Star formation

Dr Jennifer Hatchell
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Astrophysics

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http://www.astro.ex.ac.uk/people/hatchell/sfmap.pdf

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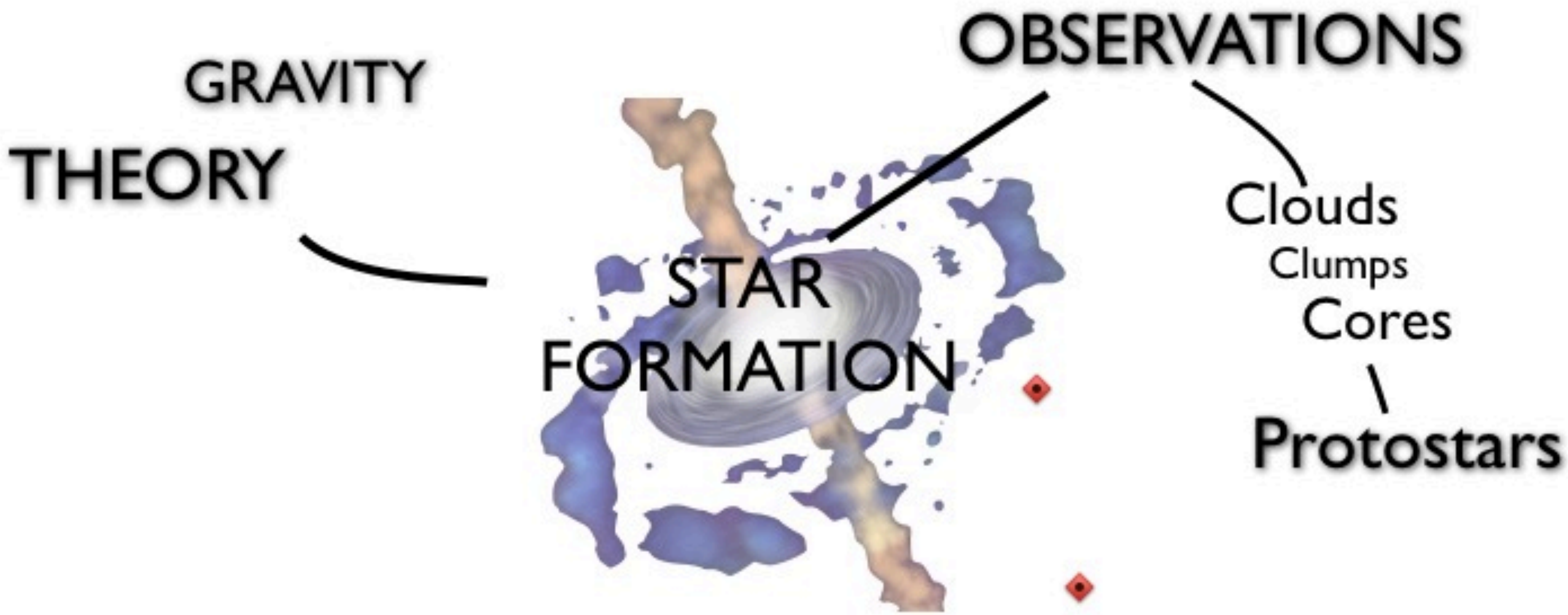

Stars form in molecular clouds

JCMT Gould Belt Legacy Survey

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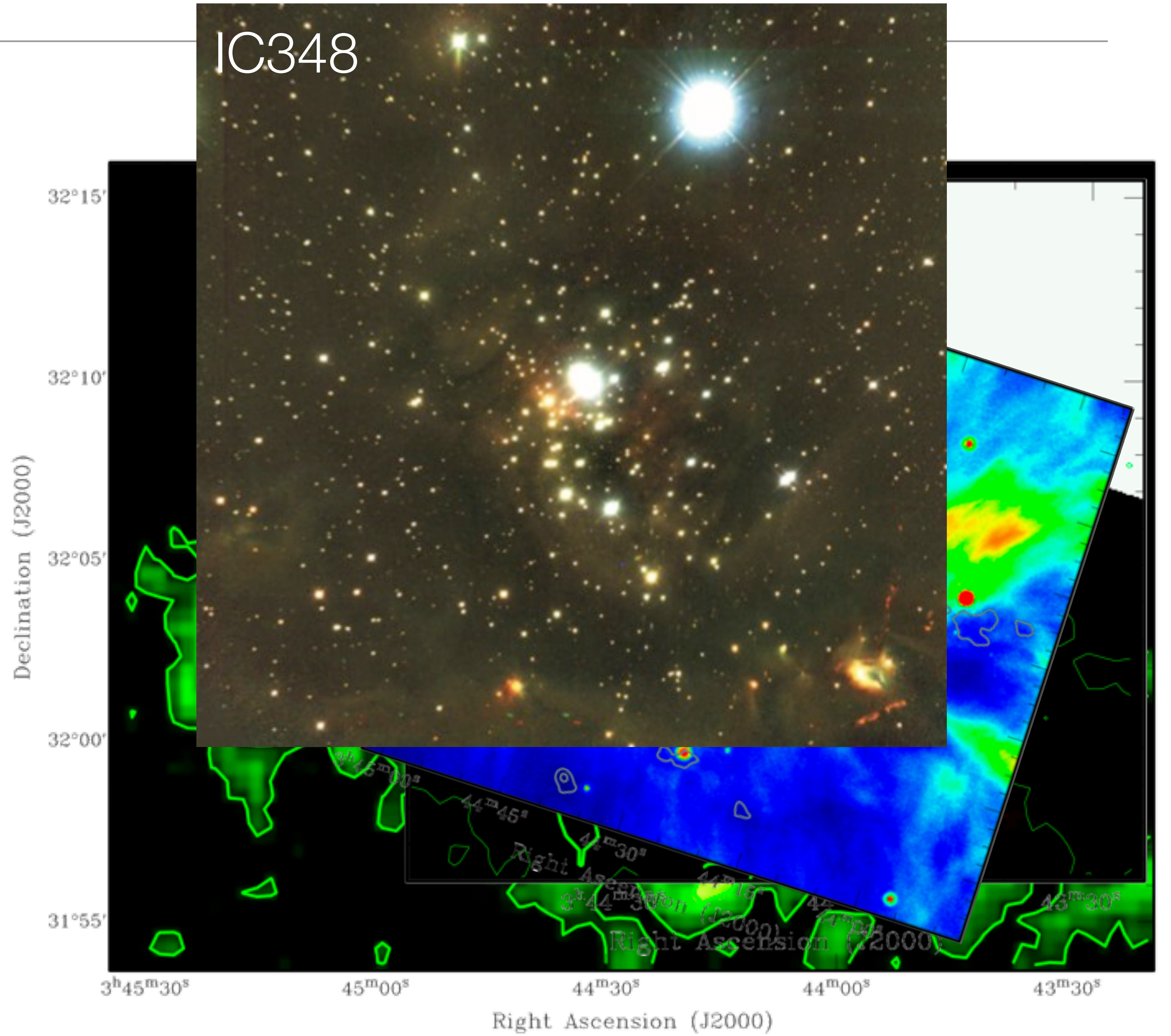
mm: C18O 1-0 FCRAO
Hatchell et al. 2005

submm: 850 μm SCUBA
Hatchell et al. 2005

MIR: – 8μm Spitzer
Jorgensen et al. 2006

NIR: 1-2μm JHK
Muench et al. 2003



Unanswered questions

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- Where do stars form and why?
- Origin of the stellar initial mass function (IMF)?
- What is the role of feedback?
- Are magnetic fields ever important?
- Is massive star formation a scaled-up version of low mass?

Theory

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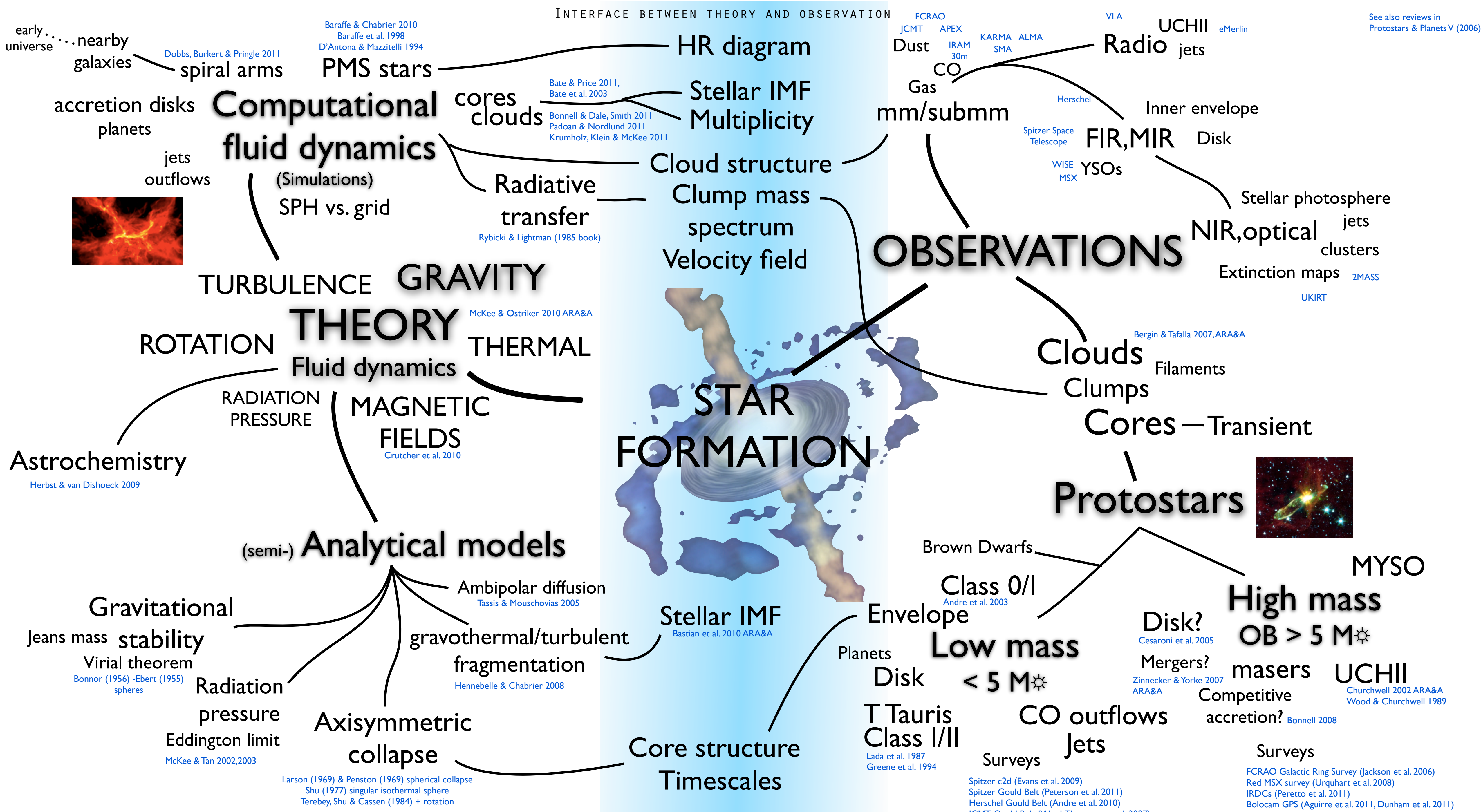

A BIASED AND INCOMPLETE OVERVIEW OF STAR FORMATION. DR JENNIFER HATCHELL, AUG 2011

Simple estimates of gravitational stability

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University of Exeter

- Jeans length / mass: gravitational instability against thermal support in a uniform density medium

$$\lambda_J^2 = \frac{\pi c_s^2}{G\rho}, \qquad M_J = \lambda_J^3 \rho \quad \Rightarrow \quad \frac{GM_J}{\lambda_J} = \pi c_s^2$$

where c_S is the sound speed and ρ density.

eg. Hartmann 'Accretion Processes in SF' book

- Virial mass: thermal /turbulent support vs. gravity for a core in equilibrium

$$\frac{3}{5}\frac{GM_{\rm vir}}{R} = \alpha\left(3\sigma_{\rm 1D}^2\right)$$

Mass; Core/clump radius; Thermal / turbulent 1D Gaussian linewidth; Virial parameter α~1

eg. Bertoldi & McKee 1992

for only thermal pressure $3\sigma_{\rm 1D}^2 = c_s^2 = P/\rho = kT/\mu m_{\rm H}$

THEORY

McKee & Ostriker 2010 ARA&A

Fluid dynamics

ROTATION

THERMAL

RADIATION PRESSURE

MAGNETIC FIELDS

Crutcher et al. 2010

Astrochemistry

Herbst & van Dishoeck 2009

(semi-) Analytical models

Gravitational stability

Jeans mass

Virial theorem

Bonnor (1956) -Ebert (1955) spheres

Radiation pressure

Eddington limit

McKee & Tan 2002,2003

Axisymmetric collapse

Larson (1969) & Penston (1969) spherical collapse

Shu (1977) singular isothermal sphere

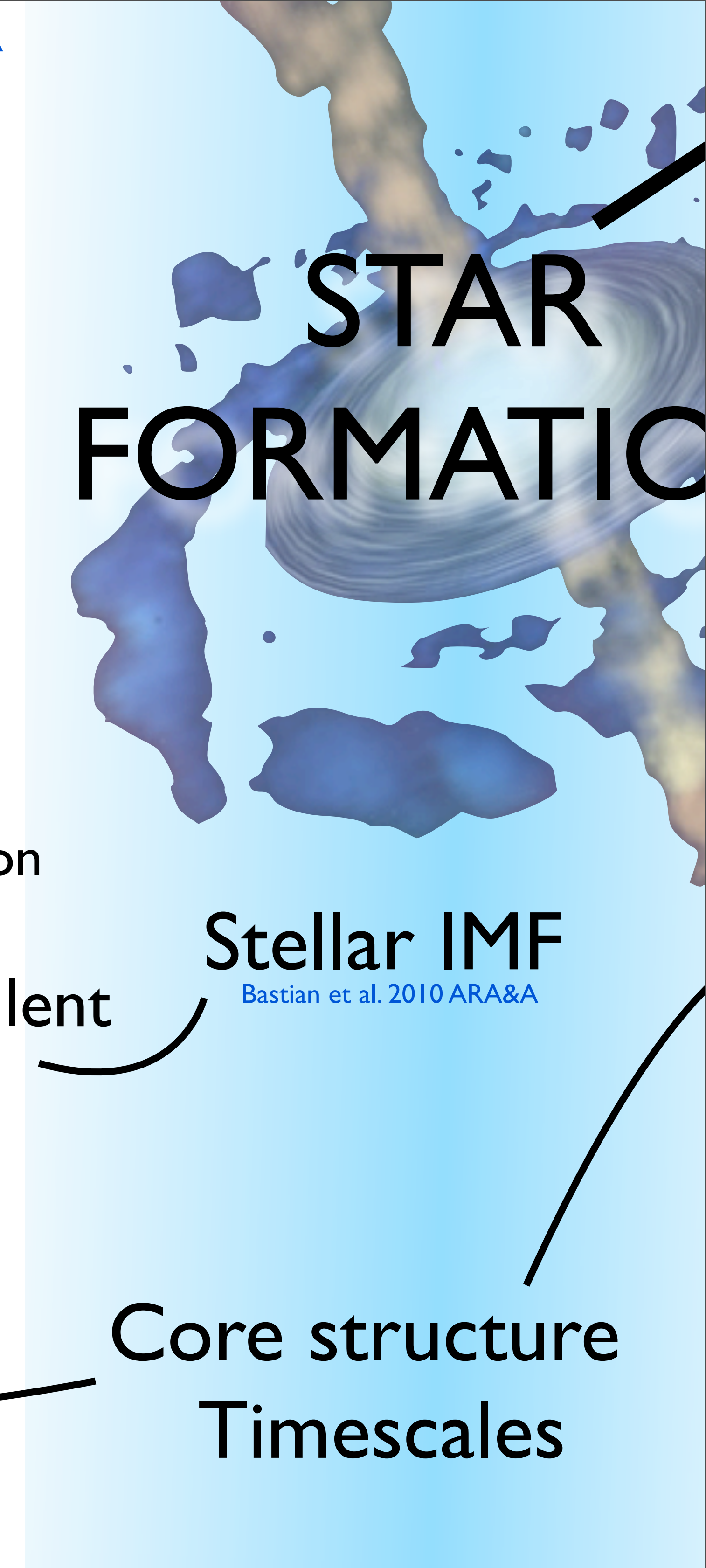
Terebey, Shu & Cassen (1984) + rotation

Ambipolar diffusion

Tassis & Mouschovias 2005

gravothermal/turbulent fragmentation

Hennebelle & Chabrier 2008



A Biased and Incomplete Overview of Star Formation. Dr Jennifer Hatchell, Aug 2011

Axisymmetric collapse solutions

DR JENNIFER HATCHELL

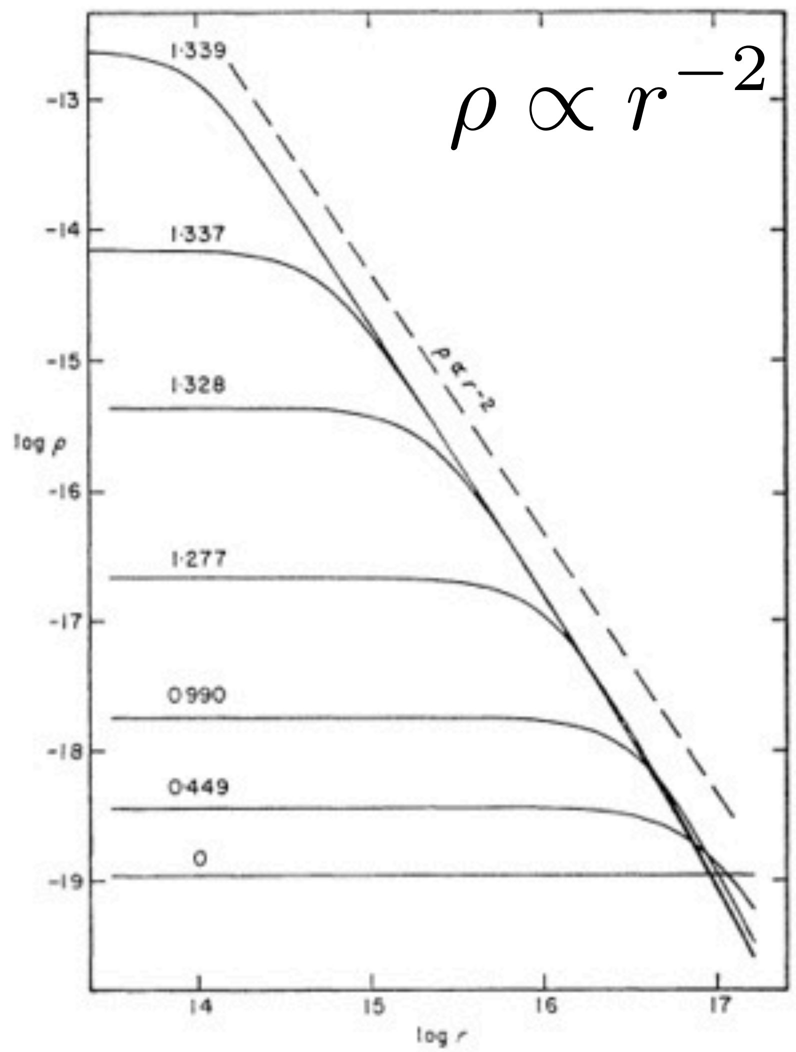
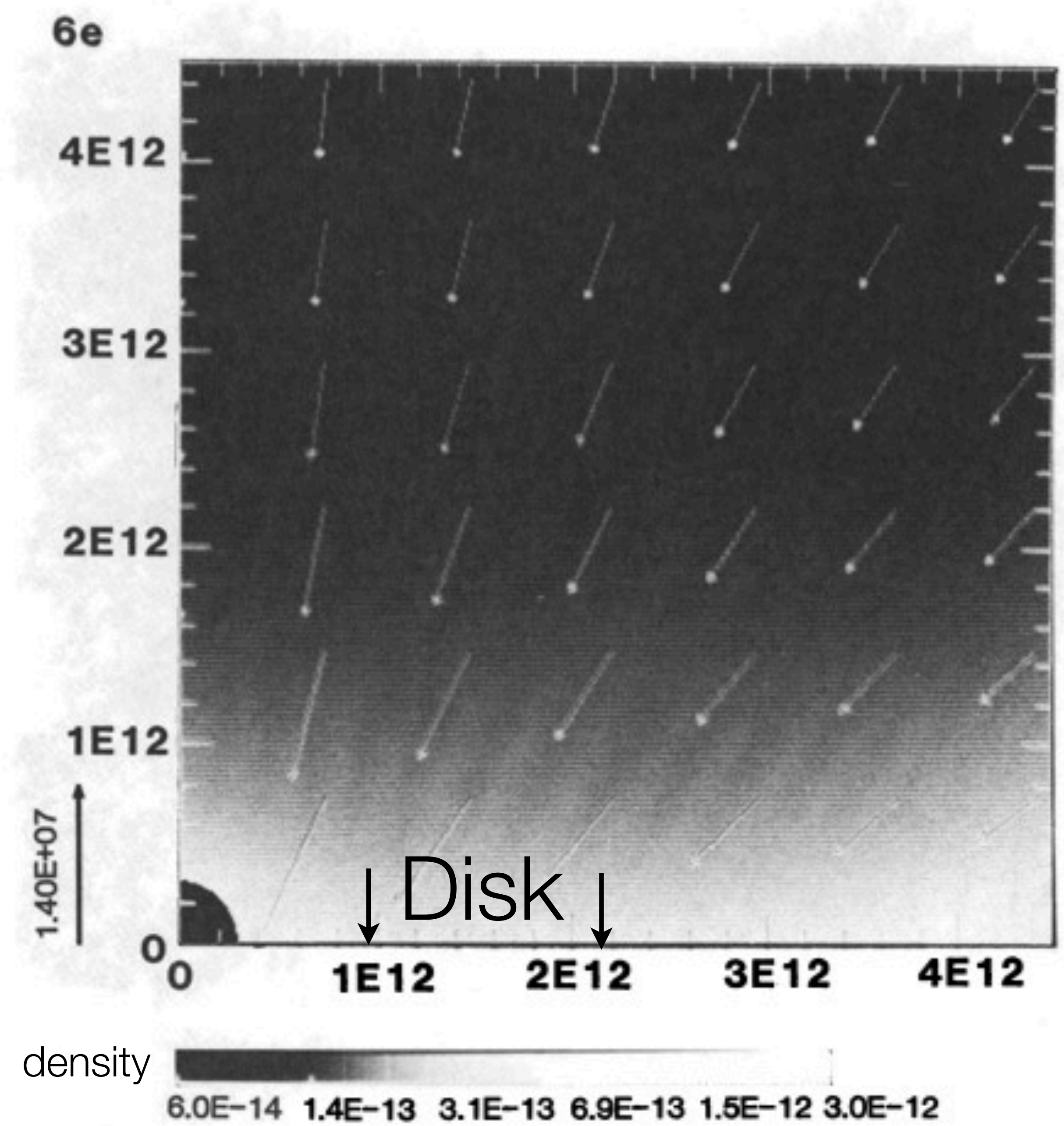


FIG. 1. *The variation with time of the density distribution in the collapsing cloud (CGS units). The curves are labelled with the times in units of* 10^{13} *s since the beginning of the collapse. Note that the density distribution closely approaches the form* $\rho \propto r^{-2}$.

Larson (1969) and Penston (1969) protostellar collapse

Shu (1977) singular isothermal sphere

Terebey, Shu & Cassen (1984) rotating collapse



THEORY

McKee & Ostriker 2010 ARA&A

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Fluid dynamics

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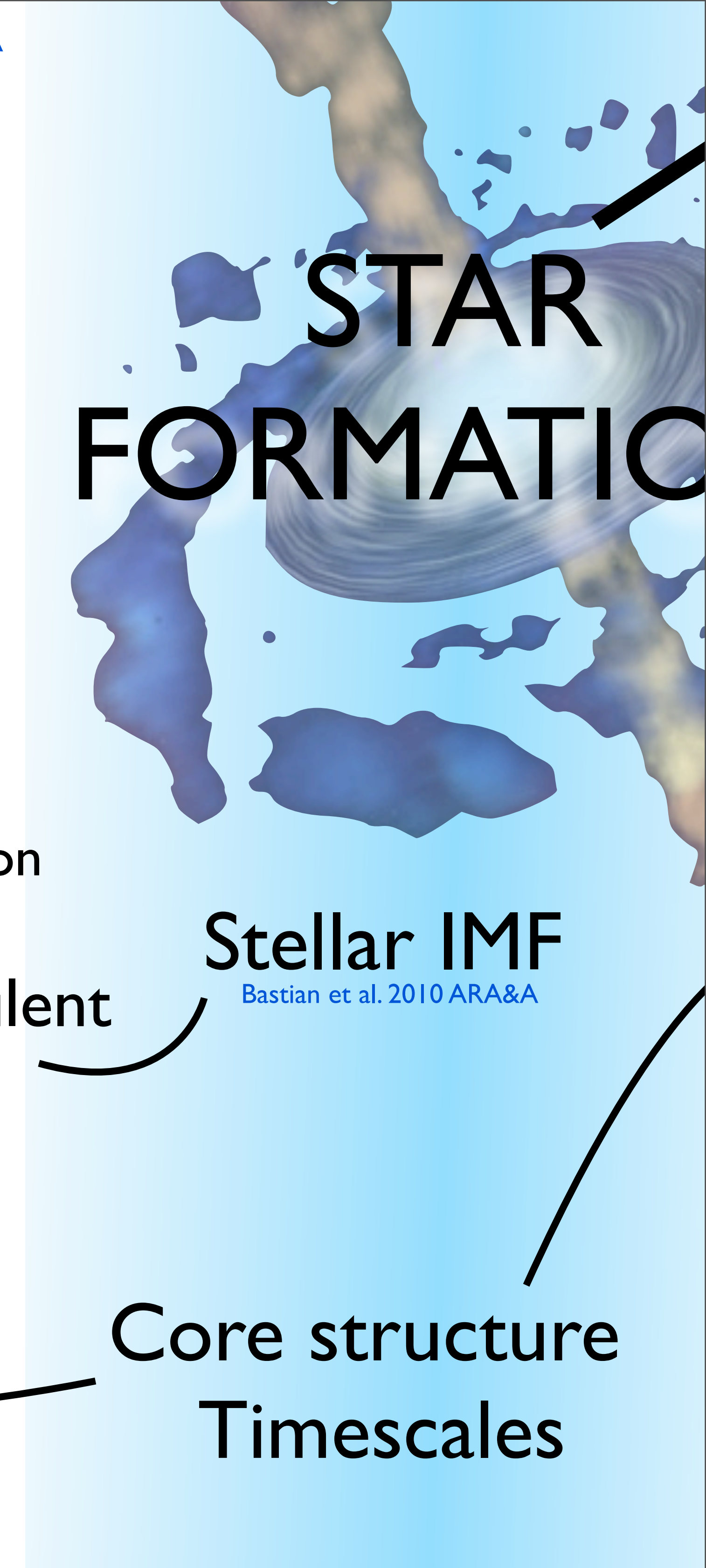

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Gravitational stability

Jeans mass

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Bonnor (1956) -Ebert (1955) spheres

gravothermal/turbulent fragmentation

Hennebelle & Chabrier 2008

Stellar IMF

Bastian et al. 2010 ARA&A

Radiation pressure

Eddington limit

McKee & Tan 2002,2003

Axisymmetric collapse

Larson (1969) & Penston (1969) spherical collapse
Shu (1977) singular isothermal sphere
Terebey, Shu & Cassen (1984) + rotation

Core structure

Timescales

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Numerical simulations

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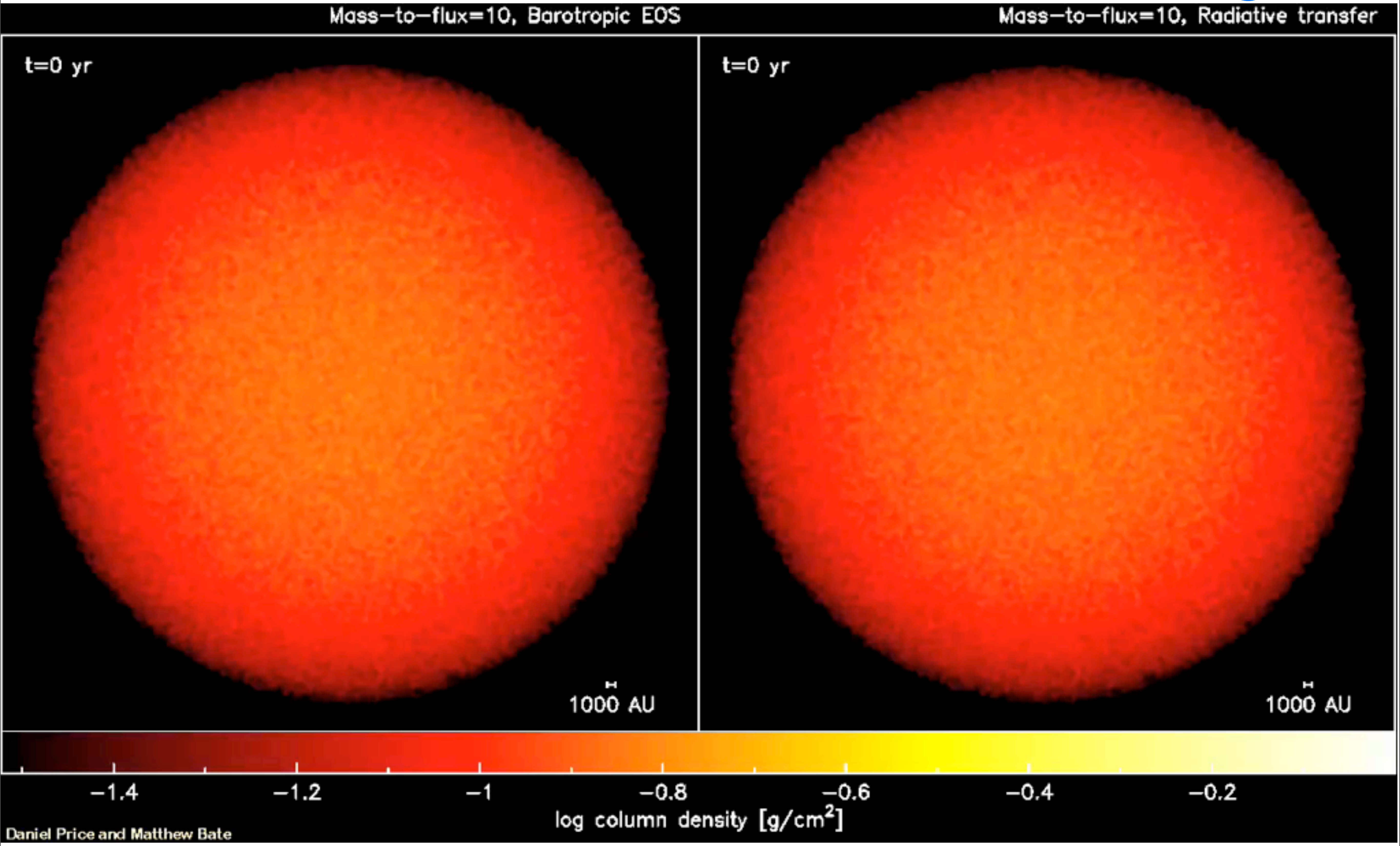
University of Exeter



- Price & Bate 2009 MNRAS 398, 33

Numerical simulations

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Interface between th

early universe .....nearby galaxies

Dobbs, Burkert & Pringle 2011
spiral arms

Baraffe & Chabrier 2010
Baraffe et al. 1998
D'Antona & Mazzitelli 1994
PMS stars

HR

Bate & Price 2011,
Bate et al. 2003

Ste

cores
clouds

Mu

Bonnell & Dale, Smith 2011
Padoan & Nordlund 2011
Krumholz, Klein & McKee 2011

accretion disks
planets

Computational fluid dynamics

(Simulations)

SPH vs. grid

jets
outflows

Cloud

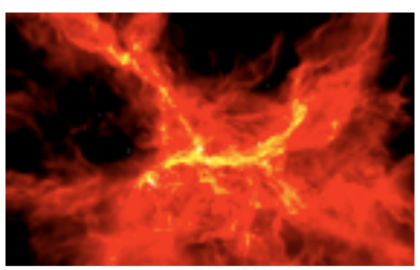
Radiative transfer

Rybicki & Lightman (1985 book)

Clur

spe

Veloc



TURBULENCE

GRAVITY

THEORY

McKee & Ostriker 2010 ARA&A

ROTATION

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Fluid dynamics

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MAGNETIC FIELDS

Galactic-scale simulations

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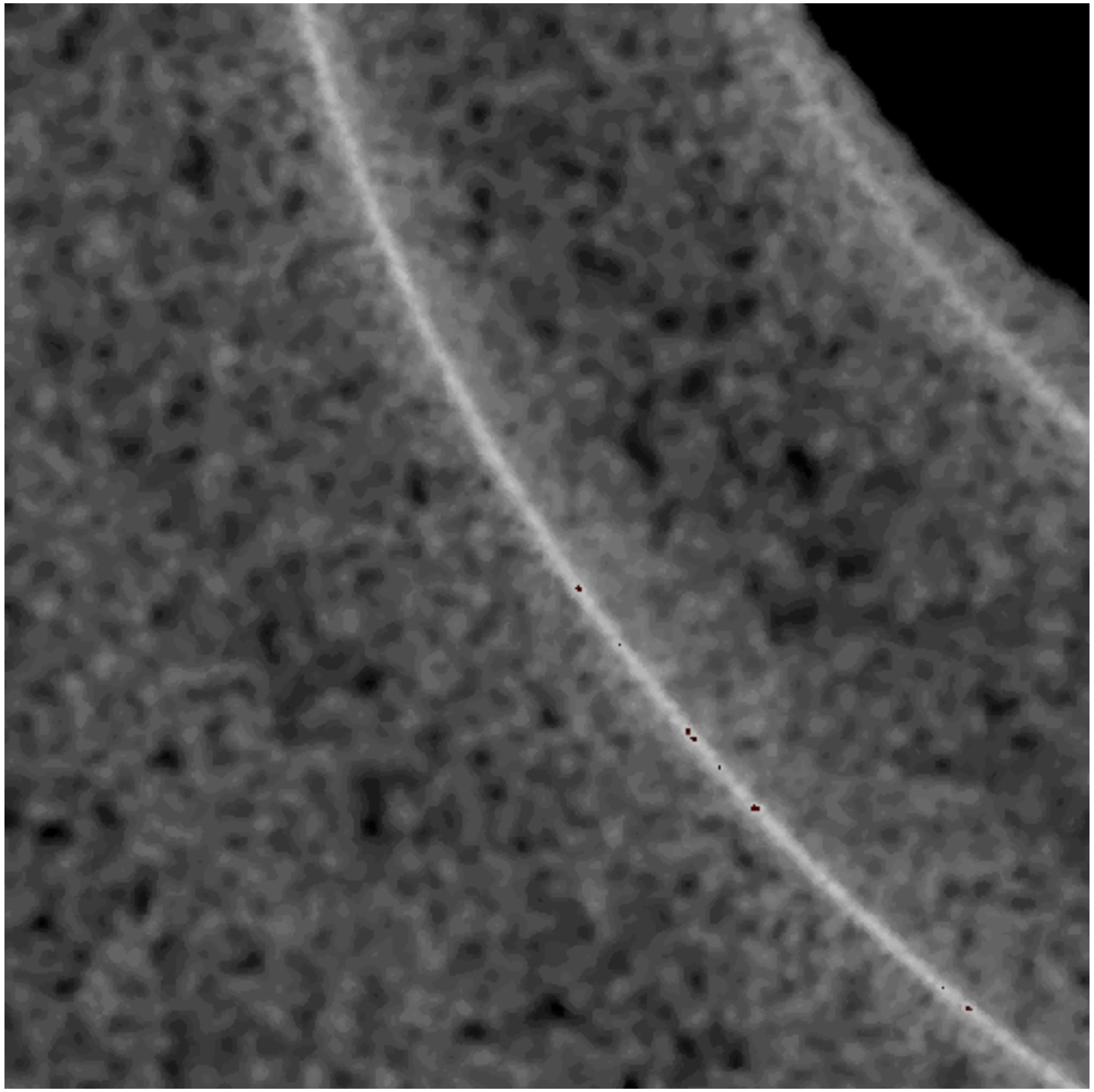
- Dobbs & Bonnell 2008 molecular H_2 cloud formation in Galactic spiral arms



http://www.astro.ex.ac.uk/people/hatchell/sfmap.pdf

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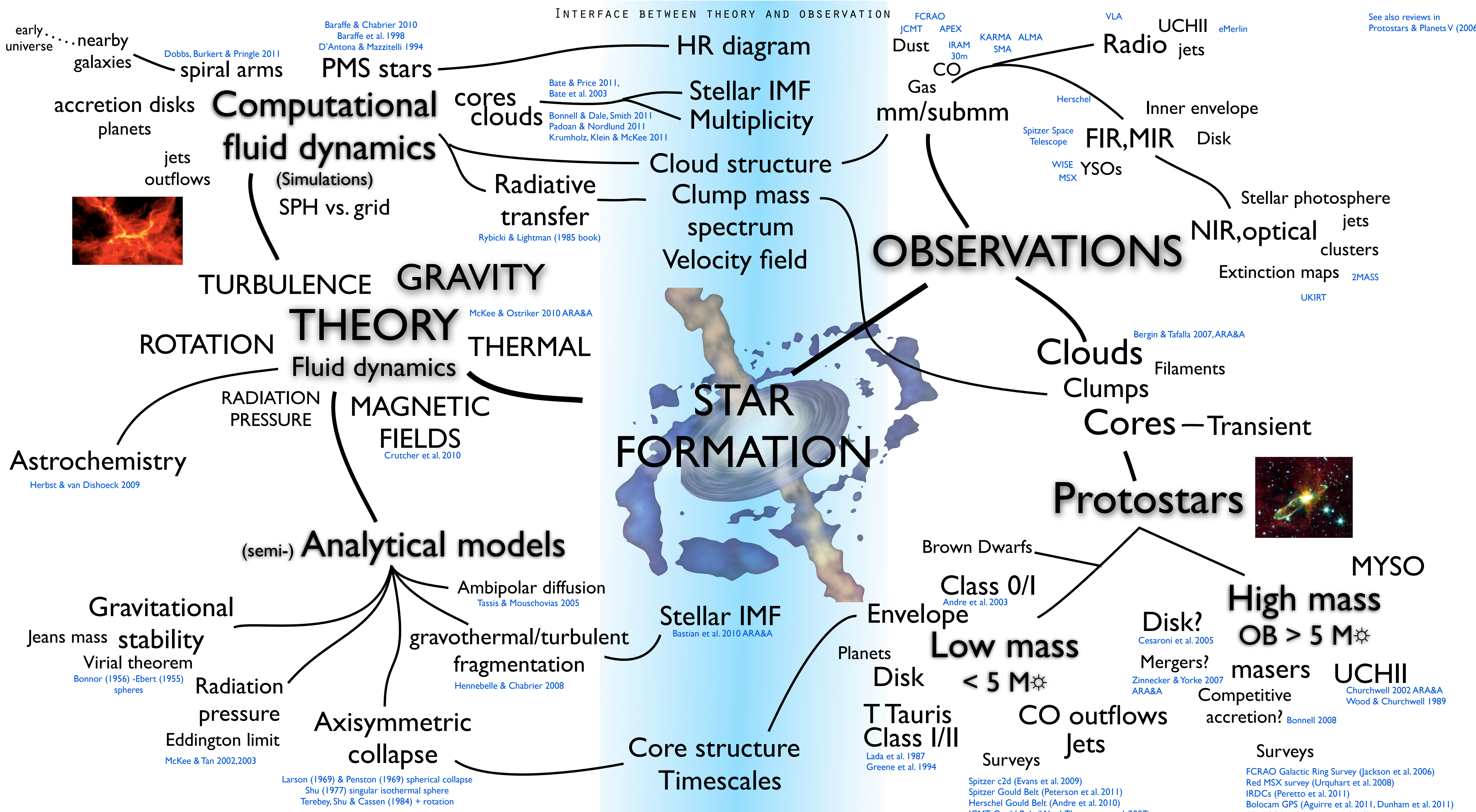

A Biased and Incomplete Overview of Star Formation. Dr Jennifer Hatchell, Aug 2011

Great star formation telescopes

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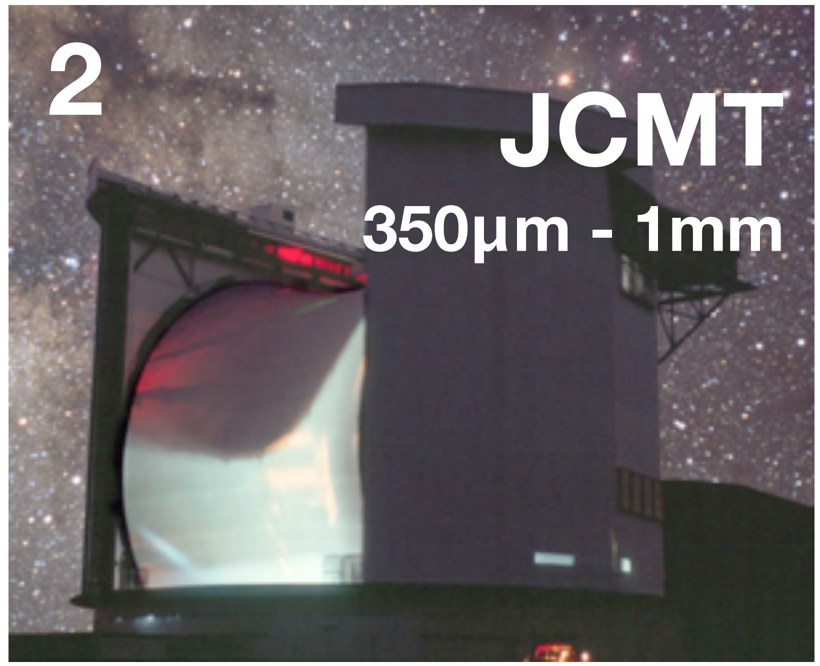

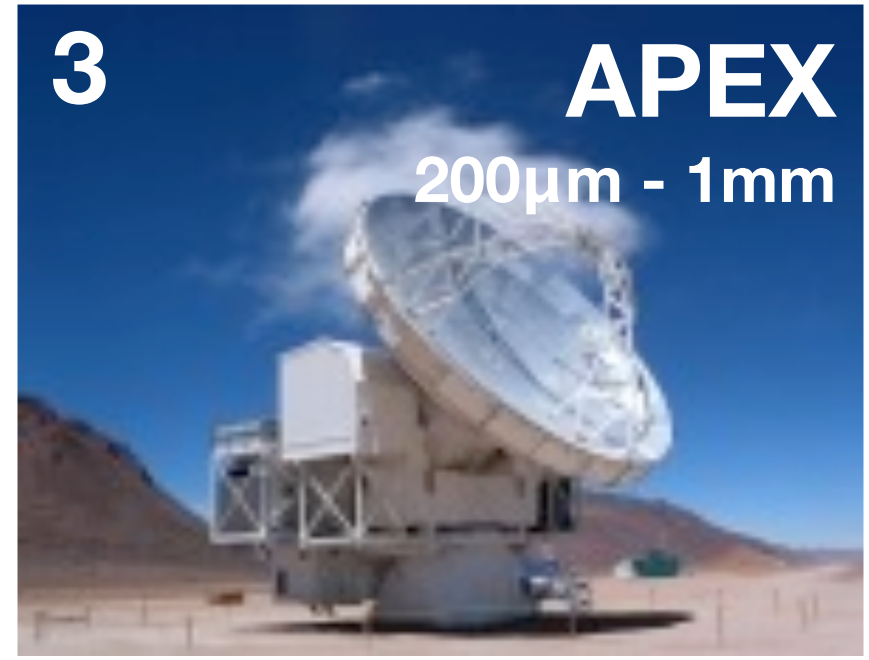

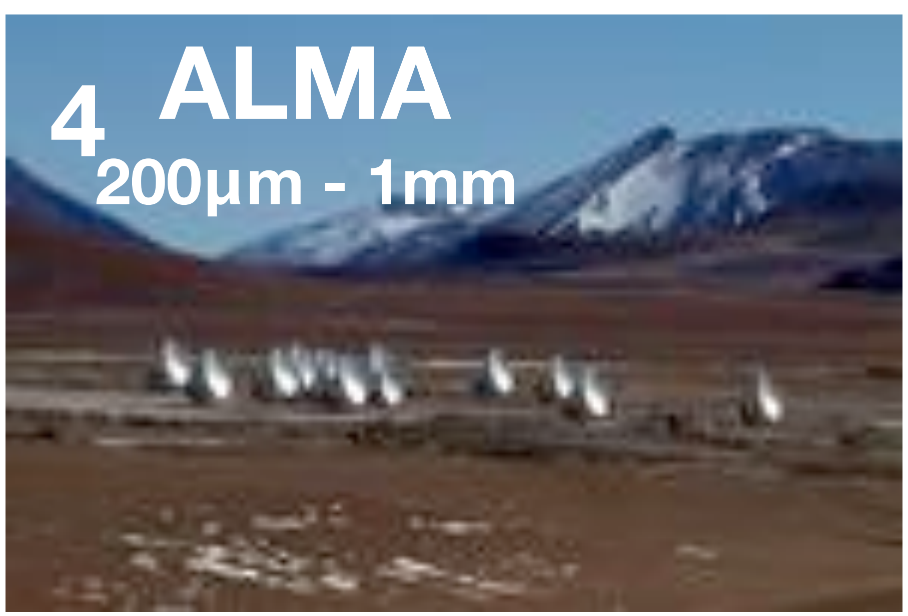

ANSWERS

- **James Clerk Maxwell Telescope** (JCMT, submm)
- **Atacama Large Millimetre Array** (ALMA, submm)
- **Herschel Space Telescope** (MIR/FIR)
- **Spitzer Space Telescope** (MIR)
- **Atacama Pathfinder Experiment** (APEX, submm)

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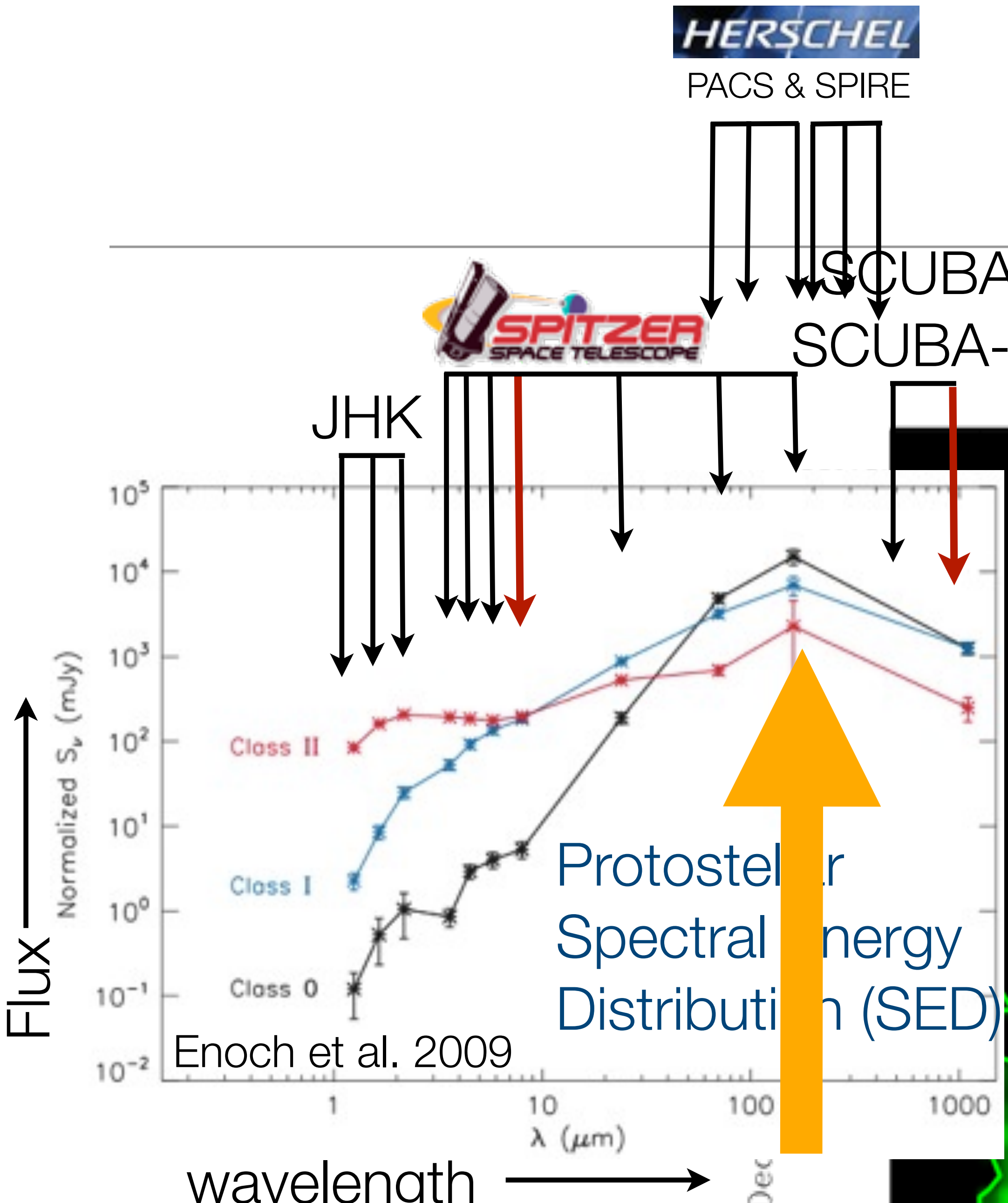
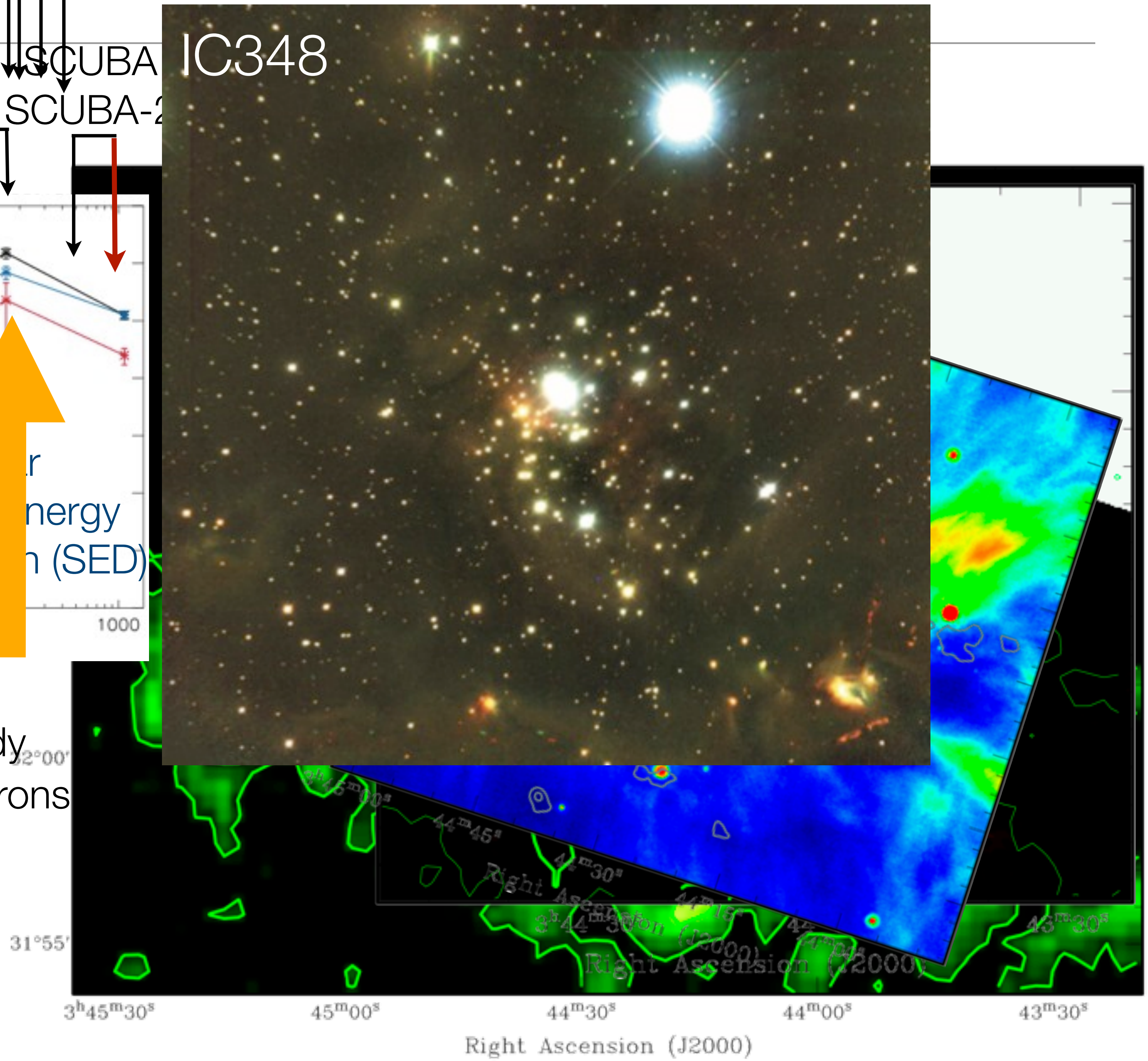


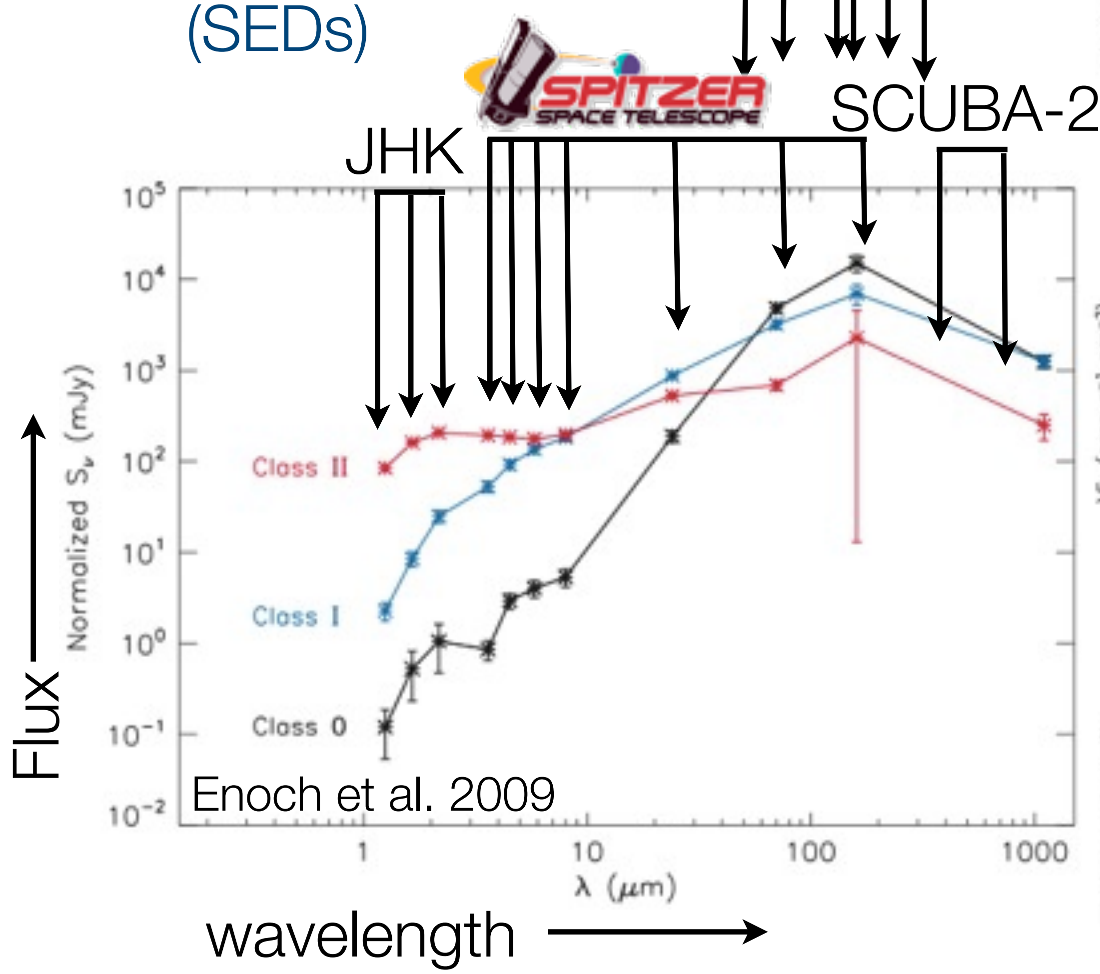


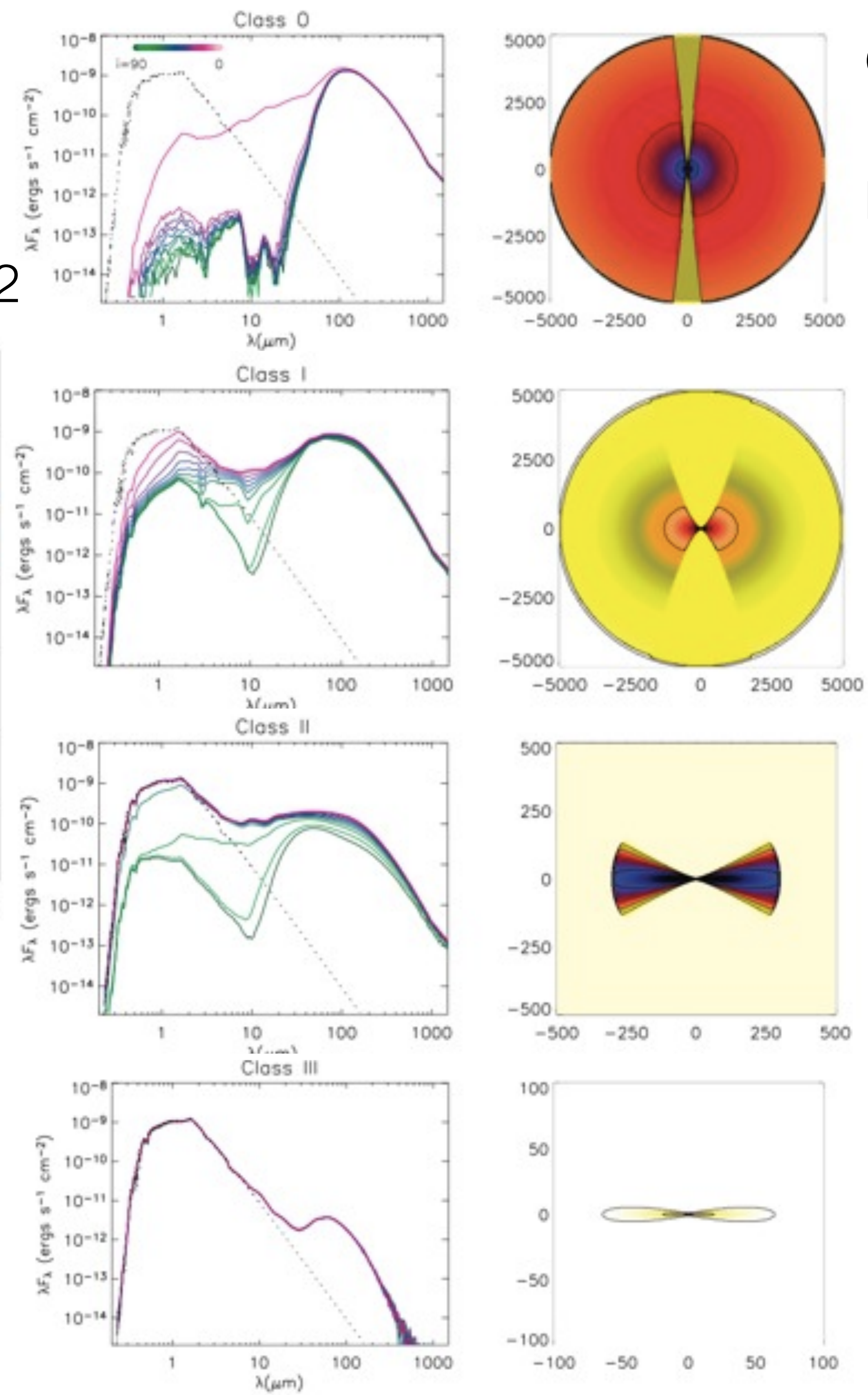
15K (-258°C) dust blackbody spectrum peaks at 200 microns

Wien's Law

$$\lambda_{\max} = \frac{289.8\mu\mathrm{m}}{(T/10\mathrm{K})}$$

Protostellar Spectral Energy Distributions (SEDs)





Class 0
Deeply embedded protostar

Class I
Embedded protostar

Class II
Classical T Tauri
2 Myr

Class III
Weak-line T Tauri

Terminology: Diskionary
Evans et al.
arXiv:0901.1691v1

Models: Whitney et al. 2003, Robitaille et al. 2006,2007, online SED fitter http://caravan.astro.wisc.edu/protostars/

http://www.astro.ex.ac.uk/people/hatchell/sfmap.pdf

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- IMF
979

10 ARA&A

ucture
cales

Clumps

Cores — Transient

Protostars

Brown Dwarfs

Class 0/I
Andre et al. 2003

Envelope

Planets

Low mass

Disk

< 5 M☼

T Tauris
Class II/III
Lada et al. 1987
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MYSO

High mass

OB > 5 M☼

Disk?
Cesaroni et al. 2005

Mergers?
Zinnecker & Yorke 2007 ARA&A

masers

UCHII
Churchwell 2002 ARA&A
Wood & Churchwell 1989

Competitive accretion? Bonnell 2008

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Bolocam GPS (Aguirre et al. 2011, Dunham et al. 2011)
ATLASGAL (Schuller et al. 2010)
Herschel Hi-GAL (Molinari et al. 2010)

Low mass star formation surveys - Spitzer

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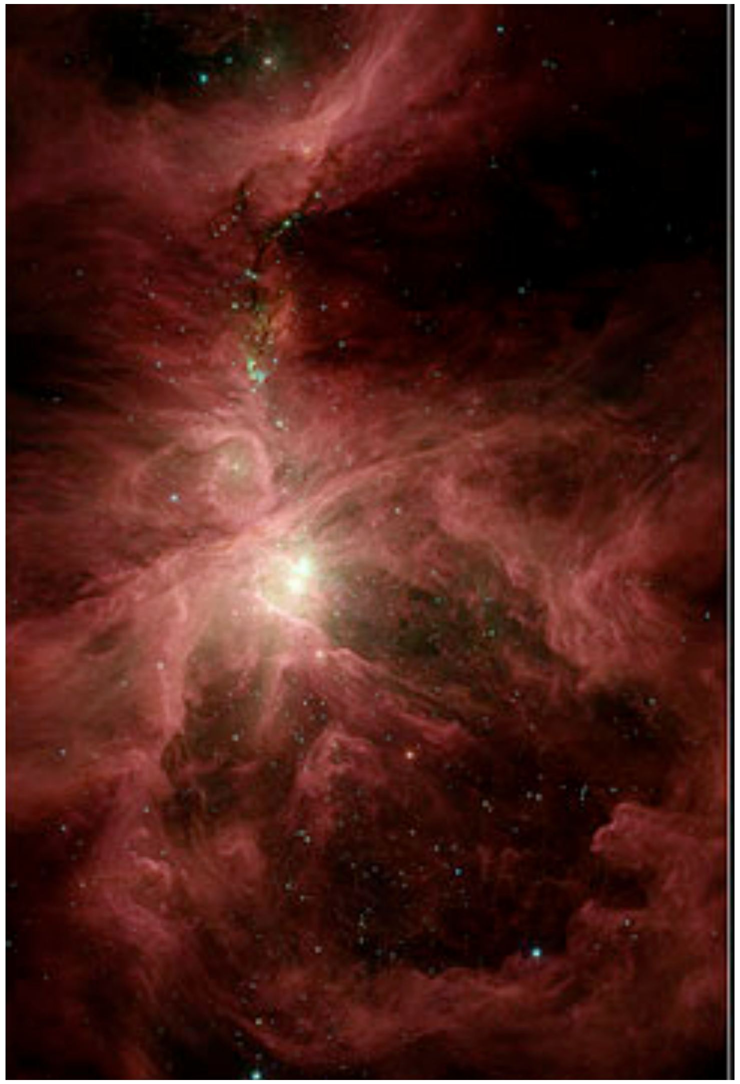
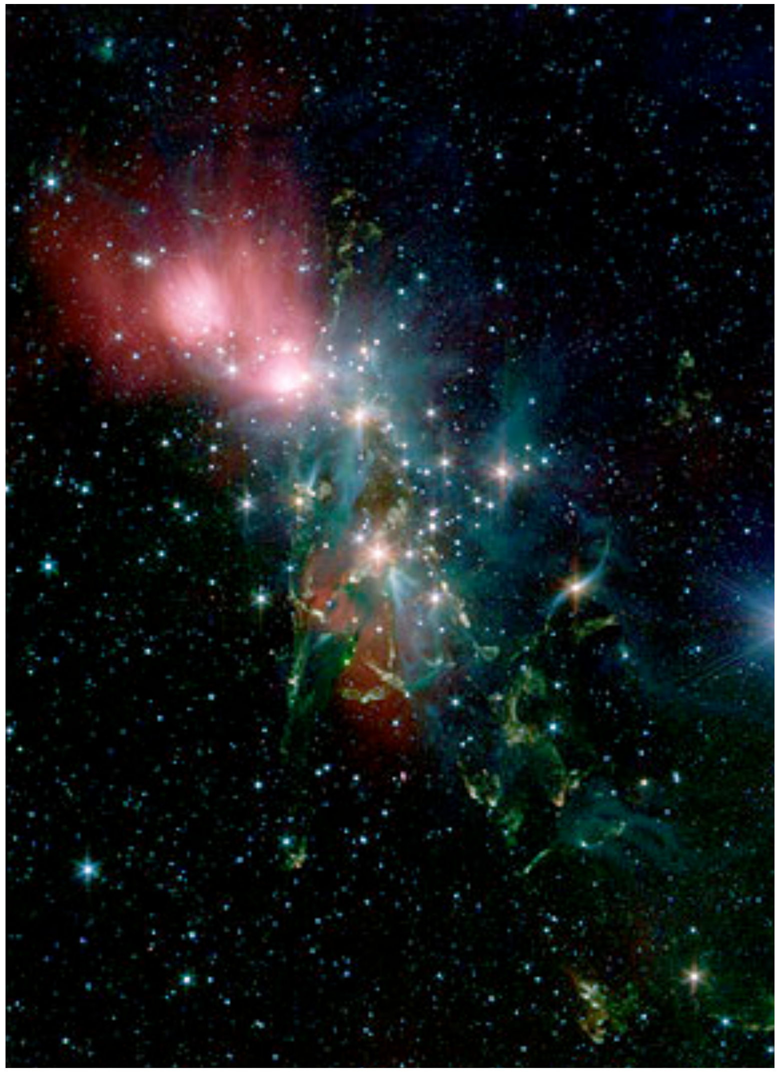


Orion NASA / JPL Caltech / S.T.Megeath (Toledo)

Serpens NASA / JPL Caltech / L. Allen (CfA)



Perseus NGC1333 NASA / JPL Caltech / R.Gutermuth (CfA)

Star formation rate per unit area

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Table 1
Measured Quantities for Clouds

Cloud	$N_{\mathrm{YSOs,tot}}$	$N_{\mathrm{YSOs,I}}$	$N_{\mathrm{YSOs,F}}$	Distance (pc)	Ω (deg^2)	A_{cloud} (pc^2)	$M_{\mathrm{gas,cloud}}$ ($M_\odot$)	$\Sigma_{\mathrm{gas,cloud}}$ ($M_\odot$ pc^{-2})	SFR ($M_\odot$ Myr^{-1})	Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Cha II	24	0	2	178 ± 18	1.03	9.91 ± 2.0	637 ± 300	64.3 ± 27	6.00 ± 3.2	0.605 ± 0.35
Lup I	13	2	1	150 ± 20	1.29	8.86 ± 2.4	513 ± 310	57.9 ± 31	3.25 ± 1.8	0.367 ± 0.22
Lup III	68	2	6	200 ± 20	1.27	15.4 ± 3.1	912 ± 520	59.2 ± 31	17.0 ± 9.2	1.10 ± 0.63
Lup IV	12	1	0	150 ± 20	0.368	2.52 ± 0.67	189 ± 95	75.0 ± 32	3.00 ± 1.6	1.19 ± 0.72
Oph	290	27	44	125 ± 25	6.21	29.6 ± 12	3120 ± 1800	105 ± 42	72.5 ± 39	2.45 ± 1.6
Per	385	76	35	250 ± 50	3.84	73.2 ± 29	6590 ± 3600	90.0 ± 33	96.2 ± 52	1.31 ± 0.88
Ser	224	31	21	260 ± 10	0.826	17.0 ± 1.3	2340 ± 640	138 ± 36	56.0 ± 30	3.29 ± 1.8
AurN	2	1	0	300 ± 30	0.088	2.41 ± 0.48	224 ± 52	92.9 ± 11	0.500 ± 0.27	0.207 ± 0.12
Aur	171	43	24	300 ± 30	1.82	50.0 ± 10.0	4620 ± 1100	92.4 ± 11	42.7 ± 23	0.854 ± 0.49
Cep	118	30	10	300 ± 30	1.39	38.0 ± 7.6	2610 ± 170	68.7 ± 17	29.5 ± 16	0.776 ± 0.45
Cha III	4	1	0	200 ± 20	2.30	28.0 ± 5.6	1330 ± 390	47.5 ± 10.	1.00 ± 0.54	0.0357 ± 0.021
Cha I	89	10	12	200 ± 20	0.772	9.41 ± 1.9	857 ± 210	91.1 ± 12	22.2 ± 12	2.36 ± 1.4
CrA	41	7	3	130 ± 25	0.588	3.03 ± 1.2	279 ± 110	92.1 ± 13	10.2 ± 5.5	3.37 ± 2.2
IC5146E	93	13	9	950 ± 80	0.223	61.4 ± 10.	3370 ± 870	54.9 ± 11	23.2 ± 13	0.378 ± 0.21
IC5146NW	38	16	3	950 ± 80	0.319	87.6 ± 15	5180 ± 1300	59.1 ± 10.	9.50 ± 5.1	0.108 ± 0.061
Lup VI	45	0	1	150 ± 20	0.983	6.74 ± 1.8	455 ± 140	67.5 ± 11	11.2 ± 6.1	1.66 ± 1.0
Lup V	43	0	0	150 ± 20	1.70	11.7 ± 3.1	705 ± 220	60.3 ± 10.	10.7 ± 5.8	0.915 ± 0.55
Mus	12	1	0	160 ± 20	0.875	6.82 ± 1.7	335 ± 110	49.1 ± 10.	3.00 ± 1.6	0.440 ± 0.26
Sco	10	2	1	130 ± 15	1.42	7.29 ± 1.7	621 ± 17	85.2 ± 23	2.50 ± 1.3	0.343 ± 0.20
Ser-Aqu	1440	146	96	260 ± 10	8.72	179 ± 14	24400 ± 3000	136 ± 13	360 ± 190	2.01 ± 1.1
Cloud Averages	156 ± 72	20.5 ± 7.9	13.4 ± 5.2	274.6 ± 53	1.8 ± 0.5	32.4 ± 9.6	2965 ± 1205	79.3 ± 5.8	39 ± 18	1.2 ± 0.2
Cloud Total	3122	409	268	...	36	648	59300	91.5	781	1.2
Data from Literature:										
Taurus[a]	148	...	...	137	44	252	27207	108	37	0.147

Notes. Columns are (1) cloud name; (2) total number of YSOs above $A_V = 2$; (3) number of Class I objects above $A_V = 2$; (4) number of Flat SED objects above $A_V = 2$; (5) distances to each cloud; (6) solid angle; (7) area (pc^2); (8) mass ($M_\odot$); (9) surface gas density ($M_\odot$ pc^{-2}); (10) star formation rate (SFR; $M_\odot$ Myr^{-1}); (11) SFR density ($M_\odot$ yr^{-1} kpc^{-2}).

[a] Total A_V mass from Pineda et al. (2010) and YSO data from Rebull et al. (2010).

Heidermann, Evans et al. 2010

Episodic accretion?

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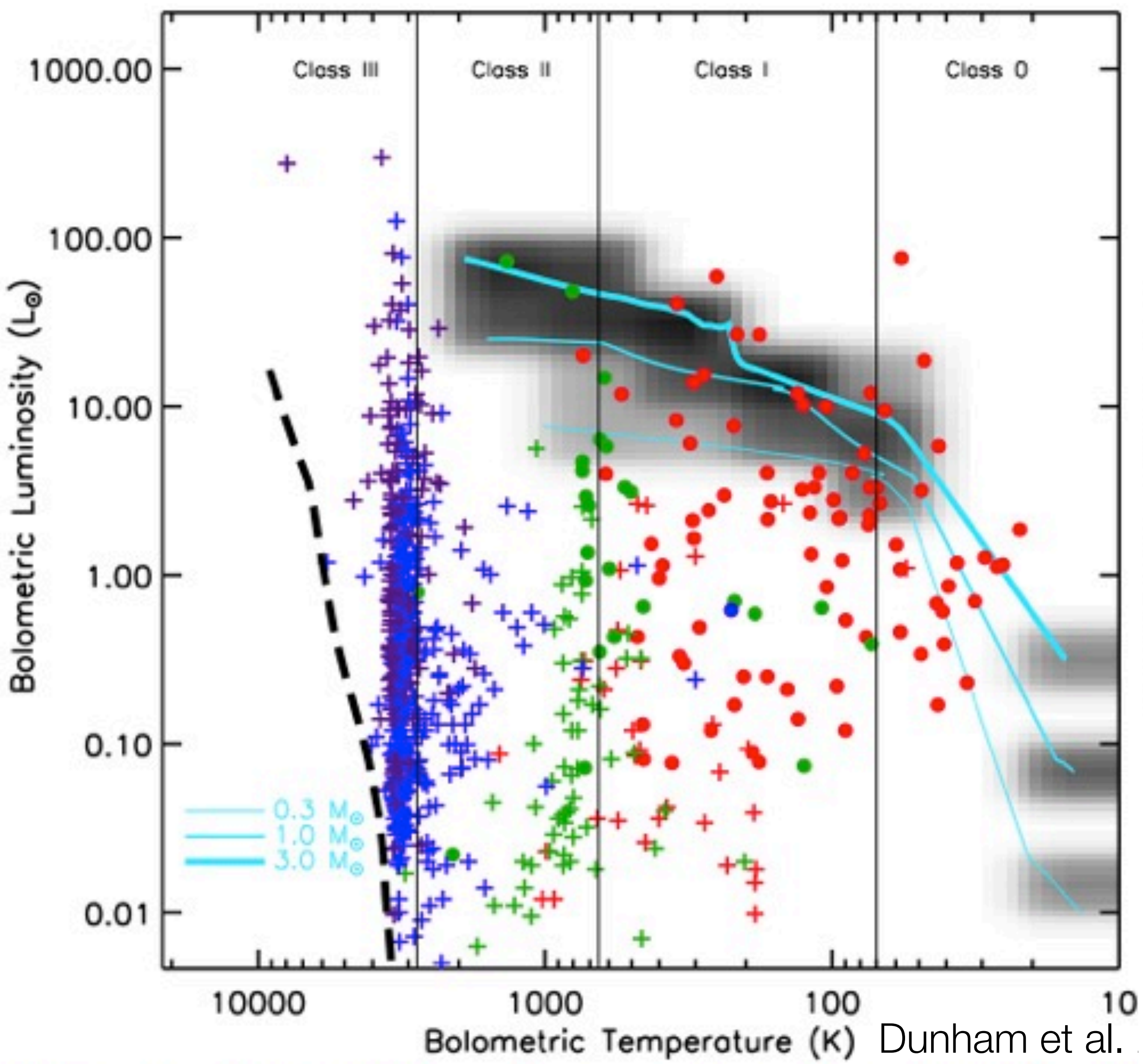
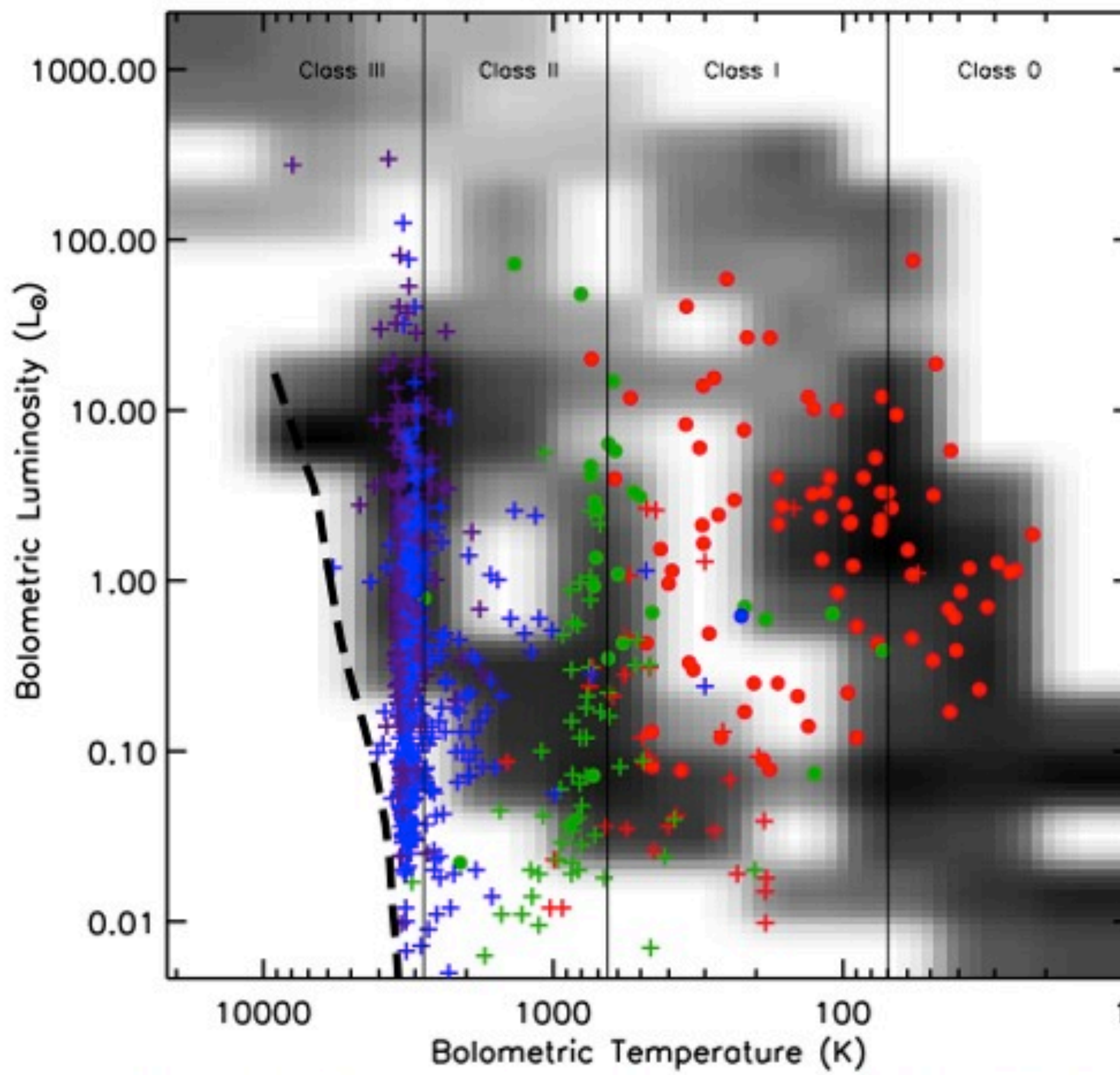


Constant accretion model



Dunham et al. 2010

Variable accretion model

Dunham et al. 2010

Herschel: Clouds - cores - (stars)

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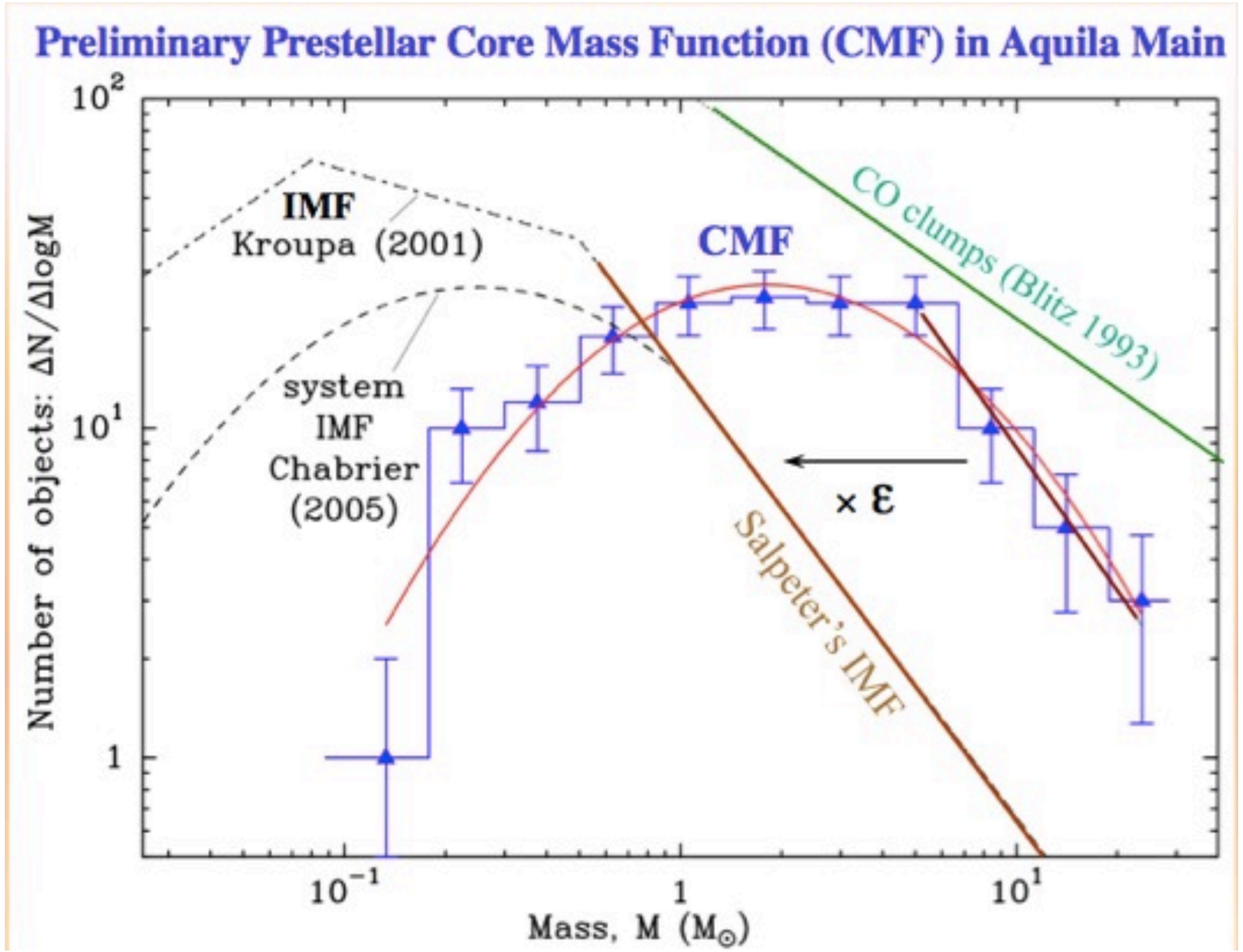
University of Exeter

Aquila Herschel GB / P. André



- Core Mass Function mirrors Initial Mass Function (but not in all clouds) André et al. 2010

Herschel filaments

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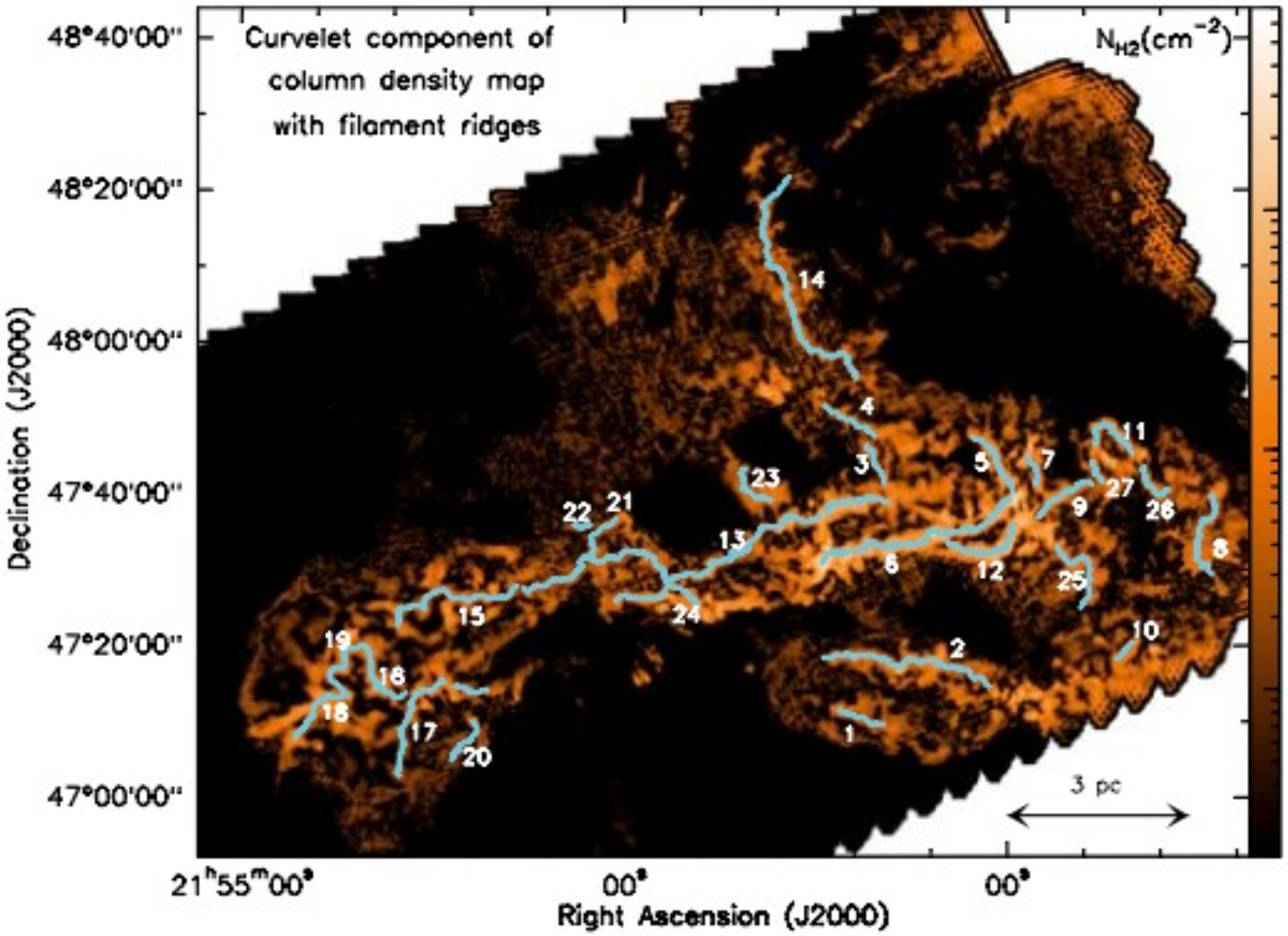
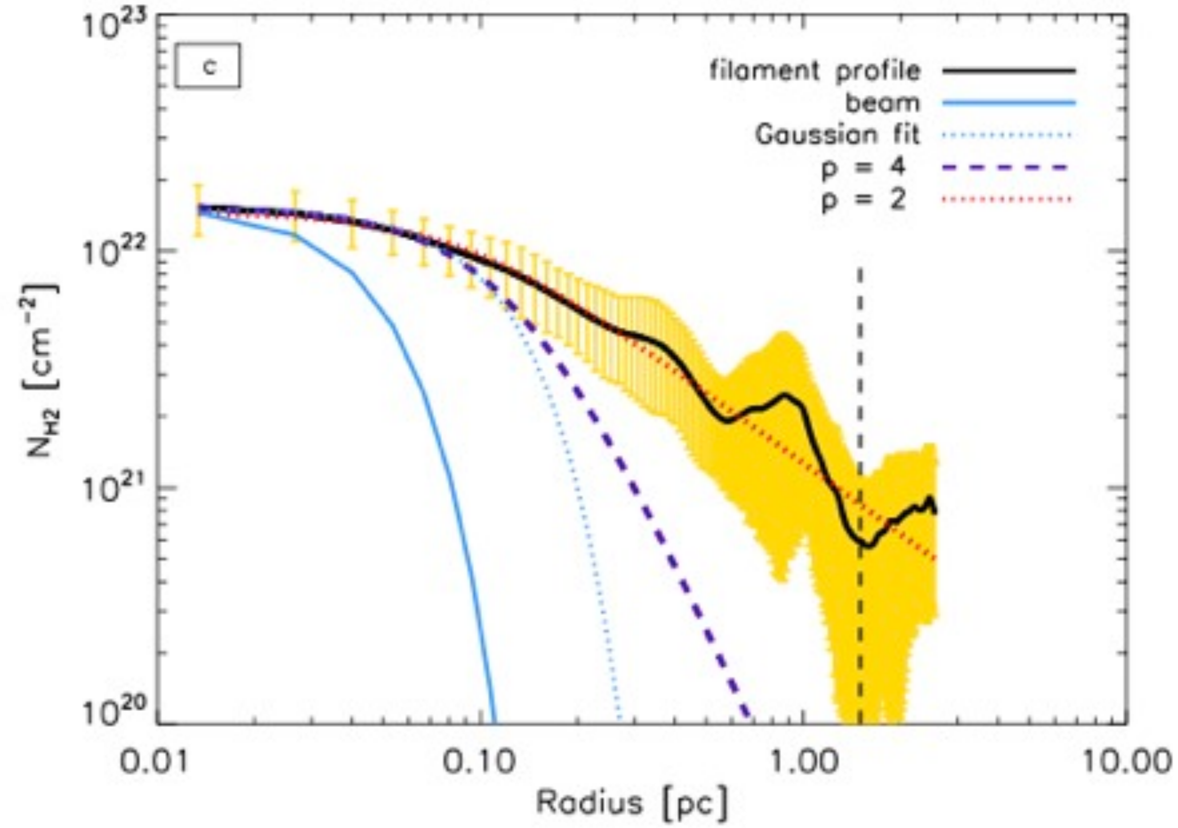
University of Exeter





Filament widths of ~0.1 pc suggest core formation through dissipation of large-scale turbulence

Arzoumanian, André et al. 2011

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Clumps

Cores — Transient

Protostars

Brown Dwarfs

Class 0/I
Andre et al. 2003

Envelope

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Herschel Hi-GAL (Molinari et al. 2010)

High mass star formation

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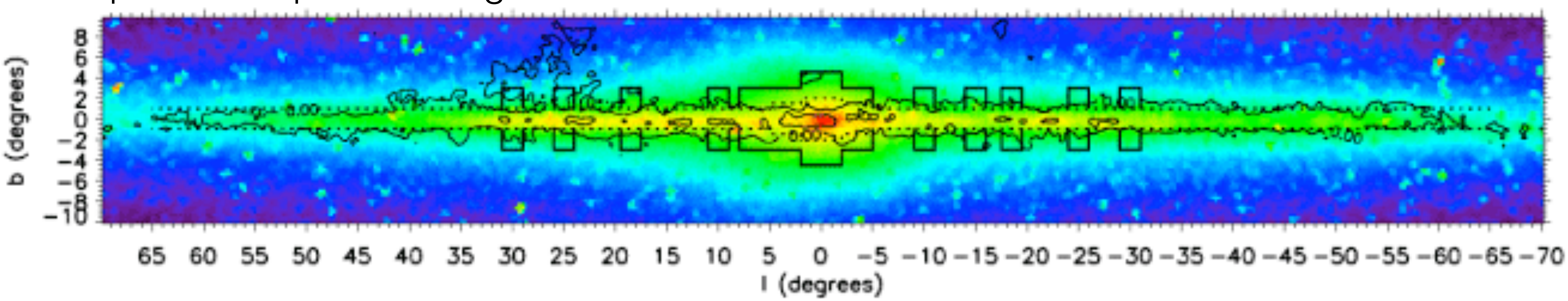
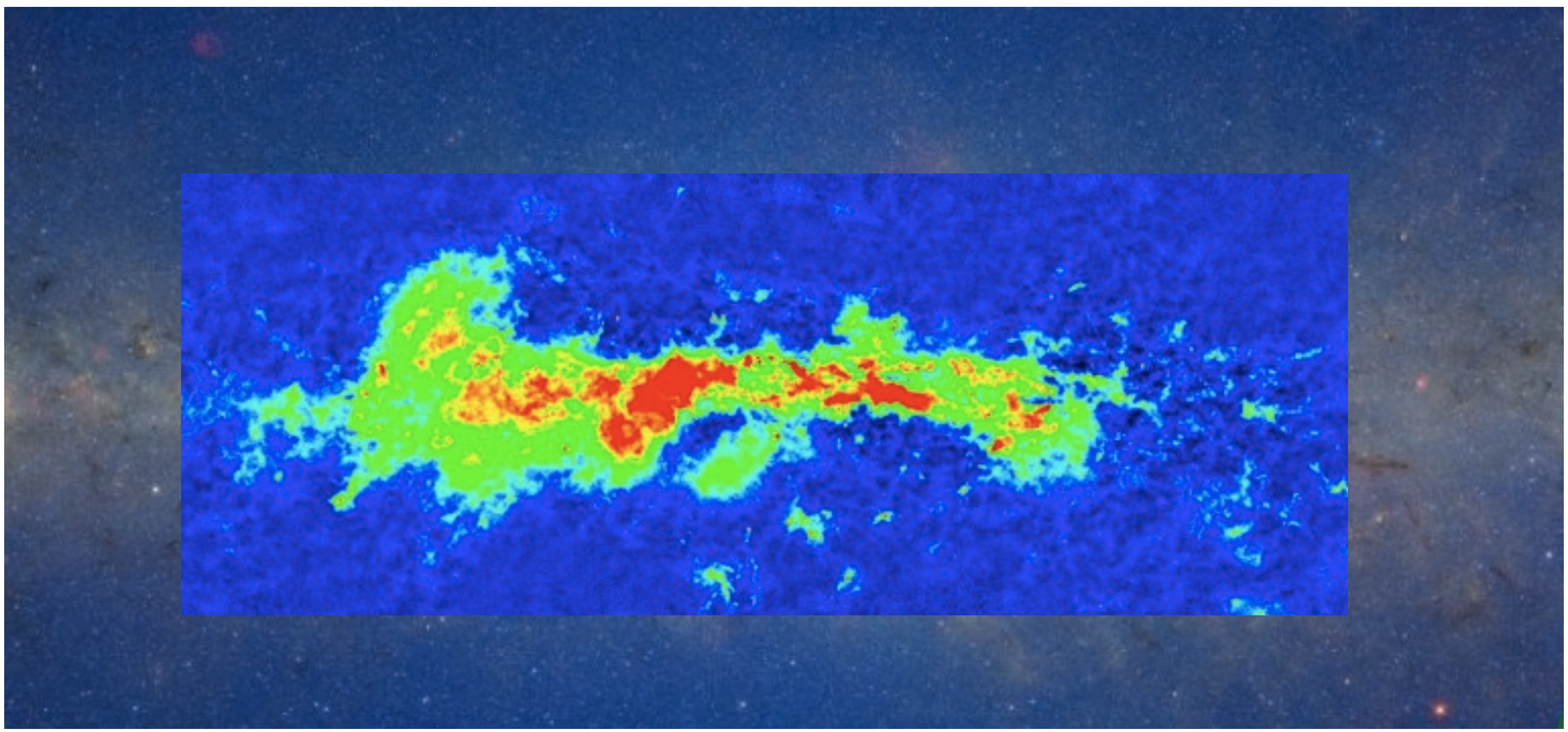
Spitzer Glimpse coverage



Spitzer GLIMPSE 3-24μm
http://www.alienearths.org/glimpse/

APEX ATLASGAL 850μm
http://www.mpifr-bonn.mpg.de/div/atlasgal/



http://www.alienearths.org/glimpse/glimpse.php

Infrared dark clouds

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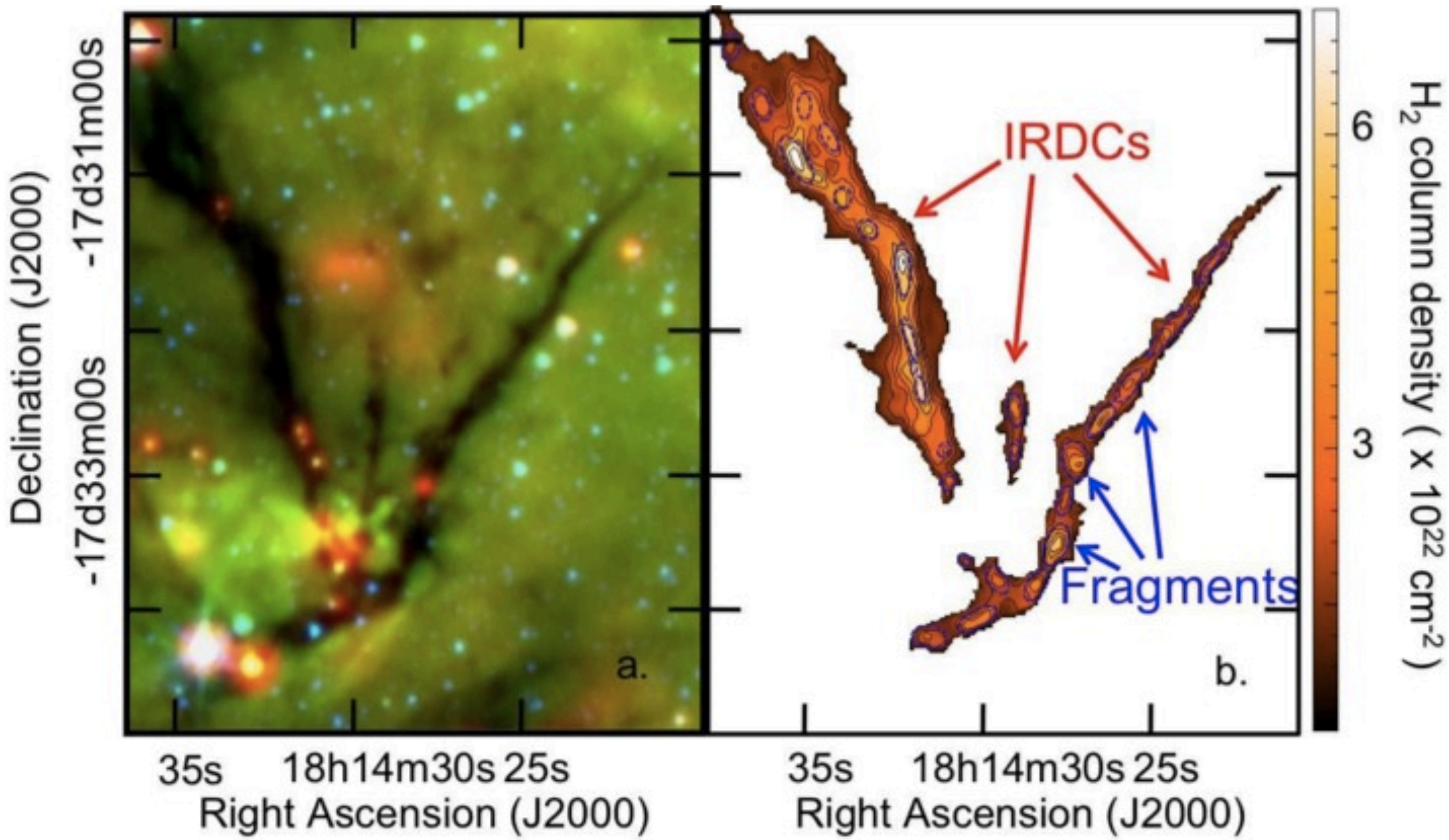
University of Exeter

Infrared Dark Clouds (Peretto et al. 2010) successors of Lynds Dark Clouds (Lynds 1962)



Hot topics 2011-21

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University of Exeter

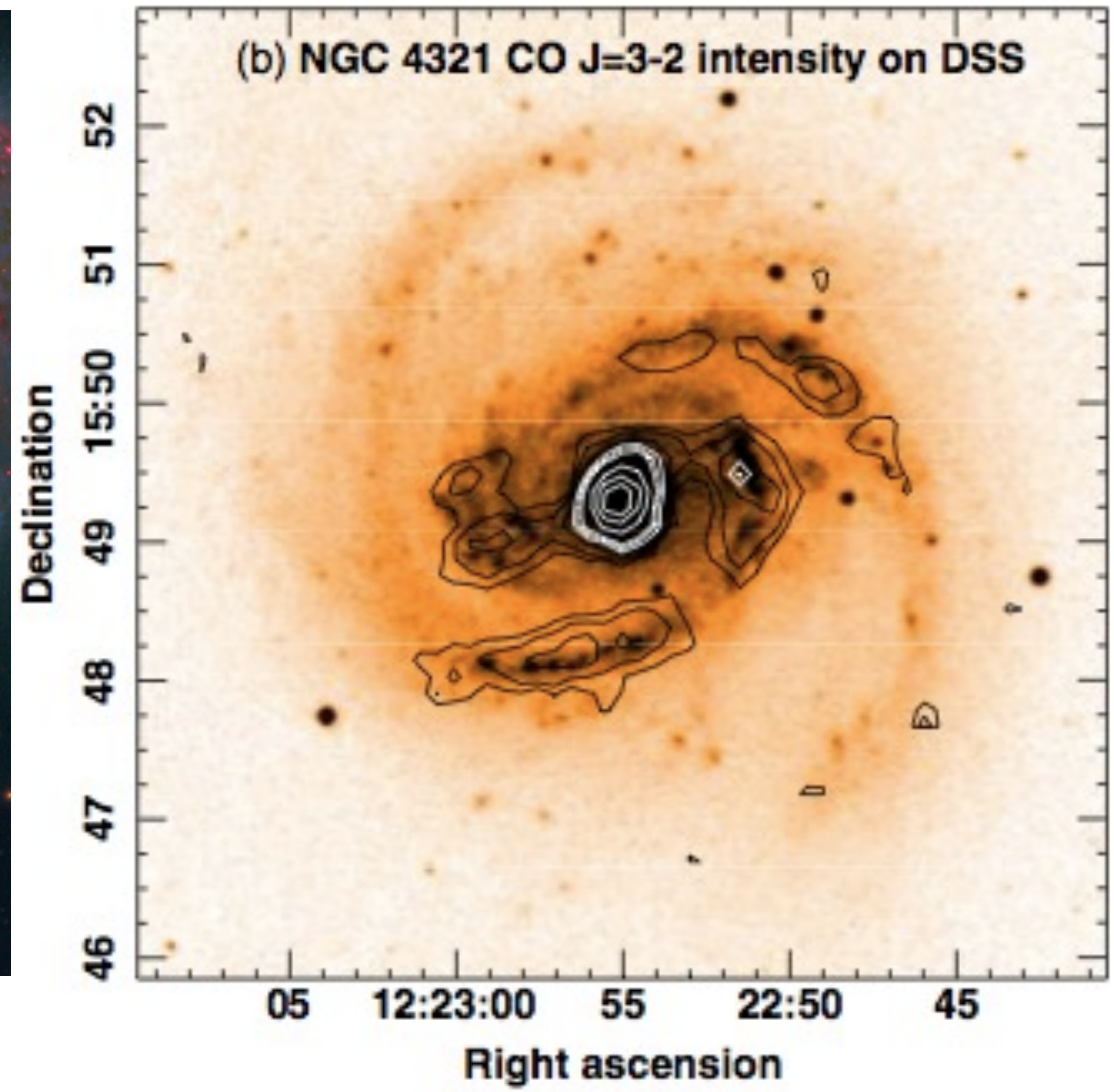
- Where do stars form and why?
  - turbulent cloud models and the star formation efficiency
  - Filament fragmentation and collapse
- Origin of the stellar initial mass function (IMF)?
  - Details of protostellar infall, accretion and ejection (jets/outflows)?
  - Formation / assembly of binaries and higher order systems?
- What is the role of feedback?
- Are magnetic fields ever important?
  - polarimetry for magnetic field geometries
- Is massive star formation a scaled-up version of low mass?
  - statistics on massive clusters

Stars form in molecular clouds

Dr Jennifer Hatchell

University of Exeter

M51 Credit: S. Beckwith (STScI), Hubble Heritage Team, (STScI/AURA), ESA, NASA, Additional Processing: Robert Gendler



Molecular gas in NGC 4321

Wilson et al. 2009 ApJ 693 1736