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Physics of Star and Planet Formation

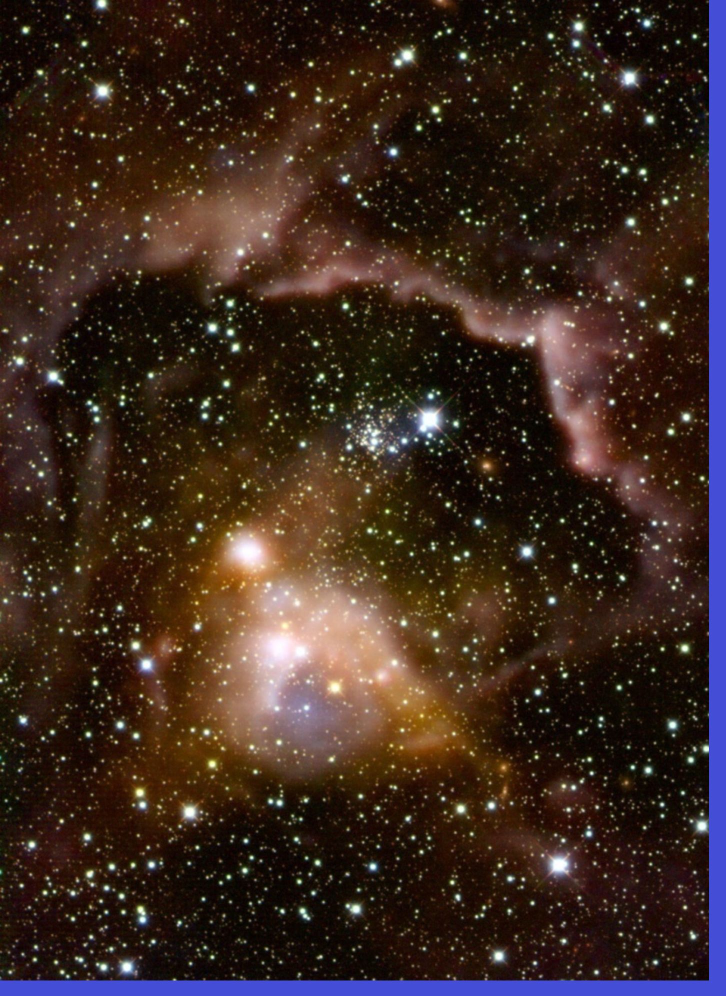
Towards a Unified Picture

ISOSS 22164+6003
(Distance = 6 kpc
$L=20\,000\ L_{sun}$)

Deep NIR CAHA Image + Herschel/PACS 70, 100, 160 μm

The Universe Explored by Herschel, ESTEC, October 2013

14/May/2009: A star is born ….

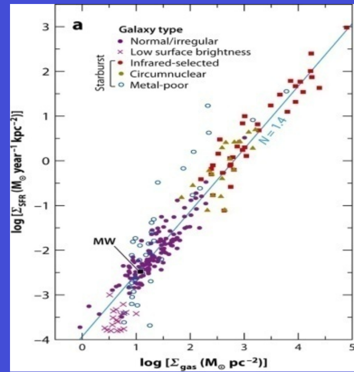


ISOSS 22164+6003
(Distance = 6 kpc
$L=20\,000\ L_{sun}$)

Deep NIR CAHA Image + Herschel/PACS 70, 100, 160 μm (Ragan et al. 2012)

Star Formation – Key Questions

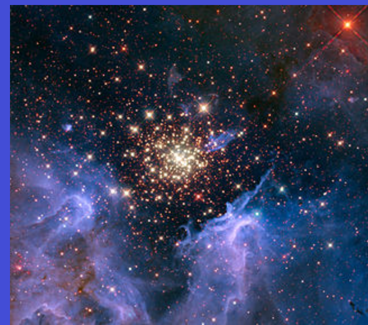
- What regulates the SF process and determines its rate?



Σ_s=f(Σ_g)

Kennicutt & Evans (2012)

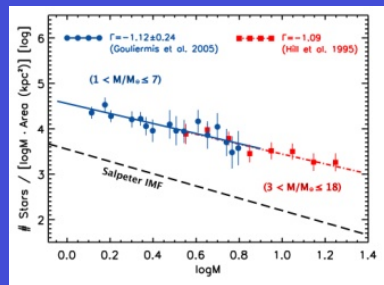
- Are there different modes of SF? (distributed vs. clustered SF)



NGC 3603

HST image

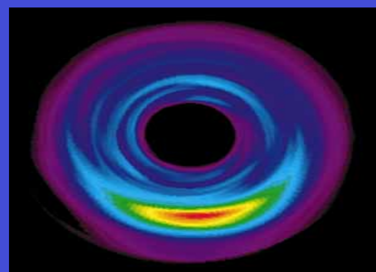
- What determines the initial mass function and is the IMF universal?



IMF

Gouliermis et al. 2005

- How is star and planet formation connected?



Disk

Wolf & Klahr (2002)

Stars form in Cold Molecular Clouds

$T = 20$ K, $n(H_2) = 300$ cm^{-3}

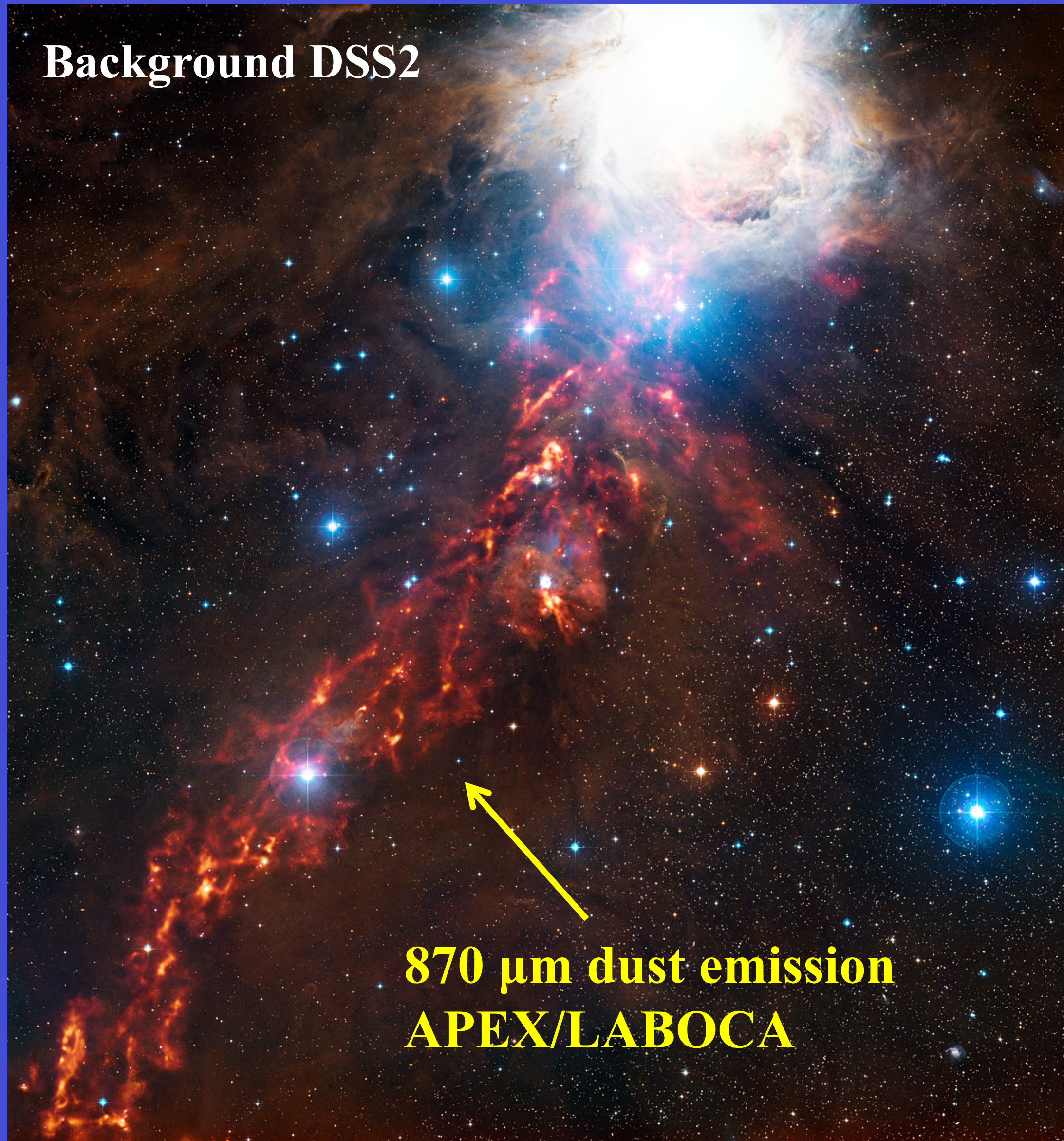
Clouds are inhomogeneous

Clouds are turbulent

Clouds are often filaments

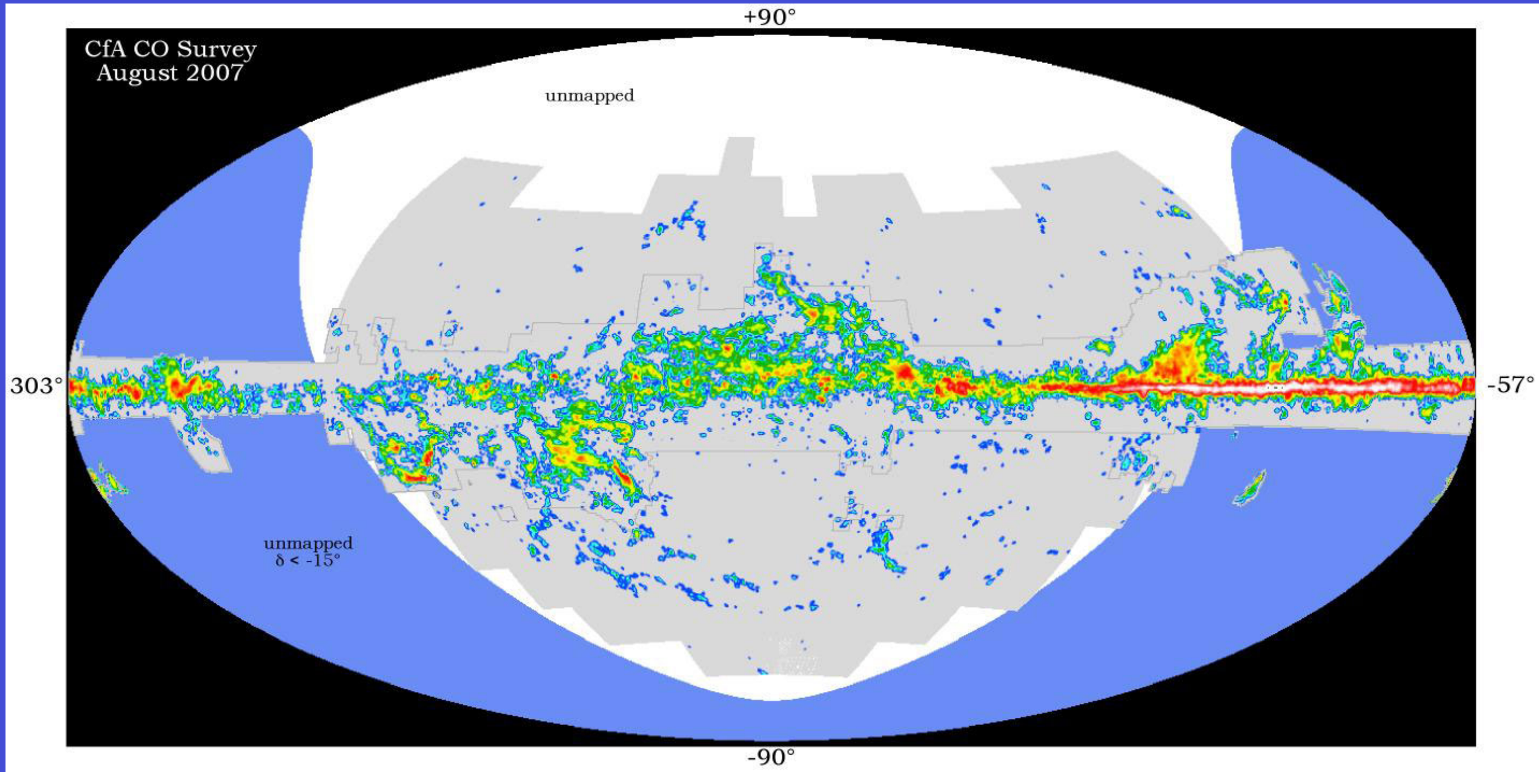
6000 GMCs in Milky Way

Total mass = $2\text{x}10^9$ M_{sun}



Protostars in Orion (Stutz et al. 2013)

Galactic Star Formation is not efficient



Total mass: $2x10^9$ M_{sun}

Free-fall time in pressure-free cloud: $t_{ff} = (3\pi/32G\rho)^{1/2}$

t_{ff} = $7x10^6$ yr $(M/10^5\ M_{sun})^{-1/2}\ (R/25pc)^{3/2}$

SFR= 300 M_{sun}/yr

SFR=1.3 M_{sun}/yr from free-free emission (WMAP): Murray & Rahman (2011)

SFR=0.68-1.45 M_{sun}/yr from population synthesis (Spitzer): Robitaille et al. (2010)

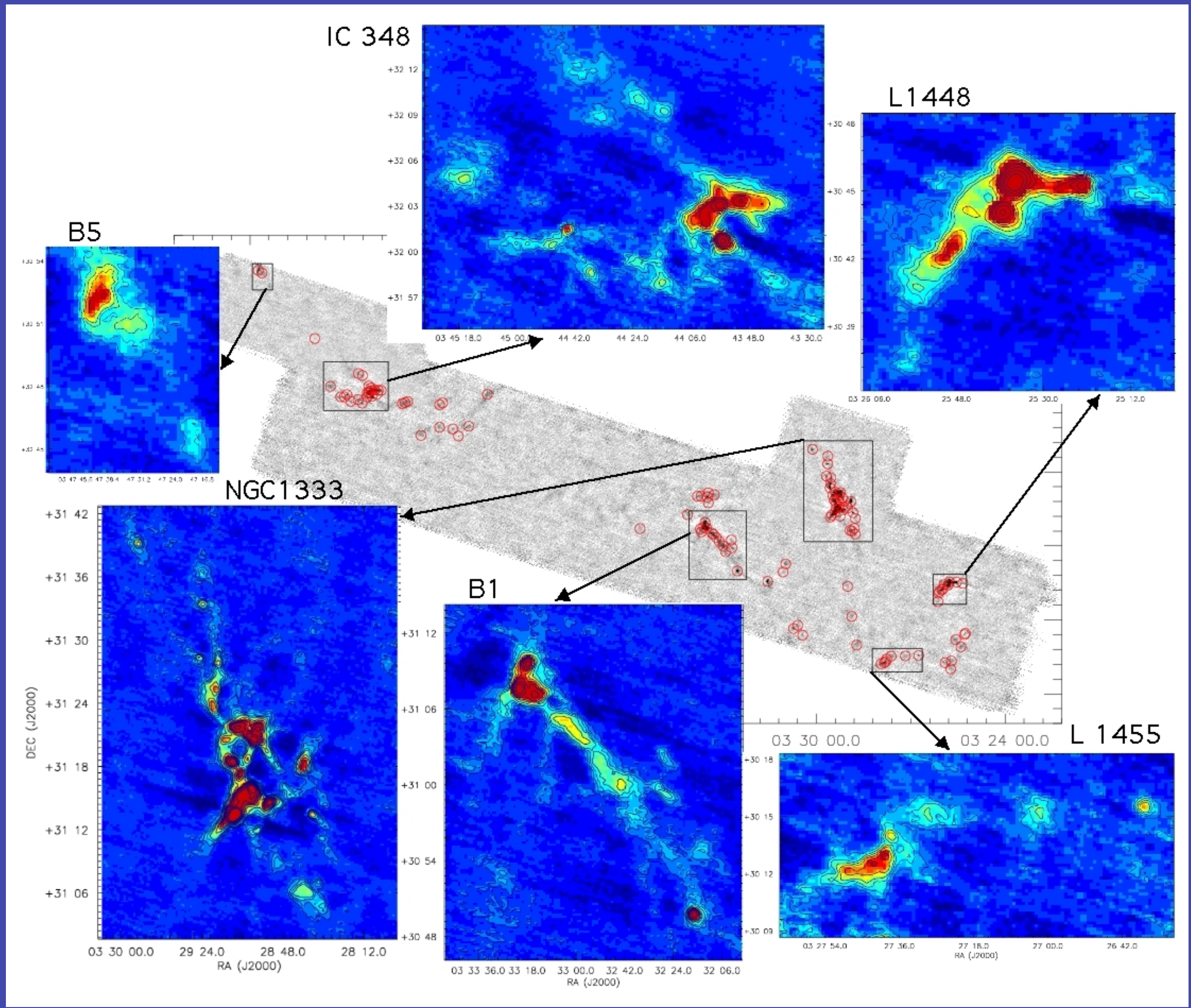
Towards a Physical Picture

Cloud-wide:

SFE is low (3-6%)

Dense cores:

SFE is high (15-20%)



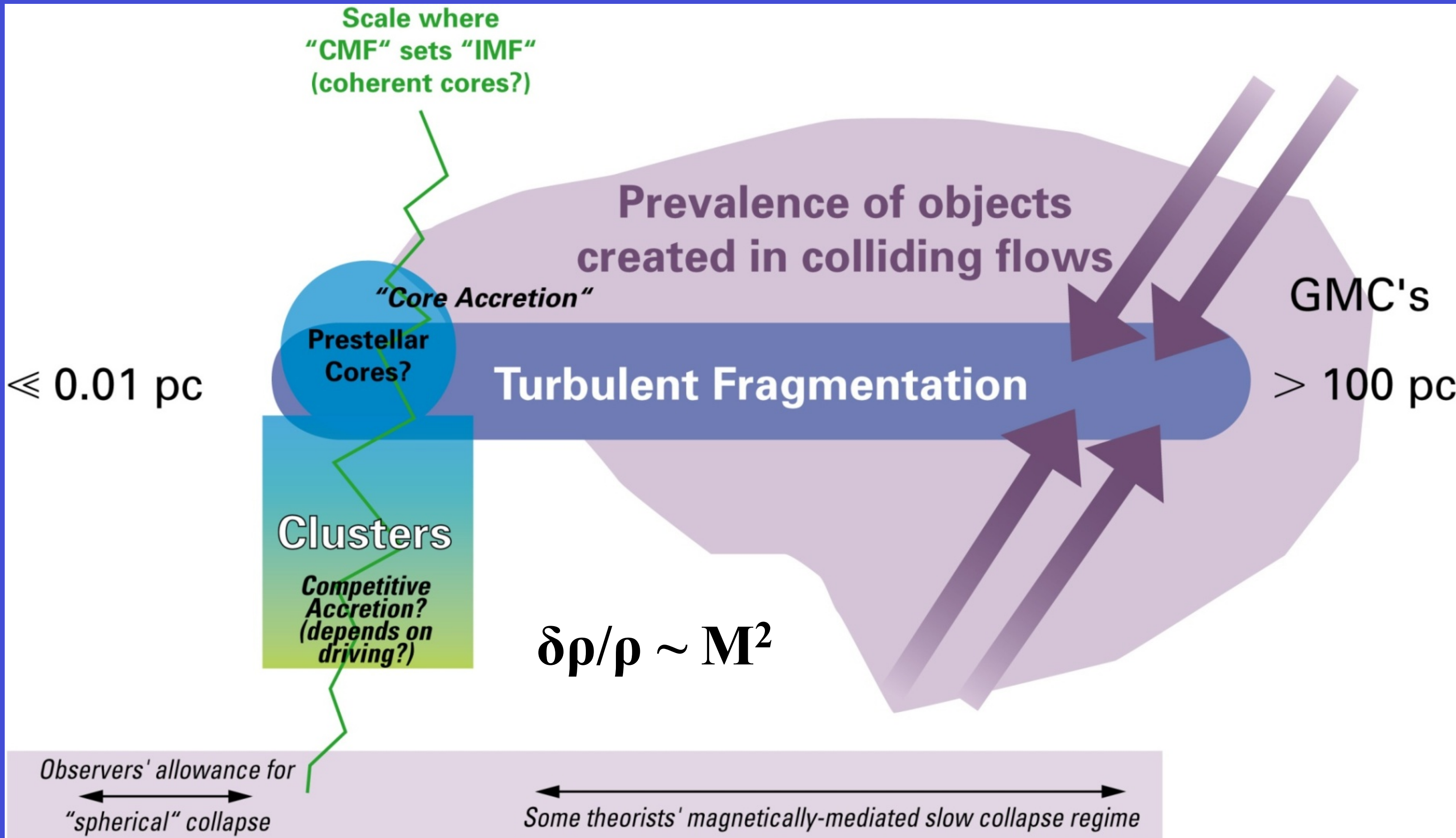
c2d Spitzer Legacy Program: Evans et al. (2009)

SF treshold: 120 $M_{sun}/pc^2 \sim 5 \times 10^{21}$ $cm^{-2} \sim A_K = 0.8$ mag

(Lada et al. 2010, Heiderman et al. 2010)

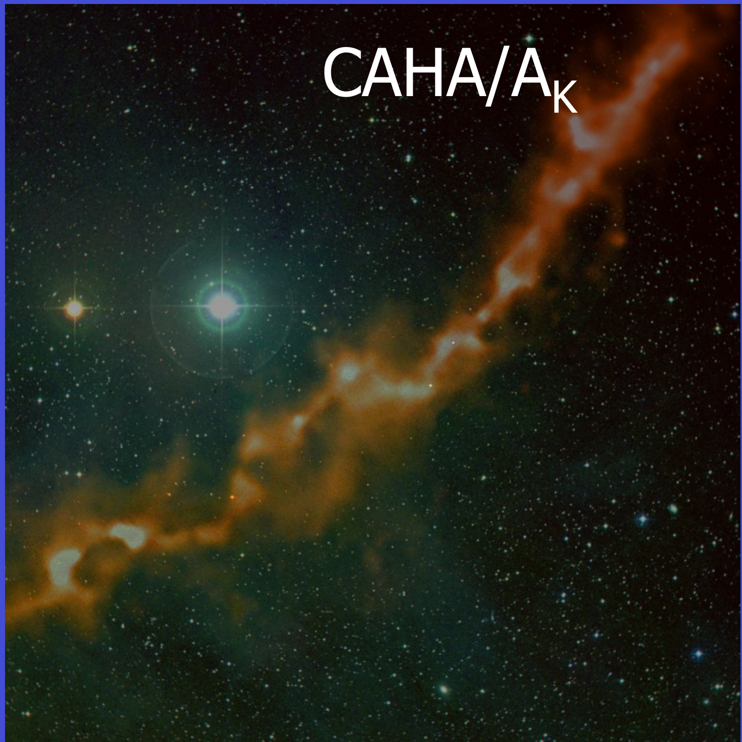
Important Steps Towards Star Formation

From 1 H-atom/cm^3 to 10^{26} H-atoms/cm^3

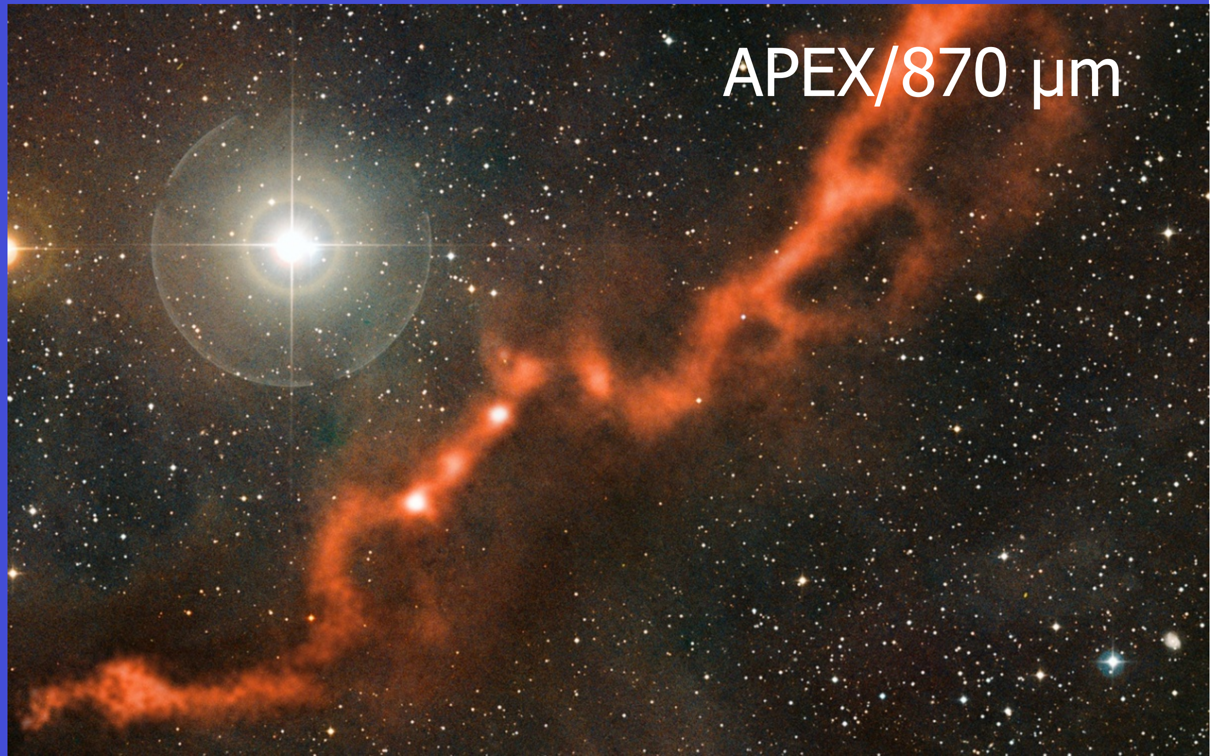


Herschel: DIGIT, EPOS, HGBS, HIGAL, HOBYS, HOPS, …

Taurus L 1495/B213 Region



Schmalzl et al. (2010)

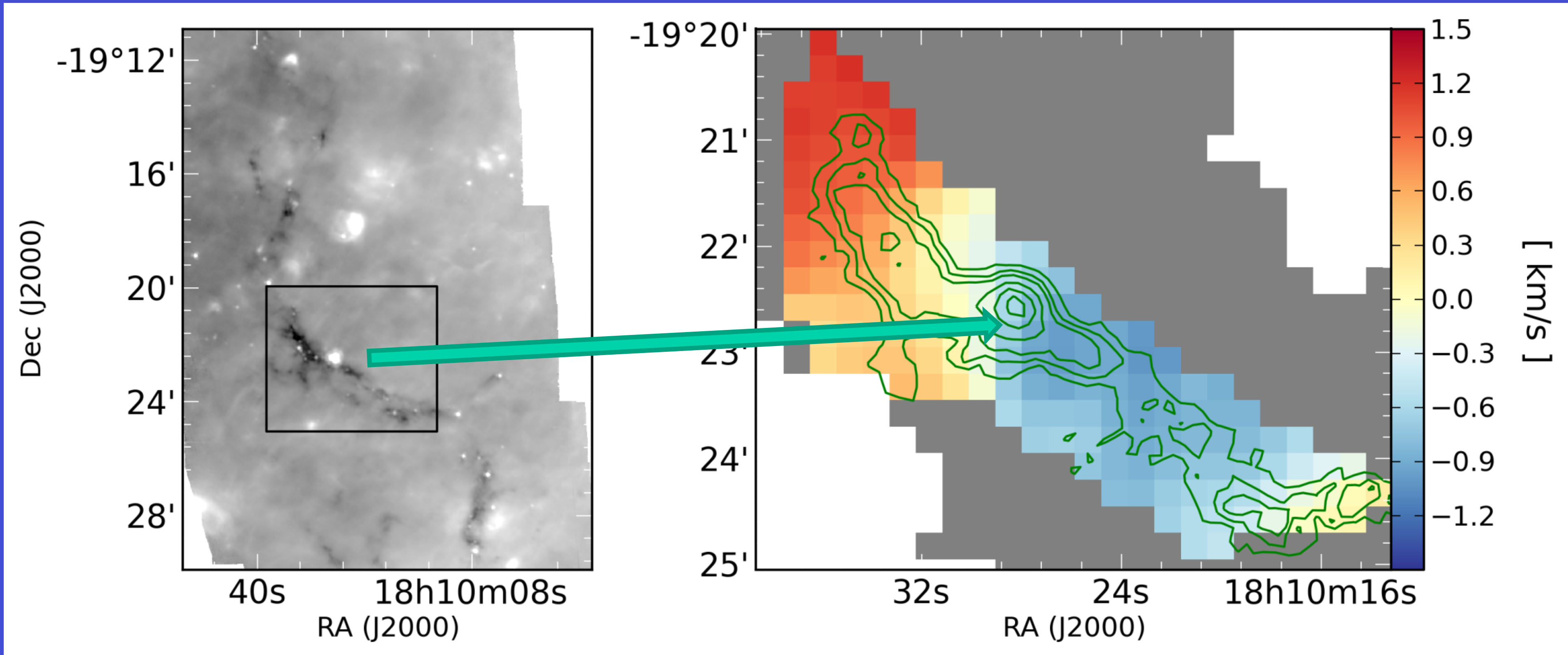


Hacar et al. (2013)

Cores form through hierarchical fragmentation of filaments

Theoretical prediction of fragmentation: Inutsuka & Miyama (1997)
(see also Myers 2009)

G11.11-0.12 - Searching for Flows …



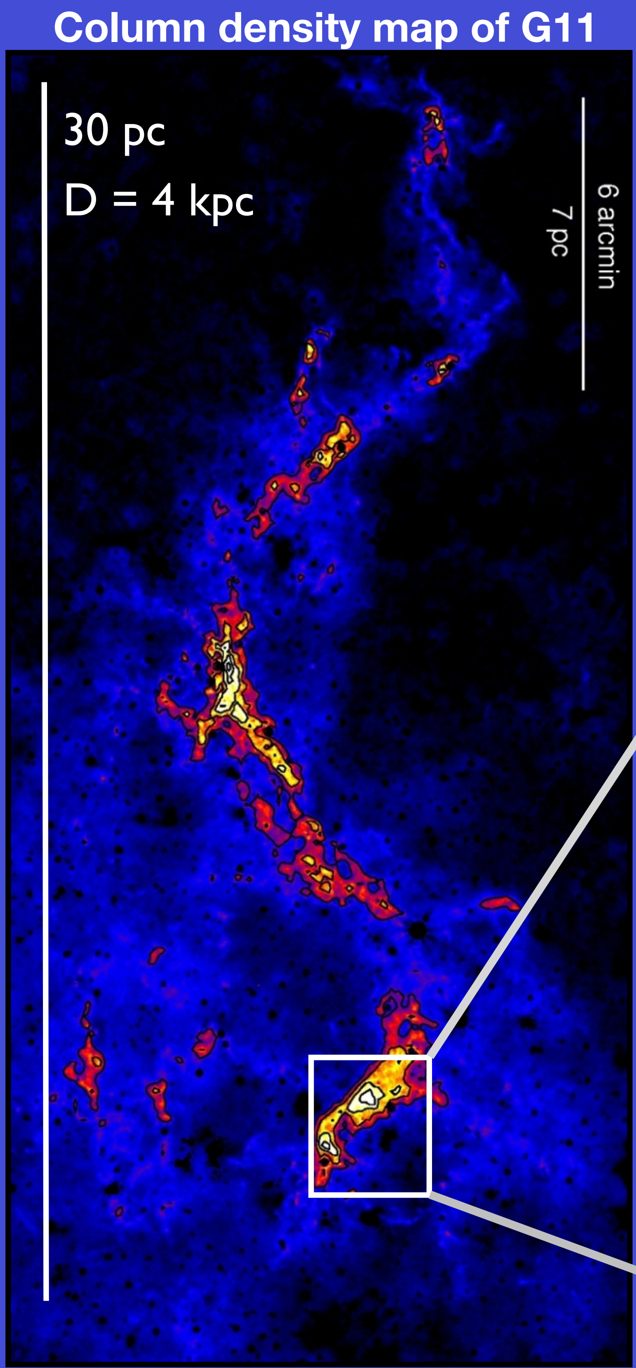
Herschel/PACS 70 μm

Mopra N_2H^+ Line Analysis

Henning et al. (2010)

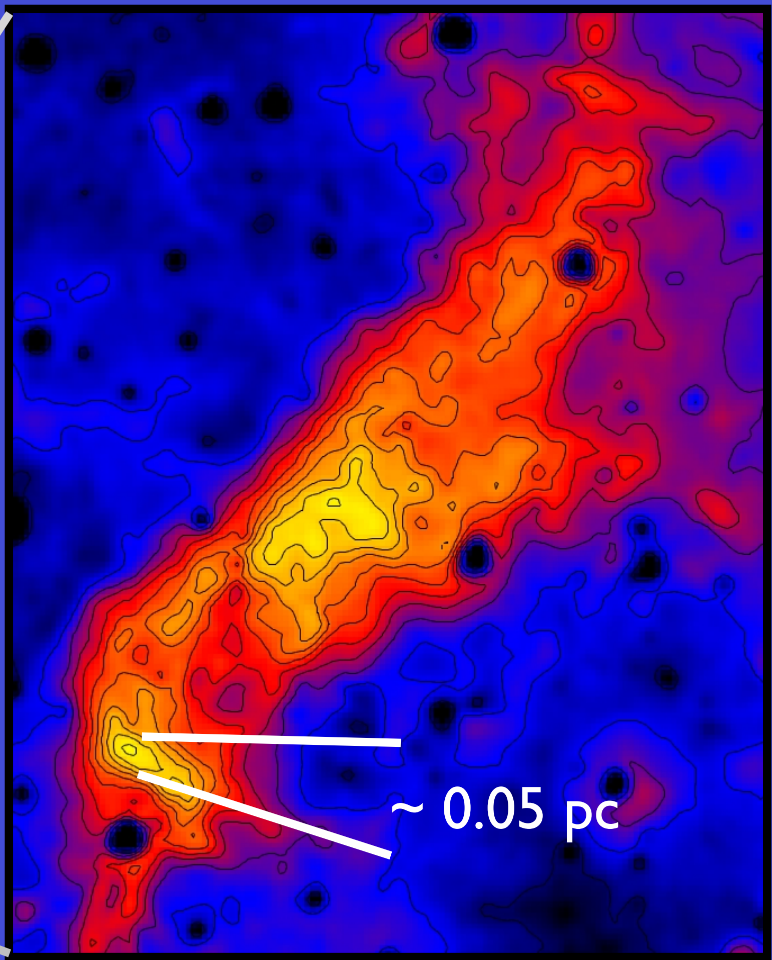
Tackenberg et al. (2013, submitted)

Hidden Mass Reservoir of Molecular Clouds



High-dynamic-range dust extinction mapping (Kainulainen ea. 13, Kainulainen & Tan 13): UKIDSS + Spitzer (2", 1 - 100x10^{21} cm^{-2}); Filaments are not isolated: Heitsch 12

10x more mass as probed by submm emission



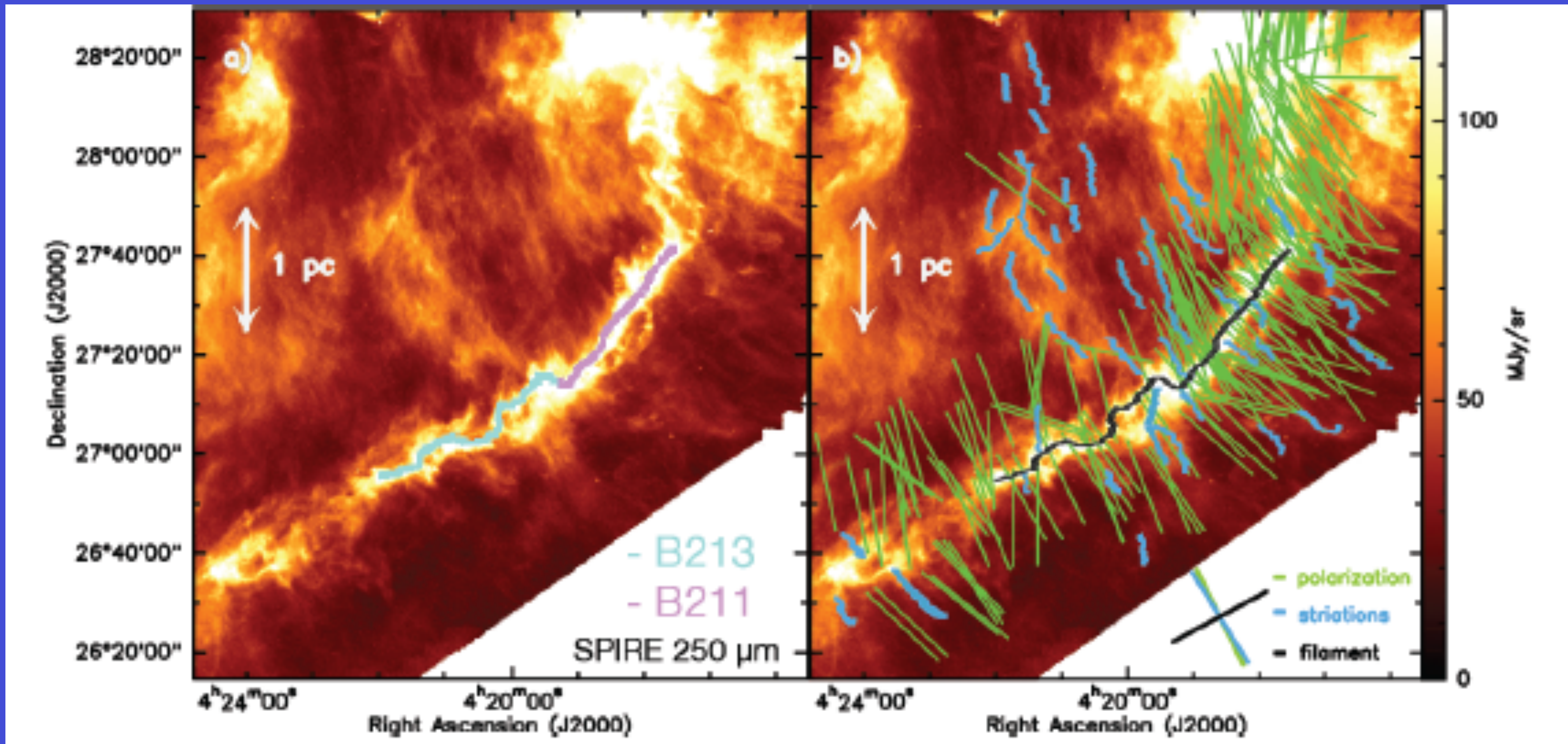
Role of Filamentary Structures – Herschel Legacy

Detected in extinction, dust emission, and line maps

(Extinction: Schneider & Elemgreen 1979, Apai et al. 2005, Jackson et al. 2010, …)
CO: Ungerechts & Thaddeus 1987, Goldsmith et al. 2008, …)

Herschel: Mapping speed - dynamic range - sensitivity

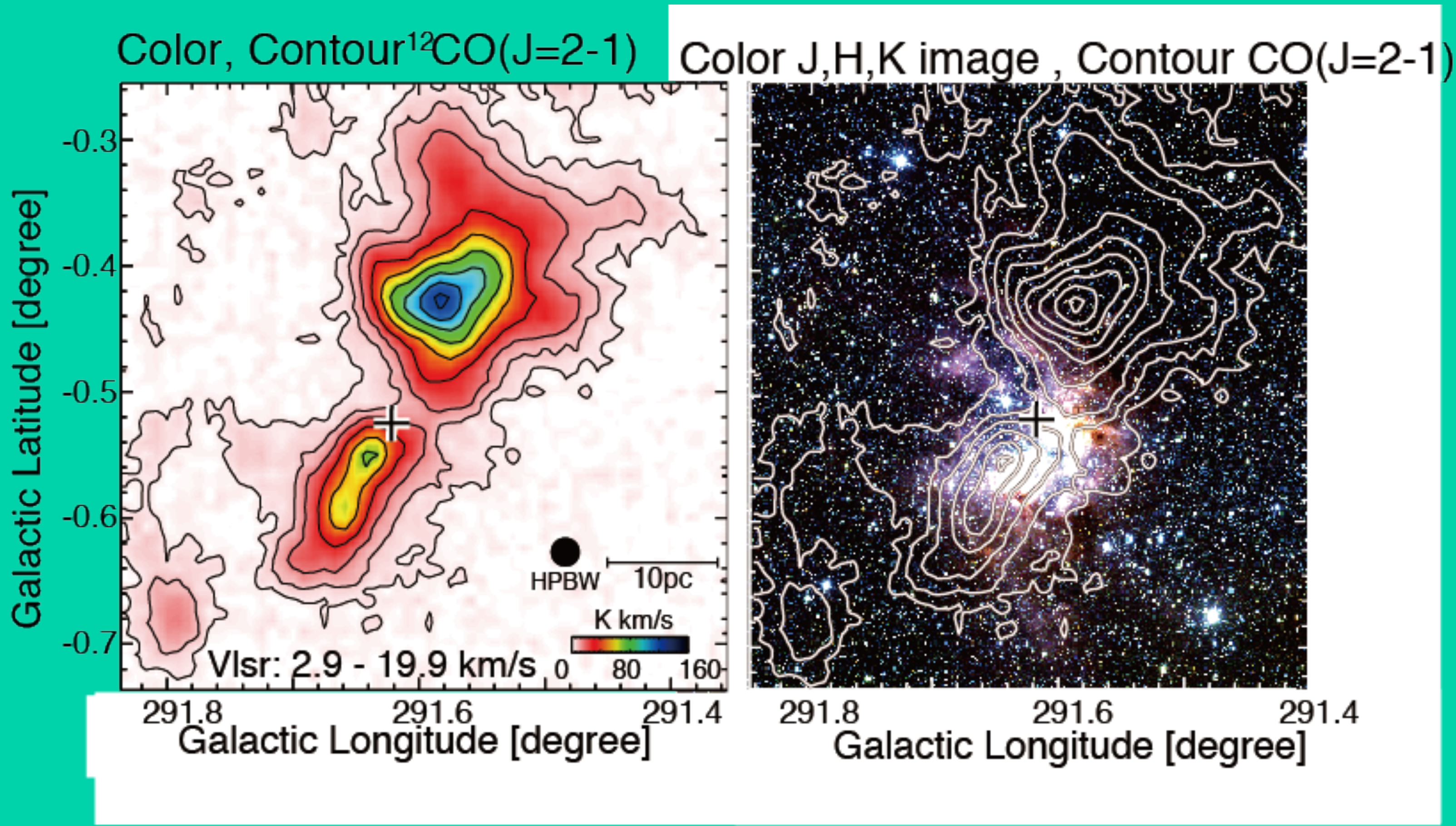
(e.g. André+ 10, Henning+ 10, Arzoumanian+ 11, Peretto+ 12, Hennemann+ 12, Cox+ 13)



Palmeirim+ 13 (Magnetic fields and filaments: Li+ 13, Soler+ 13)

Converging Flows

Formation of filaments remains an open problem „Converging flows“ (e.g. Hennebelle 2013)



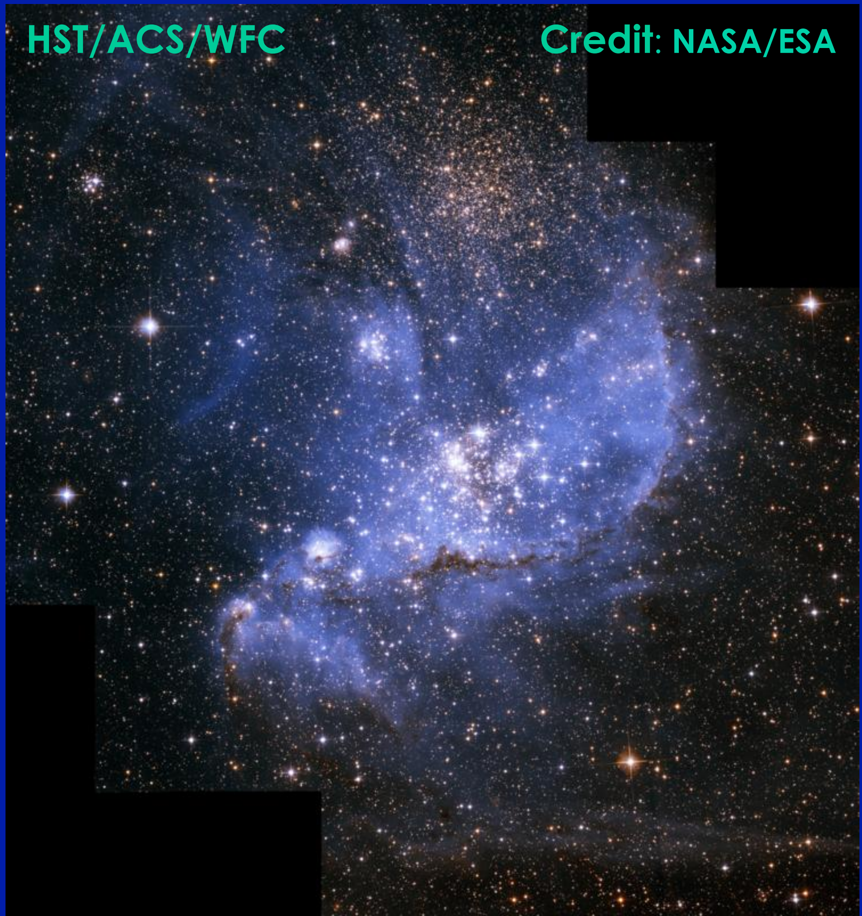
High-Velocity collision of two molecular clouds – NGC 3603

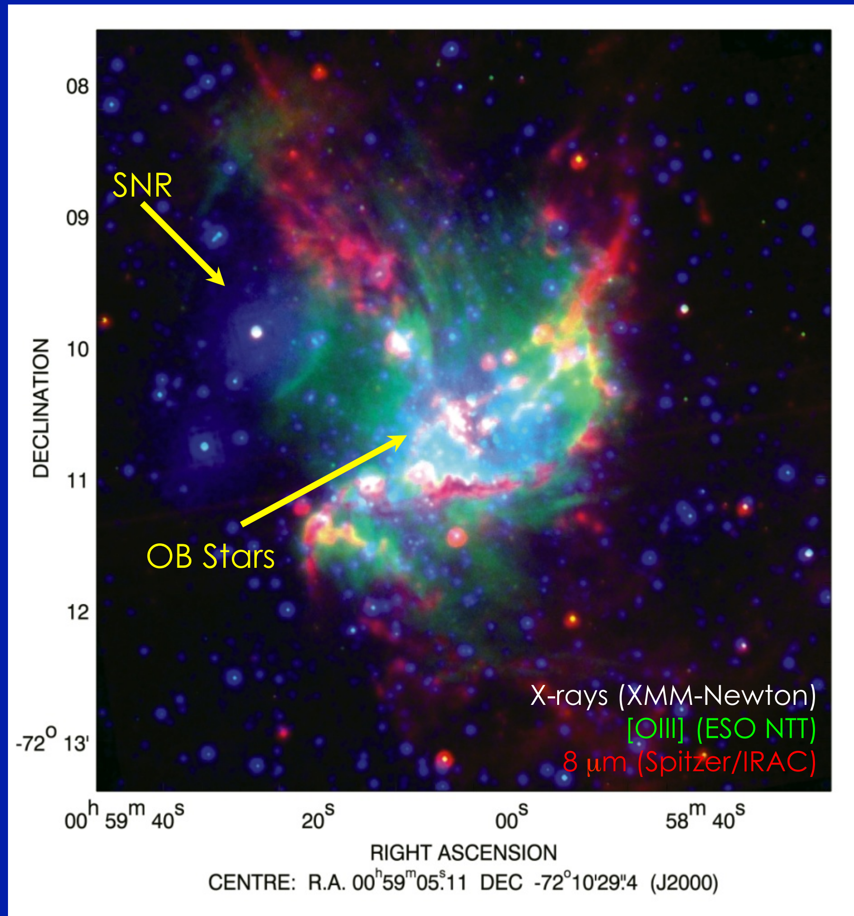
Fukui et al. (2013)

Is there evidence for triggered star formation?

NGC 346/N 66 in the SMC

Gouliermis, Henning et al. ApJ , 2008.





NGC 346 is located in the brightest HII region of the SMC, and includes the largest sample of OB stars in this galaxy.

Star Formation is shaped through photo-ionization by OB Stars and a nearby supernova remnant.

Towards a Recipe for Star Formation

$$SFR = \frac{\epsilon_{core}}{\phi} \int_{s_{crit}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0} p(s) ds$$

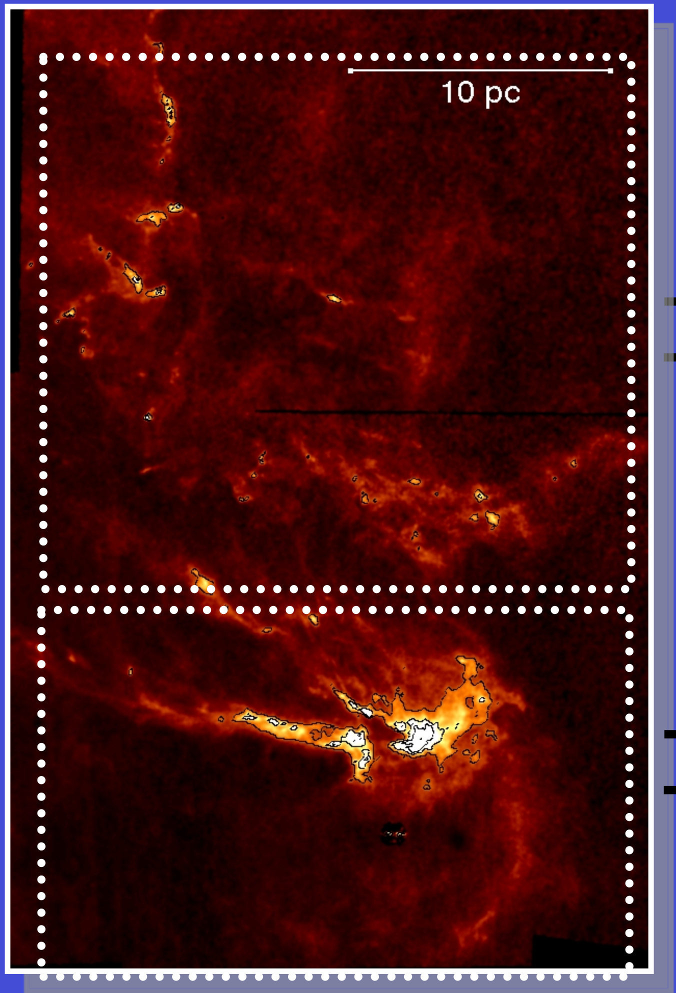
$$p(s) = \frac{1}{\sigma_s \sqrt{2\pi}} e^{-\frac{(s-\mu)^2}{2\sigma_s^2}}$$

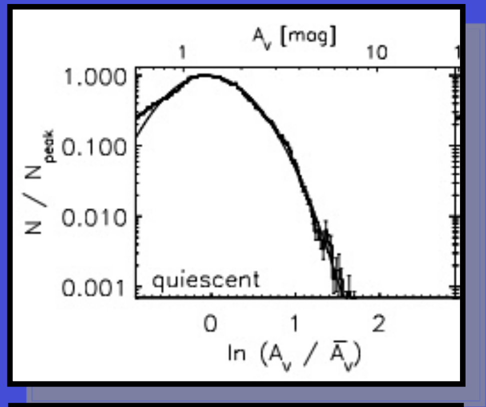
s=ln(ρ/ρ$_0$)

$$\sigma_s^2 = \ln(1 + b^2 M_s^2 \frac{\beta}{\beta + 1})$$

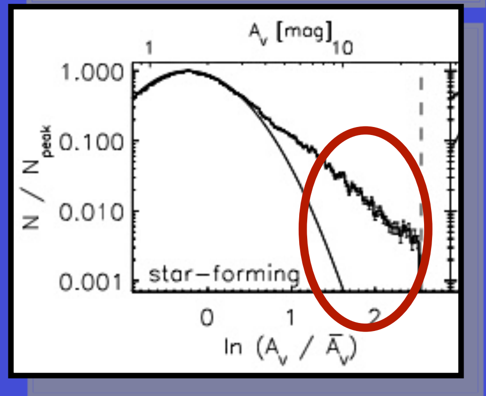
Krumholz & McKee (2005), Padoan & Nordlund (2011), Hennebelle & Chabrier (2011), Federrath & Klessen (2012)

First Systematic Surveys of N-PDFs





- Quiescent clouds: log-normal shape.



- Star-forming clouds: Excess at high-column density.

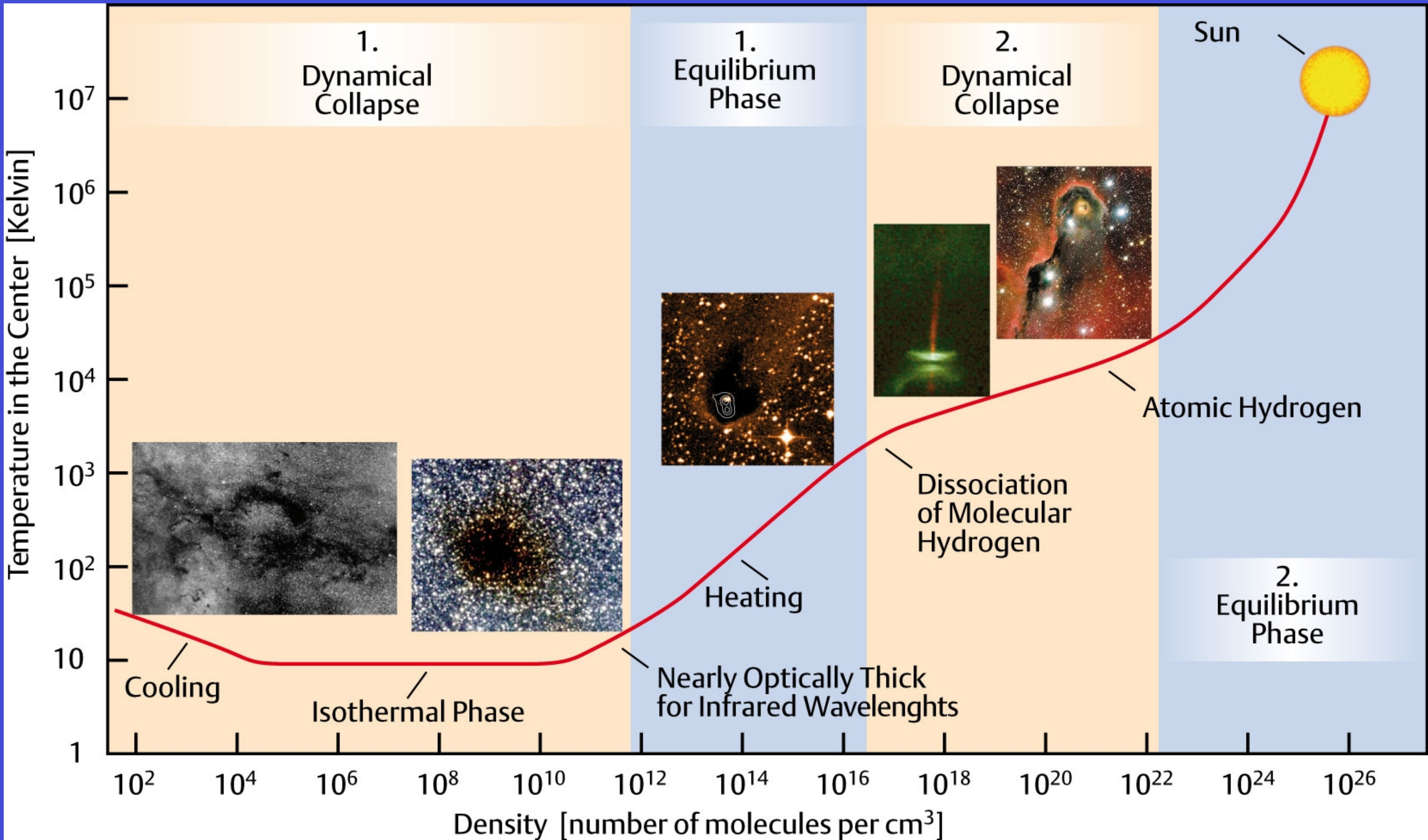
Kainulainen et al. (2009, 2011)

Observed column density map of the Ophiuchus cloud complex

Theory vs. Observations: Kainulainen & Tan (13), Kainulainen, Federrath & Henning (13)

Herschel PDFs: Schneider et al. (12, 13): Broadening of Orion B PDF by external compression

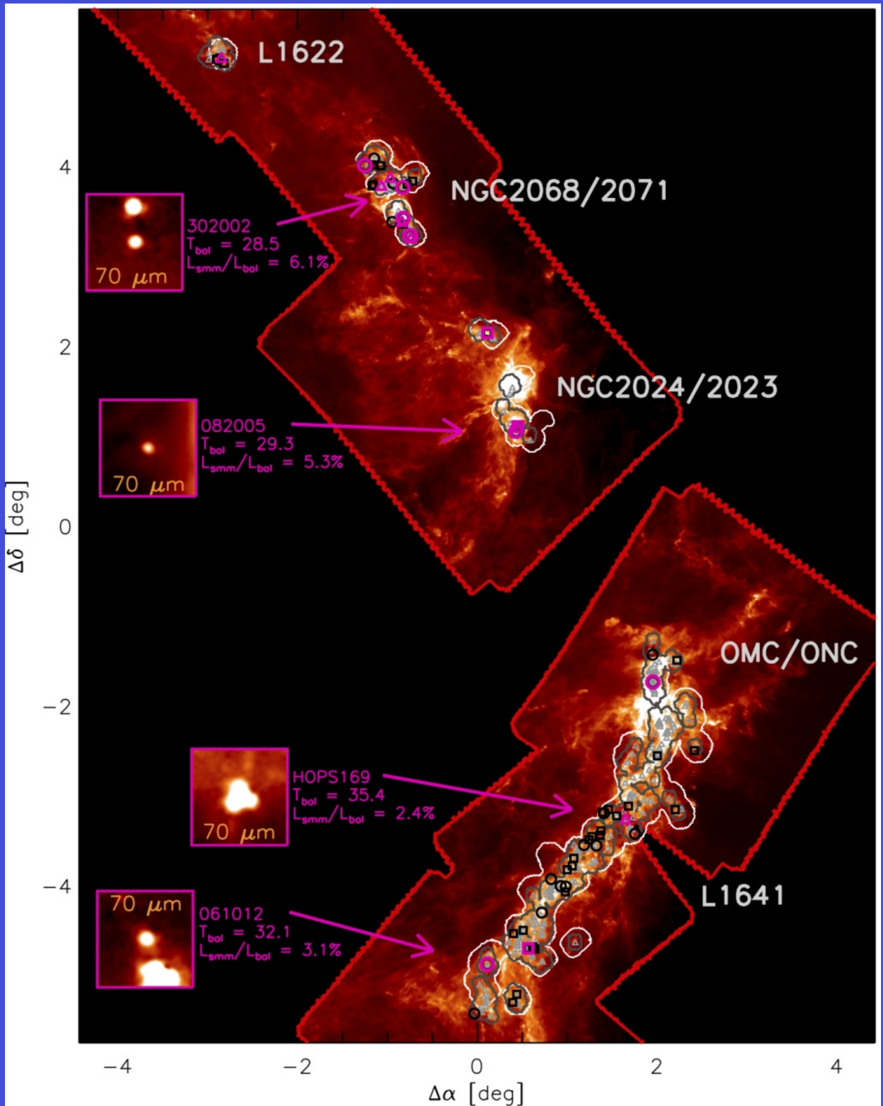
Towards Stellar Densities and Temperatures

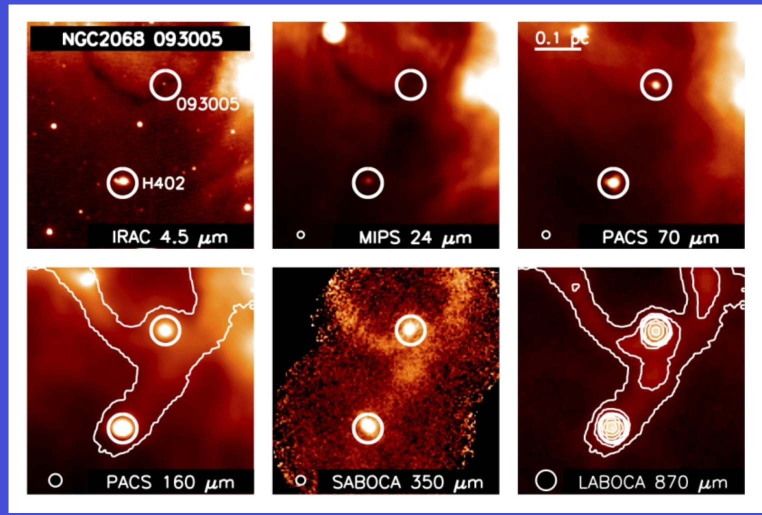


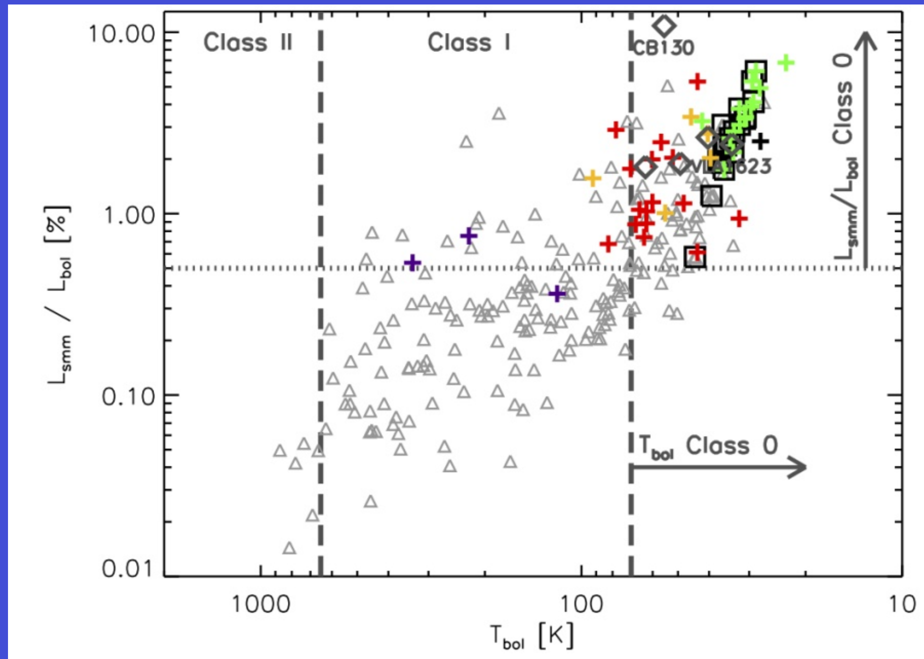
Accretion history and luminosity function (Dunham et al. 2013)

Search for first hydrostatic core (e.g. Chen et al. 2013, Tsitali et al. 2013)

New Population of Protostars in Orion - HOPS

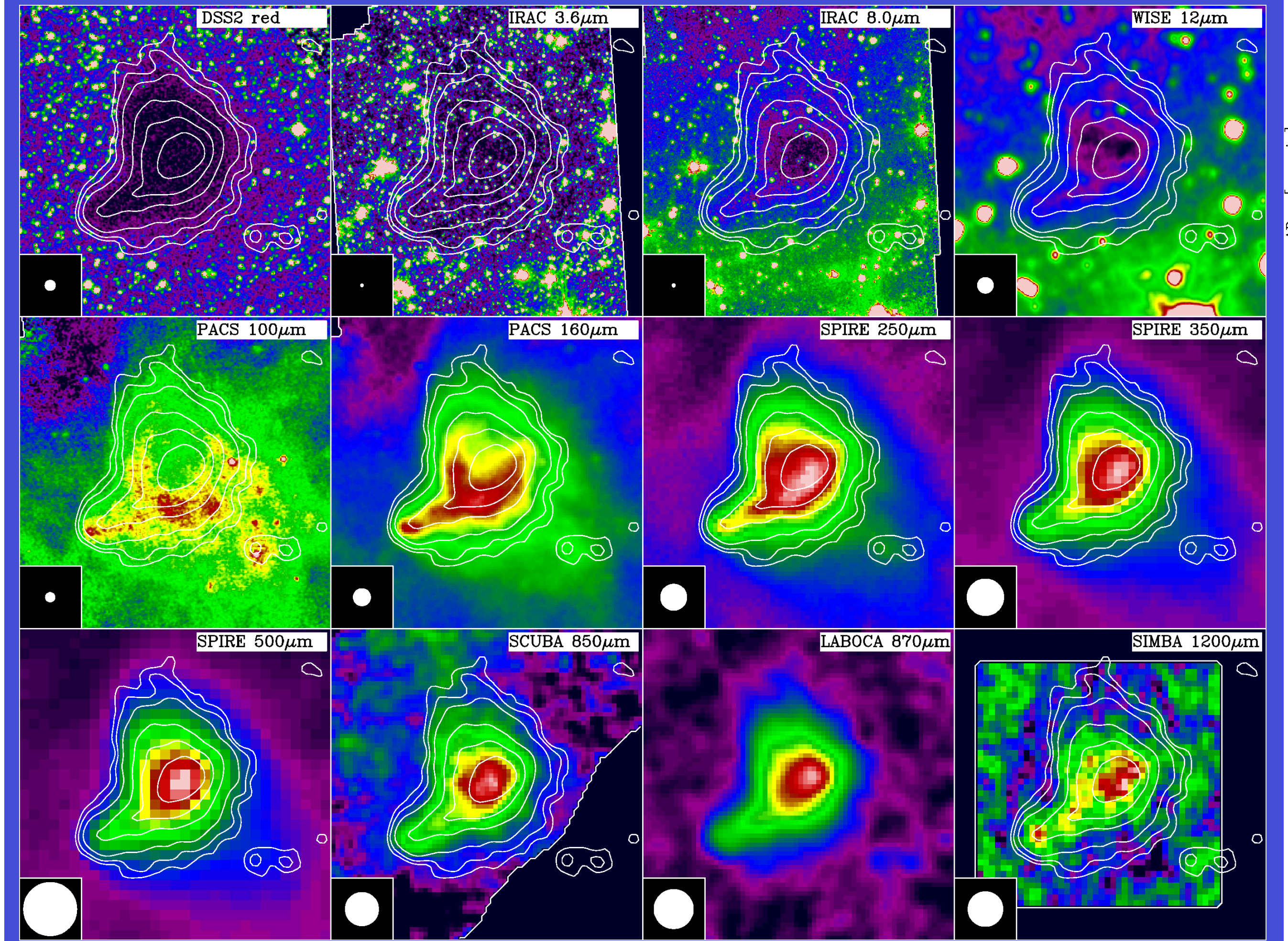


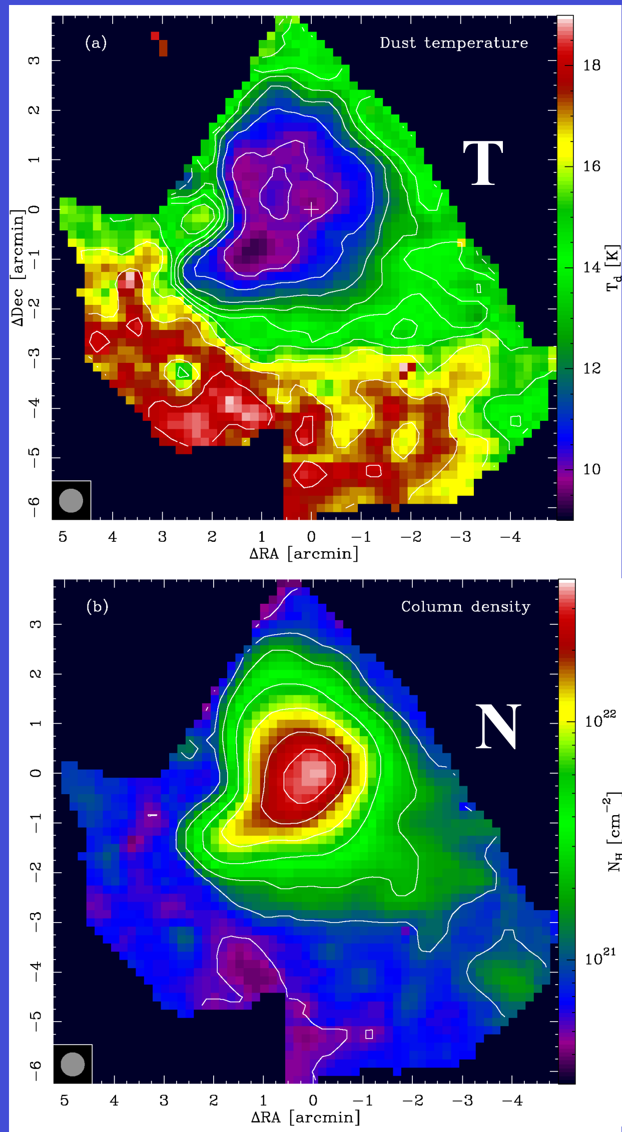




Stutz et al. + HOPS team (2013)

B 68 – From Spitzer to WISE and Herschel/EPOS





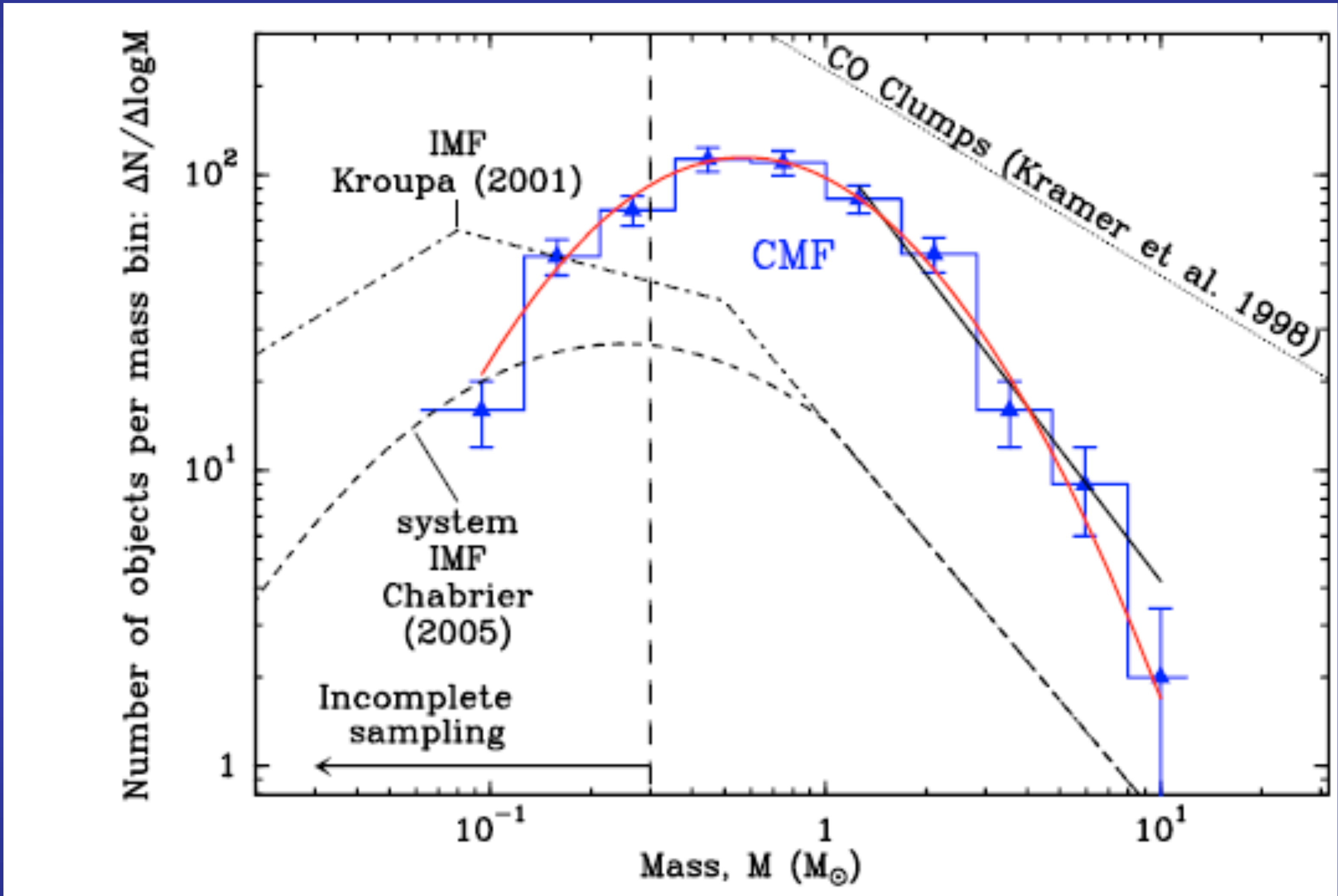
Dust continuum data

Modelled by ray tracing

Nielbock et al. 2012: Herschel Key Project/EPOS MPIA Project;

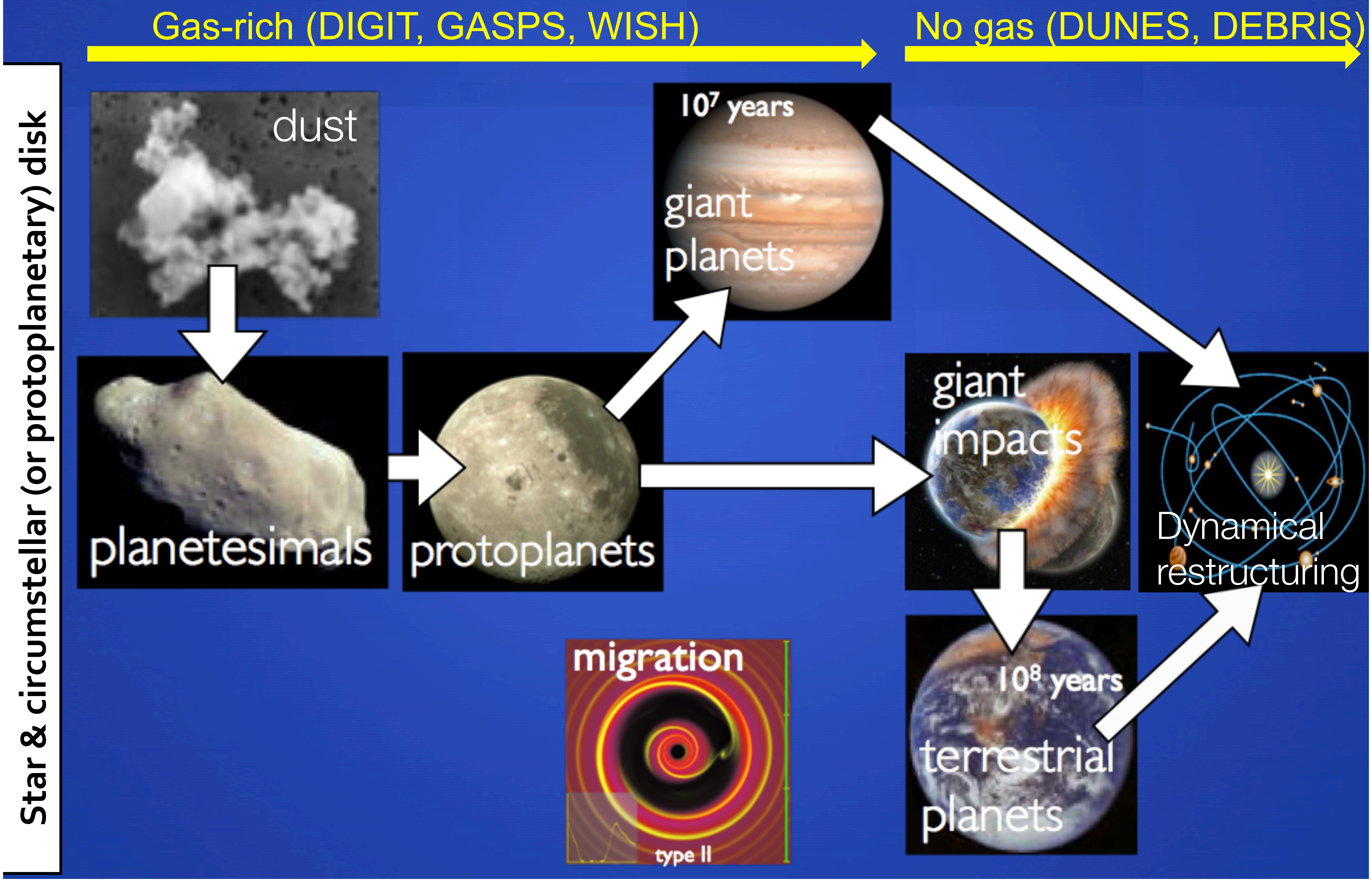
Launhardt et al. 2013; Lippok et al. 2013: Complete Sample of Low-mass Cores

The Origin of the Initial Mass Function

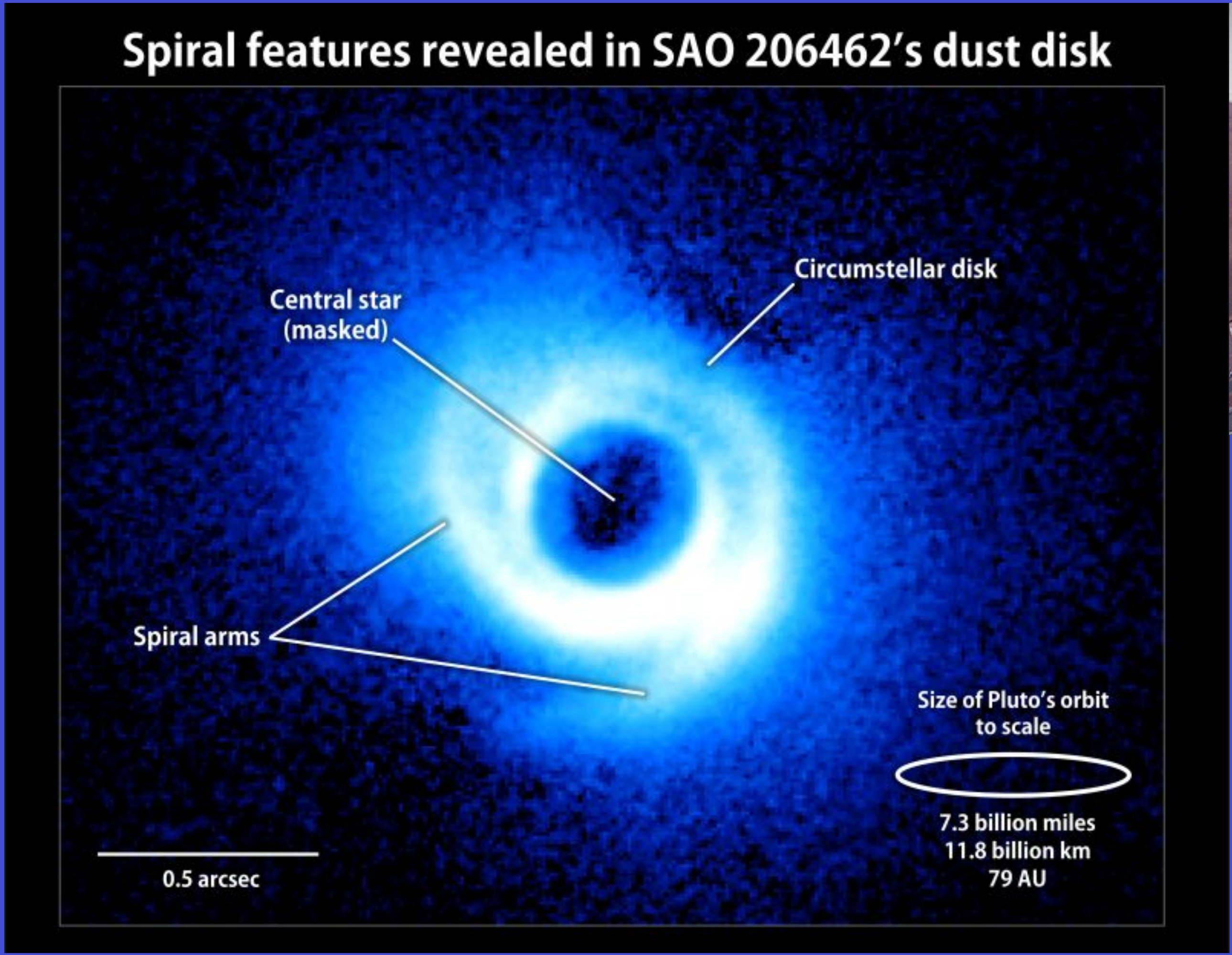


Herschel SPIRE/PACS: 541 candidate pre-stellar cores in Aquila (André et al. 2010)

Planet Formation: Stages



The End Product of Star Formation – Protoplanetary Disks



Spiral Structure
0.2” to 0.46”
(28-65 AU)

Muto et al. 2012 – SEEDS-Projekt/NAOJ-MPIA-Princeton
HD 135 344 B

Herschel Reveals Structure of Debris Disks

PACS 70 micron image of disk around Fomalhaut (Acke et al. 2012)

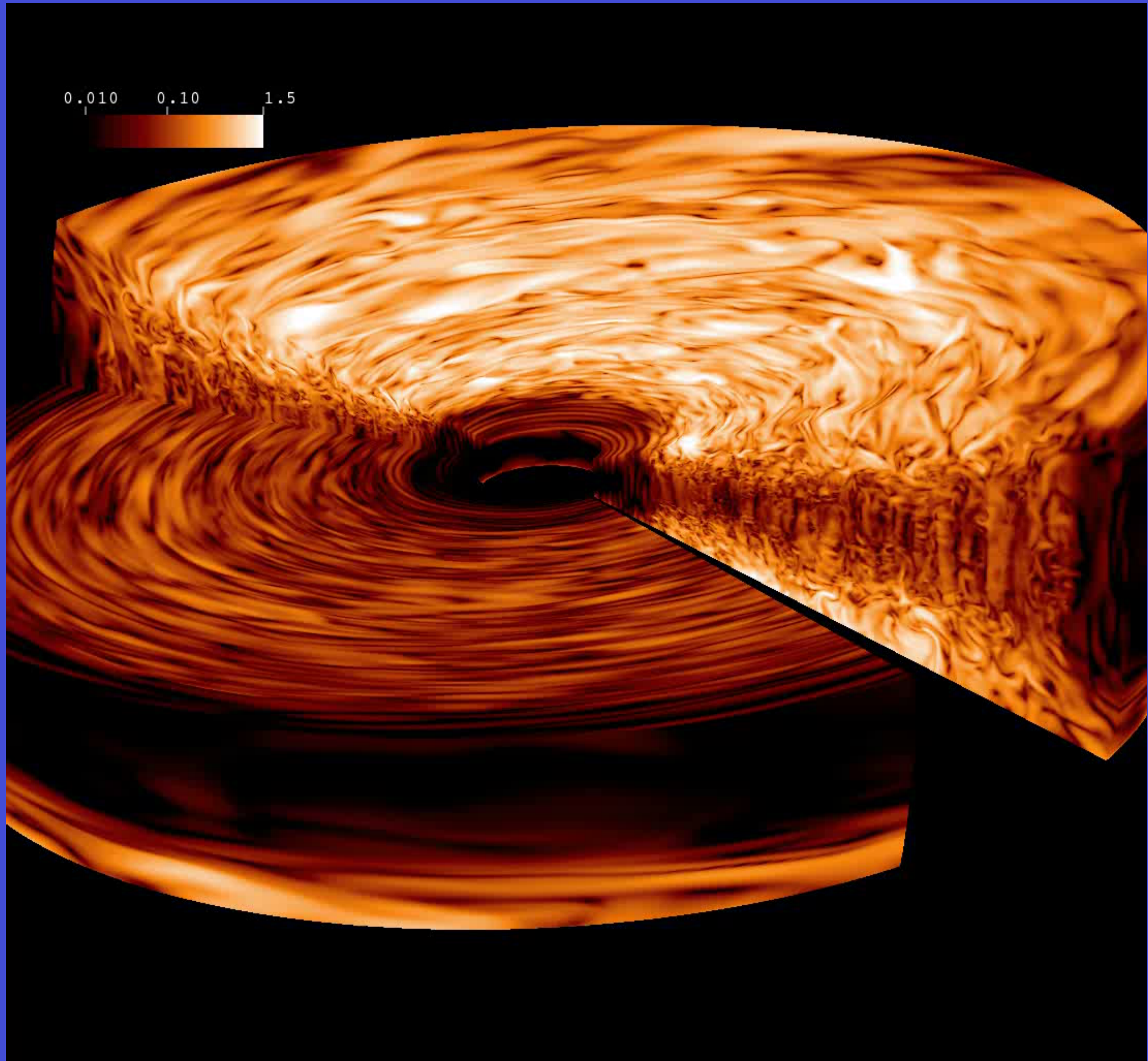
- Dynamical very active system
- Grains are fluffy aggregates

- High detection rate (20%) of disks (Eiroa+ 13)
- Detection of new class of cold disks (Eiroa+ 13, Krivov+ 13)
- Significant number of disks spatially resolved
  (e.g. Eiroa+ 13, Lestrade+ 12, Booth+ 13, Moor+ 13)

3D Global Stratified MHD Simulation

Radius:1-10 AU

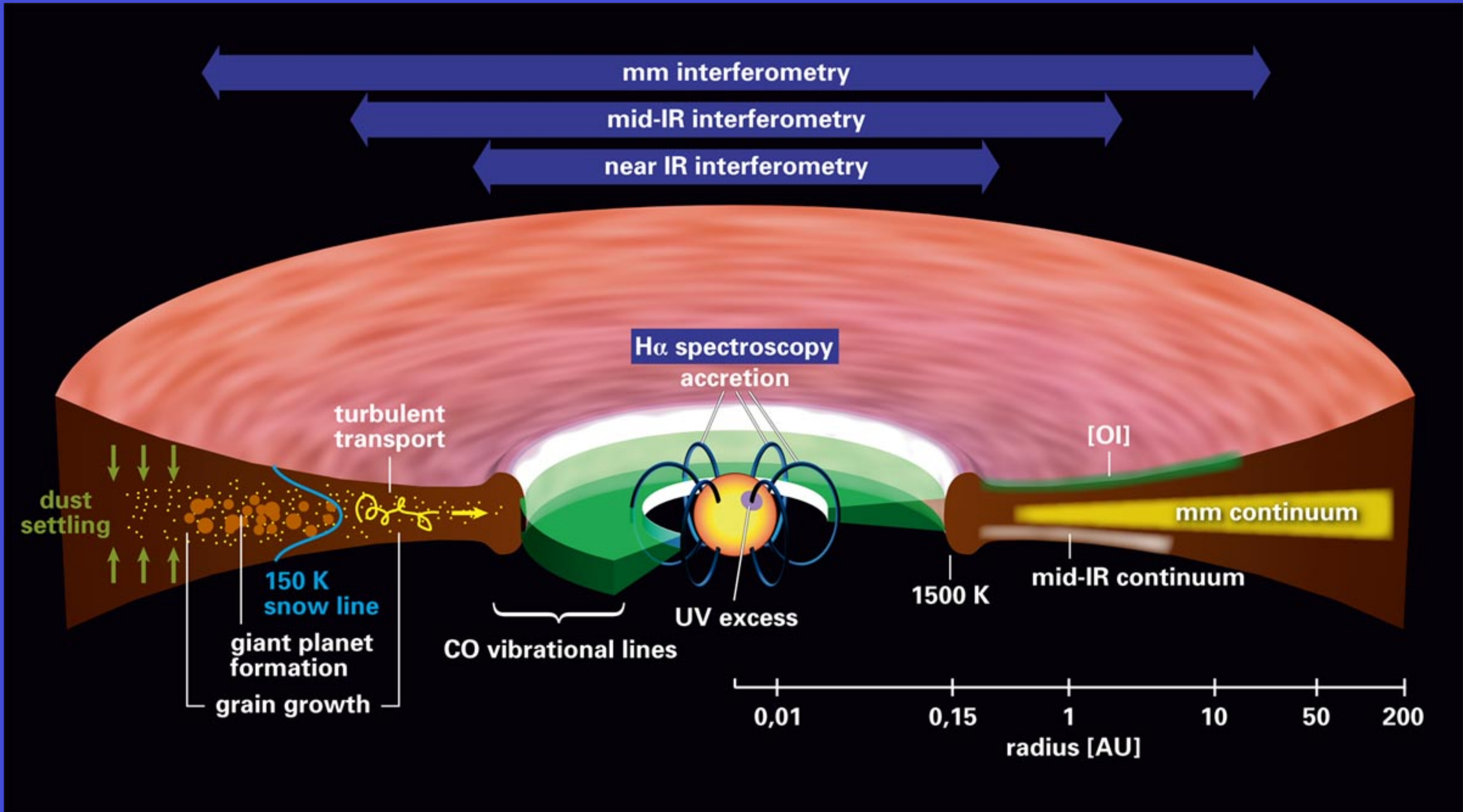
8 pressure
scale heights



Blue Gene/P and Pluto code: Flock et al. (2011)
PdBI Obs. of DM Tau in CS (3-2) (1" resolution, 0.126 km/s): Guilloteau et al. (2012)

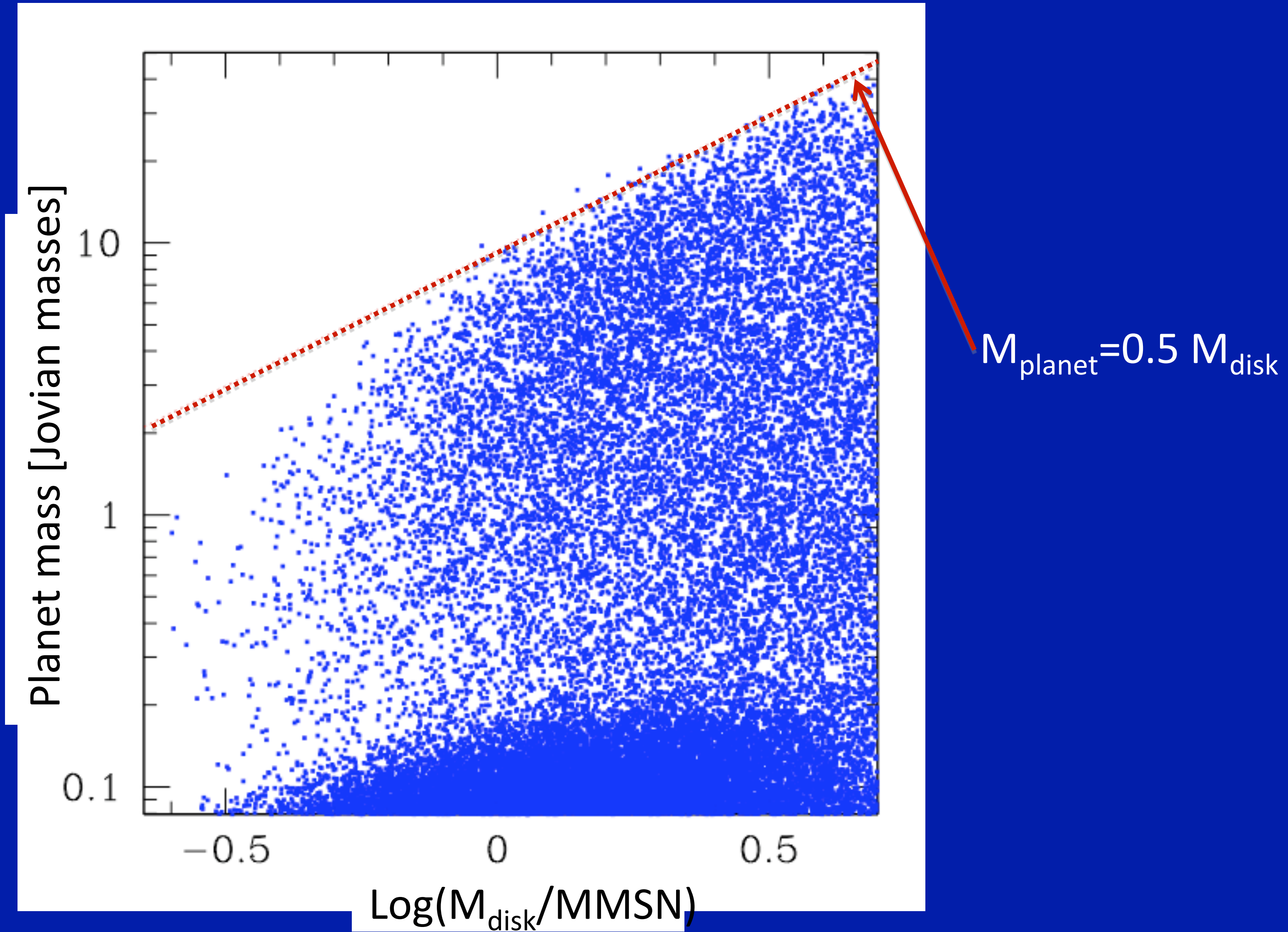
Structure of Protoplanetary Disks

Small Structures – Low Mass – Low line/continuum ratio



Planet Population = f(Metallicity, Disk Mass, Lifetime, …)

Disk mass and planet mass



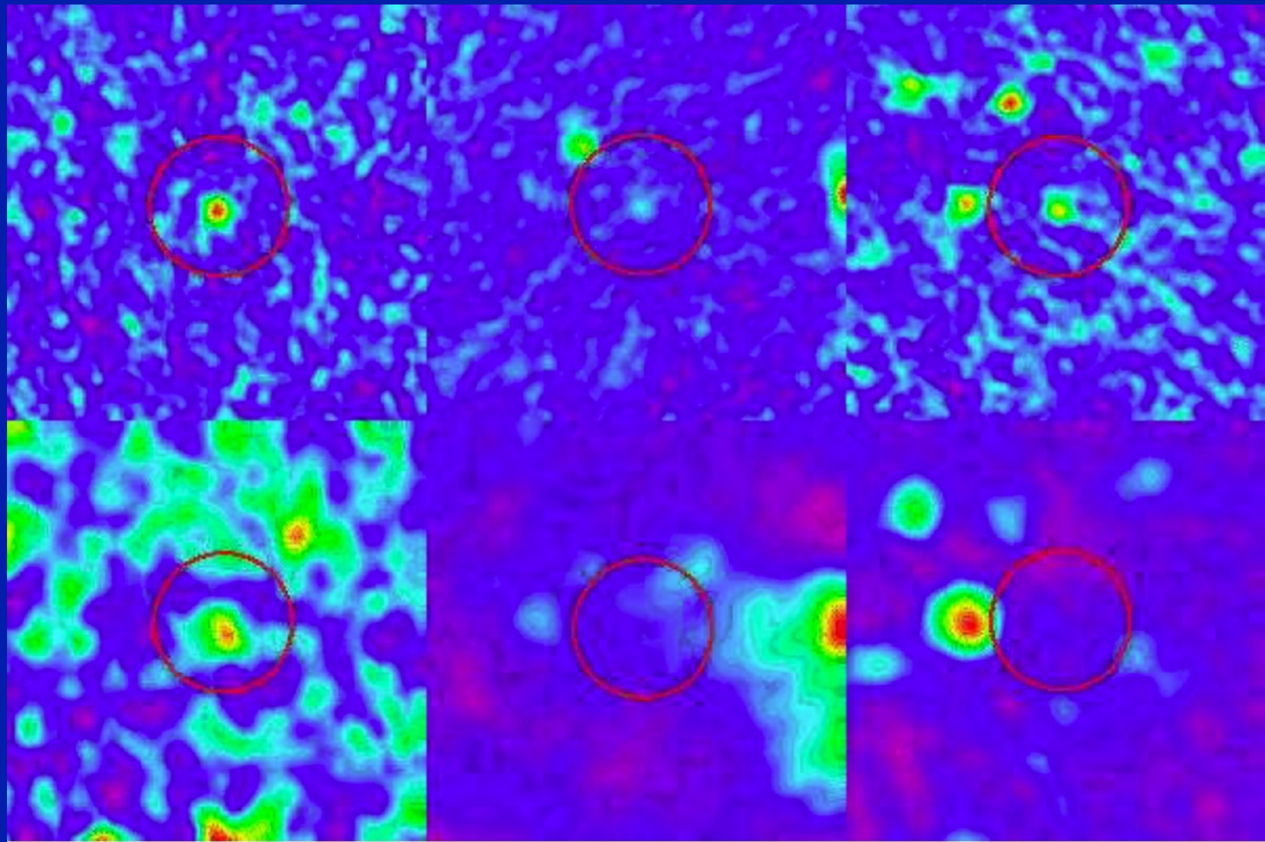
Maximal planet mass increases with disk mass.

Mordasini et al. (2012)

Herschel Finds BD Disks

70 µm

160 µm



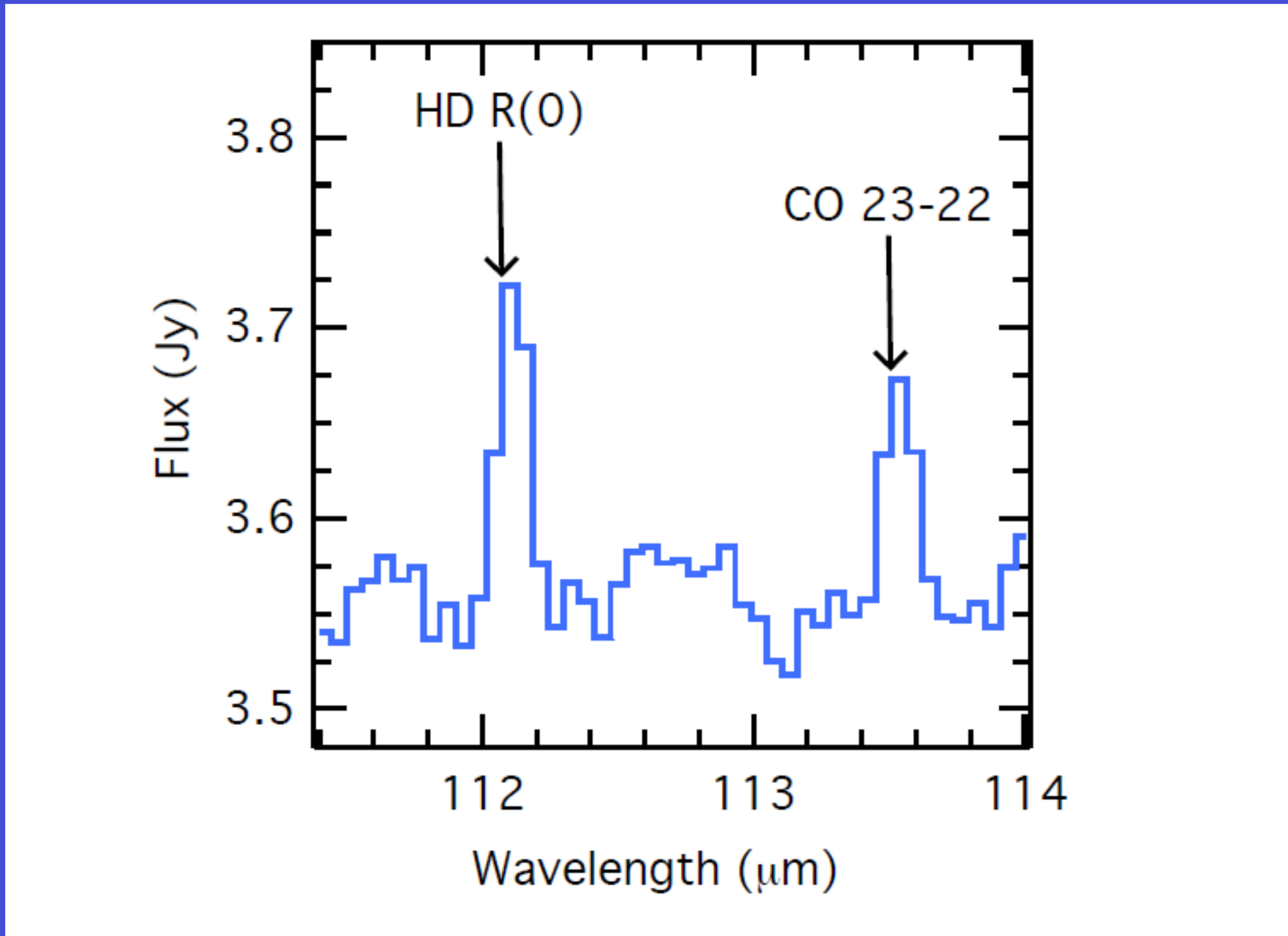
SSSPM1102 — ISO 138 — 2 MASS 1207

M8.5 in TWA — M6.5 in ChaI — M8 BD in TWA

Harvey et al. (2012a, b), Oloffson et al. (2013), Alves de Oliveira et al. (2013), …

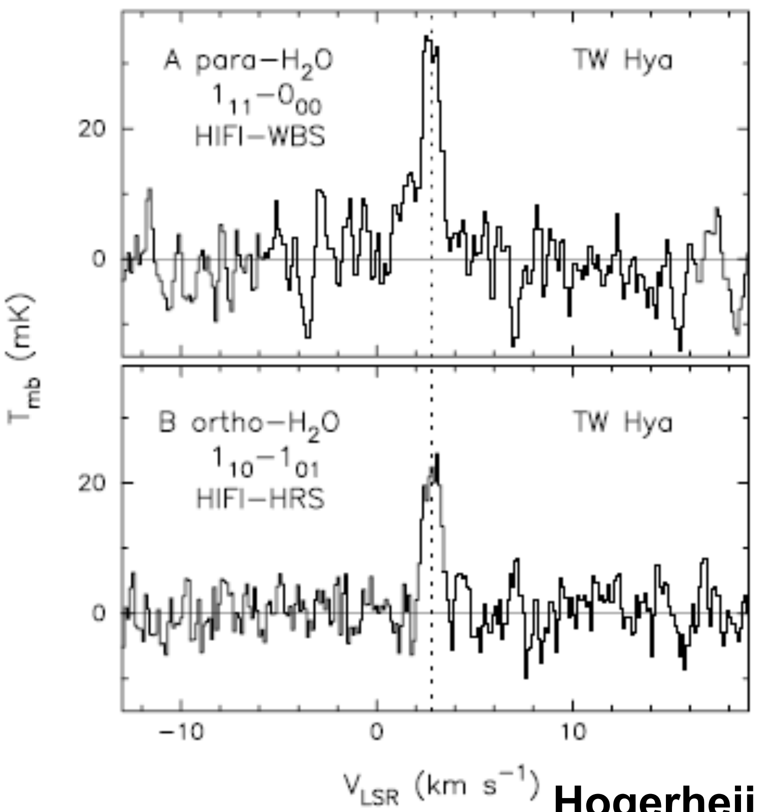
The Story Continues – Discovery of HD in TW Hya

Normally we do not measure the total disk mass, but the dust mass ...



Bergin et al. (2013, Nature 493, 644), Disk mass > 0.05 M_{sun}

Cold Water Vapour in Outer Disk

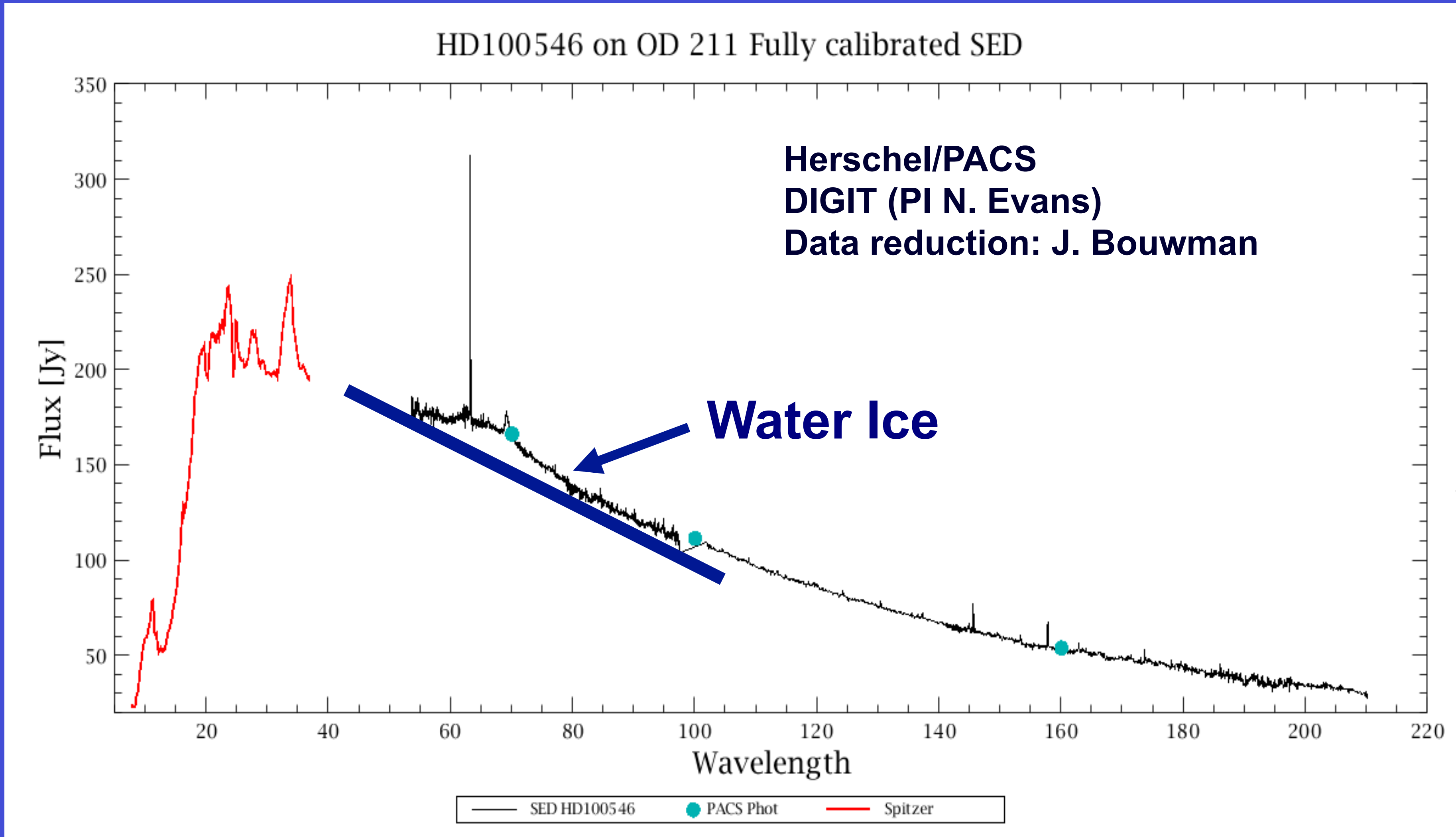


Hogerheijde+ 2011

- Detection of ground-state rotational emission of both spin isomers of water with deep Herschel/HIFI observations

- 7.3×20^{24} g of water vapour (0.005xEarth ocean) originating from a total ice reservoir of 9×10^{27}g (several thousands of Ocean masses)

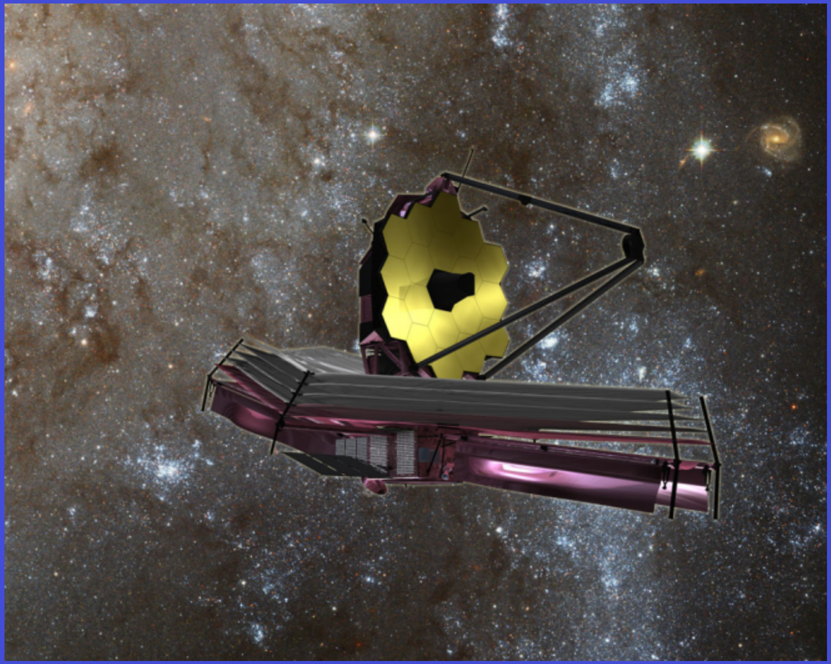
Herbig Ae/Be star HD100546



Discovery of molecular ice band; No evidence for hydrous silicates
(see also McClure et al. (2012) GQ Lupi disk spectrum)
Crystalline ice formed at ~120-150K and cooled down to about 50K

The Future is Bright

ALMA 2013

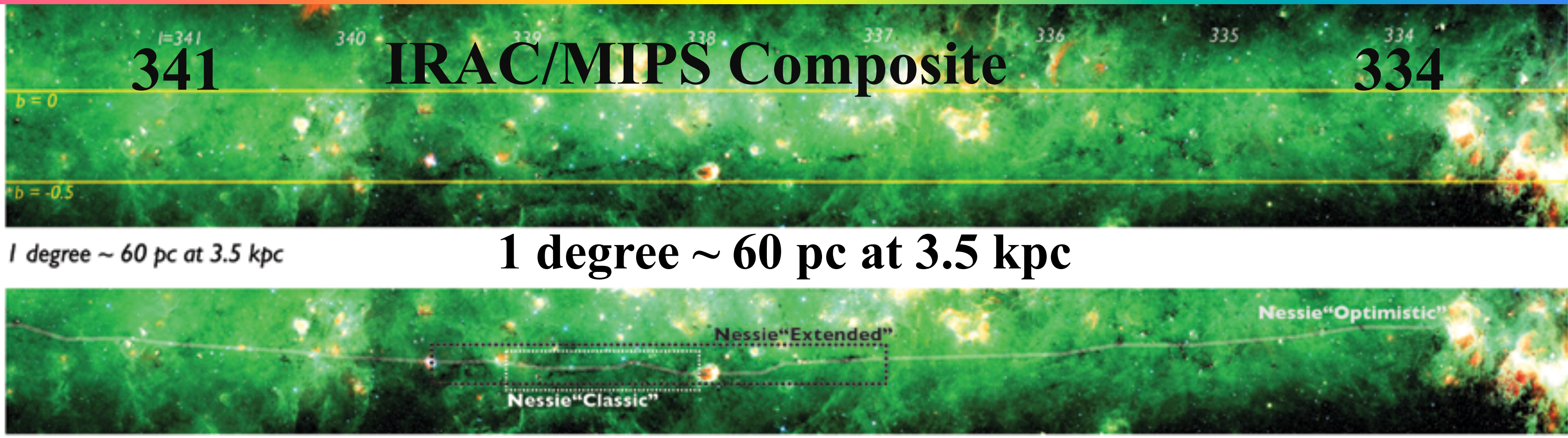


JWST 2018

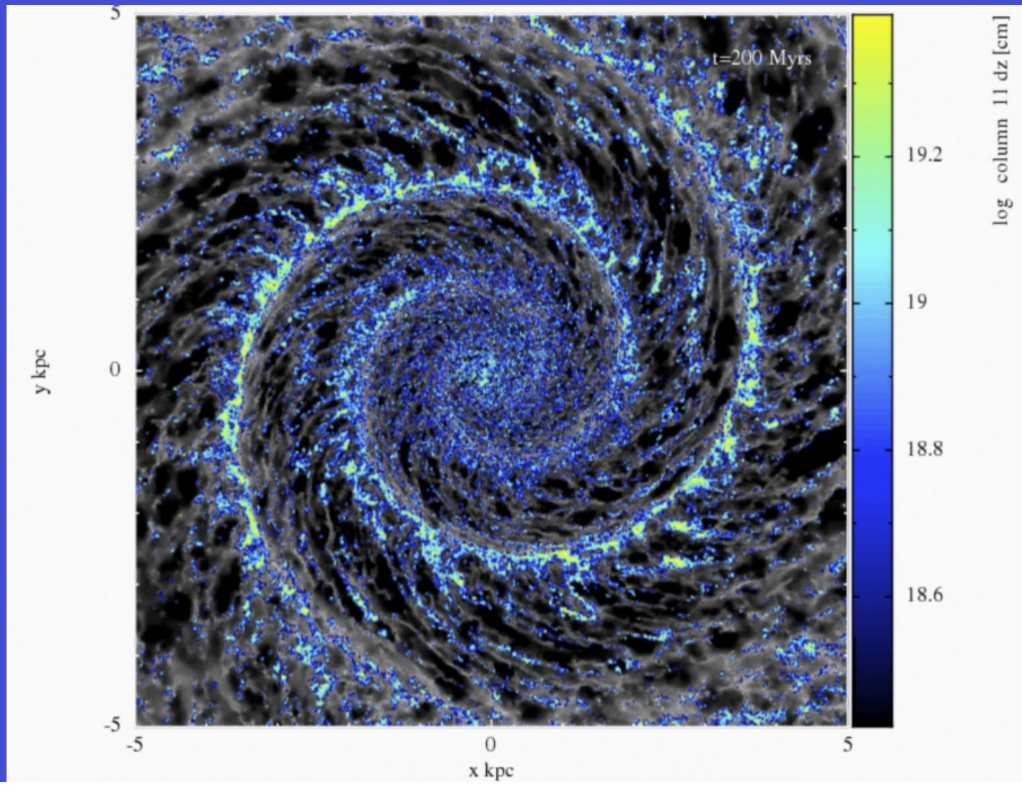
- **Stars form today in the MW galaxy with a universal IMF**
- **Stars form in structured filamentary molecular clouds**
- **PDFs are crucial ingredients for star formation laws**
- **Low-mass star formation leads to disks and planets**
- **Diversity of planetary systems is related to disk diversity**

Protostars and Planets VI (eds. H. Beuther, R. Klessen, C. Dullemond, Th. Henning), Arizona University Press, Tucson, 2014.

Next Challenge: SF in the Galactic Context



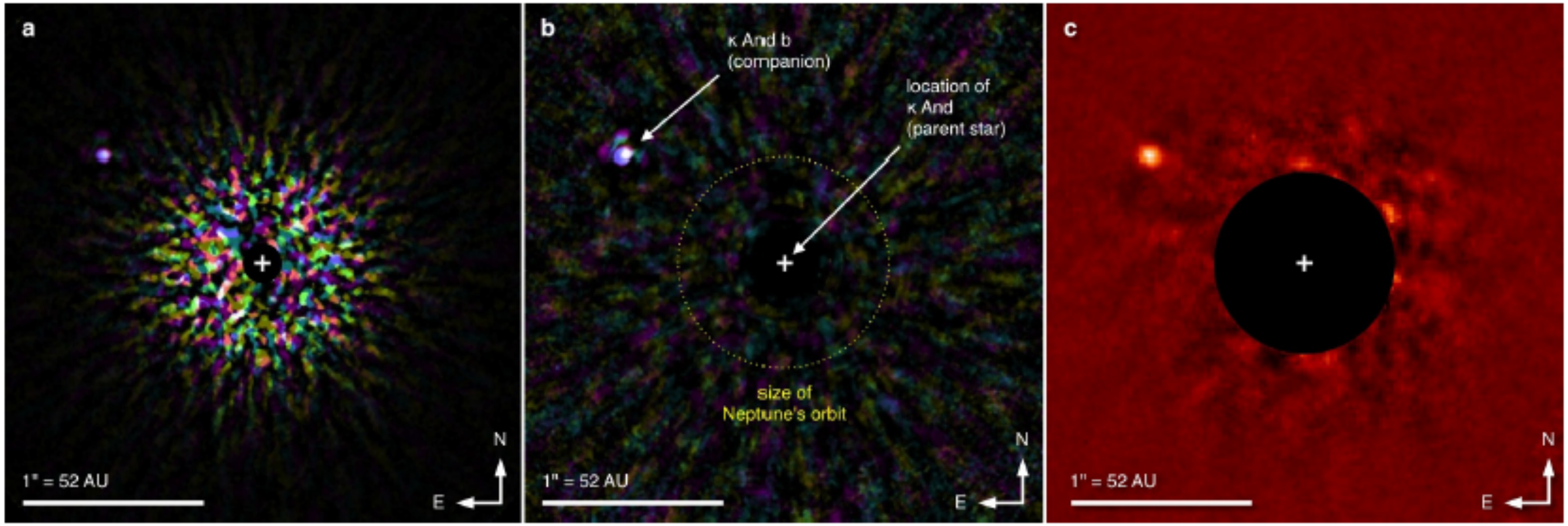
The Nessie Filament in the Galaxy (Goodman et al. in prep.)



Data:
UKIDSS, VISTA
GLIMPSE/MIPSGAL
WISE
HI-GAL
ATLASGAL, JPS

Numerical Simulation:
Dobbs & Pringle (2013)

Latest News from Direct Imaging …



Carson et al. (2013) – SEEDS Programme

Super-Jupiter (13 M_{jup}) around B-type star κ And
System age is 30 Myrs
Projected separation is 55±2 AU