Exploring the Dark Side of the Universe - Tools 2024

2-7 juin 2024, île de Noirmoutier
Domaine des Quatre Vents, l'Épine

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Dominique Thers (Subatech Nantes,FR)
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Dark Matter
Cosmology
Neutrinos and Standard Model
Gravity and Gravitationnel Waves

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https://indico.cern.ch/event/1267450/

Exploring Dark Side of the Universe

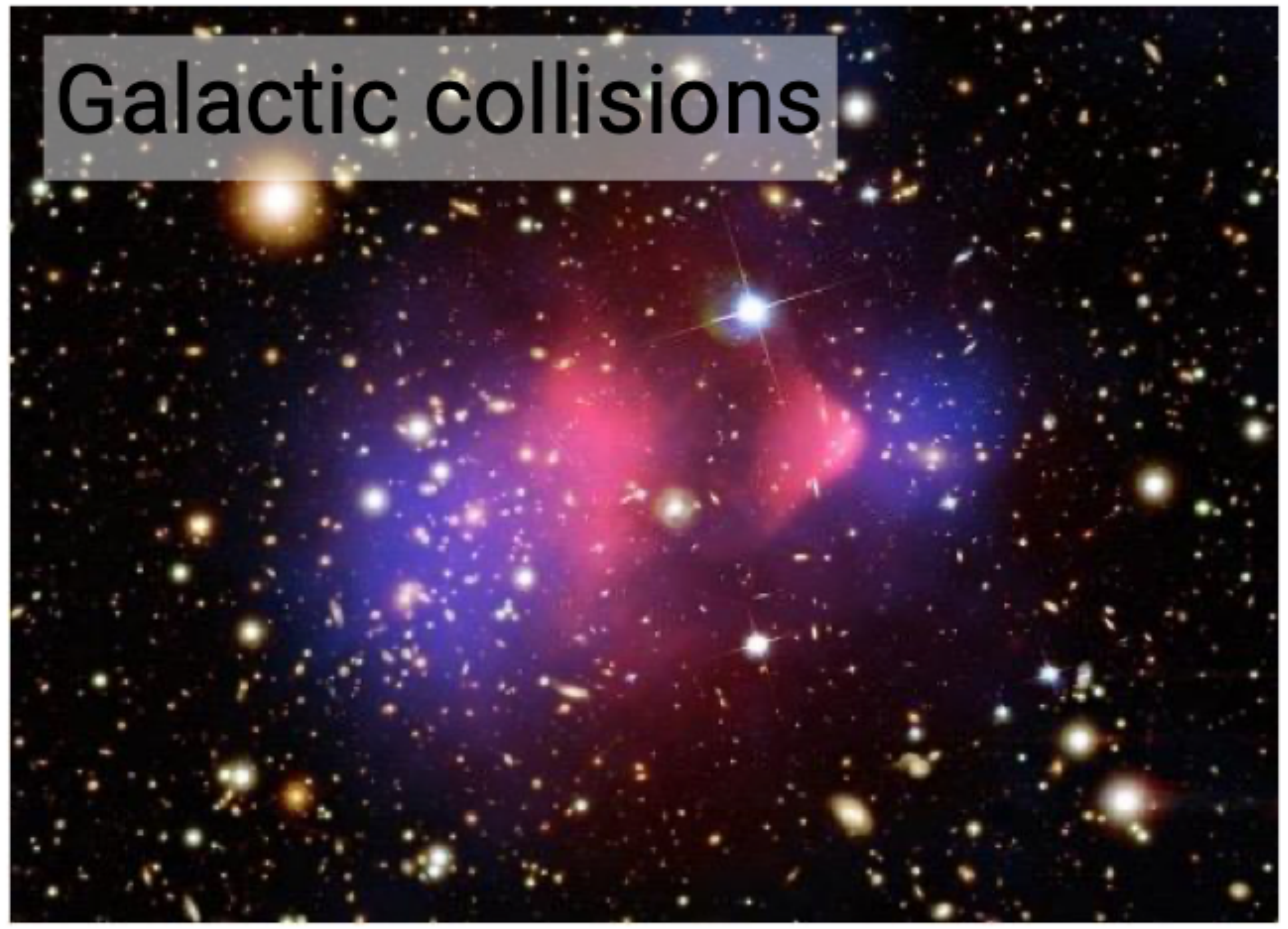
Personal summary of EDSU conference

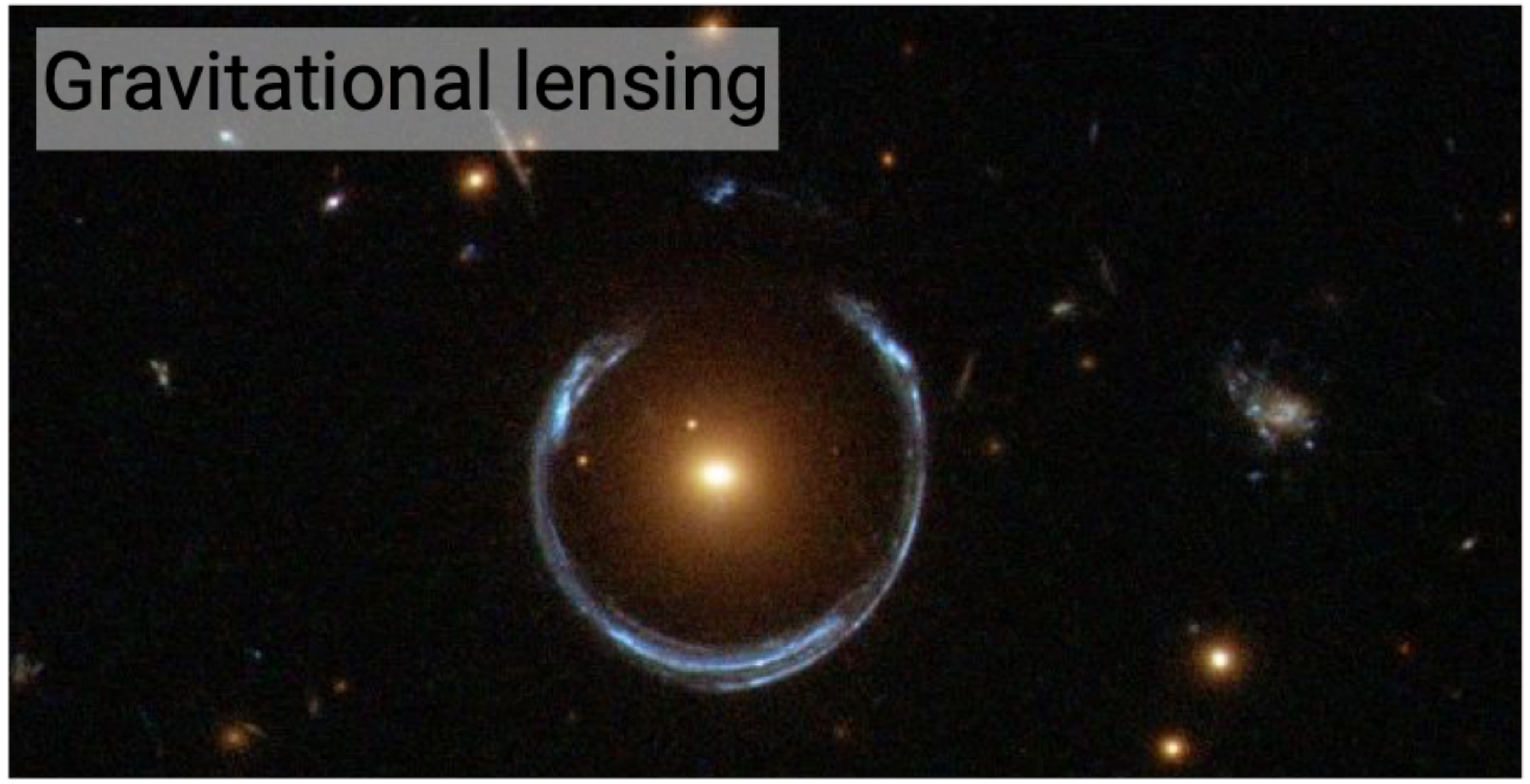
NAREI LORENZO MARTINEZ - 25/06/2024 - LSST MEETING

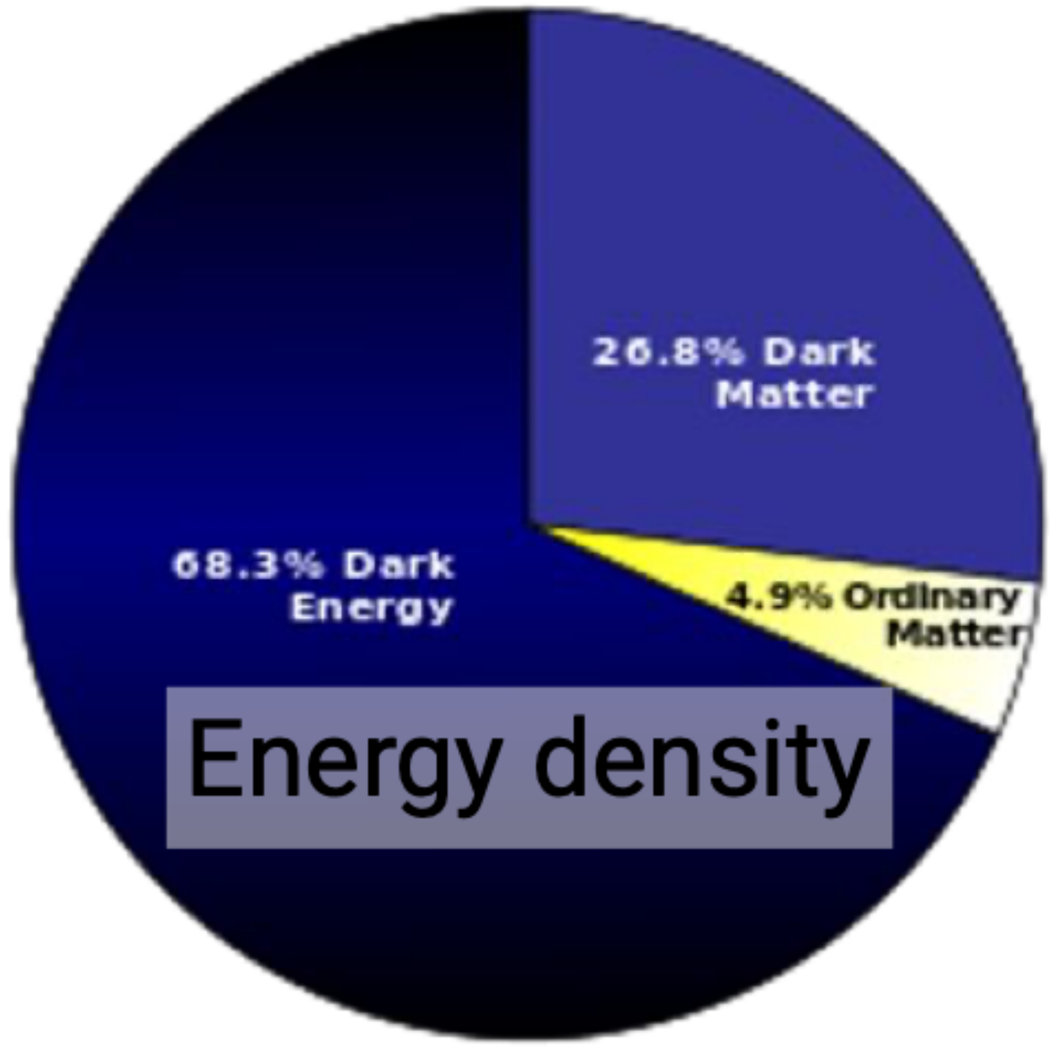
Introduction

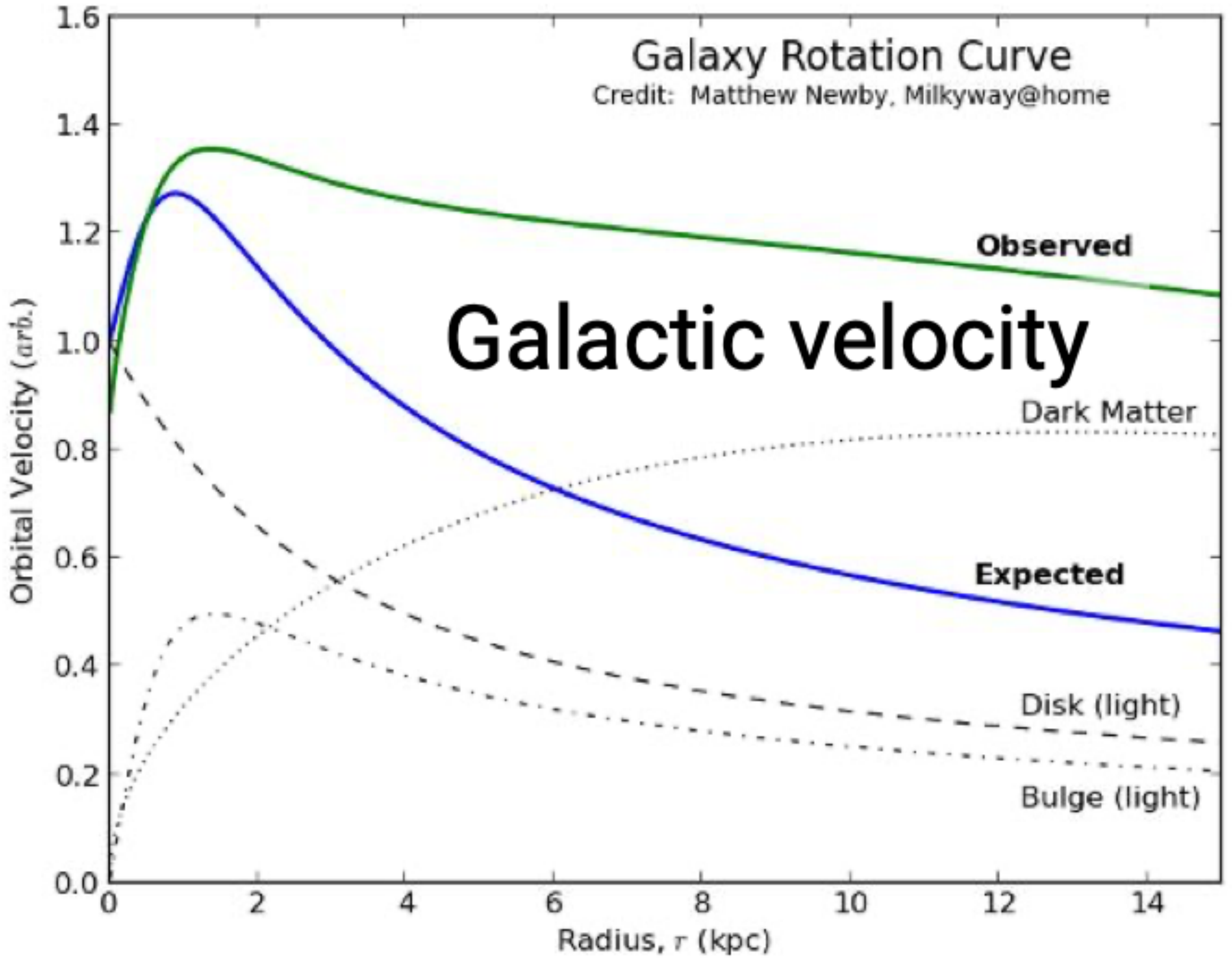
- 2nd-7th June in Noirmoutiers
- Discussions around dark matter and dark energy with different approaches : particle physics, astro-particles and cosmology
- Focus on tools (instrumentation, big data, AI, theory, models)
- One day with other topics, that use similar tools (exoplanets, quantum physics, photonics, astronomy)
    - Michel Mayor talk on exoplanets, very interesting !

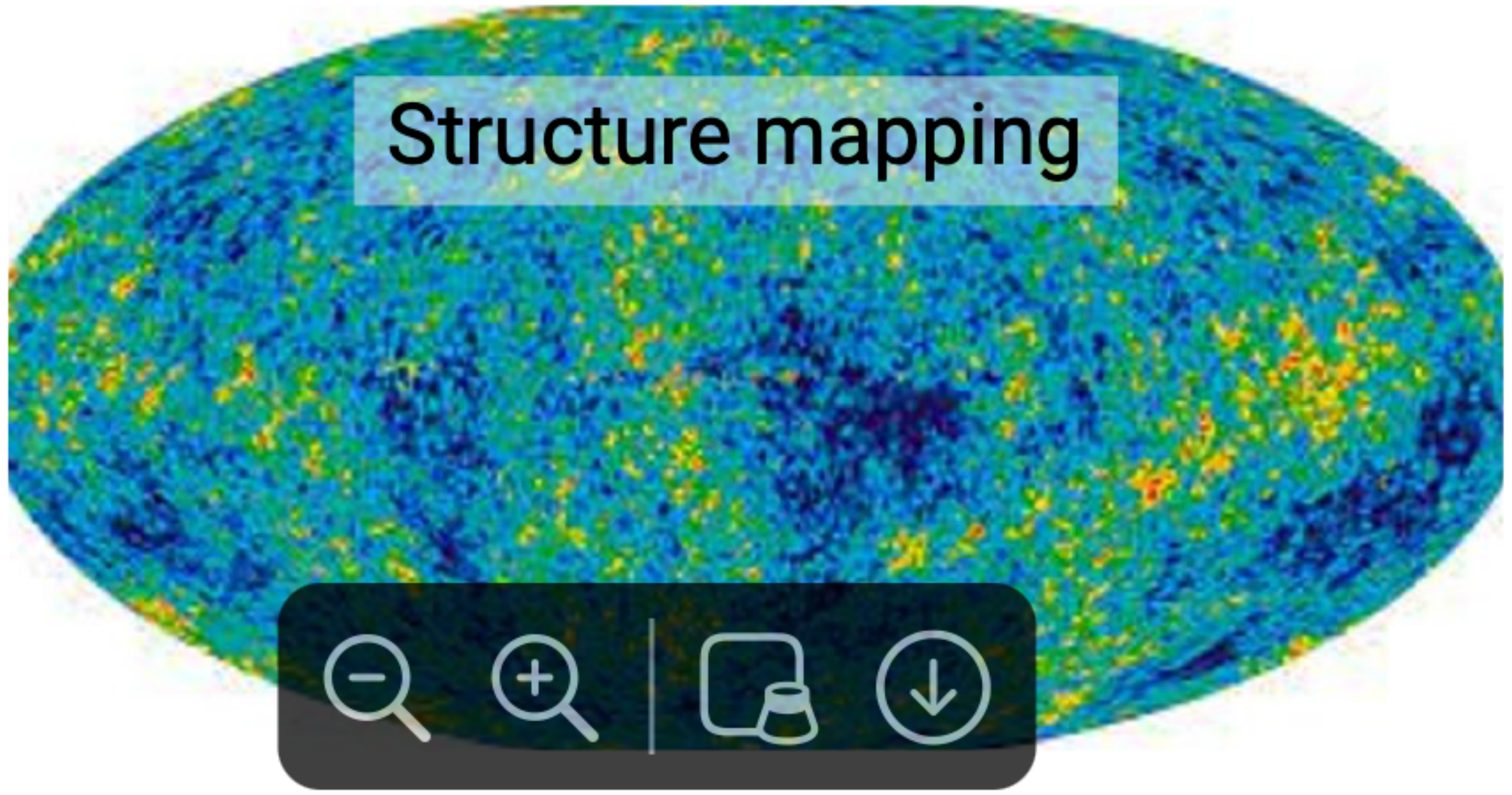
Dark Matter

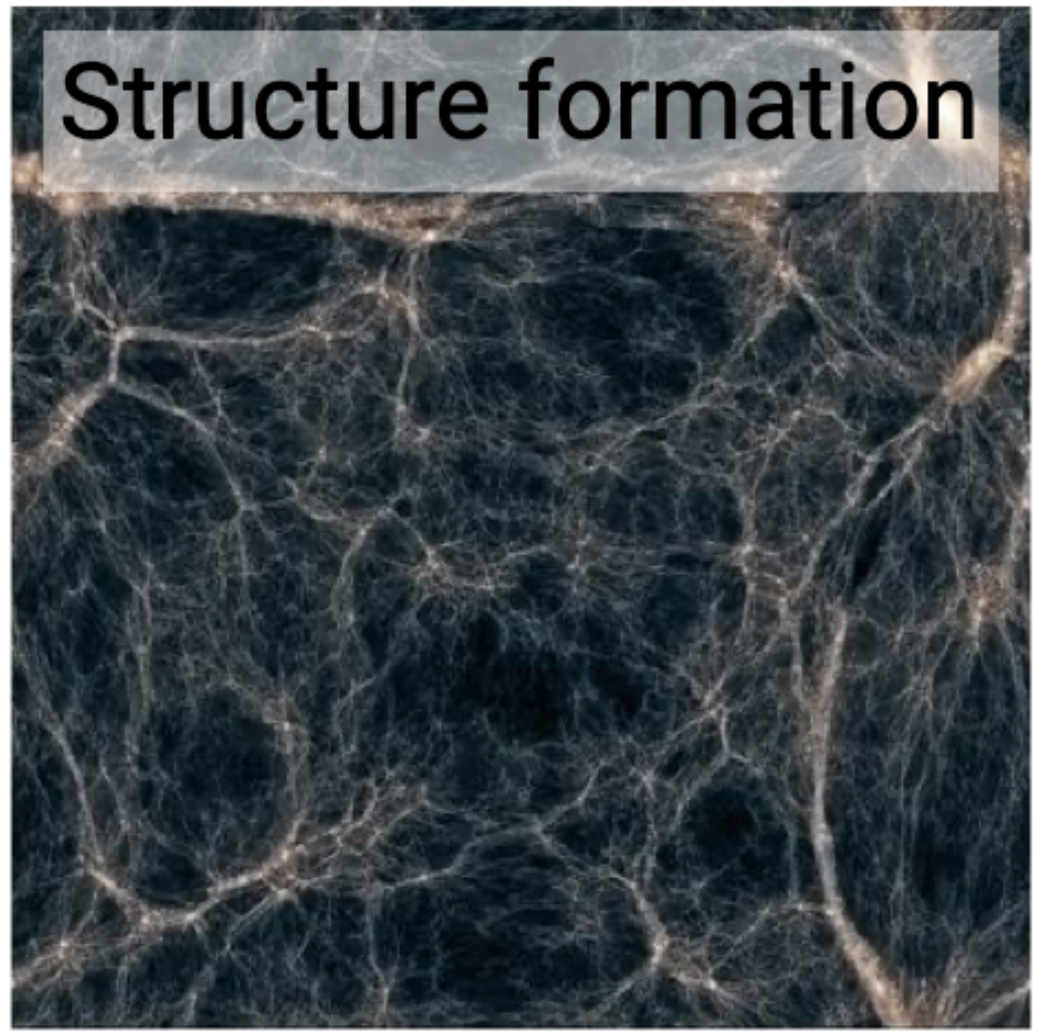

Galactic collisions


Gravitational lensing


Energy density


Galactic velocity

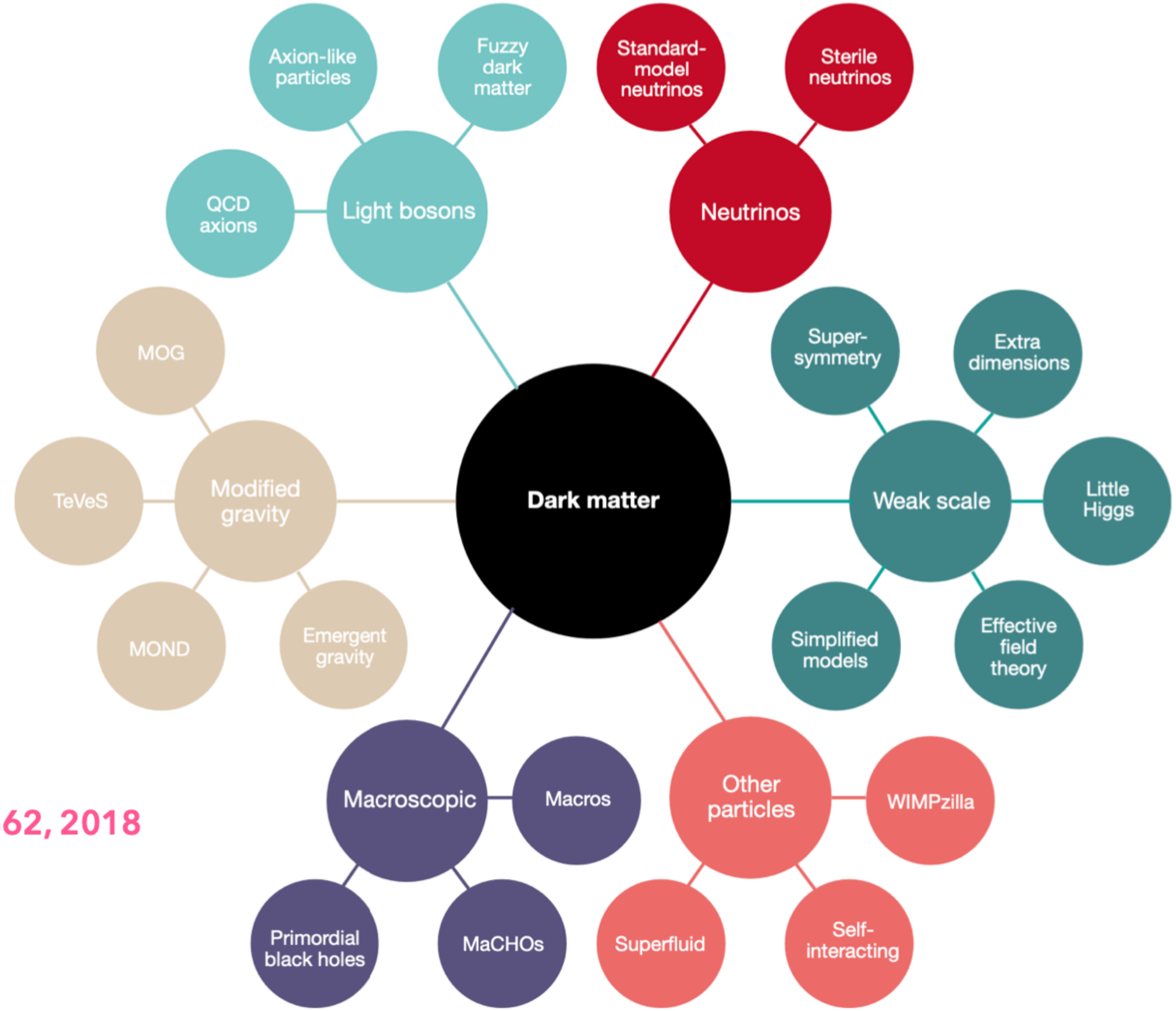

Structure mapping


Structure formation

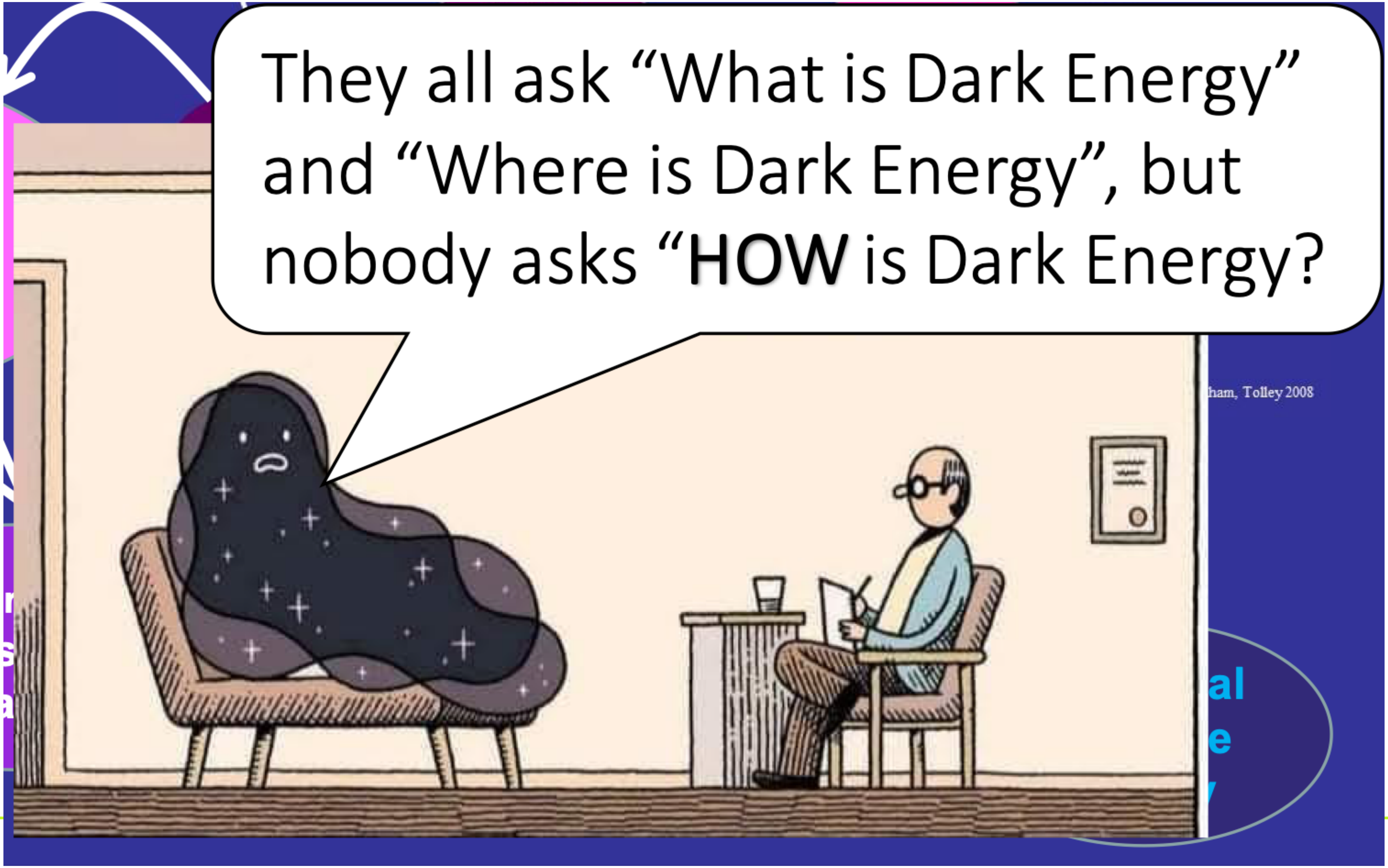
WHAT IS THE DARK MATTER?

"A component of the universe that is totally invisible is an open invitation to speculation"

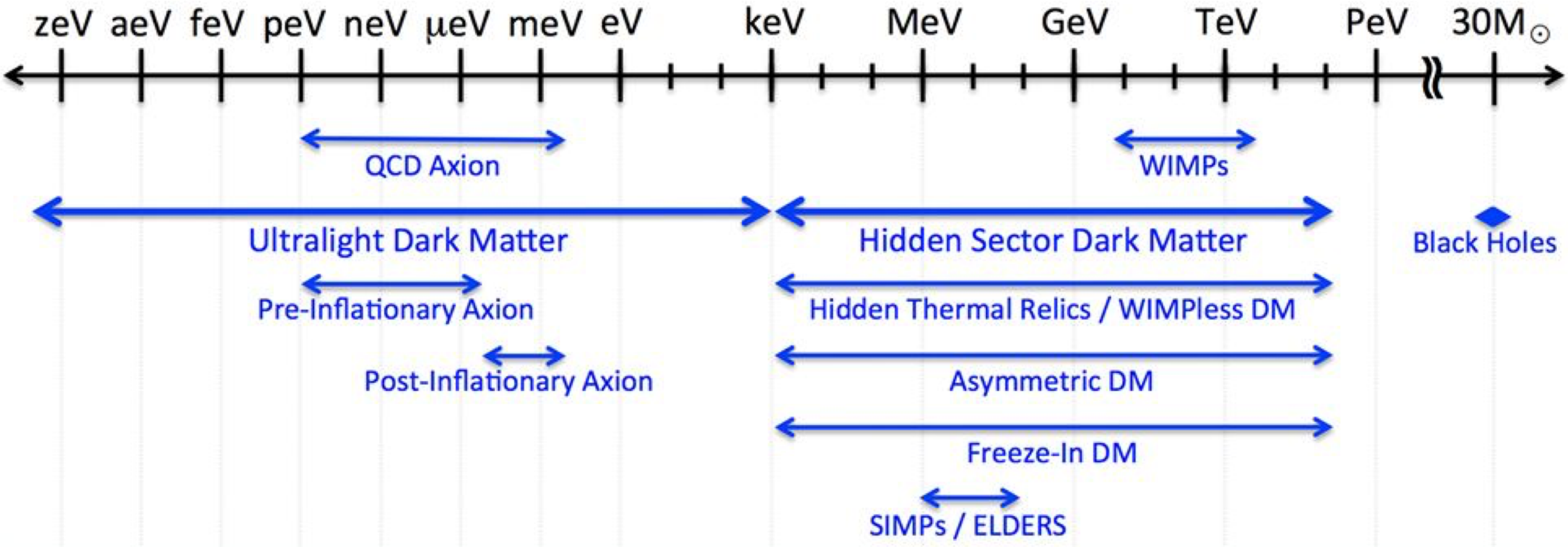
B. Ryden



Bertone, Tait, Nature 562, 2018


They all ask “What is Dark Energy” and “Where is Dark Energy”, but nobody asks “**HOW** is Dark Energy?
ham, Tolley 2008
al
e

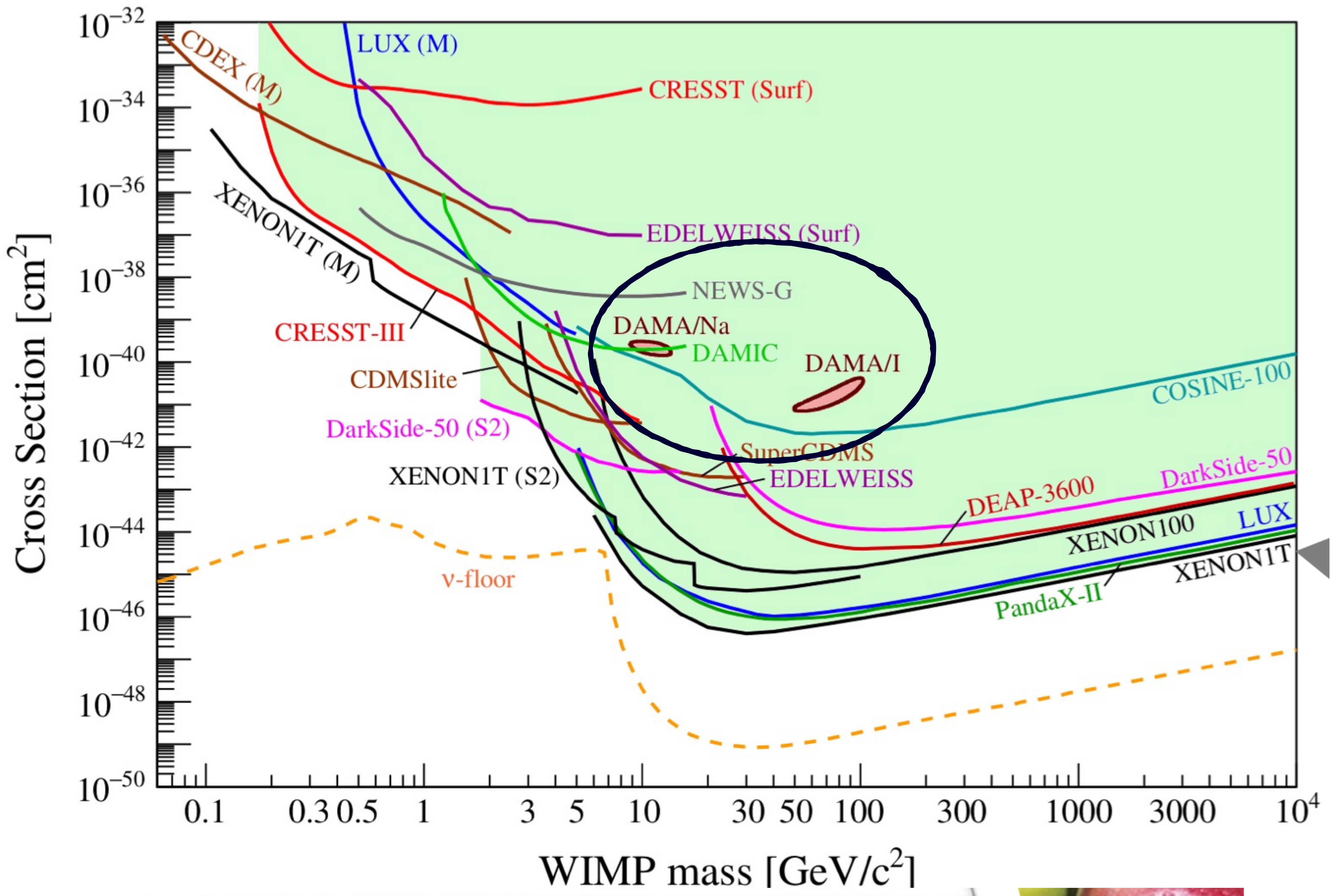
Direct search for dark matter


zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
$30M_\odot$
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS

Direct search for dark matter

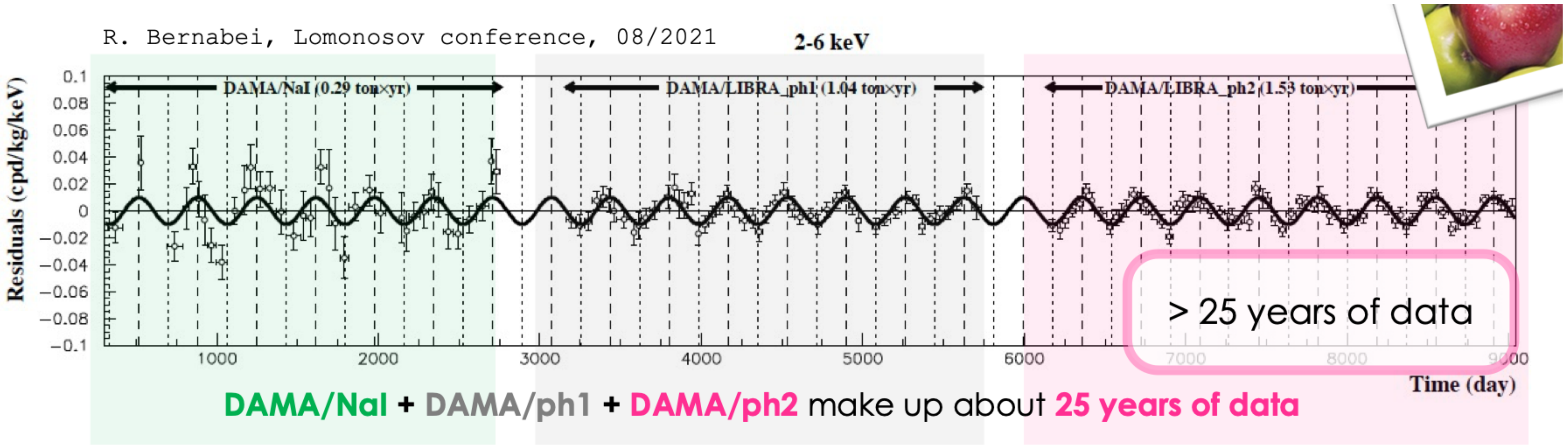
- ton-scale experiments, very low interaction rate : 0.01 counts / kev ton year
- NaI (Sodium Iodide) detectors sensitive to high DM masses (>30 GeV)
  - galactic dark matter
- No any sign of new particule…. except in DAMA !
- DAMA: matrix of NaI(TI) scintillation detectors (γ-ray detector)
  - located underground (Laboratori Nazionali del Gran Sasso)

Astroparticle Physics European Consortium APPEC, v1.02



Dark Matter signal ?

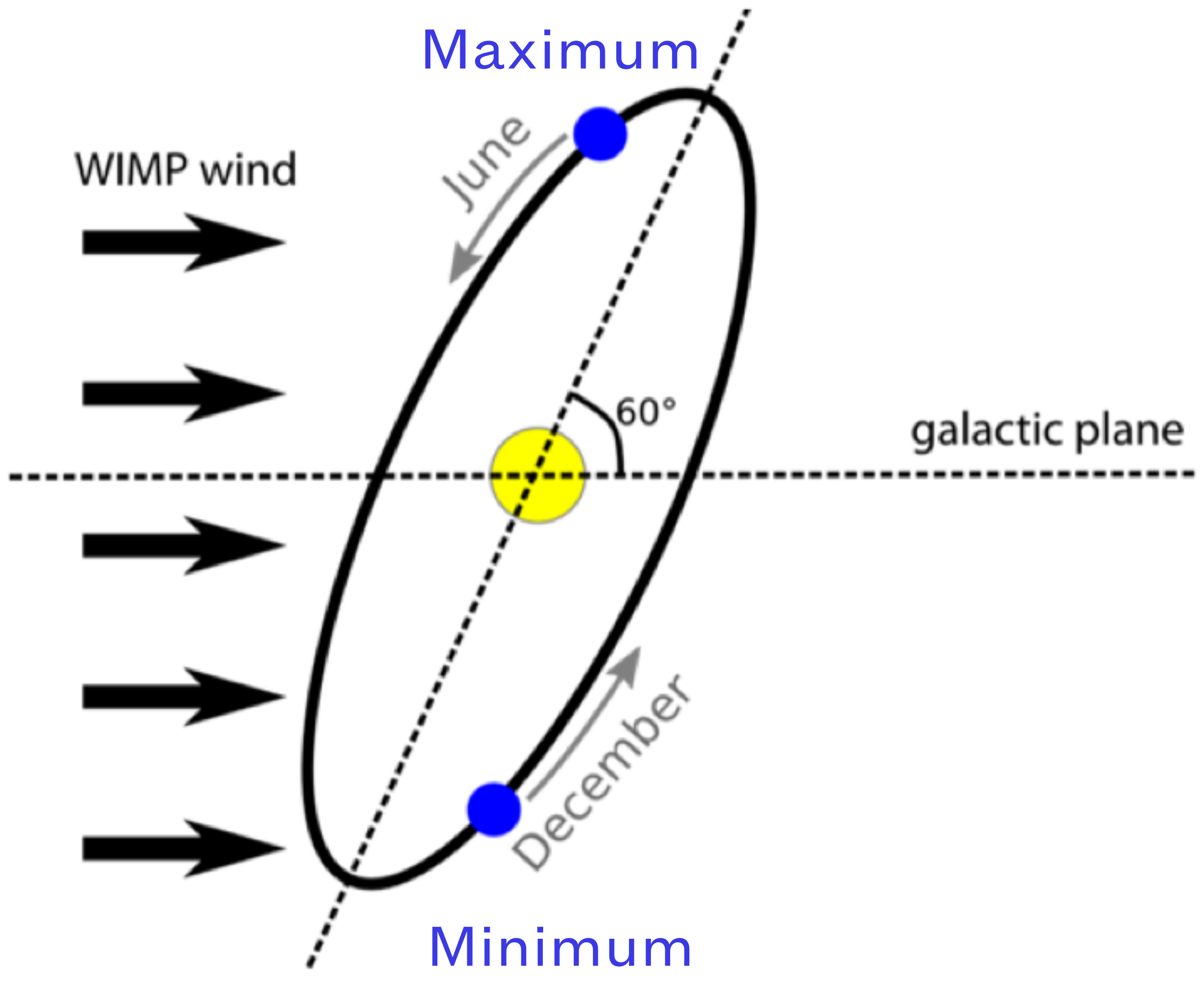
- Annual modulation of signal. Sign of DM in galactic halo ?
- APPEC Recommendation: “The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material.”



R. Bernabei, Lomonosov conference, 08/2021

> 25 years of data

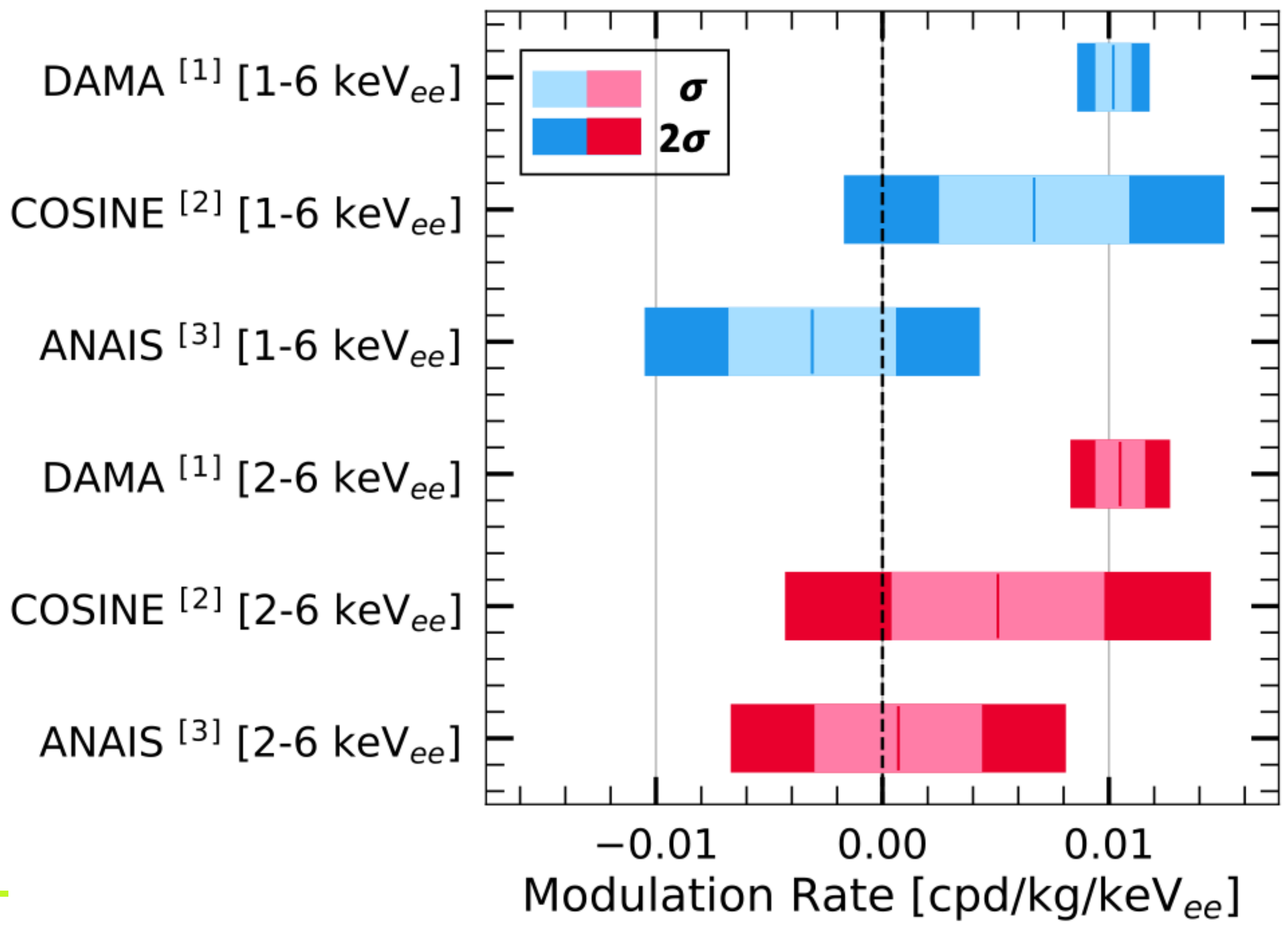
DAMA/NaI + **DAMA/ph1** + **DAMA/ph2** make up about **25 years of data**

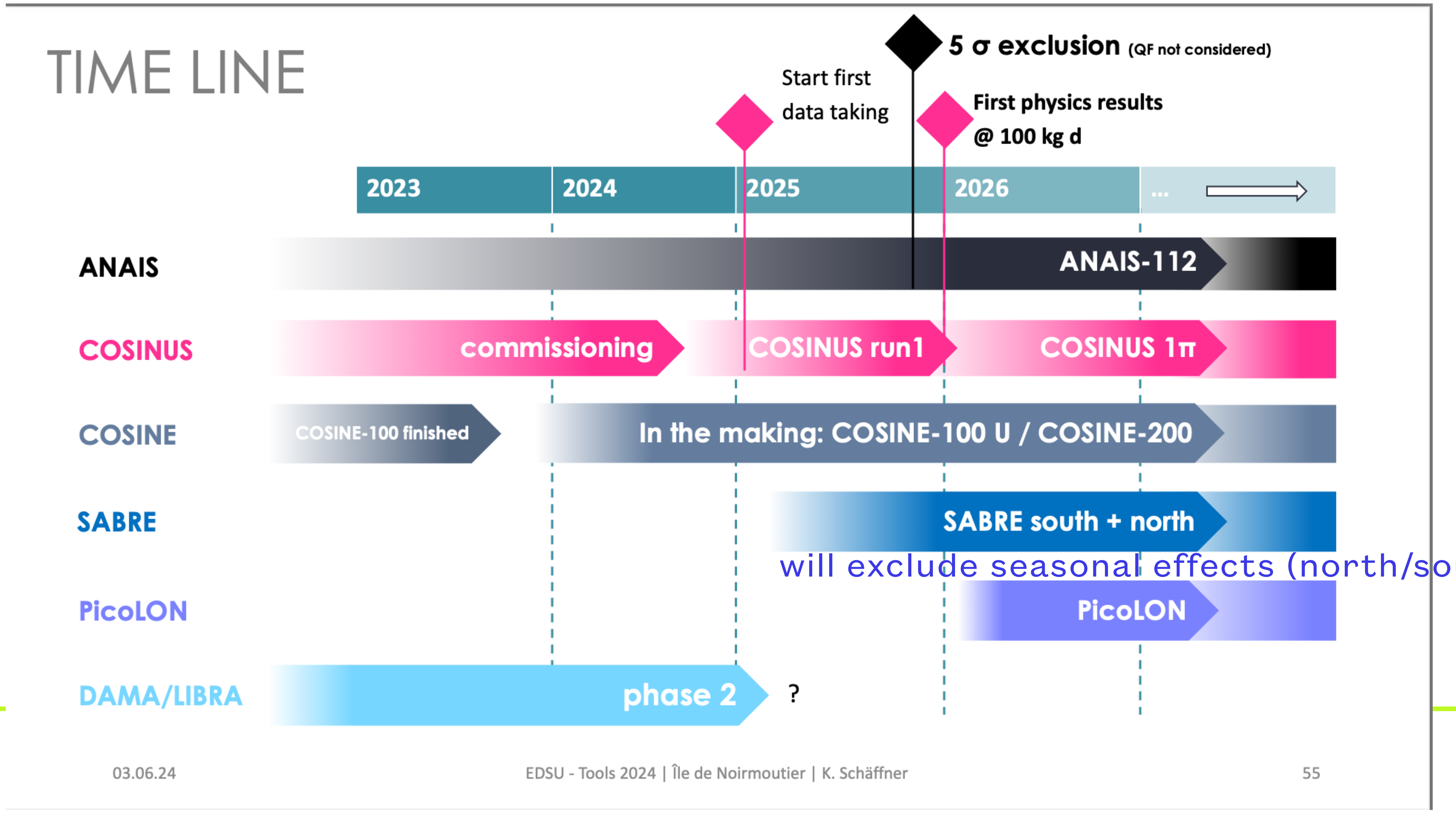


total exposure: 2.86 tonne years
statistical significance: 13.7 σ
energy region: 2-6 keV$_{ee}$ → ee = electron equivalent
period: 0.99834 ± 0.00067 years

Timeline of direct NaI experiments

- Checked by DM-Ice, Cosine-100 -> no sensitive
- Checked by ANAIS-112 -> no compatible with oscillation at ~3σ level -> 5σ at reach in late 2025
- Other experiments in construction to make the same study (SABRE, PicoLON-Japan)





TIME LINE

5 σ exclusion (QF not considered)

Start first data taking

First physics results @ 100 kg d

2023 2024 2025 2026 ...

ANAIS ANAIS-112

COSINUS commissioning COSINUS run1 COSINUS 1π

COSINE COSINE-100 finished In the making: COSINE-100 U / COSINE-200

SABRE SABRE south + north

will exclude seasonal effects (north/south)

PicoLON PicoLON

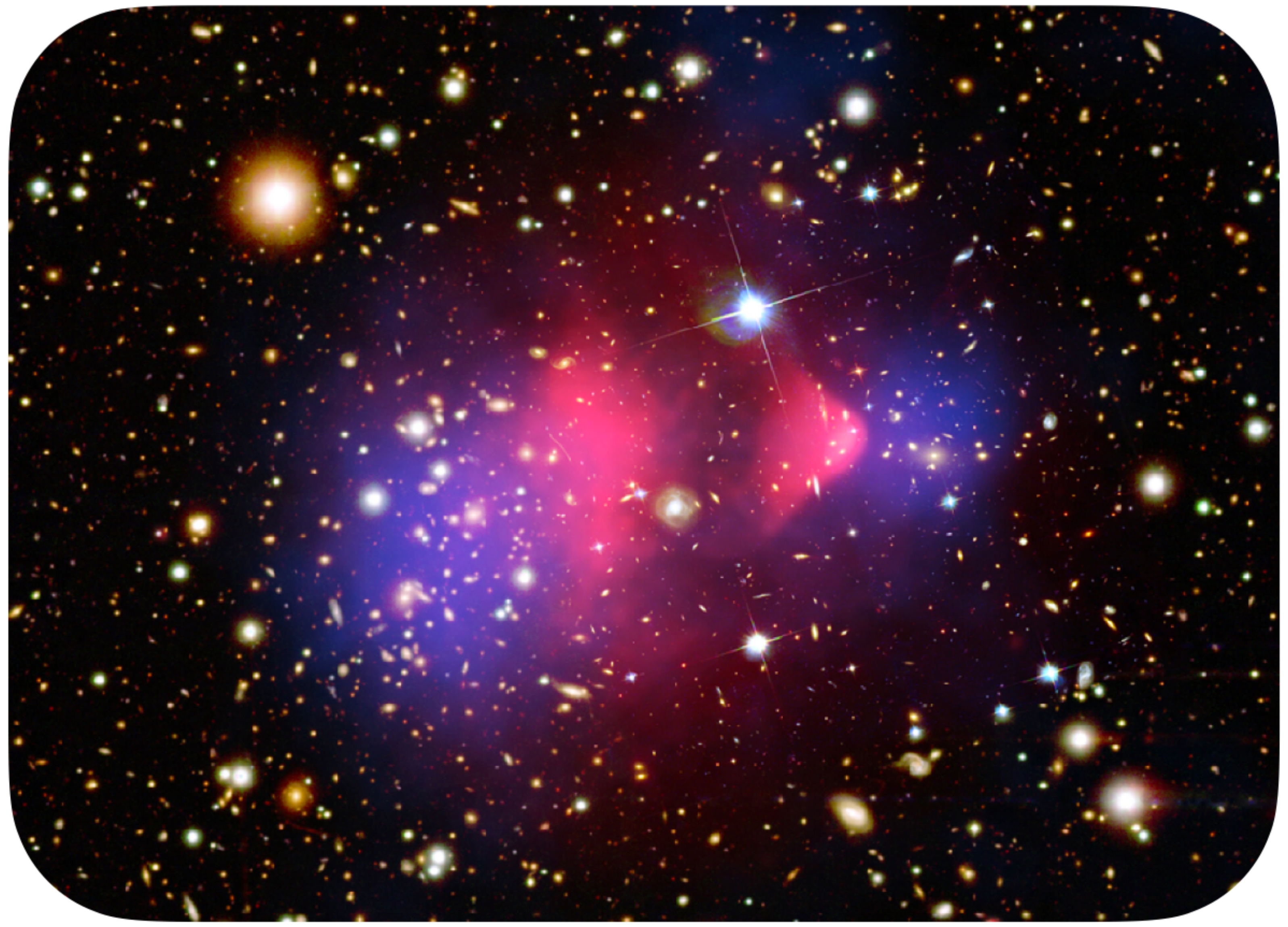
DAMA/LIBRA phase 2 ?

03.06.24 EDSU - Tools 2024 | Île de Noirmoutier | K. Schäffner 55

Cosmology

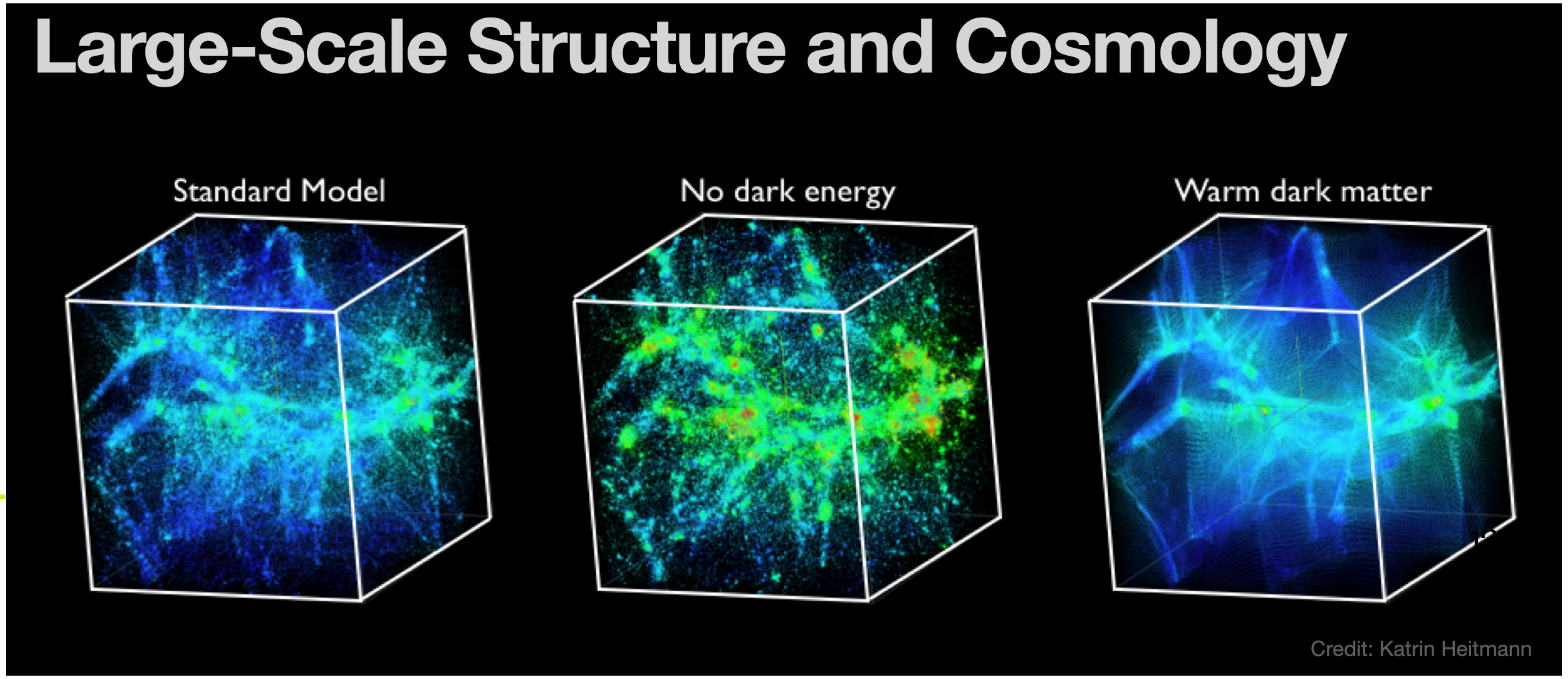
Cluster Cosmology

The most massive collapsed objects $\gtrsim 10^{14}\ M_\odot$



Bullet Cluster. X-ray: NASA/CXC/CfA/M.Markevitch, Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe, Lensing map: ESO WFI

- Composition
  - 85—90% dark matter
  - 10—15% ordinary matter, of which
    - ~ 75% (gravitationally heated) gas
    - ~ 25% galaxies/stars
- Somewhat arbitrary (but useful) definition
  - Halo ≡ *entire* thing
  - Cluster ≡ galaxies & gas (what we see)

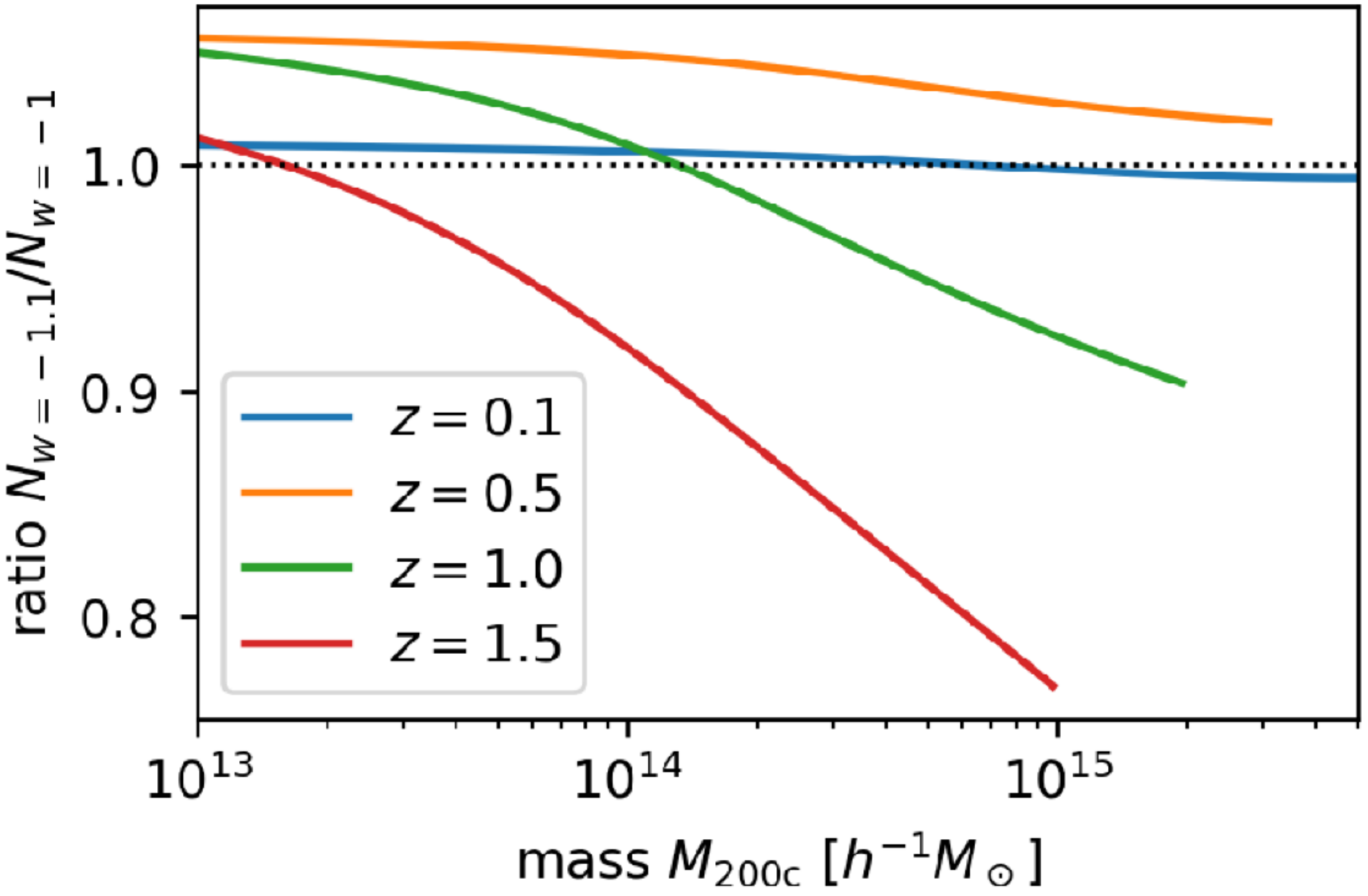


Large-Scale Structure and Cosmology

Credit: Katrin Heitmann

Halo Mass Function

Impact of changing dark energy equation of state parameter by 0.1

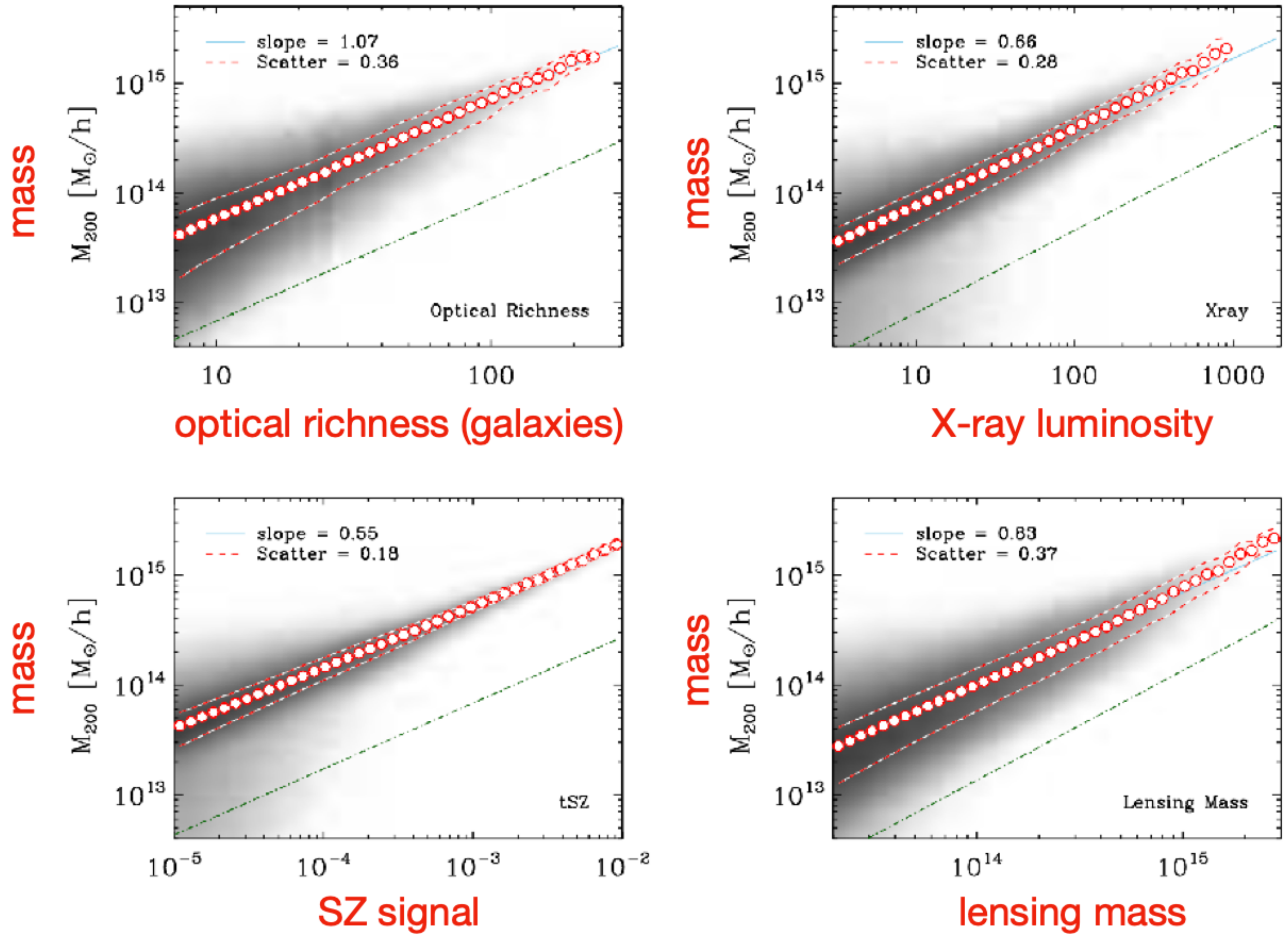


Modeling Framework

Observable — Mass Relations

- The bigger a halo, the stronger its SZ, X-ray, optical, lensing signal
  - Supported by theory and numerical simulations
  - These are average relations — there is intrinsic scatter, because no two objects are the same
- For the experts:
  - Halo morphology and evolution lead to correlated scatter among observables

Simulations (Angulo+12)

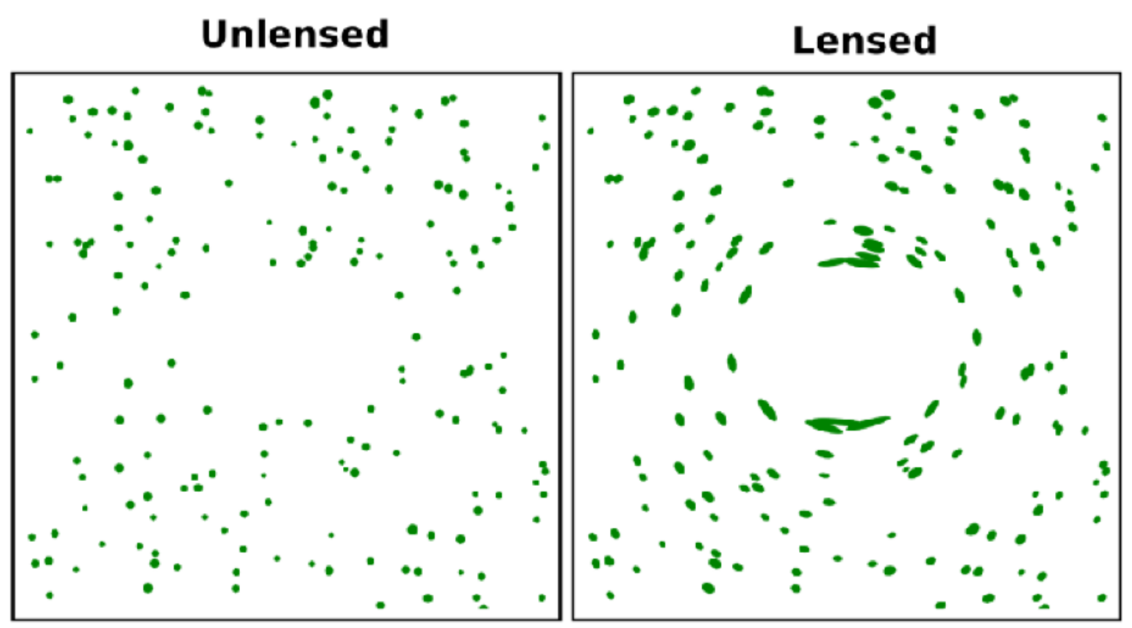


spectral distortion of the CMB through inverse Compton scattering
by high-energy electrons in galaxy clusters -> independent of z

Weak-Lensing Mass Calibration

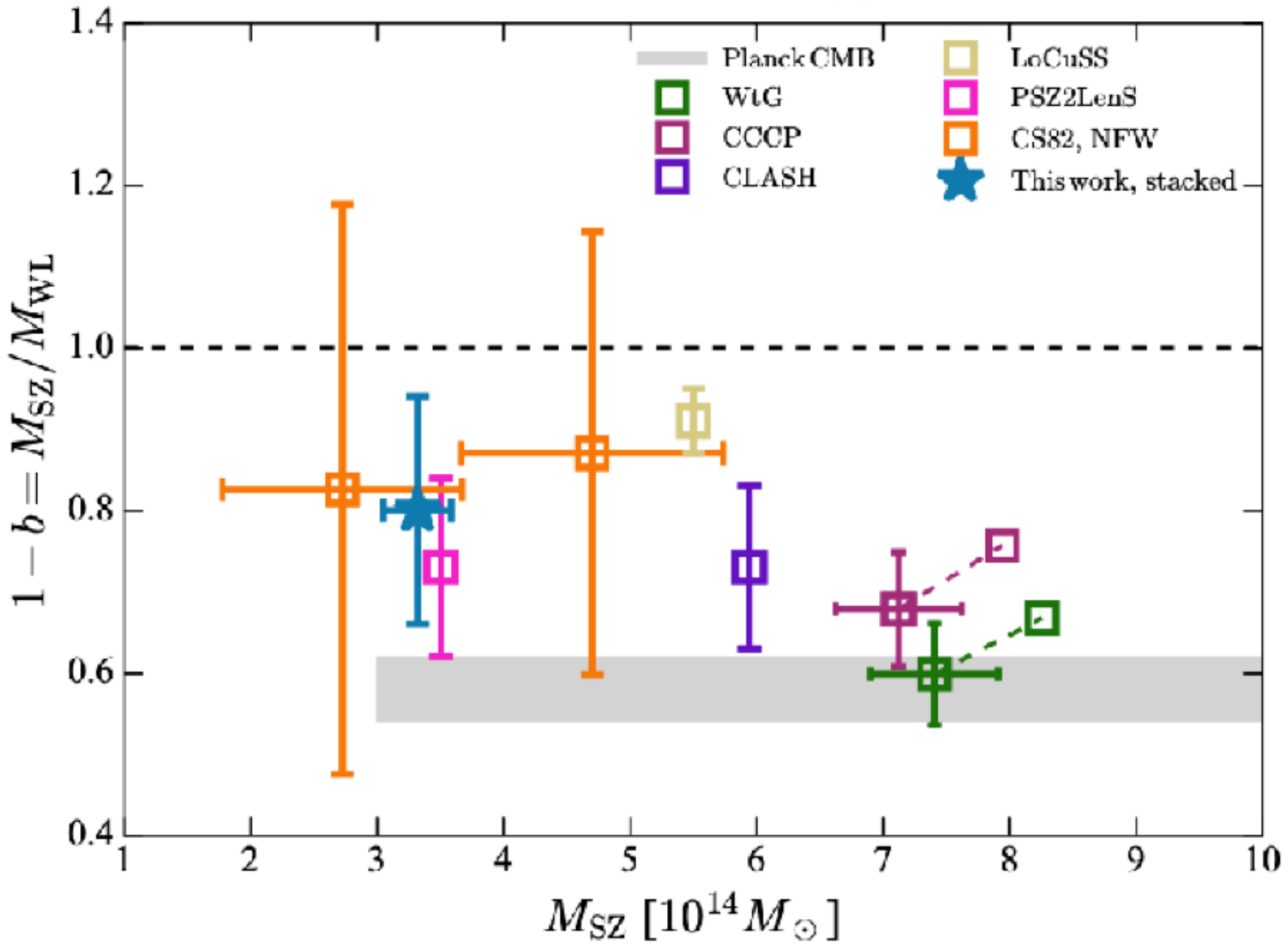
Robust observable—mass relations

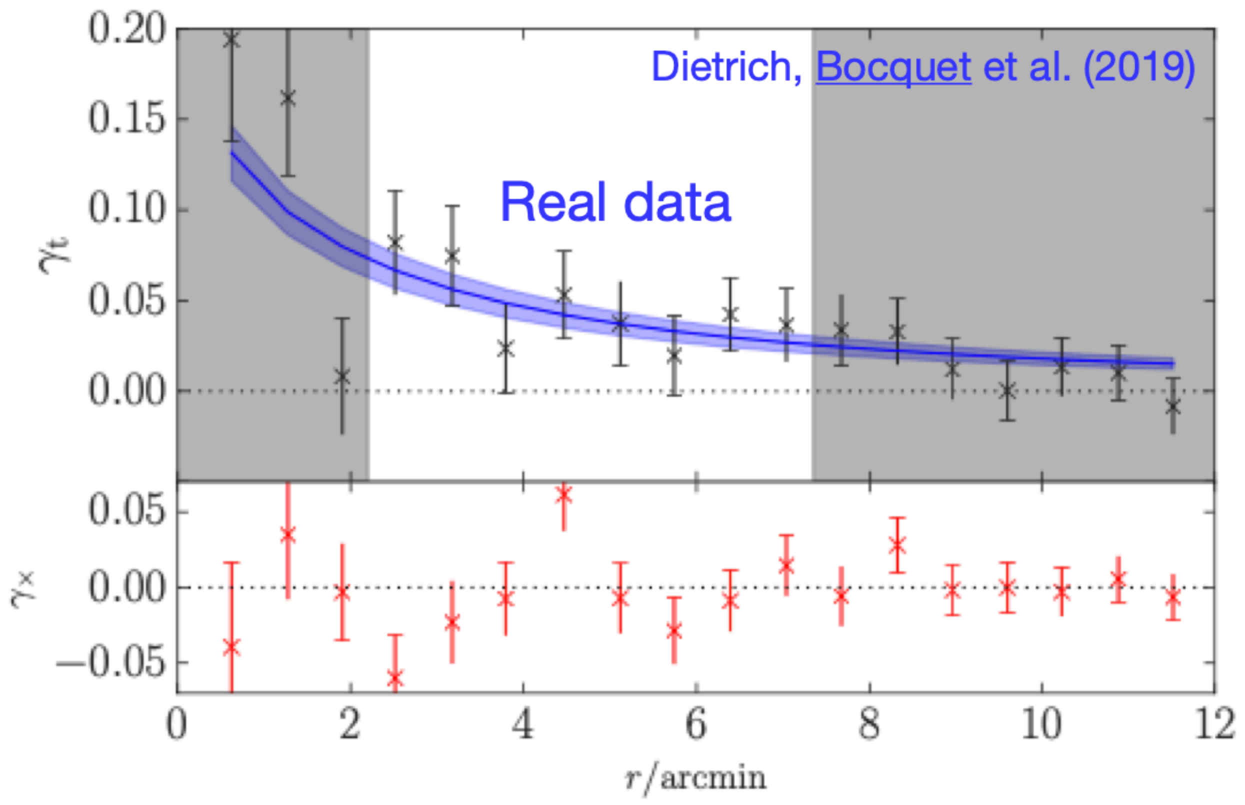
Idealized (exaggerated) situation



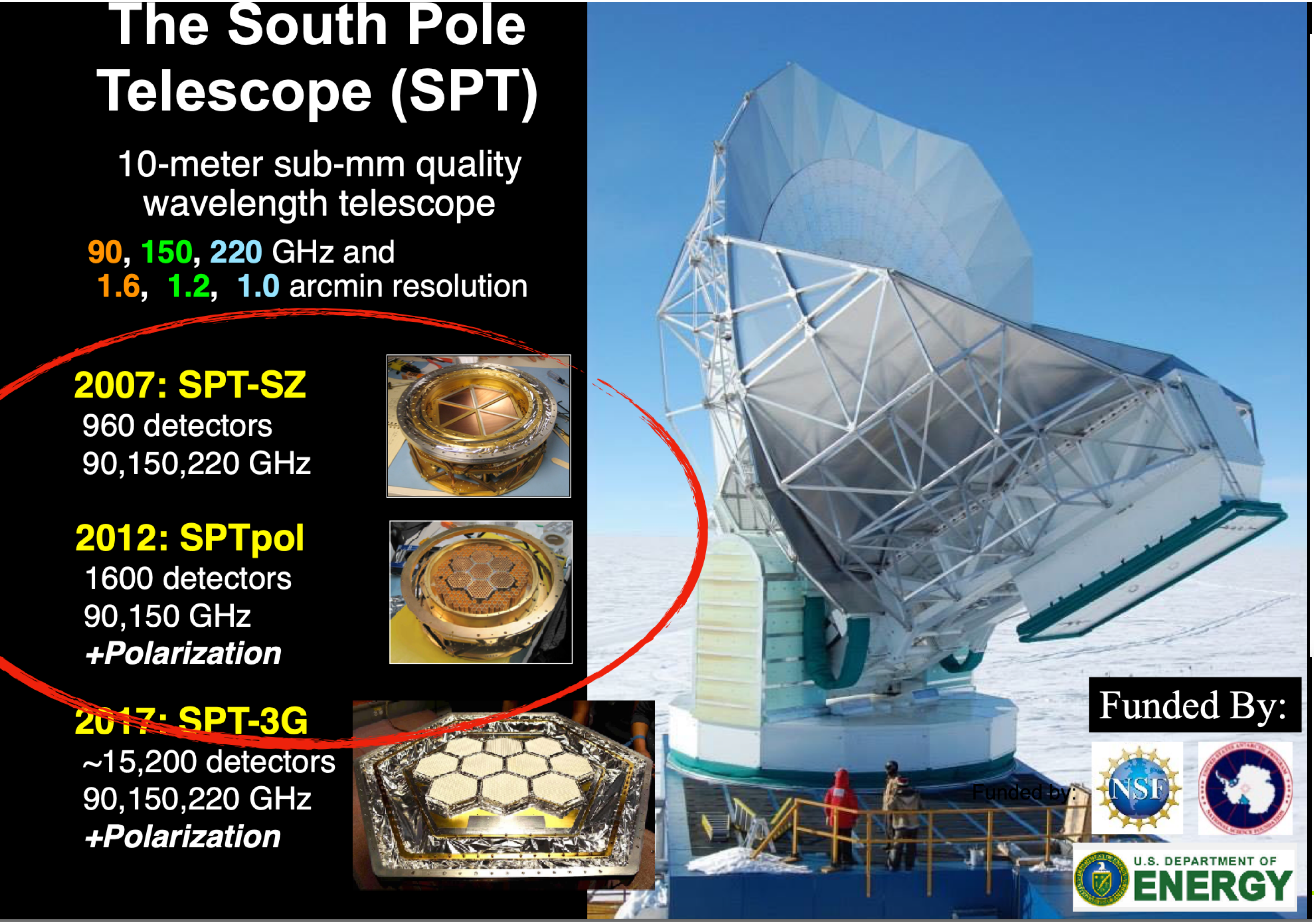
By TallJimbo - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=4150002

- We *could* use predictions from first principles (e.g., hydrostatic equilibrium) or numerical simulations
  - Systematically limited by uncertain astrophysics
- Weak-lensing-to-mass relation is known within few percents
  - Used to demonstrate that **hydrostatic mass ≠ halo mass**
  - **With lensing** measurements of sample clusters, **we *empirically* calibrate the observable—mass relations**





(b) Tangential shear profile of SPT-CL J0254−5857.



The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

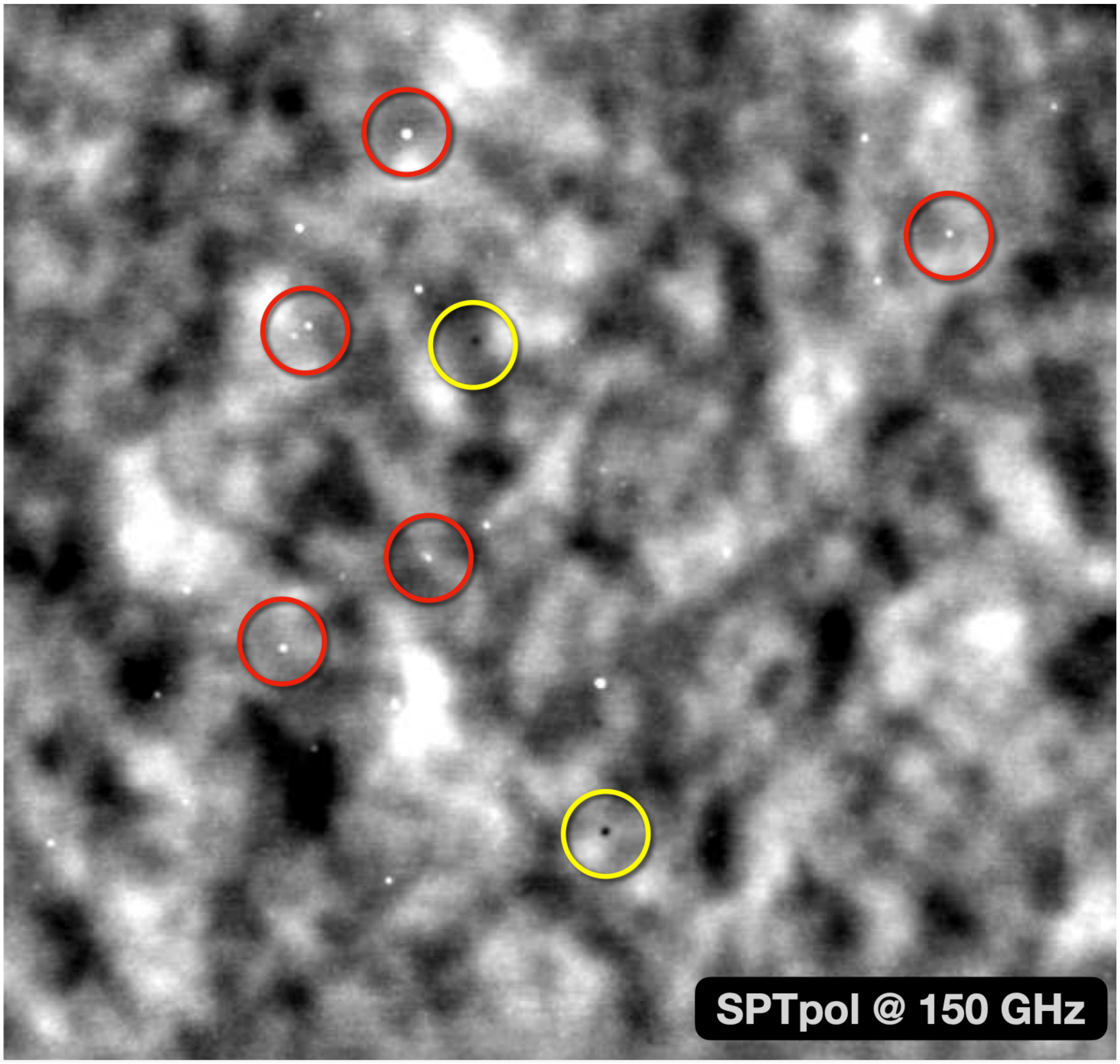
90, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

2007: SPT-SZ
960 detectors
90,150,220 GHz

2012: SPTpol
1600 detectors
90,150 GHz
+Polarization

2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization

Funded By:



- Clean and well-understood selection of candidates
- Very high redshift clusters can be detected !

The Dark Energy Survey

5000 deg^2 galaxies & weak lensing

Catalog of SPT-selected cluster candidates needs

- Confirmation
- Cluster redshifts
- Weak-lensing (mass) measurement

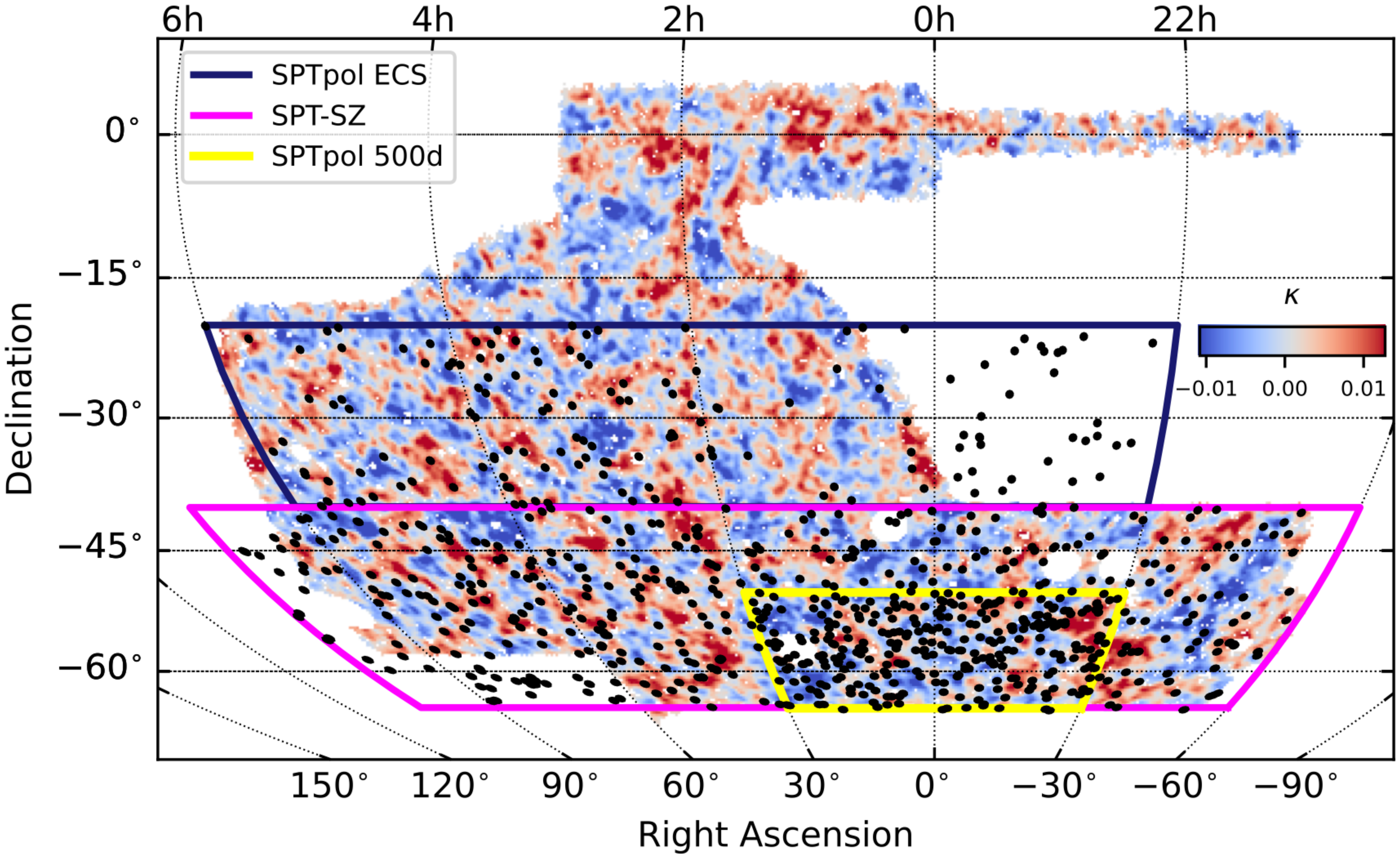
all of which DES was designed for

(here we use DES Year 3 data = Y3)

Image credit: CTIO/NOIRLab/NSF/AURA/D. Munizaga

SPT Clusters and the Dark Energy Survey

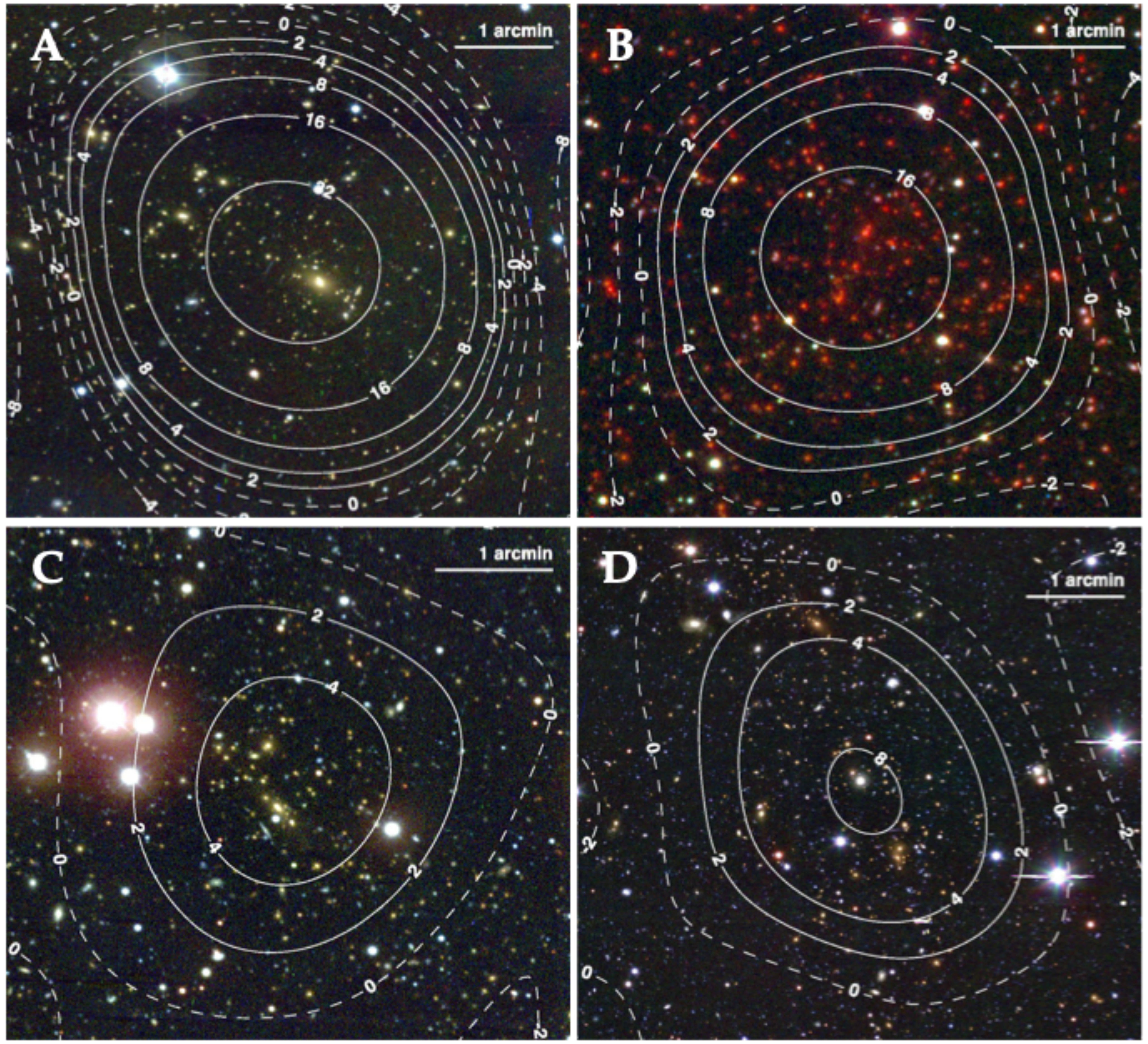
3,600 deg² overlap



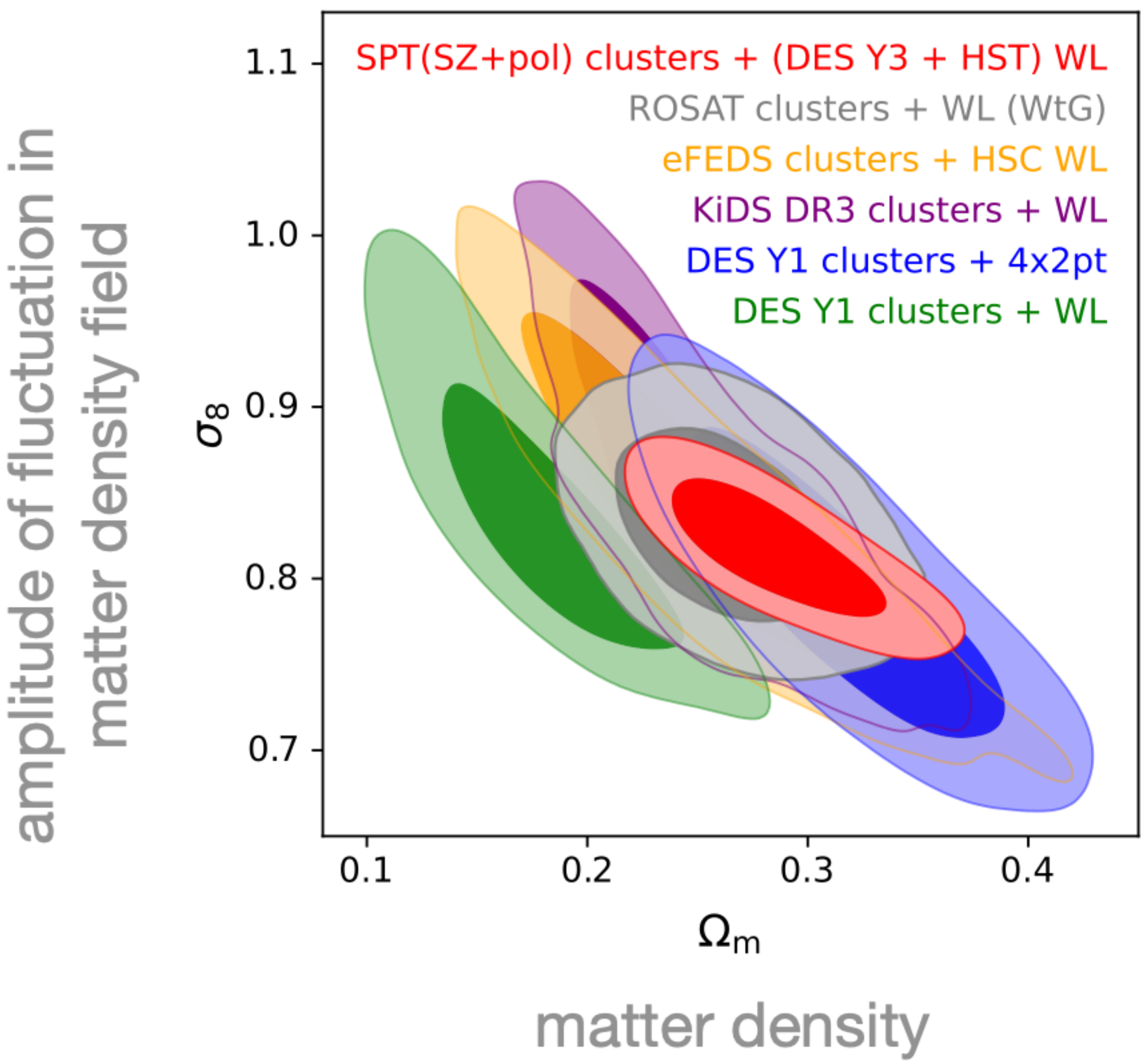
Bleem+15,20,24
Klein+24
Bocquet+24II

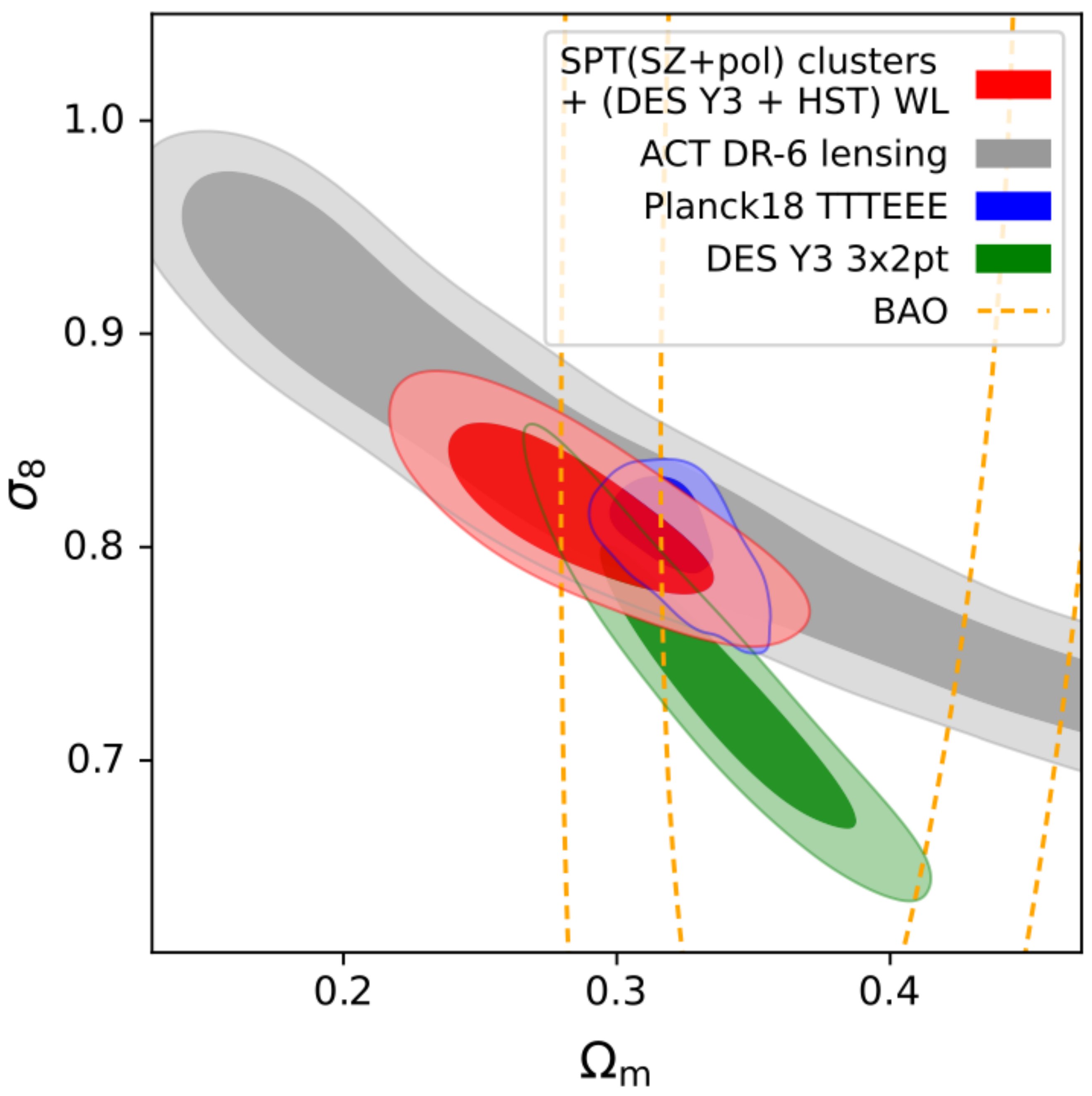
SZ Cluster Selection + Optical Confirmation

- 1005 confirmed clusters above *z* > 0.25 over 5,200 deg^2
- Almost 700 SPT clusters (redshift 0.25—0.95) with DES Y3 shear

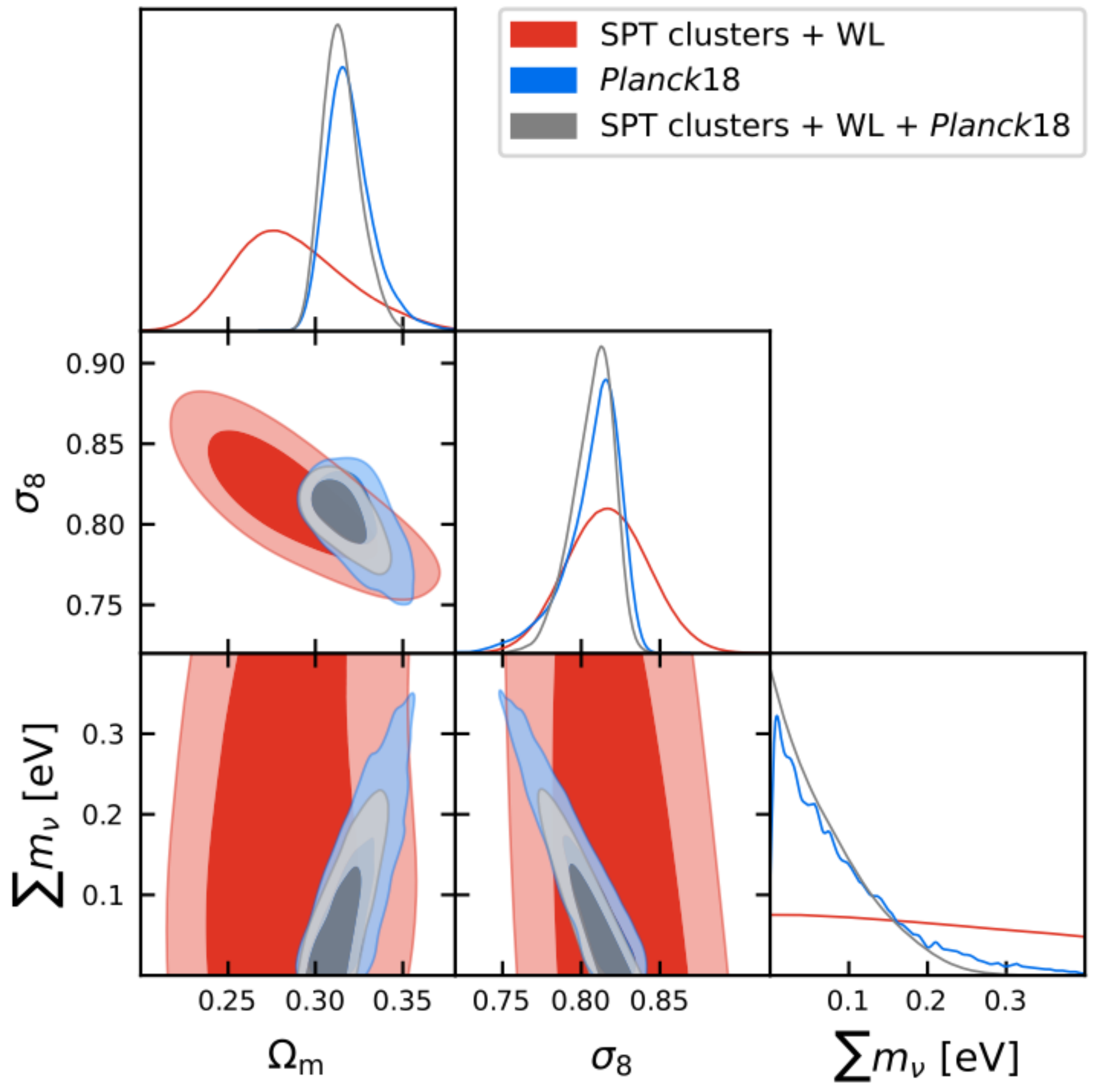


ΛCDM with massive neutrinos





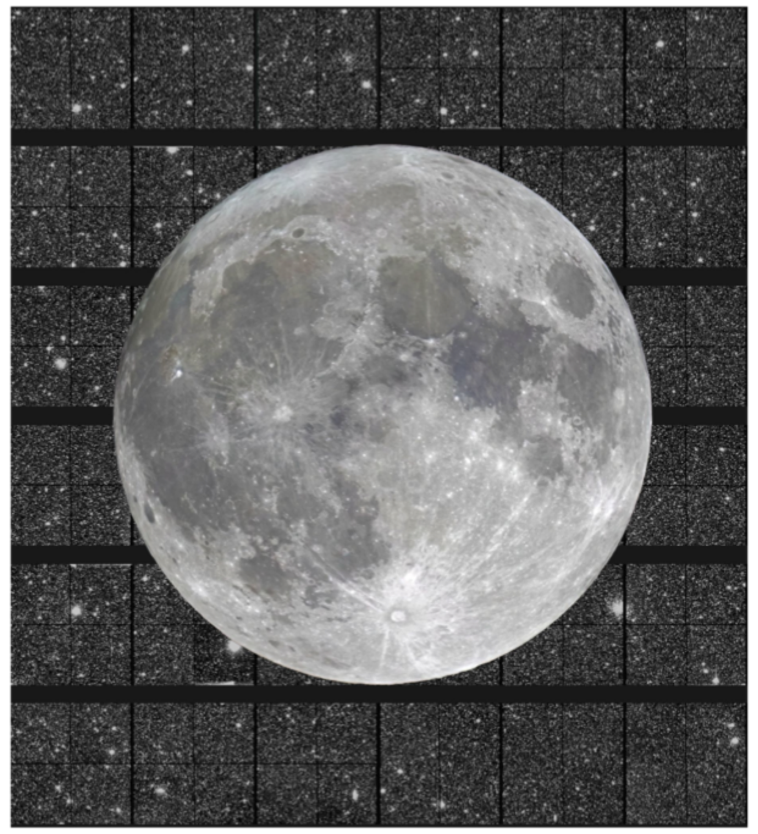
Bocquet+24II

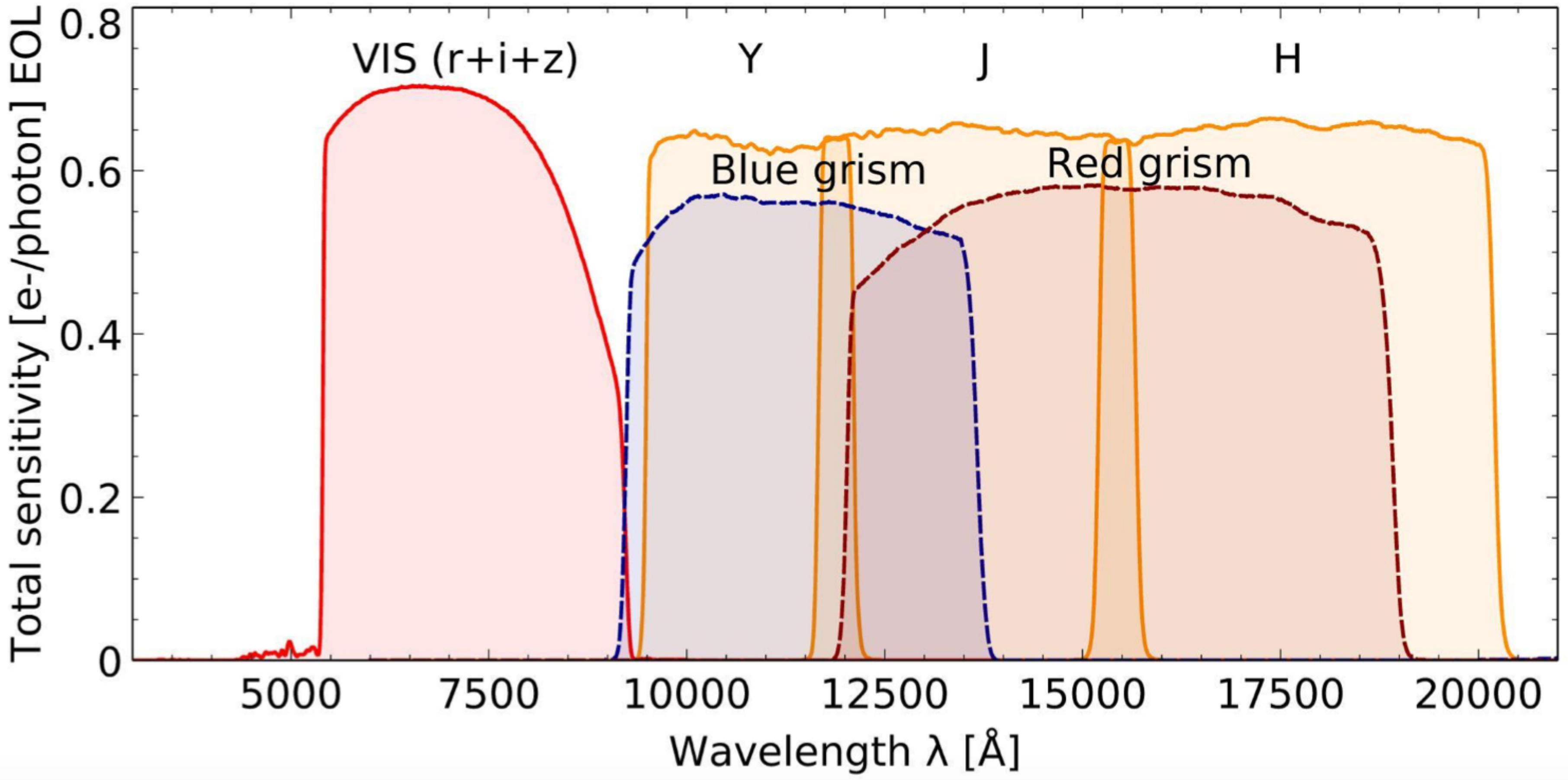


- Competitive constraints, especially on $S_8^{\mathrm{opt}} \equiv \sigma_8 \left(\Omega_\mathrm{m}/0.3\right)^{0.25}$
- No evidence for "S_8 tension" with Planck (1.1 σ)
- In combination with Planck $\sum m_\nu < 0.18\,\mathrm{eV}\,(95\,\%\,\mathrm{C.L.})$

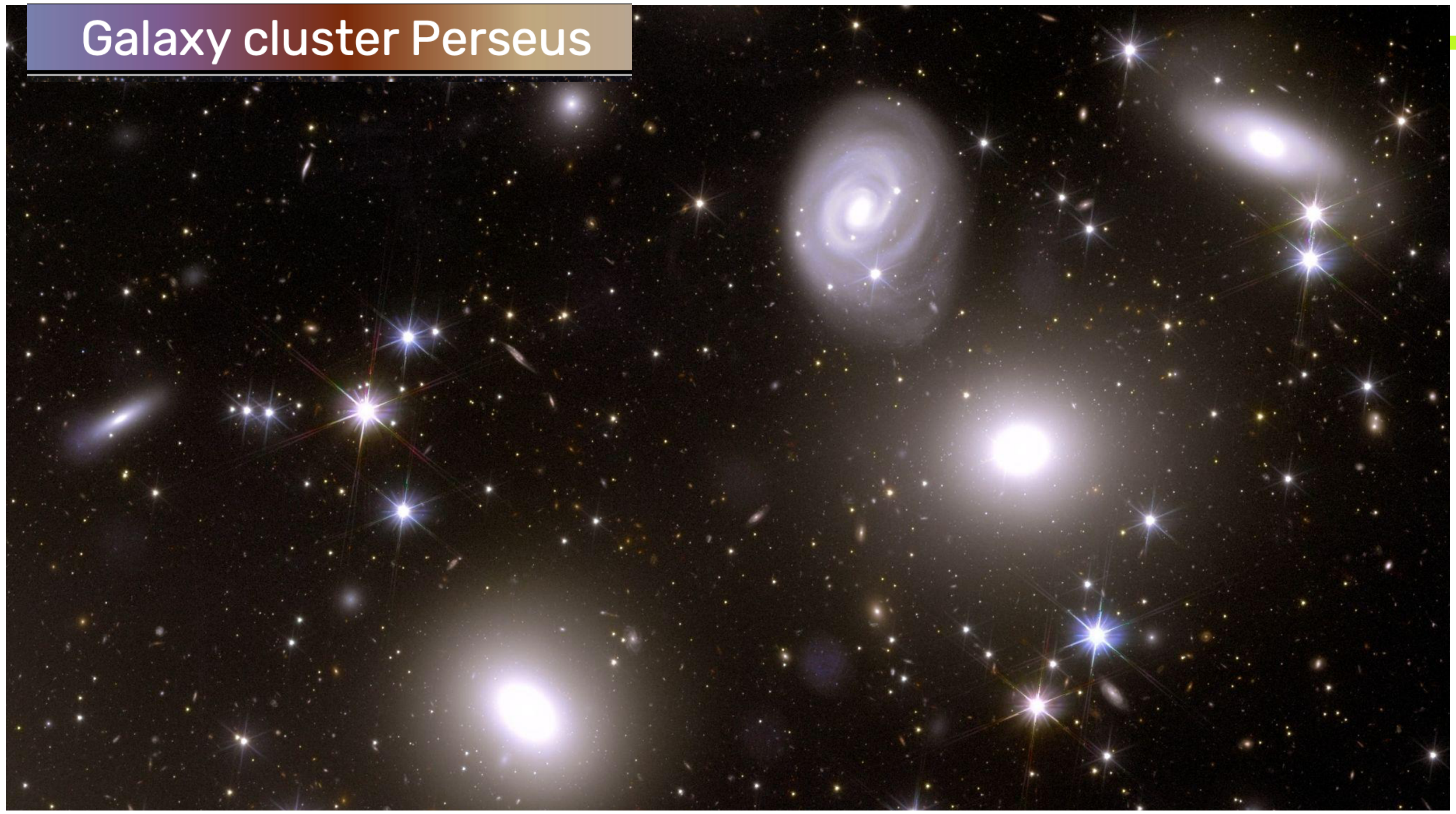
First images of Euclid

- Primary mirror: 1.2 meter
- Field of view: 0.5 square degree (matched optical/near-infrared)
- FWHM optical: 0.14” (610 Mpx CCD mosaic with 0.1”/px, one single broad band)
- FWHM near-infrared: 0.45” (64 Mpx FPA mosaic with 0.3”/px, three bands)
- Low-resolution grism near-infrared spectroscopy (R~400)
- Located at L2 for its 6 year-long DE mission to cover 14 000 square degrees





Euclid Wide Survey (blue) + Deep Survey (yellow) + 10 ERO

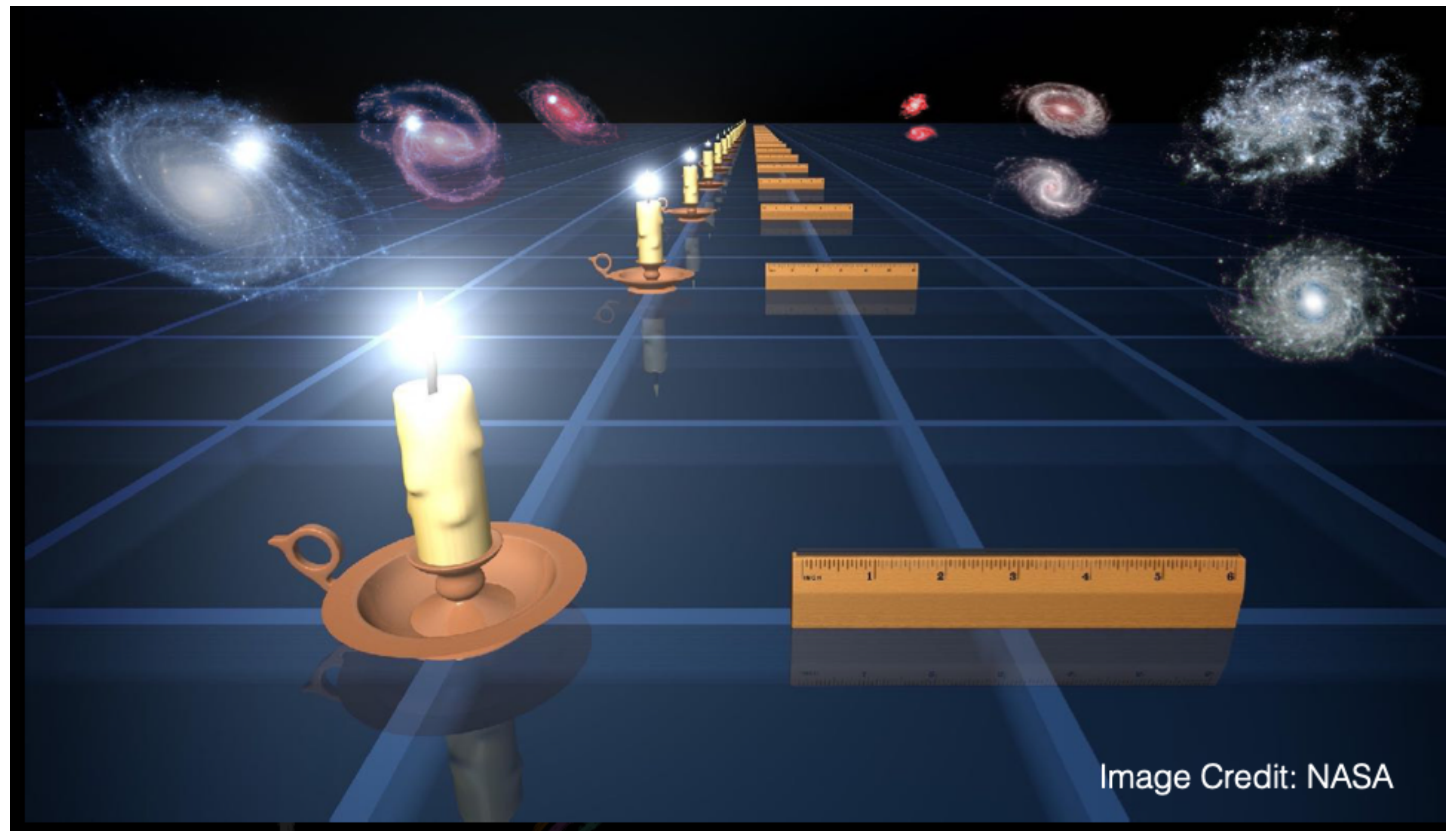

Galaxy cluster Perseus


Star formation region Horsehead


Galaxy cluster Abell 2390

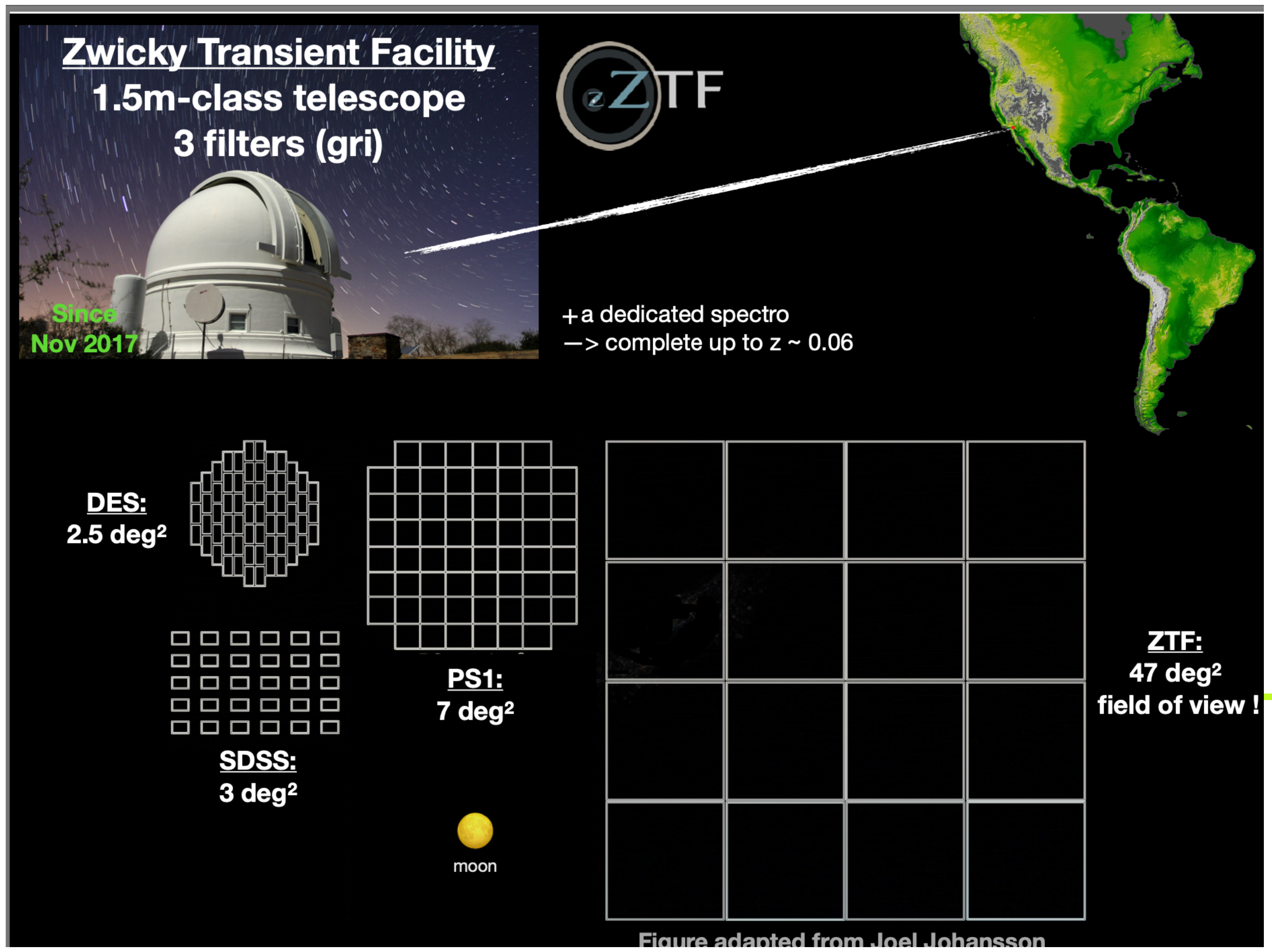

Globular cluster NGC 6397

Supernovae



standard candle:
know luminosity
infer distance

standard ruler:
know size
infer distance



Zwicky Transient Facility
1.5m-class telescope
3 filters (gri)

Since Nov 2017

+a dedicated spectro
—> complete up to z ~ 0.06

DES: 2.5 deg²

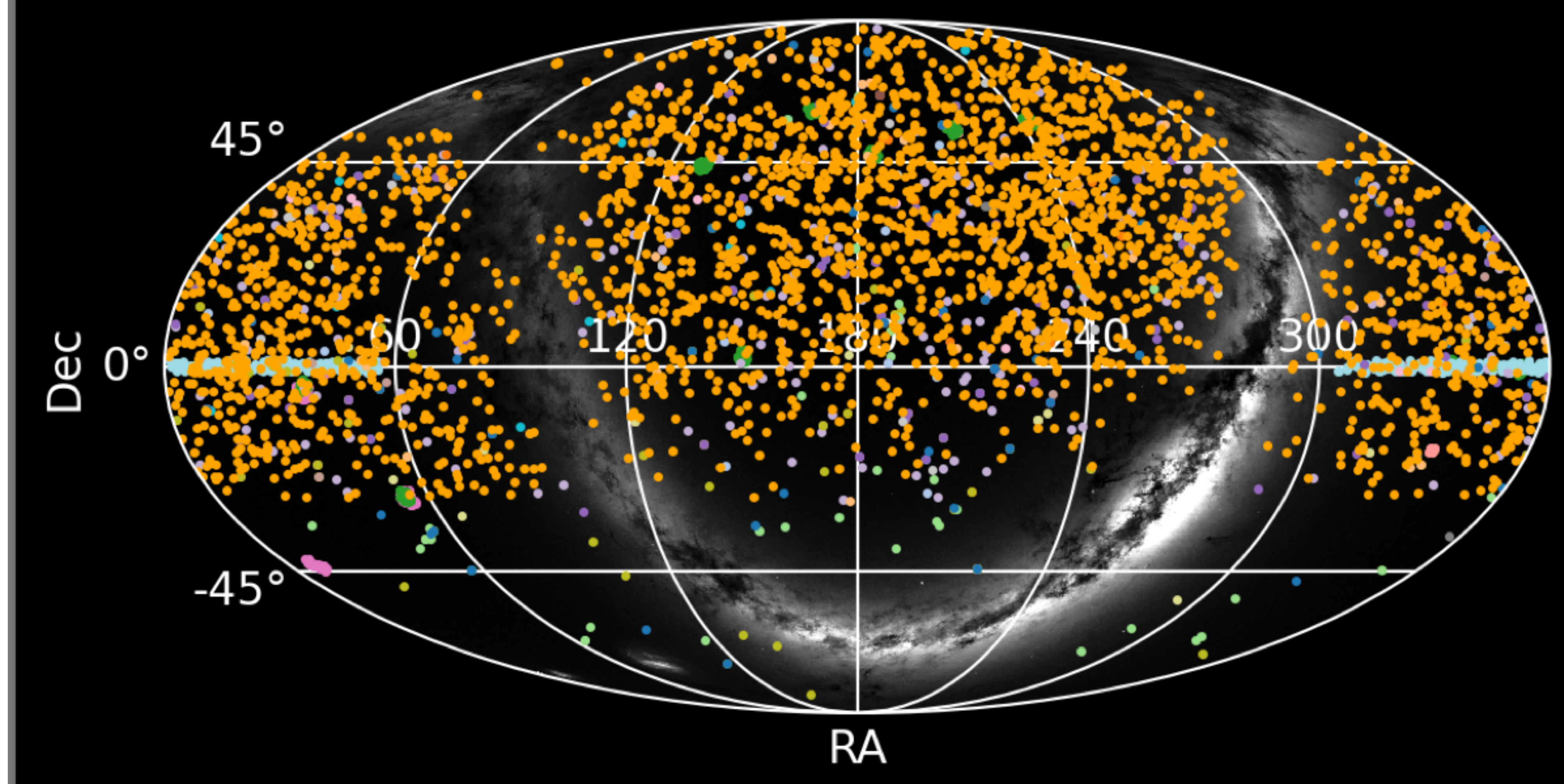
SDSS: 3 deg²

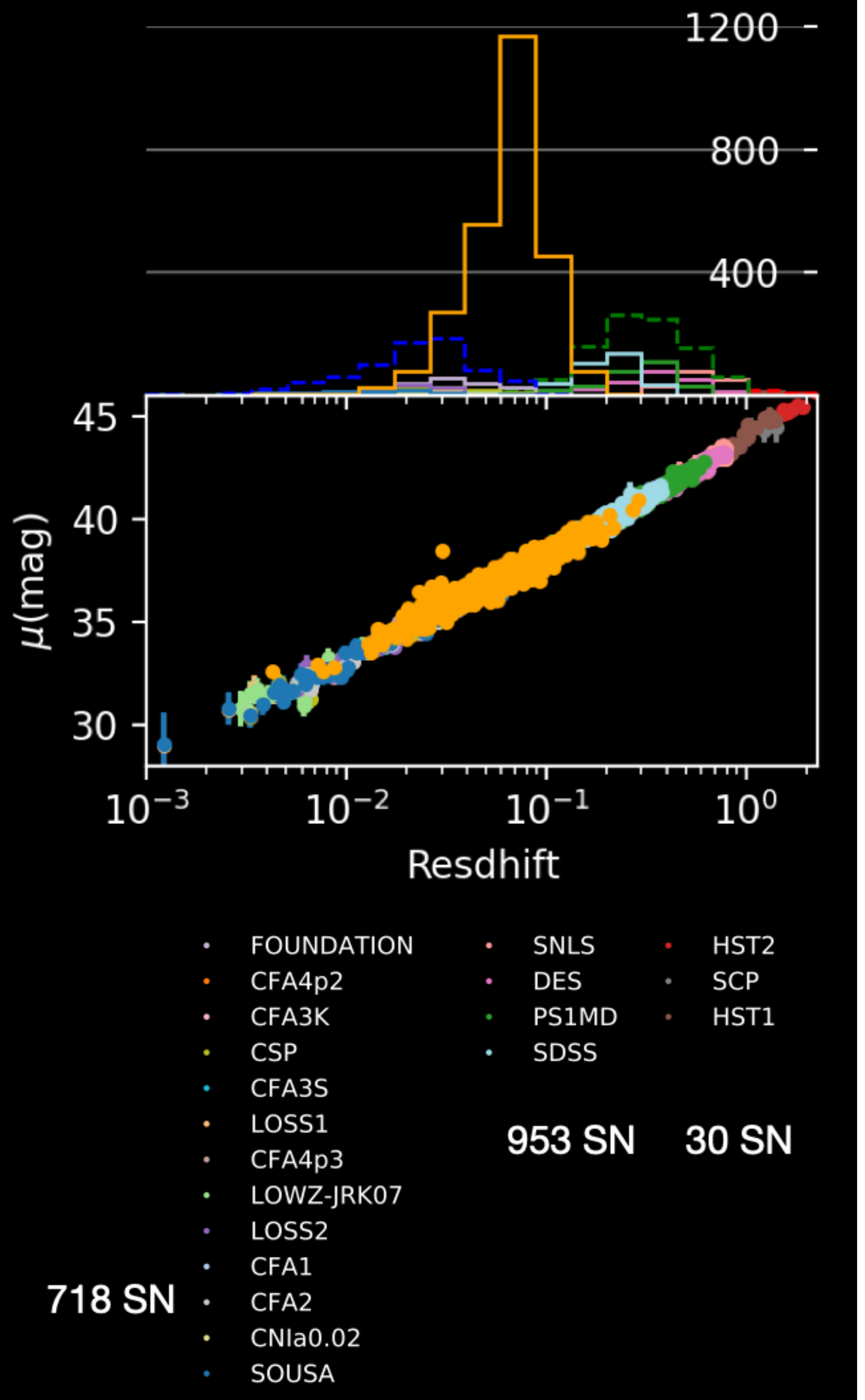
PS1: 7 deg²

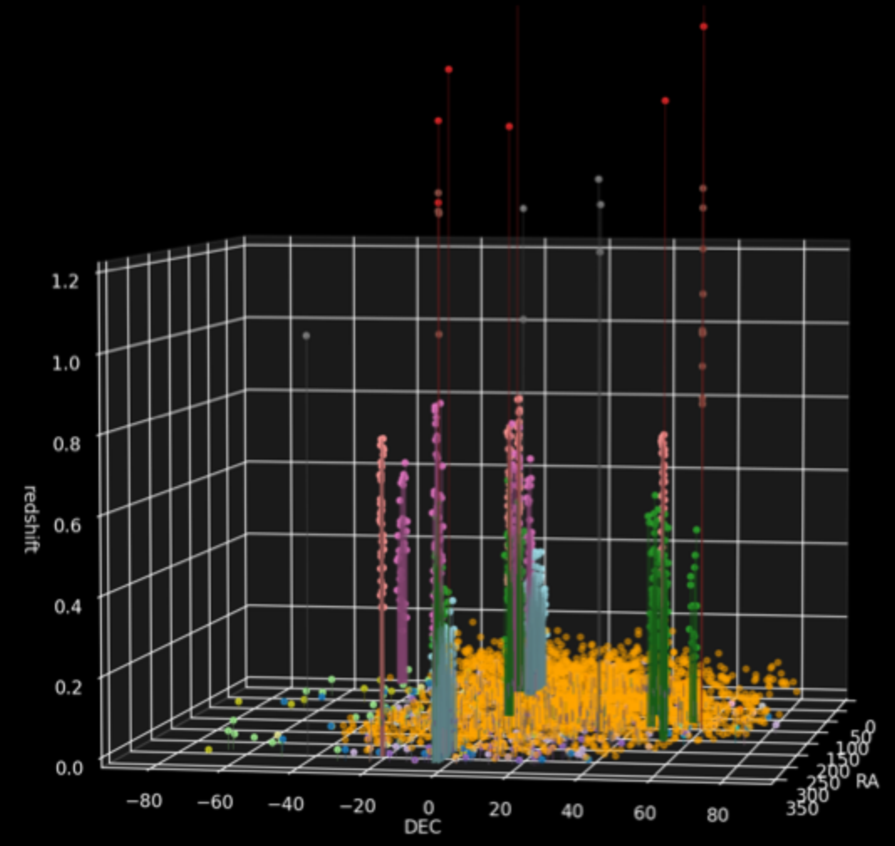
ZTF: 47 deg² field of view !

Figure adapted from Joel Johansson

ZTF DR2: ~ 2,000 SN at low redshift (~5000 at the end of ZTF)



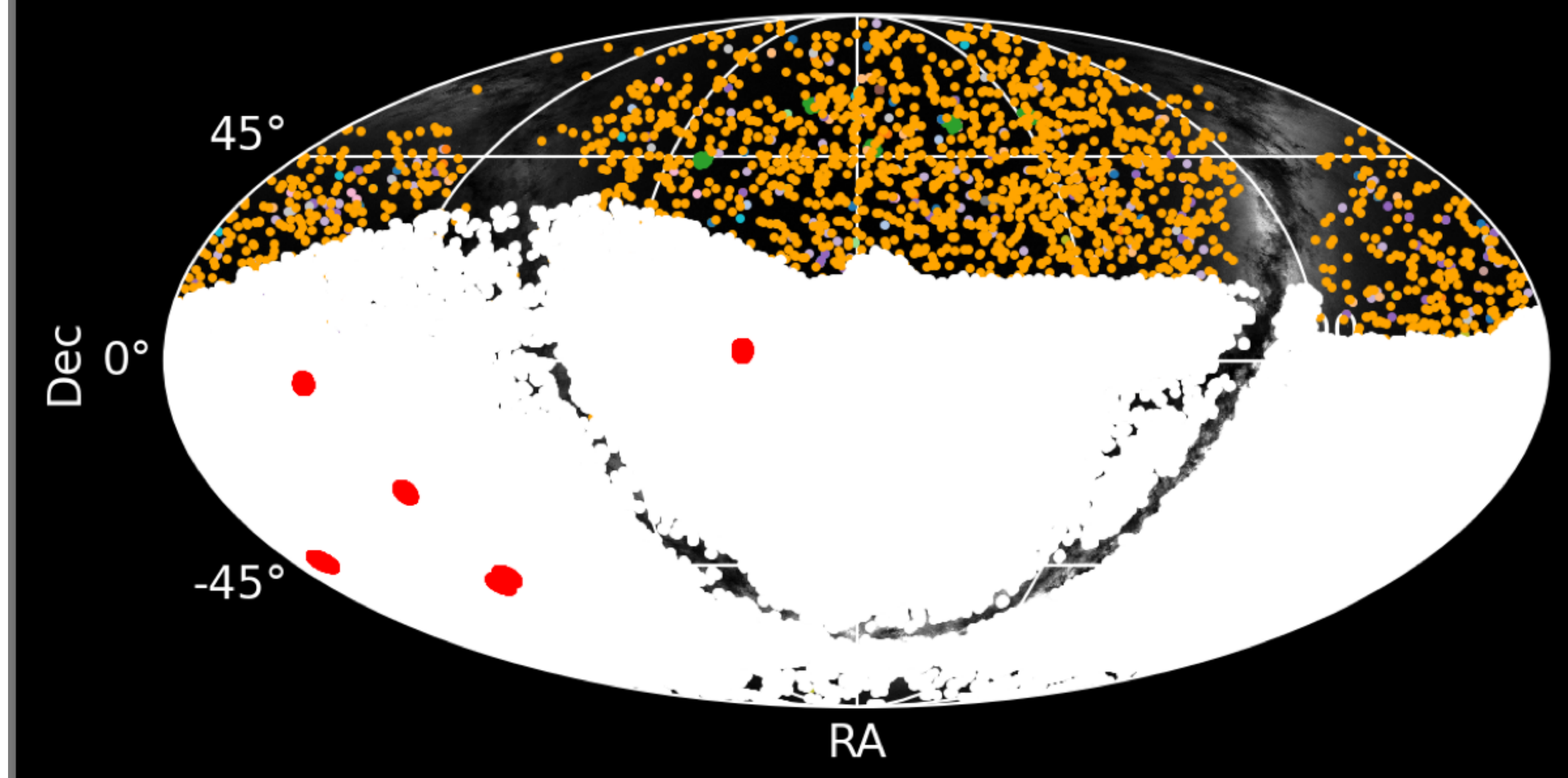


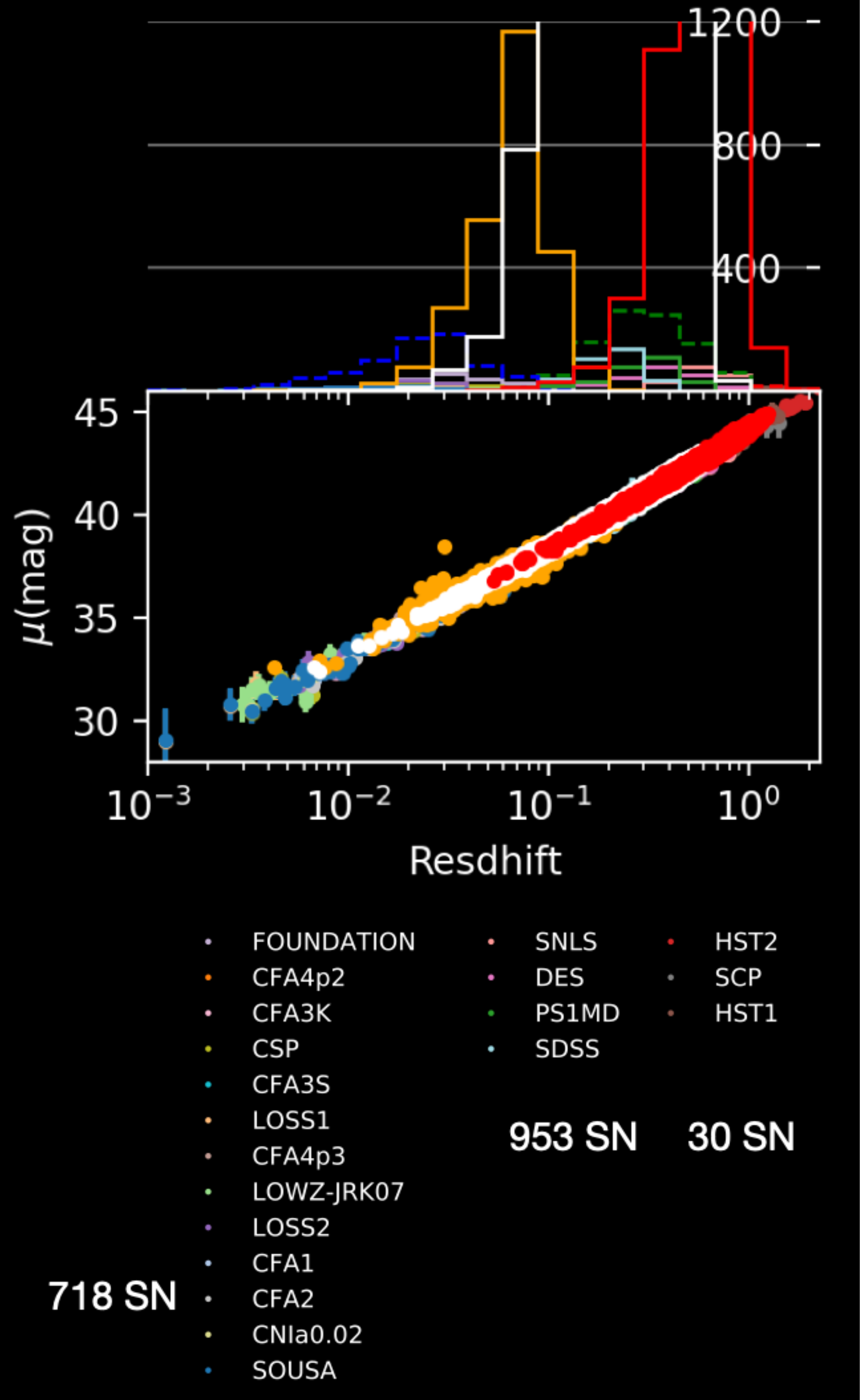


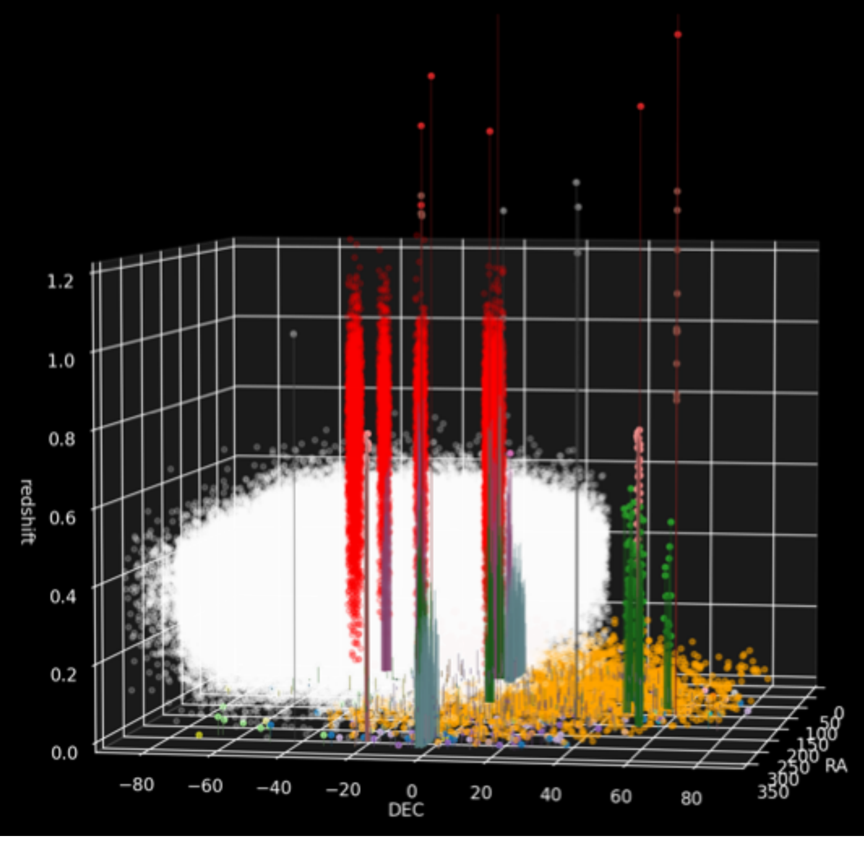
ZTF DR2: ~ 2,000 SN at low redshift (~5000 at the end of ZTF)

LSST wide-fast-deep: ~ 1,000,000 SN at intermediate redshift

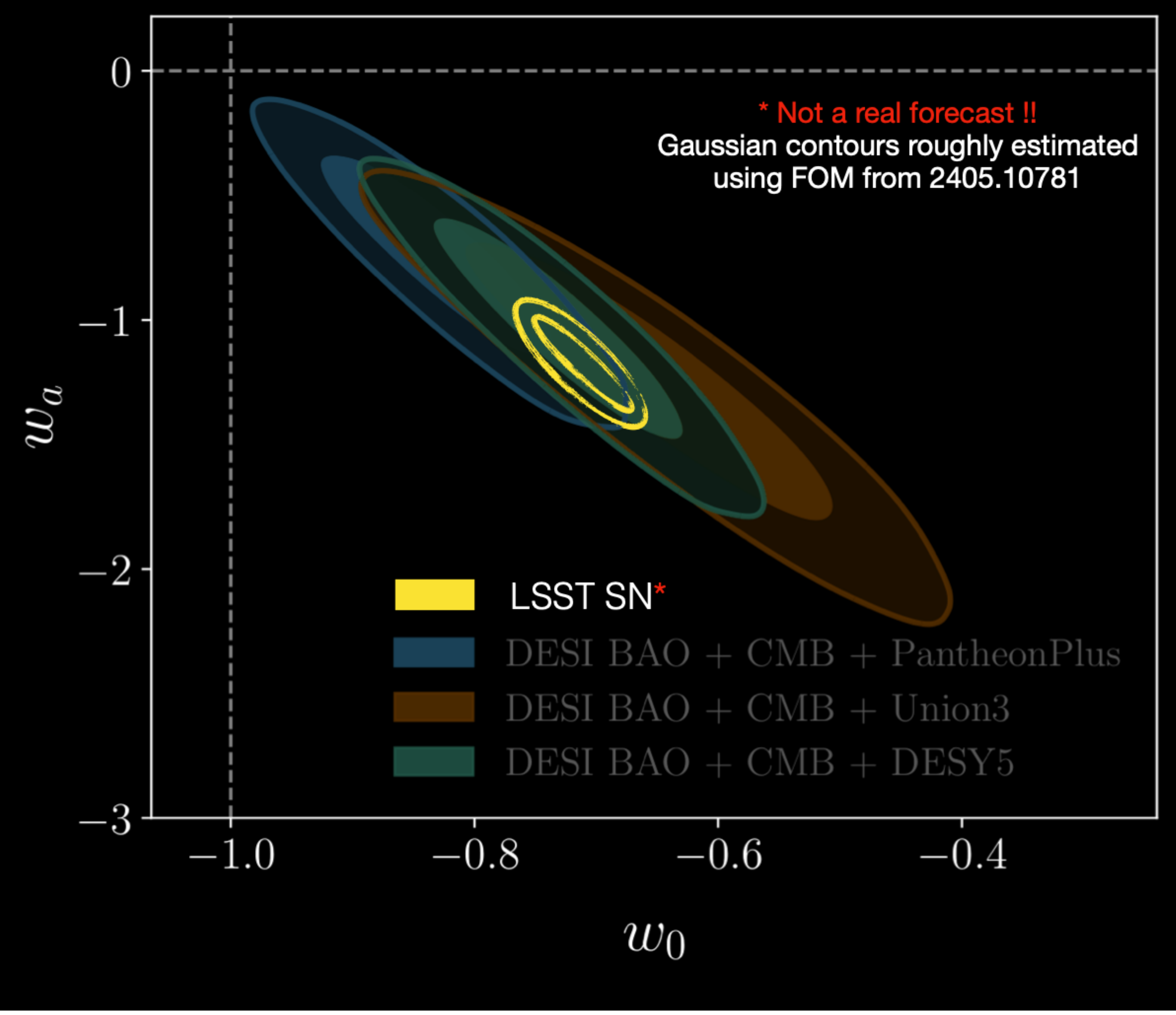
LSST deep-drilling: ~ 10,000 SN at high redshift







LSST will reduce area by ~20

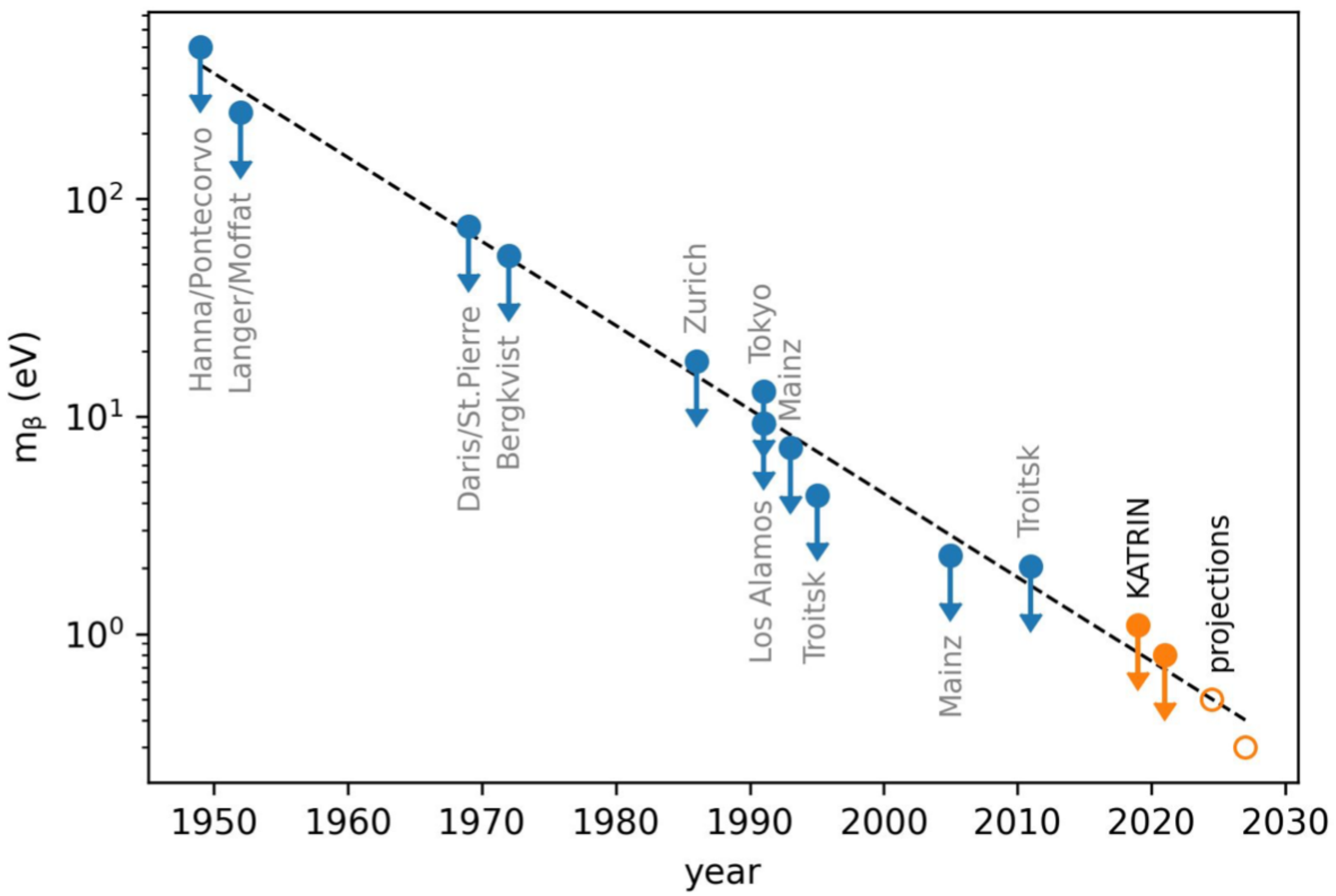


* Not a real forecast !!
Gaussian contours roughly estimated
using FOM from 2405.10781

Full sky coverage:
We will be able to measure the isotropy of the expansion, it’s acceleration, etc

Neutrinos

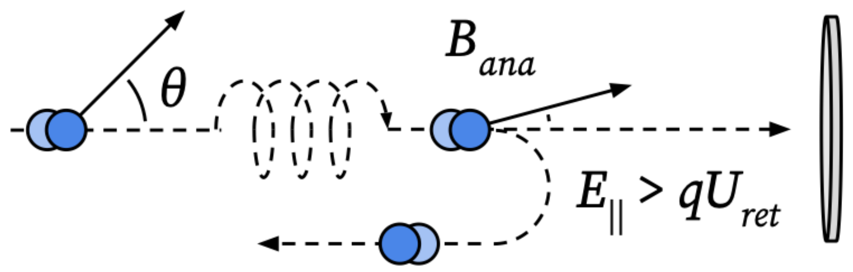
Neutrino mass



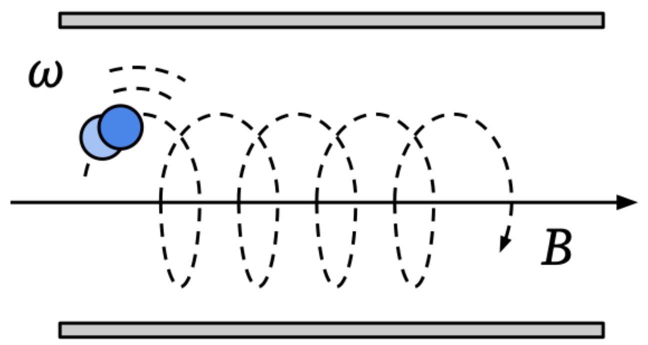
KATRIN world best measurement

Experimental approaches

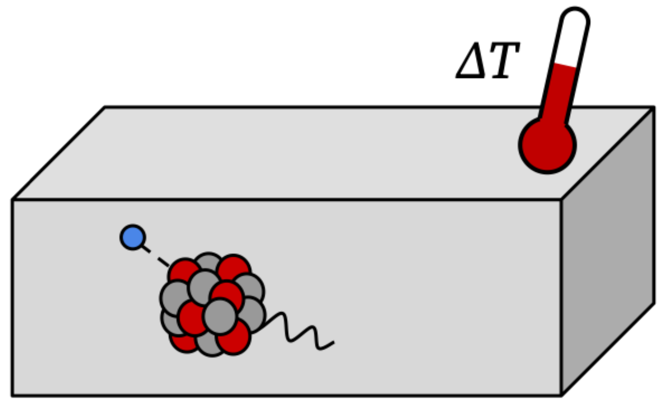
tritium-based



electrostatic
filtering (MAC-E)

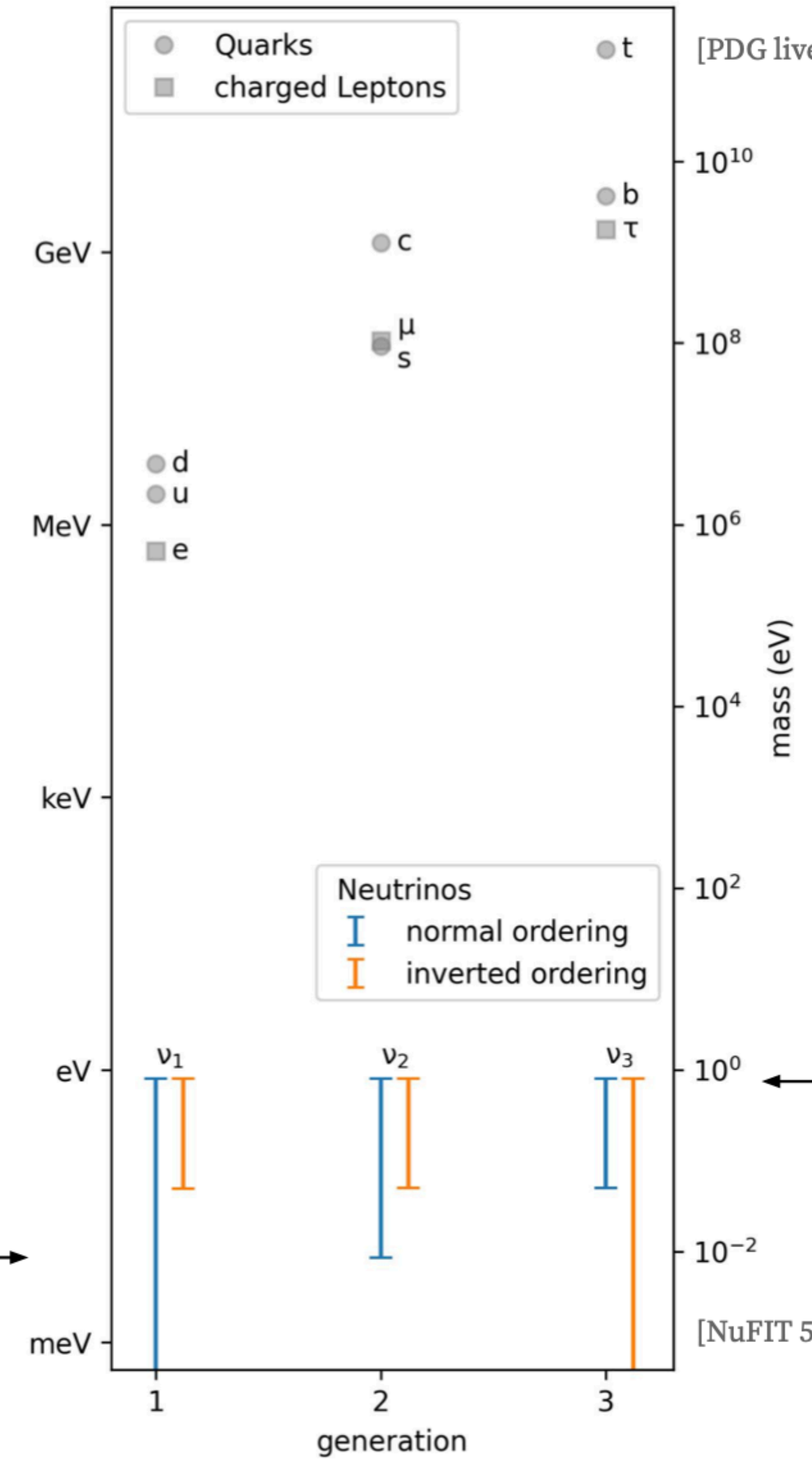


cyclotron radiation emission
spectroscopy (CRES)



cryogenic
calorimetry

R & D



[PDG live, pdglive.lbl.gov]

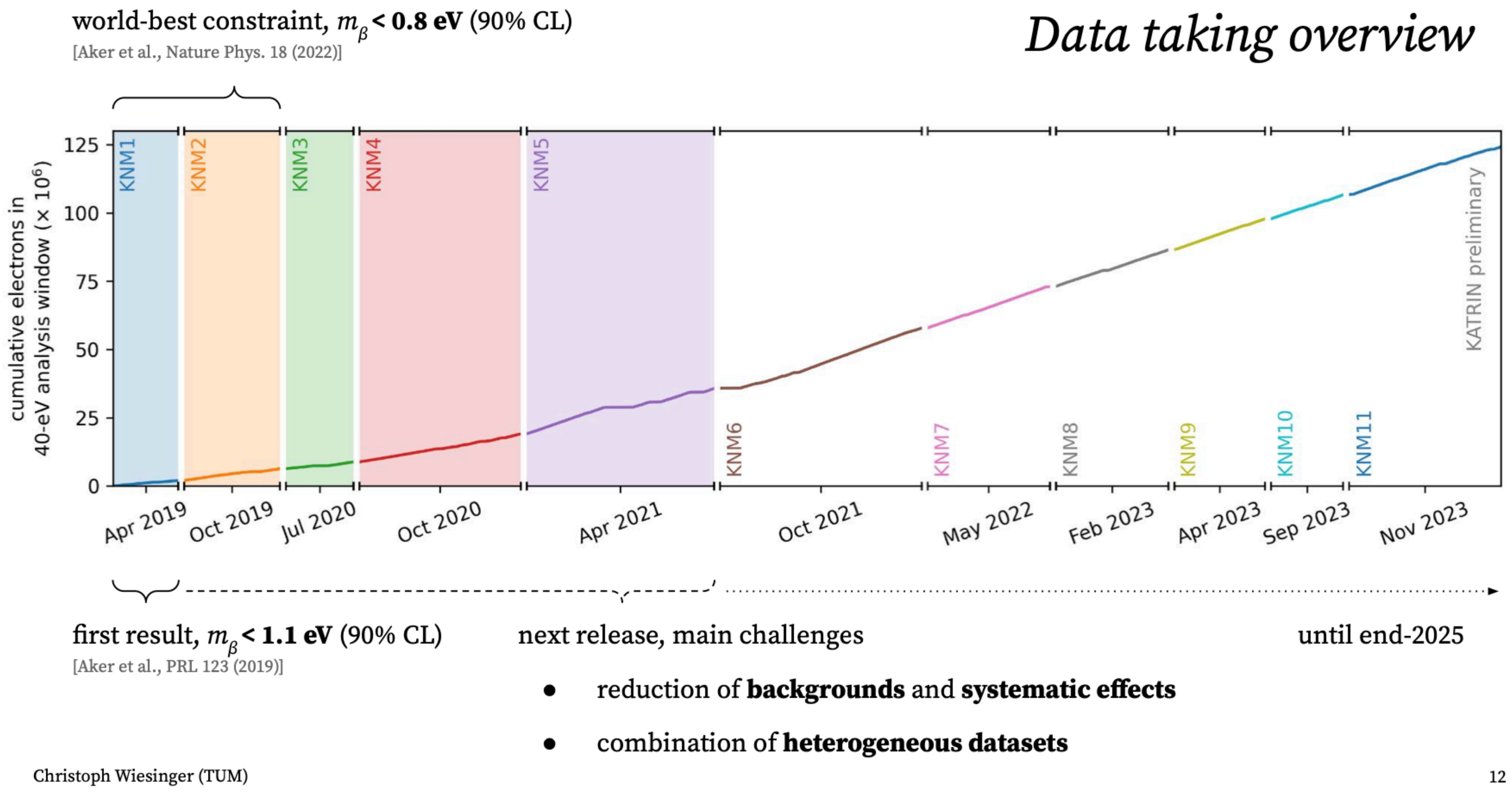
upper bound from
direct measurements

lower bounds from
oscillation experiments

[NuFIT 5.3, nu-fit.org]

Katrin

Karlsruhe Tritium Neutrino (KATRIN) experiment



world-best constraint, $m_\beta < \mathbf{0.8\ eV}$ (90% CL)

[Aker et al., Nature Phys. 18 (2022)]

Data taking overview

first result, $m_\beta < \mathbf{1.1\ eV}$ (90% CL)

[Aker et al., PRL 123 (2019)]

next release, main challenges

- reduction of **backgrounds** and **systematic effects**
- combination of **heterogeneous datasets**

until end-2025

Christoph Wiesinger (TUM)

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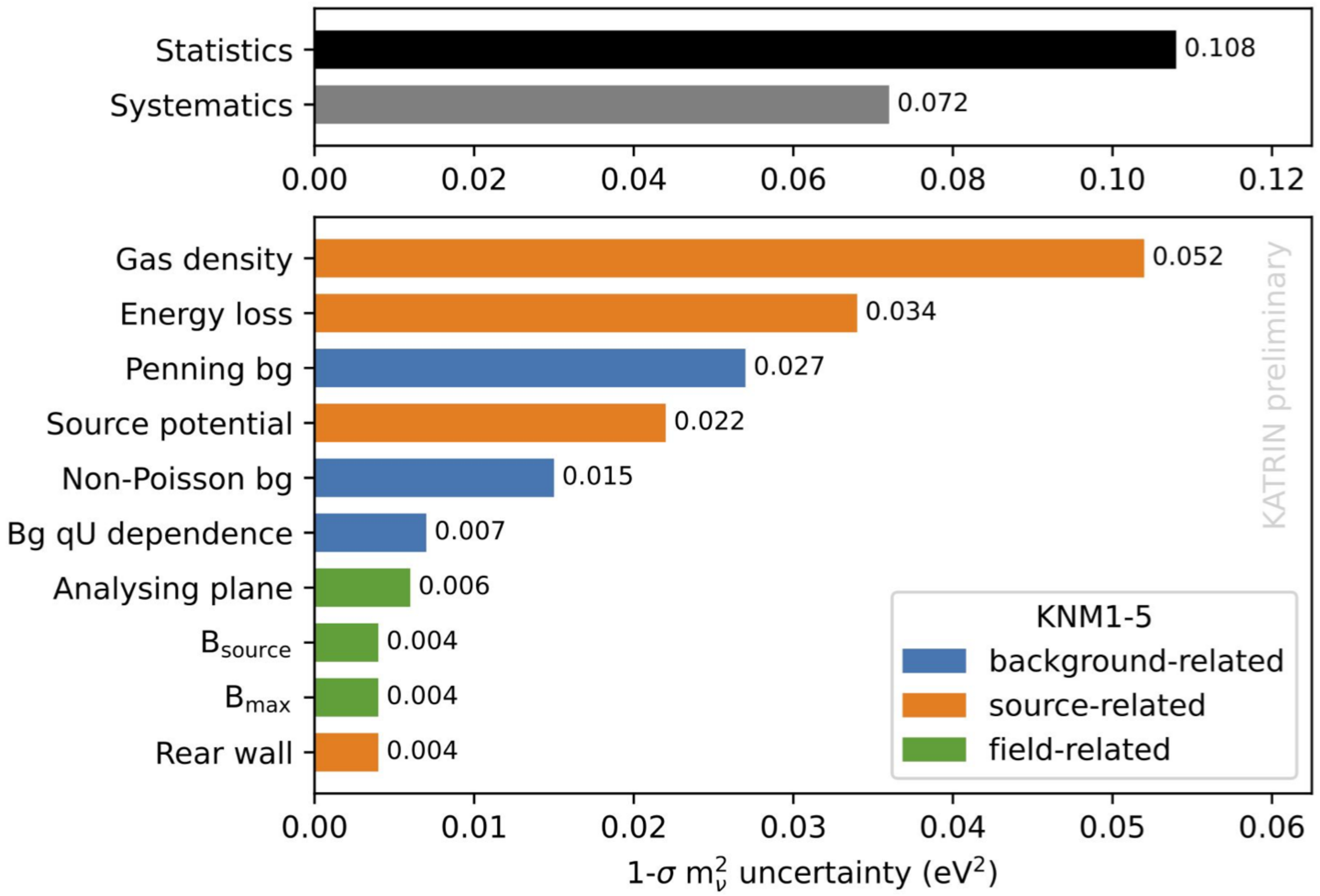
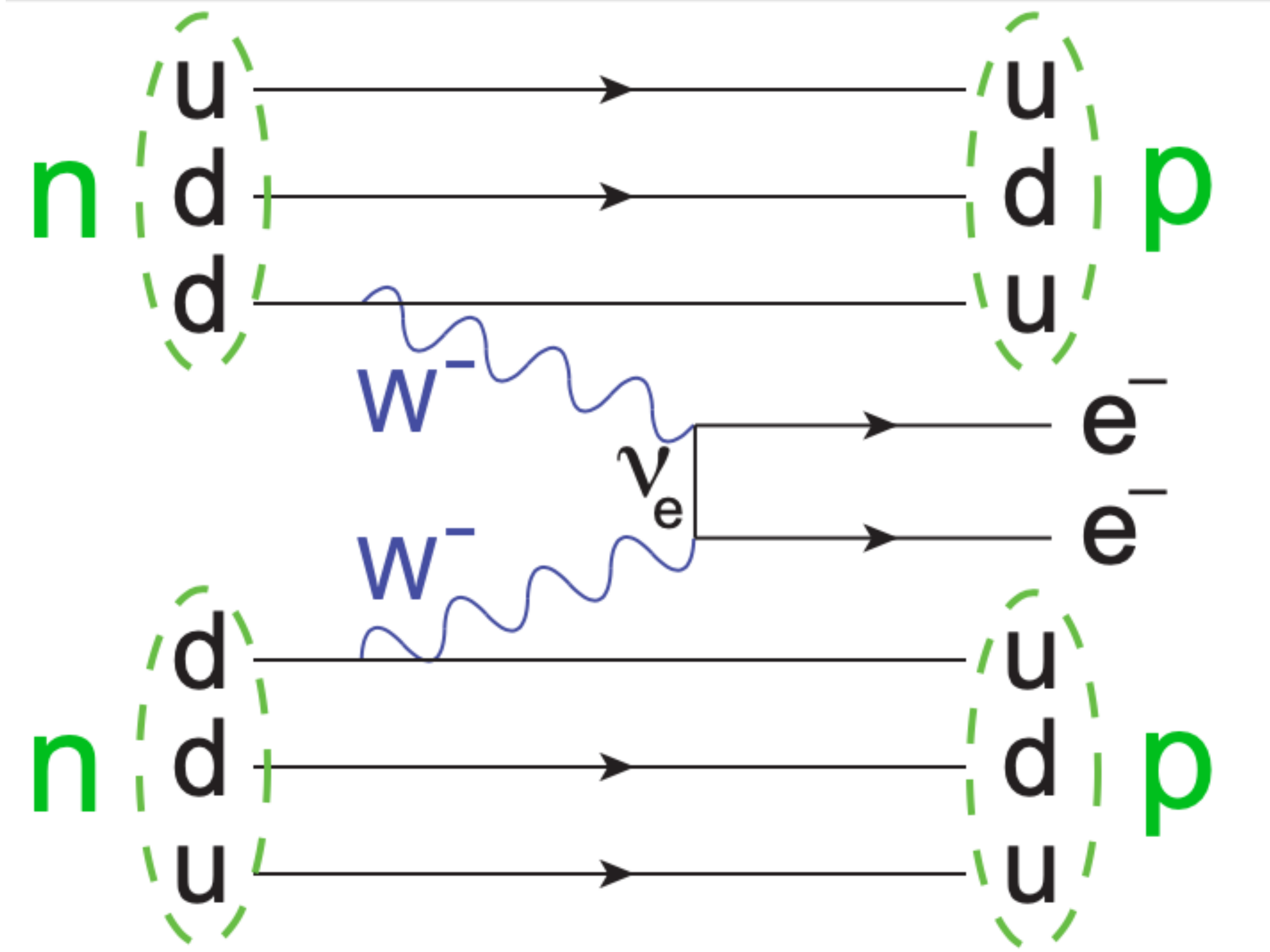
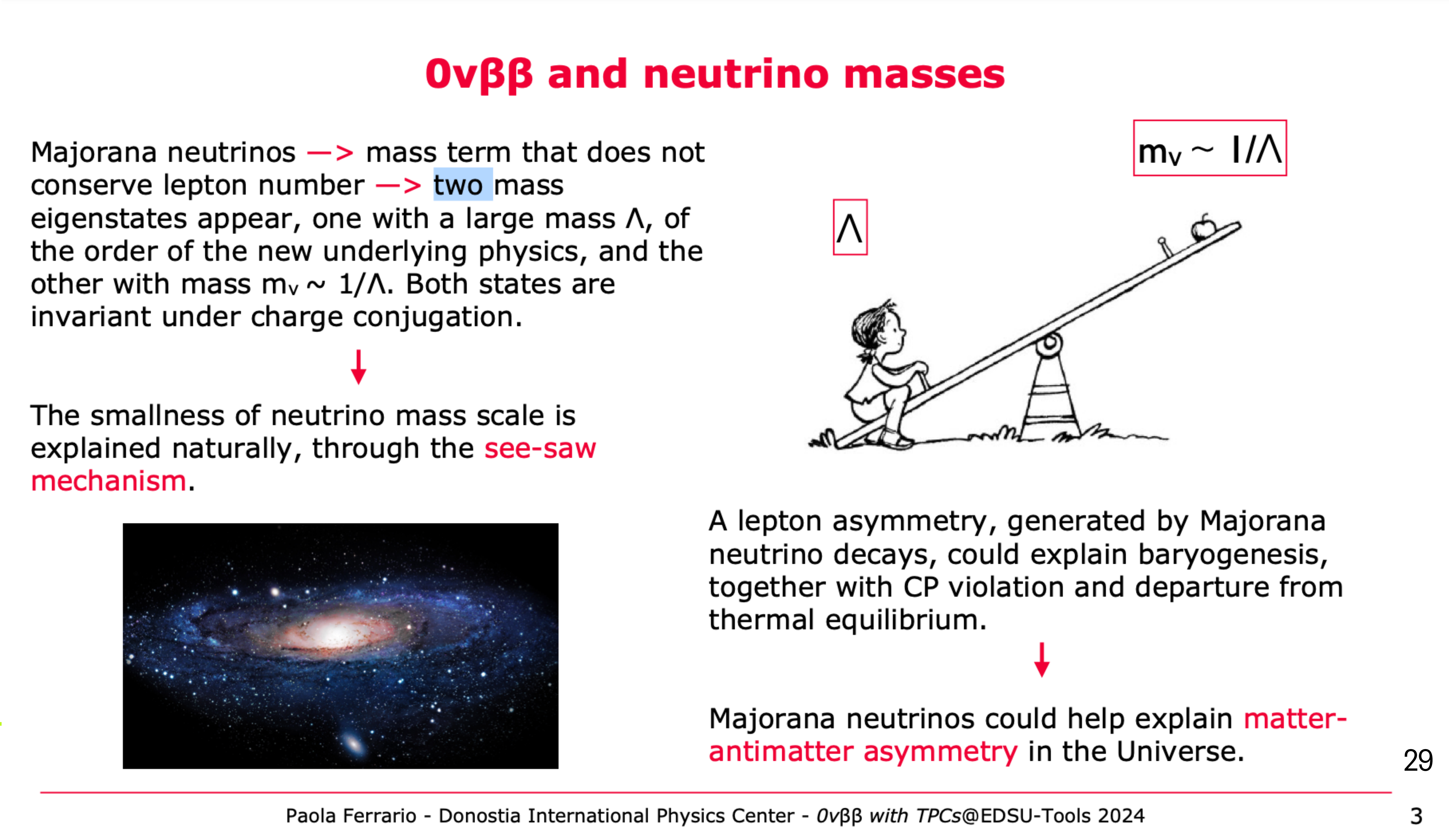


➔ statistics dominated, **projected sensitivity** $m_\beta < \mathbf{0.5\ eV}$ (90% CL)

Neutrinoless double beta decay



- Particle and antiparticle (Majorana)
- Violation of lepton number



0νββ and neutrino masses

Majorana neutrinos —> mass term that does not conserve lepton number —> two mass eigenstates appear, one with a large mass Λ, of the order of the new underlying physics, and the other with mass $m_\nu \sim 1/\Lambda$. Both states are invariant under charge conjugation.

↓

The smallness of neutrino mass scale is explained naturally, through the see-saw mechanism.

A lepton asymmetry, generated by Majorana neutrino decays, could explain baryogenesis, together with CP violation and departure from thermal equilibrium.

↓

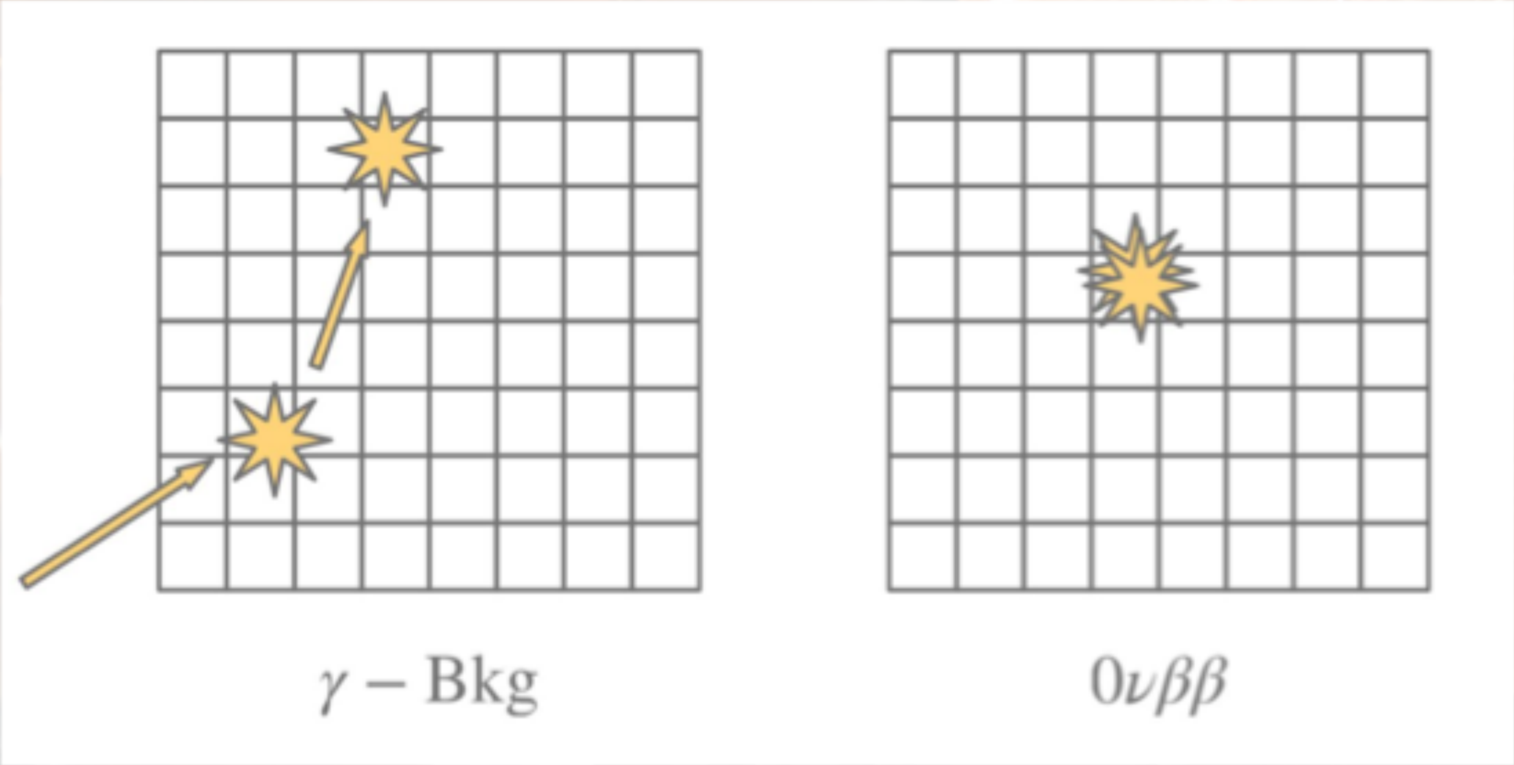
Majorana neutrinos could help explain matter-antimatter asymmetry in the Universe.

Two options

Liquid xenon

- Larger masses in smaller volumes
- Possibility of self-shielding
- Lack of information on electron tracks

Multi Site (background) vs **Single Site** (ββ0ν)

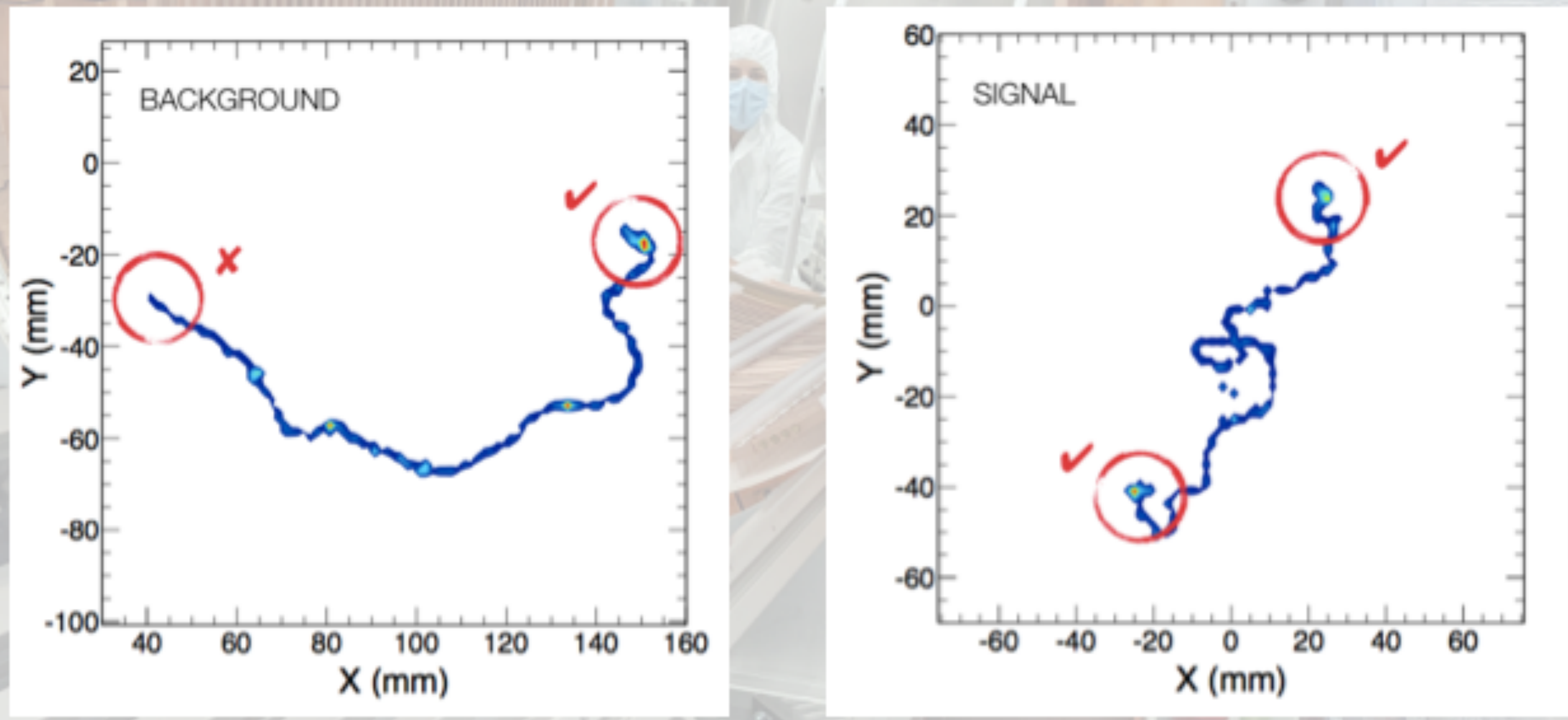


B. Lenardo, Lale Louise Winter Institute (2022)

Gaseous xenon

- Smaller Fano factor —> better intrinsic energy resolution
- Possibility of exploiting electron tracks

One blob (background) vs **Two blobs** (ββ0ν)



JHEP01 (2016) 104

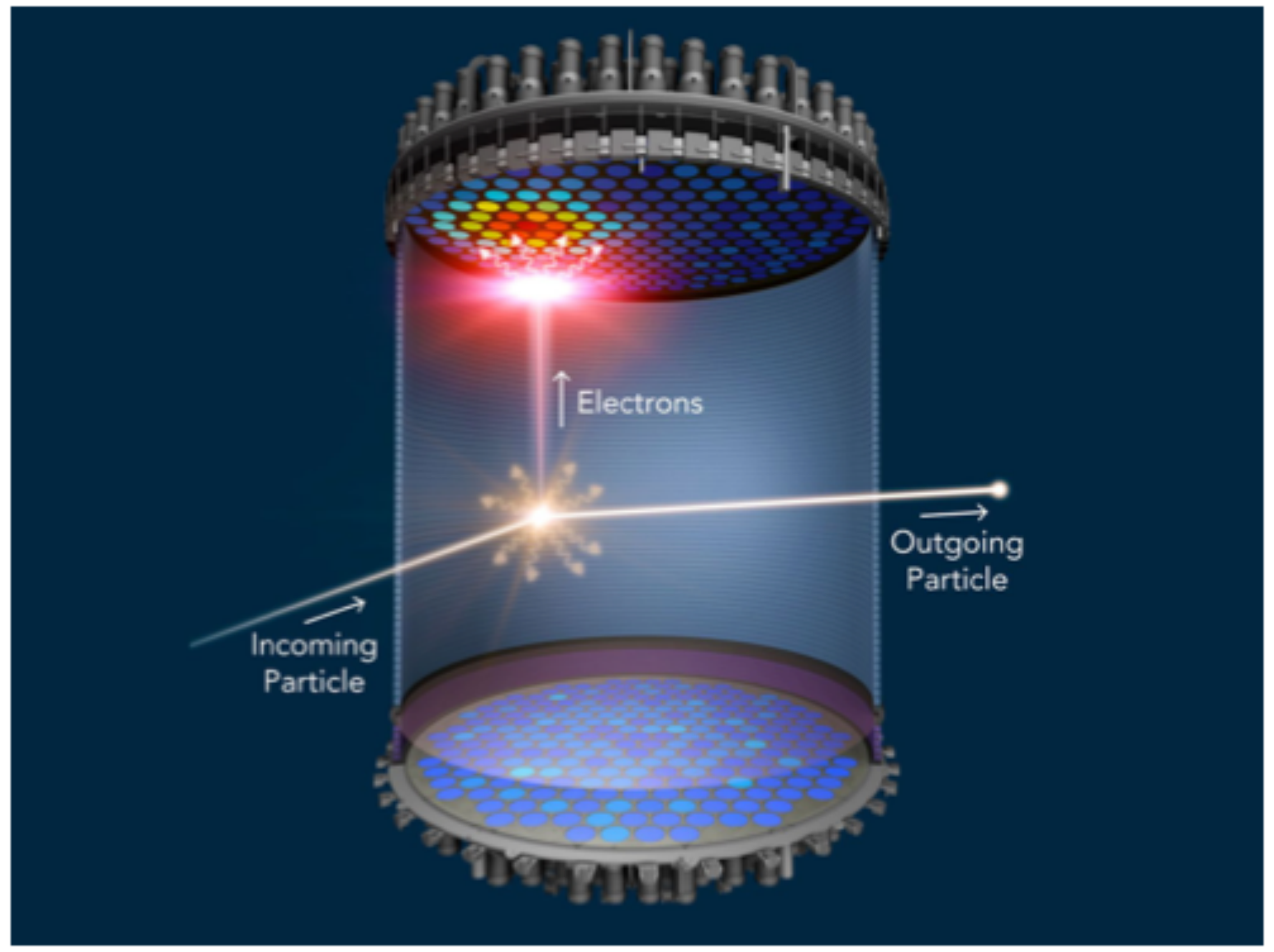
ββ measurements by dark matter detectors

PandaX-II

- 580 kg of natural xenon (~51.6 kg of ^{136}Xe).
- Lower limit on 0νββ half-life: **2.1 x 10^{23}** yr (with 242 kg yr of data).

PandaX-4T

- 3.7 tonne of natural xenon (~60 kg of ^{136}Xe in the fiducial volume).
- 1.185 m length and diameter.
- Measurement of 2νββ half-life: **2.27 x 10^{21}** yr.



Dual phase TPC read out by PMTs

LUX-ZEPLIN

- 7 tonne of xenon in the active volume (~ 600 kg of ^{136}Xe).
- Expected sensitivity on 0νββ half-life: **1.1 x 10^{27}** yr after 3 years.

XENON1T

- 1 tonne of natural xenon (~ 36 kg of ^{136}Xe in the fiducial volume).
- 97 cm length, 96 cm diameter.
- Lower limit on 0νββ half-life: **1.2 x 10^{24}** yr.

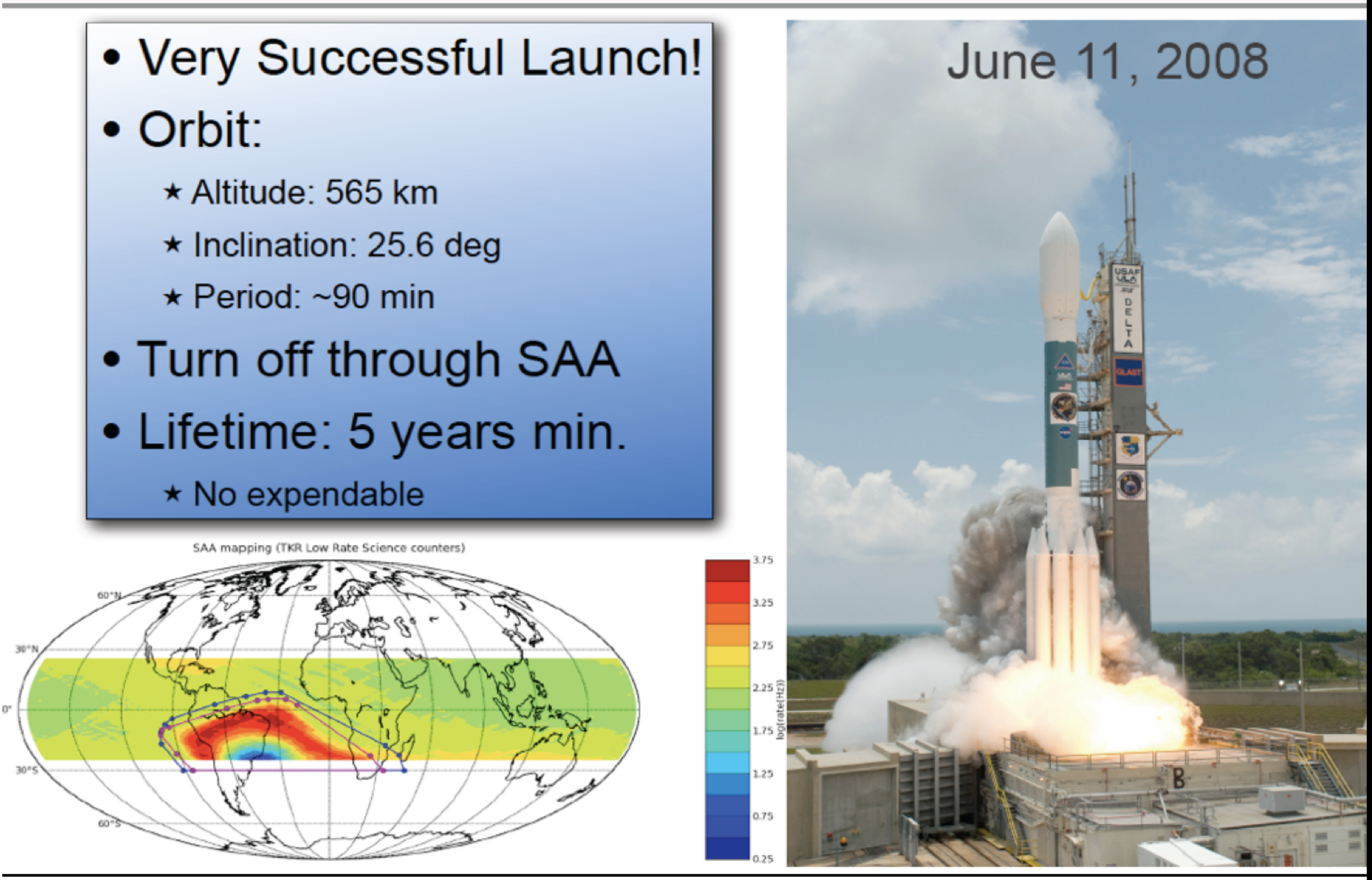
XENONnT

- 5.9 t of xenon (1088 kg of ^{136}Xe in the fiducial volume).
- 1.3 m diameter x 1.5 m drift.
- S1 and S2 read by PMTs.
- Expected sensitivity: **2.1 x 10^{25}** yr with 275 kg yr exposure.

Astroparticules

gamma-ray from galactic center

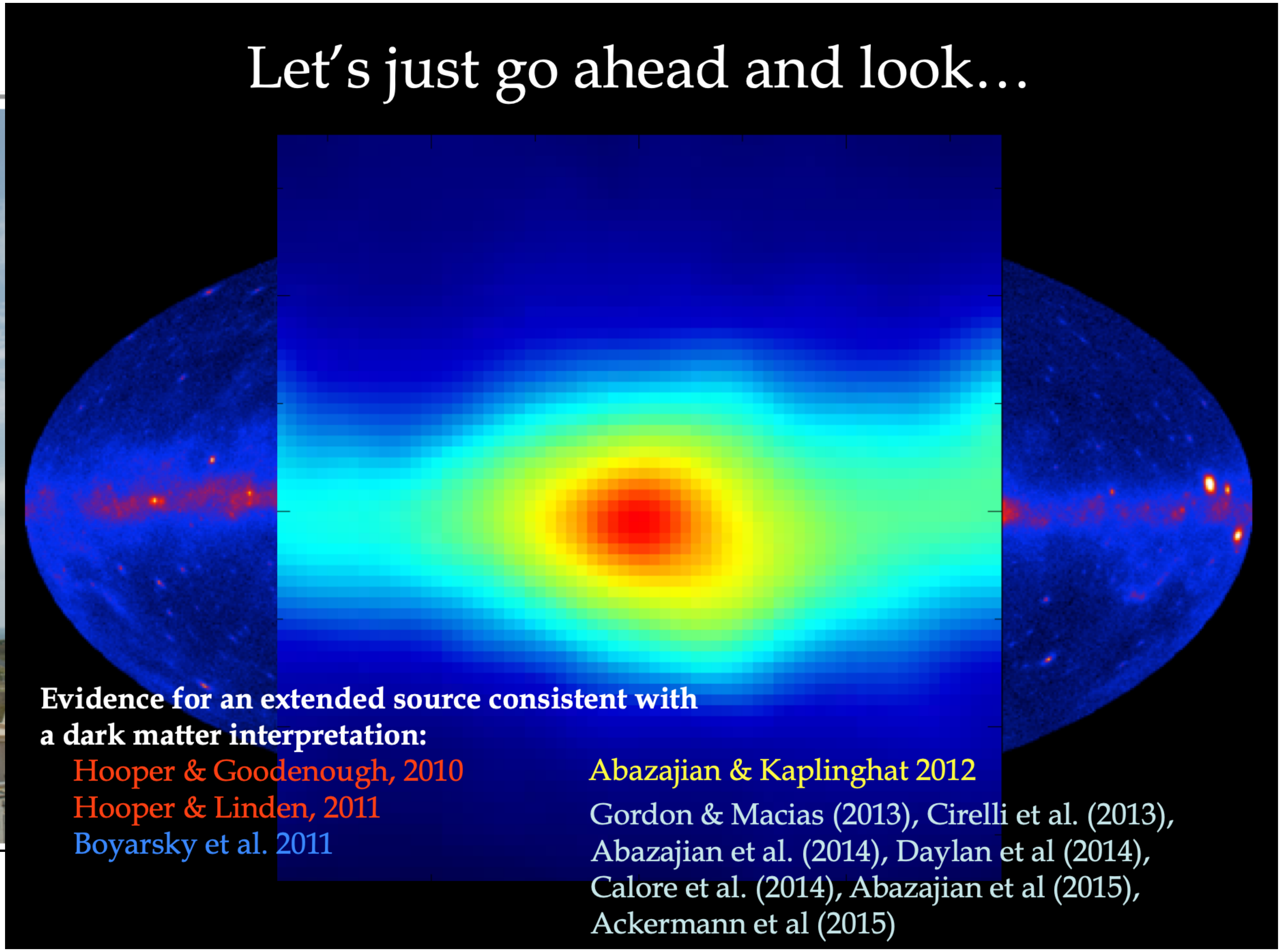
- **Fermi** experiment launched in 2008 (particle detector in space : trigger, calorimeter, tracker, anticoincidence detector)



- Very Successful Launch!
- Orbit:
  - Altitude: 565 km
  - Inclination: 25.6 deg
  - Period: ~90 min
- Turn off through SAA
- Lifetime: 5 years min.
  - No expendable

SAA mapping (TKR Low Rate Science counters)

June 11, 2008



Let's just go ahead and look…

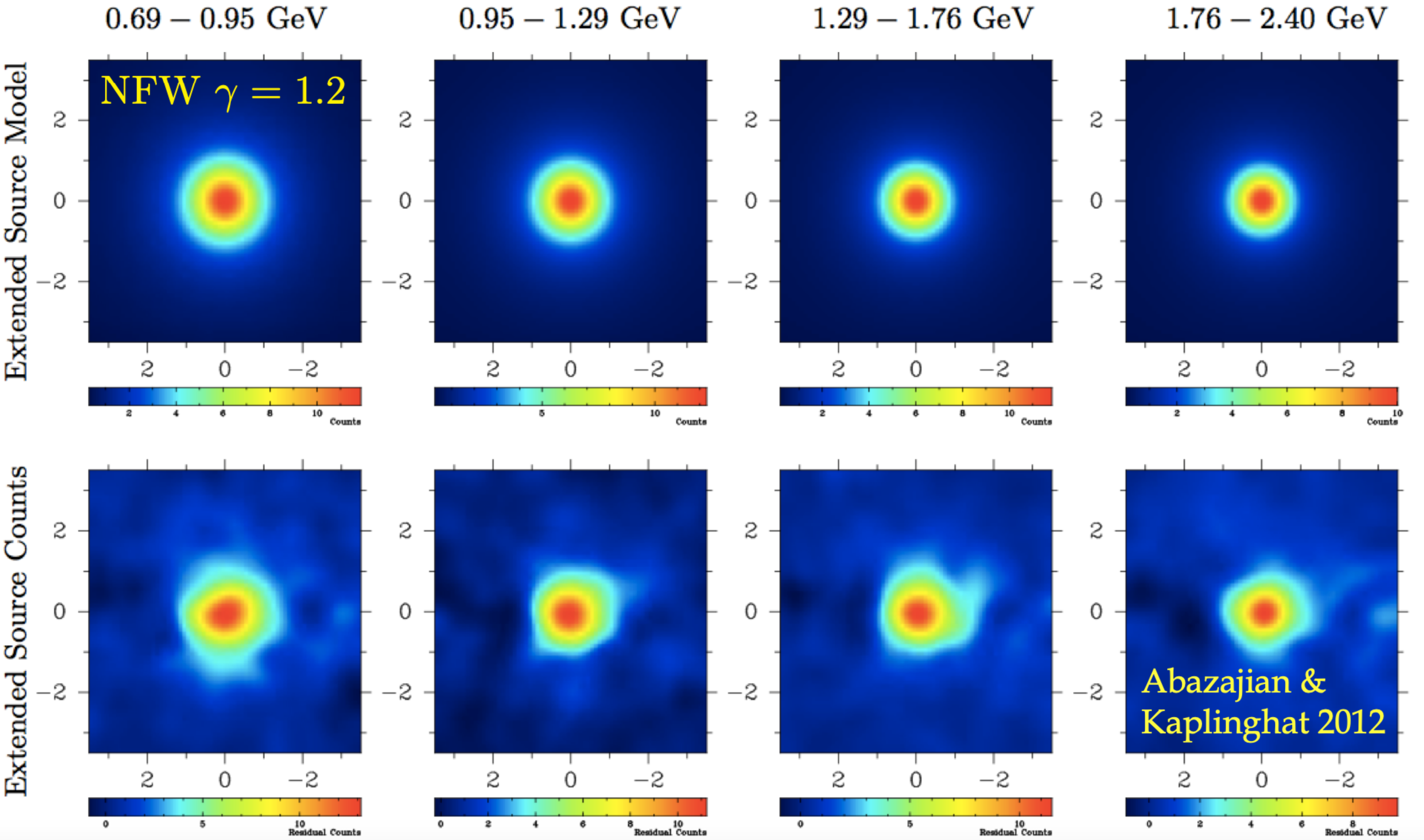
Evidence for an extended source consistent with a dark matter interpretation:

Hooper & Goodenough, 2010
Hooper & Linden, 2011
Boyarsky et al. 2011

Abazajian & Kaplinghat 2012
Gordon & Macias (2013), Cirelli et al. (2013), Abazajian et al. (2014), Daylan et al (2014), Calore et al. (2014), Abazajian et al (2015), Ackermann et al (2015)

WIMP Dark Matter in the Galactic Center?!

$m_\chi = 30\ \mathrm{GeV}\quad \mathrm{TS_{true}} = 2\Delta\ln\mathcal{L} = 824,\ 28.7\sigma,\ p = 4\times10^{-181}$

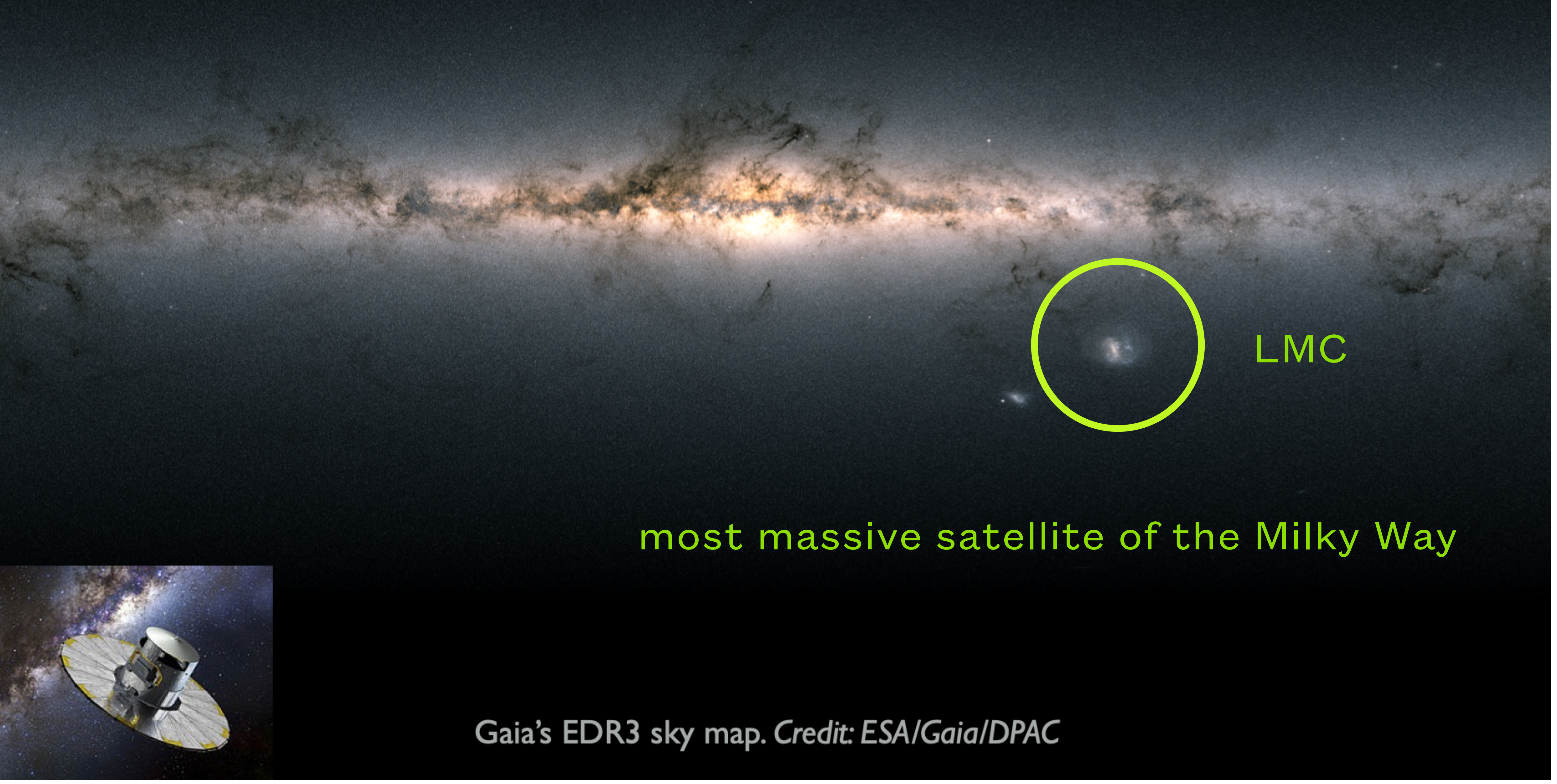


Abazajian & Kaplinghat 2012

- But could be rather interpreted as stellar bulge
- Being investigated by many teams

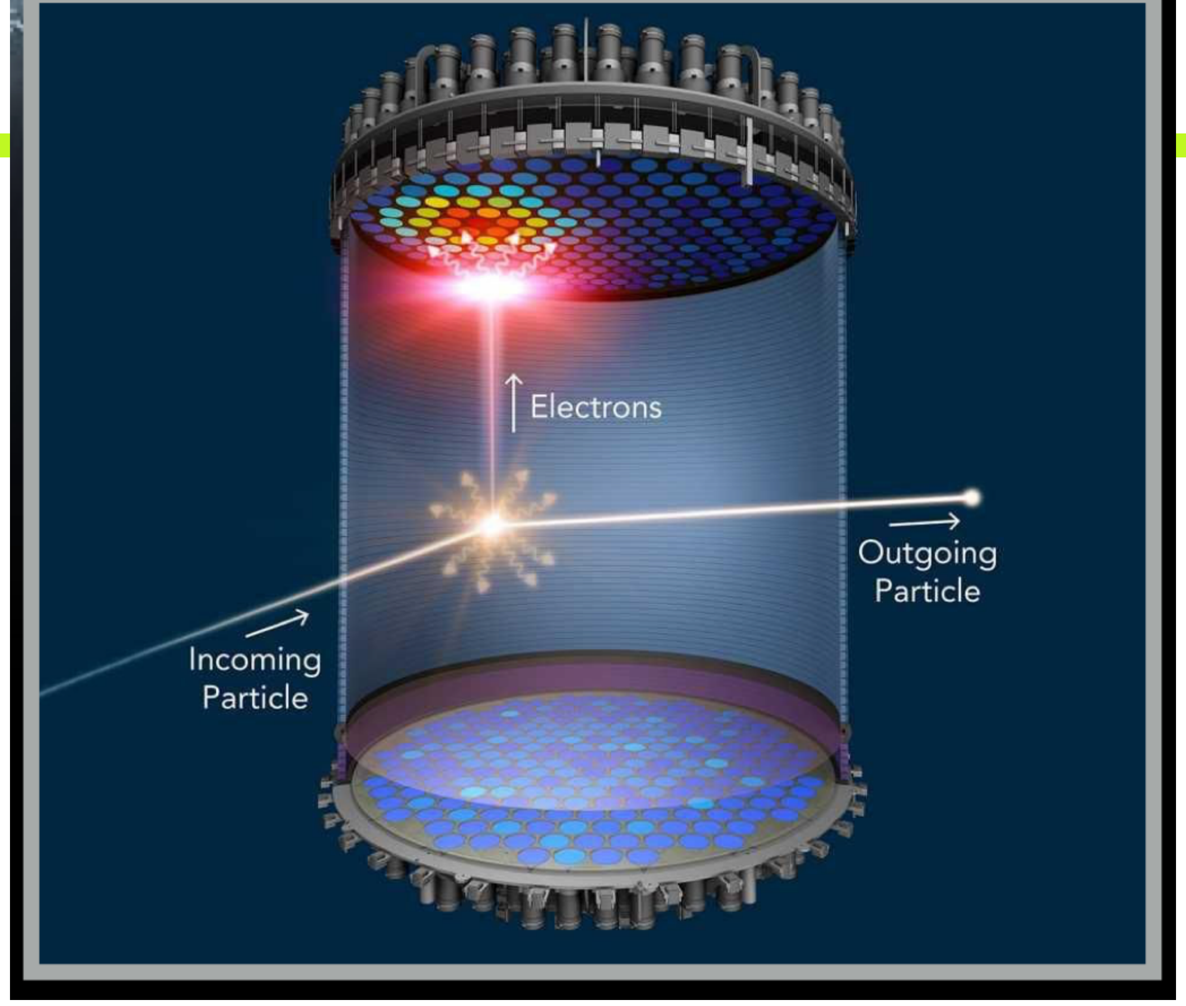
A massive satellite encounter

Could a recent ($\lesssim 100$ Myr) and close ($\lesssim 100$ kpc) approach of a massive satellite significantly impact the dark matter (DM) distribution in the Solar neighborhood?



Gaia's EDR3 sky map. *Credit: ESA/Gaia/DPAC*

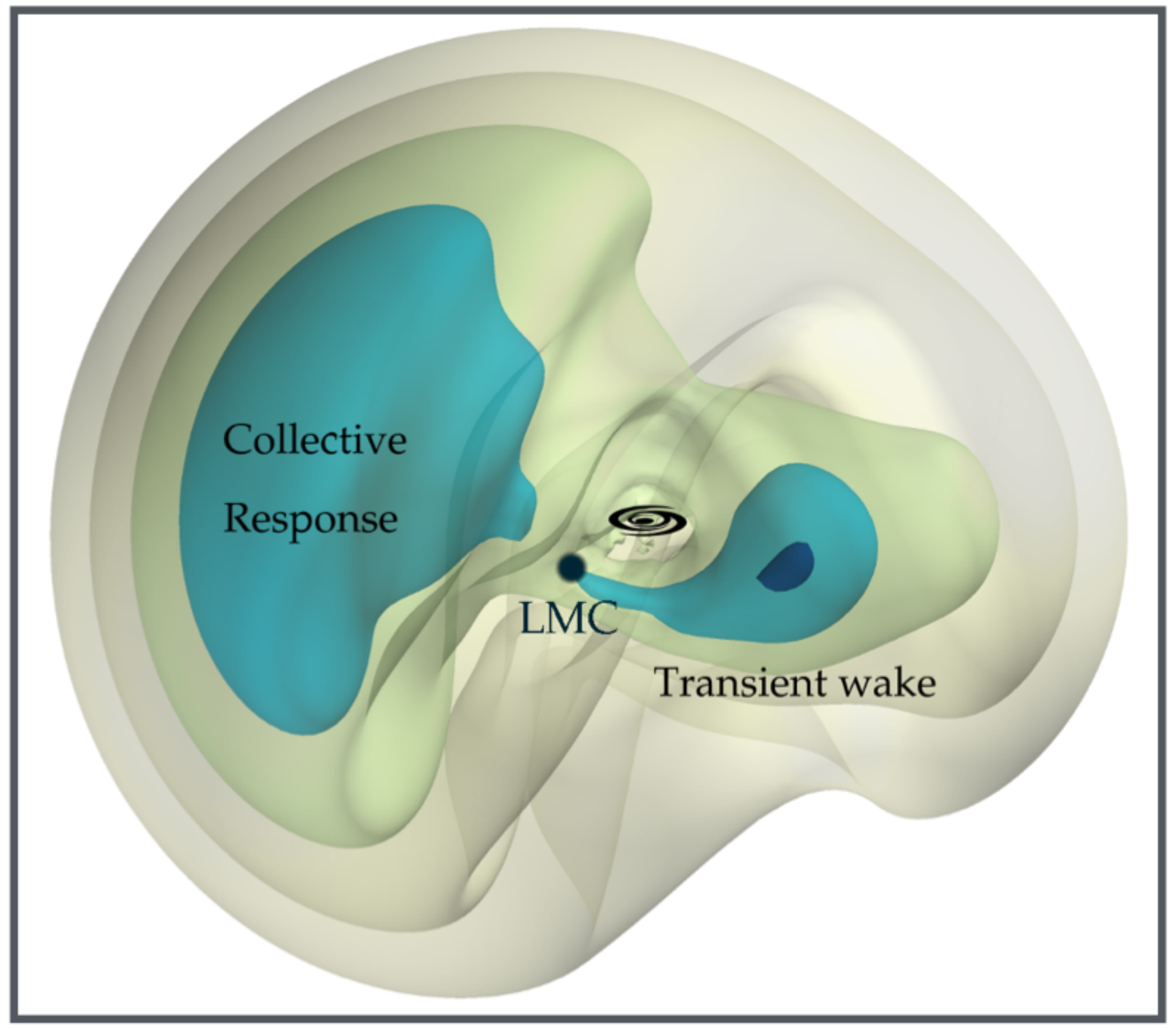
- Can deduce properties of dark-matter by studying velocities of stars in satellite galaxy



Gaia

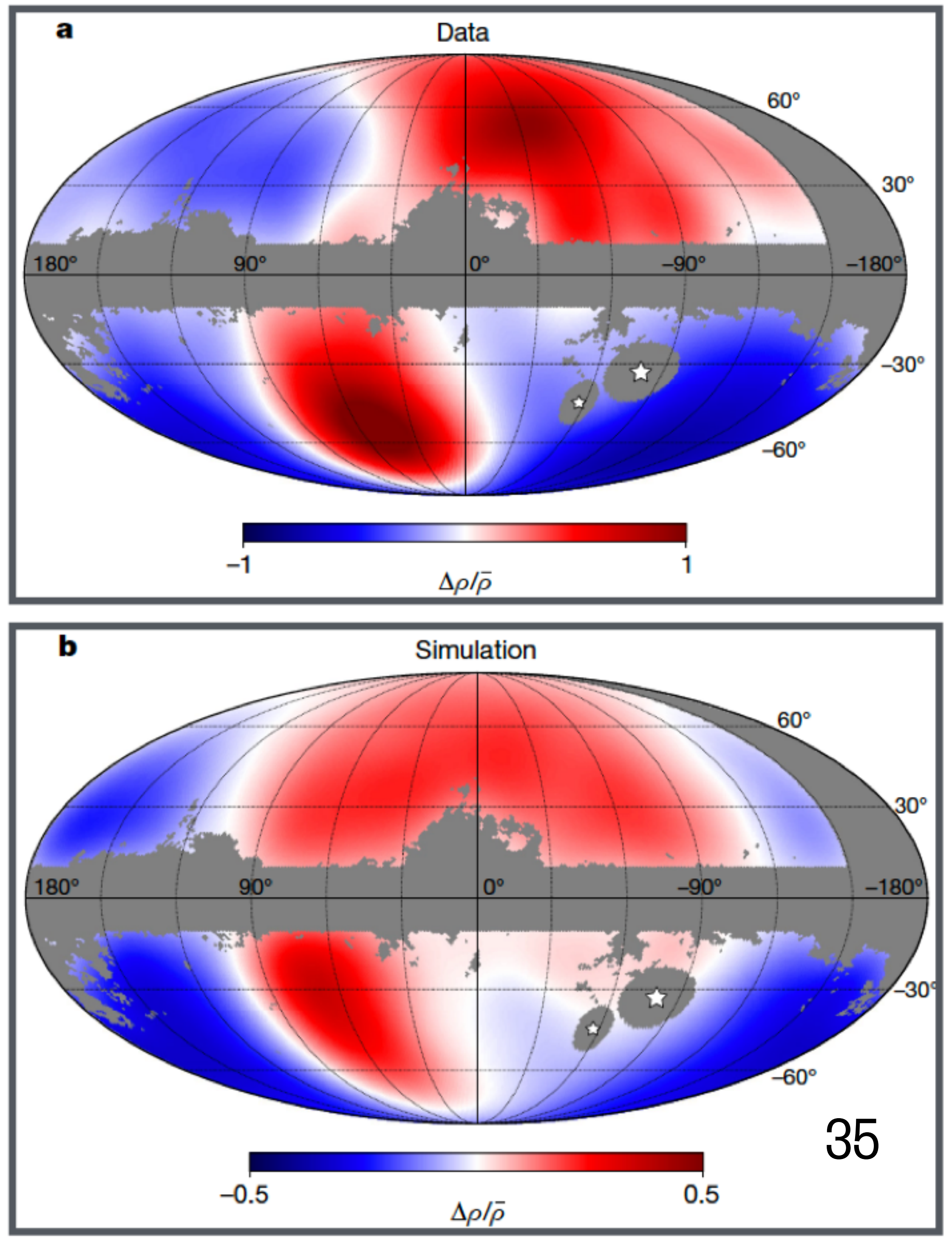
The **LMC** introduces perturbations in the DM and stellar halo.

DM halo



Garavito-Camargo et al, ApJ 919, 2, 109 (2021)
Garavito-Camargo et al, ApJ 884, 51 (2019)

Stellar halo



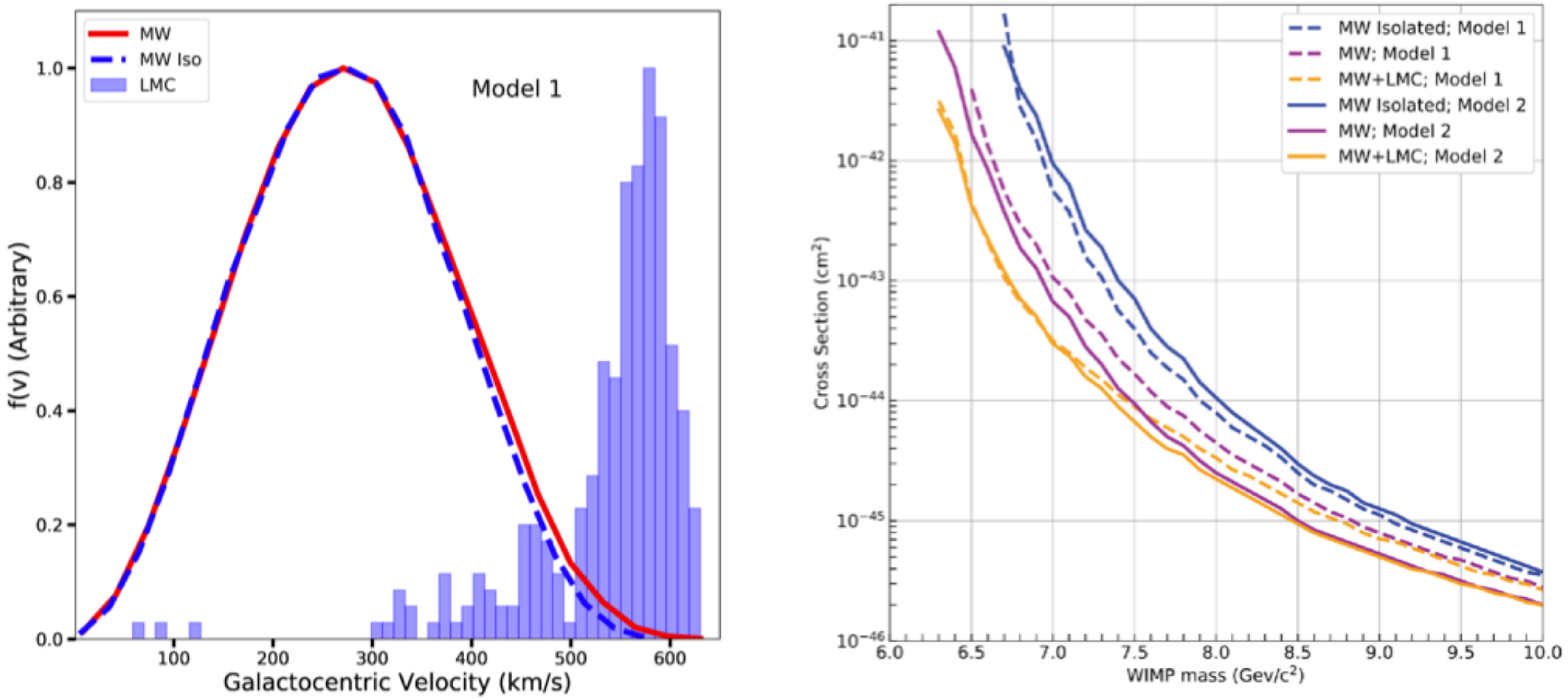
Conroy et al, Nature 592, 534–536 (2021)

Effect of LMC on direct detection

- The **LMC** could perturb the high speed tail of the local DM velocity distribution. → ***Affects direct detection implications for low mass DM.***

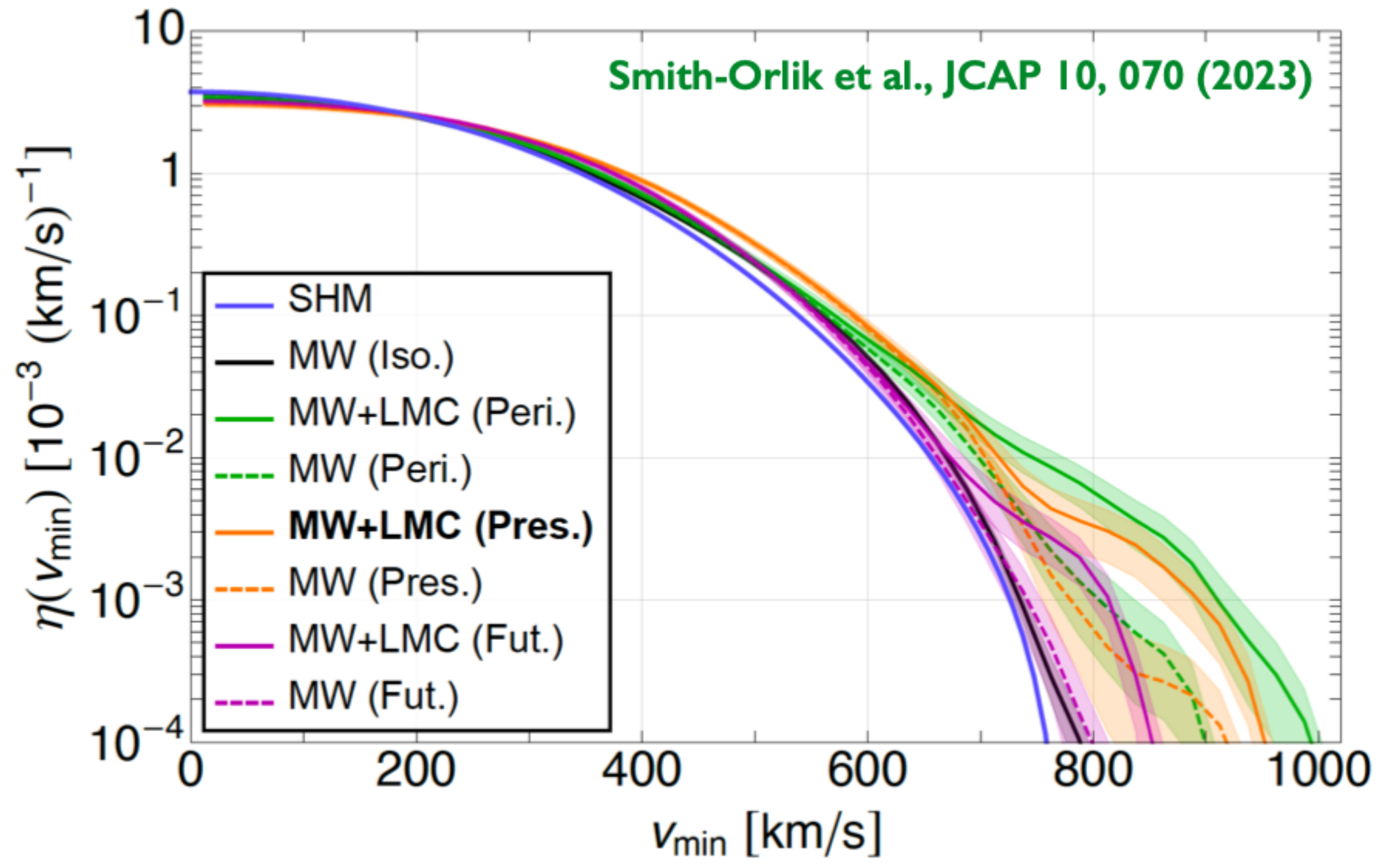
Besla et al, JCAP 11, 013 (2019)
Donaldson et al, MNRAS 513, 1, 46 (2022)

- Studied in specially designed idealized simulations.



Besla et al, JCAP 11, 013 (2019)

Halo integrals



- **Two effects:** High speed LMC particles in the Solar region + Milky Way's response to the LMC.
  → ***Shift of*** > 150 km/s ***in the high speed tail of the halo integrals at the present day.***

Gravitational waves

Standard sirens

The GW waveform (in time-domain at the lowest Newtonian order) used to detect GWs and measure the parameters of the system is (for the × polarisation)

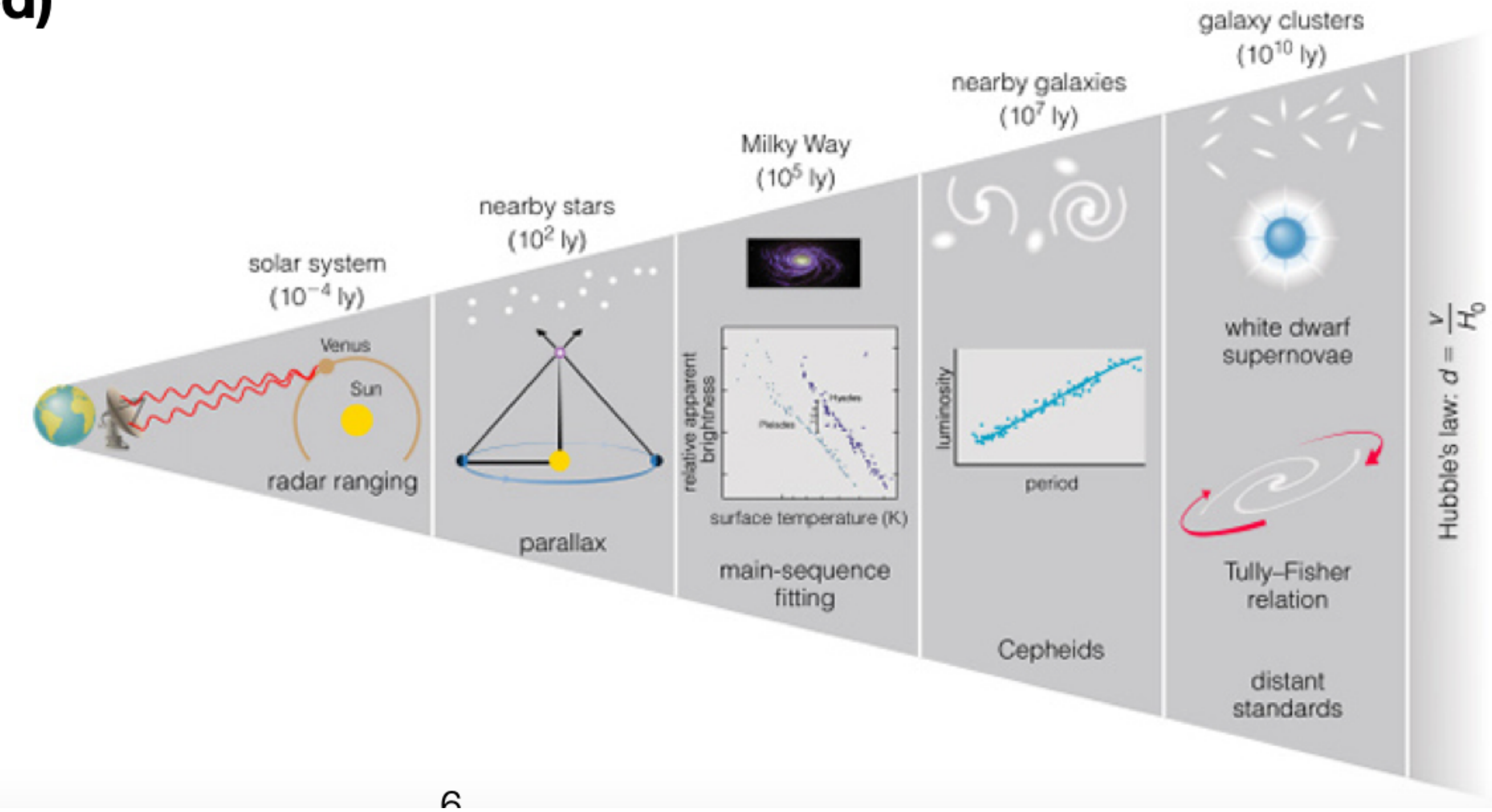
$$h_\times(t_o) = \frac{4}{d_L}\left(\frac{G\mathcal{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\sin\left[-2\left(\frac{5G\mathcal{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

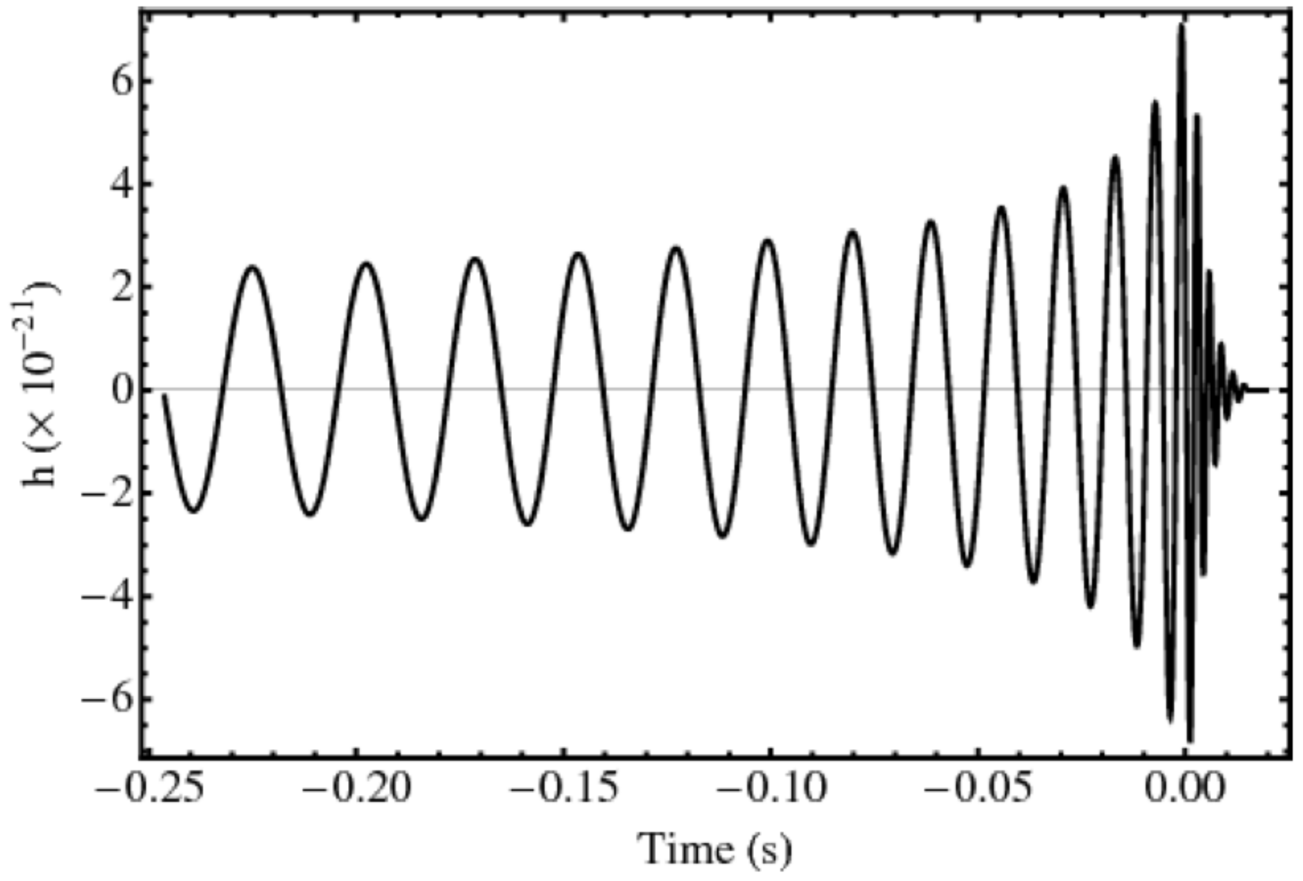
Most importantly for cosmology, one can measure the luminosity distance d_L of the source directly from the GW signal without relying on the *cosmic distance ladder* (only GR has been assumed)

This means that GW binaries are absolute cosmological distance indicators!

↓

Free of possible calibration systematics





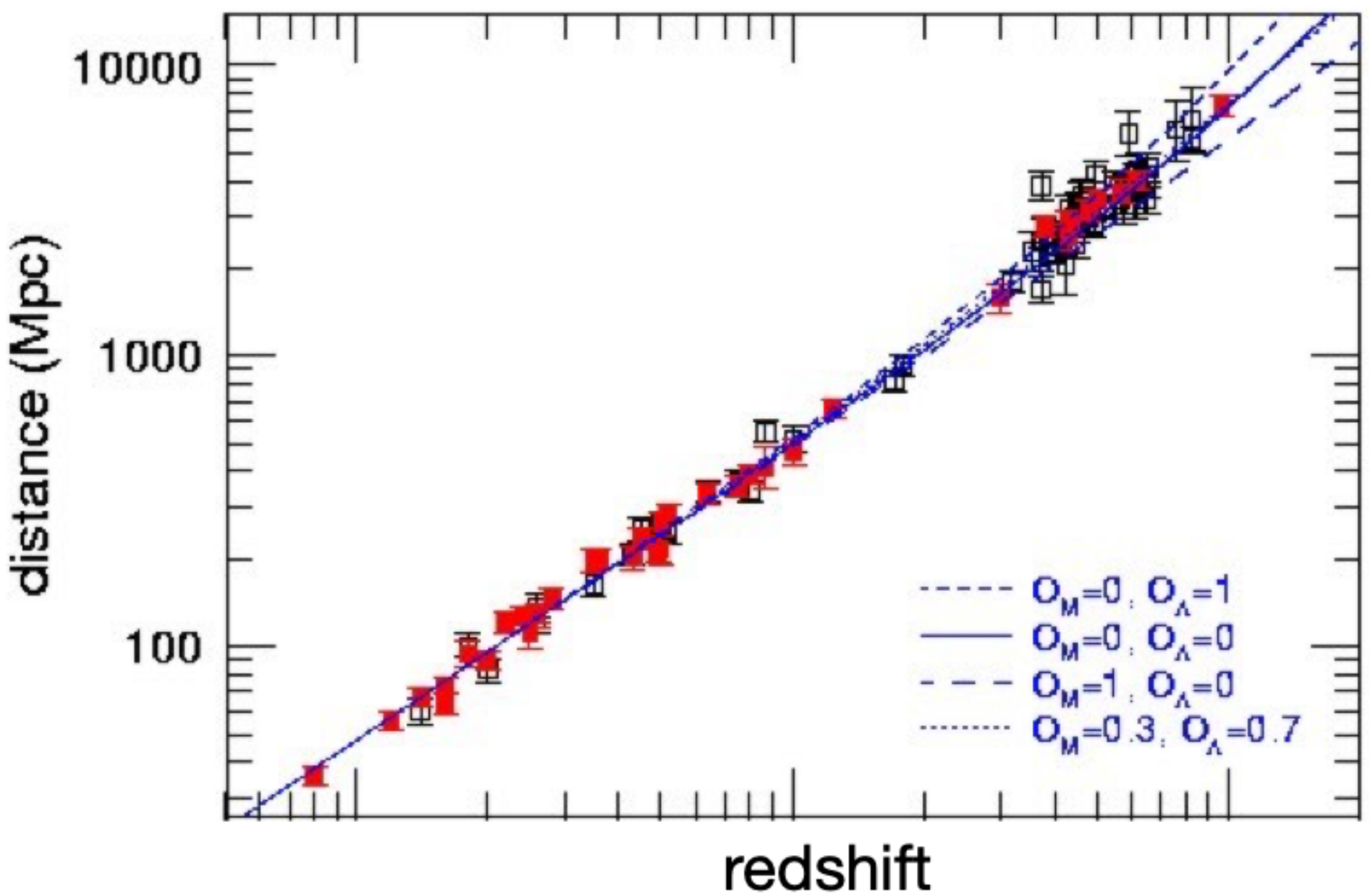
Note however that the waveform above does not depend explicitly on the redshift z, which cannot thus be measured directly from GWs

One needs independent information on the redshift of the source to do cosmology: if both d_L and z are known one can fit the *distance redshift relation*

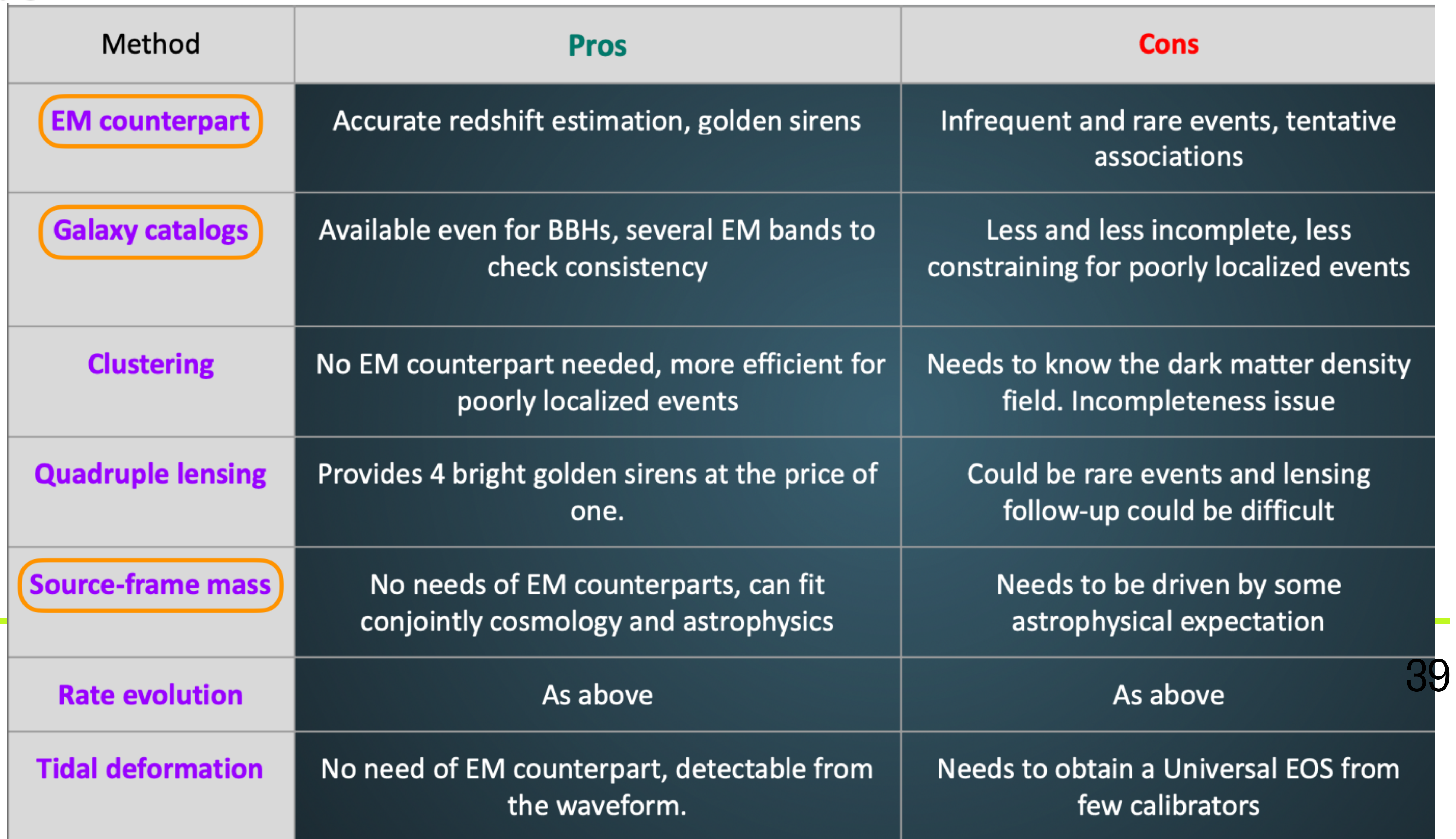
$$d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]$$

This is very similar to standard candles (supernovae type-Ia), from which the name standard sirens (using the analogy between GWs and sound waves)

[Schutz, *Nature* (1986)]



To get the redshift-distance relation



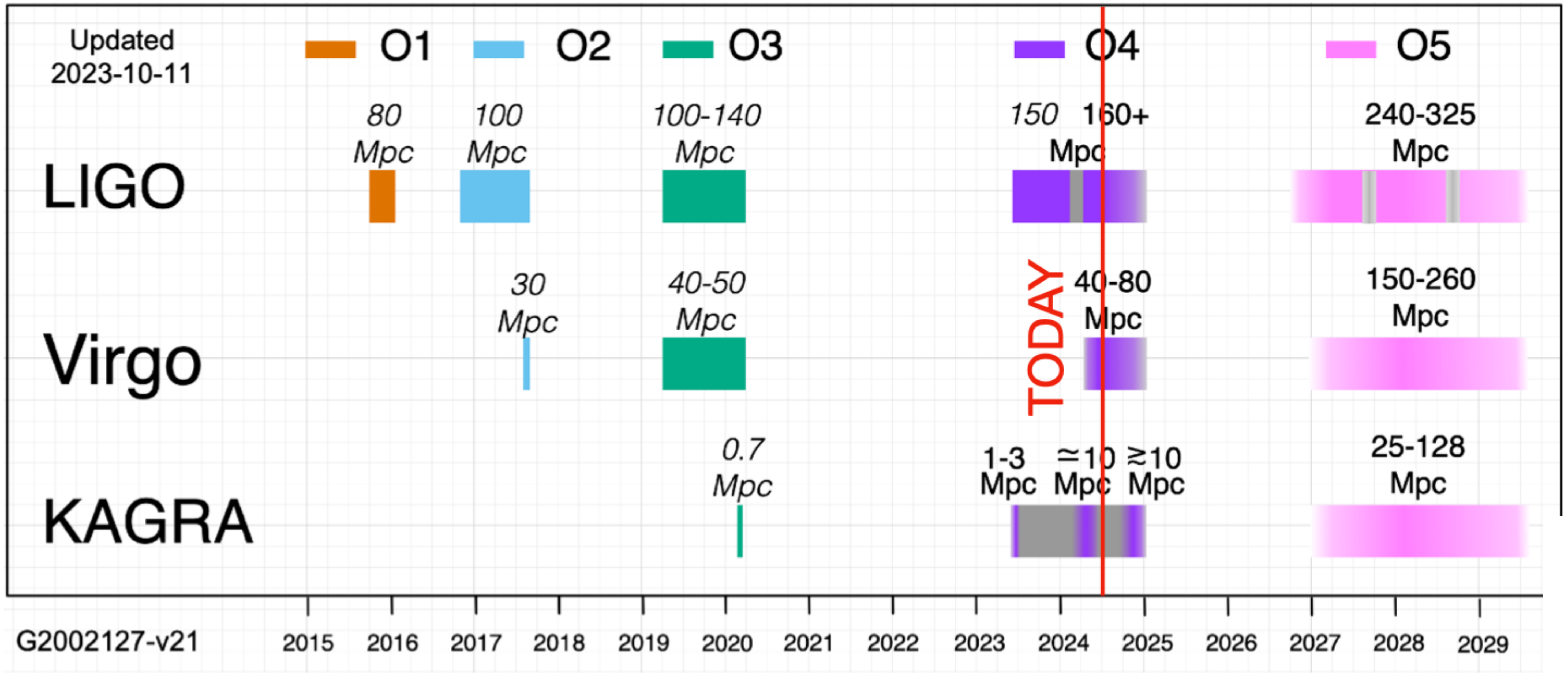
Method	Pros	Cons
EM counterpart	Accurate redshift estimation, golden sirens	Infrequent and rare events, tentative associations
Galaxy catalogs	Available even for BBHs, several EM bands to check consistency	Less and less incomplete, less constraining for poorly localized events
Clustering	No EM counterpart needed, more efficient for poorly localized events	Needs to know the dark matter density field. Incompleteness issue
Quadruple lensing	Provides 4 bright golden sirens at the price of one.	Could be rare events and lensing follow-up could be difficult
Source-frame mass	No needs of EM counterparts, can fit conjointly cosmology and astrophysics	Needs to be driven by some astrophysical expectation
Rate evolution	As above	As above
Tidal deformation	No need of EM counterpart, detectable from the waveform.	Needs to obtain a Universal EOS from few calibrators

Current results from LVK

Status of Earth-based GW observations:

O(+KAGRA)

https://observing.docs.ligo.org/plan



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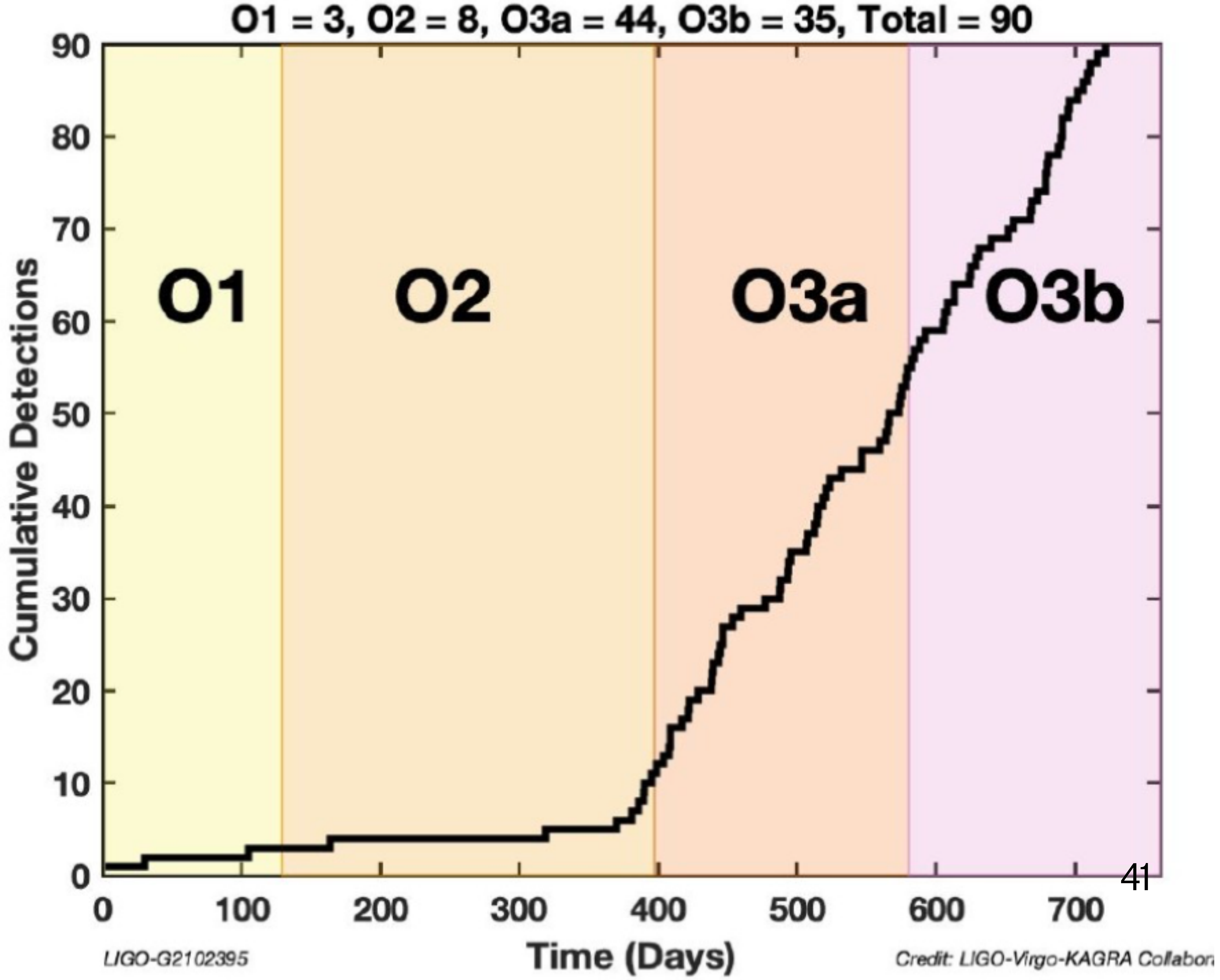
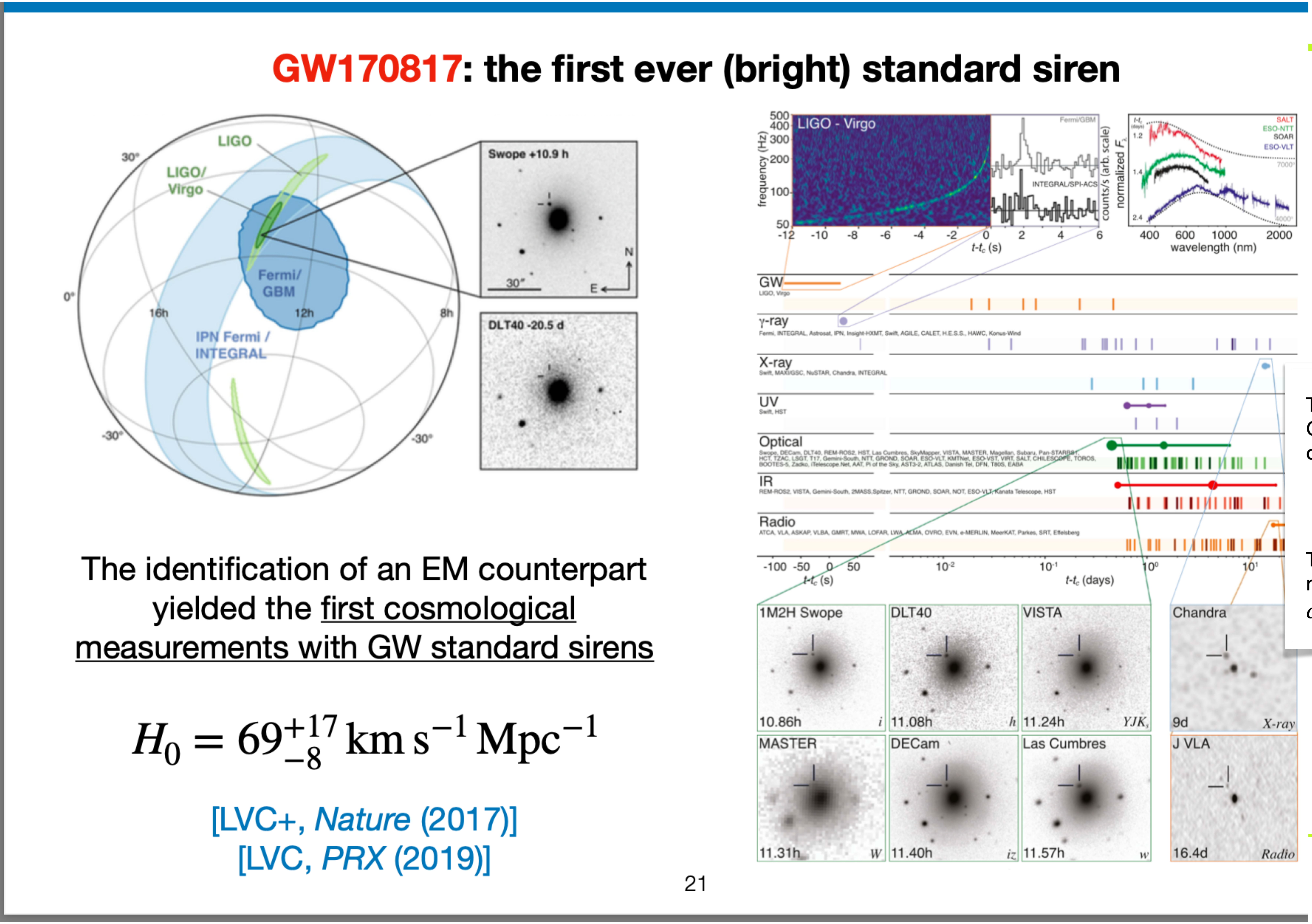




GW170817: the first ever (bright) standard siren

The identification of an EM counterpart yielded the <u>first cosmological measurements with GW standard sirens</u>

$$H_0 = 69^{+17}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[LVC+, *Nature* (2017)]
[LVC, *PRX* (2019)]

The coincident GW-EM detection of GW170817 puts stringent constraints on the speed of GW:

$$\boxed{c_T = c^{+7\times10^{-16}}_{-3\times10^{-15}}}$$

This observation rules out several modified gravity models predicting $c_T \neq c$ [see e.g. 1807.09241 and refs therein]

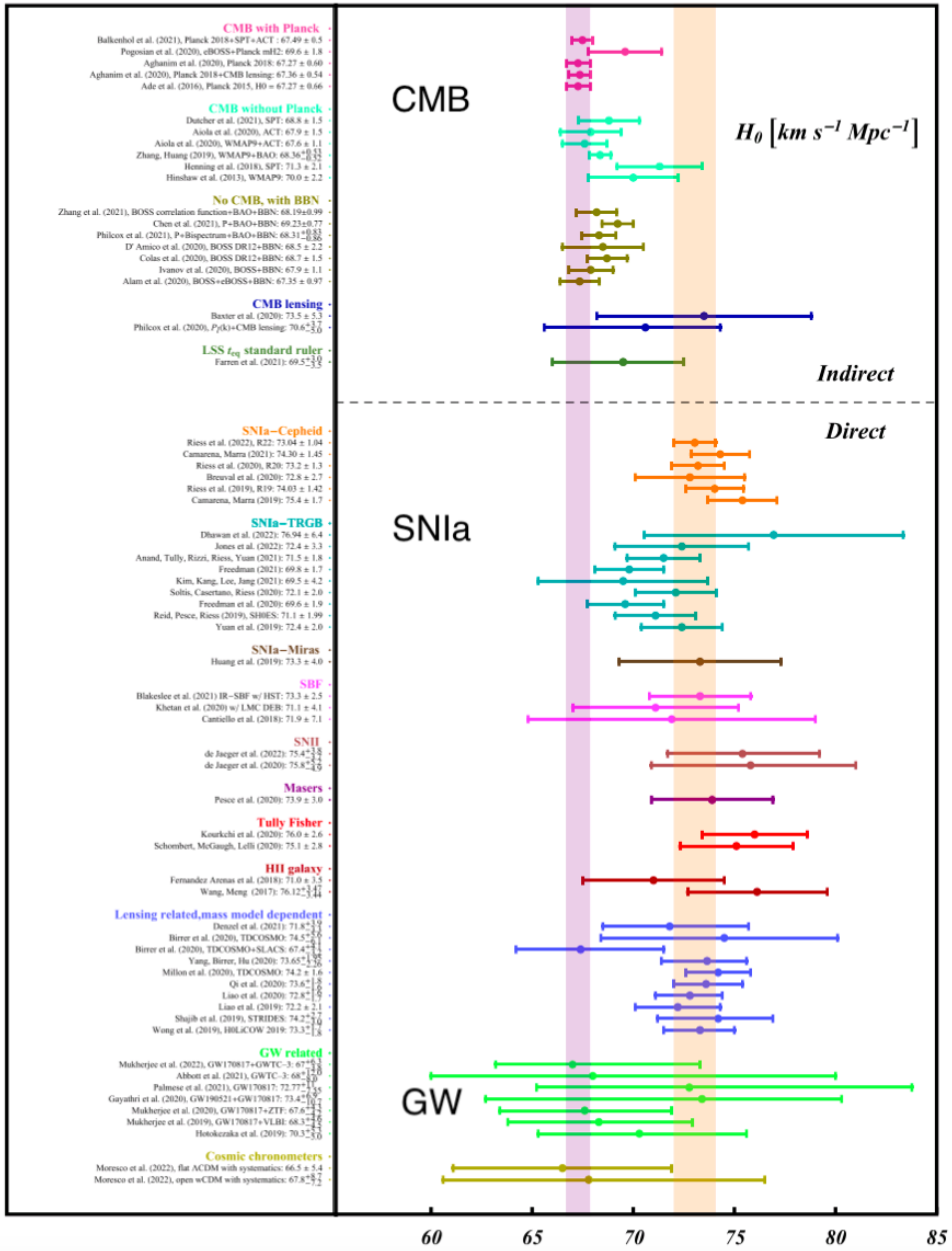
The Hubble tension

A few % constraints on H0 with GWs could solve the current tension between local and CMB measurements

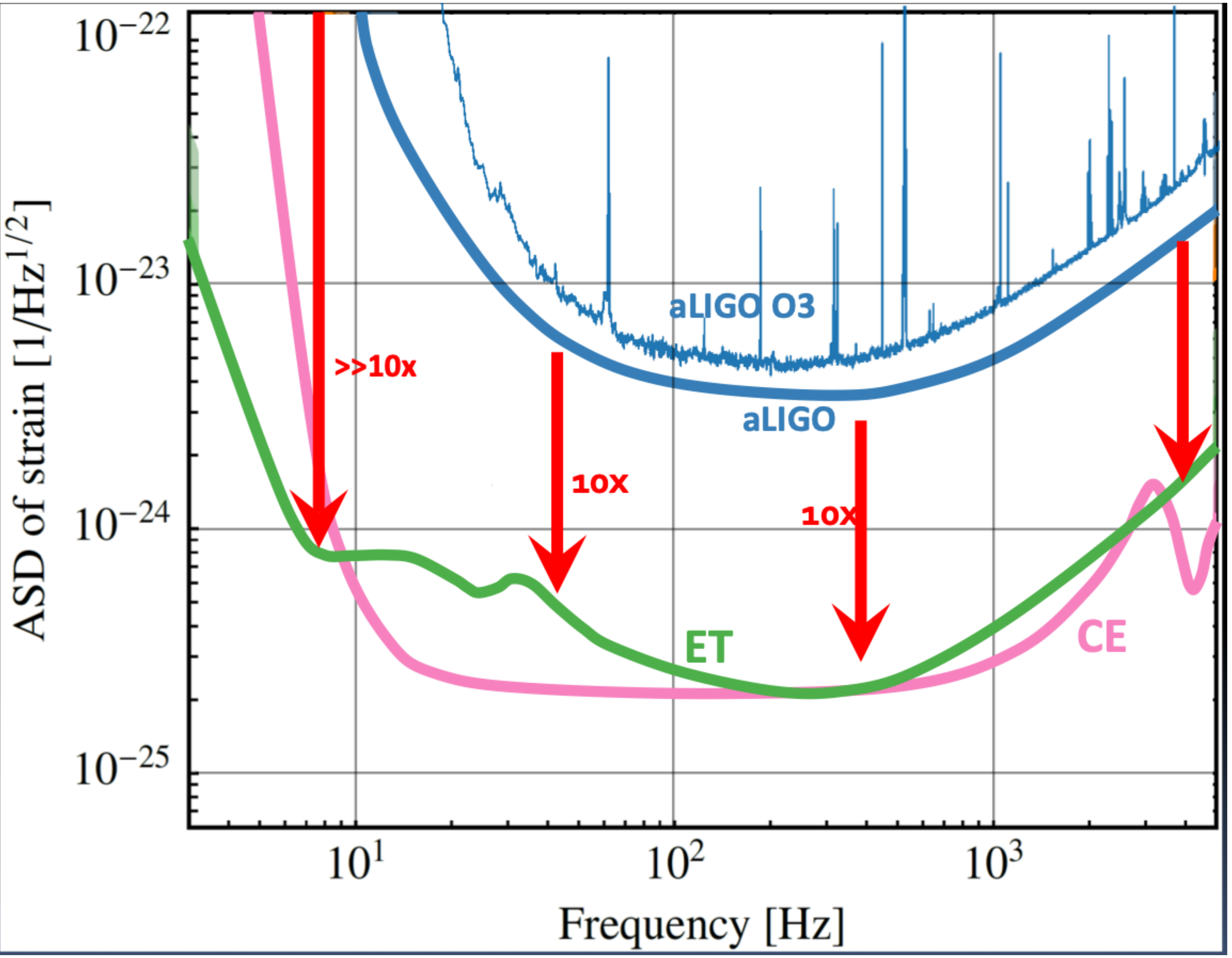
Ground detectors currently not providing competitive measurements

Future detectors (LISA, Einstein Telescope, Cosmic Explorer) could improve a lot precision

[Abdalla+, *JHEAp* (2022)]



3rd generation of GW detectors



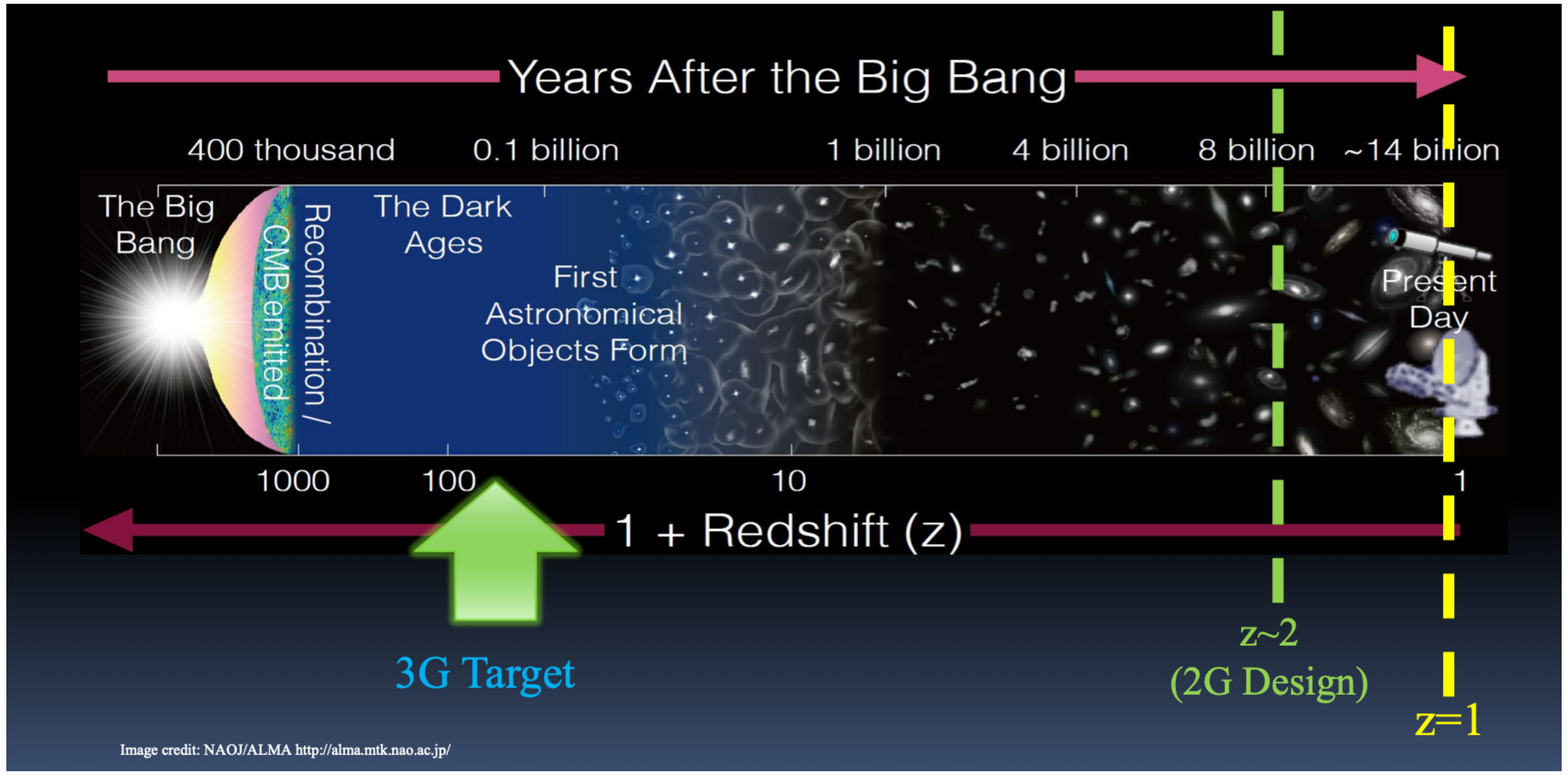
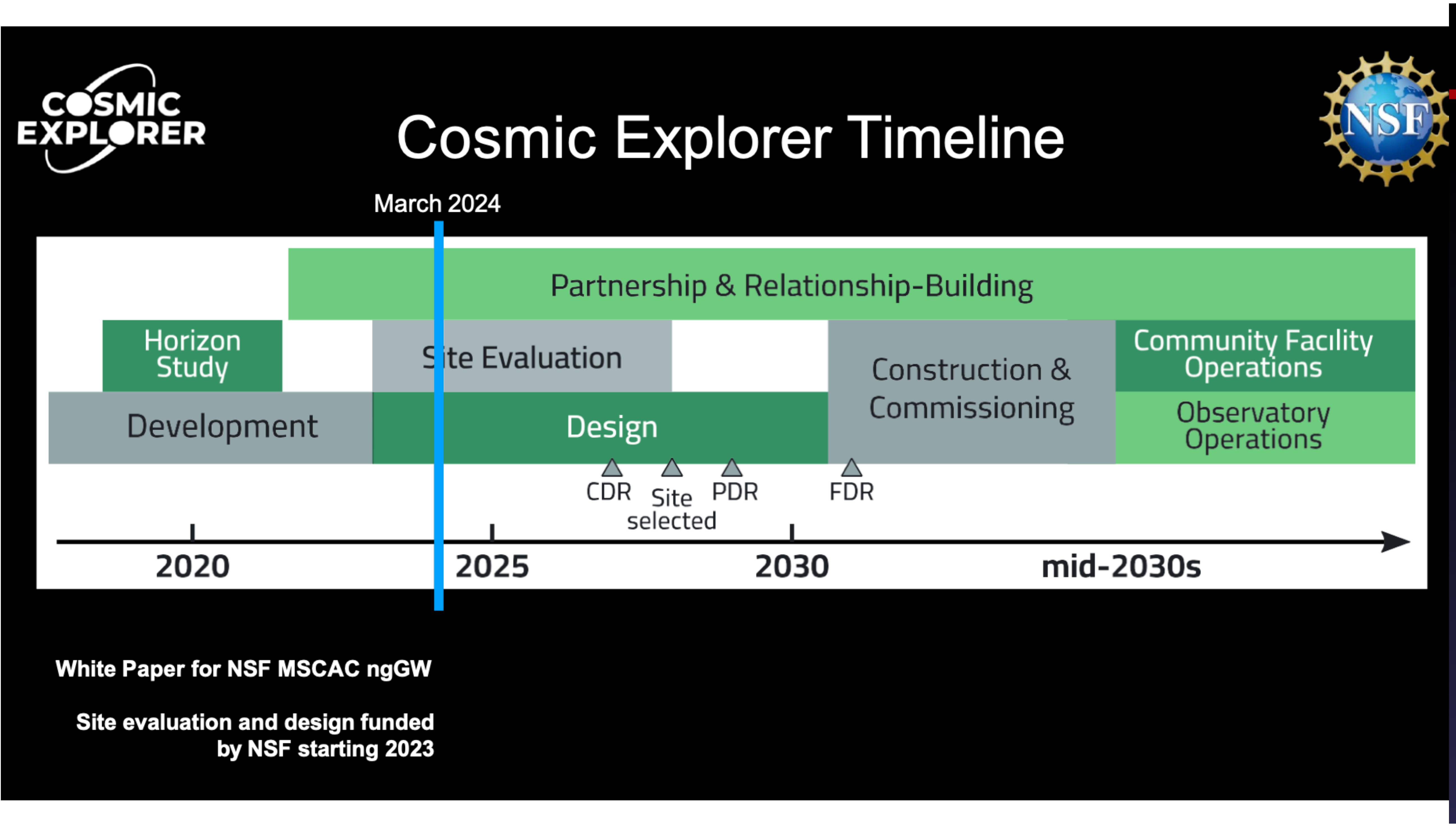


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

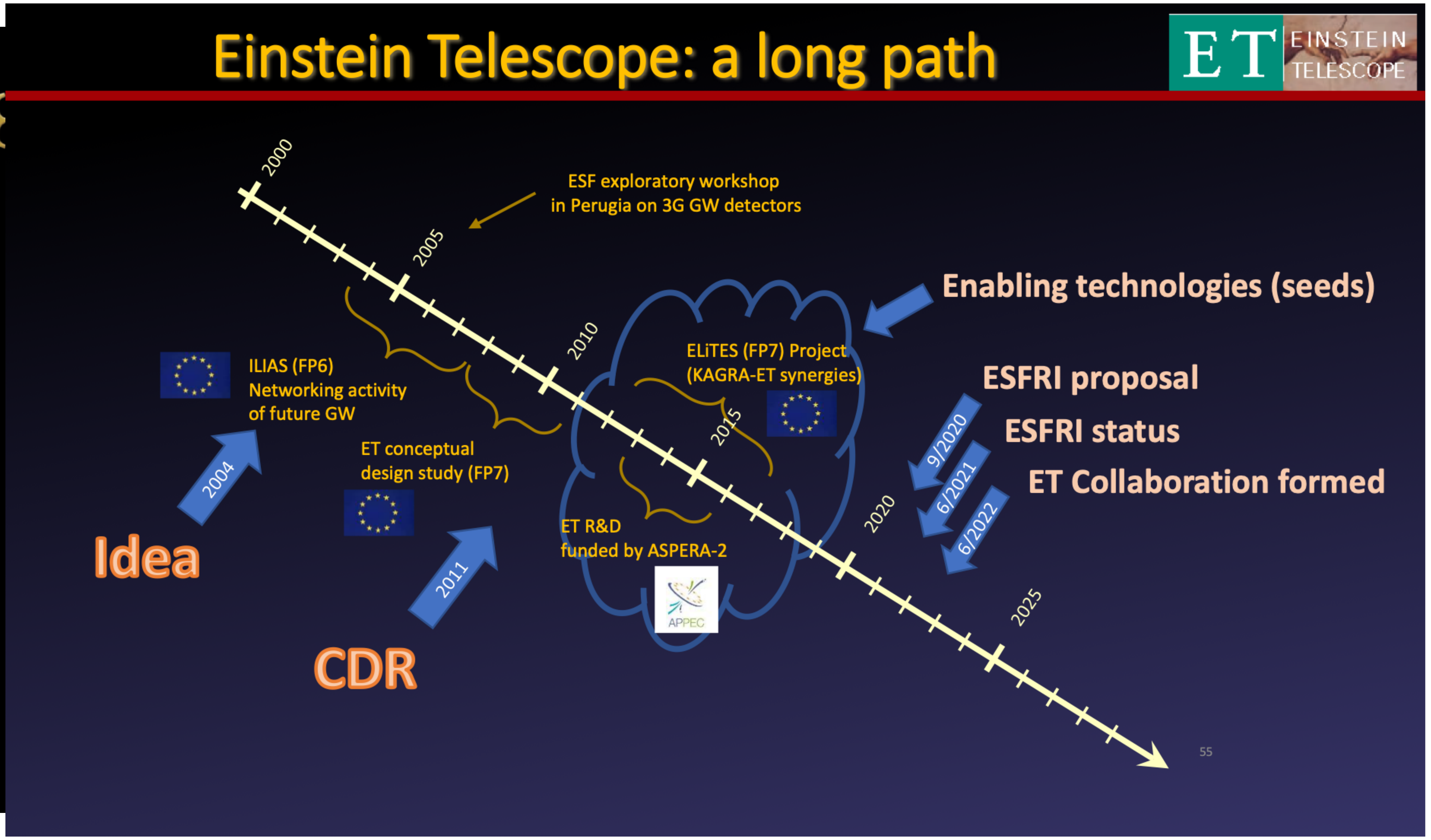
Timelines



Cosmic Explorer Timeline

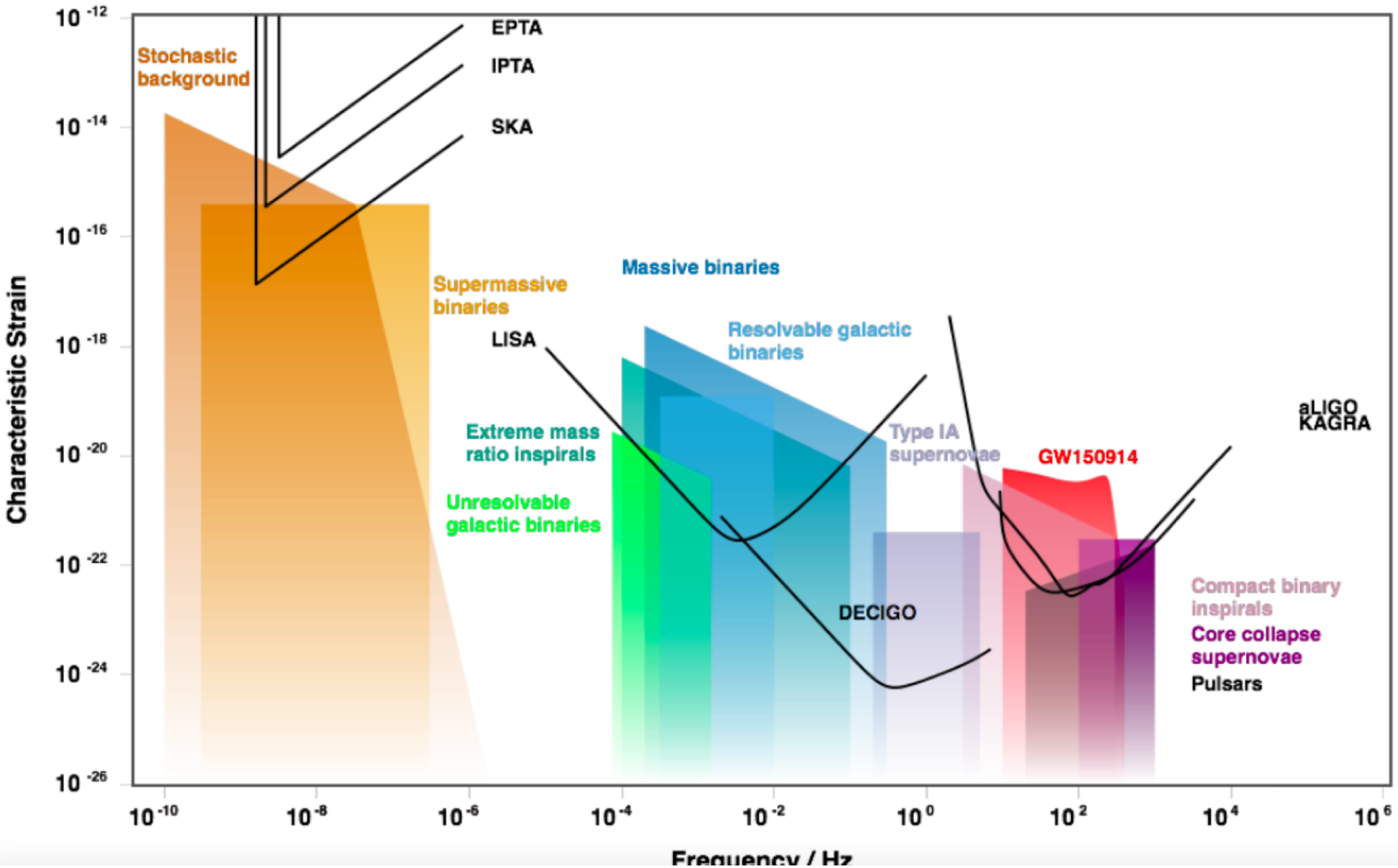
White Paper for NSF MSCAC ngGW

Site evaluation and design funded by NSF starting 2023



Einstein Telescope: a long path

the gravitational landscape



The nanoHertz domain

Super Massive Black Hole Binaries (SMBHB)

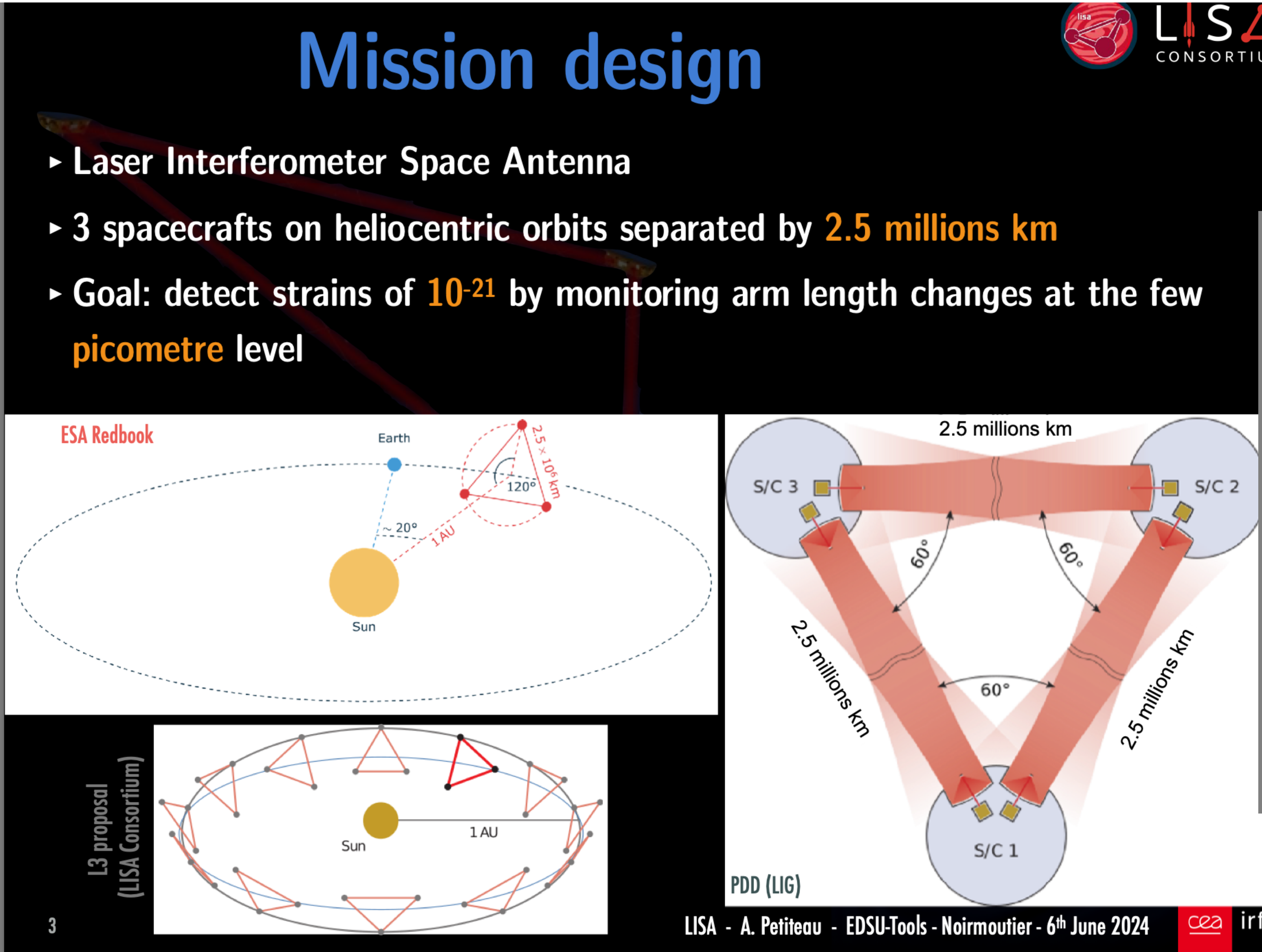
Cosmic string loops

Relics of inflation

First-order phase transition

+ fuzzy dark matter

LISA



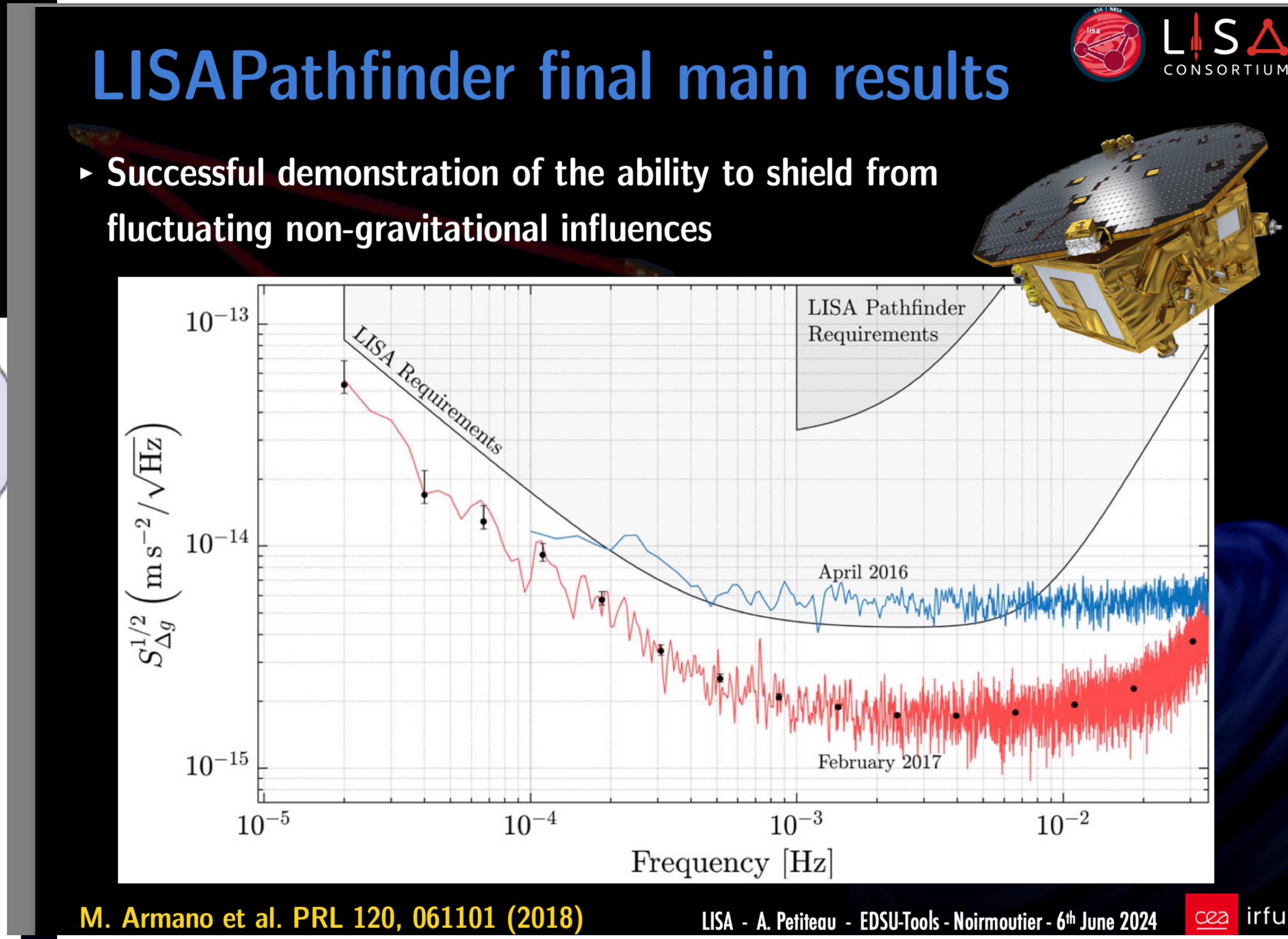
Mission design

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits separated by 2.5 millions km
- Goal: detect strains of 10^{-21} by monitoring arm length changes at the few picometre level

3

LISA - A. Petiteau - EDSU-Tools - Noirmoutier - 6th June 2024

cea irfu



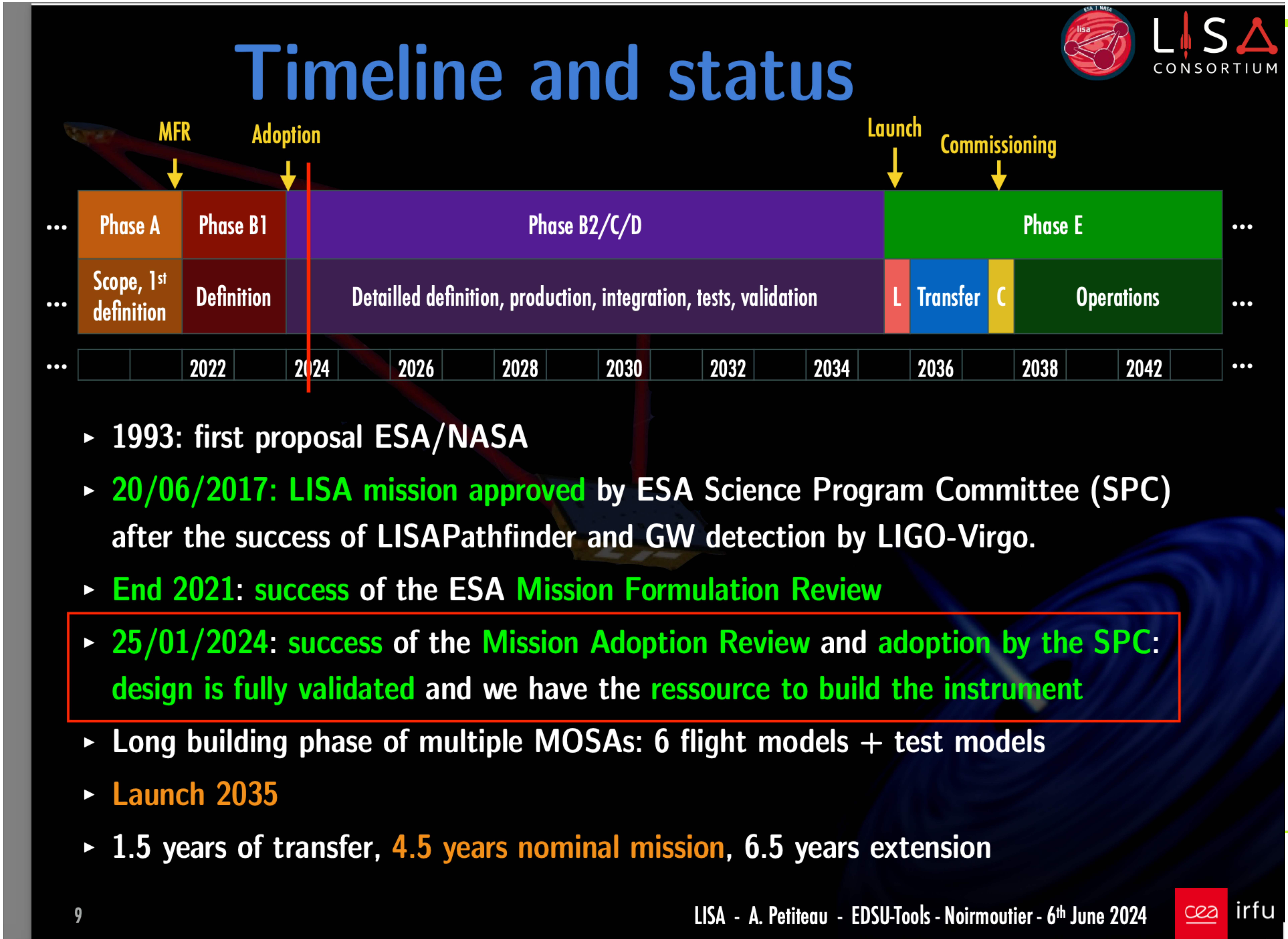
LISAPathfinder final main results

- Successful demonstration of the ability to shield from fluctuating non-gravitational influences

M. Armano et al. PRL 120, 061101 (2018)

LISA - A. Petiteau - EDSU-Tools - Noirmoutier - 6th June 2024

cea irfu



Timeline and status

LISA CONSORTIUM

MFR

Adoption

Launch

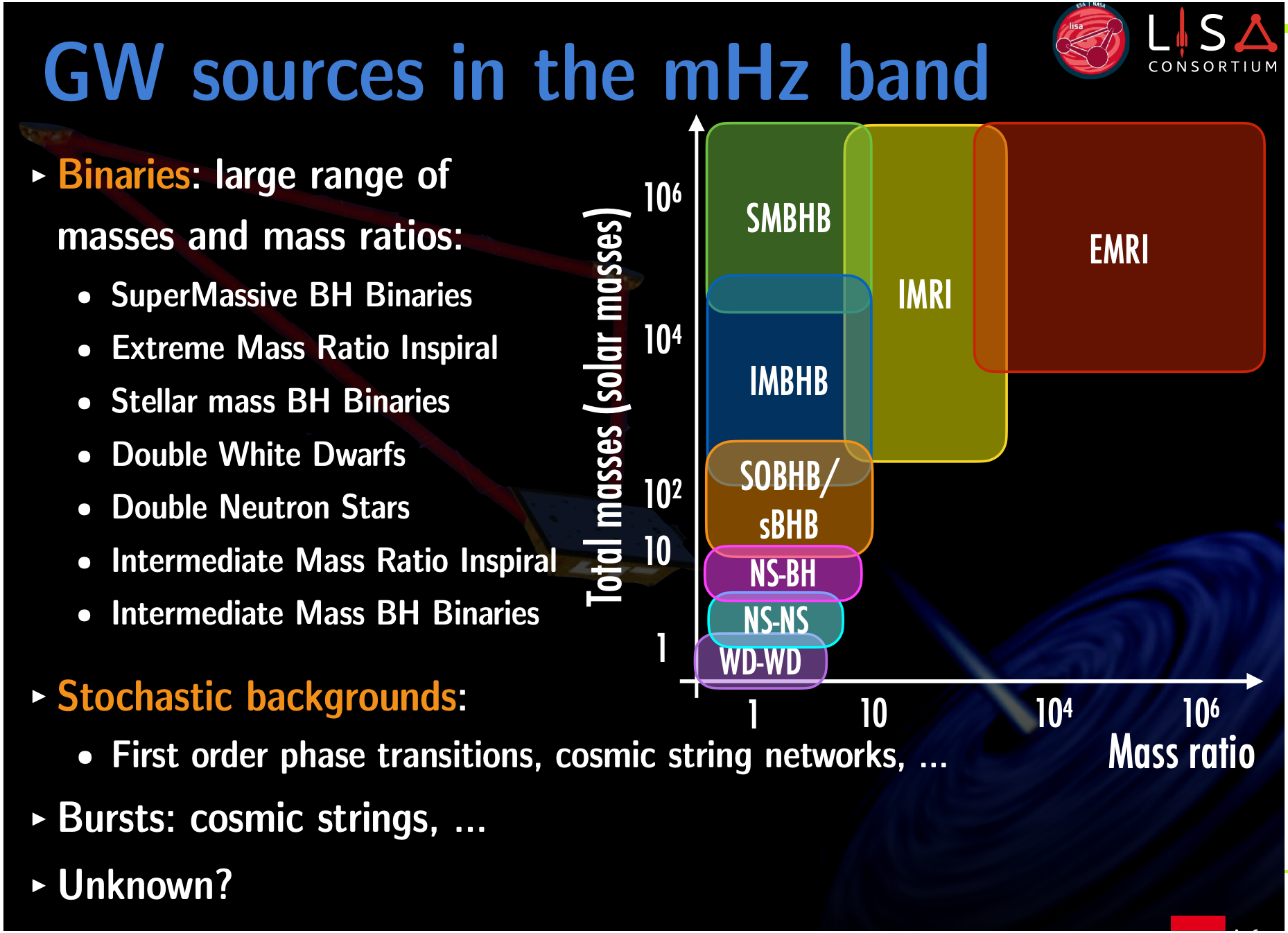
Commissioning

… Phase A | Phase B1 | Phase B2/C/D | Phase E …

… Scope, 1st definition | Definition | Detailled definition, production, integration, tests, validation | L | Transfer | C | Operations …

… 2022 | 2024 | 2026 | 2028 | 2030 | 2032 | 2034 | 2036 | 2038 | 2042 …

- 1993: first proposal ESA/NASA
- 20/06/2017: LISA mission approved by ESA Science Program Committee (SPC) after the success of LISAPathfinder and GW detection by LIGO-Virgo.
- End 2021: success of the ESA Mission Formulation Review
- 25/01/2024: success of the Mission Adoption Review and adoption by the SPC: design is fully validated and we have the ressource to build the instrument
- Long building phase of multiple MOSAs: 6 flight models + test models
- Launch 2035
- 1.5 years of transfer, 4.5 years nominal mission, 6.5 years extension



LISA CONSORTIUM

GW sources in the mHz band

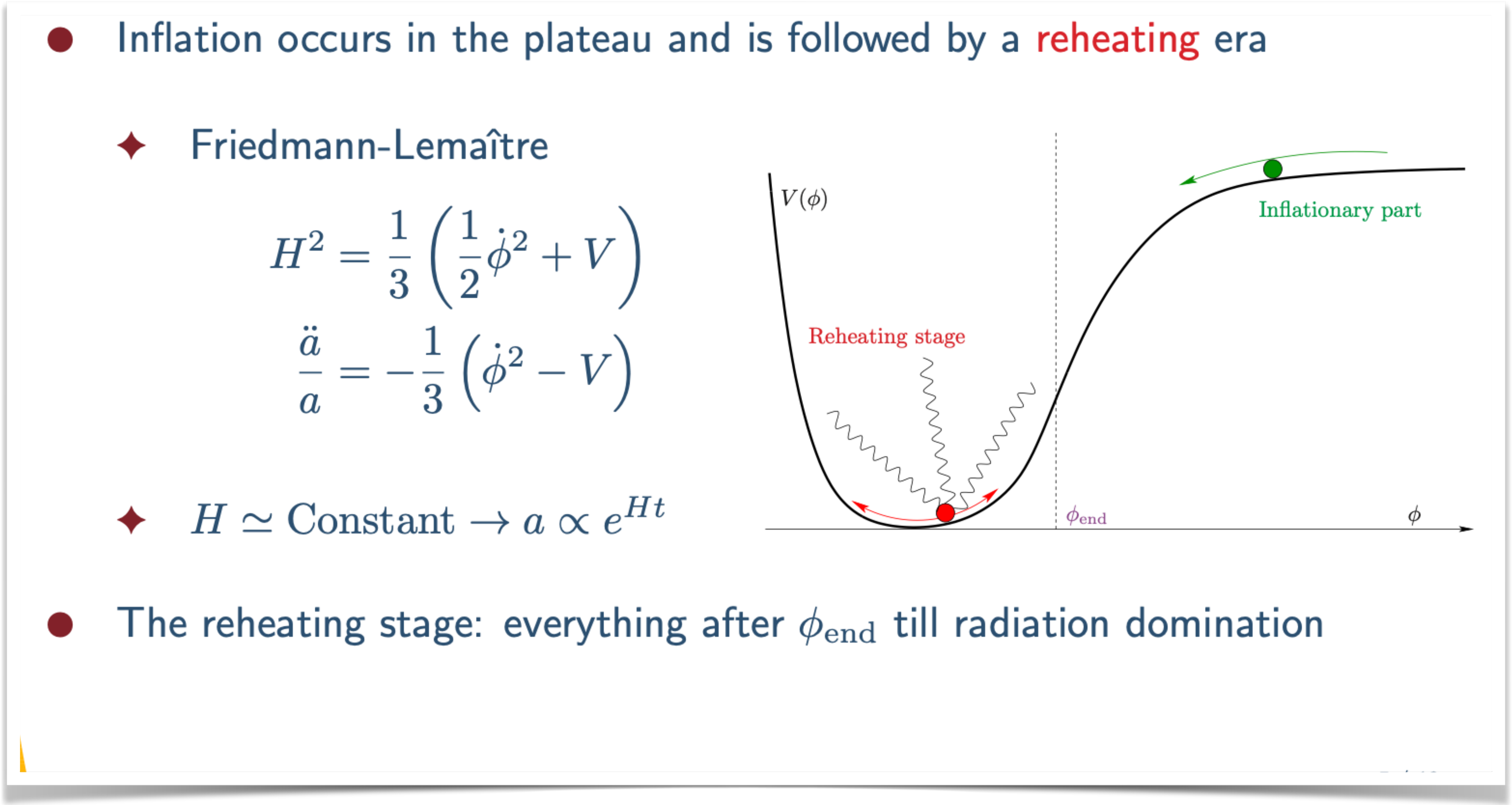
- **Binaries**: large range of masses and mass ratios:
  - SuperMassive BH Binaries
  - Extreme Mass Ratio Inspiral
  - Stellar mass BH Binaries
  - Double White Dwarfs
  - Double Neutron Stars
  - Intermediate Mass Ratio Inspiral
  - Intermediate Mass BH Binaries
- **Stochastic backgrounds**:
  - First order phase transitions, cosmic string networks, …
- Bursts: cosmic strings, …
- Unknown?

Primordial universe

Inflation

What is inflation?

- Predictive, testable and tested early universe paradigm
  - Hypothetical accelerated expansion of the universe at $E_{\text{inf}} > \text{MeV}$ (BBN)
  - Addresses some unexplainable features of the Friedmann-Lemaître model
- For the **simplest incarnation** of inflation. . .
  - Historically introduced to dilute monopoles formed at GUT
  - Flatness of the spatial sections ($\Omega_{\text{K}} = 0.0009 \pm 0.0018$)
  - Statistical isotropy of the observable universe (horizon problem)
  - Origin of CMB and LSS (quantum fluctuations)
  - Gaussianities of the cosmological perturbations ($f_{\text{NL}} < -0.9 \pm 5$)
  - Adiabaticity of the cosmological perturbations (isocurv. $< 1\%$)
  - Almost scale invariance ($n_{\text{S}} = 0.9649 \pm 0.004$)



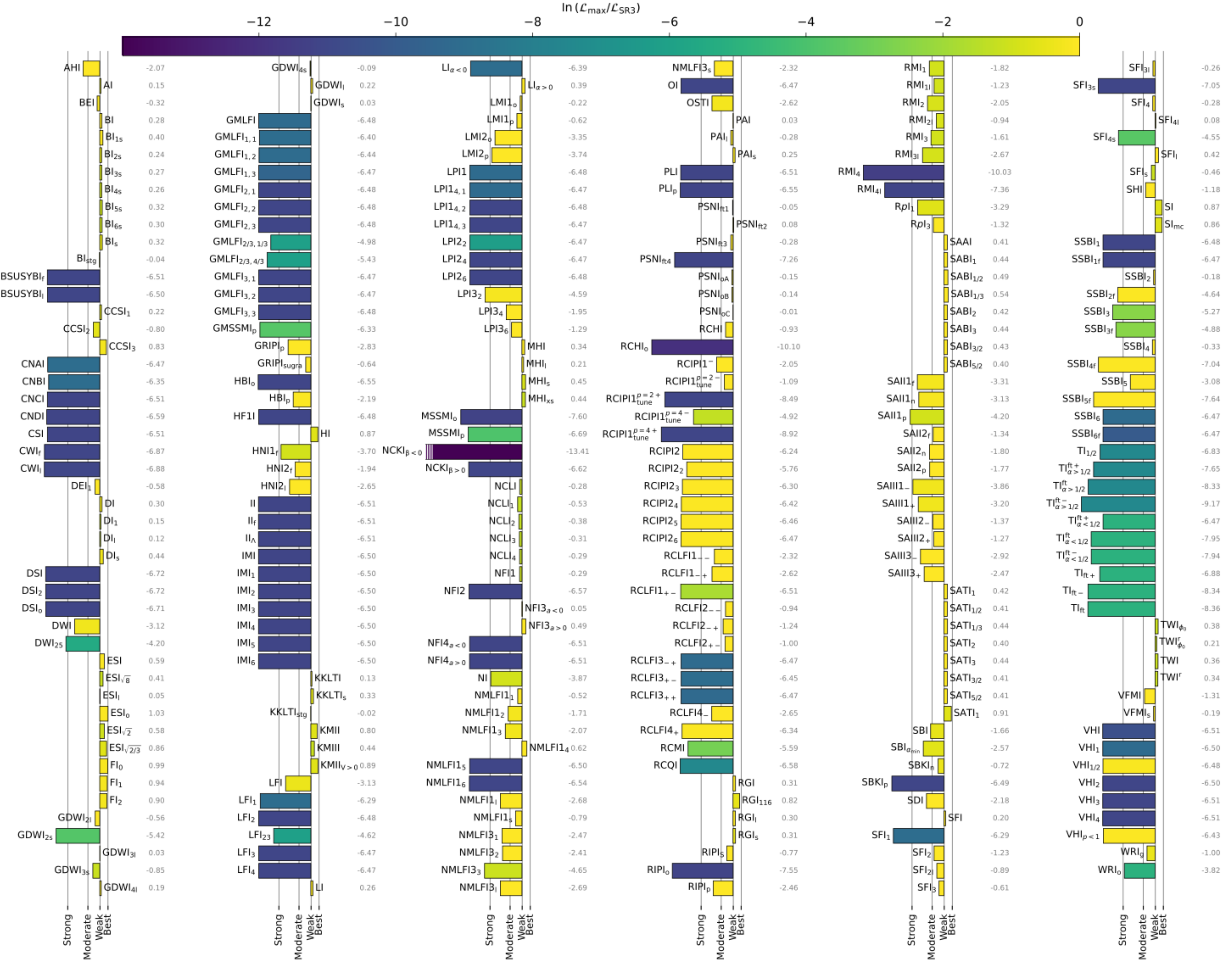
- Inflation occurs in the plateau and is followed by a reheating era
  - Friedmann-Lemaître

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V\right)$$

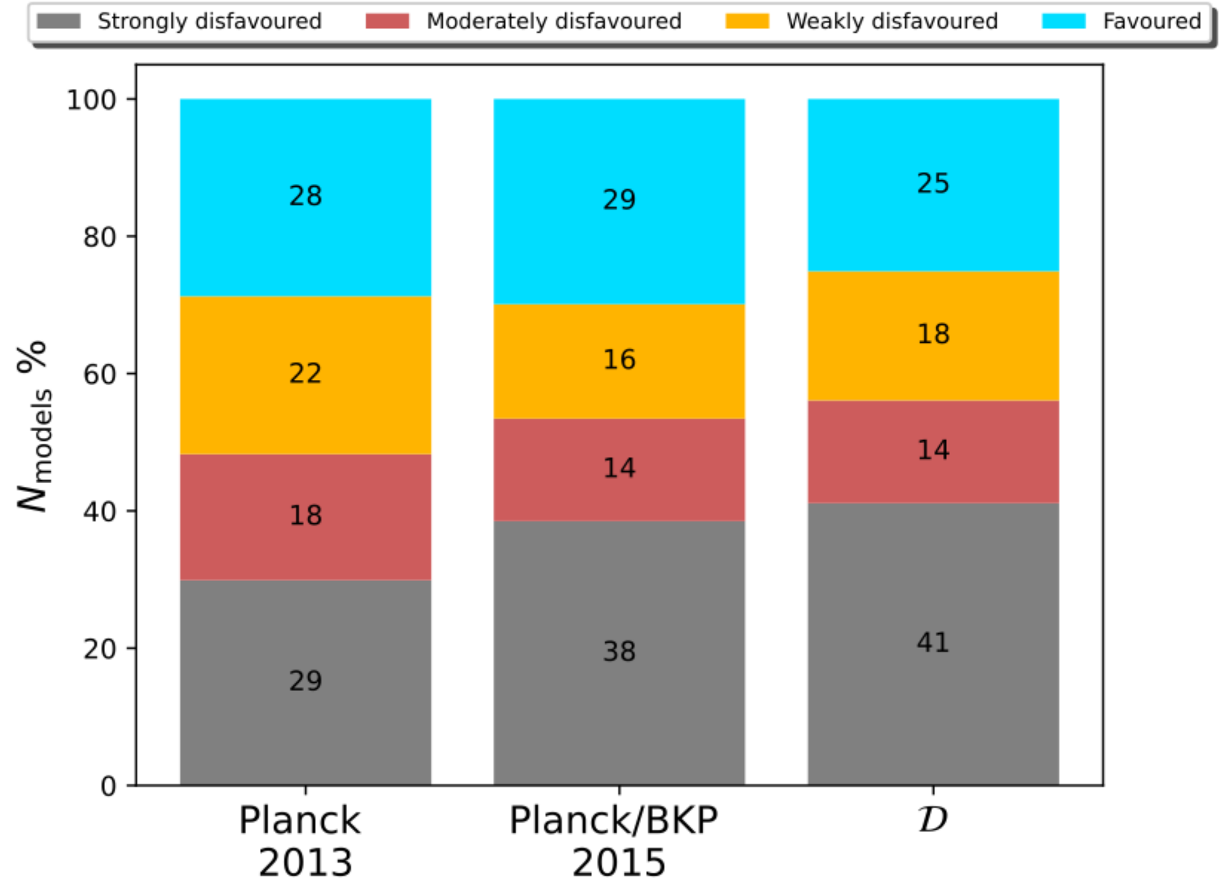
$$\frac{\ddot{a}}{a} = -\frac{1}{3}\left(\dot{\phi}^2 - V\right)$$

  - $H \simeq \text{Constant} \to a \propto e^{Ht}$
- The reheating stage: everything after ϕ_{end} till radiation domination

Bayes factors for all models



- Data constraining power is winning against theoretical proposals

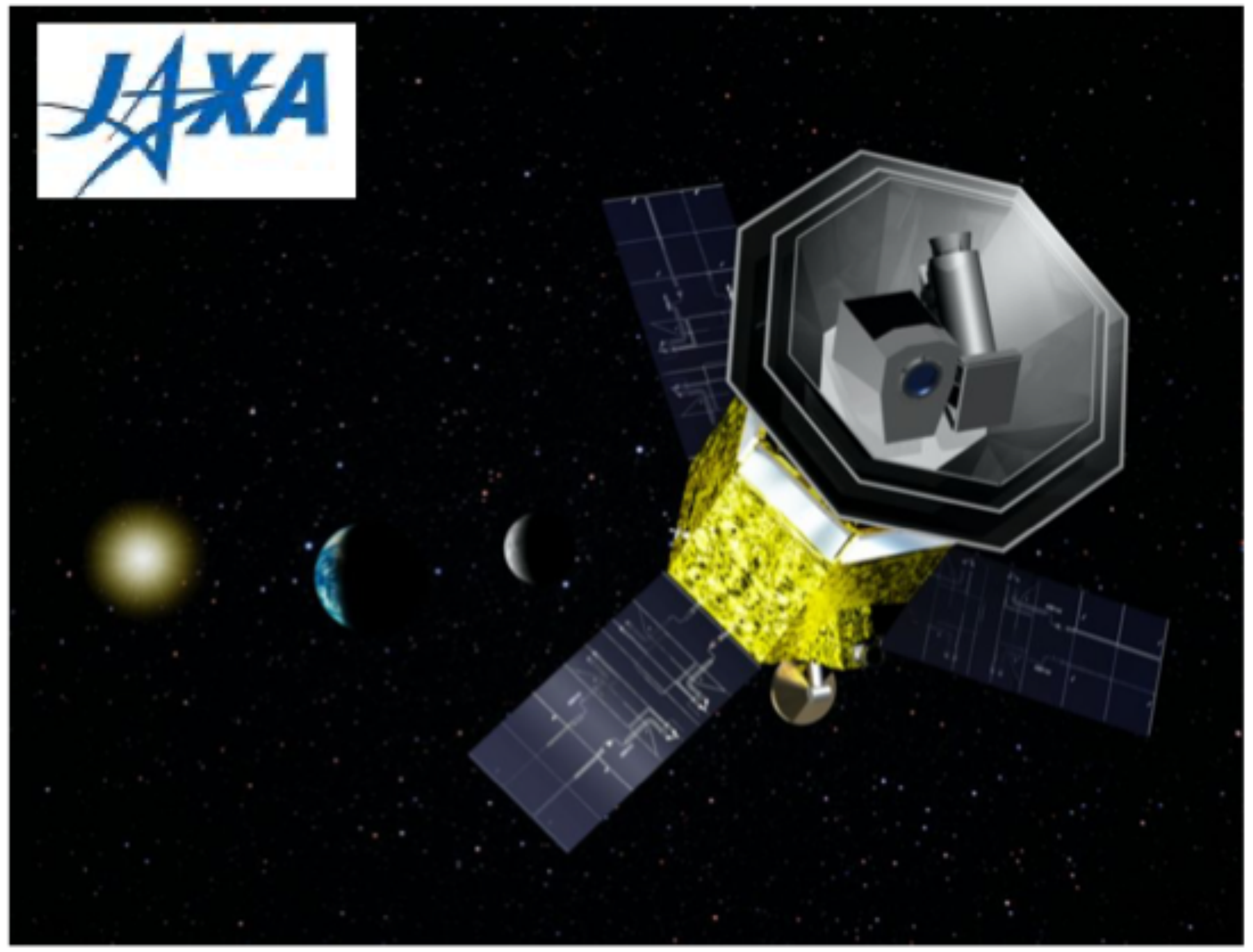


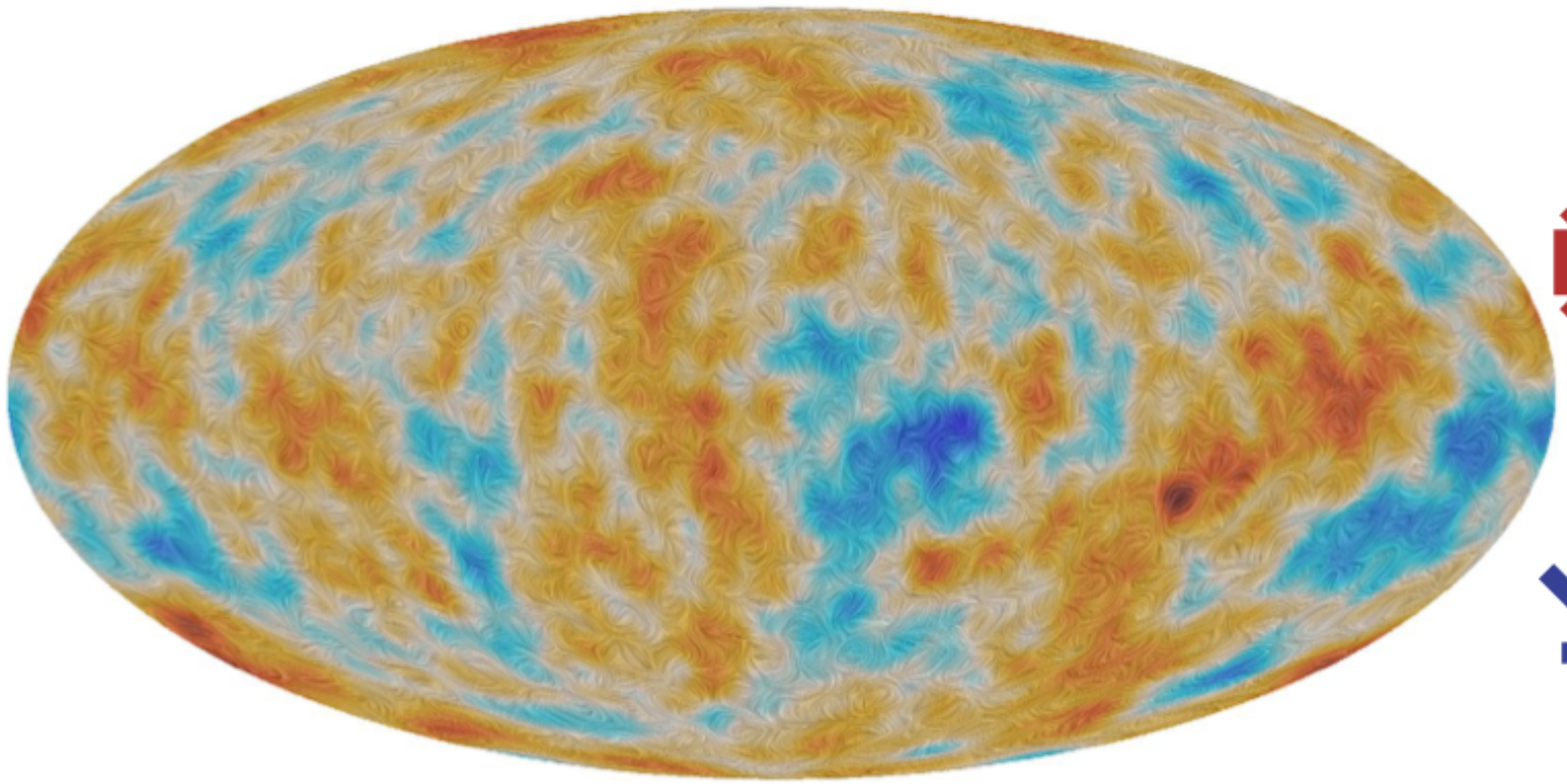
- Looking forward to the Euclid, LSS & CMB-S4 data!

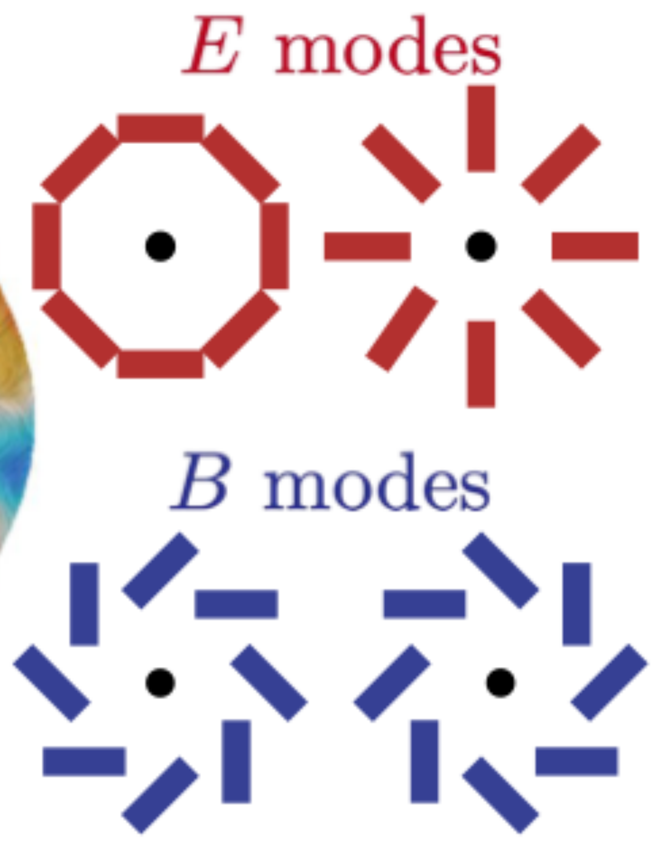
LiteBIRD overview

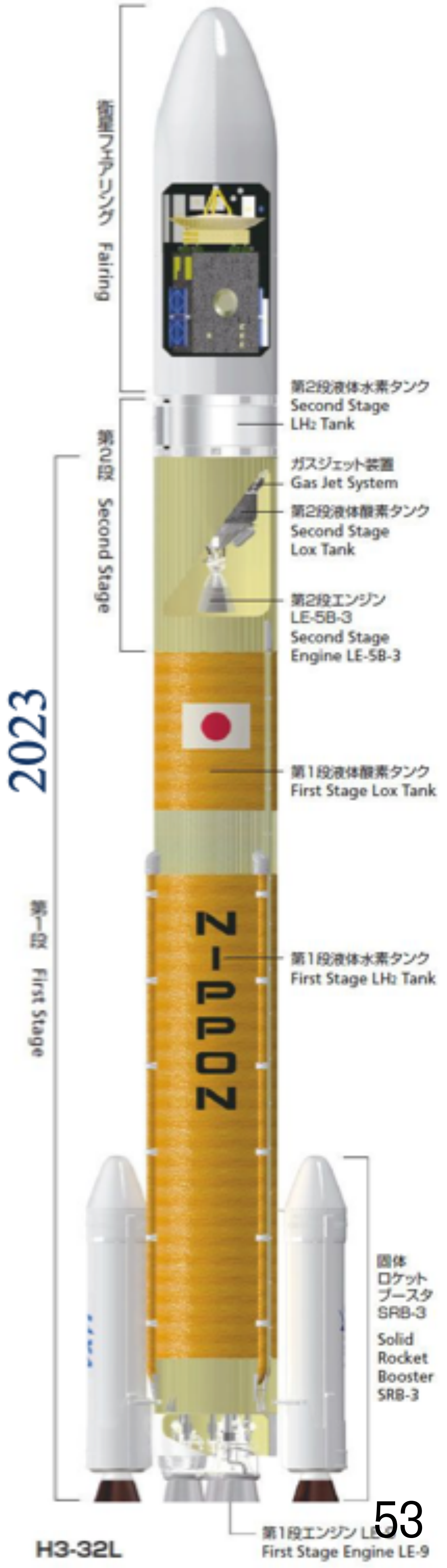
- *Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection*
- **JAXA**'s L-class mission selected in May 2019 to be launched in **~2032** with JAXA's H3 rocket
- LiteBIRD collaboration: Over 400 researchers from **Japan**, **North America** and **Europe**
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
- Making a discovery or ruling out well-motivated inflationary models, insight into the quantum nature of gravity, the primordial *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***.
- LiteBIRD will improve current sensitivity on *r* by a factor ~50

LiteBIRD collaboration PTEP









The challenge of B-modes detection

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- LiteBIRD is targeting a sensitivity level in polarization ~30 times better than Planck
- This extremely good statistical uncertainty must go in parallel with exquisite control of:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination
  3. **“Lensing B-mode signal”** induced by gravitational lensing
  4. Observer biases

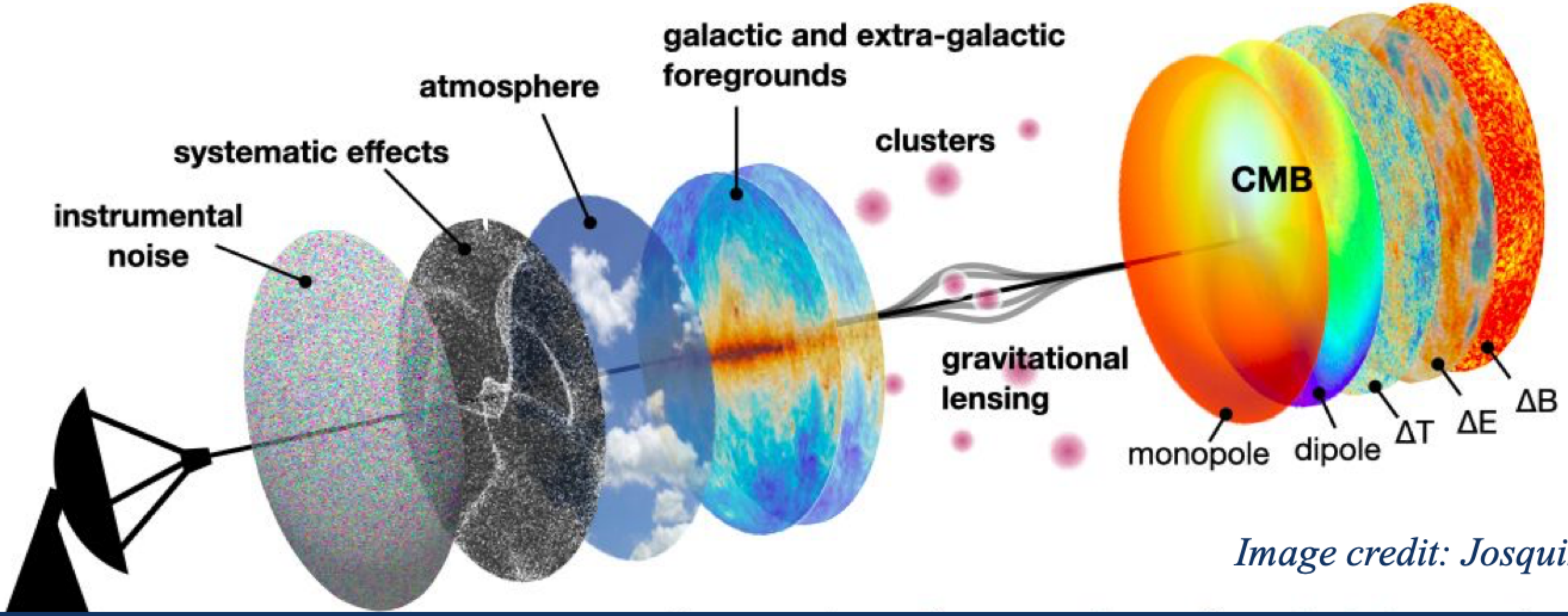
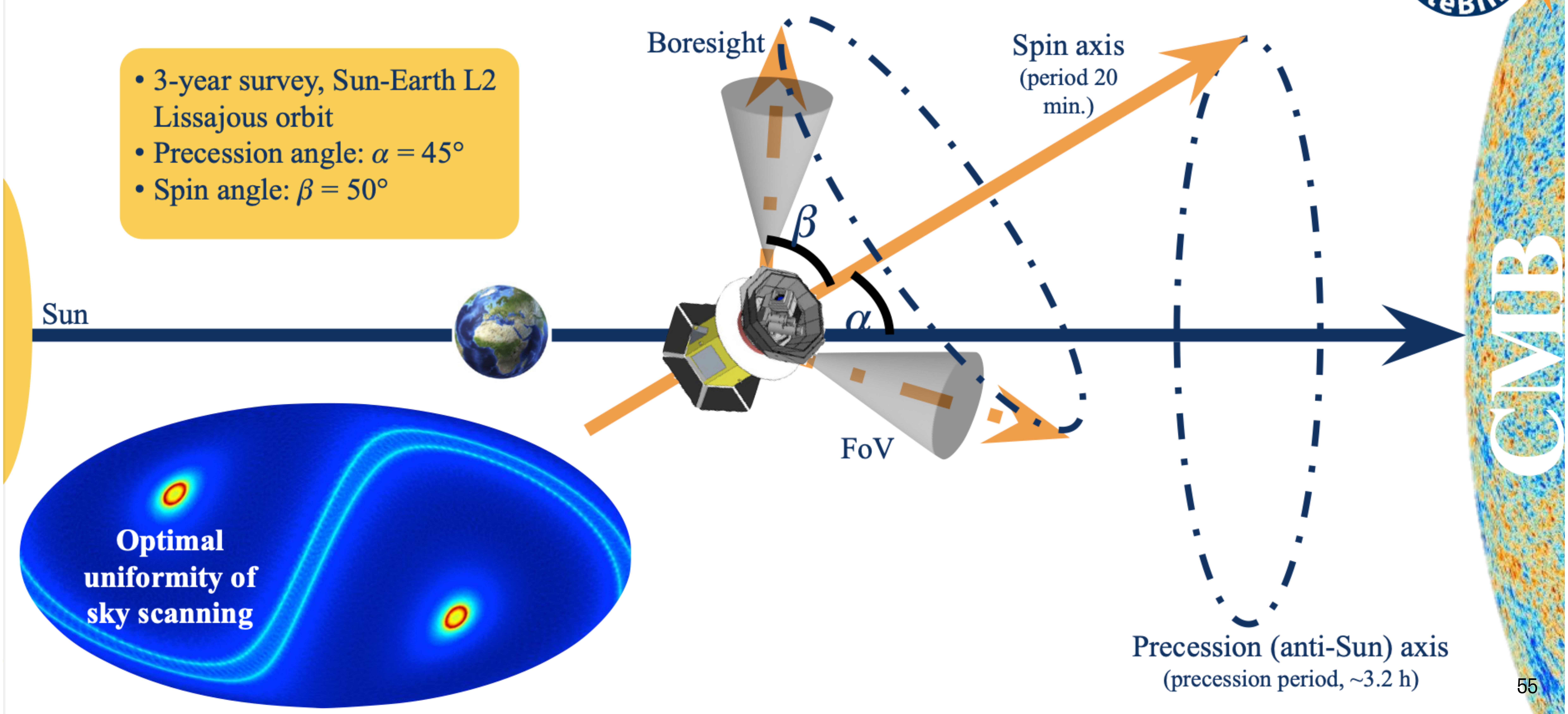


Image credit: Josquin Errard

LiteBIRD scanning strategy

- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: $\alpha = 45°$
- Spin angle: $\beta = 50°$

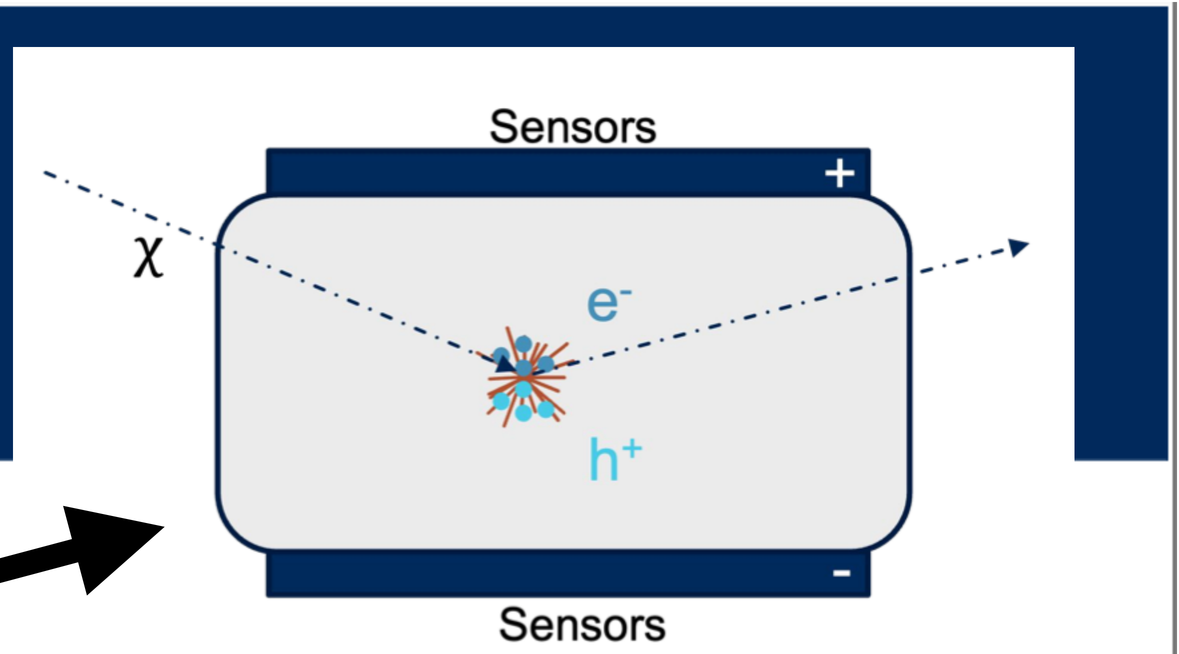


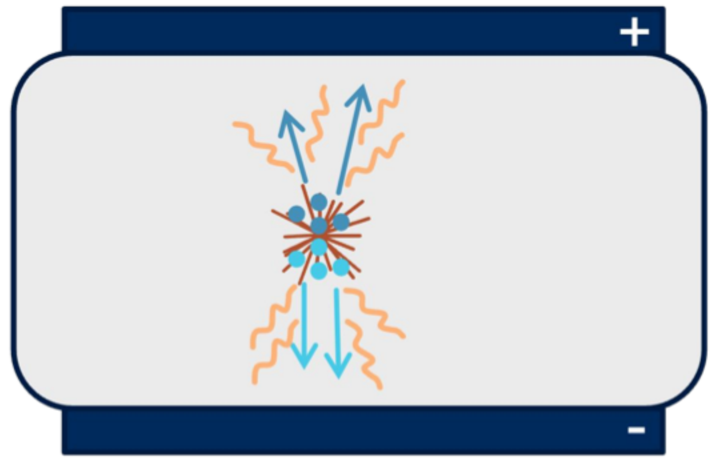
Summary

- Only a small subset of results shown here, many other interesting presented ! (also in backup)
  - https://indico.cern.ch/event/1267450/timetable/?view=standard
- Many interesting project staring soon, or being planned
  - useful for prospectives :-)

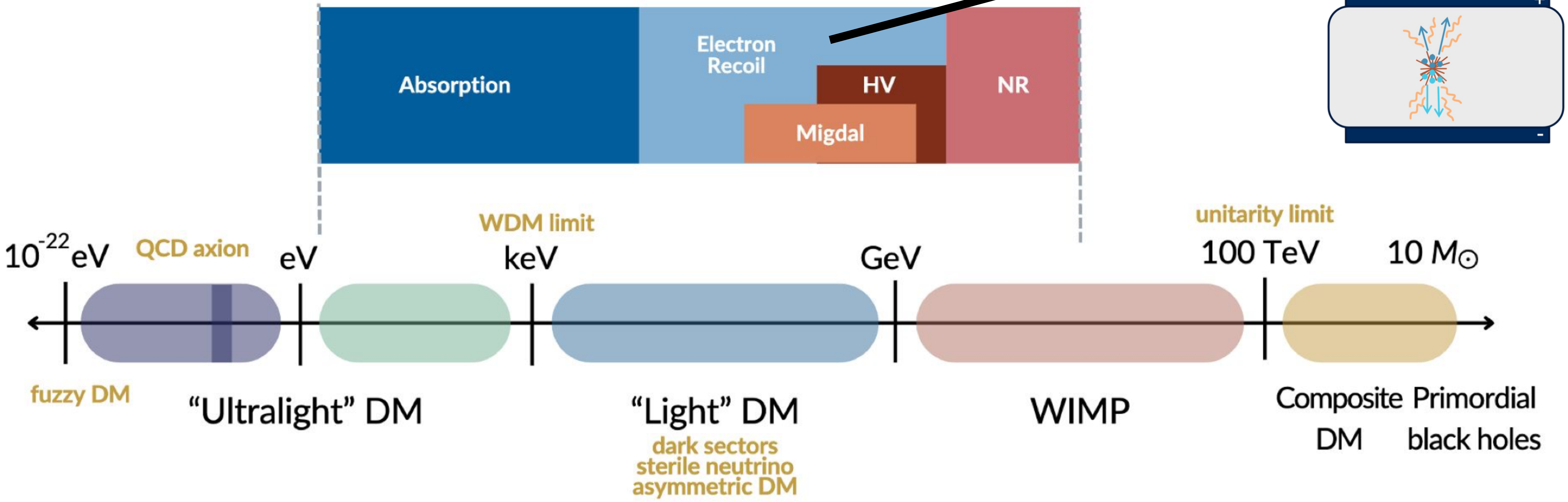
Additional topics

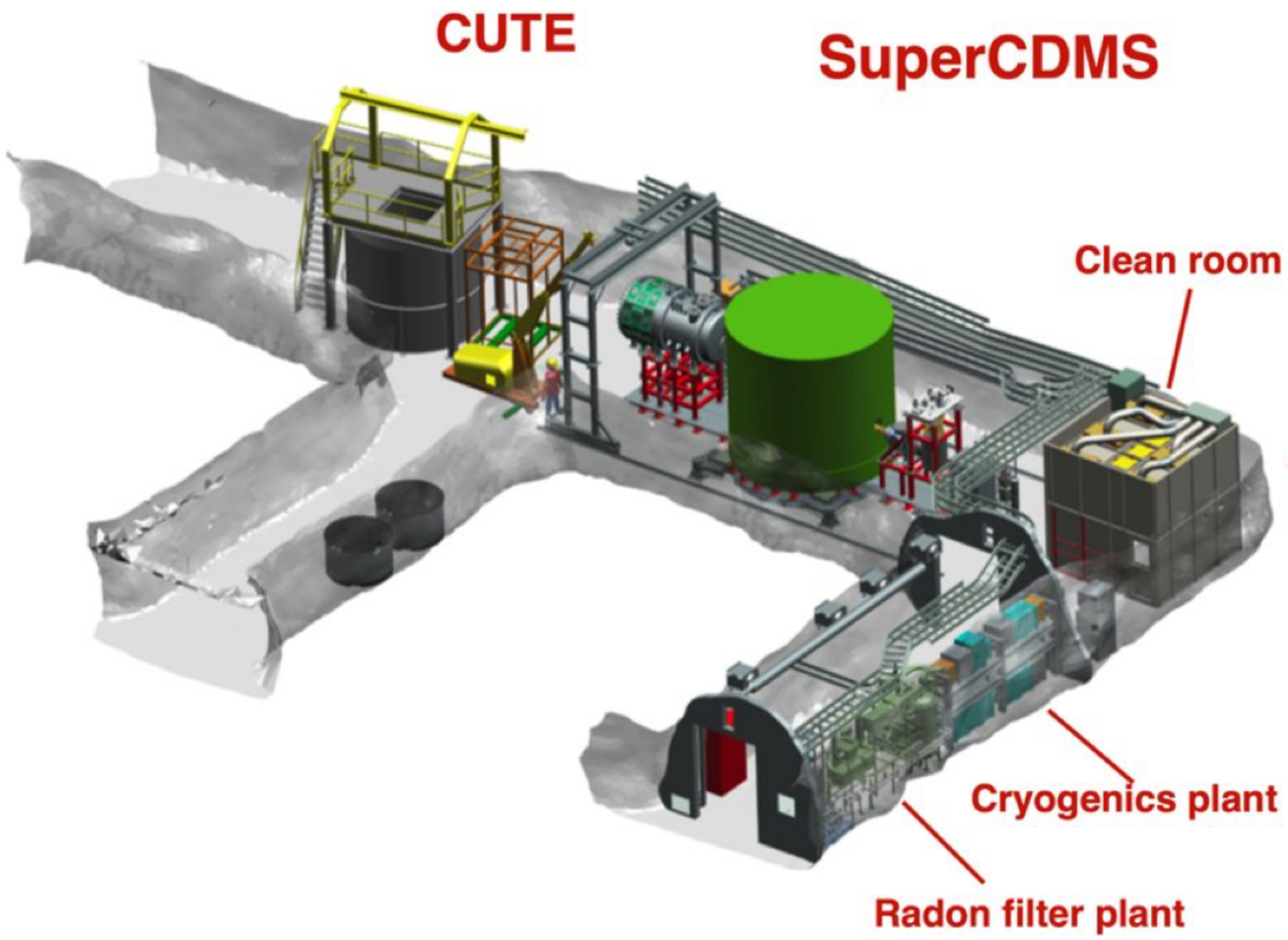
Dark Matter + SuperCDMS -> cryogenic experiments

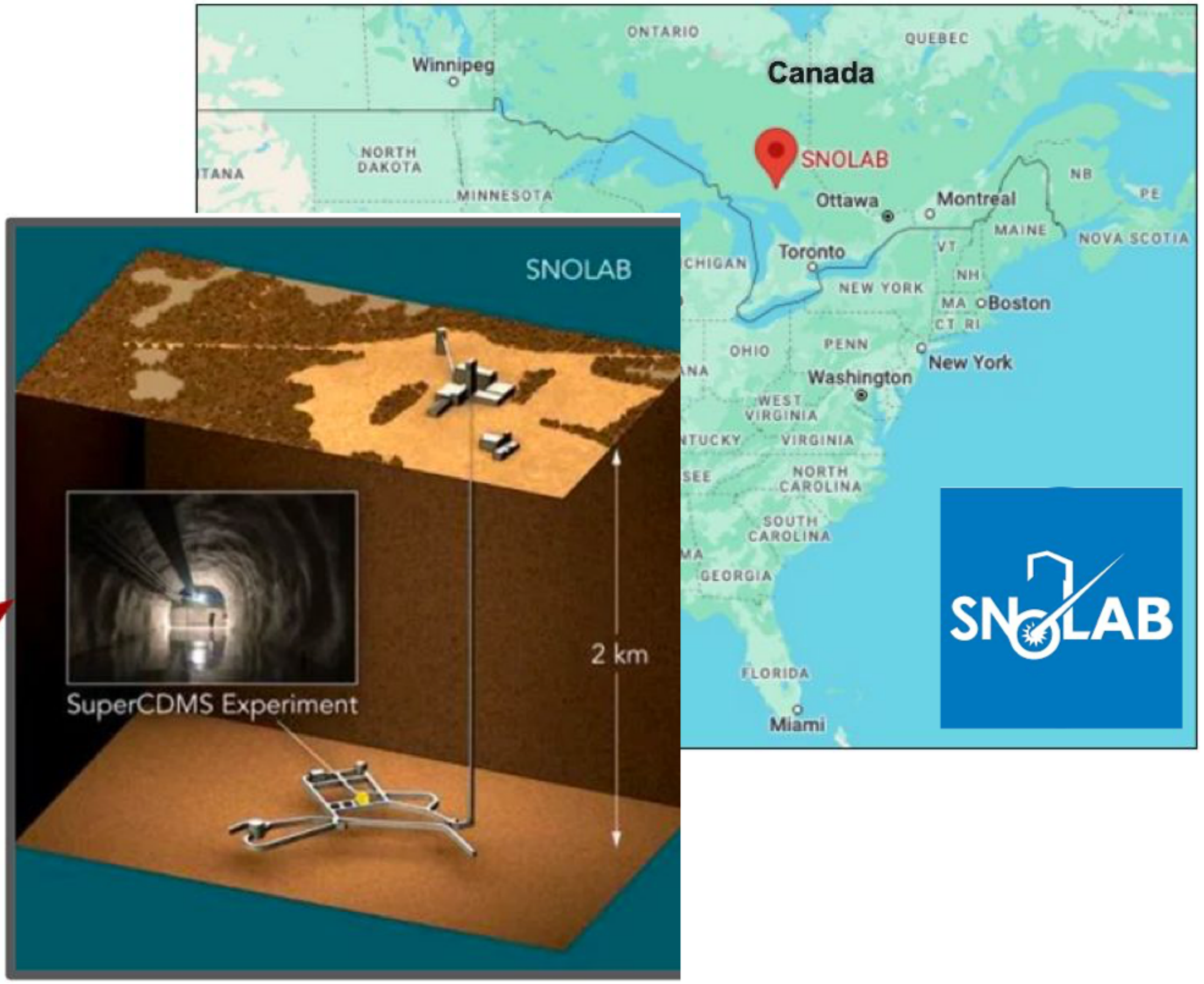




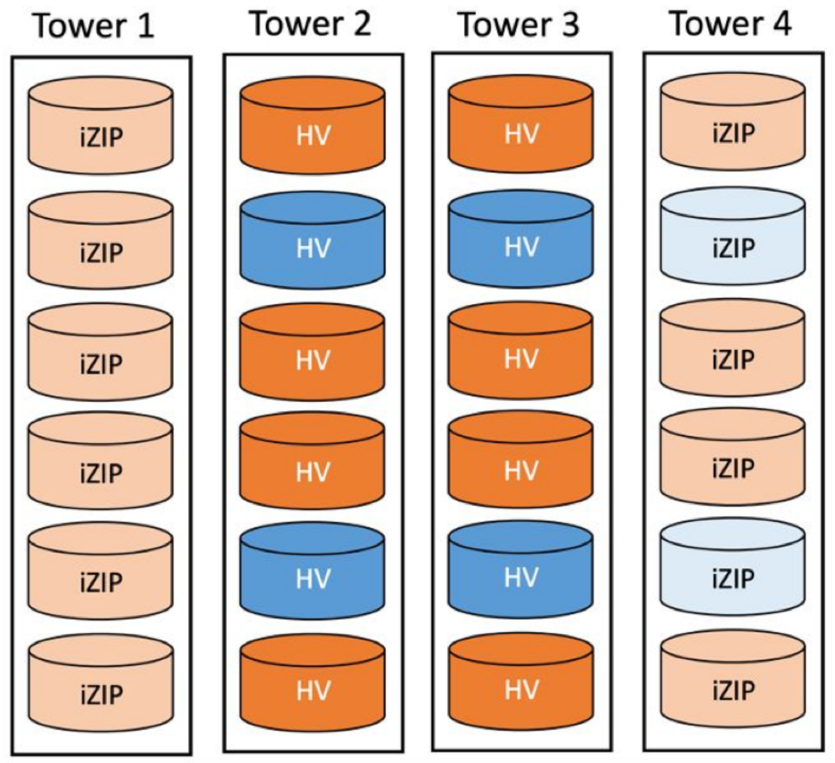
Where and how we're looking



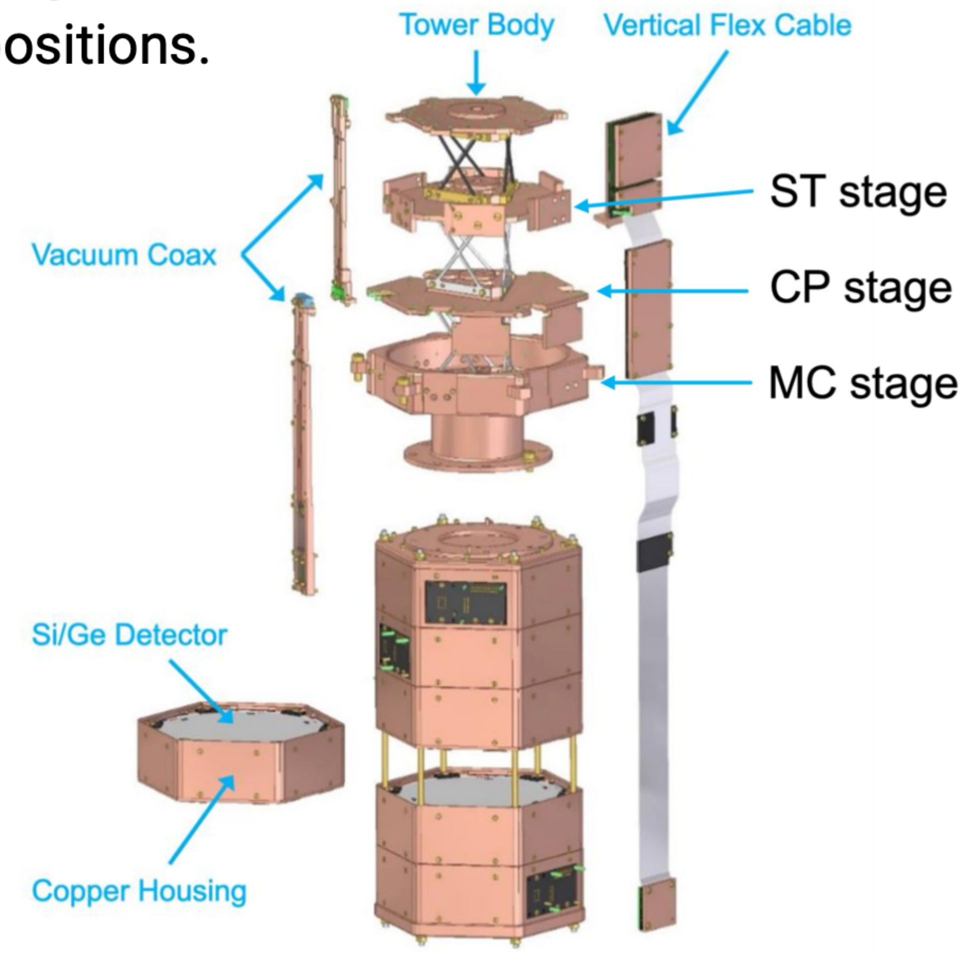




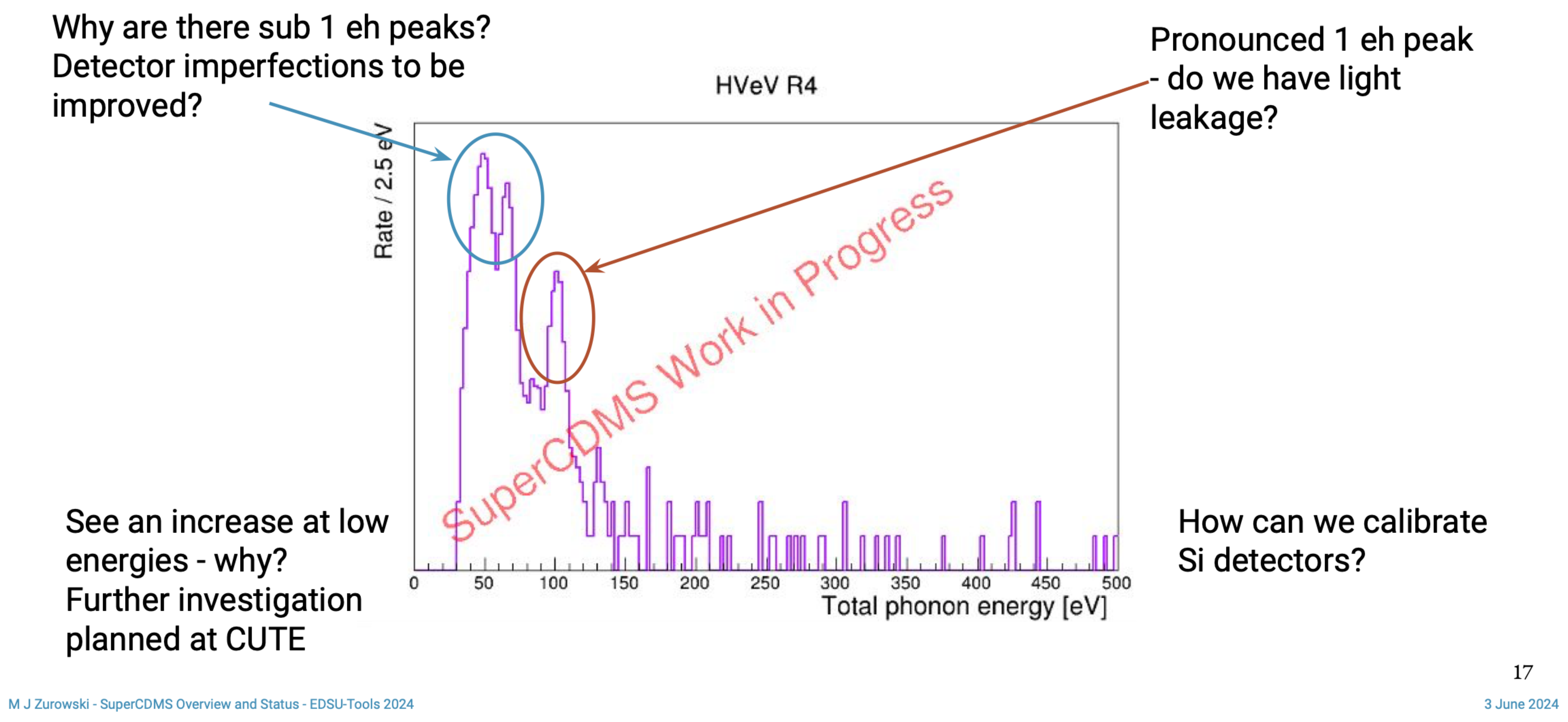
Detectors organised into 4 towers with layouts designed based on detector type and shielding/veto for different positions. Orange ⇒ Ge, blue ⇒ Si



Tower 1	Tower 2	Tower 3	Tower 4
🟧 iZIP	🟧 HV	🟧 HV	🟧 iZIP
🟧 iZIP	🟦 HV	🟦 HV	🟦 iZIP
🟧 iZIP	🟧 HV	🟧 HV	🟧 iZIP
🟧 iZIP	🟧 HV	🟧 HV	🟧 iZIP
🟧 iZIP	🟦 HV	🟦 HV	🟦 iZIP
🟧 iZIP	🟧 HV	🟧 HV	🟧 iZIP



Current and projected results



Why are there sub 1 eh peaks? Detector imperfections to be improved?

Pronounced 1 eh peak - do we have light leakage?

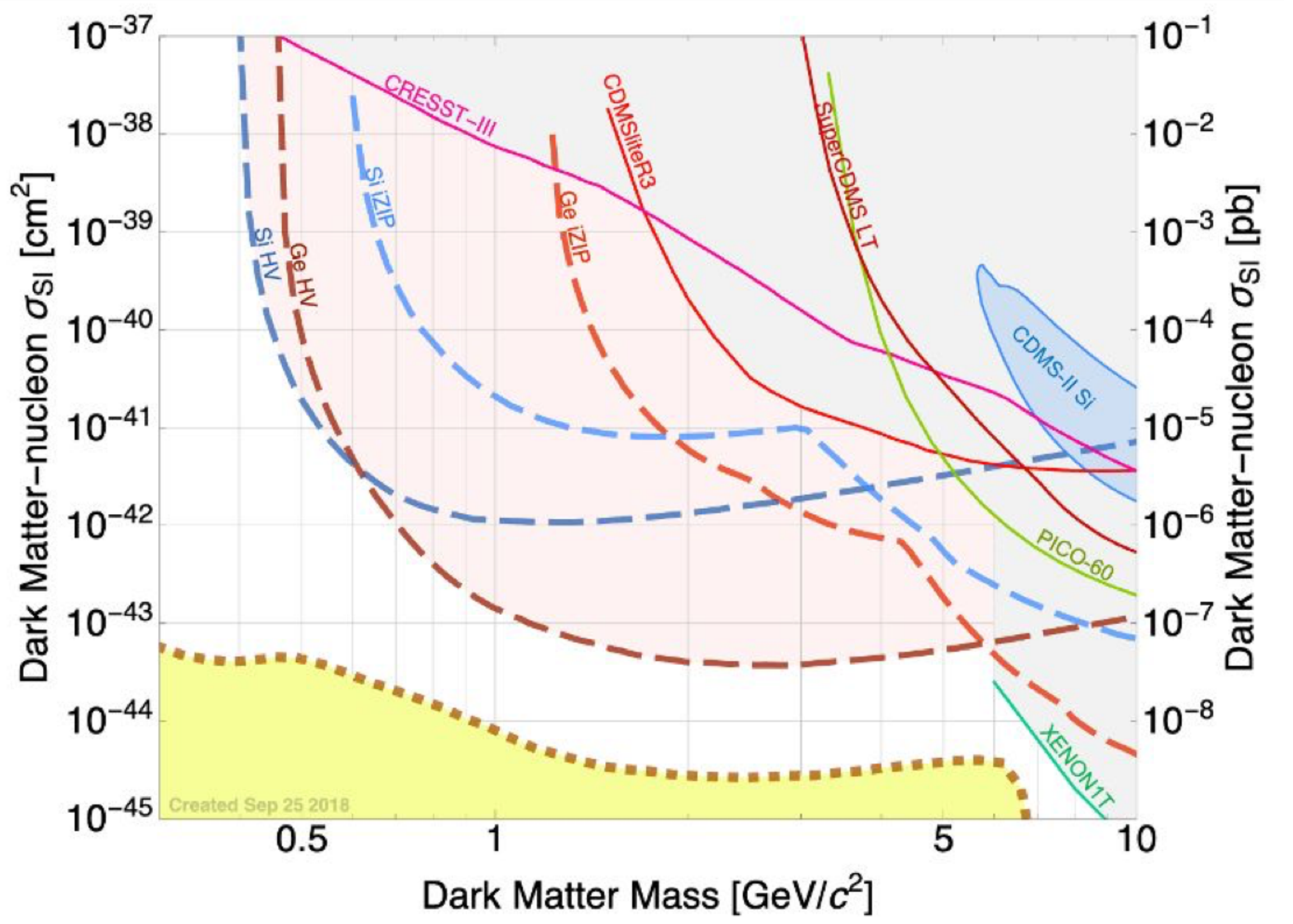
See an increase at low energies - why? Further investigation planned at CUTE

How can we calibrate Si detectors?

M J Zurowski - SuperCDMS Overview and Status - EDSU-Tools 2024

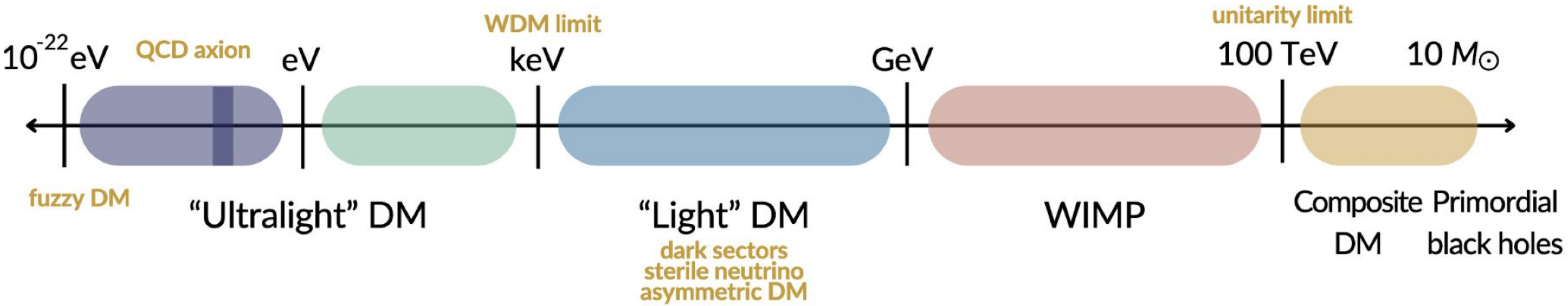
17

3 June 2024



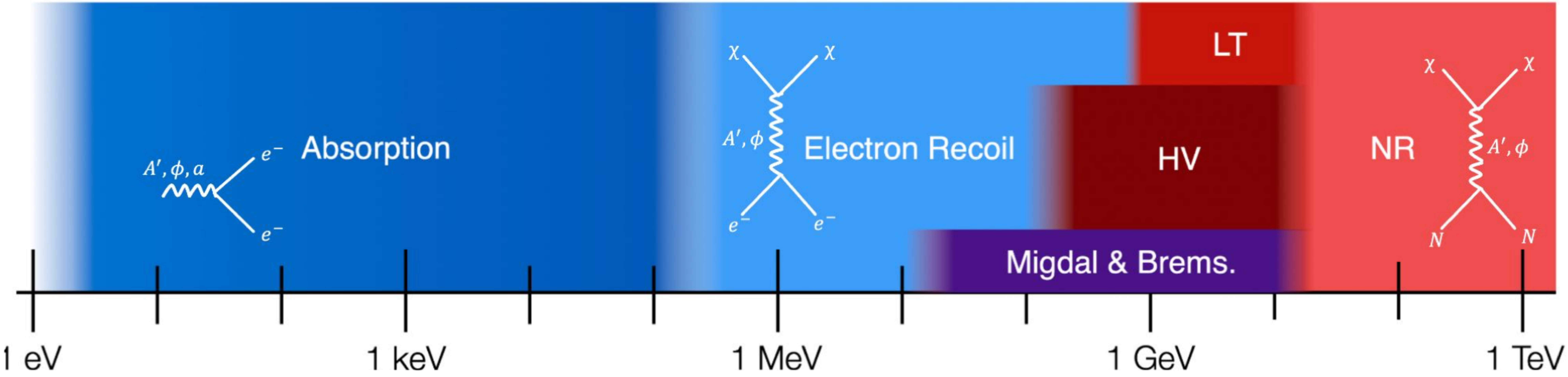
Dark Matter

We're pretty sure it's out there, but where to look…
Lots of well motivated theories and experimental techniques



SuperCDMS search methods

○	"Traditional" Nuclear Recoil:	Full discrimination,	≳ 5 GeV
○	Low Threshold NR:	Limited discrimination,	≳ 1 GeV
○	HV Detector:	HV, no discrimination,	~0.3 – 10 GeV
○	Migdal & Bremsstrahlung:	no discrimination,	~0.01 – 10 GeV
○	Electron recoil:	HV, no discrimination,	~0.5 MeV – 10 GeV
○	Absorption (Dark Photons, ALPs):	HV, no discrimination,	~1 eV – 500 keV ("peak search")

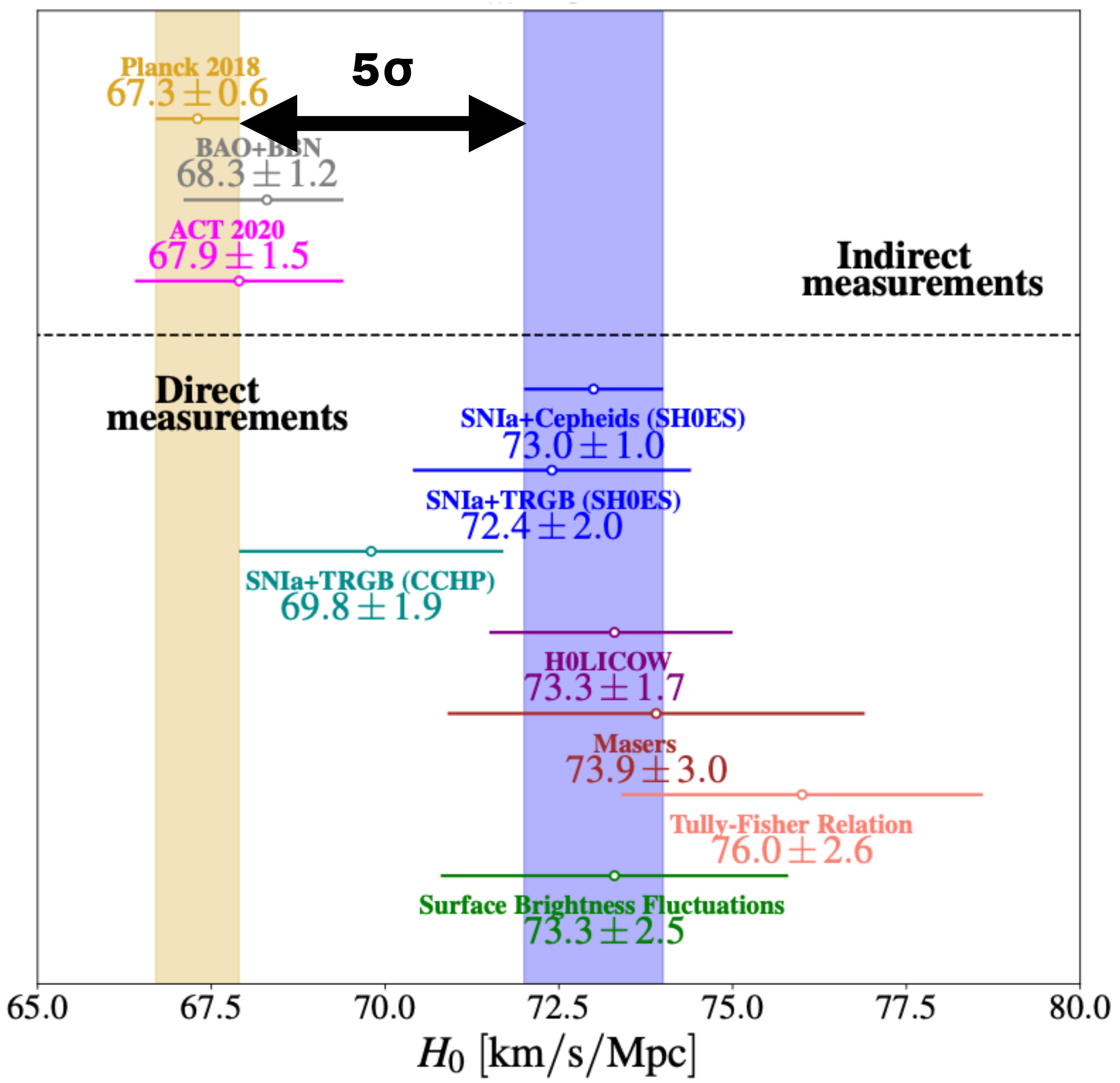


Modified gravity

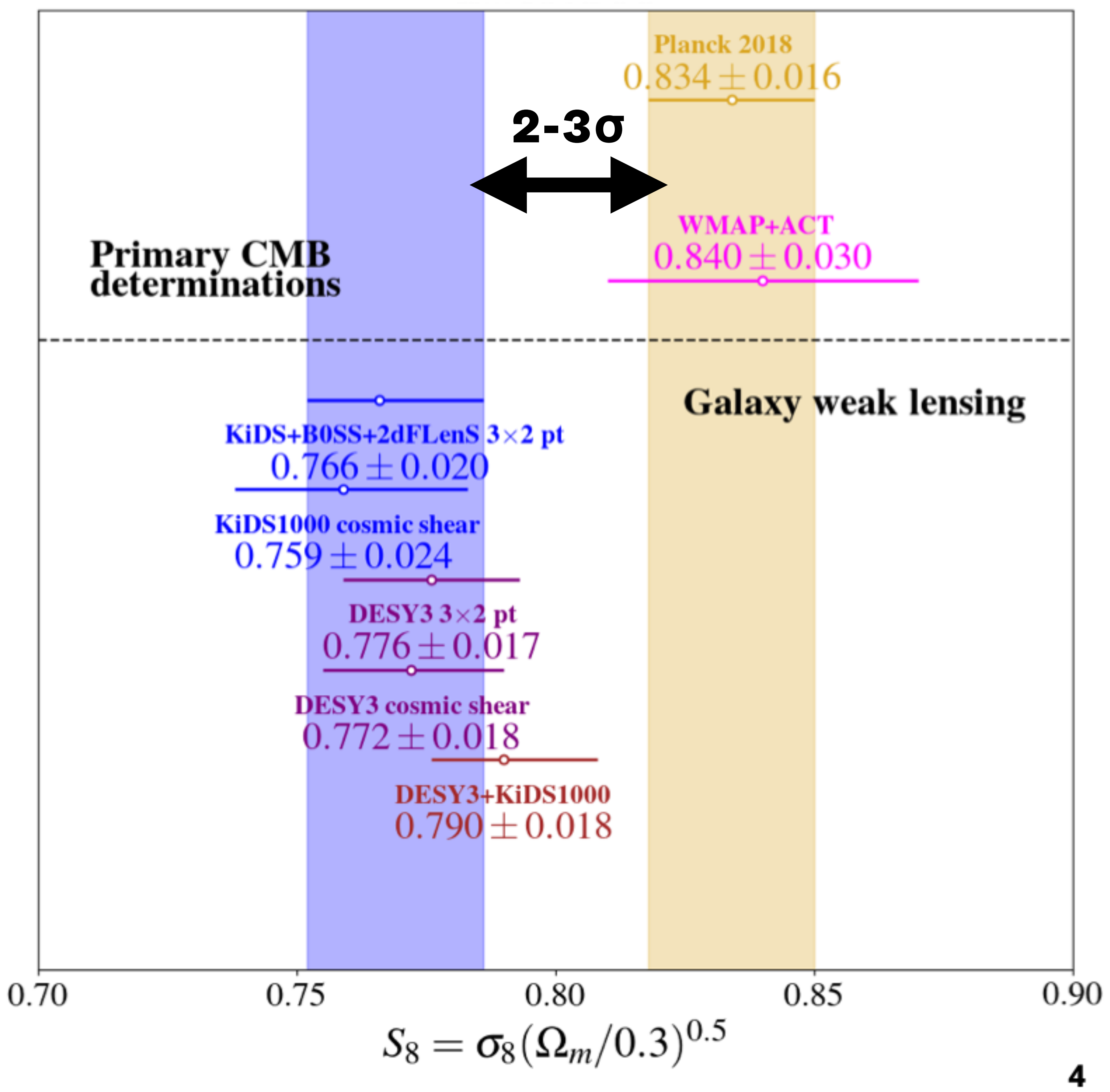
Tensions in LCDM

In addition, **discrepancies have emerged**

H_0 tension



S_8 tension



What is needed to explain low S_8 values ?

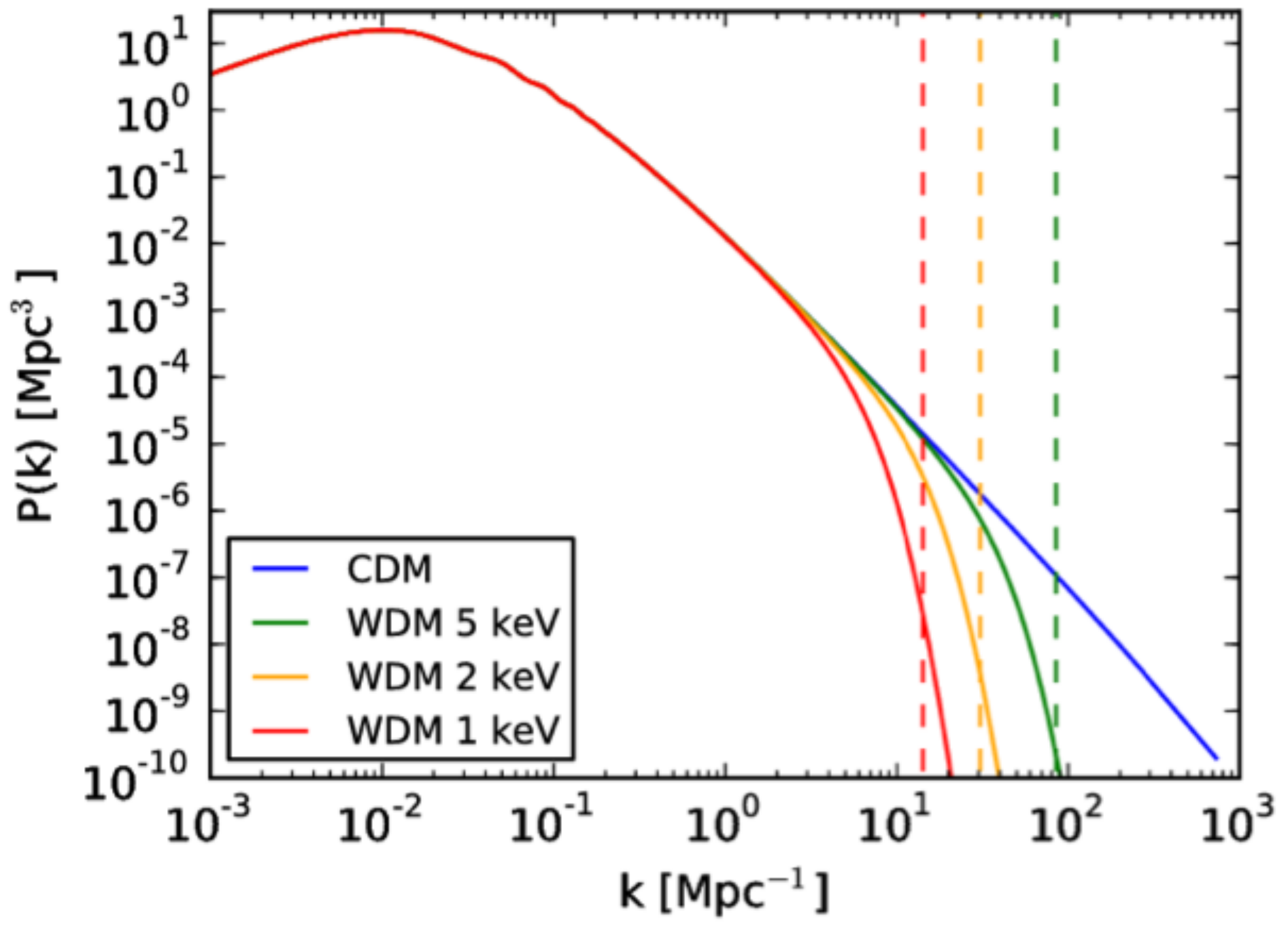
$$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$$

$$\sigma_8^2 = \int P_m(k, z=0)\, W_R^2(k)\, d\ln k$$

with $R = 8\ \mathrm{Mpc}/h$

One needs to **suppress matter growth**
at scales $k \sim 0.1 - 1\ h/\mathrm{Mpc}$
while **keeping a good fit** to other data

Ex: Warm dark matter

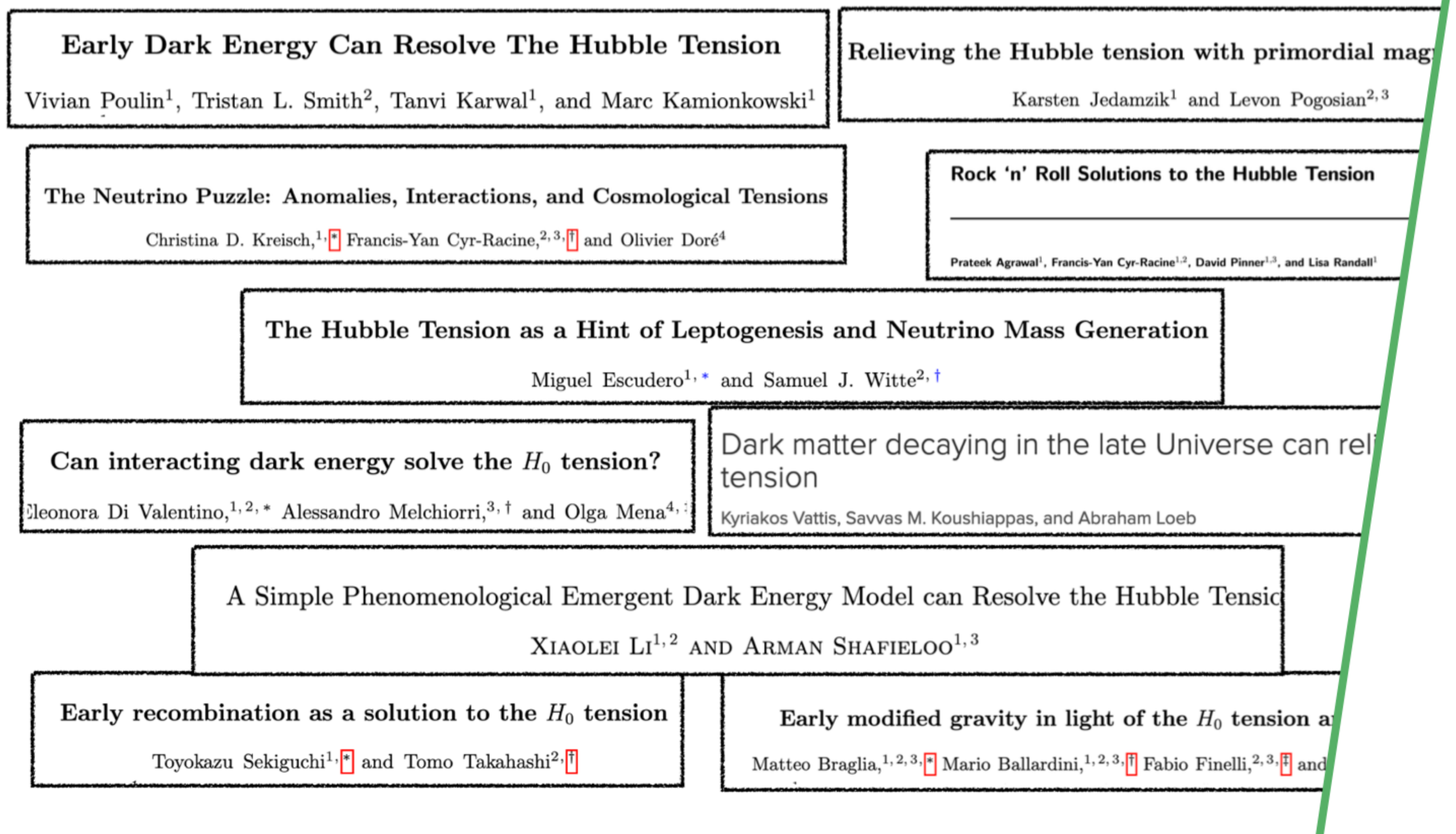


Very constrained by Ly-α !
[Iršič+ 17]

Theoretical solutions ?

- Decaying Dark Matter (DDM) is a potential candidate -> can explain S8 tension
- Early Dark Energy can be a candidate to explain H0 tension

Lost in the landscape of solutions



Early Dark Energy Can Resolve The Hubble Tension
Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]

Relieving the Hubble tension with primordial mag
Karsten Jedamzik[1] and Levon Pogosian[2,3]

The Neutrino Puzzle: Anomalies, Interactions, and Cosmological Tensions
Christina D. Kreisch,[1,*] Francis-Yan Cyr-Racine,[2,3,†] and Olivier Doré[4]

Rock 'n' Roll Solutions to the Hubble Tension
Prateek Agrawal[1], Francis-Yan Cyr-Racine[1,2], David Pinner[1,3], and Lisa Randall[1]

The Hubble Tension as a Hint of Leptogenesis and Neutrino Mass Generation
Miguel Escudero[1,*] and Samuel J. Witte[2,†]

Can interacting dark energy solve the H_0 tension?
Eleonora Di Valentino,[1,2,*] Alessandro Melchiorri,[3,†] and Olga Mena[4,]

Dark matter decaying in the late Universe can reli
tension
Kyriakos Vattis, Savvas M. Koushiappas, and Abraham Loeb

A Simple Phenomenological Emergent Dark Energy Model can Resolve the Hubble Tensi
XIAOLEI LI[1,2] AND ARMAN SHAFIELOO[1,3]

Early recombination as a solution to the H_0 tension
Toyokazu Sekiguchi[1,*] and Tomo Takahashi[2,†]

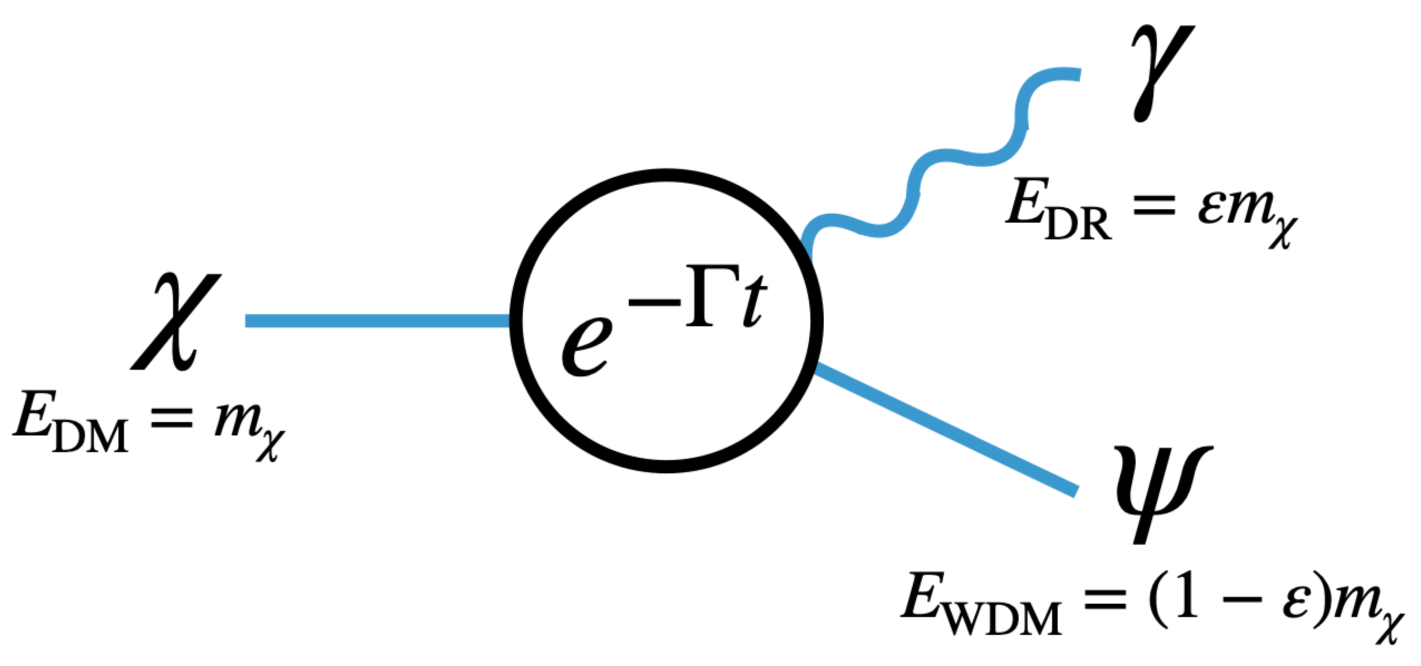
Early modified gravity in light of the H_0 tension a
Matteo Braglia,[1,2,3,*] Mario Ballardini,[1,2,3,†] Fabio Finelli,[2,3,‡] and

Each author uses a **different** compilation of **data**...

... is it possible to **rank** the different models?

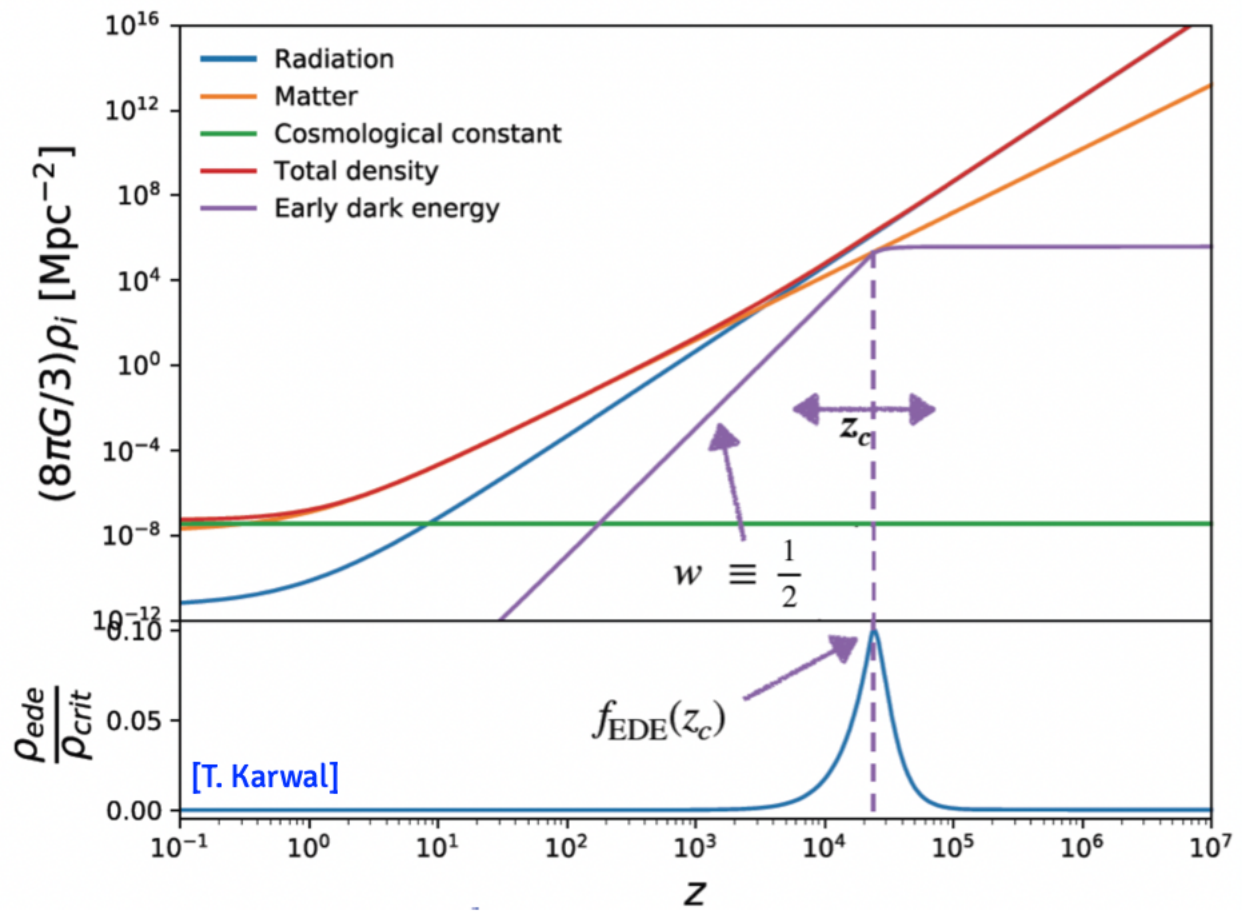
Invisible Dark Matter Decay

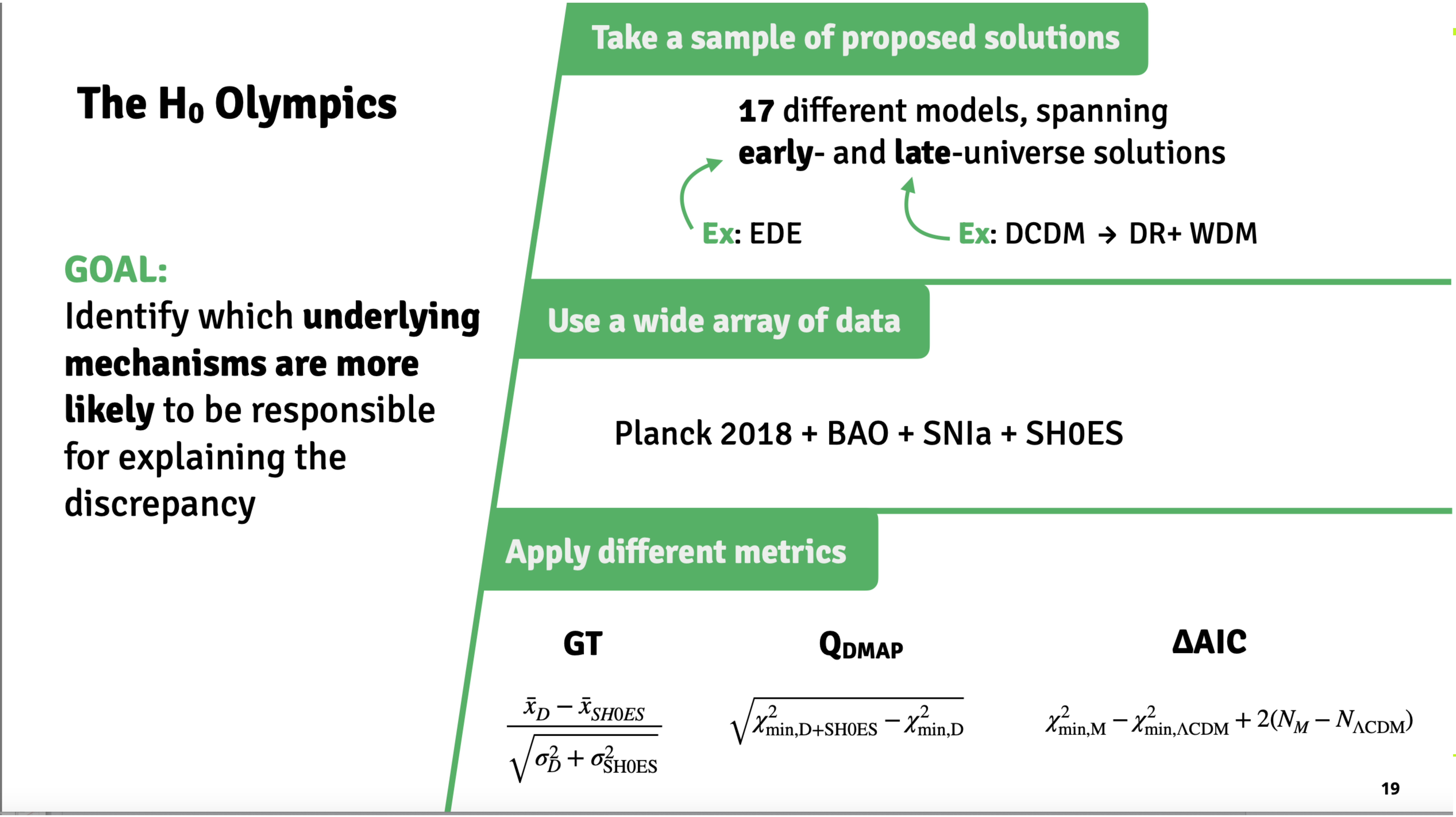
We explore DM decays to massless (Dark Radiation) and massive (Warm Dark Matter) particles



Early Dark Energy (EDE)

Scalar field initially frozen, dilutes faster than radiation afterwards





The H₀ Olympics

GOAL:
Identify which **underlying mechanisms are more likely** to be responsible for explaining the discrepancy

Take a sample of proposed solutions

17 different models, spanning **early**- and **late**-universe solutions

Ex: EDE

Ex: DCDM → DR+ WDM

Use a wide array of data

Planck 2018 + BAO + SNIa + SH0ES

Apply different metrics

GT

$$\frac{\bar{x}_D - \bar{x}_{SH0ES}}{\sqrt{\sigma_D^2 + \sigma_{\rm SH0ES}^2}}$$

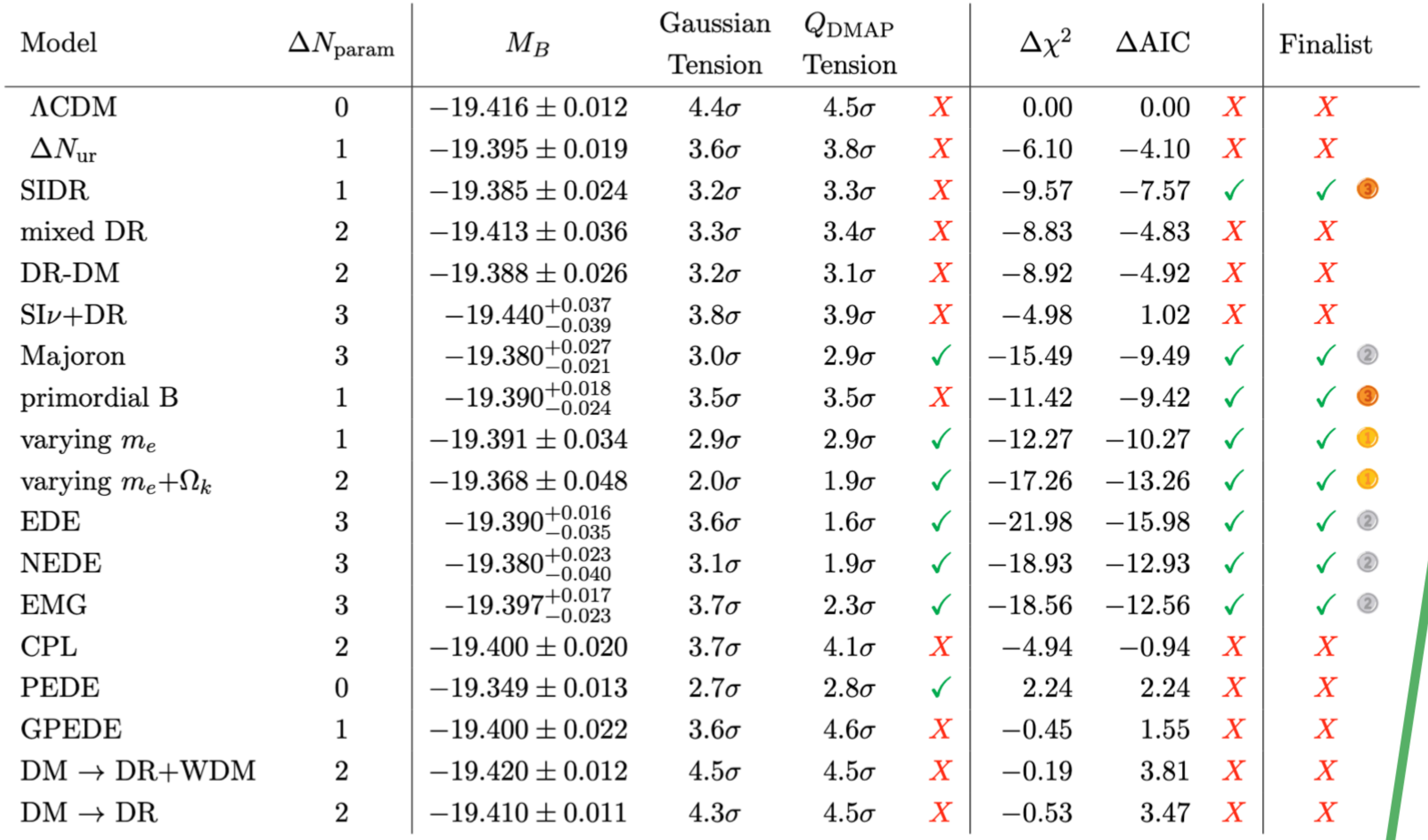
Q_DMAP

$$\sqrt{\chi^2_{\rm min,D+SH0ES} - \chi^2_{\rm min,D}}$$

ΔAIC

$$\chi^2_{\rm min,M} - \chi^2_{\rm min,\Lambda CDM} + 2(N_M - N_{\Lambda\rm CDM})$$

Results of the contest



Model	$\Delta N_{\mathrm{param}}$	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗	
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓	③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	②
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓	③
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	①
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	①
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	②
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	②
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓	②
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	✗	-4.94	-0.94	✗	✗	
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗	
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗	
DM → DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗	
DM → DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗	

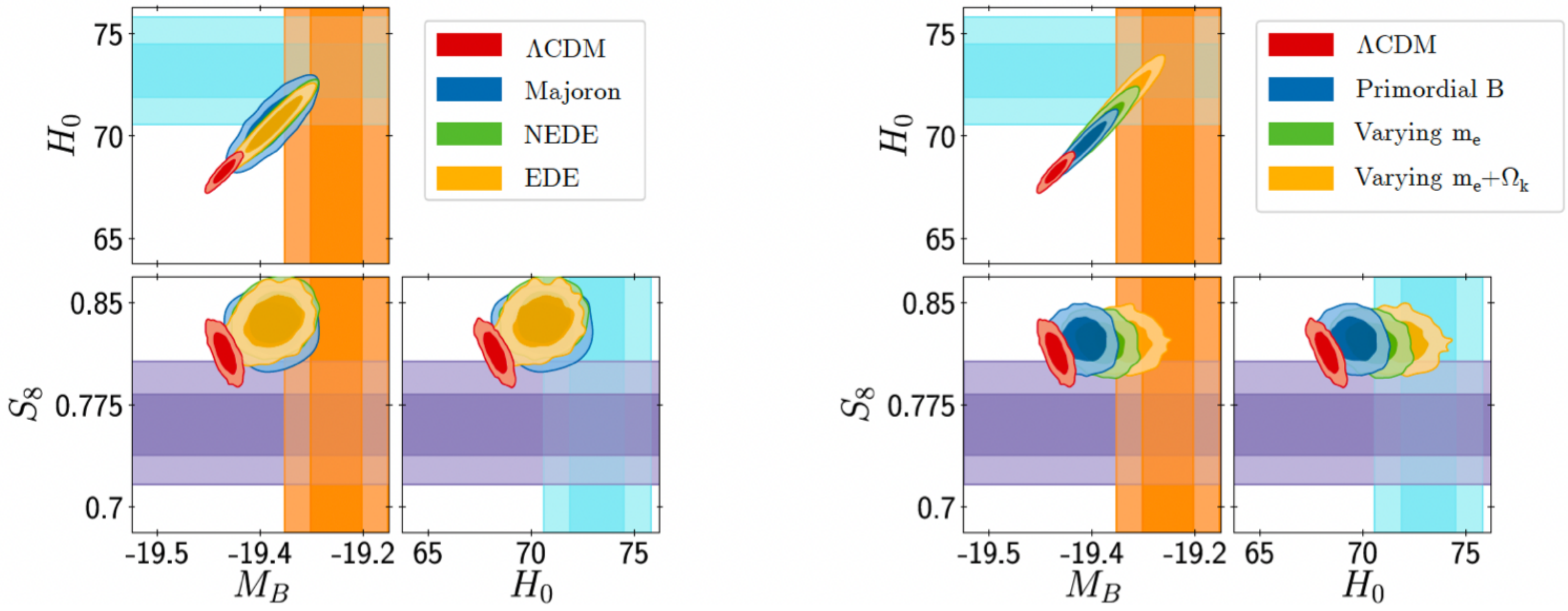
[Schöneberg, GFA++ 22]

Late-time solutions are the most **disfavored**

Early-time solutions (like EDE) appear the most **successful**

Results of the contest

Unfortunately, the most successful models are **unable to explain the S_8 tension**



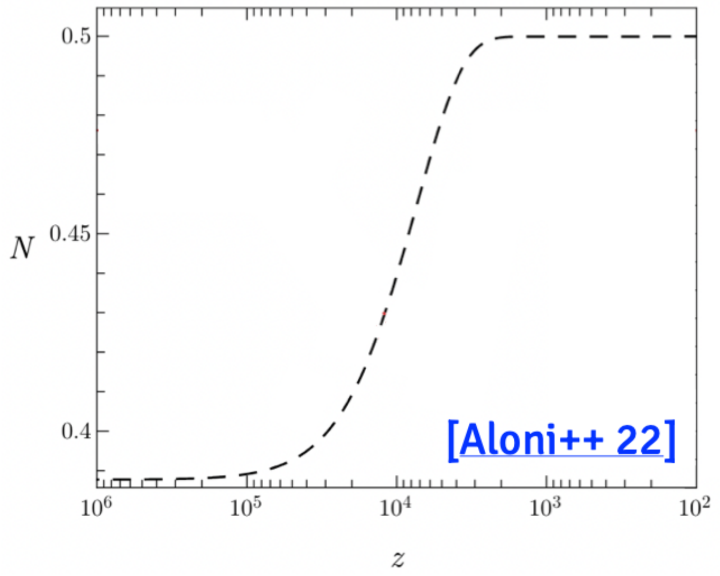
[Schöneberg, GFA++ 22]

[Khalife++ 24] ⟶ Updated version of the contest

What kind of mechanism is required to **address both tensions** simultaneously?

Interacting (Stepped) Dark Radiation

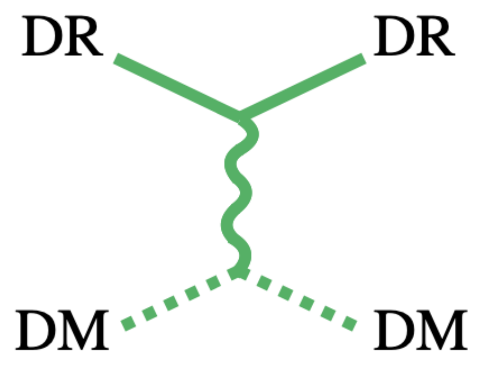
Self-interacting **dark radiation fluid undergoing a "step"** in its abundance (when T<m)...



[Aloni++ 22]

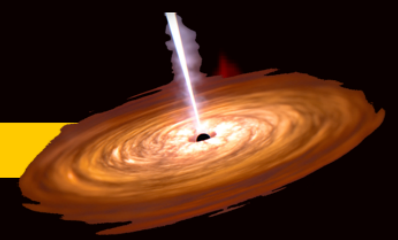
→ allows to lower r_s and hence **increase H_0**

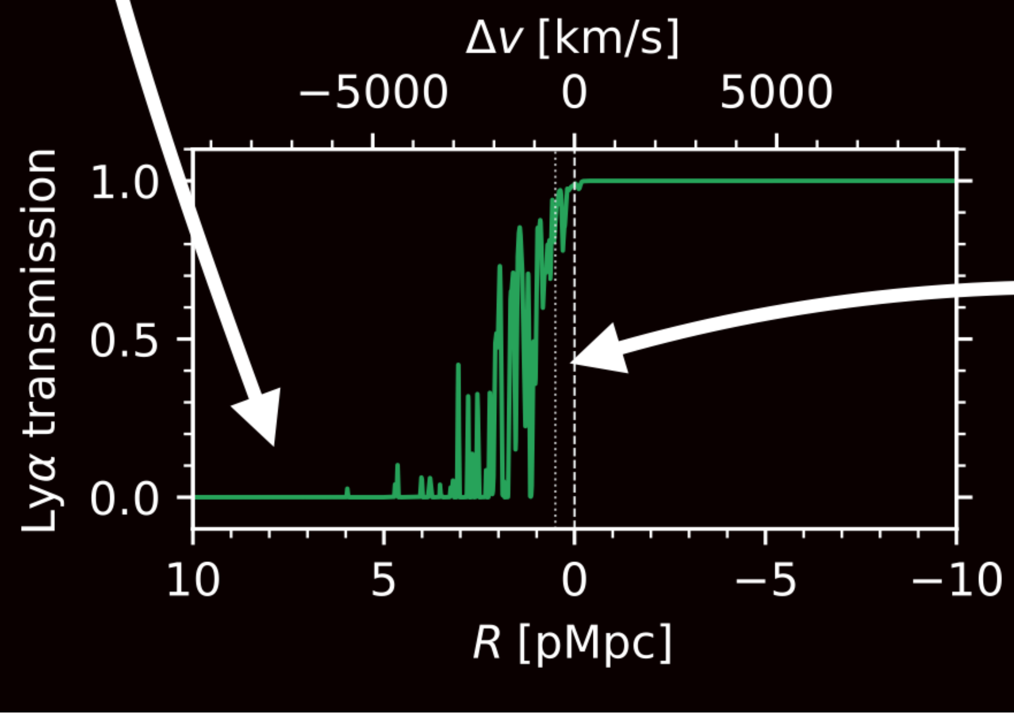
...which additionally **scatters with dark matter**



→ suppresses matter clustering, leading to a **smaller S_8**

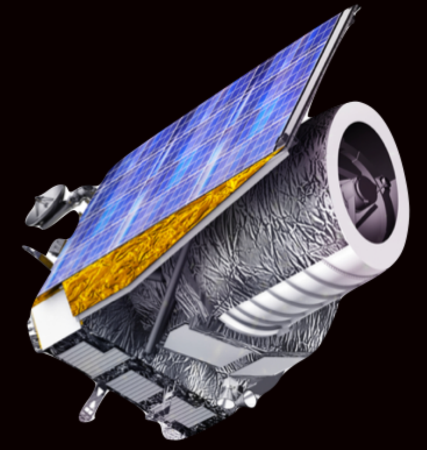
Gunn-Peterson trough:
Complete absorption in the Ly-α forest region starting at IGM neutral fractions $\langle x_{\rm HI} \rangle \gtrsim 10^{-4}$

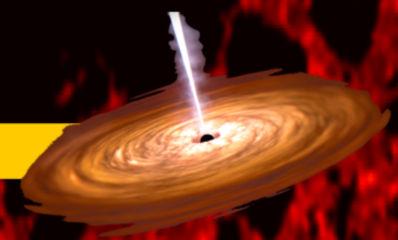


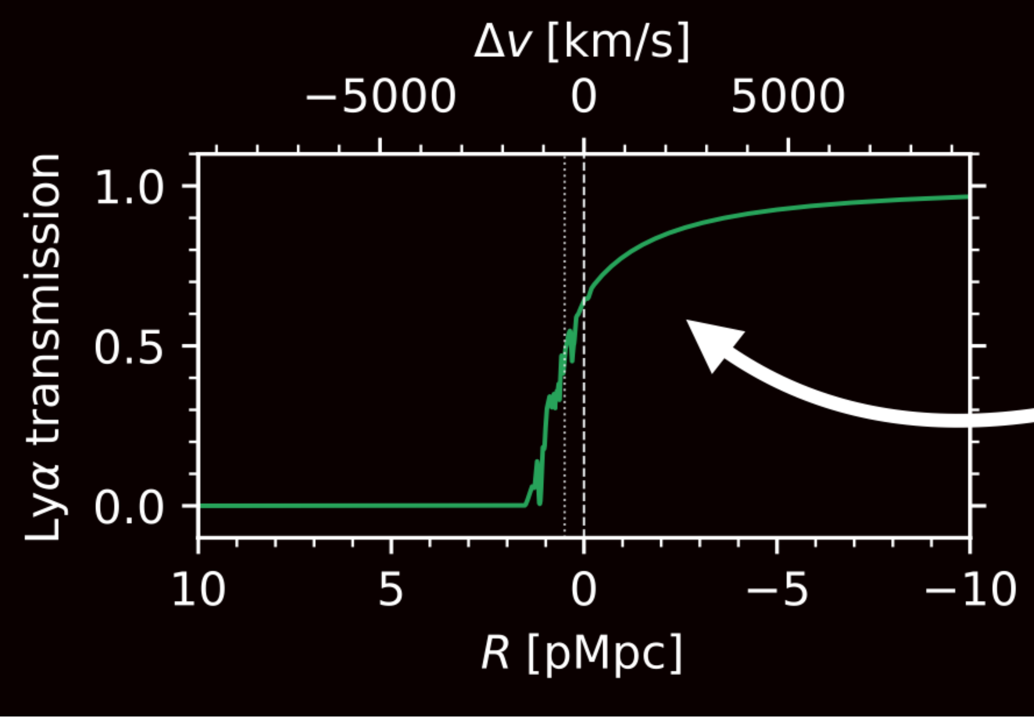


Quasar proximity zone:
The quasar carves out an ionized bubble whose size depends on its lifetime

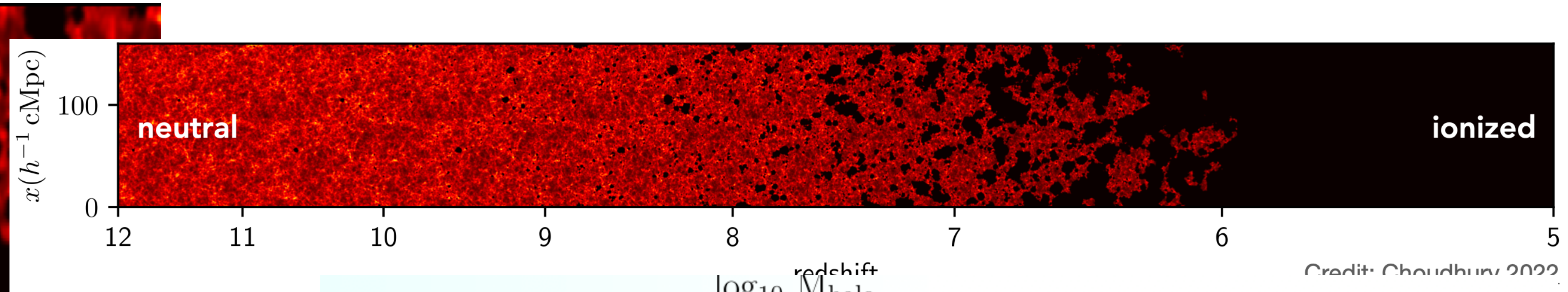
Euclid will find hundreds of QSOs at $z > 6$



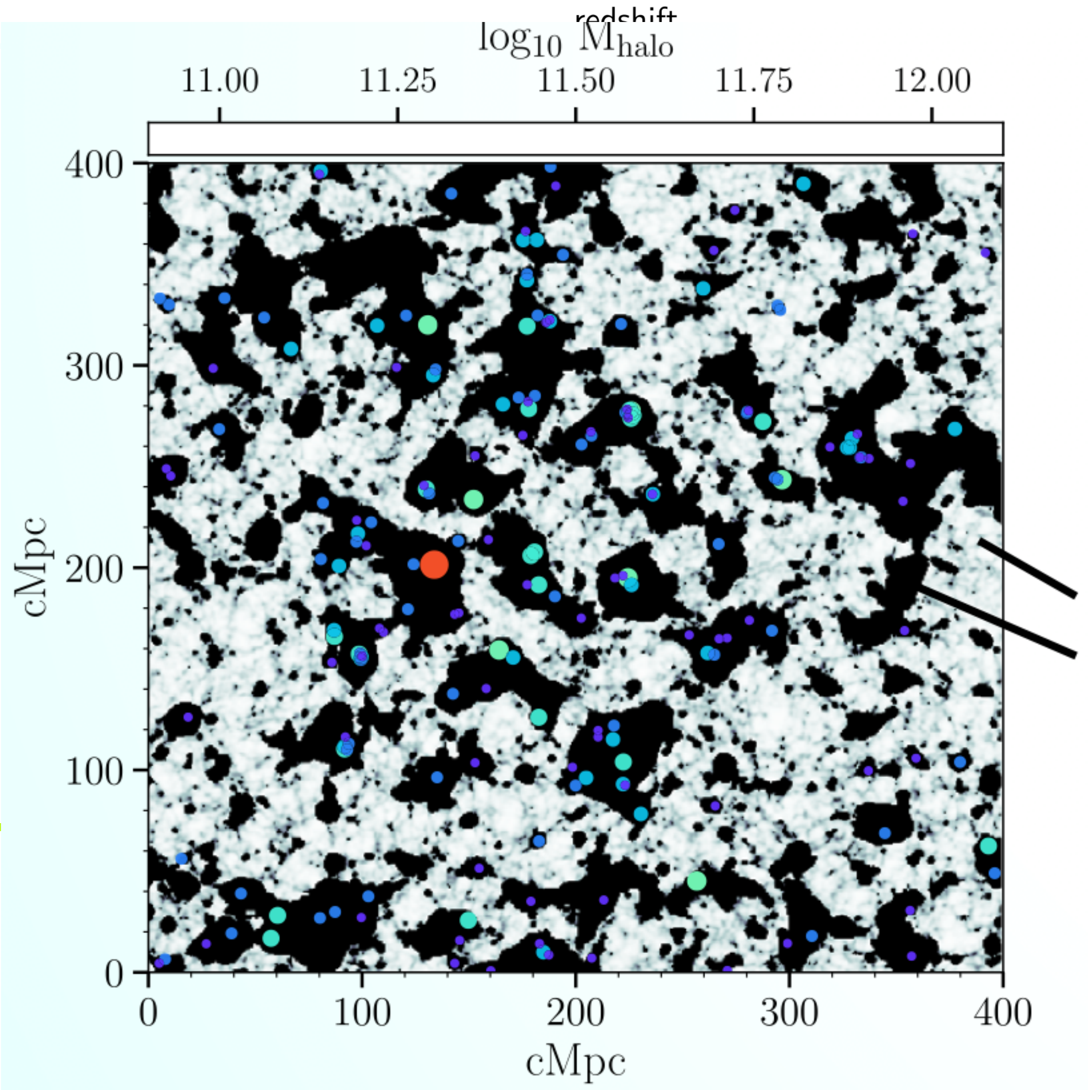




IGM damping wing:
At $\langle x_{\rm HI} \rangle = O(0.1)$, even the Lorentzian wing of the Lyman-α cross section becomes visible



Credit: Choudhury 2022

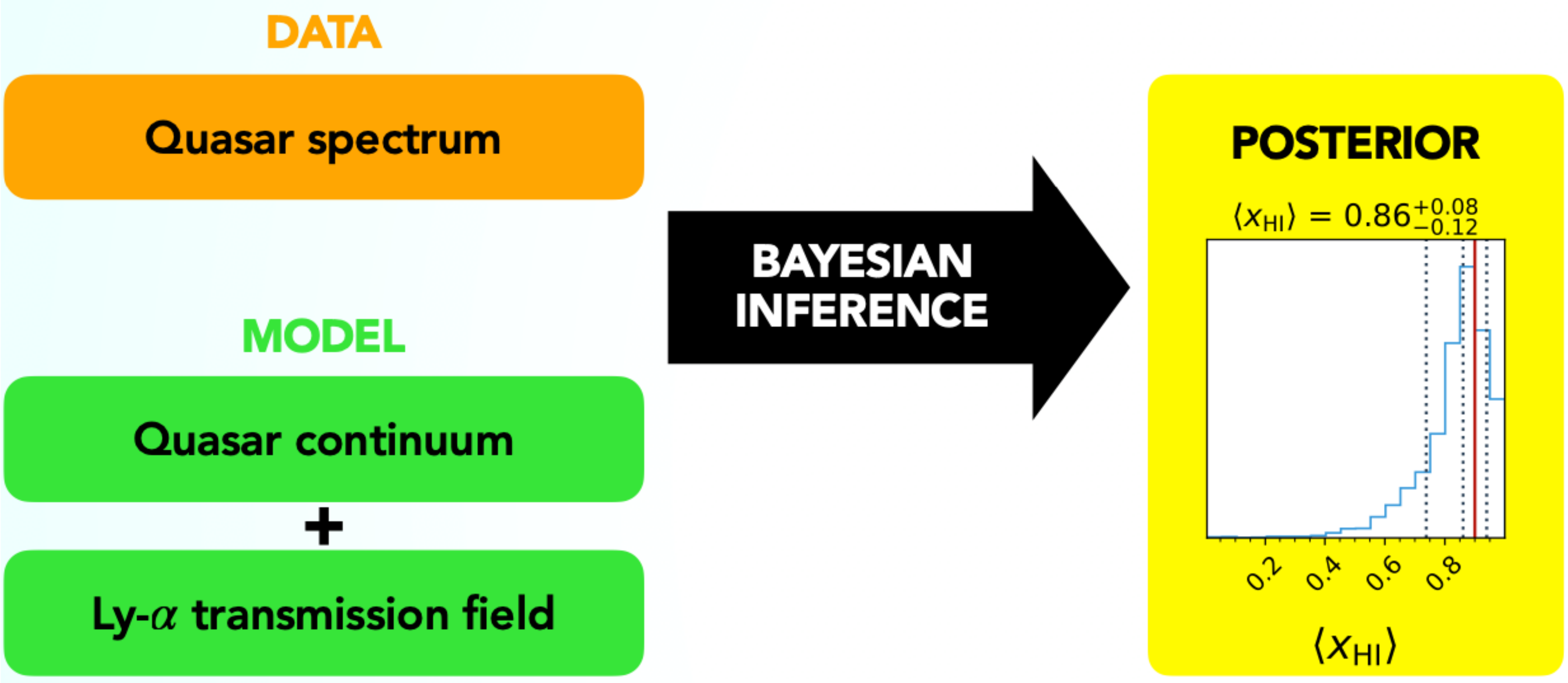


white: neutral
black: ionized

Credit: Davies+ 2018

1200 x 21

Summary



DATA

Quasar spectrum

MODEL

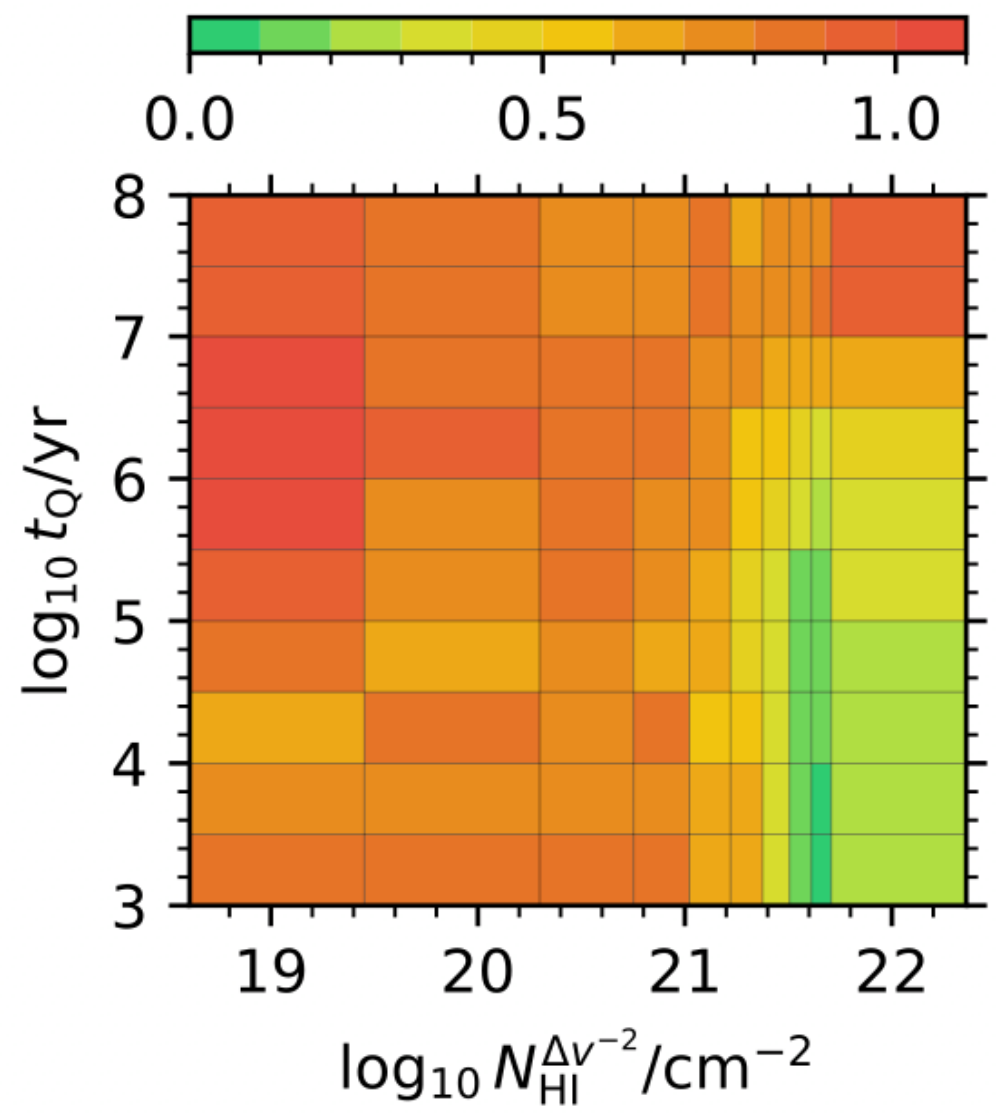
Quasar continuum

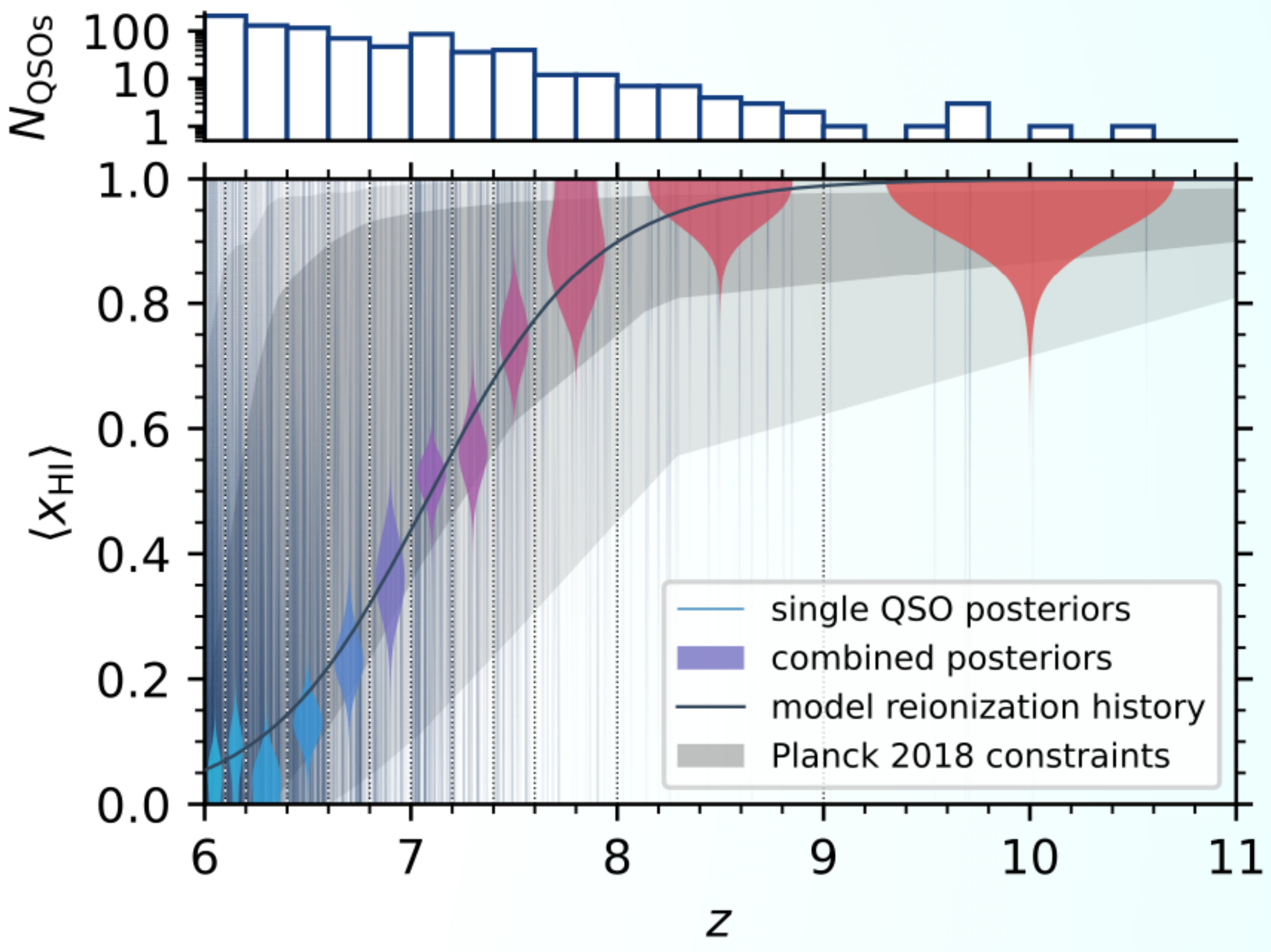
+

Ly-α transmission field

BAYESIAN INFERENCE

POSTERIOR





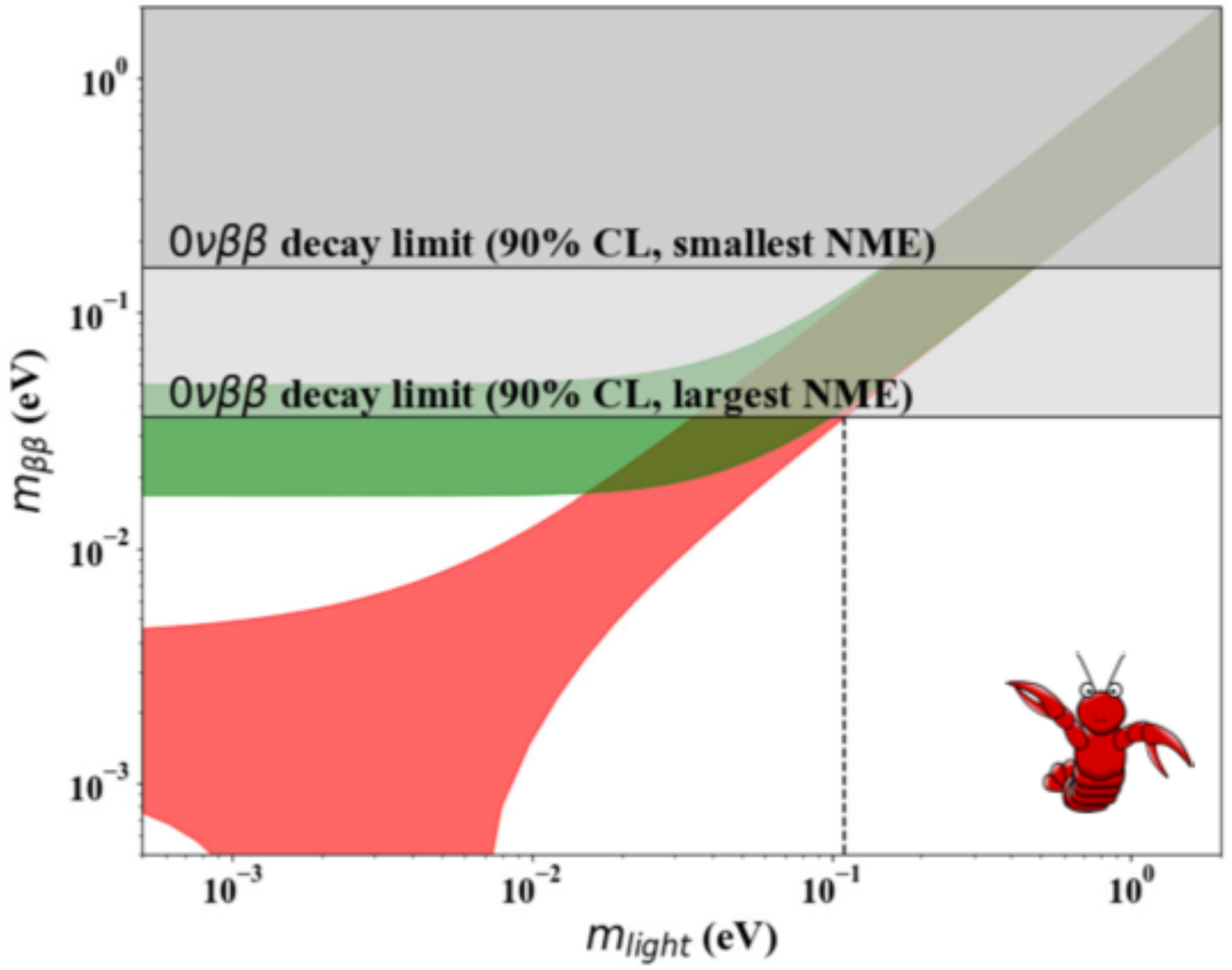
Fast HMC pipeline to infer $\langle x_{\rm HI}\rangle$ and $t_{\rm Q}$ using the damping wing imprint of high-redshift quasars

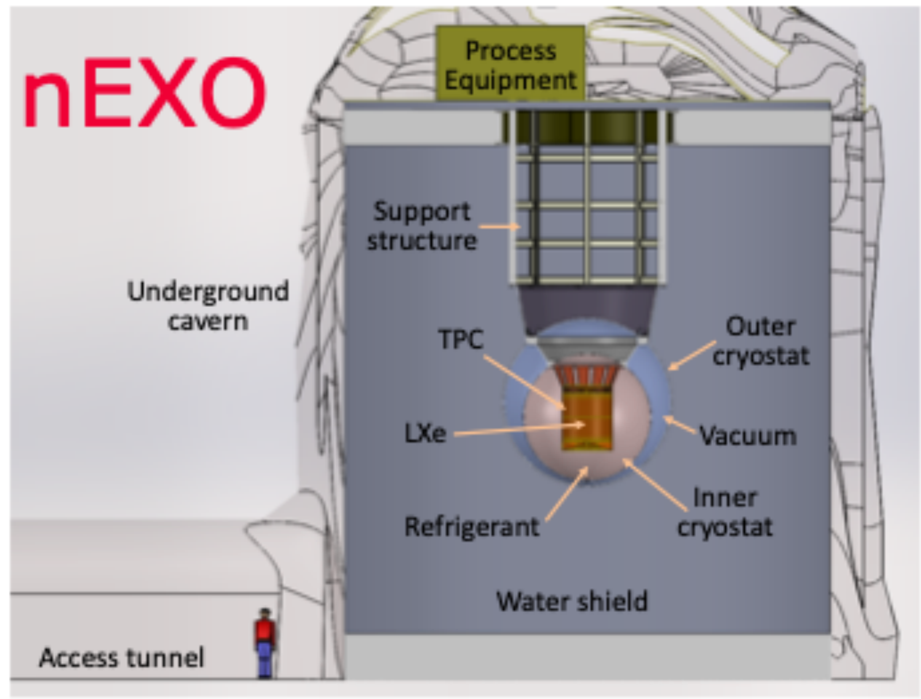
Inferring $\langle x_{\rm HI}\rangle$ at $28.0^{+8.2}_{-8.8}\,\%$ precision, or even the local HI column density at $0.69^{+0.34}_{-0.53}$ dex

EUCLID & JWST:
3-8% constraints on $\langle x_{\rm HI}\rangle(z)$ between $6 \lesssim z \lesssim 11$

Future experiments

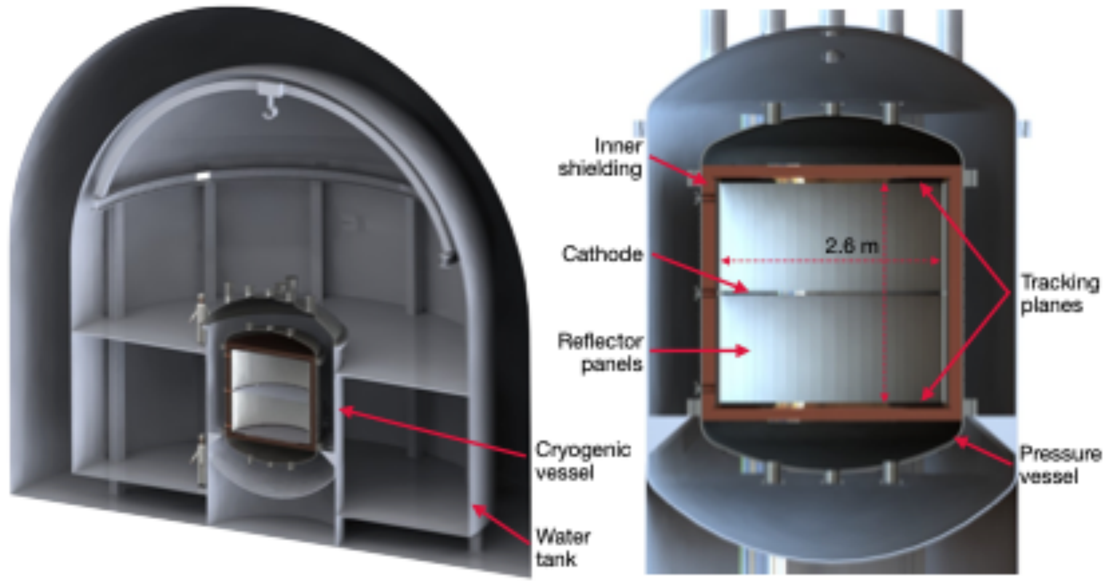
- Current experiments exploring O(100 kg).
- Tonne scale generation is being prepared.
- Need to reduce background to 10^{-3} c/(tonne keV yr).
- 10^{28} yr sensitivity to half-life needed to explore the full inverted hierarchy.





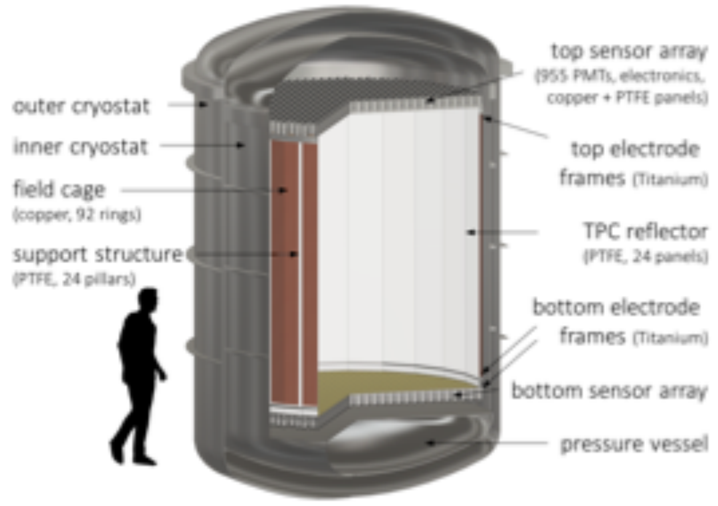
- 5 tonne, 3 t of self-shielding.
- Single drift.
- Charge collected at the anode with crossed electrode strips.
- Scintillation read by SiPMs.

NEXT-HD



- Symmetric TPC with central cathode.
- Fiber barrel to read S1 and S2, dense SiPM array for tracking.
- Gas additives (e.g., ^{4}He) to reduce diffusion.

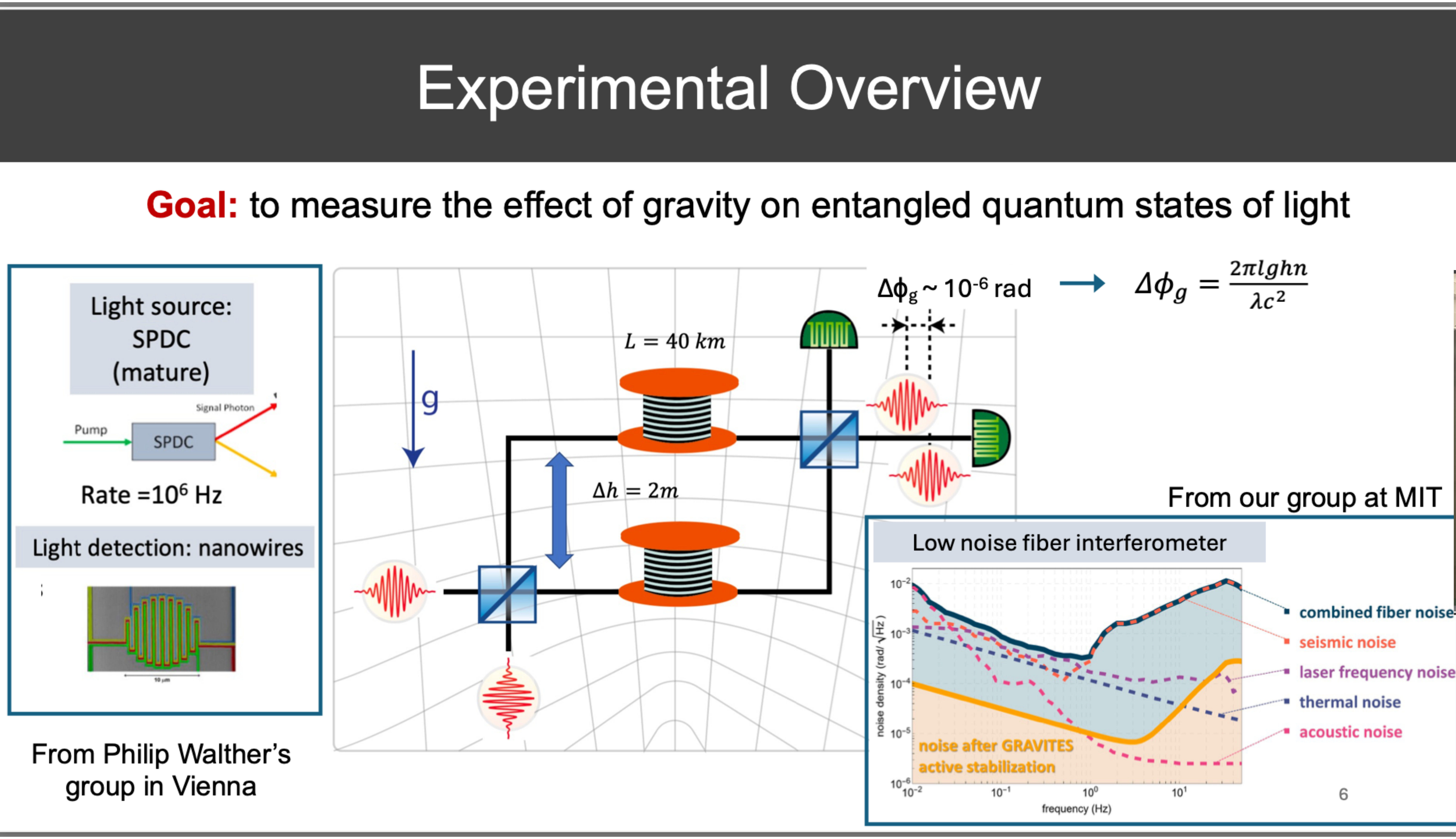
Darwin/XLZD



- 40 t of xenon, 3.6 t of ^{136}Xe.
- 2-phase TPC (2.6 m diam. x 2.6 m height).
- S1 and S2 read by PMTs and SiPMs (or new sensors).

Quantum gravity

Gravitational effects on entangled photons



Experimental Overview

Goal: to measure the effect of gravity on entangled quantum states of light

Light source: SPDC (mature)

Rate $=10^6$ Hz

Light detection: nanowires

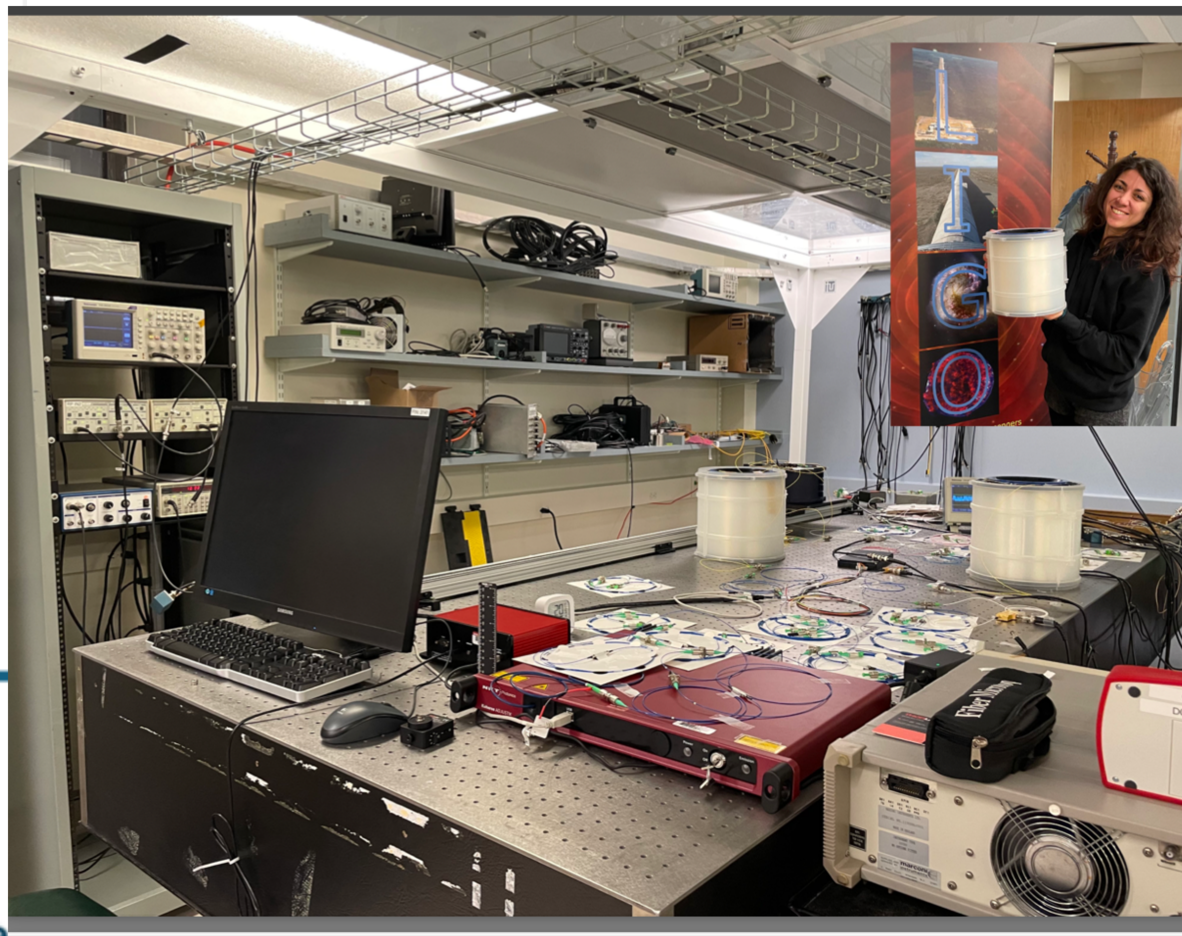
From Philip Walther's group in Vienna

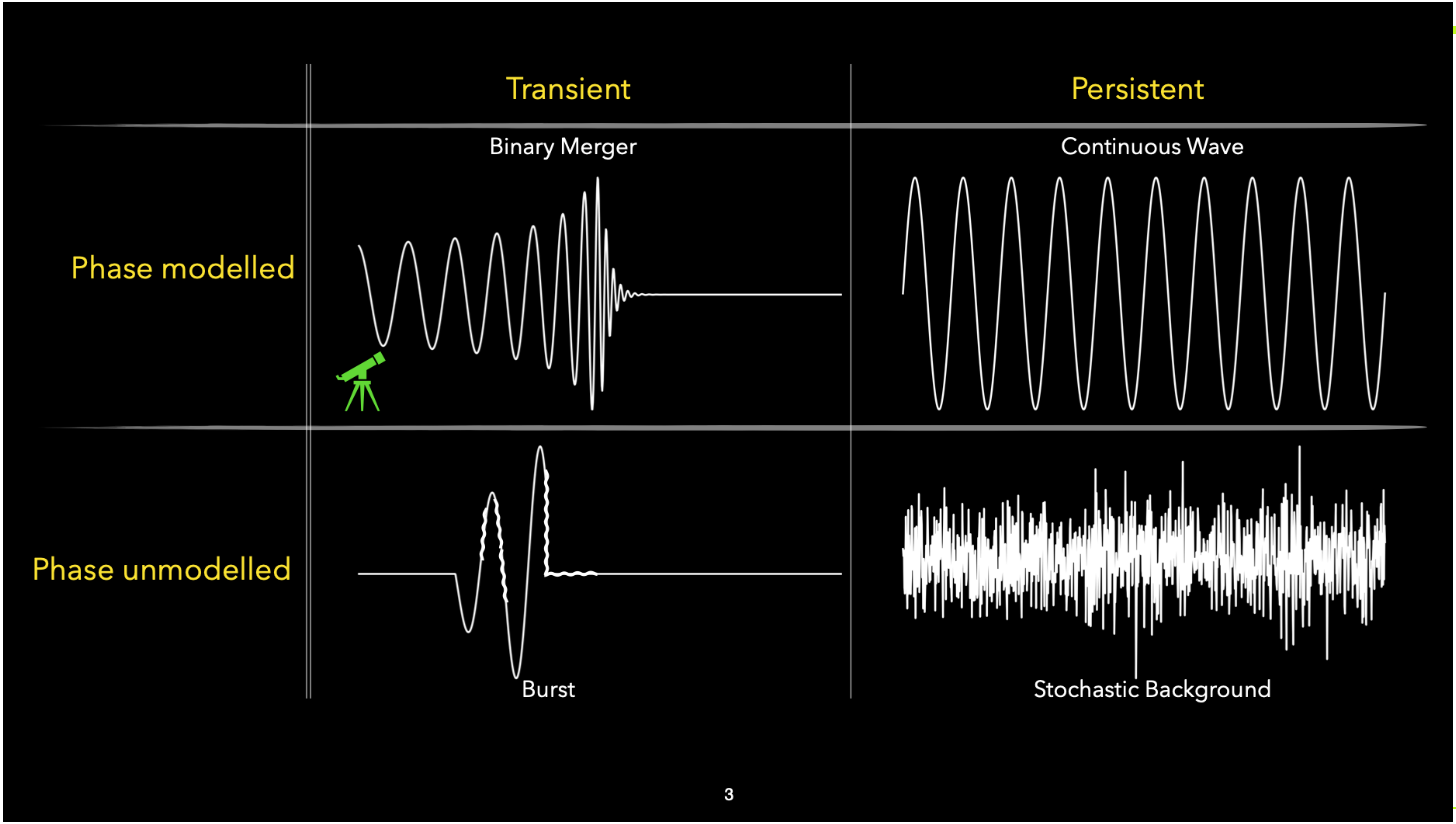
$\Delta\phi_g \sim 10^{-6}$ rad → $\Delta\phi_g = \frac{2\pi l g h n}{\lambda c^2}$

From our group at MIT

Low noise fiber interferometer

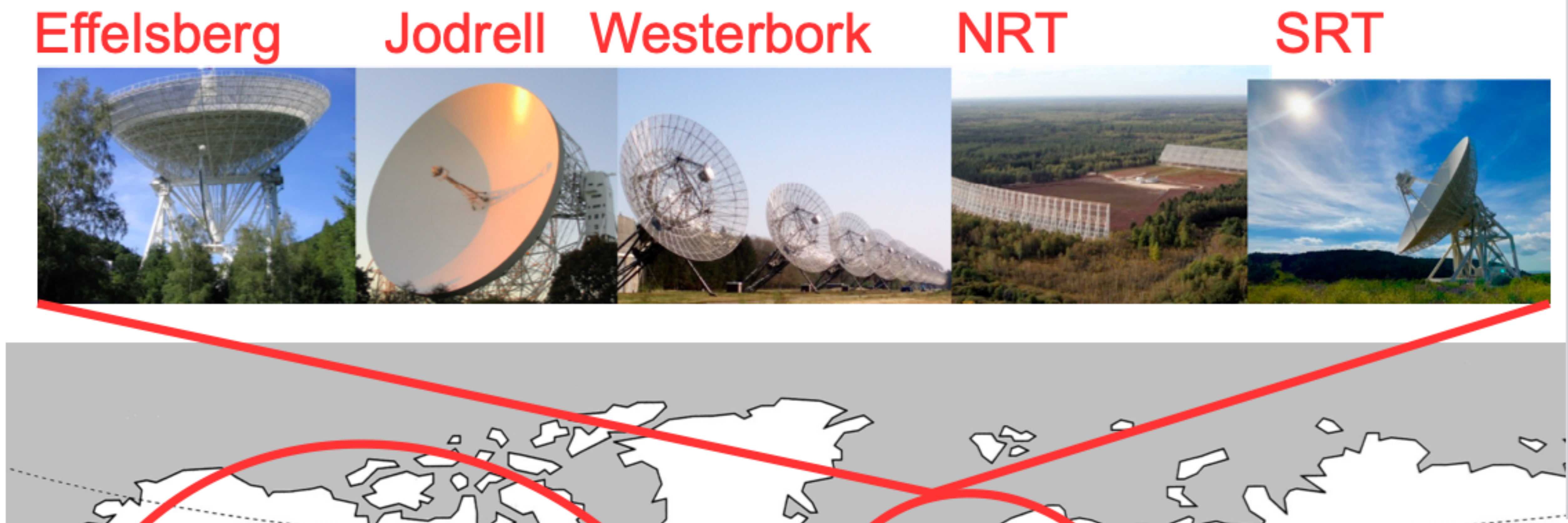
- Still in construction

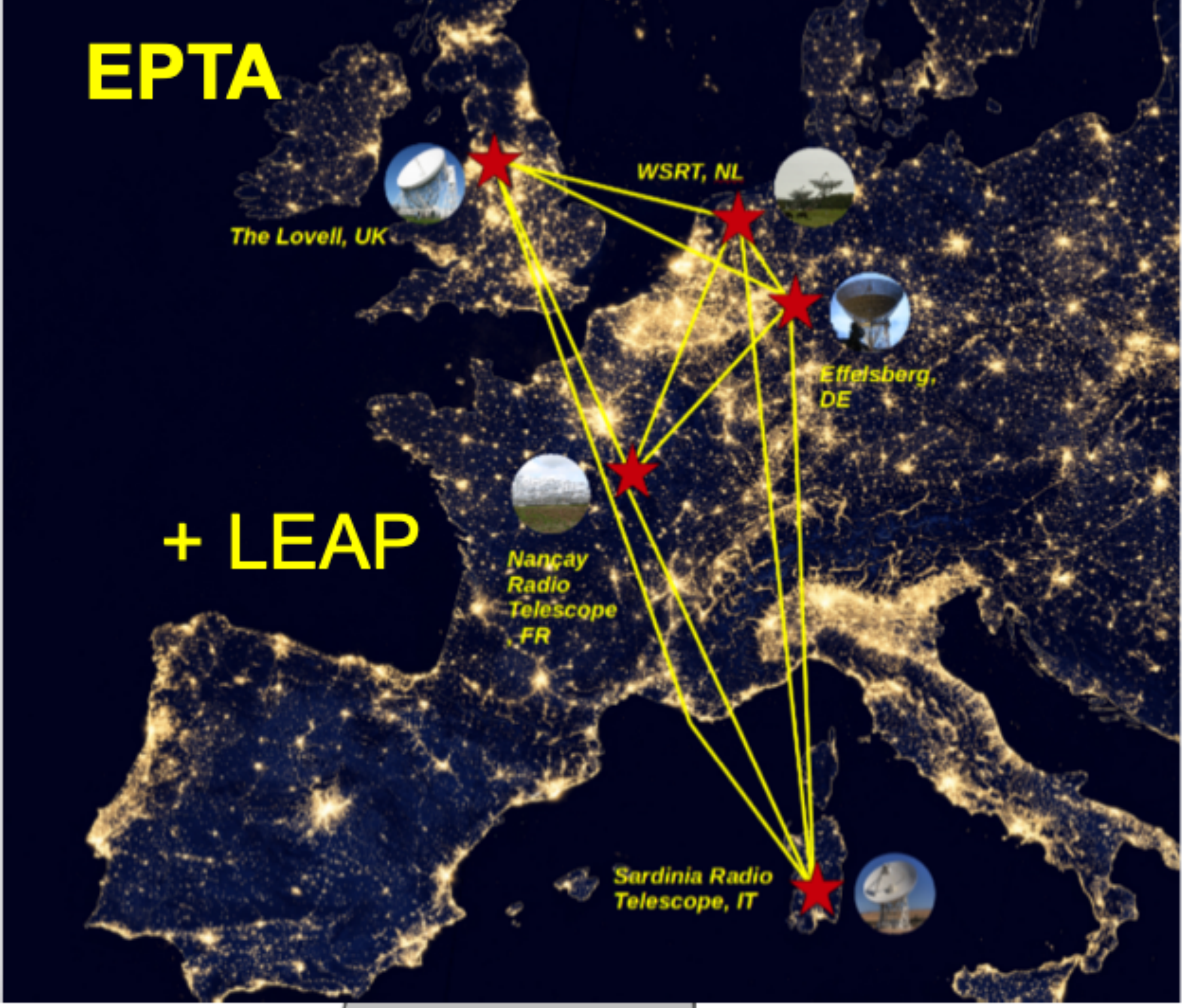


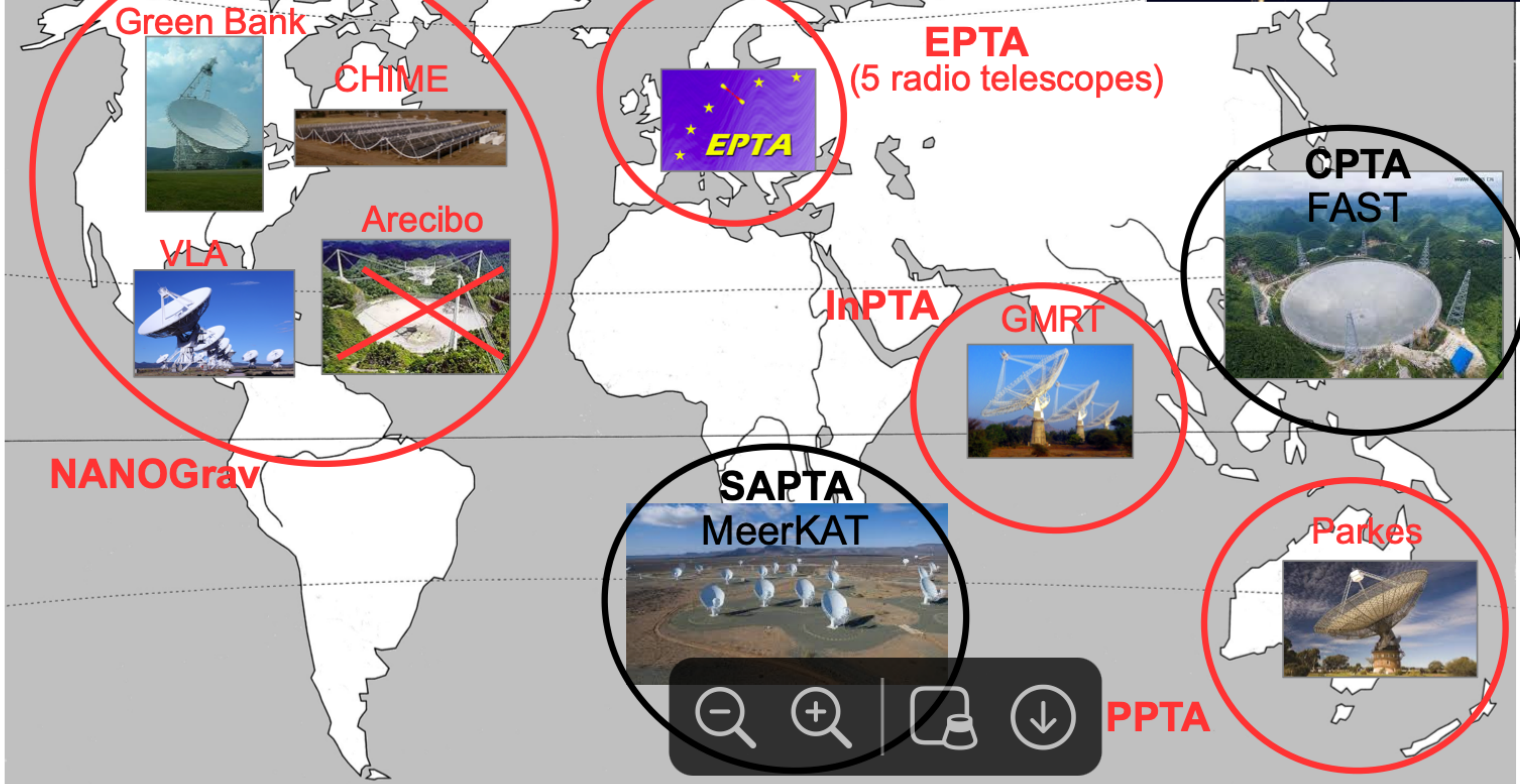


	Transient	Persistent
Phase modelled	Binary Merger	Continuous Wave
Phase unmodelled	Burst	Stochastic Background

The International Pulsar Timing Array





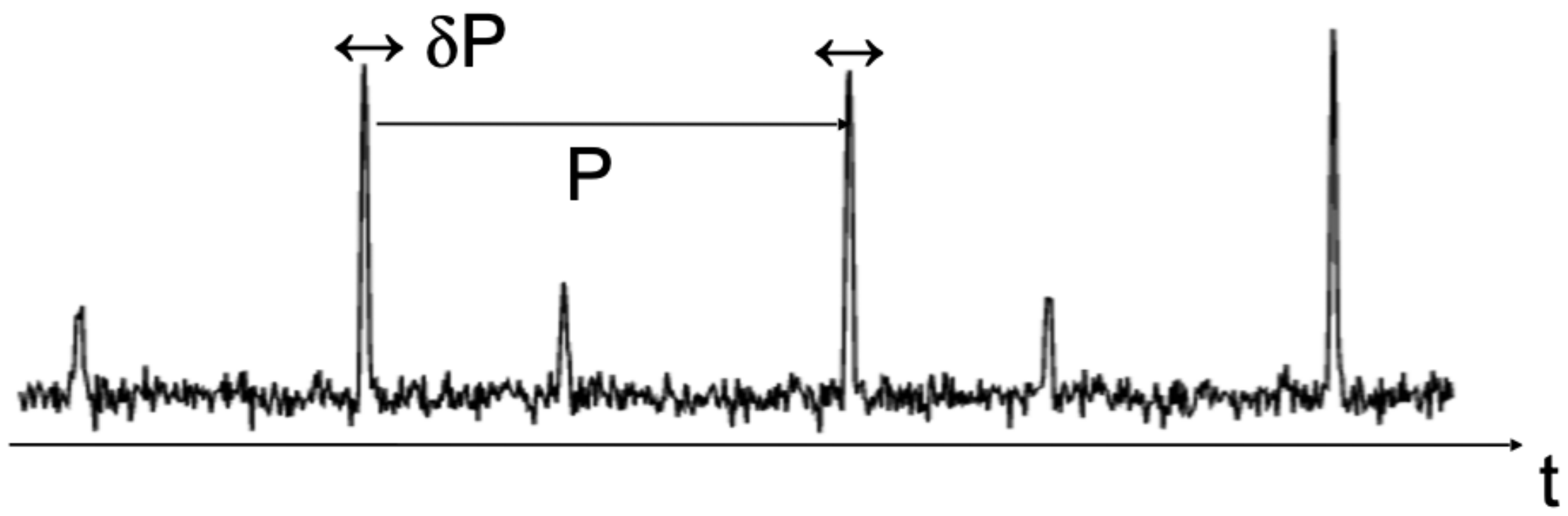


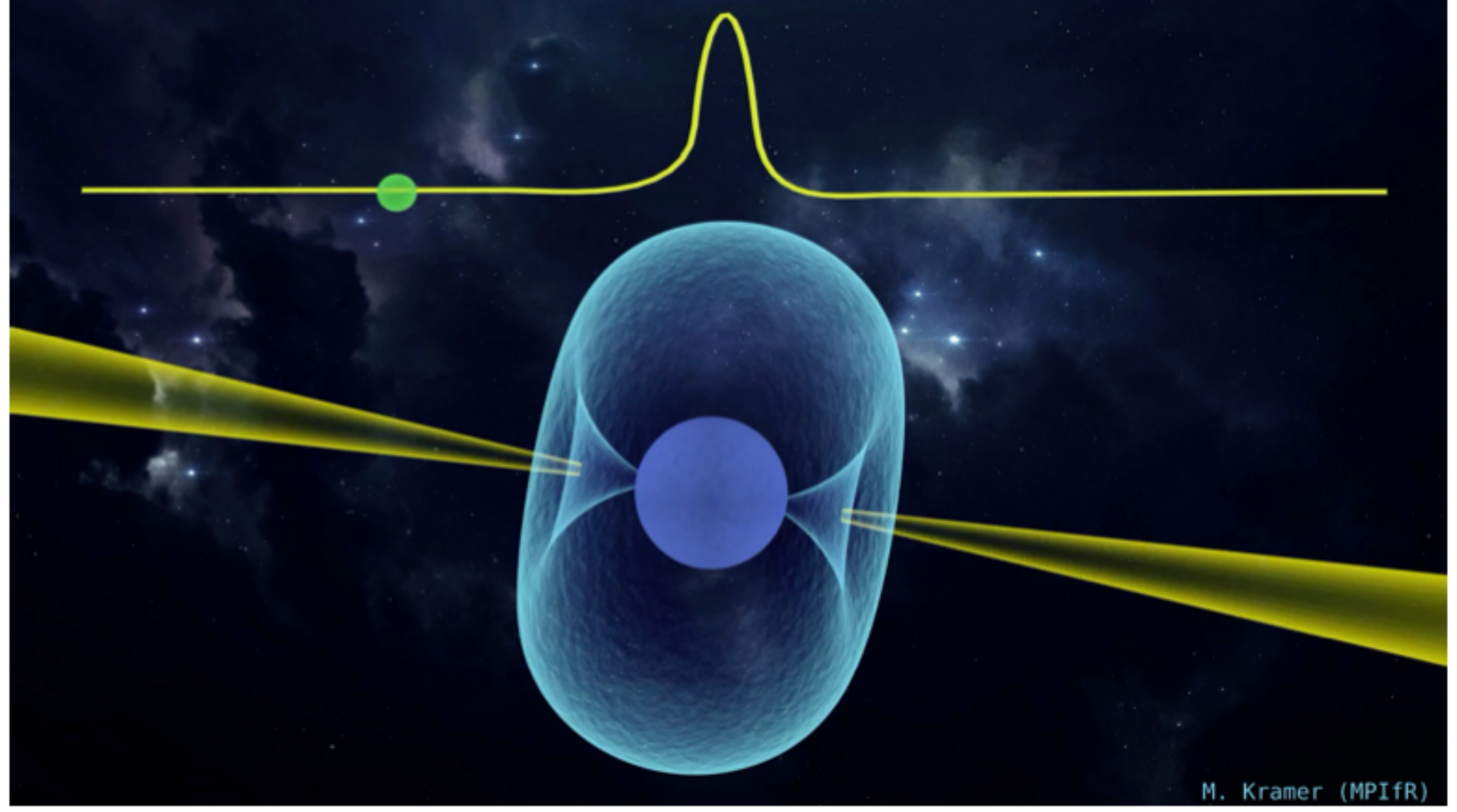
EPTA/InPTA, PPTA and NANOGrav

publish coherent results !

« a low-frequency quadrupolar signal common to all pulsars »

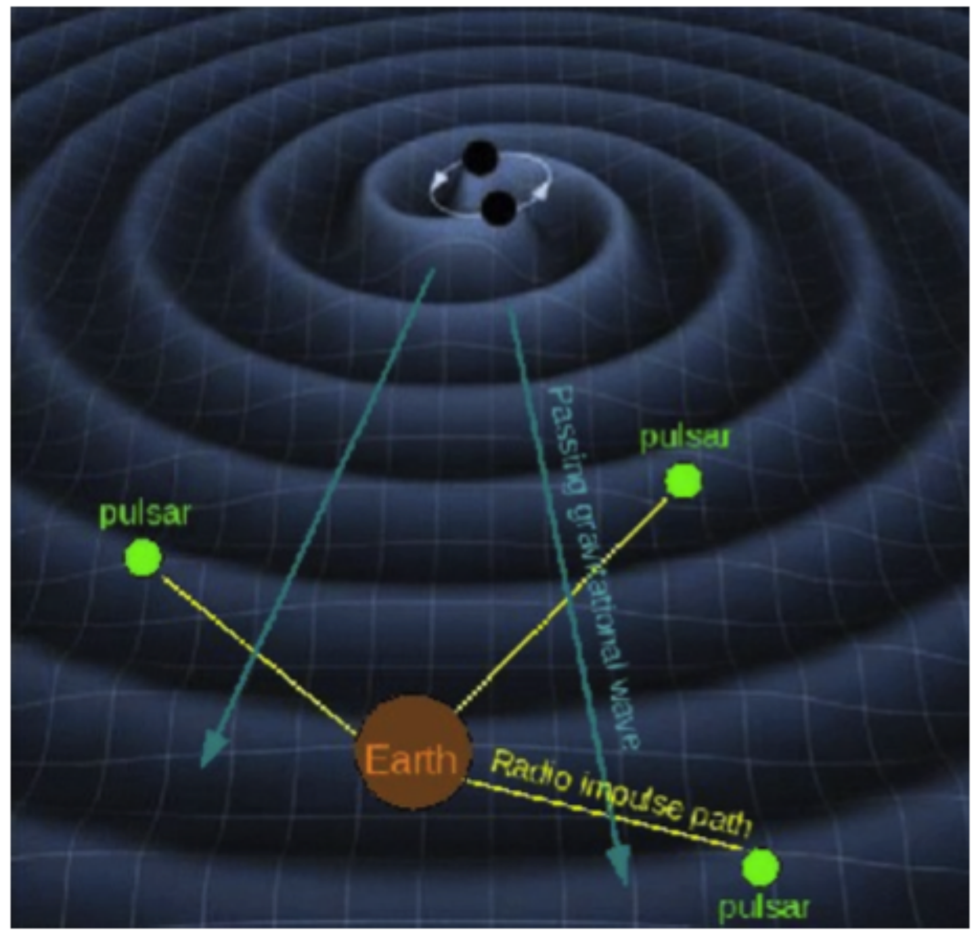
Pulsar Timing Arrays : principles





The Earth and the distant pulsar are considered as free masses whose position responds to changes in the metric of space-time

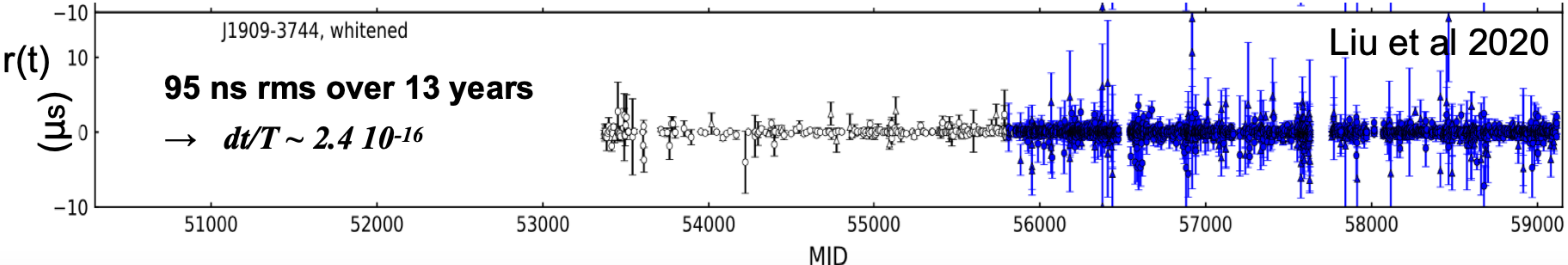
→ *The passage of a gravitational wave disturbs the metric and produces fluctuations in the arrival times of the pulses*



With timing uncertainties dt (~100 ns) and observation time spans T (~25 years)
→ PTA are sensitive to *amplitudes ~ dt/T and to frequencies f ~ 1/T*

Sensitivity ~ 100 10^{-9} / 25 x 3 10^{7} → A ~ 1.3 10^{-16}

Frequency domain (25 years - 1 week) → 10^{-9} – 10^{-6} Hz

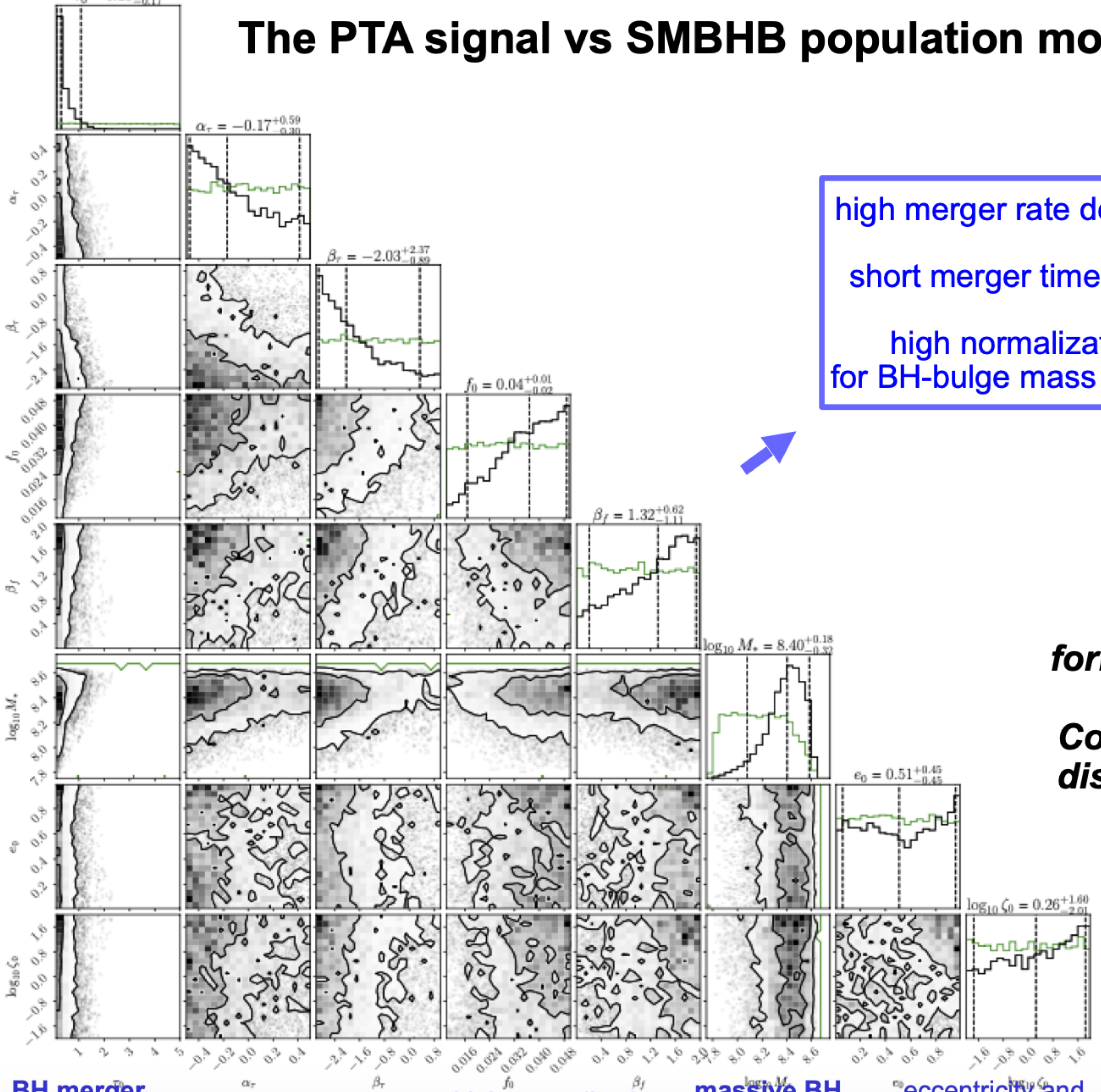


Liu et al 2020

95 ns rms over 13 years

→ ***dt/T ~ 2.4 10^{-16}***

The PTA signal vs SMBHB population models



BH merger timescale < 1Gyr

shorter merger times for massive galaxies

high normalisation of pair fraction

massive BH compared to bulge mass

eccentricity and environment effects poorly constrained

high merger rate densities

short merger timescales

high normalization for BH-bulge mass relation

Massive galaxies and massive black holes form earlier than expected ?

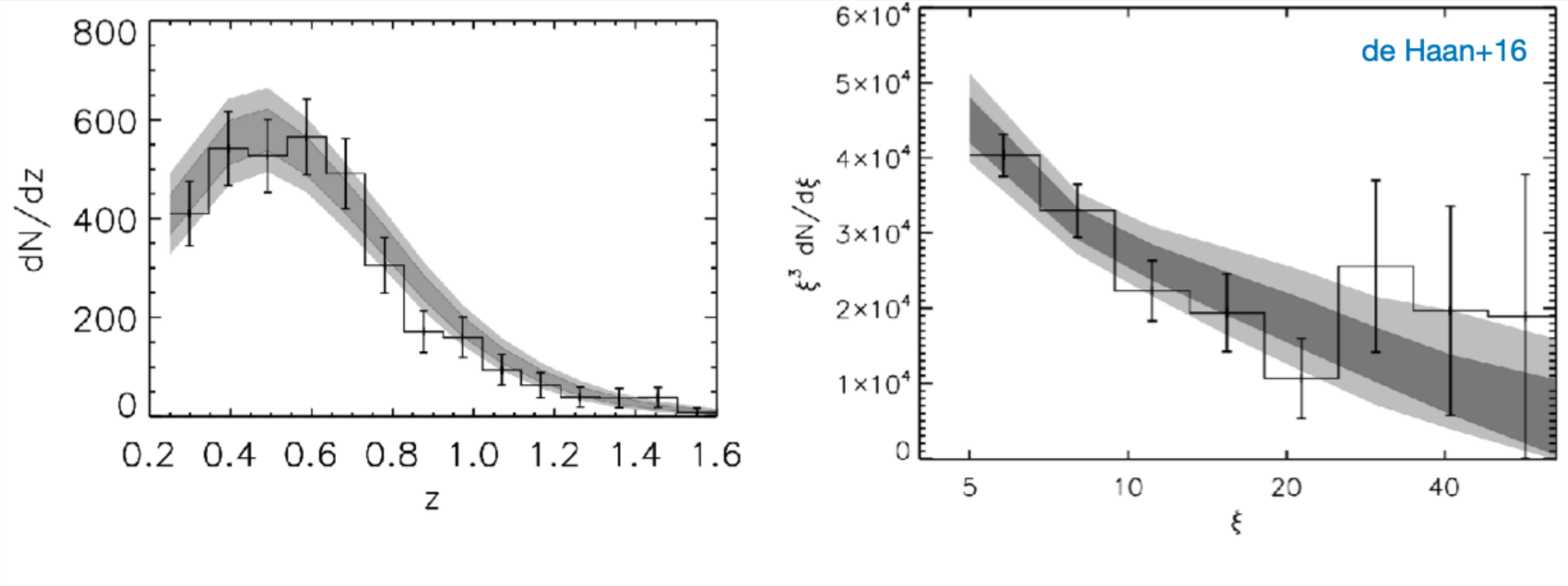
Coherent with JWST recent discoveries at high redshift

Results from Antoniadis et al 2024 EPTA - paperIV

Observable vs. Mass

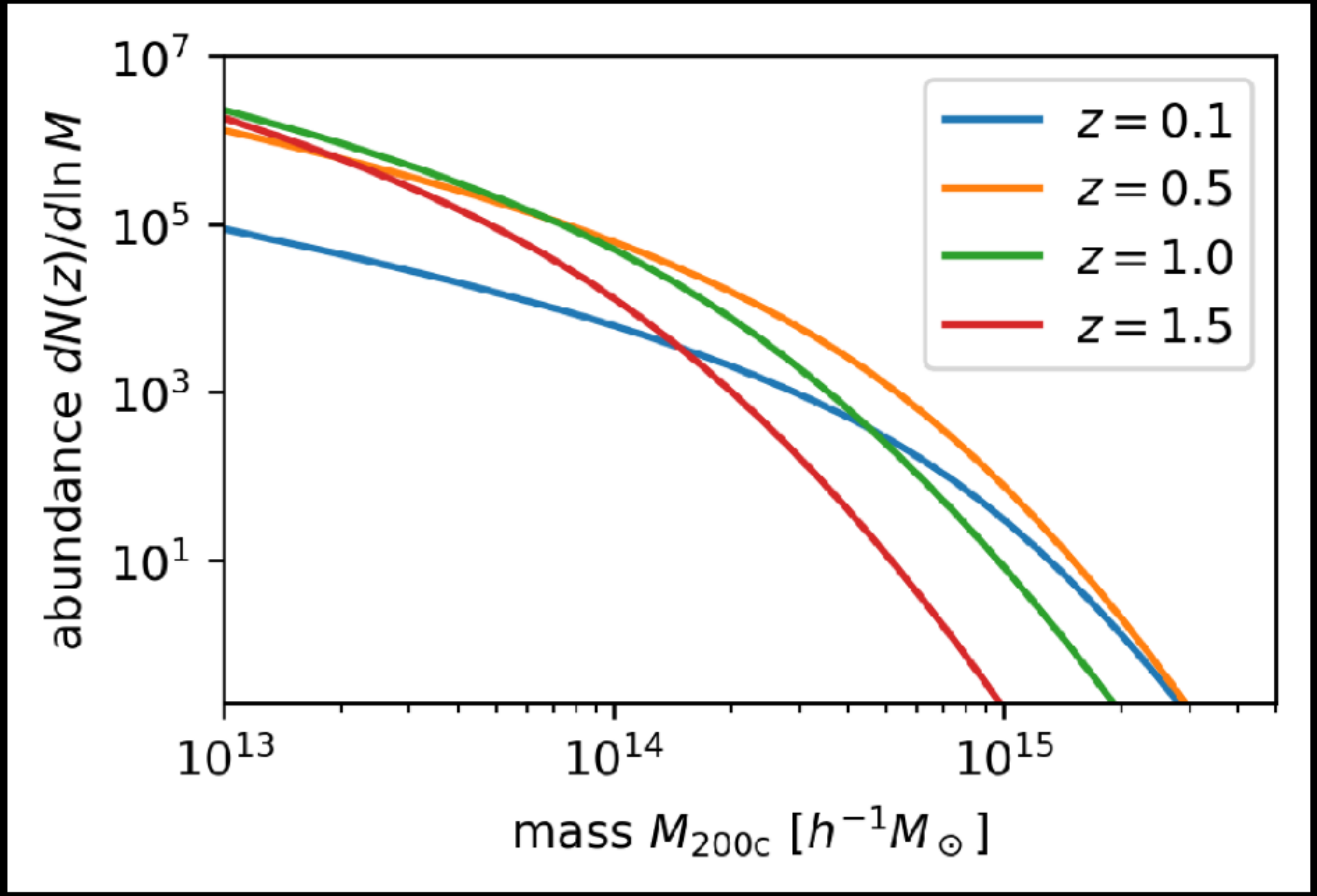
clusters

halo observable function



halos

halo mass function



observable—mass relation

$$\frac{dN}{d\mathrm{obs}} = \int dM \boxed{P(\mathrm{obs}\,|\,M)} \boxed{\frac{dN}{dM}}$$

halo mass function

cluster cosmology = cluster selection + mass calibration