Magnetic Fields in the Star Formation Process: The SMA view

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The Submillimeter Array: First Decade of Discovery, June 10th 2014

Outline

- Why should we care to do polarization observations?

- **NGC 1333 IRAS 4A:** A textbook case of slowing rotating core threaded by an hourglass magnetic field

- IRAS 16293-2422: A magnetized disk: **see Rao's talk**

- **G31.41+0.31:** An hourglass magnetic field threading a 500 $M_\odot$ core

- G35.2-0.74N & G240.31+0.07 massive cores: **see Keping's talk**

- **New methods for analyzing polarization:** Triggered by SMA results!

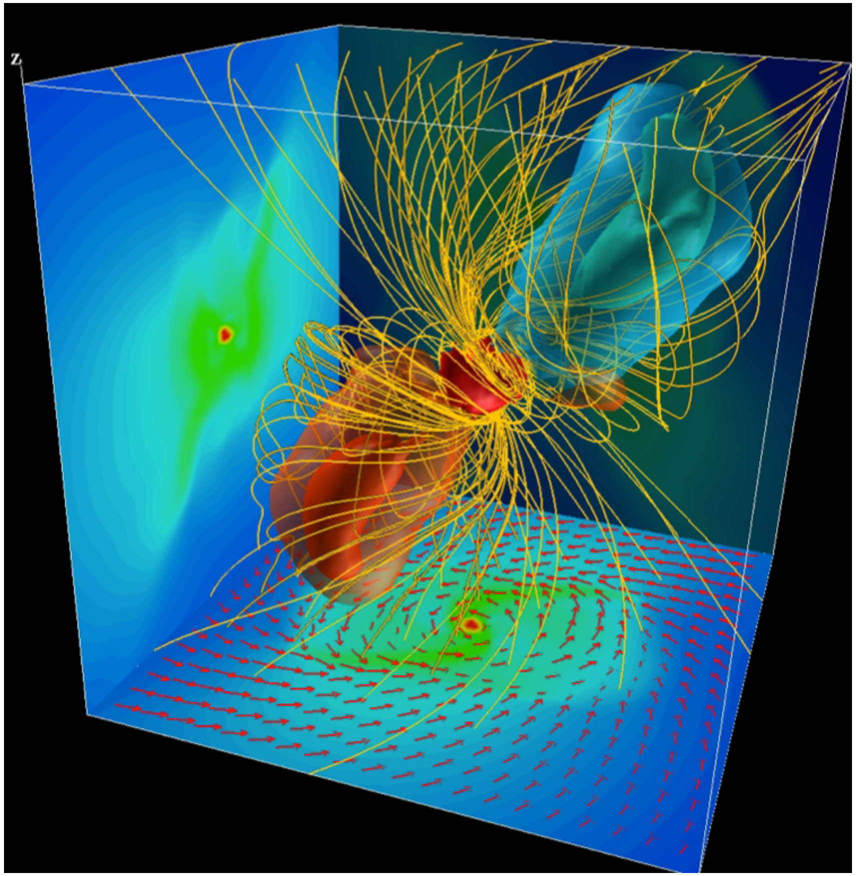
- **SMA Legacy project:** On going survey, first results

- **Magnetic fields in massive cores:** A possible evolutionary trend

Posters: F-2 G34.3 (H. Chen), F-4 IRAS4A CO pol (T-C Ching), F-9 W43 (TK Sridharan) + F-15 NGC 7538IRS1 (J-H Zhao),

Motivation: The role of magnetic fields in SFR

- Cloud support – magnetic / turbulence / both?
- Ambipolar diffusion - allows cloud to contract
- Magnetic braking - remove angular momentum
- Some mechanism must also remove magnetic flux, otherwise disk catastrophe
- Launch highly collimated jets

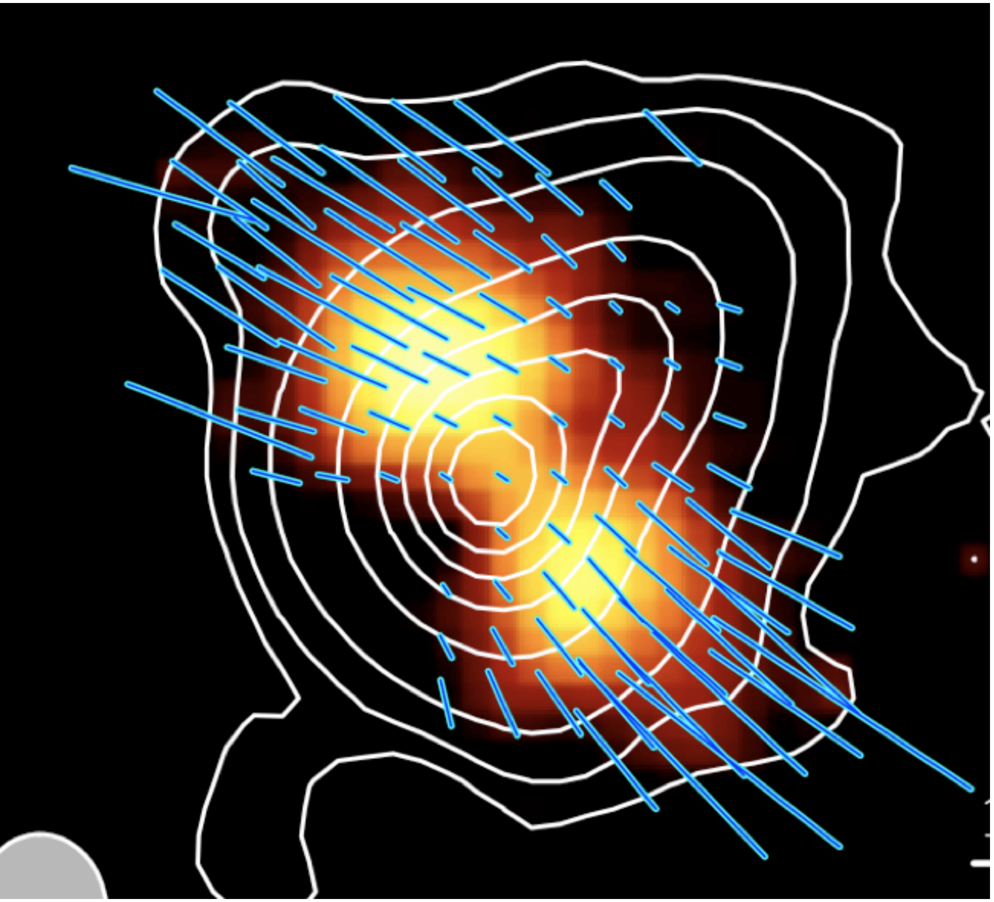


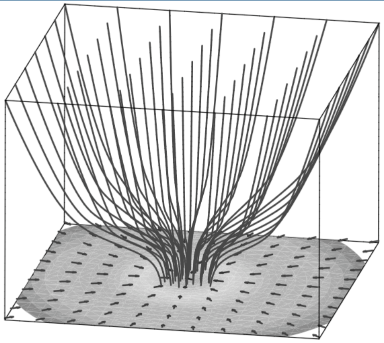
Machida et al. 2005, 2006; Shinnaga et al. in prep.

… but star formation in massive clouds: a highly dynamic process
… so, are magnetic field relevant?

Crutcher 2012, ARA&A

NGC 1333 IRAS4A - Hourglass B field

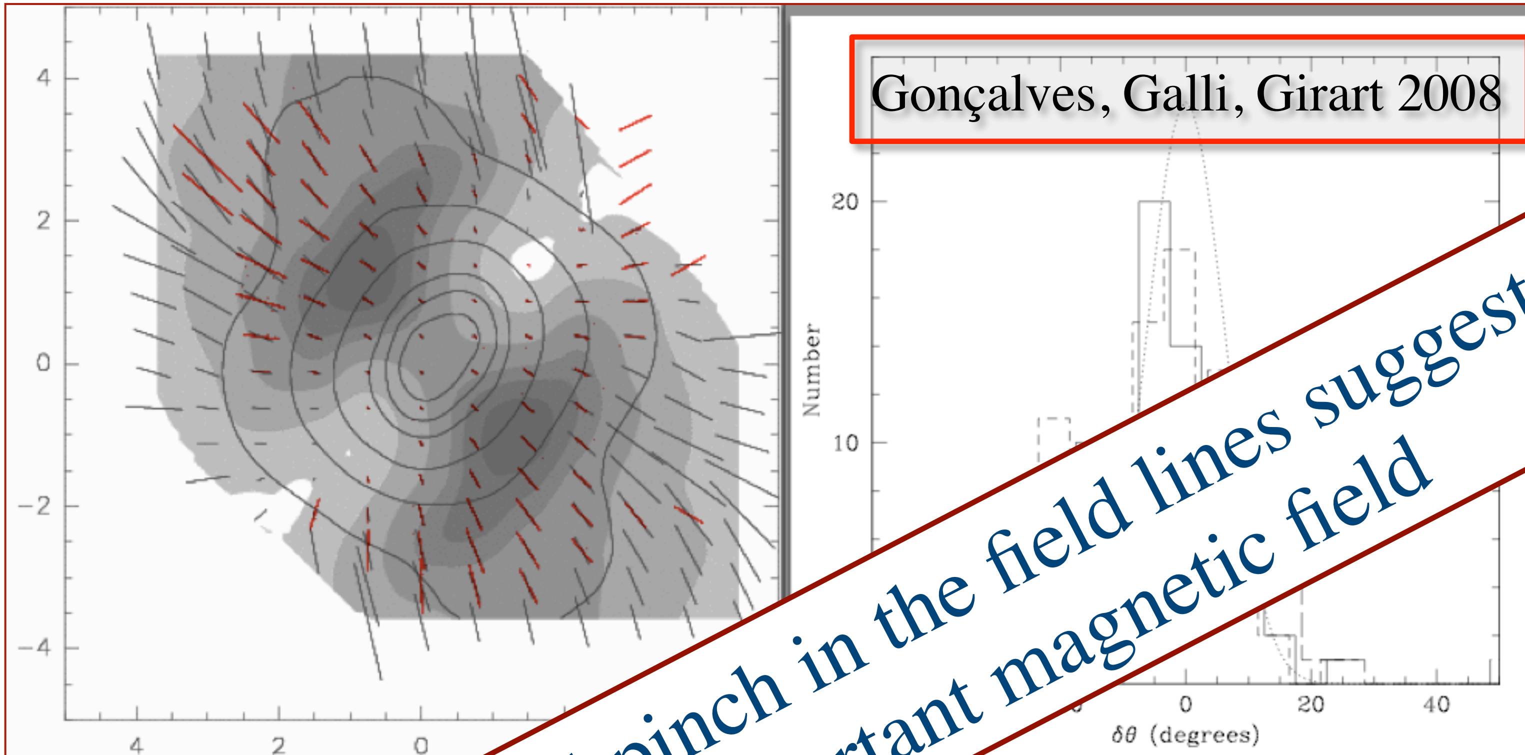




- SMA observations at 880μm resolved the magnetic field in the envelope
- Hour glass shape of the magnetic field structure in the circumbinary envelope
- The detected field axis is well aligned with the large scale field
- The field axis seems aprox. well aligned with the minor axis

Girart, Rao & Marrone 2006, Science

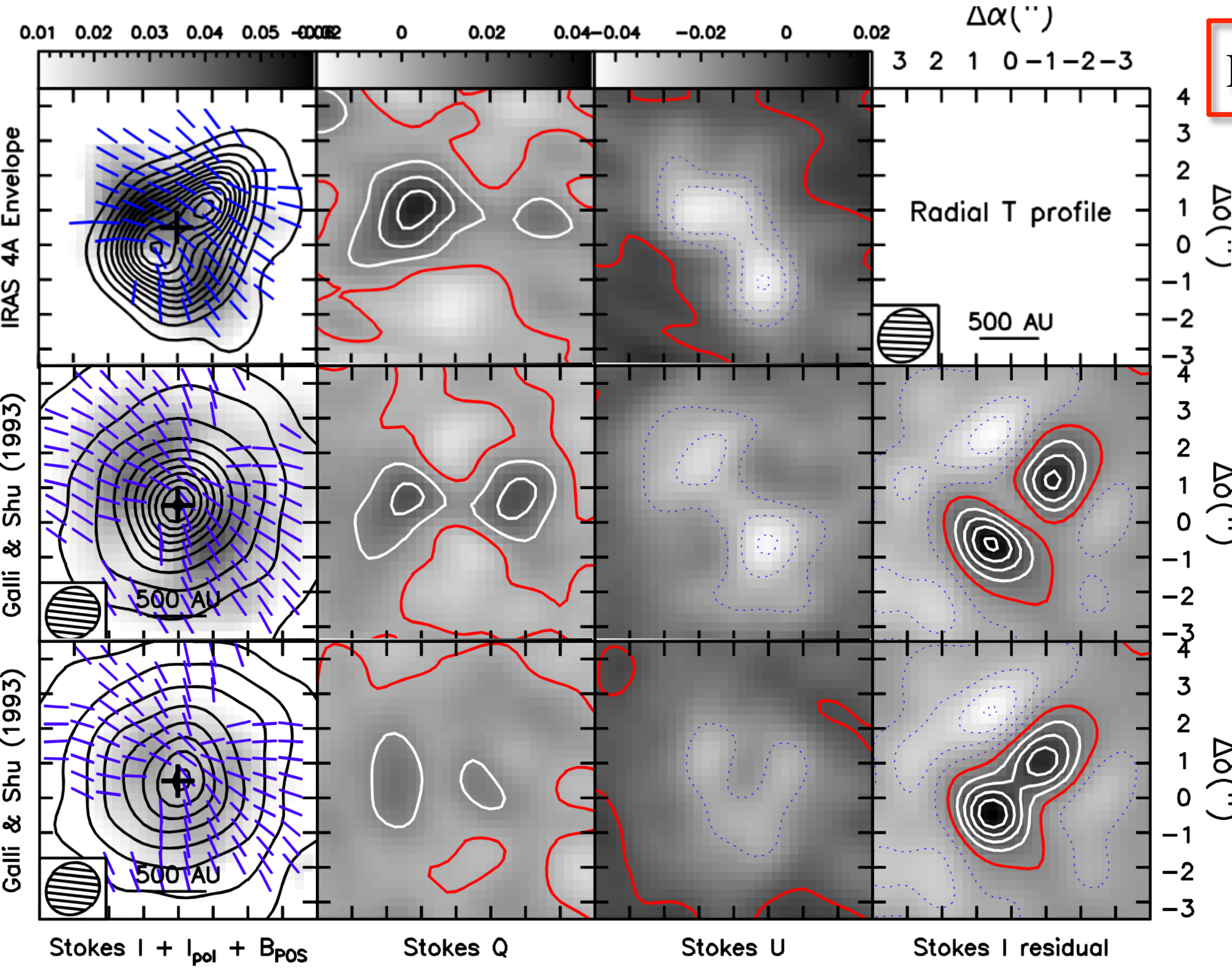
IRAS 4A: Modelling the B field. I



The relatively small pinch in the field lines suggests
a dynamically important magnetic field

- Model used: an a… …ependent, calculation of the inside-out collapse o… …etized cloud with or without ambipolar diffusion… …).
- S… …of Stokes I,Q, U the models are generated to co… …SMA data
- Bes… …ts for stellar age of 8.6×10^4 yr and a mass of 0.8 $M_{\odot}$

IRAS 4A: Modelling the B field. II



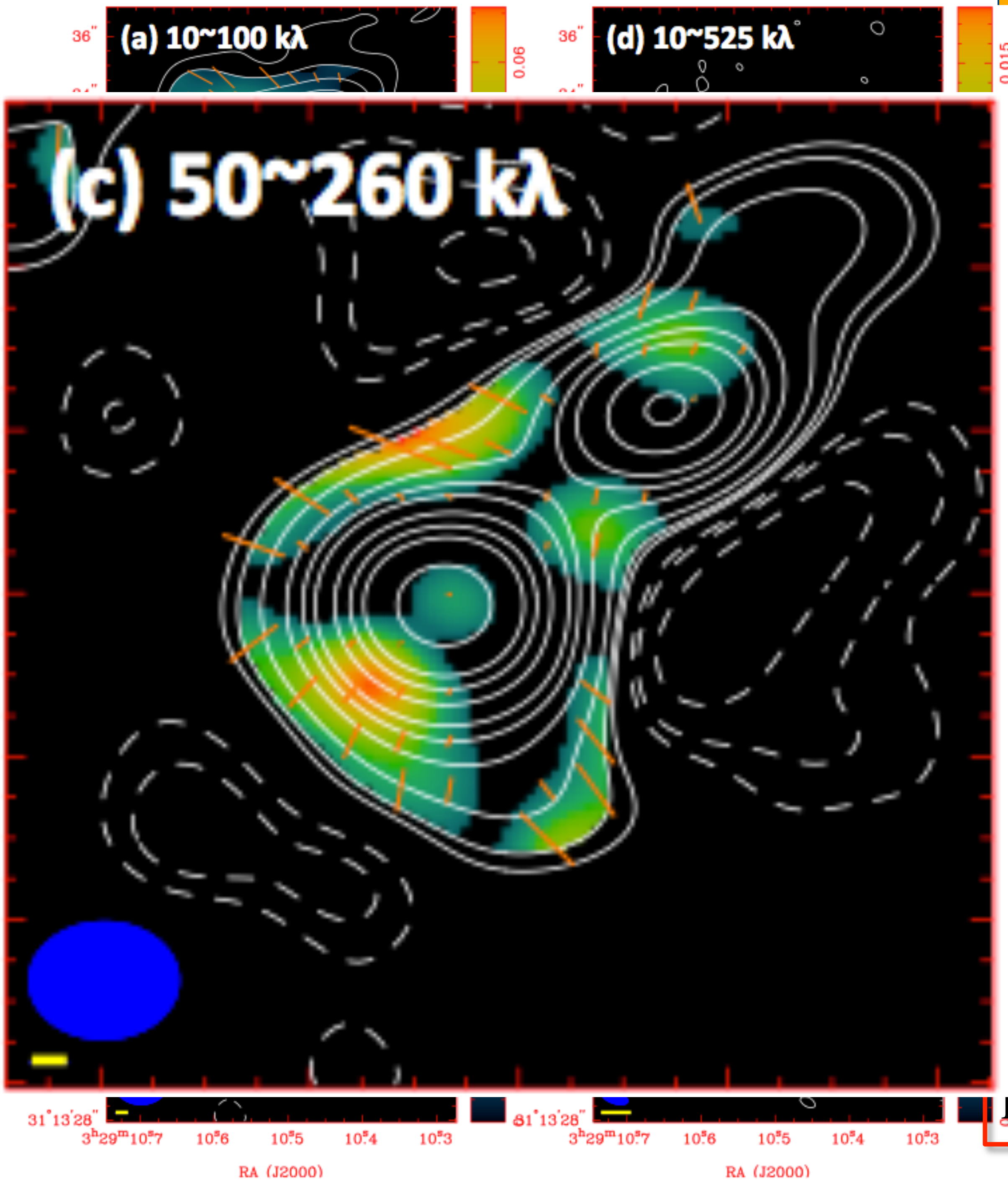
Collapse of a singular isothermal sphere threaded by an initially uniform magnetic field. The cloud is assumed to be non rotating.

Frau, Galli, Girart 2011

For all the different models

- Adding the expected temperature dependence improves the total and polarized intensity
- Stokes I: the residual shows clearly the circumstellar dust emission associated with 4A1 and 4A2
- $\boldsymbol{B_0}$ **=** 0.4-0.9 mG
- $\boldsymbol{t}$ **=** 10^4 yr

IRAS 4A: SMA all configurations

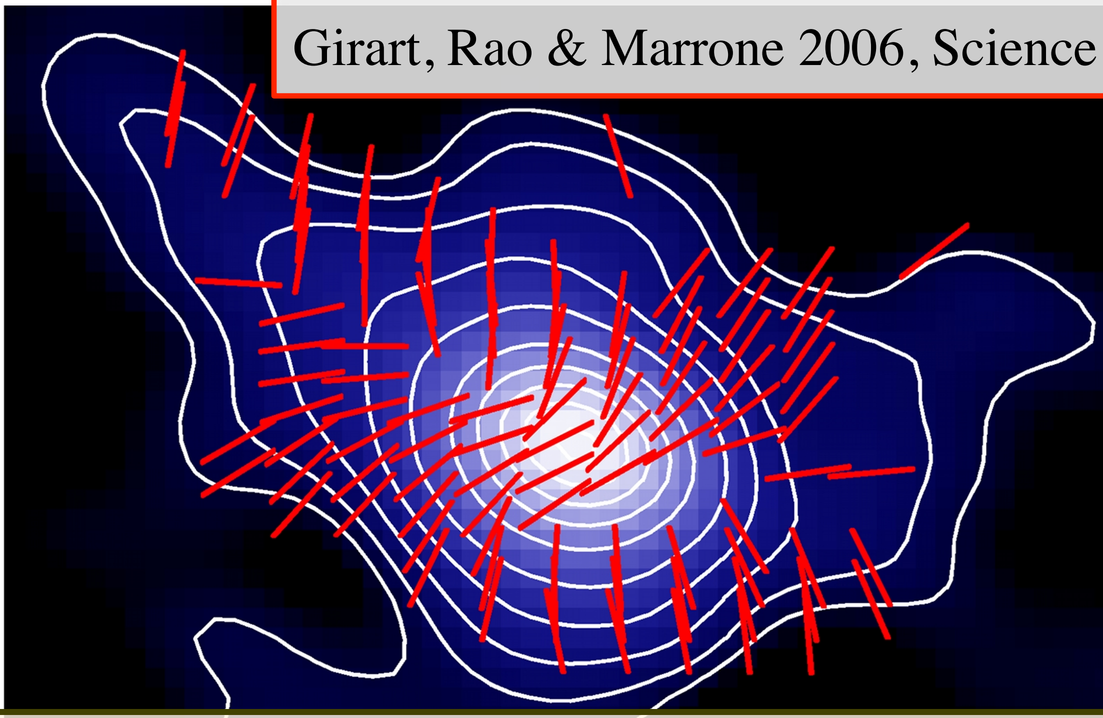


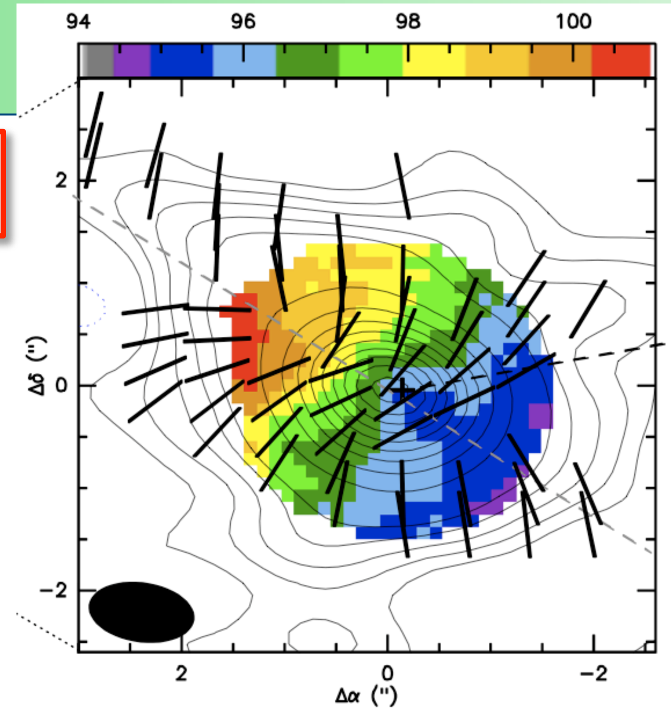
Observing IRAS 4A with all the configurations allows to start zooming down to scales < 100 AU and revealing a possible **transition from poloidal (hourglass) to toroidal (disk formation?) configuration**

Lai, Girart et al, in preparation

Magnetic fields towards G31.41+0.31

Girart, Rao & Marrone 2006, Science





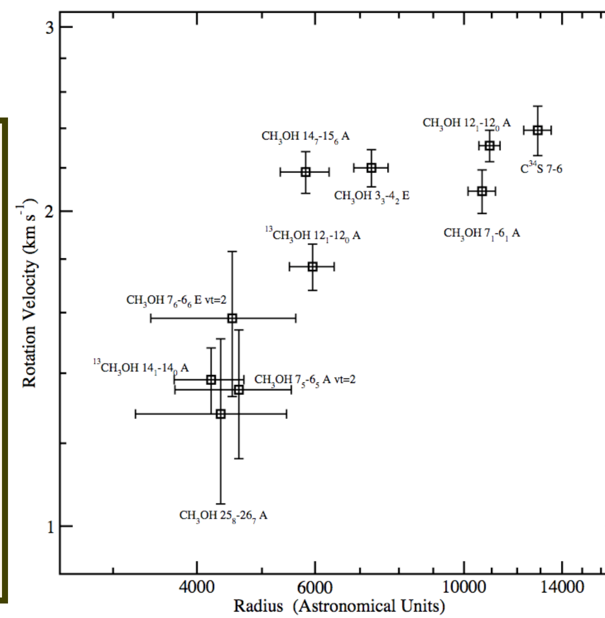
Very massive core **($M_{core} \approx 577\ M_{\odot}$)** harboring possibly O-type stars **($L \approx 3\ 10^5\ L_{\odot}$)**

Magnetic field shows hourglass morphology, **B ~ 10 mG**

Magnetic energy > Turbulent energy

Supercritical core M/Φ > 2.7

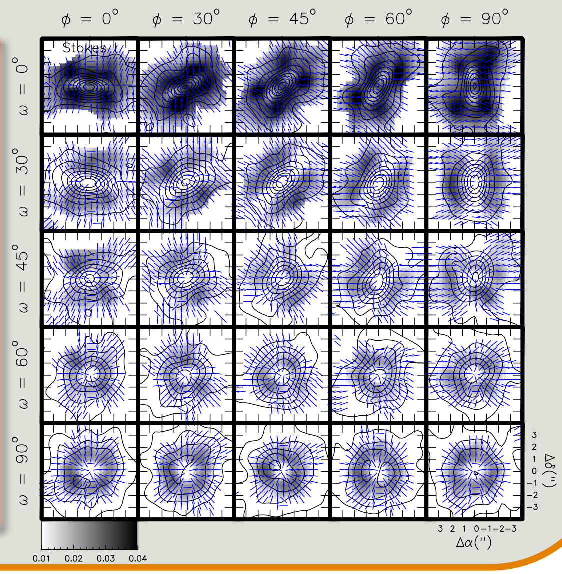
Angular momentum is not conserved: **Magnetic braking**



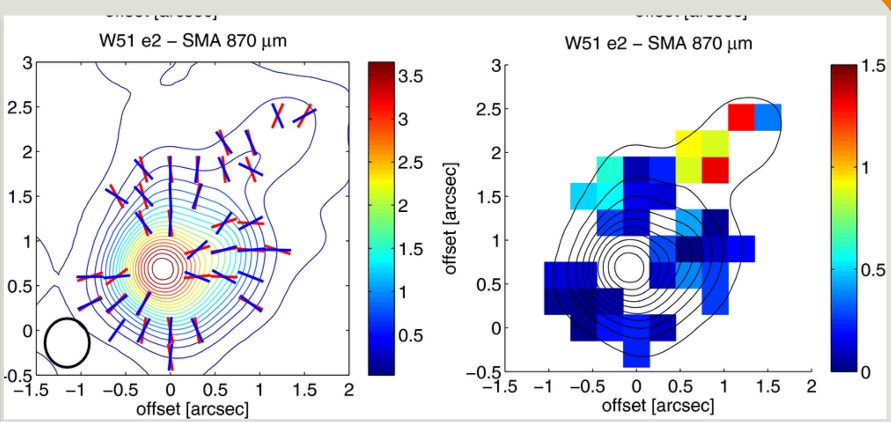
SMA polarization results have triggered NEW analysis techniques of polarization to better understand B fields

Synthetic pol maps of magnetized, star forming core models

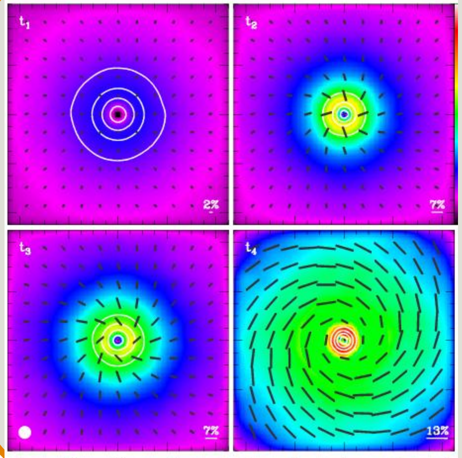
Gonçalves, Galli, Girart 2008
Frau, Galli, Girart 2011



Koch et al. 2012a,b, 2013



Analysis of the dust intensity gradient and the polarization directions: Magnetic fields to gravity force ratio



ARTIST dustpol: radiative transfer package tool to derive pol maps from MHD simulations / models

Padovani, Brinch, Girart et al 2012
http://youngstars.nbi.dk/artist

Analytic form for the B hourglass to get physical relevant information

Ewertowski & Basu 2013

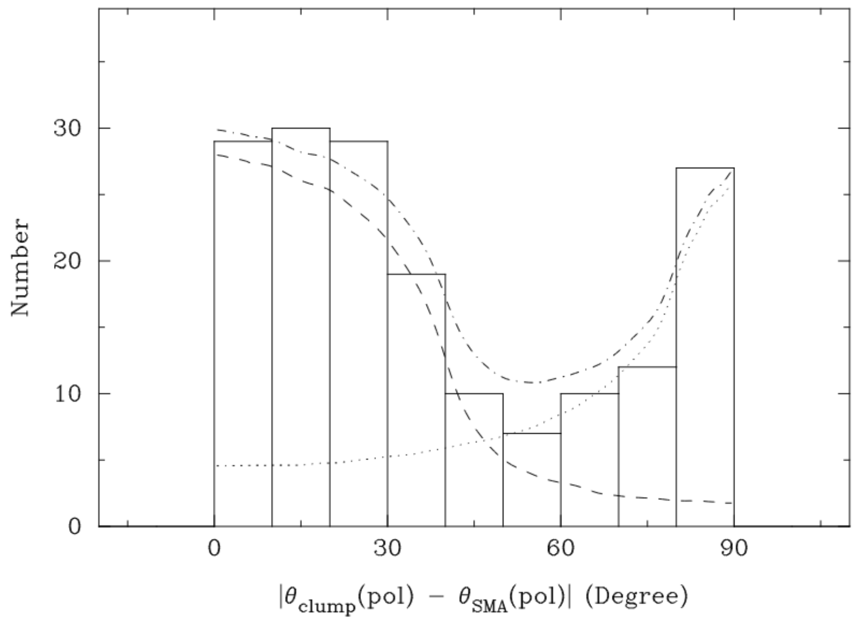
$$B_r = \sum_{m=1}^{\infty} k_m \sqrt{\lambda_m} J_1(\sqrt{\lambda_m}\, r) \left[\operatorname{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} - \frac{z}{h} \right) e^{-\sqrt{\lambda_m}\, z} - \operatorname{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} + \frac{z}{h} \right) e^{\sqrt{\lambda_m}\, z} \right], \tag{45}$$

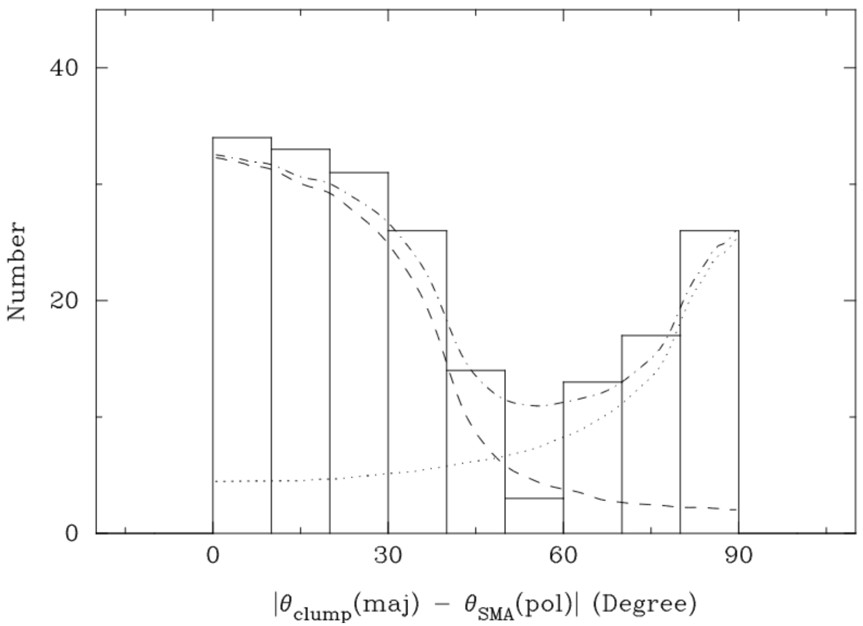
$$B_z = \sum_{m=1}^{\infty} k_m \sqrt{\lambda_m} J_0(\sqrt{\lambda_m}\, r) \left[\operatorname{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} + \frac{z}{h} \right) e^{\sqrt{\lambda_m}\, z} + \operatorname{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} - \frac{z}{h} \right) e^{-\sqrt{\lambda_m}\, z} \right] + B_0 . \tag{46}$$

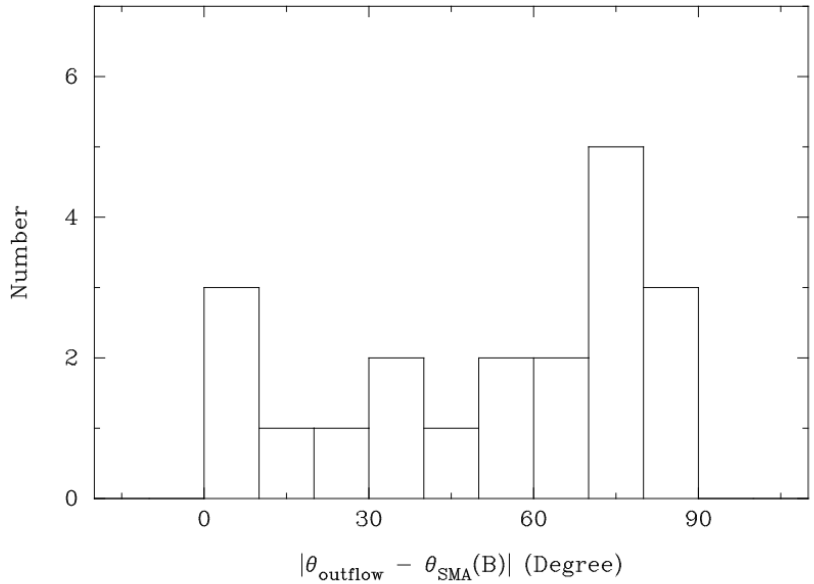
SMA Legacy project: Filaments, Star Formation & Magnetic Fields

- ✓ 870 μm SMA observation of 14 massive molecular to investigate the role of magnetic fields in massive star formation.
- ✓ Selected sample: early stages of massive star formation (without HII regions)
- ✓ Most of the targets are at a distance of 1.5-5.0 kpc
- ✓ More than 30 tracks in different configurations (mostly compact and extended) with typical angular resolution of ≈ 1´´
- ✓ There is a high fraction of dust polarization detections
- ✓ **Observations sensitive to the B field structure at 0.01-0.1 pc scales (core's scales)**
- ✓ **In general, the projected B morphology in the p-o-s tend to be more organized rather than chaotic**
- ✓ **A summary paper with the main results is underway (submitted to ApJ)**
- ✓ Published results on individual sources: Liu et al. 2013 (G192.16-3.84); Qiu et al. 2013 (G35.2-0.74 N); Girart et al. 2013 (DR 21(OH))

SMA Legacy project: Statistics





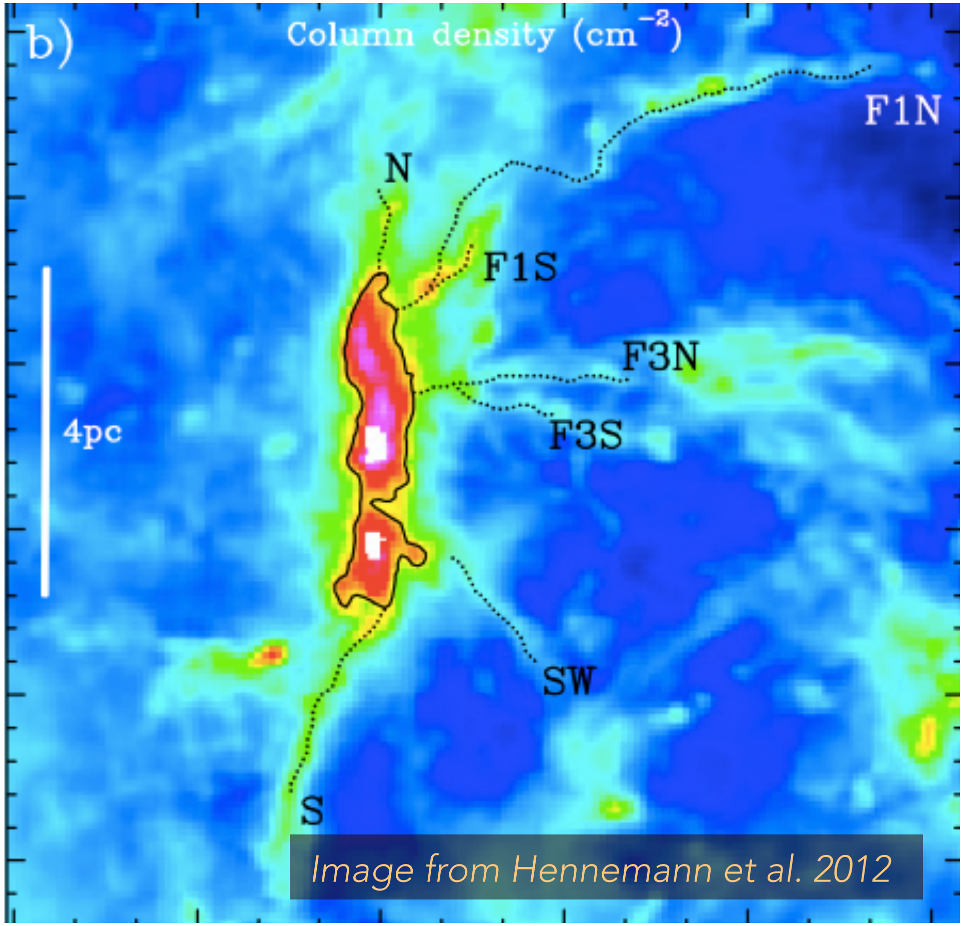


- Bimodal distribution for difference between B_{core} and the $B_{filament}$ and $PA_{filament}$

- No correlation between B_{core} and $PA_{outflow}$

Zhang, Qiu, Girart, et al. 2014, submitted

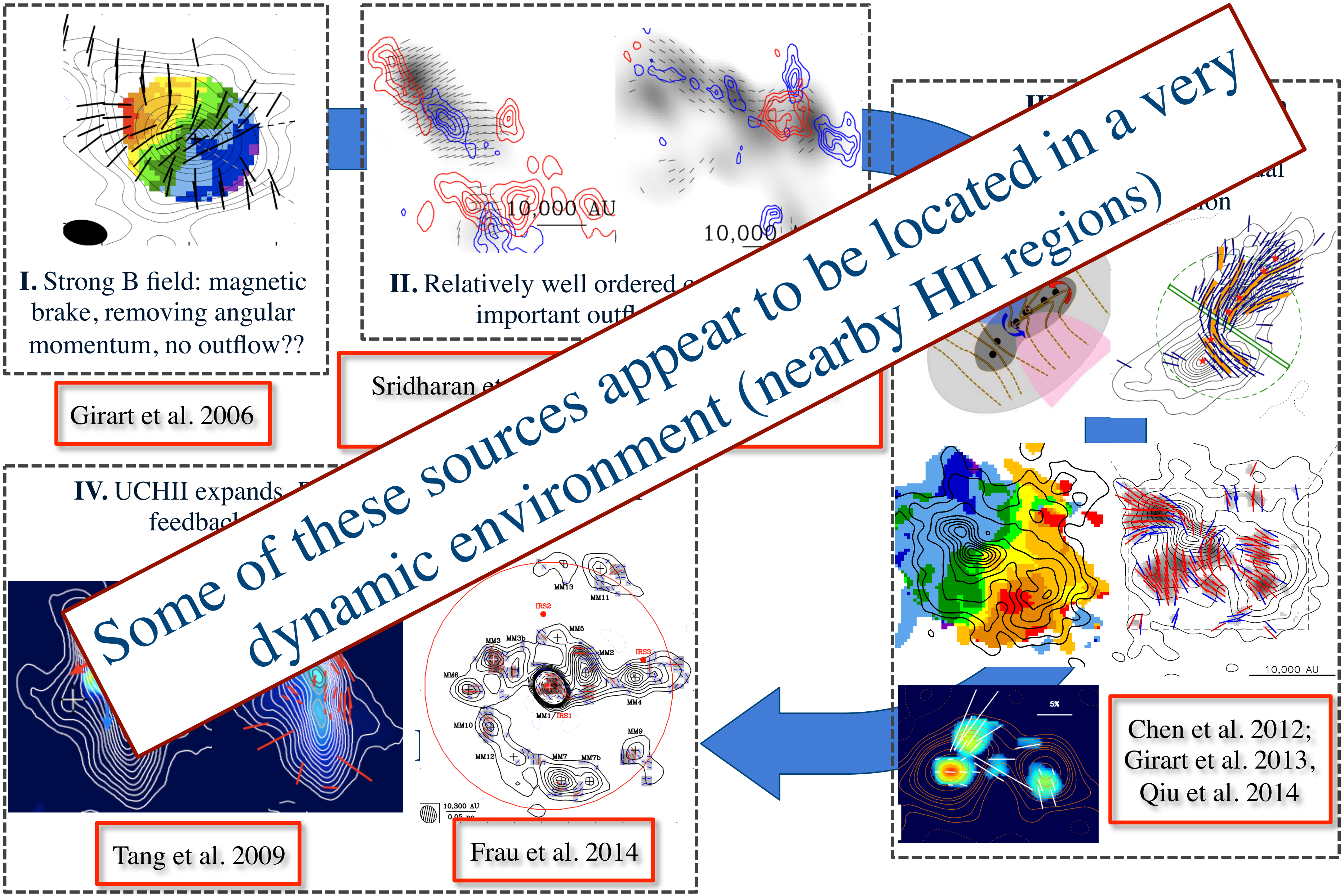
SMA Legacy project: Filaments, Star Formation & Magnetic Fields



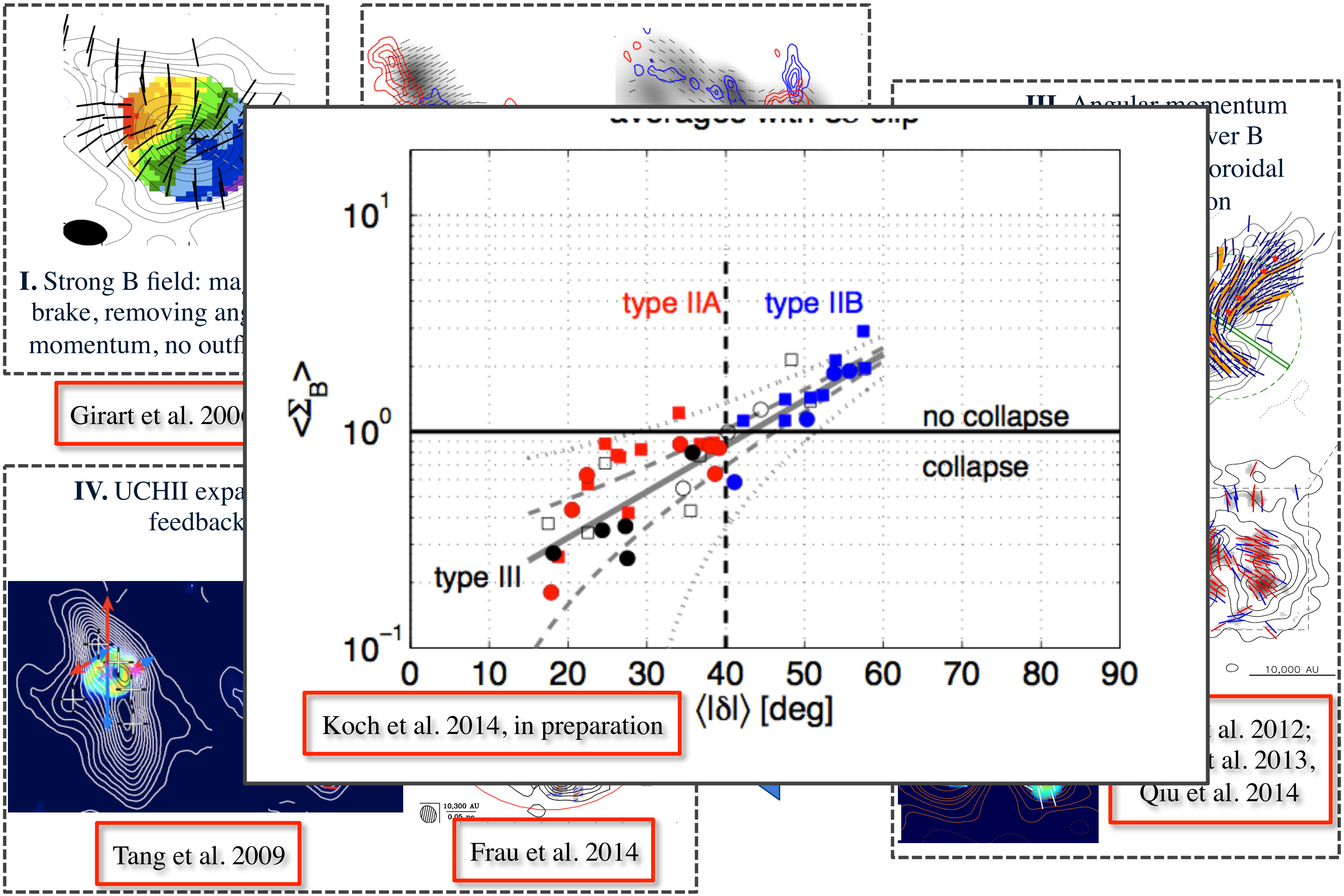
- Filamentary molecular clumps from:
  - Surveys of IRDCs
  - Cygnus-X region
  - Galactic Plane with BOLOCAM
  - polarization with SCUBA
- Continuum flux limit of 0.5 Jy/beam (interfero.)
- Most of sources in a relatively nearby distances (1-4 kpc)
- Earliest stages of star formation: avoid HII regions
- Several cores observed for some of the filaments
- Frequency tuning to observe good molecular tracers of:
  - the core's kinematics ($H^{13}CO^+$ 4-3, SO lines),
  - hot core lines (CH_3OCH_3, CH_3CH_2CN))
  - outflow activity (CO 3-2, SiO 8-7)

DR 21, NGC6334, NGC2264C, G14.2, G34.4

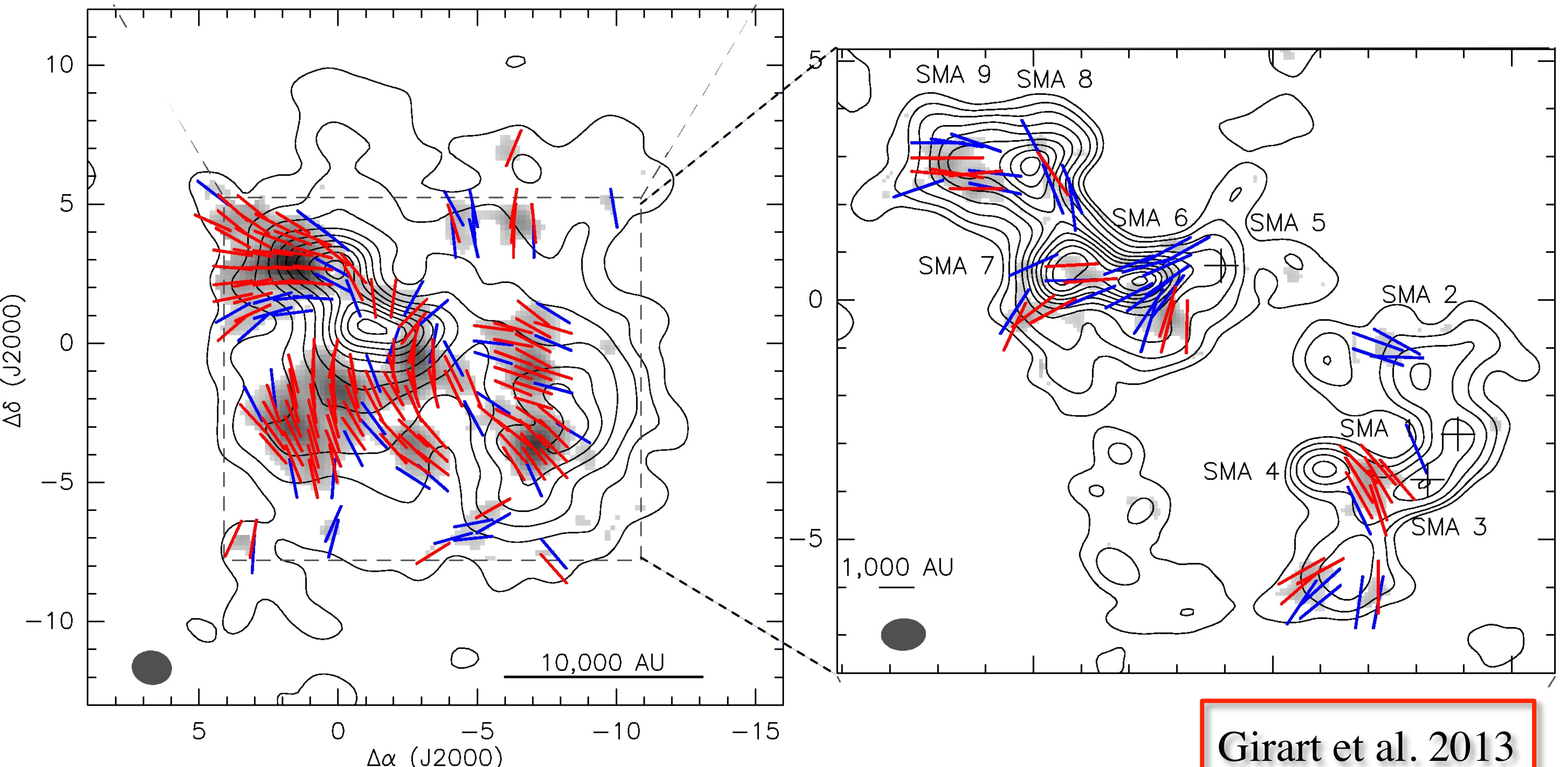
A sequence for magnetic field evolution in massive cores



A sequence for magnetic field evolution in massive cores



DR21(OH): B-field maps at 10^4 to 1000 AU

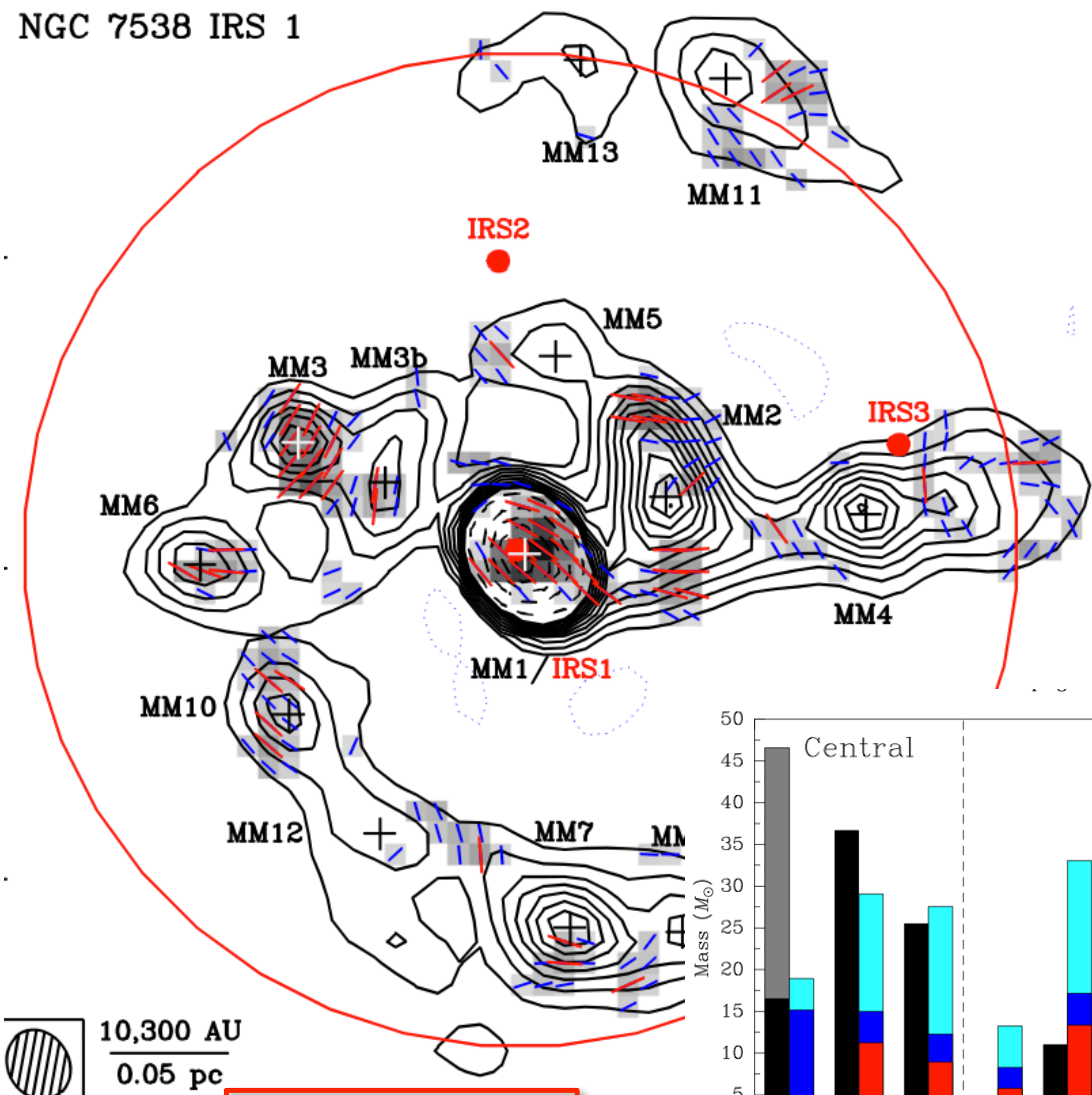


Girart et al. 2013

Complex B morphology: difficult to understand what is going on

High fragmentation observed (see Palau et al. 2013)

NGC 7538 IRS1: complex magnetic field



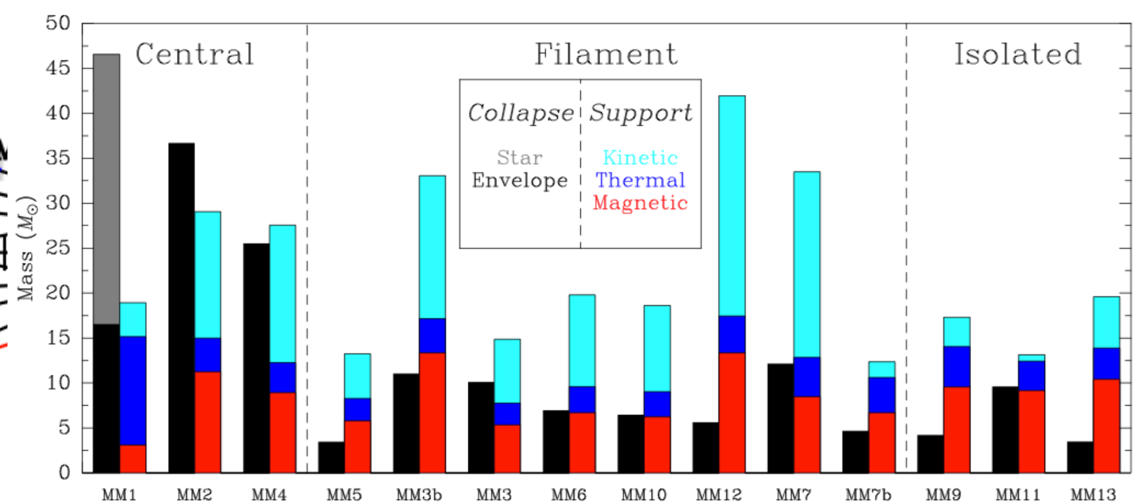
D = 2.65 kpc

IRS 1, 2, 3 UCHII

8, 5, 0.6 10^4 $L_\odot$

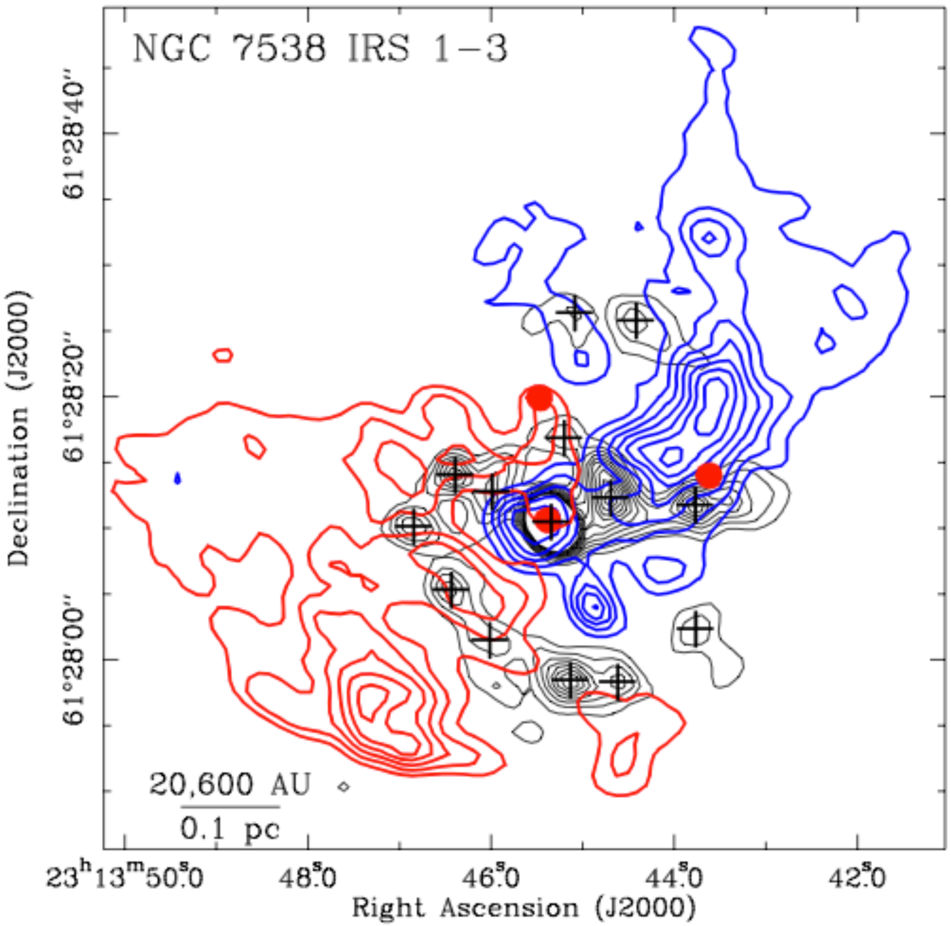
885 μm dust traces a clumpy and filamentary structure around IRS 1

M_{clump} ~4-37 $M_\odot$

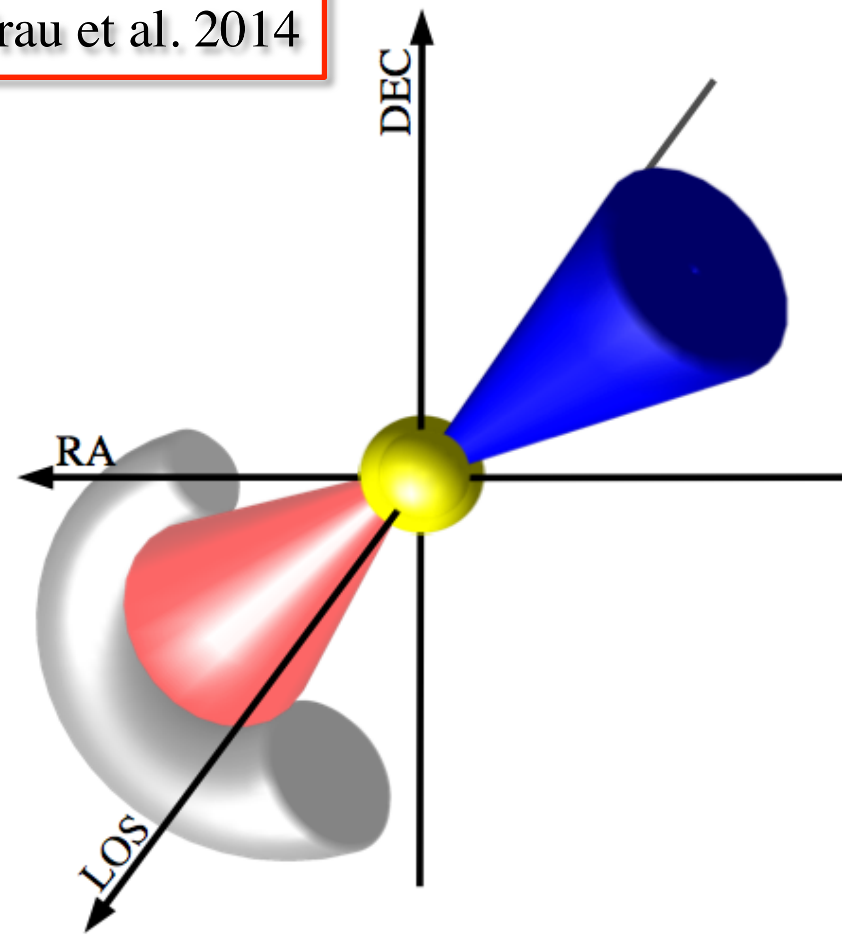


Frau et al. 2014

NGC 7538 IRS1: expanding filament



Frau et al. 2014



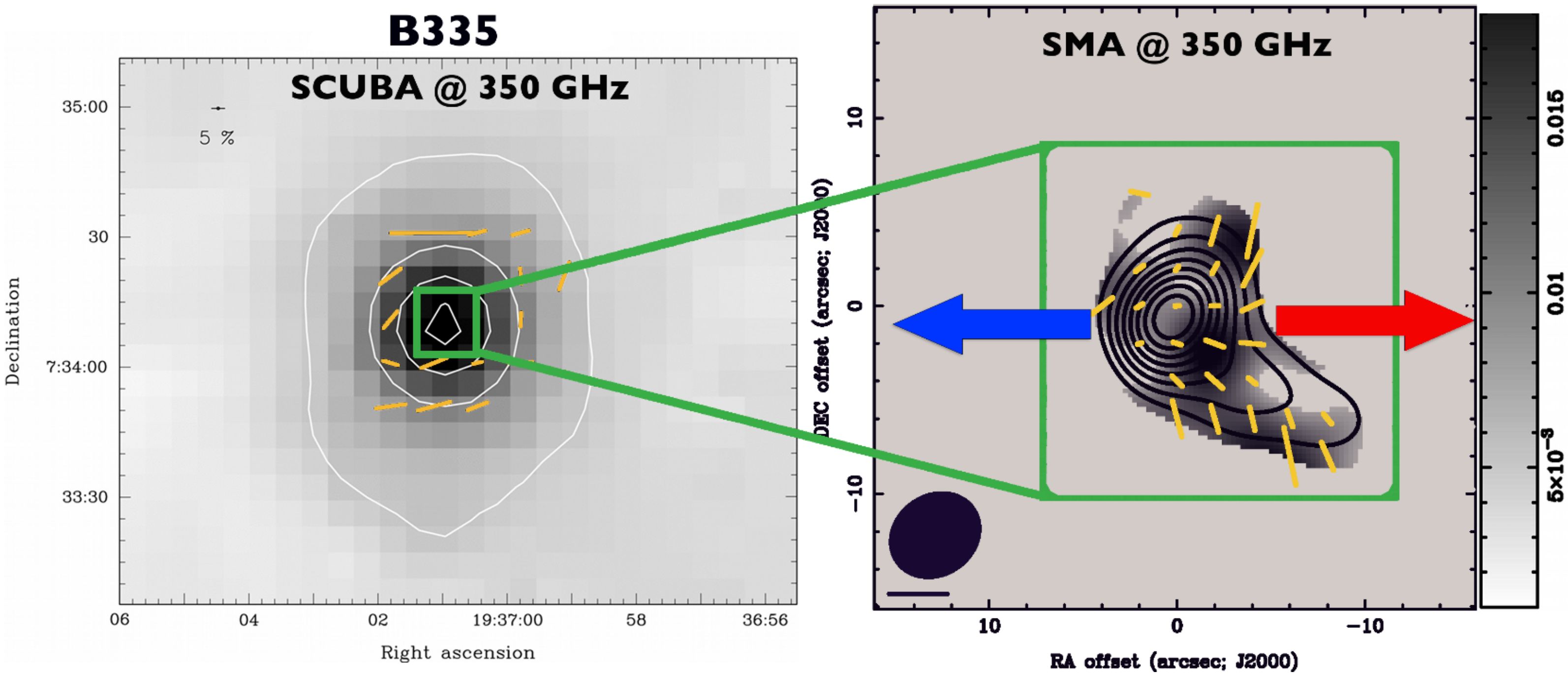
The powerful outflow powered by IRS 1 has enough energy to push the filament (in a snow-plow way?)

SMA detects dust polarization in B335

Maury et al. 2014, in preparation

Facts

Yen et al. (2010, 2011) : kinematical analysis of B335 envelope with SMA observations down to ~400 AU.
Infalling motions are detected at ~1000 AU scales in the flattened envelope,
But the C18O emission shows no signature of rotation down to a radius of ~400 AU in the equatorial plane.
The upper limit of the specific angular momentum at the small in B335 is one order of magnitude smaller than the angular momentum around other protostellar sources,
+ the specific angular momentum in B335 decreases from scales ~10000 to 300 AU.



Early collapse stage + low specific angular momentum + collimated outflow + lack of multiplicity + lack of large circumstellar disk

=

B335 a very strong candidate for magnetically-regulated collapse.

Conclusions

- **SMA polarimeter has allowed to make a major progress in the understanding of magnetic fields role in the star forming cores**
- General trend: magnetic fields appear to be organized rather than chaotic: dynamically relevant
- There is a diversity of magnetic field configurations both in low and high mass star forming cores but ….
- At least in the low mass cases, the field morphology agree with the expected configuration as shown by simulations
- It seems that there is a significant change of B field properties before/after onset of HII