Exploring the Chemodynamical Evolution of the Milky Way and the Local Group through Wide and Deep Stellar Surveys

恒星系の深・広視野探査で拓く銀河系・局所銀河群の化学動力学進化

Implementation period: FY 2025-2033

Miho N. Ishigaki（Subaru Telescope/NAOJ) on behalf of the research collaborators

2024年度 国立天文台の将来シンポジウム 〜国立天文台のサイエンスロードマップ〜

December 3-6, 2024 (NAOJ, Mitaka Campus)

Preliminary

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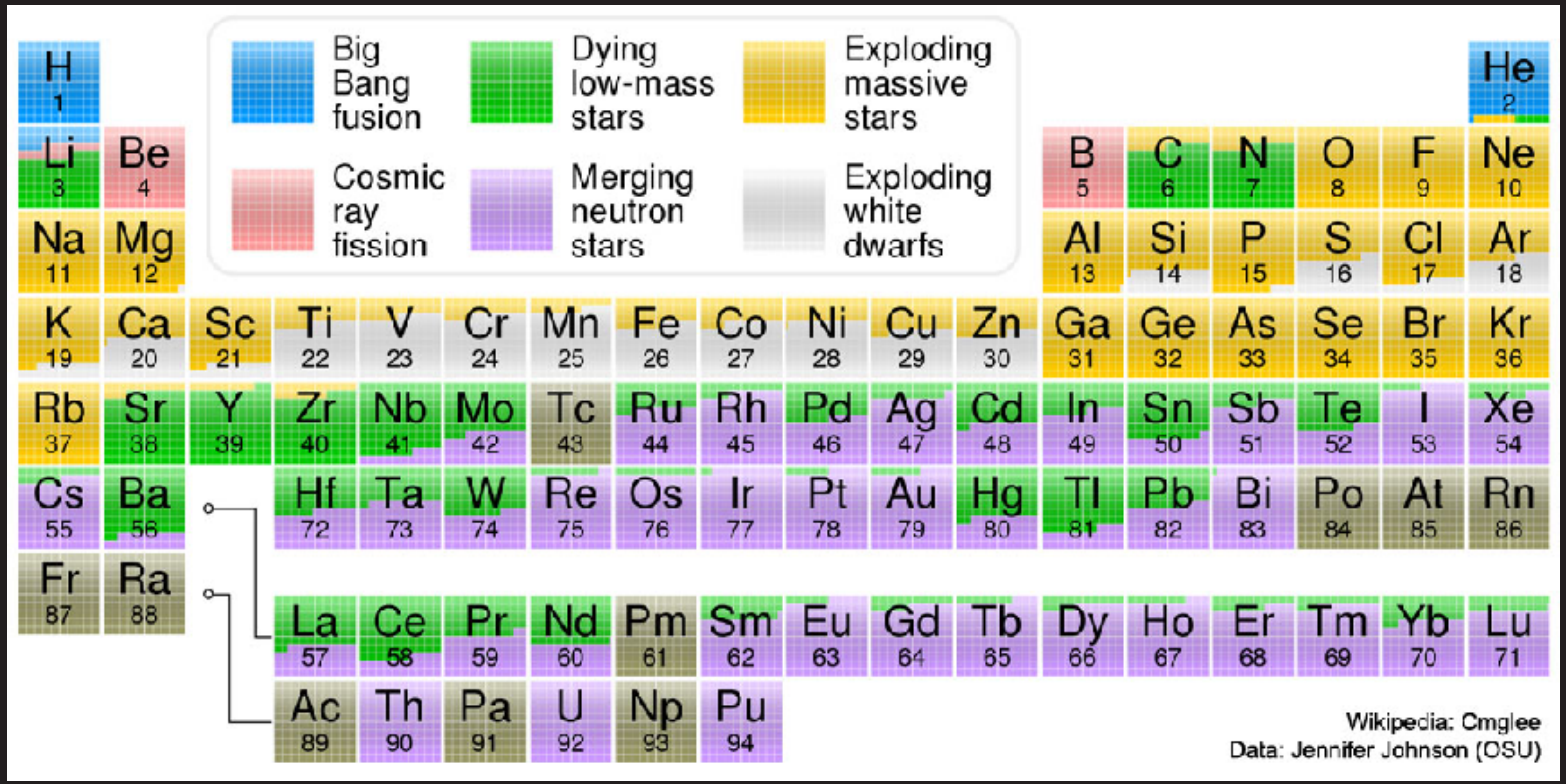
- The proposal is based on inputs and discussions with many other researchers in the community
- Many on-going projects are lead by graduate students and young carrier researchers

Scientific question: origins of matter in the universe

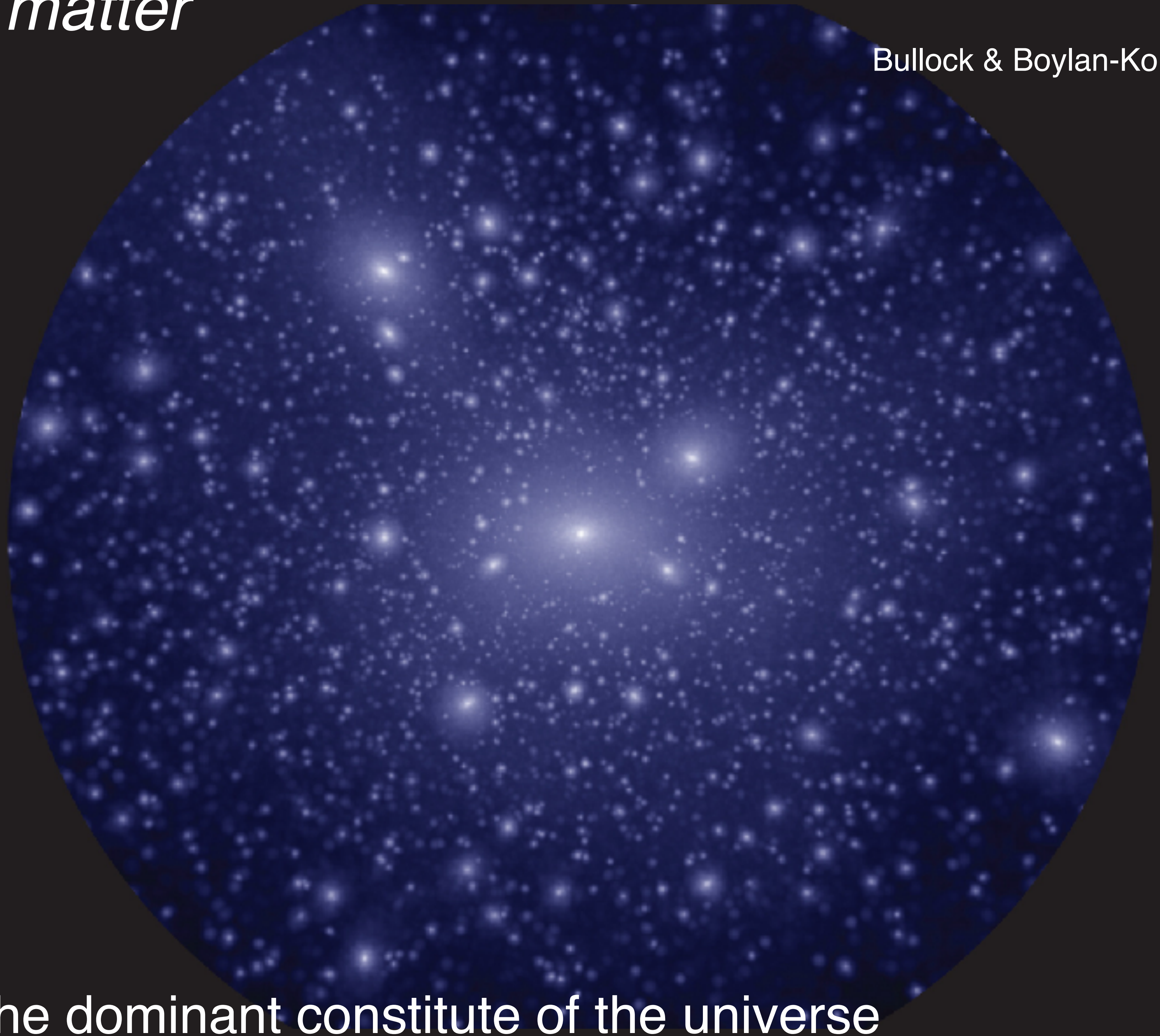
Baryonic matter (chemical elements)



- The ingredients of planets and life, the origin of ourselves
- The tracer of extreme astrophysical phenomena: stellar interior, supernovae, degenerate matter ➡ *Impossible to directory observe*
- Products of various stellar evolution channels: binary, star clusters, black holes, neutron stars, first super-massive stars ➡ *Specific chemical patterns in stars and high~z galaxies*

Ouchi-san's talk

Dark matter



Bullock & Boylan-Kolchin 2017

- The dominant constitute of the universe
- Unknown particle nature
- Played a fundamental role in galaxy formation
- The current dynamical properties of gas and stars in galaxies

Kohri-san's talk

Scientific objectives

This proposal:

The chemodynamical evolution of our Galaxy as a powerful probe of origins of matter

Using stellar observations in our Galaxy as a laboratory: Galactic Archaeology

Objectives:

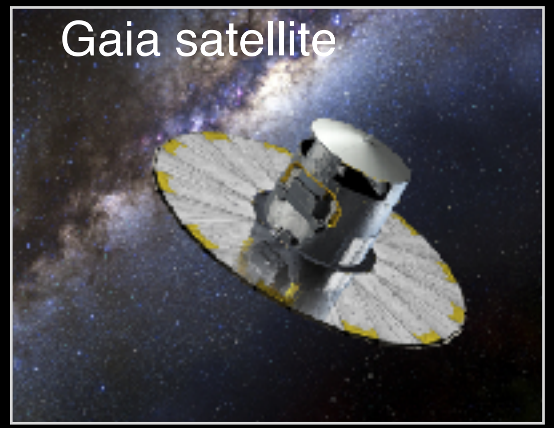
Conduct wide and deep photometric, spectroscopic, and astrometric surveys of stellar populations to obtain 6D phase-space and chemical abundance distributions in all Galactic environments

① Establish the chemodynamical evolution of stellar populations that have various star formation histories, including the bulge, disk system, stellar halo, globular star clusters, dwarf satellites, and the surrounding Local Group galaxies

➡ Chemical evolution of different chemical elements, astrophysical nucleosynthesis sites

② Precisely estimate the local density and the density profiles of dark matter in the Galaxy and its dwarf satellites using stars as a dynamical tracer

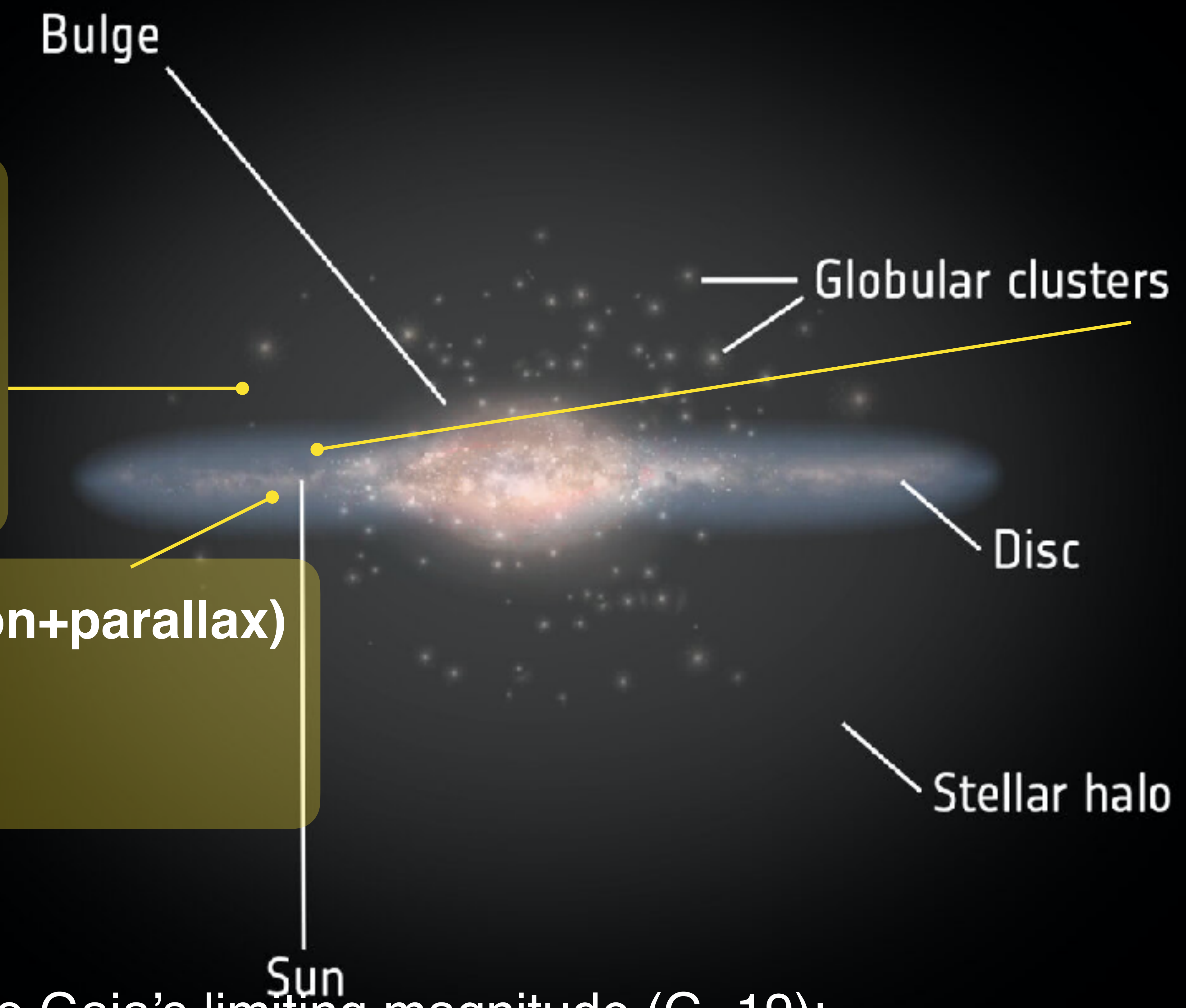
➡ Particle nature of dark matter



Major advancements in the past decade


Subaru/HSC

Wide-field imaging and astrometric surveys of stars near covering the local disk and halo



Stellar spatial distributions

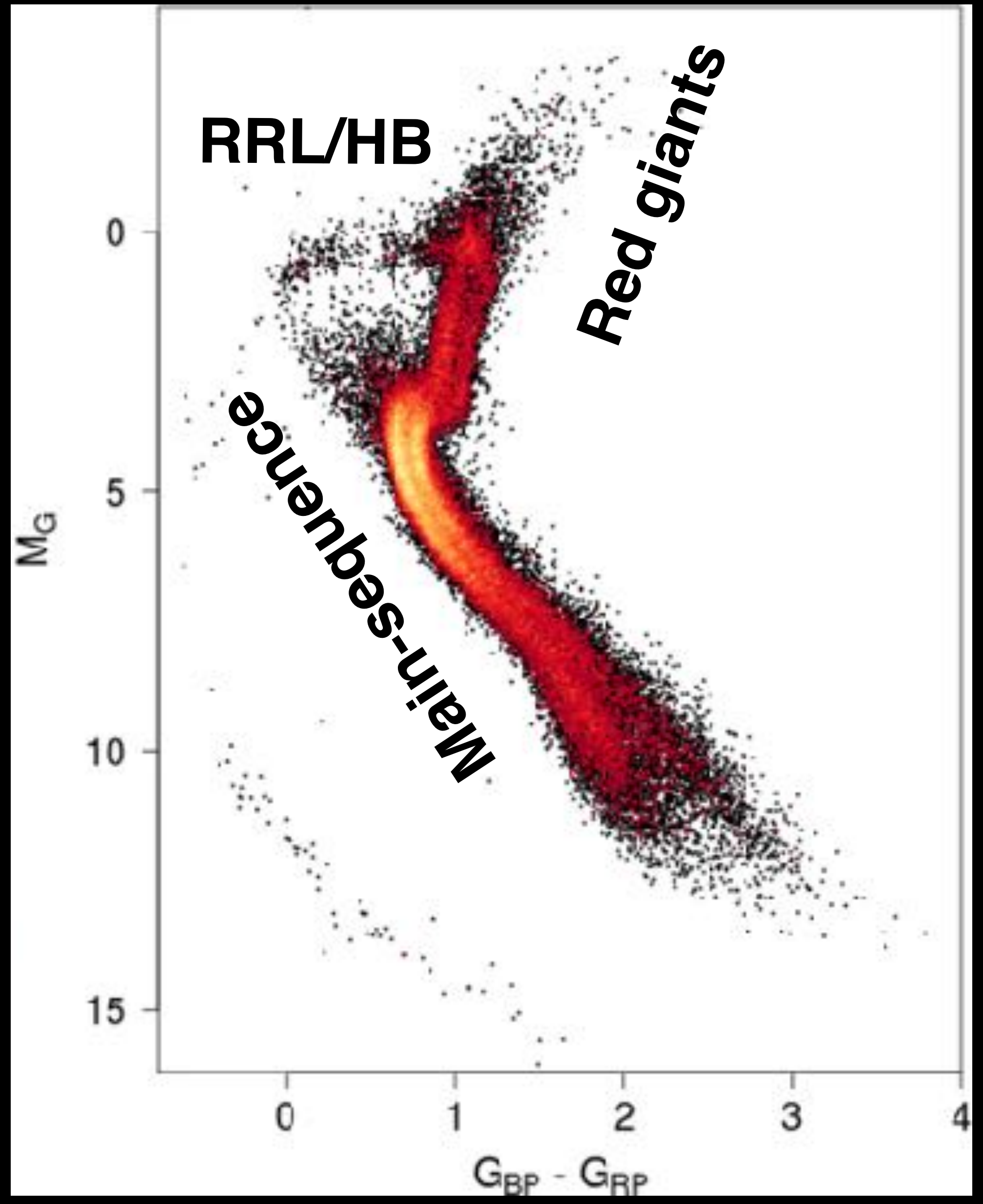
- Discoveries of ultra-faint dwarf satellites
- Spatially-coherent stellar streams
- Stellar density profiles using various tracers

Phase-space distribution (proper motion+parallax)

- Phase-space spiral in the Galactic disk
- Merger history of the Galactic halo

Chemical abundances and stellar ages

- Stellar ages from asteroseismology with 10-20% precision
- Discoveries of the most metal-poor and chemically peculiar stars



What is missing?

① Wide-field spectroscopic data down to Gaia's limiting magnitude (G~19):

Lack of precise kinematics to constrain dark matter models, lack of detailed elemental abundances to constrain astrophysical sites of nucleosynthesis ➡ Medium-resolution spectroscopy with DESI, WEAVE, 4MOST, etc..

② Restricted to the solar neighborhood ($d_{\odot} < 10$ kpc) or with luminous but sparse tracers ➡ Vera Rubin Observatory (LSST), **HSC(+NB)**, **PFS**, etc.

Development of theoretical studies

Fundamental understanding stellar and supernova physics

- Evolution of massive stars, including its rotation
- Physics of supernova explosions
- Evolution of binary star systems, gravitational wave sources

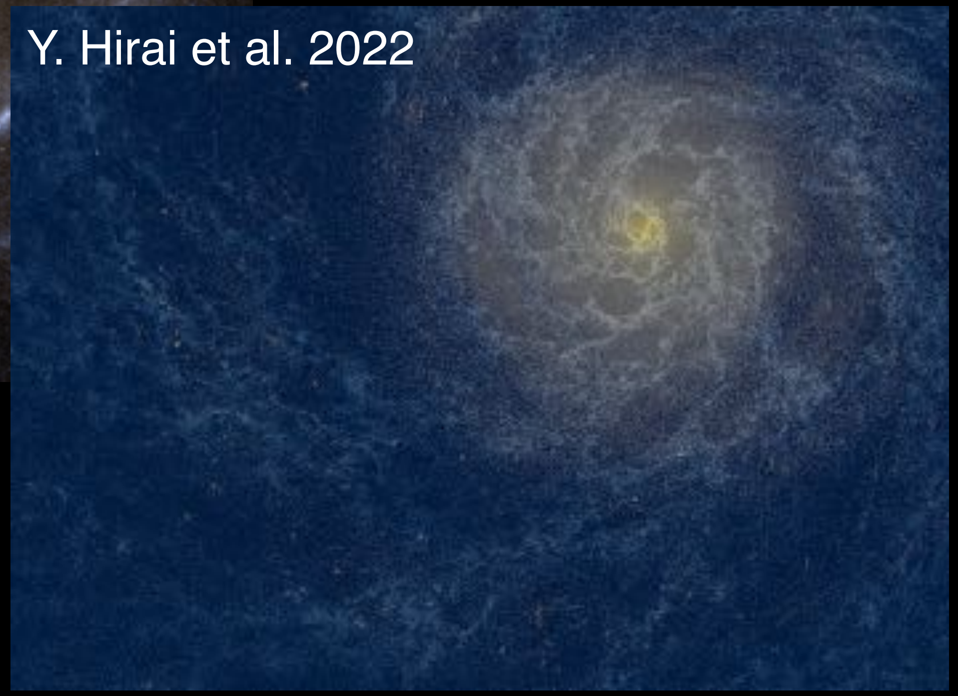
Chemo-dynamical properties of our Galaxy and the local group galaxies

- Density profiles of dark matter in the Galaxy and LG galaxies
- The formation of the major components of our Galaxy
- Chemical evolution of specific elements (e.g., α-elements, s/r-process elements, etc) to explain results from high-resolution spectroscopic surveys (e.g., GALAH, R~28K, up to 30 different elements)

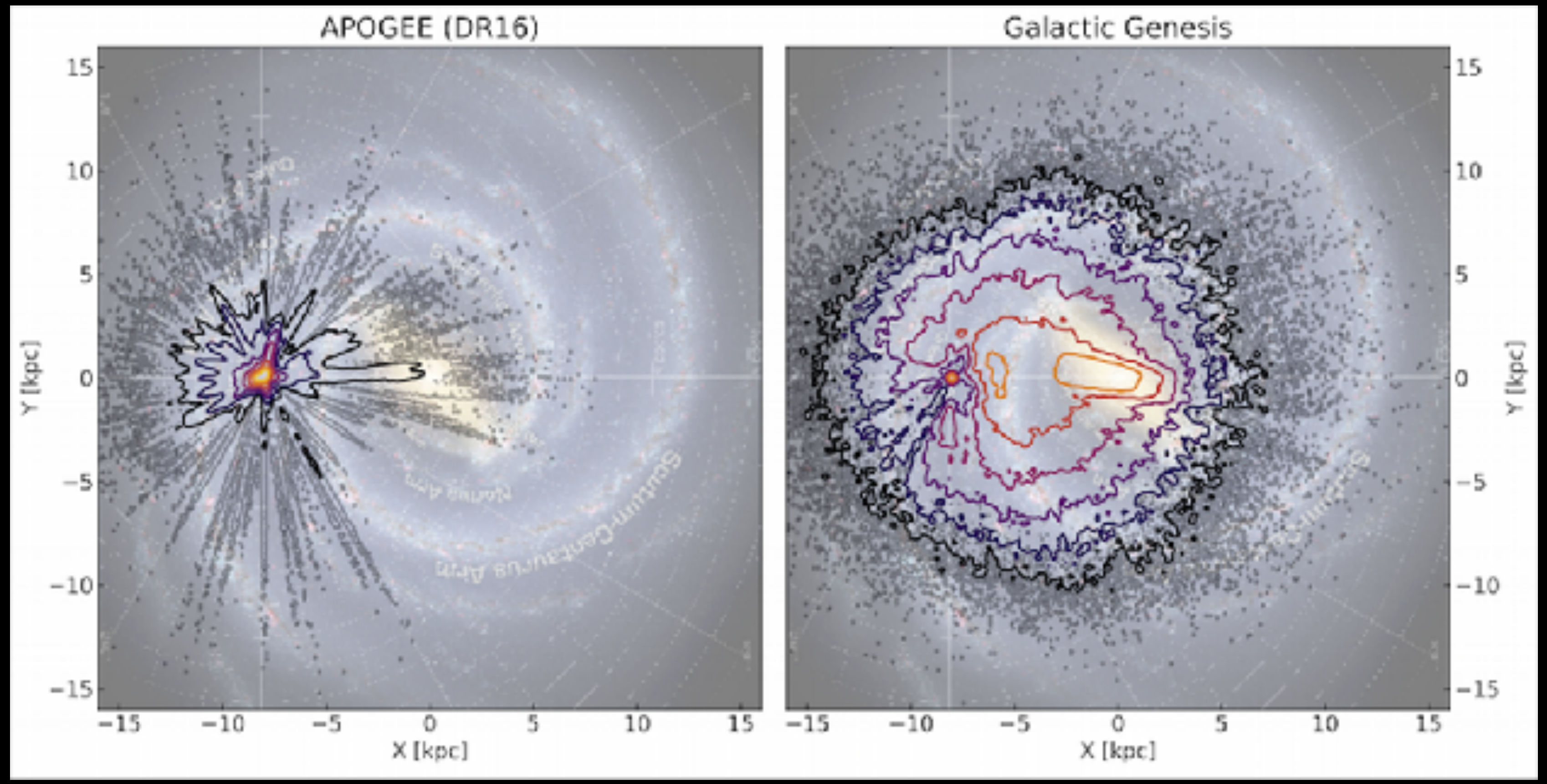
Cosmological simulations

- Properties of the first stars
- Missing-satellite problems
- Galaxy mergers

J. Baba, et al. 2022



Ongoing HR spectroscopic survey of the disk, "Milky Way Mapper"/SDSS-V
https://www.sdss.org/dr18/mwm/about/



What is missing?

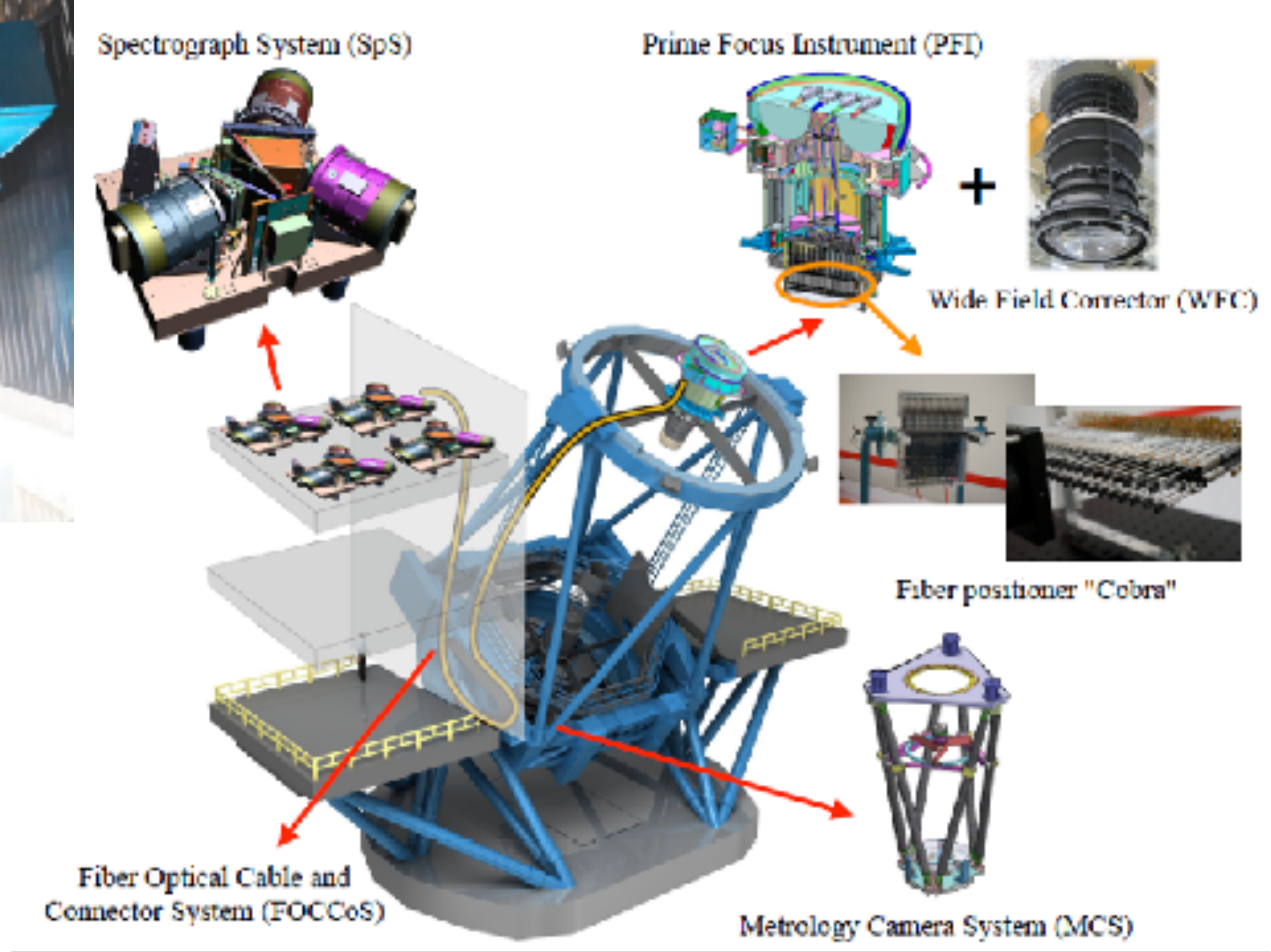
① Statistical samples of multi-element stellar chemical abundances covering a wider range of Galactic environments ➡ SDSS-V (R~22K, up to 18 elements)

② Understanding of input physics, e.g., mechanisms of supernovae, element synthesis, etc…

This proposal: by 2033

Observations and instrumentation

HSC



PFS-LR/MR
+ HR

Threshold science

- Technical assessment, development, and construction of "**PFS high-resolution (R~20K) mode**"
- Combining HSC, PFS-LR/MR and Roman data to obtain stellar spatial distribution, 3D velocities, and chemical abundances ([Fe/H], [α/Fe] ratios) in the outer Milky Way, globular clusters, dwarf satellites, M31/33, and Local Group galaxies
- Comparisons with cosmological and chemodynamical simulations of the Milky Way-like galaxies

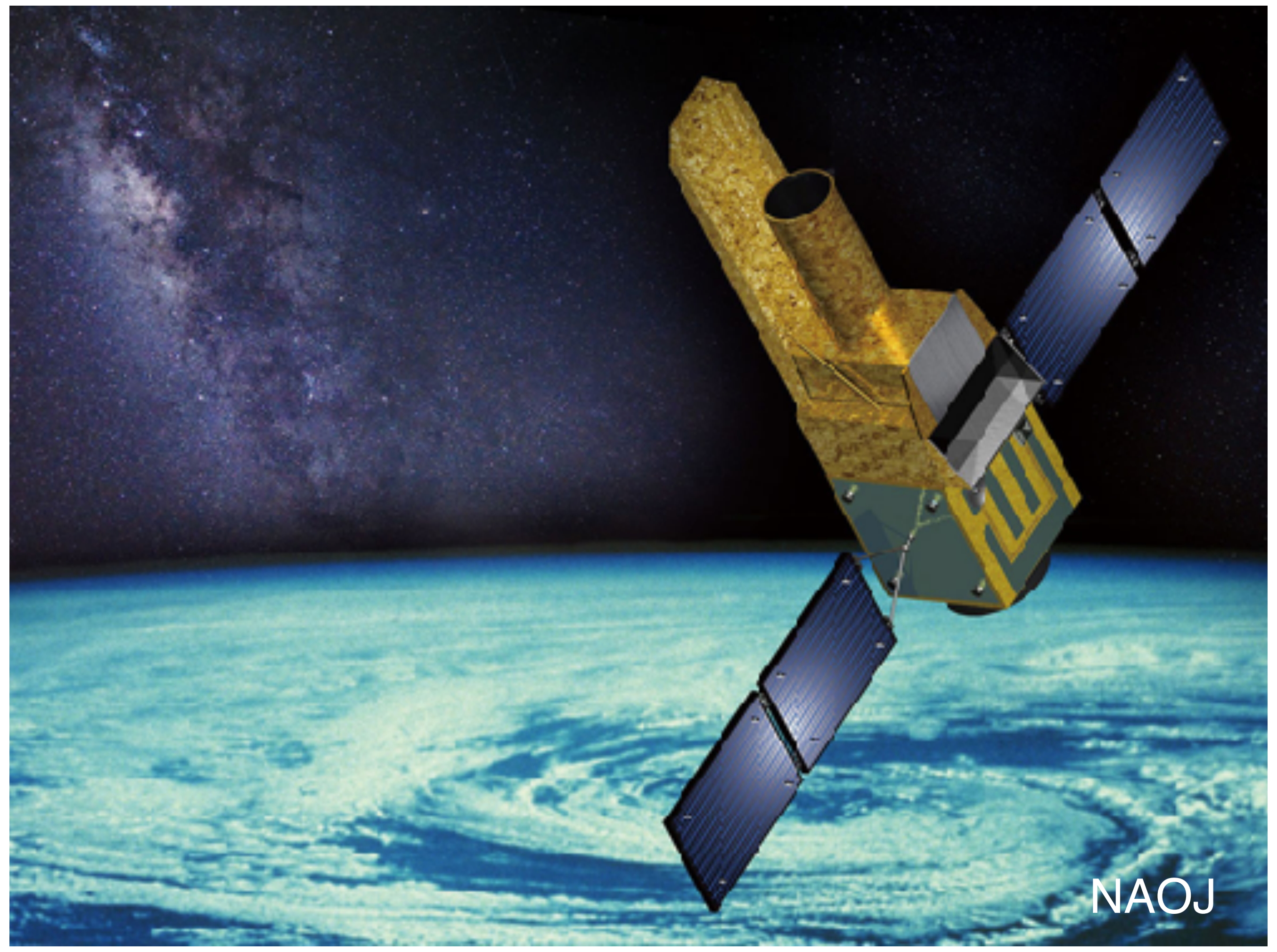
Theoretical interpretation

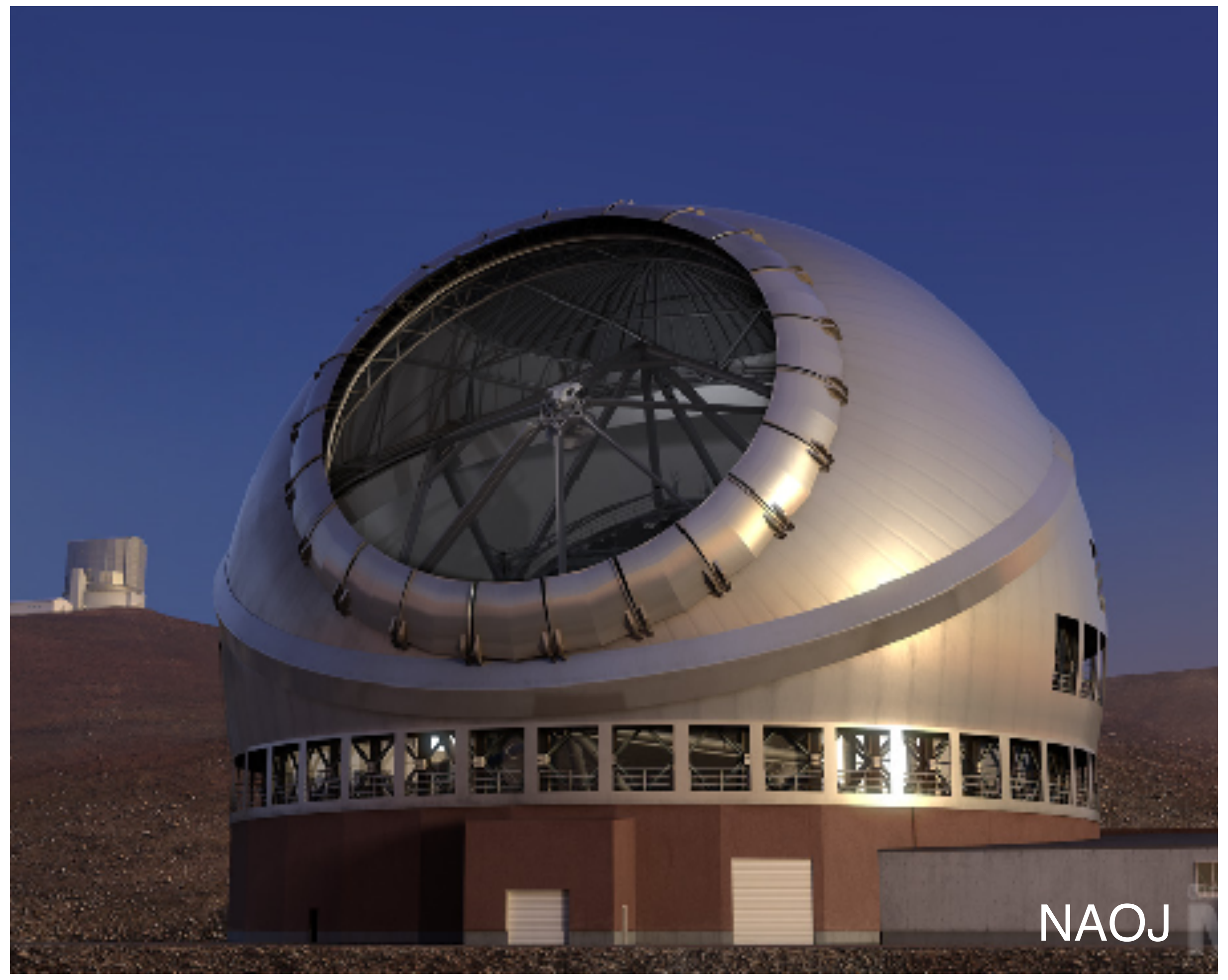
- Development of the models of dark matter density profiles to interpret 3D velocity data of dwarf satellites
- Development of theoretical models of stellar evolution, supernovae, neutron-star mergers to predict elemental yields
- Chemodynamical evolution of the Galaxy
  - Include various nucleosynthesis yields (supernovae, ABG stars, neutron-star mergers, etc.)
  - Chemodynamics in various Galactic environments including dwarf galaxies, globular star clusters, the Galactic center

Synergy with multi-wavelength observations

- Detection of metal lines in highest redshift galaxies with ALMA/JWST
- Metal abundances in supernova remnants from XRISM
- Indirect DM detection through γ-ray observations (e.g., Cherenkov Telescope Array)
- Multi-messenger observations (Tominaga-san's talk)

This proposal: Beyond 2033



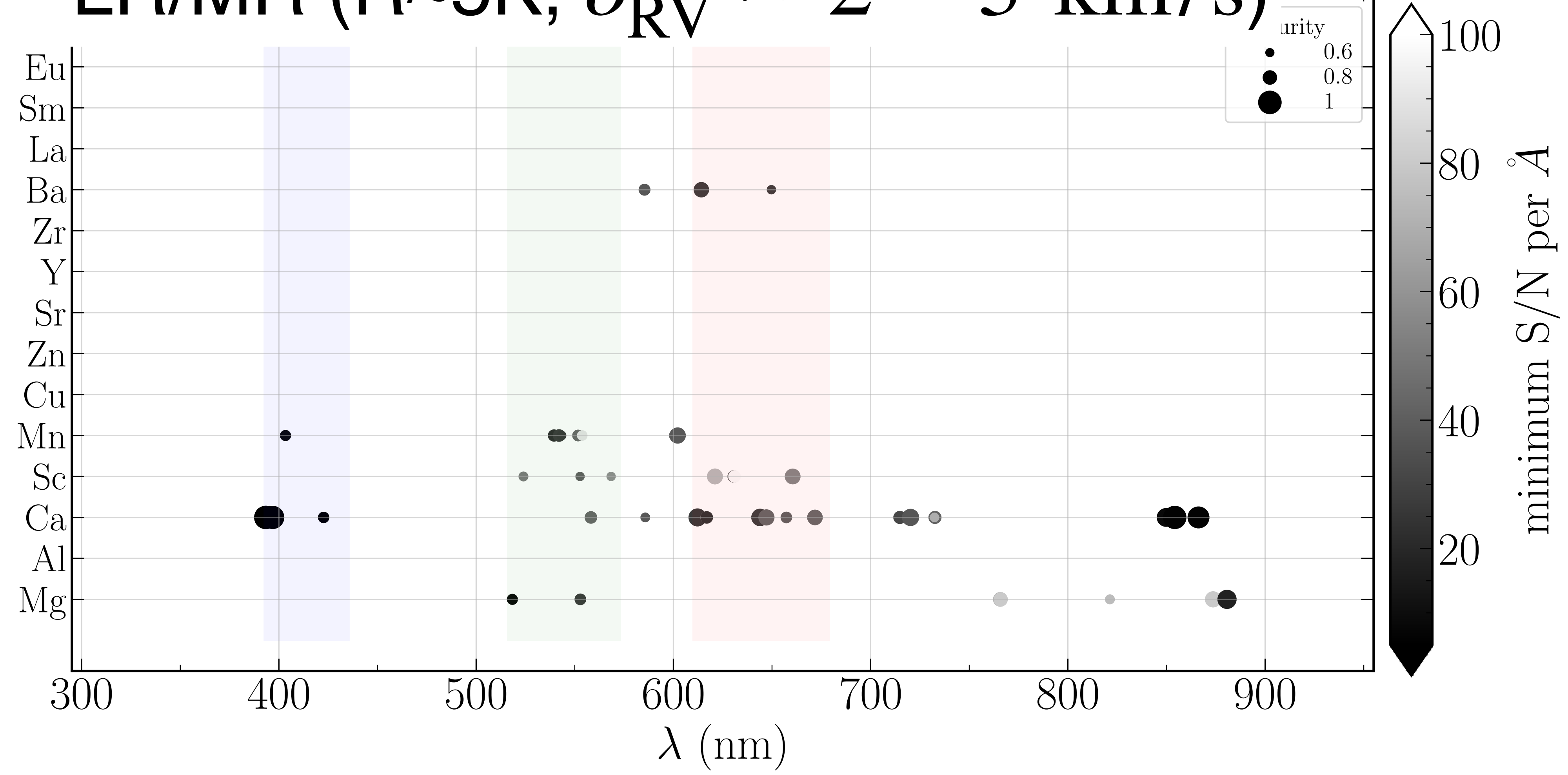


- Full operation of PFS-HR to precisely measure line-of-sight velocity and detailed elemental abundance down to $G \sim 19$
  ➡ Accurate 6D phase space coordinates (ra, dec, parallax, proper motion, radial velocity) and multi-element abundances
- Stable operation and upgrade of supercomputers
- Utilizing time-domain/cadence multi-object spectroscopy: detection of BHs, globular cluster dynamics, stellar activities
- JASMINE + ULTIMATE + PFS: chemodynamical analysis of the Galactic center and the bulge
- TMT: Follow-up multi-object spectroscopy of the PFS-LR/MR catalog

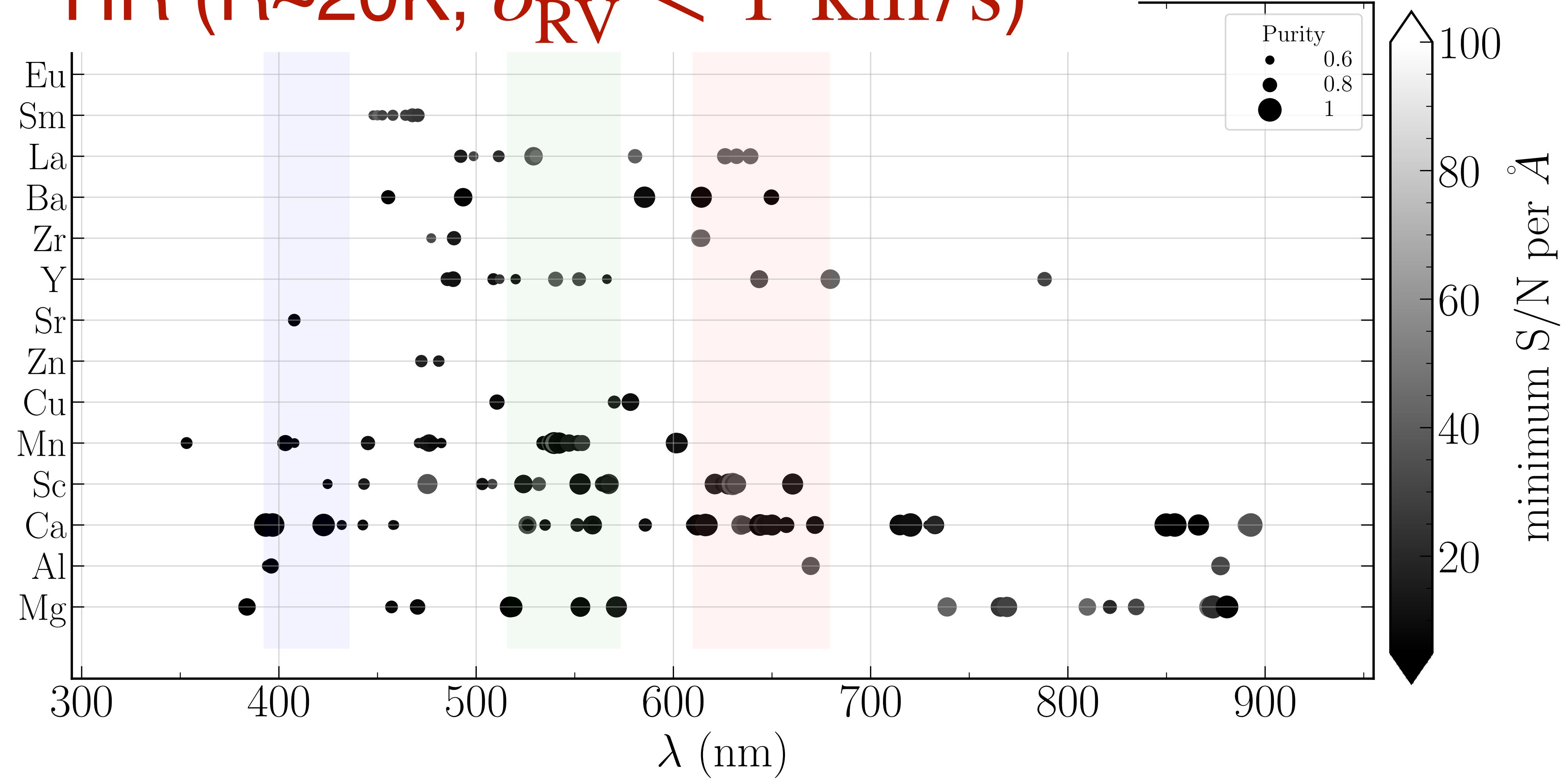
Originality and competitiveness of PFS-HR

WST white paper

LR/MR (R~5K, $\sigma_{RV} \sim 2-3$ km/s)



HR (R~20K, $\sigma_{RV} < 1$ km/s)



A HR MOS in wide-field instruments (>1deg^2) at 8-10m telescope <u>does not exist</u>

- High-precision velocity (<1km/s) for dark matter investigation through stellar dynamics
- Elemental yields in various astronomical sites
  - CNO: low-mass stars, stellar rotation/mixing
  - Mg: massive stars
  - Mn, Al: metallicity-dependent stellar yields
  - Sc, Ti, Cu, Zn: supernova explosion physics
  - Y, Sr, Ba: s- and r-process in AGBs, neutron-star mergers

➡ Demanding for all the relevant science addressing matter origins

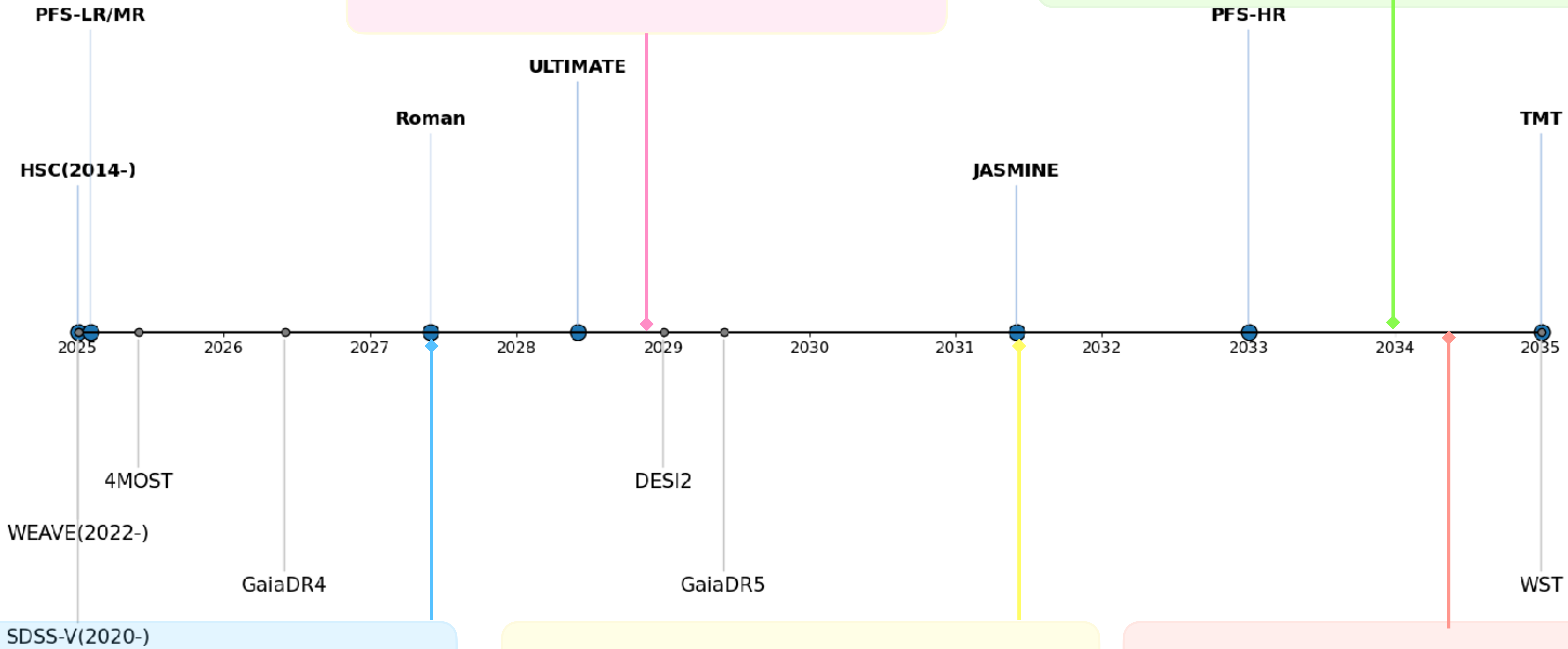
Competitiveness

- Previous wide-field high-resolution spectroscopic surveys have been conducted with smaller (~2m) telescopes (e.g., APOGEE/SDSS, GALAH)
- The planned high-resolution MOS instrument, MOONS@VLT: small FoV (25 arcmin diameter) compared to PFS FoV (1.3 deg diameter) and at NIR
- WST: high-resolution MOS @ 10m telescope (2033+)

Instrument/project timeline and data delivery milestones

Milestone 2 [PFS-LR/MR]
Start of cadence / time-critical multi-object spectroscopy to detect radial velocity variation, stellar activities, etc.

Milestone 4 [ULTIMATE, JASMINE, PFS-LR/MR]
Phase-space information of the Galactic center and the bulge regions



Milestone1 [PFS-LR/MR]
Radial velocity ($\sigma_{RV} \sim 2-3\ \mathrm{km}$), [Fe/H], and [α/Fe] ratios of outer MW, dwarf satellites, M31/33, LG galaxies

Milestone 3 [HSC, PFS-LR/MR, Roman]
3D velocities (proper motions) of the outer MW, dwarf satellites, M31/33

Milestone 5 [GaiaDR5, PFS-HR]
Precise 3D velocities ($\sigma_{RV} < 1\ \mathrm{km}$), detailed elemental abundances (α-element, F-peak, s/r-process elements)

Project organization, current status

Organization

Current collaborators cover a wide range of research fields

Origins of matter in the universe

Stellar observations
- Galactic center, Bulge
- Disk system
- Halo, Globular Clusters
- Local Group galaxies

Dark matter
- Stellar dynamics
- Cosmology
- Particle physics

Data science
- Statistics, machine learning

Black holes
- stellar-mass BHs
- IMBHs

Stellar evolution, nucleosynthesis
- Chemical yields
- Supernova physics

Galaxy evolution
- Simulations
- high-z galaxies

Current status of PFS-HR

Specification of technical requirements based on scientific needs is underway (An initial concept design has been done under “WFMOS” project)

M. Chiba-san’s presentation at Subaru3 workshop (Subaru SAC / Aug 2024)
https://drive.google.com/file/d/1m7gelsMhtspmEZfqsTssPQ0xg-oSa5A4/view

Cost (unit: JPY)

- Kakenhi: ~500M for construction (TBD)
- NAOJ: ~200M total, ~20M/year (TBD)
  - Technical assessment by ATC
  - Necessary upgrades of the telescope (e.g., a new floor to host PFS-HR)
  - Hiring new staff members to lead scientific analysis, development/construction of PFS-HR

Relevant projects at NAOJ

Subaru Telescope (HSC/PFS), Division of Science, ADC, ATC, Institute of Statistical Mathematics, CfCA, JASMINE, TMT

This proposal in the NAOJ Science Road Map

Why at NAOJ?

- Exploration of the fundamental question in science
- Full exploitation of the wide-field capabilities and their upgrades of Subaru Telescope
- Function as a center for integrating theoretical and observational research
- Utilization of the framework for graduate education and training of early-carrier researchers

Required platforms and cost from NAOJ

1. Startup of the development of PFS-HR
   - Technical assessment with ATC
   - Hiring staff to lead technical investigation and development
   - Necessary renovation of Subaru Telescope
2. Database to host multi-wavelength data and analysis platforms
3. Stable operation of supercomputers

Summary

Science question: Origins of matter (chemical elements and dark matter) in the universe

Objectives: Full chemodynamical (6D phase-space coordinate + multi-element chemical abundances) characterization of stellar populations in all Galactic environments as a powerful probe

This proposal:

- Technical assessment, development, and construction of “PFS high-resolution (R~20K) mode”
- Combining HSC, PFS-LR/MR, and Roman data to obtain stellar spatial distribution, 3D velocities, and chemical abundances ([Fe/H], [α/Fe] ratios) in the outer Milky Way, globular clusters, dwarf satellites, M31/33, and Local Group galaxies
- Comparisons with cosmological and chemodynamical simulations of the Milky Way-like galaxies

Synergy with multi-wavelength/multi-messenger observations and a wide range of scientific impacts

Highly competitive in early 2030s and prepares for science cases in the era of TMT