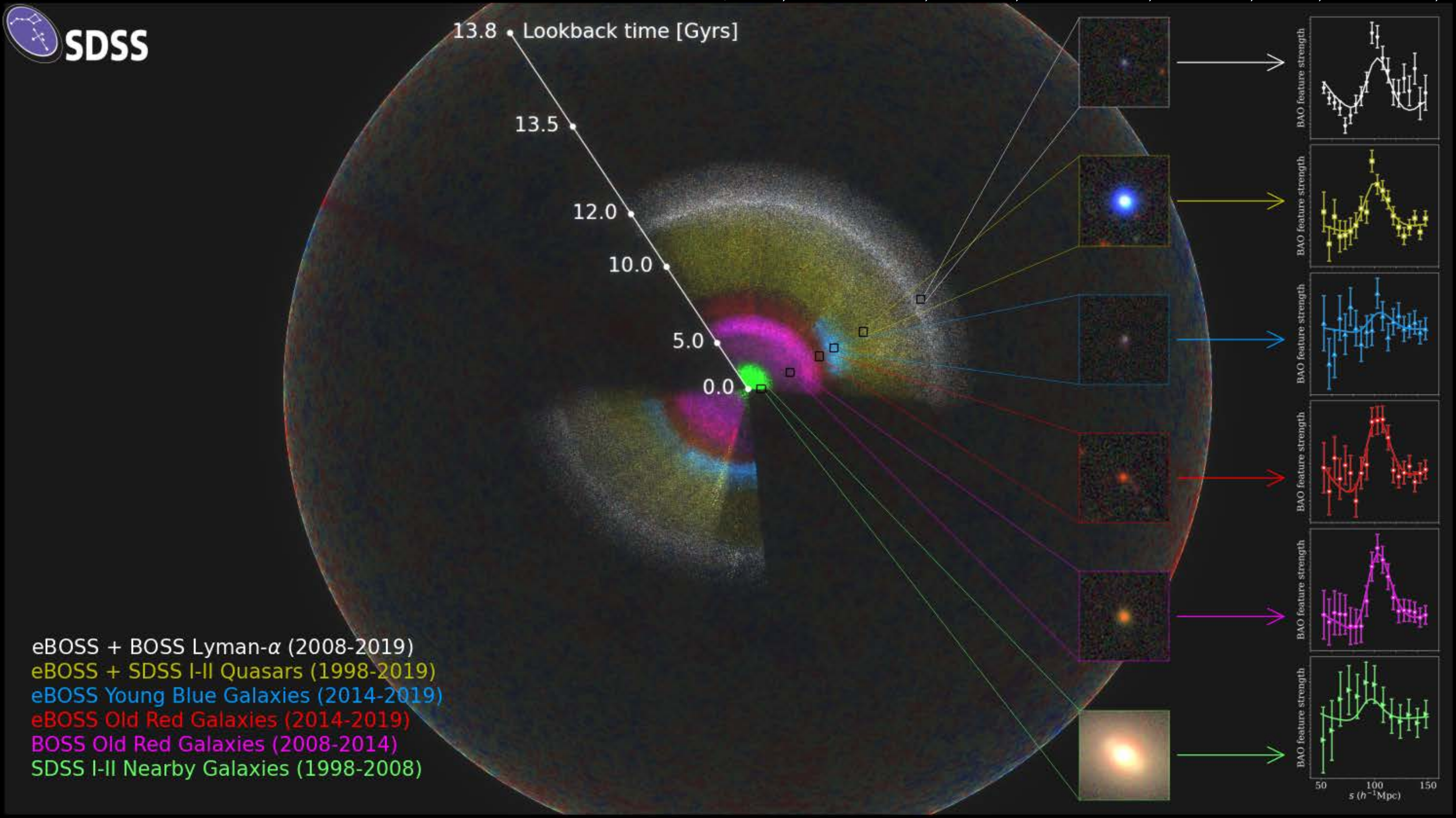
Current status and Future prospect of cosmology
– DE, DM, neutrino mass, early universe –

Masahiro Takada
(Kavli IPMU)

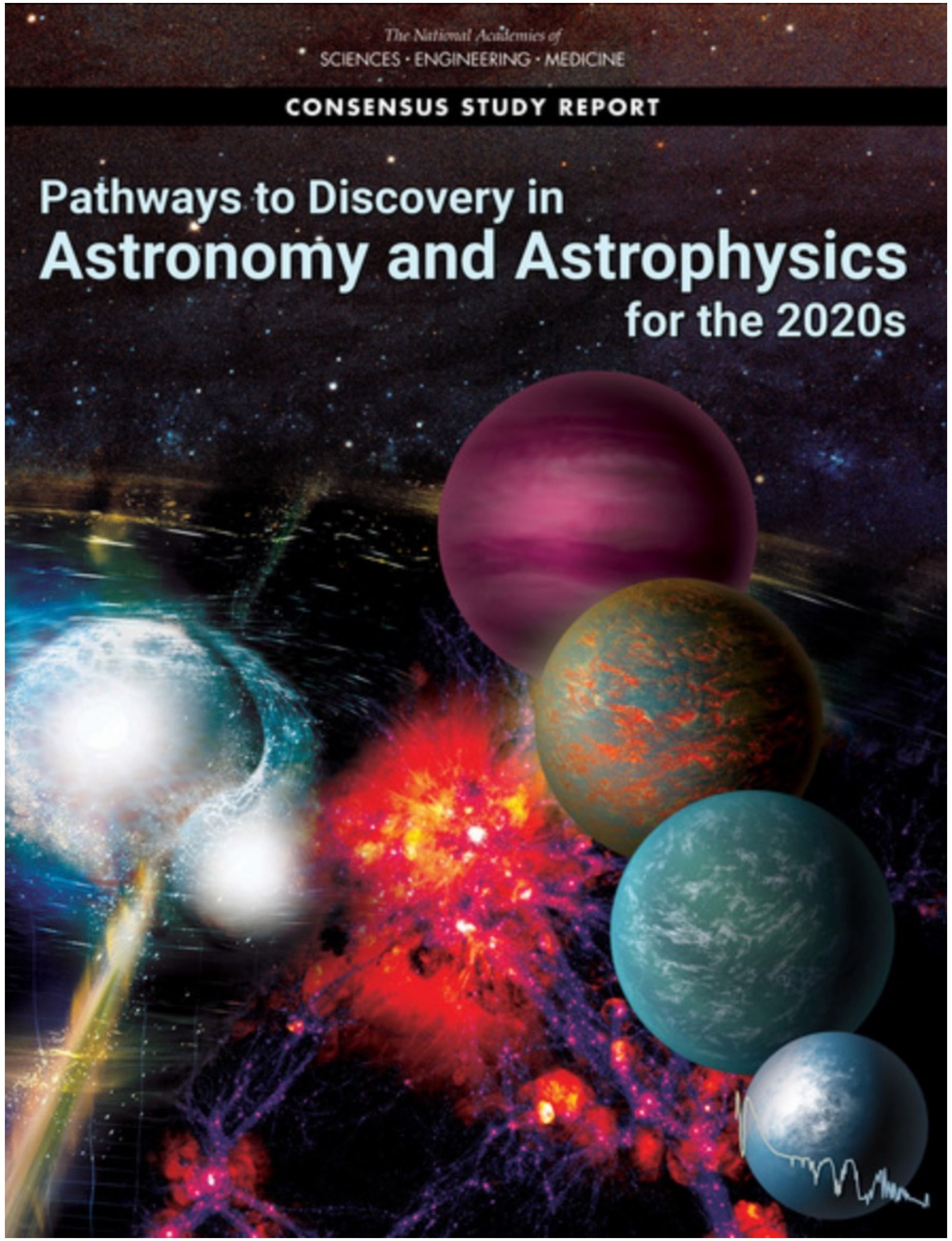
“Cosmology” survey = Mapping of the Universe (wider solid angle (& higher redshift))

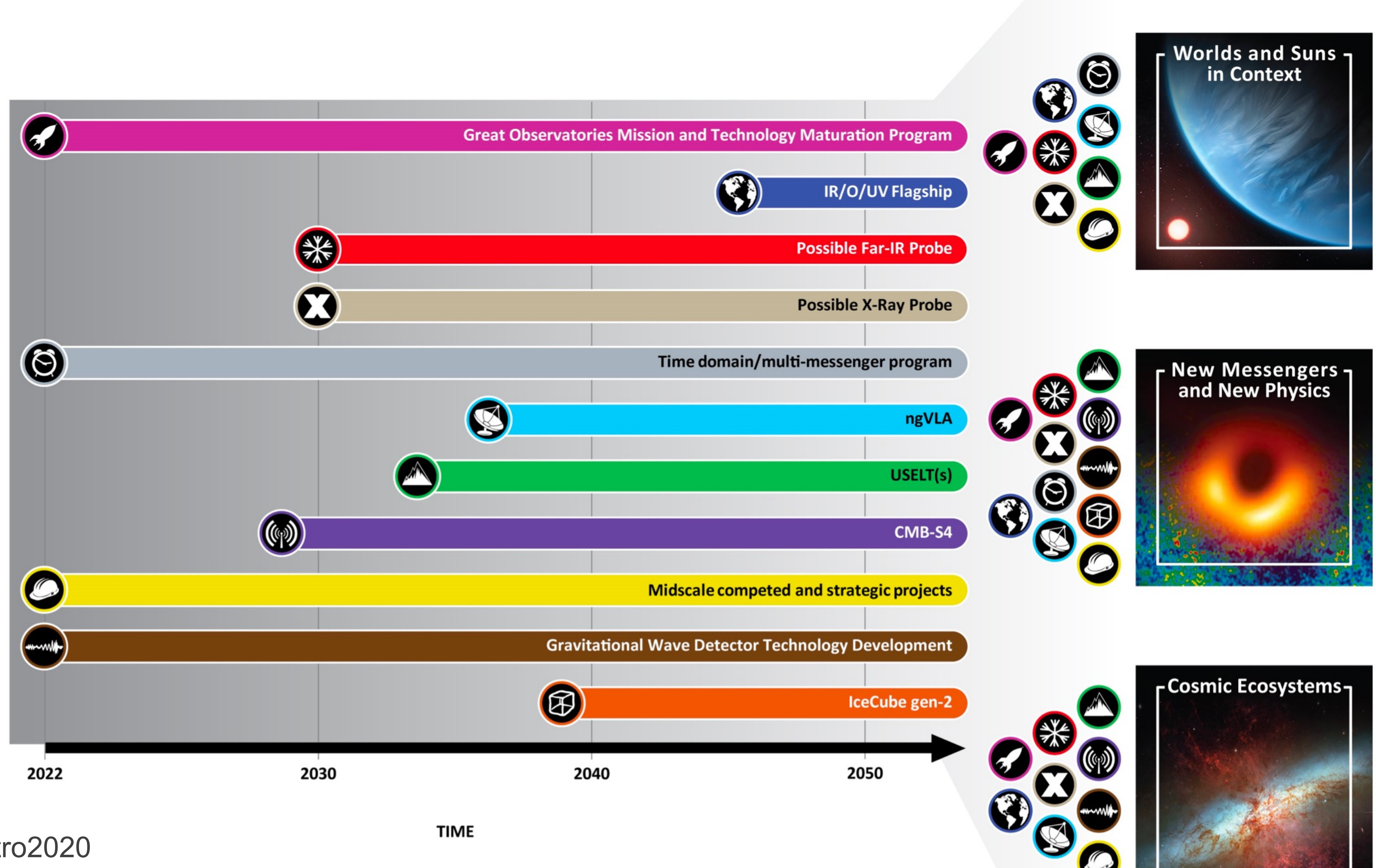
Subaru HSC/PFS, VRO LSST, Euclid, SPHEREx, Roman, SKA, CMB-S4, …



Astro2020 – US case

- Priority areas
  - Pathways to Habitable Worlds
  - New Windows and the Dynamic Universe
  - Cosmic ecosystem: Unveiling the Diverse of Galaxy Growth
- Cosmology is not explicitly mentioned, because the previously-recommended projects, VRO LSST and Roman haven't yet started (so we don't know the outcome) (note CMB-S4)
  - Astronomical projects now take two decades (20 yrs) to realize




Great Observatories Mission and Technology Maturation Program
IR/O/UV Flagship
Possible Far-IR Probe
Possible X-Ray Probe
Time domain/multi-messenger program
ngVLA
USELT(s)
CMB-S4
Midscale competed and strategic projects
Gravitational Wave Detector Technology Development
IceCube gen-2
2022
2030
2040
2050
TIME
Worlds and Suns in Context
New Messengers and New Physics
Cosmic Ecosystems

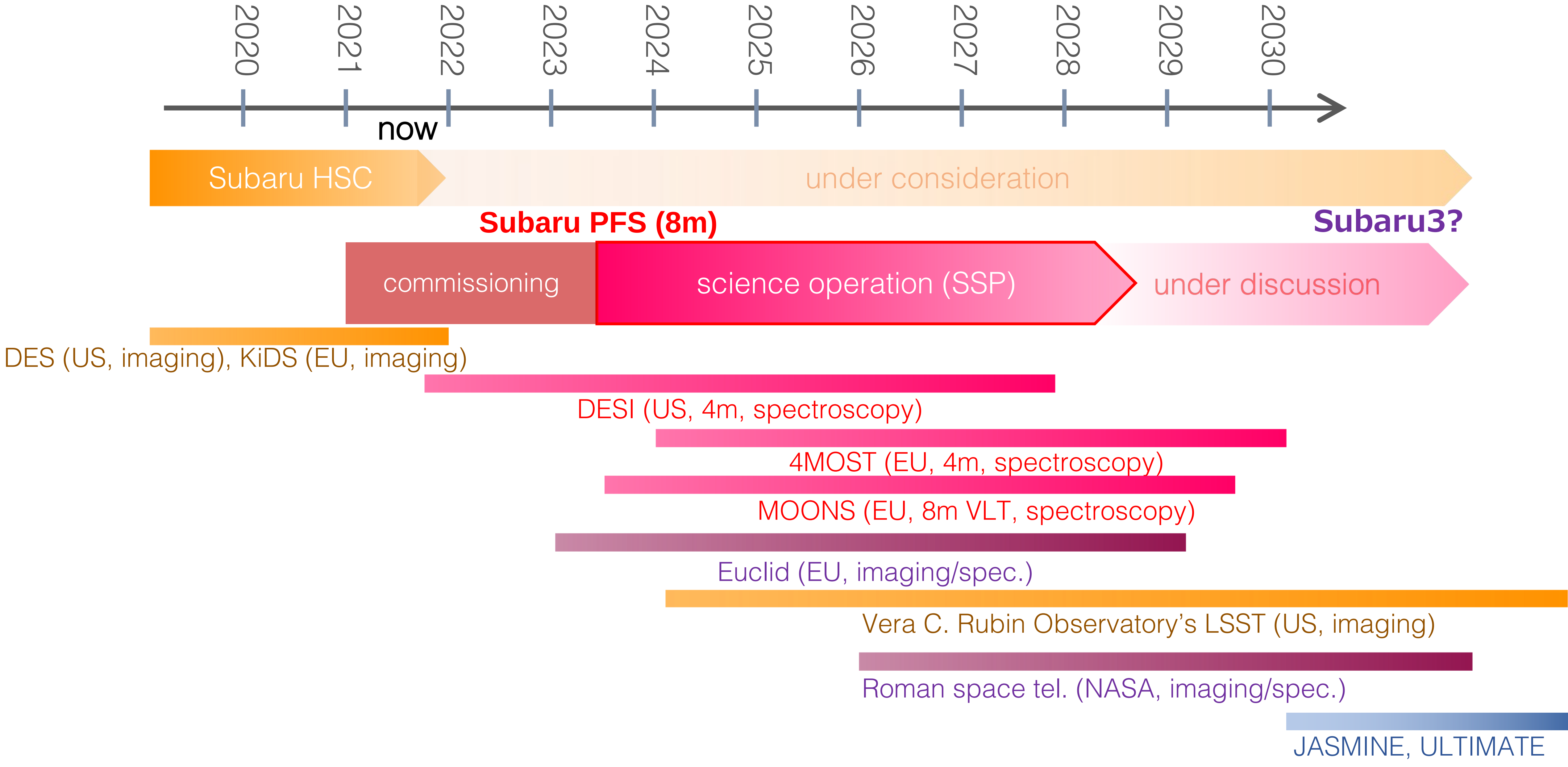
Astro2020

Discovery areas in cosmology

- The nature of dark energy – the origin of cosmic acceleration
  - Time-varying dark energy – galaxy surveys (HSC, PFS)
  - Very light axions (1e21 – ~1e-30eV) – CMB (Minami & Komatsu 21)
- The nature of dark matter
  - Primordial black holes – HSC, PFS, JASMINE, ULTIMATE, CMB-S4
  - Neutrino mass – PFS, HSC, CMB-S4, LiteBIRD
  - Axions (>~1e-21eV) – PFS, HSC, X-ray, CMB
- Physics in the early universe – the physics of inflation
  - Primordial gravitational wave – LiteBIRD, CMB-S4
  - Primordial non-Gaussianity – HSC, PFS, other surveys

- Note: Interdisciplinary field between astronomy and physics
- Strength of wide-area imaging/spectroscopic surveys – “Legacy” value or “multi-purposed” value; the same dataset enables a broad range of science cases; e.g. HSC, SDSS

Landscapes in 2020s cosmology



2024 –
Note: HSC can now do what LSST will do

From VRO LSST site

Strategy: uniqueness and complementarity

- Need not to compete with US/EU. Good examples are
  - *Gaia* in Europe: US gives up exploring astrometry satellite
  - SKA: instead explore ngVLA
  - Canada-led *CHIME* (21cm experiment) – has led to transformative progresses in FRB sciences
- Where can Japan be unique in cosmology science?

Astro2020

These contributions from NSF, private foundations and philanthropy, NASA, and the DOE have helped to maintain the vitality of the instrumentation on ground-based OIR telescopes, but fall short of what is needed to maintain the competitiveness of the facilities. As one useful benchmark, ESO currently invests ~$10 million per year in instrumentation across its OIR telescopes, with another $15 million to $20 million invested by the partner organizations. Two major instruments on the Japan-led Subaru 8.4 m telescope, the Hyper Suprime-Cam and the future Prime Focus Spectrograph, have associated costs of $50 million and $86 million, respectively. Funding even shares of such instruments will require larger allocations than historically have been awarded through the TSIP or MSIP programs. The second challenge is the loss of public access time over the past decade, arising both from the discontinuation of the TSIP program and the effective withdrawal of the CTIO 4m Blanco and KPNO 4m Mayall telescopes from general public use during the course of the DES and DESI (and their associated) multi-year surveys. The point is not to criticize whatsoever the decisions to undertake these important surveys, but rather to emphasize the ever-dwindling general public access to 3.5—10m class OIR telescopes in recent years.

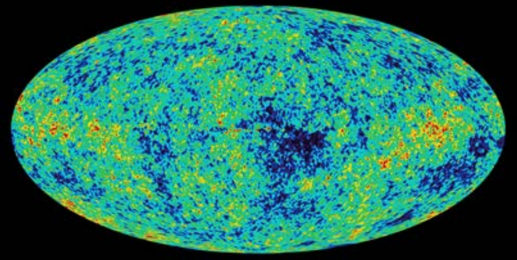
✓ PFS is mentioned in several places of Astro2020. The Maunakea Spectroscopic Explorer (MSE; 11m, ~4000 fibers) isn't recommended

✓ Astro2020 recommends mid-scale program to keep access to existing ground facilities (e.g. PFS) for the US community

Dark energy: The current status of ΛCDM model

- The standard model ΛCDM model has been remarkably successful to explain a broad range of cosmological observations
- sigma8 or S8 tension? (see later)
    - Galaxy surveys (SDSS, HSC, DES, KiDS, …) indicate a tension for sigma8 and S8 value compared to the ΛCDM model inferred from the CMB experiment
    - A new physics beyond ΛCDM model?
- H0 tension?
    - The H0 measurement in the local universe (e.g., distance ladder) indicates a tension compared to the CMB experiment
    - Systematics or New physics
    - The gravitational wave sirens of NS-NS mergers will resolve whether this tension is genuine, hopefully within 5yrs (LIGO/Virgo/Kagra + multi-messenger astronomy)

Large-scale structure formation: DM vs. DE



CMB at z~1000

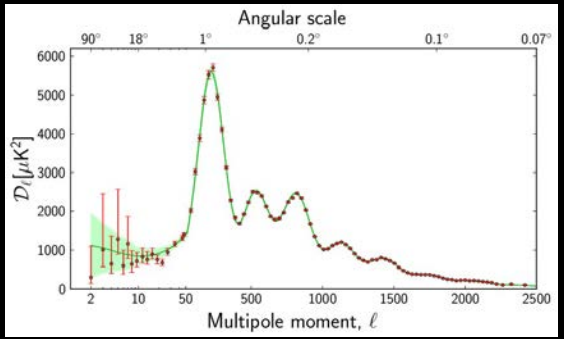
ΛCDM extrapolation

$\sigma_8^{\mathrm{CMB}}(z \sim 0)$
$S_8^{\mathrm{CMB}}(z \sim 0)$

time

gravity (dark matter)

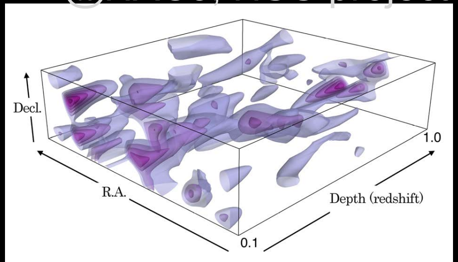
cosmic expansion (dark energy)



ΛCDM=~6 parameters

@Planck collaboration

@NAOJ, HSC project

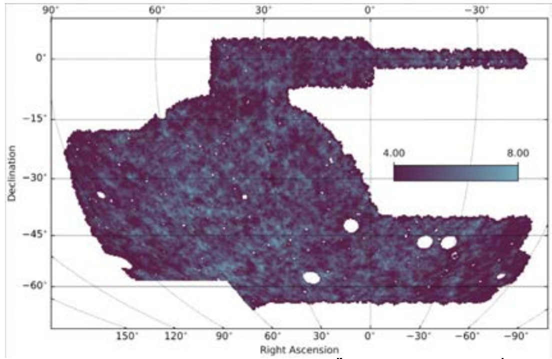


Galaxy surveys directly measure “**lumpiness**” of the universe

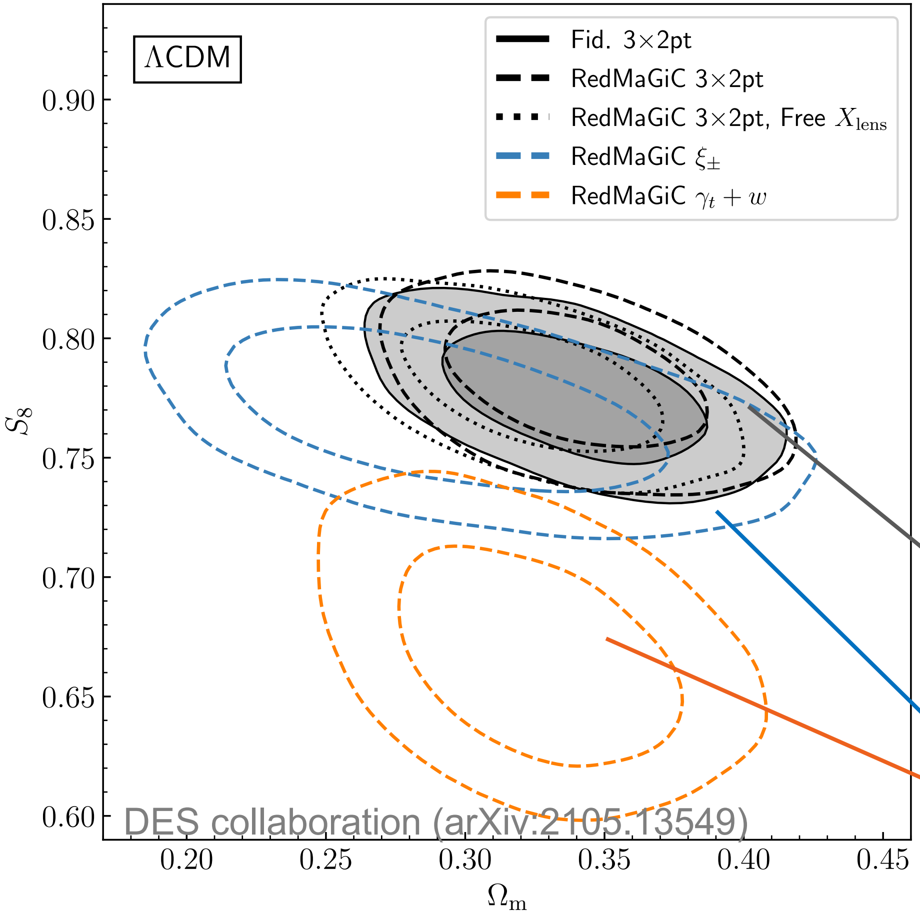
$$\sigma_8^{\mathrm{obs}}(z \sim 0), \quad S_8^{\mathrm{obs}}(z \sim 0)$$

LSS cosmology: systematics vs. statistical errors

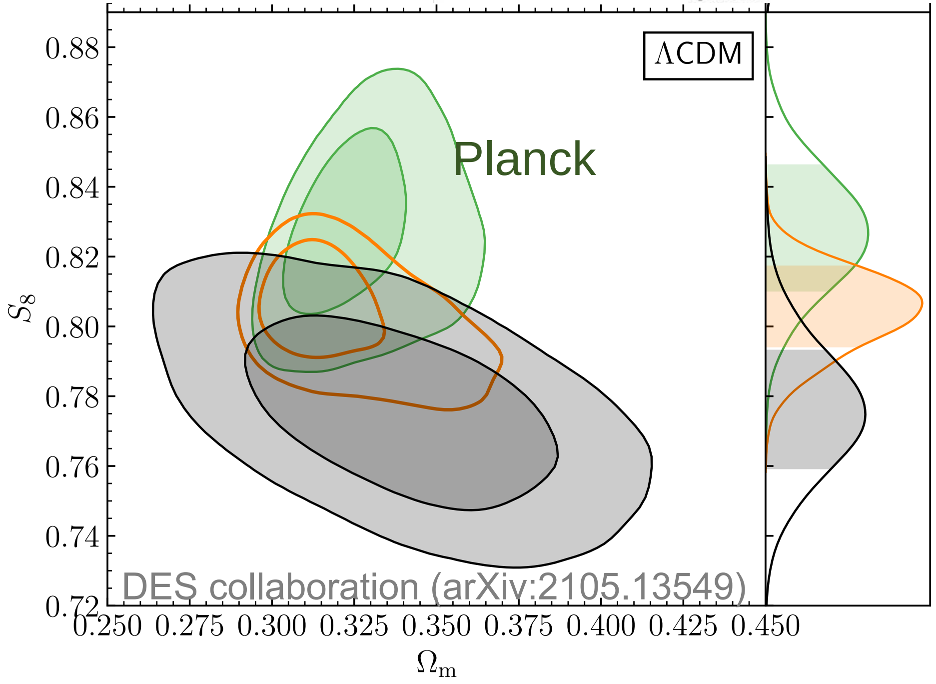
- Dark Energy Survey (US; 2013-), Year-3 data~4000 sq. deg.
- DES reported the cosmology results with the DES-Y3, in May 2021
- Some results done after blind analysis (post-unblinding)



S_8: "clumpiness" of the universe



Ω_m: energy fraction of matter



"maglim" sample (magnitude limited sample): blue galaxies + RedMaGiC sample

"RedMaGiC" galaxy sample (luminous, early-type galaxies): good photo-z, the sample well-studied by SDSS

Unknown systematics??

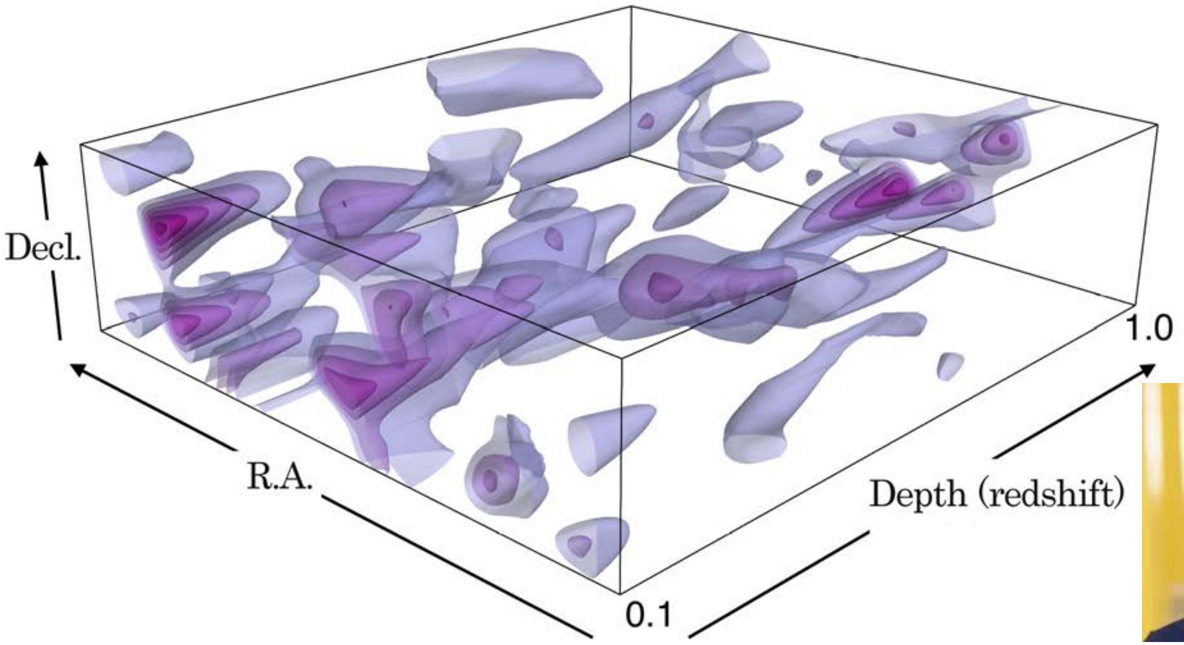
The nature of dark energy – the origin of cosmic acceleration

⇒ The intermediate goal is to make a stringent test of ΛCDM model

- Gravitational lensing enables to probe the DM distribution – can be measured with wide-area imaging surveys (HSC, LSST, Euclid, Roman)

distortion in galaxy shape at z_s

$$\gamma(\boldsymbol{\theta}, z_{\rm s}) \sim \int_0^{z_{\rm s}} {\rm d}z\, W(z, z_{\rm s})\bar{\rho}_{\rm m}\delta_{\rm m}(z, \chi\boldsymbol{\theta})$$

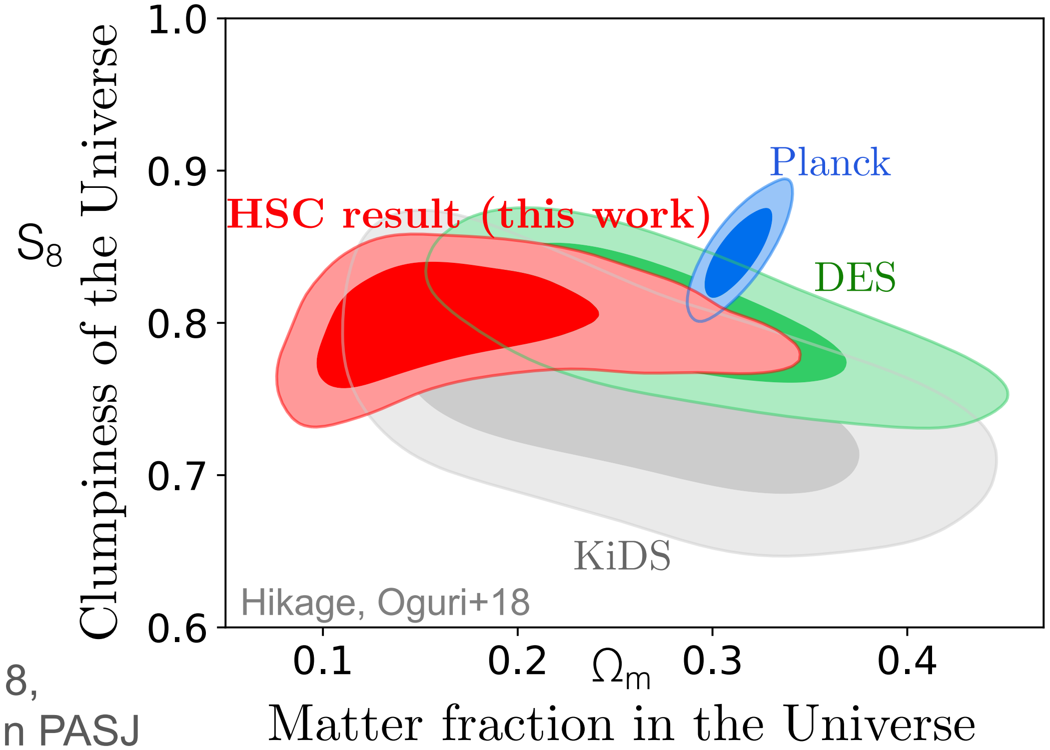


© Oguri+18, HSC project

Hikage, Oguri+ 18, the most cited paper in PASJ

✓ A tension between Planck cosmology (~380K yrs) and HSC cosmology (late universe)

✓ A hint of new physics beyond ΛCDM?



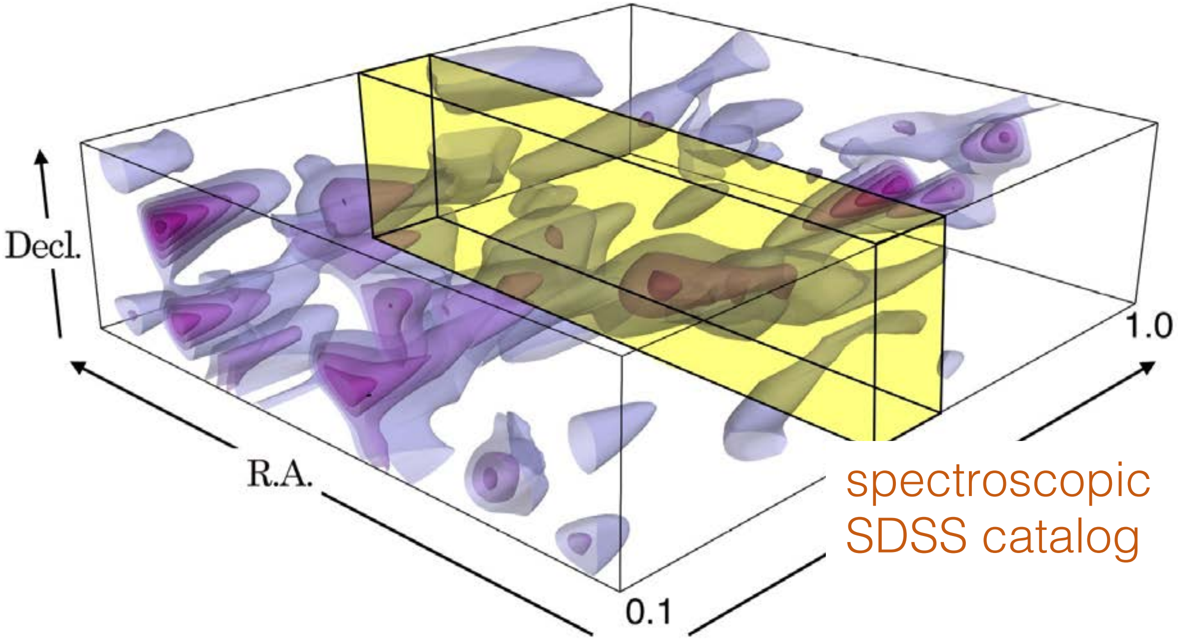
The nature of dark energy – verify or falsify S8 tension

- New results: cosmological constraints, robust to photo-z errors (Miyatake+21)
- The Japan-led international team has gained expertise on cosmology (data, analysis, measurements, blinded analysis, parameter inference)

Hironao Miyatake (Nagoya U.)

S. Sugiyama (IPMU)

$$\gamma(\boldsymbol{\theta}, z_{\rm s}) \sim \int_0^{z_{\rm s}} {\rm d}z\, W(z, z_{\rm s})\bar{\rho}_{\rm m}\delta_{\rm m}(z, \chi\boldsymbol{\theta})$$



✓ Cross-correlation of HSC galaxy shapes and positions of spectroscopic SDSS galaxies

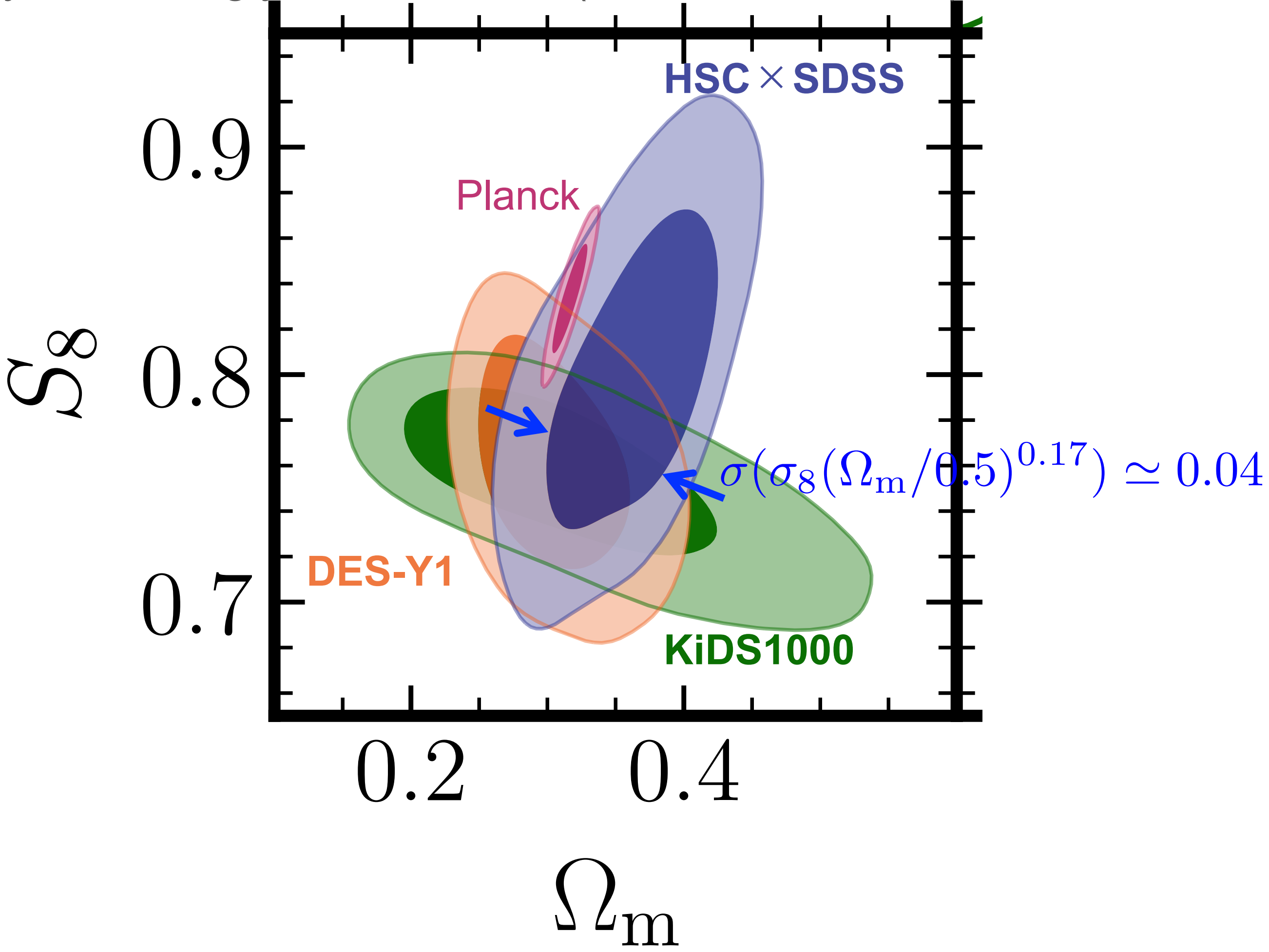
$$\langle\delta_{\rm g}(z_{\rm l})\gamma(z_{\rm s})\rangle \to \xi_{\rm gm}(r; z_{\rm l}) \simeq b_{\rm g}\xi_{\rm mm}(r; z_{\rm l})$$

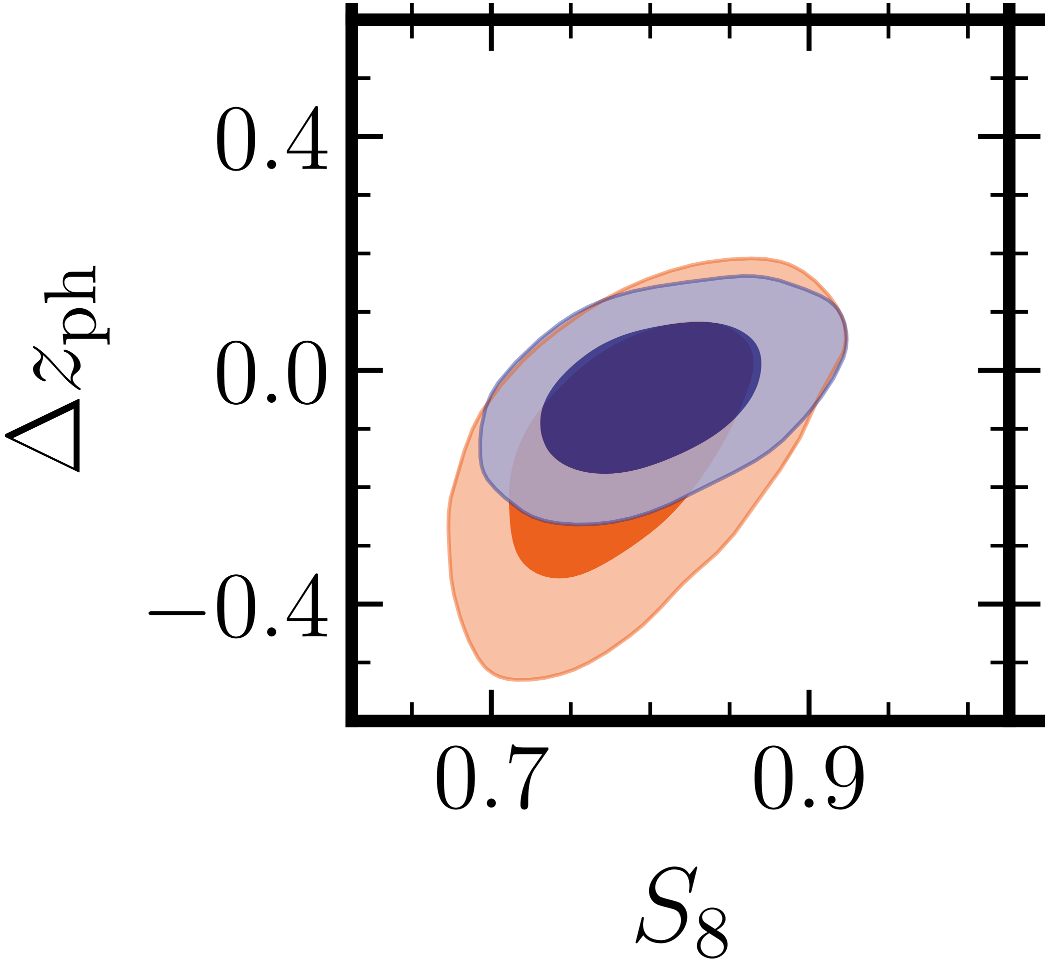
✓ Auto-correlation of spectroscopic SDSS galaxies

$$\langle\delta_{\rm g}(z_{\rm l})\delta_{\rm g}(z_{\rm l})\rangle \to \xi_{\rm gg}(r; z_{\rm l}) \simeq b_{\rm g}^2\xi_{\rm mm}(r; z_{\rm l})$$

✓ Combining these two allows to observationally disentangle galaxy bias uncertainty and matter correlation function

Miyatake, Sugiyama, MT +21 (arXiv:2111.02419)



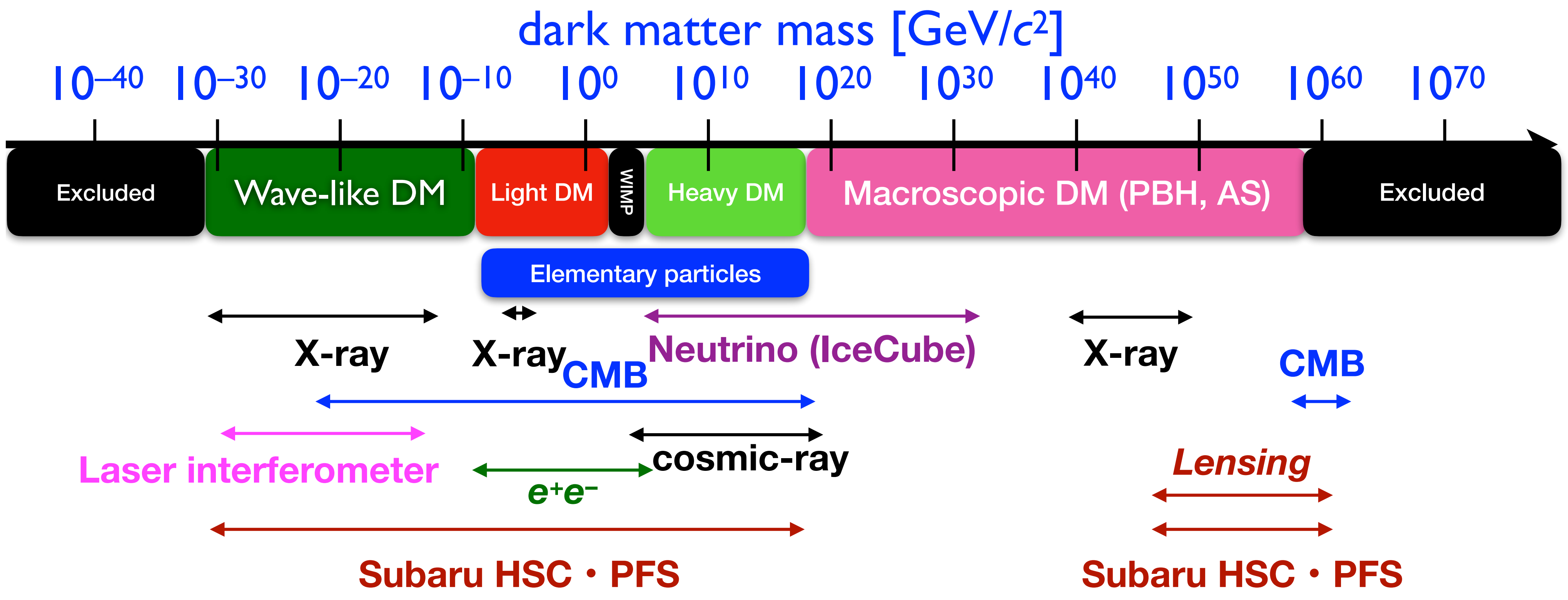


- ✓ HSC-Y1 at Ω_m~0.3 still indicates a tension with Planck?
- ✓ The upcoming HSC Year 3 data promises a significant improvement in cosmological parameters

- ✓ The constraint on S8 is not changed even if treating residual photo-z bias as a free parameter (other weak lensing surveys assume ~1% prior on photo-z, and uses COSMOS calibration)

Ideally Subaru HSC/PFS gives stringent test of ΛCDM model, e.g. finding a breakdown of ΛCDM, and then LSST/Euclid/Roman will "confirm" the Subaru results

What is dark matter? – Astronomical DM search

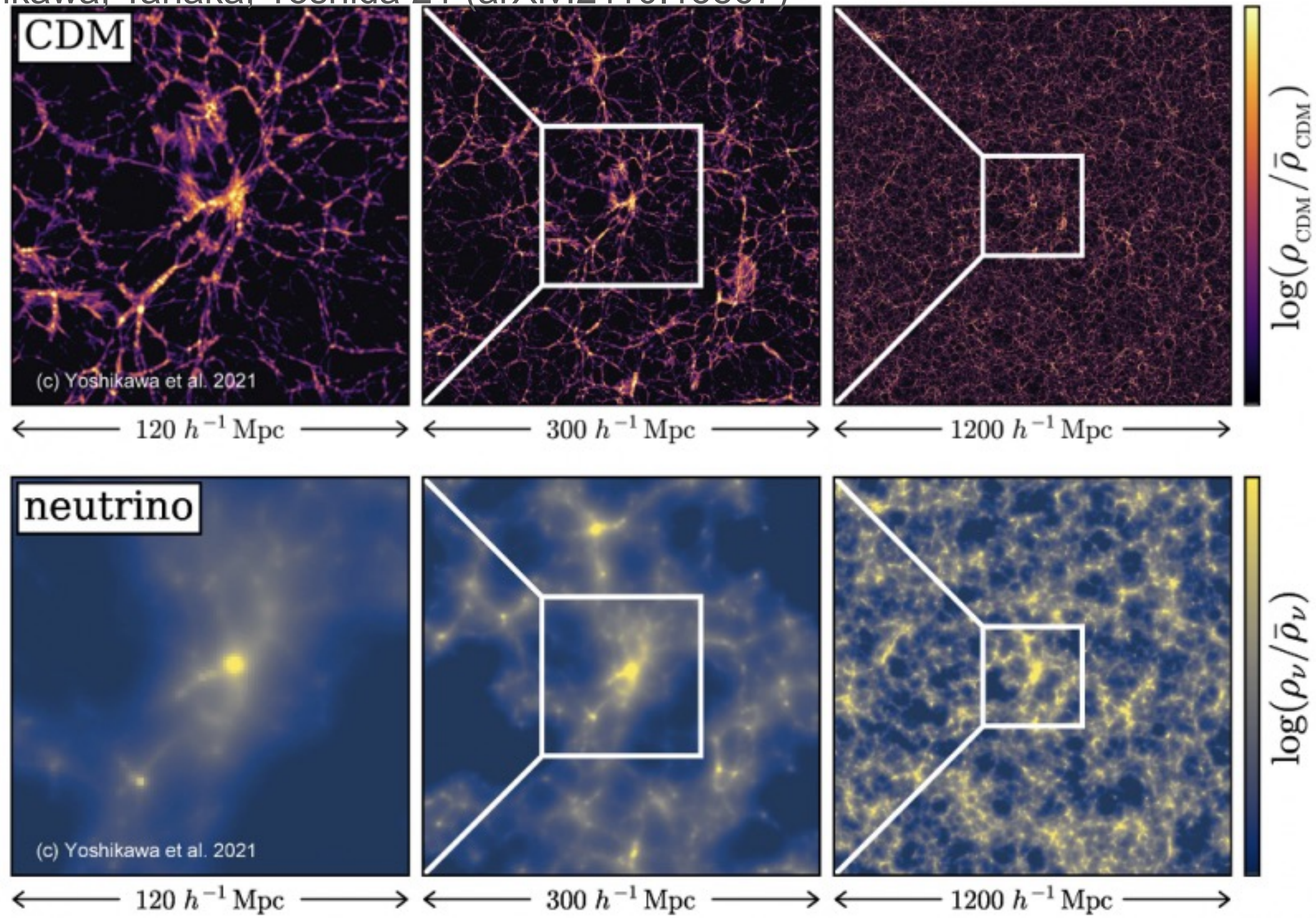


- DM candidates span 90 orders of magnitudes in mass scales
- No hint by terrestrial experiments (e.g., LHC)
- Candidates explored by astronomical observations
  - Axions (~1e-10 – 1e-30 GeV): predicted by string theory, XRISM, Kagra, Subaru HSC・PFS, CMB
  - Macroscopic DM (PBH, axion stars): Subaru HSC・PFS, JASMINE, VRO LSST, Roman, CMB

Neutrino mass determination – guaranteed science

- Neutrinos have finite mass (<0.1eV) – part of DM
- Neutrinos imprint characteristic features in large-scale structure, seen by wide-area galaxy surveys

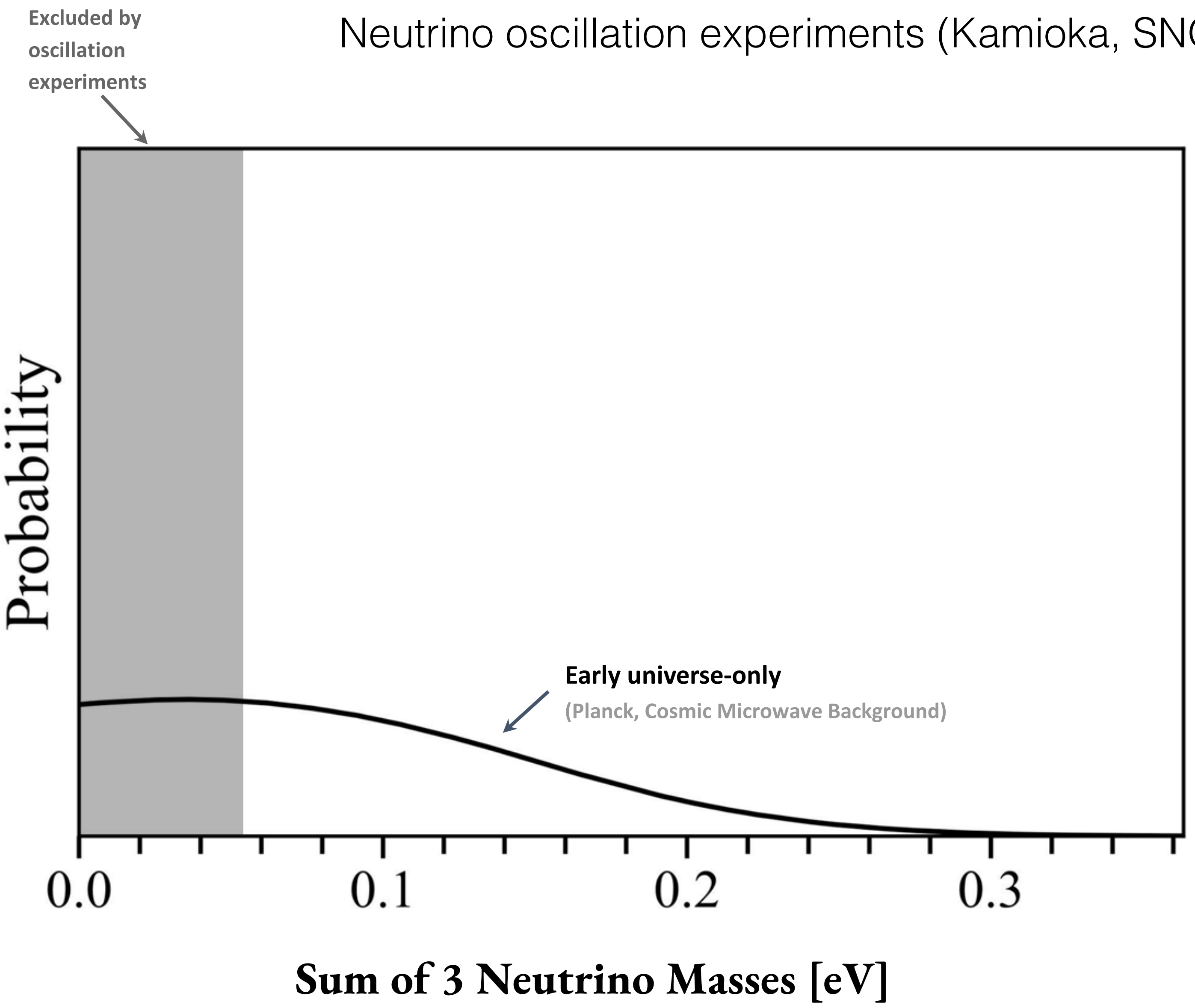
Yoshikawa, Tanaka, Yoshida 21 (arXiv:2110.15867)

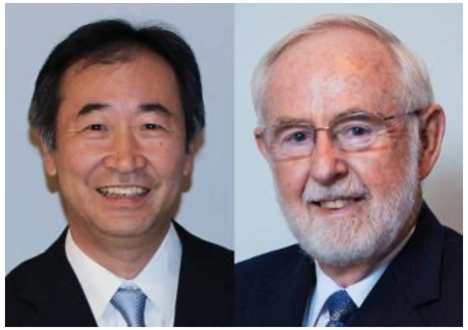


Neutrinos (hot DM) smooth out small-scale structures, compared to the case without massive neutrinos

Also see, Hu 98;
MT, Komatsu & Futamase 06;
Saito, MT, Taruya 08; Shoji & Komatsu 10;
many other studies

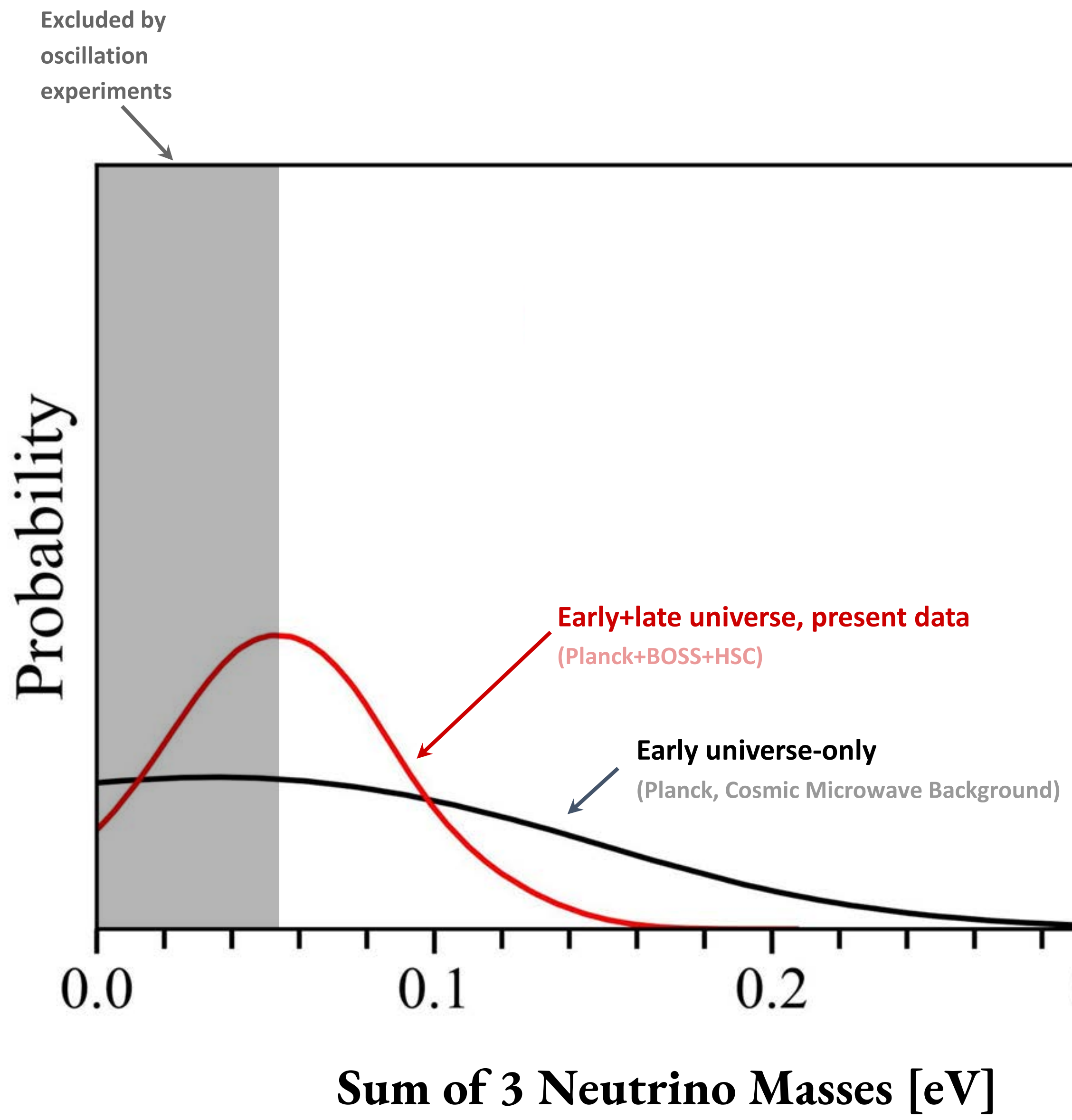
Neutrino oscillation experiments (Kamioka, SNOSK,+) >0.06eV for NM
>0.1eV for IM



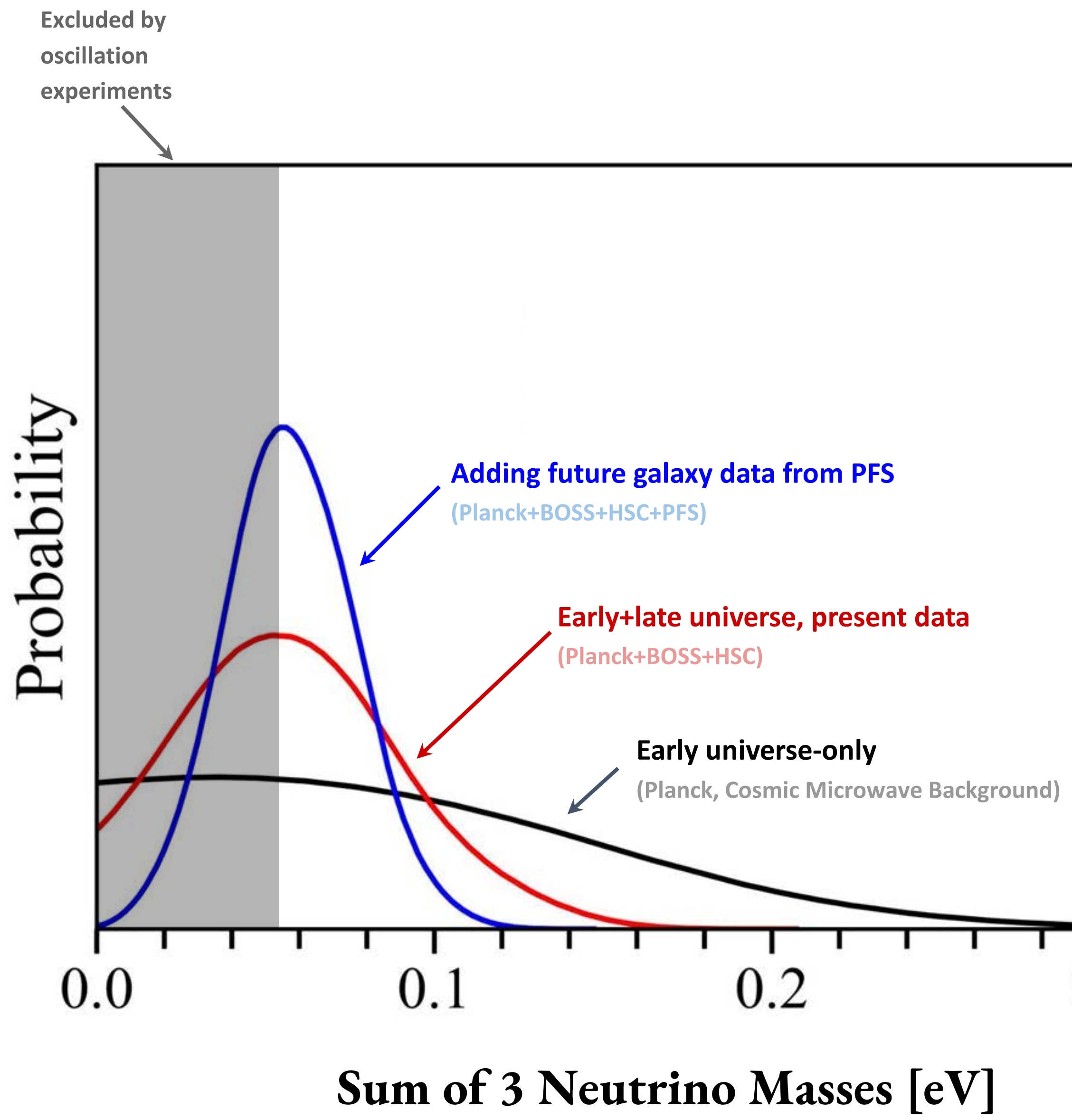


Nobel Prize 2015

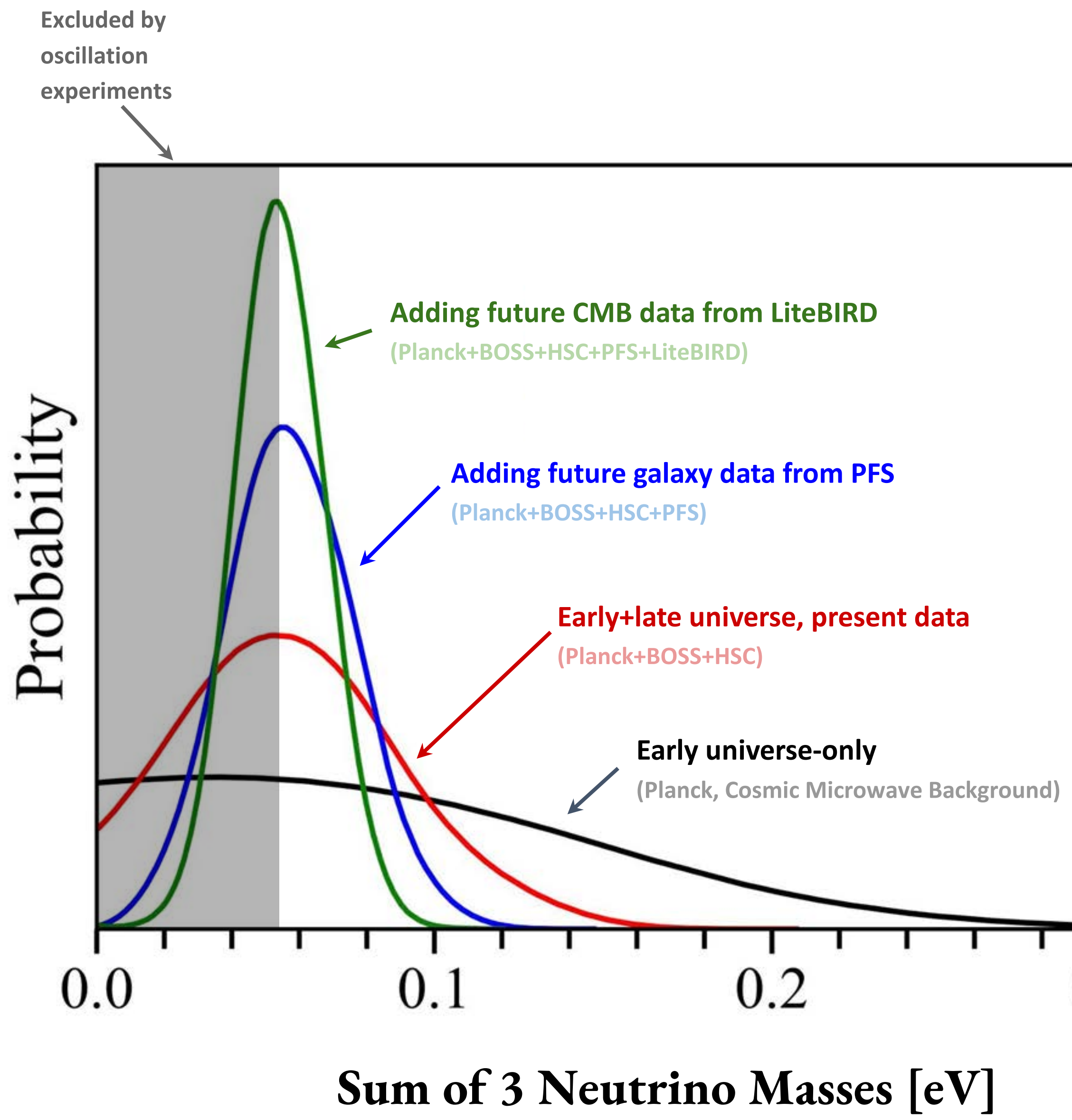
Credit: Ryu Makiya, PFS Cosmology WG



Credit: Ryu Makiya, PFS Cosmology WG



Credit: Ryu Makiya, PFS Cosmology WG



$$C_\ell^{\rm CMB} \propto A_{\rm s} e^{-2\tau}$$

A_s: primordial fluctuation amplitude

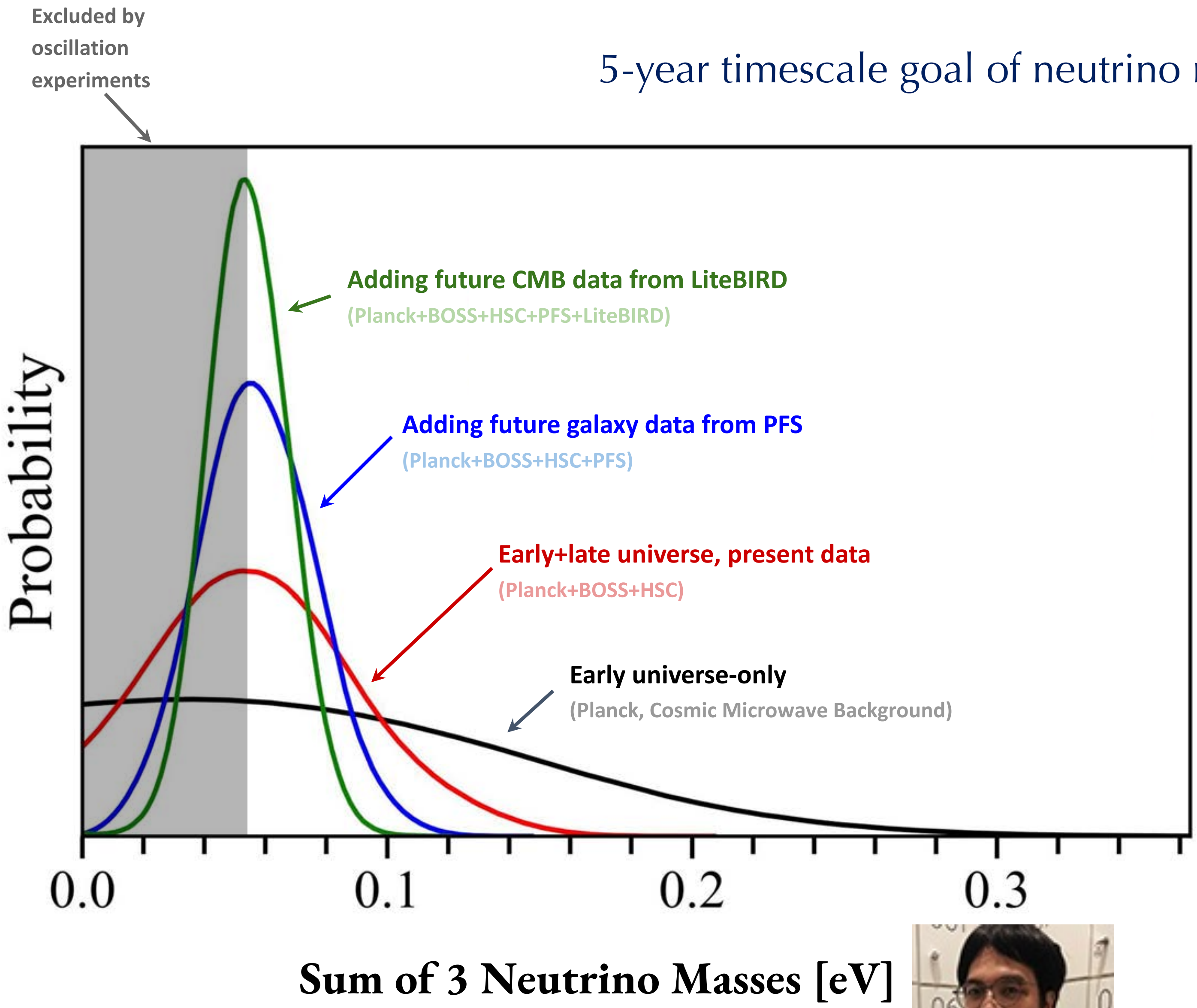
tau: optical depth

LiteBIRD can measure "tau" very precisely

A great synergy btw Subaru PFS and LiteBIRD

Credit: Ryu Makiya *Animation Courtesy: Jia Liu (Kavli IPMU)*

5-year timescale goal of neutrino mass determination



Credit: Ryu Makiya, PFS Cosmology WG

- ✓ Wide-area galaxy surveys (Subaru HSC/PFS, DESI, Euclid, Roman) enable a precise "measurement" of neutrino mass
- ✓ Competition: Subaru PFS can achieve the similar precision to that of DESI (~2025): the goal $\sigma(m_\nu) \approx 0.02$eV
- ✓ Eventually CMB-S4 (2030-)
- ✓ Neutrino experiments (Hyper-K, DUNE) can determine the neutrino mass hierarchy in 2030's

Ryu Makiya (ASIAA)

Tomomi Sunayama (Nagoya U.)

Dark matter science: **dwarf galaxies**

- ✓ DM dominated system

$$M \sim 10^{7-8} M_{\odot}$$
$$M \sim 10^{3-4} M_{\rm star}$$

- ✓ Size: ~1kpc
- ✓ Velocity dispersion-supported system

$$\sigma_v^2 \sim \frac{GM(< r)}{r}$$

Motion of member stars allow us to infer dynamical mass (note back/fore-ground stars; Horigome+20)

- ✓ Line-of-sight velocities of member stars can be used to infer dynamical mass (mostly DM)

Dark matter search for dwarf galaxies

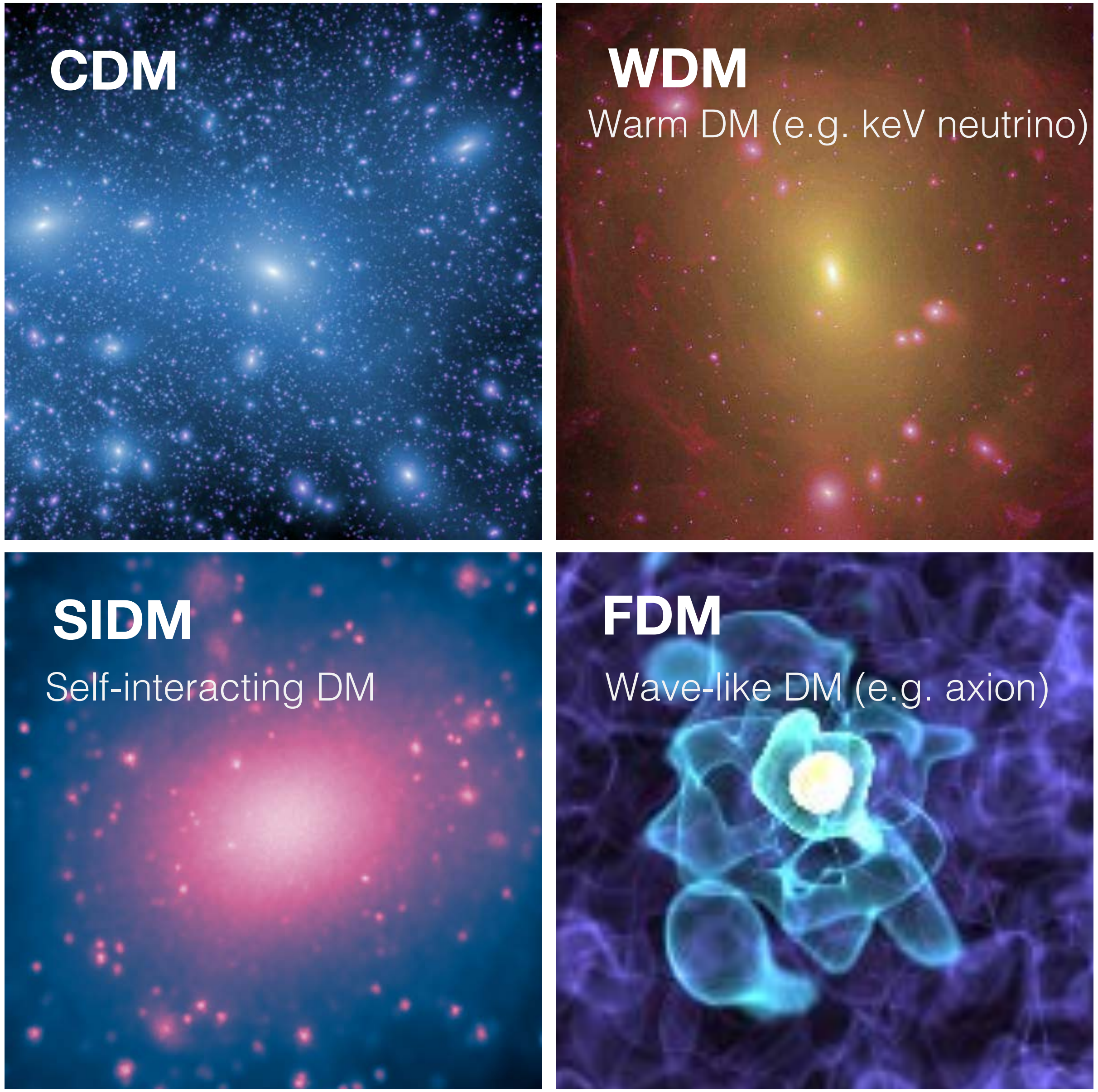
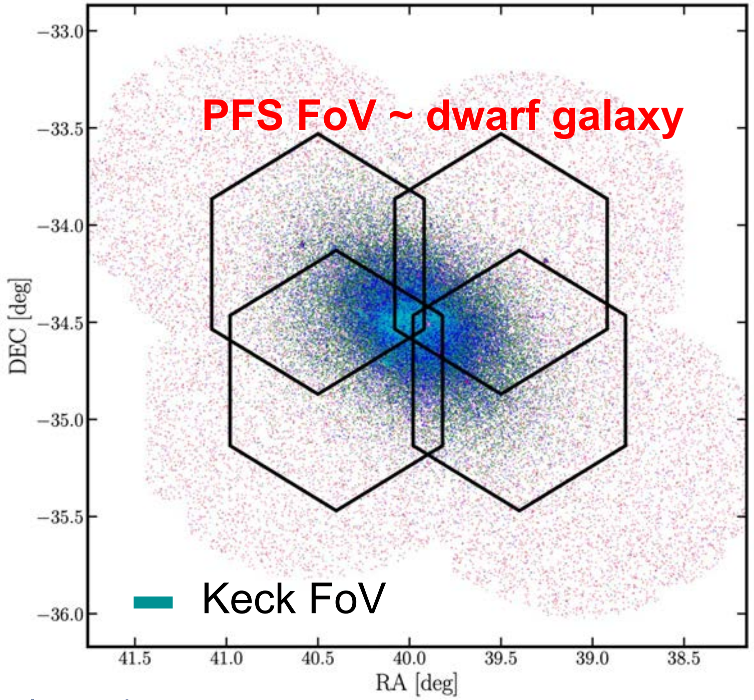


Figure credit: Shi'nichiro Ando (Amsterdam U.)

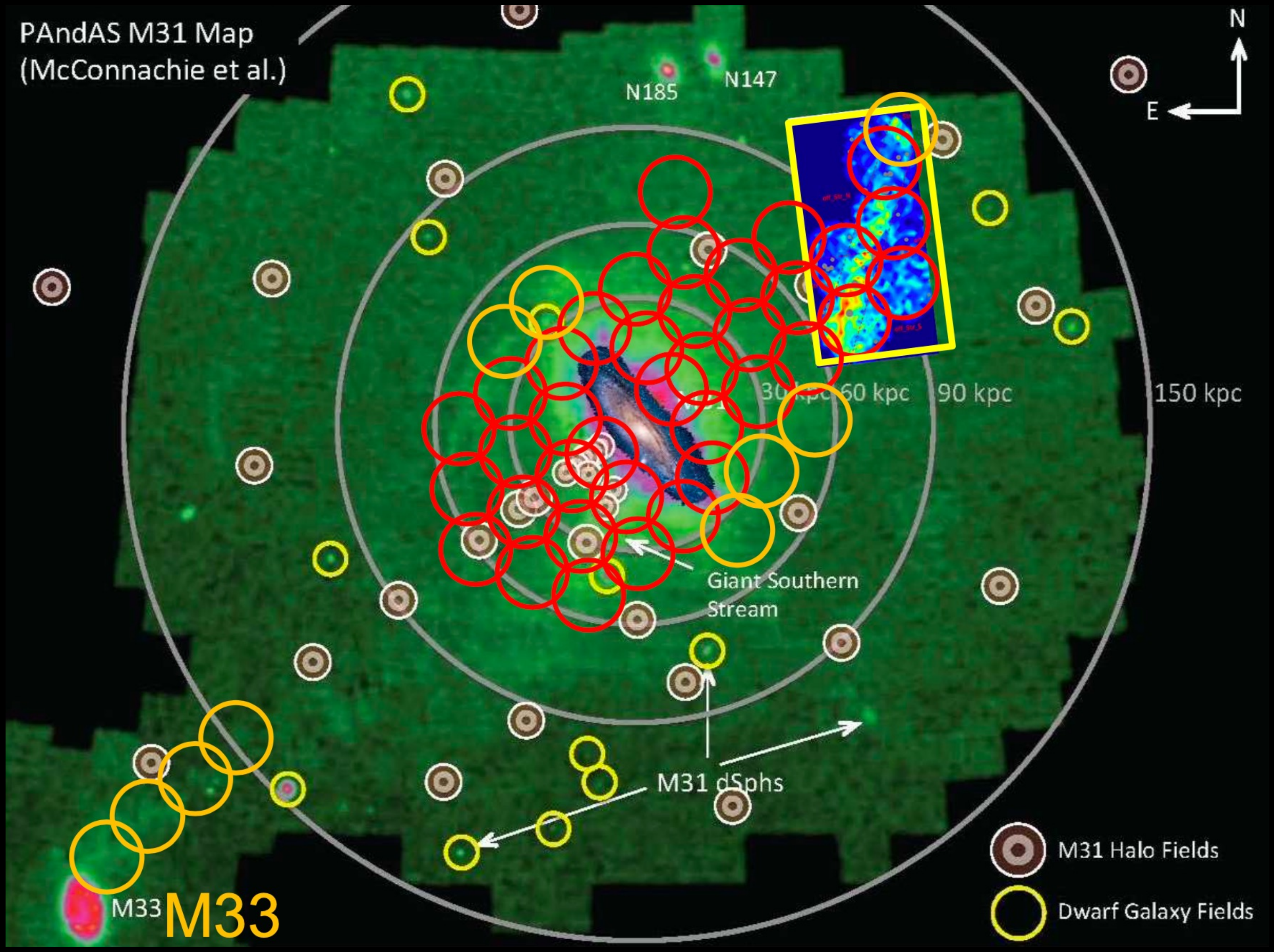


de Broglie wavelength

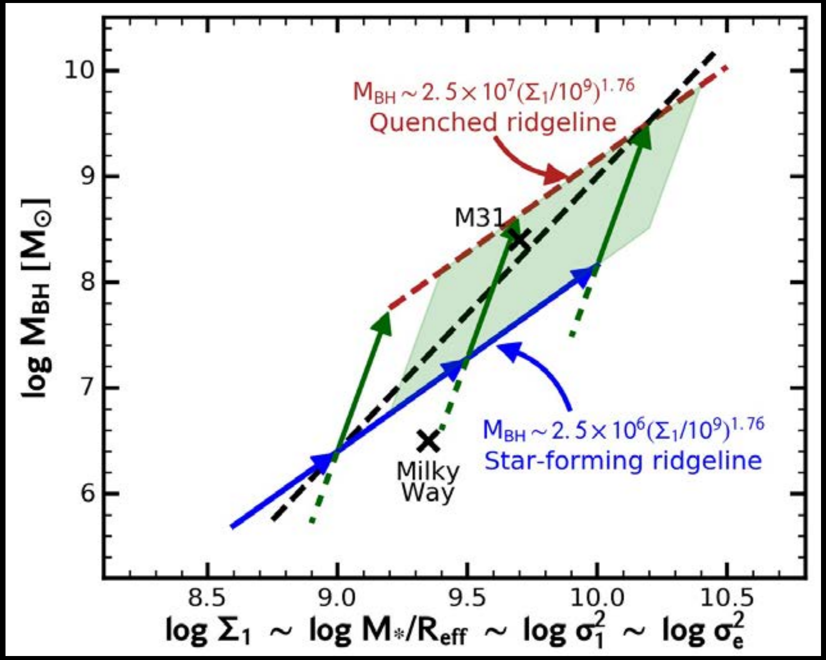
$$\lambda = \frac{h}{mv} \sim 1\,\mathrm{kpc}\left(\frac{m}{10^{-21}\mathrm{eV}}\right)^{-1}\left(\frac{v}{10\,\mathrm{km/s}}\right)^{-1}$$

- DM variants can imprint characteristic signatures in the gravitational potential of a dwarf galaxy (scales that can't be probed by CMB and galaxy surveys)
- E.g., wave-like DM (axion) leads to a core profile
- DM profile of each dwarf galaxy can be probed by spatial and kinematical structures of member stars (Subaru HSC・PFS)
- Unique: can't be done by other instruments
- Byproduct: binary fraction

Near-field cosmology



Chen, Faber+20



- MW and M31 are special because these allow us to study detailed their assembly history
- M31 is a unique target for 8m PFS (cannot be done by 4m-instruments)
- Need strategic observation (e.g., CFHT M31 survey in 2010's)

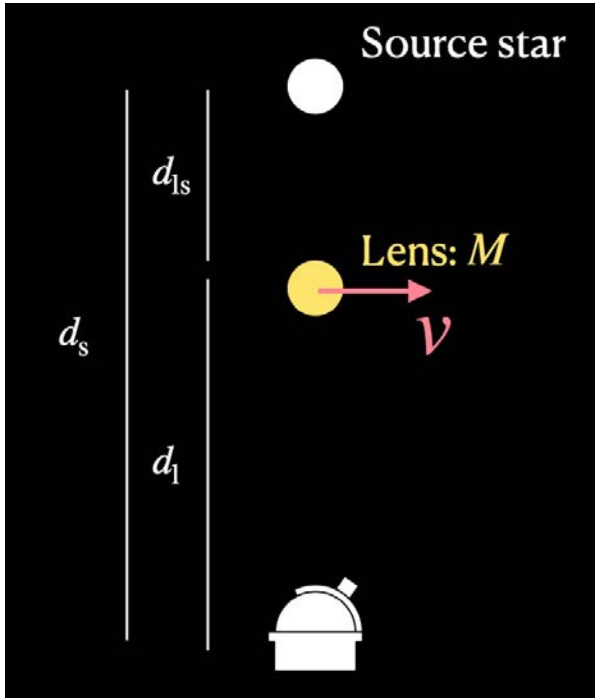
Dark matter – macroscopic DM candidates

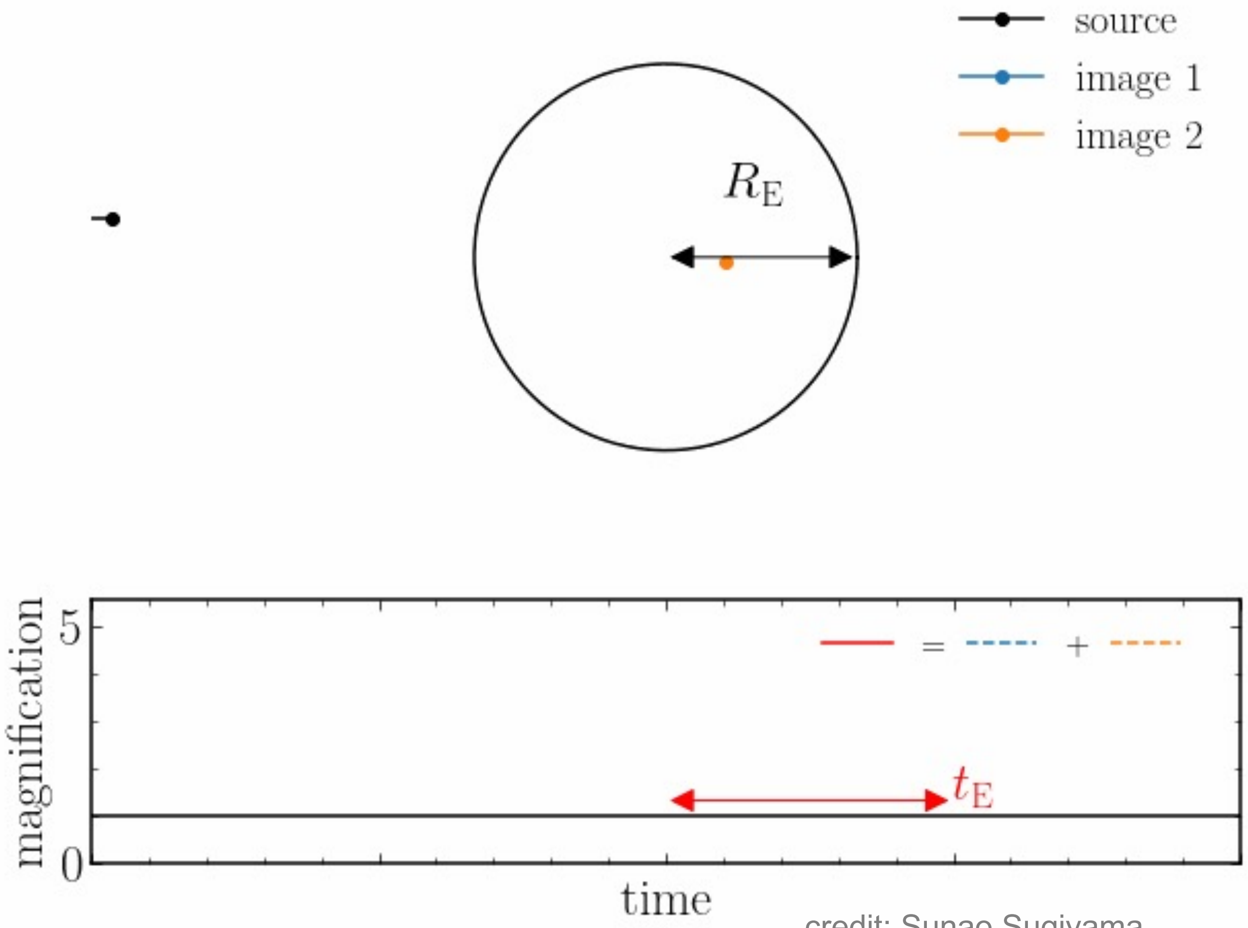
- Micro-gravitational lensing enables to search for “dark” compact objects (PBH, BH, NS, planets)
- Einstein radius

$$R_E = \sqrt{\frac{4\pi G M_{\mathrm{PBH}} d(1 - d/d_s)}{c^2}}$$

- Light curve timescale (=time duration with A>A(R_E)=1.34)

$$t_E \sim \frac{2R_E}{v_{\mathrm{rel}}}$$

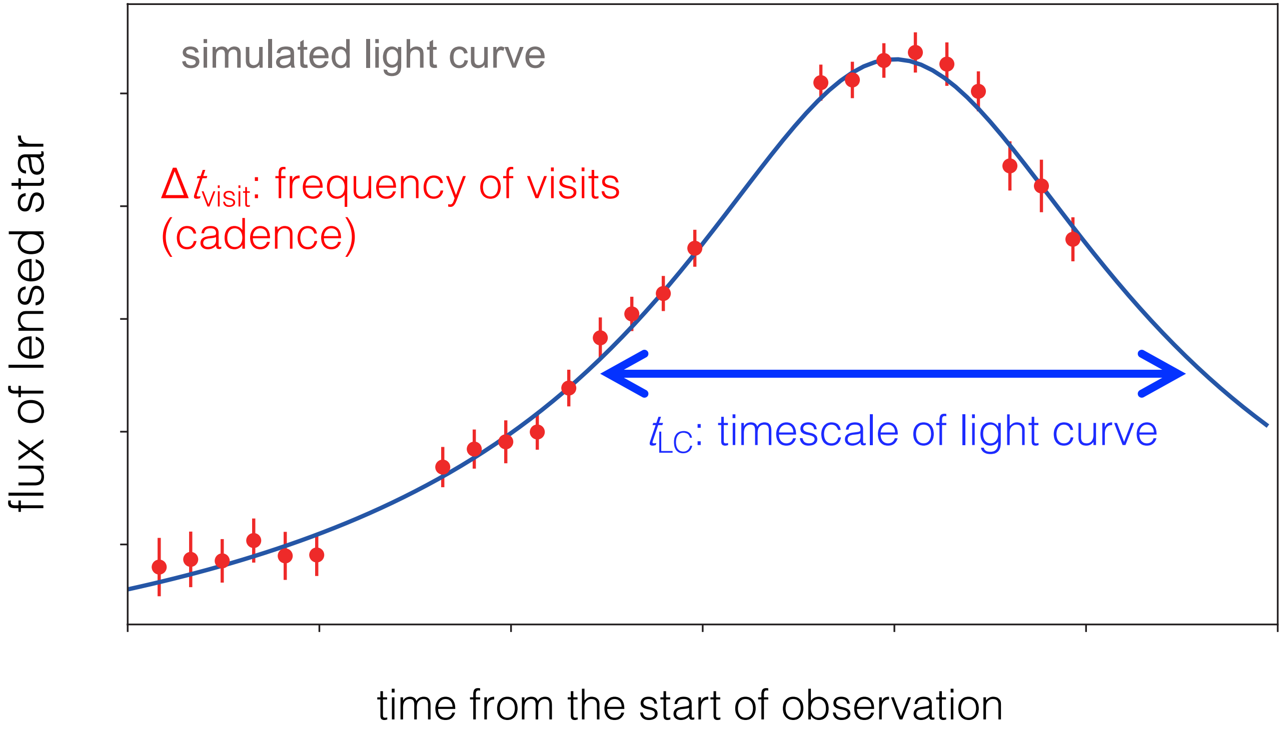




credit: Sunao Sugiyama

What is needed for a strategic microlensing survey?

- Need a right cadence strategy for targets objects (small mass requires a dense cadence); a new detector, such as CMOS, could open up a new window (LSST, 2sec readout; HSC ~30sec)
- Need to monitor as many source stars at one time as possible
  - Target fields: Galactic bulge, disk, star clusters, M31
  - A large aperture and infrared observation help – HSC, ULTIMATE, JASIMINE, VRO LSST, Roman
- ML events depend on spatial and velocity structures of lenses
- Byproducts: search for stellar BHs (LIGO-counterpart BHs), a binary fraction of BH system

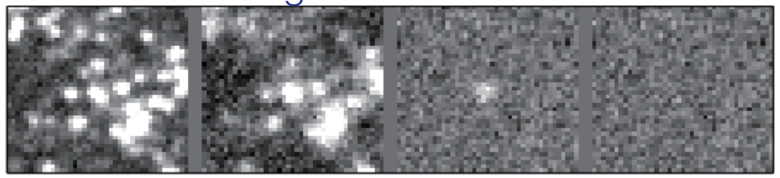


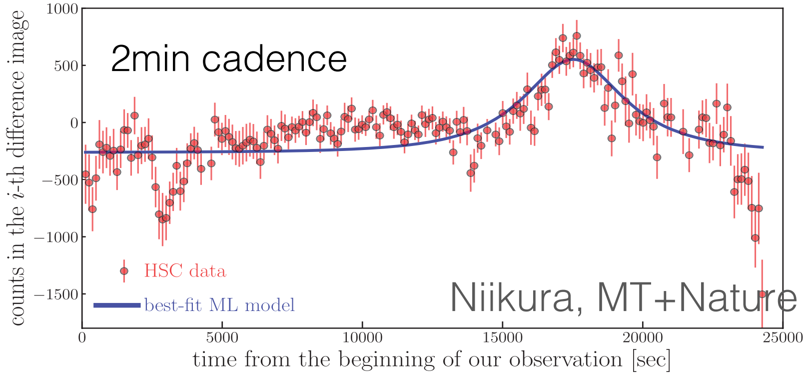
✓ If we find any BH with <a few Msun, it should be primordial-origined (*discovery!*)

✓ A typical timescale for a given mass-scale lens, if assuming v~200km/s (halo objects), is

- ✓ 10Msun, t_LC~a few years
- ✓ 1Msun, t_LC~a year
- ✓ 10^{-3}Msun (Jupiter mass), t_LC~a week
- ✓ 10^{-5}Msun (Earth mass), t_LC~a day
- ✓ 10^{-9}Msun (Moon mass), t_LC~10 hrs

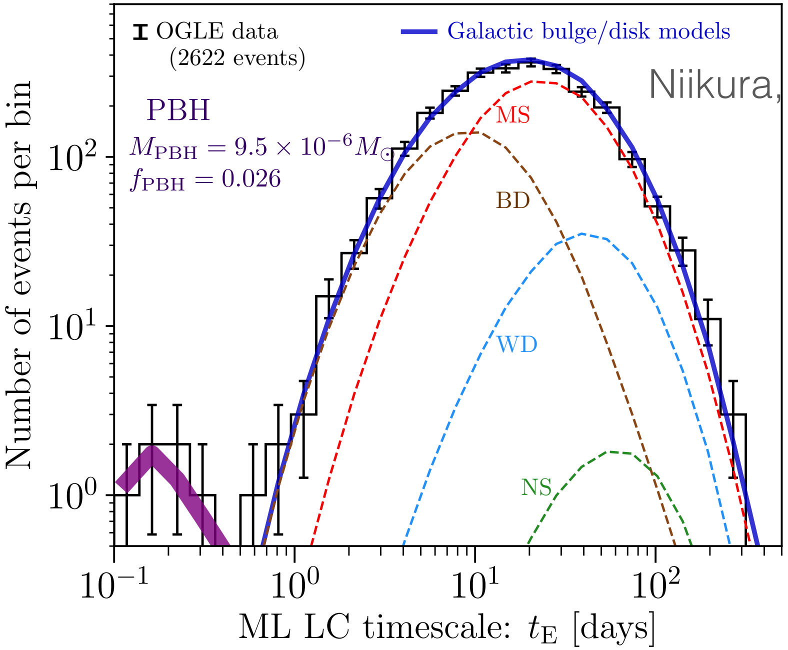
Subaru HSC M31 microlensing





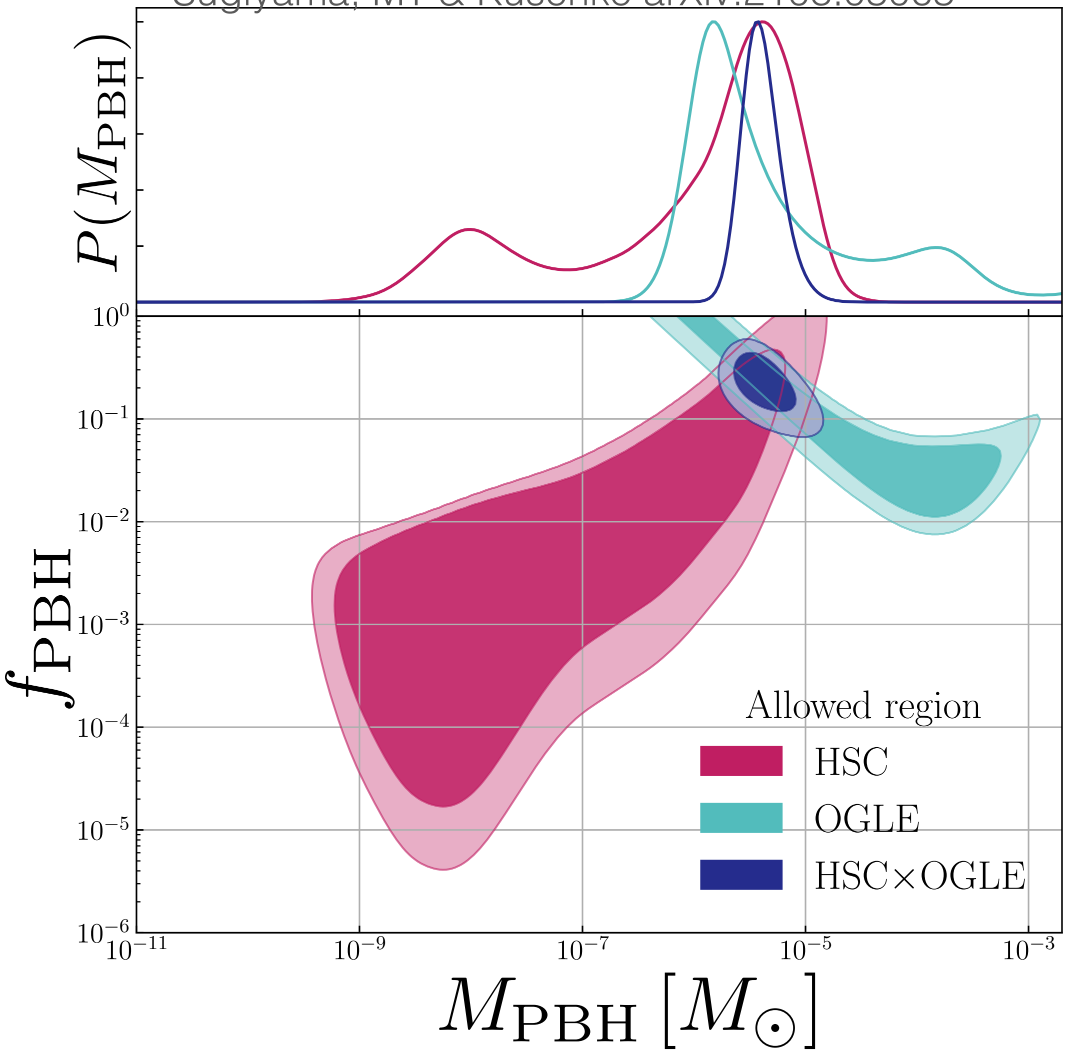
Niikura, MT+Nature Astron. 19

Optical Gravitational Lensing Experiment of Galactic bulge (OGLE, 1.3m in Chile)



Niikura, MT+PRD 19

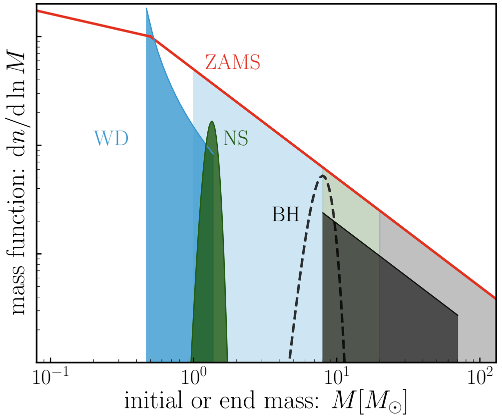
Sugiyama, MT & Kusenko arXiv:2108.03063

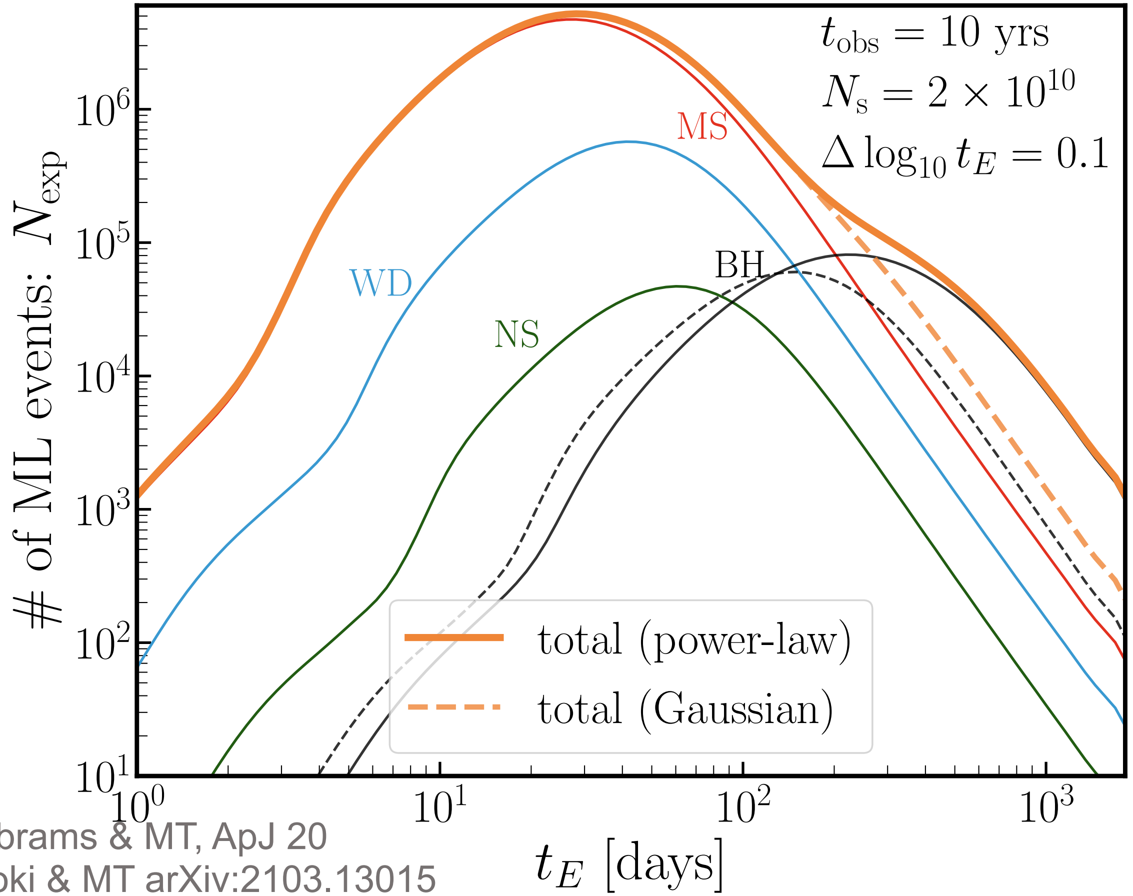


Sunao Sugiyama

- PBH search is currently the hottest topic in particle physics and cosmology
- Verify/falsify OGLE/HSC results
- See Kohri san’s talk

Byproduct of microlensing PBH search





$$\frac{dN_{\rm event}}{dt_E} \propto \int_0^{d_s} dd_l \; n_l(d_l) \frac{R_E^4}{t_E^4} f(v_\perp)|_{v_\perp = 2R_E/t_E}$$

$$\propto M^2$$

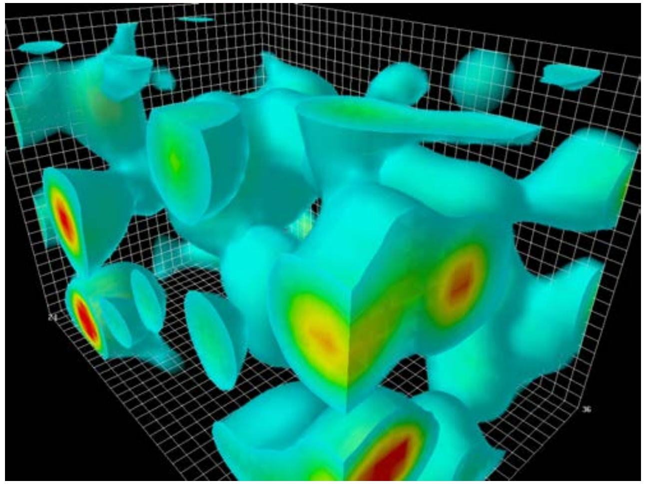
for events with $v_\perp = \frac{2R_E}{t_E} \ll v_{\rm typical}$ or $t_E \gg \frac{2R_E}{v_{\rm typical}}$

- The event rate of microlensing depends on the spatial and velocity structures of lenses
  - Bulge, ~100km/s; disk, ~30km/s; halos, ~200km/s
- If LIGO-Virgo BBHs are stellar-origined, long-timescale events are dominated by BH events
  - VRO LSST's bulge search will find >10^4 BH events
  - Can also study wide-orbit binary BHs: binary fraction, properties of binaries (separation, mass ratio, …)
- Microlensing events also enable to study properties of stars, WDs, BDs and planets
- Proper motion measurements can help the study: JASMINE, ULTIMATE, ….

Abrams & MT, ApJ 20
Toki & MT arXiv:2103.13015

Physics in inflation

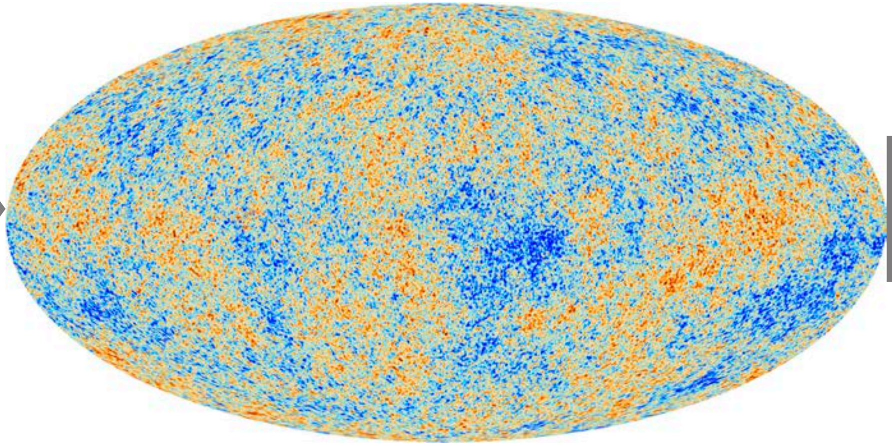
- The so-far cosmological data is consistent with "a single field inflation" scenario – the simplest inflation model ⇒ "single degree of freedom" (adiabatic initial conditions)
- The primordial non-Gaussianity (Komatsu 01, 02) is a key to understanding physics in inflation



$$\delta\phi_{\rm inf}(\mathbf{k}) \to \zeta(\mathbf{k})$$

quantum fluctuations

primordial curvature perturbation



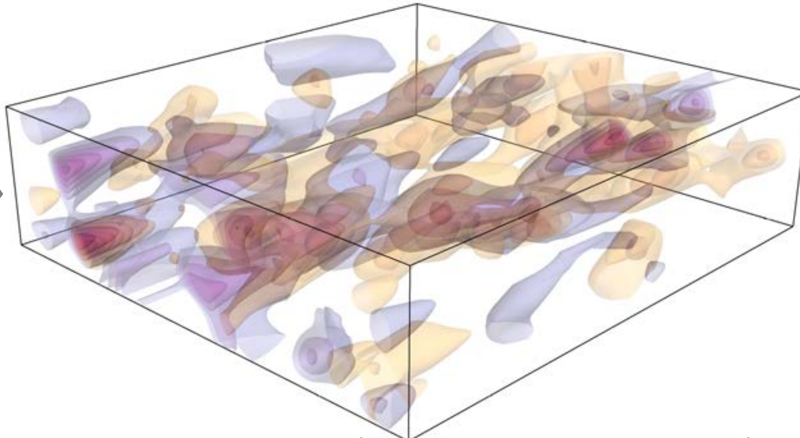
z~1000

$$\Theta_\gamma(\mathbf{k}) \equiv \frac{\delta T_\gamma}{\bar{T}_\gamma} = T_\gamma(k)\zeta(\mathbf{k})$$

$$\delta_\nu(\mathbf{k}) = T_\nu(k)\zeta(\mathbf{k})$$

$$\delta_{\rm cdm}(\mathbf{k}) = T_{\rm cdm}(k)\zeta(\mathbf{k})$$

$$\delta_{\rm b}(\mathbf{k}) = T_{\rm b}(k)\zeta(\mathbf{k})$$



In late universe (matter dominated) on large scales (>100Mpc)

$$\rho_{\rm m} \gg \rho_i$$

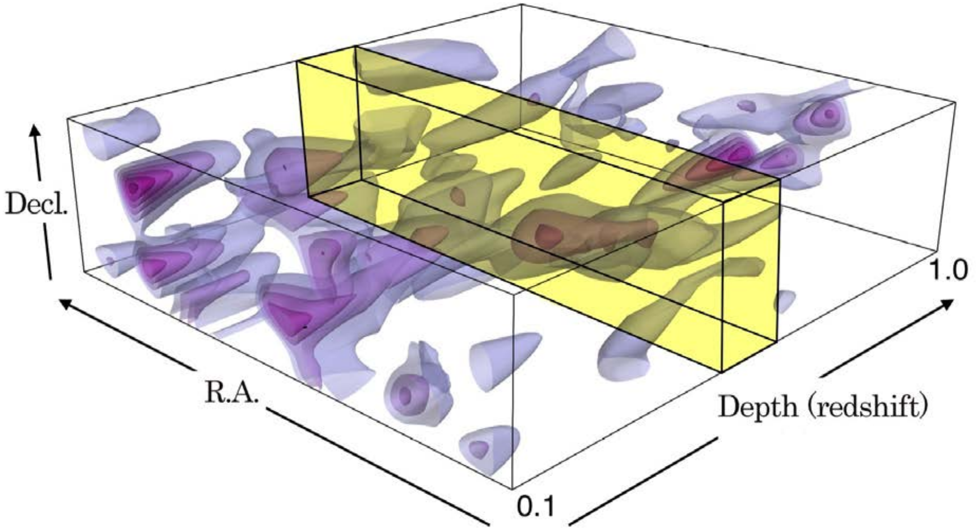
$$\delta_{\rm m}(\mathbf{k}) = T_{\rm m}(k)\zeta(\mathbf{k})$$

$$\delta_{\rm galaxy}(\mathbf{k}) = b_{\rm galaxy}\delta_{\rm m}(\mathbf{k})$$

$$\delta_{\rm BH}(\mathbf{k}) = b_{\rm BH}\delta_{\rm m}(\mathbf{k}), \dots$$

Test of single inflation with galaxy surveys

- If imaging (lensing) and spectroscopic (3D map) surveys for the same solid region are available …



✓ Cross-correlation between shapes of background gals (imaging) and positions of foreground gals (spec-z) (also CMB lensing – spec-z gals)

$$\langle\gamma(\mathbf{k})\delta_{\rm g}(\mathbf{k};z_{\rm g})\rangle \to P_{\rm gm}(k;z_{\rm g}) \simeq b_{\rm g}P_{\rm mm}(k;z_{\rm g})$$

✓ Auto-correlation of spec-z galaxies

$$\langle\delta_{\rm g}(\mathbf{k};z_{\rm g})\delta_{\rm g}(\mathbf{k};z_{\rm g})\rangle \to P_{\rm gg}(k;z_{\rm g}) \simeq b_{\rm g}^2P_{\rm mm}(k;z_{\rm g})$$

✓ "bias" function on large scales, not yet has been explored by data

✓ If a single inflation scenario is correct, it predicts, on large scales (>100Mpc)

$$b_{\rm g}(k) = \frac{\langle\delta_{\rm g}(\mathbf{k})\delta_{\rm g}(\mathbf{k})\rangle}{\langle\gamma(\mathbf{k})\delta_{\rm g}(\mathbf{k})\rangle} = \frac{P_{\rm gg}(k)}{P_{\rm gm}(k)} \propto \underline{k^0}$$

✓ This scale-independent bias violates *for* the primordial non-Gaussian perturbations (or more generally also for a case of modified gravity or DE clustering) – a smoking-gun observational evidence

$$\delta_{\rm g}(\mathbf{k}) = b_{\rm g}\delta_{\rm m}(\mathbf{k}) + b_\phi\zeta(\mathbf{k})^2$$

Intrinsic alignments of galaxy shapes

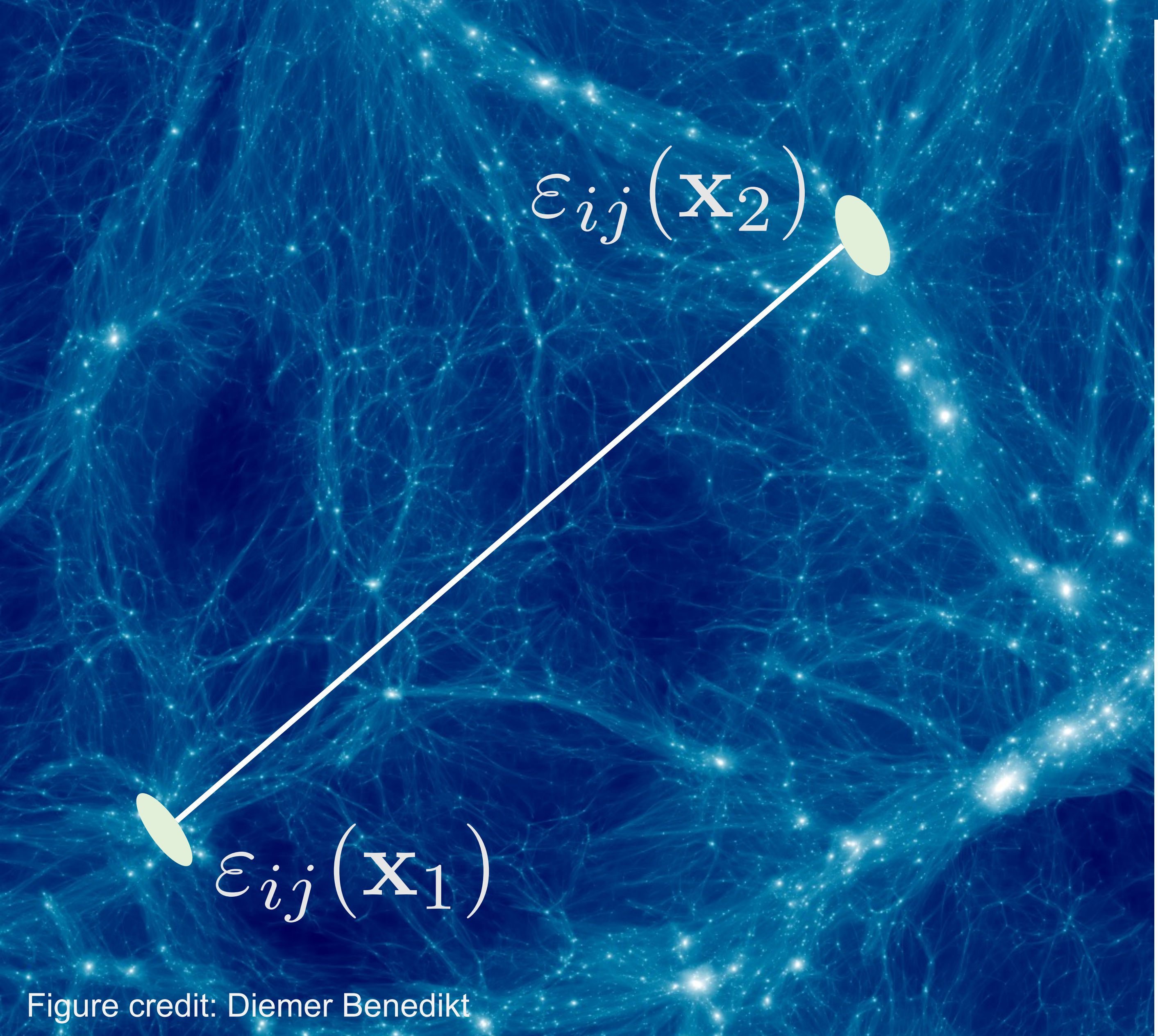


Figure credit: Diemer Benedikt

- ✓ Galaxy shapes (e.g., ellipticities and orientation) originate from the primordial perturbation field
- ✓ Galaxy shape is a vector-like quantity (both positive and negative)
- ✓ On large scales (≫galaxy physis scales), galaxy shapes are related to the tidal field of matter, for ΛCDM model

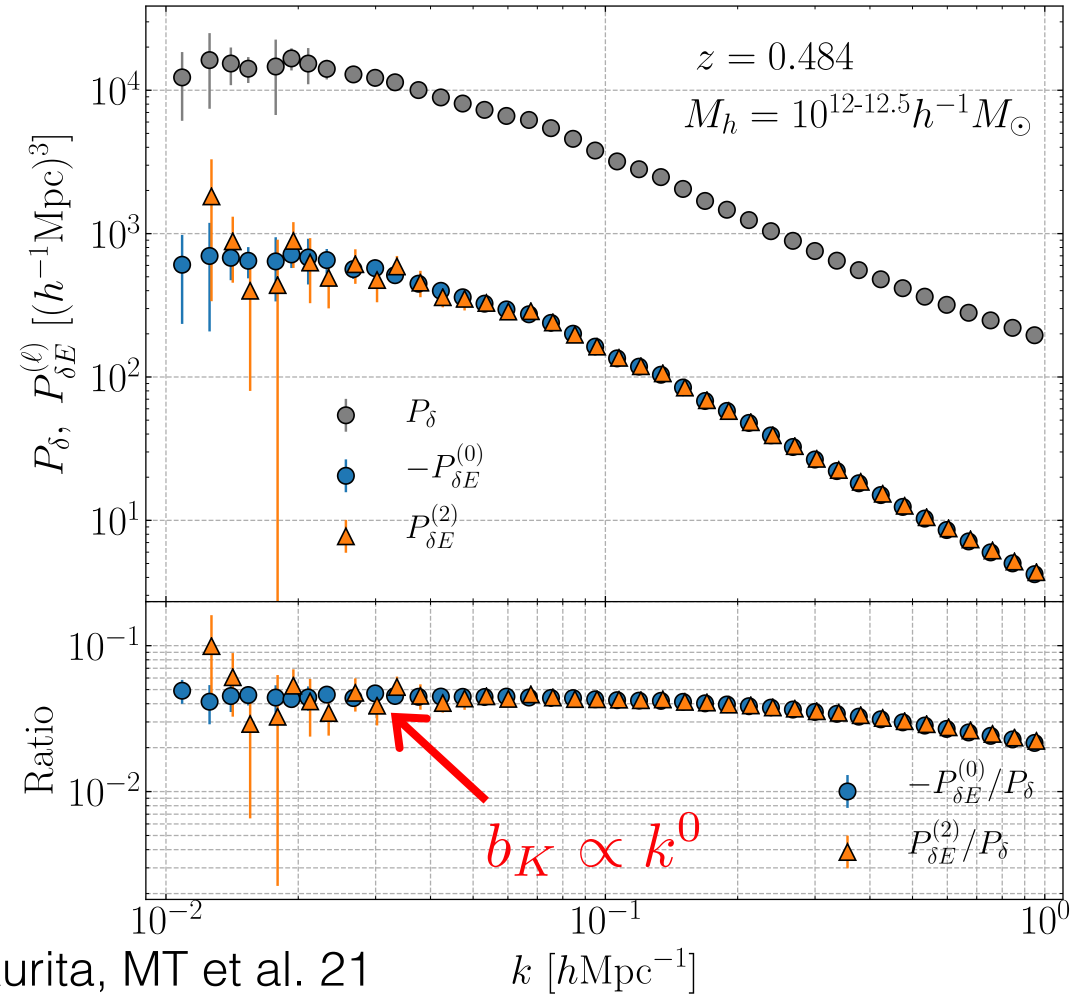
$$\varepsilon_{ij}(\mathbf{x}) = b_K \nabla^{-2} \left(\partial_i \partial_j - \frac{\delta^K_{ij}}{3} \nabla^2 \right) \delta_{\mathrm{m}}(\mathbf{x})$$

- ✓ Hence the single-field inflation predicts

$$b_K \propto k^0$$

Intrinsic alignments as a test of single-field inflation

- Cross-correlation of galaxy shapes (imaging) and positions of galaxies (spectroscopy), in the *same* large-scale structure (not lensing)
- HSC+PFS can measure the intrinsic alignments up to z~2.4 (Shi et al. 21)



Kurita, MT et al. 21

- ✓ Used ΛCDM simulations
- ✓ Used "halo" shapes as a proxy of galaxy shapes
- ✓ Confirmed b_k ~ k^0 (scale independent)
- ✓ Different behaviors from number clustering
  - ✓ Very dense region (many mergers): the overdensity boosts, while halo shapes get randomized
- ✓ Confirmed by hydrosimulations
- ✓ Detected from data, SDSS red galaxies
- ✓ Galaxy spin? (e.g., Iye+21), not predicted on large scales by ΛCDM model

Credit: NCSA, NASA, B. Robertson, L. Hernquist

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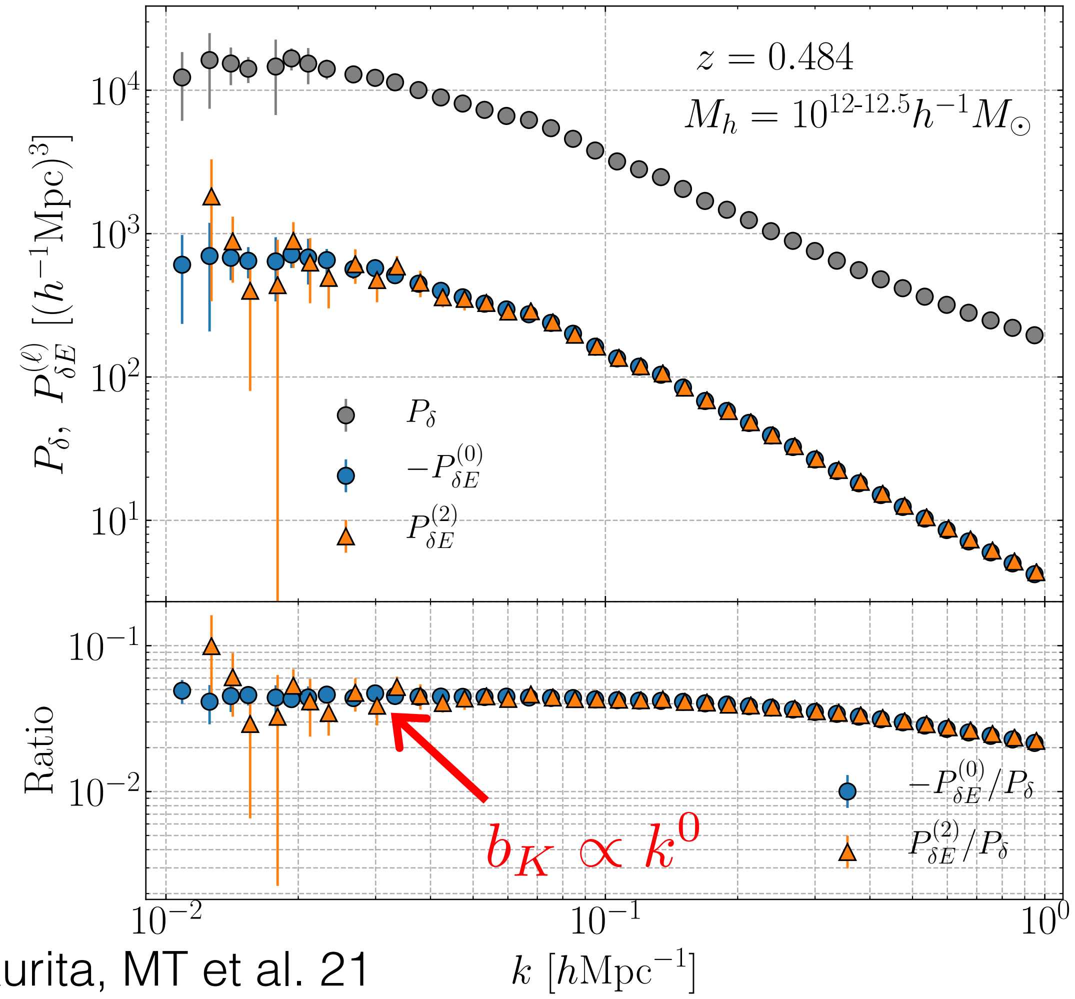
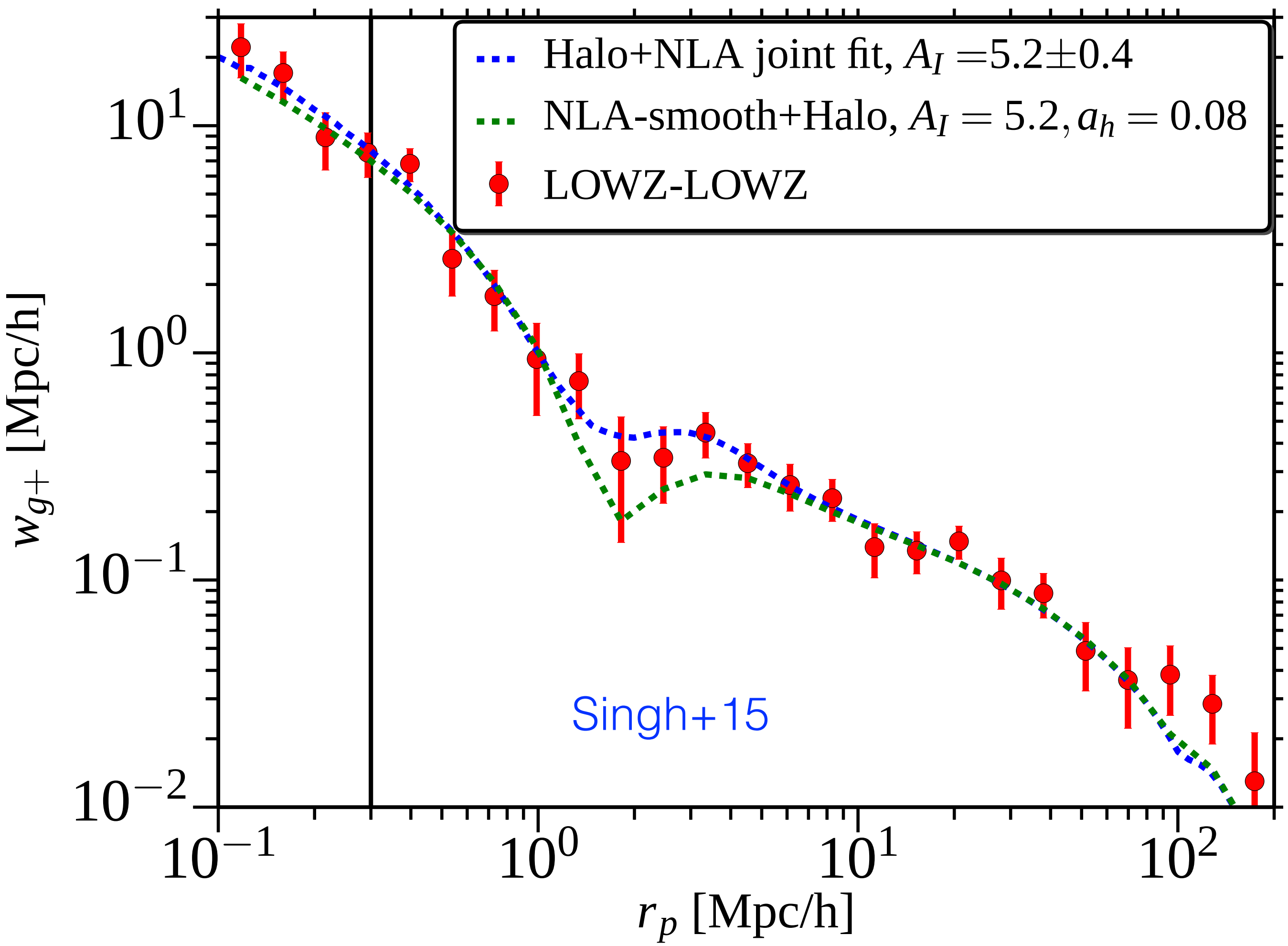


Kurita, MT et al. 21

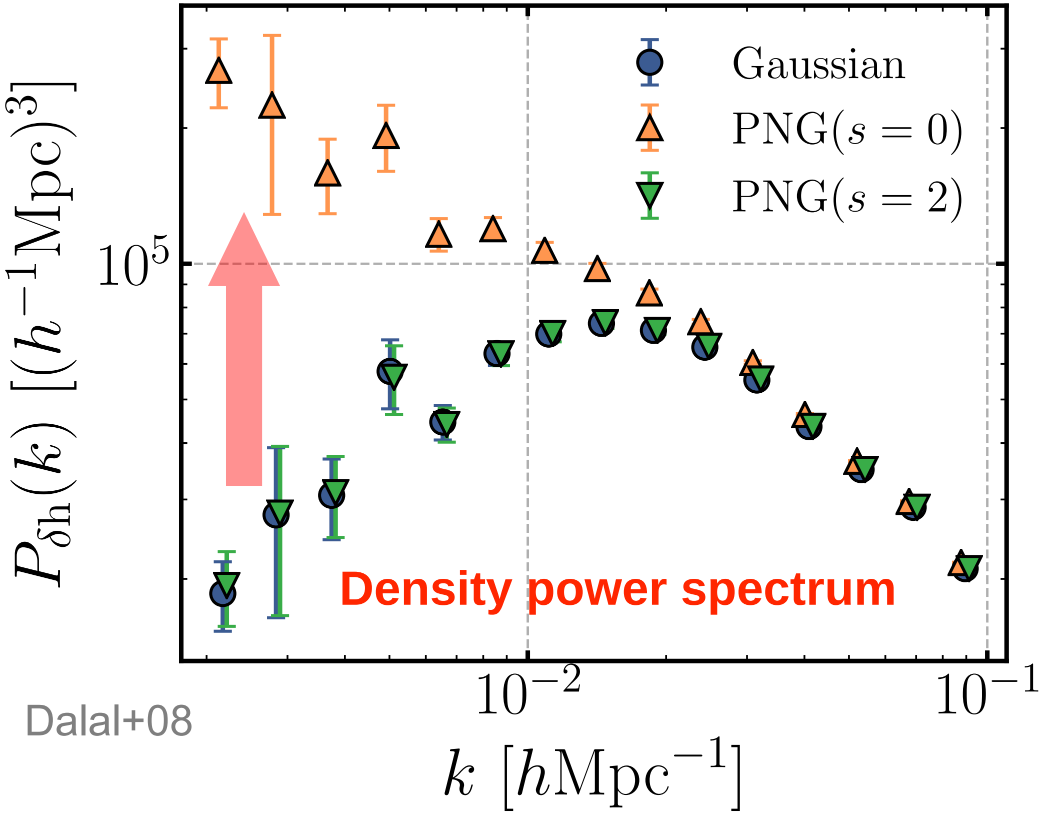


Intrinsic alignments as a test of single-field inflation

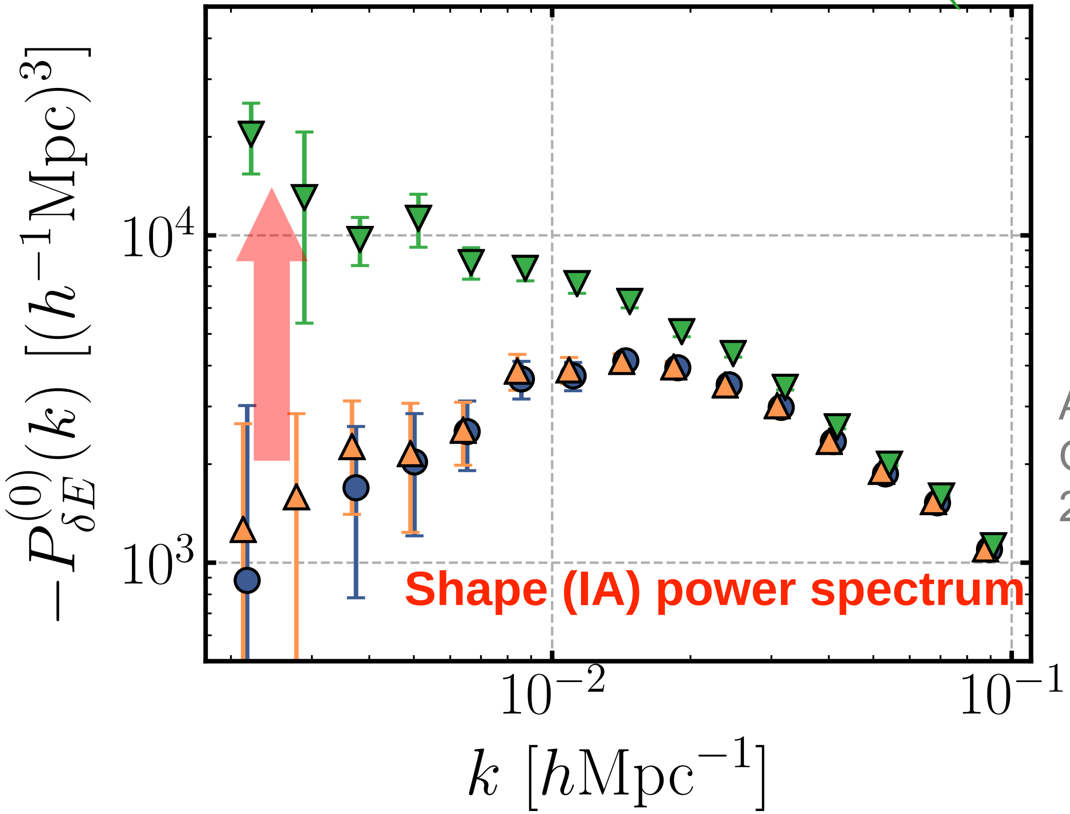
- Tests of different types of primordial non-Gaussianity (ΛCDM predicts f_NL<1)

$$\zeta^{\rm NG}(\mathbf{x}) = \zeta(\mathbf{x}) + f_{\rm NL}\left[\zeta(\mathbf{x})^2 - \langle\zeta^2\rangle\right]$$

$$\zeta^{\rm NG}(\mathbf{x}) = \zeta(\mathbf{x}) + f_{\rm NL}^{s=2}\left[(\psi_{ij})^2 - \langle(\psi_{ij})^2\rangle\right] \qquad \psi_{ij}(\mathbf{x}) \equiv \nabla^{-2}\left(\partial_i\partial_j - \frac{\delta^K_{ij}}{3}\nabla^2\zeta\right)$$



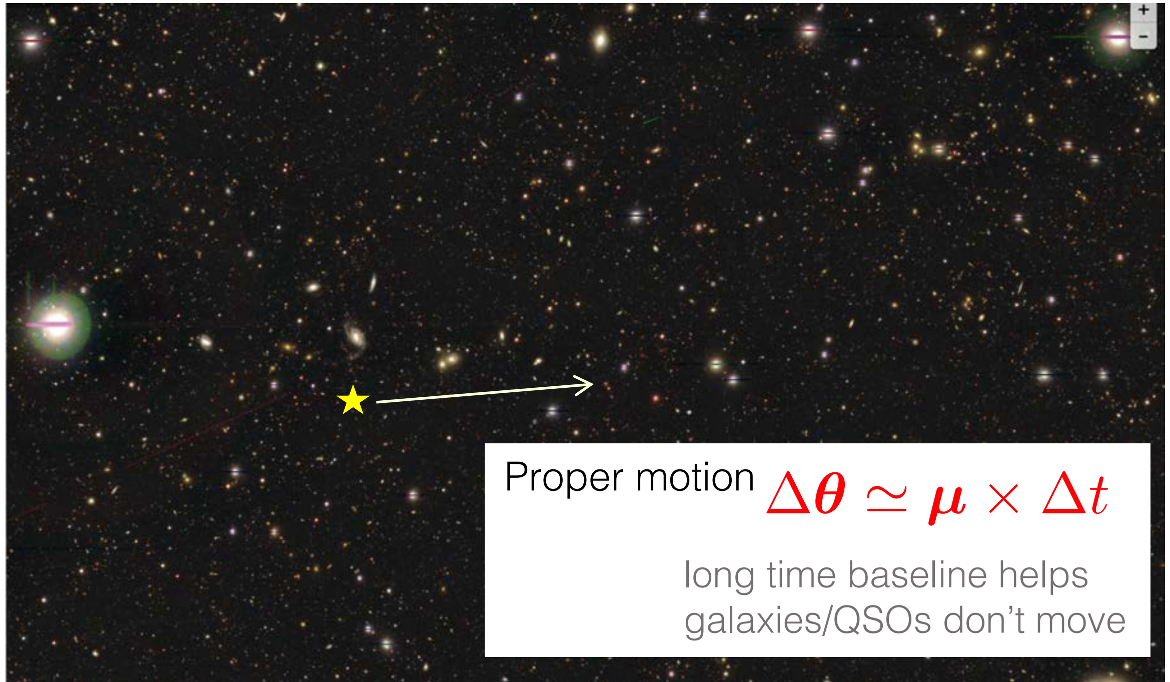
Dalal+08

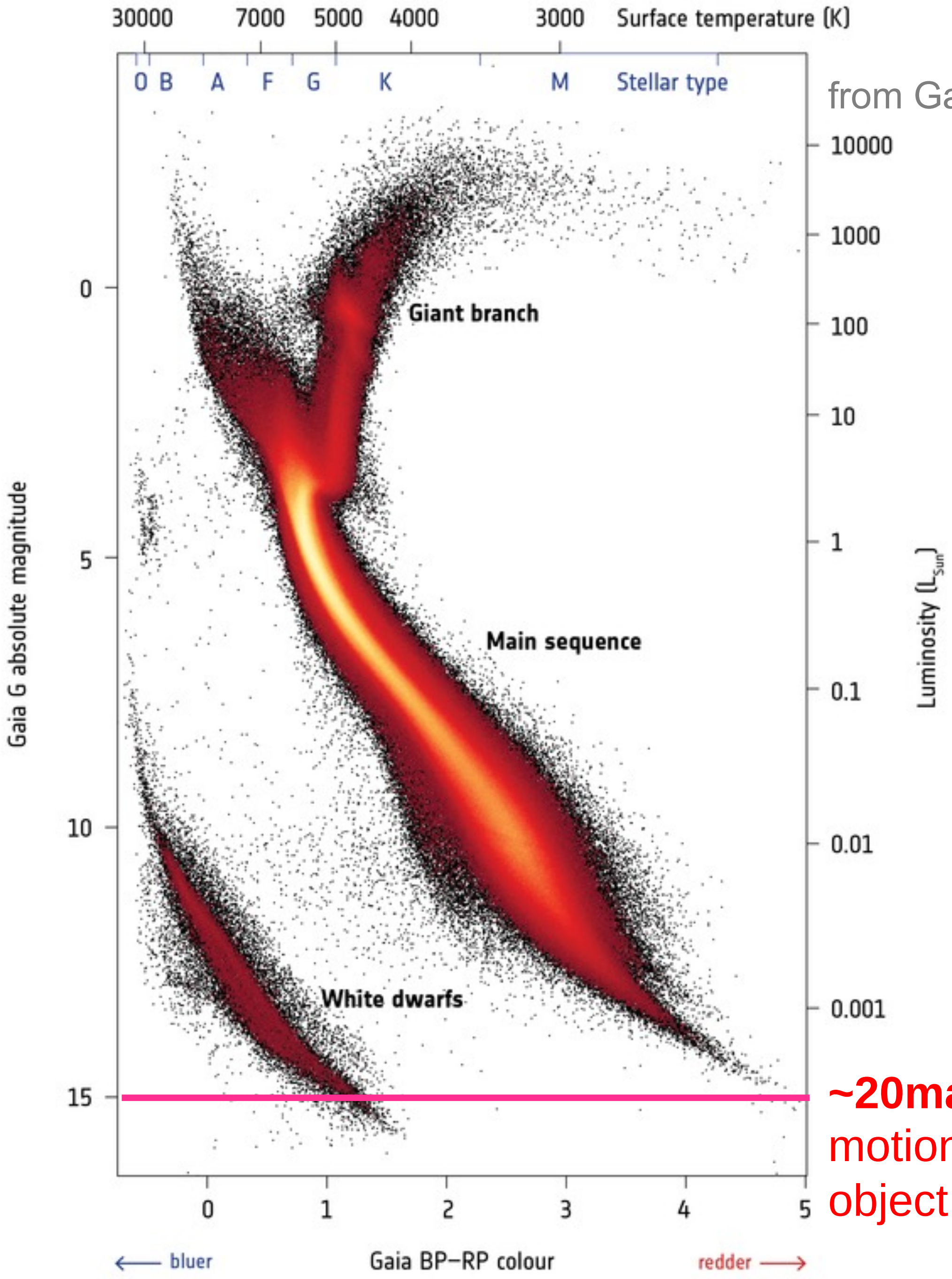


Akitsu et al. PRD 21
Okumura & Taruya 21a,b

Legacy value of "wide-area" surveys

- Northern-hemisphere has been well studied: SDSS (~2005) – PS (~2013) – HSC (~2014-21) – Euclid (2022-) – VRO LSST (2024-) ⇒ proper motion measurements
    - For southern hemisphere, VRO LSST needs 10yrs from 2024
    - Moving objects, variable stars/galaxies, …
- For example, Gaia, ~19mag, over 40,000 sq. deg., HSC, ~24mag over ~1,000 deg ⇒ HSC can detect more distant objects, by a factor of 100, than does Gaia
    - HSC Survey Volume (for halo, faint stars): $V_{\rm HSC} \sim 250 V_{\rm Gaia}$





from Gaia collaboration

cadence (time-domain) + variabilities
+ "proper motions", for faint stars/objects

~20mag @ 100pc, **~25mag** @1kpc (~24mag for HSC proper motion measurements) (~19mag or so for Gaia PM). Very red object (BD) can be found?

Things I can't cover due to time limitation/my capability

- Cosmic curvature: CMB, galaxy surveys
- Direct measurement of cosmic acceleration: TMT, B-DECIGO, …
- Cosmic birefringence as a probe of very light axion: CMB, optical/IR, …
- Near-field cosmology: Subaru, TMT
- Cluster cosmology: Subaru, XRISM, Athena, …
- Time variations in the physical constant (e.g. α): TMT
- Intensity mapping via cross-correlation methods: e.g., thermal history of the universe (Chiang, Makiya, Komatsu): CMB, galaxy surveys
- Cross-correlation between galaxy surveys and gamma-ray map to search for dark matter signals: CTA, galaxy surveys, …
- H0 tension, strong lensing: galaxy surveys: VRO LSST
- Pulsar timing as a probe of stochastic gravitational background: SKA, ngVLA
- GRB standard candles: HiZ-GUNDAM
- AI/ML applications to big data; data science, NAOJ

Summary

- This (not next) decade is important for cosmology: Subaru HSC/PFS, DESI, Euclid (2022), VRO LSST (2024), Roman (2026), CMB, +time domain astronomy (Ioka san's talk)
- Subaru HSC (perhaps, CMOS upgrade) and PFS are unique even in 2030era
  - Maunakea Spectroscopic Explore is not recommended in Astro2020
  - Upgrade of PFS, in 2030: high-resolution mode, IFU, … for "Subaru3"
  - The community has gained expertise/experience in precision cosmology, from HSC-SSP
- Dark energy: A stringent test of ΛCDM model
  - Falsify or verify S8 or sigma8 tension, between late universe and Planck-inferred cosmology
- Dark matter
  - Neutrino mass: the main target of PFS-SSP Cosmology
  - PBHs: microlensing surveys by HSC, LSST, JASMINE, ULTIMATE
- The physics in the early universe
  - Primordial non-Gaussianity
  - Explore PNG signals in shapes and positions of galaxies up to z~2.4, with HSC/PFS
- Wide-area surveys in other wavelengths (e.g. SKA) can be used to explore the above science