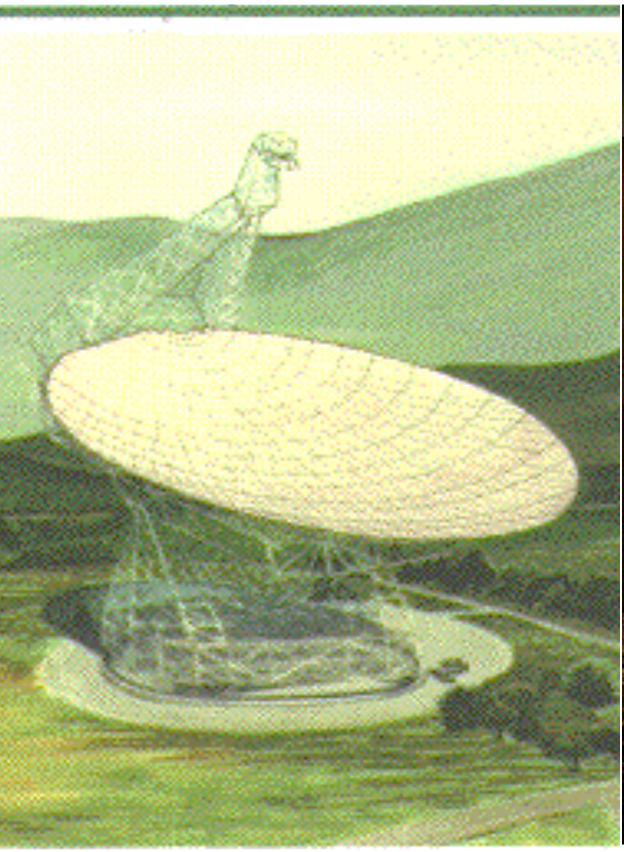
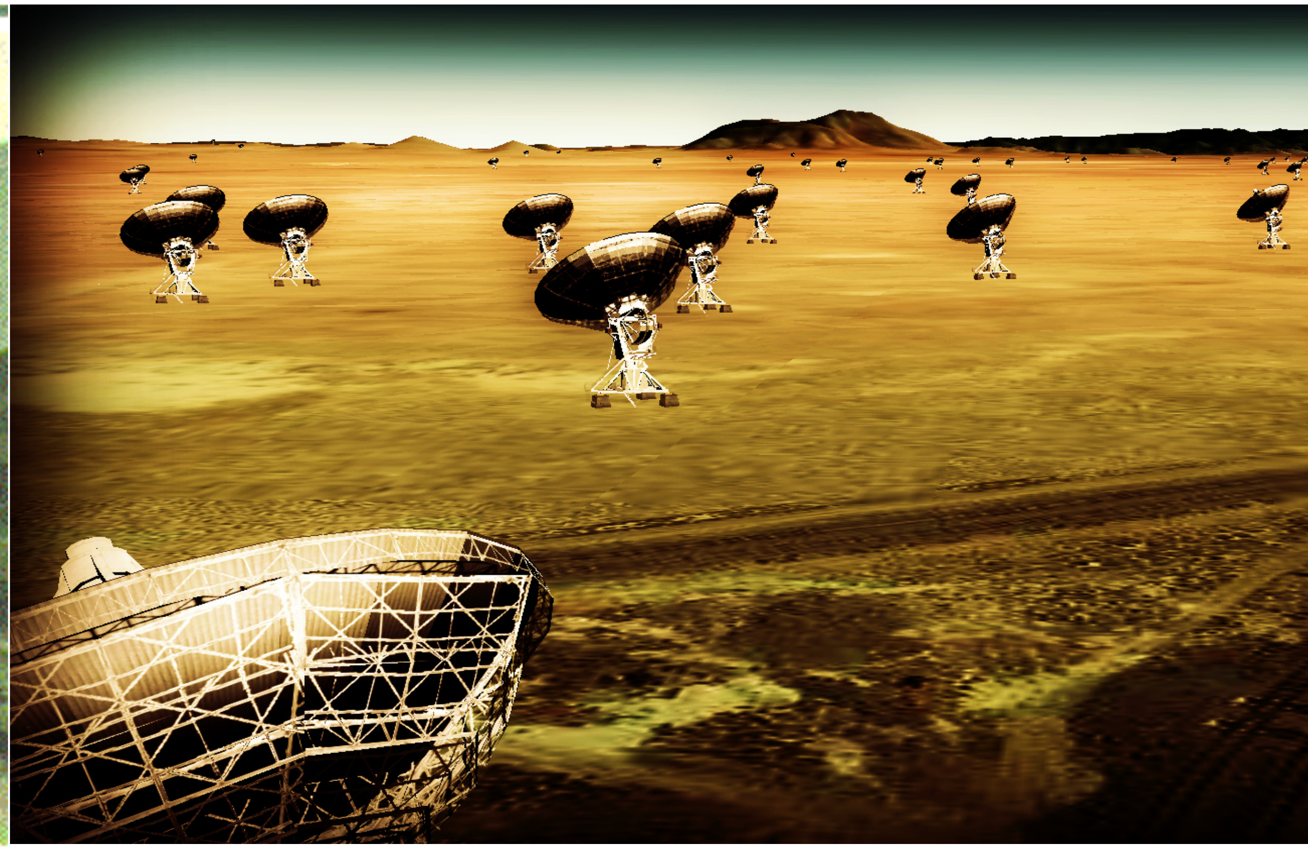
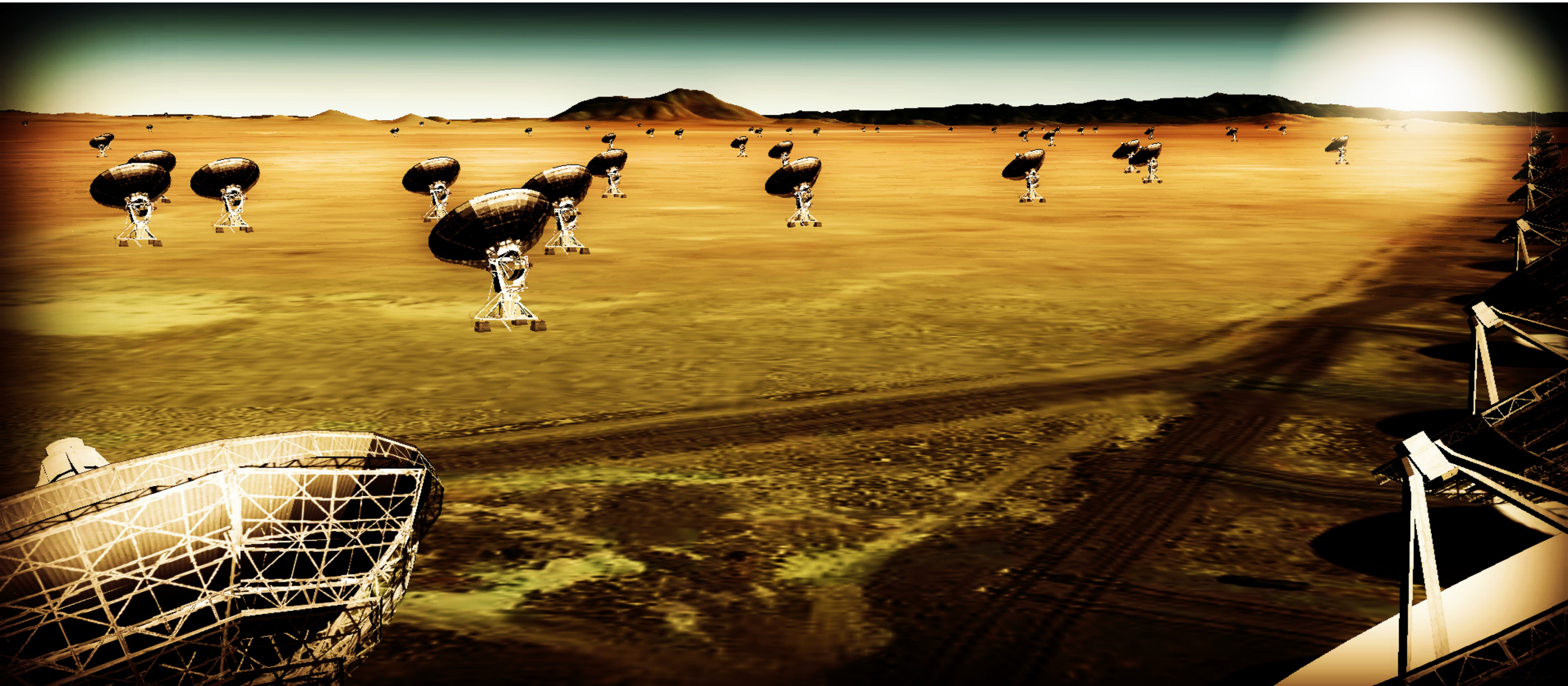
The next generation VLA and the GBT
Power on all Scales

THE VERY LARGE ARRAY
THE NEXT GENERATION

- Effective area at 40GHz ~ 10x JVLA
- Frequency range: 1 – 50, 70 – 115 GHz
- ~300 18m antennas w. 50% to few km + 40% to 200km + 10% to 3000km?
- Design goal: minimize mass production and operations costs



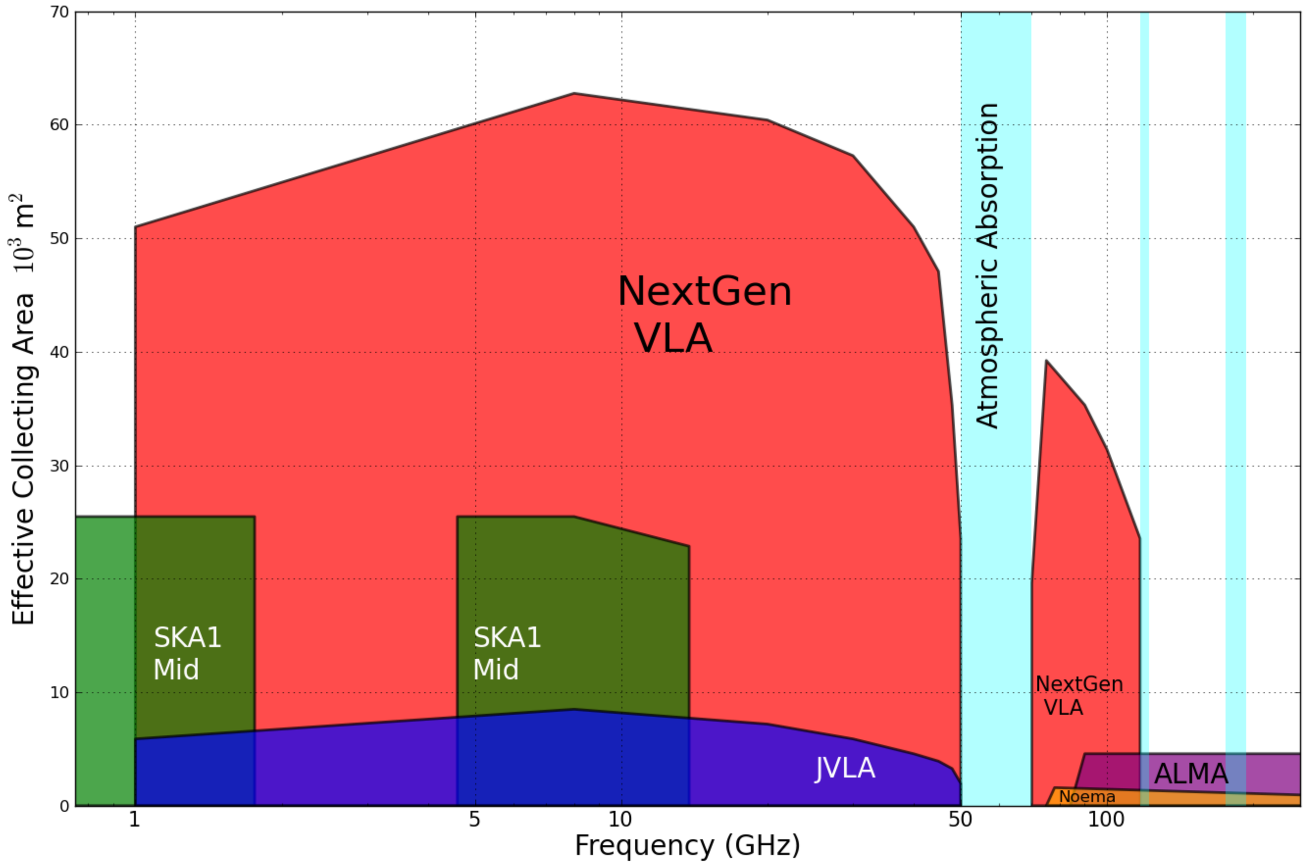
Process to date

- Science working groups
  - Circle of Life (chairs: Isella, Moullet, Hull)
  - Galaxy ecosystems (chairs: Murphy, Leroy)
  - Galaxy assembly (chairs: Lacy, Casey, Hodge)
  - Time domain, Cosmology, Physics (chairs: Bower, Demorest)
- Jan 2015: AAS Jan community discussion

  https://science.nrao.edu/science/meetings/2015/aas225/next-gen-vla/ngvla
- April 2015: Pasadena technology meeting
  - Antennas, correlators, receivers
- Fall 2015
  - SWG final White papers end September
  - Key Use Cases → science requirements → telescope specs
  - Second technical meeting: LO/IF, data transmission, operations, computing

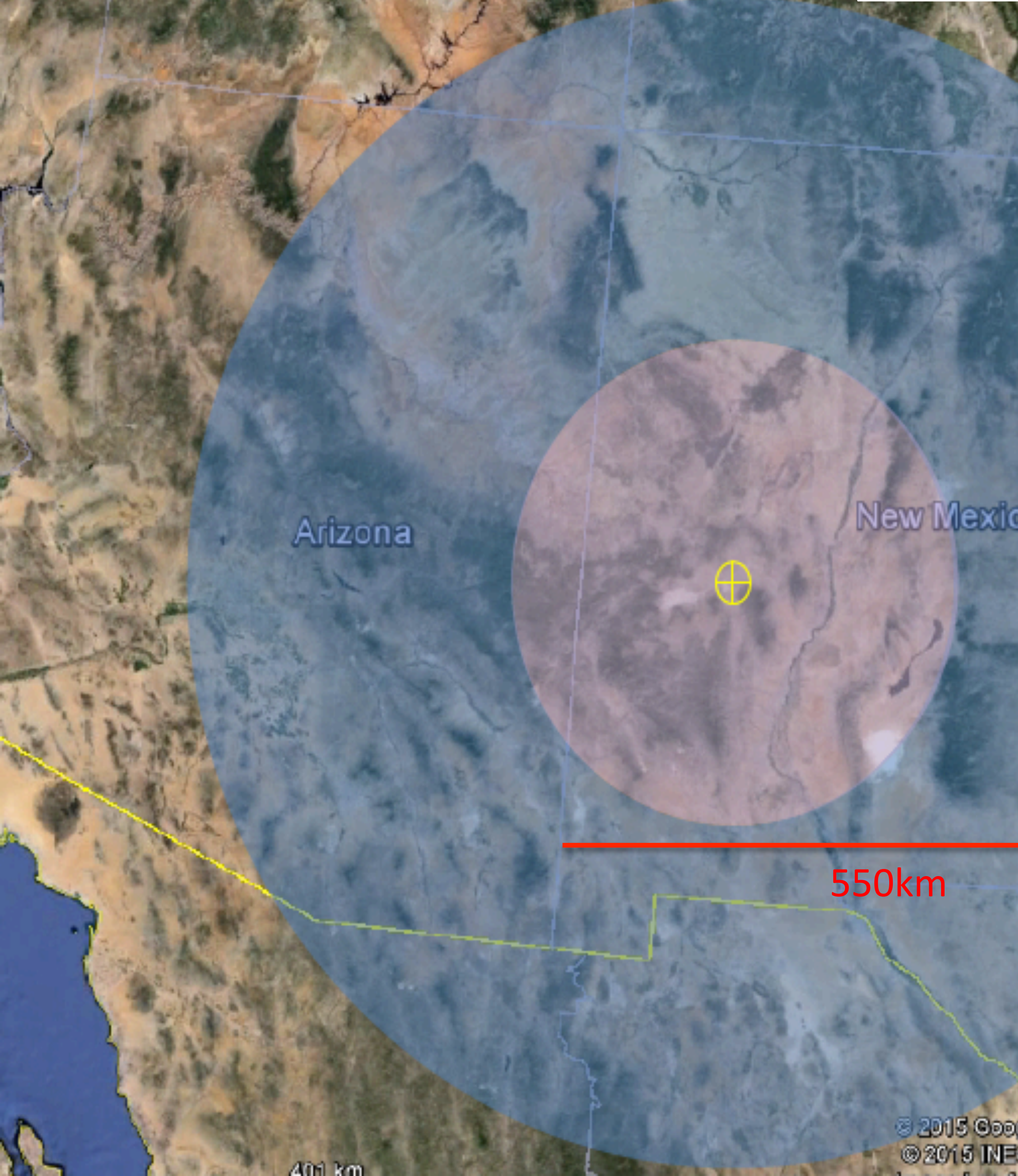
Killer Gap

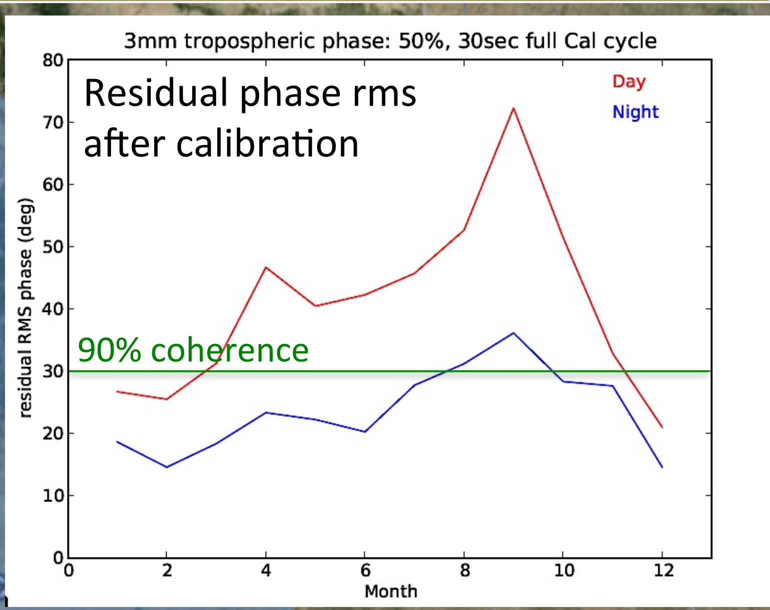
Thermal imaging on mas scales at $\lambda \sim 0.3$cm to 3cm



- Sensitivity ~ 0.1uJy @ 1cm, 10hr, BW = 20GHz
- $T_B \sim 1$K @ 1cm, 10mas
- Molecular lines become prevalent above 15GHz

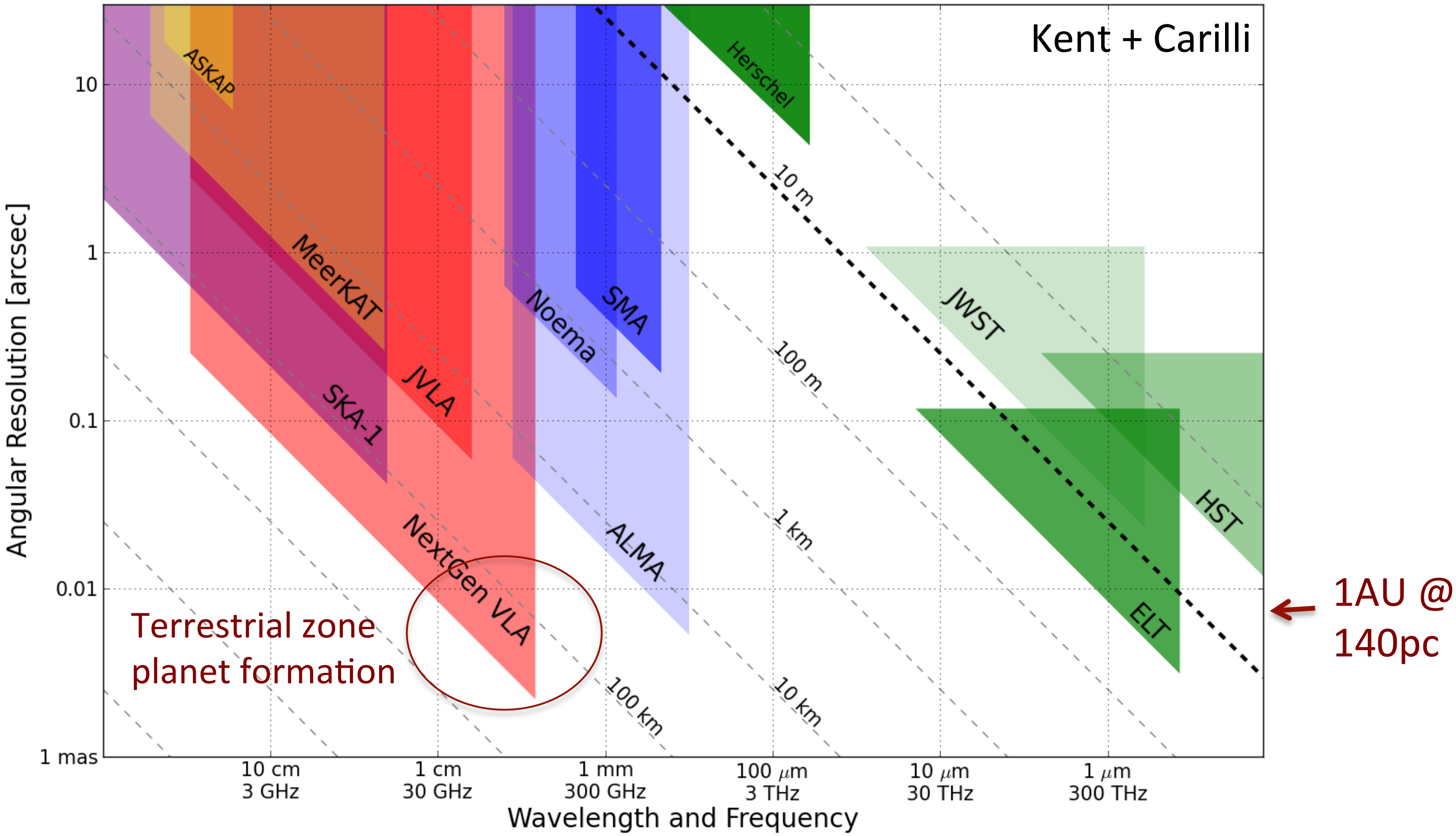
JVLA: Good 3mm site, elev. ~ 2200m





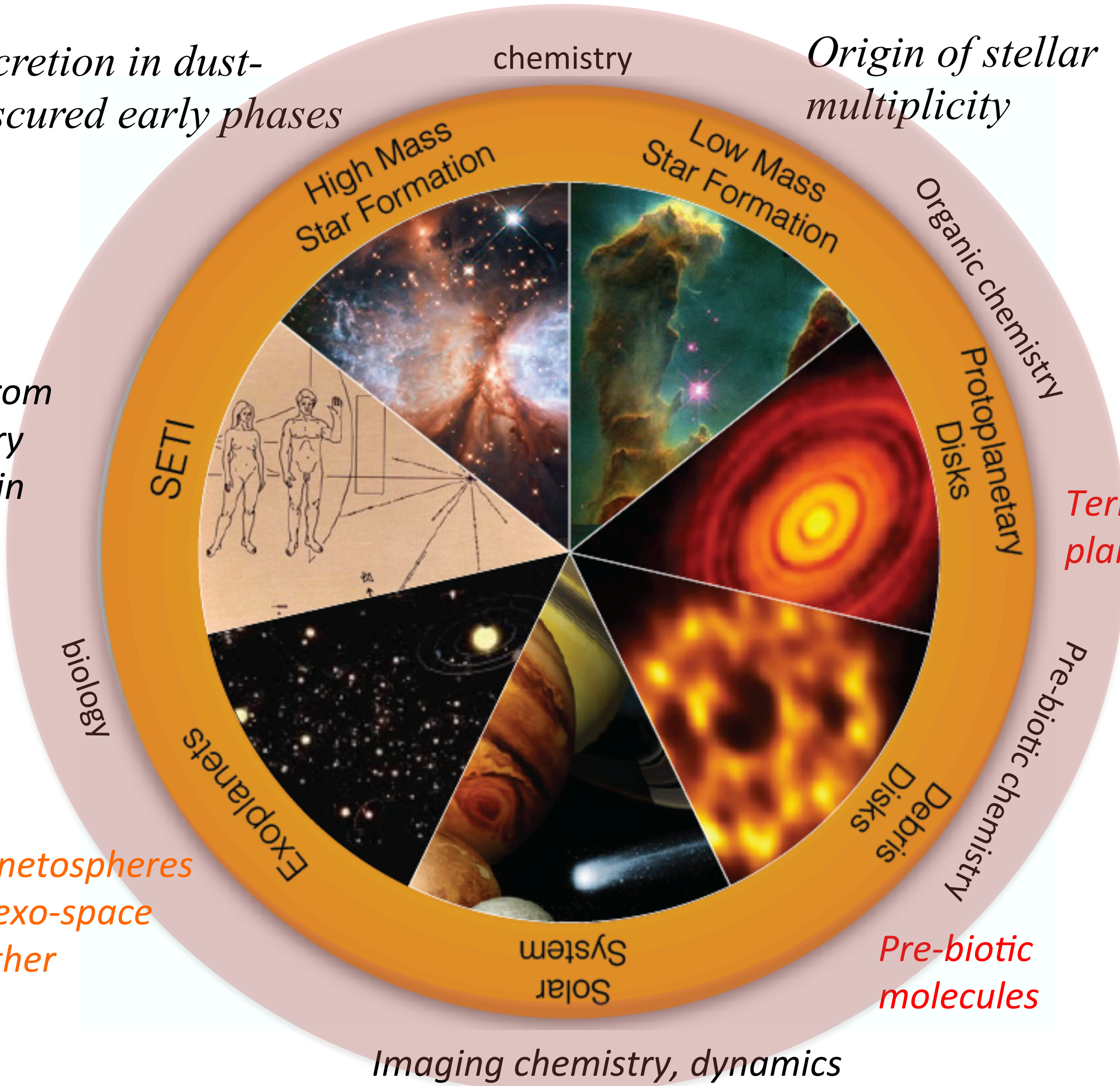
Killer Gap

Thermal imaging on mas scales at λ ~ 0.3cm to 3cm



- Resolution ~ 10mas @ 1cm (300km)

Circle of Life: origin stars, planets, life



Accretion in dust-obscured early phases

Origin of stellar multiplicity

Aircraft radar from nearby planetary systems in 10min

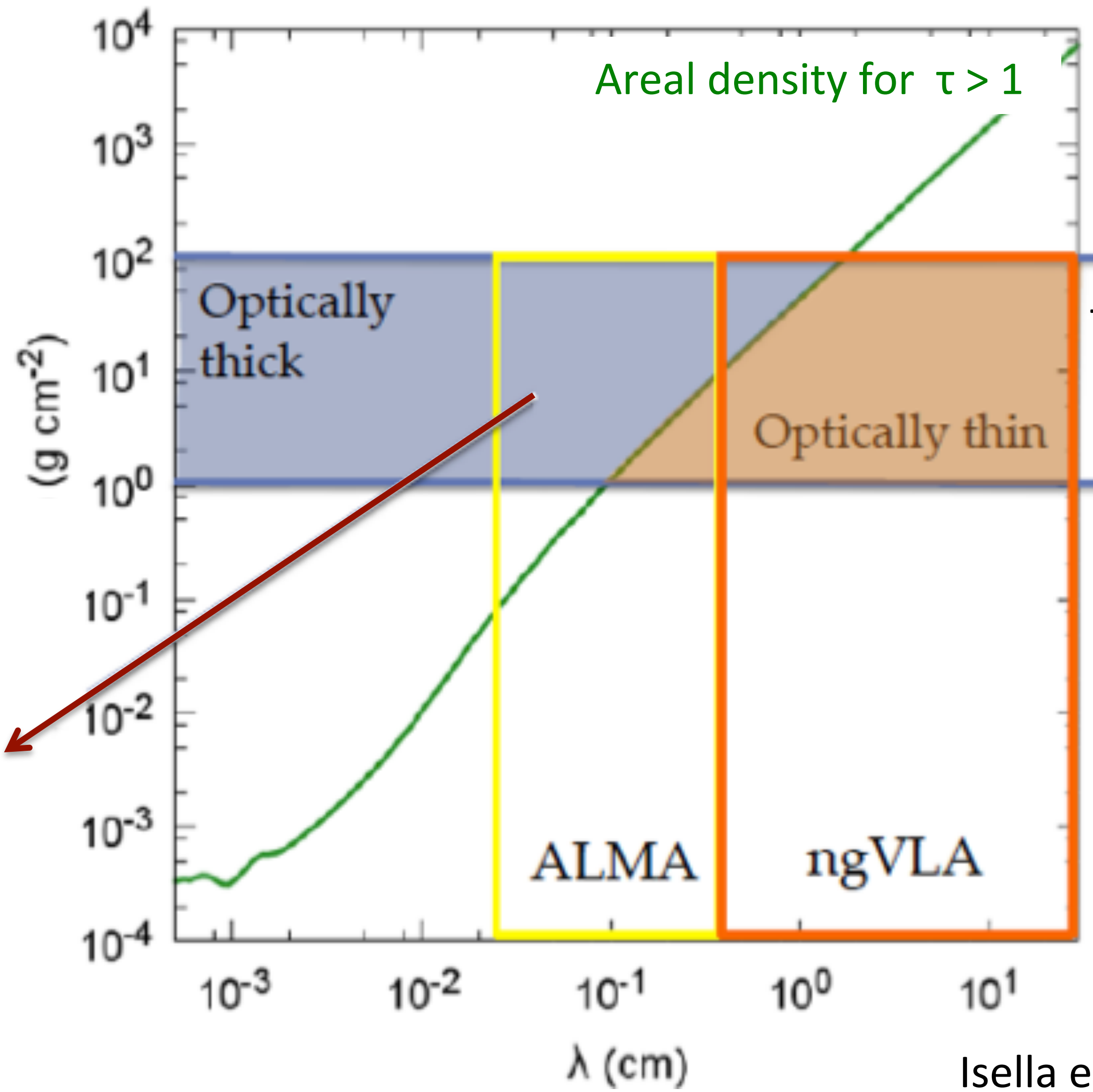
Terrestrial zone planet formation

Magnetospheres and exo-space weather

Pre-biotic molecules

Imaging chemistry, dynamics deep in planetary atmospheres

Terrestrial zone planet formation = 'ngVLA zone'



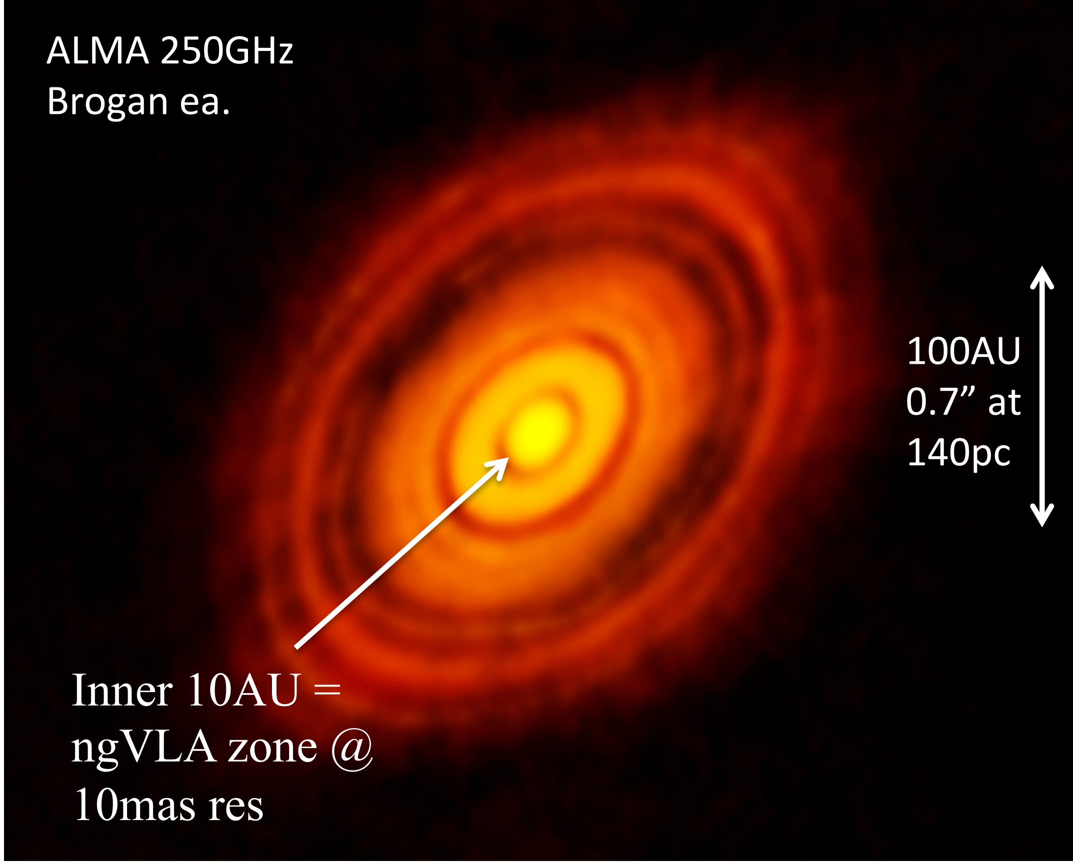
Typical ~ 1Myr protoplanetary disk at R ~ few AU

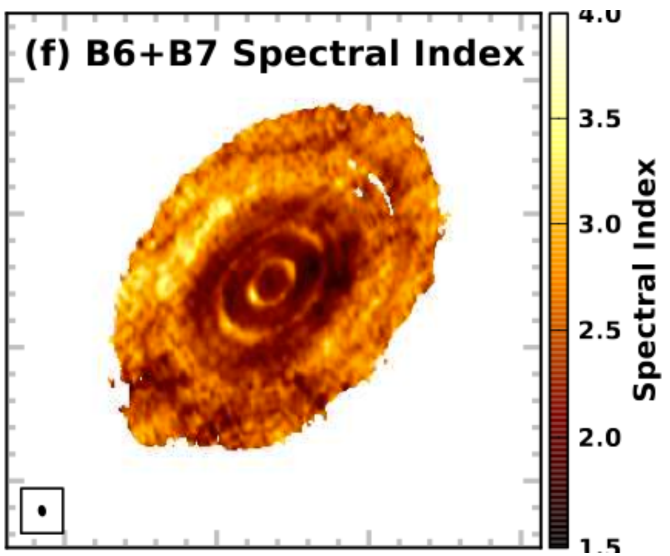
Optically thick at short ALMA wavelengths, but unresolved at long ALMA wavelengths

Isella ea.

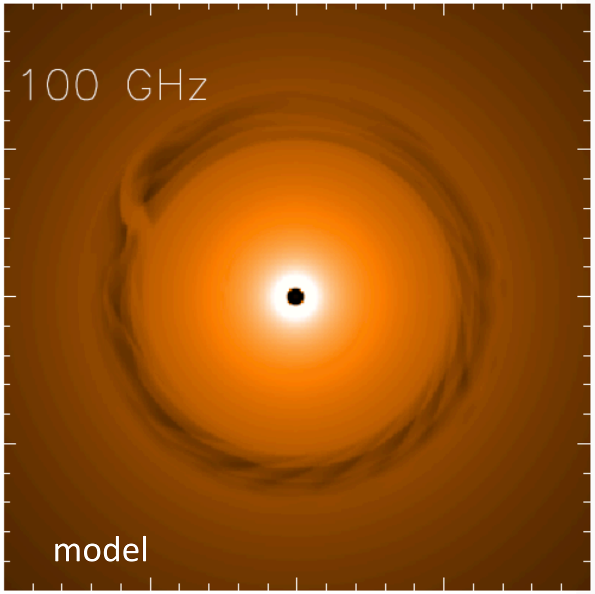
ngVLA: Terrestrial zone planet formation imager

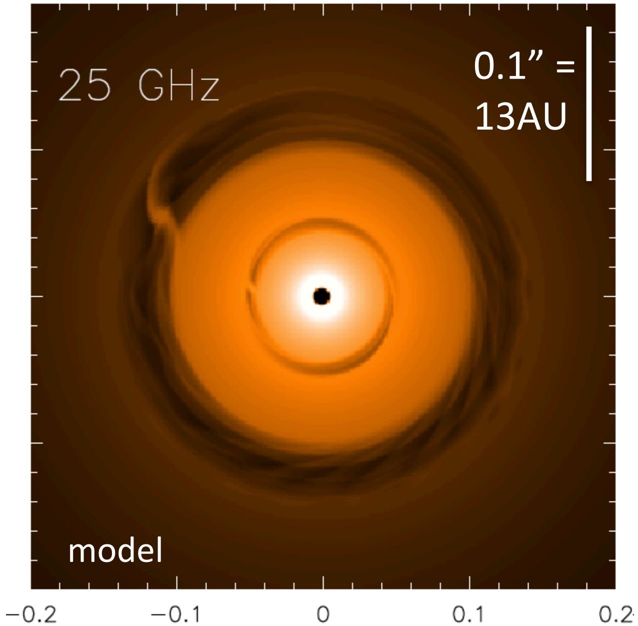
- See through dust to pebbles: inner few AU disk optically thick in mm/submm
- Grain size stratification at 0.3cm to 3cm
  - Poorly understood transition from dust to planetesimals
  - SI => combination of grain growth and optical depth

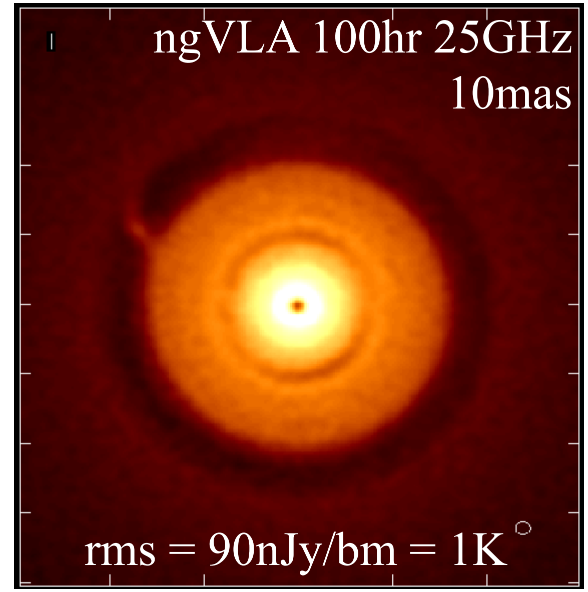




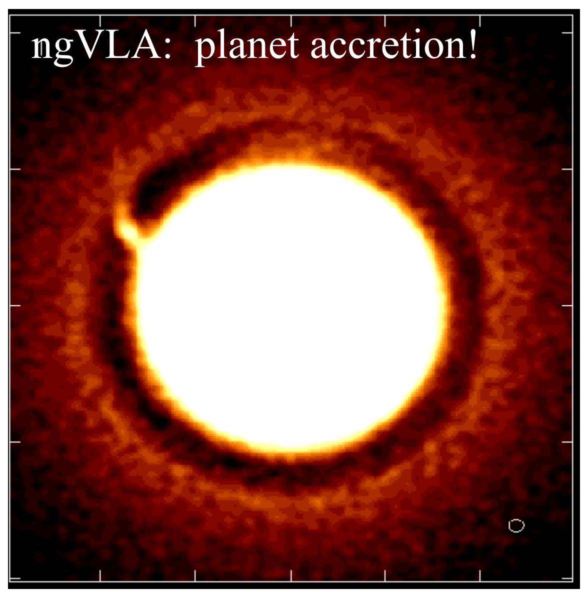
NGVLA: Protoplantary disk at 130pc distance

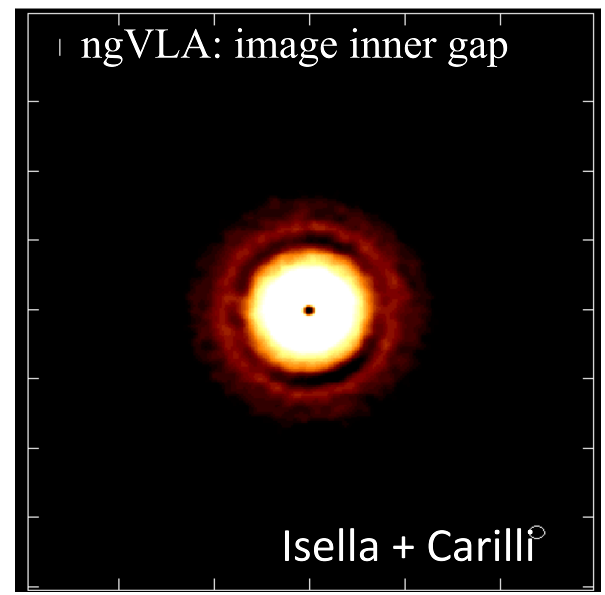






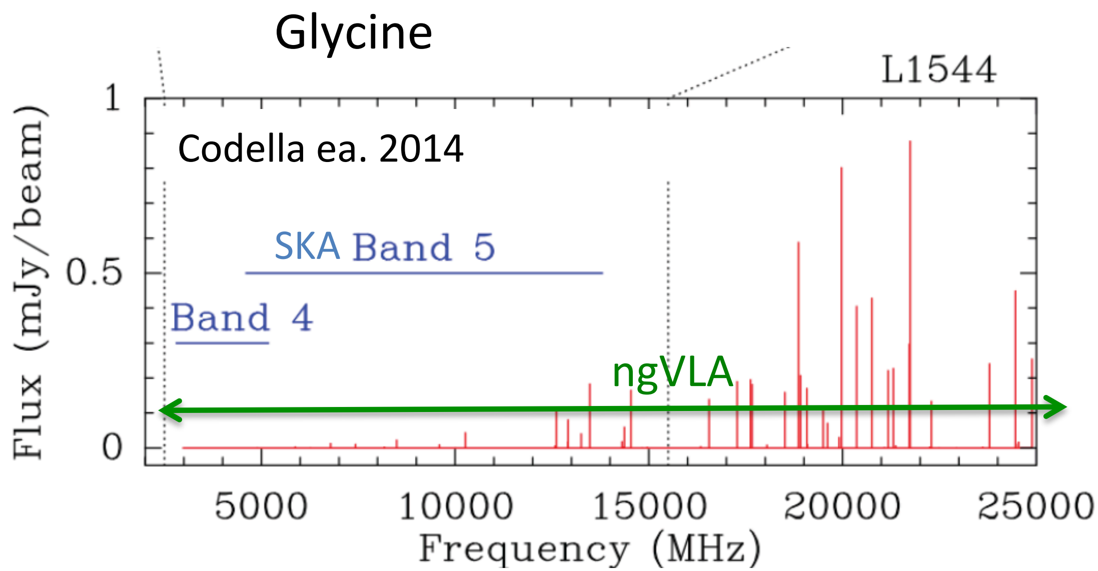
- Jupiter at 13AU, Saturn at 6AU
- Inner gap optically thick at 100GHz
- Image both gaps + annual motions
- Circumplanetary disks: imaging accretion on to planets

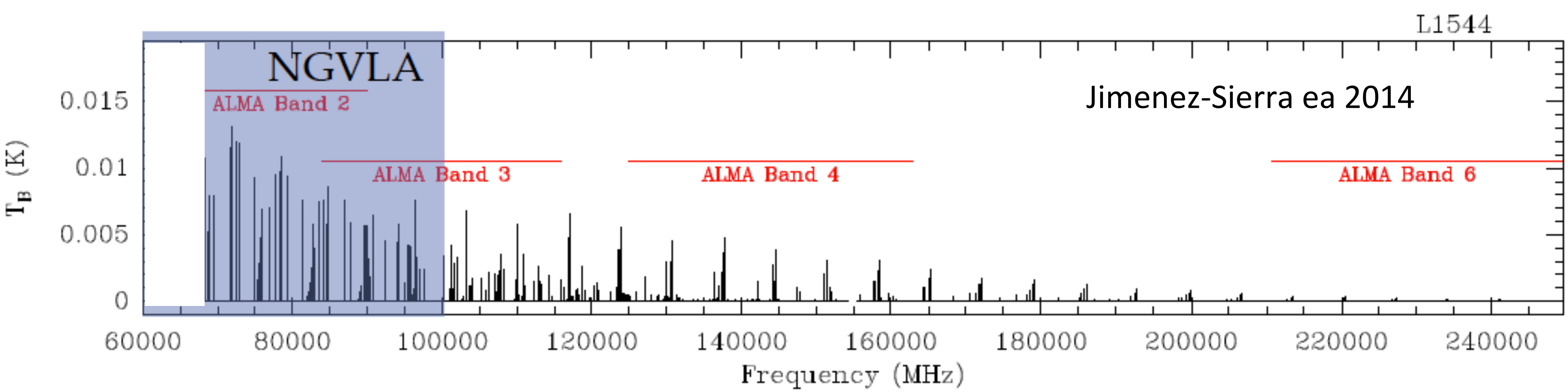




Circle of life: pre-biochemistry

- Pre-biotic molecules: rich spectra in 0.3cm to 3cm regime
- Complex organics: ice chemistry in cold regions
- Ammonia and water: temperature, evolutionary state, PP disks, comets, atmospheres..





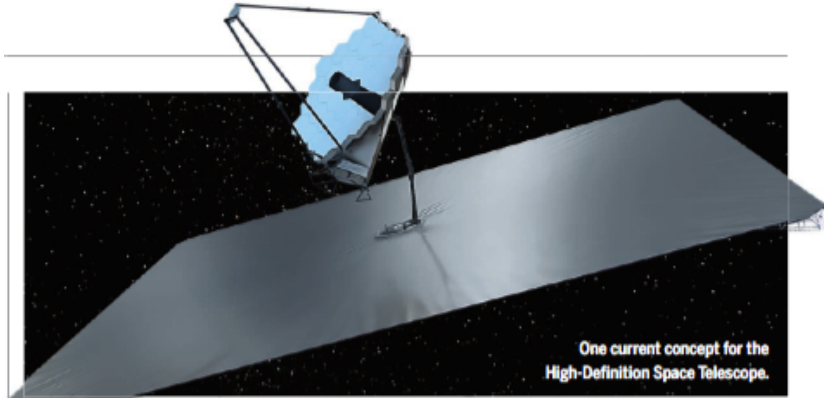
ng-Synergy: Solar-system zone exoplanets

‘ALMA is to HST/Kepler as ngVLA is to HDST’

High Definition Space Telescope

Terrestrial planets: top science goal

- Direct detection of earth-like planets
- Search for atmospheric bio-signatures

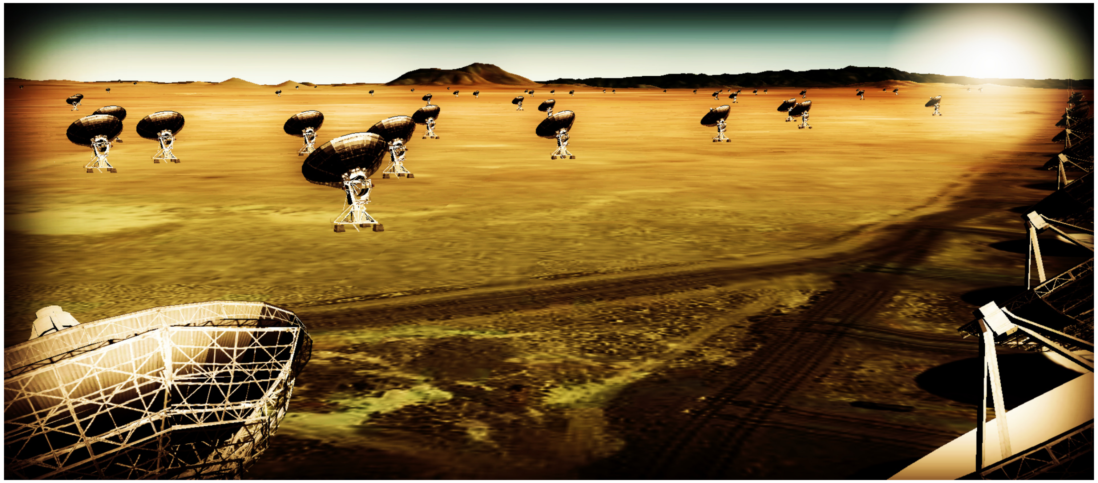

One current concept for the High-Definition Space Telescope.

Hubble on steroids

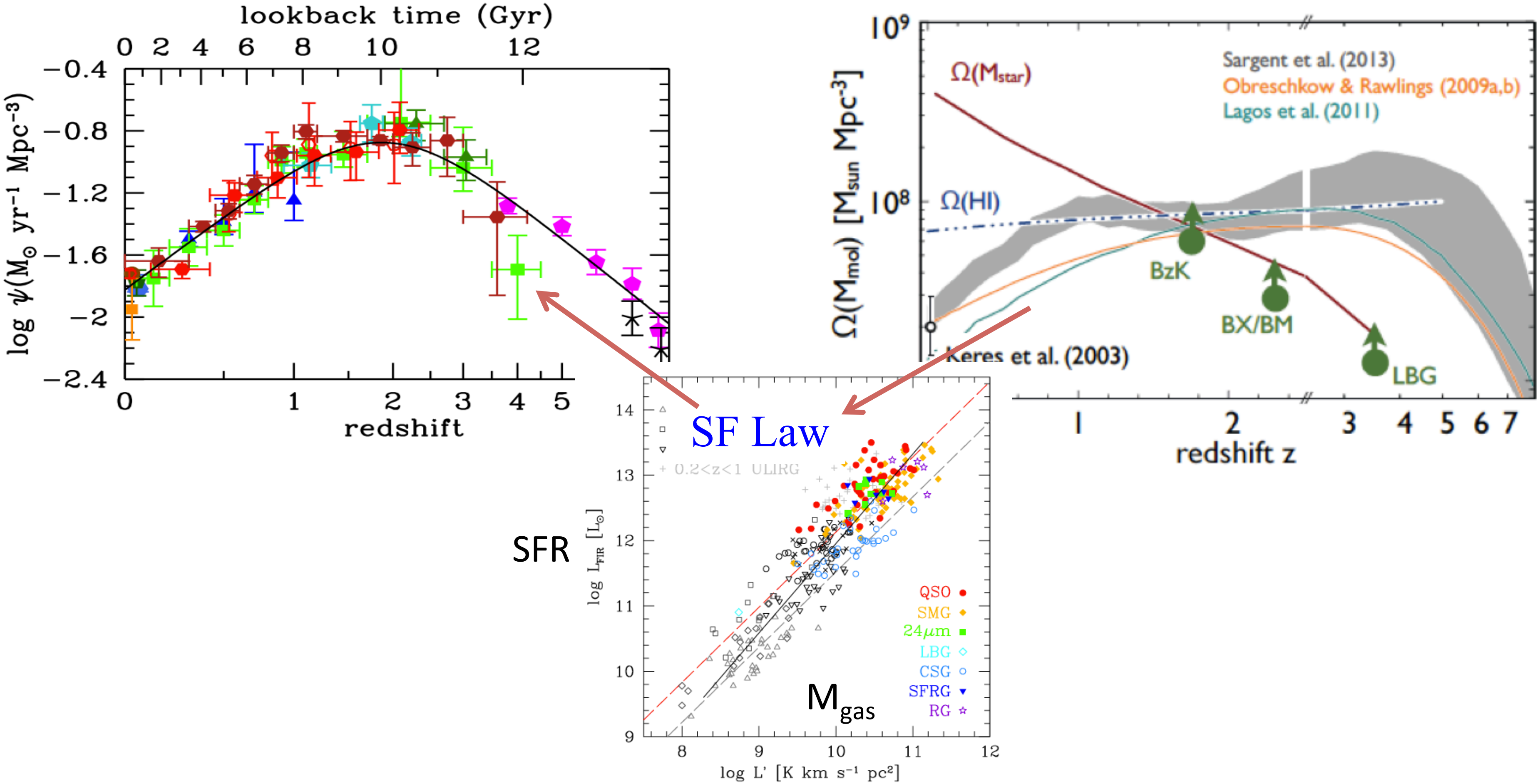
For astrophysicists, HDST would be “transformational,” says commit-

ngVLA

- Imaging *formation* of terrestrial planets
- Pre-biotic chemistry



Cool Gas History of the Universe

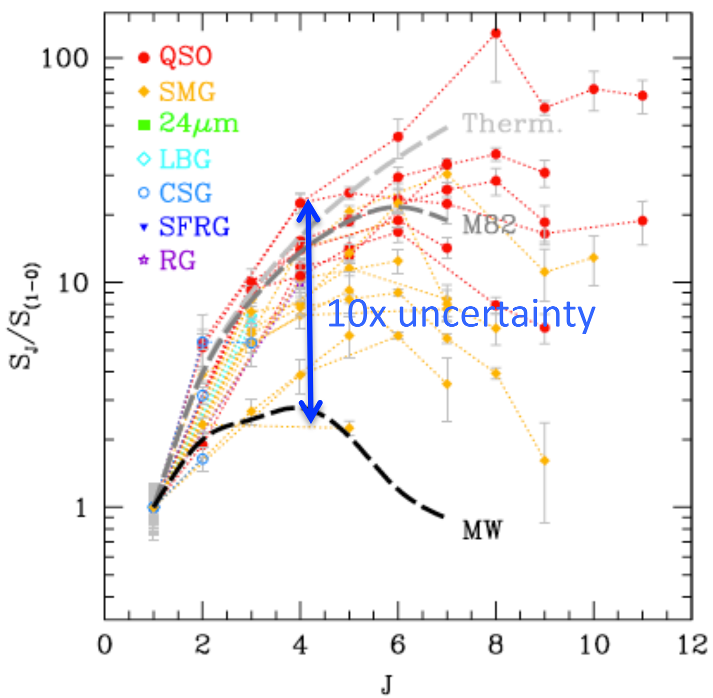


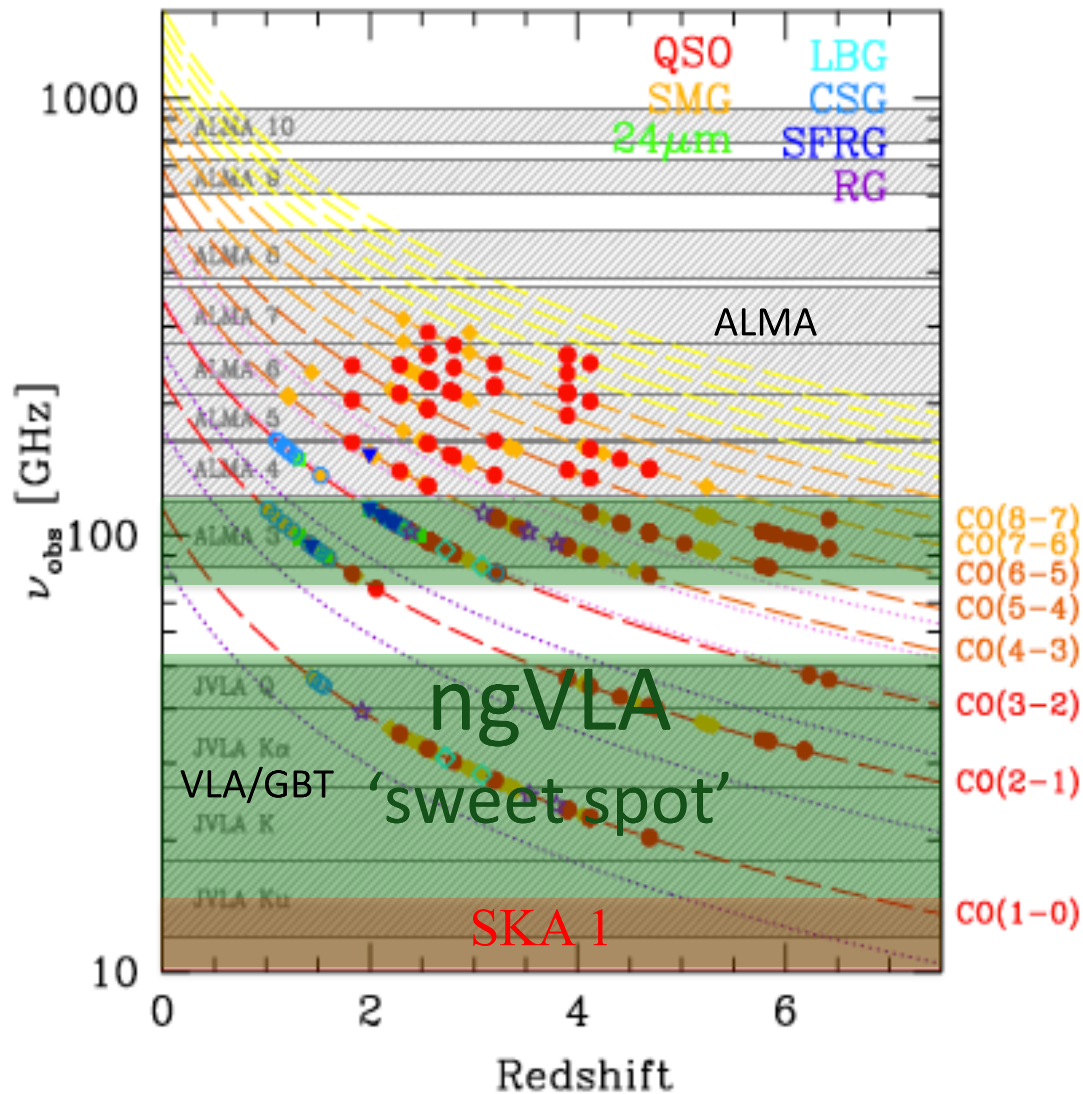
- SFHU has been delineated in remarkable detail back to reionization
- SF laws => SFHU is reflection of CGHU: study of galaxy evolution is shifting to CGHU (source vs sink)

Low order CO: key total molecular gas mass tracer

$M_{H2} = \alpha \times L_{CO1-0}$

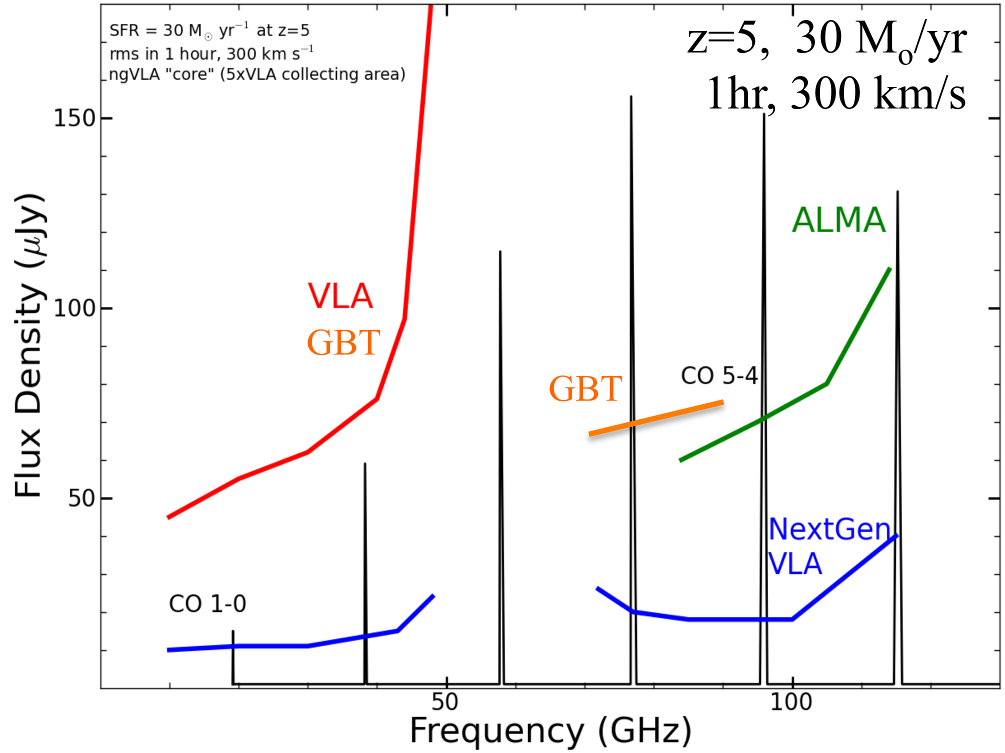
- Total molecular gas mass
- w. ALMA => gas excitation
- Dense gas tracers associated w. SF cores: HCN, HCO^+



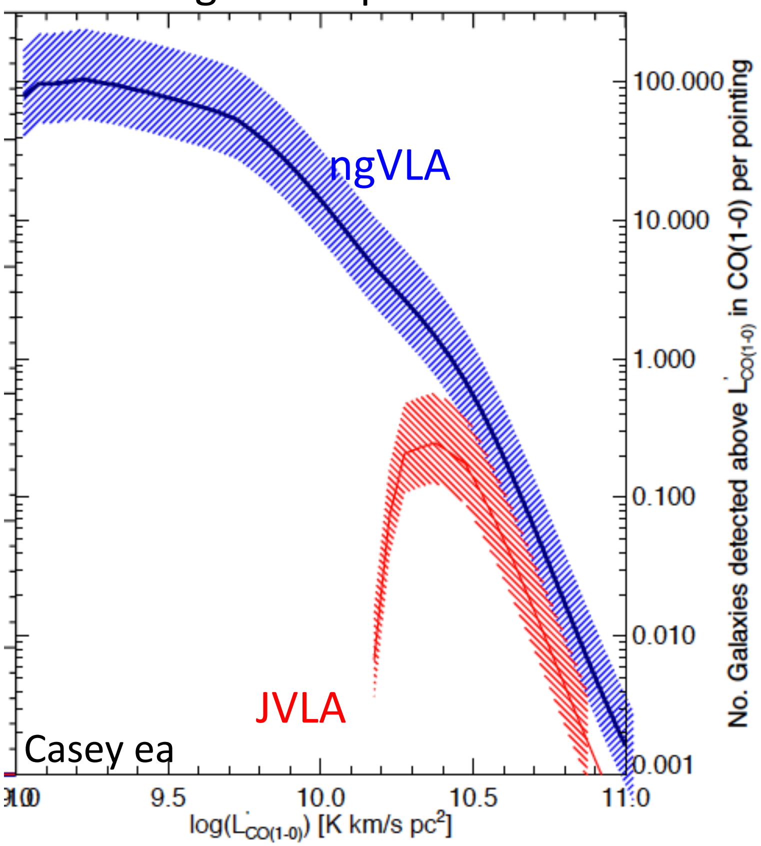


New horizon in molecular cosmological surveys

CO emission from typical star forming, 'main sequence' galaxies at high z in 1 hour



Number galaxies per hour

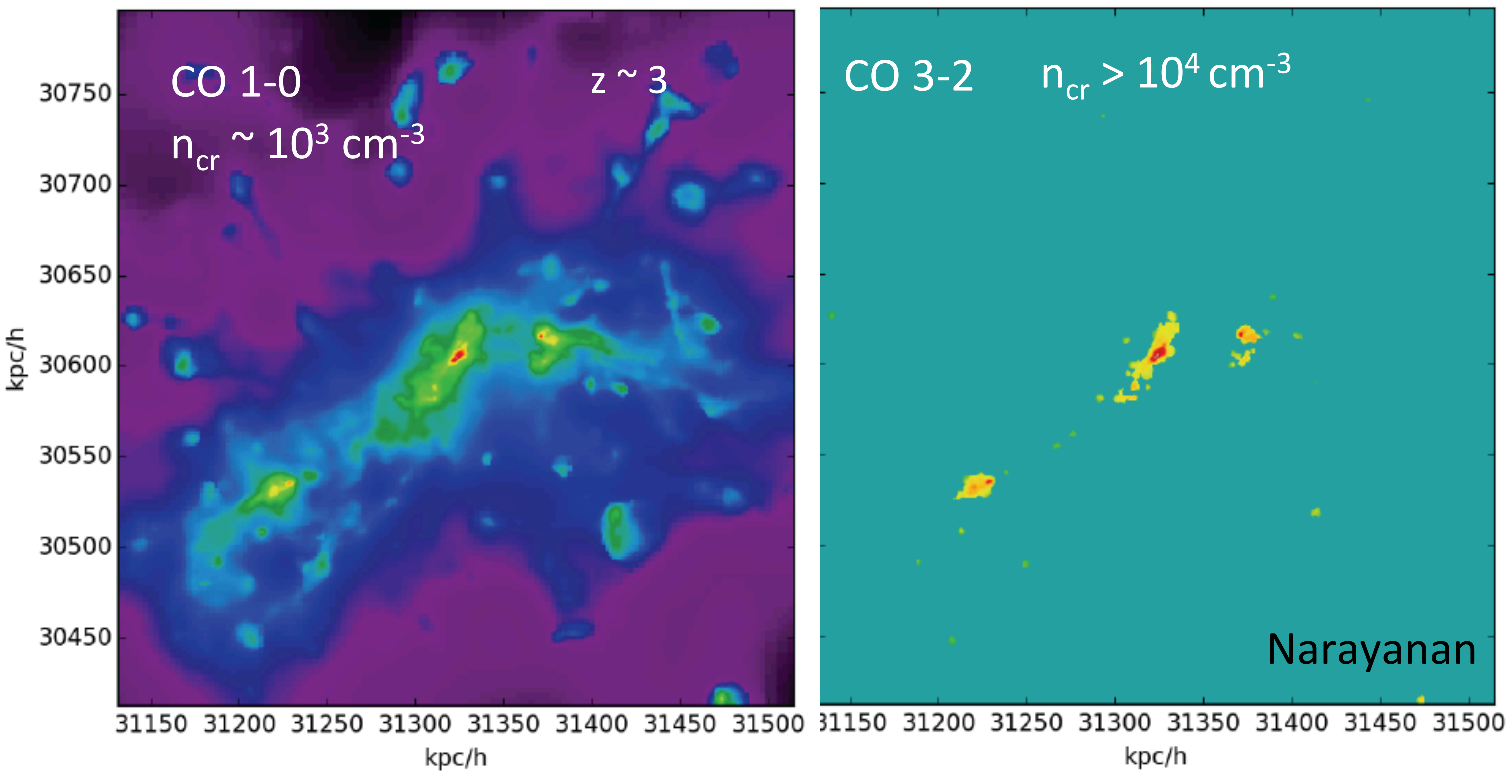


Increased sensitivity and BW => dramatic increase molecular survey capabilities. Number of CO galaxies/hour, 20 – 40 GHz:

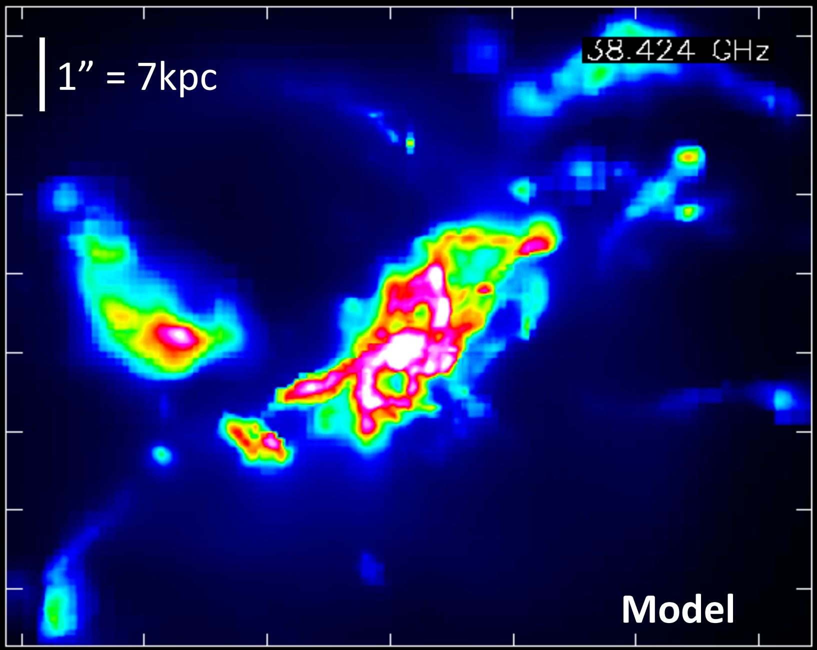
- JVLA ~ 0.1 to 1, $M_{gas} > 10^{10}$ M_o
- ngVLA: tens to hundreds, $M_{gas} > 2\times10^9$ M_o

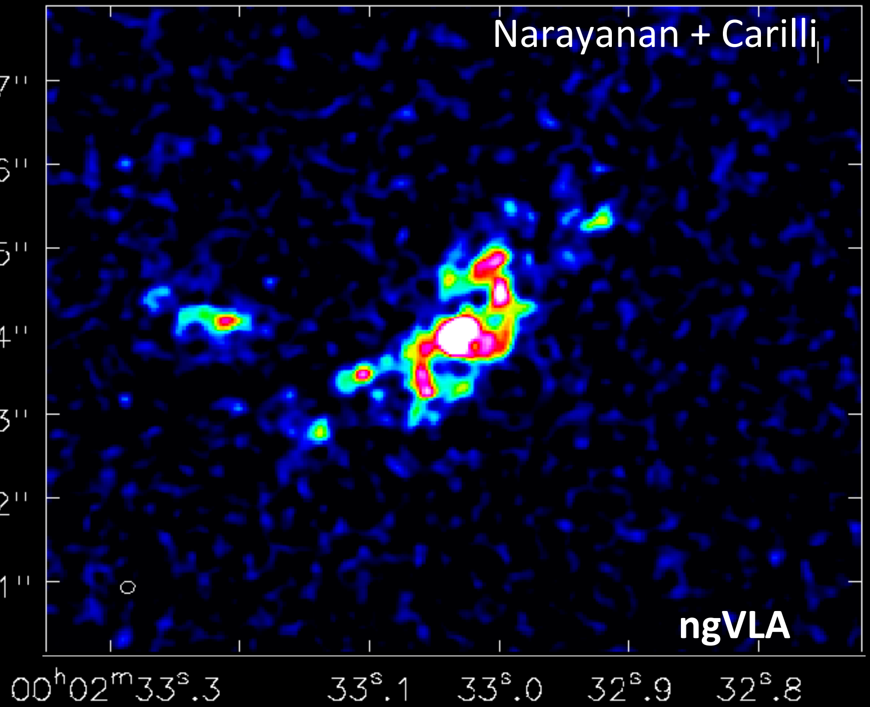
Galaxy assembly: Imaging on 1 kpc-scales

- Low order: large scale gas dynamics, not just dense cores
- w. ALMA dust imaging: resolved star formation laws at ~ 1kpc



ngVLA: SMG at z=2, CO1-0



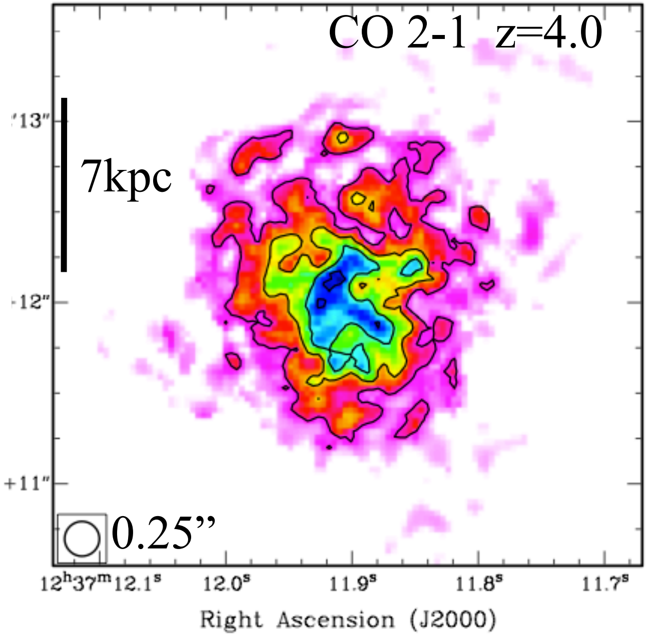


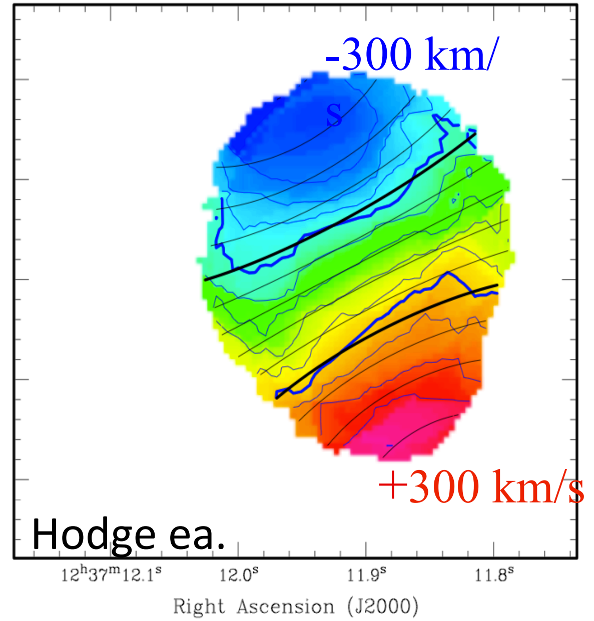
- 38GHz, 10hrs
- rms(100 km/s) = 12uJy => 2e8 (α/0.8) M_o !
- Resolution = 0.15"
- Low mass sattelite galaxies, streamers, accretion?

JVLA state of art
Beyond blob-ology

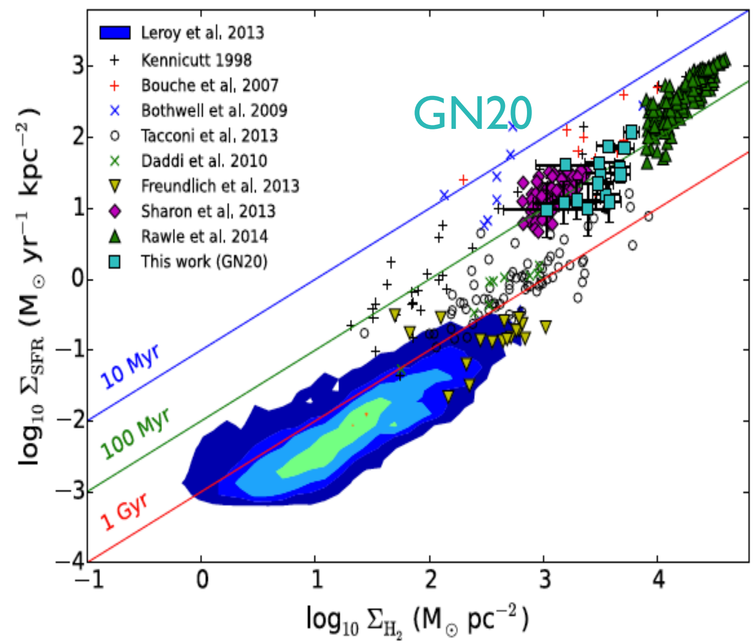
GN20 z=4.0

- CO2-1 at 0.25”
- Resolved gas dynamics
    - ➢ 14kpc rotating disk
    - ➢ $M_{dyn} = 5.4\ 10^{11}\ M_o$
- Resolve SF law





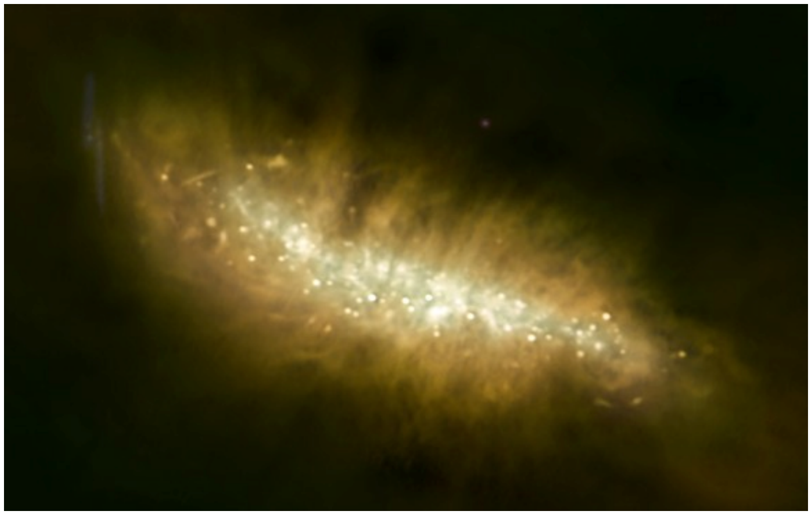
- 120 hours on JVLA
- Few hours on ngVLA

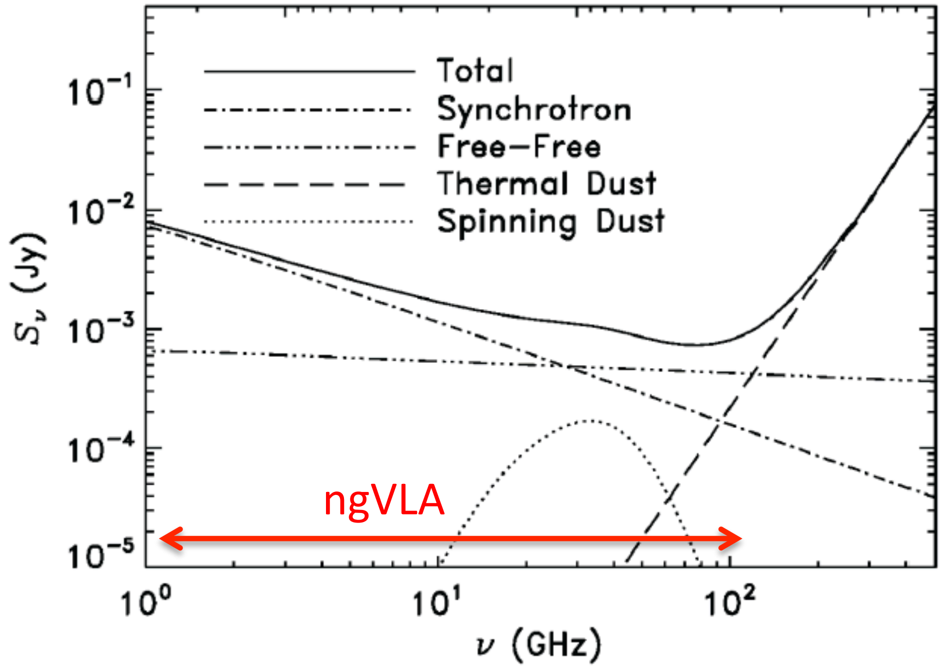


Spatially resolved SF Law

Galaxy eco-systems

Wide field, high res. mapping of Milky Way and nearby Galaxies

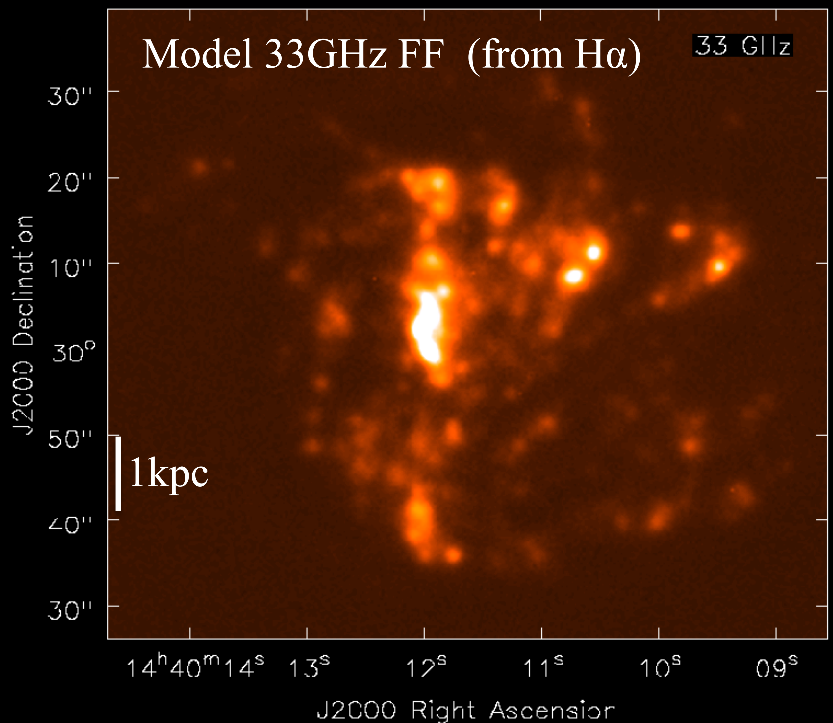


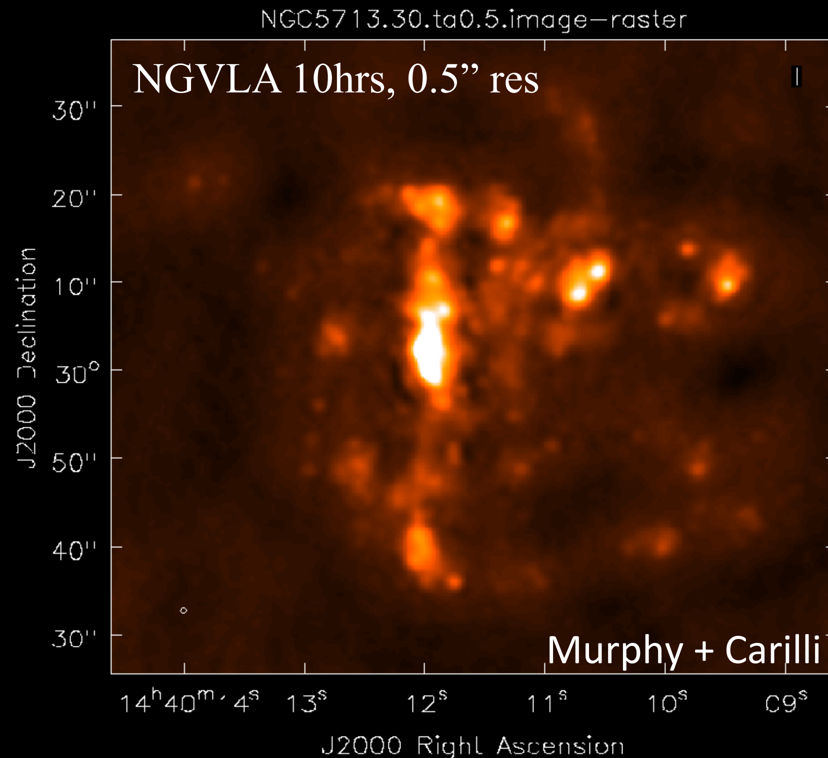


Broad-Band Continuum Imaging

- Cover multiple radio emission mechanisms: synchrotron, free-free, cold (spinning?) dust, SZ effect
- Independent, obscuration free estimates of SFR
- Physics of cosmic rays, ionized gas, dust, and hot gas around galaxies

NGVLA: Free Free emission from peculiar spiral in Virgo

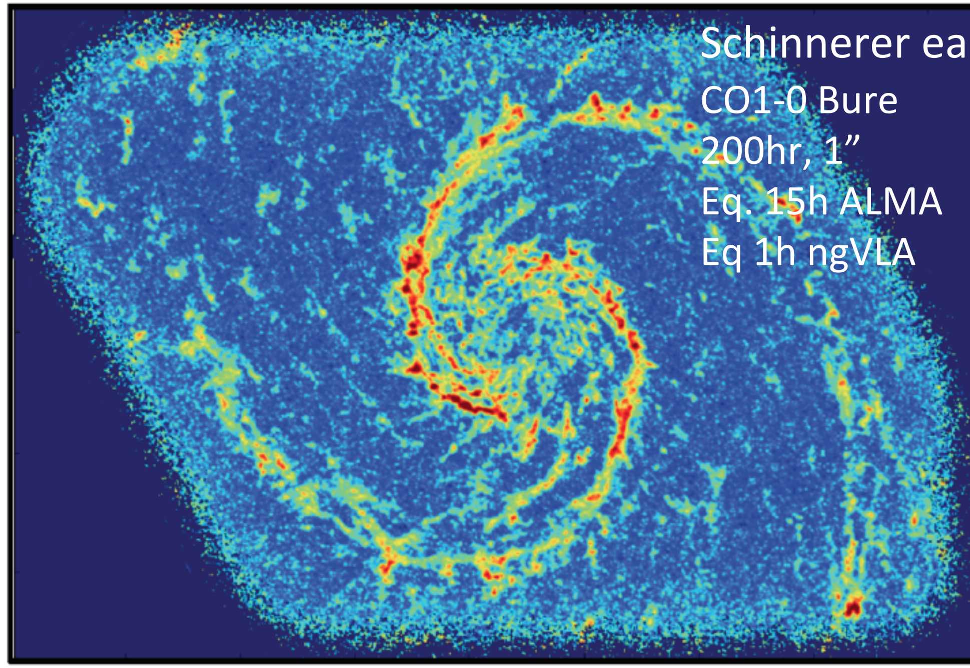


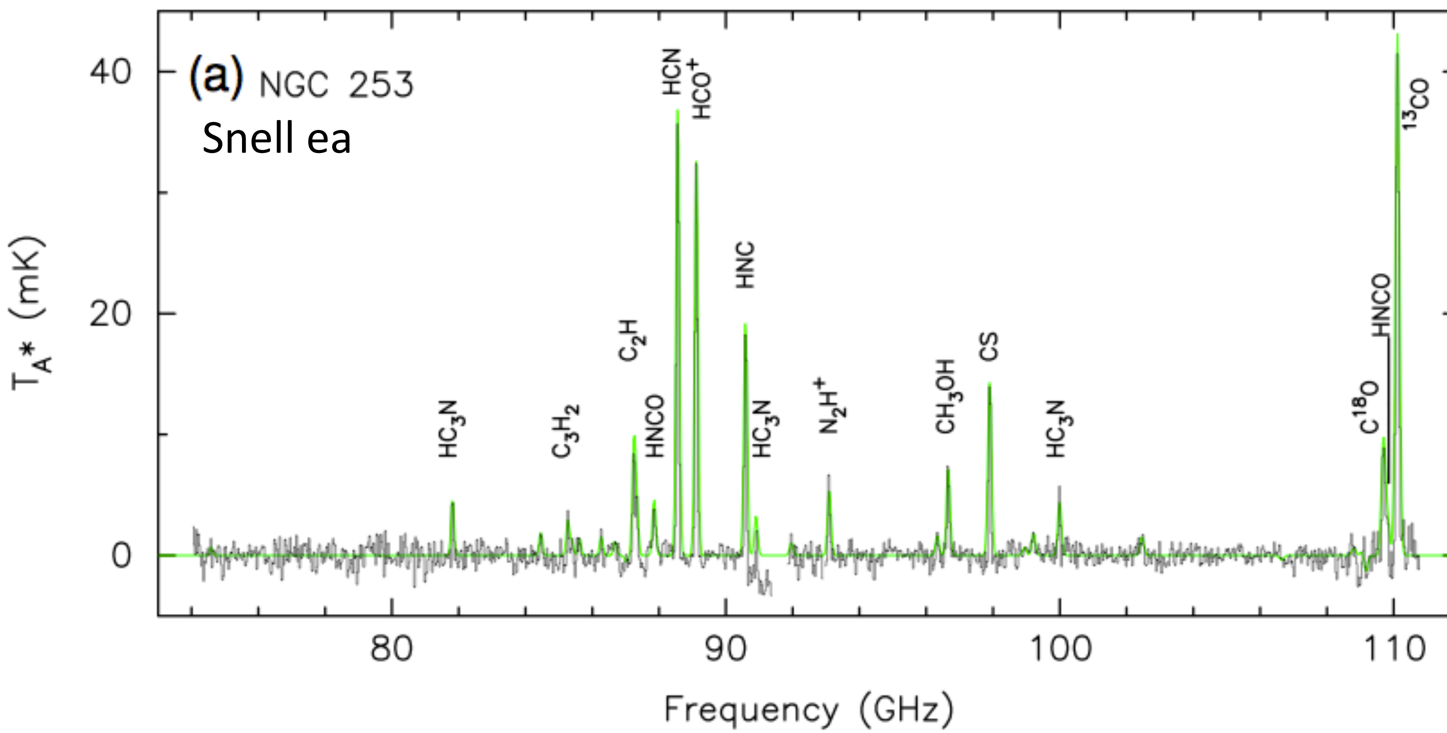


- NGC 5713: distance ~ 30Mpc, total SFR ~ 5 M_o yr^{-1}
- Free-Free ideal estimator of ionizing photon rate
- Full array point source sensitivity at 1cm, 10hrs is 0.1uJy => *HII region associated single O7.5 main sequence star*
- BW+resolution => spatially/spectrally separate thermal/non-thermal
- Local-group-type studies out to Virgo!

Spectral Line Mapping: Map cool ISM 10x faster than ALMA ('gold mine' A. Leroy)

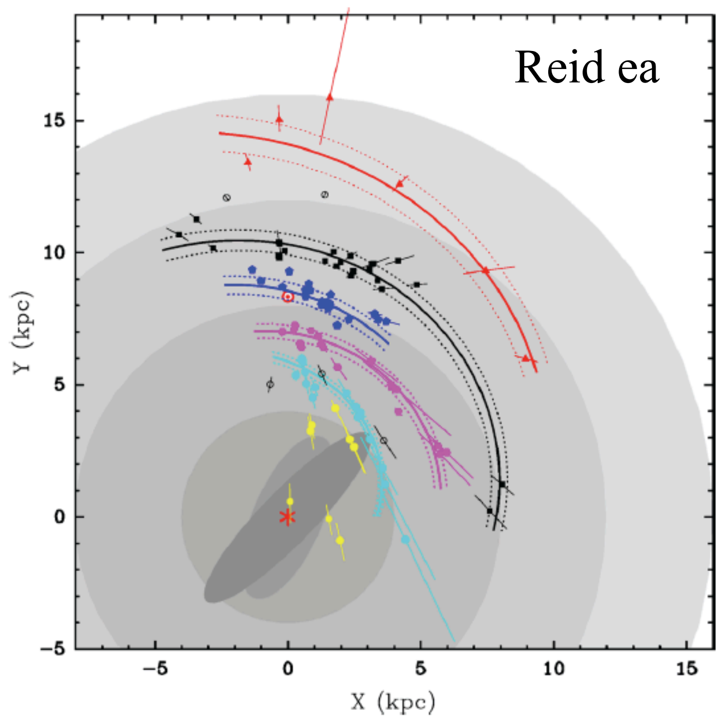
- Rich frequency range: 1st order transitions of major astrochemical, dense gas tracers
- Current CO mapping: tens hours
- Other tracers: 10x fainter => need ngVLA

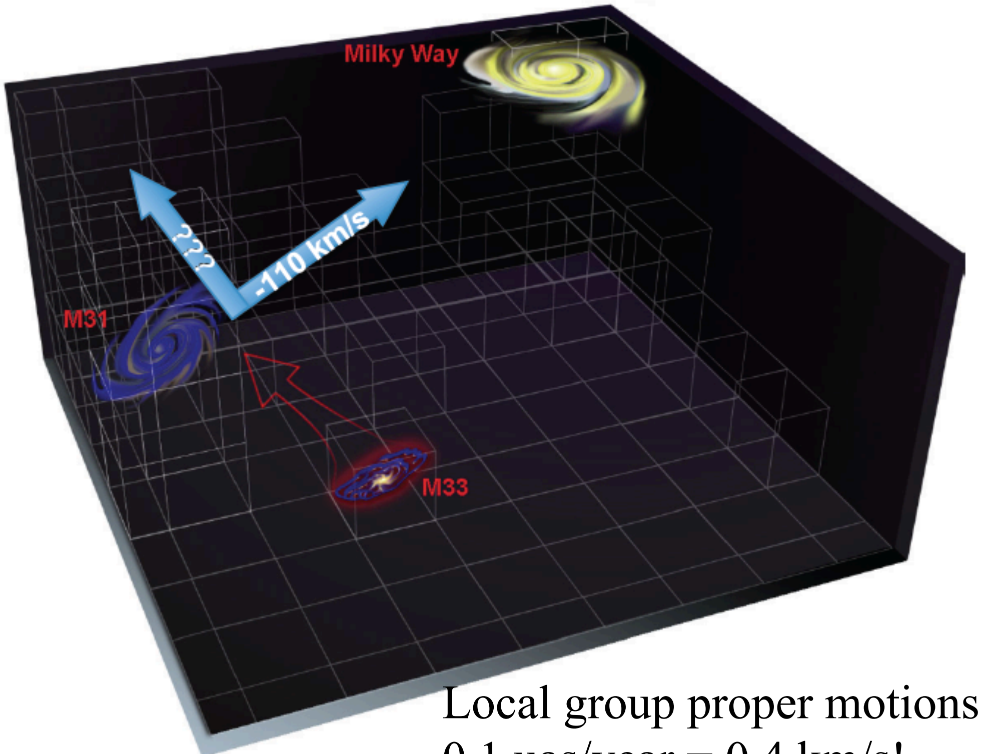




VLBI uas astrometry

- Spiral structure of MW: masers in SF regions to far side of Galaxy
- Local group cosmology: proper motions + parallax w. masers + AGN: 0.1 uas/ yr => dark matter, fate MW, real-time cosmology (local Hubble expansion)
- Not DNR limited imaging => include few big antennas ~ 10% area?





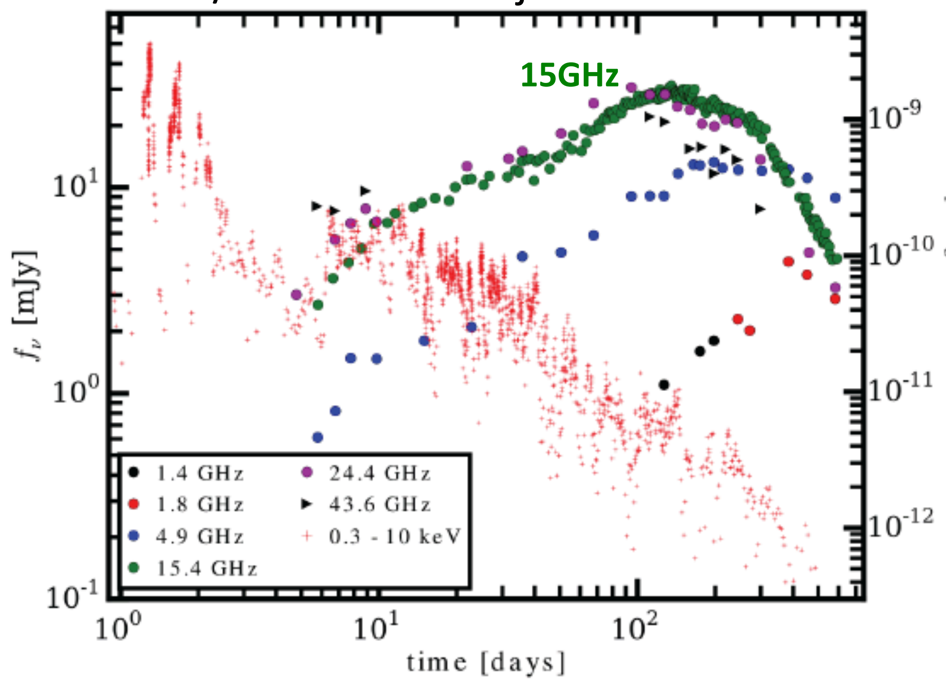
Local group proper motions
0.1 uas/year = 0.4 km/s!
(Darling)

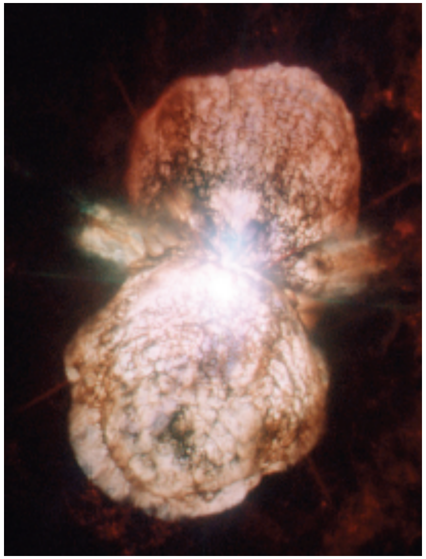
Physics, cosmology, time domain
(Bower et al. SWG4)

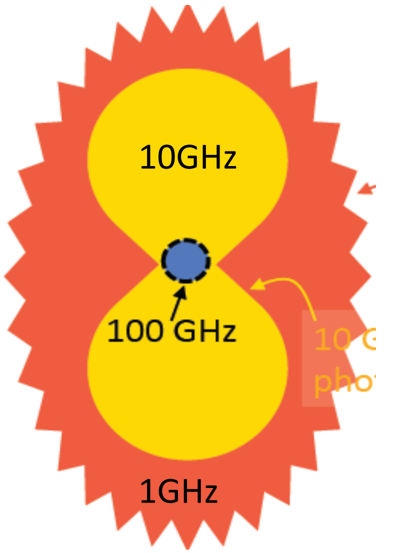
Time domain: bursts brighter and peak earlier at high frequency (0.3cm to 3cm)

- GRB, TDE, FRB
- Novae: ‘peeling onion’
- Radio counterparts to GW events
- Galactic Center Pulsars

GBR/TDE: late time jet shock

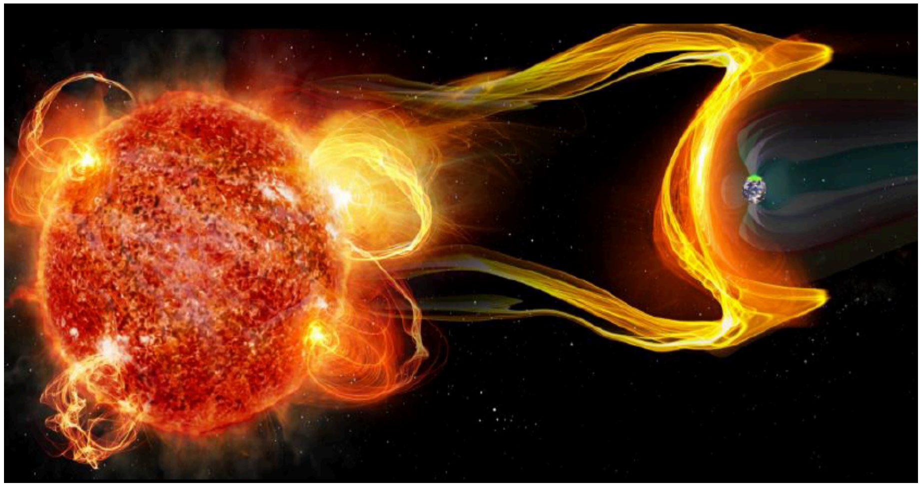


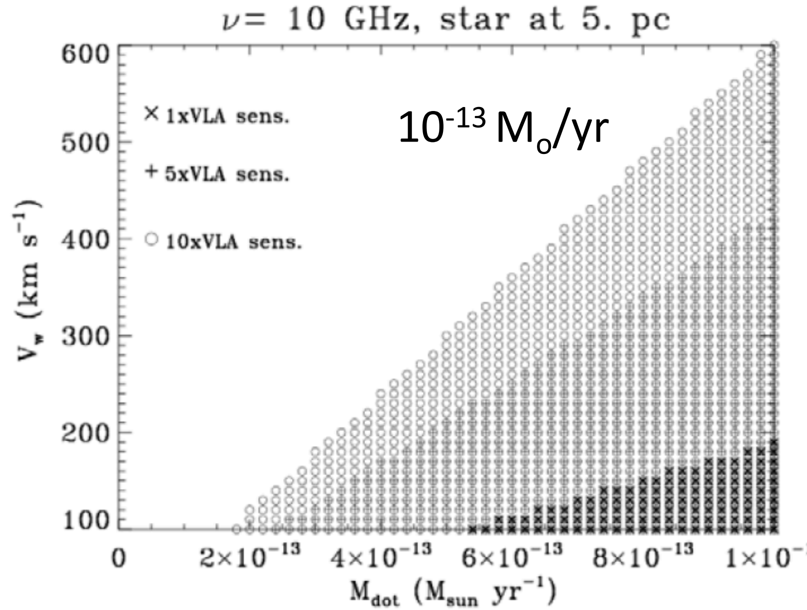




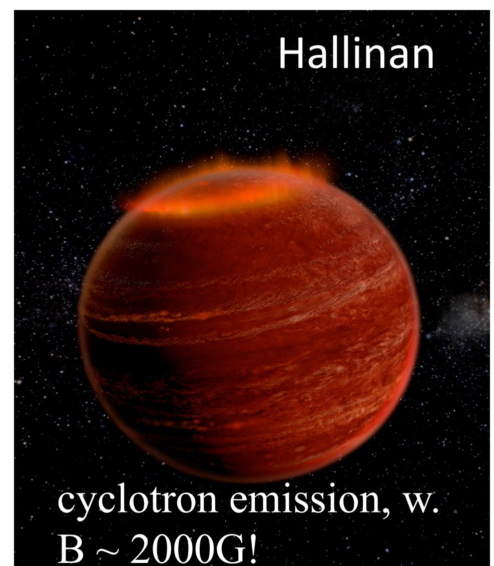
Star – Planet interactions: exo-space weather

NGVLA most sensitive telescope to study broad-band stellar radio phenomena

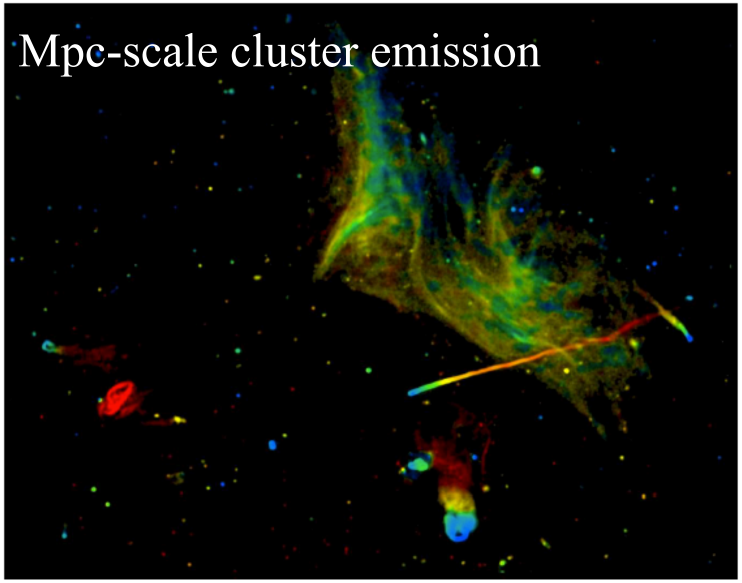


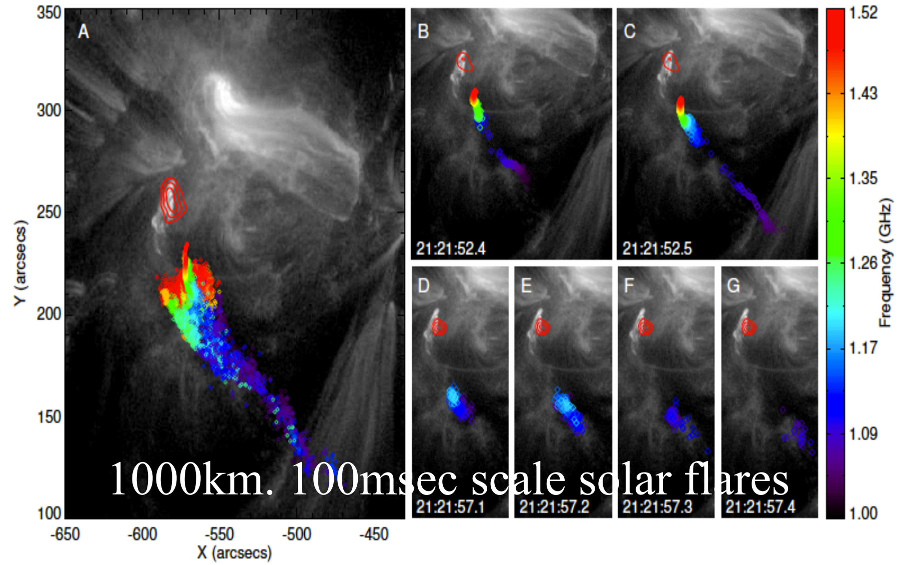


- Thermal stellar winds
  - M dwarfs most likely hosts habitable planets, but very active, flares up to 10^4 x Sun
  - Wind – planet interactions => early evaporation of planetary atmospheres?
- Brown dwarf Auroras! Star-planet magnetospheric interactions
- Key drivers of exo-space weather: dictate exo-planet environments (and the development of life)

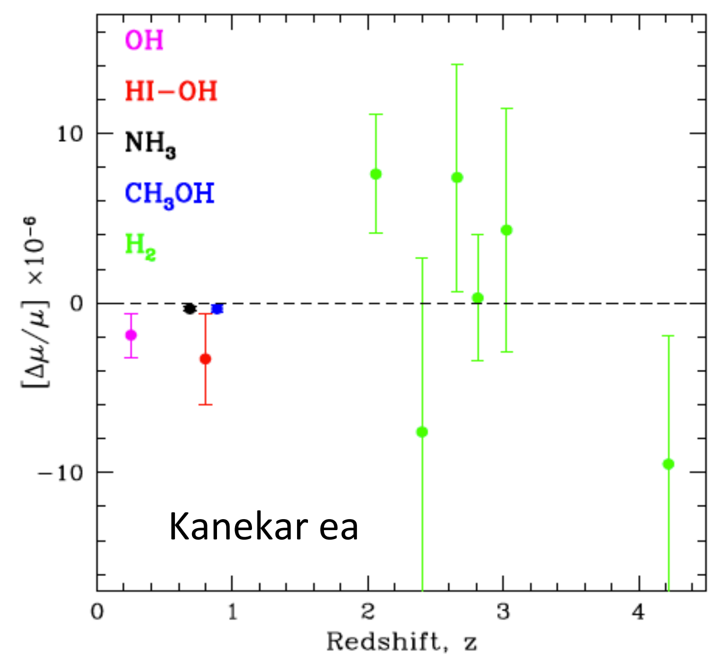


Plasma Universe





- Magnetic reconnection vs. shock acceleration: broad band phenomena
- S-Z for individual galaxies
  - ngVLA-short (1cm, 3”, 10hrs) ~ 1uK
  - nT ~ 10^6 over 10kpc => 20uK
- Evolution of fundamental constants using radio absorption lines: most promising ~ 1cm



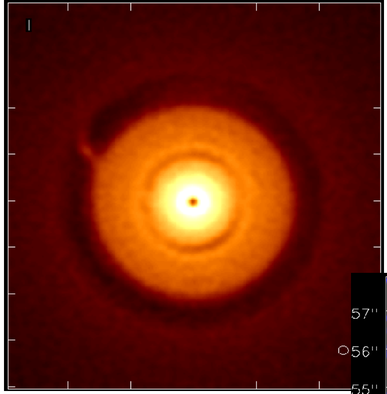
Preliminary Key Science

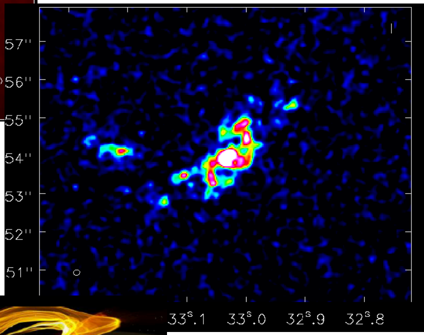
- Imaging Solar-system zone planet formation + prebiotic chemistry – synergy with HDST
- Cool gas history of Universe – synergy JWST, TMT…
- Time domain: exospace weather – synergy LSST
- Baryon cycle: wide field, high res. thermal line + cont. imaging – synergy Far IR surveyor
- VLBI astrometric applications: local group cosmology

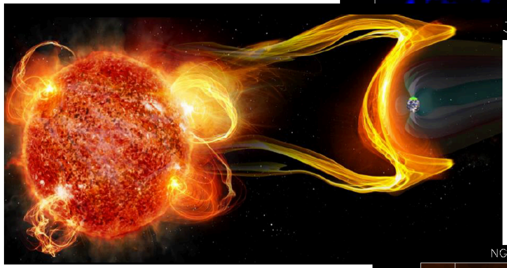
- White papers posted early October 2015,

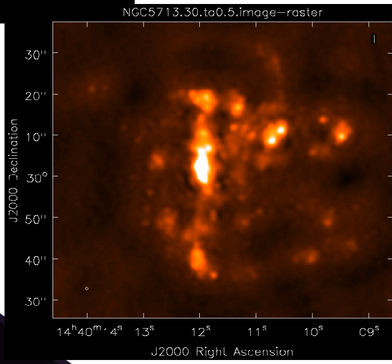
  detailed calculation of telescope requirements

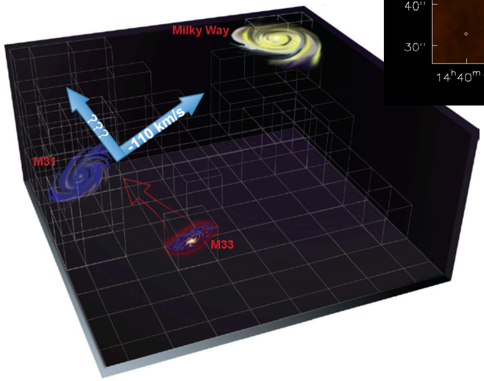
  thereafter







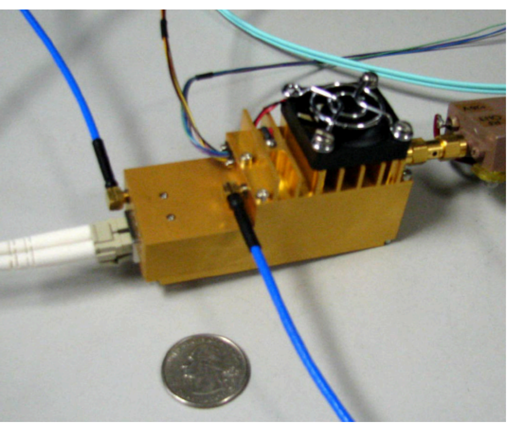




Pasadena Technical Meeting (Weinreb)

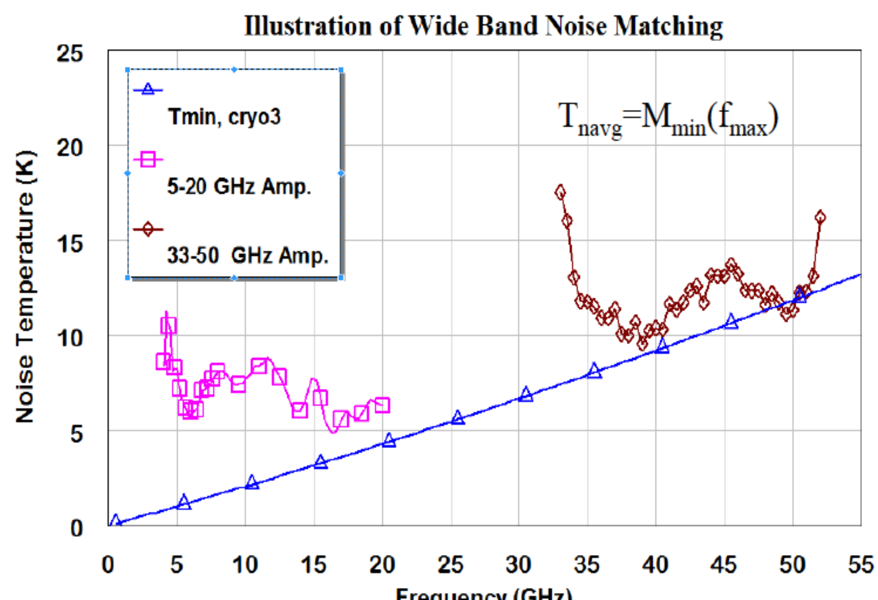
https://safe.nrao.edu/wiki/bin/view/NGVLA/NGVLAWorkshopApril2015

- Antennas (Padin, Napier, Woody, Lamb…)
  - 12m to 25m? 75% eff at 30GHz
  - Offaxis (high/low), symmetric?
  - Hydroform, panel?
  - Reconfigurable?
- Feeds, Receivers (Weinreb, Pospiezalski, Morgan…)
  - 1 – 115GHz: 3 bands? 4 bands? more?
- Correlator: FPGA (Casper), GPU (nVidia), ASIC (JPL), Hybrid (DRAO)



RF/IF Amplification
Filtering
Power leveling
RF-to-baseband conversion
Analog-to-digital conversion
Copper-to-fiber conversion

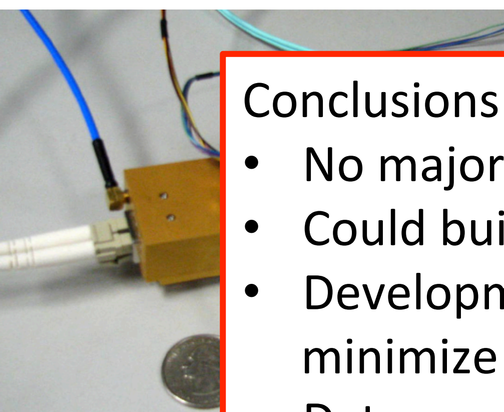
Morgan mmic: Rack full of warm electronics in your hand



Pasadena Technical Meeting (Weinreb)

https://safe.nrao.edu/wiki/bin/view/NGVLA/NGVLAWorkshopApril2015

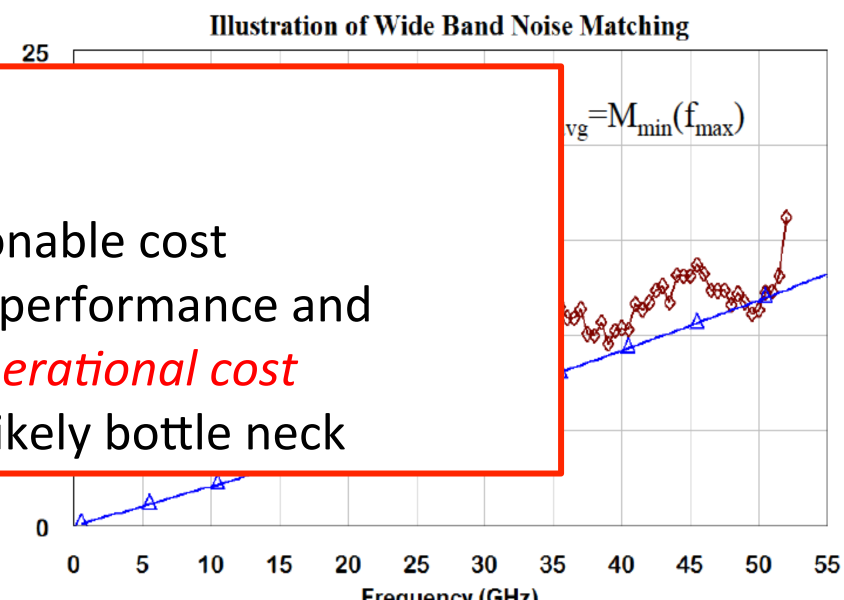
- Antennas (Padin, Napier, Woody, Lamb…)
  - 12m to 25m? 75% eff at 30GHz
  - Offaxis (high/low), symmetric?
  - Hydroform, panel?
  - Reconfigurable?
- Feeds, Receivers (Weinreb, Pospiezalski, Morgan…)
  - 1 – 115GHz: 3 bands? 4 bands? more?
- Correlator: FPGA (Casper), GPU (nVidia), ASIC (JPL), Hybrid (DRAO)



Morgan mmic: Rack full of warm electronics in your hand

Conclusions

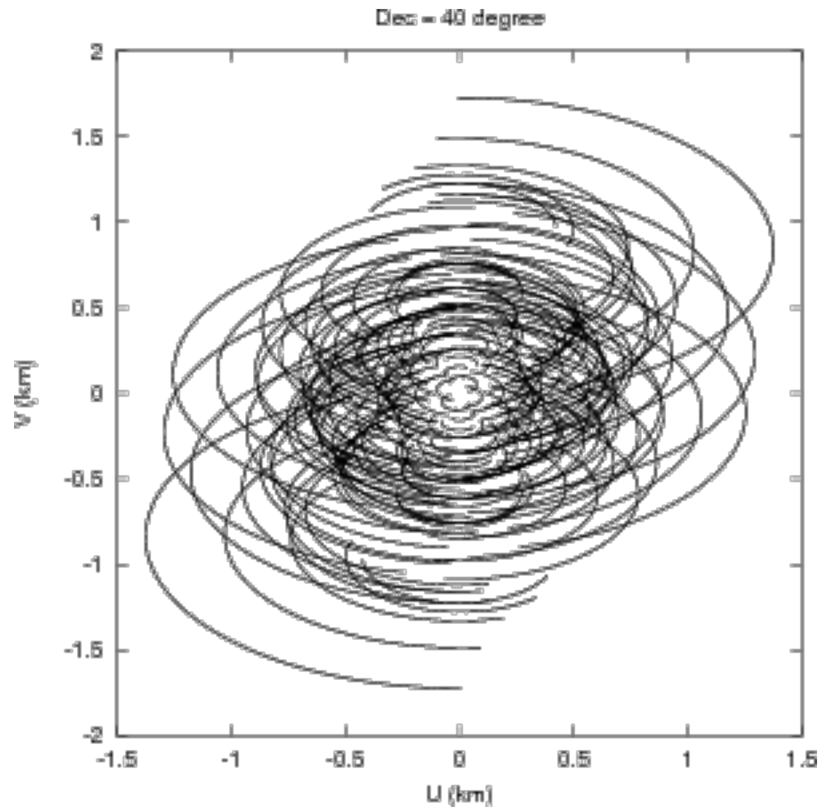
- No major single-point failures
- Could build today for not-unreasonable cost
- Development geared to optimize performance and minimize mass production *and operational cost*
- Data processing for KSP also not likely bottle neck



Possible Roles of GBT…

Systemic disadvantages of a pure interferometer: shortest baseline defined by ~antenna diameter

- Missing zero spacings (total flux)
- Missing short spacings
- Reduced surface brightness sensitivity (filling factor)
- (Need for deconvolution)



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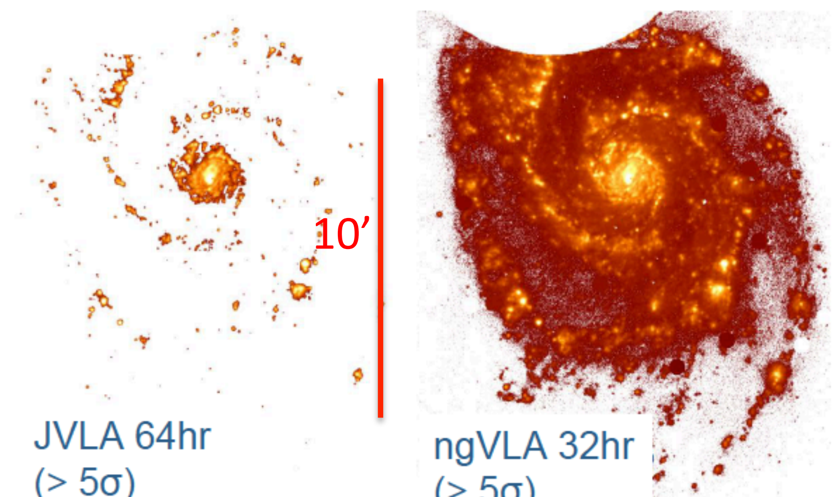
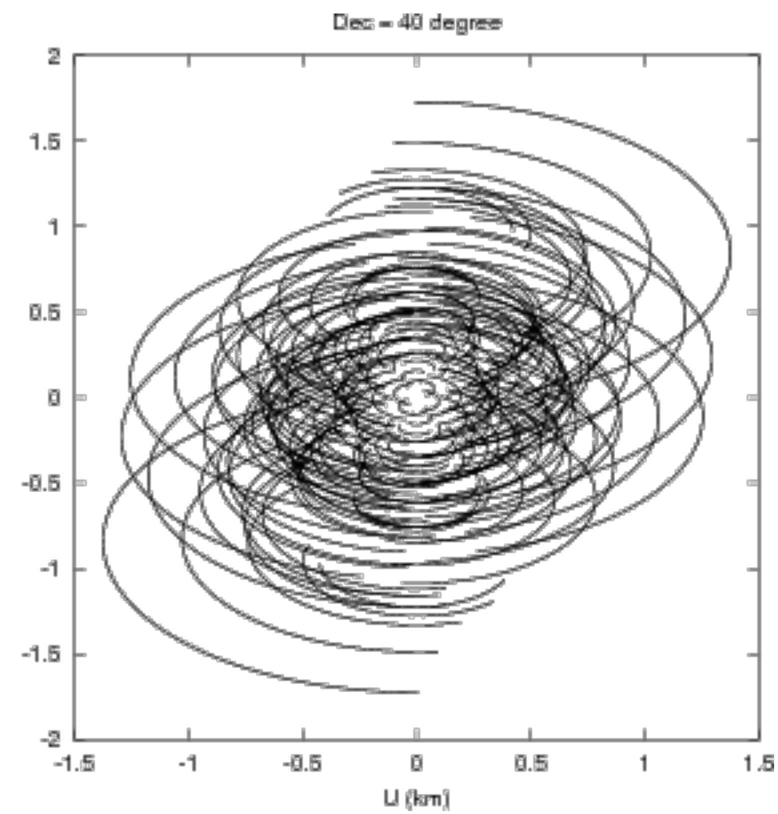
M51 at 33GHz (free-free emission)





- A primary goal of the ngVLA will be **extreme surface brightness sensitivity** (VLA E-config is scientifically compelling but was not funded)

FILFAC
GBT: 1
E-EVLA: 0.2

Surface brightness sensitivity:

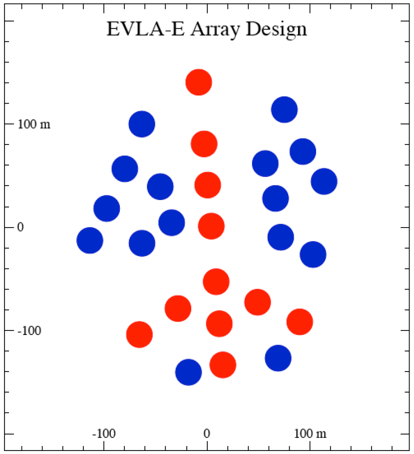
$$\sigma T_b = 2.14\,\alpha\,T\,\frac{1}{\eta\sqrt{\Delta f \tau}}\,\frac{1}{FILFAC}$$

where T is the antenna system noise temperature
Δf is the bandwidth
τ is the time of averaging
$\alpha = 1 - 2$ stands for the noise increasing because digitizing of signals
η is the antenna efficiency

The filling factor FILFAC is determined by the following expression:

$$FILFAC = \left(\frac{D_{ant}}{D_{eff}}\right)^2$$

where $D_{eff} = 1.04\,\frac{\lambda}{\theta_{0.5}}$ is the diameter of the equivalent circular dish with the uniform illumination which has the given beam width at the level 0.5
$\theta_{0.5}$ is the full(double) width of the array beam at the level 0.5
$D_{ant} = D\,\sqrt{N}$ is the diameter of the equivalent circular dish with the uniform illumination which has the geometric area equaled to the area of all antennas of the array
D is diameter of the array antenna



EVLA memo 65, Kogan/Perley

Zero spacings:

- Single dish will be *required* to derive those. But they need matched sensitivities, frequency range, and bandwidth of the ngVLA
- Spectral line and continuum capable SD instrumentation
- Field of view of ngVLA is to be matched (~30x that of a single pixel GBT? could lead to ~100 beam requirement for FPAs)
- Possibility to use ngVLA autocorrelations? (little experience from other arrays so far, stability requirements, may need mapping or extra OFF time)

Short spacings:

- 18m antennas of the ngVLA will be able to image
    - <60arcmin @1GHz
    - <6arcmin @10GHz
    - <1arcmin @50GHz
    - <0.5arcmin @100GHz

Additional solutions for
Short spacings are required for many
of the most prominent objects,
Smaller antennas (e.g. 7m) will help
but only by some amount

Imaging a spiral arm (10kpc):
@1.4GHz would cover all scales outside the MW
@50GHz the galaxy will have to be outside the Local Volume

Imaging a molecular cloud (40pc):
@20GHz it has to be at the far end of the MW
@115GHz it has to be beyond Andromeda

Imaging a molecular clump (1pc):
@20GHz it has to be at least at a distance of ~1kpc
@115 GHz it has to be on the far side of the MW

Imaging a molecular core (0.1pc):
@115 GHz it has to be beyond the Gould Belt

No problems for protoplanetray disks (100AU)

Long Baselines:

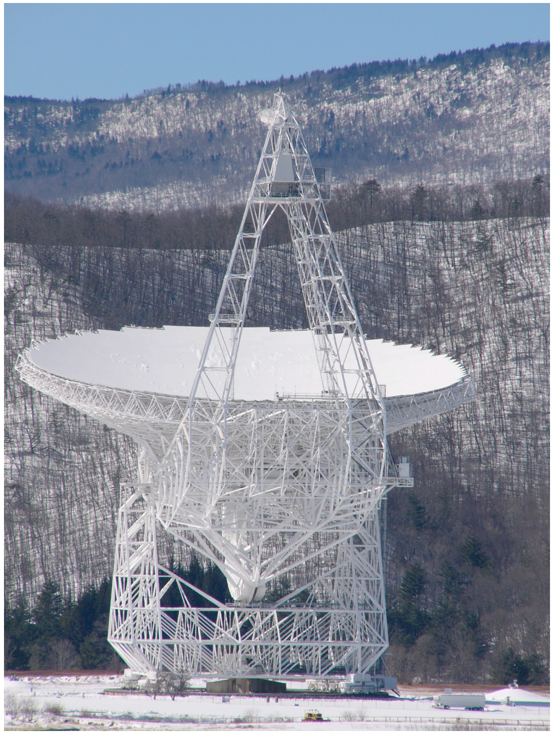
- A science case is made for astrometry of Local Group objects & cosmology that would require large collecting areas on long baselines
- The "system equivalent flux density" SEFD ~ T_{sys}/A_e

$$\Delta S_{ij} = \frac{1}{\eta_s} \times \sqrt{\frac{SEFD_i \times SEFD_j}{2 \times \Delta\nu \times \tau_{acc}}}$$

- ~3 times more sensitive baselines with the ngVLA-GBT over the VLA-GBT
- 3mm VLBI
- Potentially larger bandwidth
- Other large apertures that may be used now and within 10 years: Effelsberg, Sardinia, PKS, Tidbinbilla, Arecibo, LMT, FAST, Shanghai (65m Tianma), ALMA, IRAM, Nobeyama, EHT?, RadioAstron?, SKA?
- Factor of 3 in sensitivity for all baselines with the ngVLA → powerful HSA

The GBT advantage

- Operates in the ngVLA frequency range (1-115GHz)
- Has started camera multi-pixel/feed array development and observations
- Provides options for partnerships
- 2500 km baseline to VLA site
- Very large collecting area
- Very large diameter for plenty of uv overlap with ngVLA baselines
- Same hemisphere as ngVLA
- In operation and constantly being better understood and refined (PTCS etc.)



The GBT could become an integral part of the ngVLA concept, similar to what ACA is to ALMA

ngVLA: Next Steps

project manager: Mark McKinnon

- Working Group reports end of September, then:
- Broad, open community participation beyond the Working Groups
- Setup of a Science Advisory Board/Project Scientist/web presence
- Studies of weather impact, array configs, short spacing needs, Rx recommendations, VLBI, calibration strategies, simulations, …
- 2nd technical meeting Dec 8/9 2015 Socorro

(operations, clock transfer, data transmission, algorithmic work, computing reqs ..)

- AAS meeting full day 4 January 2015 (½ science, ½ technical implications, with call for abstracts)
- Large ngVLA science meeting in 2016
- Goal to submit a solid project for the upcoming decadal plan in 2019