NAOJ Future Planning Symposium
2021/11/09

# (Near) Future of Star Formation Studies

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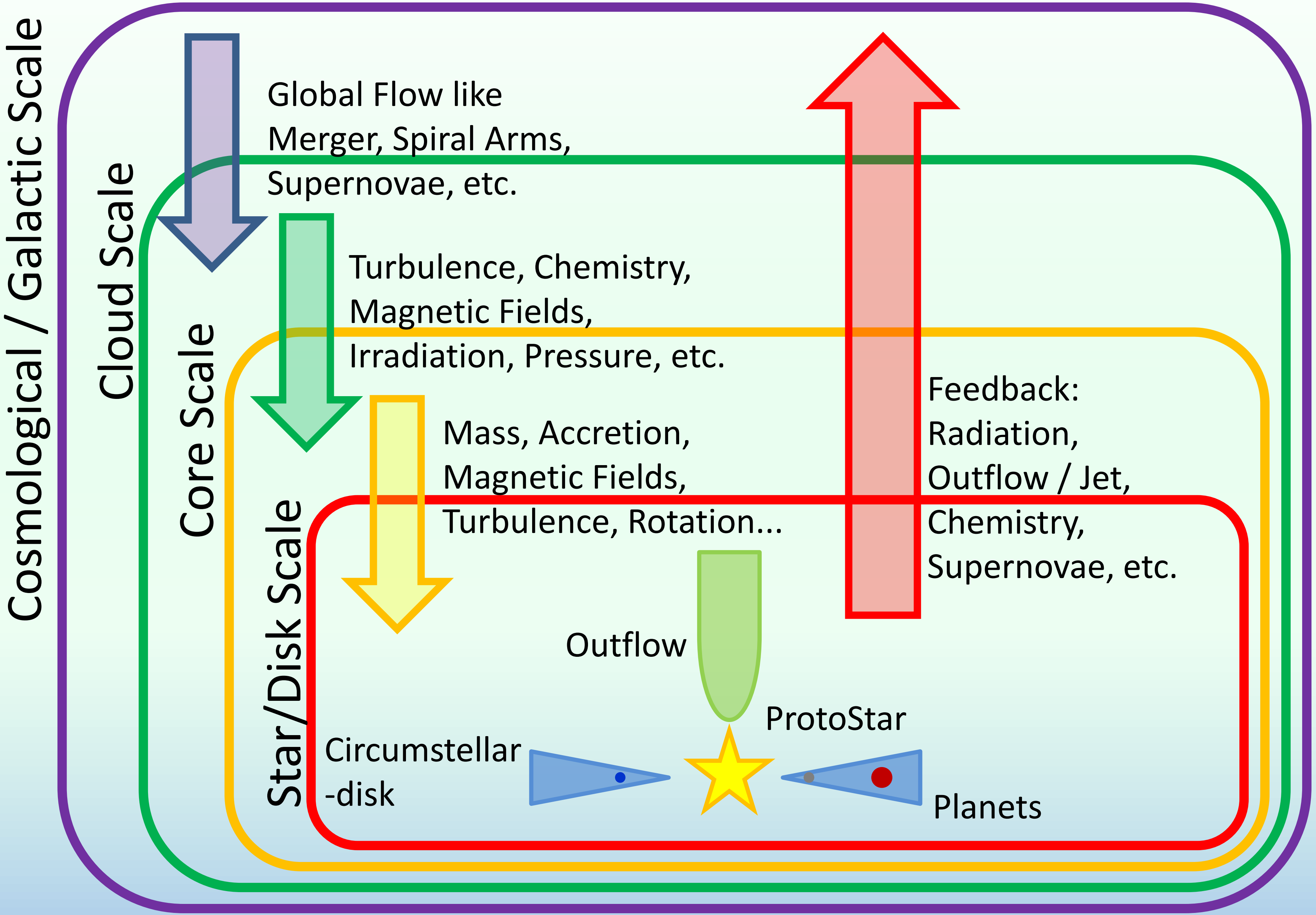
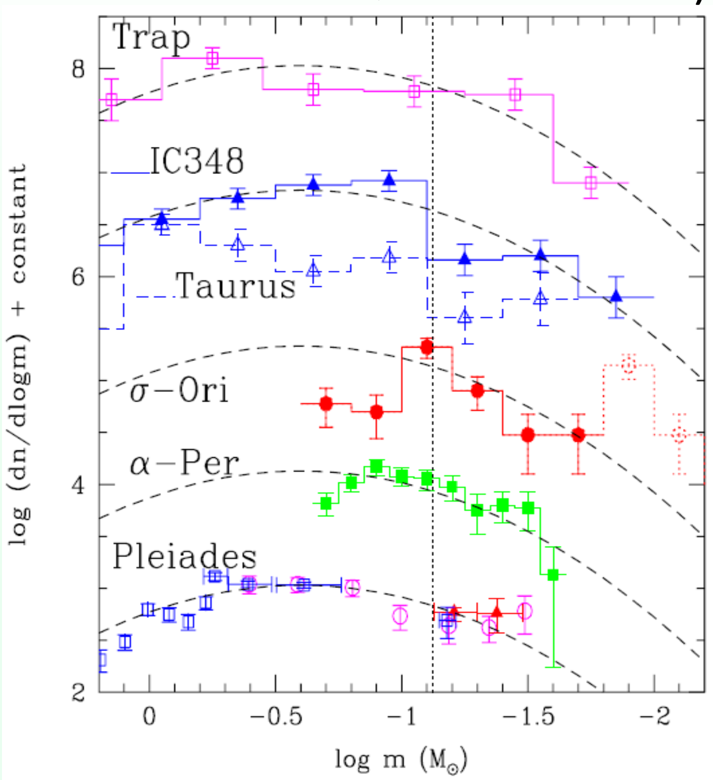
# Multi-Scale, Multi-Physics nature of Star Formation



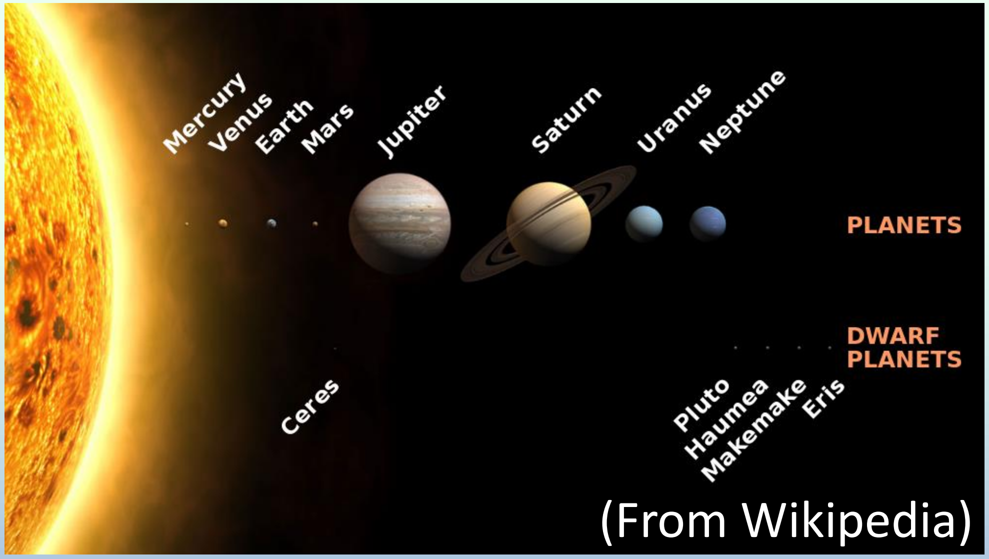
# Ultimate Goals of Star Formation Studies

(Chabrier 2005)




## 1. Stellar Initial Mass Function

Stellar mass determines stellar evolution.
Chemical and Dynamical feedback from massive stars control the universe.
→ Mass distribution of stars is crucial.
⇒What is the origin of the IMF?

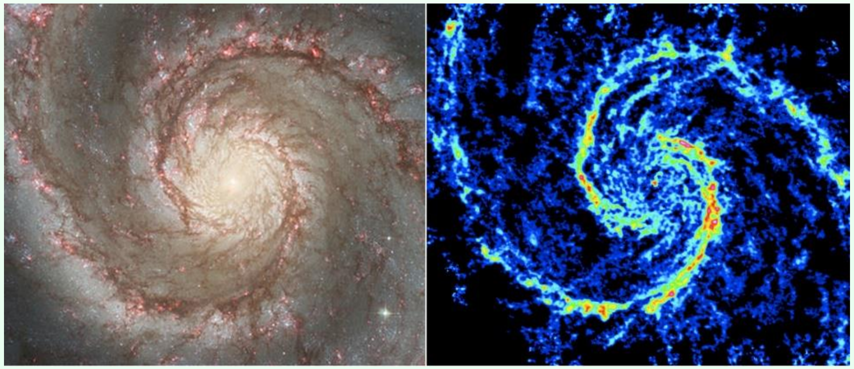



(From Wikipedia)

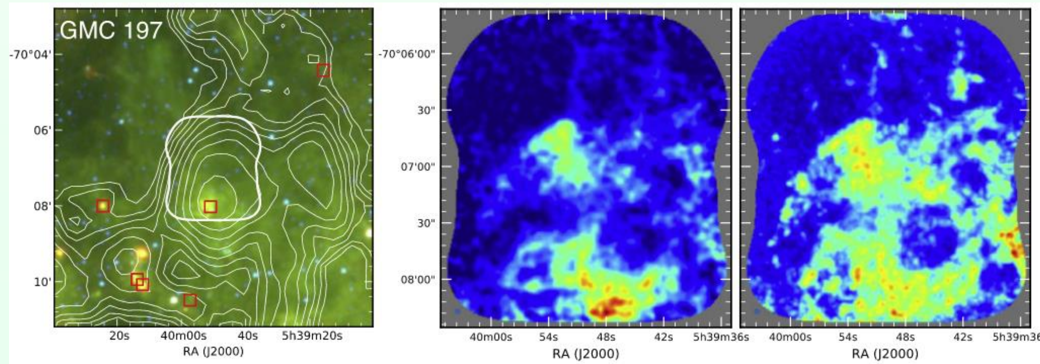
## 2. Origin of the Sun, Earth, other planets, and ourselves

Formation of our solar system is still unclear, and now more than 4,500 exoplanets are reported.
⇒ Formation scenario of star, disk and planets = stellar system

# Galaxy to Cloud Scale



(M51, left: NASA, right: PAWS project)




(MC in LMC, ALMA, Sawada et al. 2018)

Status: We are seeing internal structures and environments of star forming regions in other galaxies with ALMA (e.g. PHANGS), JVLA, NOEMA.

Key Questions:

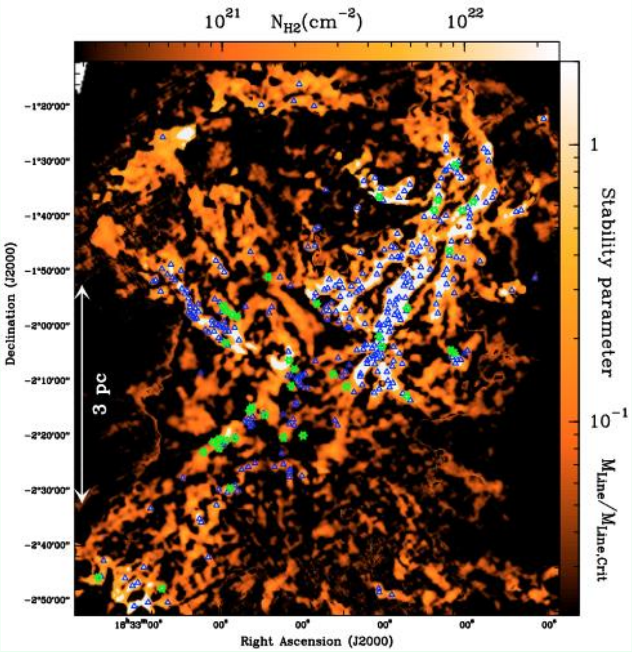
- Where and how molecular clouds form, and how they disappear?
- What is the relation between MCs and environment (e.g. the KS law)?
- What are the conditions required for dense cluster formation / star burst?

What we need:

- Complete statistics of down to small molecular clouds
- Detailed kinematic and chemical information in forming MCs and ISM

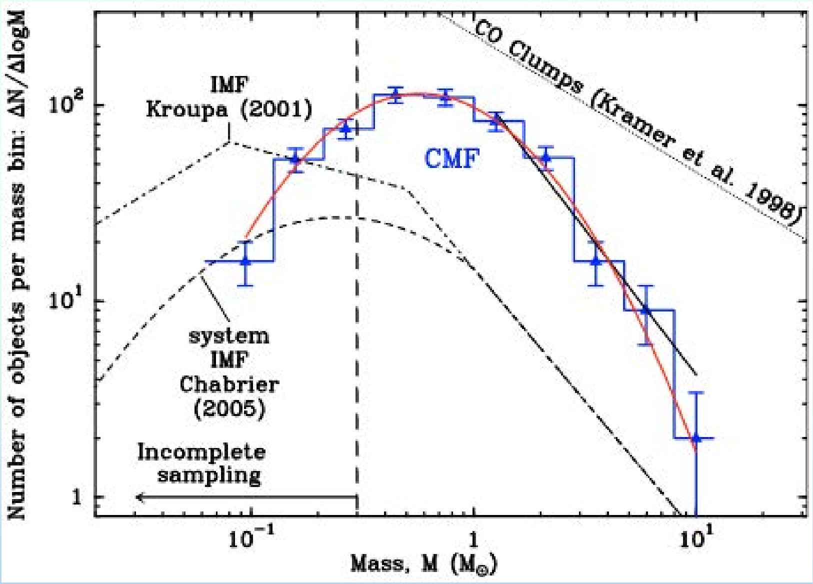
# Cloud to Core Scale

(Andre et al. 2010, Herschel)




Status: Herschel and ALMA observations provided detailed information about star formation in MCs.

Key questions:
- What determines the structure and properties of molecular clouds such as turbulence, magnetic fields, filaments (e.g. 0.1pc width), etc.?
- What controls the star formation efficiency?
- How cloud structures such as filaments and cores relate to star formation?

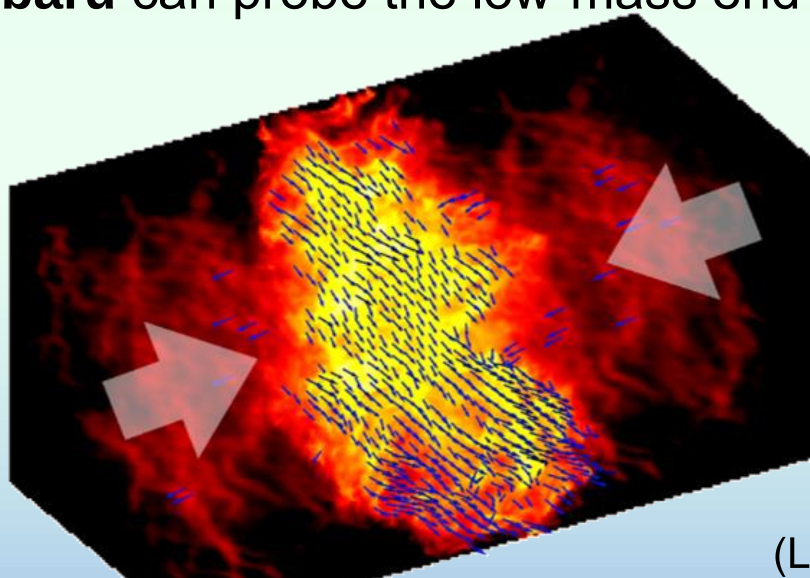



What we need:
- High resolution (both spatial and spectral) information of the turbulence and magnetic fields, as well as feedback from YSOs.
- Core and stellar initial mass functions down to the low-mass end
- Chemical diagnosis → Nomura-san

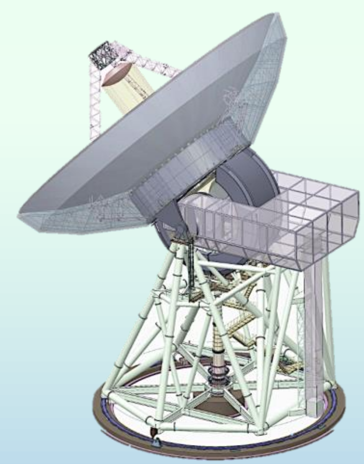
# Future: Galaxy-Cloud Scale

- **LST** can play a crucial role to map molecular clouds in other galaxies as well as structures within nearby molecular clouds including magnetic fields. It also can enable high resolution chemical diagnosis.
  (**LST** is complementary to interferometers like ALMA, and can cover some sciences of cancelled SPICA. Also **ATT10** and **Far-IR Probe** in ASTRO2020?)
- **ALMA-2** and **ngVLA** will allow us to resolve detailed structures in HI and molecular clouds in other galaxies, and provide detailed view in nearby MCs.
- **Roman** and **PFS on Subaru** can probe the low-mass end of IMF, and **LST** can probe CMF.

Note: understanding the galactic ISM (e.g. dust polarization) is very important in the context of cosmological foreground, too.

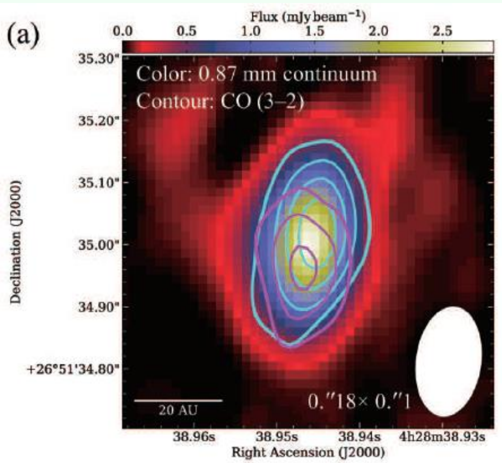


→ K. Tanaka et al. in prep. Synthetic observation of gas and B-fields in a forming MC.

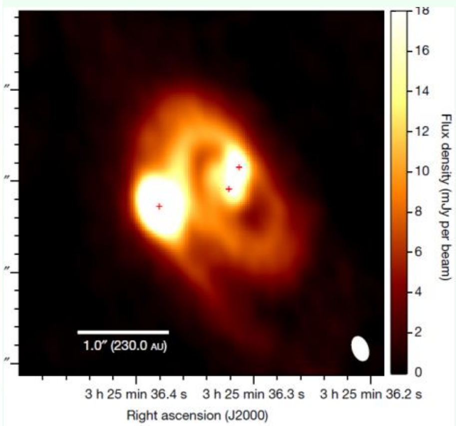


(LST, Kawabe et al. 2016)

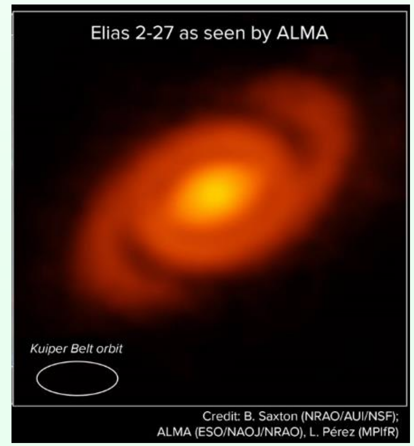
# Disk Scale



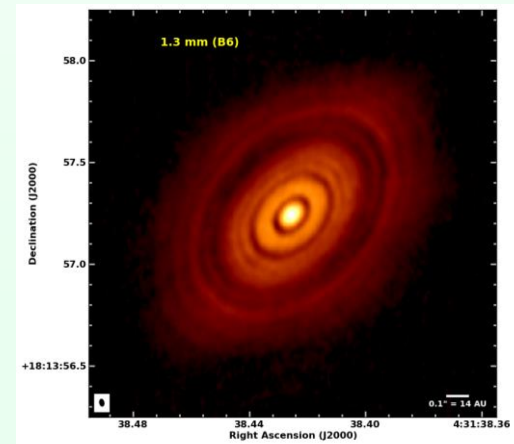

L1521-F (Tokuda+)




L1448 IRS3B (Tobin+)




Elias 2-27 (Perez+)



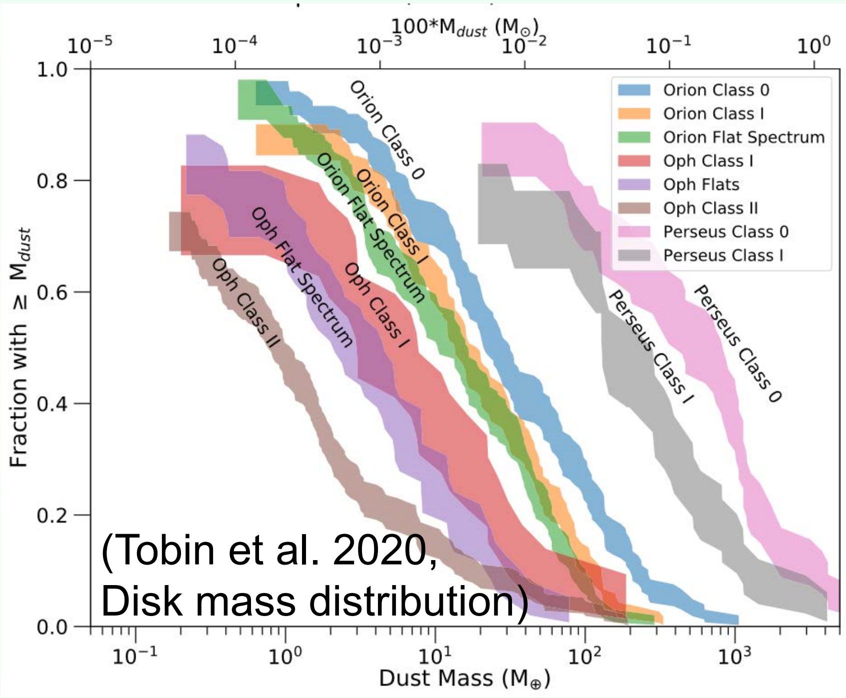

HL Tau (ALMA SV)

←Young Evolved→

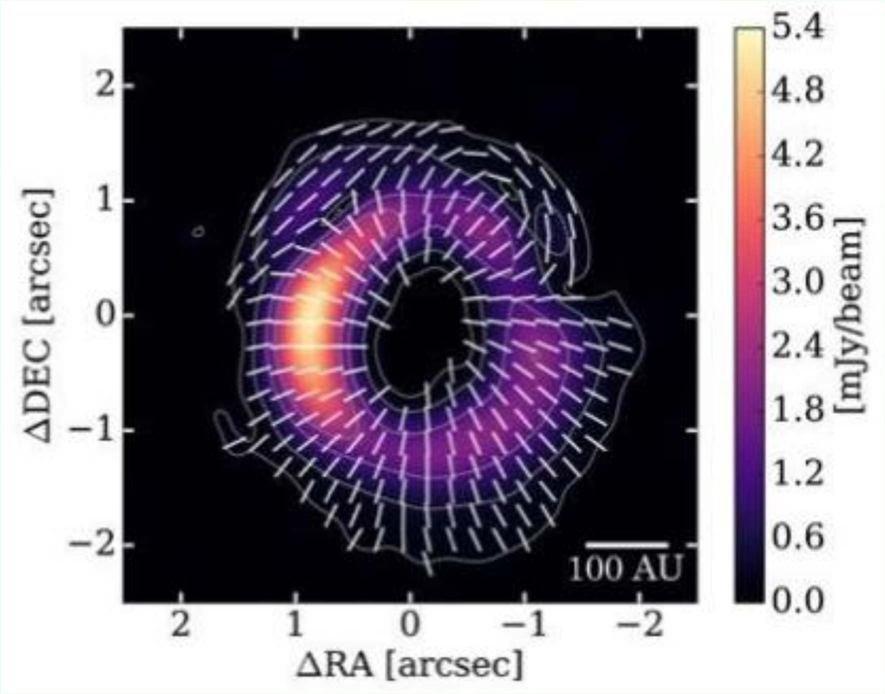
Status: ALMA, NOEMA, JVLA, particularly systematic surveys like DSHARP (Class-II) and eDisk (Class-0/I, on going), drastically changed our view.

- Disks are initially small, but massive in the early phase, and grow by accretion.
- Massive disks can fragment by gravity → binary (possibly planet) formation.
- Rich substructures like ring, gaps and spirals → signatures of planets (?)
- Disk winds are rotating, carrying angular momentum away from disks.
- Polarization pattern can infer grain growth, though it is not very simple.

# Disk Scale



(Tobin et al. 2020, Disk mass distribution)

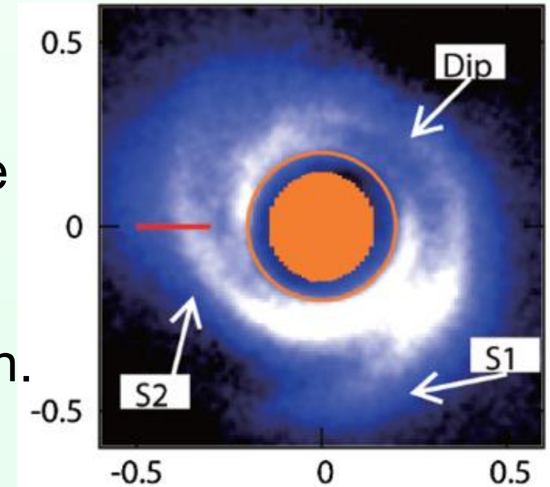


(Kataoka et al. 2016, Polarization pattern)

Key questions:

- What physics controls the disk structure and evolution?
- How are binaries formed, disk fragmentation vs turbulent fragmentation?
- How, where and when small grains grow into planetesimals and planets?
- What is the role of substructures in disk evolution and planet formation?
- The origin of life - how and where complex chemical species are formed?

# Toward Solar System Scale



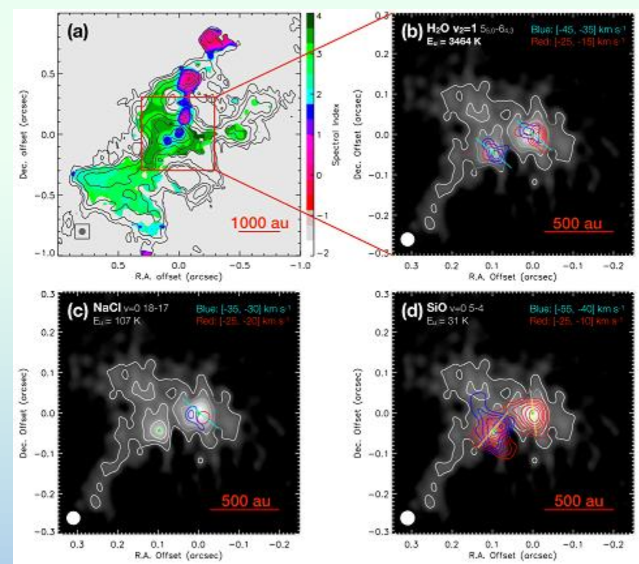
(Muto et al. 2012, HiCIAO)

While ALMA and Subaru revealed detailed structures in protoplanetary disks, those are way larger than the scale of our solar system.
To approach this scale **TMT**, **ALMA-2** and **ngVLA** are crucial, and will bring us new insights on planet formation.

- Direct imaging of inner disks of ~ a few AU scales
- Detection of snow lines of various species
- Inner disks of transitional disks - how disks disappear?

Note: the innermost regions of accreting YSOs can be optically thick to mm dust continuum.
→ **ngVLA** and low-frequency bands of **ALMA-2**.
(NB: dust opacity is highly uncertain in low frequency.)

Also, we need to find good molecular tracers to observe kinematics in such warm/hot disks.
→ refractory species (SiO, NaCl etc.) and $H_2O$ can be used as good tracers (Tanaka et al. 2020 →)

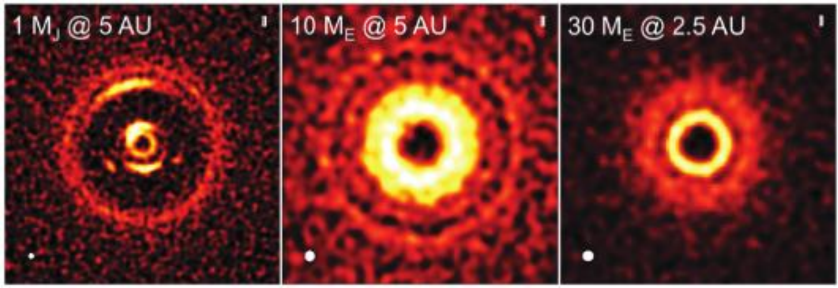


# Future: Disk-Planet Scale

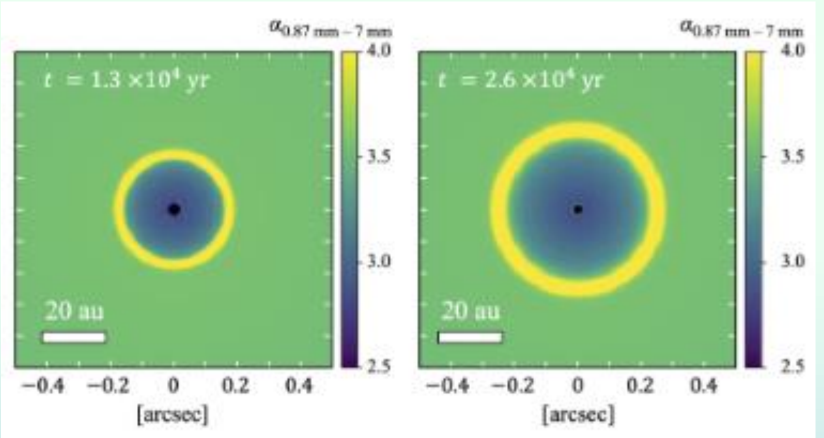
**ALMA-2**, **ngVLA** as well as **TMT** will open new windows to a new world.

- Systematic observations of young disks, outflows and jets (including FHSC).
- Resolving interaction between planets and protoplanetary disks.
- Spatially resolving the solar system scale.
- Broad spectral range and polarization will provide rich information of dust properties.
- **ngVLA** as well as **ALMA Band-1** and **2** will provide various chemical diagnosis.

| | ngVLA バンド | 周波数帯域 | 主要スペクトル線 |
|---|---|---|---|
| センチ波 | 1 | 1.2 - 3.5 | H, $H_2CO$, $H_2CS$, OH |
| | 2 | 3.5 - 12.3 | CH, $H_2CS$, $SO_2$ |
| | 3 | 12.3 - 20.5 | $CH_3CN$, $CH_3OH$, $H_2CO$, $H_2CS$, $NH_3$, SO |
| ミリ波 | 4 | 20.5 - 34.0 | $H_2CS$, $HC_3N$, HNCO, $H_2CO$, $H_2O$, $NH_3$, $NHD_2$, SO |
| | 5 | 30.5 - 50.5 | c-HCCCH, $CH_3OH$, $CH_3CN$, CS, $H_2CO$, HNCO, $NHD_2$, SiO |
| | 6 | 70.0 - 116 | CO, CS, CN, $CH_3OH$, c-HCCCH, $CH_3CN$, HDO, HNCO, HCN, HNC, $H_2CO$, $HCO^+$, $N_2H^+$, $NHD_2$, N2D$^+$, SiO, $SO_2$, SO |




Imaging simulations of planet-disk interaction, 100 GHz with ngVLA, (Ricci et al. 2018)



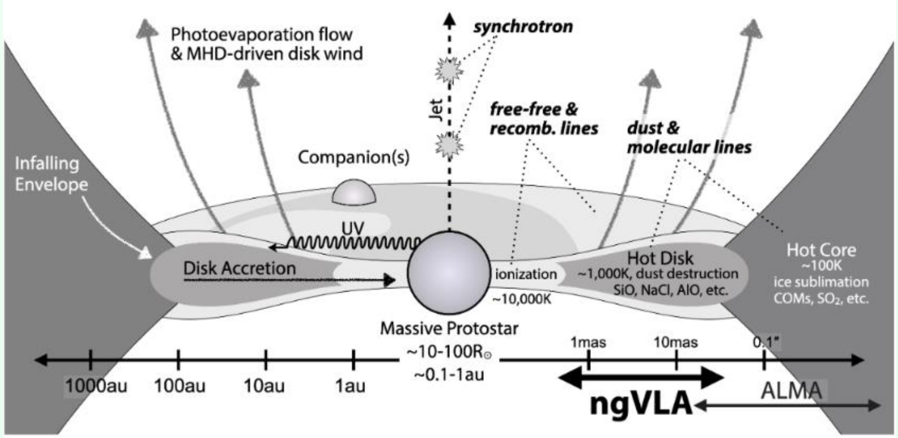

Spectral index maps can trace grain growth (Ohashi et al. ngVLA memo)

(← ngVLA Project Book)

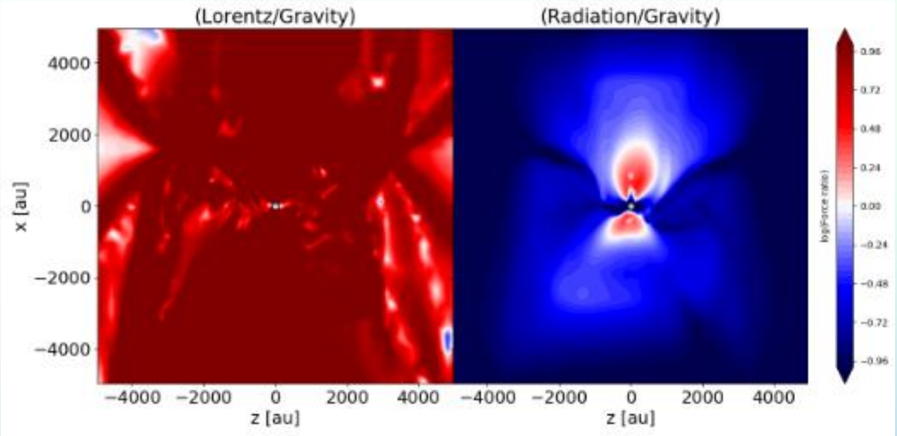
# Toward the Scale of Stars

With the resolution of **ngVLA**, we can approach even smaller scale of the star. In that scale, the dynamical time scale becomes months or even shorter.

- Photospheres of inflated massive stars
  → direct comparison w/ stellar evolution
- Orbital motion of tight binaries
- Inner structure of the accretion flow
  → How stars gain their mass, angular momentum and magnetic fields?
- Launching points of jets and outflows
  → constraining the driving mechanism
- What regulate masses of stars (star formation efficiency)? Magnetic or radiation feedback?



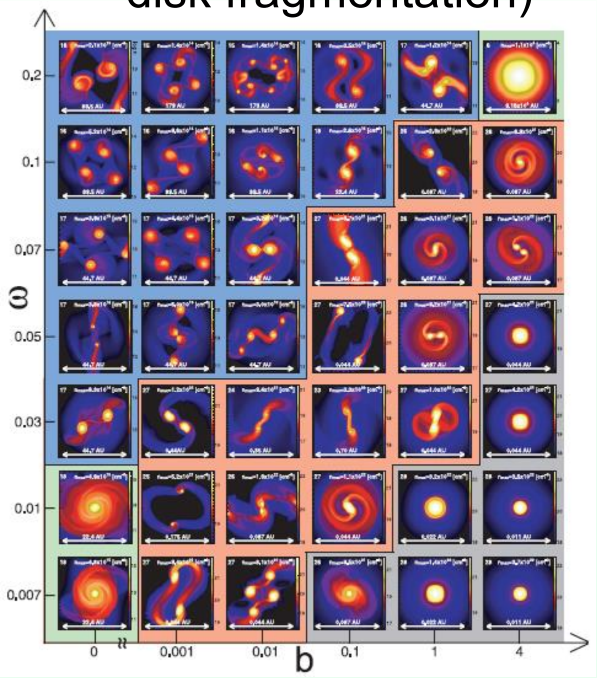

(K. Tanaka, ngVLA memo series)




(Commerçon et al. 2021, RMHD simulation of SF, comparing magnetic vs radiation forces)

# Binary Formation

(Machida et al. 2008, disk fragmentation)




As many stars form in binaries/multiples, binary formation is important in various contexts but still remains as a big mystery:

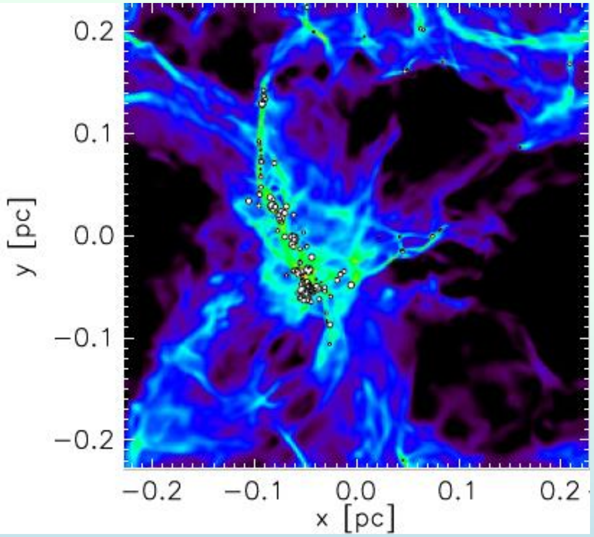
- Determining IMF
- Redistributing angular momentum
- Stellar evolution
- Planet formation

Two major processes:

- Disk fragmentation by gravitational instability
- Core fragmentation by turbulence

We can distinguish them using **ngVLA** and **ALMA**. They produce different orbital separation, mass ratio, alignment, and eccentricity distributions.

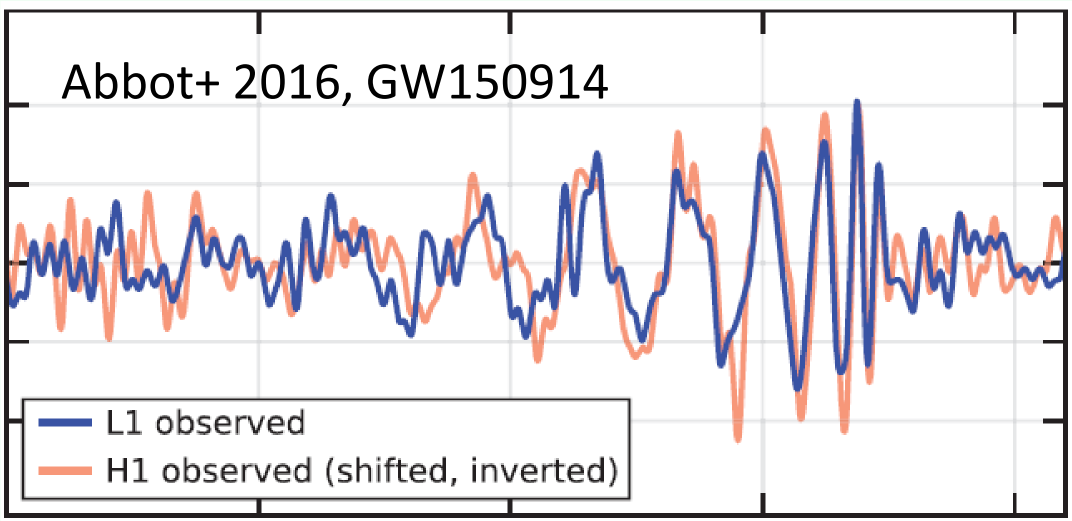
(Note: probably these are not mutually exclusive - both can work but at different scales.)

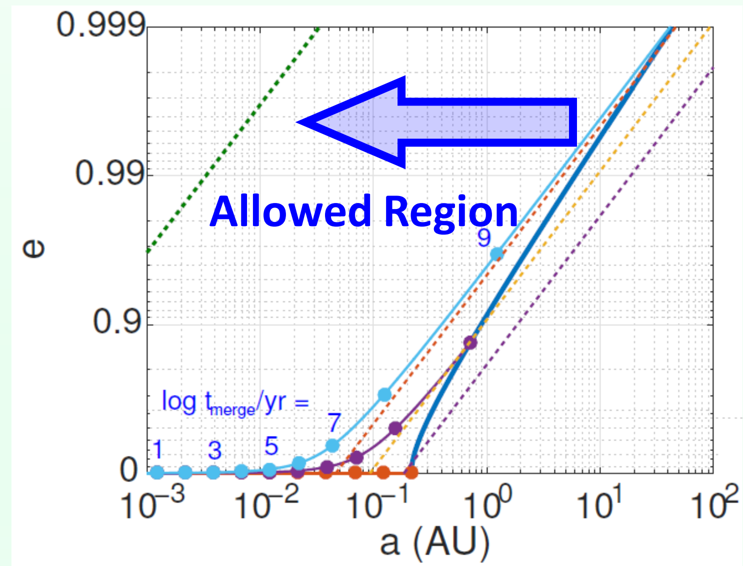



(Krumholz et al. 2012, turbulent fragmentation)

# Origin of GW Sources?

(Abbot et al. 2016)



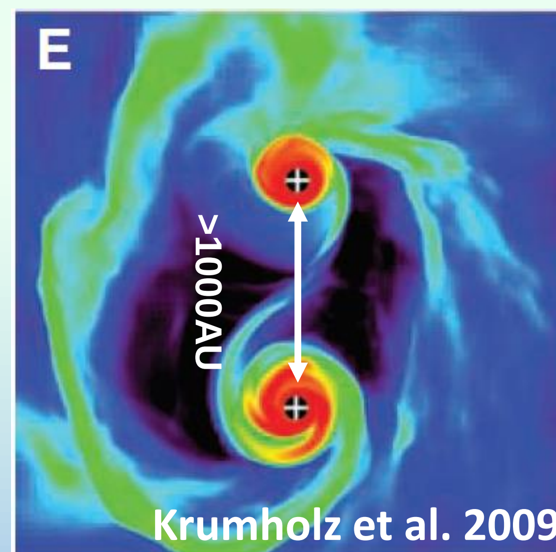

GW150914: $36M_\odot$+$29M_\odot$ Binary BHs

(Progenitor mass is > $40M_\odot$, favors low-metal)

The initial binary must be very tight: < ~ 1AU

(c.f. RHD simulation → 40 + 30 $M_\odot$ but wide)

⇒ **GW** + **ALMA-2** / **ngVLA** + simulations



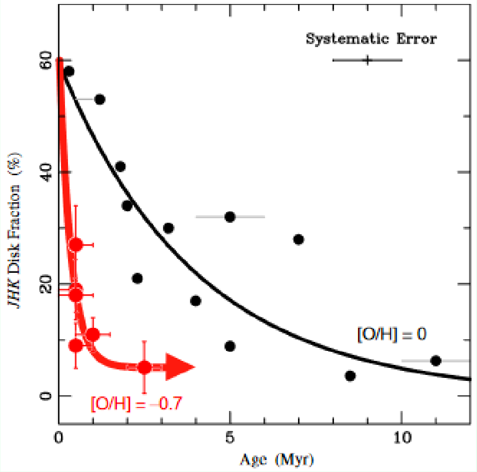

Note: Since they are rare, they may form in special environments like the center of dense clusters, and we do not need to explain them from star formation. But it is an interesting, new challenge.

# SF in Different Environments

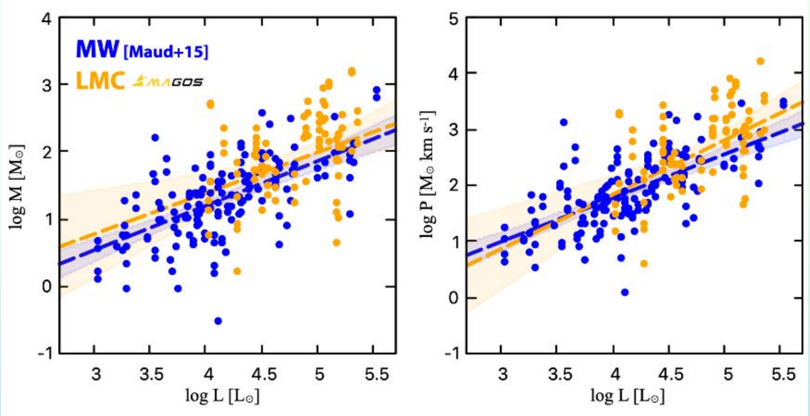
IMF is considered to be universal in various environments - but why?

There are many environmental parameters:
- Metallicity (chemical composition)
- Irradiation / temperature
- Magnetic fields
- Turbulence
- Density and pressure

We are already seeing diversity/universality:



(Yasui et al. 2010, disks disperse faster in low-metal SF regions)

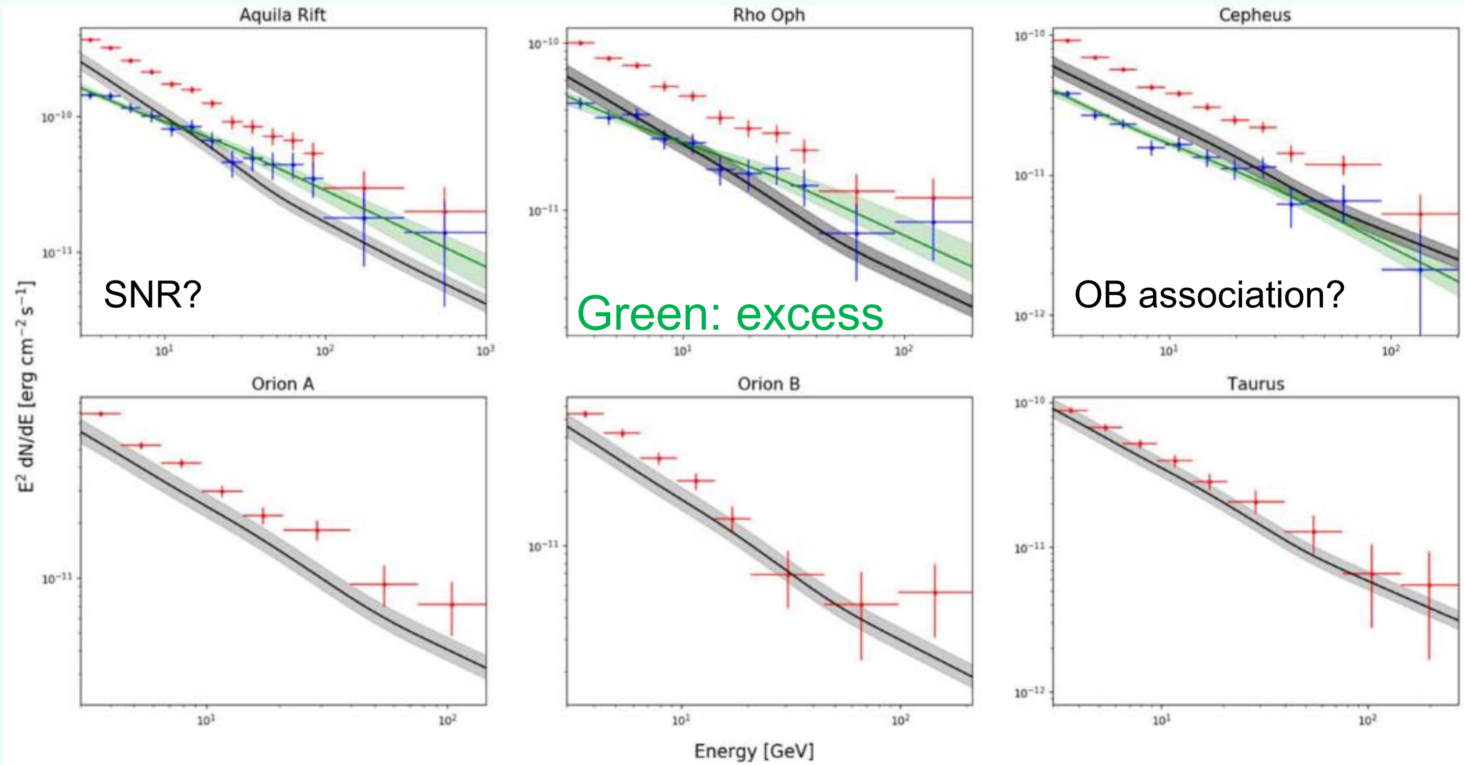


(Tanaka et al. in prep., outflows are universal, at least in LMC)

With **ALMA-2**, **ngVLA** and **TMT**, we will be able to observe disks and outflows in other environments (which typically are far away):
- low metal: LMC/SMC, outer Galaxy
- high metal, dense, warm: inner Galaxy

→ Constrain how environments affect SF.

# “High-Energy” Phenomena in SF

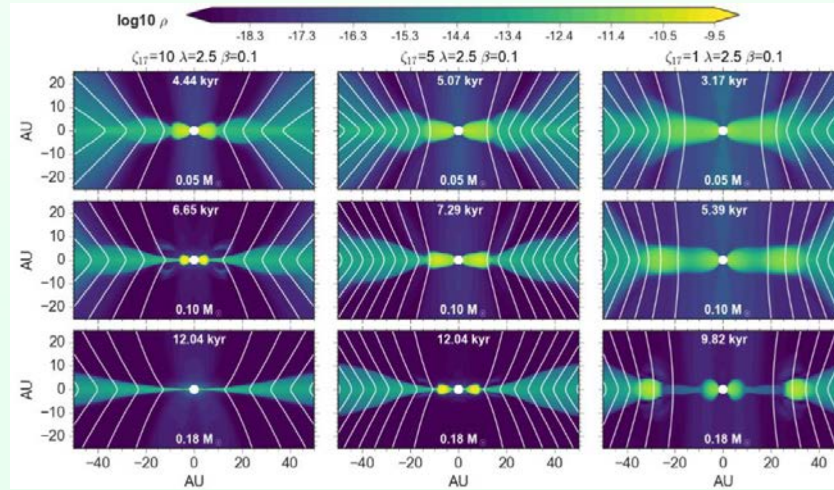



(Baghmanyan et al. 2020, Fermi)

Recently, potential CR excess in some star forming regions is reported.
Also, from the depletion timescale of CO, the ionization rate of $\zeta \gtrsim 10^{-16}\ s^{-1}$ (c.f. the fiducial ISM value $10^{-17}\ s^{-1}$) is favored (e.g. Zhang et al. 2020).
→ Star formation activity itself may be producing cosmic rays?
(Note: other ionization sources like stellar UV and X-ray are also important.)

# Why Is This Interesting?

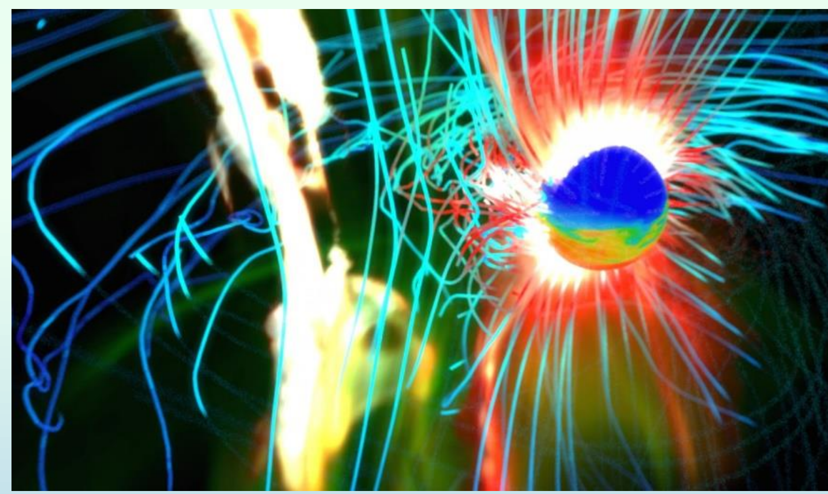
(Küffmeier et al. 2020)




- In the first place, we thought that star formation is "low-energy" and did not expect that it can produce CRs.
- The ionization degree affects the disk structure via non-ideal MHD effects →
- The ionization rate in protoplanetary disks is set by itself, not by environment.
- The ionization rate in disks can be highly variable both in space and time.
- CRs can trigger complex chemical reactions in star forming clouds.

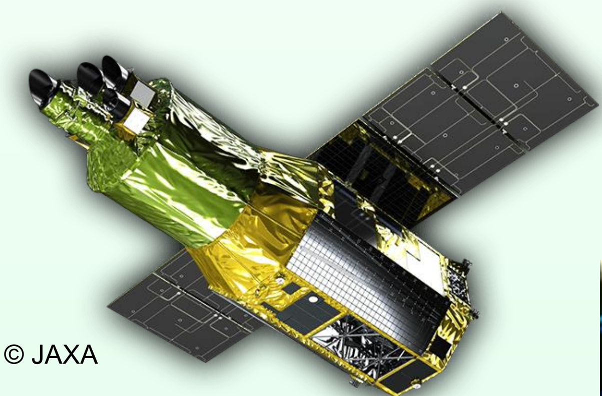
Flares (reconnection), jets and shocks accelerate CRs. (Padovani et al. 2020).

Note: reconnection can be also important to determine the stellar magnetic flux.



(Takasao et al. 2019, visualization: T. Takeda @ VASA Entertainment)

# How Can We Confirm?



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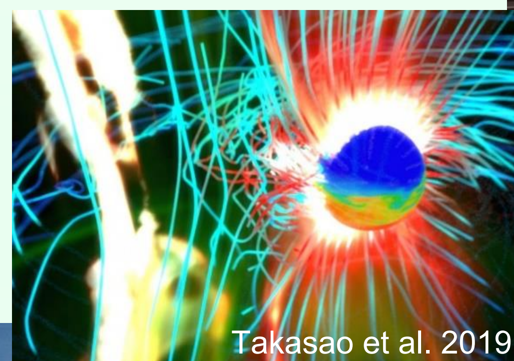
**XRISM/ATHENA/FORCE** etc.
- X-ray flares

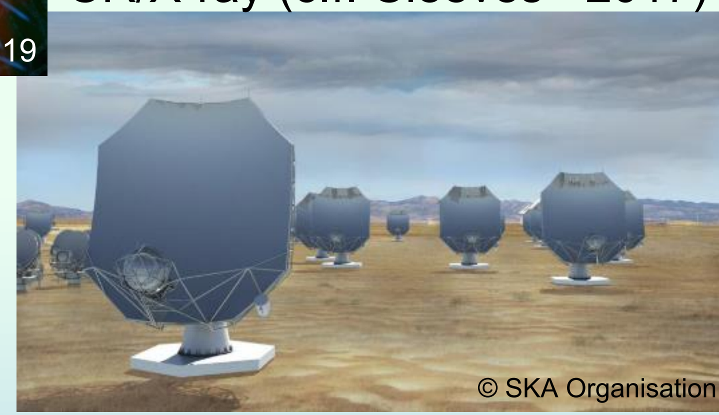


Takasao et al. 2019

**ALMA-2** - chemistry triggered by CR/X-ray (c.f. Cleeves+ 2017)

Northern Hemisphere Site Rendering; credit: Gabriel Pérez Diaz, IAC

**CTA** - time-dependent gamma-ray observations → CRs from bursts



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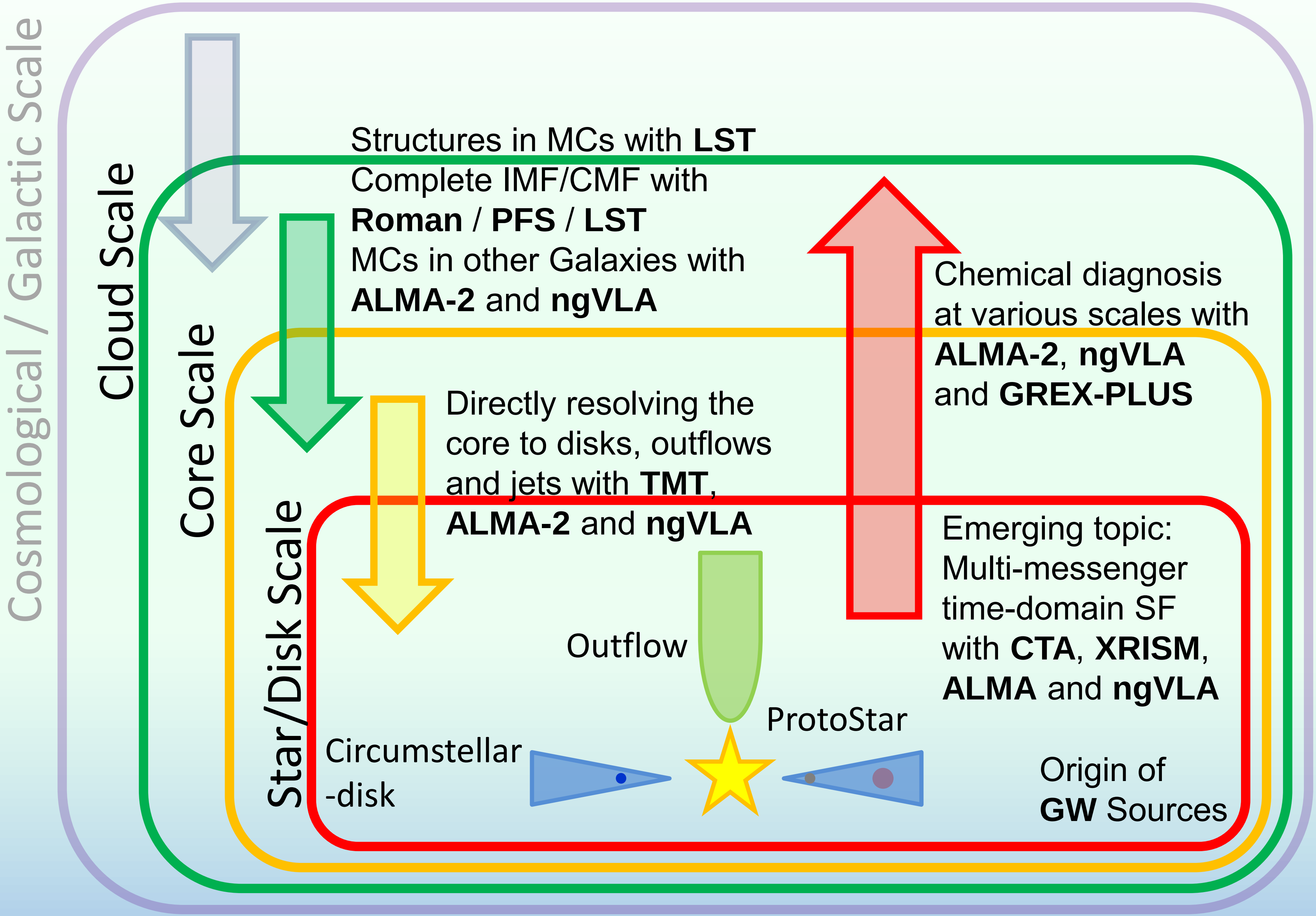
**ngVLA** (or **SKA**) - synchrotron, free-free, small-scale kinematics

⇒ Multi-messenger time-domain astronomy in star formation

# Multi-Scale, Multi-Physics nature of Star Formation



# A Few Words on HPC in Astrophysics

HPC: High-Performance Computing

# Diversifying Needs


Today, large computing power is necessary in every field →
High performance computing is essential research infrastructure.

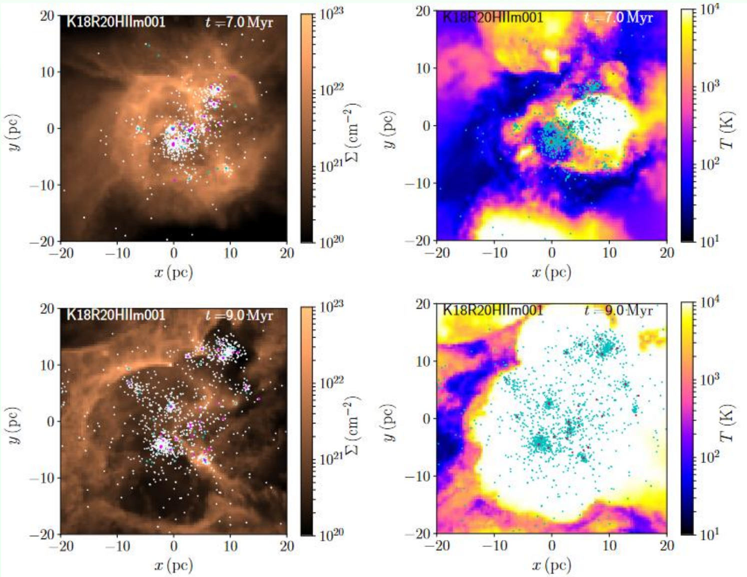
And computing needs are getting diverse:
• Hydrodynamics & radiation - high precision, memory intensive
• N-body simulations - computation intensive
• Data science - require less precision, IO intensive
• Data archive - database / storage technology
→ various software and hardware techniques are required.

Therefore, it is of crucial importance for NAOJ to maintain its own computing center, and flexibly cover various needs, in terms of both hardware and software.
(Although, it is also important to collaborate with other centers.)

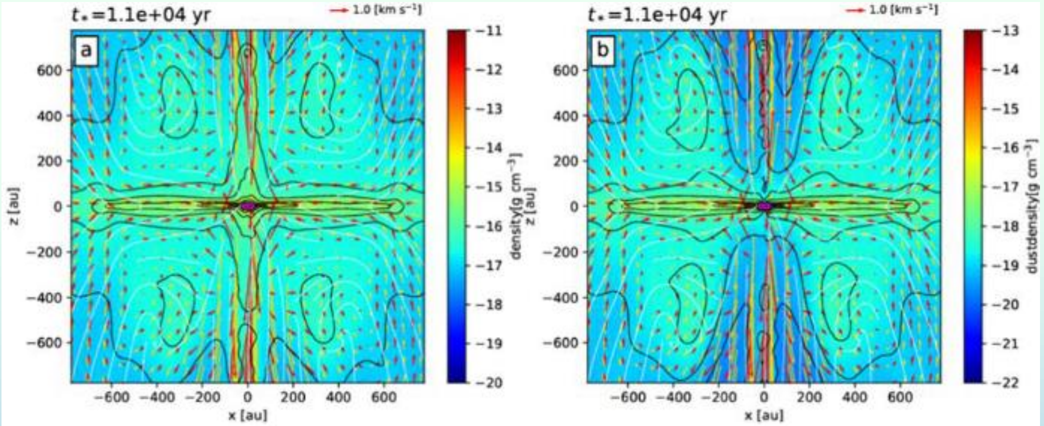
# Just a Few Examples...

Numerical simulations with realistic physics are now being carried out:

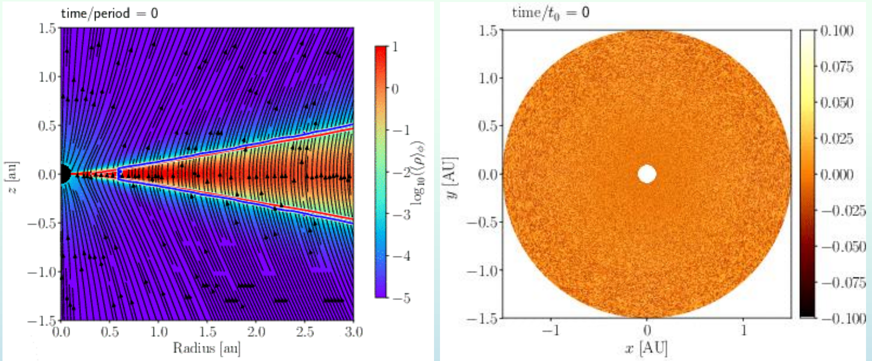
- Cluster formation simulations with feedback resolving each star: e.g. SIRIUS project →
- Non-ideal MHD simulations of star and disk formation including dust grains ↓
- High resolution 3D global disk simulations directly resolving MRI turbulence




(Hirai et al. 2021, SIRIUS star-by-star simulations of cluster formation)




(Tsukamoto et al. 2021, star/disk formation simulation including dust grains)




(Iwasaki et al. in prep., global 3D non-ideal MHD simulation of a disk resolving MRI)

# Toward the Future of HPC

Computing is diversifying but also inflating (c.f. Fugaku: >$7 \times 10^6$ cores)

It is not easy to fully utilize large supercomputers.
In the near future, the situation will be actually worse:
- "General-purpose" CPUs are not very energy efficient.
- Memory/network per computing resource will shrink.
- GPUs/accelerators require special programming technique.

Also, the code development cost is inflating:
- Increasing demand for realistic simulations with more physics
- Complicated (often architecture-specific) parallelization/optimization

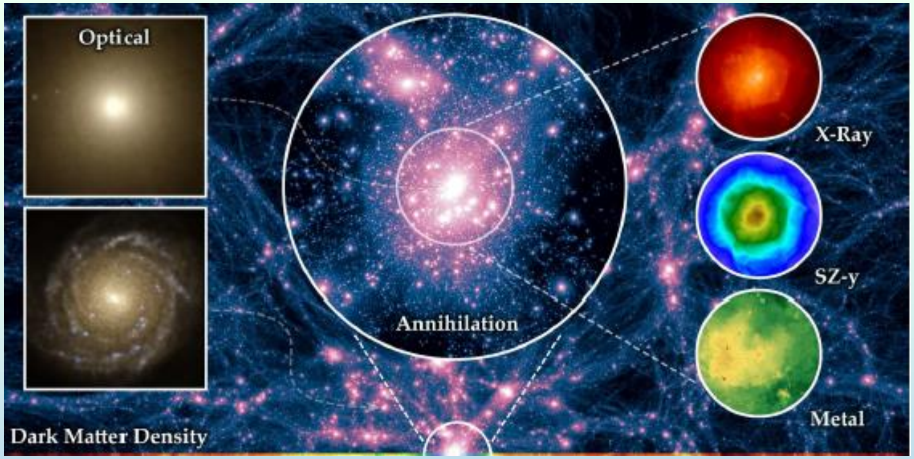
Buying a larger machine does not mean we can do better research any more - we need **strategic research and development**, for both software and hardware. It is like developing a telescope.
→ NAOJ's supercomputer is very important to facilitate such initiatives.

# NAOJ's Role (MY Expectation)

It is difficult for university groups to lead such big and long-term projects.
As the center of astronomy in Japan, I want NAOJ to play a leading role.

- Science-driven, mission-oriented, long-term projects
- Lead world-wide collaborations
- Coordinate large grant programs（e.g. 学術変革 / 特別推進 / 富岳成果創出）
- Bridge observations and theories
- Database and analysis
- Code development
- Planning future directions
- Outreach and press release
- Fostering young generations

Here I am thinking of large projects like **Illustris** (MPI) and **Enzo** (UCSD), and also **DSHARP** and **eDisk** (ALMA LP). Such initiatives do not necessarily need much money - just will and right strategy.




(Illustris, Vogelsberger+)

# Personal Thoughts on Future of Our Community

Japanese Version of the Decadal Survey?

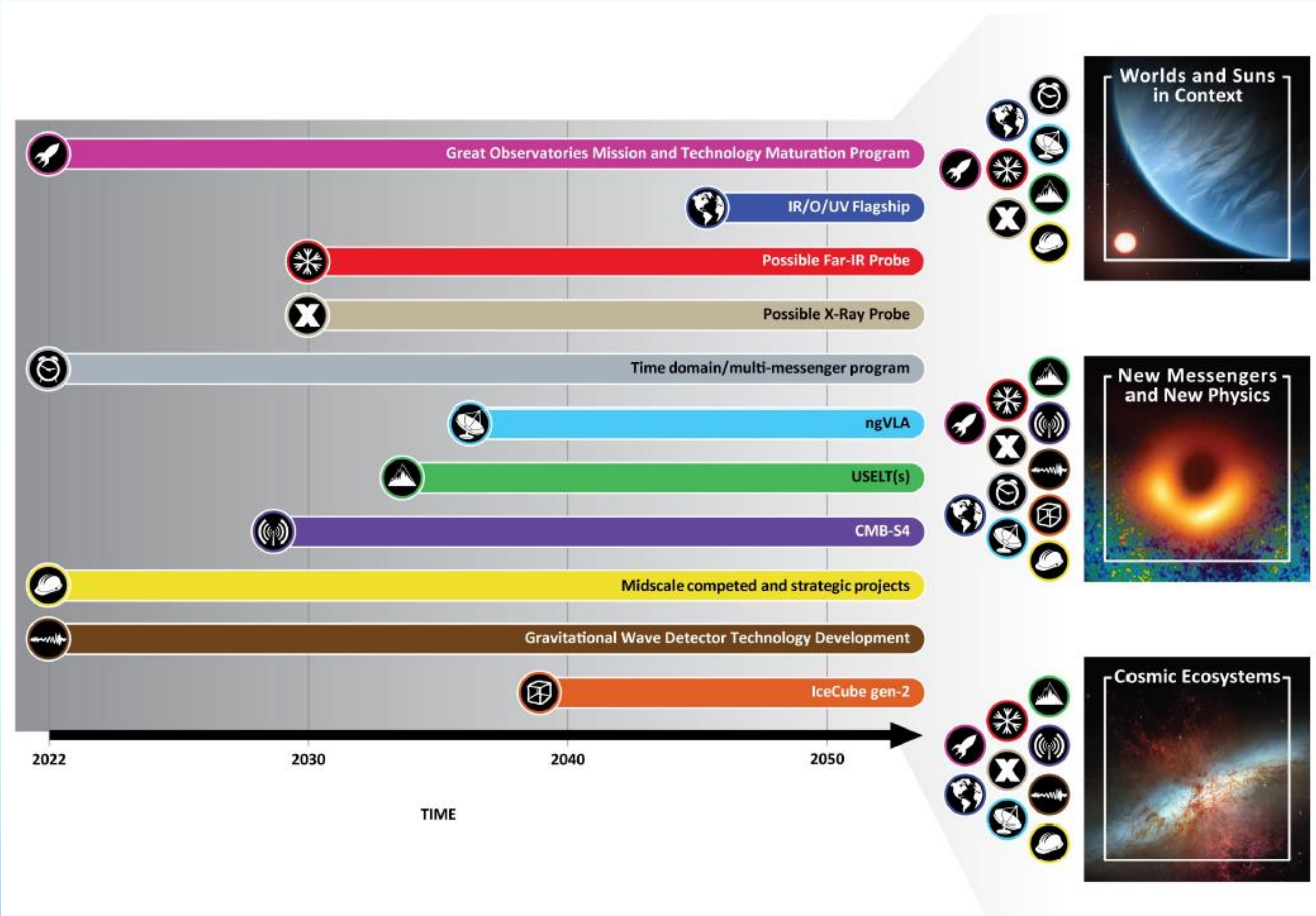
# Decision Making

The current decision making process in Japan (i.e. Master Plan led by Science Council of Japan) may not work well any more.

- Categorized by wavelengths and ground vs space
  - Today's cutting-edge research is intrinsically multi-messenger
  - Budgetary limitations - new instruments are expensive
    → We have to give up "one telescope per field" at some point
- Unclear decision making process
  - Co-optation (not election) of the SCJ members
  - The report does not explain why/how each project is selected
  - Young generations are not actively involved

⇒ How can we improve this process?

# ASTRO2020 Released



# Master Plan vs Decadal Survey

| | **Master Plan** | **Decadal Survey** |
|---|---|---|
| Frequency | Every 3 years | Every ~10 years |
| Organization | SCJ members<br>Proposals from<br>each community<br>(based on wavelengths) | Selected by NAS (sponsored by<br>NSF, NASA, DOE)<br>Panels: **6 Science** + 5 Program +<br>1 State of the profession<br>>100 (including **young**) members |
| Target | Only big projects | Projects and Policies |
| Input | 34 (physics) | 573 +294 whitepapers |
| Report | ~ 50 pages, mostly admin. | **> 600 pages** |
| Outcome | Just selection results | **Detailed recommendation**<br>including budget assessments<br>e.g. 6m space telescope =<br>(HabEX + LUVOIR) / 2 |

# My Personal Thoughts

• We probably cannot afford the cost of the decadal survey
→ start from something tractable, including some key essences

• What are the key essences?
- **Fair and transparent** decision making process
- Scientific assessments **beyond wavelengths** (→ **science panels**)
- Detailed assessments including budget and feasibility ("TRACE")
- The selection process and results are **respected and trusted**.

⇒ Assemble a new committee **under the Astronomical Society**
- The members should be selected by election.
- The members should include young generation.
- Combination of scientific-oriented review and project-oriented review.
- Detailed report should be published.
- The committee members' effort must be respected and trusted.
- The outcome should be used by the SCJ and other policy makers.


Thank you!