“Indirect Dark Matter Searches”

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Prospective IN2P3
Annecy, 12/11/2019

Contributions et contributeurs

Indirect searches for dark matter in a multi-messenger context
Auteurs : F. Calore (LAPTh), C. Combet (LPSC), L. Derome (LPSC), J. Lavalle (LUPM), D.M. (LPSC), V. Poulain (LUPM), P. Salati (LAPTh), P. Serpico (LAPTh)
Co-auteur : J. Cohen Tanugi (LUPM)

Identification de la Matière Noire à l'ère du grand relevé optique LSST
Auteur : J. Cohen Tanugi (LUPM)
Co-auteurs : M. Moniez, E. Nuss (LUPM)
Endosseurs : D. Boutigny (LAPP), C. Combet (LPSC), D. Fouchez (CPPM), E. Gangler (LPC), J. Lavalle (LUPM), D.M. (LPSC), J. Neveu (LAL), V. Poireau (LAPP), V. Poulain (LUPM), C. Renault (LPSC)

Cosmic-ray phenomenology from sub-GeV to ZeV *[aspects « basses énergies » uniquement]*
Auteurs : D. Allard et A. Marcowith
Co-authors : B. Bruny (APC), J. Cohen-Tanugi (LUPM), L. Derome (LPSC), F. Casse (APC), S. Gabici (APC), J. Lavalle (LUPM), D. Maurin (LPSC), A. Neronov (APC), E. Parizot (APC), D. Semikoz (APC)

CTA Science Prospective at IN2P3 *[aspects matière noire uniquement]*
Contact : T. Suomijärvi (IPNO)
Signataires : APC (A. Djannati-Ataï, M. Punch, S. Pita, R. Terrier, A. Lemière, B. Khélifi, S. Gabici, P. Goldini, A. Neronov, D. Semikoz), CENBG (J. Devin, M.-H. Grondin, M. Lemoine-Goumard, T. Reposeur CPPM: E. O. Angüner, F. Cassol, H. Costantini, G. Verna), IPNO (B. Biasuzzi, J. Biteau, Z. Ou, T. Suomijärvi), LAPP (A. Fiasson, G. Lamanna, J. P. Lees, G. Maurin, V. Poireau , D. Sanchez), LLR (R. Adam, M. de Naurois, S. Fegan, G. Fontaine, D. Horan), LPNHE (J. Bolmont, S. Caroff, G. Emery, J.-P. Lenain, C. Levy), et LUPM (Y. Gallant, A. Marcowith, F. Piron, Q. Remy, M. Renaud, A. Sinha)

(Primordial) Black Holes *[aspects matière noire uniquement]*
Auteur : A. Arbey (IP2I)
Co-auteurs : J. Auffinger (IP2I), A. Barrau (LPSC), M. Khlopov (APC), J. Silk (IAP)

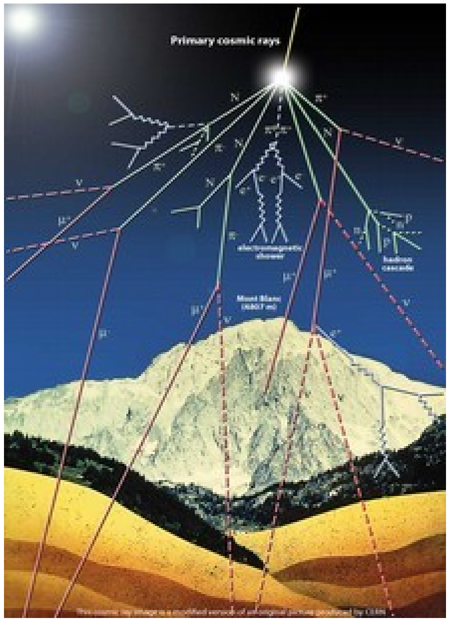
1. GCRs
   - Introduction
   - Charged CRs
   - Challenges
   - Gamma rays (including CTA)

2. PBH
3. DM with LSST

4. Conclusions

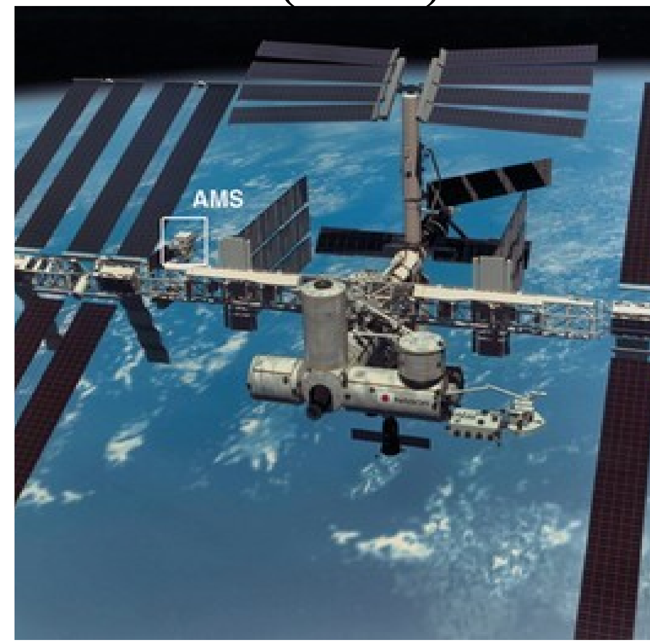
Experimental milestones

Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



CR discovery

Extensive showers

e^-, e^+

Diffuse γ

$\bar{p}$

TeV astronomy

ν

GW

$\bar{d}$?

1910 1930 1950 1980 2000 2020

e^+, μ, π, K, Λ

Elements up to U

^{10}Be - ^{54}Mn

Cosmic rays = Particle physics

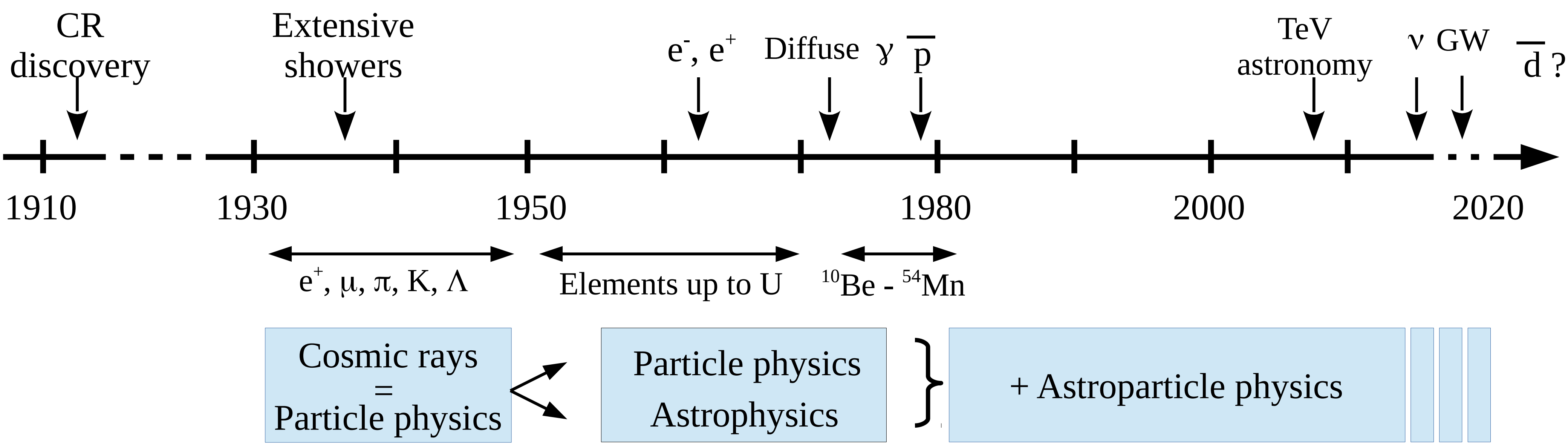
Particle physics
Astrophysics

+ Astroparticle physics

Milestones

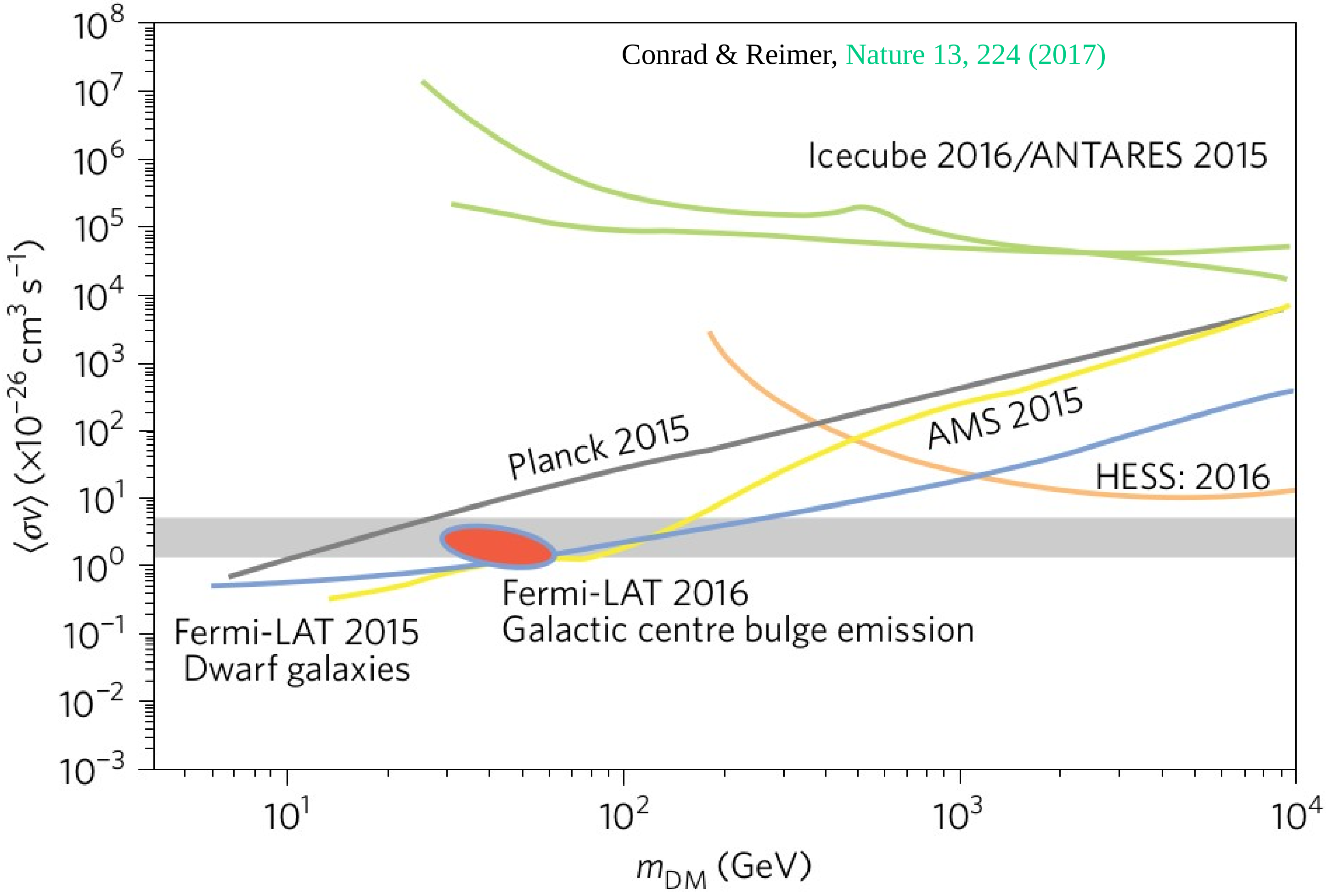
2019 Cosmology Gruber prize (N. Kaiser and J. Silk)

“[…] for their seminal contributions to the theory of cosmological structure formation and probes of dark matter.
[…] while Silk recognized dark matter's indirect signatures such as antiprotons in cosmic rays and high energy neutrinos from the Sun



After 40 years of efforts...

→ **γ-rays from dSphs and antiprotons provide best targets for DM searches**



High precision era

→ need conjoined effort from community to fully exploit data

Charged vs neutral cosmic rays

Two categories

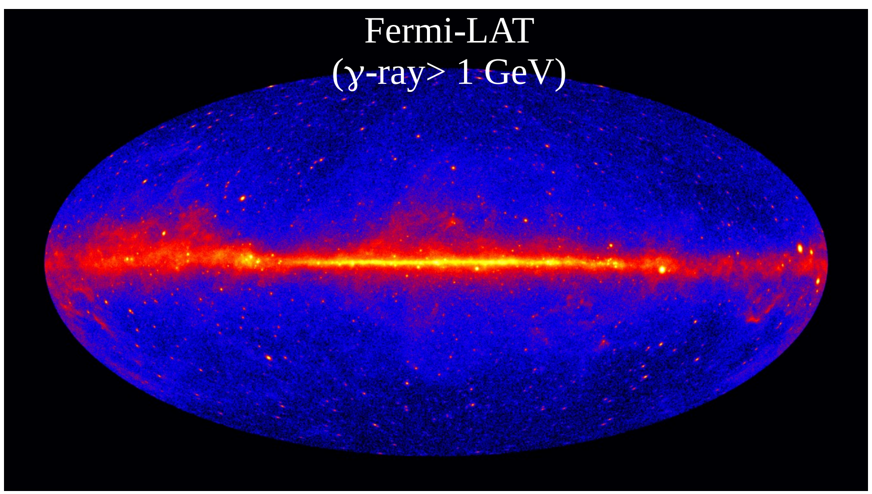
- *Neutral species*
  - Gamma-rays
  - Neutrinos

Multi-messenger approaches
Multi-wavelength observations

- *Charged species*
  - Leptons
  - Nuclei

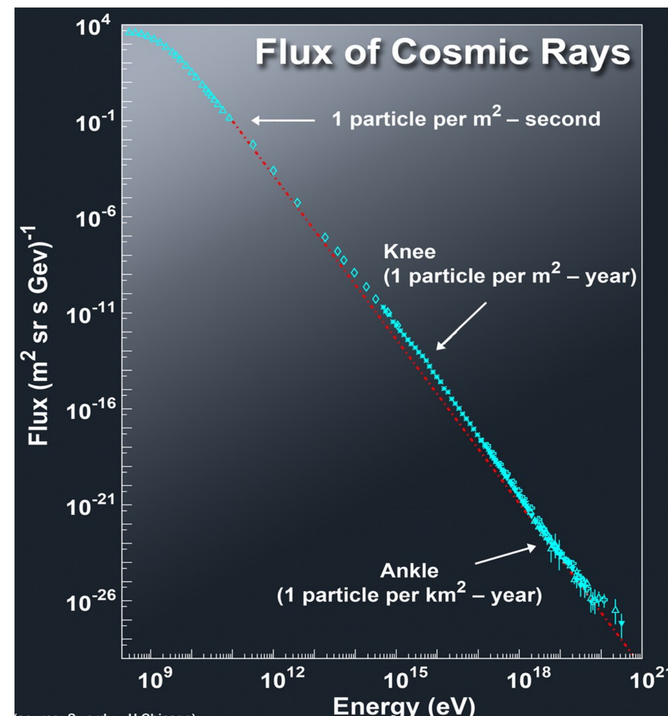
Observation types

→ *Astronomy*
point-like, extended, diffuse emissions



→ *Spectra & anisotropy maps*
(diffusion/deflection in B)

30 orders of magnitude



12 orders of magnitude

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Detection: direct vs indirect

“Direct” CR detection (< 10^{15} eV ~ PeV)

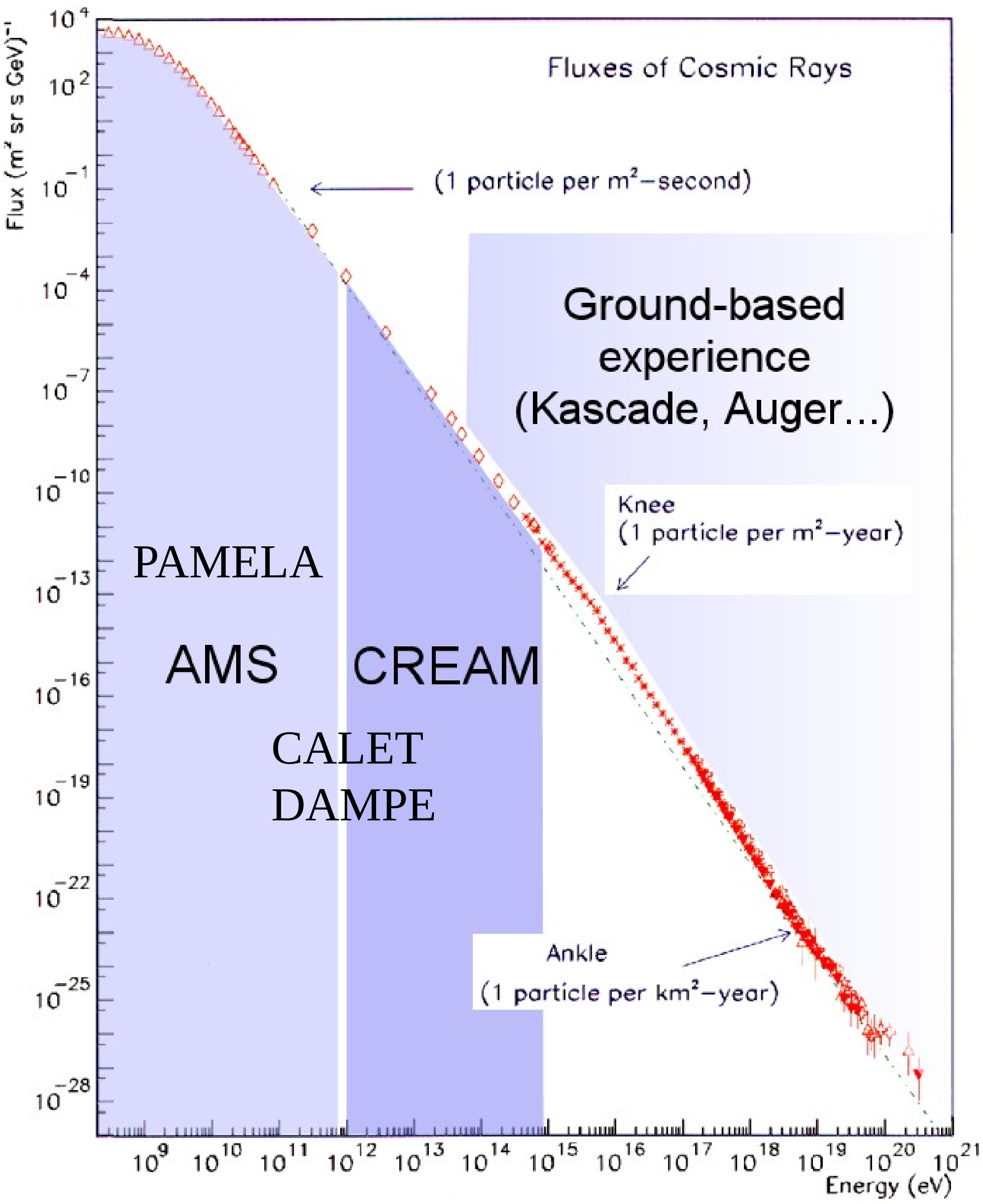
- Detectors “above” atmosphere (balloon or space)
- “Particle physics”-like detectors

→ Identification of CR nature and energy

“Indirect” CR detection (> 10^{15} eV)

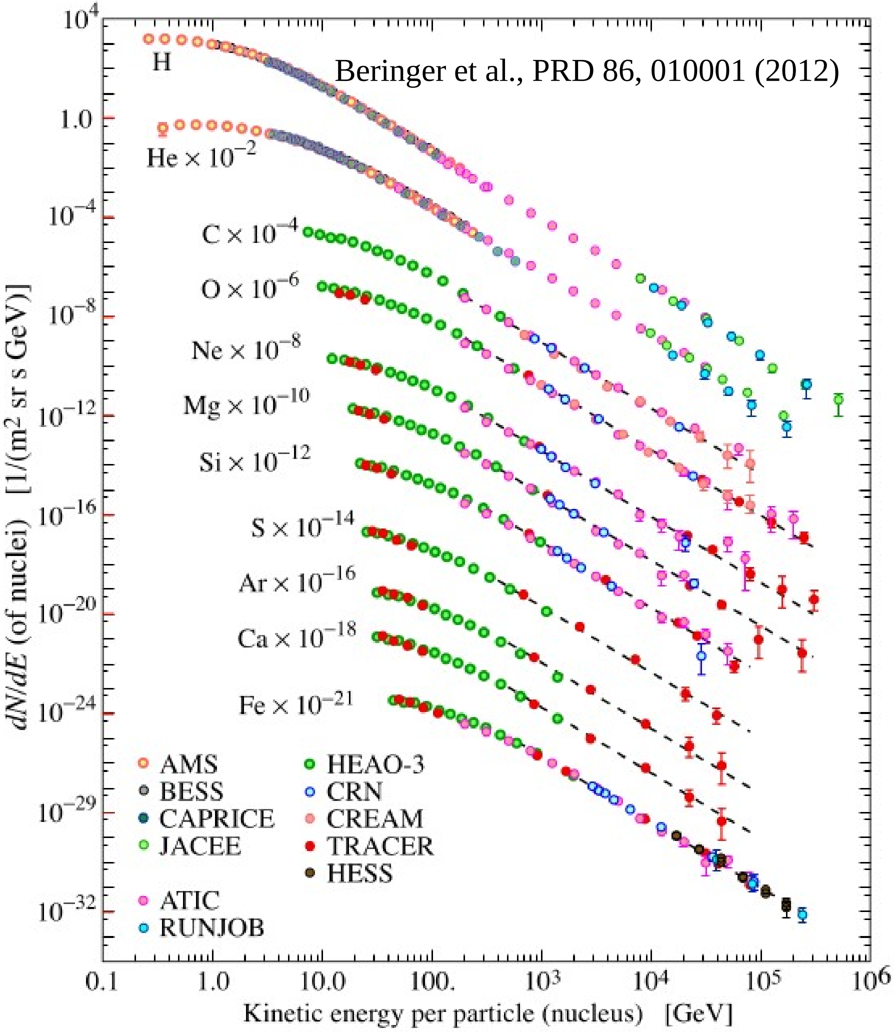
- Ground-based detectors
- Use atmosphere as “calorimeter”
- Measure shower properties

→ Reconstruct CR most likely nature and energy



Galactic CR data ($E \sim 10^{8}$-10^{15} eV)

Elemental spectra

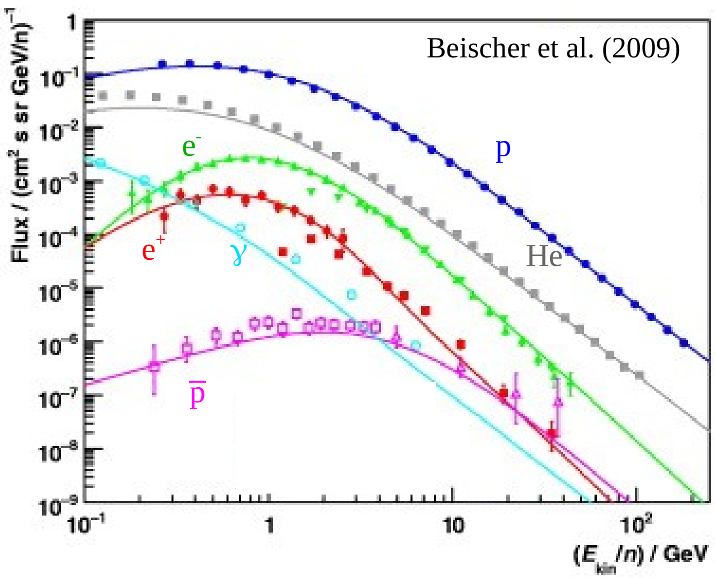


→ Origin of quasi-universal power law ($E^{-2.8}$)?
→ Maximum energy of Galactic sources?
→ Abundances of elements and isotopes?
→ Patterns in small-scale anisotropies ($\delta<10^{-3}$)

Protons and He

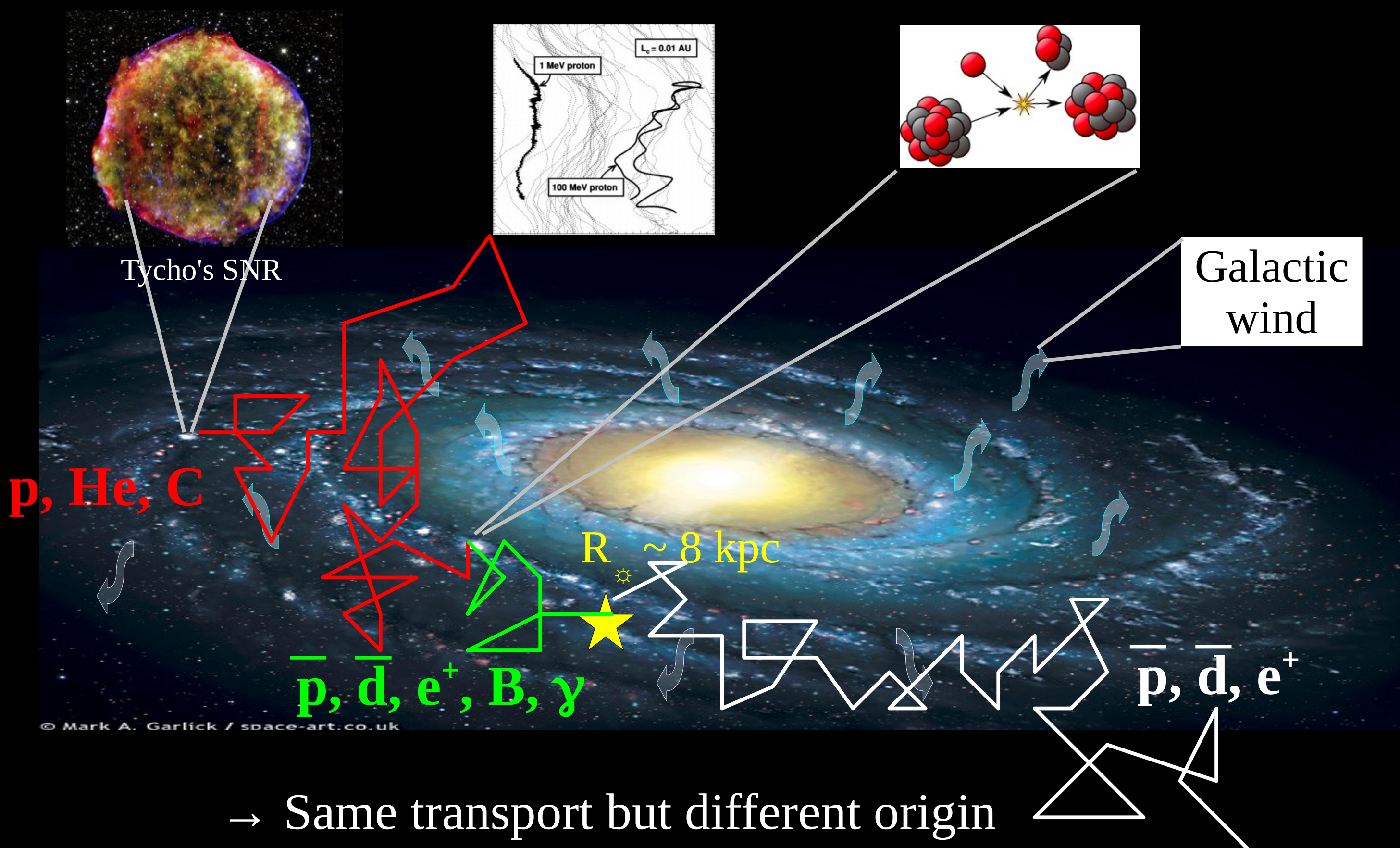
vs

diffuse γ-rays, pbar, e^- and e^+



N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Are there primary sources?
→ Is it a good place to look for dark matter?

DM indirect detection: charged CRs



→ Same transport but different origin
(from DM halo)

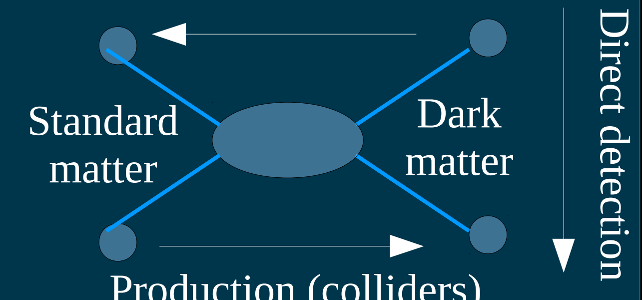
Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

→

Milky-Way dark matter halo
- ~ spherical halo
- radius ~300 kpc

→

Indirect detection

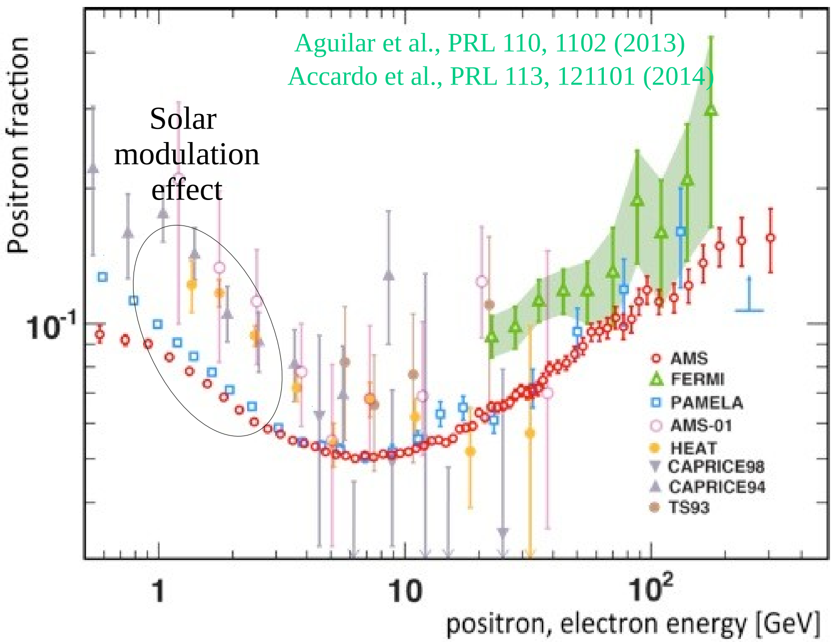


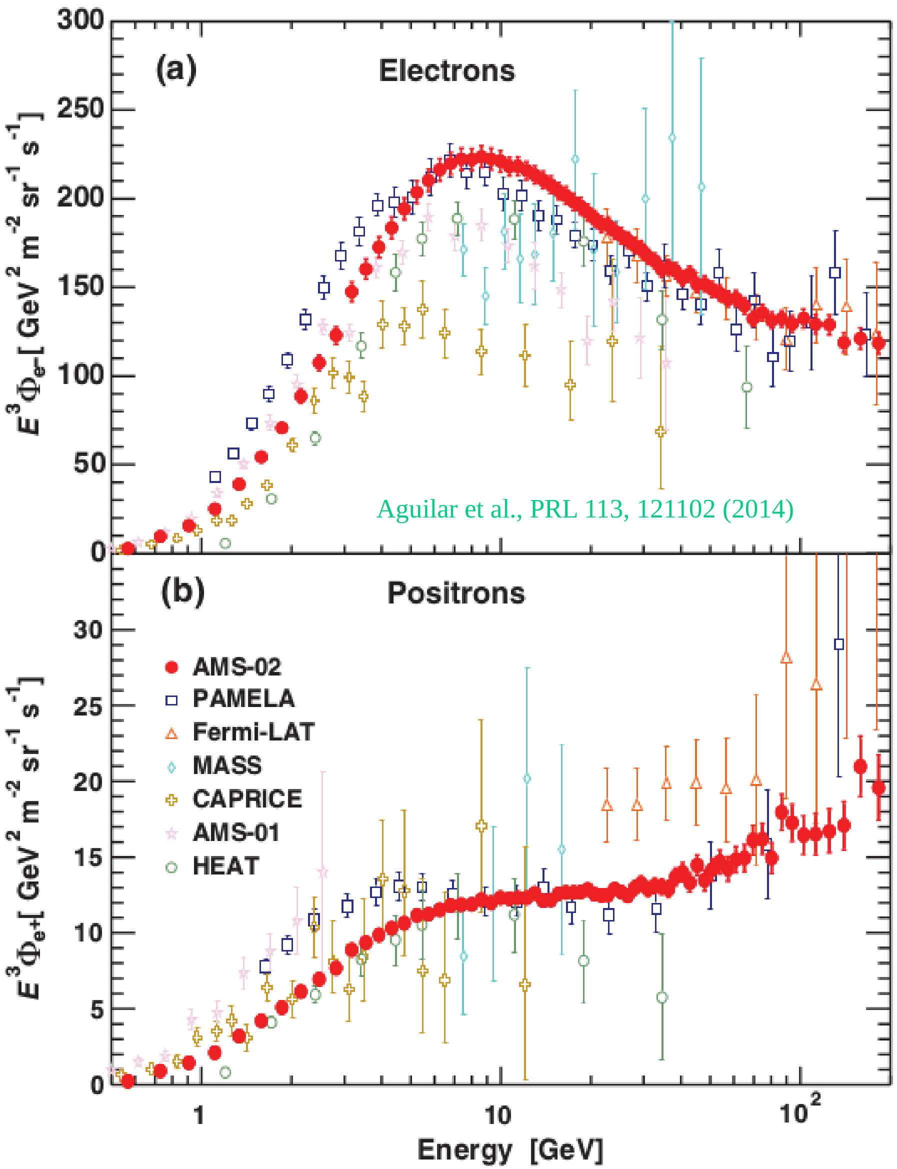
Installed on ISS in May 2011

- → Circular orbit, 400 km, 51.6°
- → Continuous operation 24/7
- → Average rate ~700 Hz (60 millions particles/day)

More than 140 billion events so far!

Rise of the positron fraction and leptons





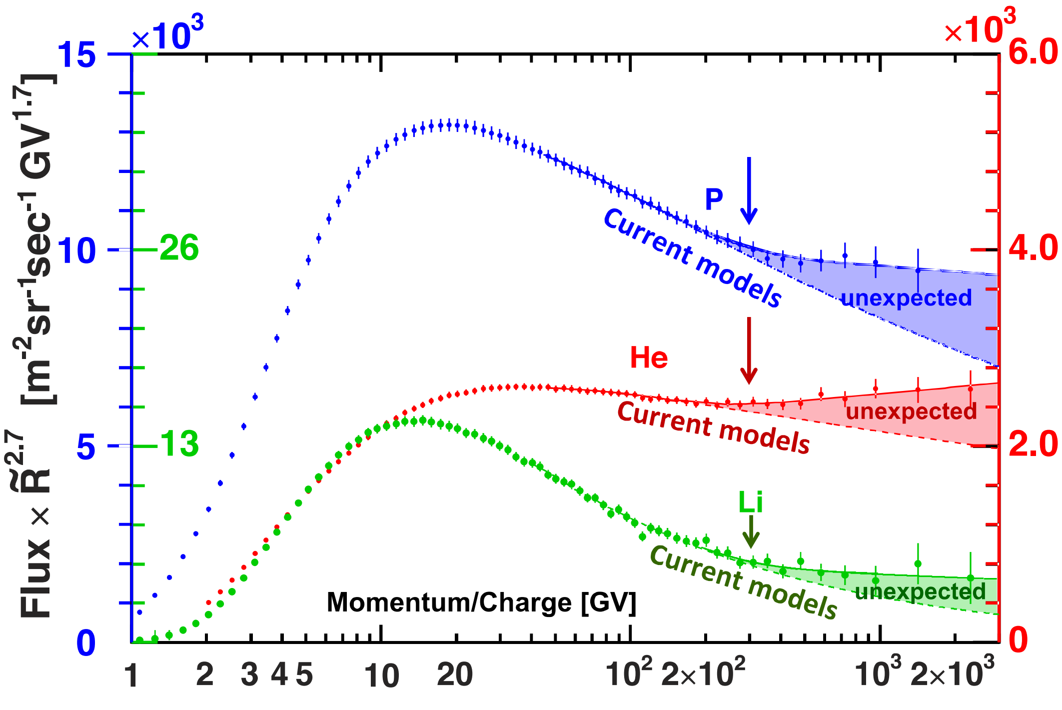
Positron fraction, e^-, e^+ and e^-+e^+ spectra used to test astrophysical and/or dark matter hypothesis

- Contribution from local SNRs/pulsars?
  → e.g., Delahaye et al., A&A 524, A51 (2010)
- Dark matter hypothesis?
  → e.g., Boudaud et al., A&A 575, 67 (2015)
  [N.B.: no boost, Lavalle et al., A&A 479, 427 (2008)]

High rigidity break and species-dependent slopes

→ Spectral break at ~ 300 GV
→ Different slope H and He

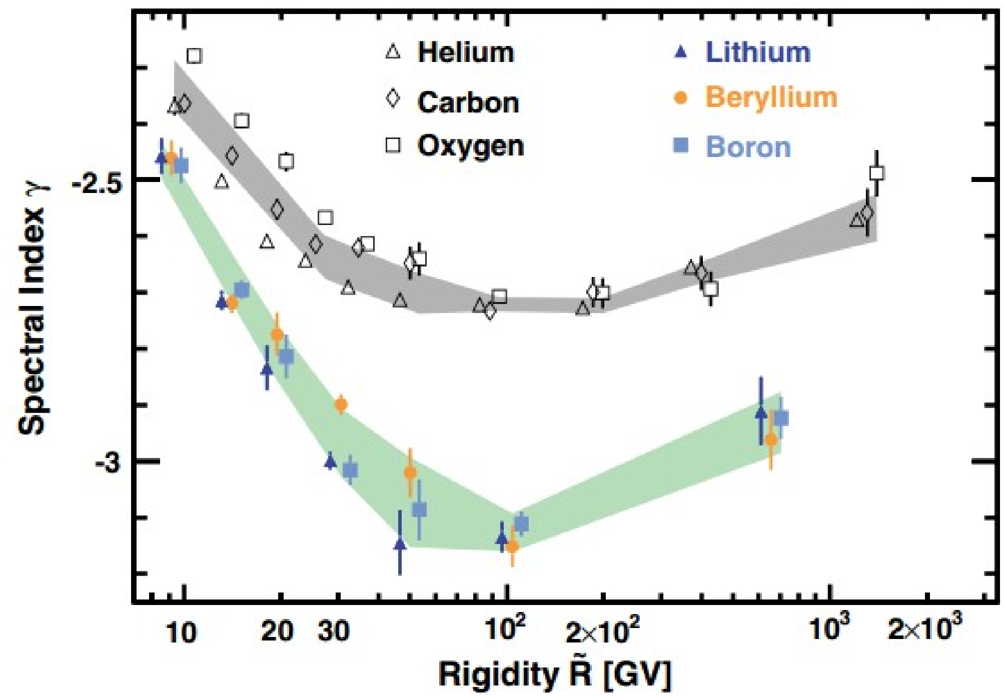
(see also PAMELA and CREAM)



Origin of difference in slopes?
→ Acceleration, spatial segregation, different kind of sources...

→ Break seen in all data (primary and secondary species)

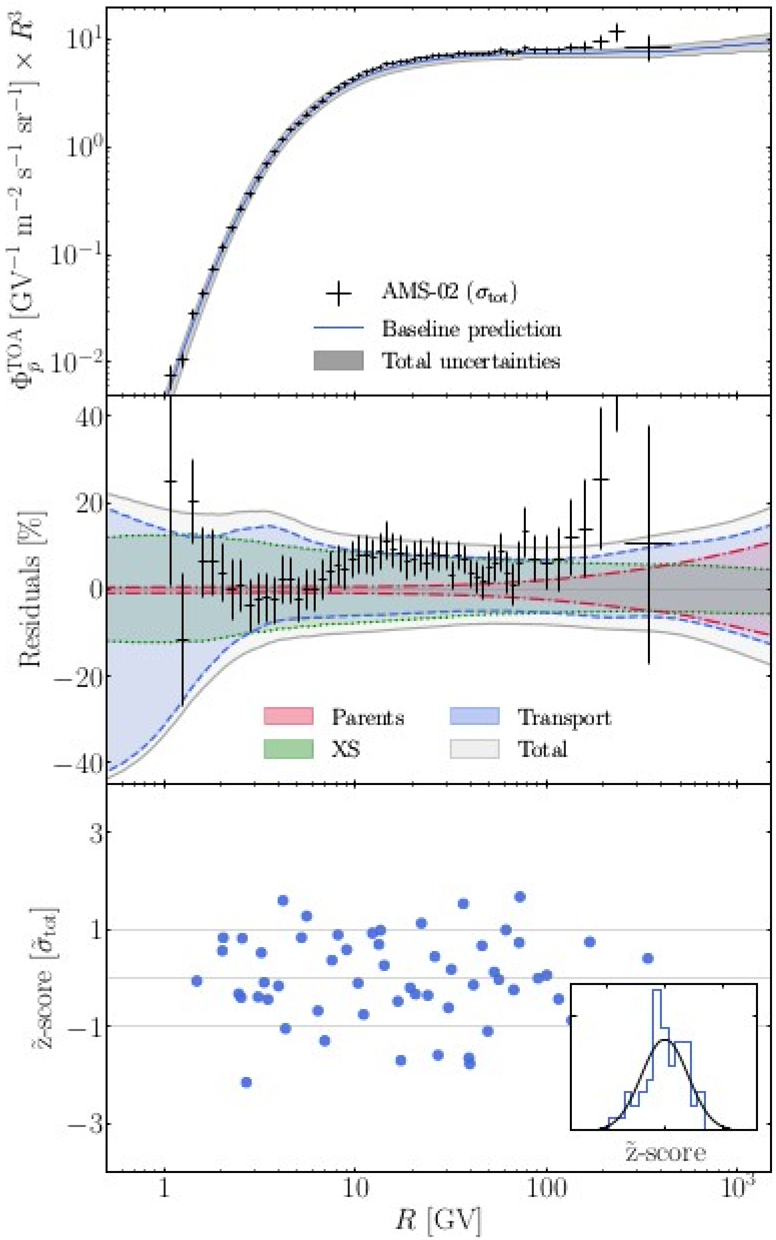
Aguilar *et al.*, PRL 120, 021101 (2018)



Origin of spectral break?
→ spatial dependence of diffusion coefficient, time-dependent propagation, break in diffusion coefficient (coupling CR/waves)

Antiproton analysis: origin of uncertainties

Boudaud, Génolini et al., arXiv:1906.07119



$$\chi^2 = (\text{data}-\text{model})^{\rm T} (\mathcal{C}^{\rm model} + \mathcal{C}^{\rm data})^{-1} (\text{data}-\text{model})$$

→ **Statistically consistent with pure secondary origin**

Visualisation in rotated base

→ Systematics are diagonal

$$\tilde{\mathcal{C}} = U\,\mathcal{C}\,U^{\rm T}$$

→ Rigidities replaced by pseudo ones

$$\tilde{R}_i = \sum_j U_{ij}^2\, R_j$$

→ Residuals in rotated base now account for correlations in systematic

$$\chi^2 = \sum_i \tilde{z}_i^2 \qquad \tilde{z}_i = \tilde{x}_i/\tilde{\sigma}_i \qquad \tilde{x}_i = U_{ij}\,x_j$$

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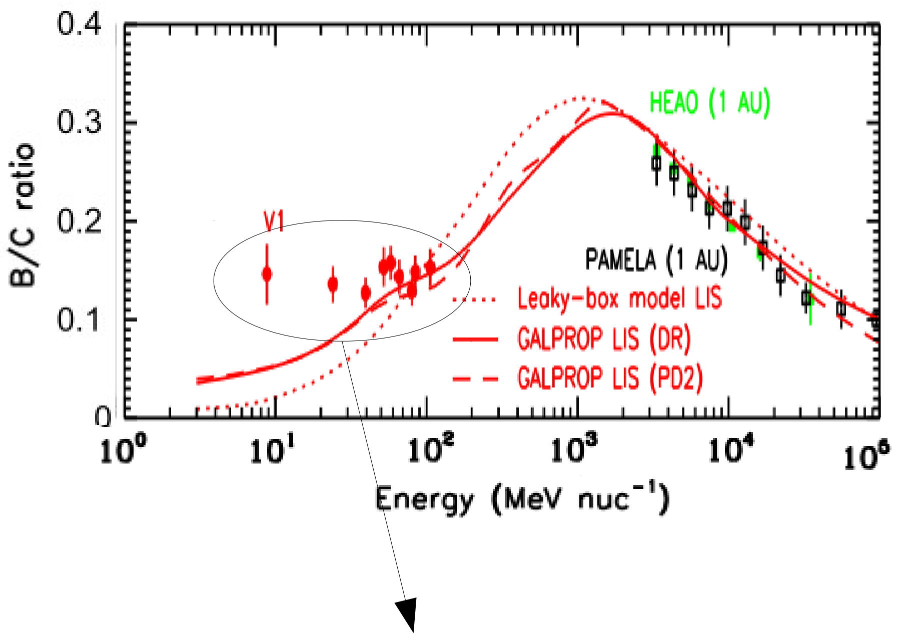
Low-energy data

Voyager IS data

Stone et al., Science 341, 150 (2013)
Cummings et al., ApJ 831, 18 (2016)

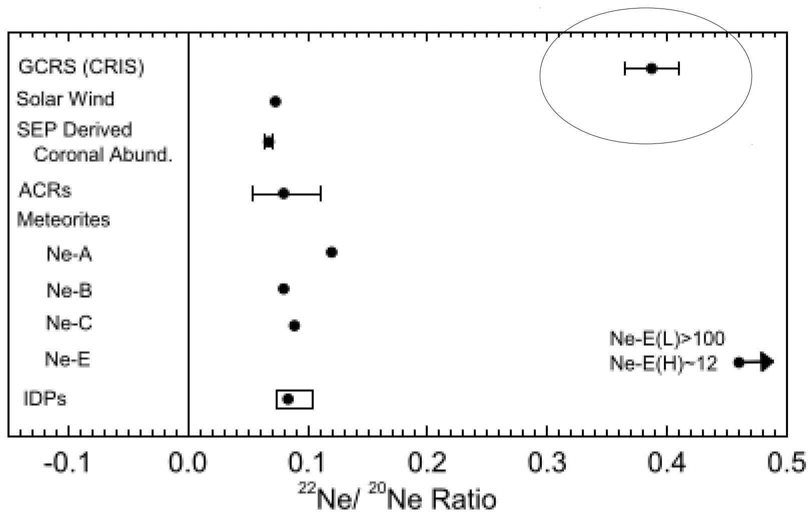


B/C not compatible with current models

→ light isotopes soon from Voyager (and Voyager 1)

→ Anomalies in isotopic abundances

Binns et al., ApJ 634, 361 (2005)



Excess ~ 5 times Solar System abundances

[Wolf-Rayet stars (evolutionary products of OB stars) in OB associations that form superbubbles]

→ Part of CRs from superbubbles?

The local interstellar medium (LISM) puzzle

→ Nearby SN events

Fields et al., Astro2020 Science White Paper

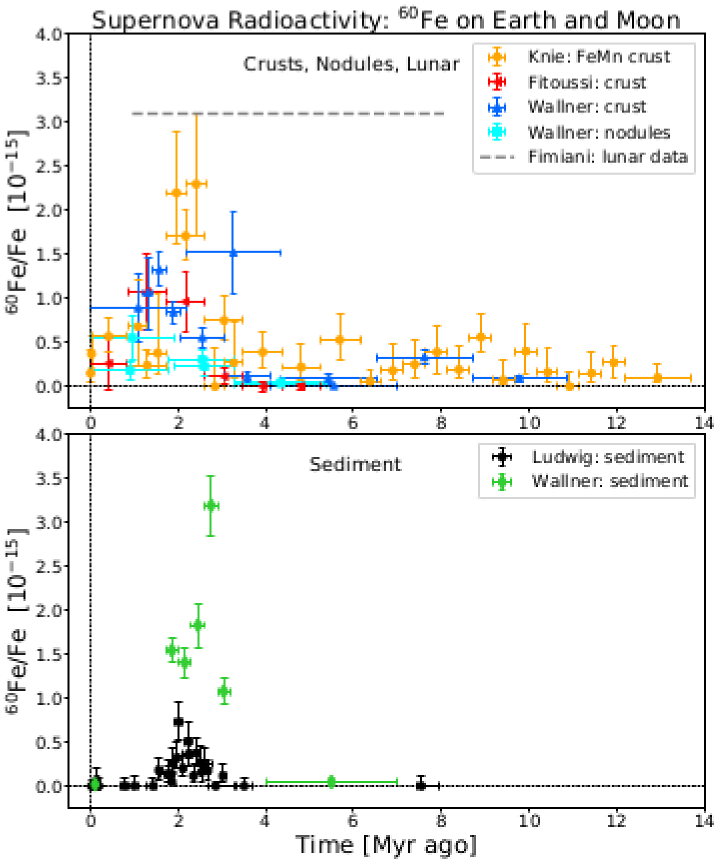
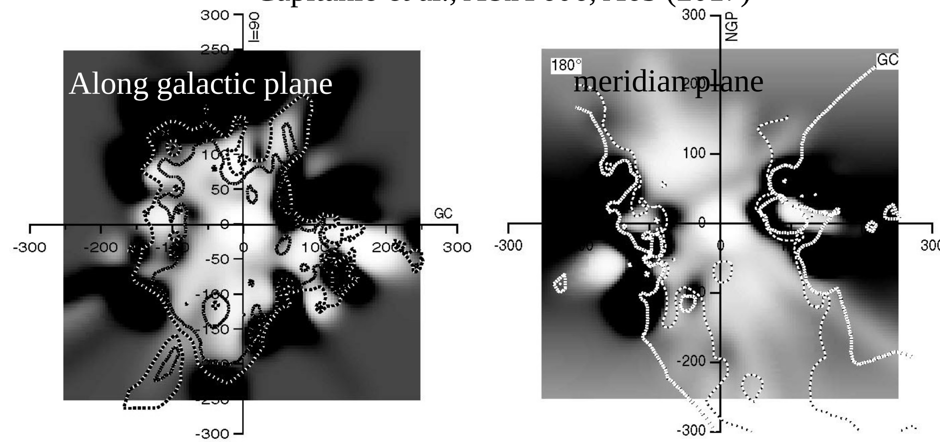


Figure 1: Global and lunar detections of ^{60}Fe, not corrected for decay. All data show a signal around ~2–3 Myr. Amplitude differences may reflect iron uptake variations, or latitude variations in iron fall-out. *Upper panel:* ^{60}Fe/Fe ratios in deep-ocean Fe-Mn crusts. *Lower panel:* ^{60}Fe/Fe in deep-ocean sediments, showing signal duration $\gtrsim$ 1 Myr. Data: refs. [40, 23, 70, 22, 46].

→ LISM origin...

NaI absorption measurements (5890 Å)
Lallement et al., A&A 411, 447 (2003)
Welsh et al., A&A 510, A54 (2010)
Capitanio et al., A&A 606, A65 (2017)



→ 20 SN explosions during the past 10-20 Myr (age of the local bubble)

→ 1 more SN ~ 1 Myr ago?
(as close as ~ 40 pc, related to Pliocene-Pleistocen extinction?)

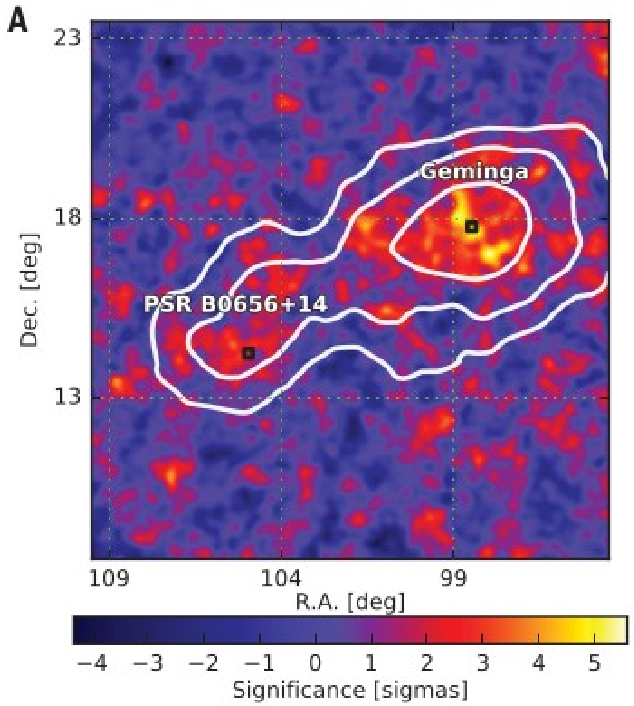
Maíz-Apellániz, ApJ **560**, L83 (2001)
Berghöfer & Breitschwerdt, A&A **390**, 299 (2002)
Benítez et al., PRL **88**, 081101 (2002)

→ Impact on CR fluxes?

HAWC, local diffusion, and back to leptons...

→ Extended γ-ray emission around pulsars

Abeysekara et al., Science 358, 911 (2017)
HAWC collaboration



Di Mauro, Manconi, Donato, arXiv:190305647
Fermi-LAT data

→ 7.8 − 11.8σ significance around Geminga
→ Geminga pulsar proper motion detected

→ Pockets of "inefficient" diffusion ($D_{pocket} << D_{halo}$)

Hooper & Linden, PRD 98, 083009 (2018)
Profumo et al., PRD 97, 123008 (2018)

"Lessons from HAWC pulsar wind nebulae observations: The diffusion constant is not a constant; pulsars remain the likeliest sources of the anomalous positron fraction; <u>cosmic rays are trapped for long periods of time in pockets of inefficient diffusion</u>"

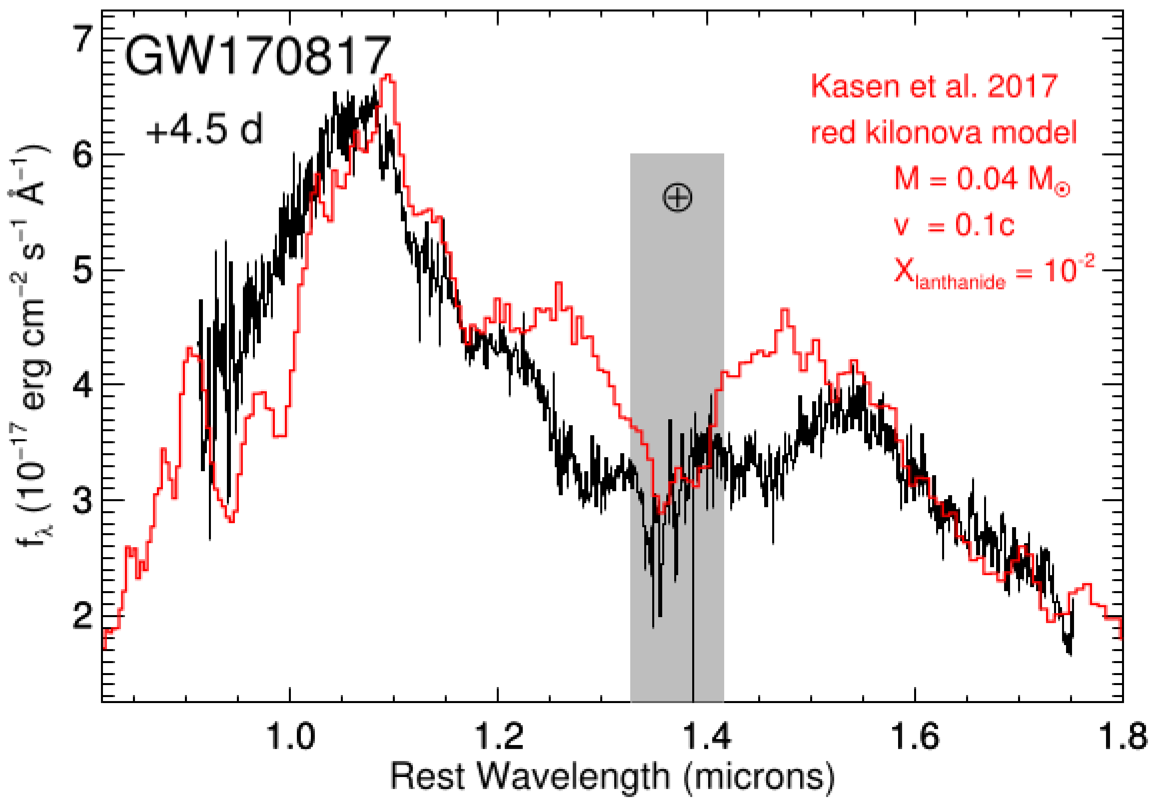
→ May further "decouples" predictions from nuclei and leptons...

Super-heavy CRs and gravitational waves

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. III. Optical and UV Spectra of a Blue Kilonova from Fast Polar Ejecta

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. IV. Detection of Near-infrared Signatures of *r*-process Nucleosynthesis with Gemini-South

III. Early emission ~ 'blue KN': ~0.3 Msol ejecta @ 0.3c, lanthanide frac. <10^{-4} => light r-process (A<140)
IV. Late (>2.5 d) ~ 'red KN': 0.04 Msol ejecta @ 0.1c, lanthanide frac.~10^{-2} => heavy r-process elements
→ Consistent with NS merger (r<12km), favours NS as major contributors to r-process nucleosynthesis



\+ **The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars**

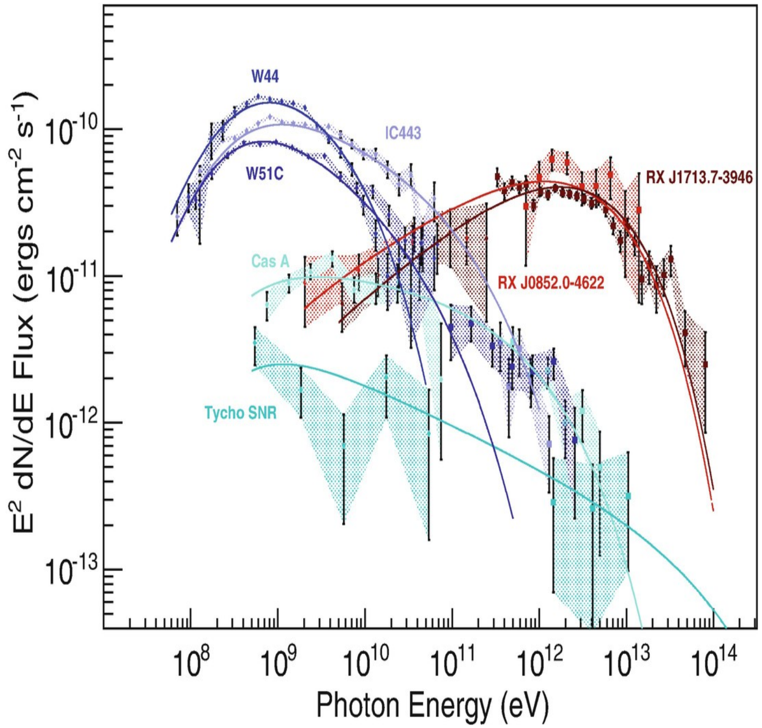
GCR sources: gamma-rays and neutrino

A. Marcowith

- SNR are gamma-ray sources, but origin still uncertain (hadronic/leptonic) **Lemoine-Goumard & Renaud 2012**

- Where are the PeVatrons (**Cristofari et al** 2013)?
  - massive star clusters and superbubbles (**Parizot** et al 2004)
  - galactic center (HESS collaboration 2016)
  - young SNR (Schure & Bell 2013, **Marcowith et al** 2018)

- CTA should provide an answer (**Cristofari et al** 2018) and probe gamma-ray/neutrinos diffuse emission (**Neronov & Semikov 2019**)



Broadband emission from SNR of different ages
(Funk 2015)

→ Highest energies are obtained for the youngest objects, with the fastest shocks

→ Oldest objects (W44, IC 443…) show a bump associated with neutral pion production.

Acceleration (theoretical) studies

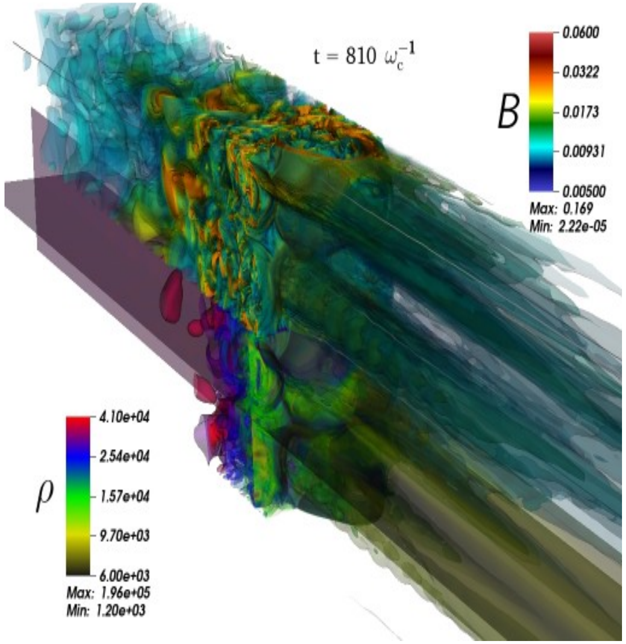
A. Marcowith

→ Strong progress from PIC, hybrid codes, and PIC-magnetohydrodynamics (**Marcowith** et al 2016)

Survey of parameter space to test Fermi acceleration : 3 main parameters

- Shock speed (non- to ultra-relativistic).
- Magnetic field obliquity (orientation of ambient magnetic field wrt shock normal).
- Ambient (un-shocked) medium magnetization (ratio of magnetic to rest mass energy).
- Studies done for both electron-positron/ electron-proton plasma.

→ Illustration from PIC-MHD (MHD for the fluid and PIC for non-thermal particles)



3D simulations of non-relativistic shock
(up = magnetic field, down = gas density)

→ CRs injected upstream generate magnetic perturbations due to their current : non-resonant streaming instability (Bell 2004, **van Marle** et al 2018, 2019).

→ Longest, to date, simulations of a 3D non-relativistic shock

→ The shock front is strongly corrugated = CR back-reaction over the flow and impact over the CR injection process.

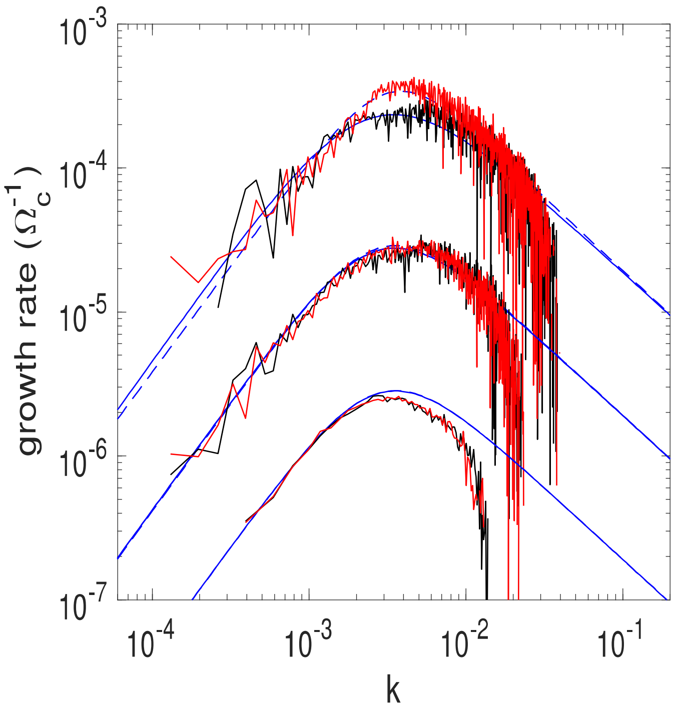
Transport (theoretical) studies

A. Marcowith

→ Progress from new theoretical ideas and also from hybrid and PIC-MHD

- Role of self-generated turbulence
  - to explain spectral hardening ~200 GeV/n (Blasi et al 2012)
  - around sources (Nava et al 2016, Brahimi et al 2019) => CR halos around pulsars and SNRs
- Role of CR anisotropy to constrain properties of the local ISM turbulence (**Giacinti** & Kirk 2017)

→ Illustration of PIC-MHD resonant streaming instability (Bai, … **Plotnikov** et al 2019)



Linear growth rate of the resonant streaming instability
(3 different set-ups)
Bai et al (2019)

- black= left-handed polarized modes
- red = right handed polarized modes
- solid = theoretical growth rate for left modes
- dashed = theoretical growth rate for right modes.

→ Linear growth rate solution well reproduced, saturation due to CR diffusion (the instability is quenched)

Summary and ‘recommendations’ for GCRs

Experimentally

- Should we participate to next generation GeV-TeV experiments (Aladino, AMS-100)?
- Should we participate to gamma-ray GeV-TeV LHAASO experiment
- Should we support more MeV mission?

Phenomenology/theory

- Improve contacts between phenomenologists in the GeV-TeV and in the EeV domain
- IN2P3 has strengthen its support to theory in particle physics and DM research. But the theory to study CR acceleration/propagation is not yet fully recognized.
- Increase the support to numerics through code development and exploitation (e.g. for CTA)
- Develop the links with other communities involved in particle acceleration problems (space physics in the perimeter of INSU), power laser physics (INP/CEA).

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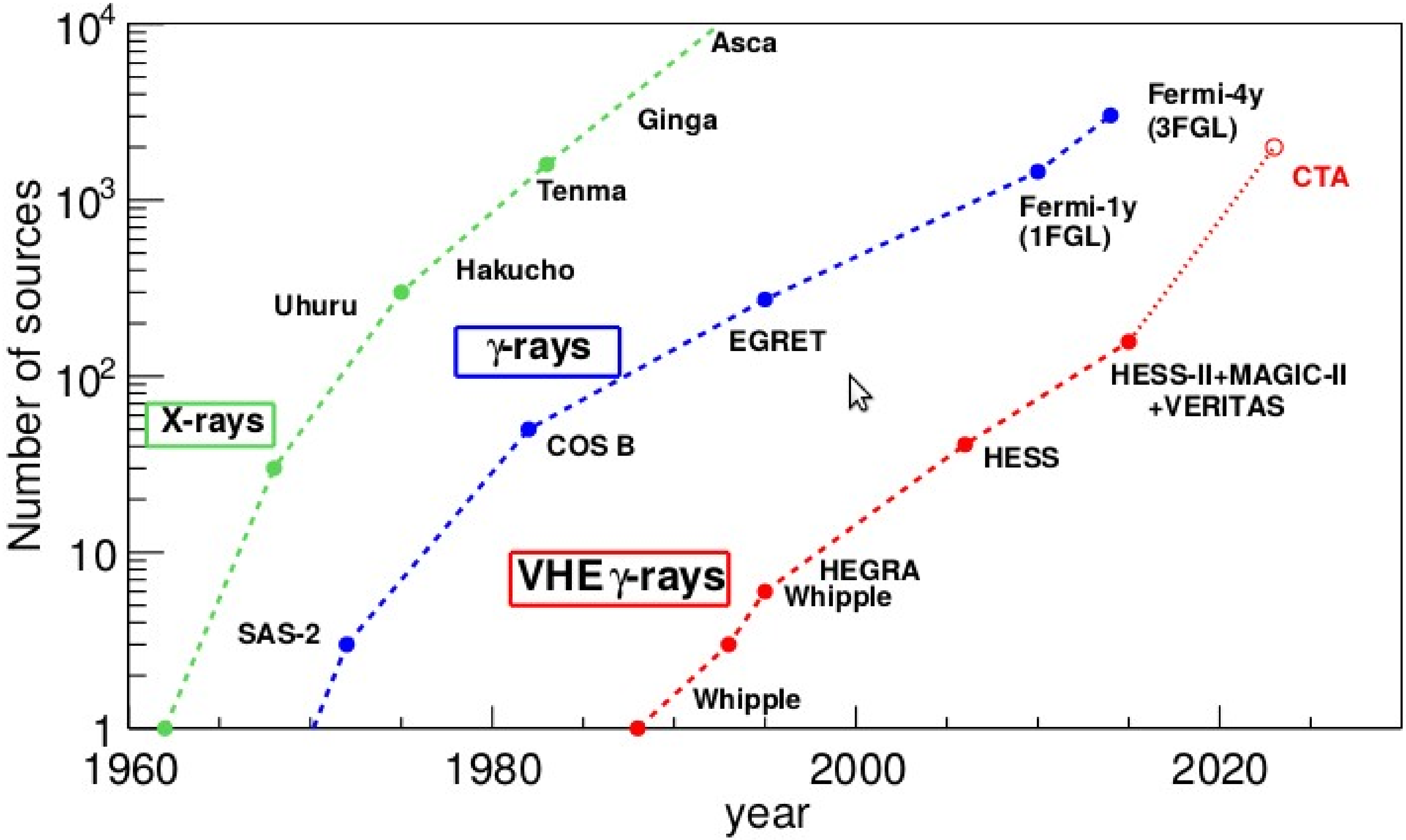
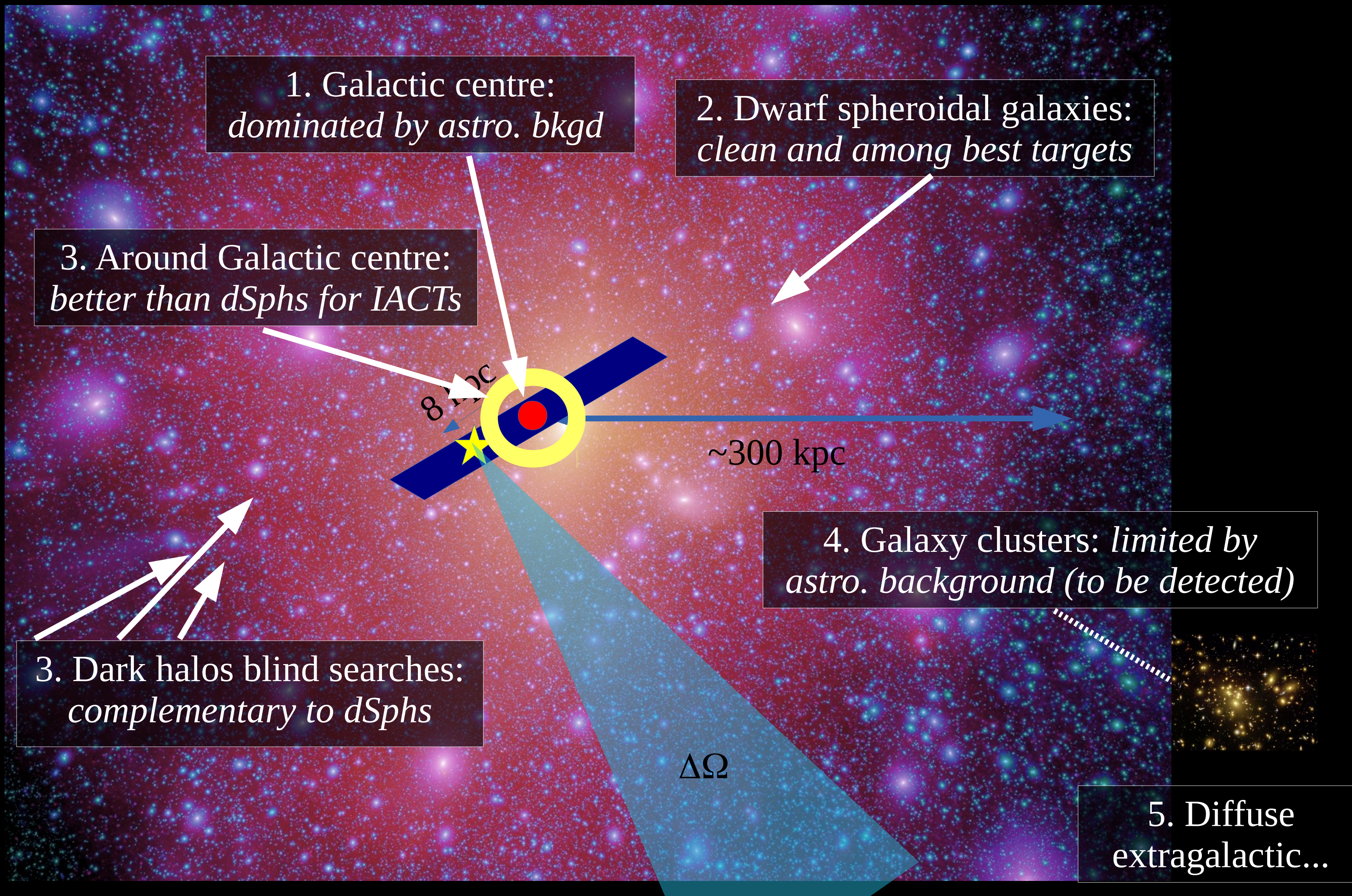
CTA: a bright (soon to be) future

De Naurois & Mazin, arXiv:1511.00463



→ Better energy coverage
→ Better angular resolution
…
→ Better sensitivity

Gamma-ray targets for DM indirect detection



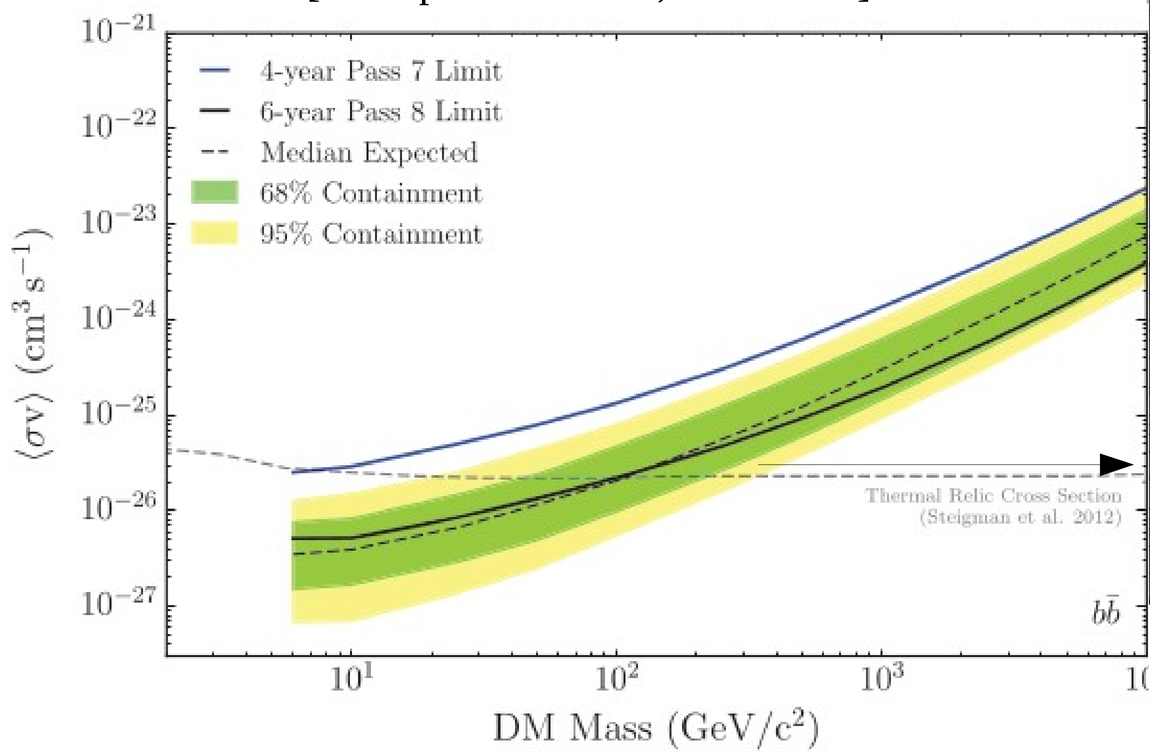
→ Fermi-LAT now probes very exciting <σv> regions of DM parameter space
→ CTA online in a couple of years can probe to higher masses
→ Possible improvements: (i) more data, (ii) more dSphs, (iii) cleverer analysis

Typical Fermi-LAT and (forecast) CTA exclusion plots

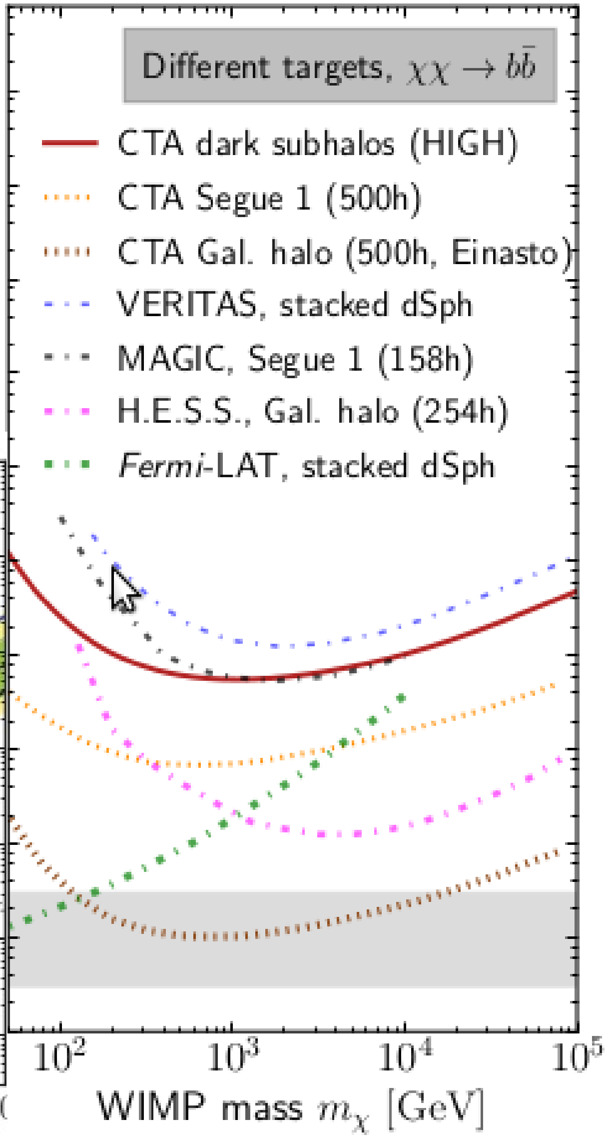
$$\langle\sigma_{\rm ann} v\rangle \propto m_\chi^2 \times J(\alpha_{\rm int}) \times \text{Sensitivity} \times \frac{dN^{pp}}{dE}$$

→ After ~30 years of effort,
WIMP dark matter may be within reach

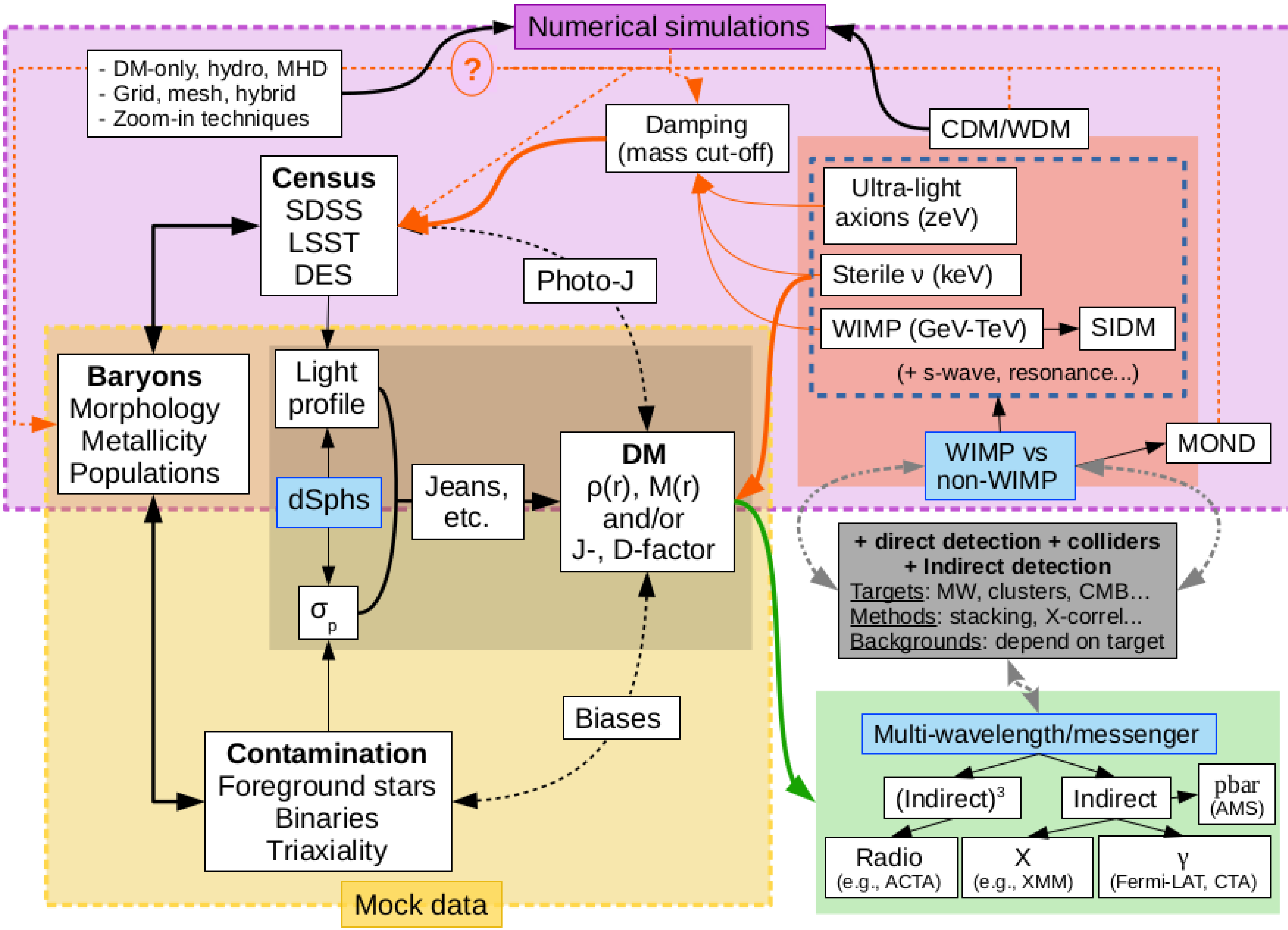
Ackermann et al. (2014, 2015)
[15 dSphs combined, 70 months]



Hütten et al. (2016)
[CTA prospects]



Even simple targets require complex approaches



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Primordial black holes with ‘HE physics’

B. Carr talk

“High”(Stellar)-mass PBH

$$10 - 100\ M_\odot$$

Mechanism: Gas accretion onto (P)BH*

Probes: Radio (GHz), X rays (keV)

Exp: VLA, Chandra, NuSTAR

Low-mass PBH

$$10^{-19} - 10^{-16}\ M_\odot$$

Mechanism: Emission of charged cosmic rays and photons at low energies via Hawking radiation*

Probes: Extragalactic gamma rays, electron/positron yields (sub-GeV)

Exp: EGRET, Voyager, AMS02, Fermi-LAT

* Complementary to CMB and other cosmological bounds

Small window to explain all DM?

A. Arbey

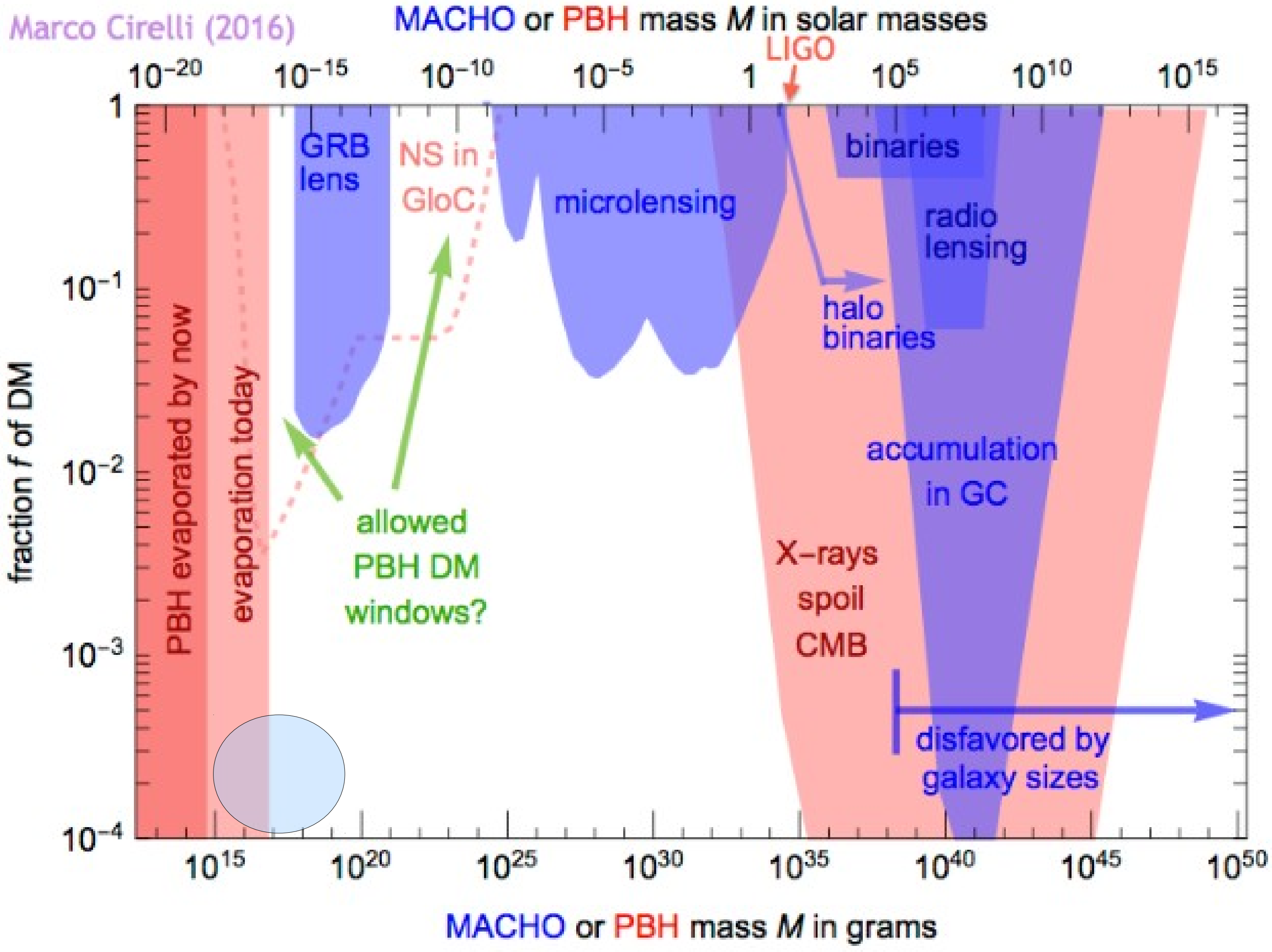
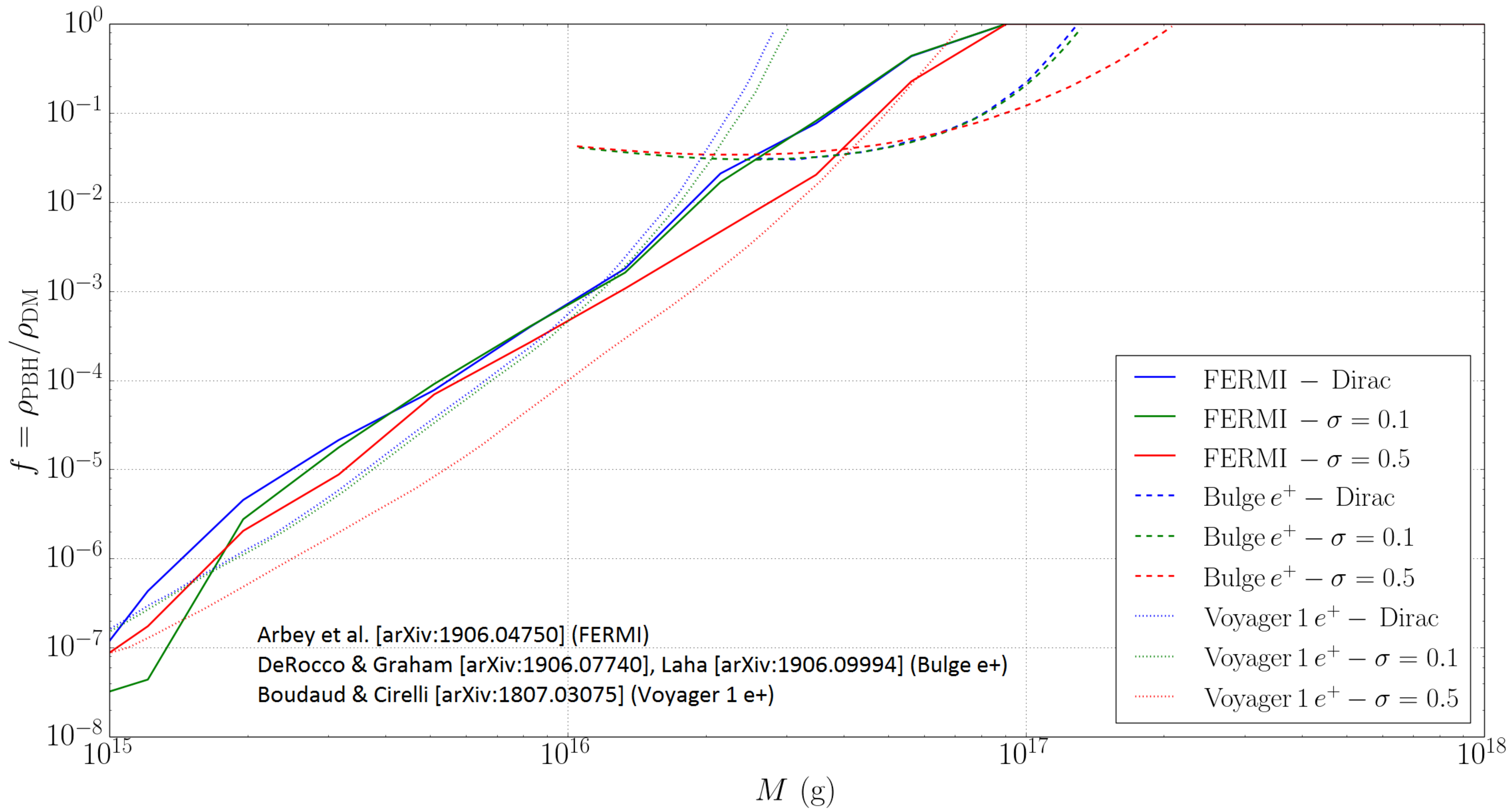


Figure: fraction of PBHs as dark matter, as a function of their mass. The colored regions correspond to different exclusions [2]. It was noted in [4] that PBH formation in clusters may strongly influence these constraints.

Best limits from CRs and gamma-rays

A. Arbey



Summary for PBH

→ From the proposal (more than DM indirect searches)
[my fault for only having this, probably more from A. Arbey in discussions]

[…] we propose that IN2P3 gets more strongly involved on studies and searches for black holes

1. GCRs
    - Introduction
    - Charged CRs
    - Challenges
    - Gamma rays (including CTA)

2. PBH

3. DM with LSST

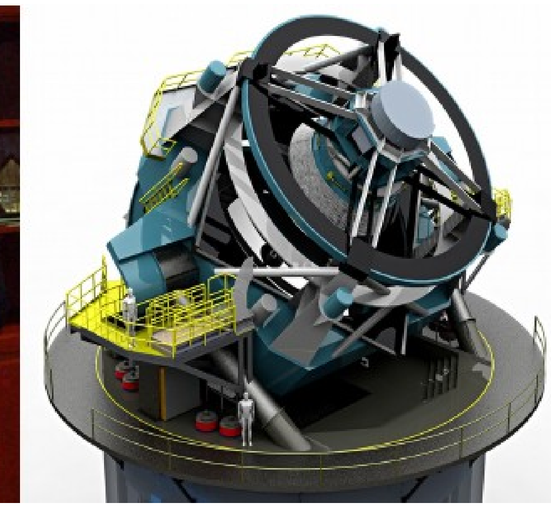
4. Conclusions

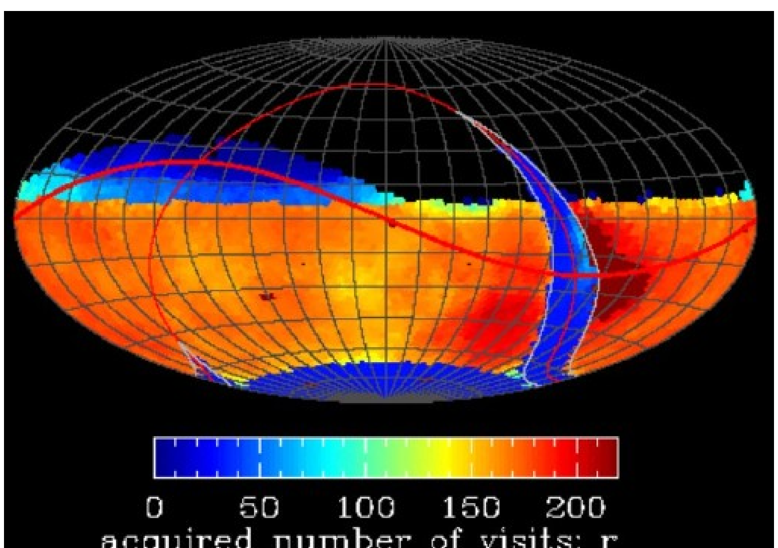
LSST basics

J. Cohen-Tanugi

A stage-IV survey

- 8.4(6.7)m telescope (Cerro Pachon, Chile)
- 3.2 Gpix camera 9.6°FOV
- 0.2’’ pixel/0.7’’seeing
- First Light 2020
  Survey 2022





A synoptic survey

- Southern sky (18000°) every 3 days
- ugrizy bands (r~24.4/visit)
- $\gtrsim$800 visits everywhere (all bands)
- Dynamic time range from sub-minute (hard to use in practice) to 10 years (survey duration)

LSST – technical contributions

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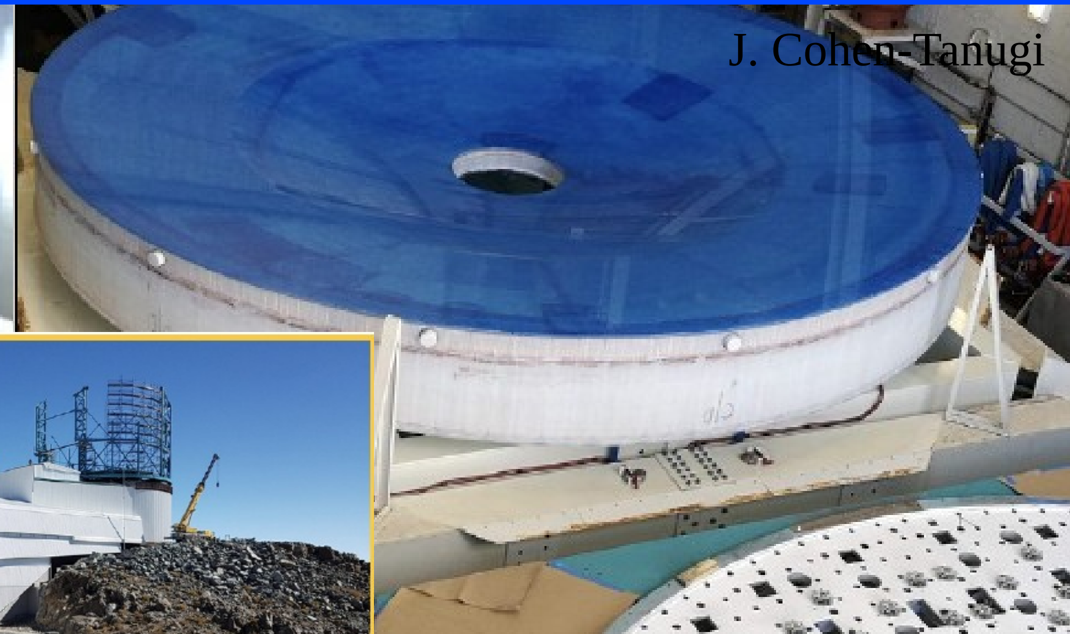
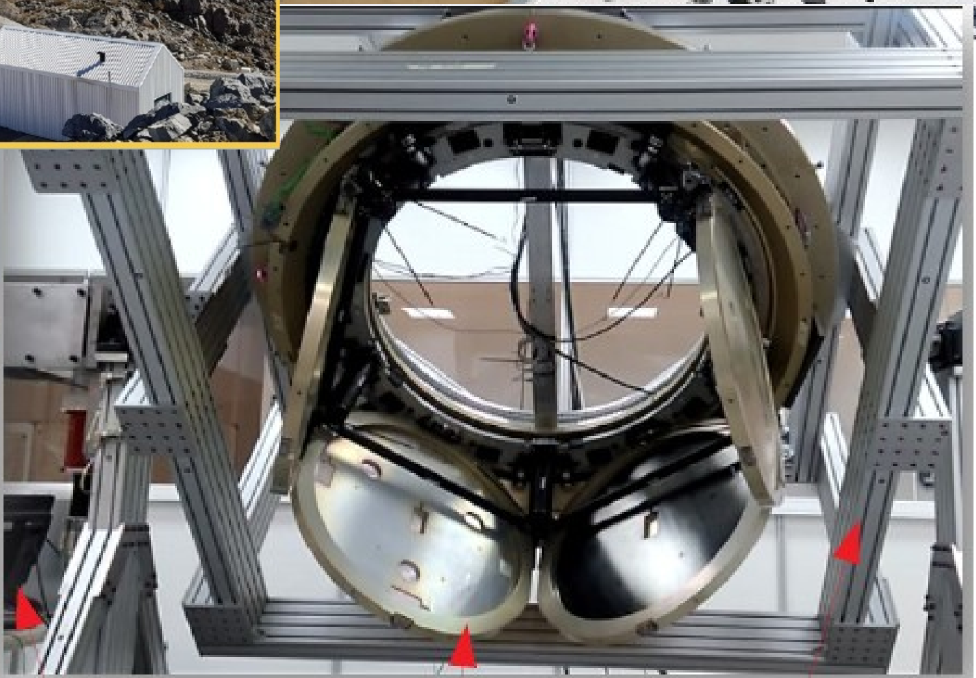


Filter Autochanger

Filter loader on transport cart



5 Filter capacity carousel

LSST – Data management system

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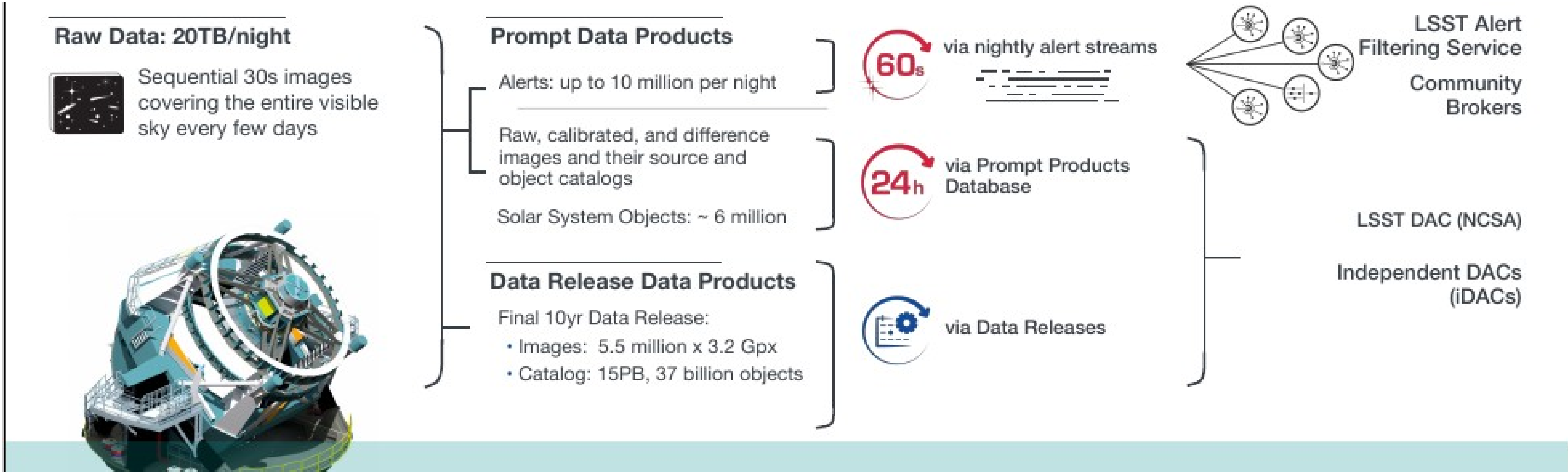

Data reduction, storage, management, and accessibility constitute a major challenge

Take away message : LSST is a telescope, a baseline cadence, and a computing framework for science!

Science collaborations in LSST

J. Cohen-Tanugi

Note : the LSST project is **not** in charge of science

- Galaxies
- Stars, Milky Way, and Local Volume
- Solar System
- Dark Energy (DESC)
- Active Galactic Nuclei
- Transients/variable stars
- Strong Lensing

https://www.lsstcorporation.org/science-collaborations for further details

Dark Matter interest rose up within DESC, but clearly concerns several other collaborations (actually Dark Energy as well)

Several Dark Energy probes actually also probe Dark Matter

Dark Matter is now in DESC!

Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope

arXiv:1902.01055

The following people have contributed to or endorsed the LSST dark matter science case as presented here:

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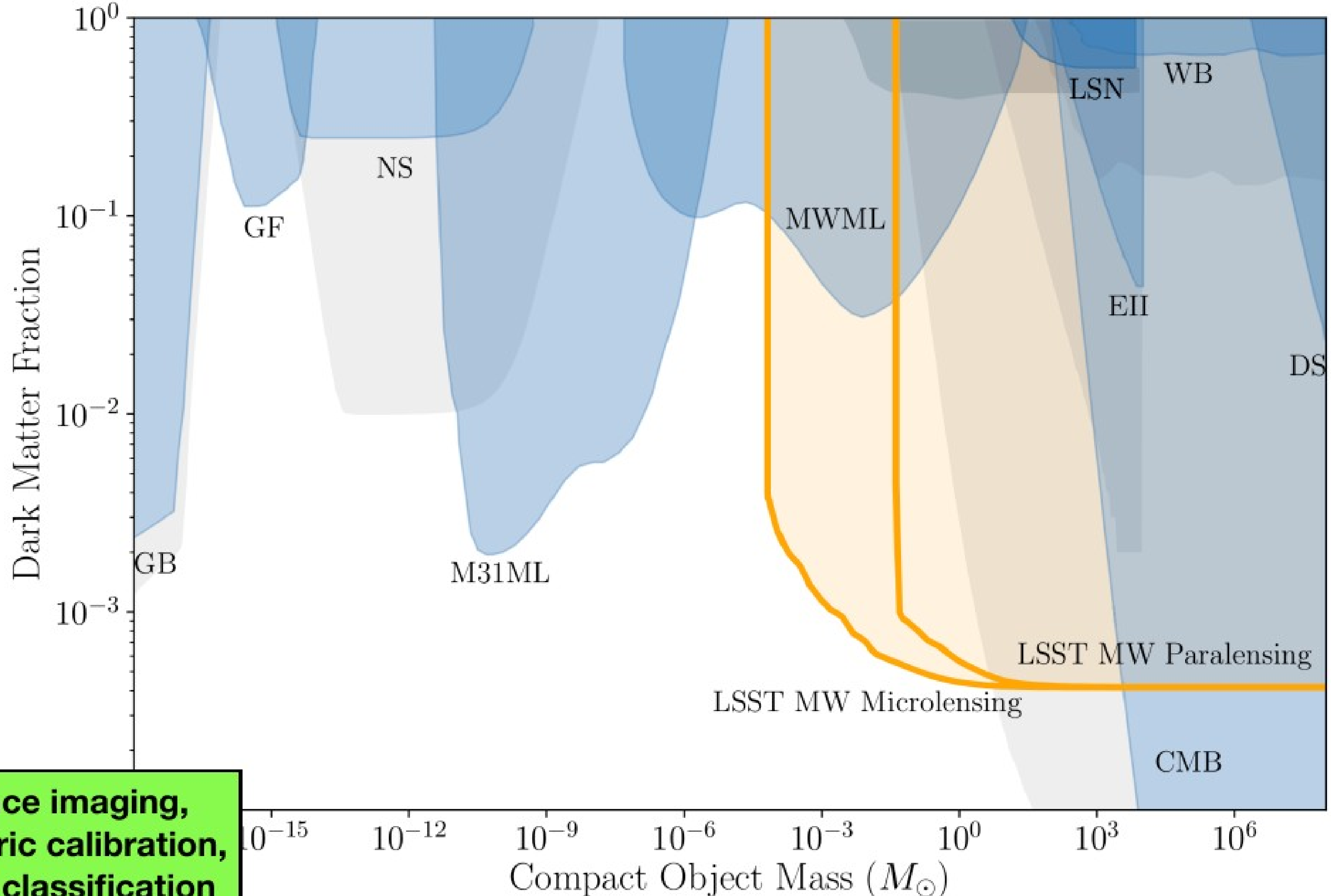
Dark Matter probes in the LSST sky

J. Cohen-Tanugi

- Minimum halo mass
  - Satellite galaxies
  - Stream gaps
  - strong lensing
- Halo profiles
  - dwarf galaxies as lenses
  - Galaxy clusters
- Compact object abundance
- Anomalous energy loss
- Large scale structure

Microlensing forecast with LSST



Difference imaging, photometric calibration, transient classification

Reach could be further extended with fast observing cadences in dense stellar fields

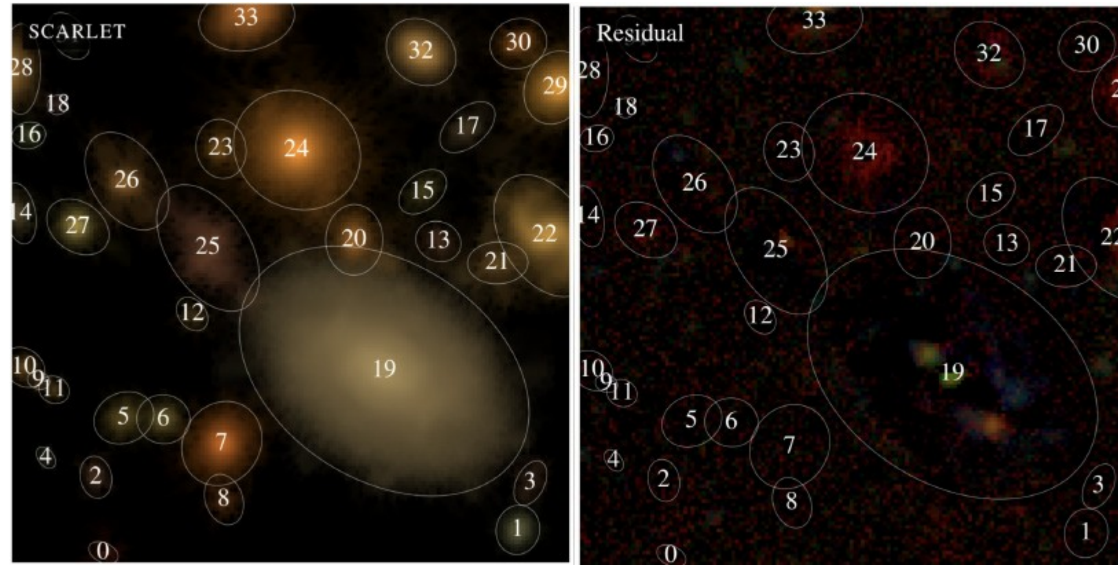
LSST and machine learning

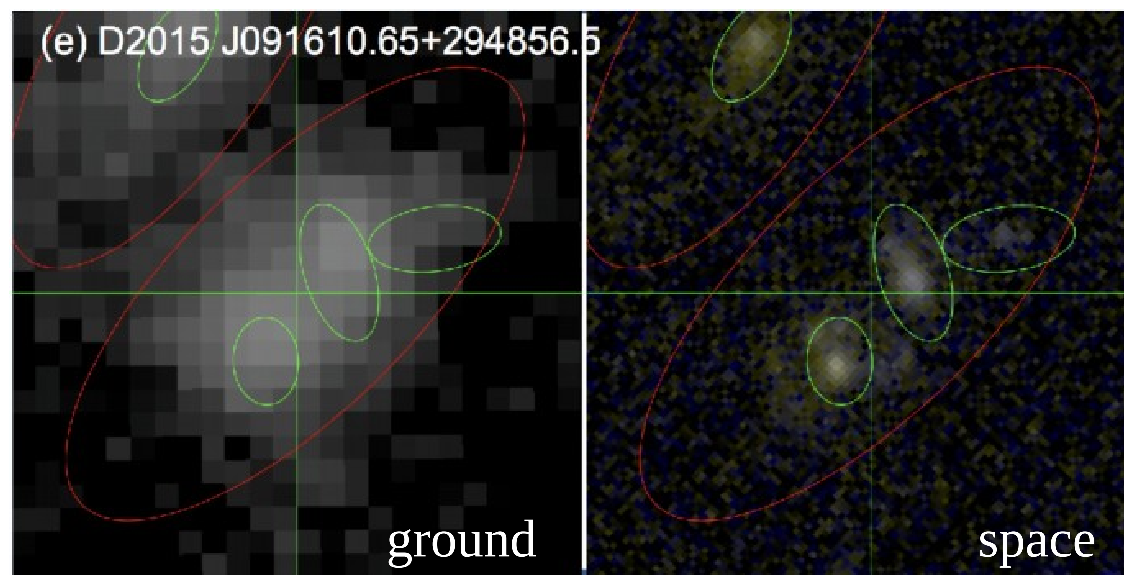
- There is a very basic level where ML is used in the context of LSST
  - Star/galaxy separation
  - Photometric classification
  - Photometric distance (photo-z) estimation
  - Deblending

→ At the bright end, this is easy : Gaia!

→ At the faint end, this is hard (small galaxy vs point-like source?)

Illustration of deblending





- SCARLET https://github.com/fred3m/scarlet is state-of-the-art non-ML alg around
- Neural Nets are closing in
- How to efficiently incorporate external observations when LSST dataset is already so large?

LSST conclusions/prospective

- LSST has a very rich potential for Dark Matter search
  - From stars to large scale structure
  - and from static to multi-timescale transient sky

- Dark Matter search needs Machine Learning to deal with larger and more complex/heterogeneous data
  - and clearly the low hanging fruit season is over….
  - Many areas are still ML-R&D !

Thus there is every reason to believe that LSST will open new avenues in utilising Machine Learning techniques for constraining Dark Matter nature

But this has not (yet?) been concretely investigated, so let’s get started!

1. GCRs
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    - Challenges
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General conclusions / perspectives

Evolution in the last 20 years

1) For all astro-particles and DM studies, evolution from ‘single messenger’ to
   - Multi-wavelength
   - Multi-messenger
   - … and now multi-probe

2) All projects, for best scientific return, always involve
   - Multi-scale physics
   - Inter-disciplinary (astro/particle/nuclear/plasma physics)
   - Inter-institute (IN2P3/INP/INSU...)

3) At any level (data analysis, modelling, interpretation)
   - Heavy numerical simulations (GCRs and DM)
   - Machine learning

So what?

→ No single institute has all the manpower/competences
→ Many excellent student who could lead the field in 5 yrs do not fit in the ‘institute’ boxes

Possibilities

→ GDR ‘dark matter’?
→ CNRS interdisciplinary committee?