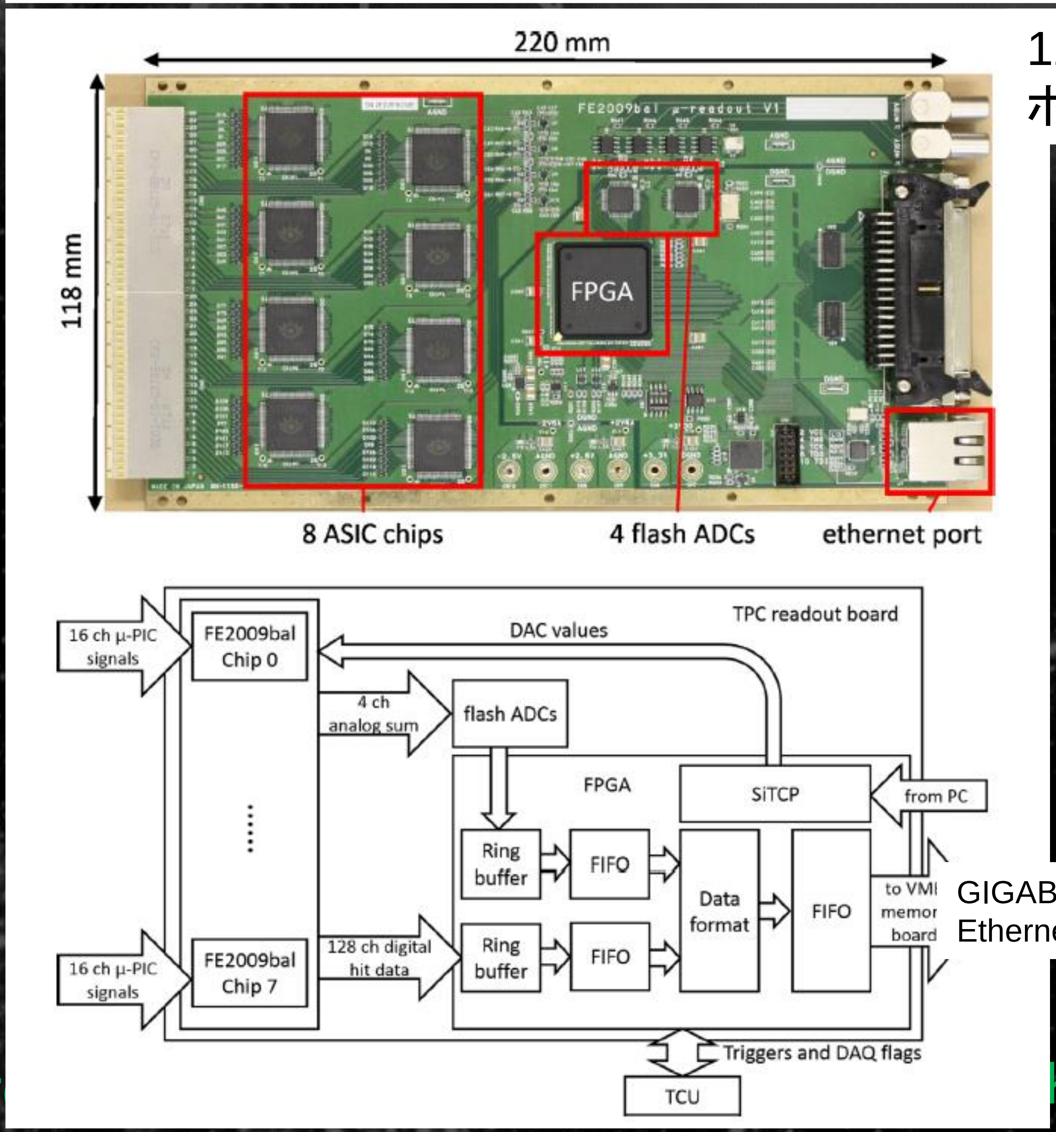
R. Orito, O. Sasaki, H. Kubo, K. Miuchi, T. Nagayoshi, Y. Okada, A. Takada, A. Takeda, T. Tanimori, and M. Ueno

T. Mizumoto et al. / Nuclear Instruments and Methods in Physics Research A 800 (2015) 40–50



- 現行システム
  - 30cm角μ-PIC
  - 400μmピッチ読み出しで1500ch

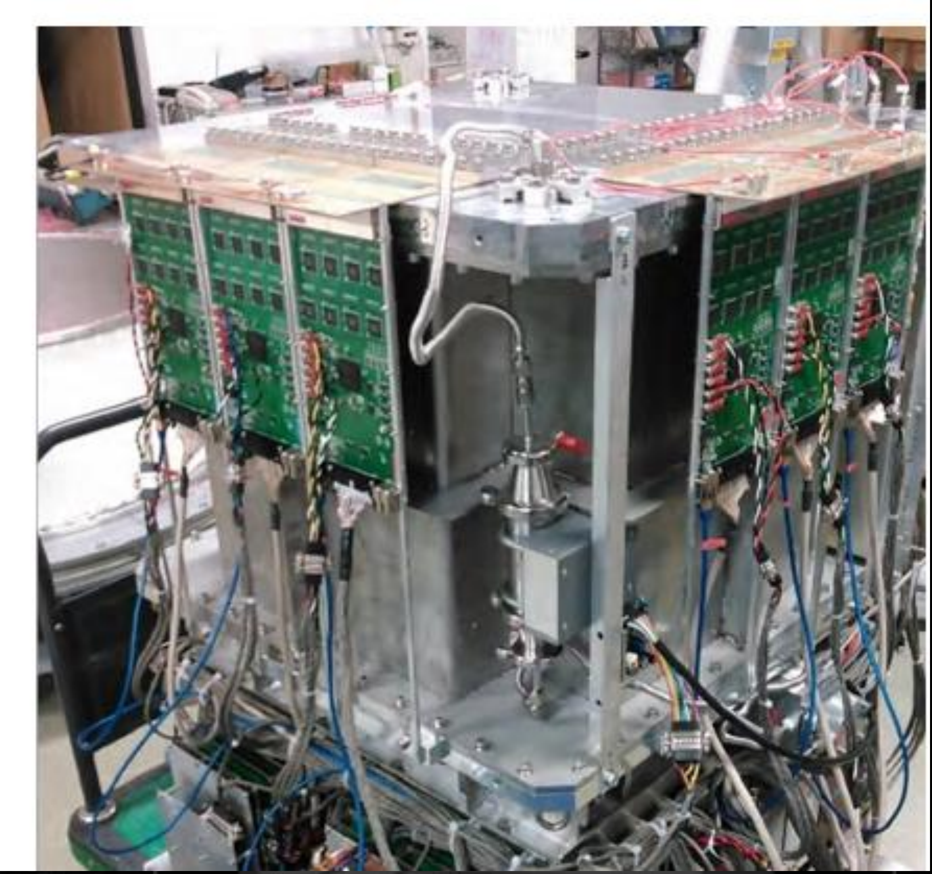
T. Mizumoto et al. / Nuclear Instruments and Methods in Physics Research A 800 (2015) 40–50



128ch
ボード

GIGABIT
Ethernet

arXiv:2107.00180v1



- ボード
  - FPGA SPARTAN6
  - FADC 10bit AD9218BSTZ-65

３ このさき：発展途上な回路たち

- わがまま① ダイナミックレンジを大きくしたい

LTARS: analog readout front-end ASIC for versatile TPC-applications

2020 JINST 15 T09009

T. Kishishita,[a,1,2] S. Sumomozawa,[b] T. Kosaka,[b] T. Igarashi,[b] K. Sakashita,[a] M. Shoji,[a] M.M. Tanaka,[a] T. Hasegawa,[a] K. Negishi,[b] S. Narita,[b] T. Nakamura[c] and K. Miuchi[c]

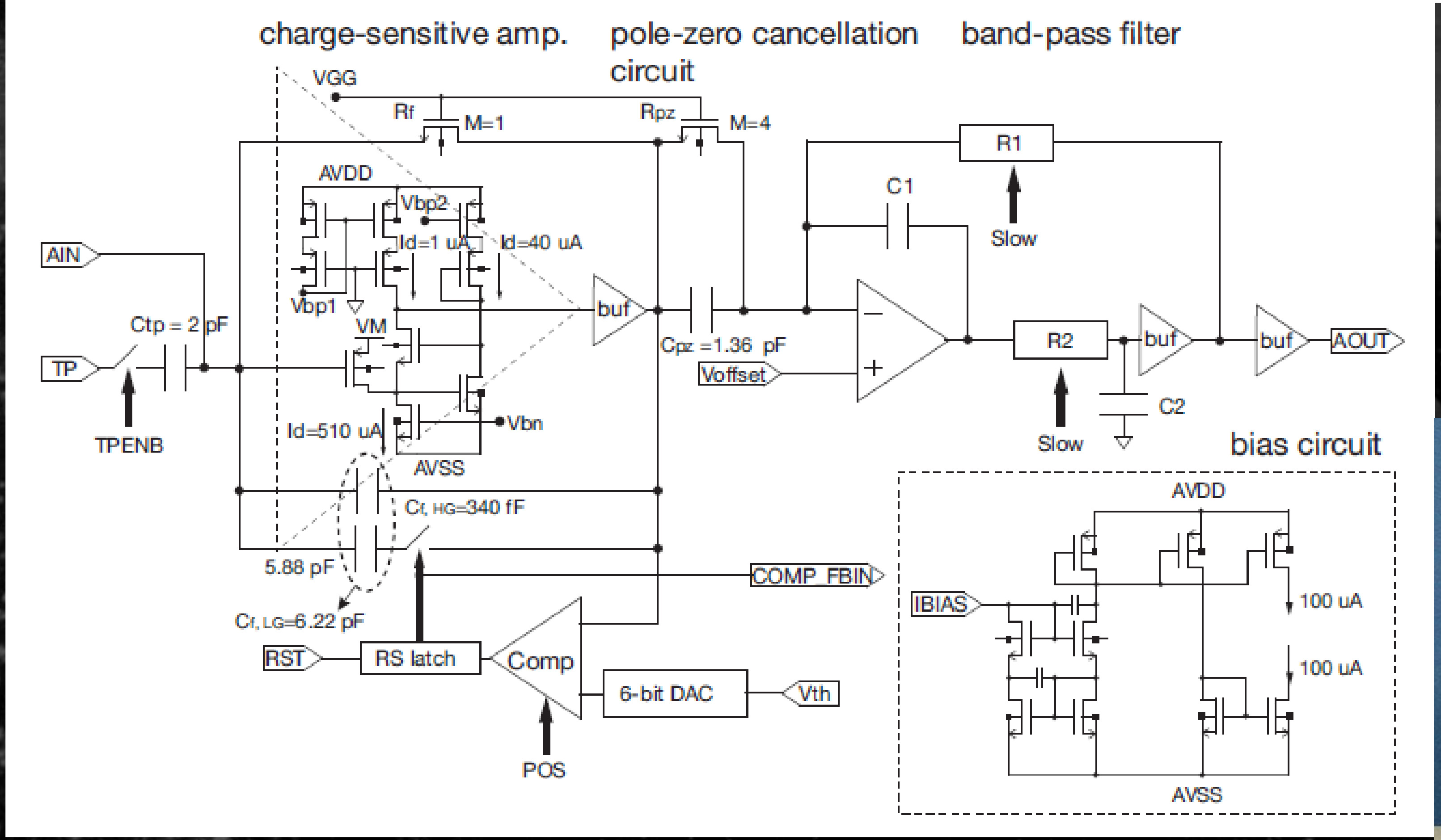
Table 1. Technological parameters and requirements to the ASIC.

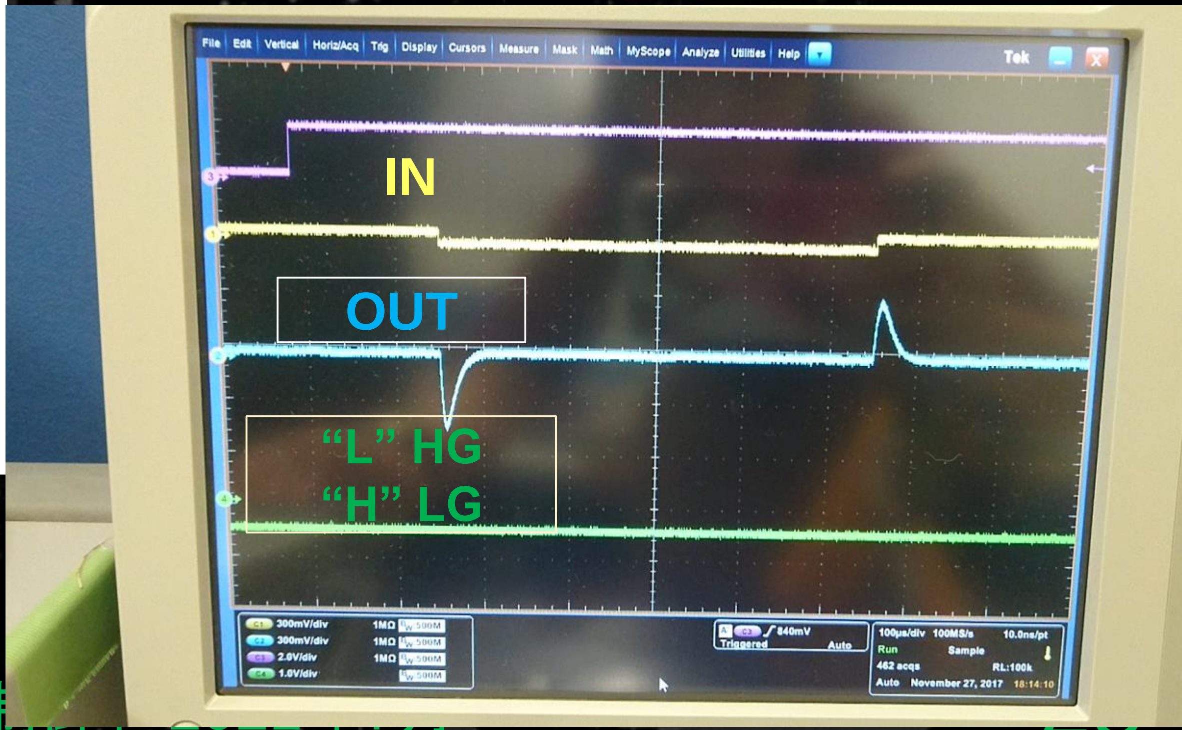
Technology	Silterra 180 nm CMOS	
Chip size	2.5×5 mm^2	
The number of channels	16	
Supply power	1.8 V core/IO, max. 2.4 mW/ch	
Fabrication options	6 metals, deep N-well, high-value poly res., MIM cap.	
Detector type	NIμ-TPC	LAr-TPC
Minimum signal charge	≈3 fC	≈10 fC
Shaping time	4 µs	1 µs
Operating condition	room temperature	−185 °C
Detector capacitance (C_{det}) [a]	~300 pF	
Dynamic range	±80 fC for narrow range, ±1600 fC for wide range	
Voltage gain	10 mV/fC for narrow range, 0.5 mV/fC for wide range	
ENC	3000 e$^-$ (S/N>20) for small signals, < 6.4 × 10^4 e$^-$ for large signals	

[a]: Estimated from the pad size of MPGDs.

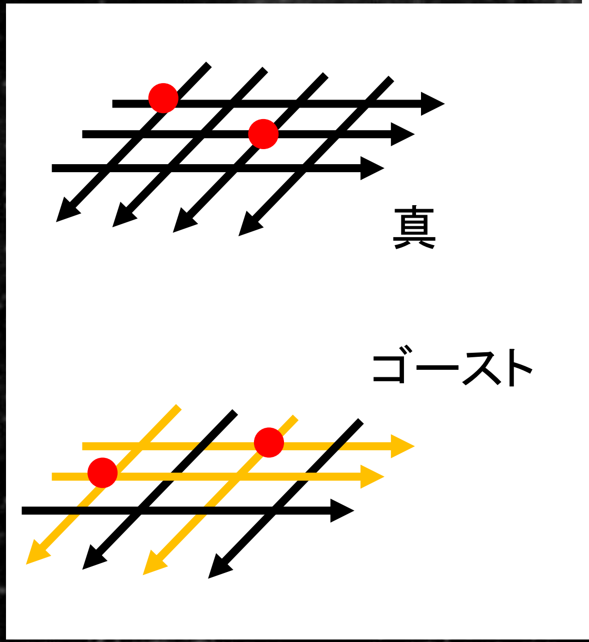
- 「岸下回路」
  - きっと講義を受けていたみなさんは読めるはず

2020 JINST 15 T09009





- わがまま② ピクセルで読みたい
  - 今まではストリップ（XY） 「ゴースト」問題
  - ピクセルで読み出せば解決
  - チップと全体としてのシステム制御



Nuclear Instruments and Methods in Physics Research A 623 (2010) 477–479

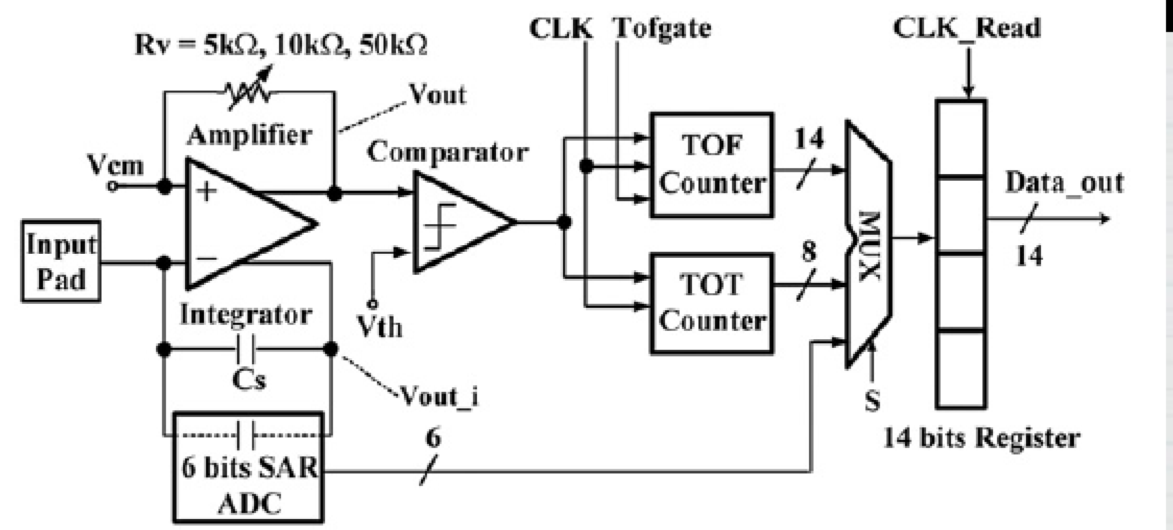
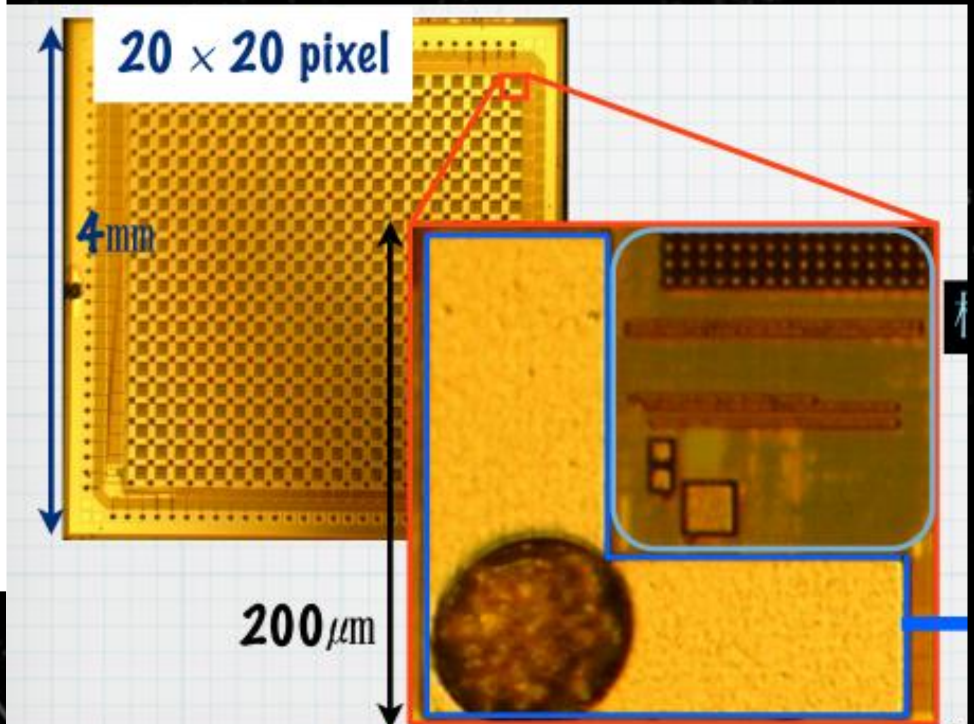
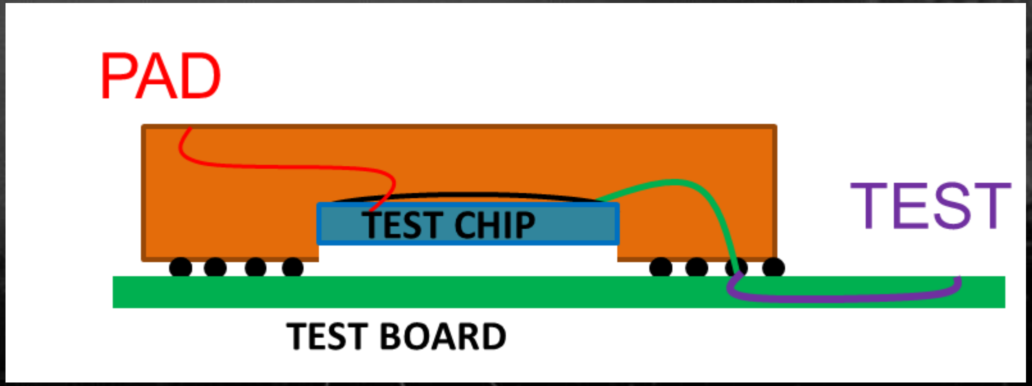


Fig. 1. Pixel structure.

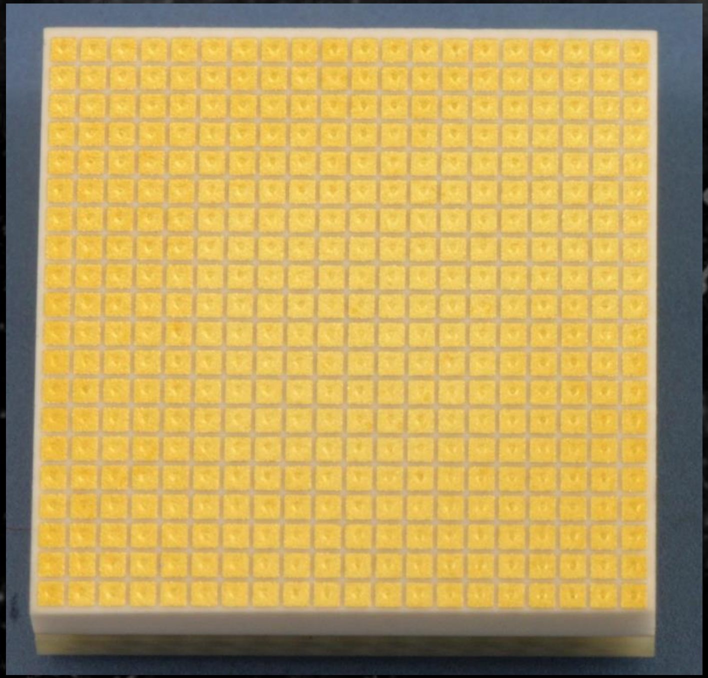


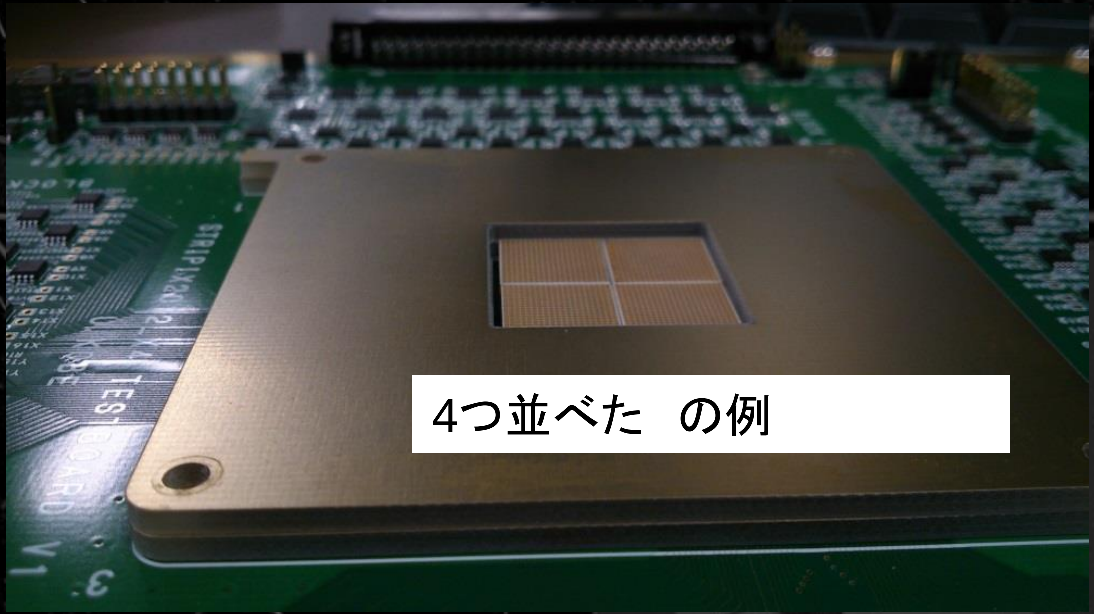
ピクセルチップの例

- 大面積を隙間なく読めるようなピクセルASICはまだない
  - セラミック基板インターポーザーの利用



ピクセルチップの実装例





4つ並べた　の例

エレキマンになったみなさんの力に期待！

まとめ

- 暗黒物質直接探索
  - 低放射能技術などに特化して進んできた。
- 新しい技術：ガスTPC
  - 回路技術も重要！