Molecular Cloud Cores

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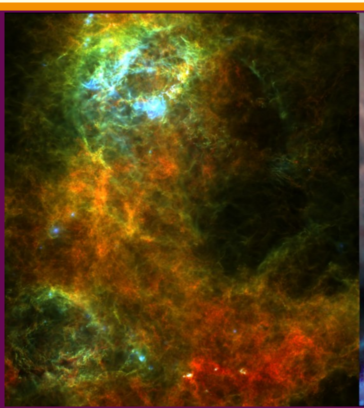
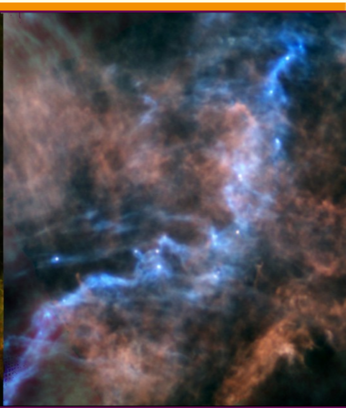

Contents

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- How do cores grow?
- How do cores fragment and contract?
- Connections
  - Larger scales → filaments
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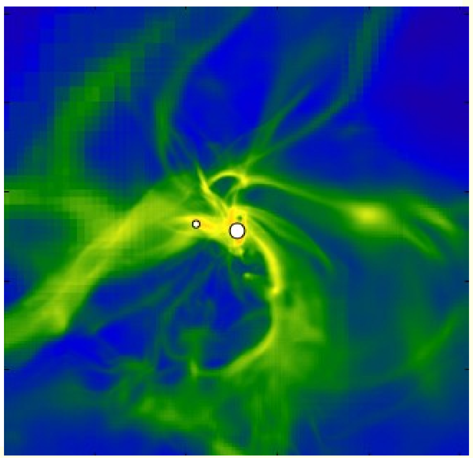
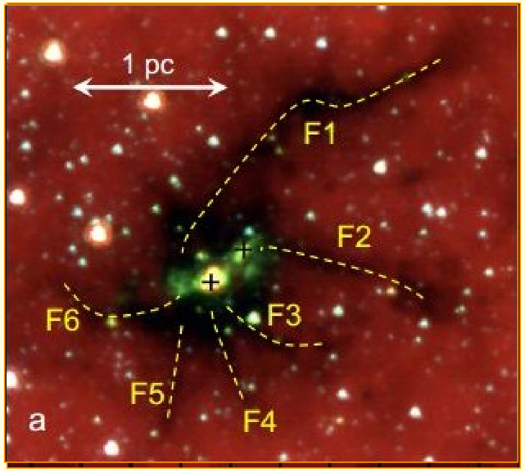
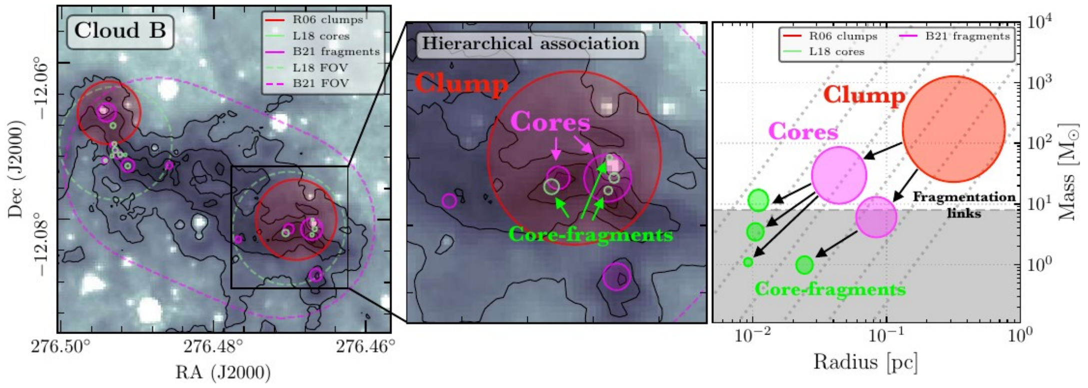




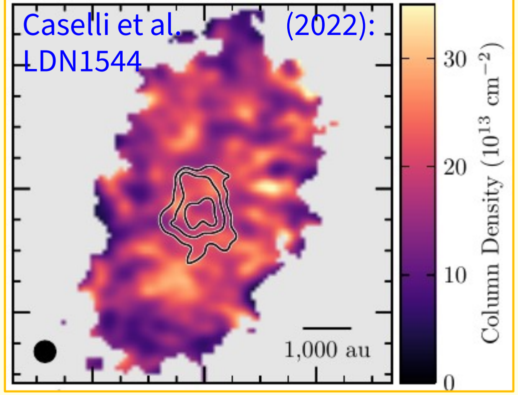
What is a core

- **Physical**: dense gas, (almost) gravitationally bound; roundish, static or dynamic; collapsing or accreting… or not, something of the order of ~0.1 pc in size
  - smaller than *clumps* but larger than *substructures* (*kernels*, *condensations*, *fragments*)
- **Technical**: clumpfind, gaussclumps, fellwalker, getsources, CSAR, CuTEx, dendrograms

Bergin & Tafalla (2007)	Cores[c]
Mass ($M_\odot$)	0.5–5
Size (pc)	0.03–0.2
Mean density (cm^{-3})	10^4–10^5
Velocity extent (km s^{-1})	0.1–0.3
Crossing time (Myr)	0.5–1
Gas temperature (K)	8–12
Examples	L1544, L1498, B68

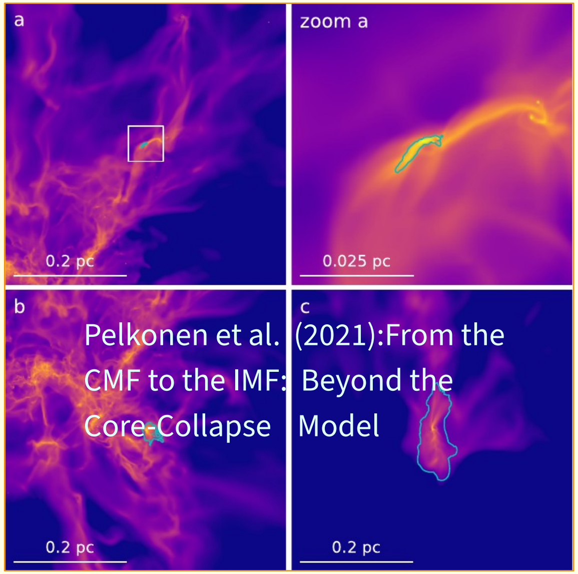


Barnes et al. (2021): *ALMA-IRDC: Dense gas mass distribution from cloud to core scales*

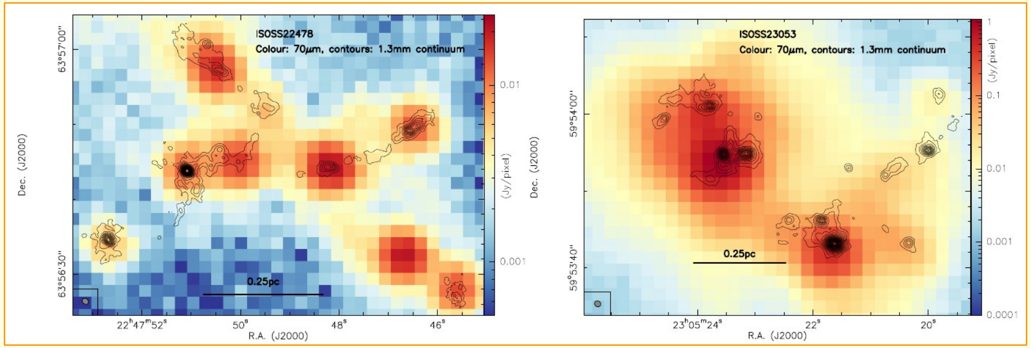


Caselli et al. (2022): LDN1544

- cores are physical objects residing between clumps (~ 1 pc) and substructures (~0.01 pc), at densities $10^4 - 10^5$ cm^{-3}
- or just leaves of the dendrogram
  - dependent on the target selection, detection method, thresholds, noise, tracer, distance and angular resolution, velocity resolution, LOS confusion
    - Betti+ (2021), Lu Z.+ (2022a)
- all potentially changing between regions, between different evolutionary stages

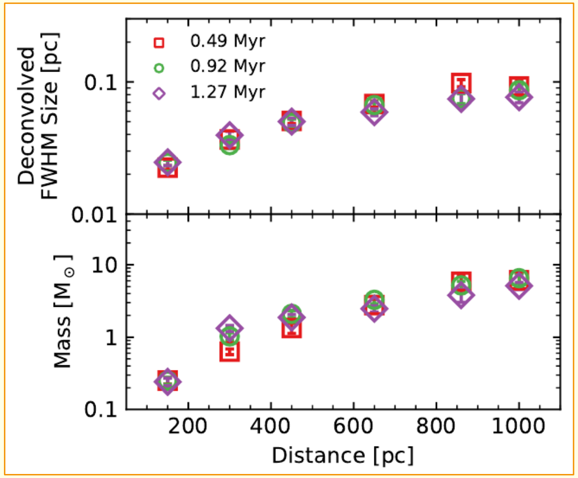


Pelkonen et al. (2021):From the CMF to the IMF: Beyond the Core-Collapse Model



Betti et al. (2021): *Robustness of Synthetic Observations in Producing Observed Core Properties: Predictions for the TolTEC Clouds to Cores Legacy Survey*

Beuther et al. (2021): *Fragmentation and kinematics in high-mass star formation CORE-extension...*



- cores in relation to **star formation**
  - **starless cores**
  - **prestellar cores**
    - virial **mass** (*50*)

$$M_{\rm vir} = \frac{5-2n}{3-n}\frac{R\sigma_{3D}^2}{G}, \qquad \rho(r) \propto r^{-n}$$

$$M_{\rm vir} = 210\left(\frac{r}{\rm pc}\right)\left(\frac{\Delta v}{\rm km\ s^{-1}}\right)^2 M_\odot$$

or Bonnor-Ebert **mass** (*42*)

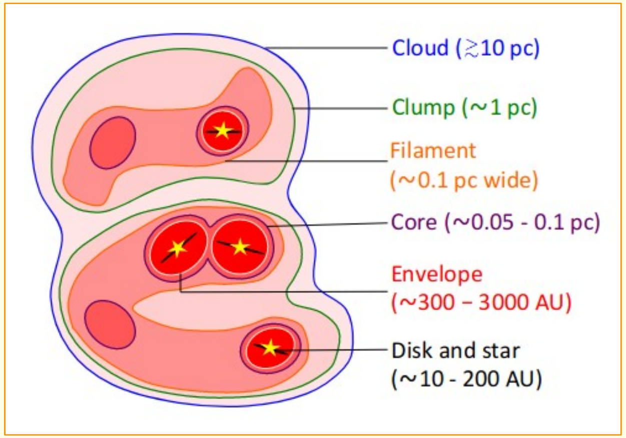
$$M_{\rm BE} \approx 1.182\frac{\sigma^4}{\sqrt{G^3 P}} = 1.182\frac{\sigma^3}{\sqrt{G^3\rho}} \qquad M_{\rm BE,crit} \approx 2.4 R_{\rm BE} c_S^2 / G$$

$$M_{\rm BE} \approx 0.66\left(\frac{T\,[K]}{10}\right)^2\left(\frac{P\,[{\rm K\,cm^{-3}}]}{3\cdot 10^5\,k_B}\right)^{-\frac{1}{2}}$$

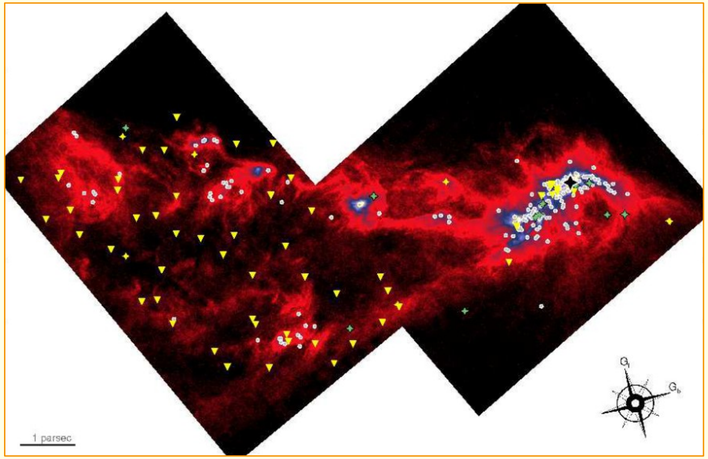
vs real **mass**

$$M_{\rm obs} = \frac{Fd^2}{\kappa B_\nu(T_d)} \qquad \text{(OH94: } 57\text{)}$$

    - external **pressure**?
    - **velocity**
      - blue asymmetry, continuum absorption, inflow, infall, accretion

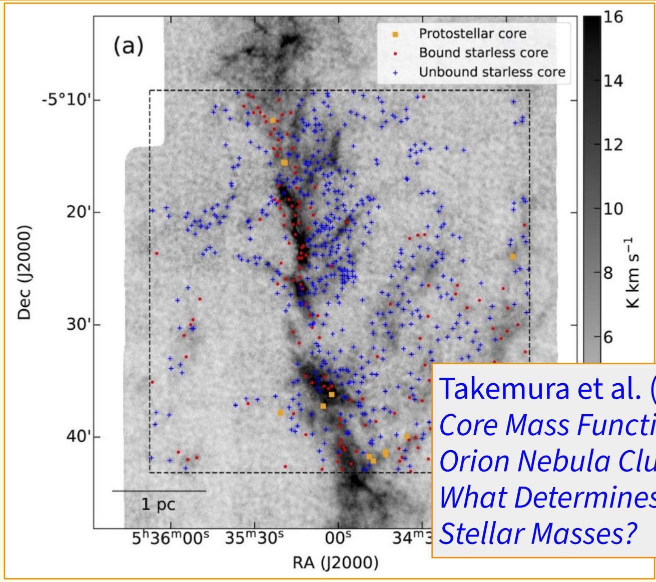


Pokhrel et al. (2018): *Hierarchical fragmentation in the Perseus Molecular Cloud*

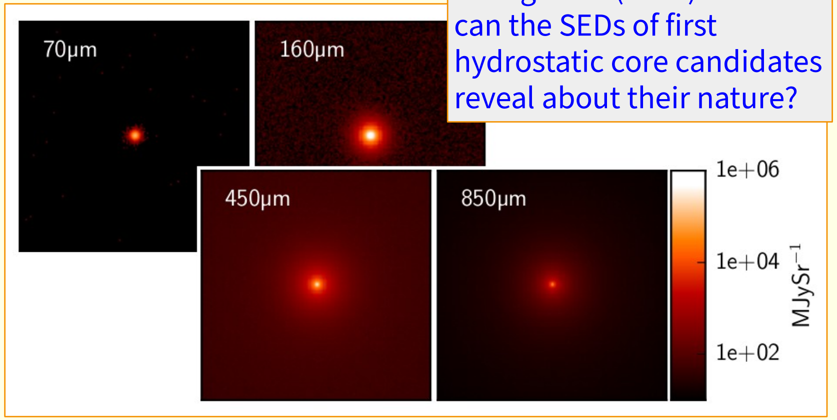


Bresnahan et al. (2018): *Dense cores and filaments in CrA*

- **protostellar cores**
  - infrared (NIR, MIR, 70µm) sources: sensitivity, resolution, extinction (colours), chance alignments
  - outflows, masers, variability, kinematics, X-ray, etc.
- **special-interest cores**
  - first hydrostatic core (FHSC)
    - a few au in size, < 0.1 $M_\odot$, with slow <2 km s^{-1} outflows
    - FHSC lifetime ~10^4, a few years for FHSC candidates
    - B1-bN, Aqu-MM1, Serp K242, SerpS-MM22, Per-Bolo 58, Cham-MMS1 (Young+2018), HOPS 404 (Karnath+2020), MC35 (Tokuda+2020), CB17-MMS (Spear+2021)
  - massive pre-stellar cores
    - ~10 000 au, >> 10 $M_\odot$ (Tan 2018), <3×10^4 yr (Motte 2017)
    - CygX-N40 (Motte+2007), CygXN53-MM2 (Duarte-Cabral+2013), W43-N* (Louvet+2016); Svoboda+2016, Tigé+2017, TUKH122 (Ohashi+2018), C1-S (Kong+2017)



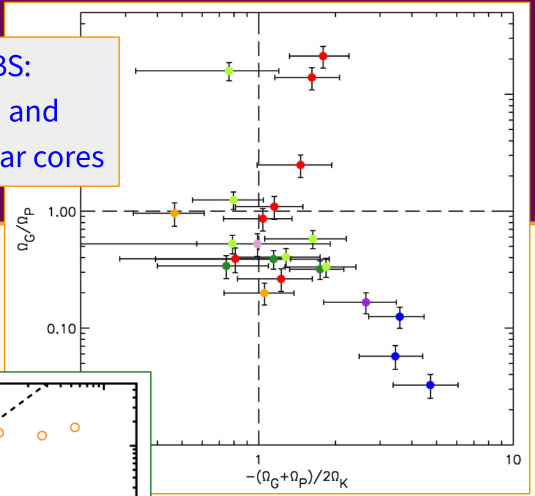
Takemura et al. (2021): *The Core Mass Function in the Orion Nebula Cluster Region: What Determines the Final Stellar Masses?*



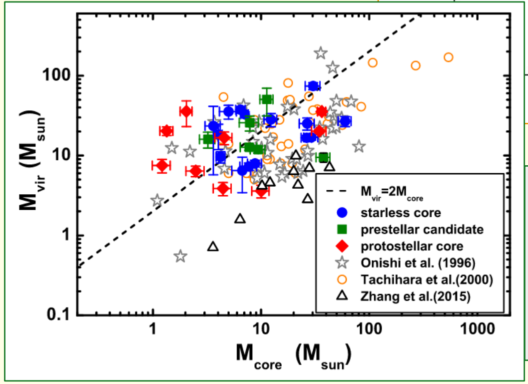
Young et al. (2018): What can the SEDs of first hydrostatic core candidates reveal about their nature?

Stability of cores

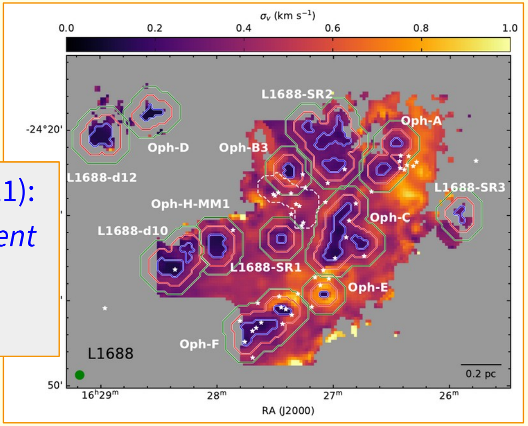
- straightforward: estimate $\alpha = \frac{5\sigma^2 R}{GM} < 2$ or measure and compare some of $E_G, E_T, E_{NT}, E_B, E_R, E_{CR}$ ...
  - Pattle+ (2015), Kirk+ (2017), Lu Z.+ (2022b)
- turbulence...
  - turbulence, if and where (core vs. envelope)
  - transition to **coherence** (Pineda+ 2010; Chen+ 2019; Choudhury+ 2021): ~0.1-0.2 pc
- magnetic fields...
  - DSF, ADF, SF, VGT, HRO, RAT, IGT, GK, Zeeman, **morphology**



Pattle et al. (2015): JCMT-GBS: Ophiuchus molecular cloud and virial analysis of its prestellar cores

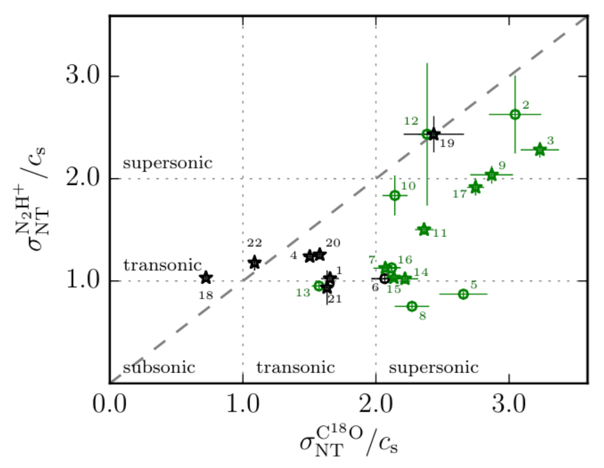


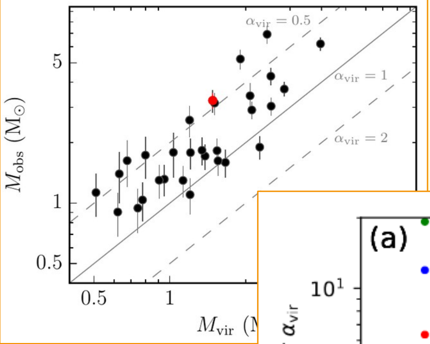
Tang et al. (2018): Properties of Planck Galactic cold clumps in the L1495 dark cloud



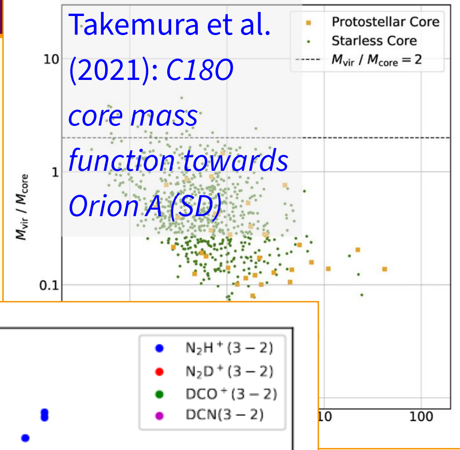
Choudhury et al. (2021): *Transition from coherent cores to surrounding cloud in L1688*

Chung et al. (2021): *TRAO Survey of Nearby Filamentary Molecular Clouds, Universal Nursery of Stars (FUNS). II. Filaments and Dense Cores in IC 5146*

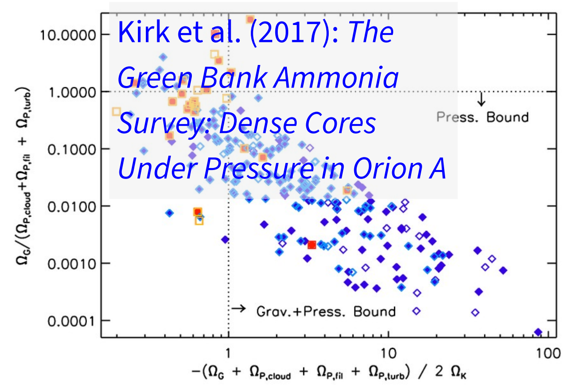


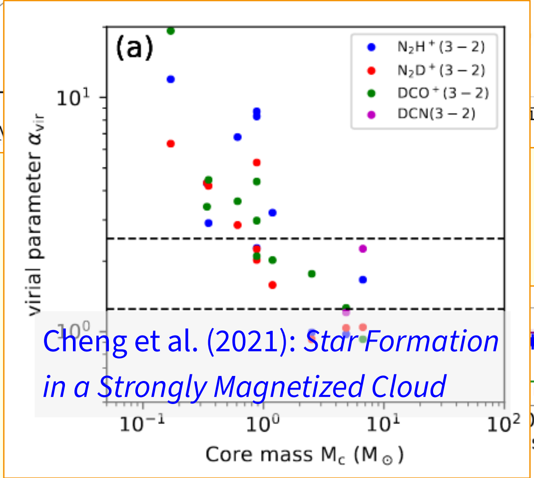


Takemura et al. (2021): *C18O core mass function towards Orion A (SD)*



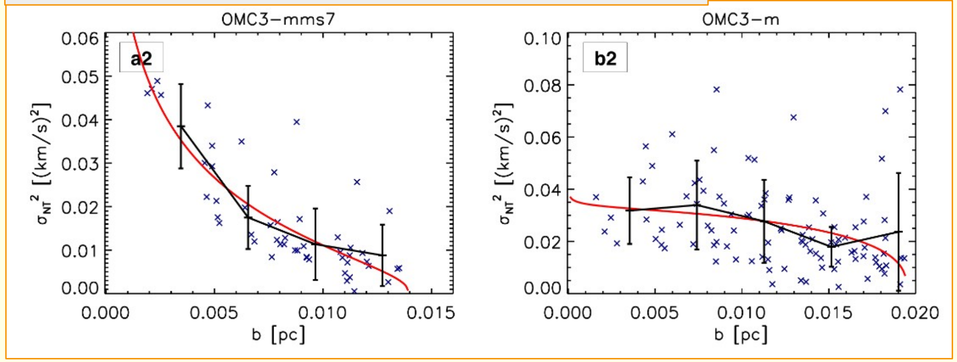
Kirk et al. (2017): *The Green Bank Ammonia Survey: Dense Cores Under Pressure in Orion A*

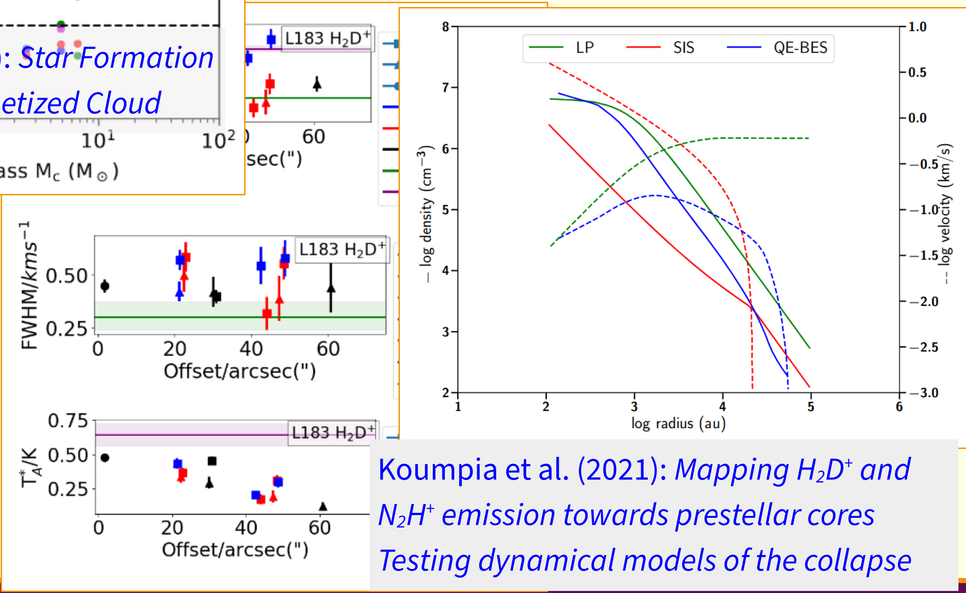




Cheng et al. (2021): *Star Formation in a Strongly Magnetized Cloud*

Yue et al. (2020): *Collapsing Index: A New Method to Identify Star-forming Cores Based on ALMA Images*



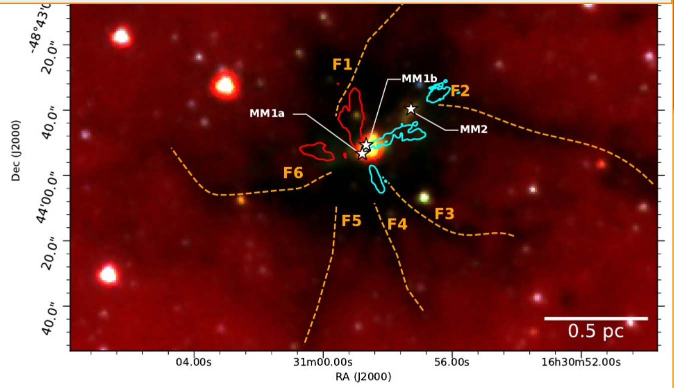


Koumpia et al. (2021): *Mapping H_2D^+ and N_2H^+ emission towards prestellar cores Testing dynamical models of the collapse*

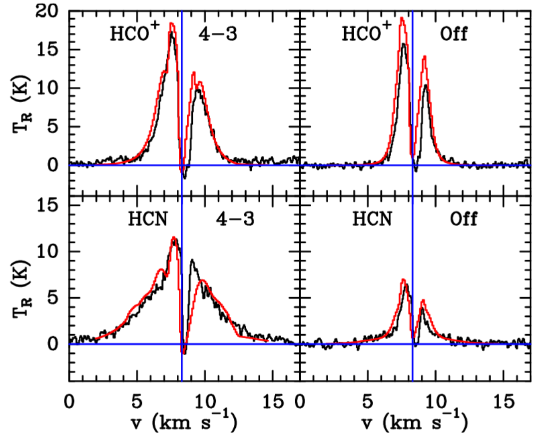
Growth of cores

- **accretion**: infall, inflow… via filaments, fibers, streamers, up to large hub-filament systems (10^{-7}-10^{-3} $M_\odot$ yr $^{-1}$)
  - Juaréz+ (2019), Izquierdo+ (2020), Avison+ (2021), etc.
- **collapse**: inverse P-Cygni, blue asymmetry, infall index, absorption against continuum, …
  - Yue et al. (2020), Liu S.-Y. (2021), Gomez+ (2021)

Avison et al. (2021): *Continuity of accretion from clumps to Class 0 high-mass protostars in SDC335*

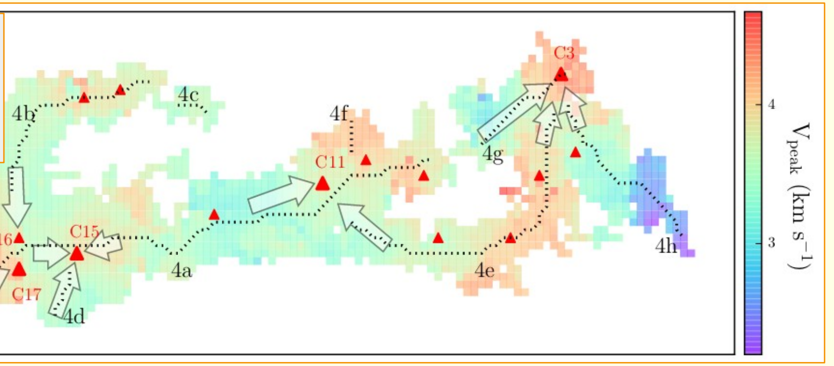


- Andrea Socci: Characterisation of filament hubs in Orion (P15)
- Molly Wells: Dynamical Accretion Flows (P19)
- Asmita Bhandare: Interplay of gas and dust dynamics during star and disc formation

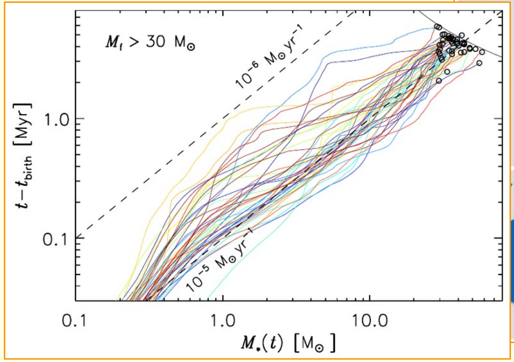


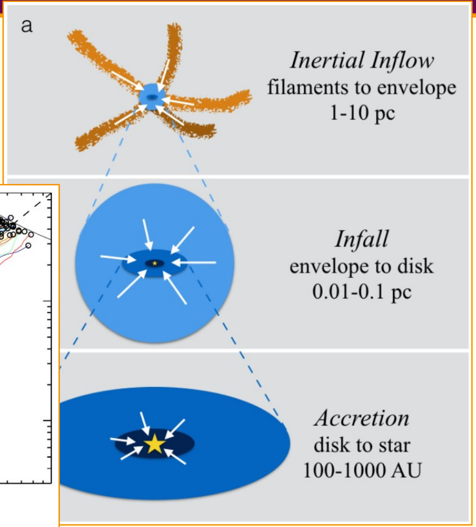
Evans et al. (2015): *Detection of infall in the protostar B335 with ALMA*

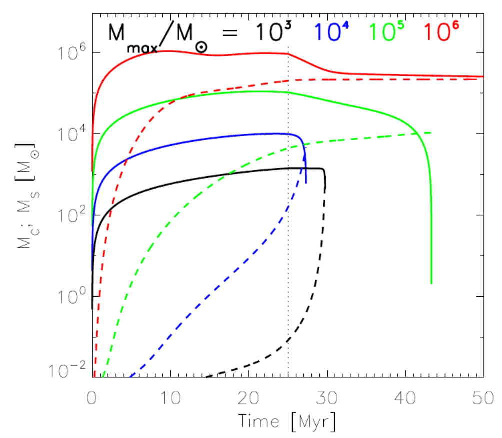
Chung et al. (2021): TRAO FUNS. II. Filaments and Dense Cores in IC 5146



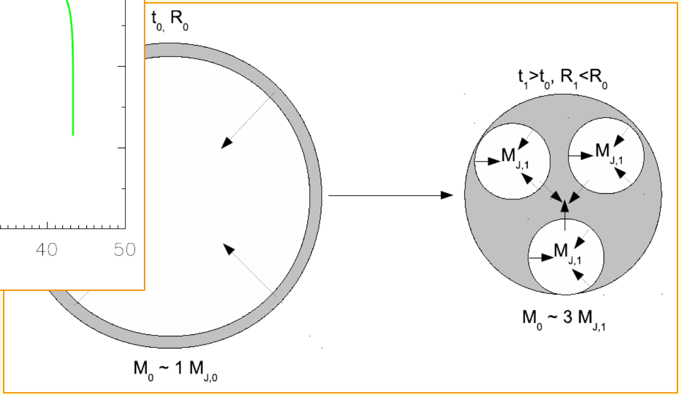
Inertial inflow
Padoan et al. (2020)
Pelkonen et al. (2021)

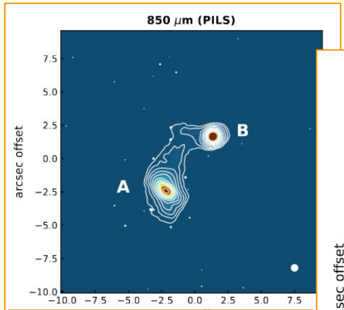




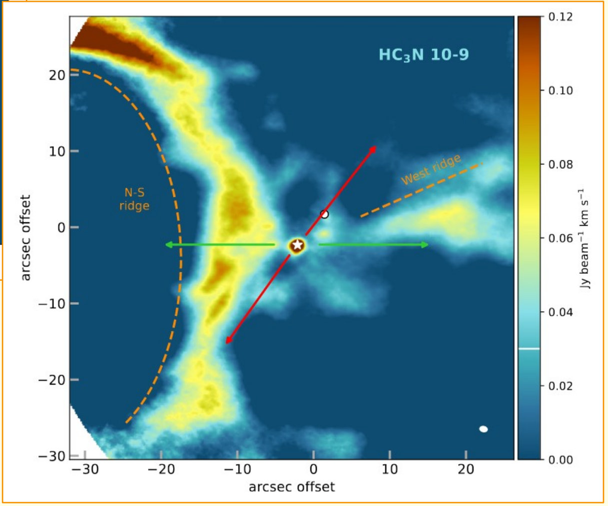


Global Hierarchical Collapse
Vázquez-Semadeni et al. (2019)

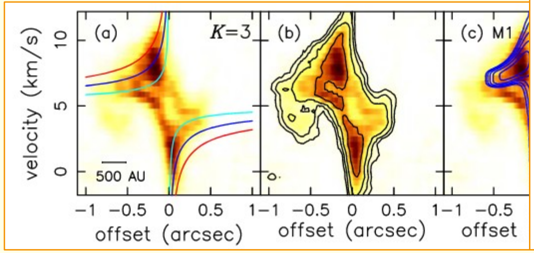


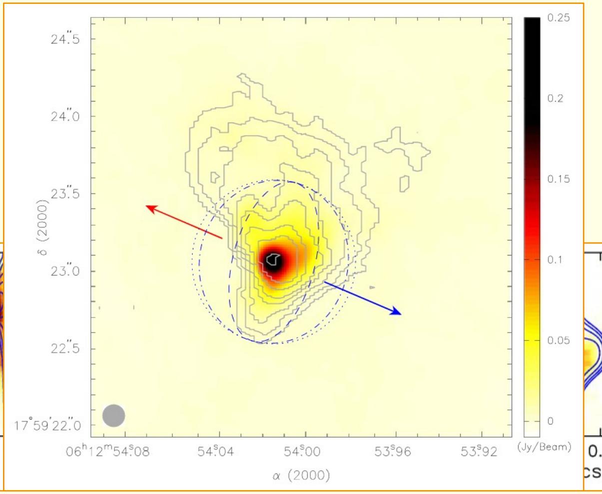


Murillo et al. (2022): *A cold accretion flow onto one component of a multiple protostellar system*



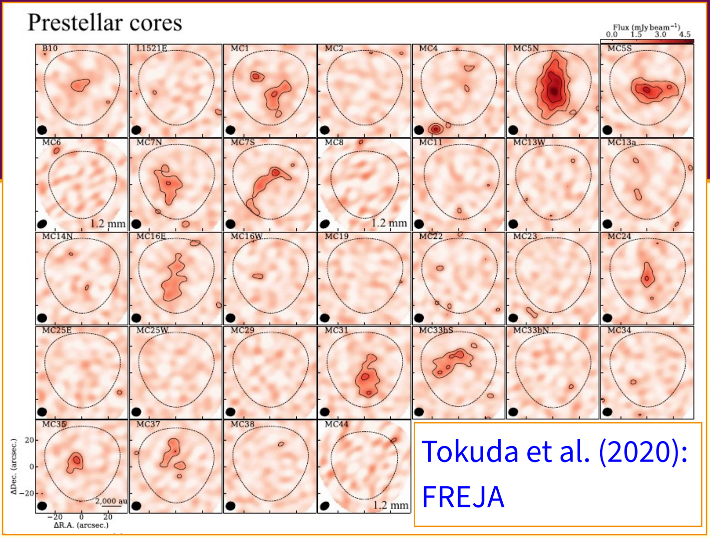
Liu, S.-Y. (2020): *ALMA View of the Infalling Envelope around a Massive Protostar in S255IR SMA1*

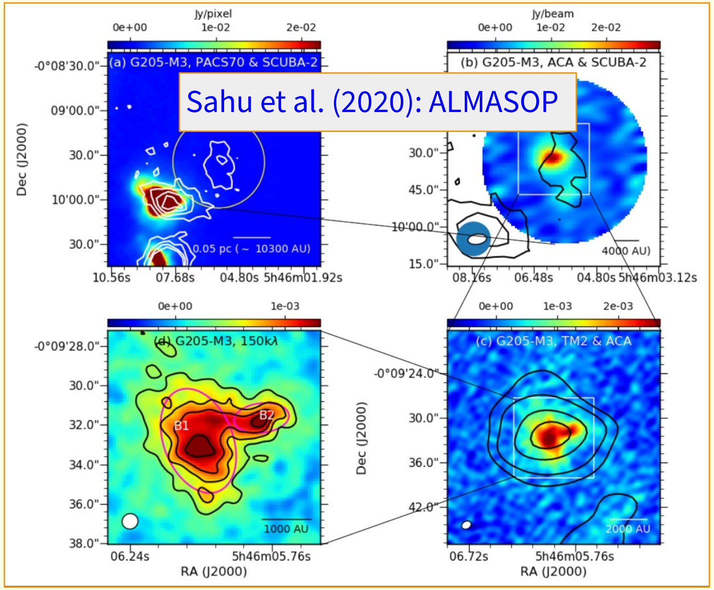


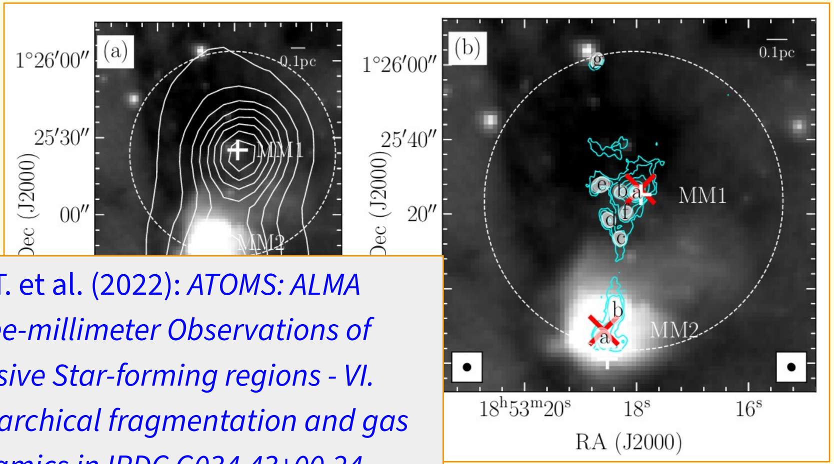


Fragmentation of cores

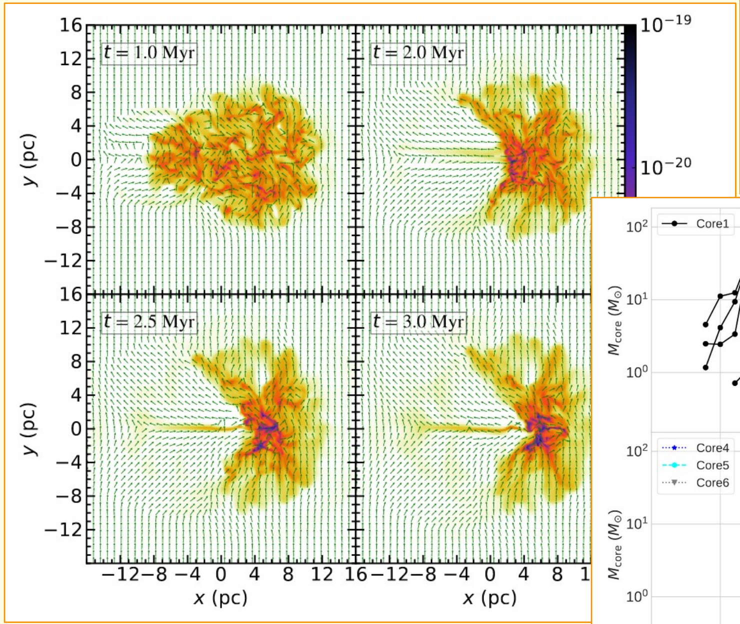
- something (*f* ?) fragment to cores, further fragmentation (turbulent-, disk-?) leads to the final stellar multiplicity
- fragmentation length, thermal vs. total Jeans?
  - Henshaw+ (2017), Cyganowski+ (2017), Juaréz+ (2019), Palau+ (2015/18/21), Beuther+ (2018, 2021), Sahu+ (2022)
  - Wang+ (2014), Barnes+ (2021), Liu H.-L. (2022)
  - feedback: Luo Q.-Y.+ (2022), Liu T.+ (2022), etc.
- **fragmentation of pre-stellar cores** difficult to find
  - Tokuda+ (2020): $\sim 10^{-2}\,M_\odot$ at 1000 au scale
  - Sahu+ (2020): potential SF fragments in one target
  - Dunham+ (2016), Kirk+ (2017): question of phase?
- high-mass cores/clumps with opposite problems…



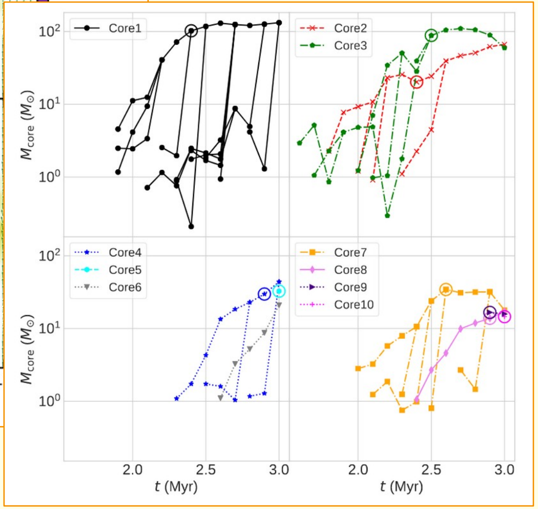




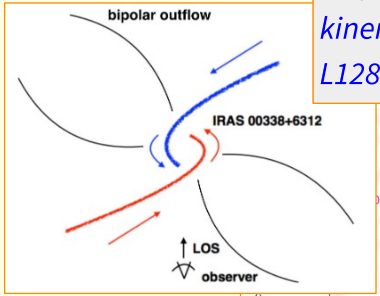
Liu T. et al. (2022): *ATOMS: ALMA Three-millimeter Observations of Massive Star-forming regions - VI. Hierarchical fragmentation and gas dynamics in IRDC G034.43+00.24*

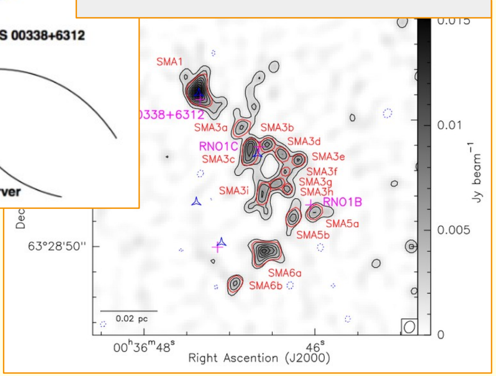


Sakre et al. (2020): *Massive core/star formation triggered by cloud-cloud collision: Effect of magnetic field*



Juarez et al. (2019): *Extreme fragmentation and complex kinematics at the center of the L1287 cloud*

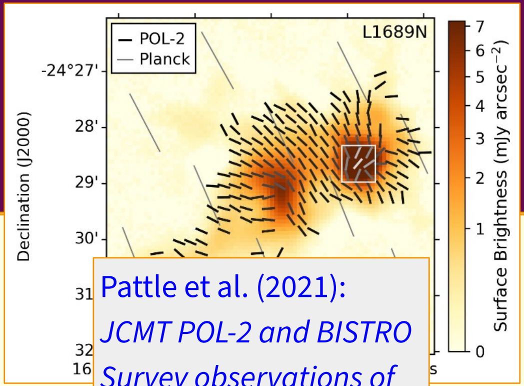




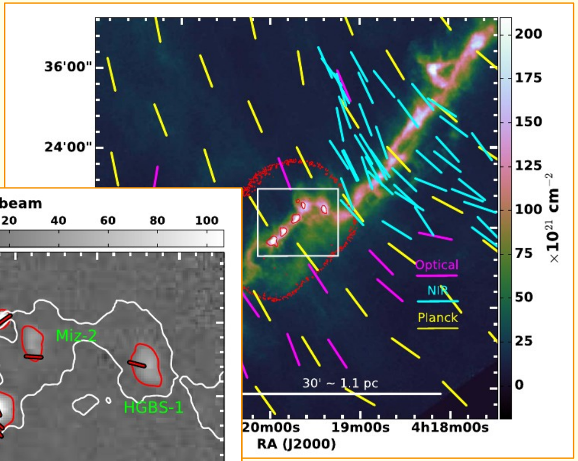
- Caroline Gieser: Physical and chemical properties during high-mass star formation (P04)
- Rajika Kuruwita: Star forming environment on multiple star formation pathways (P08)
- Alexandr Volvach: Flare phenomena in protostellar system IRAS 16293-2422 (P18)

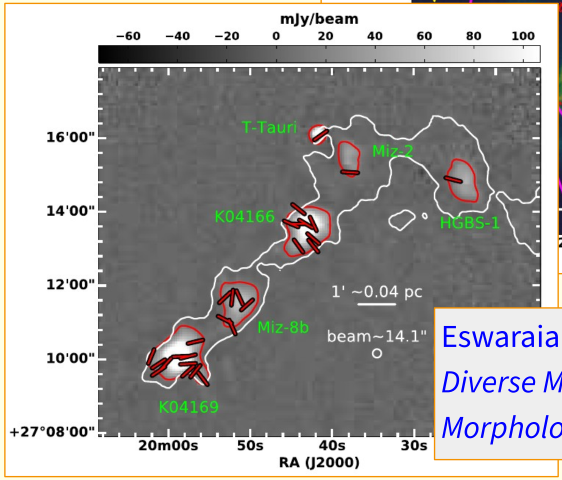
Magnetic fields of cores

- *B* morphology (linear/U/hour-glass/pinched) → **formation**
  - *B* vs. velocity and density gradients, core elongation
    - Ward-Thompson+ (2018), Fissel+ (2019), Pattle+ (2021), Eswaraiah+ (2021), ...
- *B* strength → **fragmentation** and **stability**
  - *B* ~ turbulence; ~0.1-1 mG in HMSF regions stabilise subvirial cores
    - Kong+ (2017), Liu T.+ (2018), Soam+ (2019), Nakamura+ (2019), Tang+ (2019), Barnes+ (2021); Liu J. (2021), Pattle+ (2021), ...
- *B* orientation → **protostars**, orientation
  - → disks and outflows
    - Stephans+ (2017), Gómez+ (2018), Vaytet+ (2018), Wurster+ (2018), Beuther+ (2020), Galametz+ (2020), Rosen & Krumholz (2020), Yen+ (2021a,b), Gupta+ (-22)

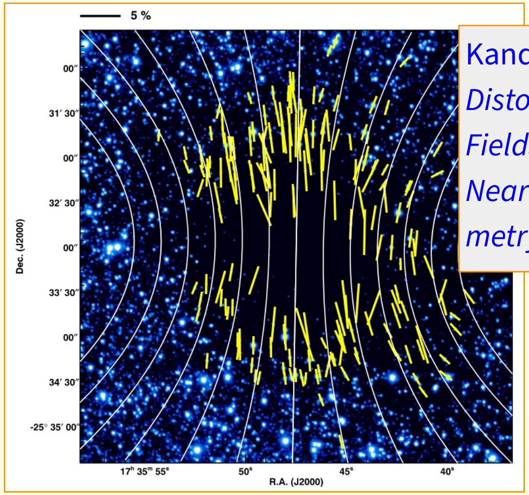


Pattle et al. (2021): *JCMT POL-2 and BISTRO Survey observations of magnetic fields in L1689*

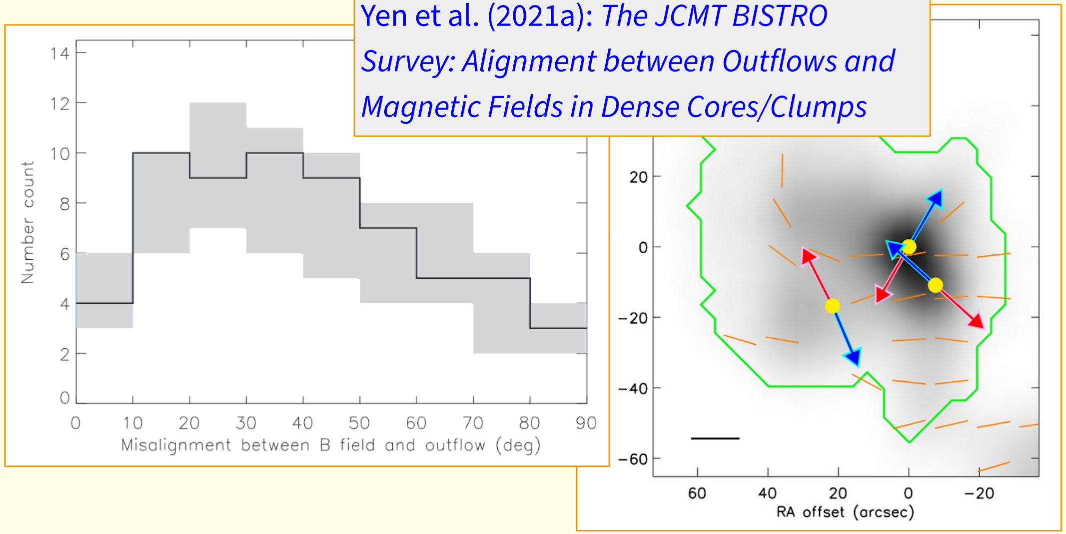




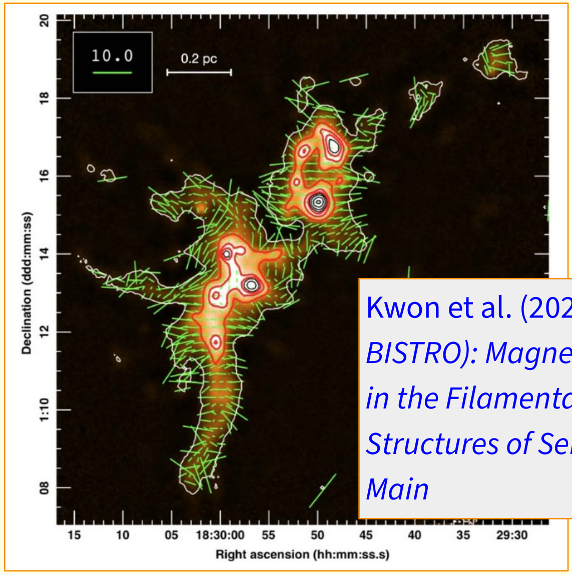
Eswaraiah et al. (2021; BISTRO): *Diverse Magnetic Field Morphologies in Taurus Cores*



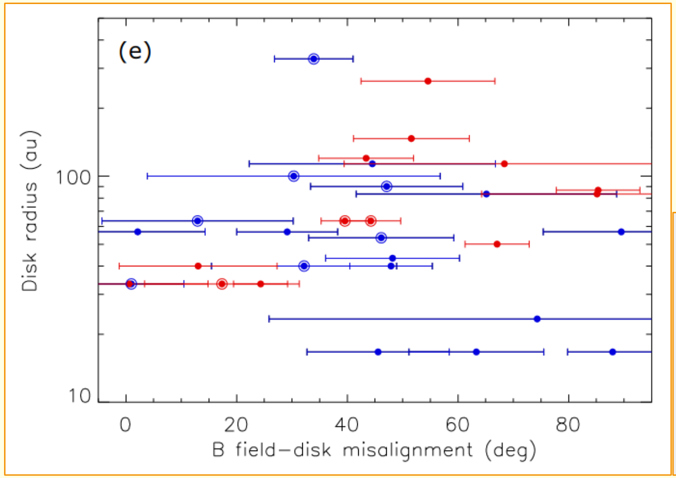
Kandori et al. (2017): *Distortion of Magnetic Fields in Starless Core: Near-infrared Polarimetry of FeSt 1–457*



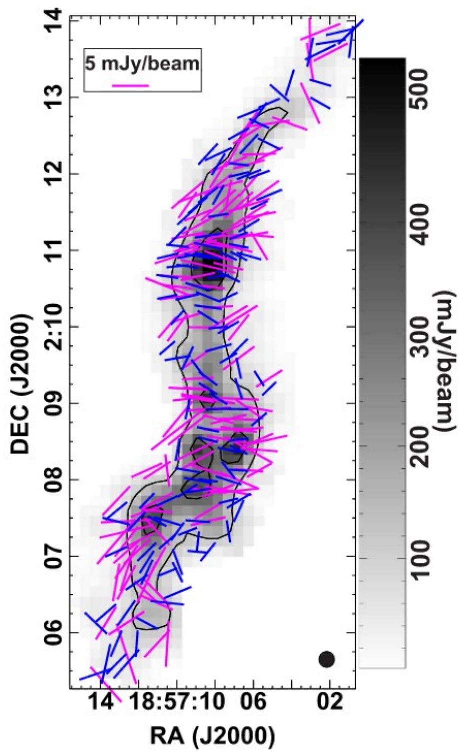
Yen et al. (2021a): *The JCMT BISTRO Survey: Alignment between Outflows and Magnetic Fields in Dense Cores/Clumps*



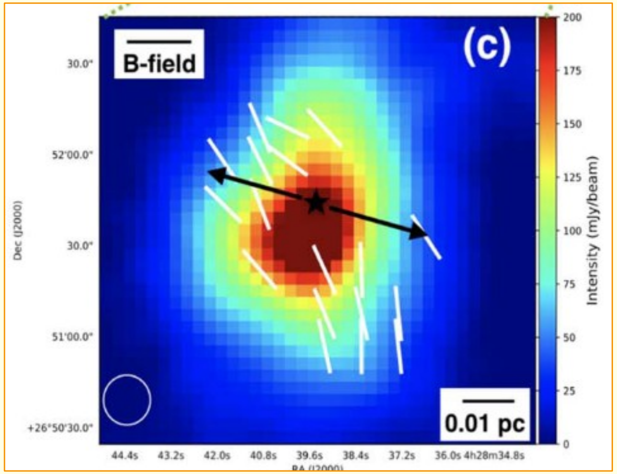
Kwon et al. (2022, *BISTRO): Magnetic Fields in the Filamentary Structures of Serpens Main*



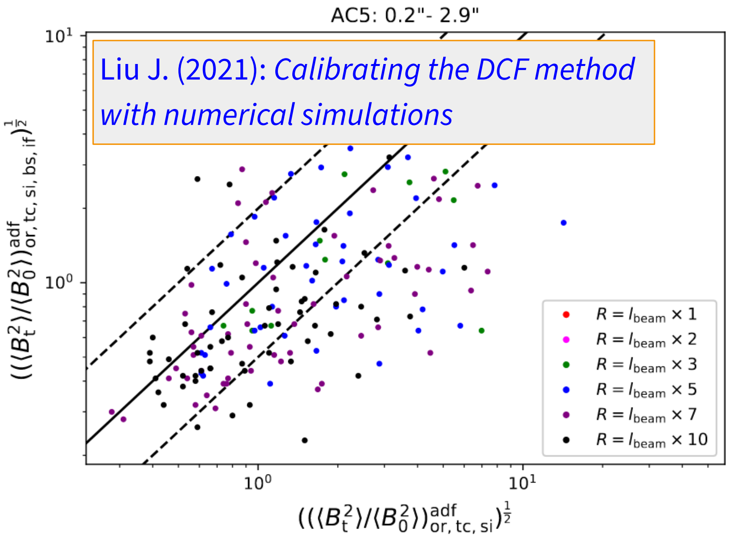
Yen et al. (2021b): No impact of core-scale magnetic field, turbulence, or velocity gradient on sizes of protostellar disks in Orion A



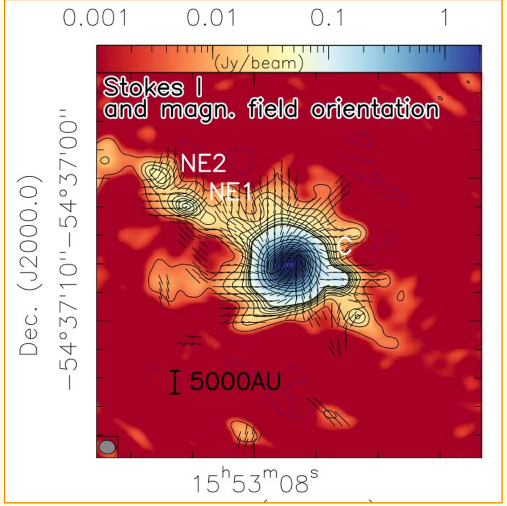
Liu T. et al. (2018): *A Holistic Perspective on the Dynamics of G035.39-00.33: The Interplay between Gas and Magnetic Fields*



Soam et al. (2019): First Sub-parsec-scale Mapping of Magnetic Fields in the Vicinity of a VeLLO, L1521F-IRS



Liu J. (2021): *Calibrating the DCF method with numerical simulations*



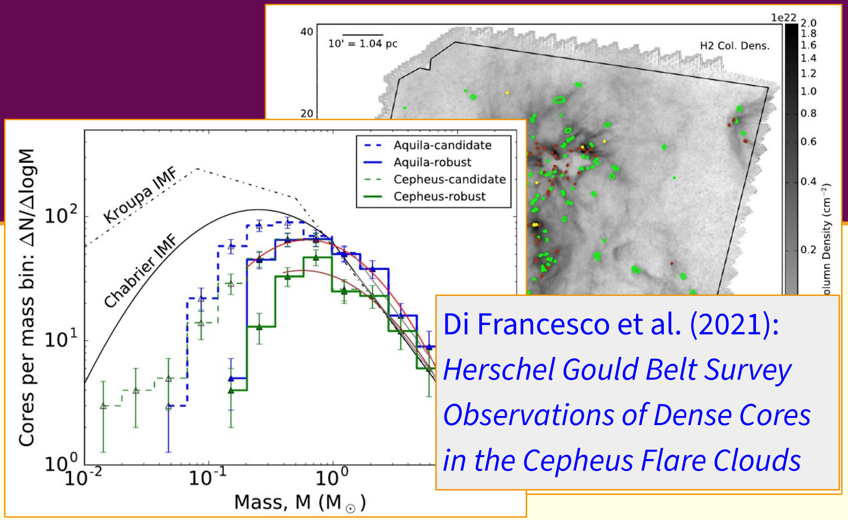
Beuther et al. (2020): *Gravity and Rotation Drag the Magnetic Field in High-mass Star Formation*

- Raphael Skalidis: Precision Galactic magnetometry from dust polarization (P14)

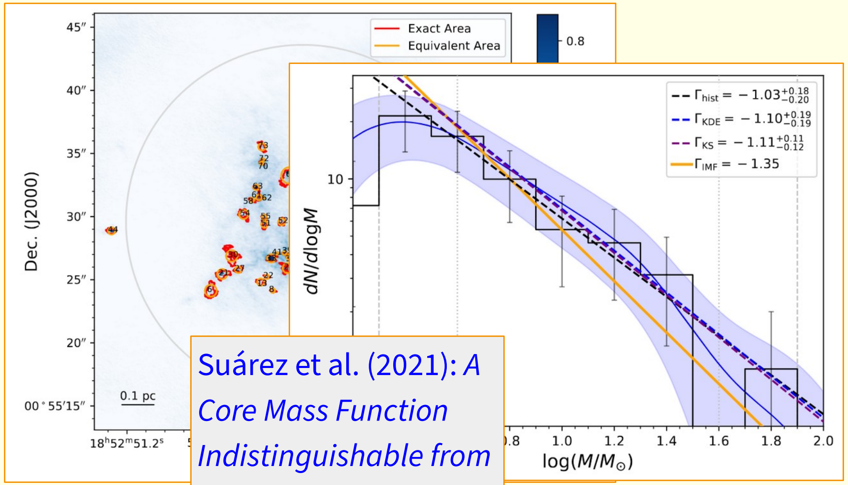
Statistics of cores

- fragmentation, density profile, size, mass, velocity dispersion, rotation… and core mass function!
  - Di Francesco+ (21), Cao+ (2021), Fiorellino+ (21), Motte+ (21), O’Neil+ (21), Pezzuto+ (21), Suárez+ (21), Takemura+ (21), Baug+ (21)
- SF thresholds; IMF ~ ε × CMF (ε~0.3 if and why); SFE ~ N-PDF
- variations of CMF with stage, environment
  - Hopkins+ (2013), Roy+ (2015), Zhang+ (2015), Lee & Hennebelle (18a,b;19;20), Motte+ (18), Pouteau+ (22)

- Yohan Pouteau: ALMA-IMF, a Large Program investigating the origin of stellar masses (P13)

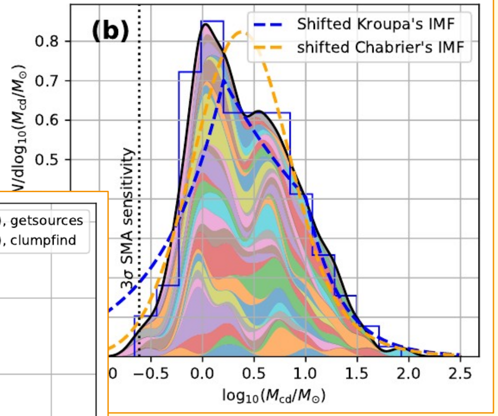


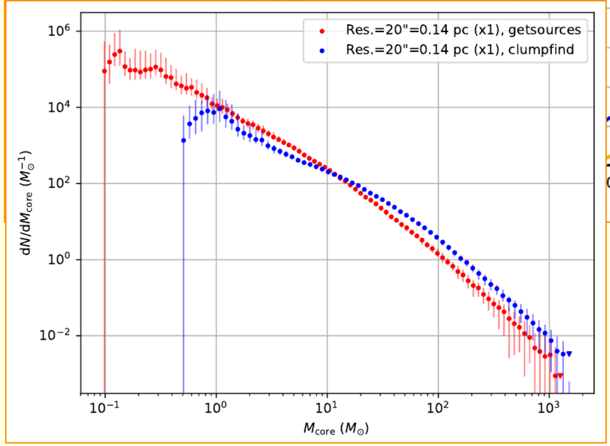
Di Francesco et al. (2021): *Herschel Gould Belt Survey Observations of Dense Cores in the Cepheus Flare Clouds*



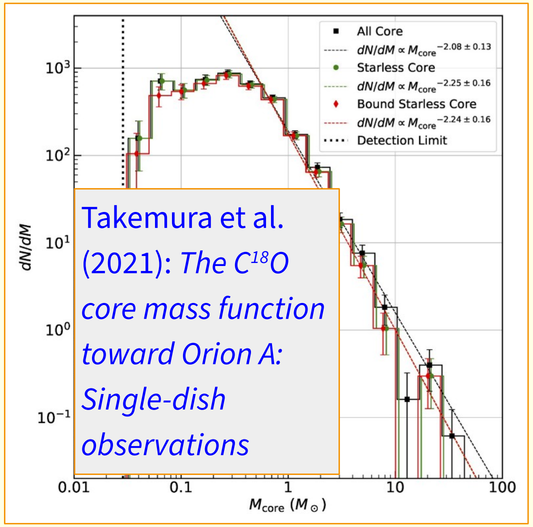
Suárez et al. (2021): *A Core Mass Function Indistinguishable from the Salpeter IMF Using 1000 au Resolution ALMA Observations*

Cao et al. (2021): *Core mass function of a single giant molecular cloud complex with ~ 10⁴ cores (Cygnus X)*

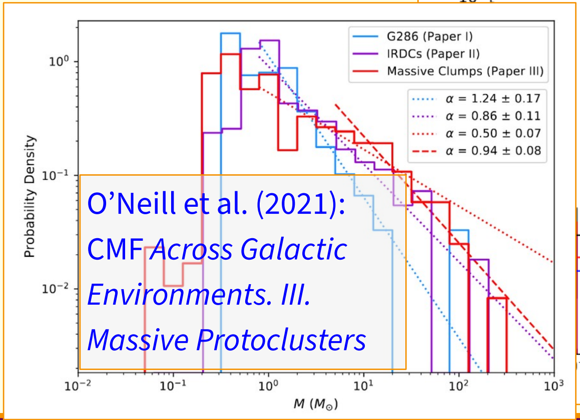


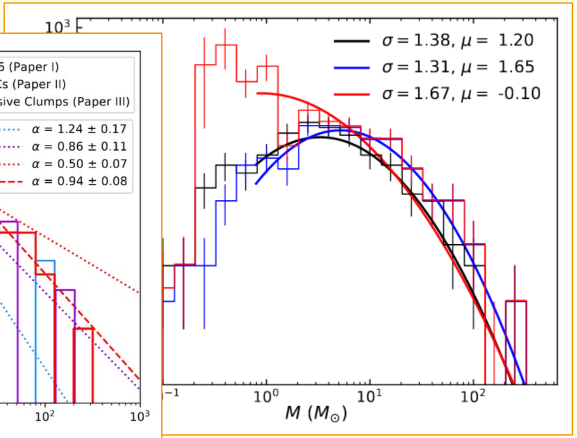


Takemura et al. (2021): *The $C^{18}O$ core mass function toward Orion A: Single-dish observations*

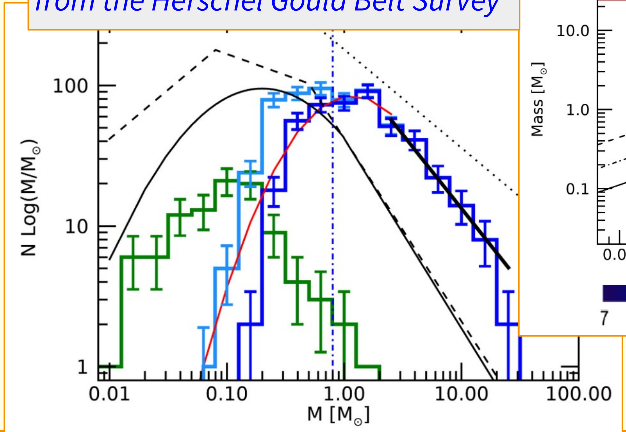


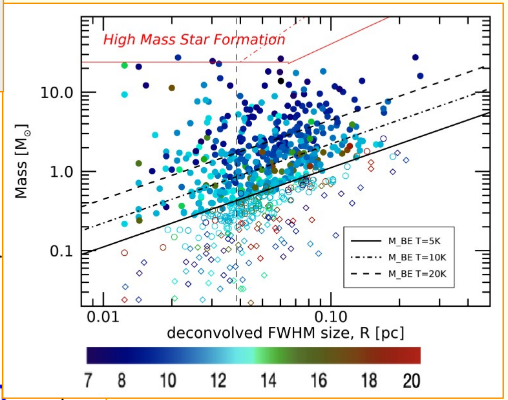
O'Neill et al. (2021): CMF *Across Galactic Environments. III. Massive Protoclusters*



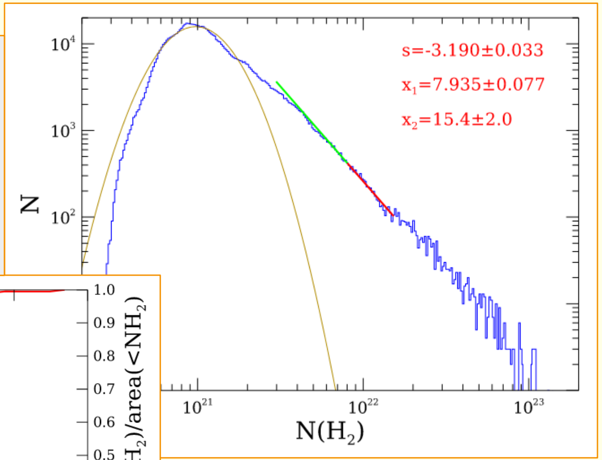


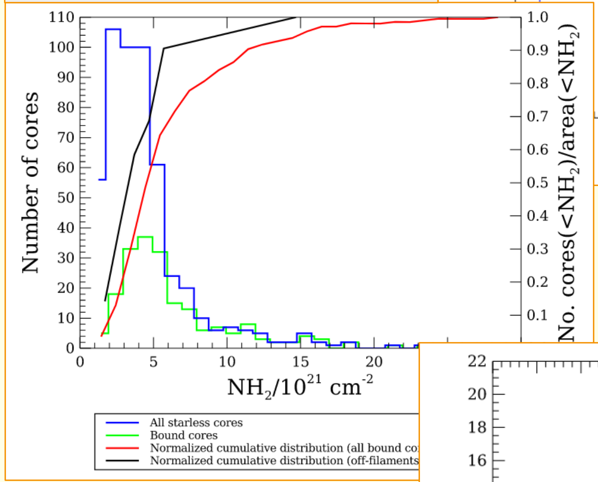
Fiorellino et al. 2021: *The census of dense cores in the Serpens region from the Herschel Gould Belt Survey*

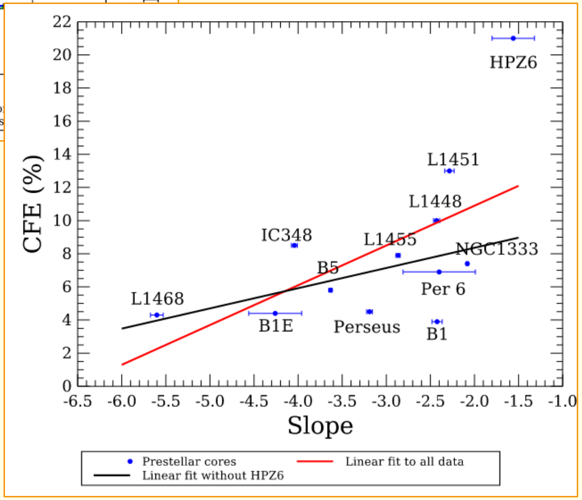


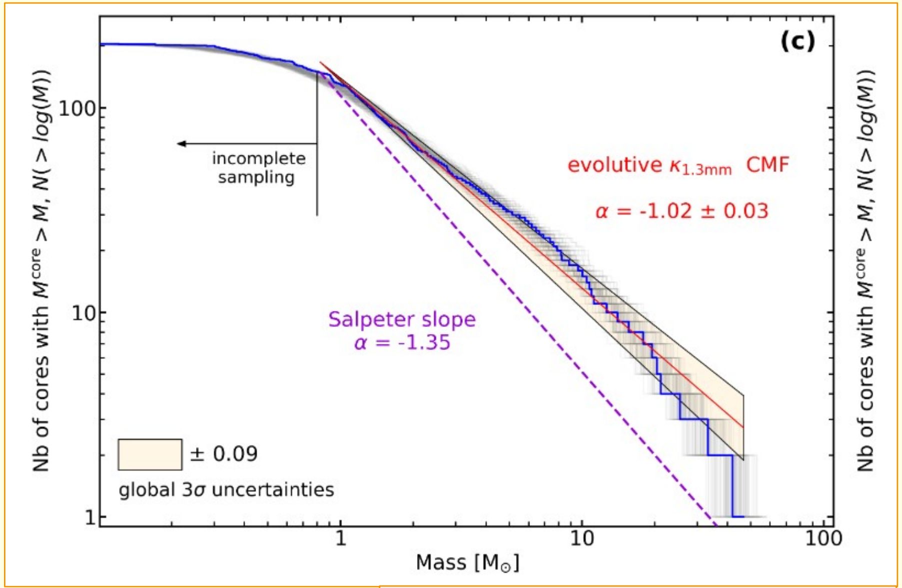


Pezzuto et al. (2021): *Physical properties of ambient medium and of dense cores in Perseus star-forming region derived from Herschel GBS observations*





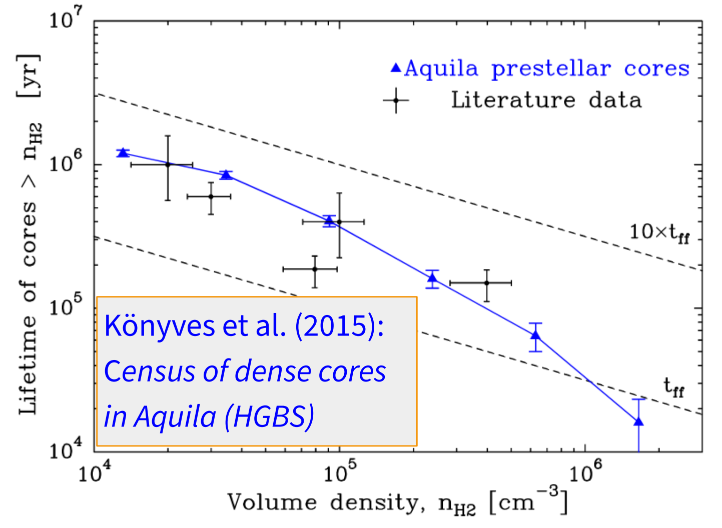




Pouteau et al. (2022): *ALMA-IMF III – Investigating the origin of stellar masses: Top-heavy core mass function in the W43-MM2&MM3 mini-starburst*

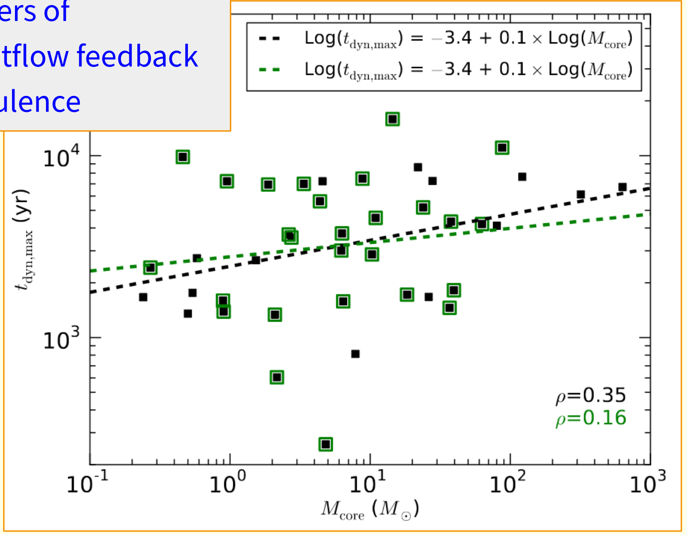
Timescales of cores

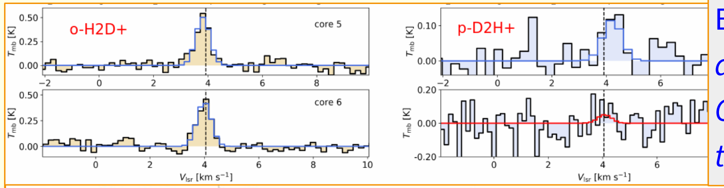
- timescale ~10^6 yr, (1–10)× t_{ff}, … <10^5 yr at the high-mass end
  $$t_{ff} = \sqrt{\frac{3\pi}{32 G \rho_0}}$$
- statistics: counting sources… at a specific time
  - with lifetime of embedded Class II sources "**1-2** Myr"
- dynamical times: outflow ages, accretion times
  - >50M$_\odot$, Class 0 <10^4 yr … t_{ff}=4×10^4 yr (Avison+21)
  - Li+ (20), Baug+ (2021); <10^4 yr, 10^{-7}-10^{-4} M$_\odot$ yr^{-1} ☞
  - Karnath+ (2020), Chung+ (2021)
- chemistry
  - Pagani+ (2013),Brünken+ (2014), Harju+ (2017)… o/p-H_2D^+ ~**1→0.5** Myr
  - Bovino+ (2021) o-H_2D+/p-D_2H^+, Oph <2×10^5 yr ~ t_{ff} ≪ t_{AD} (→ ~**10^5** yr)
  - Koumpia+ (2020),Redaelli+ (2020, -21), Hily-Blant+ (2020), Tatematsu+ (2021), Kalvans+ (2021)



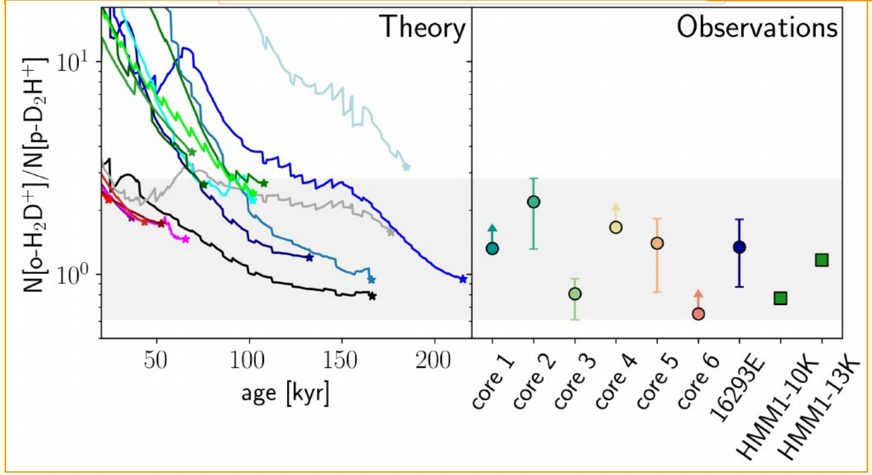
Könyves et al. (2015): *Census of dense cores in Aquila (HGBS)*

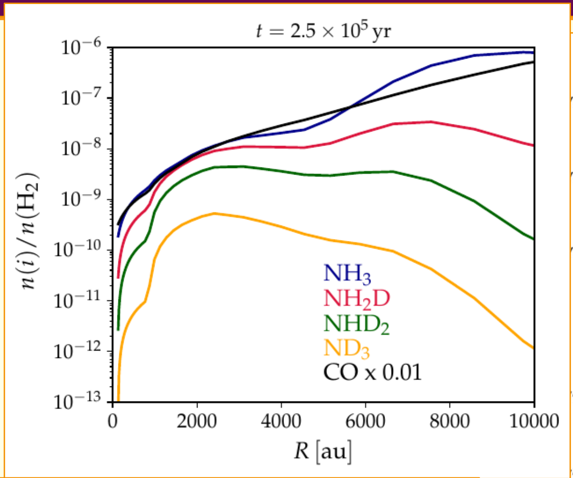
Baug et al. (2021): ALMA study of outflow parameters of protoclusters: outflow feedback to maintain turbulence

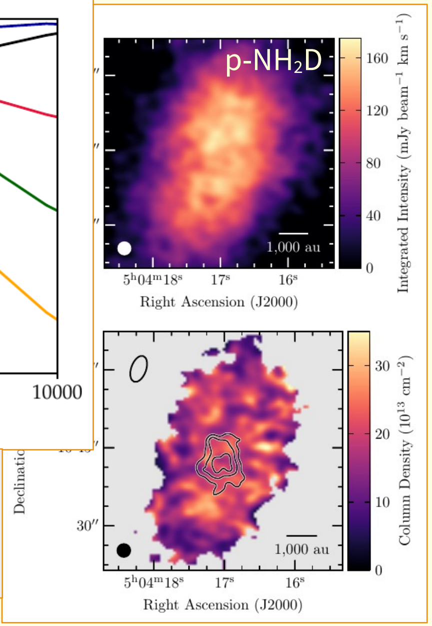




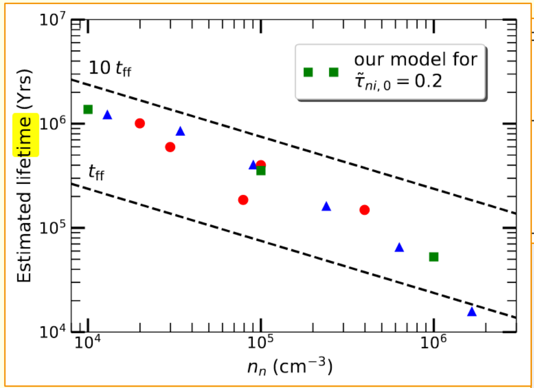
Bovino (2021): *Chemical analysis of prestellar cores in Ophiuchus yields short timescales and rapid collapse*







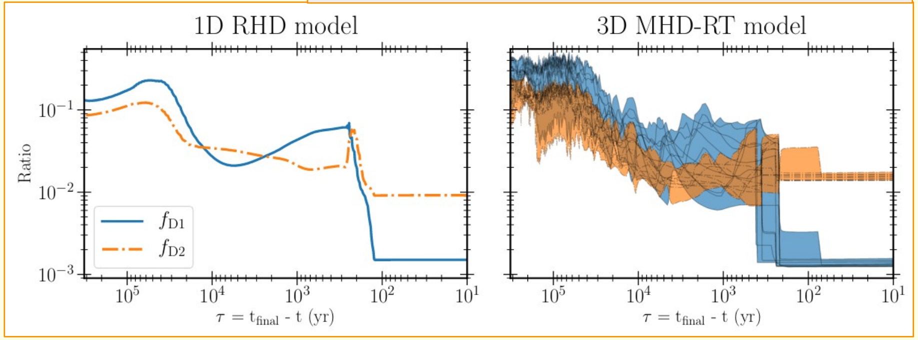
Caselli et al. (2022): *Central 1000 au of Pre-stellar Core Revealed with ALMA. II. Almost Complete Freeze-out*



σ_n (0^{-2} g cm^{-2})	B_{ref} (μG)	Estimated lifetime of prestellar cores (Myr)
1.094	16.45	1.371 ($\sim$5.777 t_{ff})
3.461	49.94	0.355 ($\sim$4.728 t_{ff})
10.944	119.57	0.053 ($\sim$2.220 t_{ff})

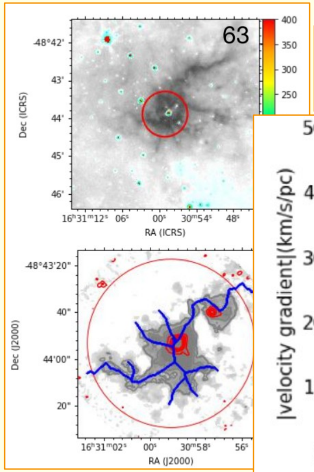
Das et al. (2021): *Variation of the core lifetime and fragmentation scale in molecular clouds as an indication of ambipolar diffusion*

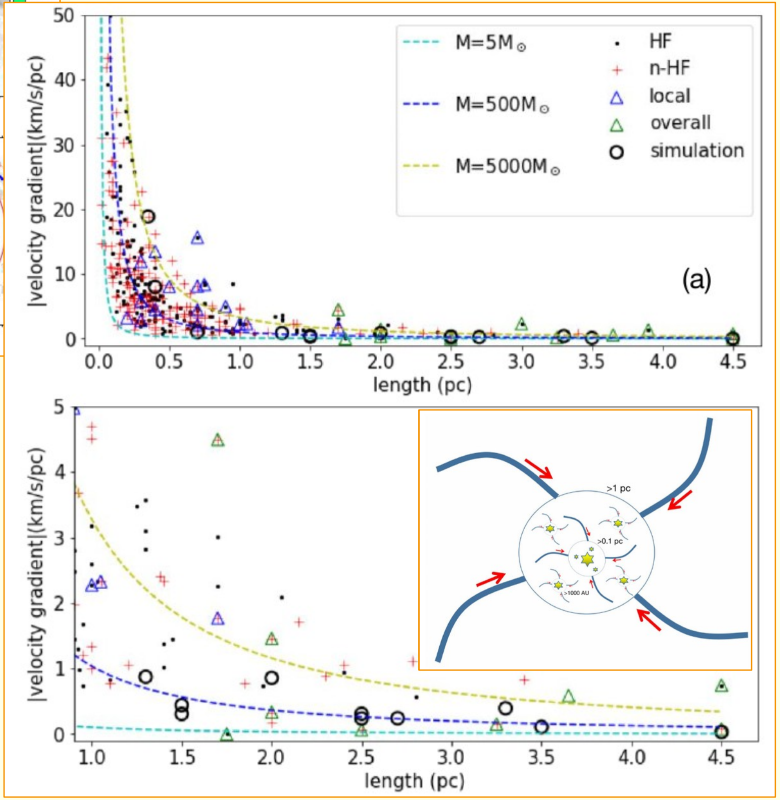
Jensen (2021): *Modeling chemistry during SF: Water deuteration in dynamic SF regions*



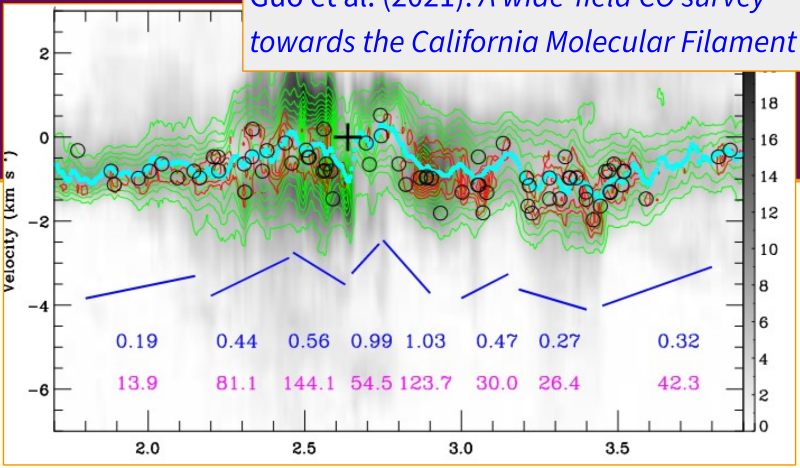
Large scales and cores

Zhou et al. (2022)
ATOMS hub-filament systems

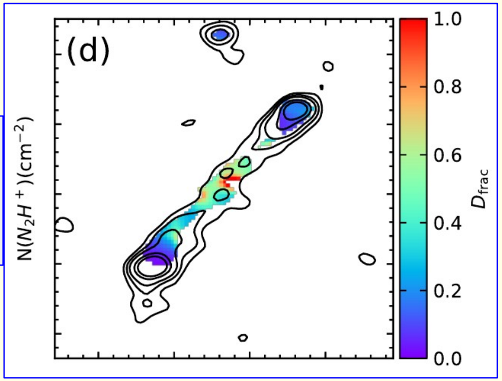




Guo et al. (2021): *A wide-field CO survey towards the California Molecular Filament*



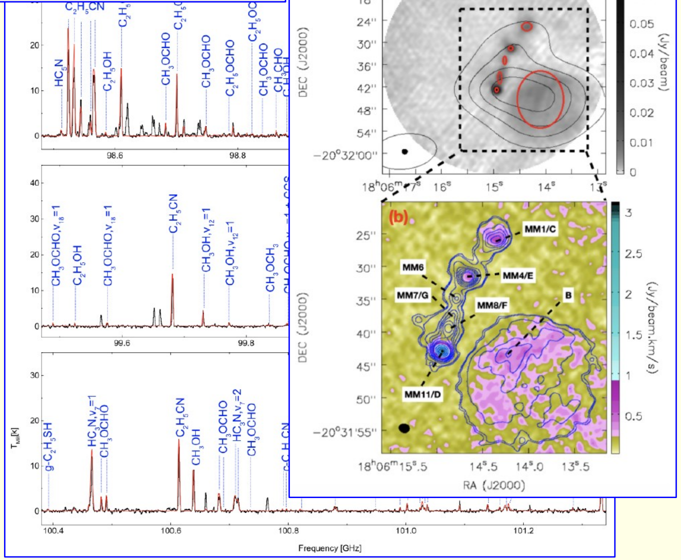
Cheng et al. (2021) :
Star Formation in a Strongly Magnetized Cloud (Vela C Ridge)



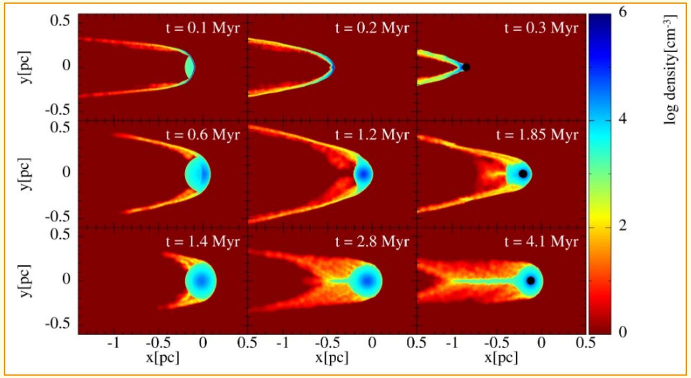
- Stefan Heigl: Turbulent origin of streamers onto protostellar disks (P05)
- Elena Hoemann: Filament collapse: A two phase process (P06)

Small scales and cores

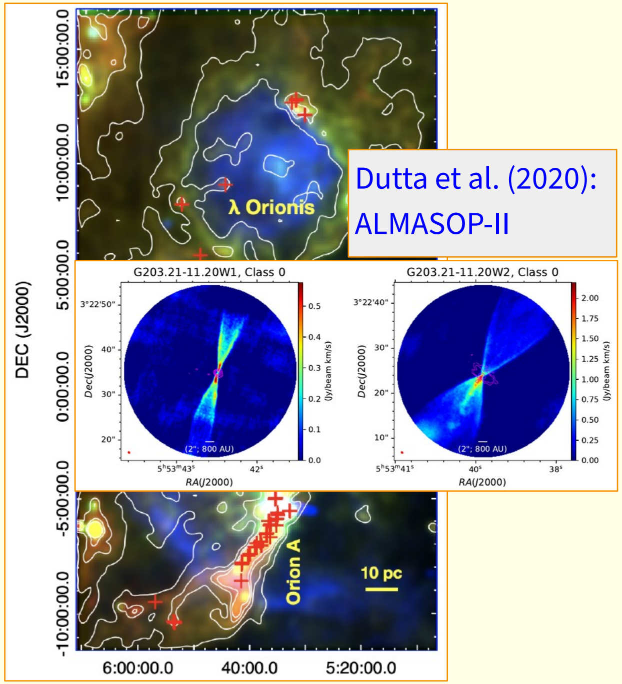
Tie et al. (2020): ATOMS I



Zier et al. (2021): *On the interaction of a Bonnor-Ebert sphere with a stellar wind*



Dutta et al. (2020): ALMASOP-II



- Mike Grudich: The dynamics of star formation with all feedback in concert (P00)
- Jan Orkisz: Tracing turbulence properties, volume densities and star formation (P11)

Open questions for cores 2022

- definition and classification of cores … …
- FHSC… massive pre-stellar cores … … …
- origin of turbulence, turbulent support …
- fragmentation: to and of cores … … … …
- stability, transition to coherence … … …
- chemical and dust evolution … … … … .
- inflow, infall, hub-filaments, streamers …
- magnetic fields … … … … … … … … … …
- timescale of core evolution … … … … …
- SFE, SFR, CMS … → ... IMF … … … … …

- cloud formation, origin of turbulence
- cloud fragmentation, description of cloud structure
- transition from turbulent cloud to quiescent core; improved understanding of chemistry
- changes in dust properties
- chemical evolution / clocks to track core evolution
- complete depletion
- emerging field of IRDCs