High-mass star formation at high-resolution

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Part I:

- Introduction to high-mass star formation
- Key questions to current theories

Part II:

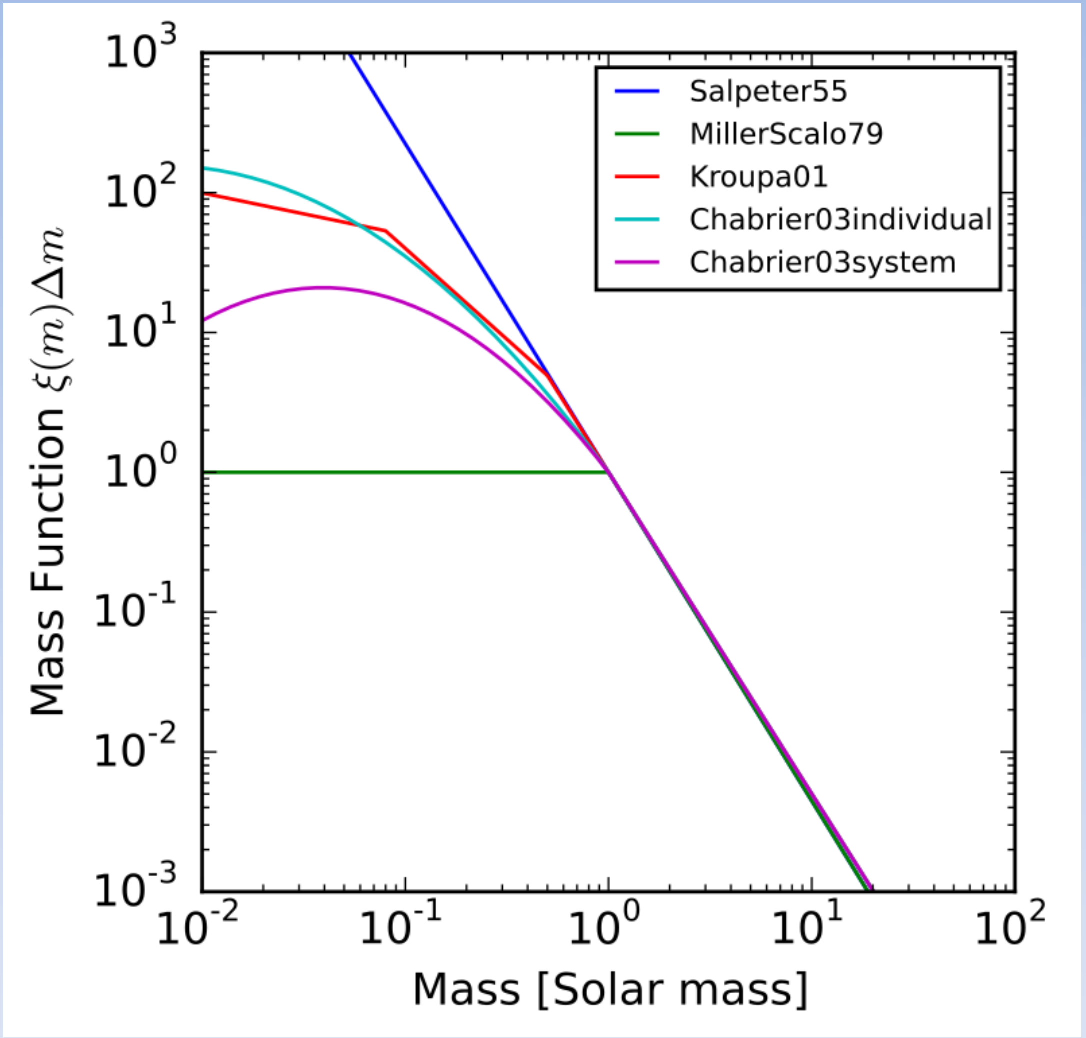
- Using interferometers to achieve high-resolution

Why study star formation?

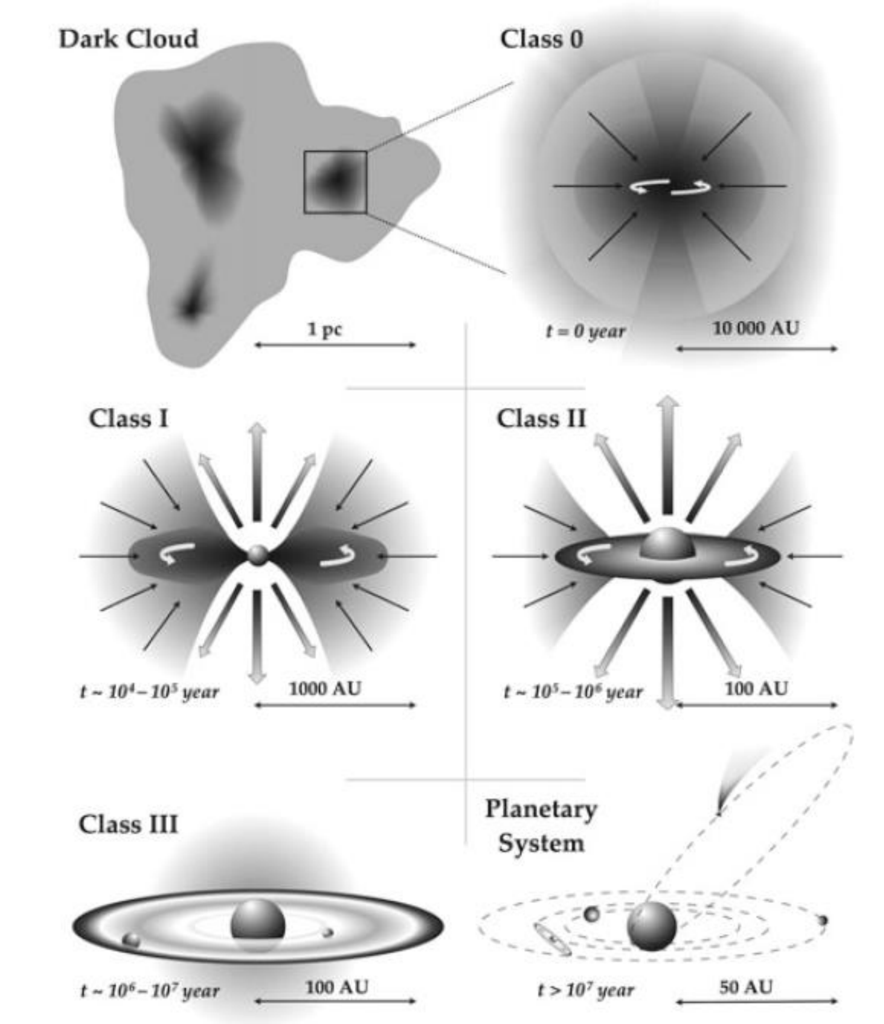
- Galaxy is made of “stars” and “interstellar” medium
- Star formation provides initial conditions for planet formation and life origin
- Mass is the most important parameter for a star; it determines color, luminosity, and lifetime
- Death of high-mass stars: supernovae, stellar-mass black holes, gravitational wave sources

Star cluster M51 observed by HST

The initial mass function IMF

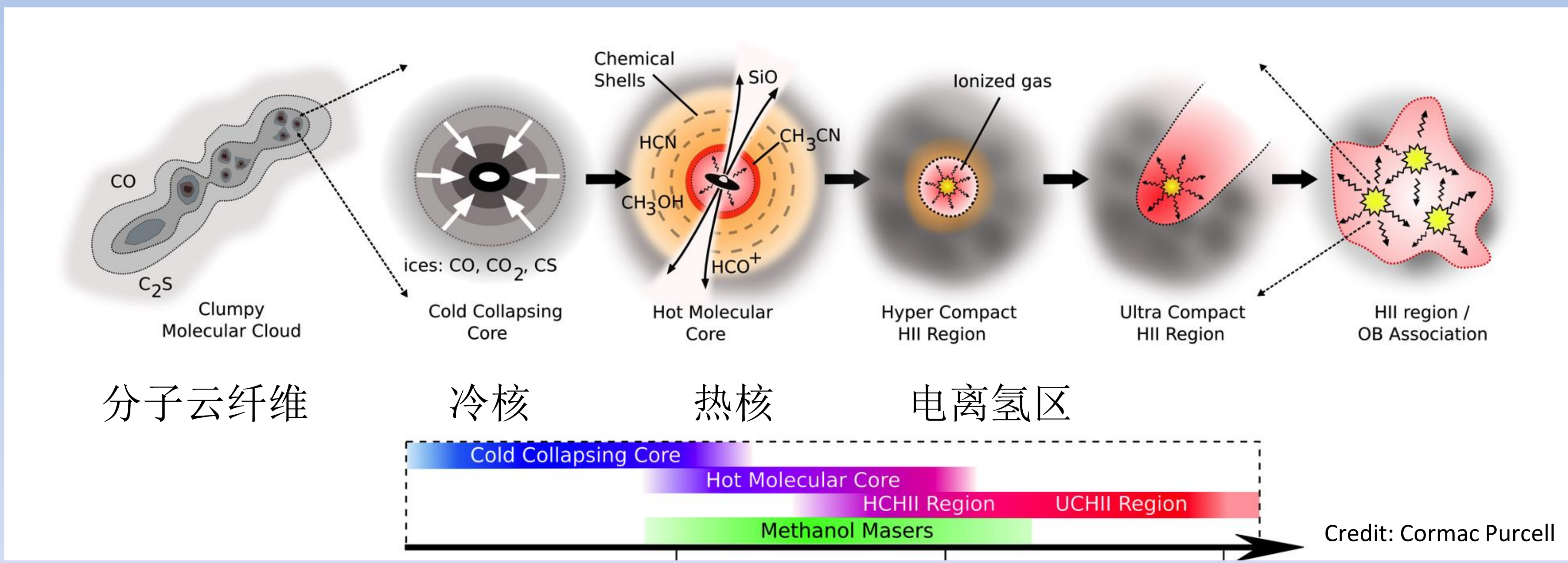


Formation of solar type stars (Shu 1987)



Cartoon by Frieswijk (2008), based on Dishoeck & Blake (1998)

Formation of high-mass stars (>8 Msun)



亚毫米波连续谱、分子谱线
(结构、分裂、塌缩、温度、密度、湍动、磁场)

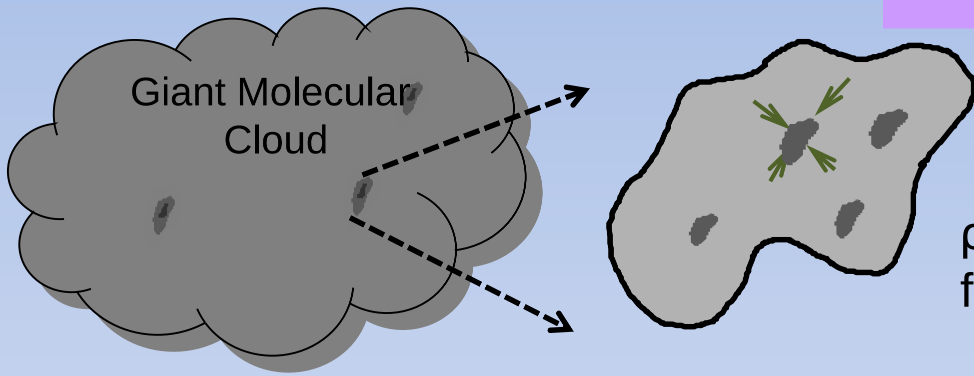
外向流、脉泽、有机分子、射电连续谱、红外点源

Keywords: fragmentation, disk, CMF, magnetic fields, turbulence

Massive star/cluster formation

$$M_J = \frac{\pi}{6}\left(\frac{\pi C_s^2}{G}\right)^{3/2} \rho_o^{-1/2}$$

$M_J \sim 1\ M_\odot$



ρ, T, g, ΔV, B, feedback

Preclucter forming Clump, IRDC

Young stellar cluster

>10 pc
$n(H_2) \sim 10^2\ cm^{-3}$
$M \sim 10^5\ M_\odot$

pc-scale clump
$n(H_2) \sim 10^{4-5}\ cm^{-3}$
$10^3 – 10^4\ M_\odot$
T~10-15K

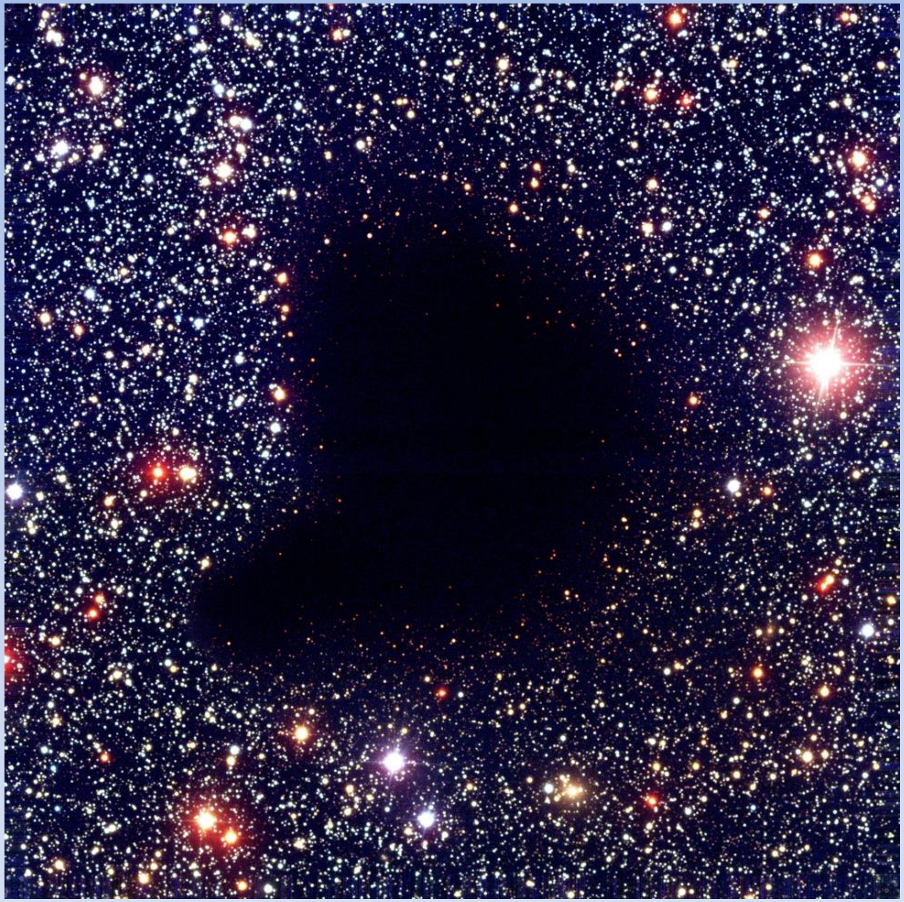
10^2-10^3 stars with a range of stellar masses
Centrally peaked

Reviews: Krumholz et al. 2014; Motte et al. 2017
Slide modified from Q. Zhang

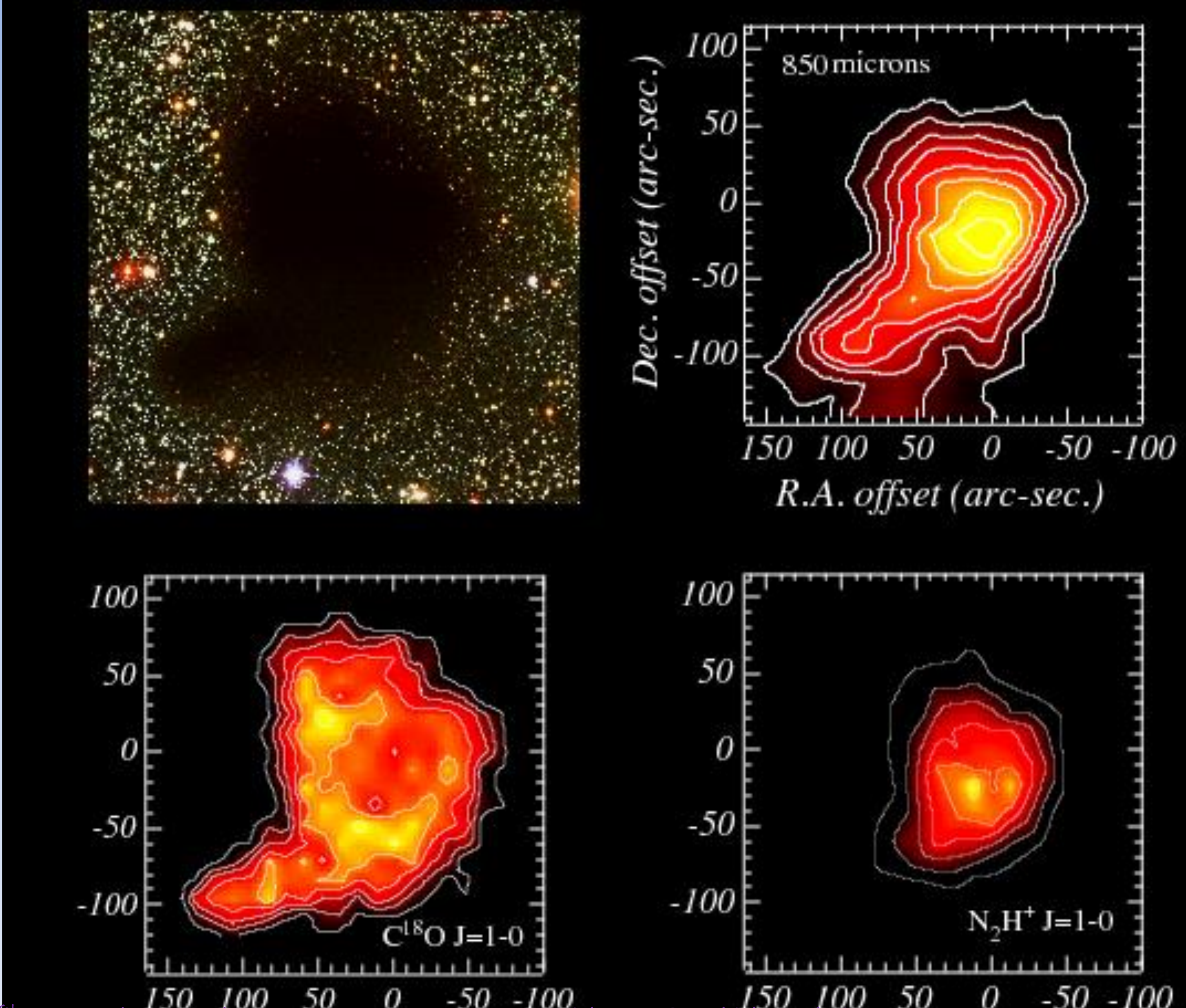
Where to look?

“holes in the heavens” Herschel 1785

William Herschel (1738-1822)



Barnard 68



850 microns
Dec. offset (arc-sec.)
R.A. offset (arc-sec.)
100
50
0
-50
-100
150 100 50 0 -50 -100
C18O J=1-0
N2H+ J=1-0

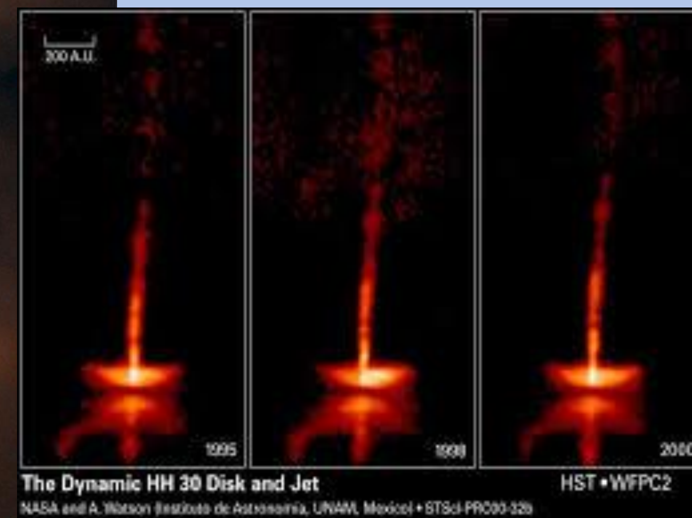
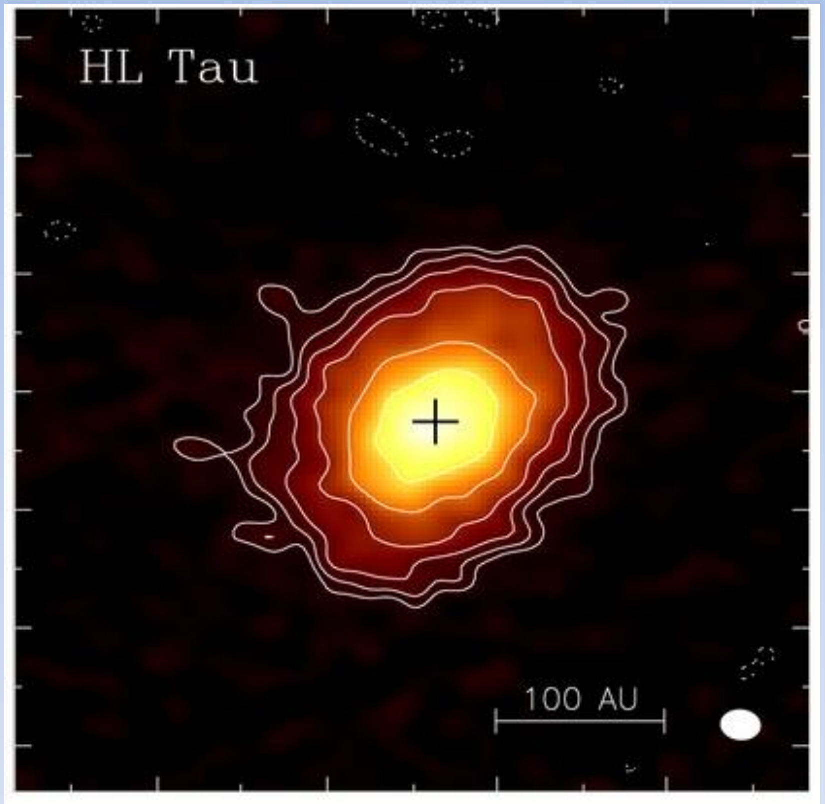
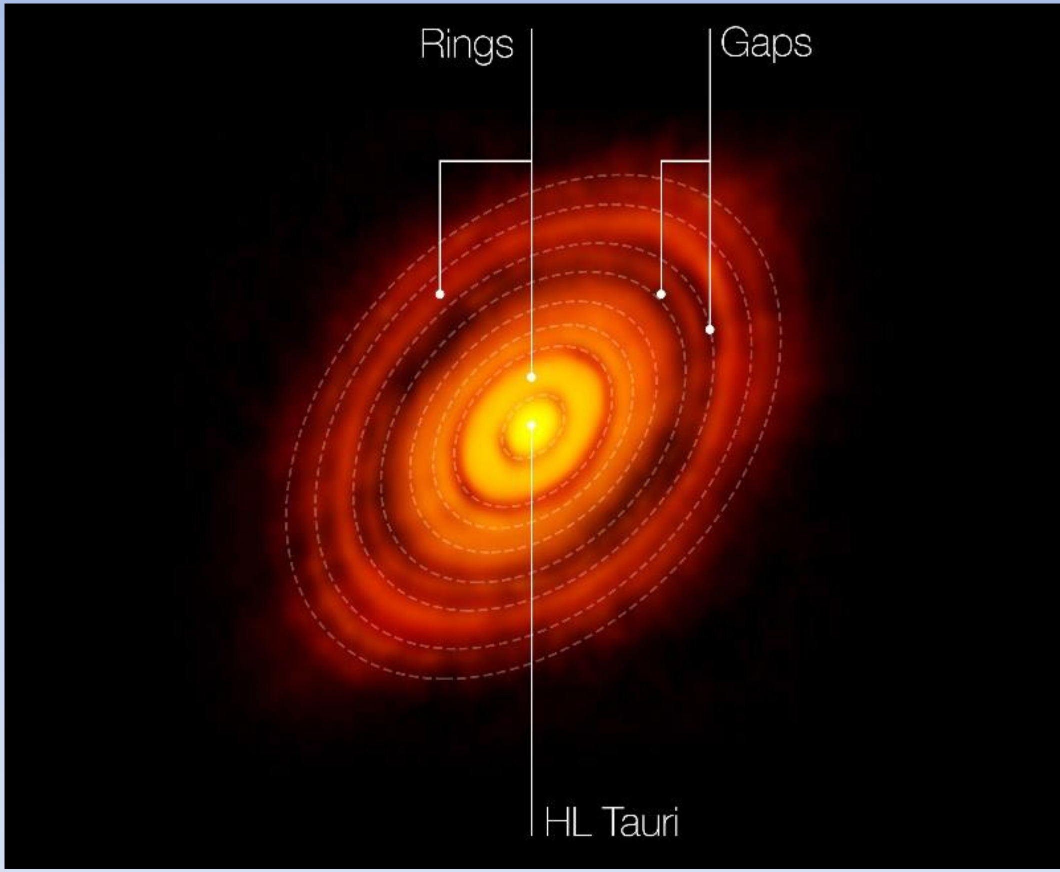


Image Credit: NASA, ESA, Hubble Heritage (STScI / AURA) / Hubble-Europe Collaboration



Kwon et al. 2011



ALMA Partnership et al. 2015

Star formation regions

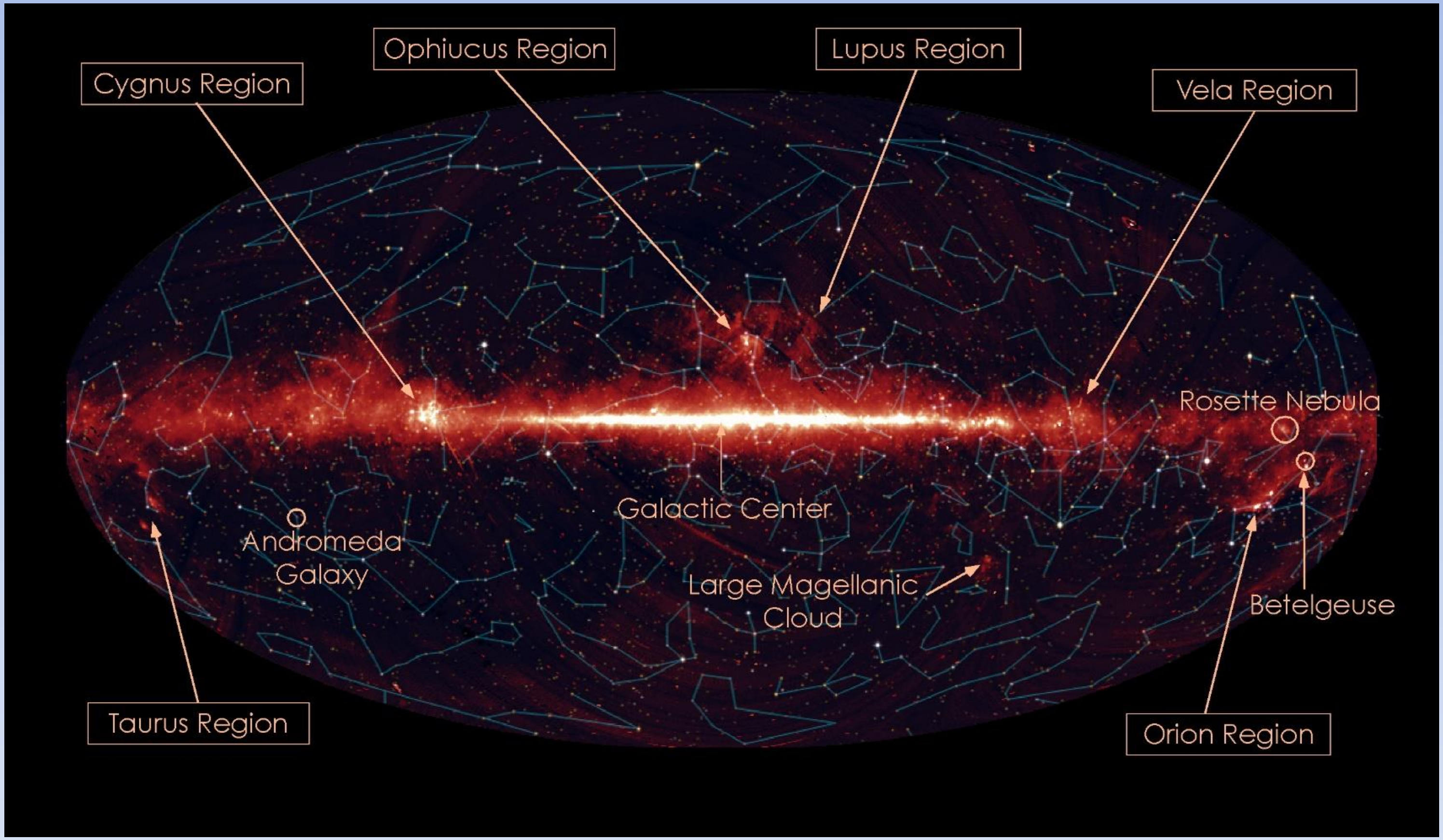
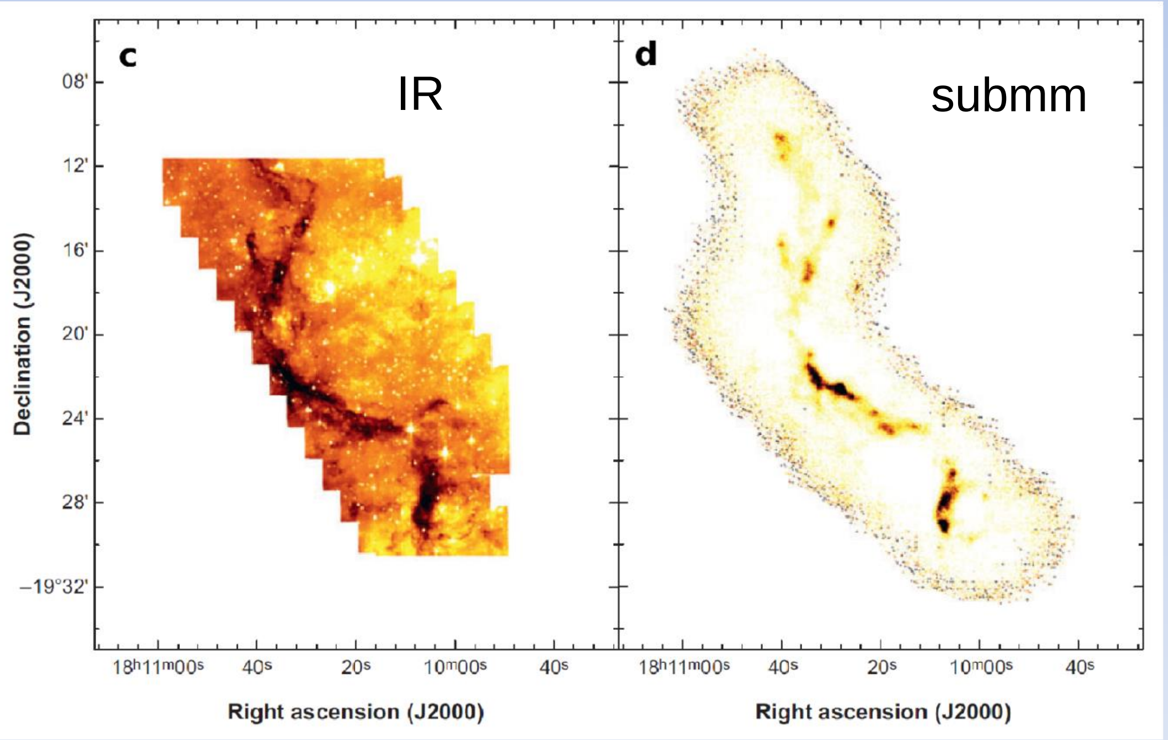
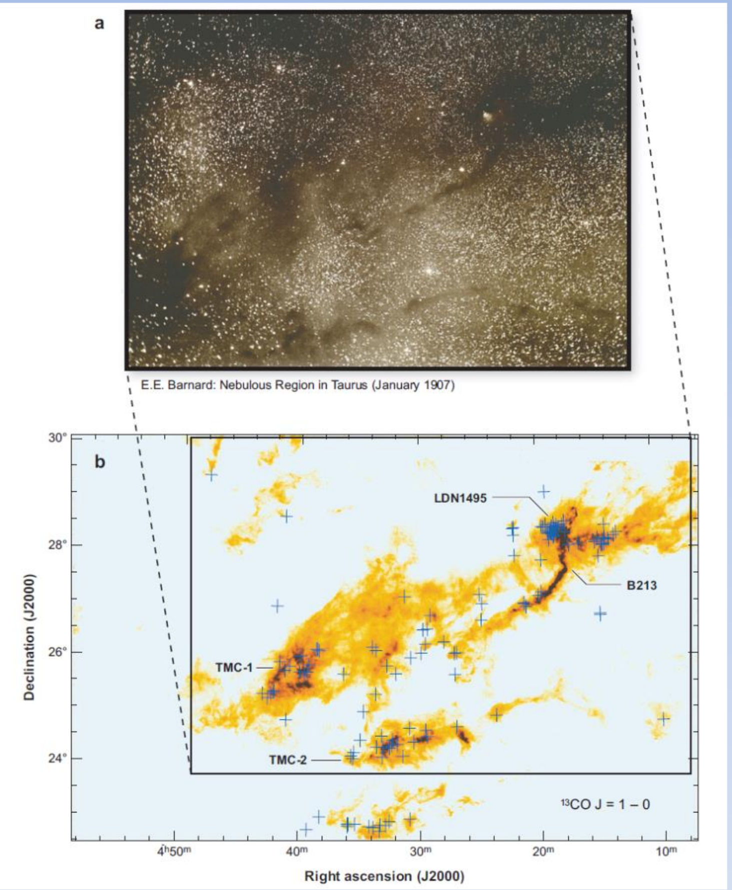


Image Credit: ESA

Optical dark cloud
1907

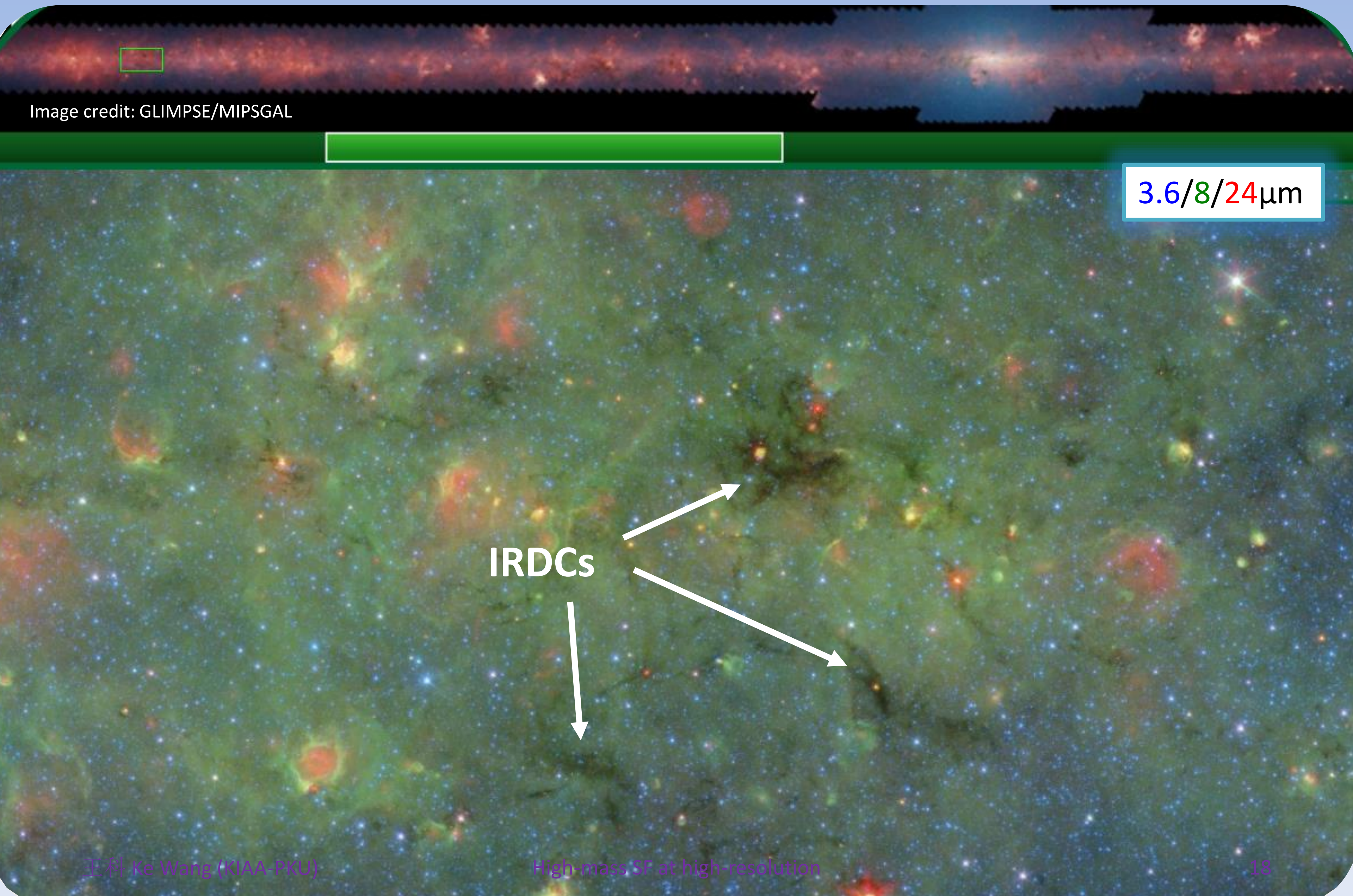
IR-dark cloud
1998

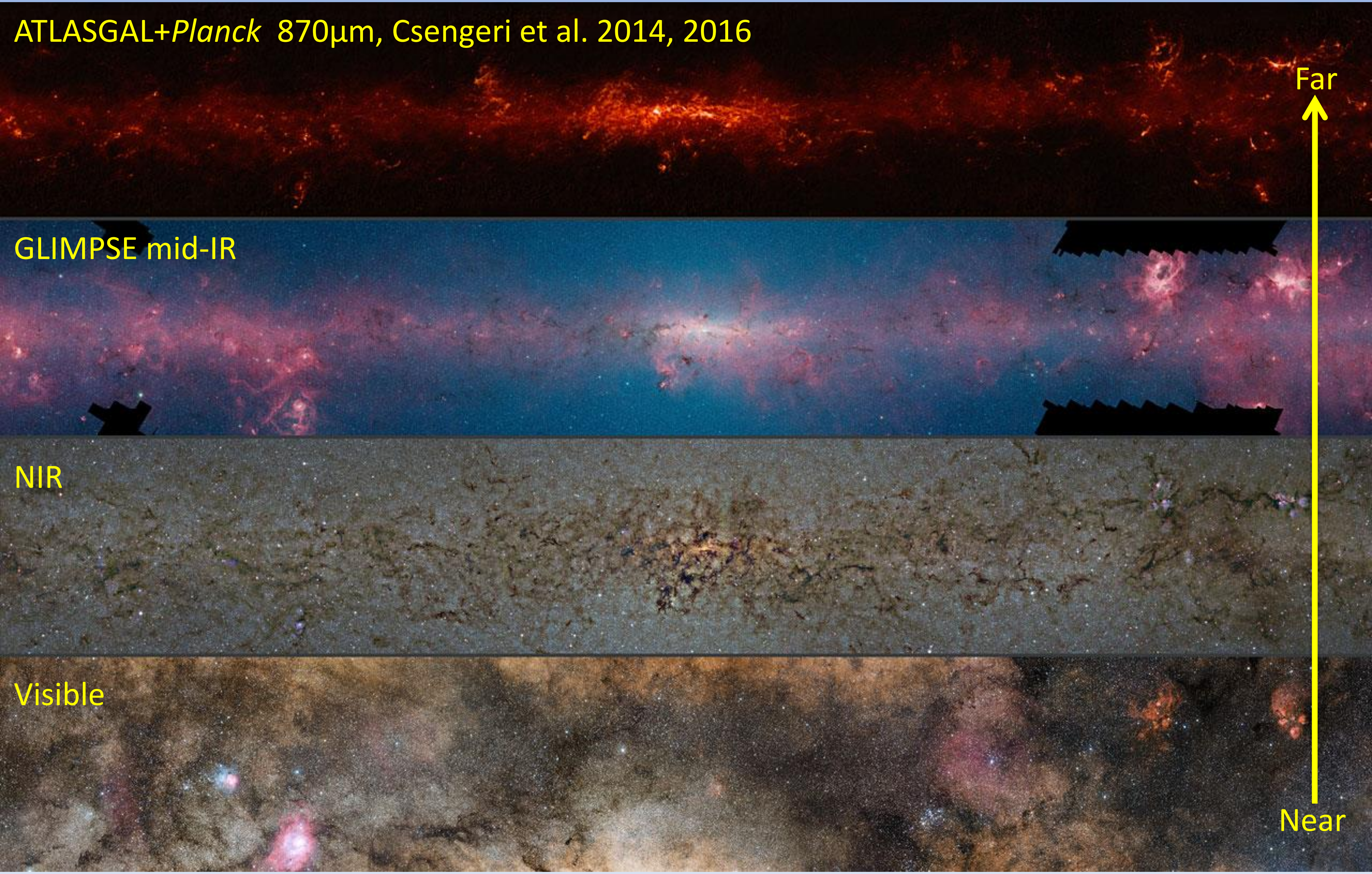




Bergin et al. 2007 ARA&A

IR-dark clouds: shadows in infrared sky





inner 20° of Galactic plane

Credit: ESO/ATLASGAL consortium/NASA/GLIMPSE consortium/VVV Survey/ESA/Planck/D. Minniti/S. Guisard

See also *Herschel* Hi-GAL at **70, 160, 250, 350, 500µm** CSO/BGPS at **1.1mm**

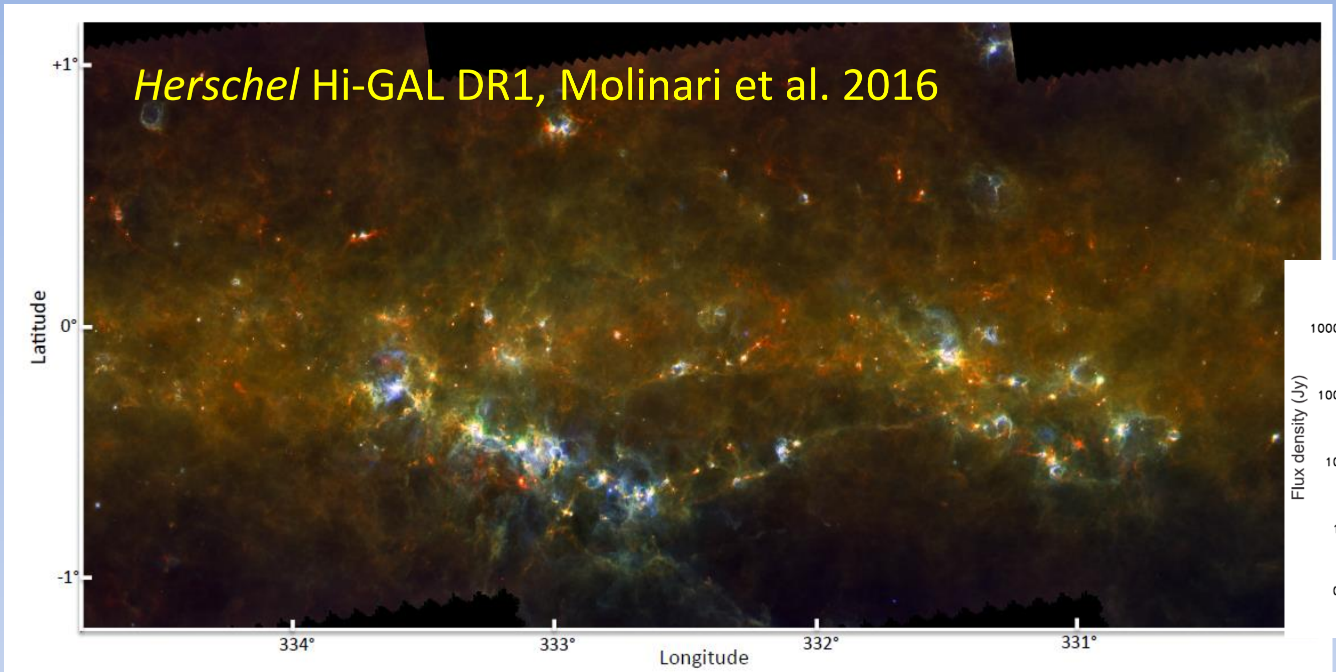
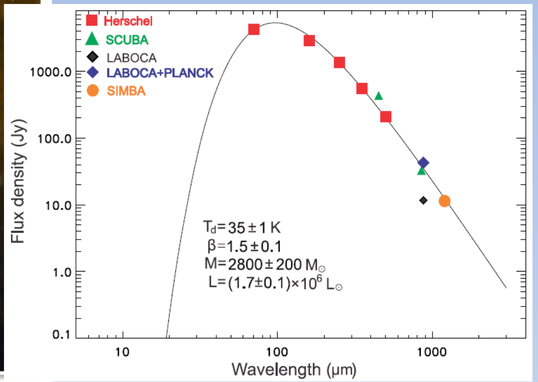
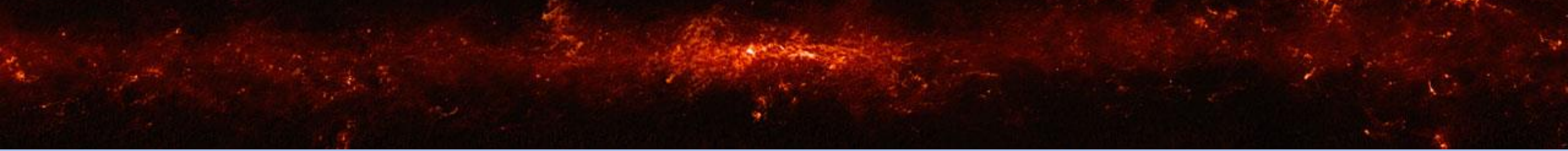


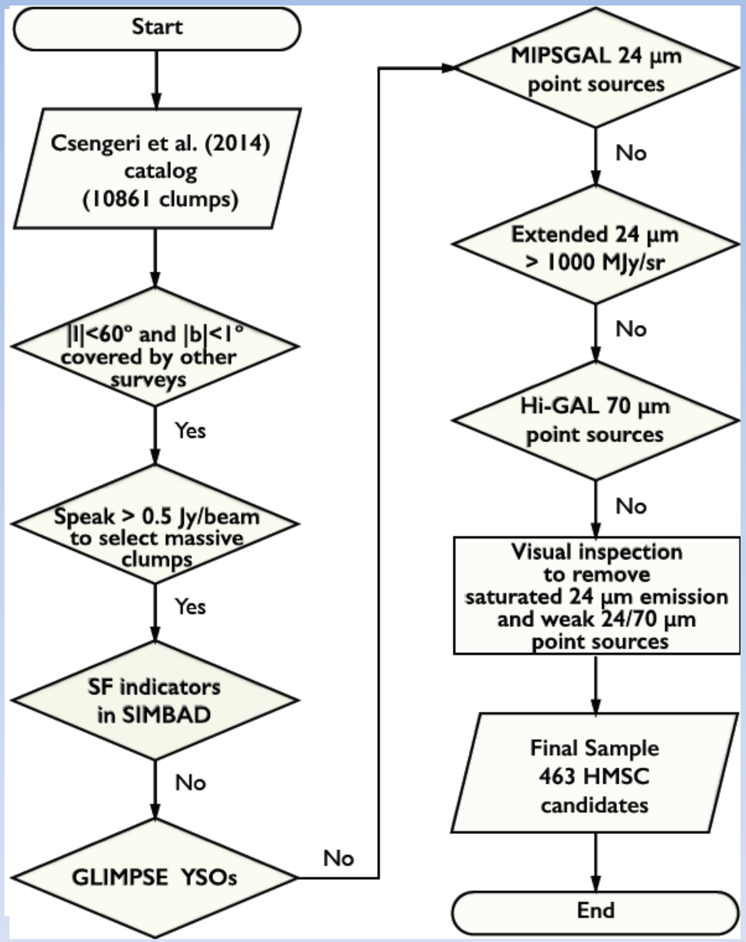
Fig. 1. Three-colour image (blue 70 μm, green 160 μm, red 350 μm) of a three-tile mosaic field around 330° ≲ ℓ ≲ 335°.

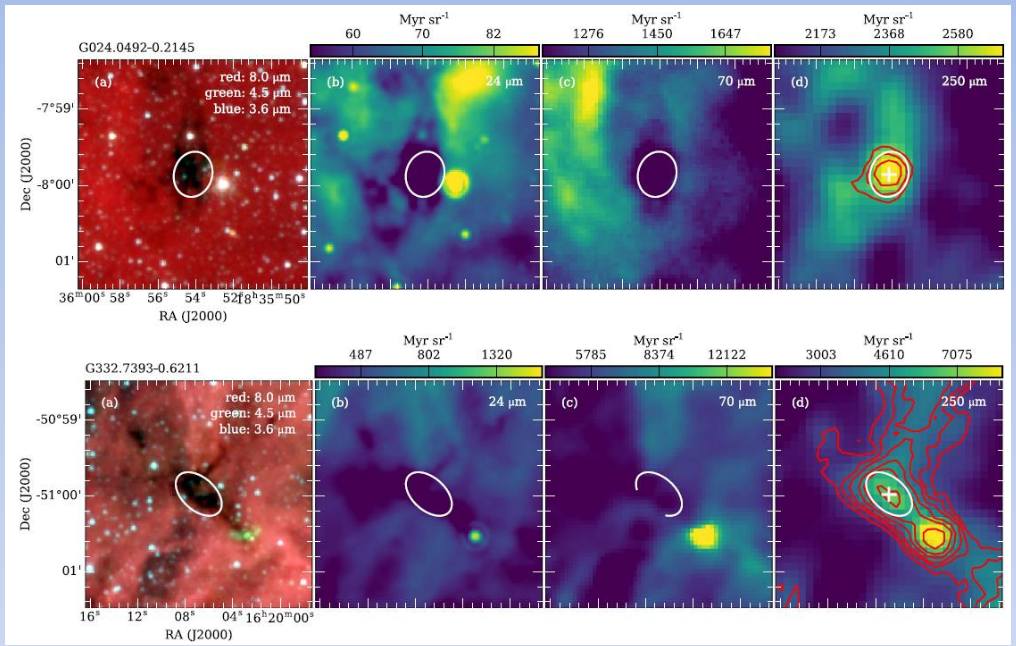


Galactic plane surveys in continuum & lines ready for source selection
+ ALMA's full capability:
now is the best time to have an in-depth investigation on MSF

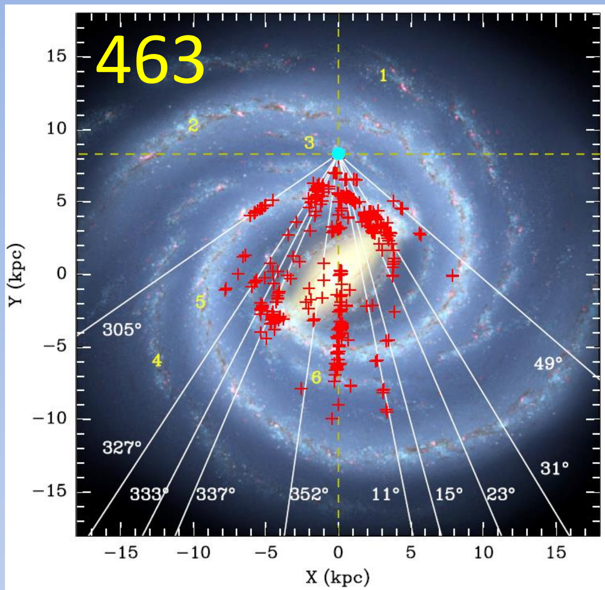
ATLASGAL

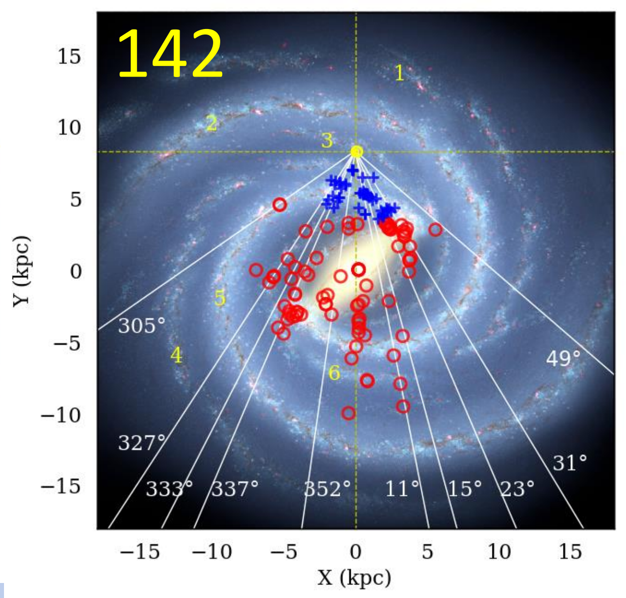


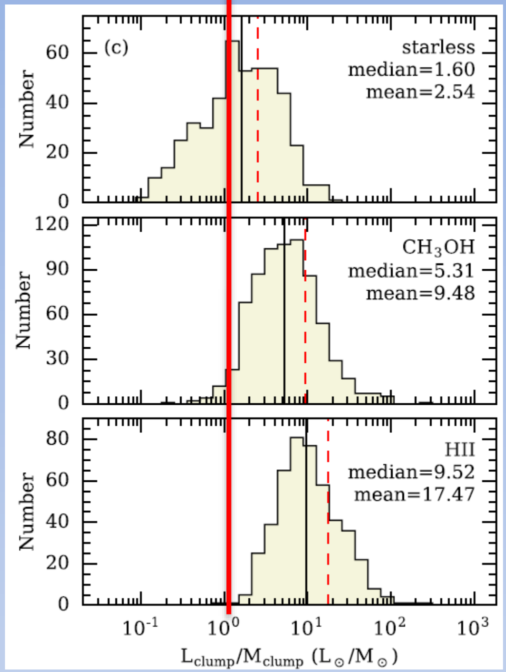




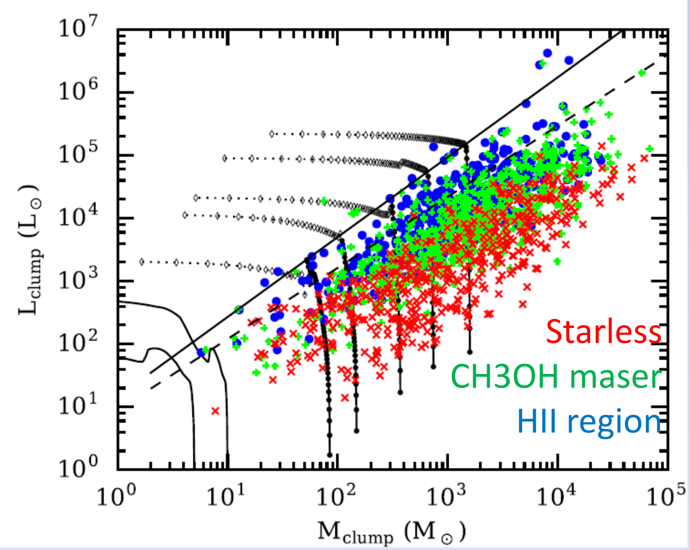
Yuan et al. 2017:
First Galaxy-wide high-mass starless clump (HMSC) catalog

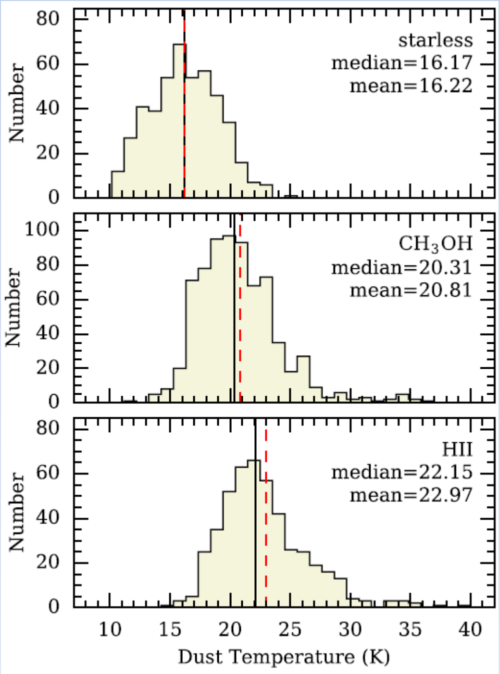






Cut on L/M ratio

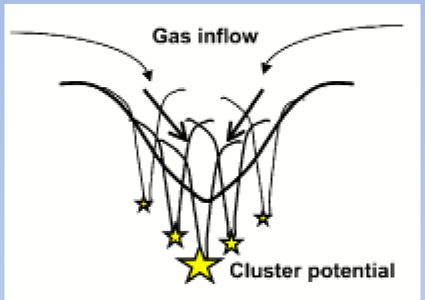




Debating theoretical models

Competitive Accretion

$M_{initial} = M_{Jeans} = 0.5\ M_{\odot}$



Bonnell et al. 1997, 2001, 2004

Turbulent Core

(a.k.a Monolithic Collapse)

Stellar heating (~100K) increase $M_{J;}$ start with massive cold core (**$10^2\ M_{\odot}$**)

McKee & Tan 2002
Krumholz et al. 2005, 2007

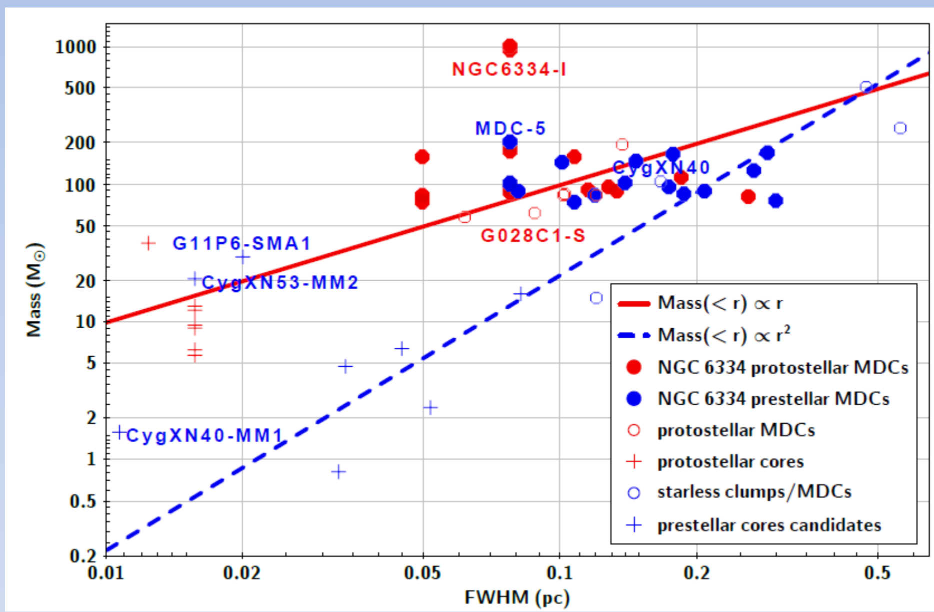
	Competitive Accretion	Turbulent Core
Initial core	~1 $M_\odot$ seeds	~100 $M_\odot$ monolithic
Virial status	Sub-virial	Equilibrium
Final stellar mass determined by	Accretion history	Pre-assembled core mass
Clump density profile	Flat	Centrally peaked
Disk	Yes	Yes
Clump global collapse	Yes	No?
Magnetic fields	Not included	Needed to increase M_J
Low-mass stars	Form with high-mass stars	Form before high-mass stars
Filamentary cloud	Not considered	Not considered

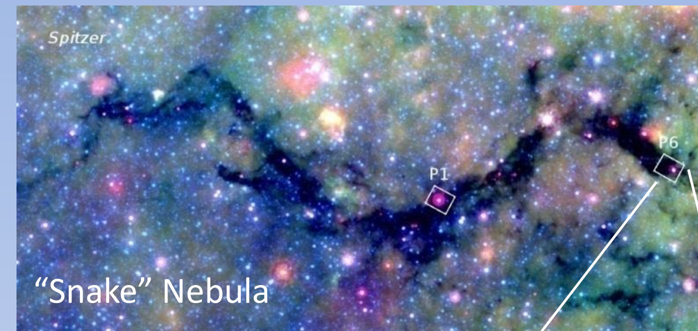
Key questions

- Do massive starless cores exist ?
- How do CMF evolve to IMF ?
- Is supersonic turbulence really necessary to form high-mass stars?
- How do filaments influence star formation ?

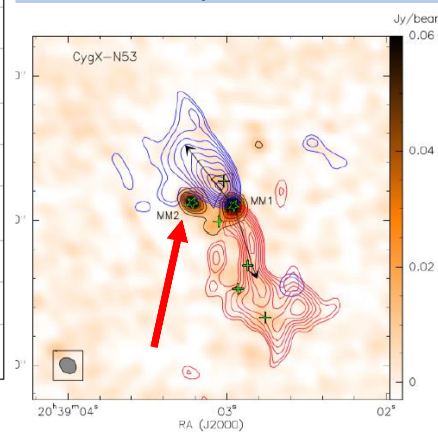
A decade of hunting for high-mass starless/prestellar cores

>100 $M_\odot$ within 0.1 pc
>30 $M_\odot$ within 0.02 pc

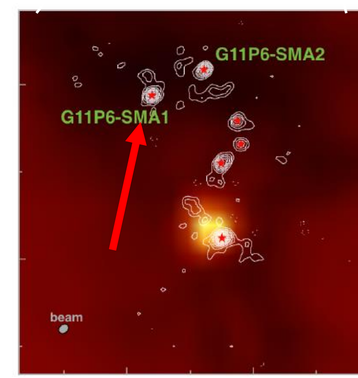




Bontemps et al. 2010



Wang et al. 2014



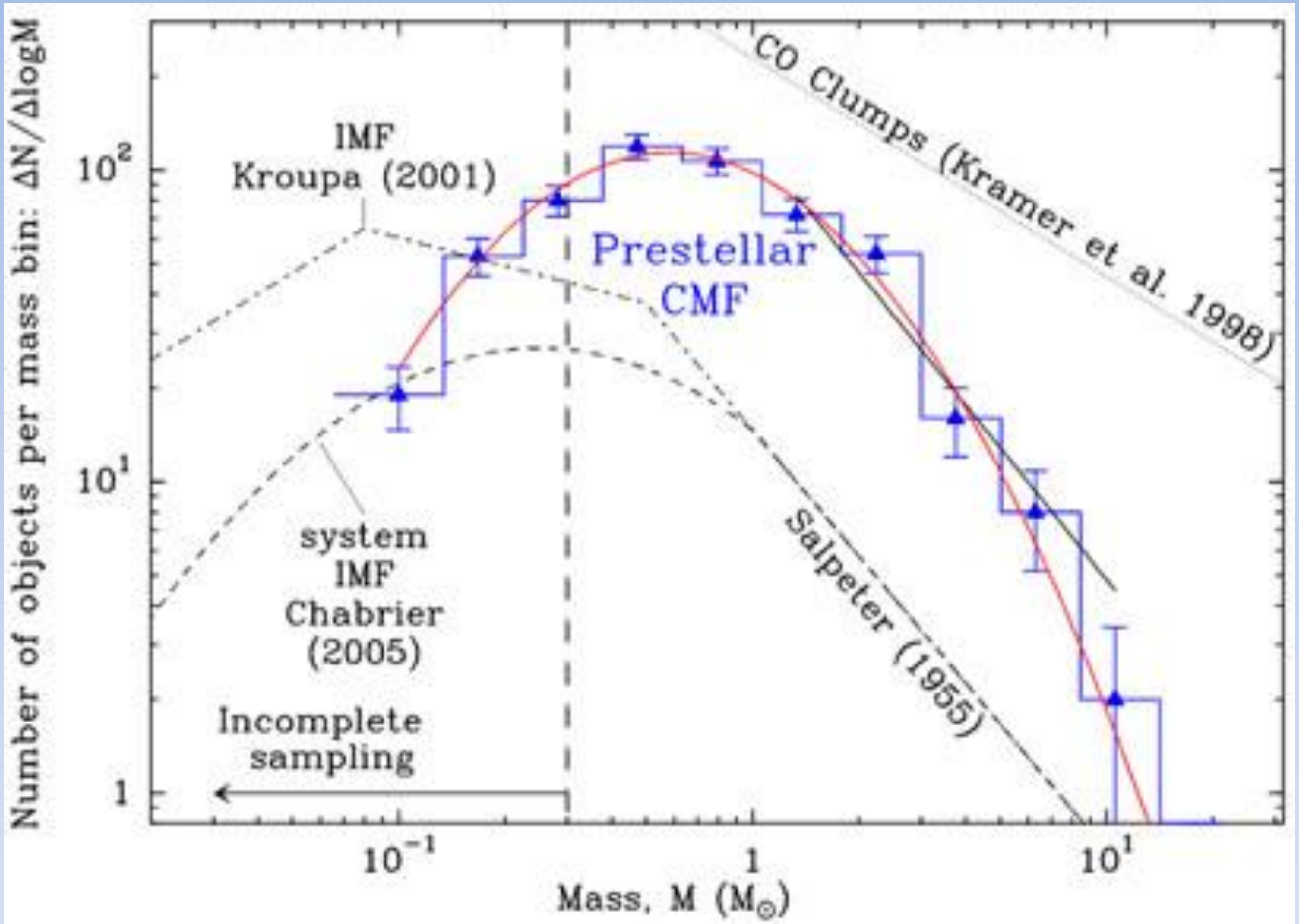
Motte et al. 2018, ARA&A review

After ten years of research, only two high-mass prestellar core candidates have therefore been identified: CygXN53-MM2 and G11P6-SMA1 (Bontemps et al. 2010b; Wang et al. 2014, see **Figures** 4 Left-Right). Interferometric studies toward large samples of starless MDC and IRDC fragments are ongoing (e.g., Csengeri et al. in prep.; Nony et al. in prep.). We are thus at the dawn of finally proving that massive prestellar cores do or do not exist.

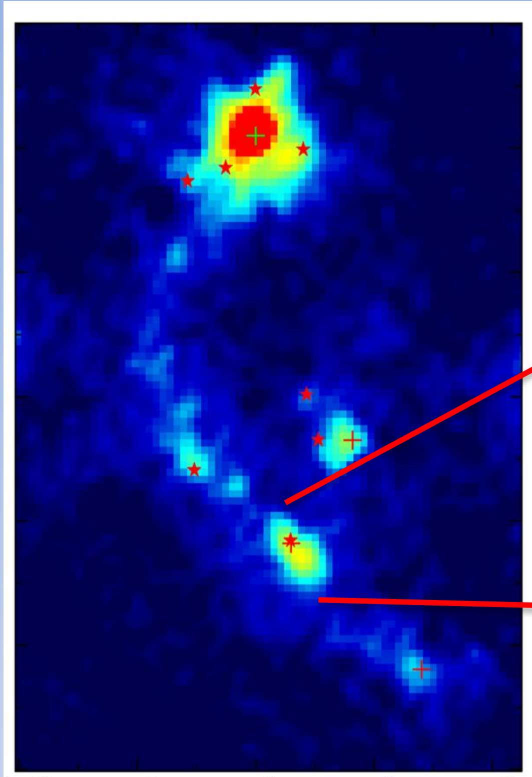
Key questions

- Do massive starless cores exist ?
- **How do CMF evolve to IMF ?**
- Is supersonic turbulence really necessary to form high-mass stars?
- How do filaments influence star formation ?

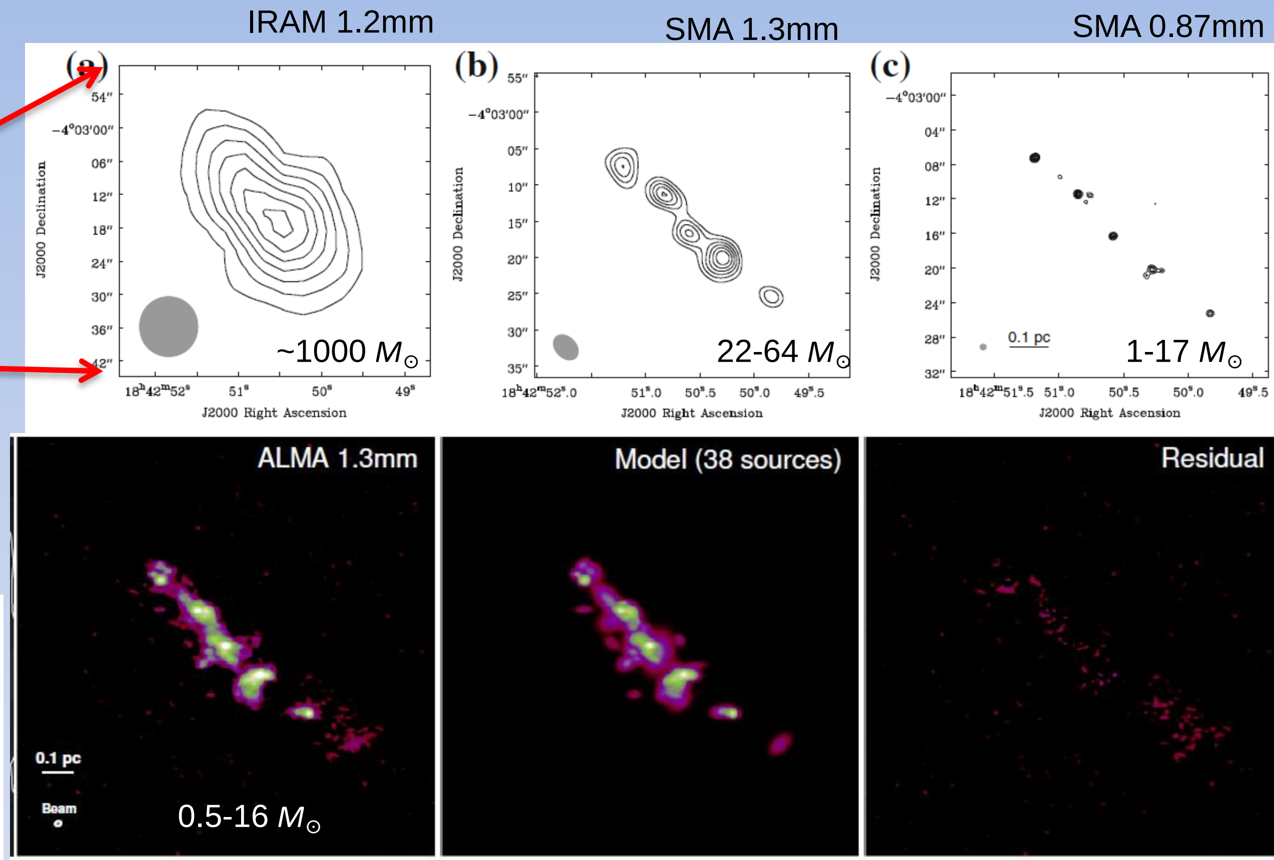
CMF→IMF one to one mapping!

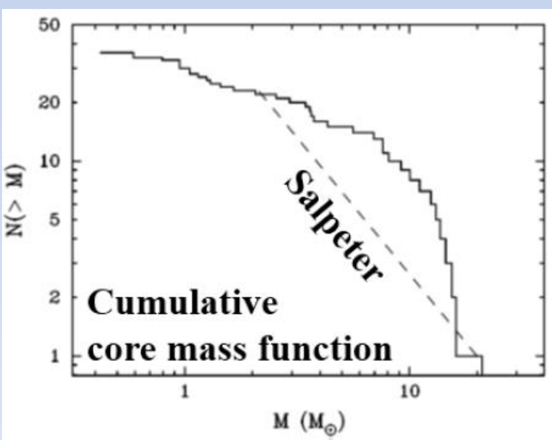


Andres et al. 2013



Top-heavy CMF in IRDC G28.34 the "Dragon"

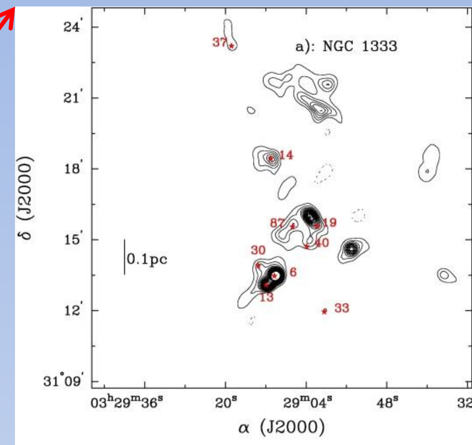




Wang et al. 2011, Zhang et al. 2009, 2015

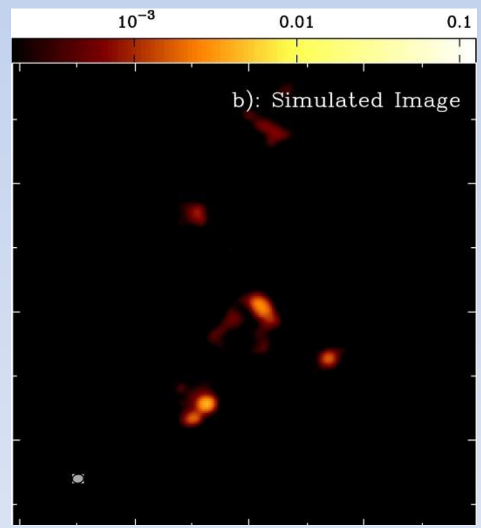
Lack of distributed low-mass protostars

Gutermuth et al. 2009



Kirk et al. 2006
SCUBA 870 µm

ALMA simulated observations at 1.3mm



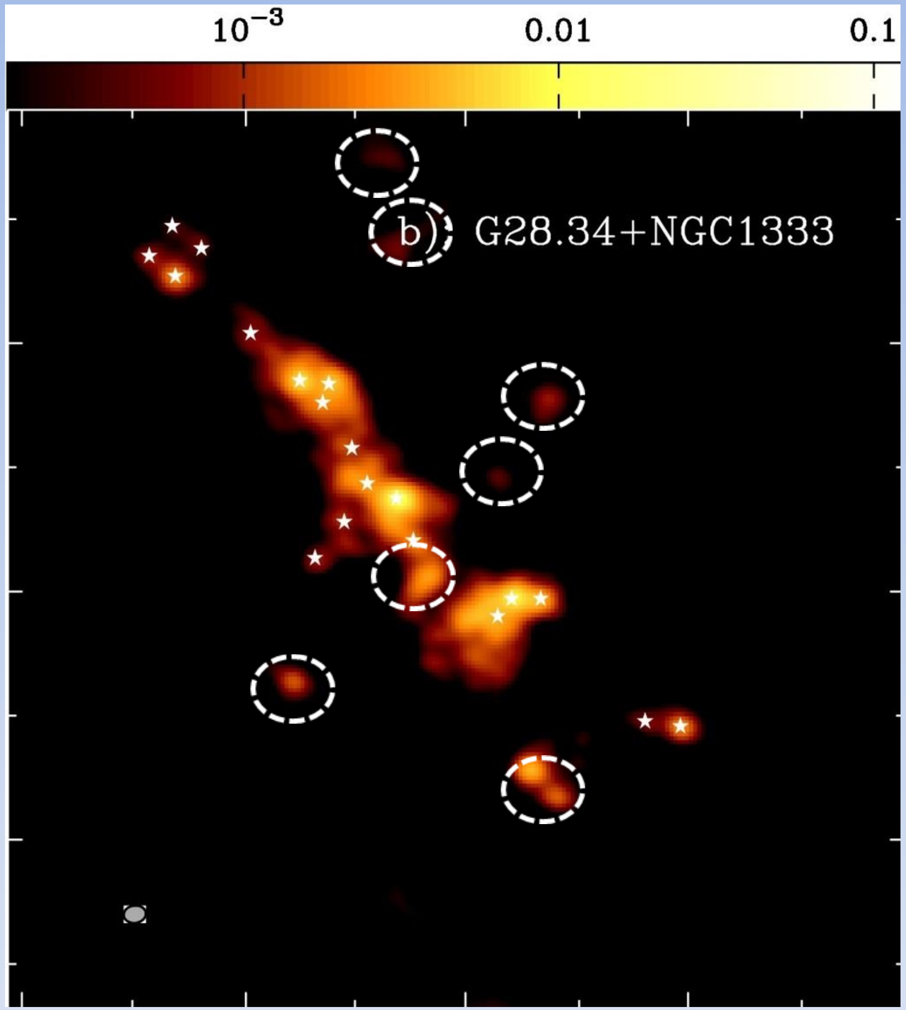
NGC 1333 Class 0 protostars detected at distance of G28.34

Lack of distributed low-mass protostars

Simulated ALMA observations using G28 and NGC1333

A low-mass cluster such as NGC1333 can be reliably detected if present

Low-mass protostars form *after* massive ones in a cluster
➔ against SF models requiring feedback from low-mass stars



Motte et al. 2018, Ohashi et al. 2018
Top-heavy CMF, unlike IMF

NATURE ASTRONOMY LETTERS

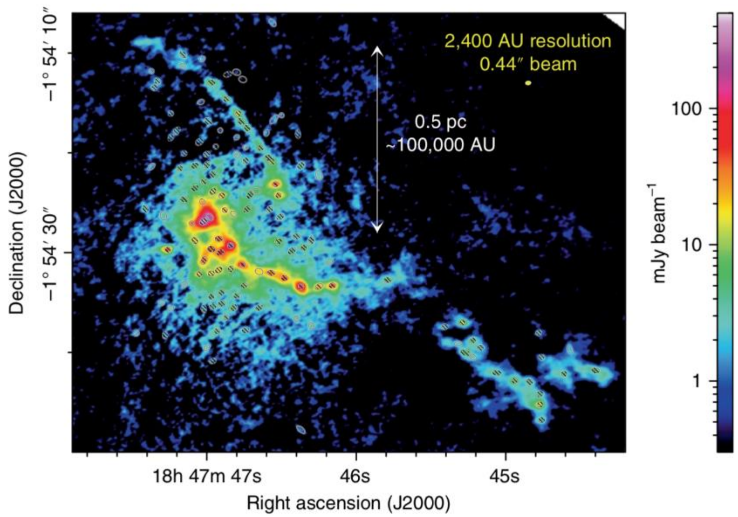


Fig. 1 | High-angular-resolution image of the W43-MM1 cloud, revealing a rich population of cores. 1.3 mm dust continuum emission, observed by the ALMA interferometer, is presumed to trace the column density of gas, revealing high-density filaments and embedded cores. The filled yellow ellipse on the right represents the angular resolution, and a scale bar is shown. Ellipses outline core boundaries (at half-maximum) as defined by the getsources[20] extraction algorithm. Core masses span the range ~1 to ~100$M_\odot$ and can therefore be expected to spawn stars with masses from ~0.4 to >40$M_\odot$ (ref. [5]; see Supplementary Table 1). All cores are shown. Hashed ellipses indicate the most robust identifications.

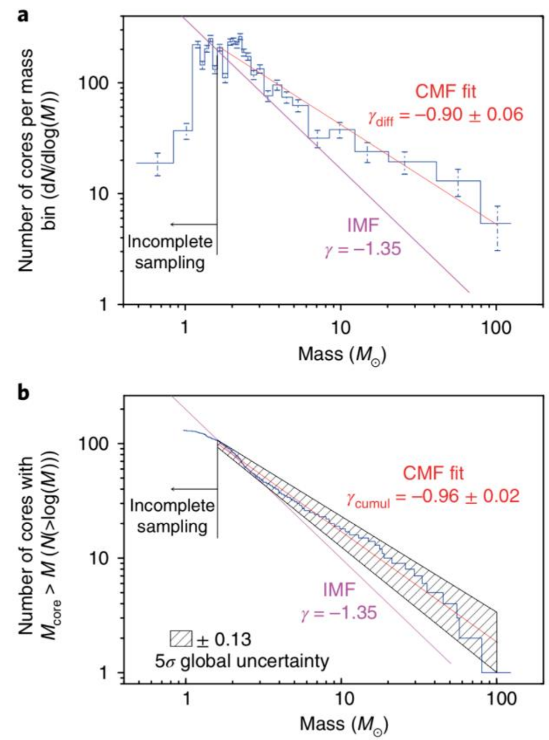


Fig. 2 | W43-MM1 CMFs challenging the relationship between the CMF and IMF. a,**b**, Differential (**a**) and cumulative form (**b**). Above the sample 90% completeness limit, estimated to be $M_{core} = 1.6 M_\odot$ (black vertical line), the W43-MM1 CMFs (blue histograms) are well fit by the single power laws $dN/d\log(M) \propto M^{-0.90}$ in **a** and $N(>\log(M)) \propto M^{-0.96}$ in **b** (red lines and 1σ uncertainties). The error bars on the differential CMF correspond to $\sqrt{N}$ counting statistics. The cumulative CMF in **b** is the more robust statistically: its 5σ global uncertainty (±0.13, hatched area) was estimated from Monte Carlo simulations. The W43-MM1 CMF is clearly flatter than the IMF[9,22], which in the corresponding mass range has slopes $dN/d\log(M) \propto M^{-1.35}$ and $N(>\log(M)) \propto M^{-1.35}$ (magenta lines).

from ~0.6 to ~40$M_\odot$), allowing a robust comparison with the higher-mass ($\gtrsim M_\odot$) IMF. The result is stable against variations in the temperature model, dust emissivity, extraction algorithm and reduction technique (see Supplementary Table 2). We conclude that at masses larger than ~1.6$M_\odot$, the CMF in W43-MM1 is markedly flatter than the IMF. This result seriously challenges the widespread assumption that the shape of the IMF is inherited directly from the CMF

Key questions

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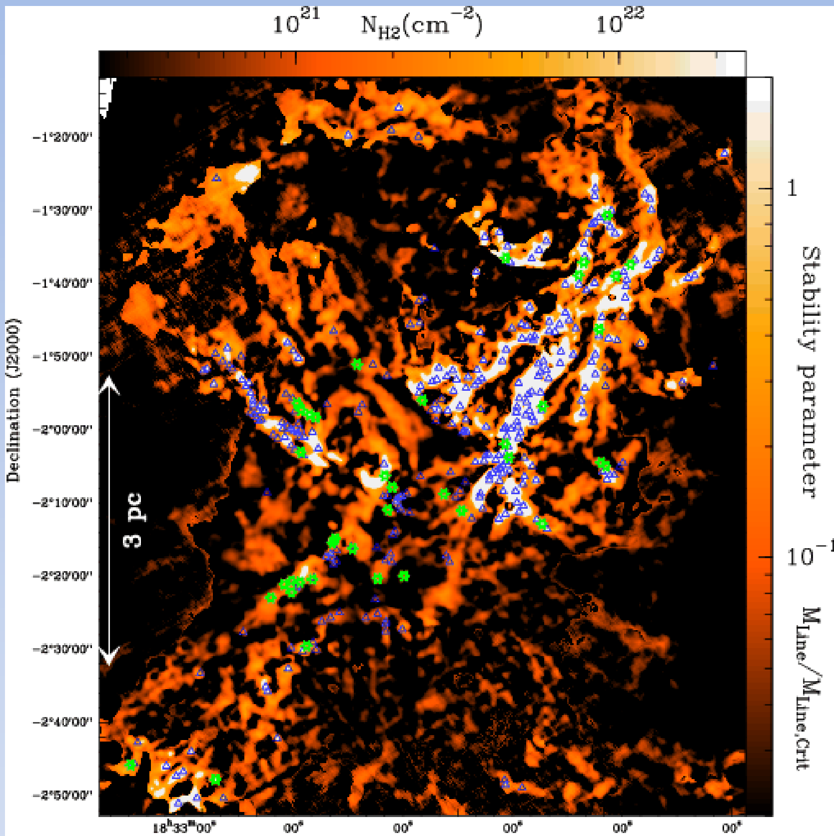
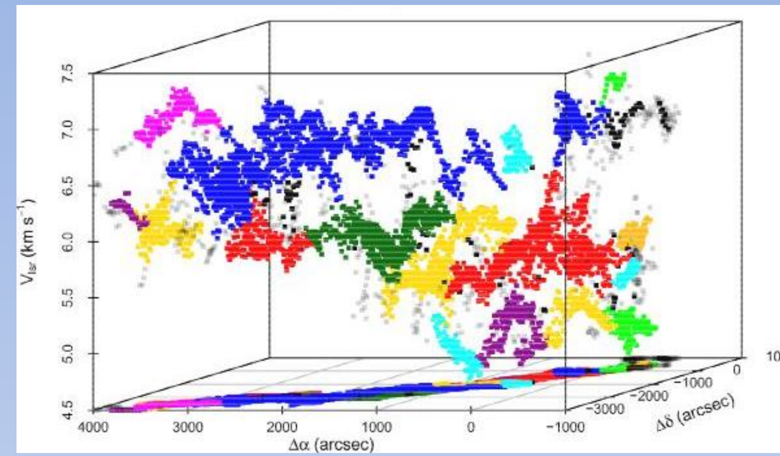
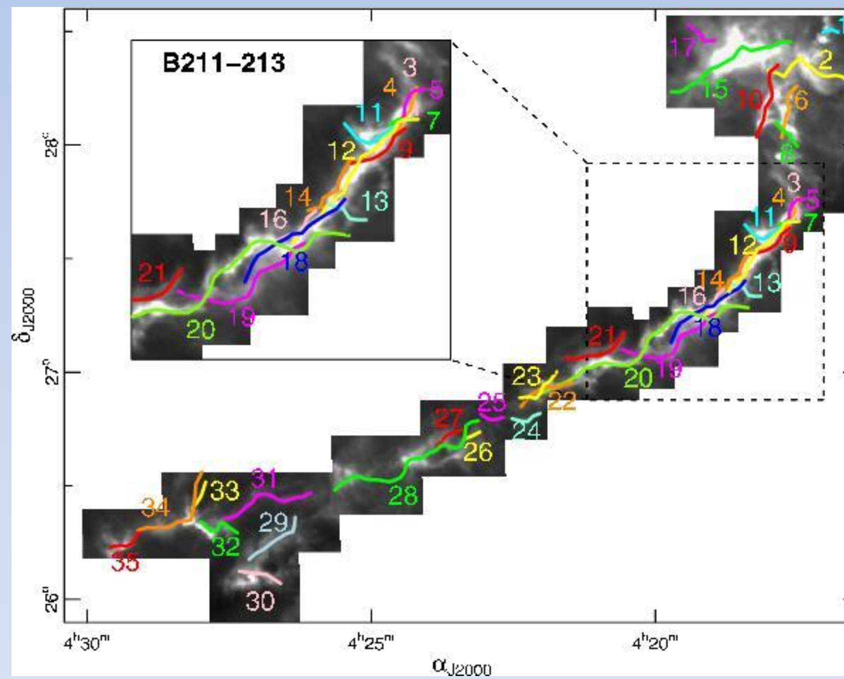
Low-mass SF, low turbulence.
High-mass SF, high turbulence?

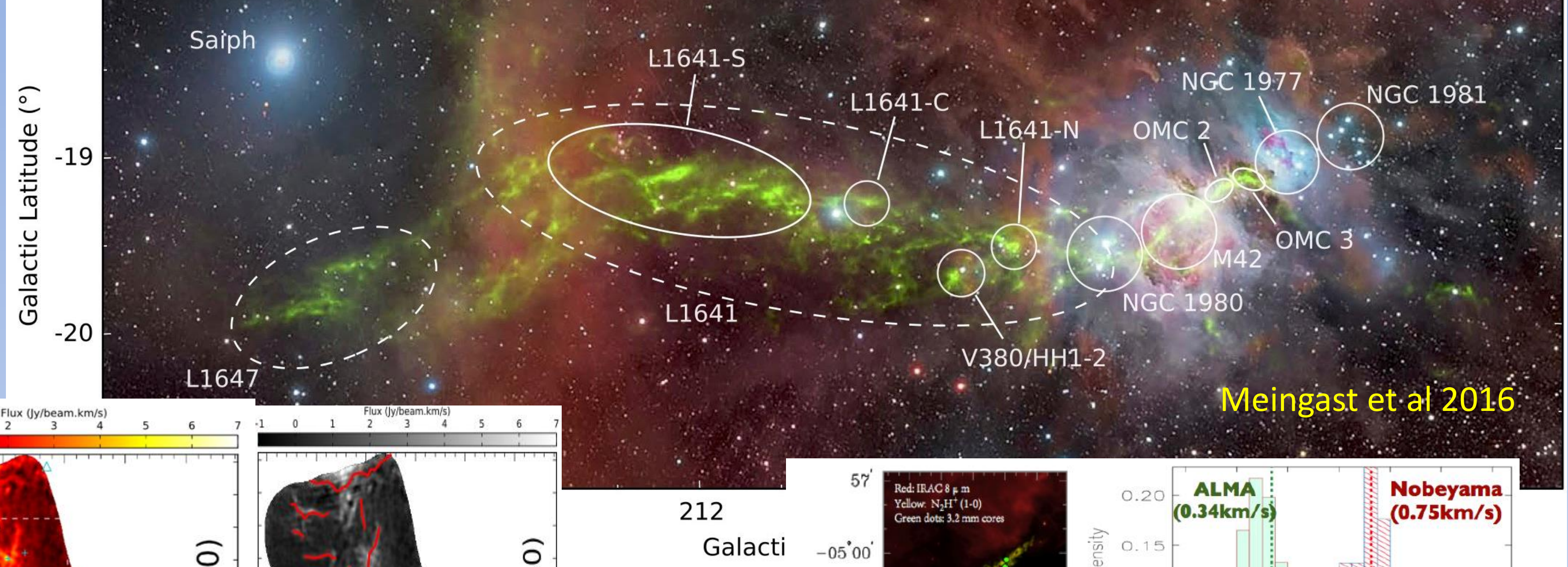


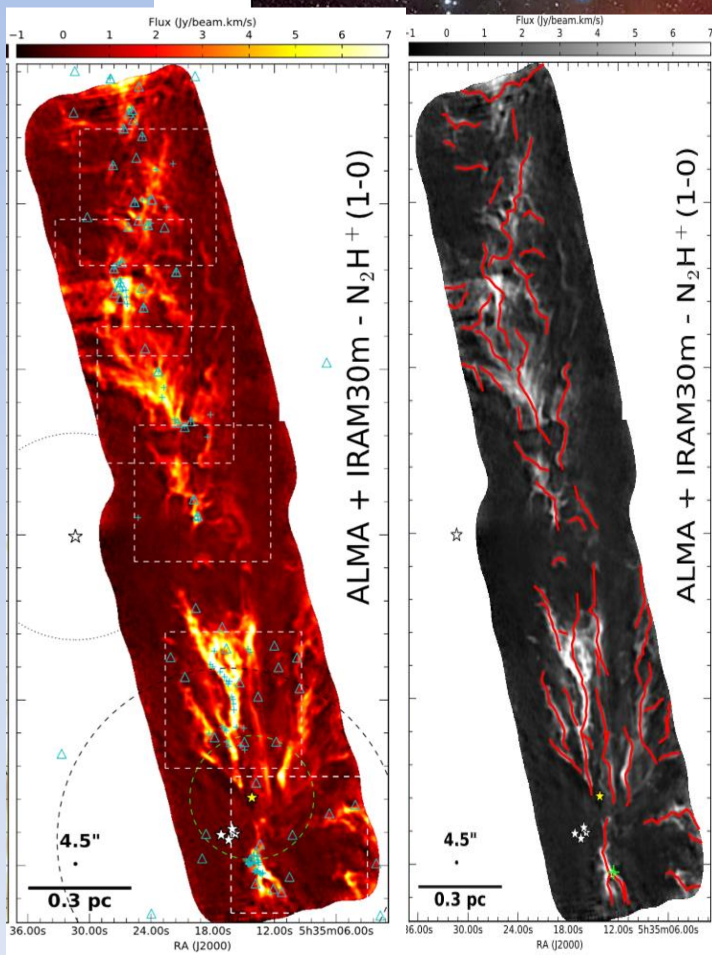
Andre et al. 2010, Aquila
Cores on filaments

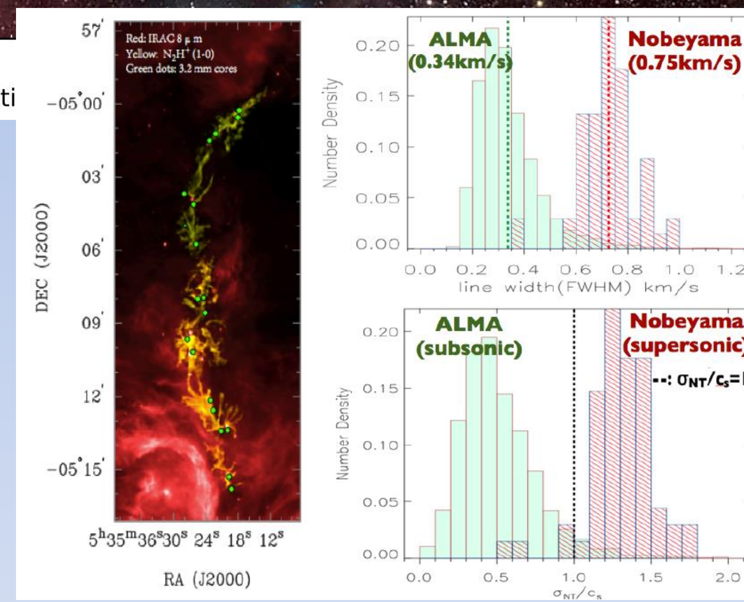




Hacar et al. 2013, Taurus
“Bundles of fibers” (thermal filaments)







Yue et al. submitted, OMC3
importance of **linear resolution**

Hacar et al submitted, OMC2
High-mass stars form in intersection of fibers

A&A 611, L3 (2018)
https://doi.org/10.1051/0004-6361/201832746

Astronomy & Astrophysics

Letter to the Editor

Subsonic islands within a high-mass star-forming infrared dark cloud

Vlas Sokolov[1], Ke Wang[2], Jaime E. Pineda[1], Paola Caselli[1], Jonathan D. Henshaw[3], Ashley T. Barnes[1,4], Jonathan C. Tan[5,6], Francesco Fontani[7], Izaskun Jiménez-Serra[8], and Qizhou Zhang[9]

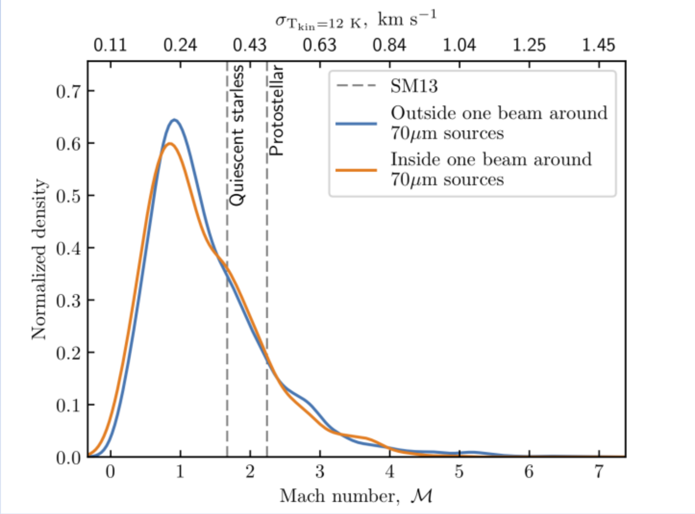
Student work:

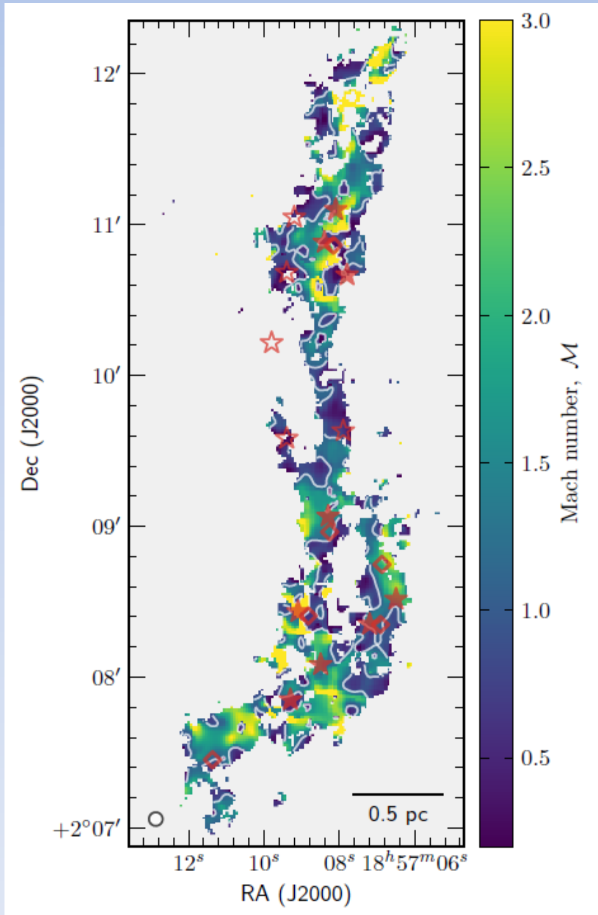
IRDC G35.39

Fitting on VLA+GBT NH_3 data

Importance of **spectral resolution**

Old VLA spectrometer gives 0.6 km/s!





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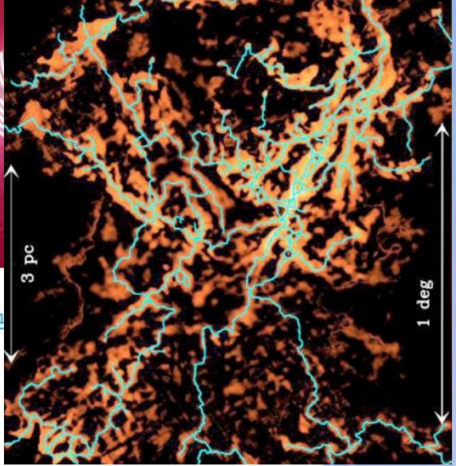
HERSCHEL'S HUNT FOR FILAMENTS IN THE MILKY WAY

28 May 2015

Observations with ESA's Herschel space observatory have revealed that our Galaxy is threaded with filamentary structures on every length scale. From nearby clouds hosting tangles of filaments a few light-years long to gigantic structures stretching hundreds of light-years across the Milky Way's spiral arms, they appear to be truly ubiquitous. The Herschel data have rekindled the interest of astronomers in studying filaments, emphasising the crucial role of these structures in the process of star formation.

Shortcut URL
http://sci.esa.int
/jump.cfm?oid=55942

Images And Videos



Some of the most prominent filaments detected in the Milky Way: G49 (top), G47 (bottom left) and G64 (bottom right). *Credit: ESA/Herschel/PACS/SPIRE/Ke Wang et al. 2015*

Largest, coldest, densest filaments in our Galaxy

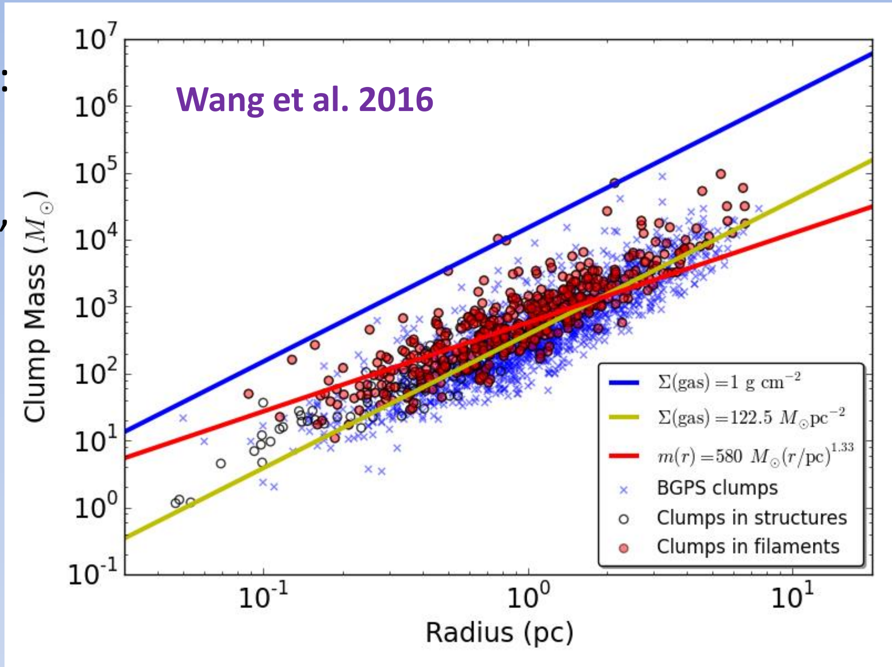
Wang et al. 2015, MNRAS.450.4043

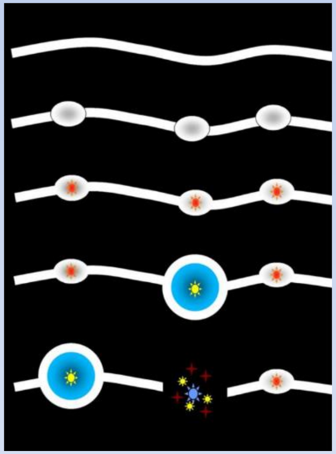
ESA feature article

纤维状结构引入各项异性，利于物质聚集

Census of large filaments in Galactic plane finds:

- 1% of ISM confined in >10 pc filaments
- ⅓ of them running at arm centers = “Bones”
- Favorable location of SF:
  - Clumps 5-10 times denser
  - cf. $M_{cl} / M_J = 4.6$



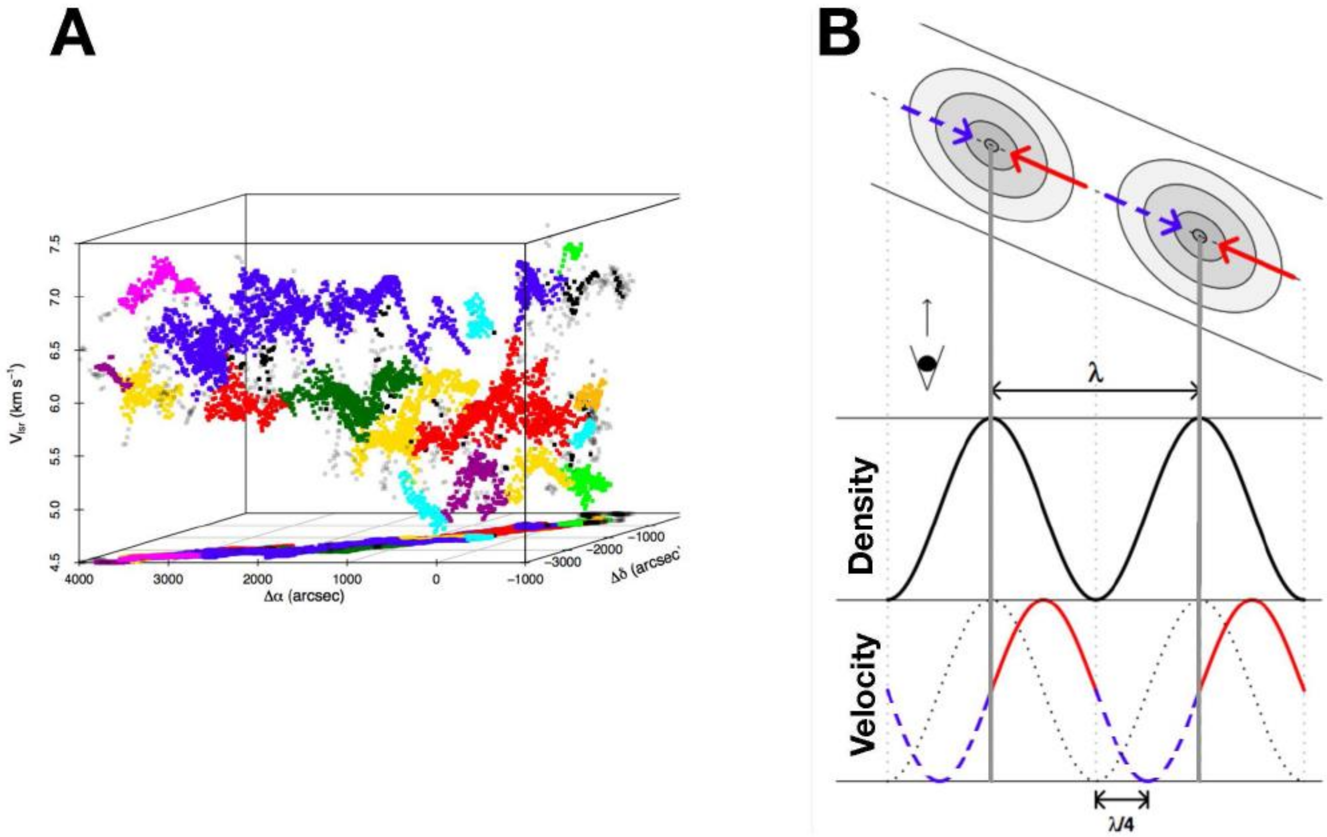


Jackson et al. 2010

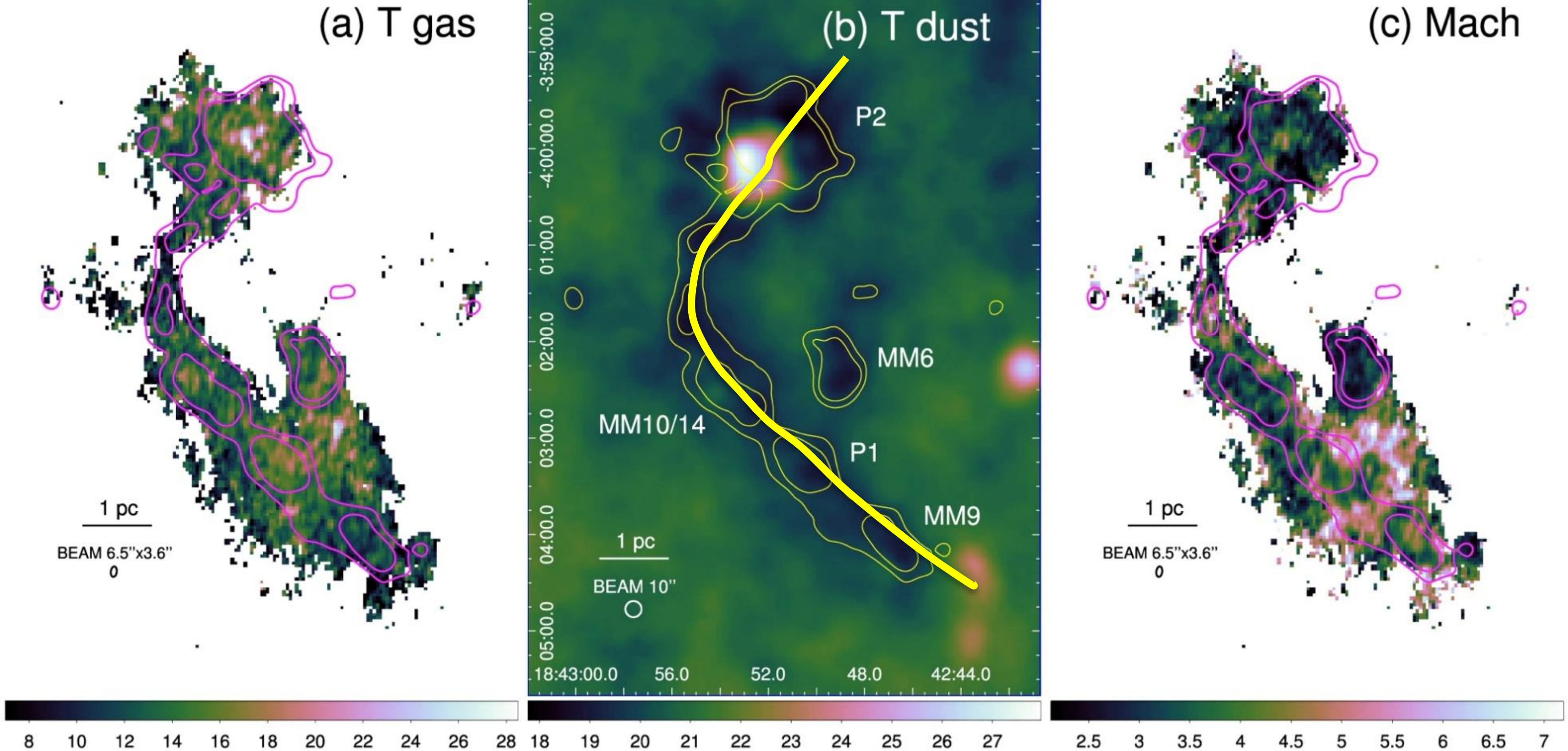
Cylinder frgmentation vs Jeans fragmentation

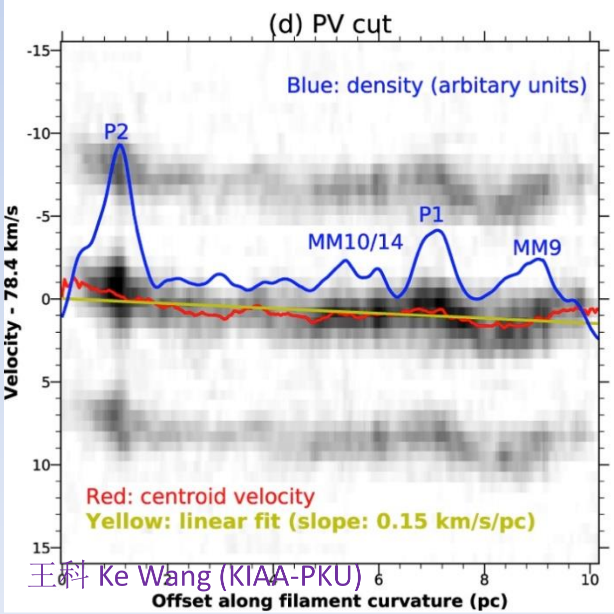
$$M_{\rm cl} = (M/l)_{\rm crit} \times \lambda = 575.3\,{\rm M}_\odot \left(\frac{\sigma}{1\ {\rm km\,s^{-1}}}\right)^3 \left(\frac{n_c}{10^5\ {\rm cm^{-3}}}\right)^{-1/2}$$

$$M_{\rm J} = \frac{\pi^{5/2} c_s^3}{6\sqrt{G^3 \rho}} = 0.877\,{\rm M}_\odot \left(\frac{T}{10\,{\rm K}}\right)^{3/2} \left(\frac{n}{10^5\ {\rm cm^{-3}}}\right)^{-1/2}$$

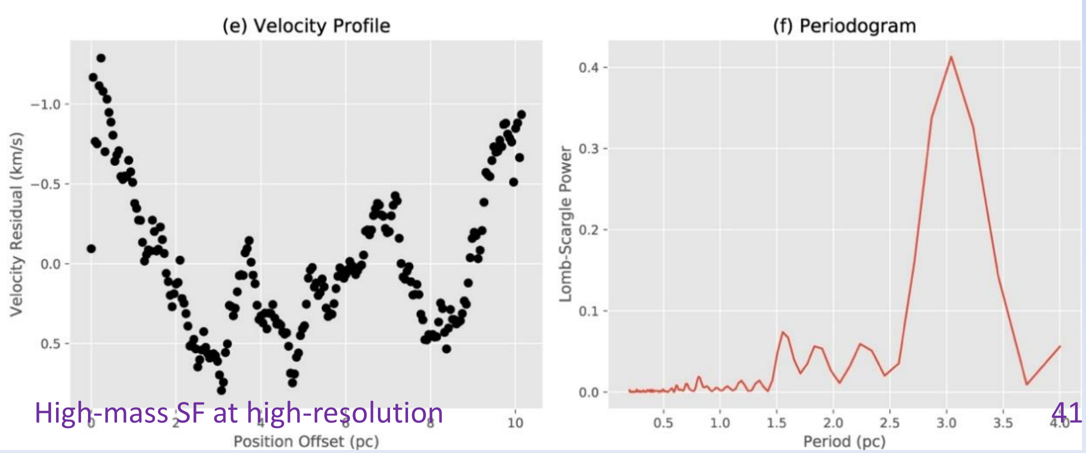


Hacar et al. 2011, 2013



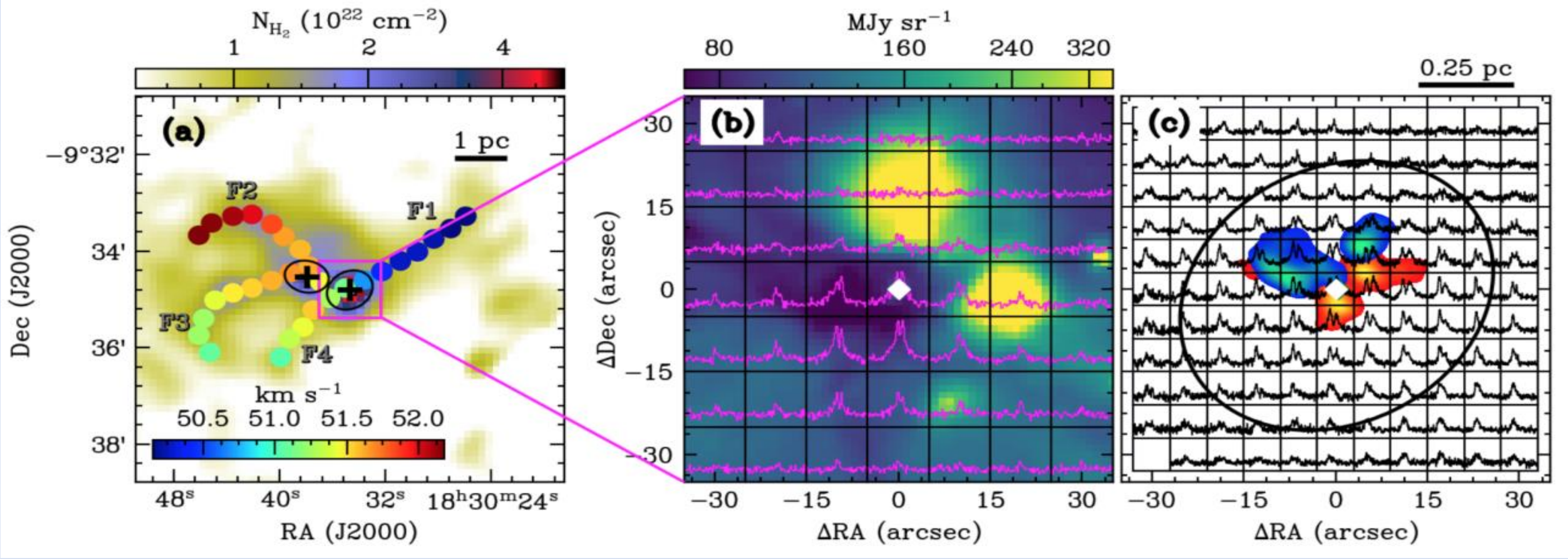


Wang et al. 2018



Filaments channel mass flows

- Type X – crossing filaments in Wang et al. 2015 classification
- Yuan et al. 2018 found evidence for mass assembly channeled by filaments at multiple scales (~10 pc to <0.1 pc)
- Other examples see Peretto et al. SDC13, Liu et al. G10.6



Key questions

- Do massive starless cores exist ?

Probably not. To be tested in hundreds of cores observed by ALMA.

- How do CMF evolve to IMF ?

CMF shapes vary from source to source. Test time evolution in individual objects harboring multiple evolutionary stages.

- Is supersonic turbulence really necessary to form high-mass stars?

Not in Orion, G35, Lancet, Snake. Could be an instrumental limitation. To be tested in more sources with dedicated observations.

- How do filaments influence star formation ?

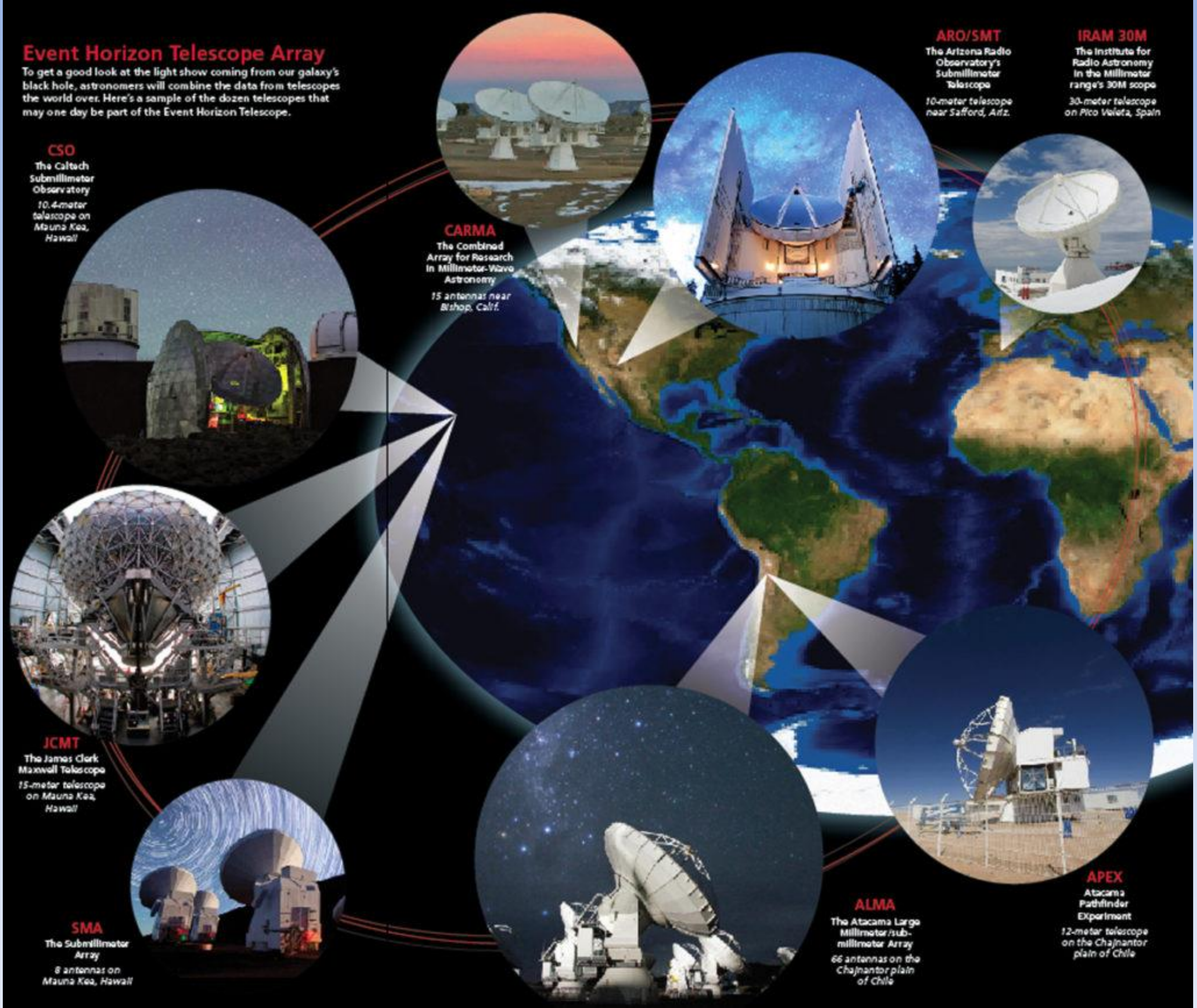
Filaments introduces inhomogeneous in star forming gas. They can channel gas flows, but the role is to be quantified.

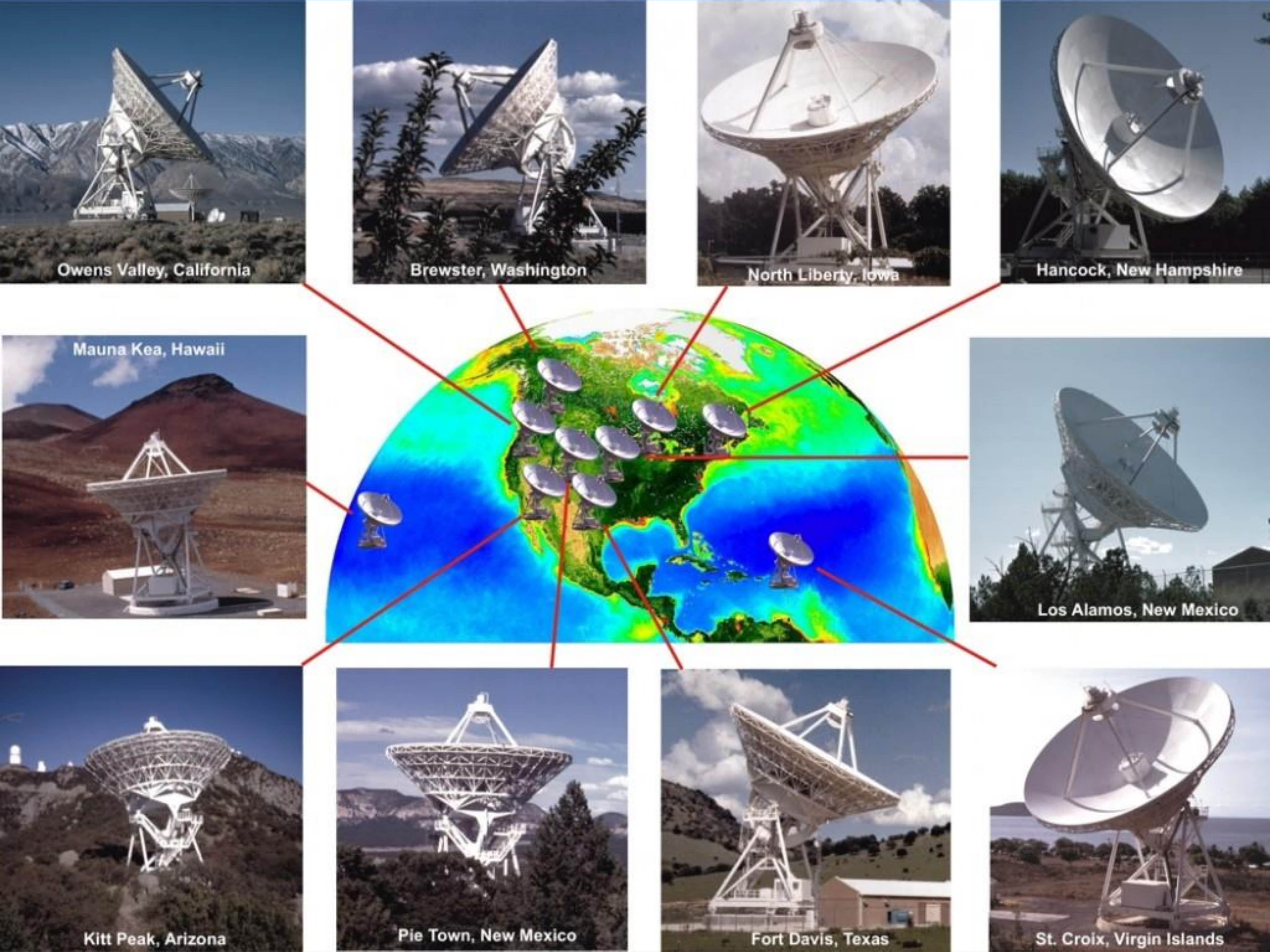
Important:

1. high spatial and spectral resolution, high sensitivity
2. dedicated source selection
3. careful design of observations

Part II

High-resolution observations: quest for interferometers

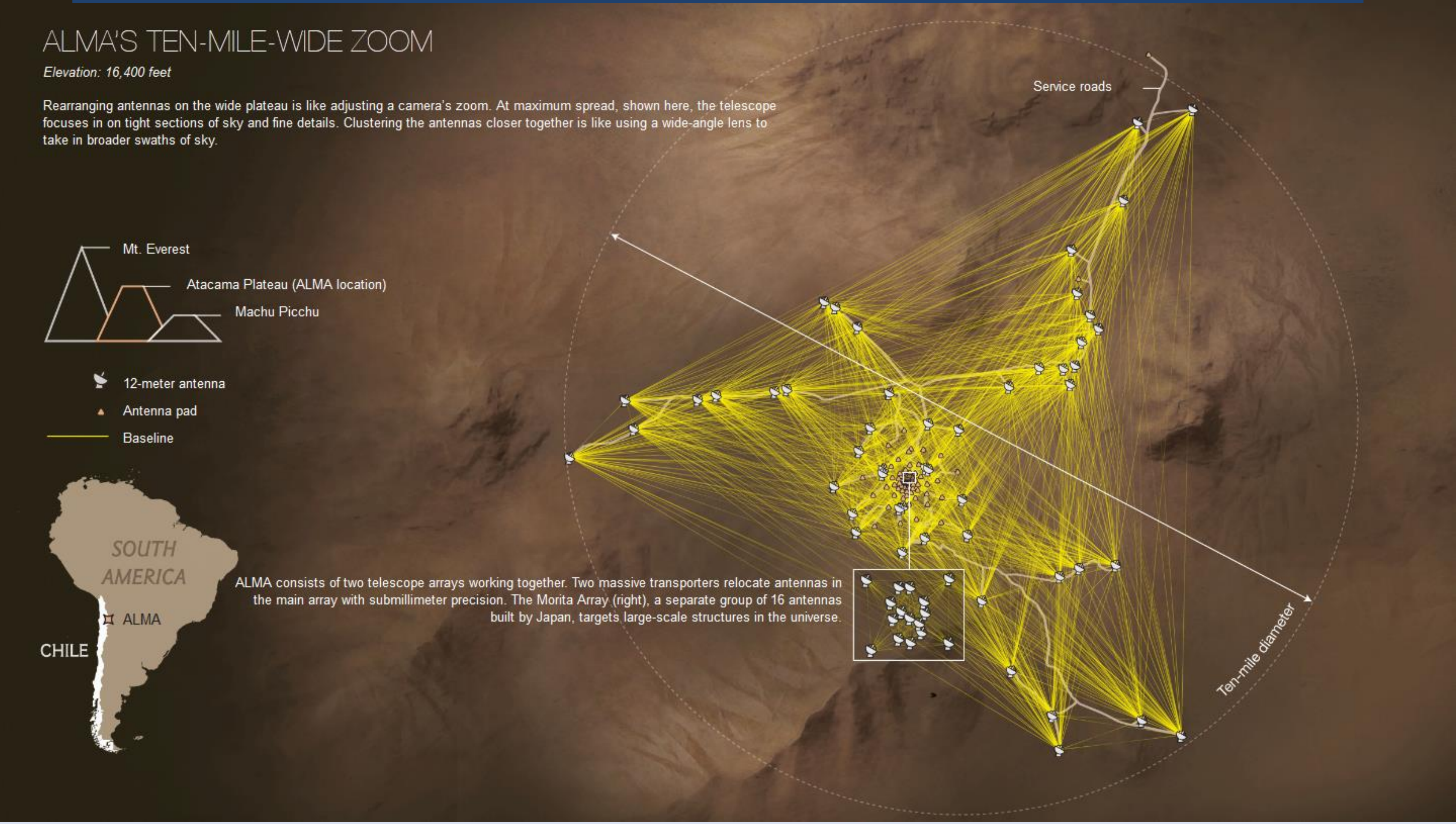

Event Horizon Telescope Array
To get a good look at the light show coming from our galaxy's black hole, astronomers will combine the data from telescopes the world over. Here's a sample of the dozen telescopes that may one day be part of the Event Horizon Telescope.
CSO
The Caltech Submillimeter Observatory
10.4-meter telescope on Mauna Kea, Hawaii
CARMA
The Combined Array for Research in Millimeter-Wave Astronomy
15 antennas near Bishop, Calif.
ARO/SMT
The Arizona Radio Observatory's Submillimeter Telescope
10-meter telescope near Safford, Ariz.
IRAM 30M
The Institute for Radio Astronomy in the Millimeter range's 30M scope
30-meter telescope on Pico Veleta, Spain
JCMT
The James Clerk Maxwell Telescope
15-meter telescope on Mauna Kea, Hawaii
SMA
The Submillimeter Array
8 antennas on Mauna Kea, Hawaii
ALMA
The Atacama Large Millimeter/sub-millimeter Array
66 antennas on the Chajnantor plain of Chile
APEX
Atacama Pathfinder EXperiment
12-meter telescope on the Chajnantor plain of Chile


Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands


JIVE
Joint Institute for VLBI
ERIC
EUROPEAN
vlbi
NETWORK
Metsähovi
Onsala
Svetloe
JIVE
WSRT
Torun
Jodrell Bank
Irbene
Zelenchukskaya
Badary
Yonsei
Cambridge
Wettzell
Effelsberg
Tamna
Medicina
Yebes
Sardinia
Noto
Urumqi
Ulsan
Tianma
Arecibo
Hartebeesthoek
Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

Atacama Large Millimeter/submillimeter Array

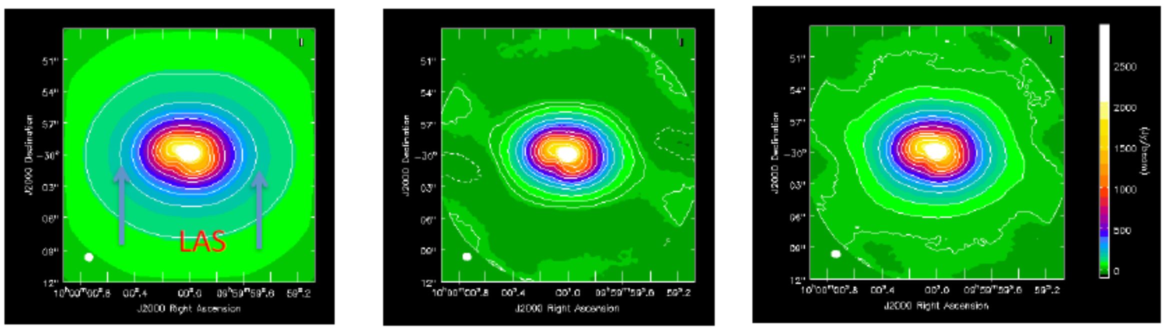
In search of our Cosmic Origins



Credit: National Geographic

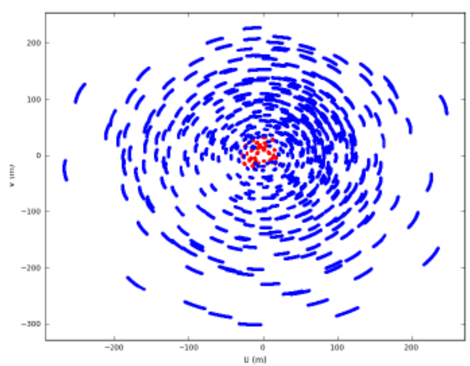
Images using 12-m C2 array with a resolution of 0.8”x0.7” in pa 80d

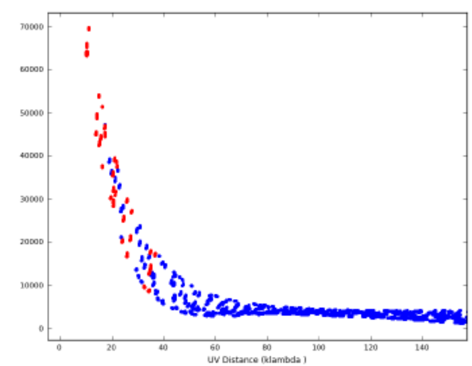
MODEL | 12-m image | 12m+7m Image



Restored flux 11000 Jy | 7000 Jy | 9000 Jy

Primary beam corrected: 20% cutoff: Contours: -20,20,50,100,200,300,400,600,800,1000,1200,1600,2000





U-V coverage (red=ACA, blue=ALMA12m) Amplitude vs uv-distance main page | discussion | view source | history

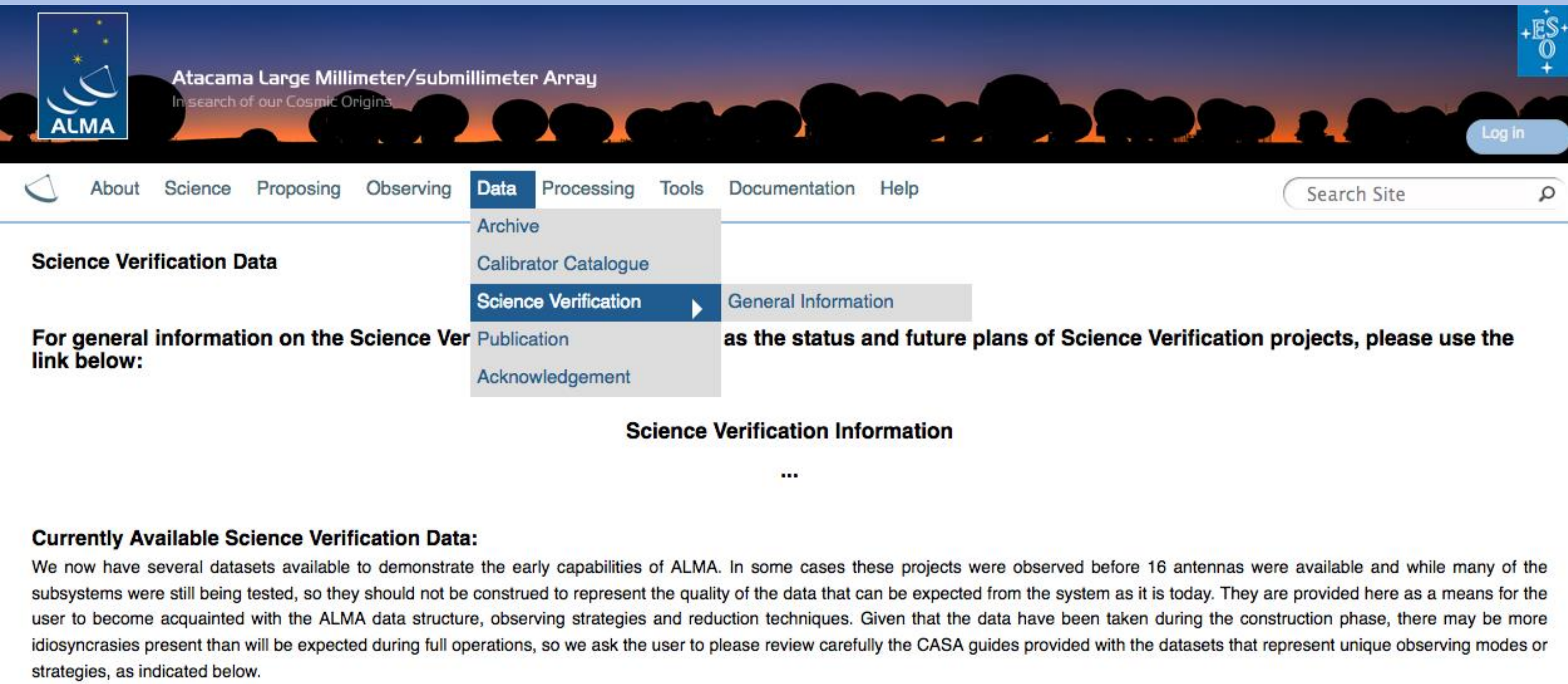
Welcome to CASA Guides

CASA (Common Astronomy Software Applications) is a comprehensive software package to calibrate, image, and analyze radio astronomical data from interferometers (such as ALMA and VLA) as well as single dish telescopes. This wiki provides tutorials for reducing data in CASA.

Homepage	Newsletter	CASA Docs	Download
Helpdesk	Subscribe	Forum	Tips

CASA Tutorials

Extracting Scripts from Tutorials


ALMA
Atacama Large Millimeter/submillimeter Array
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General Information
Publication
Acknowledgement
Science Verification Data
For general information on the Science Ver
as the status and future plans of Science Verification projects, please use the
link below:
Science Verification Information
...
Currently Available Science Verification Data:
We now have several datasets available to demonstrate the early capabilities of ALMA. In some cases these projects were observed before 16 antennas were available and while many of the subsystems were still being tested, so they should not be construed to represent the quality of the data that can be expected from the system as it is today. They are provided here as a means for the user to become acquainted with the ALMA data structure, observing strategies and reduction techniques. Given that the data have been taken during the construction phase, there may be more idiosyncrasies present than will be expected during full operations, so we ask the user to please review carefully the CASA guides provided with the datasets that represent unique observing modes or strategies, as indicated below.

almascience.eso.org//aq/

搜索

Query Form | Results Table

ALMA Science Archive

Search | Reset

Query Help

Position

Source name (Resolver)
Source name (ALMA)
RA Dec
Galactic
0 0 120
Target list
Angular resolution
Largest angular scale
Field of view

Energy

Frequency
Bandwidth
Spectral resolution
Band

Time

Observation date
Integration time

Polarisation

Polarisation type

Observation

Line sensitivity (10 km/s)
Continuum sensitivity
Water vapour

Project

Project code
Project title
PI name
Proposal authors
Project abstract
Publication count
Science keyword

Publication

Bibcode
Title
First author
Authors
Abstract
Year

Options

View:
- ◉ observation
- ○ project
- ○ publication

☐ public data only
☑ science observations only

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Query Form | Results Table

ALMA Science Archive

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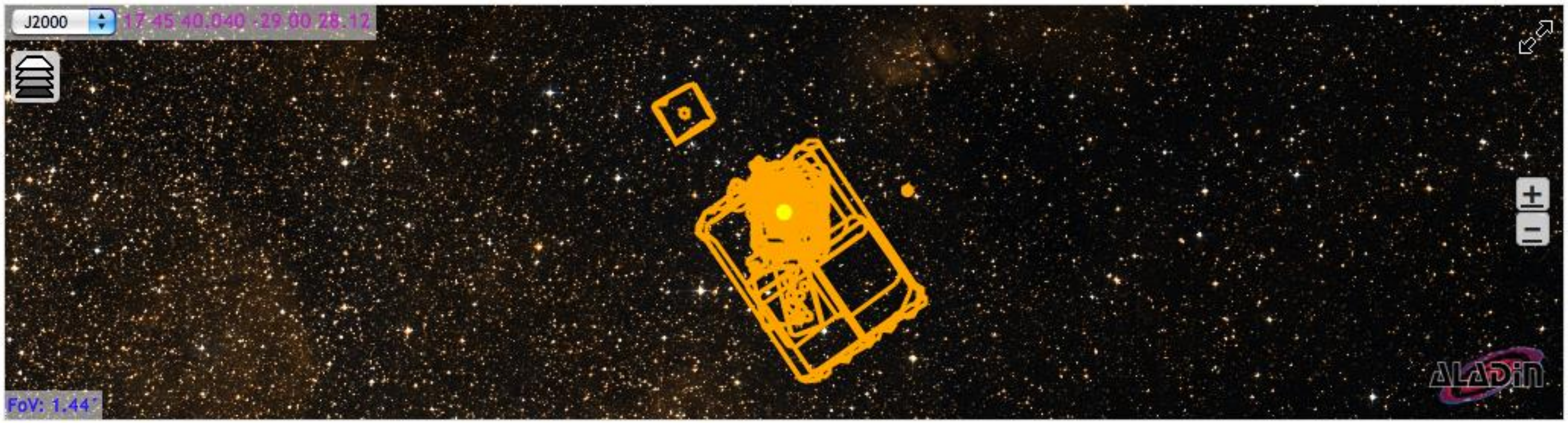

More columns Showing 180 of 180 rows.

	Project code	Source name	RA	Dec	Band	Integration	Release date	Velocity resolution	Frequency support	Pub
Filter:			H:M:S	D:M:S		seconds		m/s		
☑	2011.0.00887.S	Sagittarius A*	17:45:40.04	-29:00:28.1	7	2419.200	2013-10-01	26691.93	91.99..350.99GHz	5
☐	2012.1.00635.S	SgrA_star	17:45:40.04	-29:00:28.1	7	907.200	2015-03-17	825.67	215.03..354.58GHz	3
☐	2012.1.00635.S	SgrA_star	17:45:40.04	-29:00:28.1	7	604.800	2015-05-09	825.66	215.03..354.58GHz	3
☐	2012.1.00635.S	SgrA_star	17:45:40.04	-29:00:28.1	7	1028.160	2015-05-16	825.68	215.03..354.58GHz	3
☐	2012.1.00635.S	SgrA_star	17:45:40.04	-29:00:28.1	7	604.800	2015-07-28	825.71	215.02..354.56GHz	3

ALMA Request Handler

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Anonymous User: Request #2145611872912 ✔

Request Title: Click to edit

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☑ readme ☑ product ☐ auxiliary ☐ raw ☐ raw (semipass)

Project / OUSet / Executionblock	File	Size	Accessible
▼ Request 2145611872912			
▼ Project 2012.1.00635.S			
☑ readme	2012.1.00635.S.readme.txt		
▼ Science Goal OUS uid://A002/X5d7935/X2f9			
▼ Group OUS uid://A002/X5d7935/X2fa			
▼ Member OUS uid://A002/X79f8ed/X3f			
▶ SB Feb_SgrA_352-216_12m_C32-any			
☑ product	2012.1.00635.S_uid___A002_X79f8ed_X3f_001_of_001.tar	176.8MB	✔
☐ raw	2012.1.00635.S_uid___A002_X7b13df_Xf8a.asdm.sdm.tar	14.9GB	✔
▼ Group OUS uid://A002/X7d1738/X3e			
▼ Member OUS uid://A002/X7d1738/X3f			
▶ SB March_SgrA_352-216_12m_C32-any			
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☐ raw	2012.1.00635.S_uid___A002_X7d2ec1_Xbf7.asdm.sdm.tar	21.8GB	✔
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▼ Member OUS uid://A002/X7d1738/X42			

Simulation Output

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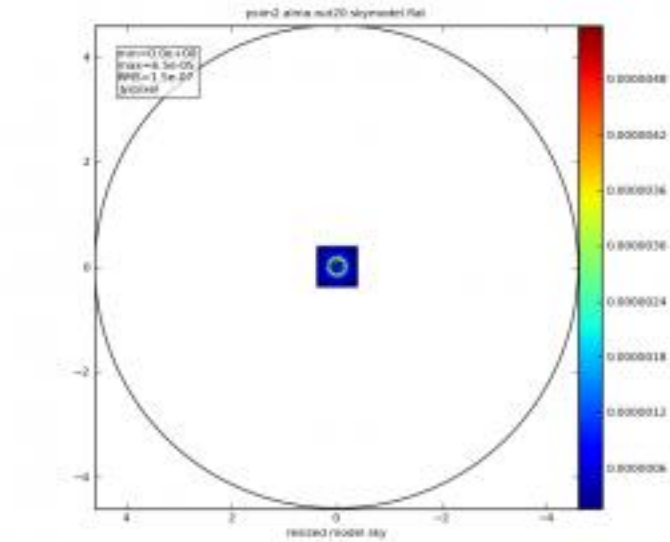
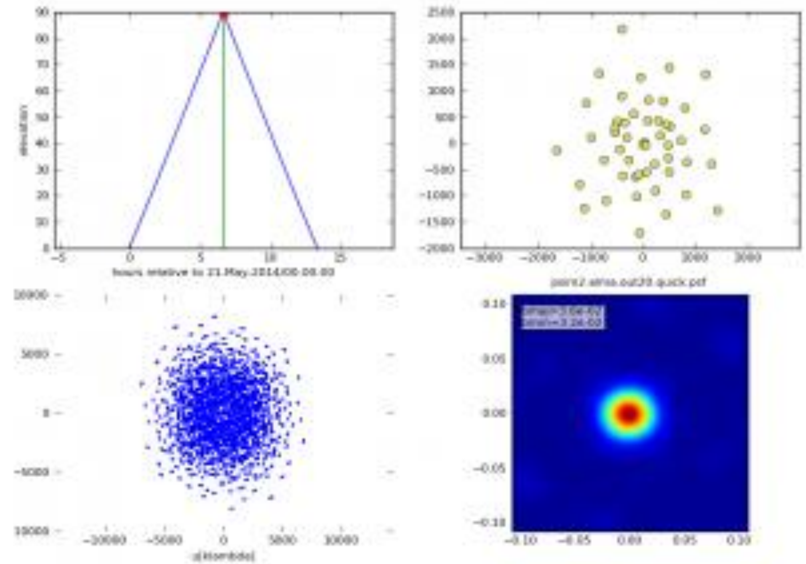
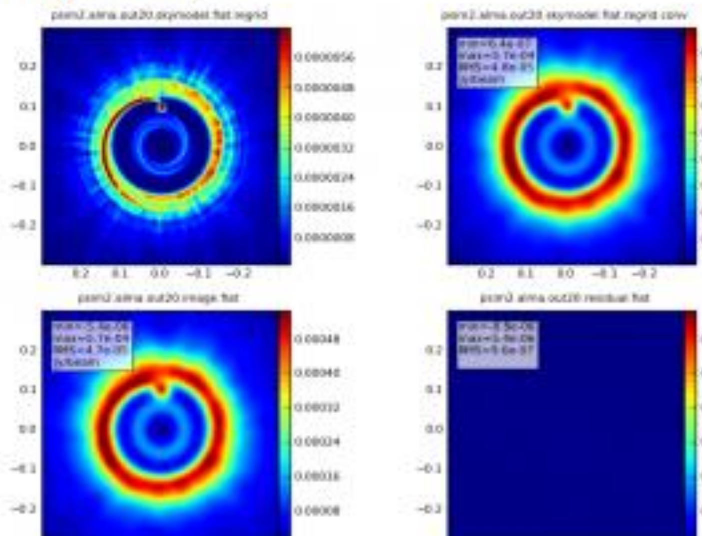


simobserve:



simanalyze image:



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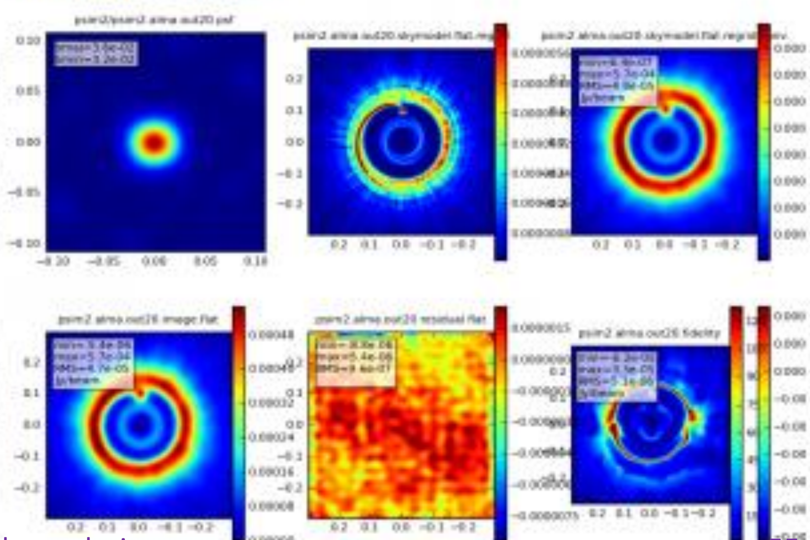

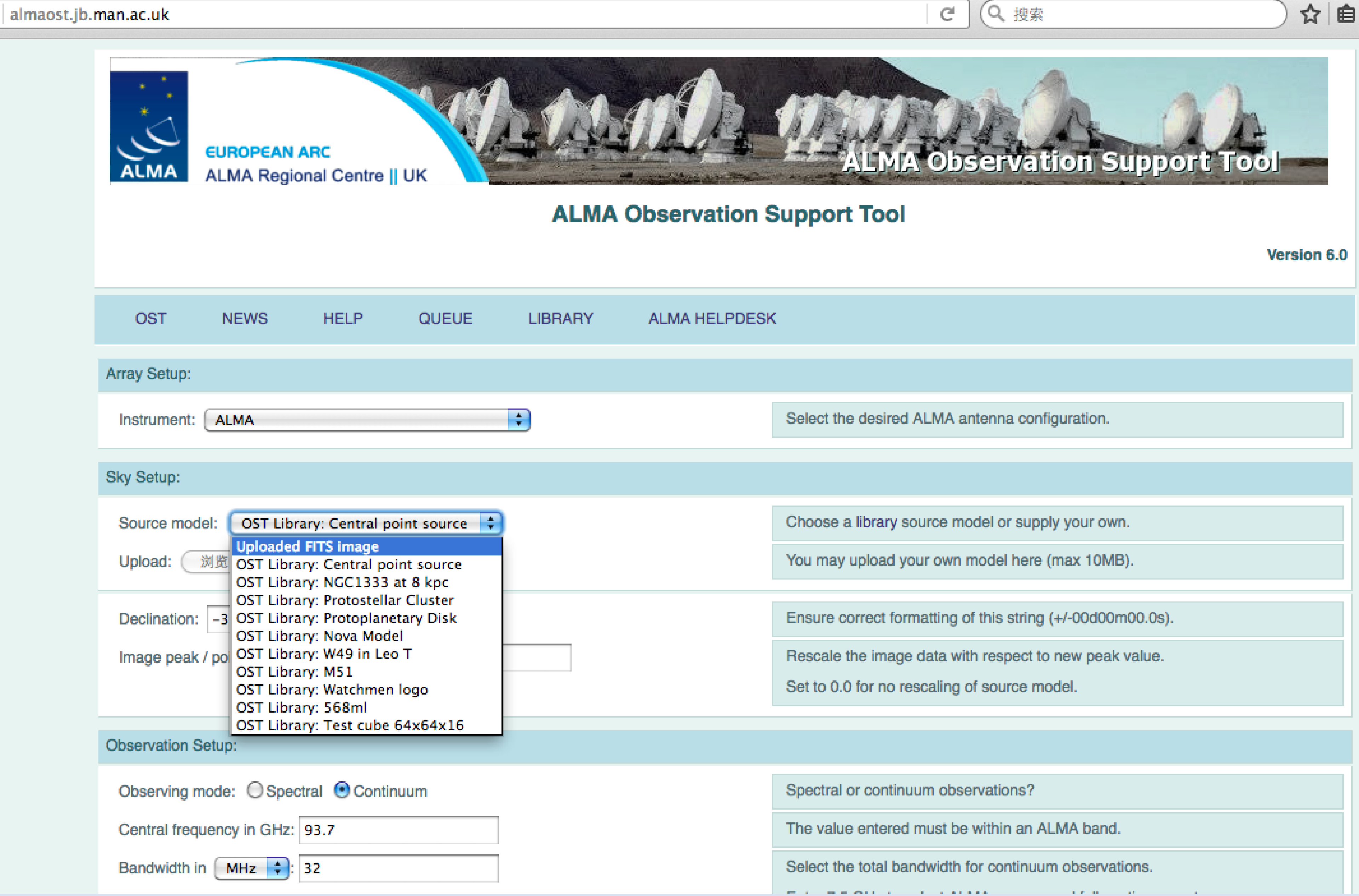
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搜索
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ALMA Regional Centre || UK
ALMA
ALMA Observation Support Tool
ALMA Observation Support Tool
Version 6.0
OST
NEWS
HELP
QUEUE
LIBRARY
ALMA HELPDESK
Array Setup:
Instrument: ALMA
Select the desired ALMA antenna configuration.
Sky Setup:
Source model: OST Library: Central point source
Uploaded FITS image
OST Library: Central point source
OST Library: NGC1333 at 8 kpc
OST Library: Protostellar Cluster
OST Library: Protoplanetary Disk
OST Library: Nova Model
OST Library: W49 in Leo T
OST Library: M51
OST Library: Watchmen logo
OST Library: 568ml
OST Library: Test cube 64x64x16
Choose a library source model or supply your own.
Upload:
You may upload your own model here (max 10MB).
Declination:
Ensure correct formatting of this string (+/-00d00m00.0s).
Image peak / po
Rescale the image data with respect to new peak value.
Set to 0.0 for no rescaling of source model.
Observation Setup:
Observing mode: Spectral Continuum
Spectral or continuum observations?
Central frequency in GHz: 93.7
The value entered must be within an ALMA band.
Bandwidth in MHz: 32
Select the total bandwidth for continuum observations.