WIMP探索
世界のロードマップ

ダークマター懇談会2019＠早稲田大学

東京大学 宇宙線研究所・数物連携宇宙研究機構
森山 茂栄

2019年7月5日

本研究会のお題

- 標準理論を超えた物理の代表格の一つ”DM”をもとにより深い物理の基礎原理を解明したい。
  - 本業ニュートリノの物理は別で議論
- 一方素粒子としてのDMはなかなか兆候を掴ませてくれない。
  - PBHもまだ候補
- 世界中での興味が散逸するなか、フォーカスする物理、ここだけはやっておくべき物理等、将来戦略（１０－２０年）を考えましょう。
- green frame: stolen “slides” (see next page)

世界のDM communityの最近の議論

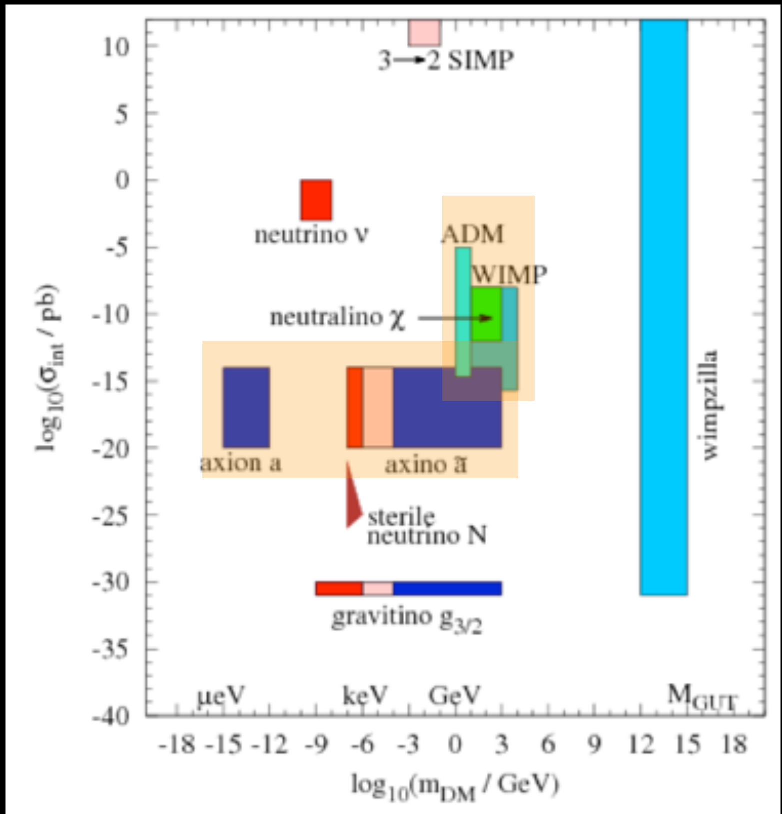
- European Particle Physics Strategy Update (EPPSU) 2018-2020, May 12-17, 2019 (Info from Shoji Asai)
  - https://europeanstrategyupdate.web.cern.ch
  - Input to the committee
    - https://indico.cern.ch/event/765096/contributions/
  - Symposium
    - https://indico.cern.ch/event/808335/timetable/#20190513.detailed
- European Astroparticle Physics Strategy 2017-2026
  - https://www.appec.org/roadmap
- US Cosmic Vision 2017 (info. from Kaixuan Ni): direct detection (accelerators)
  - https://arxiv.org/abs/1707.04591
  - Follow-up workshop after Cosmic Vision 2017 (invitation only), Oct. 15-18, 2018 (Basic Research Needs Workshop on Dark Matter Small Projects New Initiatives)
    - https://orau.gov/hepbrn2018/default.htm
  - Summary in APS
    - http://meetings.aps.org/Meeting/APR19/Session/T04.7
  - DOE announced funding opportunity
    - https://govtribe.com/opportunity/federal-grant-opportunity/dark-matter-new-initiatives-defoa0002112
  - For larger detectors: no further update yet
    - http://mitchell.tamu.edu/next-generation-dark-matter-and-neutrino-detection/

欧州での議論
Direct detection: Jocelyn Monroe

Model Space

Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity...

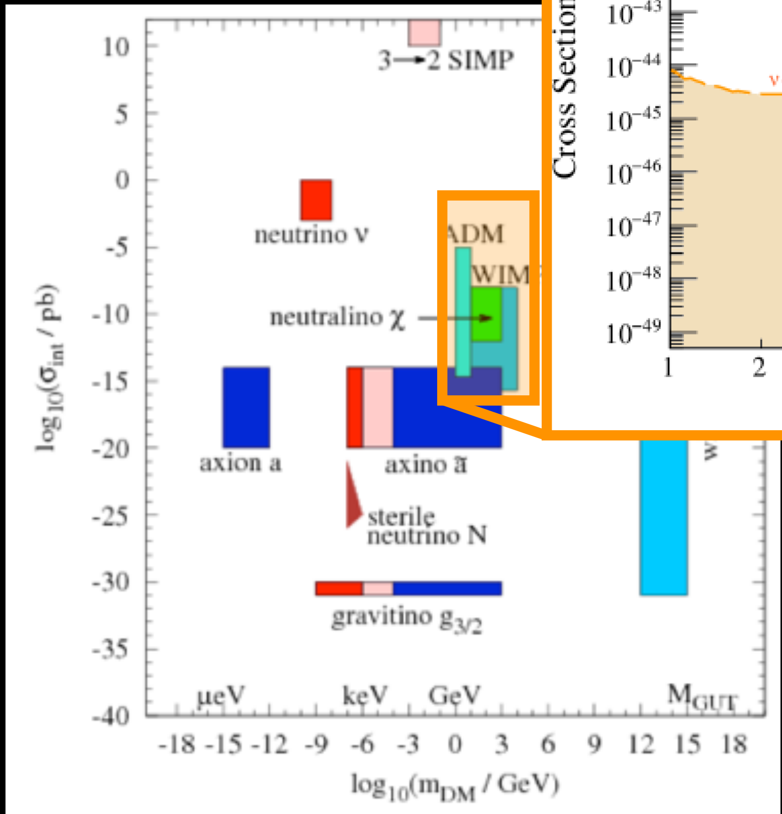


Baer et al., arXiv:1407.0017

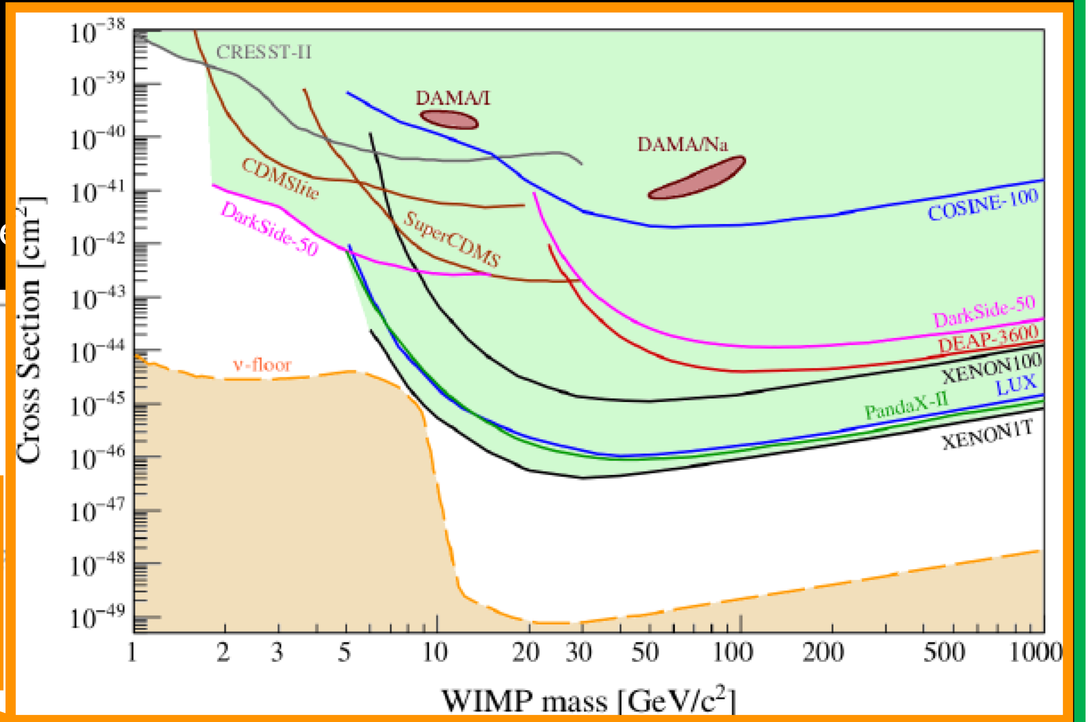
Model Space

Wide range of parameters!

Direct detection searches ge



Baer et al., arXiv:1407.0017

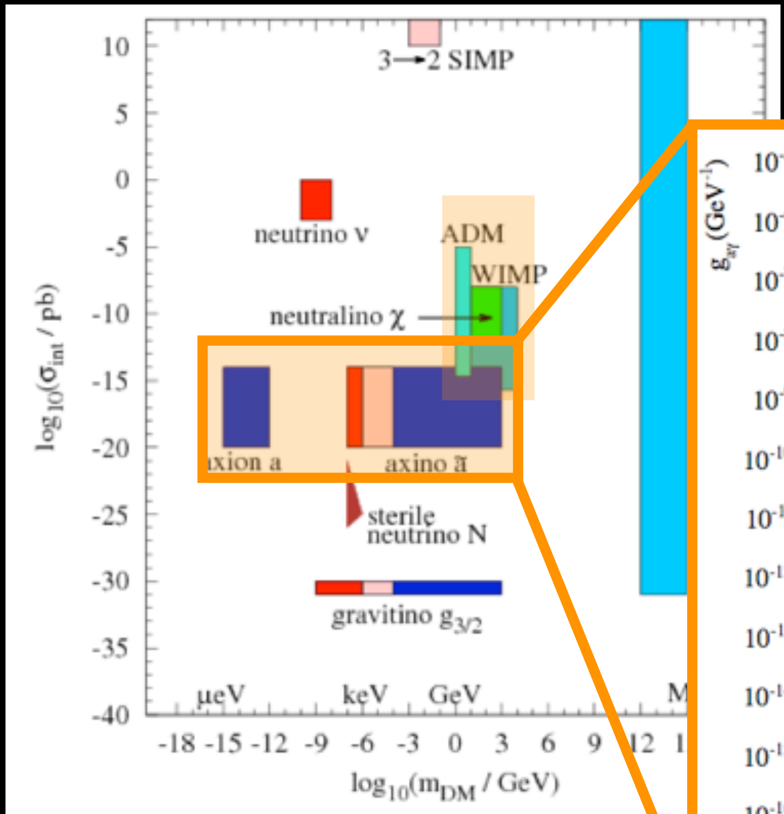


Schumann, arXiv:1903.03026

Model Space

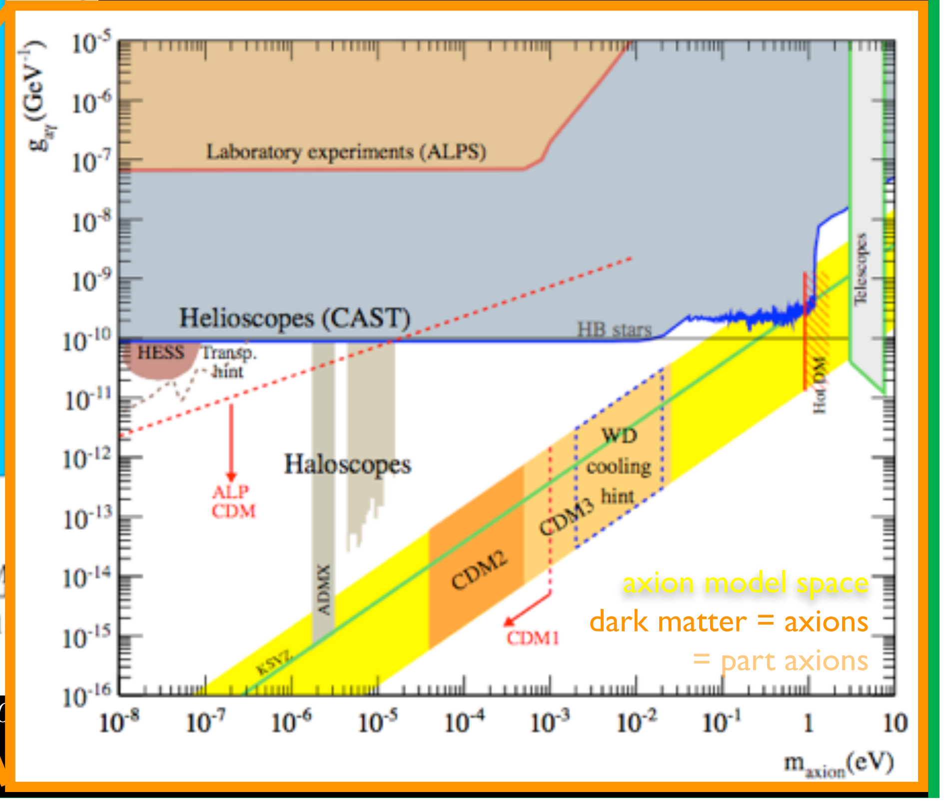
Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity…



Baer et al., arXiv: 140

starting to look for axion-like particles too!



WIMP community input to the ESPPU

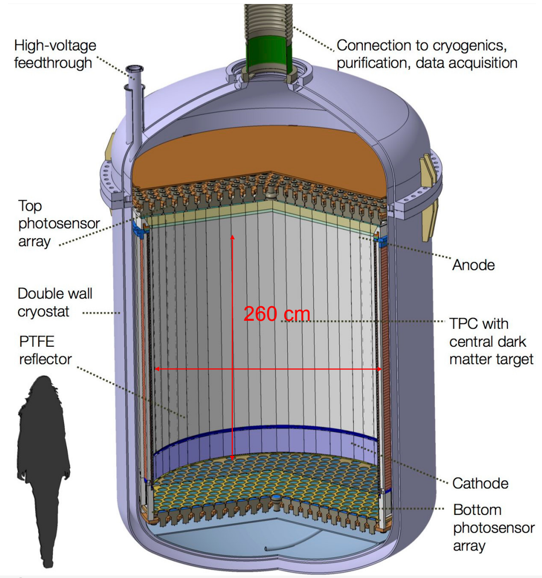
9 submissions to ESPPU 2019 in track "dark matter",
2 focussed around direct detection (in Europe):
DARWIN and Global Argon Dark Matter Collaboration

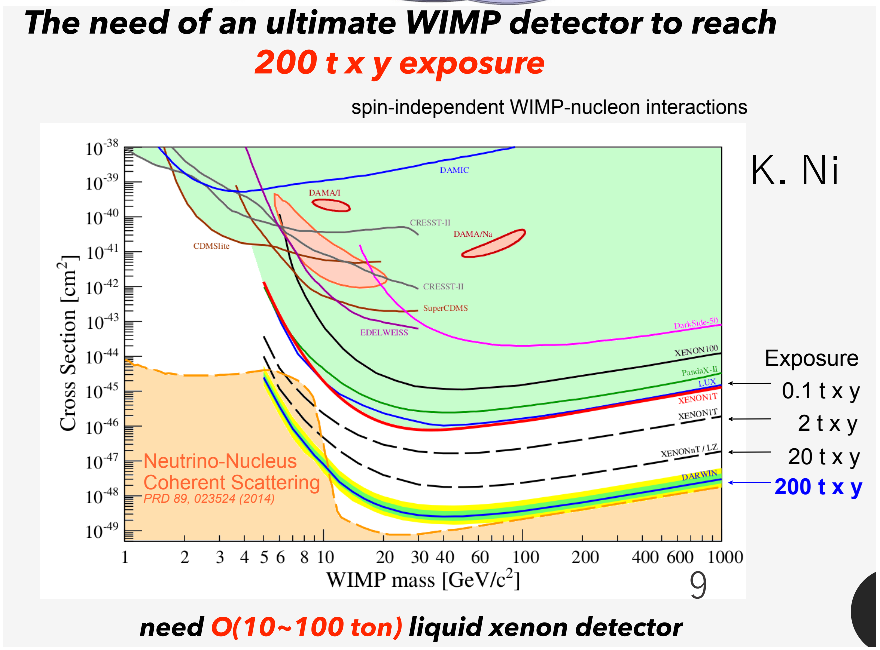
- DarkSide-20k, DS-LM, Argo: direct detection
- DARWIN: direct detection
- NA64: e dump, sub-GeV dark photon
- SHiP at SPS beam dump: search for hidden particles
- AWAKE: dark photons using 50 GeV e beam (future 3 TeV)
- IAXO: axion
- Vacuum Magnetic Birefringence: axion
- MAGIS-1K: atom interferometer for DM and GW
- …

FASER at LHC

Liquid Xenon detectors

- 2019- XENONnT, 20 tyr
- ESPPU Document #97: DARWIN collaboration
  - 40 ton of LXe target, > 5 GeV, a few x 10-49 cm2@50 GeV SI
  - Spin dependent, inelastic scattering, solar axions, pp solar nu, neutrinoless double beta decay, double electron capture, SN neutrinos
  - TDR 2022-23, XENONnT運転中(~2025)に建設、nT終了後commissioning
  - 場所は決めていないがcollaborationはLNGSへのinterestを表明。

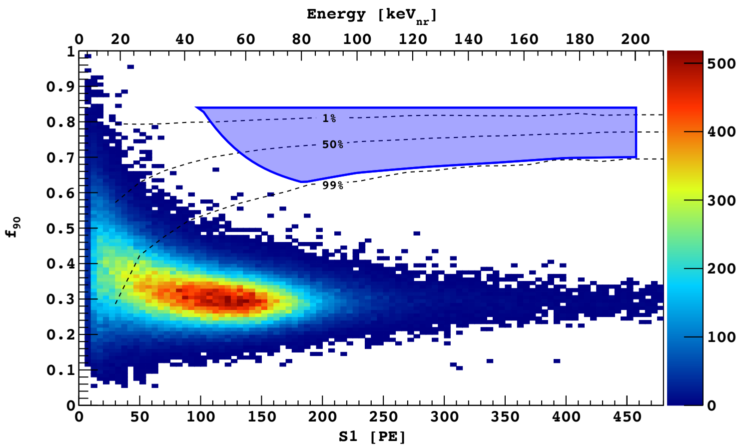


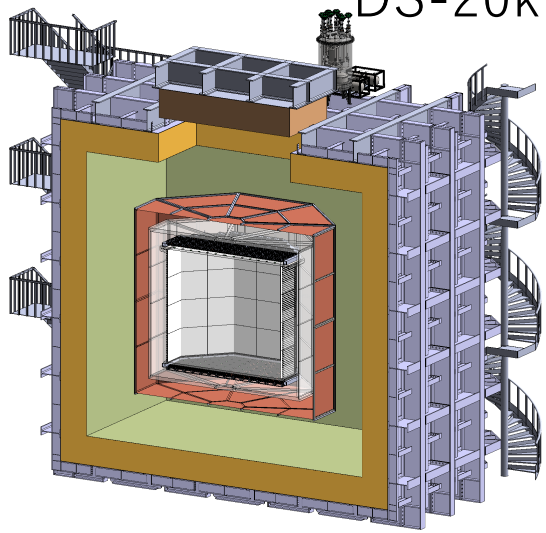


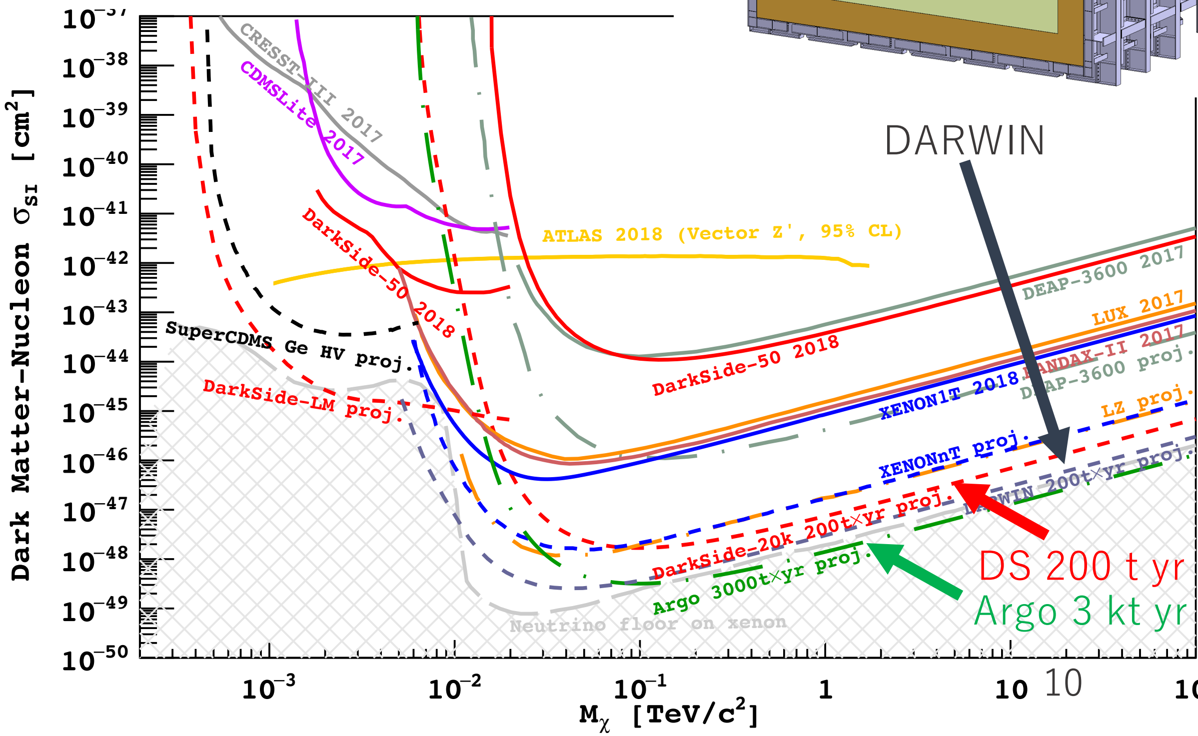
K. Ni

Liquid Ar detectors

- Global Argon Dark Matter Collaborationが結成 ~2017 (DEAP, ArDM, MiniCLEAN, DarkSide)
- ESPPU Document #62
- Underground Ar
- ProtoDune-like cryostat
- DarkSide-20k (2022- 50 ton LNGS), 1.6NR by atm nu in 100 ton year exposure
- DS-LM (light mass)
- Argo (400 ton) @SNOLAB?





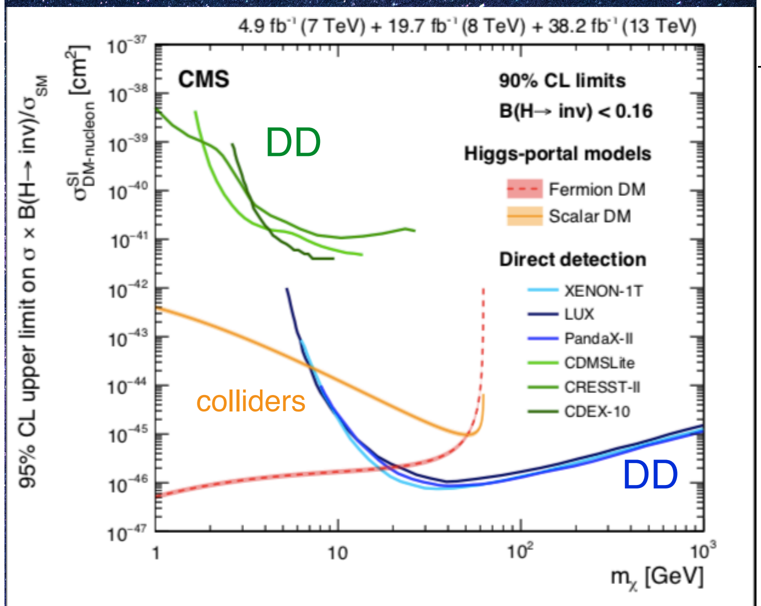


Accelerators:

- Energy frontierに加え、新たな加速器を用いた探索 MeV-GeV DM, DS

DDは軽いDMに対する
敷居値があるが

C. Doglioni's presentation, arxiv: 1809.05937

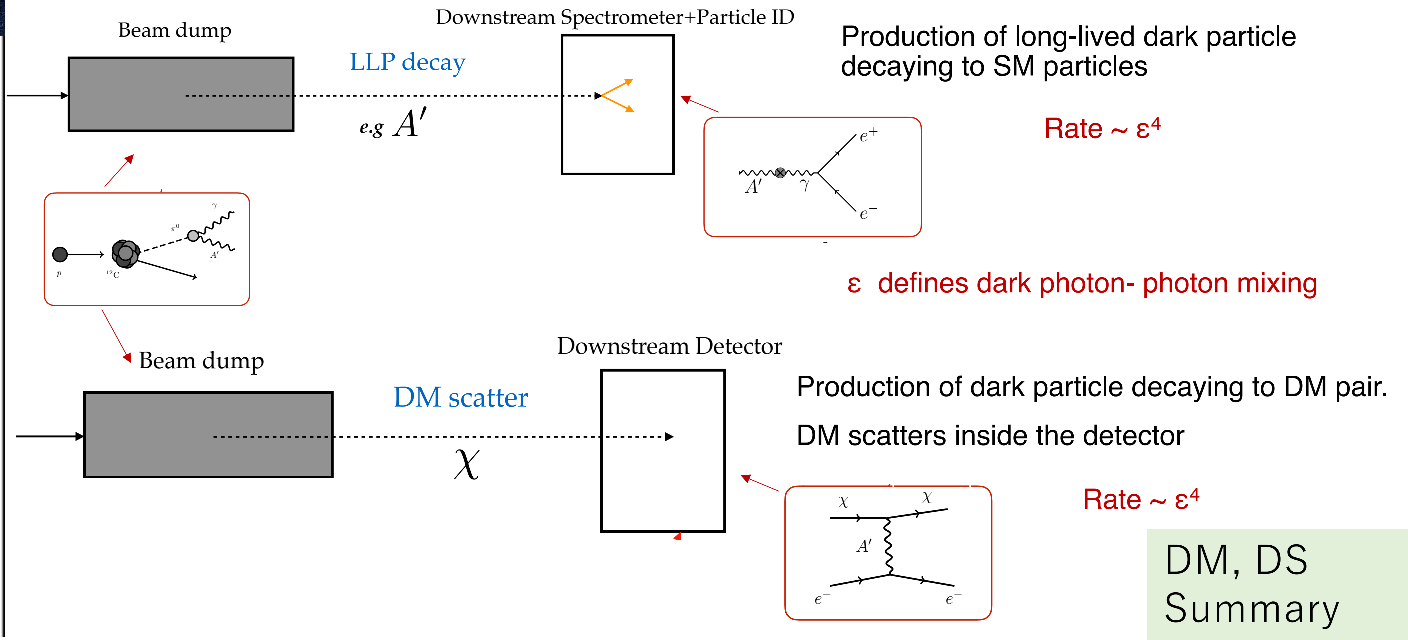


Invisible decays of the Higgs.

New accelerator based searches for MeV - GeV dark matter

Dark Portals [Vector, (Pseudo)Scalar, Neutrino] at Beam Dumps (e. g. NA62++, SHiP)

E. Graverini's talk



Production of long-lived dark particle decaying to SM particles

Rate ~ ε^4

ε defines dark photon- photon mixing

Production of dark particle decaying to DM pair.

DM scatters inside the detector

Rate ~ ε^4

DM, DS
Summary
Asai & Carena
Many other
Ideas there

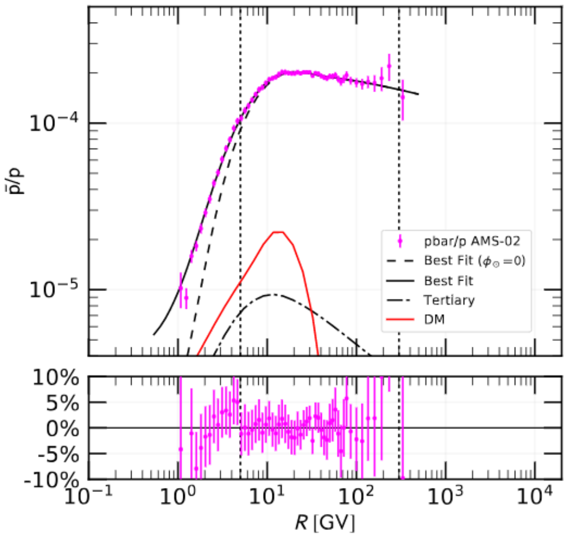
Indirect Detection: Christoph Weniger

1. Self annihilation
   - Fermi LAT: 銀河中心, dwarf spheroidal galaxies
   - HESS: 銀河中心 ~a few TeV
   - HAWK: 100TeV以上を改善できる可能性。
   - CTA: HESSを10倍改善予定(natural scaleを探索)
   - 反陽子: 天体物理学的可能性の排除は難しい, 15 GVのエクセス？
   - GAPS: エネルギーの低い反重水素
   - IceCube, Super-K, Hyper-K, KM3NeT: ニュートリノ（太陽、地球、銀河？）
2. Decay
   - Sterile neutrinos: 7 keV nu → 3.5 keV n+3.5 keV γ Hitomiは見えなかった
3. Conversion
   - Axion探索

Anti-proton ~15 GV excess?

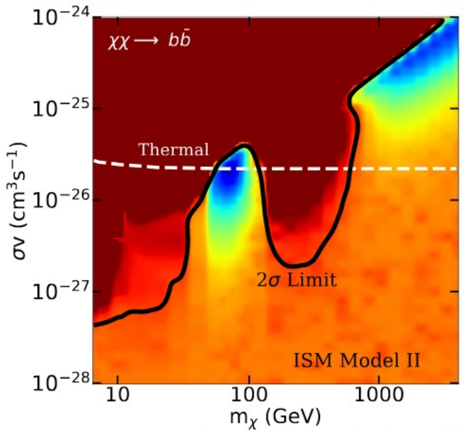
Cuoco+ 2019

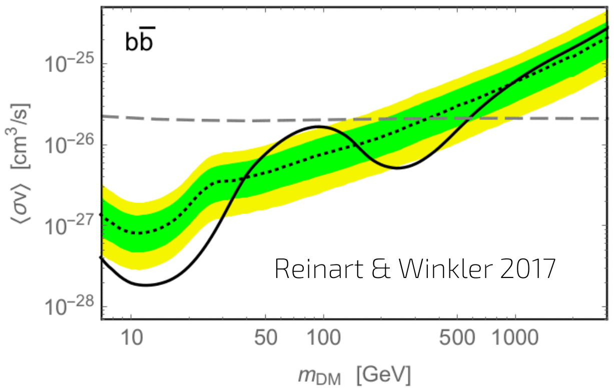
- First identified in Cuoco+ 2017, with ~4 sigma significance
- After new systematic checks, still at few sigma level
  - Marginalizing over pbar production cross section reduces significance
  - Correlated instrumental systematics are important, of same order as excess, but correlation structure is now publically available



Cholis+ 2019

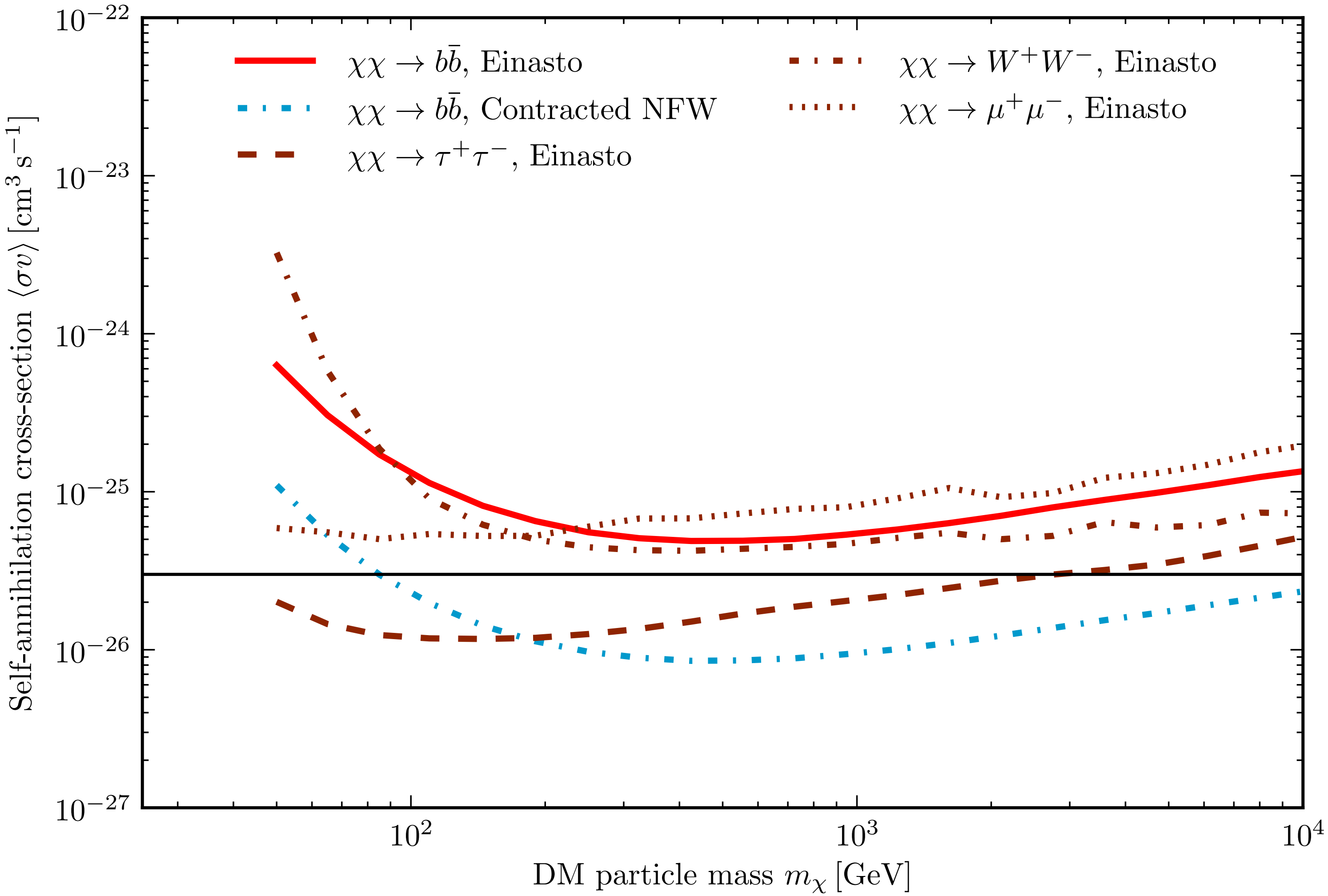
- Check time-/charge-dependend diffusion
- Confirm excess with even higher significance (though no marginalization over all parameters)





64-88 GeVのDMのせい？

CTA



- “natural scale”に手が届く

European Astroparticle Physics Strategy 2017-2026 (APPEC)

Many of the next generation of astroparticle physics research infrastructures require substantial capital investment and, for Europe to remain competitive in this rapidly evolving global field of research both on the ground and in space, a clear, collective, resource-aware strategy is essential. As a relatively

Part 2: Astroparticle Physics Research Landscape

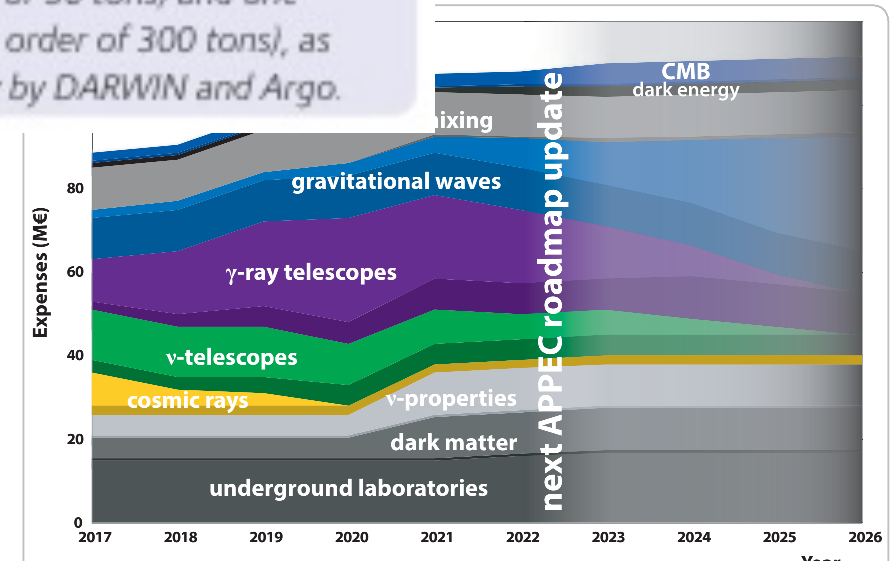
1. Connecting the Infinitely Large and Infinitely Small
2. The Extreme Universe: a Multi-Messenger Approach
3. Mysterious Neutrinos
4. The Early Universe
5. The Dark Universe
6. Outlook

5. Dark Matter

Elucidating the nature of Dark Matter is a key priority at the leading tip of astroparticle physics. Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, one category stands out: the Weakly Interacting Massive Particle (WIMP). WIMPs arise naturally, for instance, in supersymmetric extensions of the Standard Model of particle physics. Many experiments located in deep-underground laboratories are searching for WIMP interactions. For masses in excess of a few GeV, the best sensitivity to WIMPs is reached with detectors that use ultra-pure liquid noble-gas targets; such detectors include XENON1T (using 3.5 tons of xenon) and DEAP (using 3.6 tons of argon), which both started operating in 2016. Their sensitivity can be further enhanced by increasing the target mass. A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions.

European Astroparticle Physics Strategy 2017-2026 (APPEC)

APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.



Towards the ultimate direct search

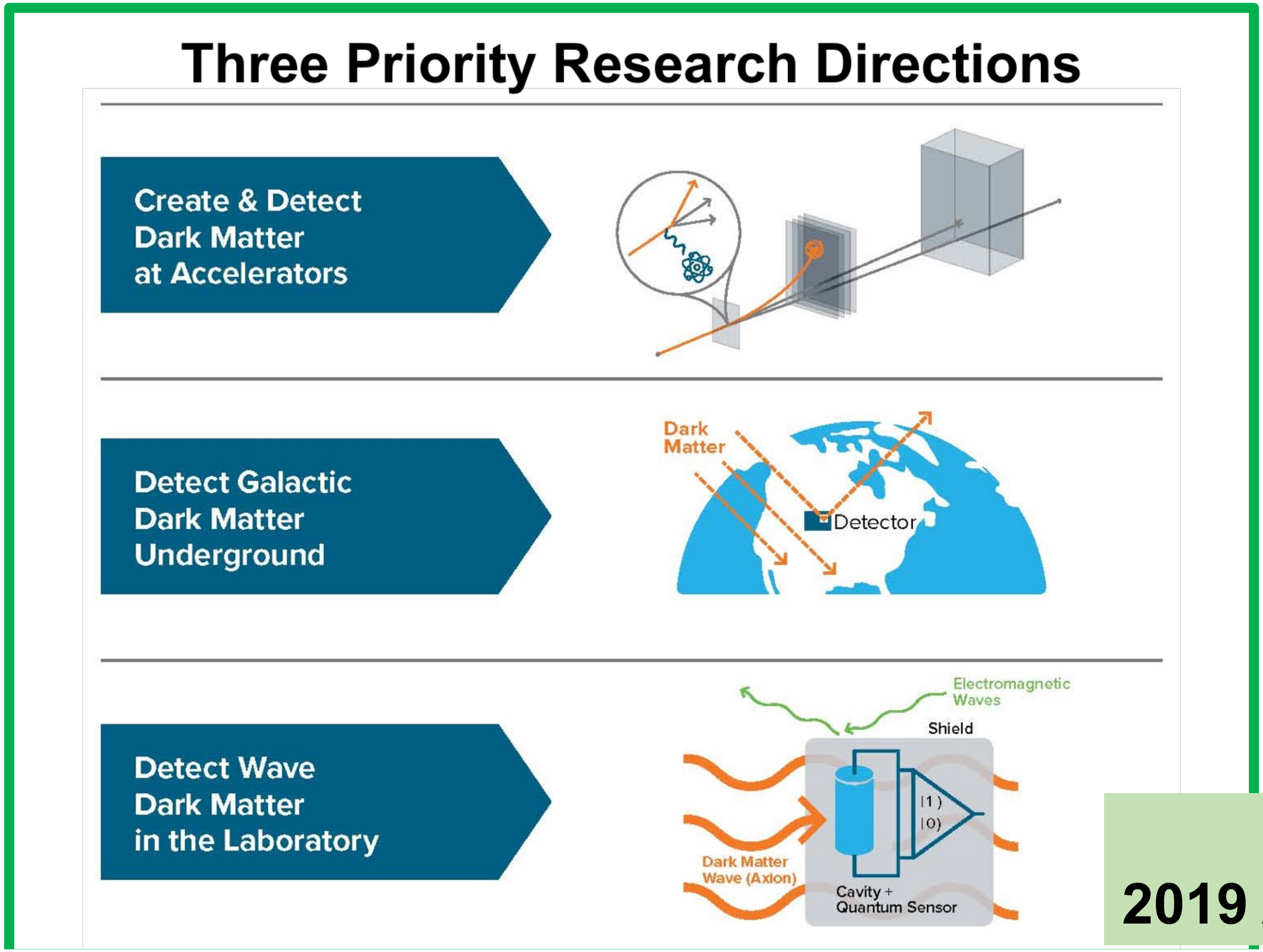
Present technologies can be pushed until they hit the background produced by coherent scattering of solar and atmospheric neutrinos – albeit an interesting signal in itself. In Europe, to probe WIMP masses up to 10 GeV, the EURECA consortium aims to push cryogenic detectors as used by CRESST and EDELWEISS to the ton-scale. Similarly, the DARWIN (50 tons of xenon) and Argo (200 tons of argon) consortia plan to construct the ultimate noble-liquid detectors to explore WIMP masses in the 10 GeV to 1 TeV range.

Going beyond the coherent neutrino-scattering wall will require direction-sensitive detectors. As long as convincing Dark Matter signals are found, such detectors will almost certainly be crucial to assessing the detailed nature as well as the astrophysical origin of Dark Matter. Anticipating this, detector R&D in this sphere has already begun.

USでの議論

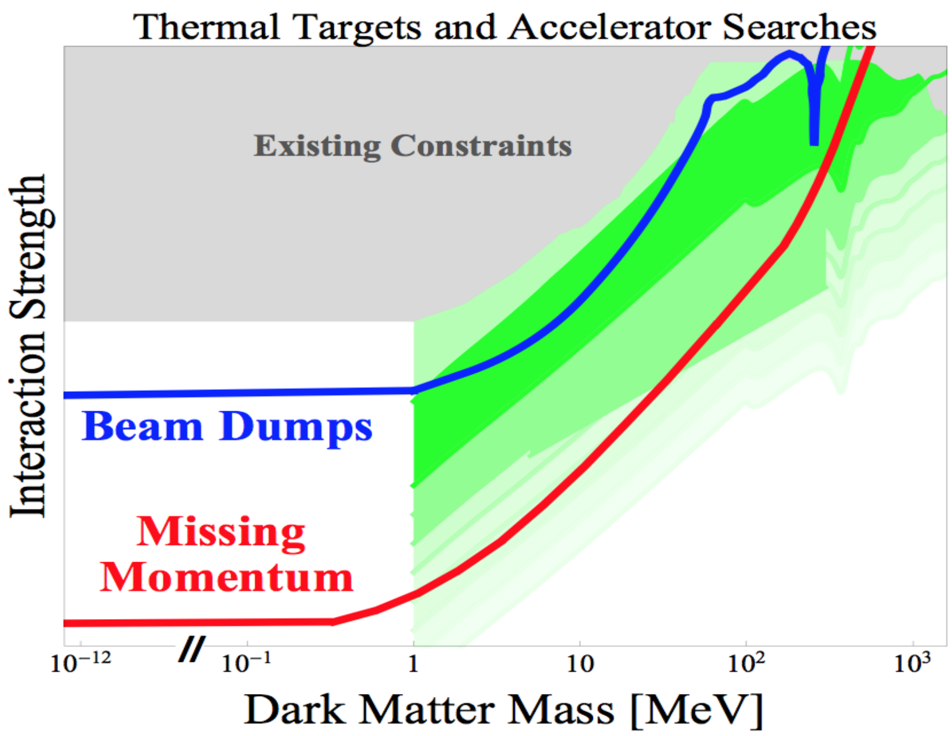
- US Cosmic Vision 2017にて、それまで進めてきたG2実験計画（LZ, SuperCDMS, ADMX）の大型計画以外のactivityを再開発。
  - DMには巨大なパラメータ空間があり、大型実験だけに集中するのはリスクが高い。
- G2実験には優先度があるが、Low-cost, high-impactのプログラムに投資。
  - “New Ideas in DM” workshop
  - $10Mかもっと安く実行できるcomplementary scienceを議論
  - 100以上のトークがあつまった
  - これをまとめてCV2017が作られた(2017 7月）

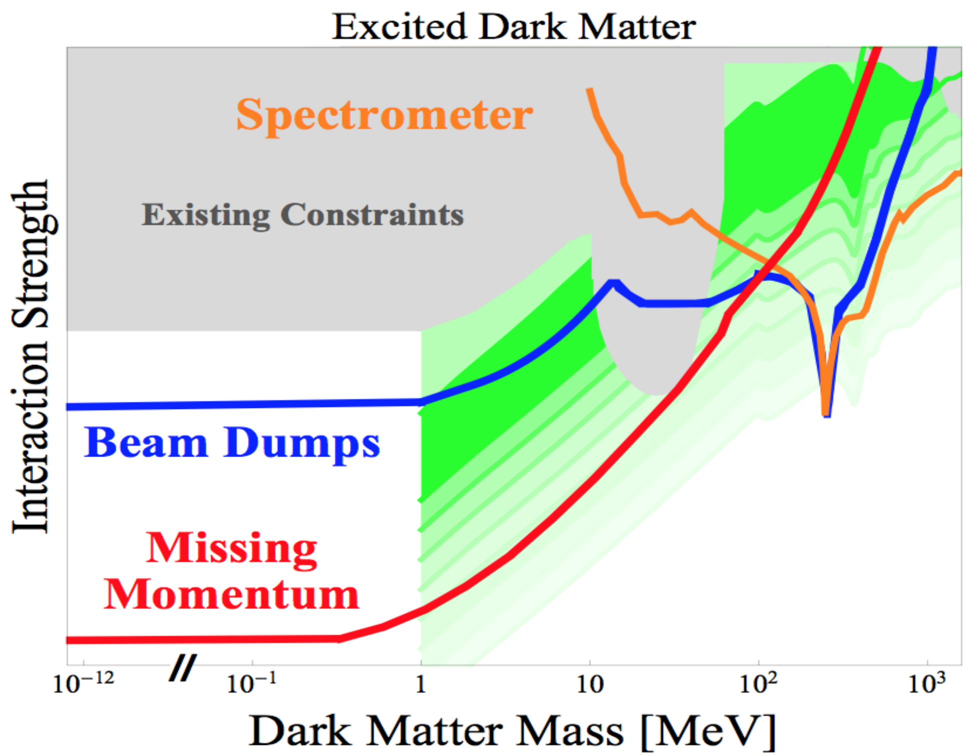
US CV 2017のfollow up workshop (2018 Oct.)のサマリ(2019 Apr)



Rocky Kolb
2019 April APS Meeting

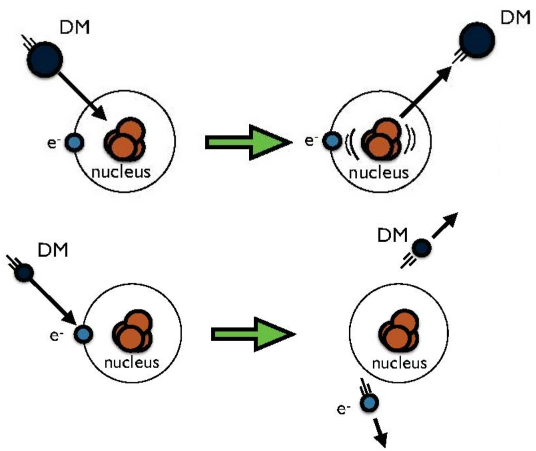
Create and detect dark-matter particles and associated forces below the proton mass, leveraging DOE accelerators.

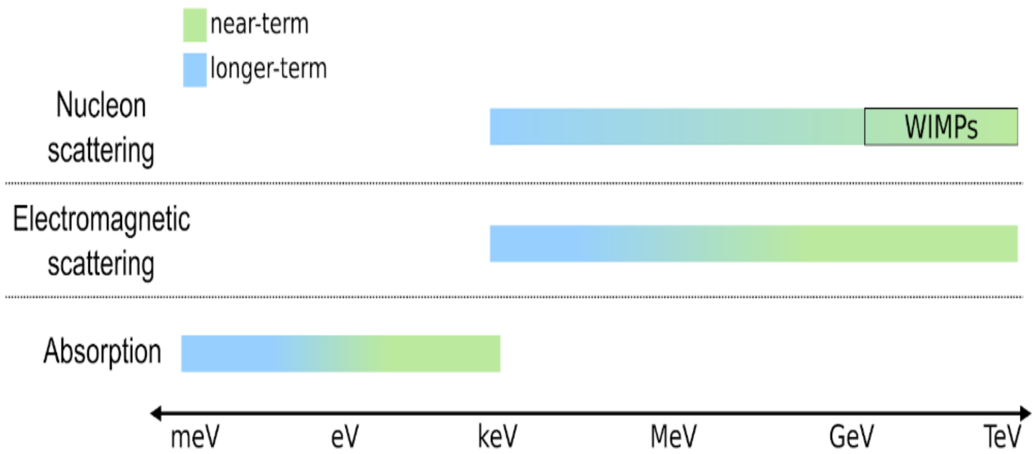




Green areas are high-priority parameter space identified at BRN, singled out by thermal models for the origin of dark matter – many are uniquely explored at accelerators

Detect individual galactic dark-matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors

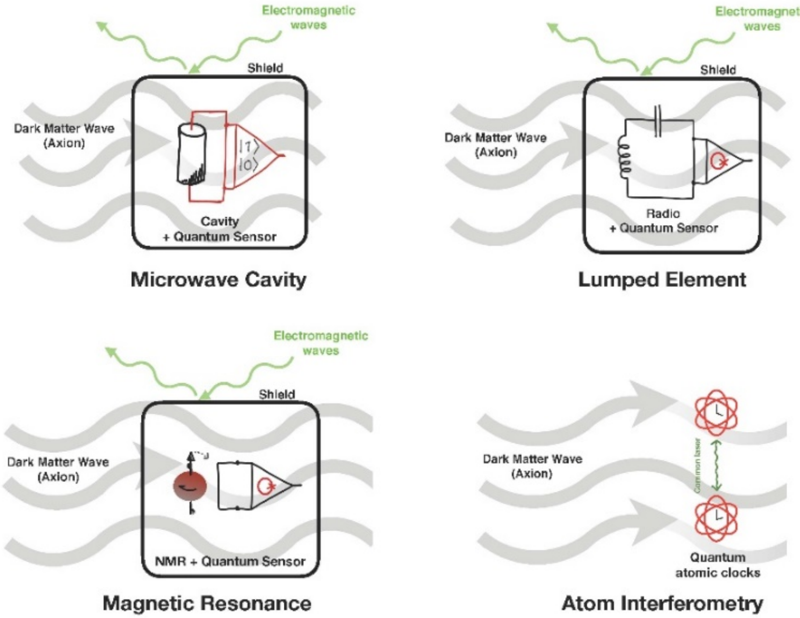




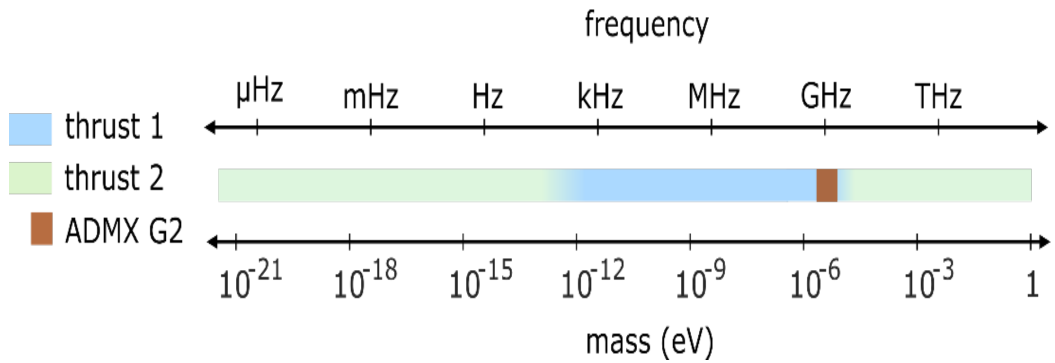
<u>Thrust 1:</u> Probe dark-matter interactions with nuclei, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

<u>Thrust 2:</u> Probe dark-matter interactions with electrons, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

Observe wave dark matter using innovative technologies



Improvements in our understanding of cosmology show these very light particles to be excellent dark-matter candidates. Techniques required to search for very light particles differ from those for previous dark-matter searches and rely heavily on advances in quantum sensing.

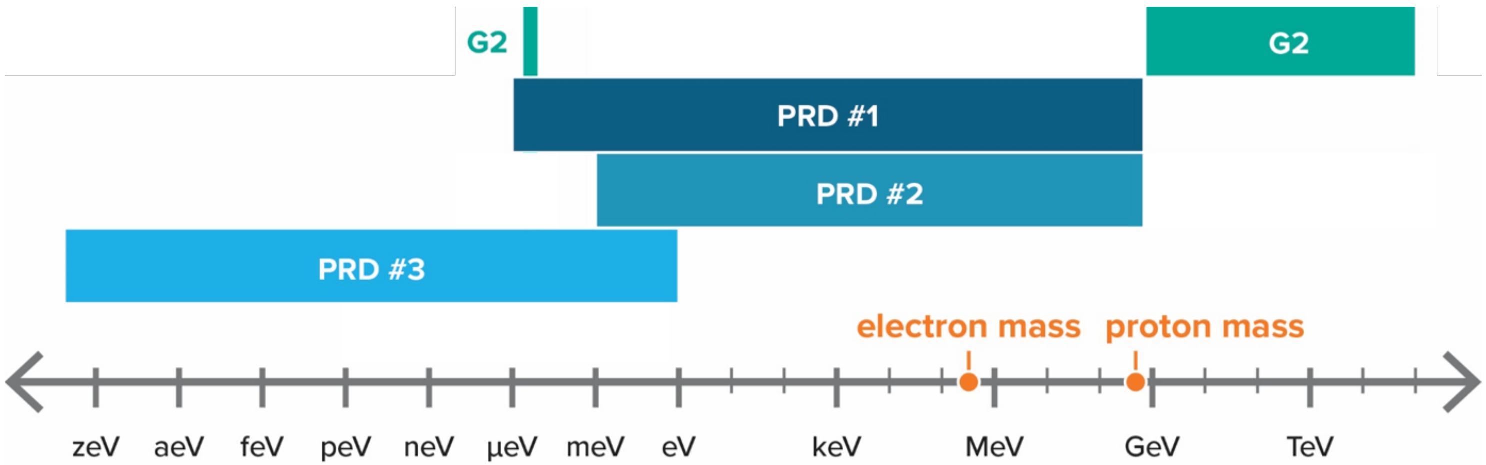


Thrust 1: Utilize new detector technologies to explore large parts of dark-matter parameter space covering a broad range of mass from 100 Hz to 10 GHz (roughly 10^{-12} eV - 10^{-4} eV), and targeting sensitivity to the QCD axion where possible.

Thrust 2: Develop or transfer new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark-matter models spanning the entire 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.

Three PRDs Cover Entire Range Below Proton Mass

- Thermally produced dark matter must have mass larger than a keV from astrophysical considerations
- Accelerator searches (PRD 1) are sensitive to much lower mass dark-sector particles even if not dark matter
- Direct detection (PRD 2) can also probe lower-mass galactic particles that can be sub-dominant component to dark matter
- Thermal particle dark-matter (freeze-out) particles must have mass less than about 200 TeV
- Dark matter must have mass larger than 10^{-22} eV so that its deBroglie wavelength is smaller than the size of the dark matter dominated objects



G3に向けたUSでの研究会

Friday, February 1	Mitchell Institute: Hawking Auditorium	
	Speaker	Title
9:00-9:15am	Lang/Strigari	Welcome/Plan for meeting
9:15-9:45 AM	Kaixuan Ni (UCSD)	Hermetically-sealed XeTPC for the ultimate dark matter search
9:45-10:15AM	Ethan Brown (RPI)	Rn-free gas and liquid xenon pumps
10:15-10:45AM	Liang Yang (Illinois)	Photodetectors for a G3 dark matter experiment
10:45-11:00 AM	Coffee break	
11:00-11:30 AM	Bjoern Penning (Brandeis)	High NR searches
11:30AM-12:00 PM	Richard Saldanha (PNNL)	VUV-reflective PTFE coatings for Xe detectors
12:00-1:30PM	Lunch	
1:30-1:55PM	Rupak Mahapatra (TAMU)	SuperCDMS
1:55-2:20PM	Andrew Renshaw (Houston)	Argon/DarkSide
2:20-2:45PM	Igor Ostrovskiy (Alabama)	Experience with Deep Learning in EXO
2:45-3:15PM	Coffee break	
3:15-3:40PM	Chris Tunnell (Rice)	NEST v2 and future
3:40-3:55PM	Louis Strigari (TAMU)	Atmospheric and solar neutrino benchmarks for G3
3:55-4:30PM	Jayden Newstead (Arizona State)	Migdal effect for neutrinos and dark matter
4:30-5:00PM	Any participant not listed	One slide overviews
5:00-6:00PM	Group discussion led by R. Lang	Discussion/Plan for Saturday
6pm: Dinner/reception		

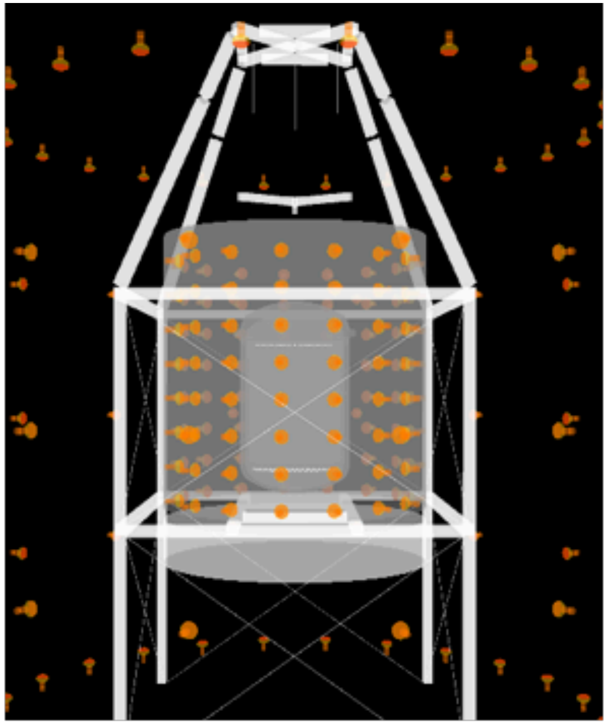
日本

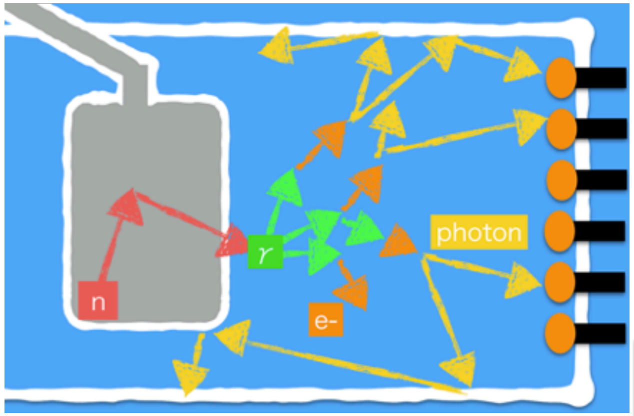
- master plan 2017, road map 2017
  - Direct detection: XMASS-1.5
  - Indirect detection: Hyper-K, IceCube,…
  - Accelerators: HL-LHC
- XMASS-Iは1 tonサイズの役割を成功裏に果たした。
- 太陽ニュートリノのバックグラウンドを十分に低減できる液体キセノン２相式検出器を世界のメンバーとともに建設・発見 or indicationを狙っている(G2, conventional SUSY)。
- その後のより高感度な装置でイニシアティブを取って研究を進めたい。大型装置は結果が出せる１つの重要な方法だと考える。(G3, EW WIMPs, and beyond)

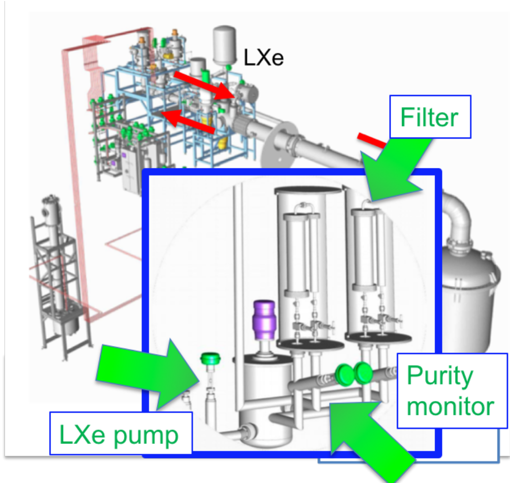
現在のステップG2

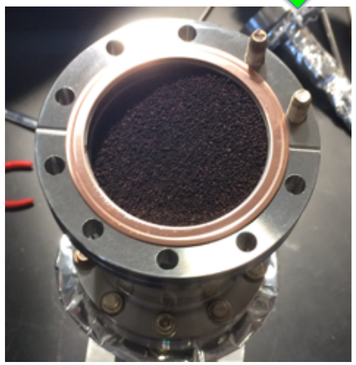
令和元年新規　新学術領域
研究代表 井上邦雄
「地下から解き明かす宇宙の歴史と物質の進化」
計画研究 森山茂栄ほか
「高感度大型装置で推進する暗黒物質直接探索」
等による科研費によるサポート

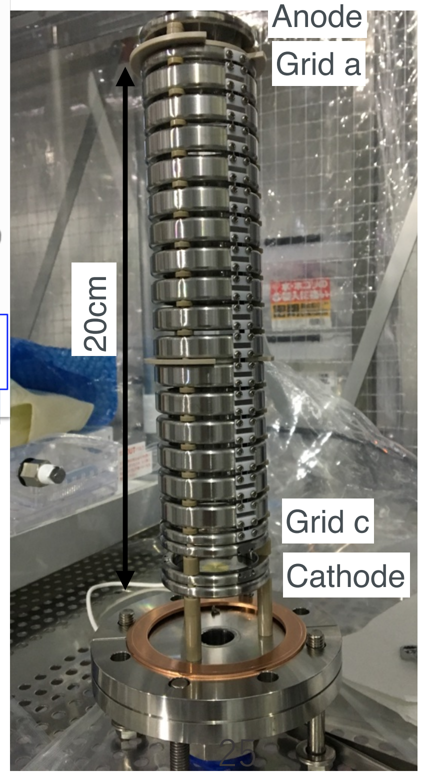
- 山下氏が説明するとおり。日本グループが活躍中。











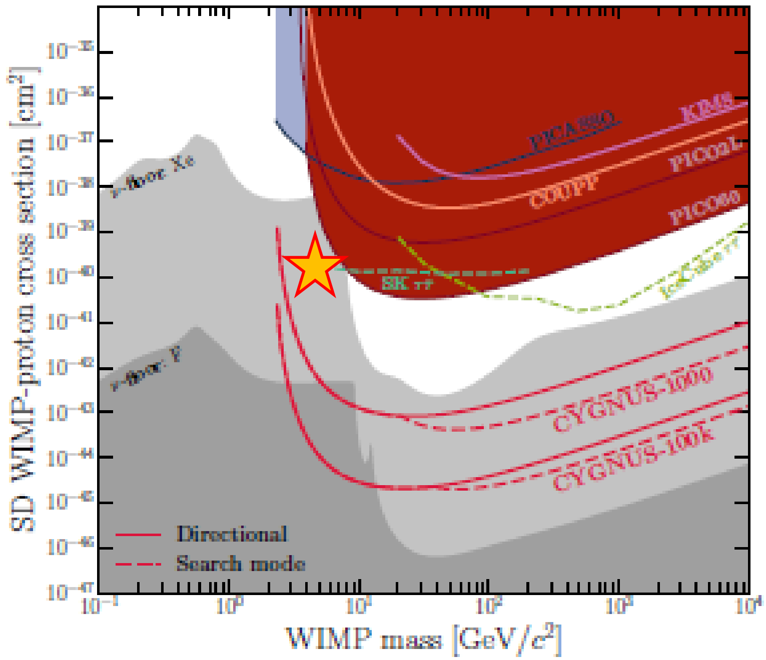
CYGNUS

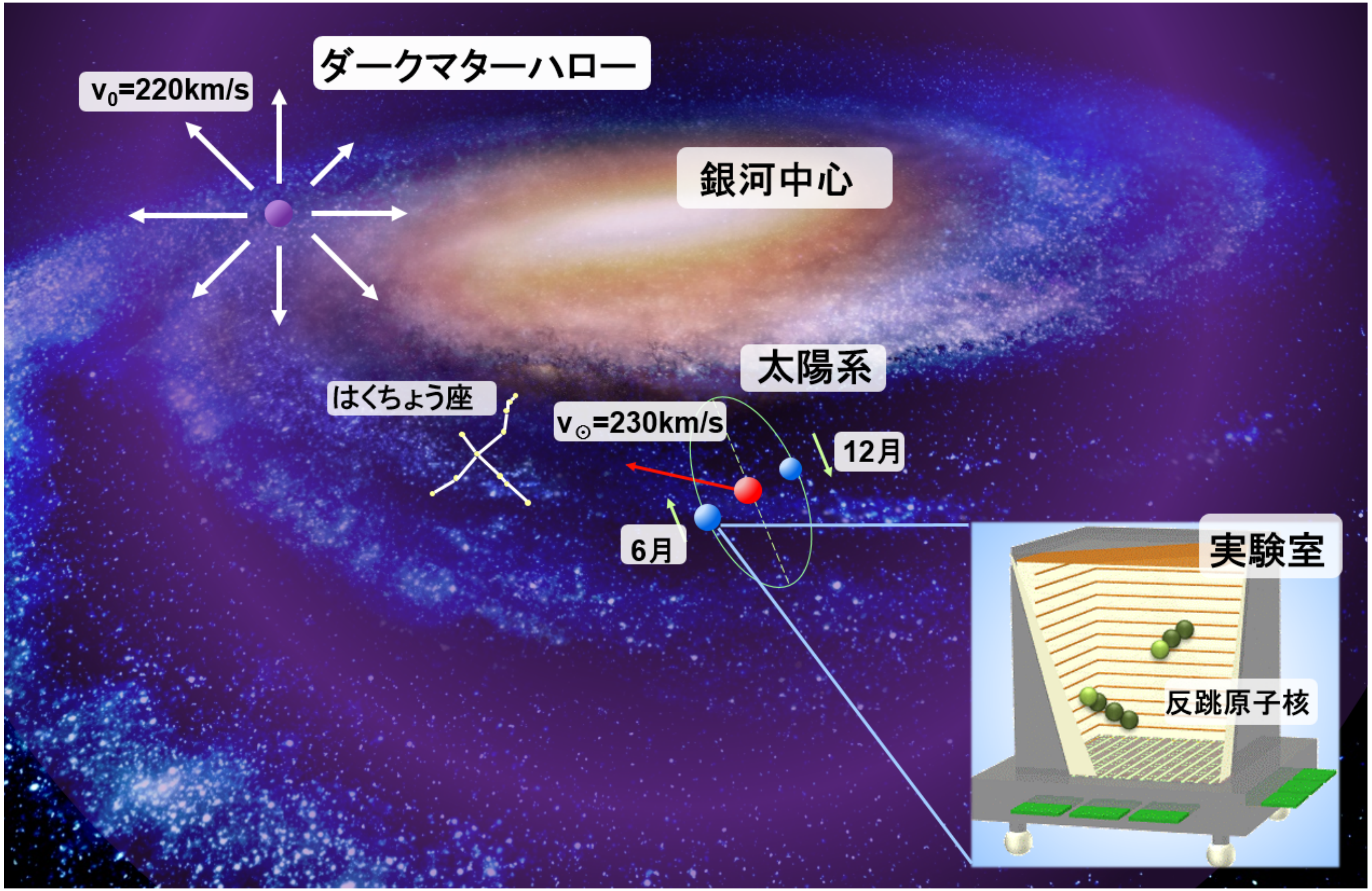
DRIFT, NEWAGE を中心とした将来の方向感度実験

Steering committee: N. Spooner, K. Miuchi, E. Baracchini, S. Vahsen, G. Lane

現状：$1m^3$ 検出器をそれぞれ開発 & $10m^3$コンセプトデザイン検討
日本：CYGNUS-KM1として$1m^3$ 検出器製作中
次CYGNUS-KM8　$8m^3$ でXeのニュートリノフロアを超えた探索(右図☆)
その後：w/水シールド　大型ガス検出器

CYGNUS-KM1 chamber@神戸

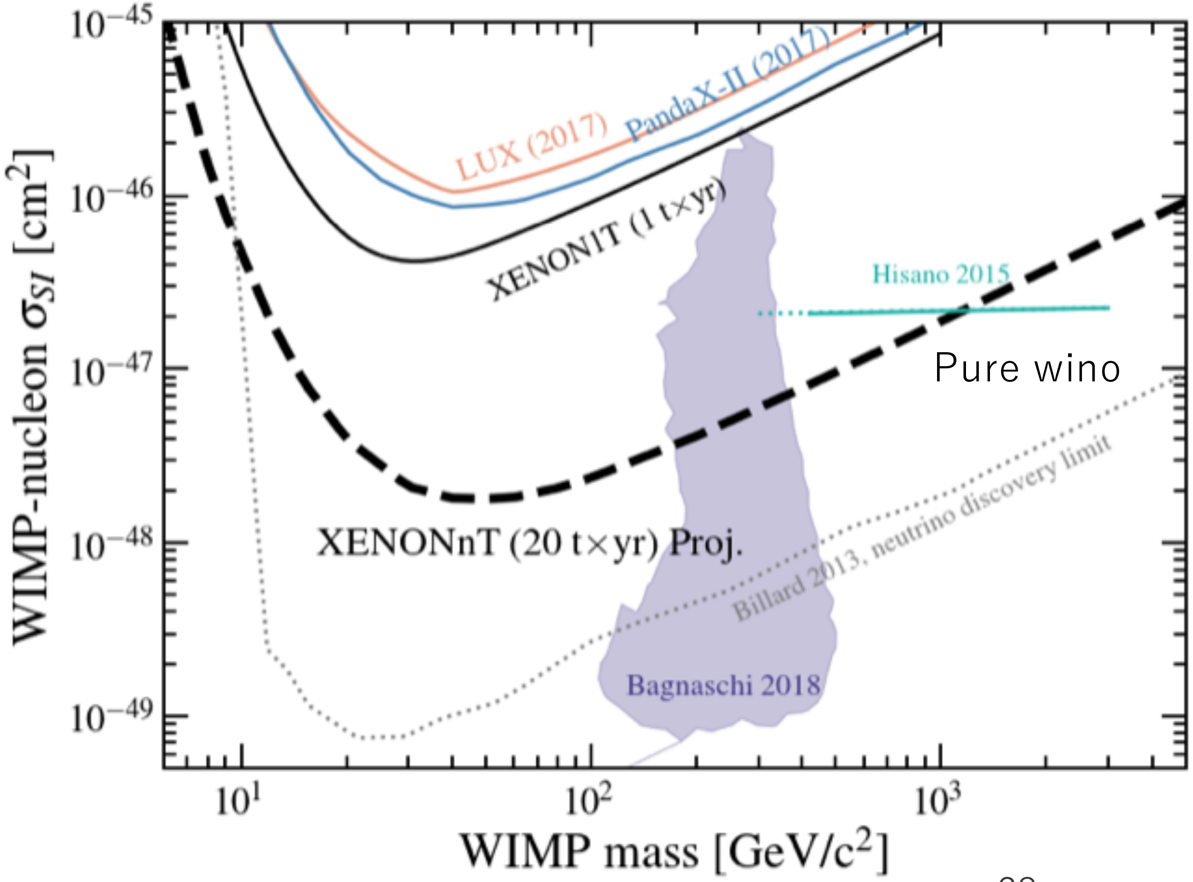




ダークマターハロー
v_0=220km/s
銀河中心
太陽系
はくちょう座
$v_\odot$=230km/s
12月
6月
実験室
反跳原子核

興味を共有するpure wino/higgsino “WIMP Standard Candles”

- Higgs 125 GeVやLHCでの結果等と矛盾せず、DMの密度をうまく説明する可能性のあるモデルが予言。
- 日本人のcontributionが大きい。
- 核子との断面積も高い精度で予言されている。
- 高いシナジーが有りうる
  - G2で兆候、G3で発見？
  - LHCやFCCでのdisappearance track探索。
  - CTAで最初の兆候が期待？



今後の戦略は？

- カミオカ地下の大きな資産を用いてさらなる発見へ結びつける具体的方法は？
- フォーカスする物理は？
- 明日議論する可能性のある質問を照会し、頭出し。
  - いくつかはグラナダのシンポジウムからパクリ

DM発見のための最適な道のりは？

DD/ID/Accで信号が見えたら
DMと信じるか？
確認のため何をするか？

DD/ID/Accのよりよい関係は

ニュートリノフロアを超えてゆく必要性と意義はなにか

大型DM検出器のさらなる多目的化は

方向検出器が信号を見るには

軽い暗黒物質（候補探索）での加速器の優位性はどうか

Breakthroughがあるとしたらなにか

地下大空洞があったらどう使いたいか