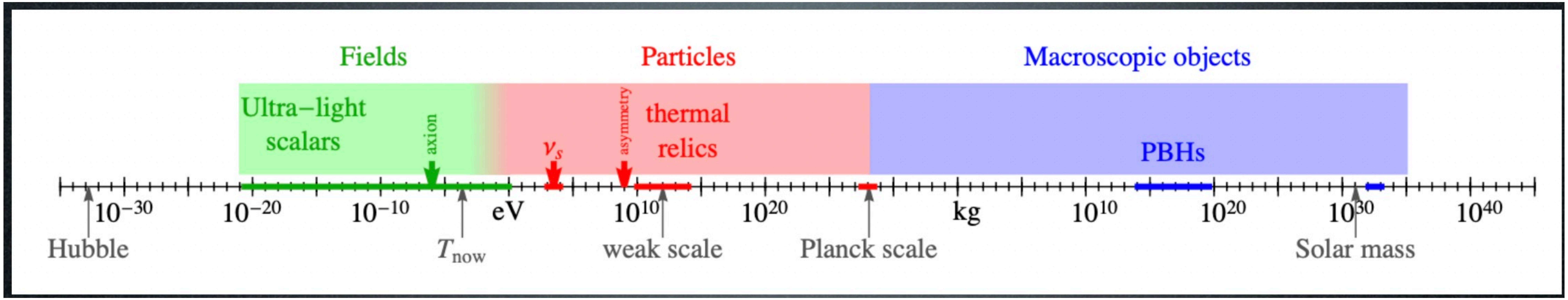
Indirect Detection of Dark Matter

Quick status and personal thoughts

Bryan Zaldívar, Valencia (IFIC)

Dark matter: theoretical possibilities

Cirelli, Strumia, Zupan, 2004



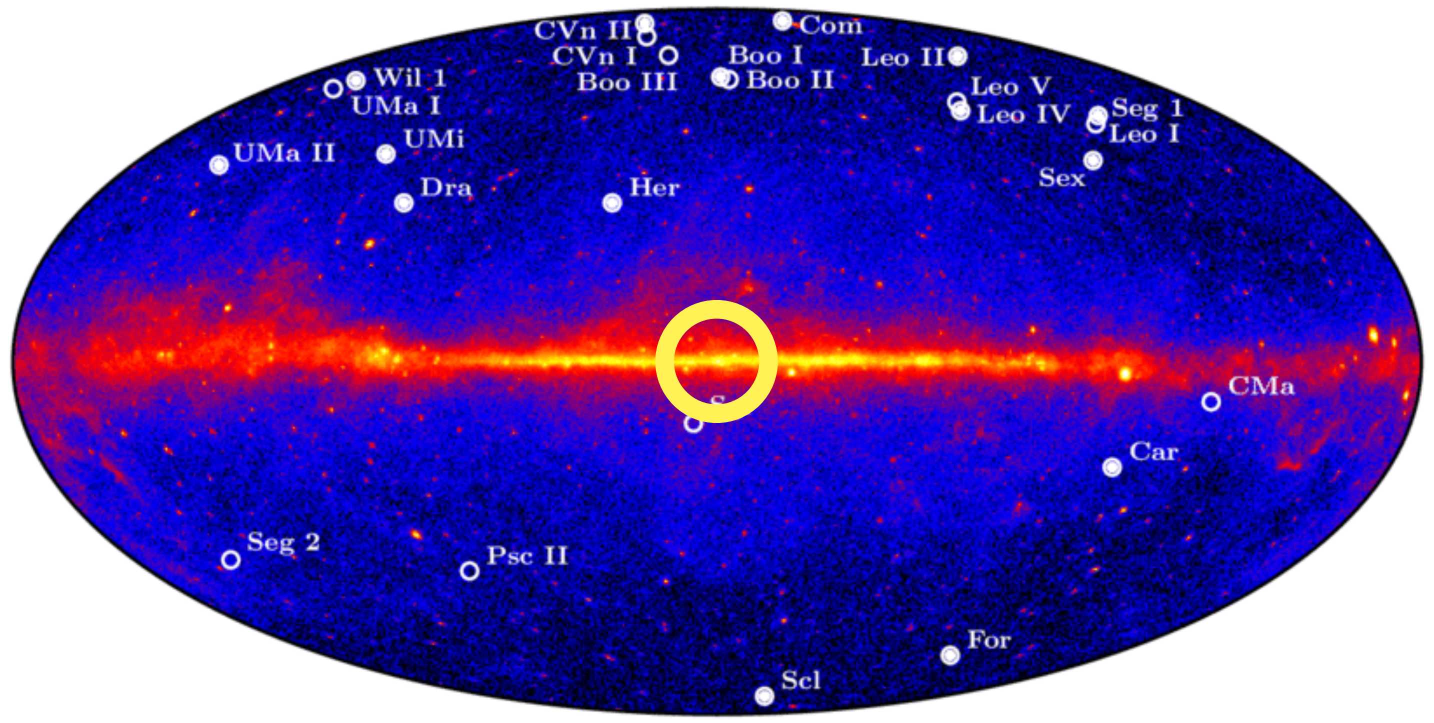
Mass range spanning ~90 orders of magnitude

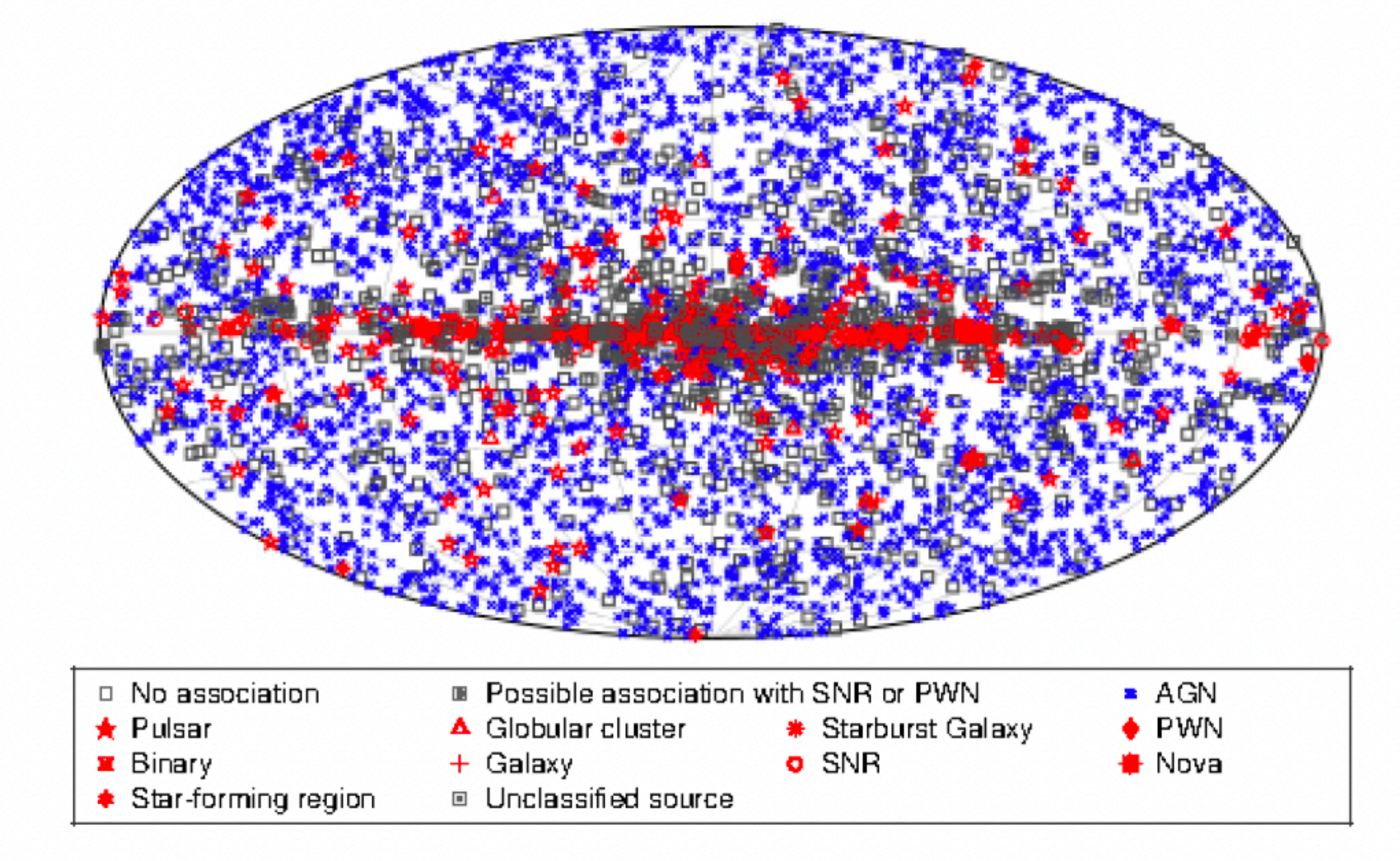
A whole zoo of DM candidate types

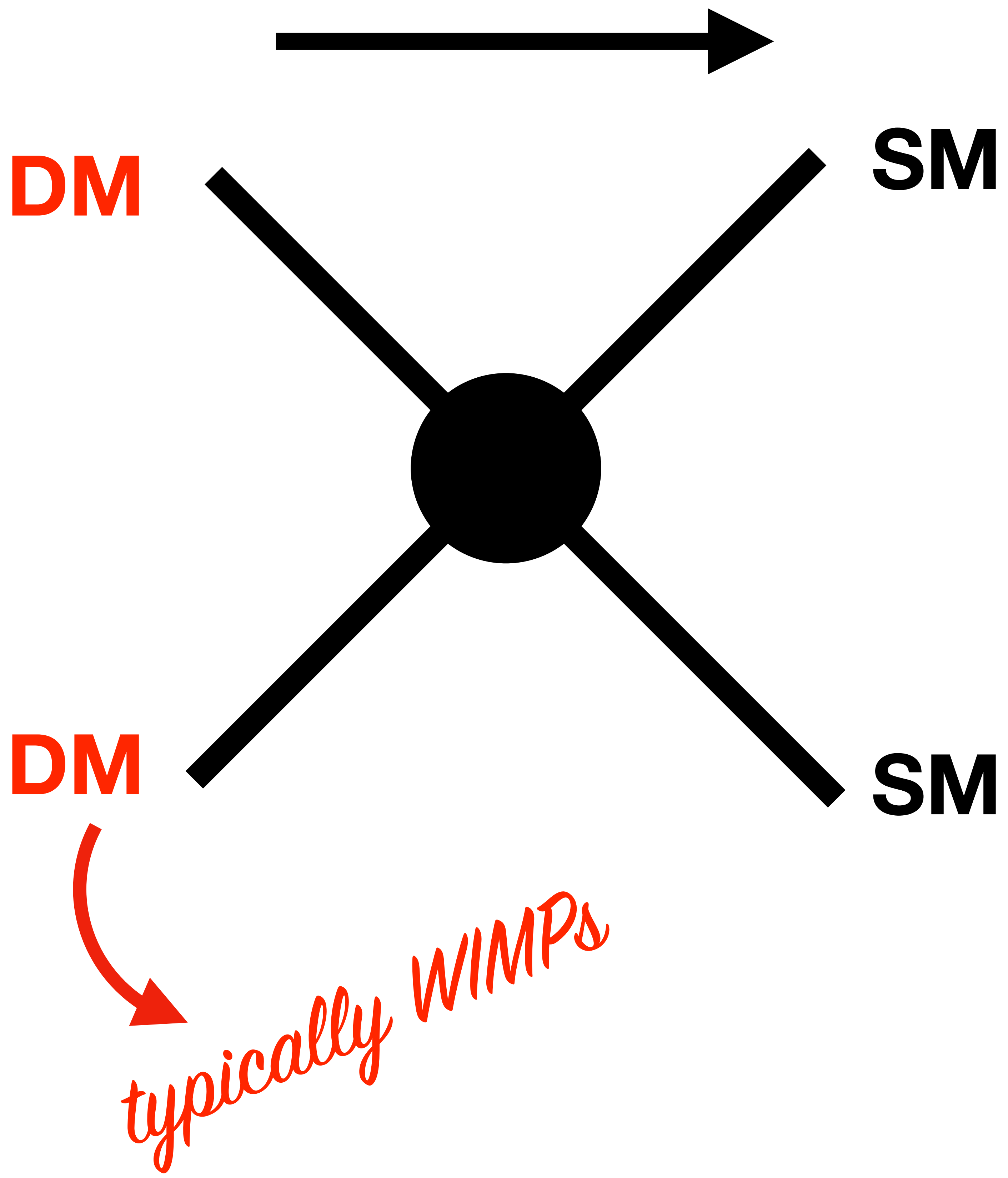
Candidate	Date	Reference(s)
Primordial BH	1966, 1971	Zeldovich & Novikov, Hawking [86]
MACHOs	1981, 1986	Petrou; Paczynski [83]
Gravitinos	1981, 1982	Fayet; Witten; Pagel & Primack [100]
Axions	1983	Preskill, Wise & Wilczek [101]
Neutralinos	1984	Ellis et al. [102]
Strangelets	1984	Witten; Fahri & Jaffe [103]
Q-balls	1984	Witten [104]
Extra-dimensional DM	1984	Kolb & Slansky; Servant & Tait [105]
WIMPs	1985	Steigman & Turner [106]
Sterile neutrinos	1993	Dodelson & Widrow [107]
Fuzzy DM	2000	Hu, Barkana & Gruzinov [108]
Sub-GeV DM	2003	Boehm, Fayet et al. [109]

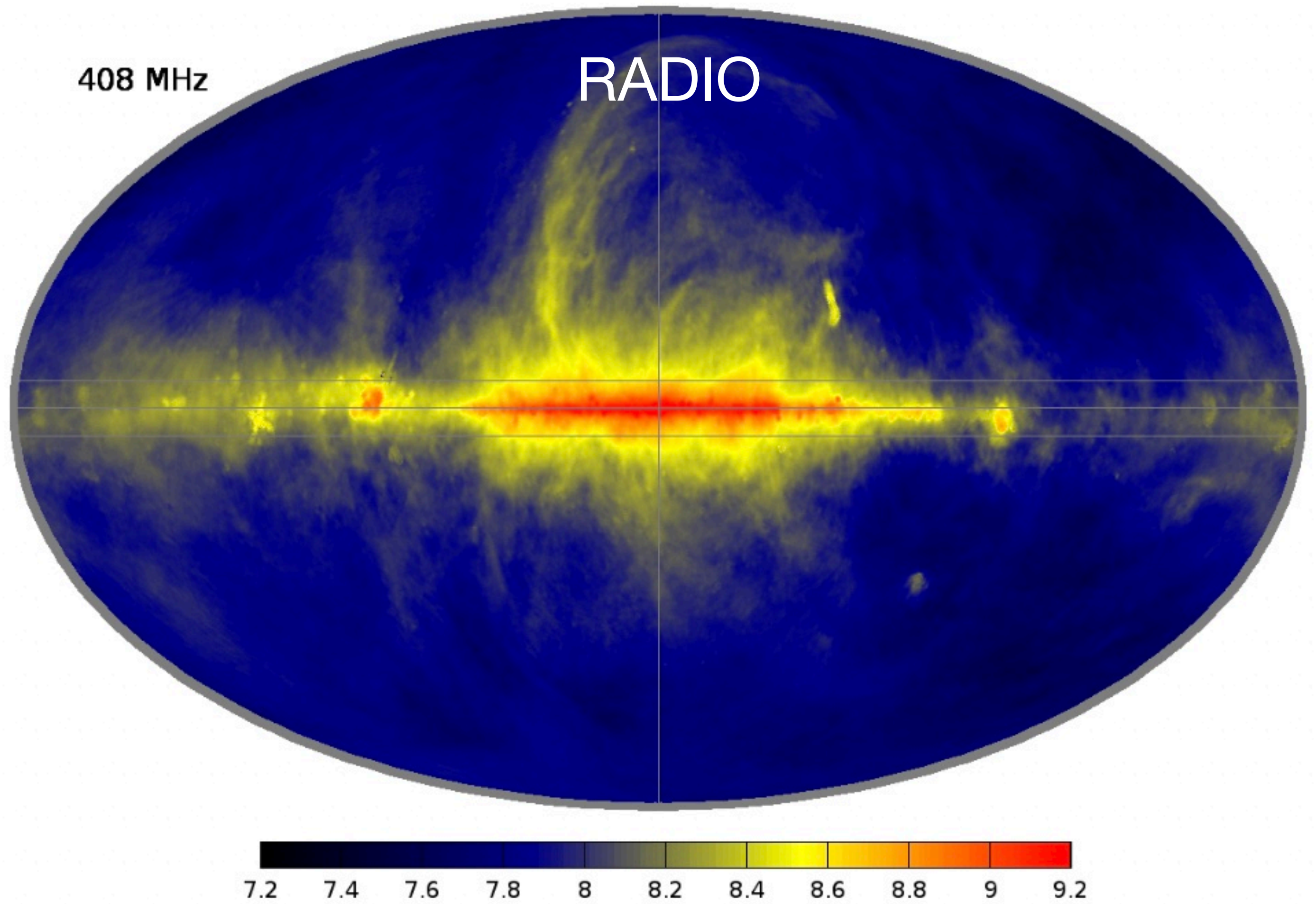
The idea of Indirect Detection

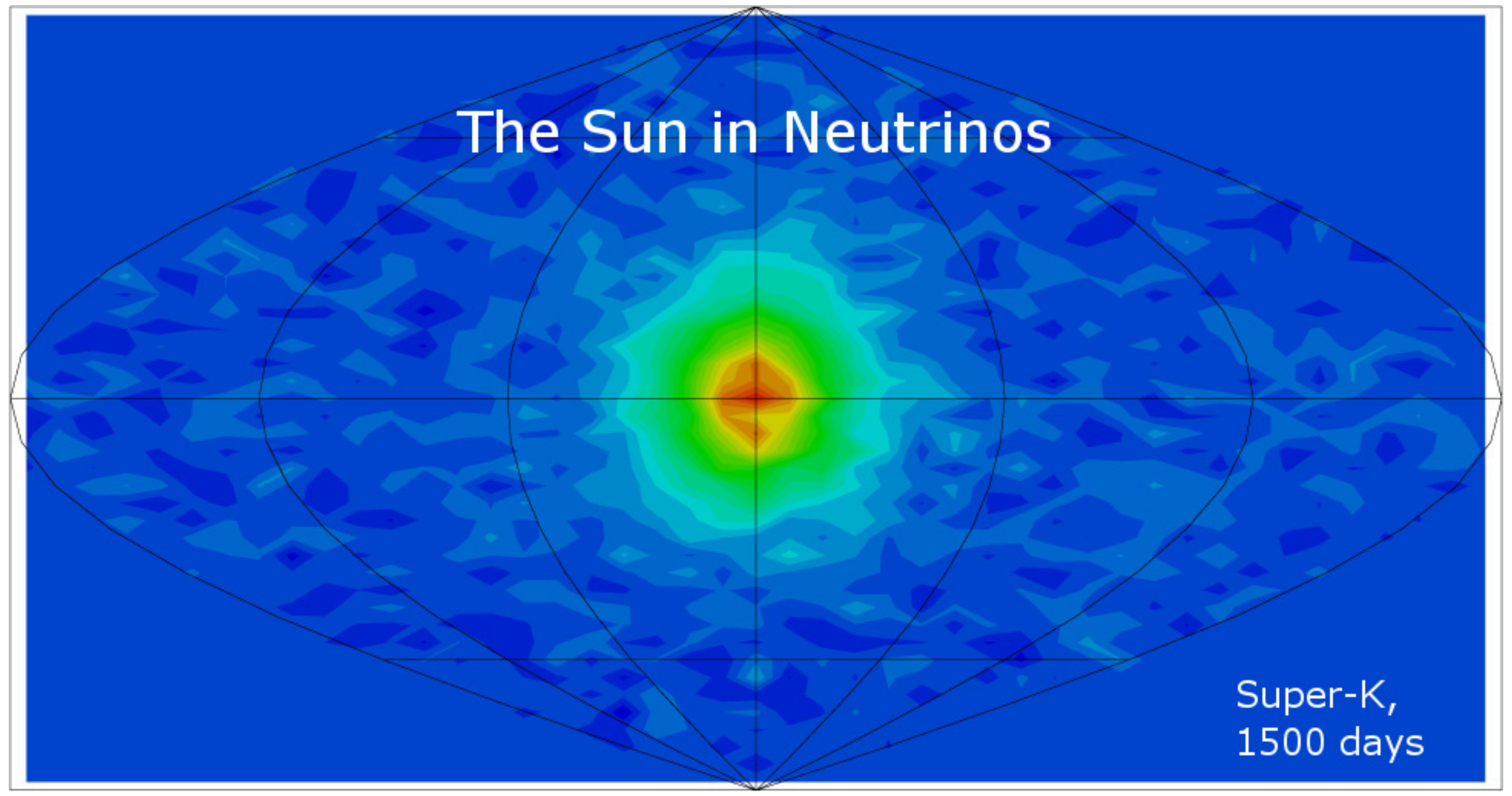
Search for anomalous astrophysical emission from DM











Search channels and (some) experiments

Radio

HASLAM
LOFAR
HERA
EDGES
ANITA
SKA

Microw.

AXDM
QUAX

PLANCK
CMB-S4 ?
Simons Obs.

IR, Optical, UV

LORRI
JWST
Hubble
Gaia
Euclid

X-ray

CHANDRA
XMM-Newton
INTEGRAL
SWIFT
NUSTAR
XHTM
MICRO-X
EROSITA
XRISM
ATHENA

γ-ray

INTEGRAL
HESS
VERITAS
MAGIC
FERMI
TAIGA
HAWC
COSI-SPB
MACE
EROSITA
LHAASO
CTA
ADEPT
GAMMA-400
AMEGO
APT

Ch. CR

AMS-02
CALET
DAMPE
ISS-CREAM
LHAASO
HERD
ALADINO
AMS-100

Neutrino

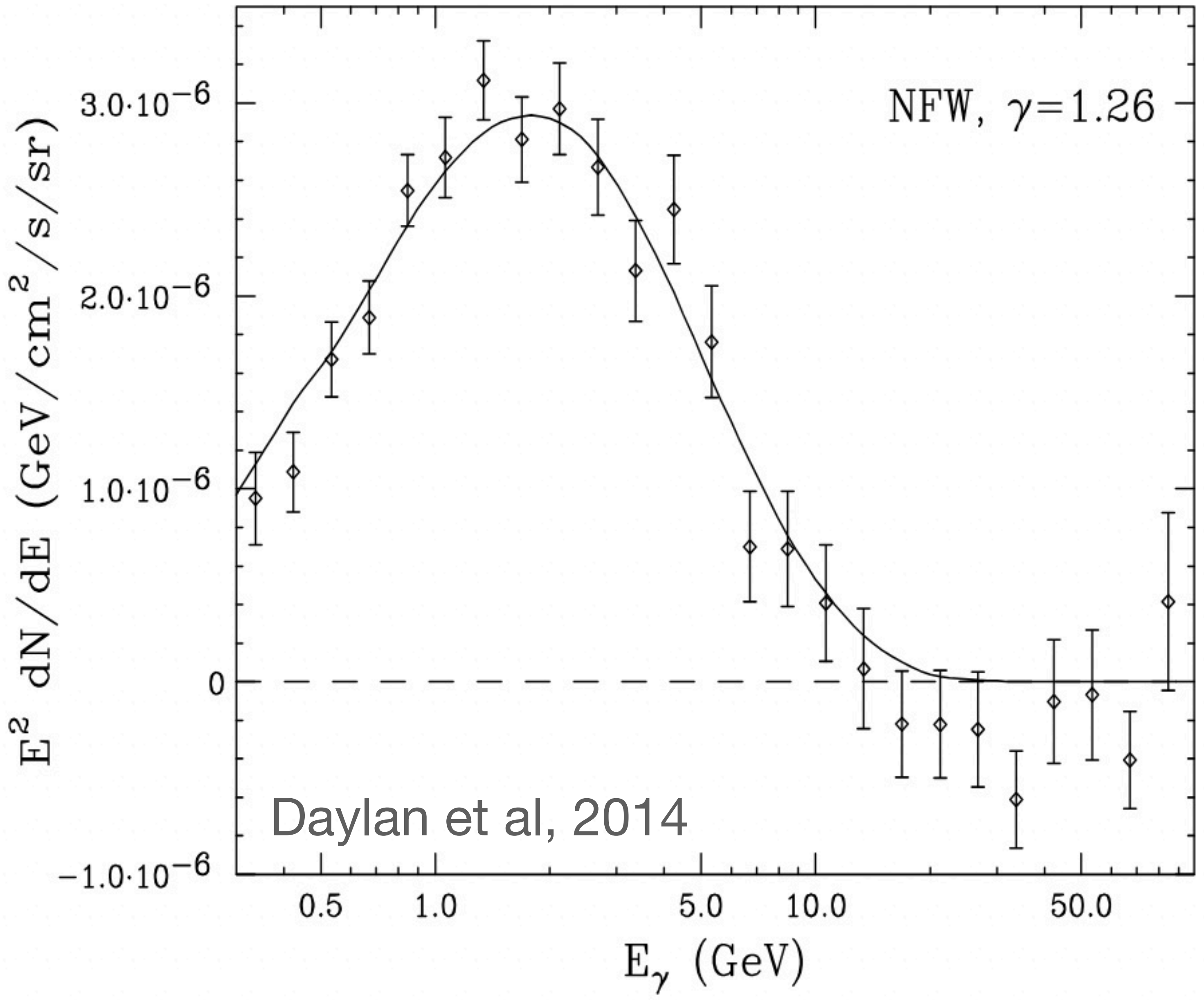
SUPER-K
ICECUBE
ANITA
KM3NET
DUNE
HYPER-K

Surviving hints?

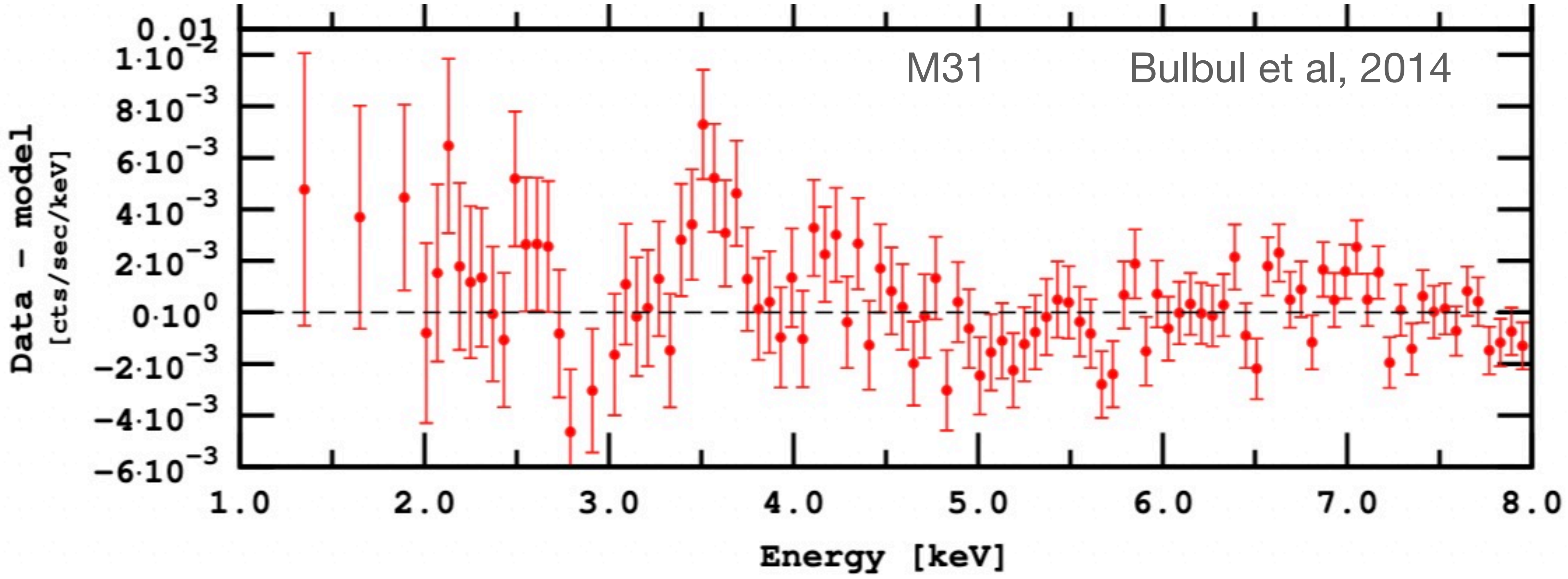
COB and CIB excesses
LORRI (2022), CIBER (2017)

γ-ray line at 511 keV
Since ~70's, now INTEGRAL, COSI (2020) — Galactic Centre

"Galactic Centre Excess"
FERMI-LAT, since 2009



X-ray line at 3.55 keV
XMM-NEWTON, CHANDRA, 2014



Anti-proton excess
AMS-02 (2015), ~ 80GeV DM hypothesis

Electron-positron excess
DAMPE (2017), ~1TeV DM hypothesis

ANITA anomaly
2018, 2020, O(EeV) DM hypothesis

21cm anomaly
EDGES, 2018

So far…no conclusive evidence

Why?

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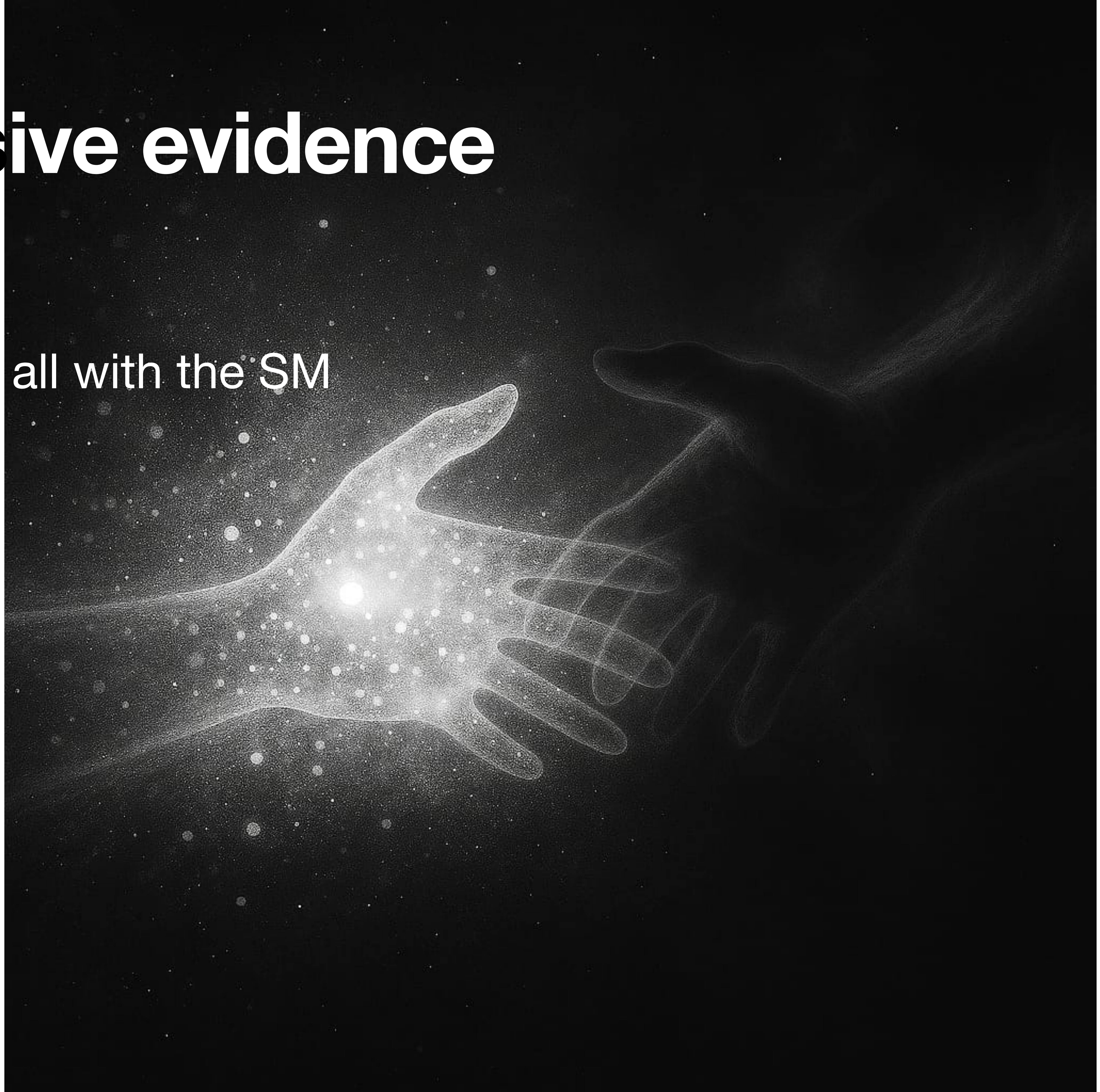

- Dark matter does not interact at all with the SM

So far…no conclusive evidence
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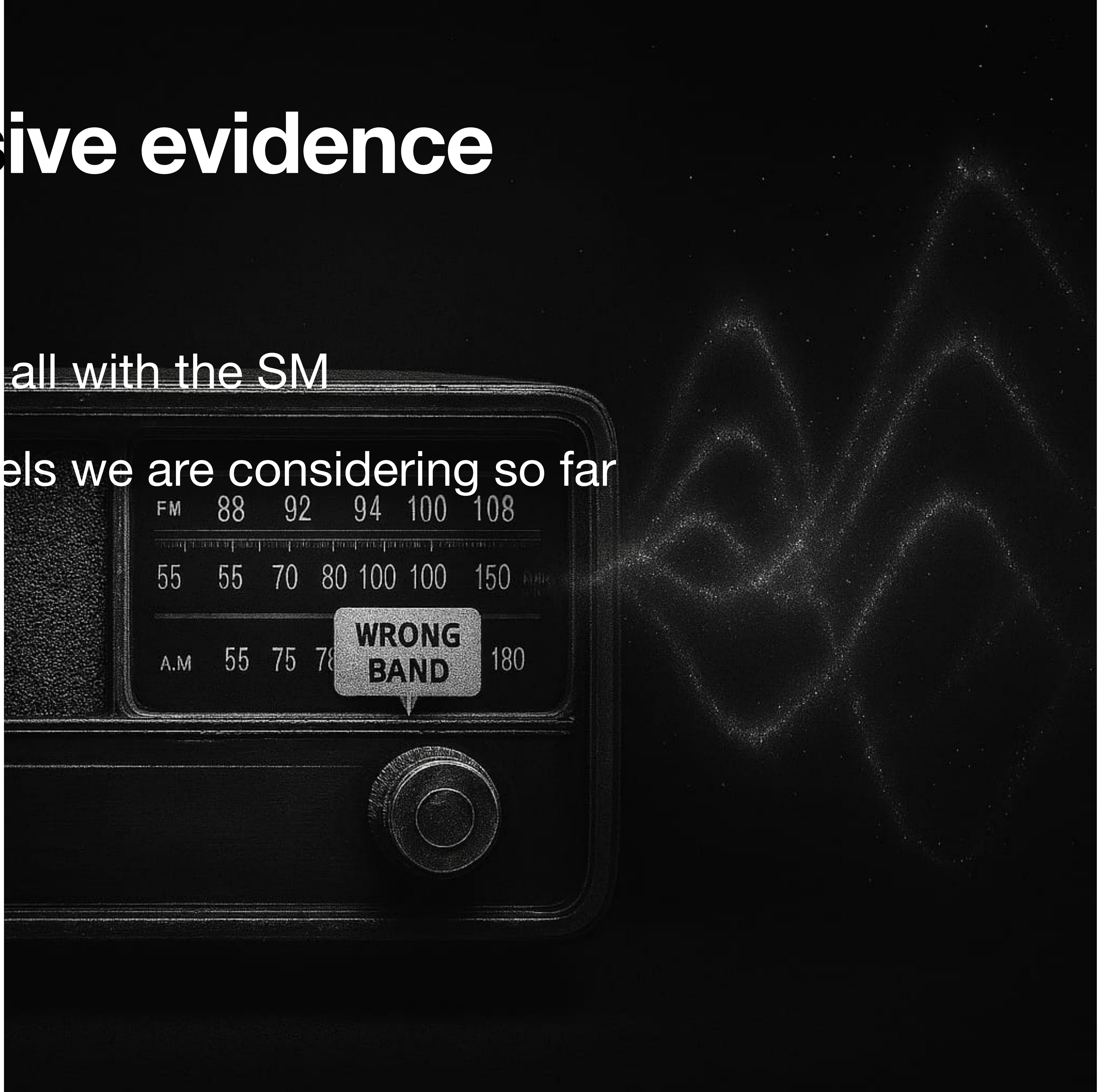
- It interacts, but not in the channels we are considering so far



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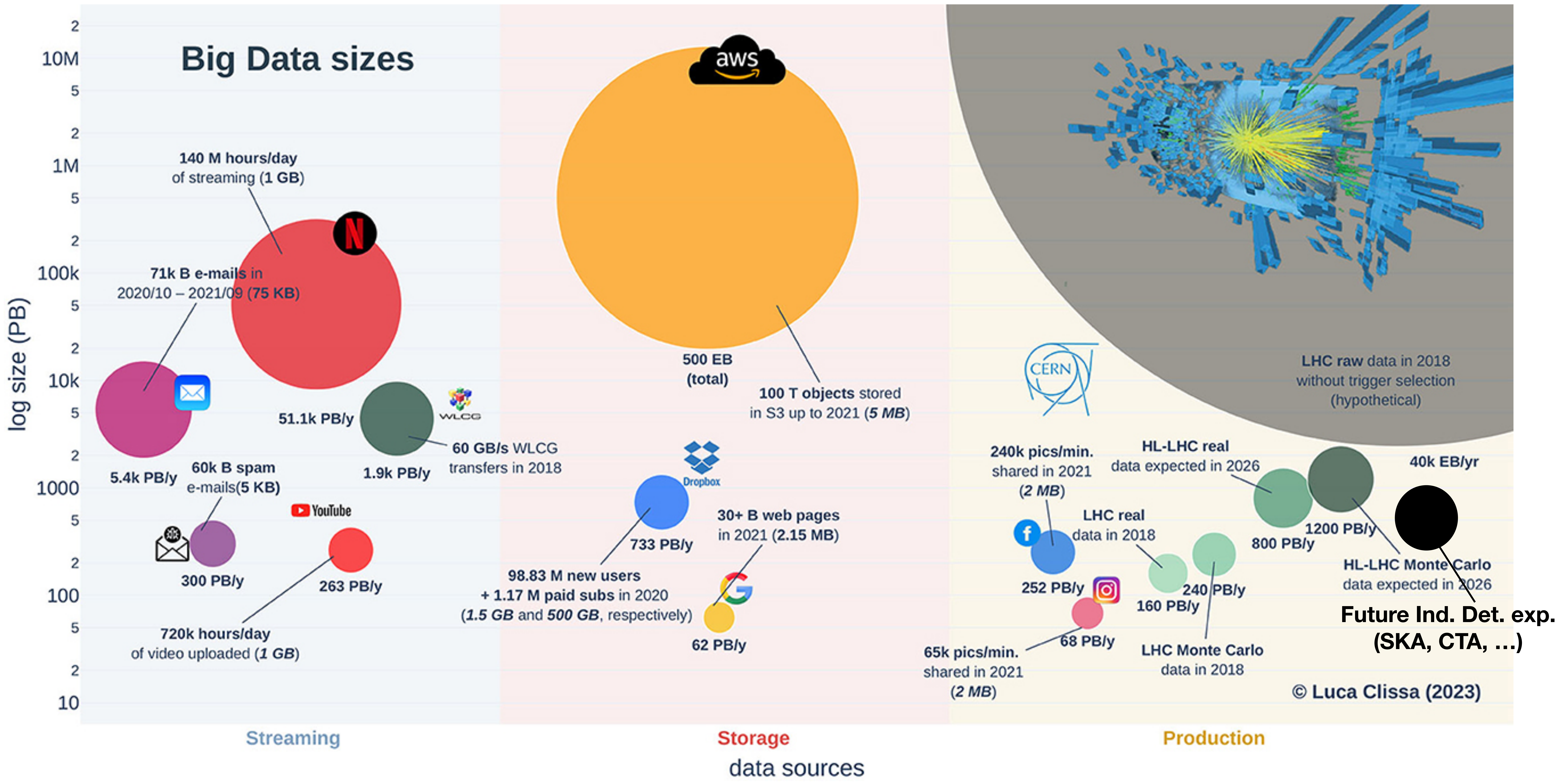
Why?

- Dark matter does not interact at all with the SM
- It interacts, but not in the channels we are considering so far
- It interacts, but too weakly (still out of experimental reach)
- **It interacts, but our limited background knowledge is a stopper**

Data, data, and more data…

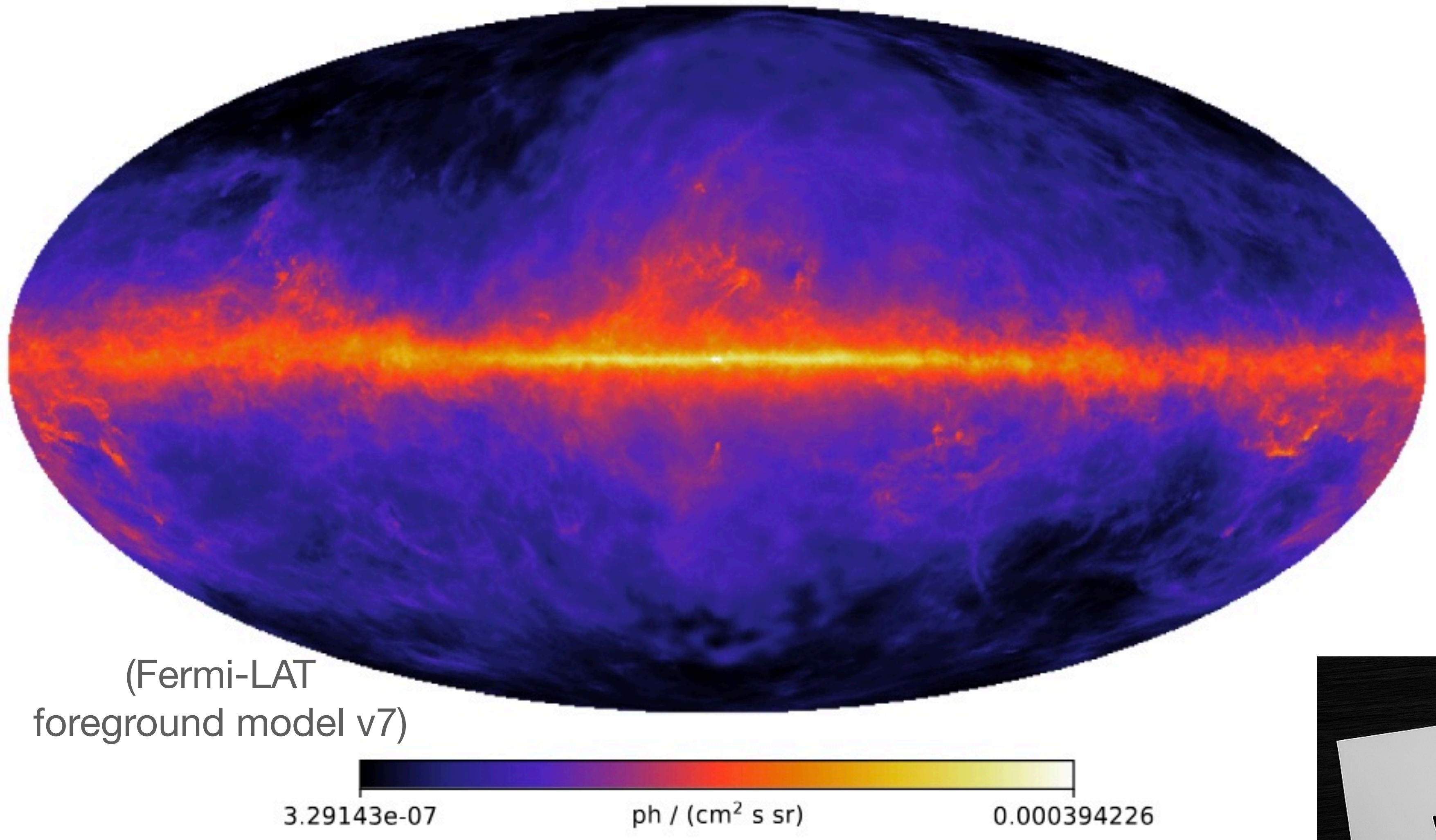


... requires better inference methods

(Marenostrum 5)

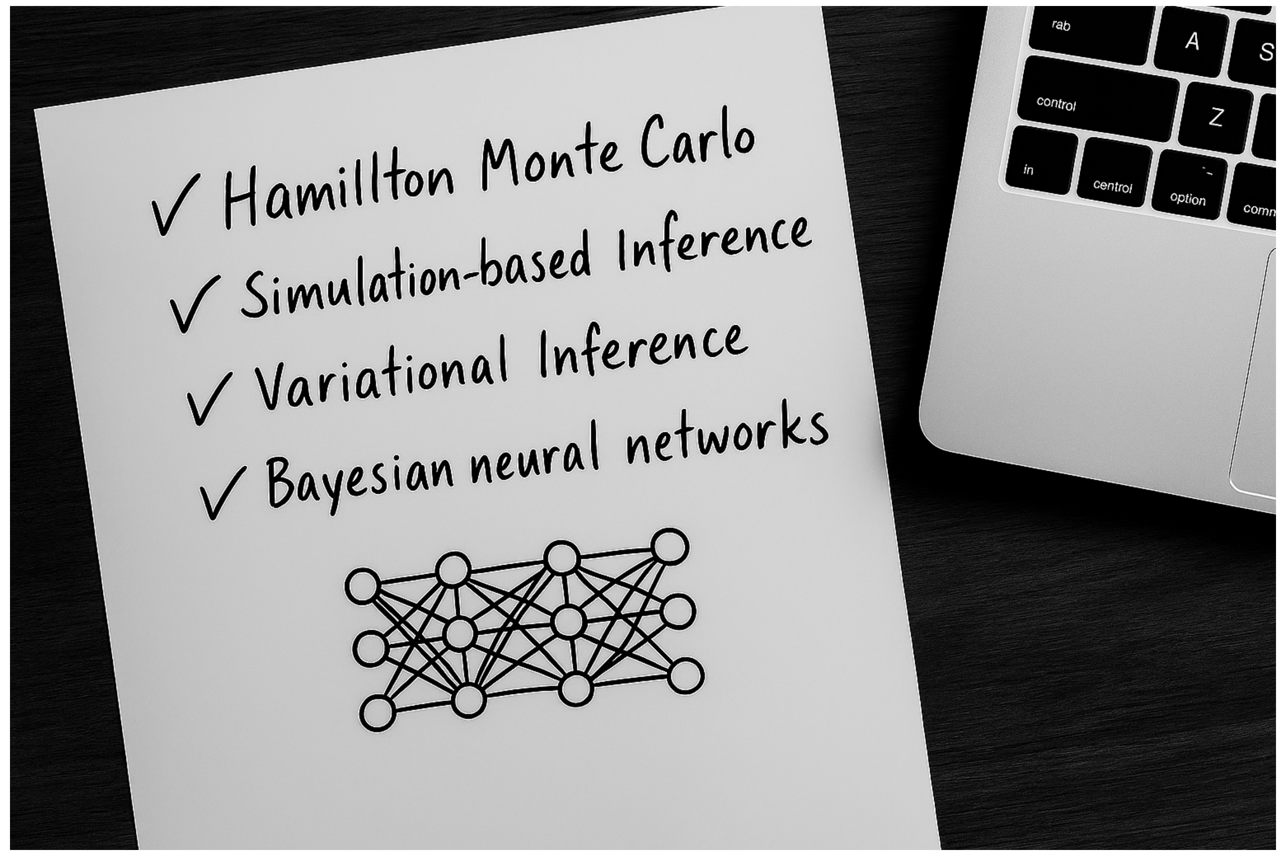
More data

Better simulations



(Fermi-LAT
foreground model v7)

More sophisticated
stats and tools



JAX

pypi package 0.25.0 | conda-forge v0.25.0 | contributions welcome
license Apache-2.0 | JOSS 10.21105/joss.07754 | NumFOCUS affiliated

sbi: Simulation-Based Inference

Swyft

Statistical treatment

Improvement — statistics vs systematics

- Build facilities with smaller instrumental noise (stats)
- Improve the background treatment (syst)

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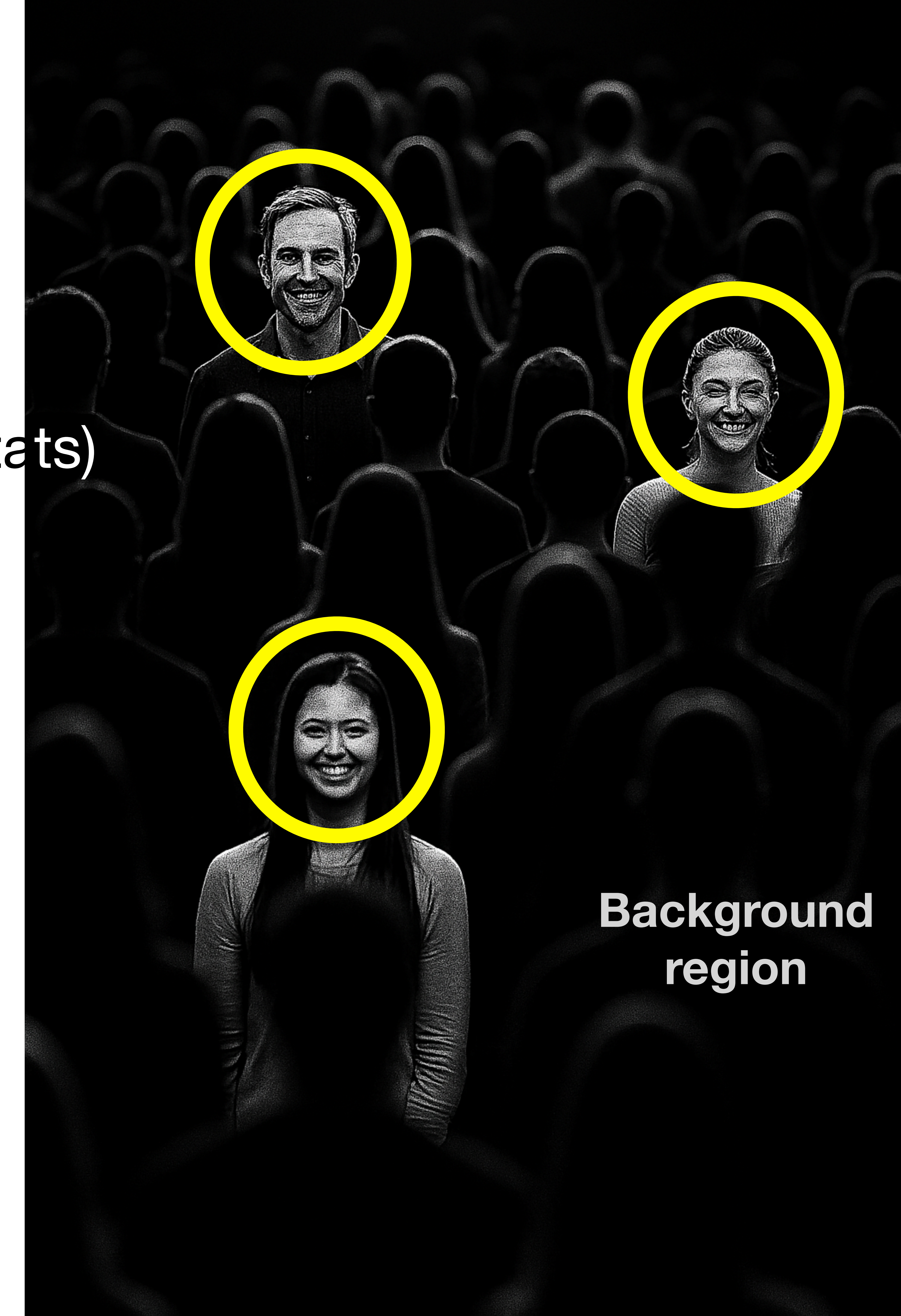
Take background as **nuisance**, and adopt data-driven methods

Signal region: Physics of interest

Background region: fitting data with convenient mathematical functions and methods



Improve background treatment

Some data-driven studies (incomplete list & of course biased)

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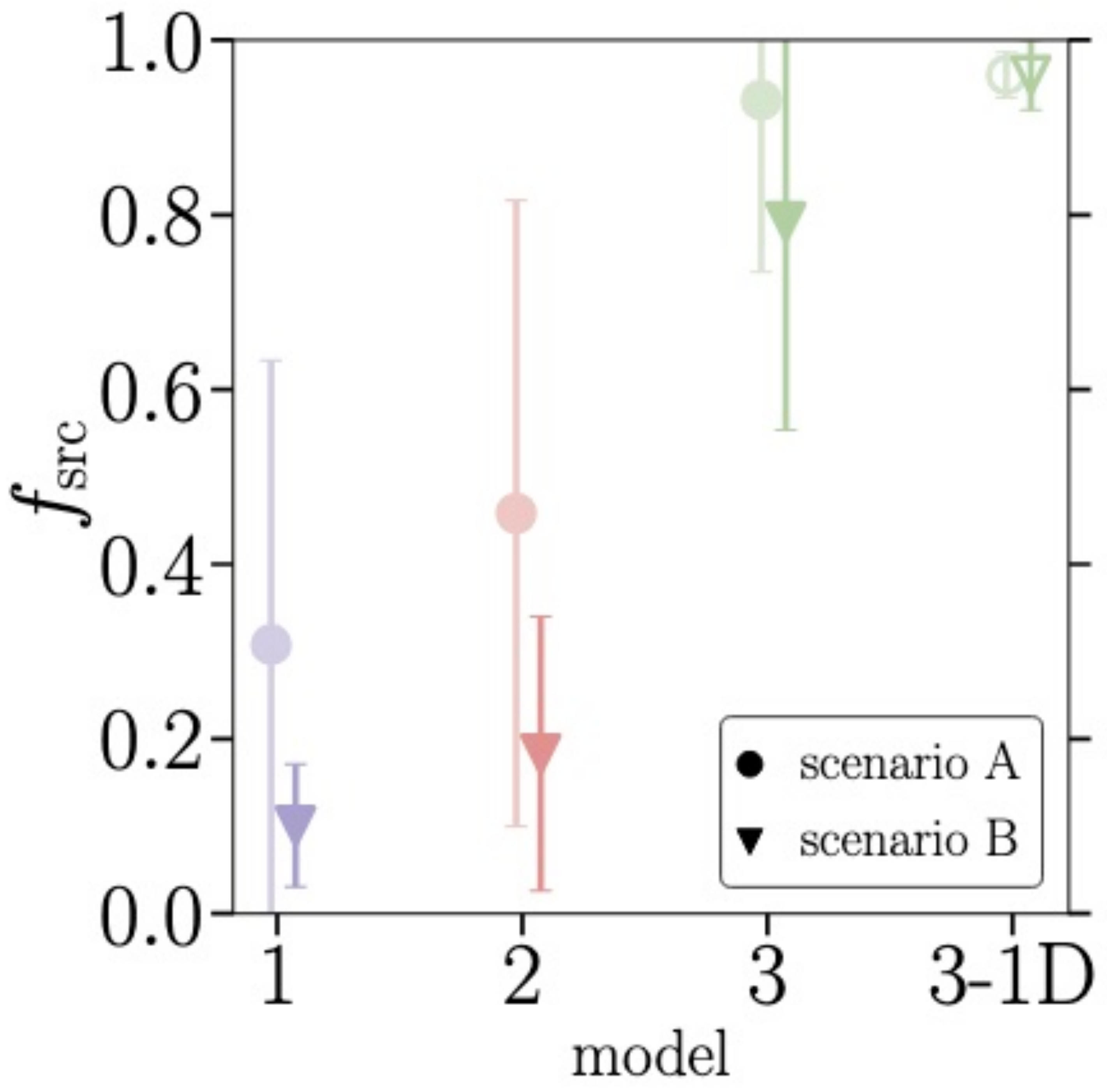
- Galactic Centre Excess problem (DM vs pulsars)

Caron et al, 2018 — *JCAP* 05 (2018) 058
Caron et al, 2023 — *JCAP* 06 (2023) 013

Prediction of the fraction of the GCE due to pulsars, based on fitted simulations of the gamma-ray emission



- Allows for direct estimation from low-level inputs (images in practice)
- Exploits full simulations (instead of summaries)
- Makes explicit the impact of simulation setups
- More robust conclusions (GCE probably due to MSP, indeed…)

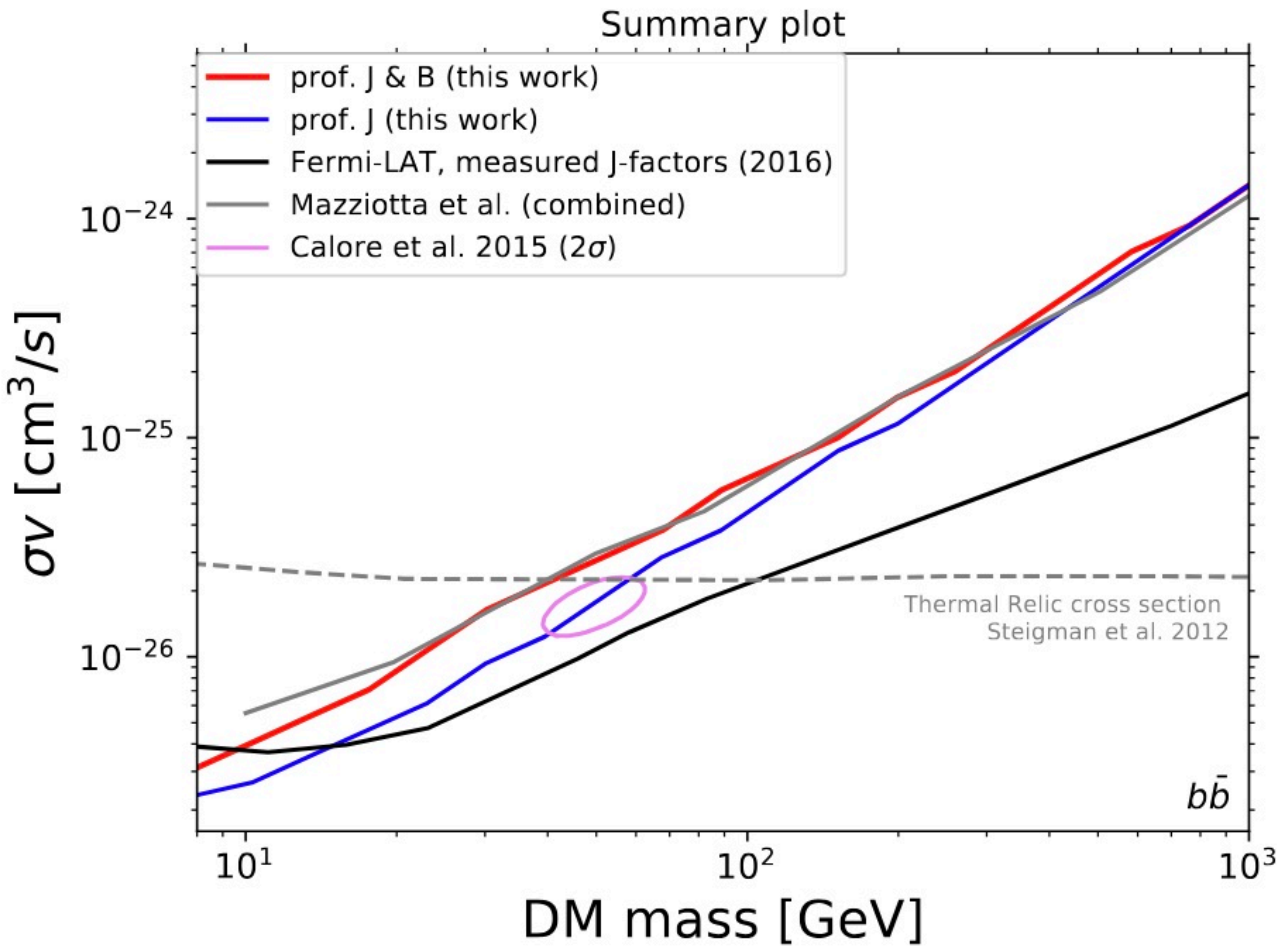
Improve background treatment

Some data-driven studies (incomplete list & of course biased)

- Searching for DM from Fermi-LAT sources (either dSphs or unIDs)

Calore, Serpico, **BZ**, 2018 — *JCAP* 10 (2018) 029

Predict the background emission at dSphs with non-parametric kernel models



- Fully data-driven alternative to traditional template fitting
- First globablly consistent statistical model of the background emission
- Allows for a robust treatment of background uncertainties
- Limits on the DM are clearly weakened !

Improve background treatment

Some data-driven studies (incomplete list & of course biased)

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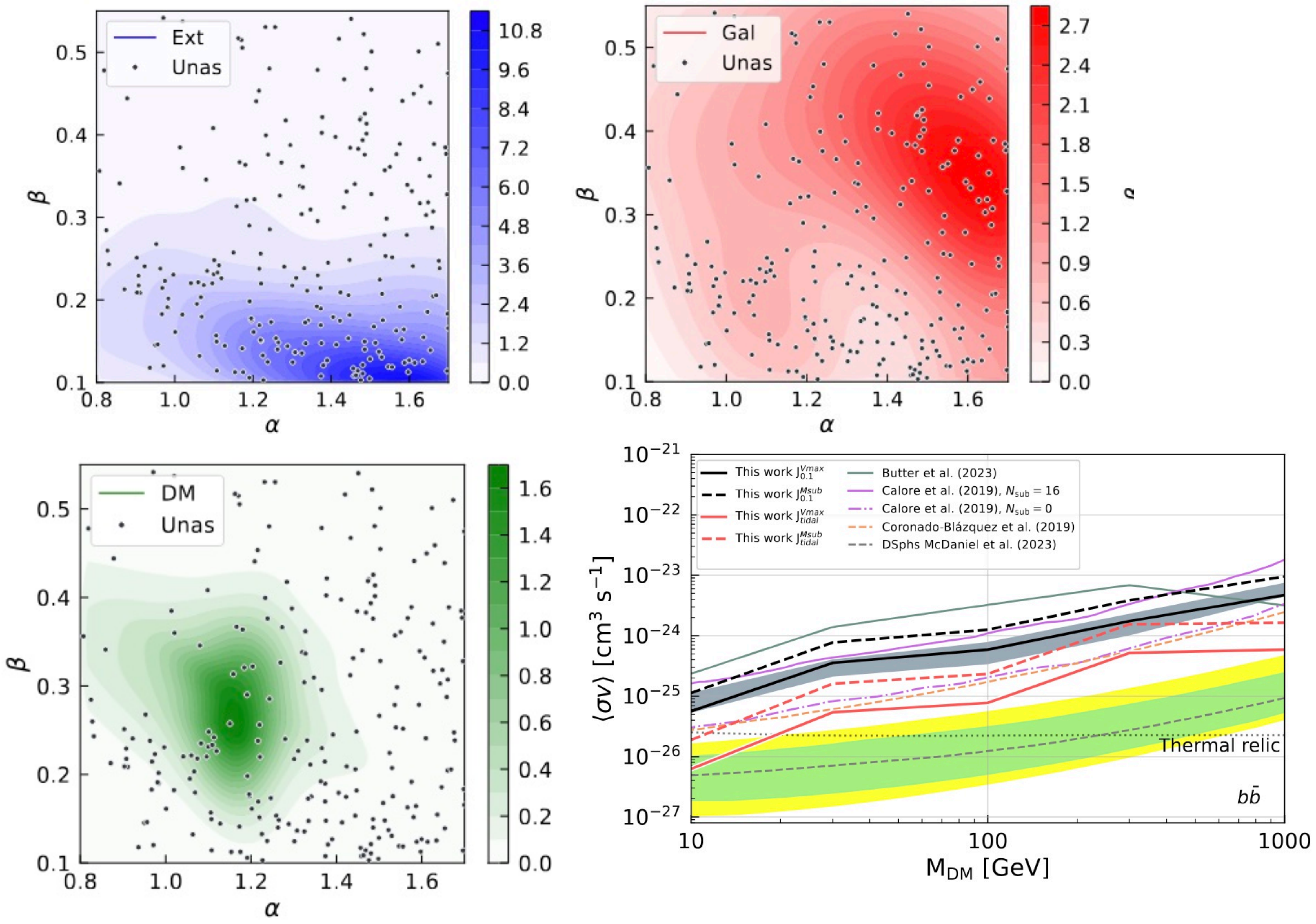
Probability density estimation of the unID spectrum with a mixture model of astro+DM

Amerio et al (incl. **BZ**), 2025 — arXiv: 2503.14584



- First statistical model of the LAT's unIDs spectra
- Thus allows to generate mock data from sampling
- Provides a robust likelihood useful for other analyses
- Competitive limits wrt other unID analyses!

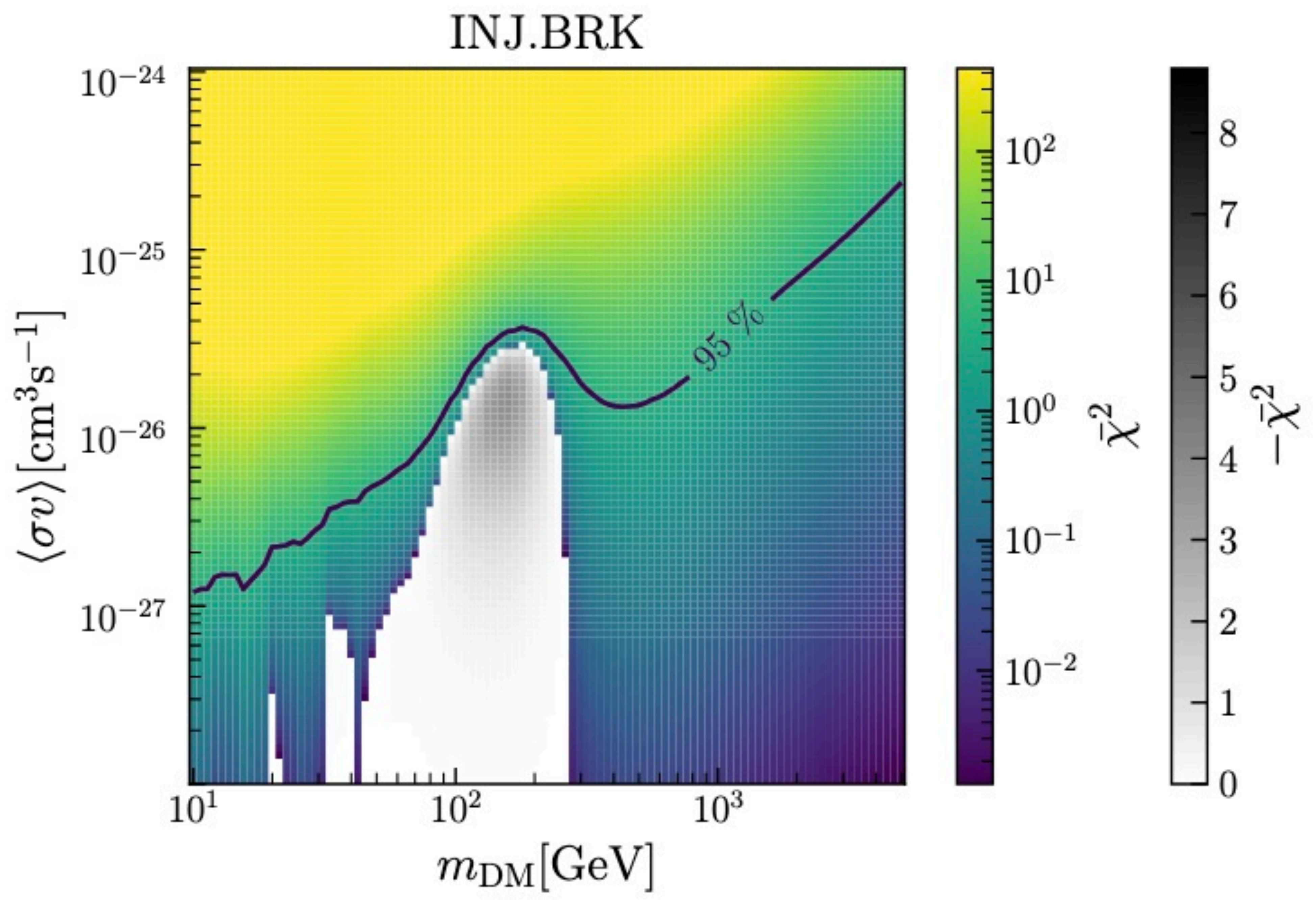
Improve background treatment

Some data-driven studies (incomplete list & of course biased)

- Searching for DM from AMS-02 anti-protons

Kahlhoefer et al, 2021 — *JCAP* 12 (2021) 12, 037

Predicting the anti-proton flux from a Neural Emulator trained on simulations fitting the AMS-02 data



- Use of nested sampling of a d=20+ parameter space
- Emulators allow for a much more efficient parameter space exploration
- Efficient marginalisation over cosmic-ray (nuisance) parameters
- Results comparable or not with previous studies, depending on the propagation model

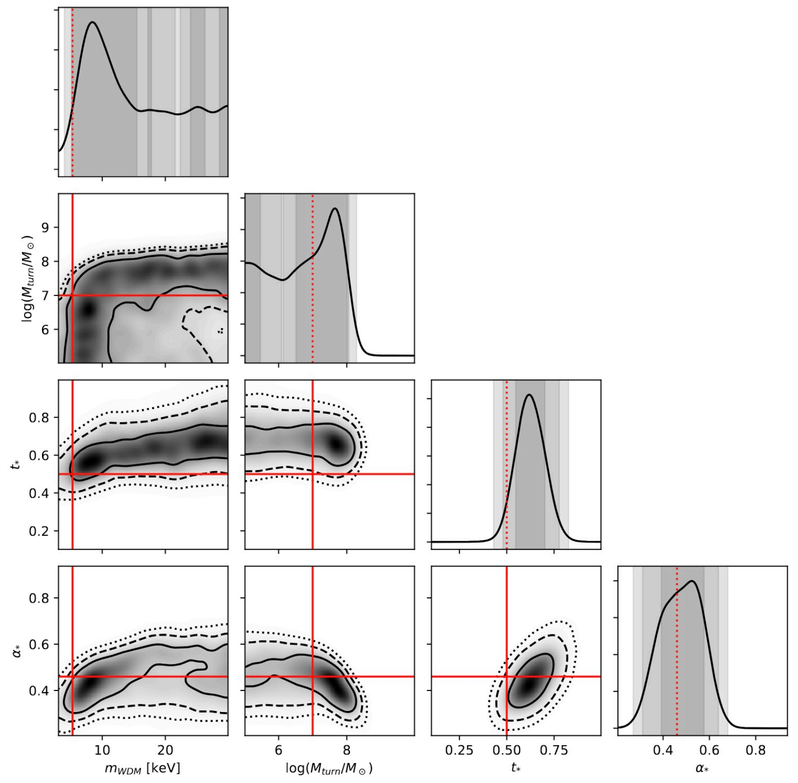
Improve background treatment

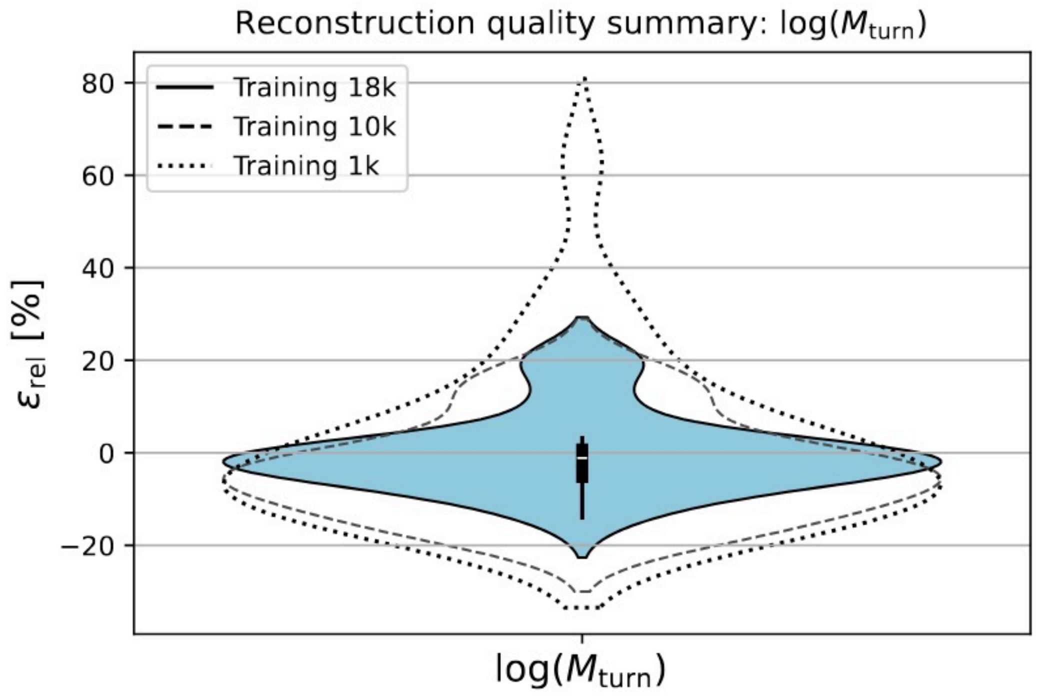
Some data-driven studies (incomplete list & of course biased)

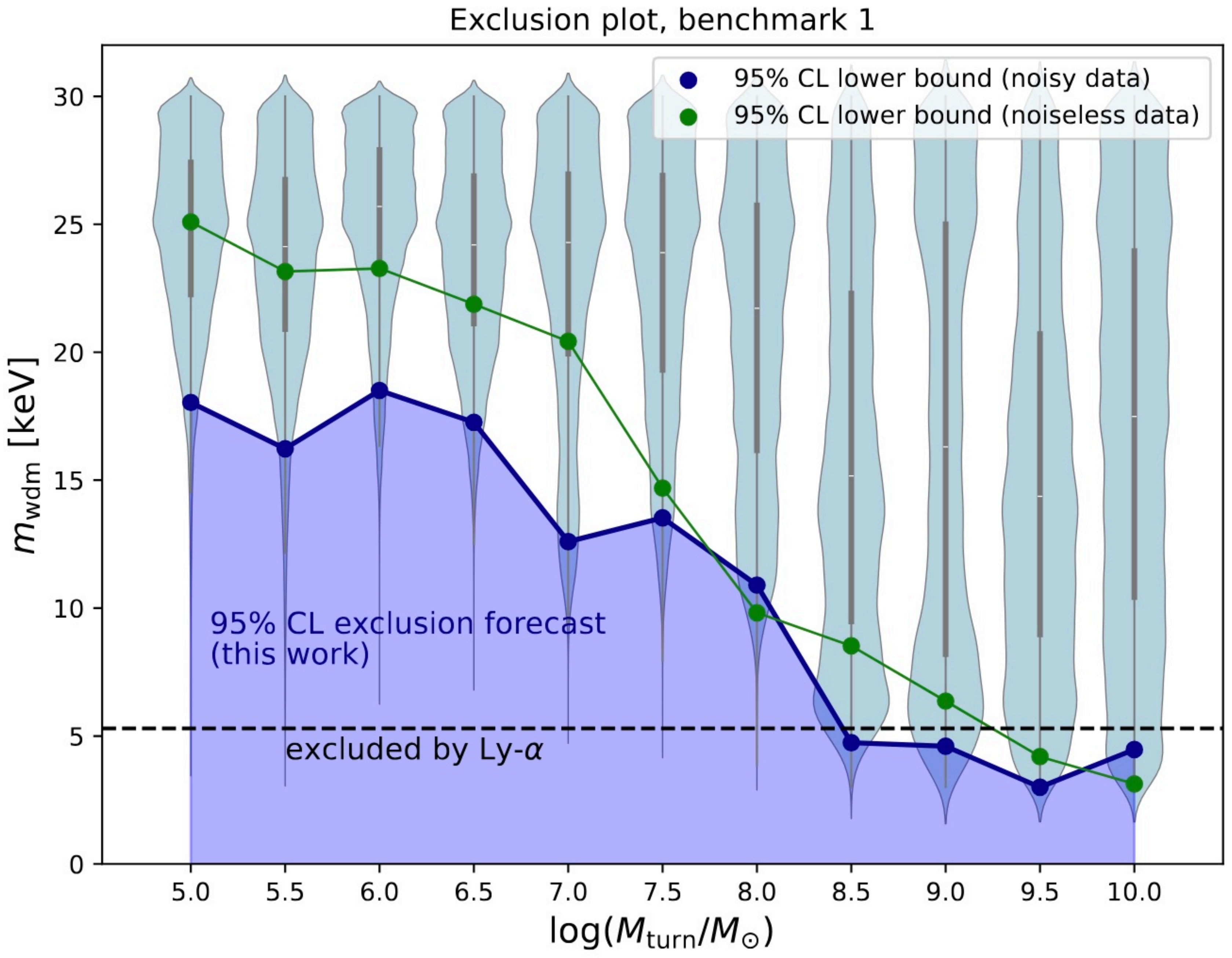
- Impact of DM on the Structure Formation Era (21cm)

Constraints on WDM from HERA forecasts with SBI

Decant, Dimitriou, Lopez-Honorez, **BZ**, 2025 — *JCAP* 07 (2025) 004

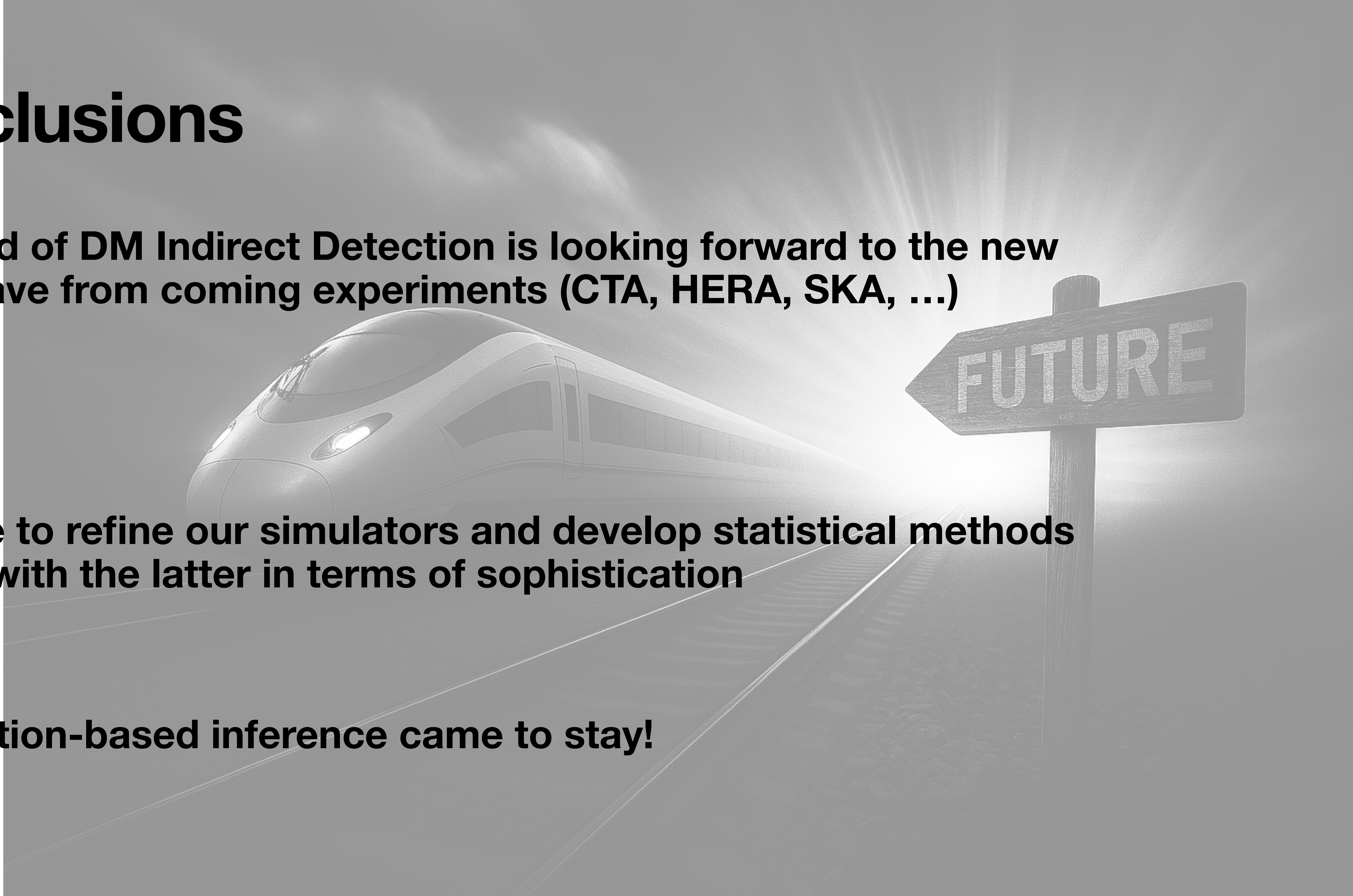






- SBI as a statistical approach much more efficient than MCMC for 21cm studies
- Explicit improvement of reconstruction precision with increasing length of training data
- Unlock a systematic study of degeneracies among the astrophysical and DM physics
- Constraints stronger than Ly-alpha for small enough values of the halo mass “threshold”

Conclusions



- The field of DM Indirect Detection is looking forward to the new data wave from coming experiments (CTA, HERA, SKA, …)
- It’s time to refine our simulators and develop statistical methods on par with the latter in terms of sophistication
- Simulation-based inference came to stay!

Conclusions

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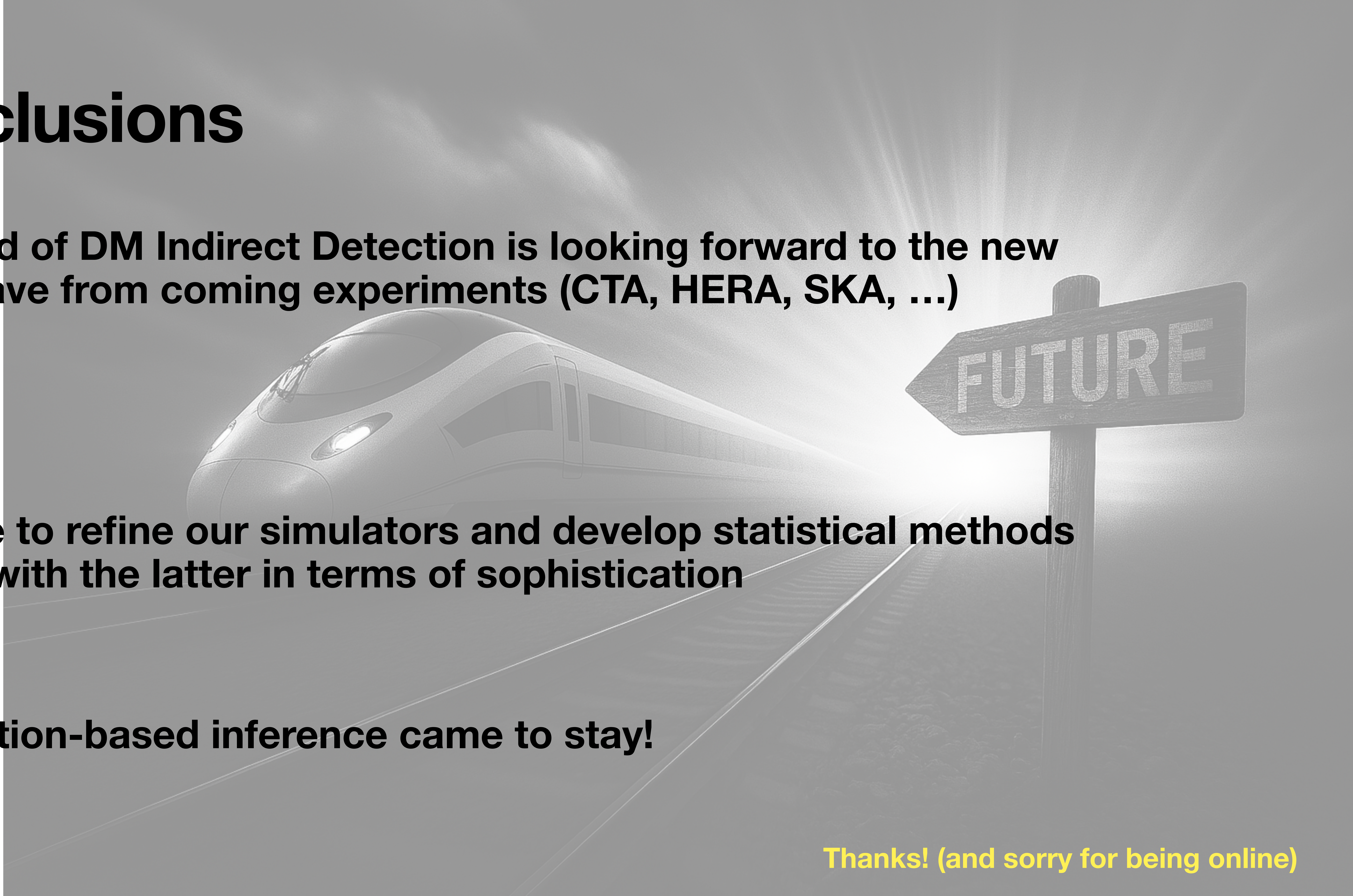

Thanks! (and sorry for being online)