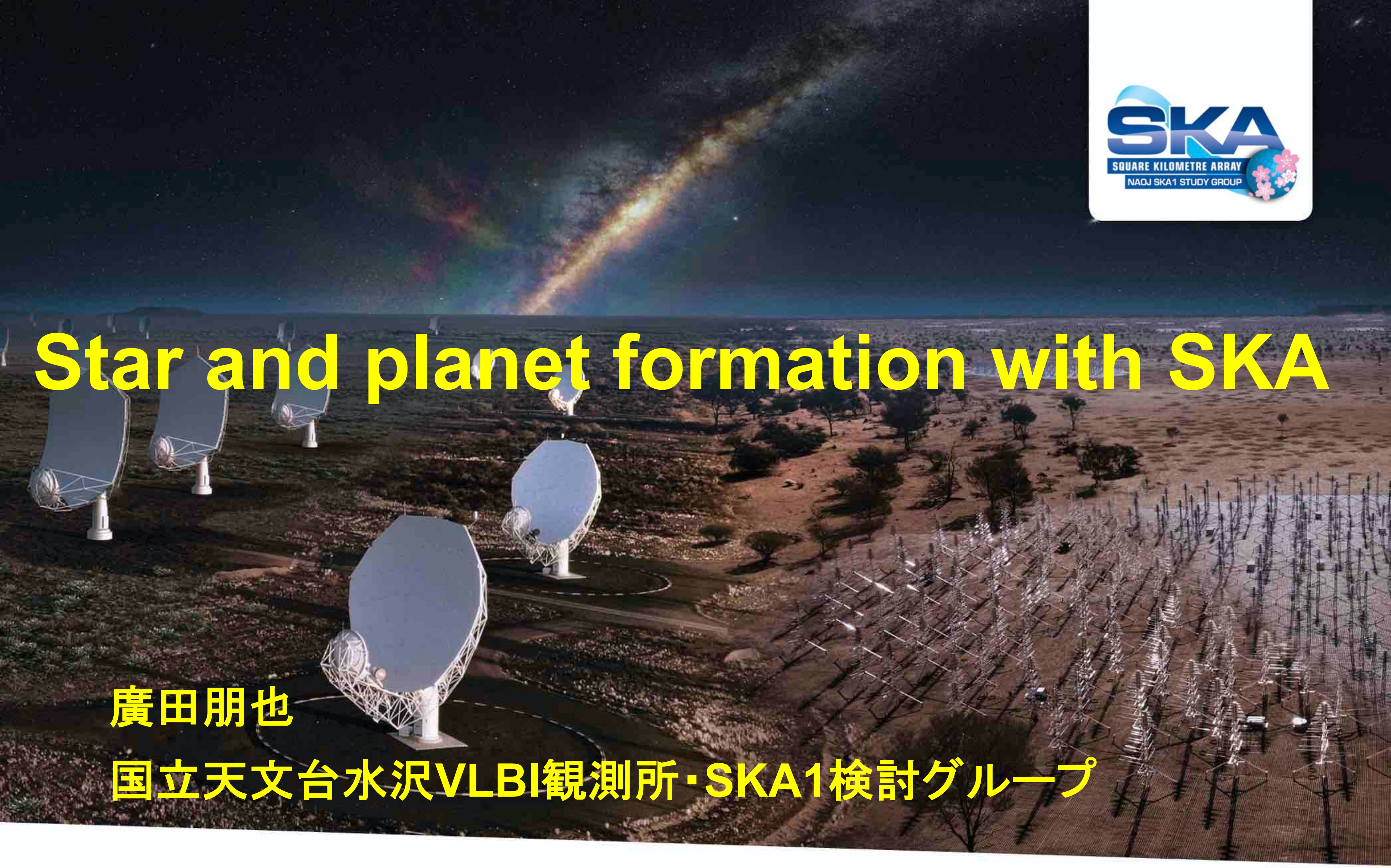
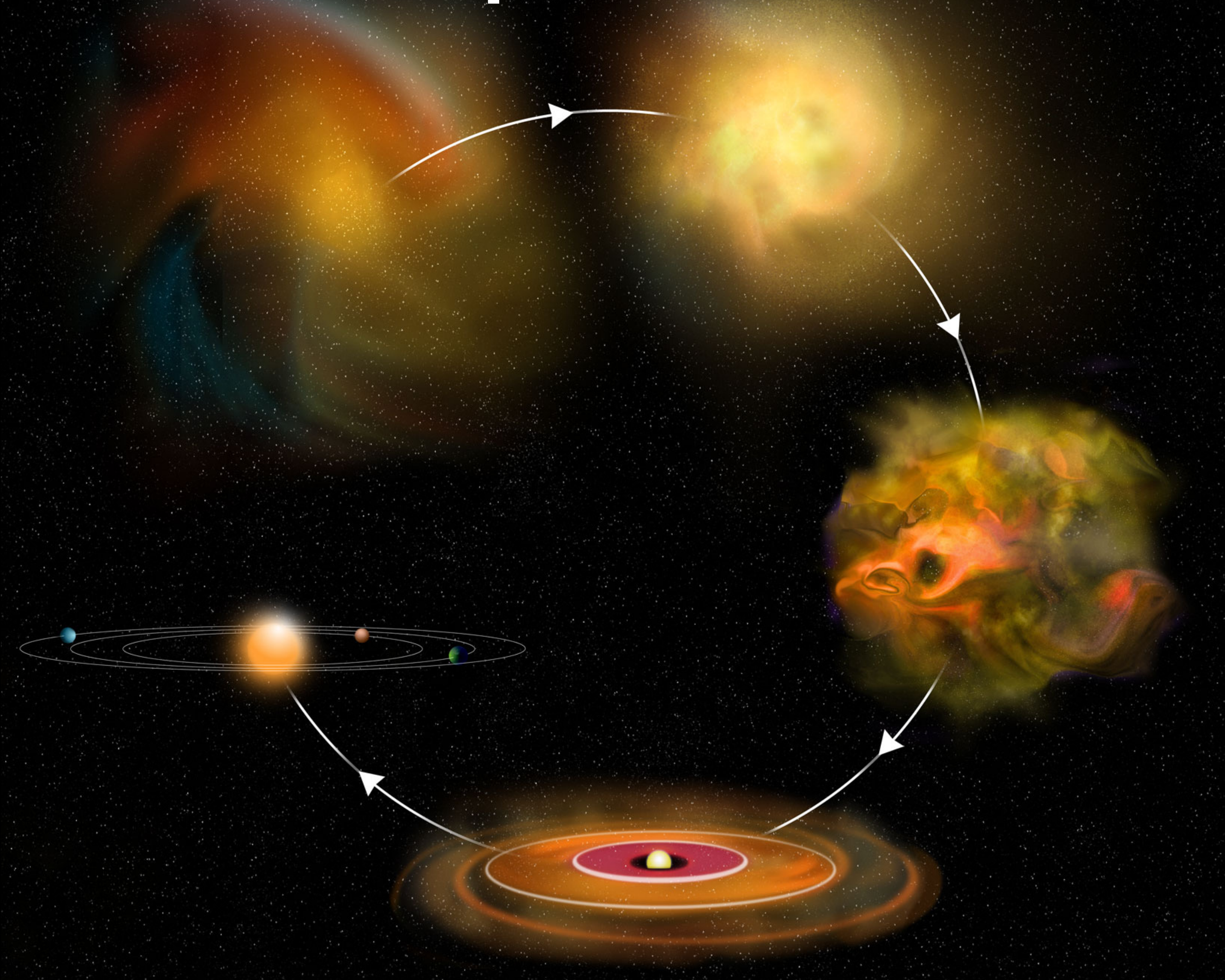


Star and planet formation with SKA

廣田朋也
国立天文台水沢VLBI観測所・SKA1検討グループ

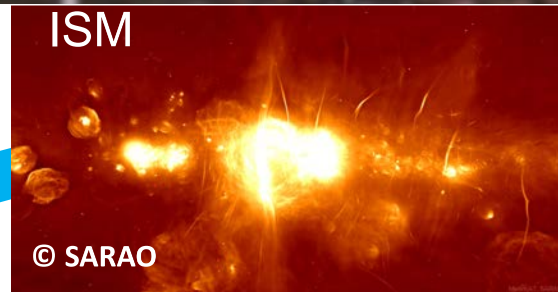
※ほとんどの資料はリーダー塚本さん＠鹿児島大によるウェビナー発表資料などから拝借

Star and planet formation



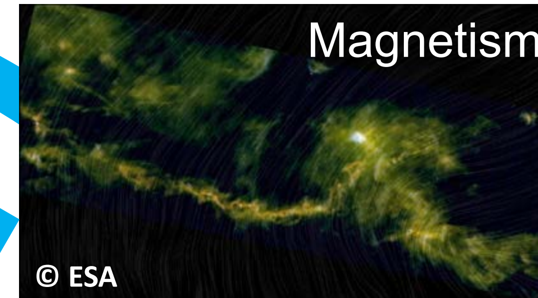
Bill Saxton, NSF/AUI/NRAO

Questions and impact on astronomy and astro-physics/chemistry/biology



Initial condition, shocked regions (e.g. CCC), Galactic center

Formation/evolution, origin of diversity, astro-chemistry/biology

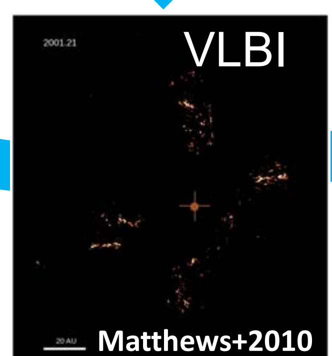


B-field in star/disk/outflow/core, B-field in clump/filament/cloud

How is a star's mass determined?
How/when/where are planets formed?
How do they physically/chemically evolve?

Episodic outflow/jet ejection, accretion burst, maser flare

Formation of the first star, IMF of BHs, pulsars, and these binaries



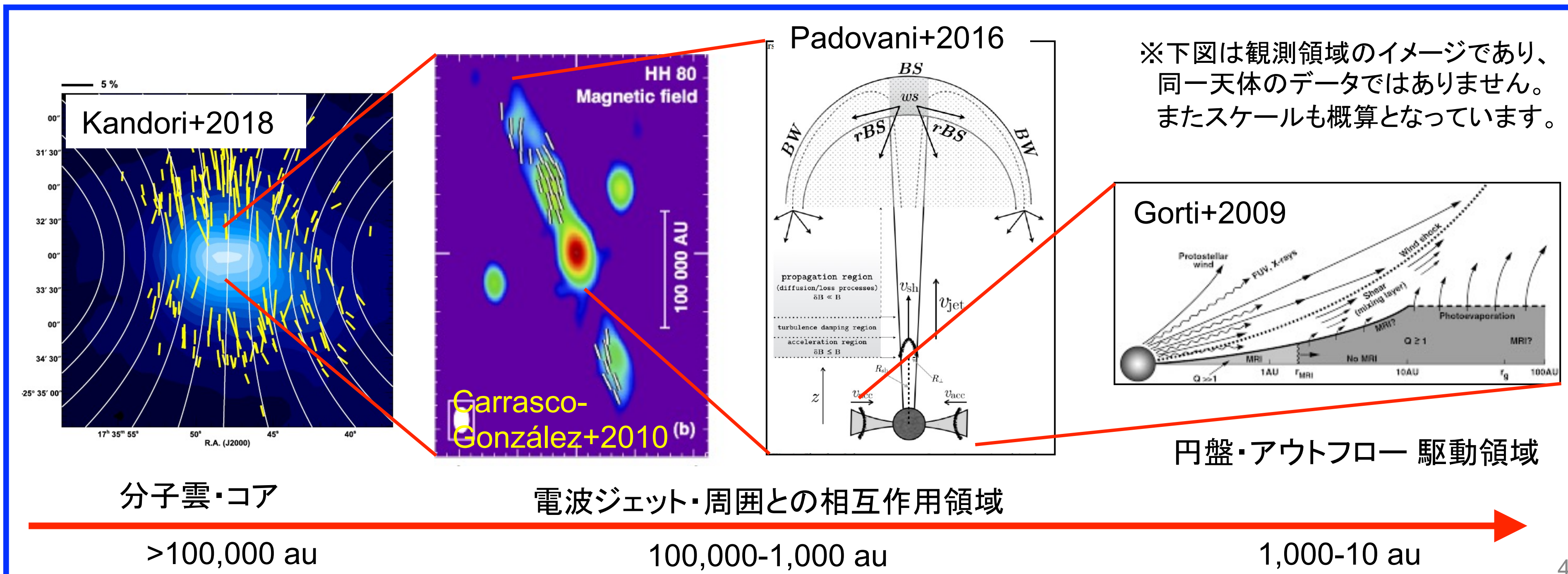
Source distance (parallax), 3D structure and time variation

Top priority science case for star and planet formation

■SKAで開拓する星形成における非熱的な世界

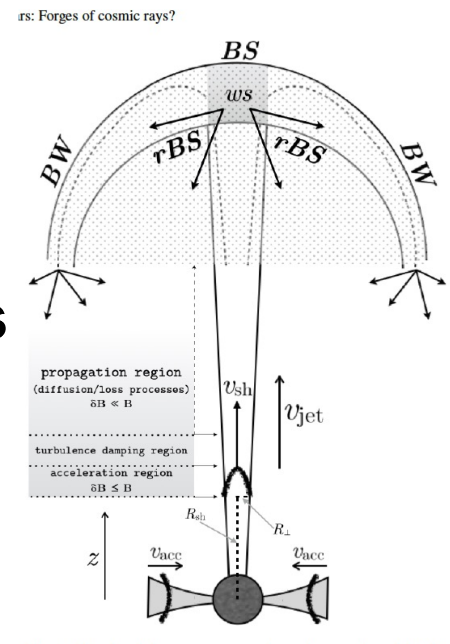
近年、星形成における長波長(100MHz-1GHz)の観測は大きな注目を集めている。例えばGMRTの観測によって低質量星周囲のジェット内でシンクロトロン放射が発見された。これに触発され、ジェット内で加速された粒子が原始惑星系円盤の新たな電離源となるのではないかといった可能性が盛んに議論されている。また、原始星におけるfree-free放射は円盤の光蒸発率ひいては円盤の寿命を決定する重要なパラメータであるがVLAでは感度不足によって十分な制限がかけられていない。

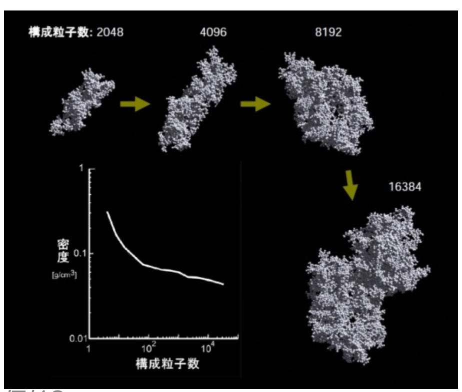
そこで我々はSKAの高感度、広視野を生かして原始星形成における非熱的な世界の開拓を目指す。特に、サーベイ研究によって原始星ジェットでのシンクロトロン放射の普遍性や光蒸発率の定量的解明を行う。また、高感度をいかした星無し分子雲コアからのシンクロトロン放射の観測にも挑戦し、分子雲コア磁場の定量的な解明にも取り組む。

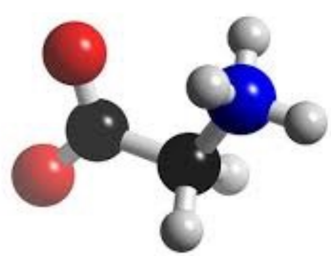


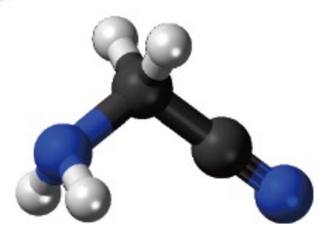
Key sciences of star and planet formation with SKA discussed in WG

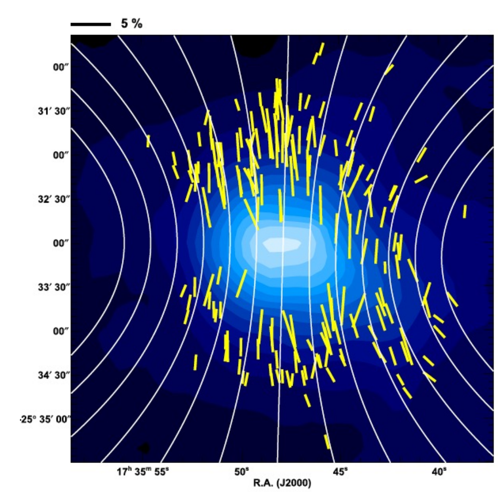
1. Radio jets from young stellar objects and relation to protoplanetary disk evolution
2. Measurement of magnetic field strength by synchrotron emission from cloud cores
3. Dust growth, Pebble accretion and planet formation
4. Search of pre-organic molecular and cradle of life





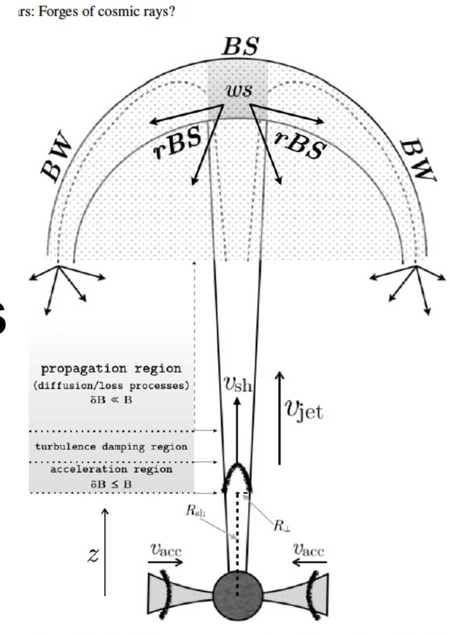


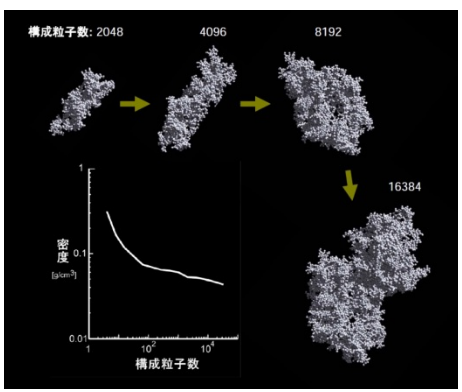


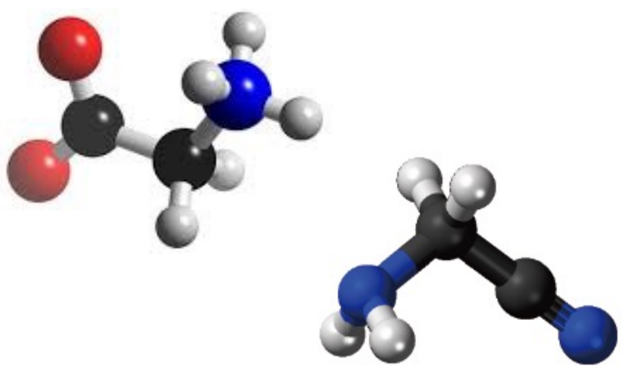


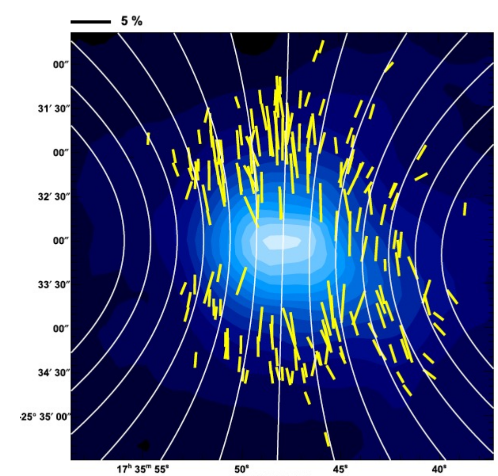
Key sciences of star and planet formation with SKA (1)

1. Radio jets from young stellar objects and relation to protoplanetary disk evolution
2. Measurement of magnetic field strength by synchrotron emission from cloud cores
3. Dust growth, Pebble accretion and planet formation
4. Search of pre-organic molecular and cradle of life





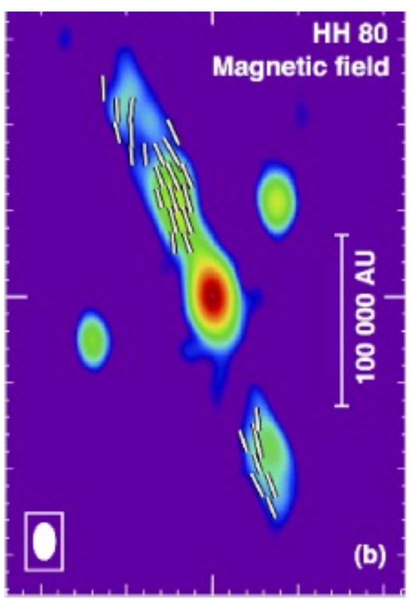




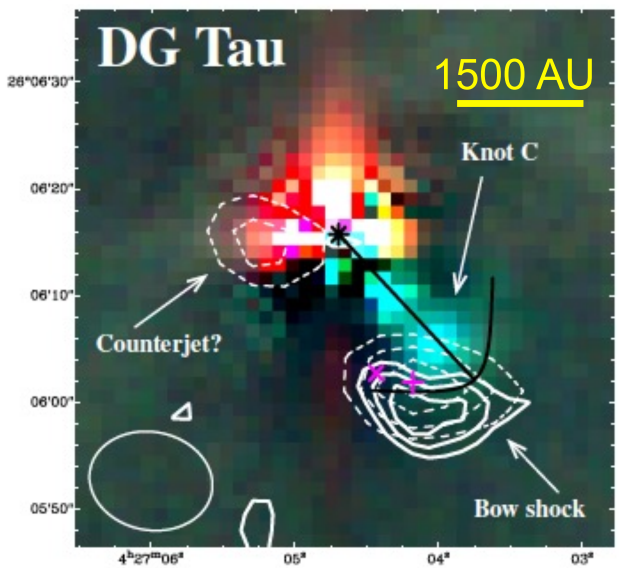
Synchrotron emission from YSO jets
Cosmic ray acceleration at strong jet

■B-field information from synchrotron emission in YSO jets

- **One of the most critical factors in star-formation, which controls accretion, ejection, and feedback for both low/high-mass YSOs**
- Strong jet proposed as an additional acceleration site of CR
- Drastically change ionization state and magnetic activity in the disk

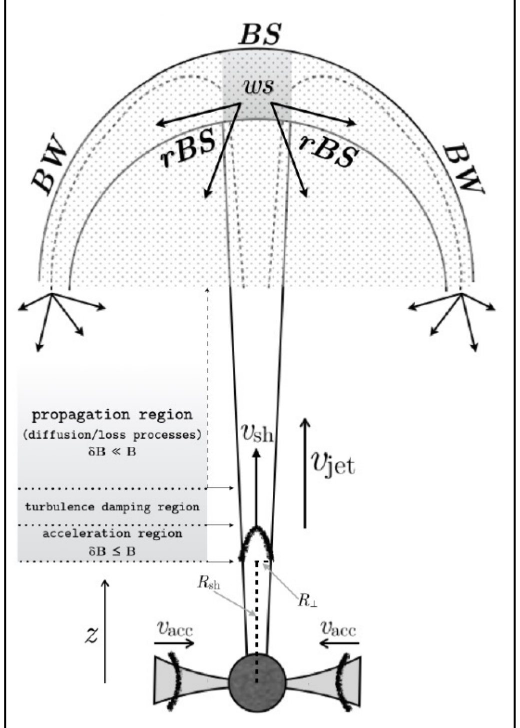


Carrasco-González+2010
HH 80-81 jet (B-star) at VLA 6 cm



Ainsworth+2014:
DG Tau at GMRT 325 and 610 MHz

Padovani+2016



Free-free emission, stellar activity and disk evolution

■UV and X-ray information from free-free emission of YSO disks

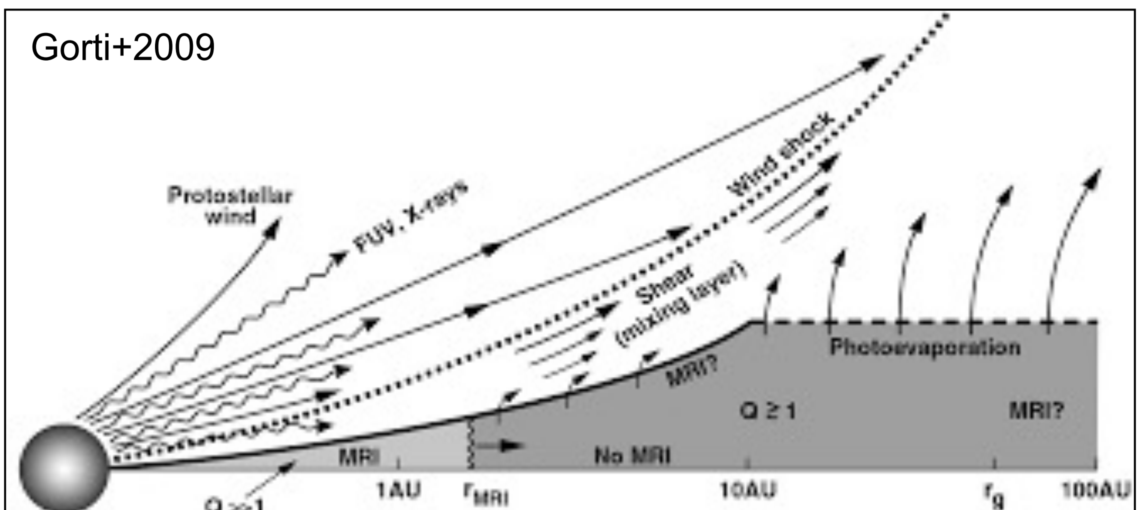
- **Key roles for disk evolution, which affect photo-evaporation, ionization, and chemistry of disks**

$$F_{3.5\,\mathrm{cm}} = 2.9 \times 10^{-39} \left(\frac{51}{d}\right)^2 \Phi_{\mathrm{EUV}} \ (\mu\mathrm{Jy}) \qquad (2)$$

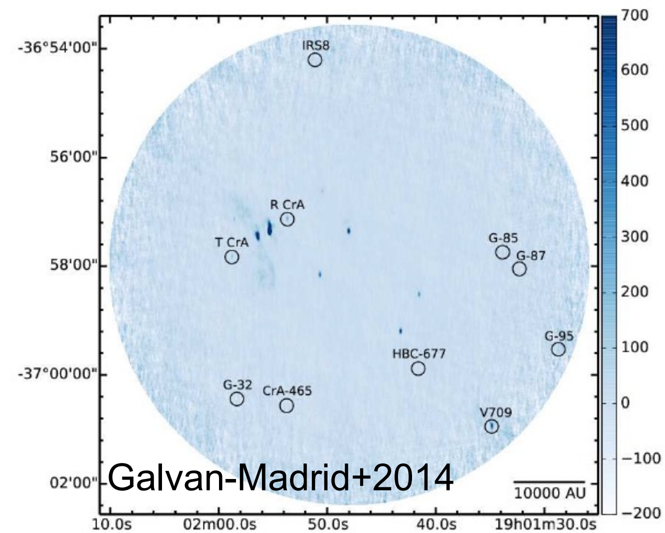
$$F_{3.5\,\mathrm{cm}} = 2.4 \times 10^{-29} \left(\frac{51}{d}\right)^2 L_{\mathrm{X}} \ (\mu\mathrm{Jy}), \qquad (3)$$

Pascucci+2012

- 8 μJy/beam @VLA 9GHz for 1.7 hrs; $\Phi_{EUV}<10^{41}$ s^{-1} , $L_x<10^{31}$ erg s^{-1}
- 1.2 μJy/beam/$hr^{1/2}$ @SKA-M 9GHz; providing more samples



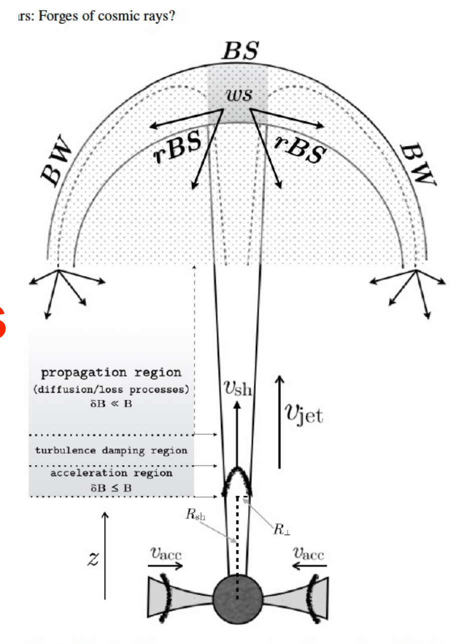
Gorti+2009

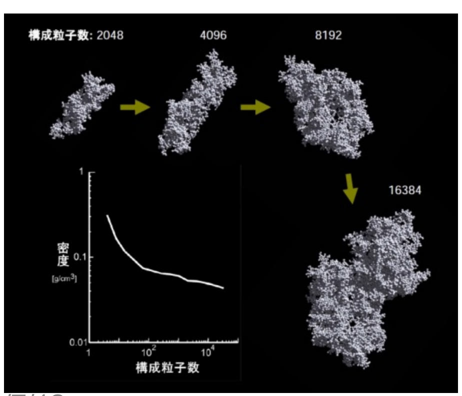


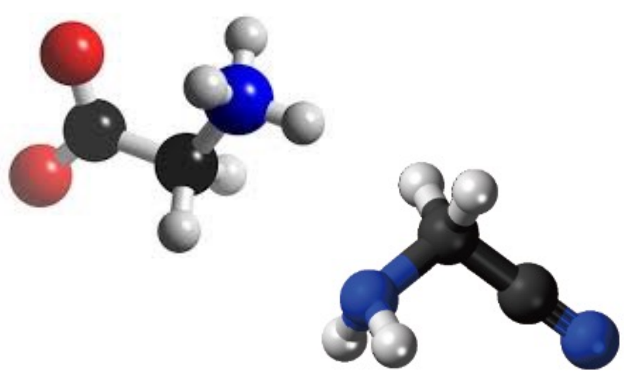
Galvan-Madrid+2014

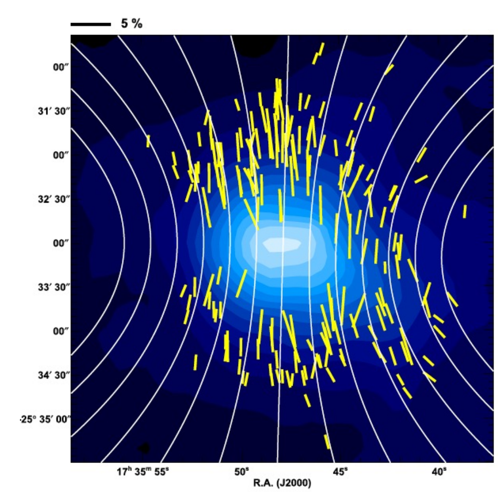
Key sciences of star and planet formation with SKA (2)

1. Radio jets from young stellar objects and relation to protoplanetary disk evolution
2. **Measurement of magnetic field strength by synchrotron emission from cloud cores**
3. Dust growth, Pebble accretion and planet formation
4. Search of pre-organic molecular and cradle of life



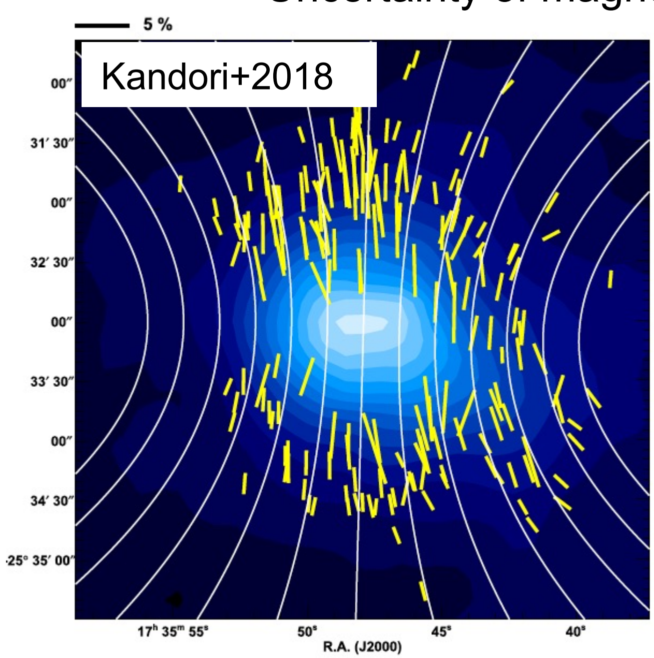




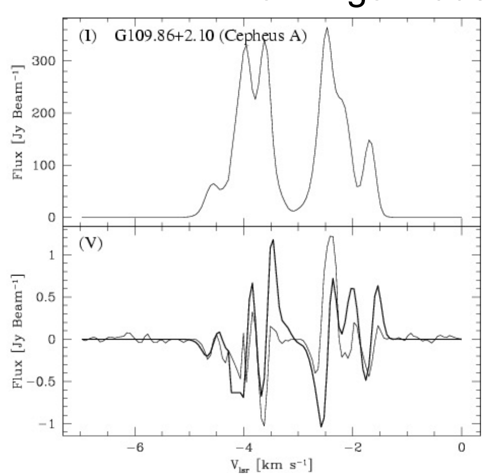


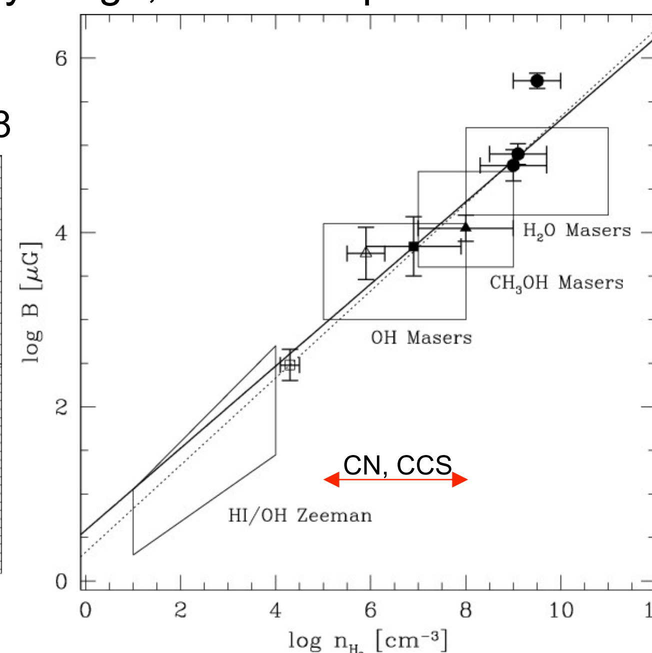
Measurement of B field in core scale

- **Also important in star-forming regions at larger scales**
- Need confirmation with new different methods
  - Chandrasekhar-Fermi method with polarized emission
    - ✓ Magnetic field obtained using the following equation: $B_{\perp} = (4\pi\rho)^{1/2}\frac{\Delta V}{\Delta\phi}$
    - ✓ Assumption on background B field, energy equipartition to turbulence
  - Zeeman effect
    - ✓ Uncertainty of magnetic moment, narrow density range, small sample



Vlemmigs+2008





Synchrotron emission from cloud core

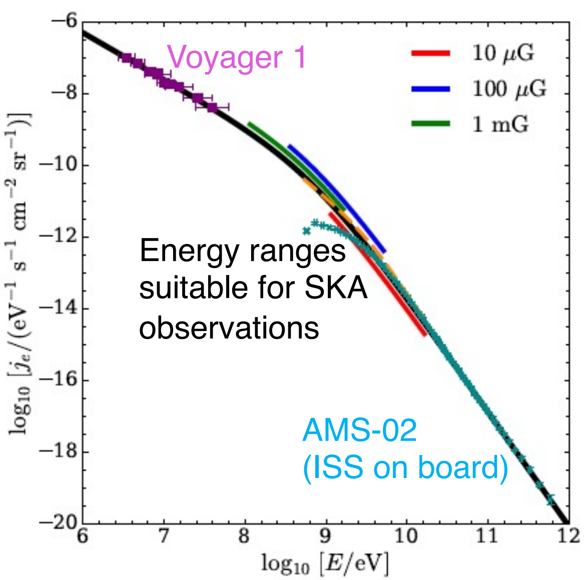
■B-field measurement with synchrotron emission (Brown+1977)

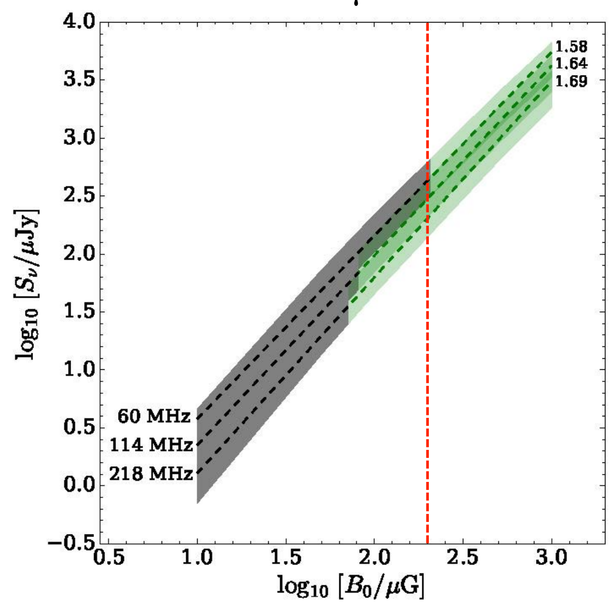
- Merit: small parameters in the model
  - ✓ Only depend on SED of electron and LoS B field
  - ✓ SED of electron in <500MeV recently measured by Voyager I (Cummings+2016), but possibly lower than in molecular clouds (Phan+2018)

$$I_\nu(b) = \int_0^{s_{\max}(b)} \epsilon_\nu(s)\,\mathrm{d}s = 2\int_b^R \epsilon_\nu(r)\frac{r\,\mathrm{d}r}{\sqrt{r^2-b^2}},$$

$$\epsilon_\nu(r) = \int_{m_e c^2}^{\infty} \frac{j_e(E,r)}{v_e(E)} P_\nu^{\mathrm{em}}(E,r)\,\mathrm{d}E,$$

- 1-hr integration for detection with B=30-100 μG at SKA-L 60-220 MHz
  - ✓ Lower detection limit than the critical B-field of ~200 μG





Padovani+2018
Padovani+2020

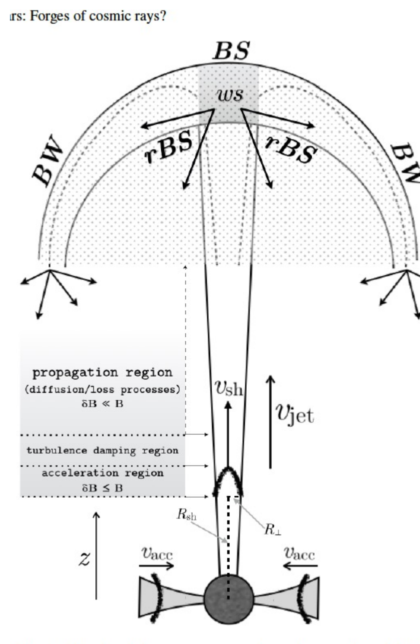
Specifications and strategy

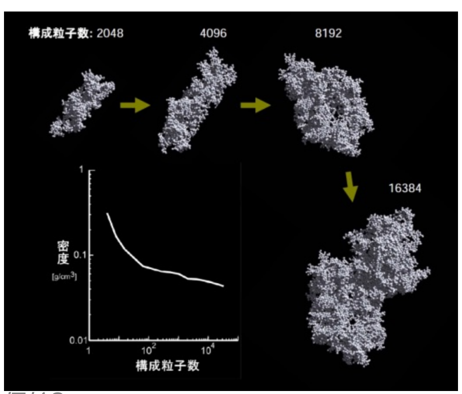
- New windows for non-thermal processes in various star/planet-forming regions within only short observing time (~1hr/field)
- Complementary to other projects at multi-wavelengths
  - Detailed view of thermal emission mm/sub-mm with ALMA and ng-VLA
  - Time-domain phenomena of optical/IR variation and X-ray flares
  - Wide-field long-term survey/monitor with SKA1

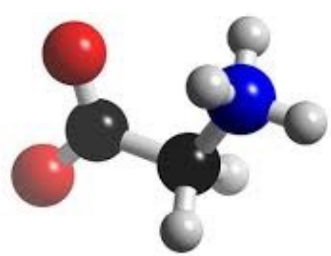
	3. Jets and disks	**4. Magnetic field**
Targets	Star/cluster-forming regions	Molecular clouds
Frequency	SKA-M (and L), e.g. 9 GHz	SKA-L, 60-220 MHz
Field of view	<100,000 au or 1000"-100"@0.1-1 kpc	>100,000 au or >1000"-100"@0.1-1 kpc
Spatial resolution	10-100 au or 0.1" @0.1-1 kpc	100-1000 au or 1"@0.1-1 kpc
Spectral setting	Only continuum mode, full polarization	Only continuum mode, full polarization
Sensitivity	~1 μJy/beam/hr$^{1/2}$	~1 μJy/beam/hr$^{1/2}$
Integration time	An order of 1hr/field	An order of 1hr/field
Number of filed	100 fields for ~1000 sources (TBD)	100 field to cover ~10,000 degrees^2 (TBD)

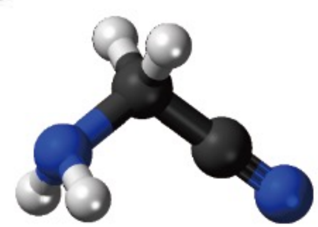
Key sciences of star and planet formation with SKA (3)

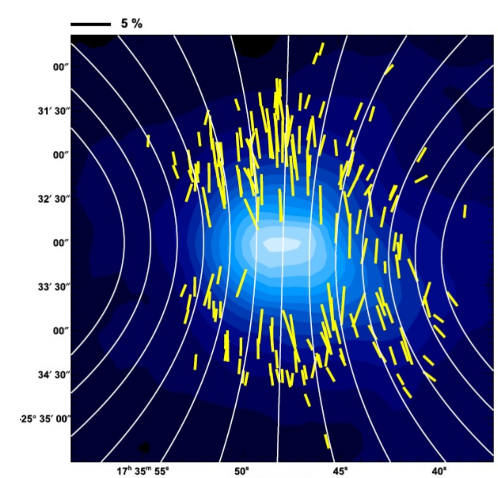
1. Radio jets from young stellar objects and relation to protoplanetary disk evolution
2. Measurement of magnetic field strength by synchrotron emission from cloud cores
3. **Dust growth, Pebble accretion and planet formation**
4. Search of pre-organic molecular and cradle of life







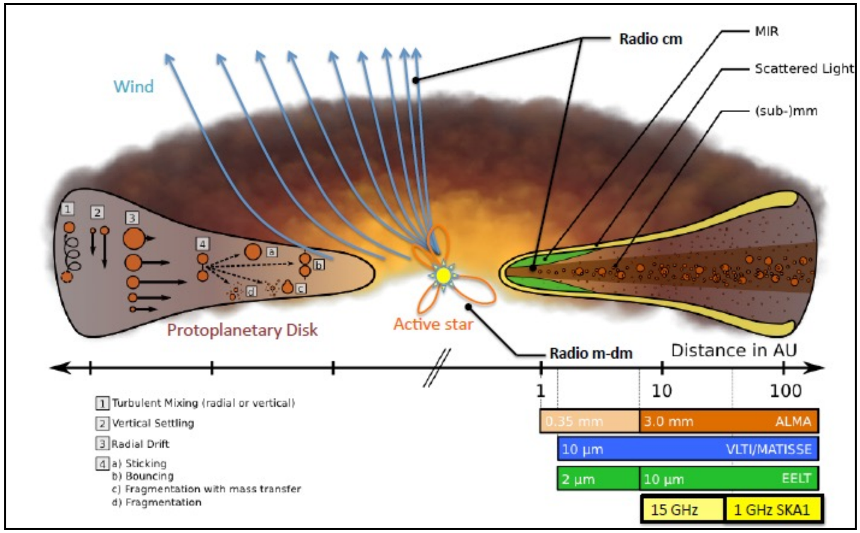


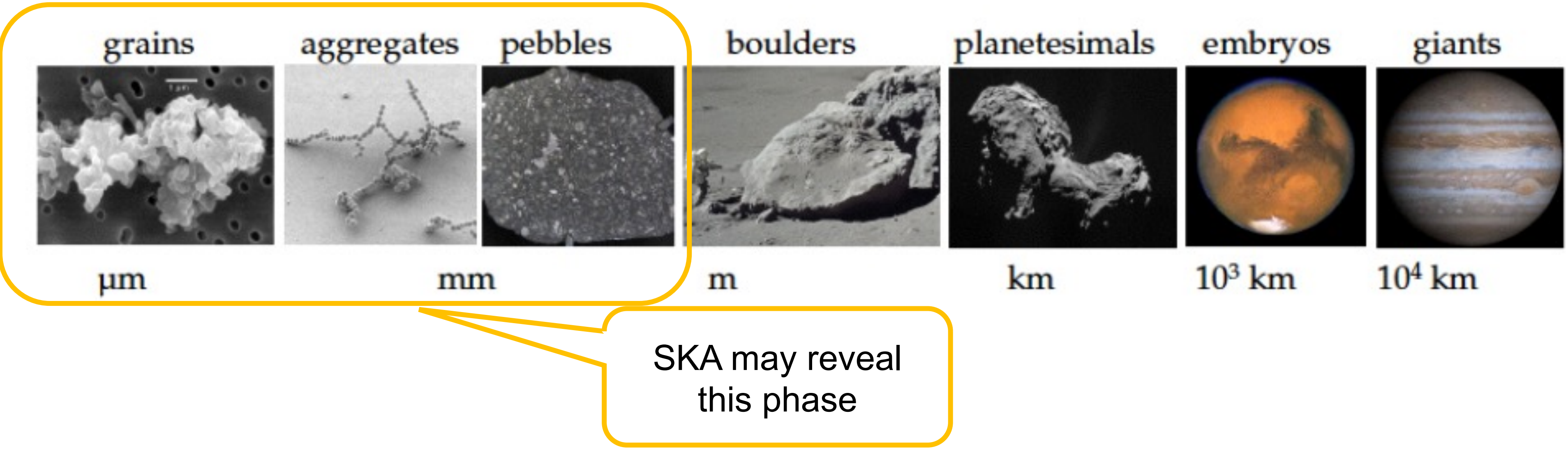


From dust to planet

- Sub-micron dust grains of ISM are fundamental building block of planets
- When and how they grow in the disk?

Testi+2015





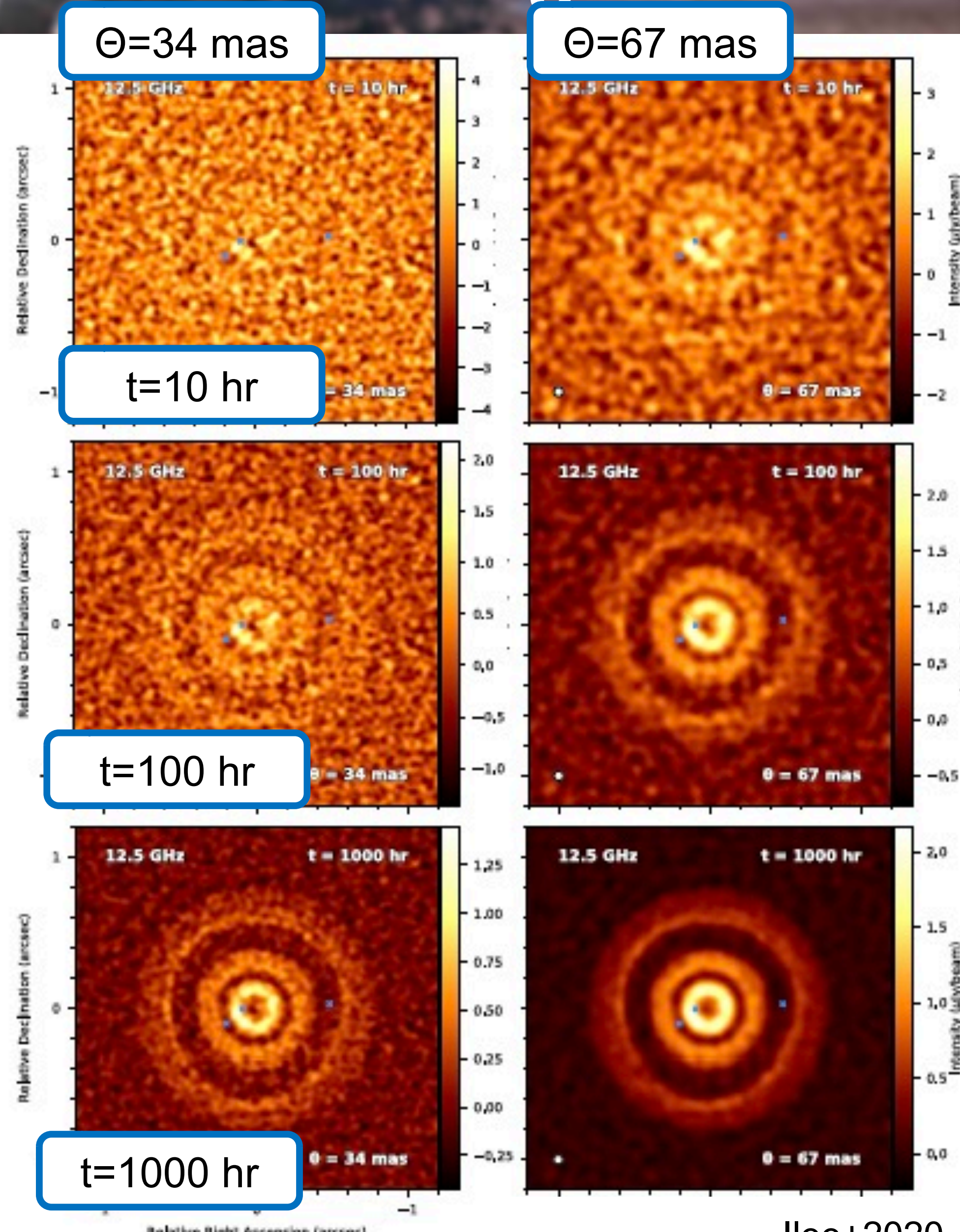
Possible evidence of dust growth?

■Spatial variation of the dust opacity index β

- $\tau_\nu \propto \kappa_\nu$; $\kappa_\nu = \kappa_0 \nu^\beta$, $F_\nu \propto \nu^{\beta+2}$
- Apparent low-β of optically thick sub-mm dust emission
- Crucial to determine β from optically thin lower frequency SED

■Feasibility test of disk observations with SKA1

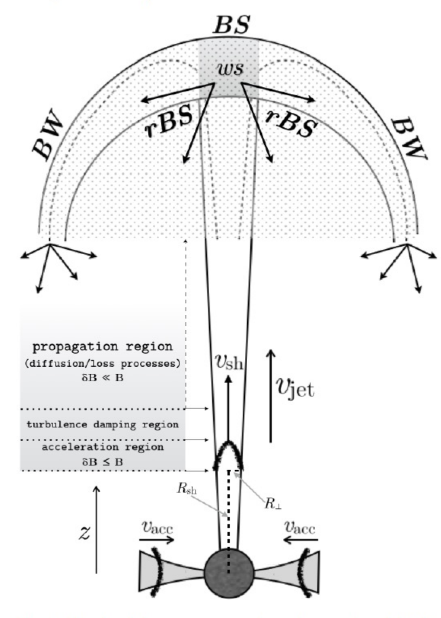
- ν=12.5 GHz (band 5b)
- 100-1000 hrs for SNR=10
  - ✓ c.f. ~150 hrs at Band 5c 20 GHz (Tsukamoto+2020, science book)
  - ✓ c.f. ~20 hrs at ng-VLA 30-100 GHz (Ricci+2018)

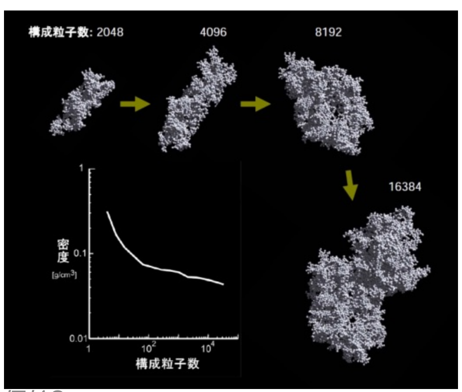


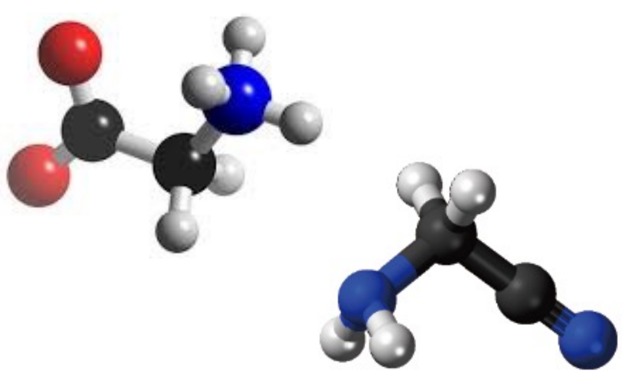
Ilee+2020

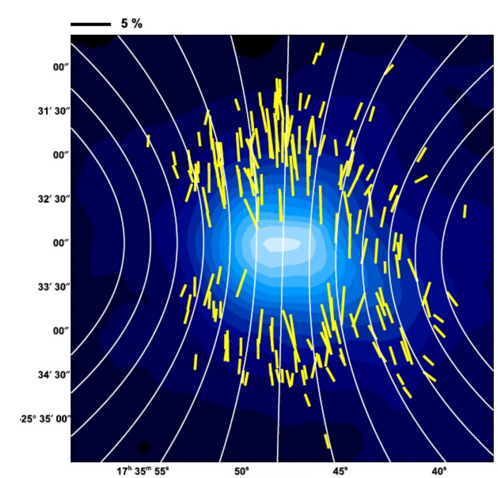
Key sciences of star and planet formation with SKA (4)

1. **Radio jets from young stellar objects and relation to protoplanetary disk evolution**
2. **Measurement of magnetic field strength by synchrotron emission from cloud cores**
3. **Dust growth, Pebble accretion and planet formation**
4. **Search of pre-organic molecular and cradle of life**



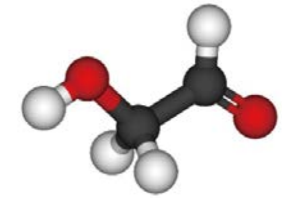


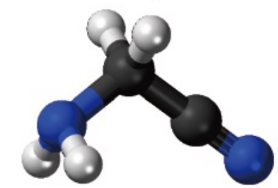




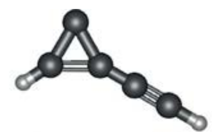
Pre-biotic COMs in ISM

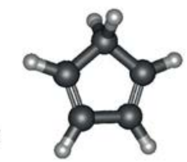
- **Several prebiotic COMs found in hot cores/corinos**
  - Glycholaldehyde, CH_2OHCHO (Beltran+09,Jorgensen+12)
  - Amino acetonitrol NH_2CH_2CN (Belloche+2008)
    - ✓ Detection of various precursor of amino-acids
    - ✓ No detection of amino-acids in molecular clouds to date

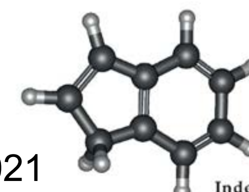




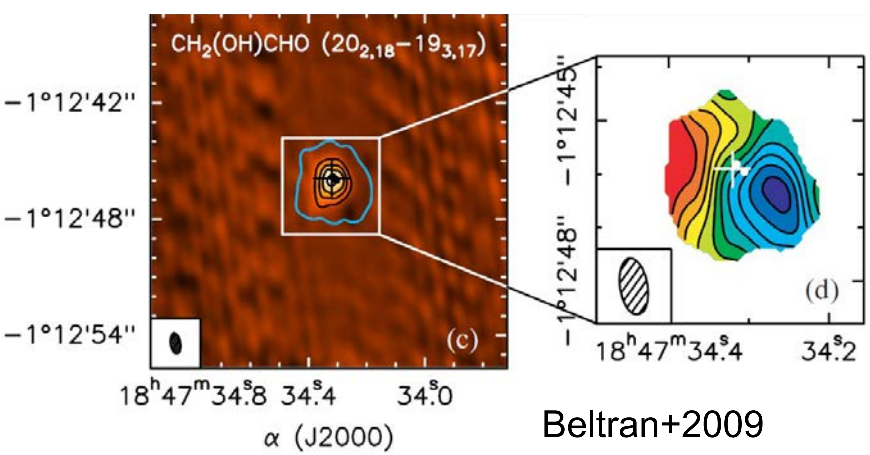
- **Grand challenge for astro-chemistory/biology**
  - Wide-band single-dish survey (GBT, Yebes 40m)
  - High resolution interferometer imaging (SMA, ALMA)
    - ✓ COMs, Long carbon-chains, aromatic molecules



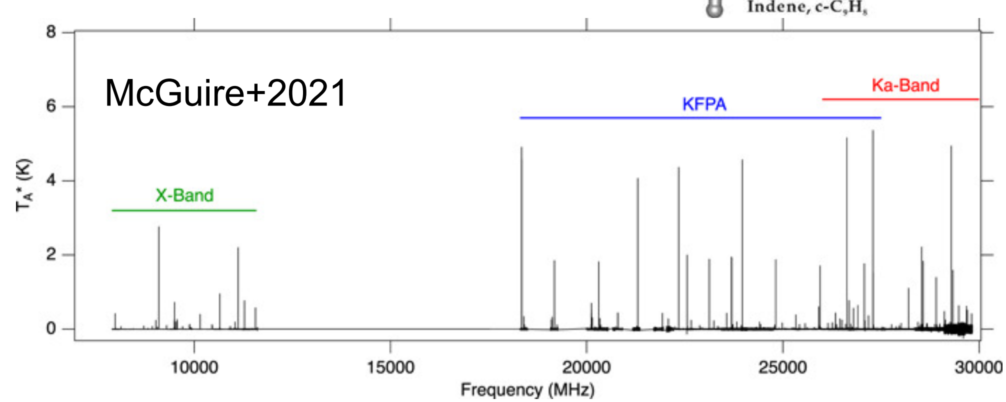




Cernicharo+2021



Beltran+2009

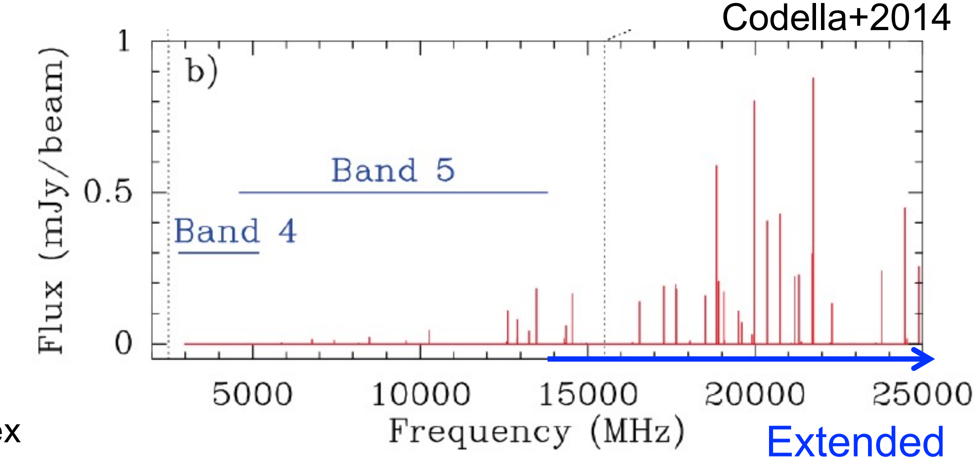


Feasibility with SKA1

■Advantage of low-frequency

- Less small/light molecules
  - ✓ $\nu \propto 2B(J+1)$
  - ✓ $B \propto (\text{molecular weight}*\text{size}^2)^{-1}$
- Smaller line broadening or overlapping
  - ✓ $\Delta\nu \propto \Delta V/c*\nu$
- More population under lower T_{ex}
  - ✓ But weak, $T_b \propto \tau T_{ex}$

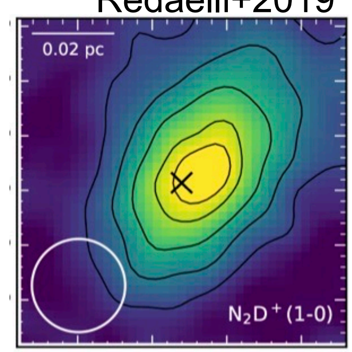
Codella+2014



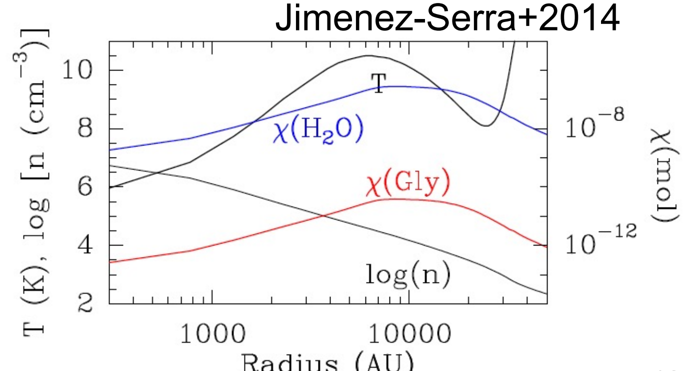
■Target: cold dark cloud L1544

- Size=12”, T=10 K
- 0.15 mJy/beam @<15 GHz
  ~300 hrs for 3σ
- 0.5 mJy/beam @~25 GHz
  ~30 hrs for 3σ

Redaelli+2019



Jimenez-Serra+2014



KSP of "Cradle of Life": Deep integration of cluster forming region

■How can we manage deep observations for dust continuum and COMs lines?

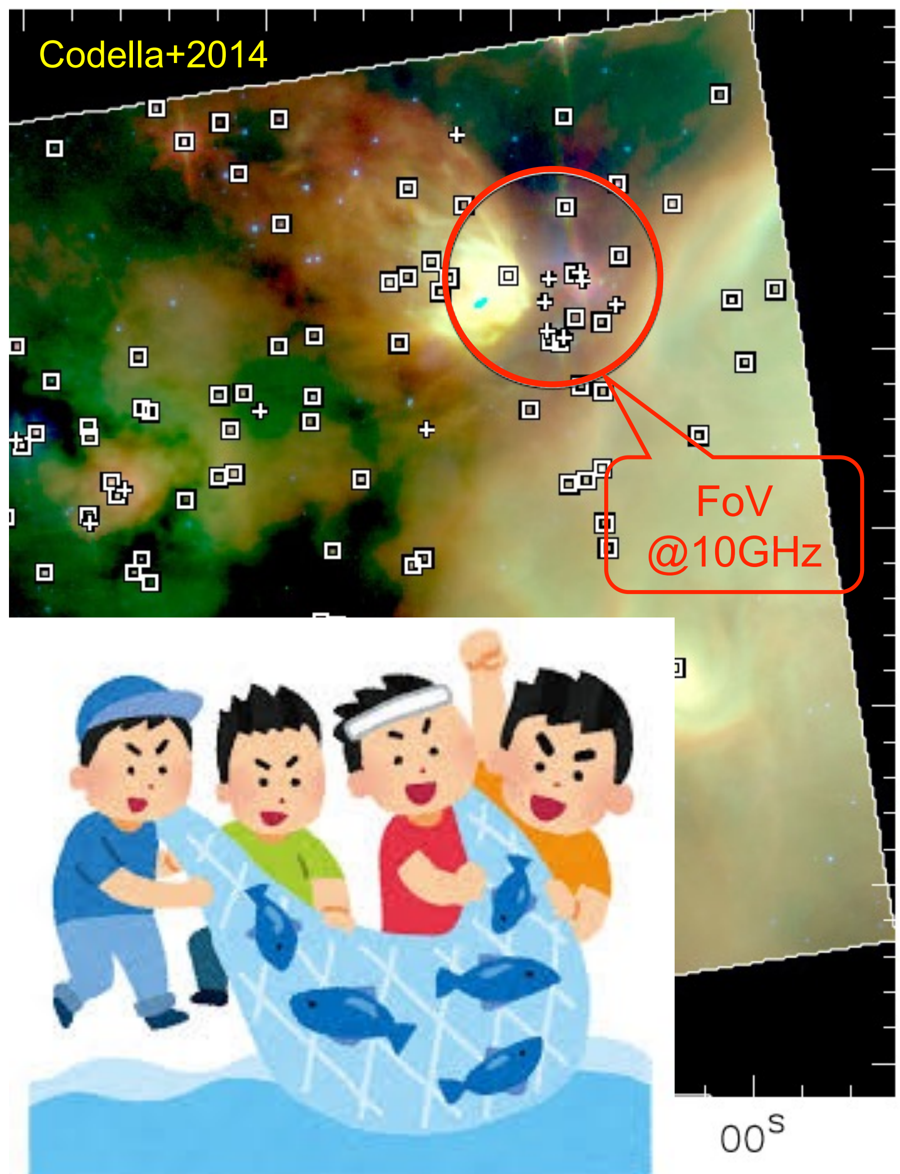
- Several 100hr or up to 1000hr integration for both cases

■Deep field at the center of a rich young cluster

- 20 YSOs within 6' FoV in a low-mass cluster ρ-Oph A at 120 pc

■About 10 hours per YSO

- Trawl (地引網) strategy to hunt large grain and pre-biotic molecules, along with other multi-purposes



Summary

1. **Radio jets from young stellar objects and relation to protoplanetary disk evolution**
2. **Measurement of magnetic field strength by synchrotron emission from cloud cores**
   - Complementary to other multi-wavelength projects in terms of wide-field and long-term survey
   - Possible collaboration through commensal surveys with other KSPs
   - Significant impact on other KSPs, directly and indirectly
3. **Dust growth, Pebble accretion and planet formation**
4. **Search of pre-organic molecular and cradle of life**
   - Too large (~1000 hrs) and risky to conduct only by Japanese WG, unless higher frequency band (>Band 5c) is available
   - Better to join international SWG of Cradle of Life rather than own KSP, or to wait for ALMA band 1 or ng-VLA