New axion models/astrometric probe

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Snowmass CF3 meeting: cosmic/astrophysical probes of DM, Aug 17, 2020

Plan

Some developing opportunities to enhance the communication/collaboration between different sub-communities on dark matter-related physics through the snowmass process.

- New developments of ALP model-building and implications for cosmic/astrophysical probes of ALP;
- Astrometric probe of dark matter: stellar surveys such as Gaia (have been discussed a bit in one previous meeting; will provide a couple more inputs for further discussion).

These topics are relevant to the discussions of CF1/CF2/TH9 as well.

Terrestrial experiments: ADMX, Casper, ABRACADBRA....

Model Building: go beyond vanilla models

Axion (QCD axion and ALP)

Astrophysical/cosmic tests: stellar probes, superradiance,...

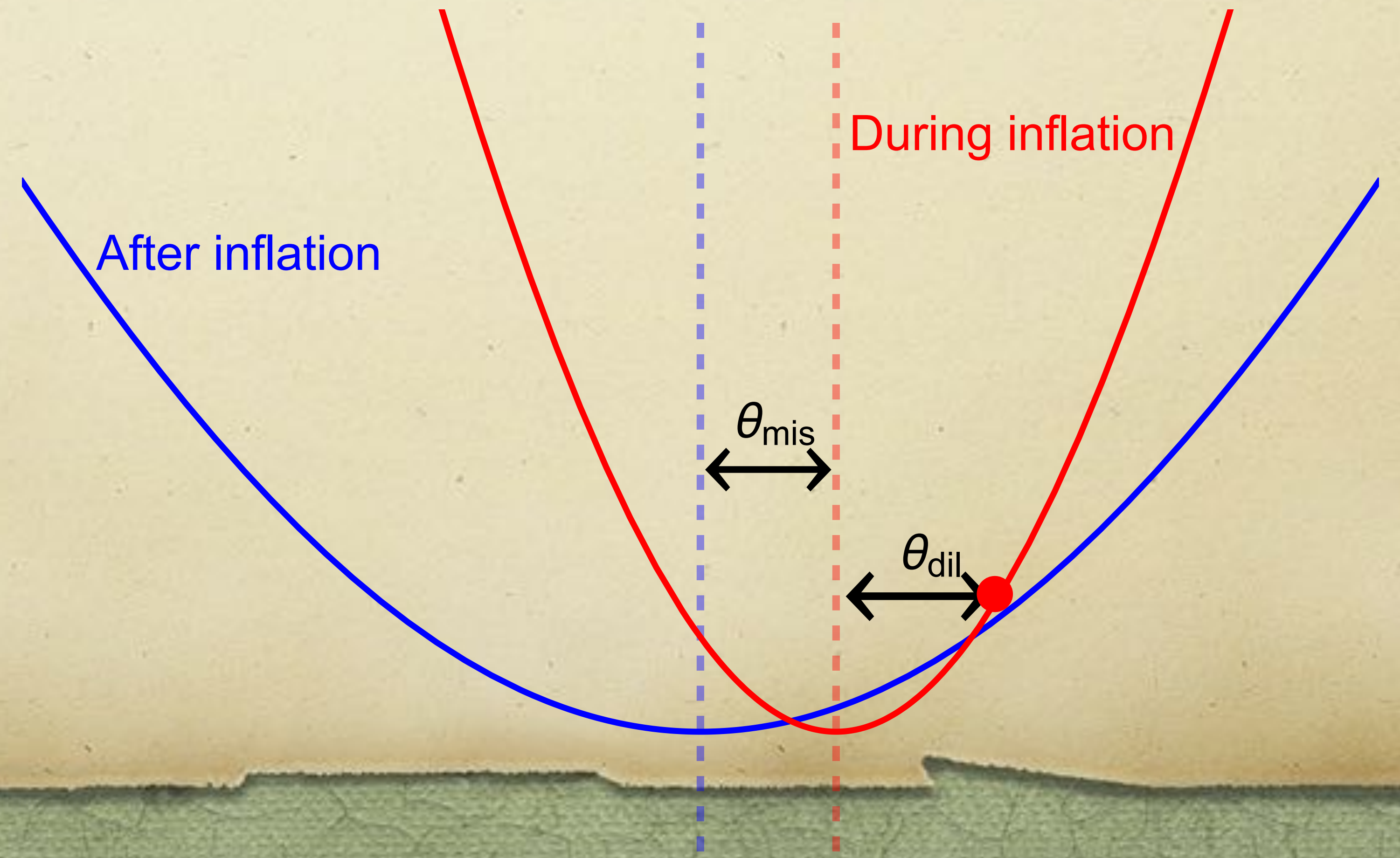
could be relevant for CF2, CF3, TF9

New QCD axion DM Models

Vanilla QCD axion DM model: axion mass ~ 10^{-6} eV (decay constant ~ 10^{12} GeV); misalignment mechanism.

Light QCD axion DM: axion mass << 10^{-6} eV, evade the cosmological upper bound on the decay constant. Some new ones with associated new phenomenology:

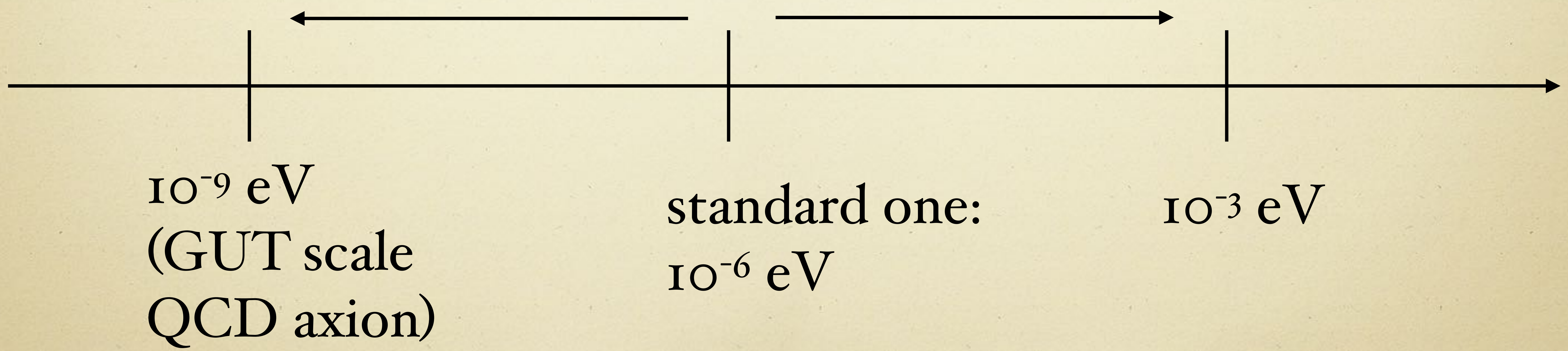
- Transferring axion energy density to other species (e.g., dark photons): Agrawal, Marques-Tavares, Xue; Kitajima, Sekiguchi, Takahashi 2017;
- Dynamical axion mass during and after inflation: Co, Gonzalez, Harigaya 2018; Manuel Buen-Abad, Fan 2019;



Heavy QCD axion DM: axion mass up to meV (decay constant down to 10^9 GeV)

- Axion initial misalignment angle is **π** after inflation: Raido, Takahashi, Yin 2017; Co, Gonzalez, Harigaya 2018; Huang, Madden, Racco, Reig 2019;

QCD axion DM

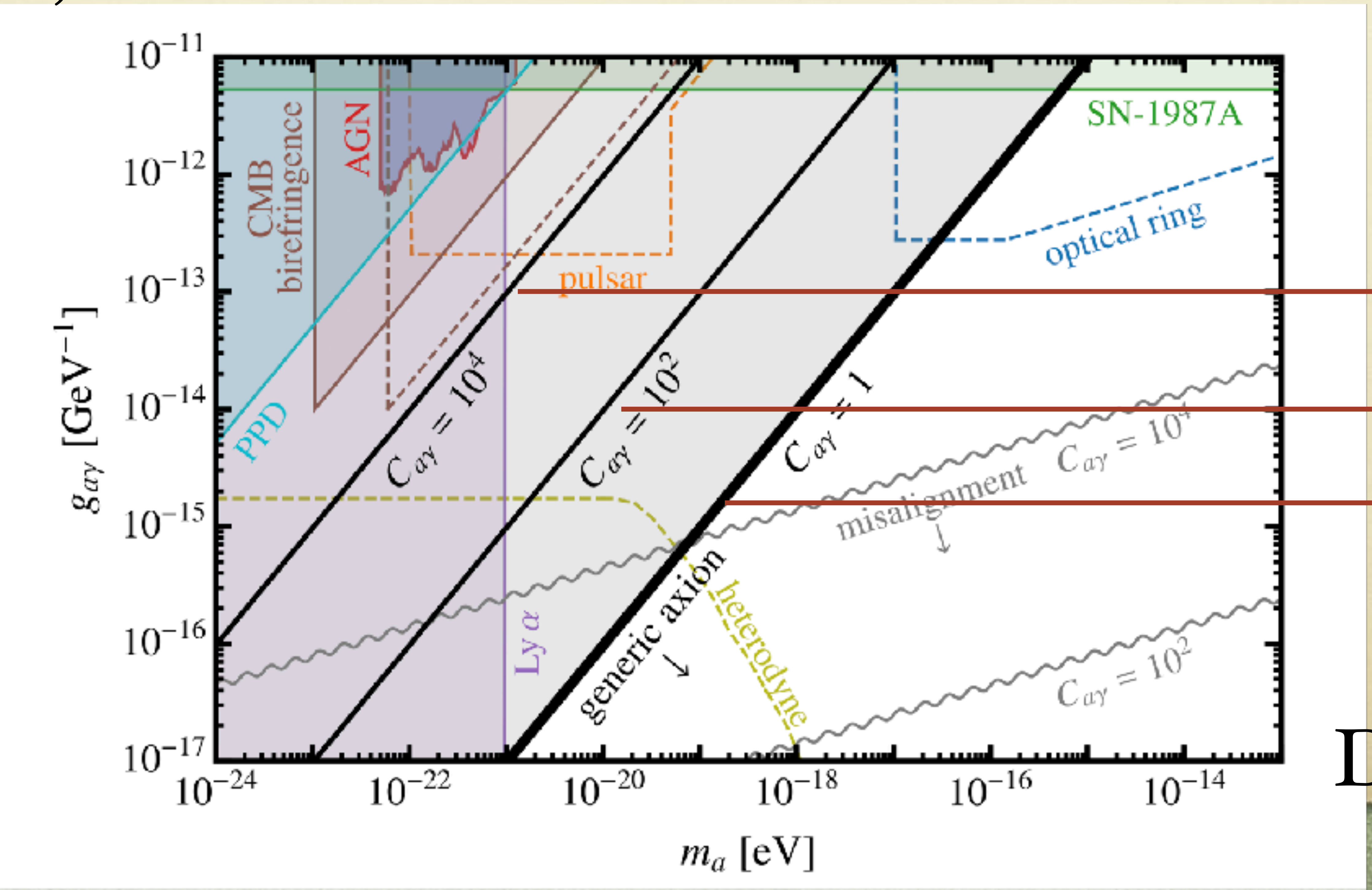


Models on very large axion couplings

Taking into account of the cosmological constraints on axions, a lot of searches (both terrestrial or astrophysical) for axions are only sensitive to very large axion couplings. Are these searches looking for any feasible axion models?

Yes! Alignment/kinetic mixing in multi-axion scenario.
Farina, Pappadopulo, Rompineve, Tesi; Agrawal, Fan, Reece, Wang 2017; Agrawal, Fan, Reece 2018; Dror, Leedom 2020

$$g_{a\gamma} \equiv \frac{C_{a\gamma}\alpha}{2\pi f_a}$$



Matter power spectrum constraints

Dror, Leedom 2020

ALP self-interactions

Usually, ALP has **attractive** leading-order self-interaction

$$V(\phi) = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right) \longrightarrow -\frac{m^2}{24 f^2}\phi^4,$$

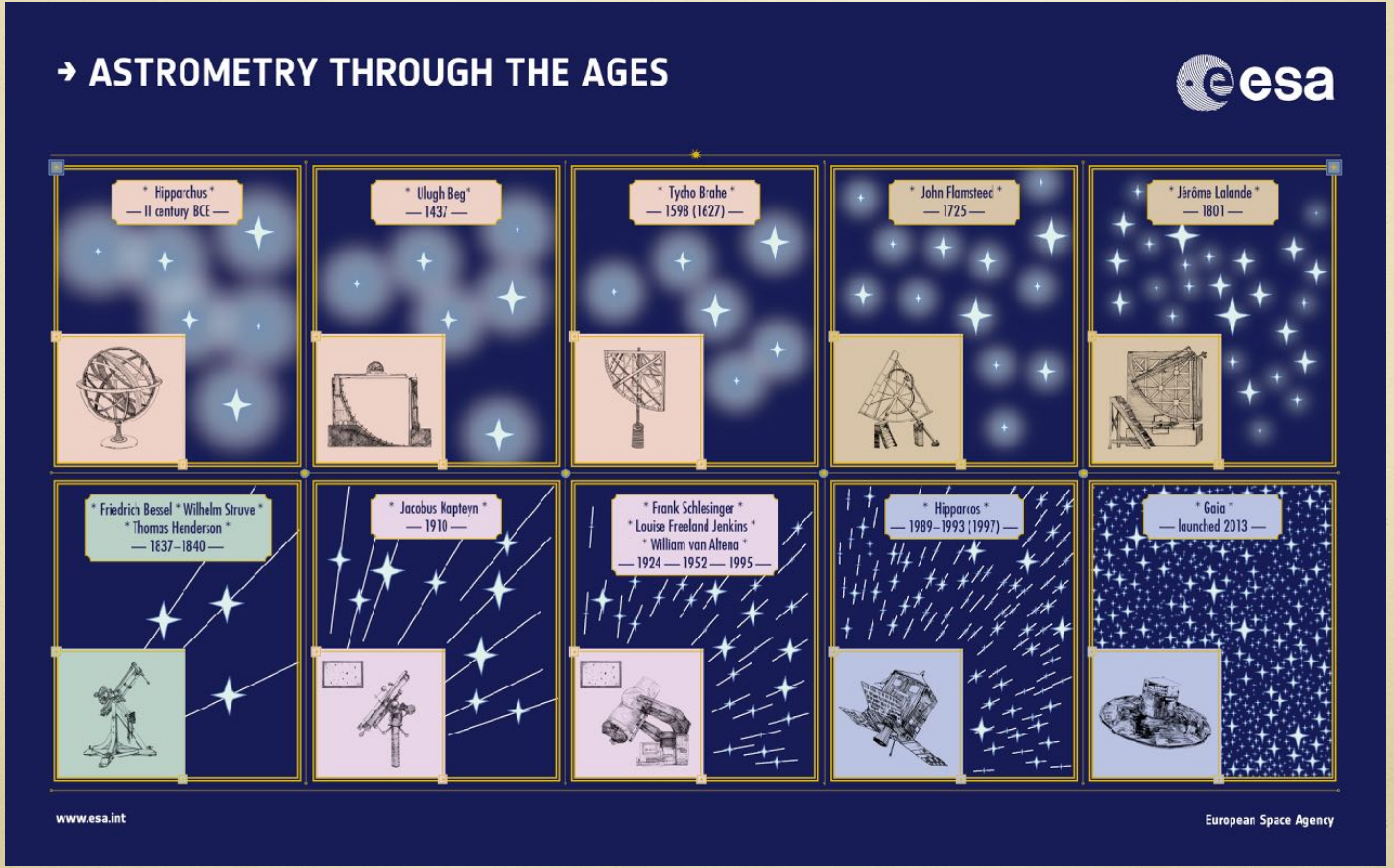
New models where ALP's leading self-interaction is ***repulsive*** (Fan 2016):

E.g: axion from 5D gauged U(1) $$V(\phi) \supset -\Lambda^4 \left(\sum_{i=1}^{n} \cos\left(\frac{q_{Bi}\phi}{f}\right) - \sum_{i=1}^{m} \cos\left(\frac{q_{Fi}\phi}{f}\right)\right),$$

Why does it matter?

- Formation of galactic scale BEC condensate: Guth, Hertzberg, Prescod-Weinstein 2014;
- Properties of boson stars and gravitational wave detection of merging boson star: Croon, Fan and Sun 2018.

Gaia: the new era in astrometry



From astrometry to particle physics

Gravitational probe of dark matter: map out and constrain dark matter distributions and substructures, which could be crucial inputs for DM searches and could probe DM cosmological history and non-gravitational interactions in the dark sector.

- Emergence of possible new model for local DM velocity distribution
  Necib, Lisanti, Belokurov… 2018 -present

- Constrain an extended thin dark disk aligned with the milky way disk
  DR1(TGAS): Schutz, Lin, Safdi and Wu 2017; DR2: Buch, Leung, Fan 2018

- Halometry: search for DM subhalos using weak gravitational lensing in the time domain
  Mishra-Sharma, Mondino, Van Tilburg, Taki, Weiner 2018 - present

- Identifying DM subhalos using gap and spur features of GD-1 stream: Price-Whelan, Bonaca 2018…

- …………

(Local) Dark Matter Distributions

Relevant for a lot of DM searches, including terrestrial experiments (CF1 and CF2).

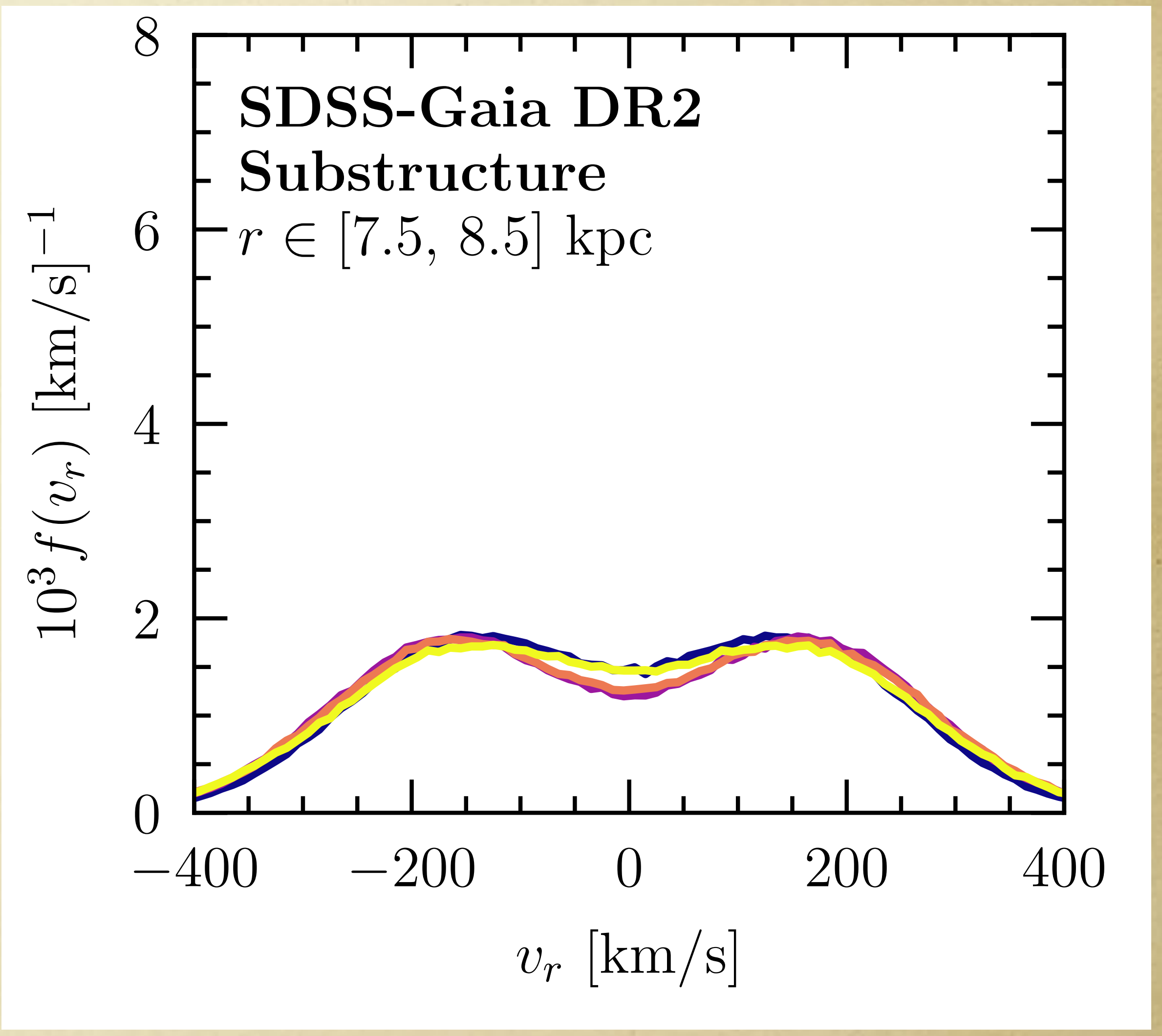
Local DM density: still a lack of analysis of Gaia higher z data (z: scale height) to determine DM local density with a high precision? Estimates of red clump stars in TGAS/Raves up to z=1.5 kpc (Hagen, Helmi 2018)

$$0.018 \pm 0.002\, M_\odot/\mathrm{pc}^3 = 0.69 \pm 0.08\, \mathrm{GeV}/\mathrm{cm}^3$$

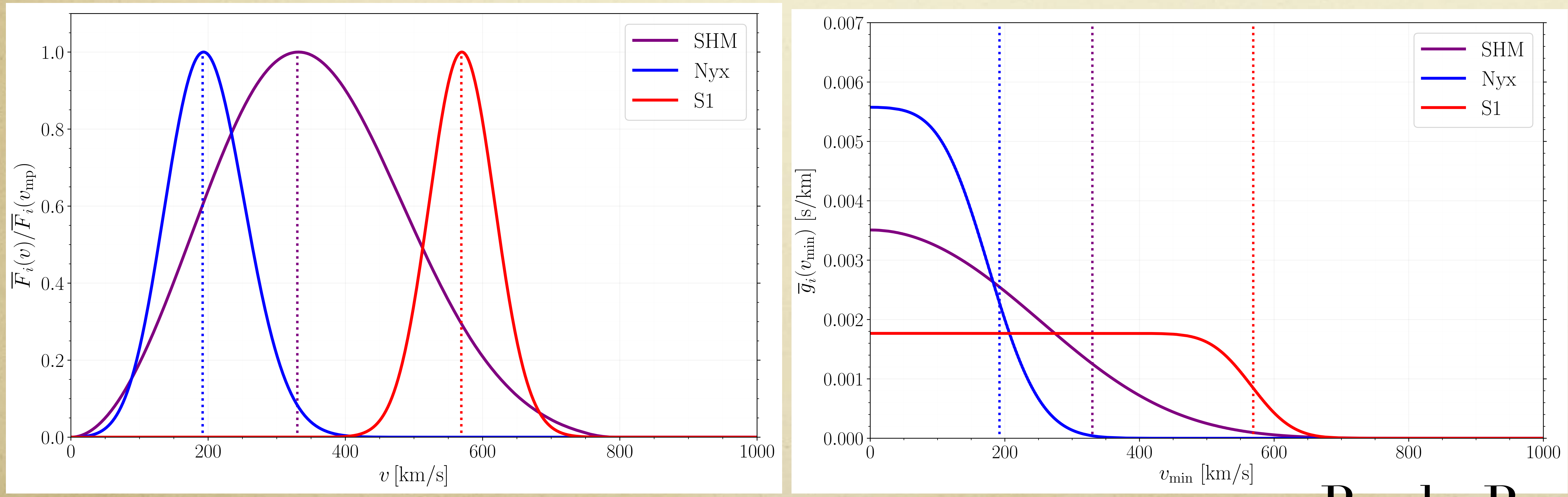
(Local) Dark Matter Distributions

Relevant for a lot of DM searches, including terrestrial experiments (CF1 and CF2).

Local DM velocity distribution: a lot of excitements and debates
- debris flow of the Gaia Enceladus (sausage): two lobes in the radial velocity distribution. Necib, Lisanti and Belokurov 2018; ...



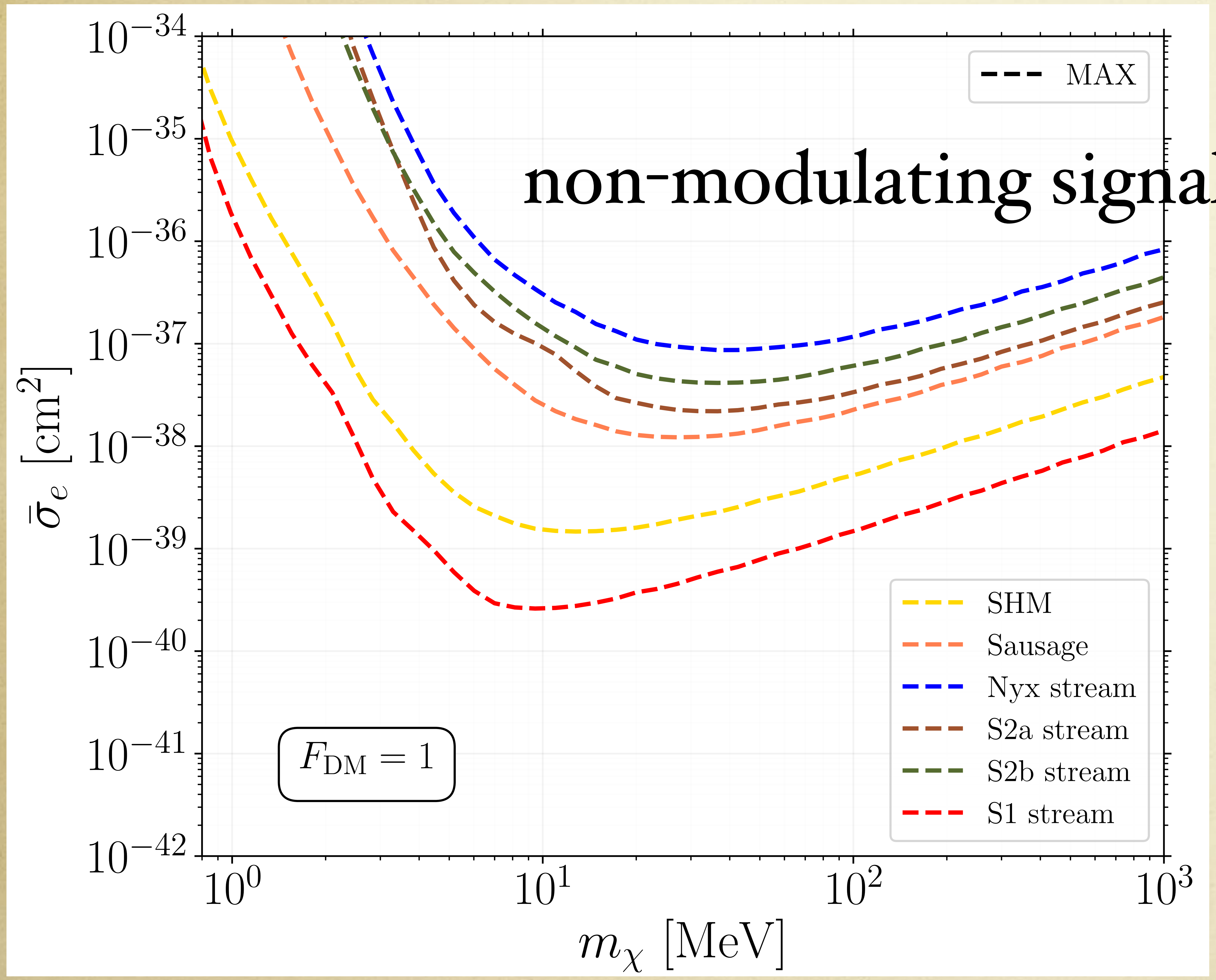
- Stellar streams: shards (S1, S2 streams) Myeong, Evans, Belokurov....2018, 2019; Nyx stream Necib, Ostdiek...2019;

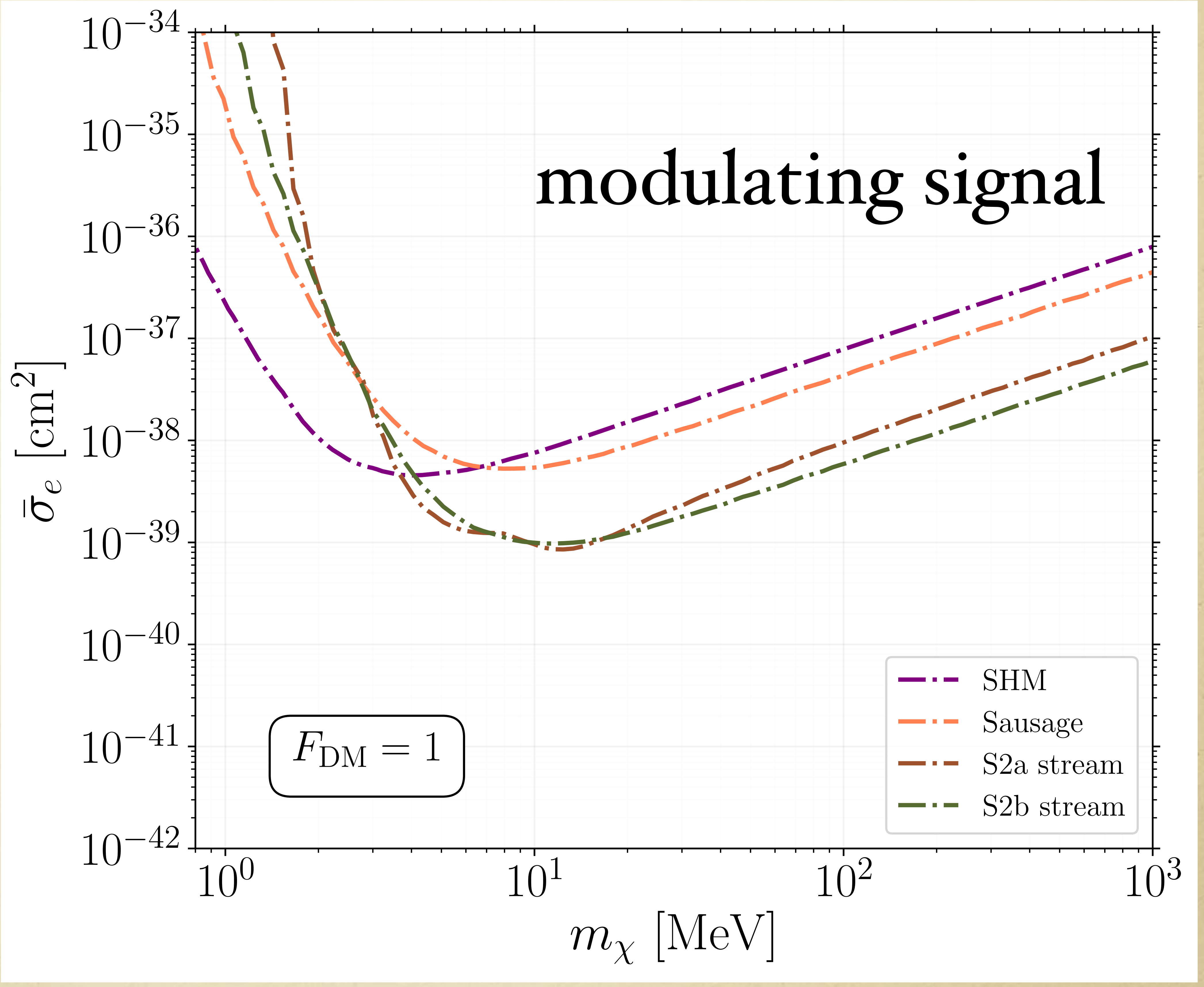


Buch, Buen-Abad, Fan and Leung 2020

Potentially big impact on dark matter searches

Eg: Discovery reach for light DM-electron scattering experiments (CF1)



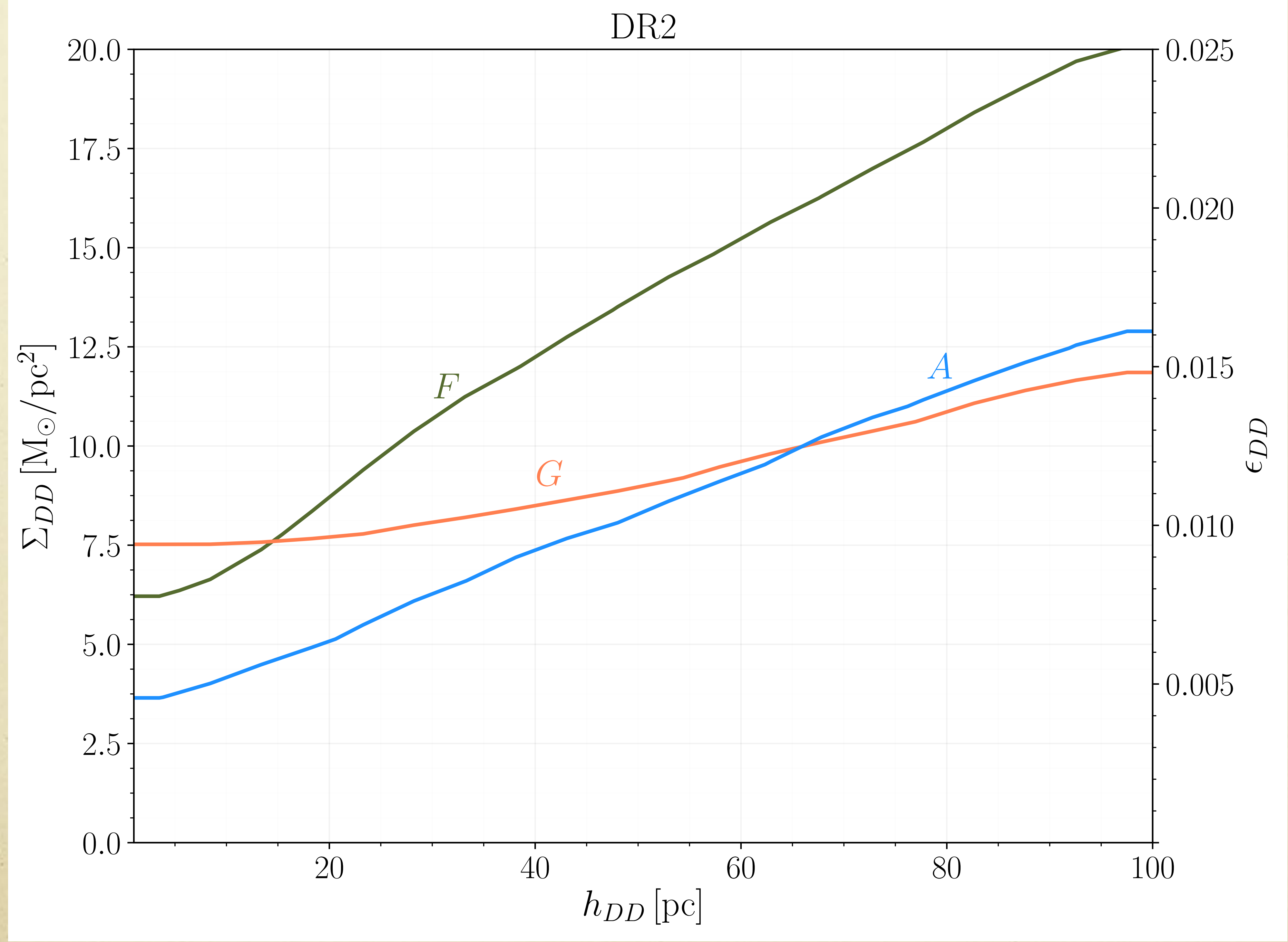


Buch, Buen-Abad, Fan and Leung 2020

Gravitational probes of DM non-gravitational interactions

A massless dark photon leads to energy dissipation of a fraction of DM and formation of a dark disk, analogous to our own baryonic disk. (Fan, Katz, Randall, Reece 2013)
DR1(TGAS): Schutz, Lin, Safdi and Wu 2017; DR2: Buch, Leung, Fan 2018

Assuming A, F, G stars are good tracers of DM and dark disk perfectly aligns with baryonic disk



At most ~ 1% of DM in the MW that could exist in a DD

Summary

New theoretical models of QCD axion/ALP DM:

- Open up new parameter space to search for;
- Point towards different phenomenology.

Gravitational probe such as stellar survey could be a new very powerful probe of DM, e.g.,

- New insights of DM distributions;
- Test DM non-gravitational interactions.

Many open questions

- Big assumption: stars are good tracers of DM. Is that true? If so, what kind of stars?

- Gaia analyses based on low z (around the baryonic disk) vs. high z (away from the baryon dense region) data?

- What other DM scenarios could be probed by Gaia results?

- A lot of the non-standard QCD axion DM models require exotic dynamics (during inflation). Feasibilities of inflationary scenarios involved? Any other experimental/observational consequences?

- Gravitational wave probe of boson star mergers: how the self-interaction could affect the gravitational wave waveforms?

- ……

Thank you!

- Gaia DR2 provides:
  -photometry in 3 bands, for ~1.7 billion sources between 3< G< 21.
  - astrometric solution for ~1.3 billion sources.
  - radial velocity spectra (RVS) for ~7 million sources with G < 12.5

- ~70 scans/source by end of survey!