Jets and Outflows: From Star to Cloud

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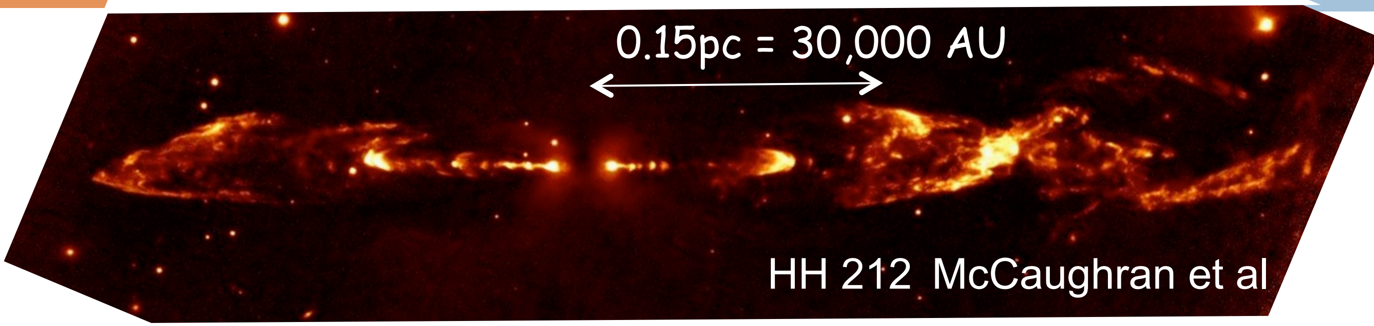
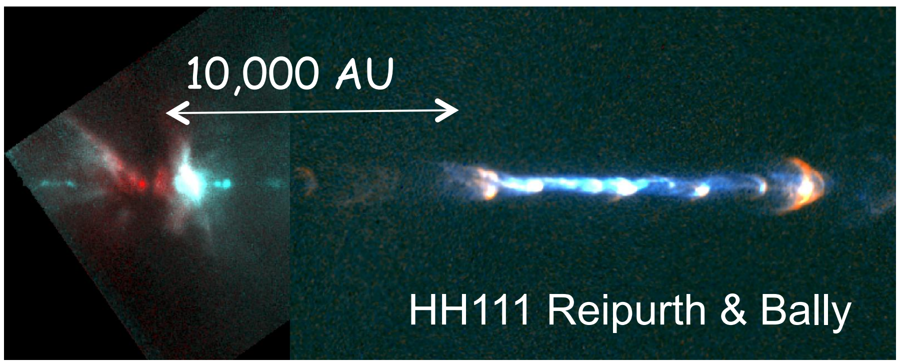
U. Rochester, Obs Paris, DIAS, Yale U., INAF, U. Colorado, IPAG, Thuringer L., U. Vienna, Rice U., IC London, UNAM

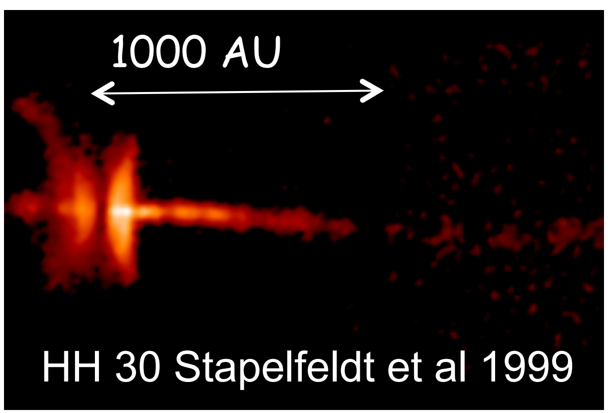
Where do we see jets ?



Class 0 Protostars



Evolved Class 1 Protostars



Class 2 Disk only

- ***Universal across evolutionary stages***
  Accretion-powered Mjet/Macc ≈ 0.1
  (Edwards+2006, Antoniucci+2008)

- ***Universal in M* : from 24 Mjup to 10 M***
  Vjet ≈ 100-800 km/s

Why Do Jets Matter ?

- Invoked to solve several major issues in SF:
  - Low SFE and SFR in turbulent clouds

    Cf. chapters by Padoan, Krumholz…
  - 30% Core to Star efficiency

    cf. chapters by Offner, Padoan…
  - Removal of star/disk angular momentum

    cf. chapters by Li, Bouvier, Turner

- Also:
  - May affect planet formation and photoevaporation

    cf. chapters by Dutrey, Pontoppidan, Alexander, Gail…
  - Unique info on source binarity, variability, axis precession

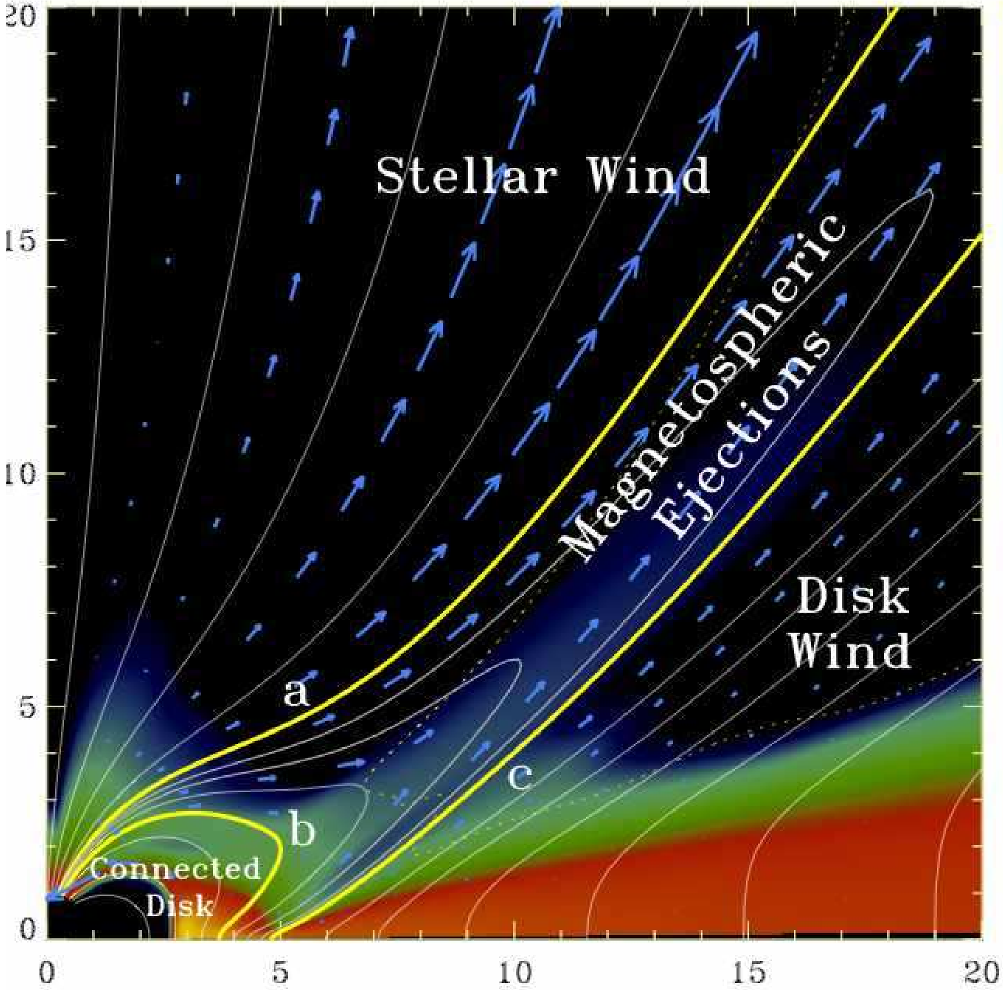
    cf. chapters by Reipurth, Audard…

Remarkable progress since PPV

- First observational access to
  - New spatial ranges <50 AU to >10pc
  - New λ ranges (Xrays, IR, submm)
  - Detailed proper motions over > 10 yr
- Large-scale collaboration networks
  - JETSET (2005-2008) EU (11 institutes)
  - JETPAC (2008-current) USA-UK (5 institutes)

Combining observations, MHD simulations & theory, and high-energy density lab experiments (HEDLA)

Small Scales: 0.1-100 AU

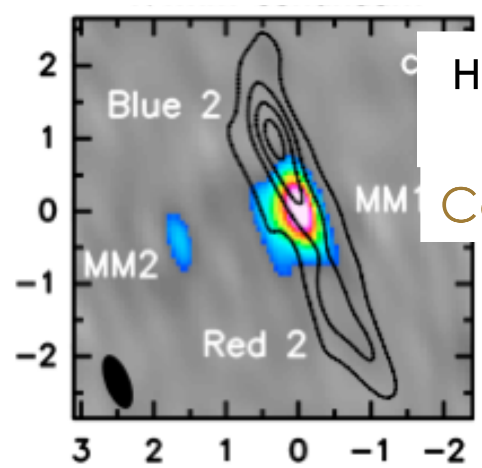


Zanni & Ferreira 2013, A&A

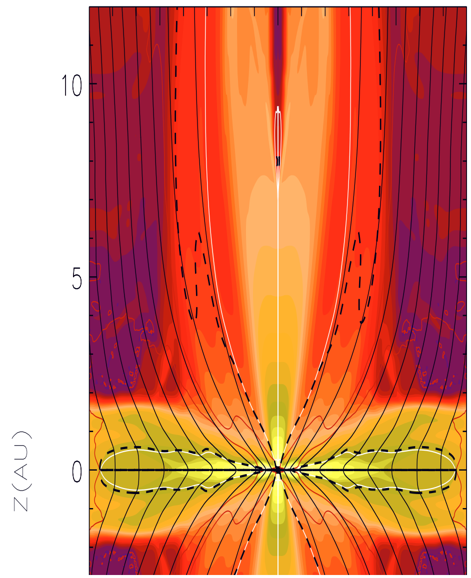
Jet angular momentum and launch process

Jet Collimation

- Same width and collimation scale in class 0 as class 2 jets ! (Cabrit et al 2007)
  - *Not hydro collimation by envelope*
- Need disk B field for jet collimation !
  - MHD disk wind is most efficient collimator.

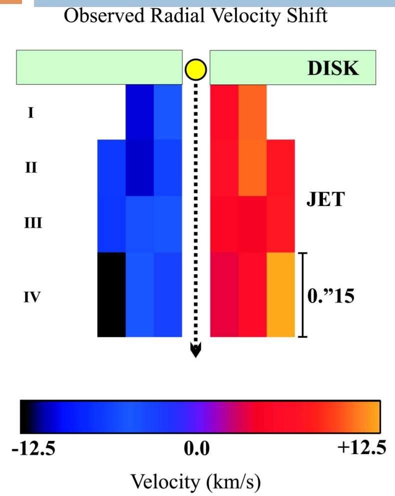


HH212 jet at PdBI
0.3" across jet
Codella etal 2007

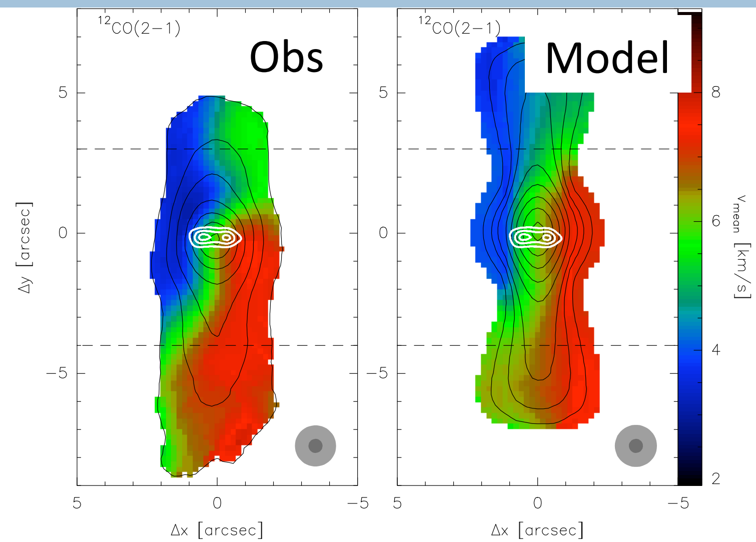


Meliani et al 2006, A&A

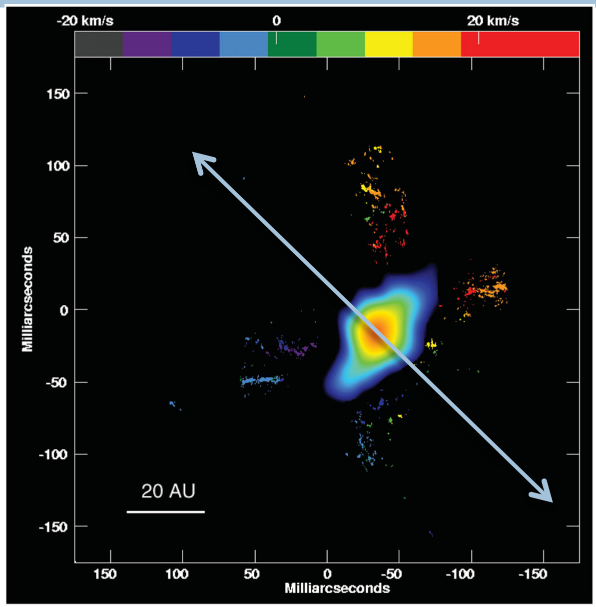
Jet rotation



Class 2: DG Tau with HST (Bacciotti+2002, Coffey+2007)



Class 1: CB 26 in CO with PdBI (Launhardt et al 2009)



Massive Class 0: Source I SiO maser VLBA (Matthews et al 2010, Vaidya etal 2013)

Stationary MHD disk winds predict (Anderson+03. Ferreira+06)

$$2rV_\phi\Omega_0 = V_p^2 + 3\Omega_0^2 r_0^2$$

➔ suggests r0 ≈ 0.1 - 5 AU for all candidates so far

➔ Feedback on disk structure in the region of formation of terrestrial planets

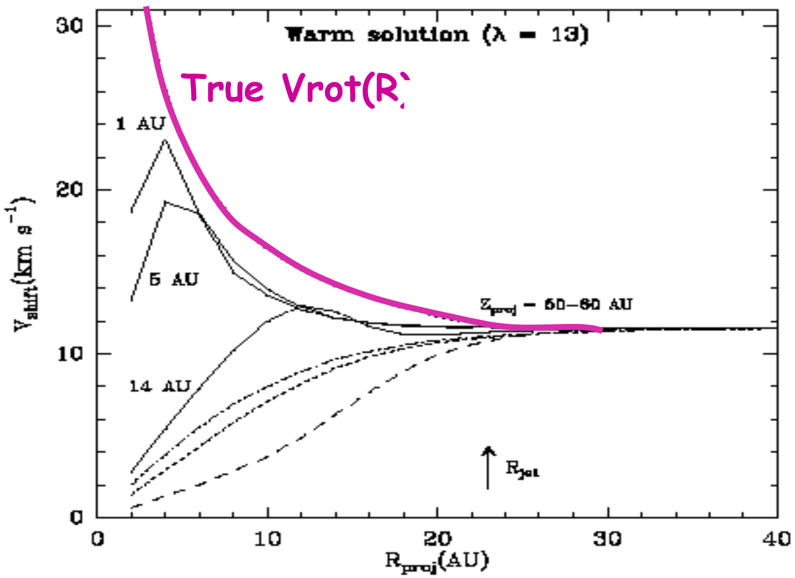
Questioning Jet Rotation

- Puzzling observations (RW Aur, HH212…)
  - Opposite rotation sense of Disk / Jet or Jet / Counterjet
  - Variability in a few years

  (Cabrit et al 2006, Codella et al 2007)
  (Coffey et al 2012, Davis etal 2001)

- Proposed interpretations
  - Shocks in MHD disk wind (Fendt 2011, Sauty 12)
  - Jet precession, orbital motion, asymmetric environment (Cerqueira etal 2006, Lee et al 2010, Soker et al 2005, Correia 2009)
  - **Beam dilution of jet rotation signatures ?** (Pesenti et al 2004)

- ***To be continued*** …



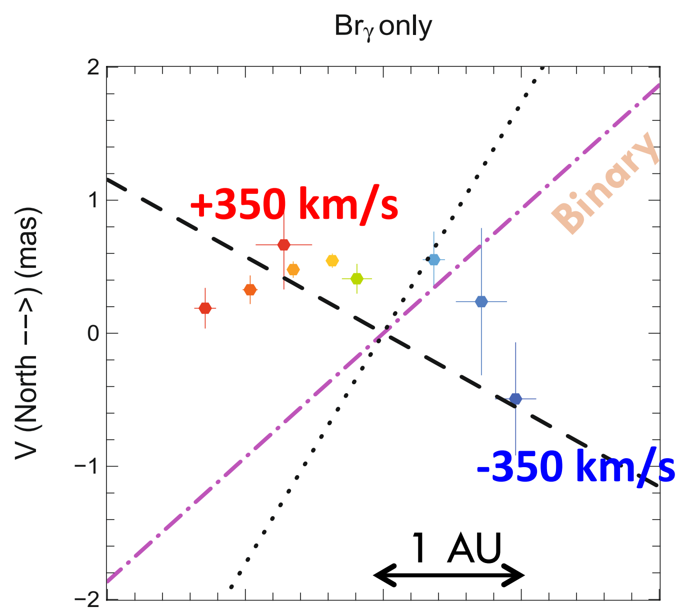
Pesenti et al. 2004, A&A

Resolving Central Engine in Brγ

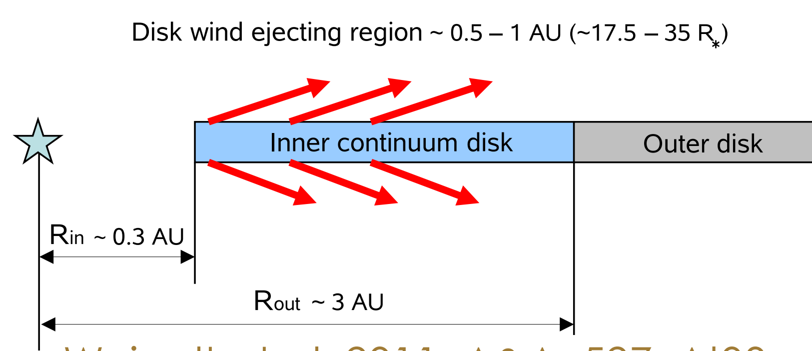
- Interferometric sizes
  - 0.1 AU < R(Brγ) < 2μm continuum
- Spectrally resolved interferometry
  - Bipolar jet in outbursting Herbig Be

  Benisty et al. 2010, A&A 517, L3
- Fitting of flux, visibility, and phase in Herbig Be MWC297
  - rotating MHD disk wind favored over polar stellar wind
  - Launch zone 0.5 – 1 AU

  See also Malbet+2007; Rousselet-Perraut+2010 for Hα in AB Aur



Benisty et al. 2010, A&A 517, L3

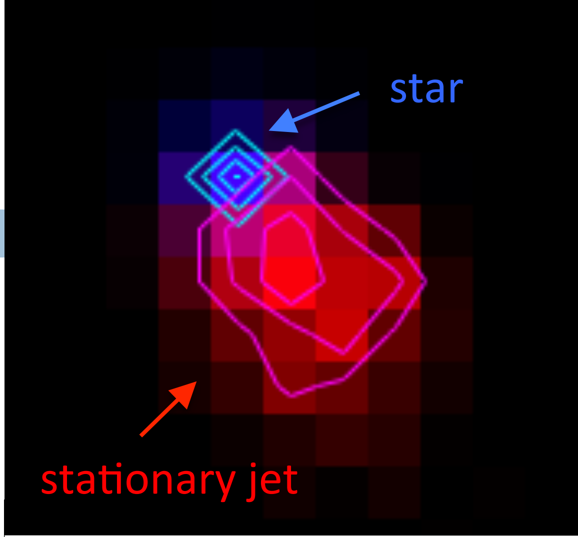


Weigelt et al. 2011, A&A 527, A!03

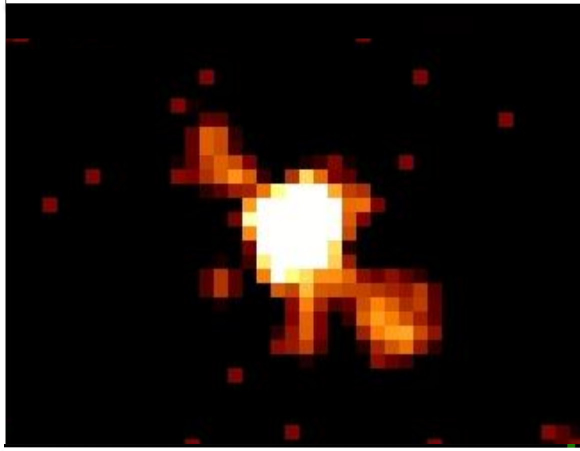
X-Ray Jets

- From 30 AU to pc scales
  - T_X implies Vs ~ 500 km/s >> optical lines
  - Tenuous fast stellar wind?
- Innermost structures seem stationary
  - Collimation shock ? Magnetic heating? (See poster by Schneider et al.)
  - Impact on disk irradiation

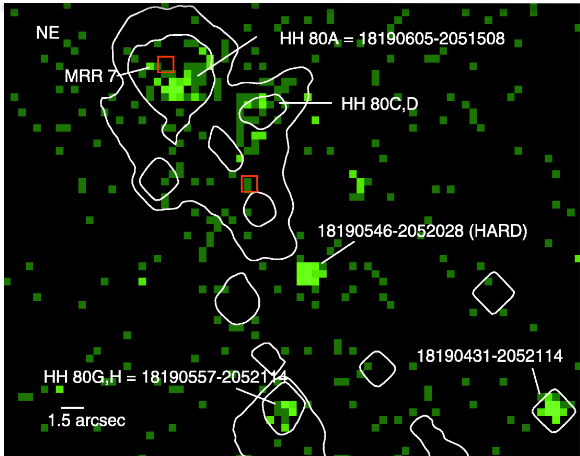
DG Tau
30 AU
Güdel+ in prep



DG Tau
1200 AU
Güdel+ 2008 A&A,478,797

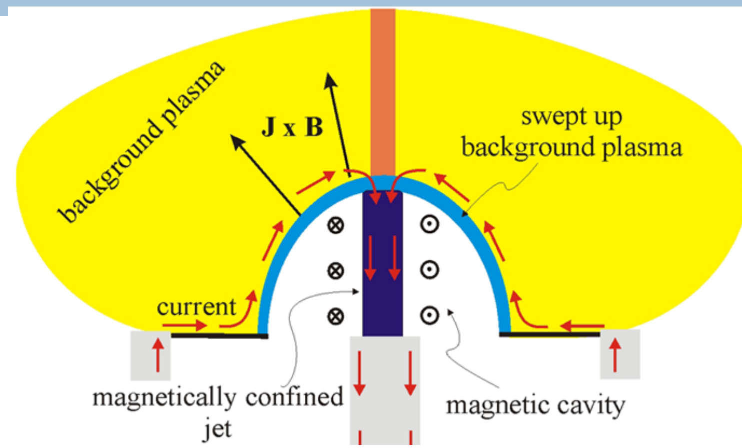


HH 80
2.5 pc
Pravdo+ 2004 ApJ, 605, 259

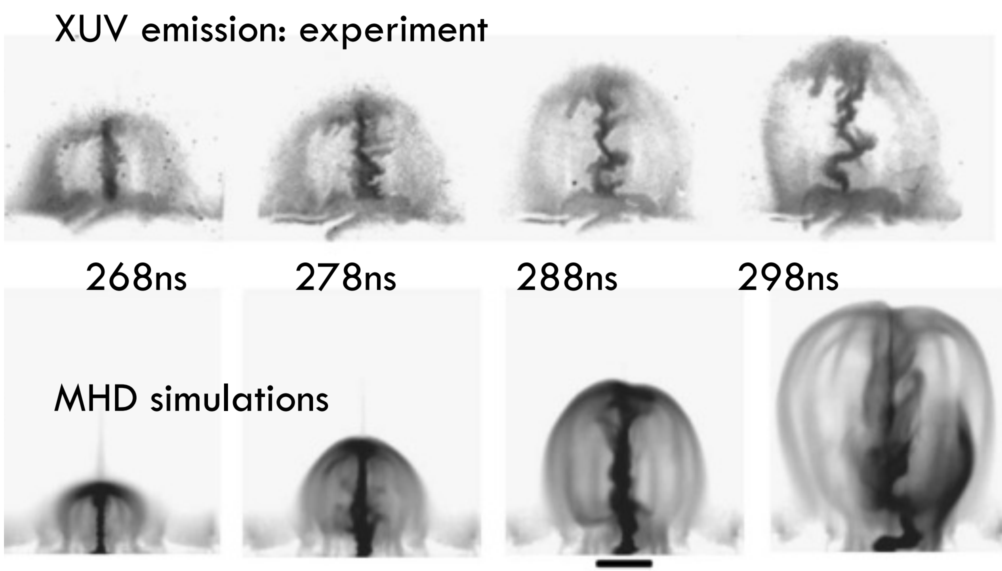


Magnetic Tower (HEDLA)

- Magnetic Driven Cavity
- Axial Jet: hoop stress
- Cavity confined by ambient medium
- *Kink unstable*: fast collimated clumps



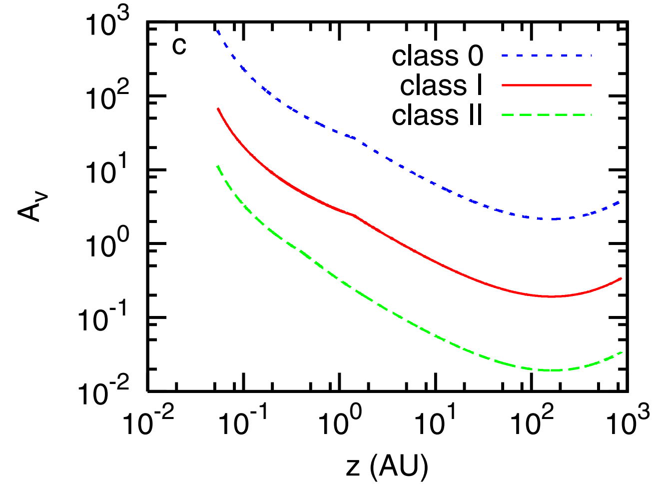
M ~ 10 β ~ 1 ReM ~ 100

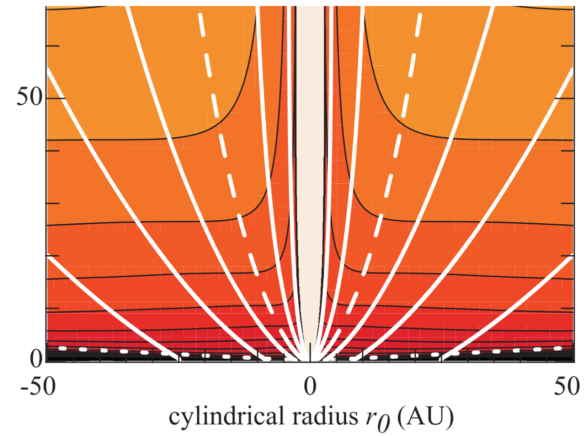


Lebedev et al, MNRAS (2005), Ciardi et al, ApJL (2009), Suzuki-Vidal et al, PoP (2010, 2012)

Impact on Planet Formation

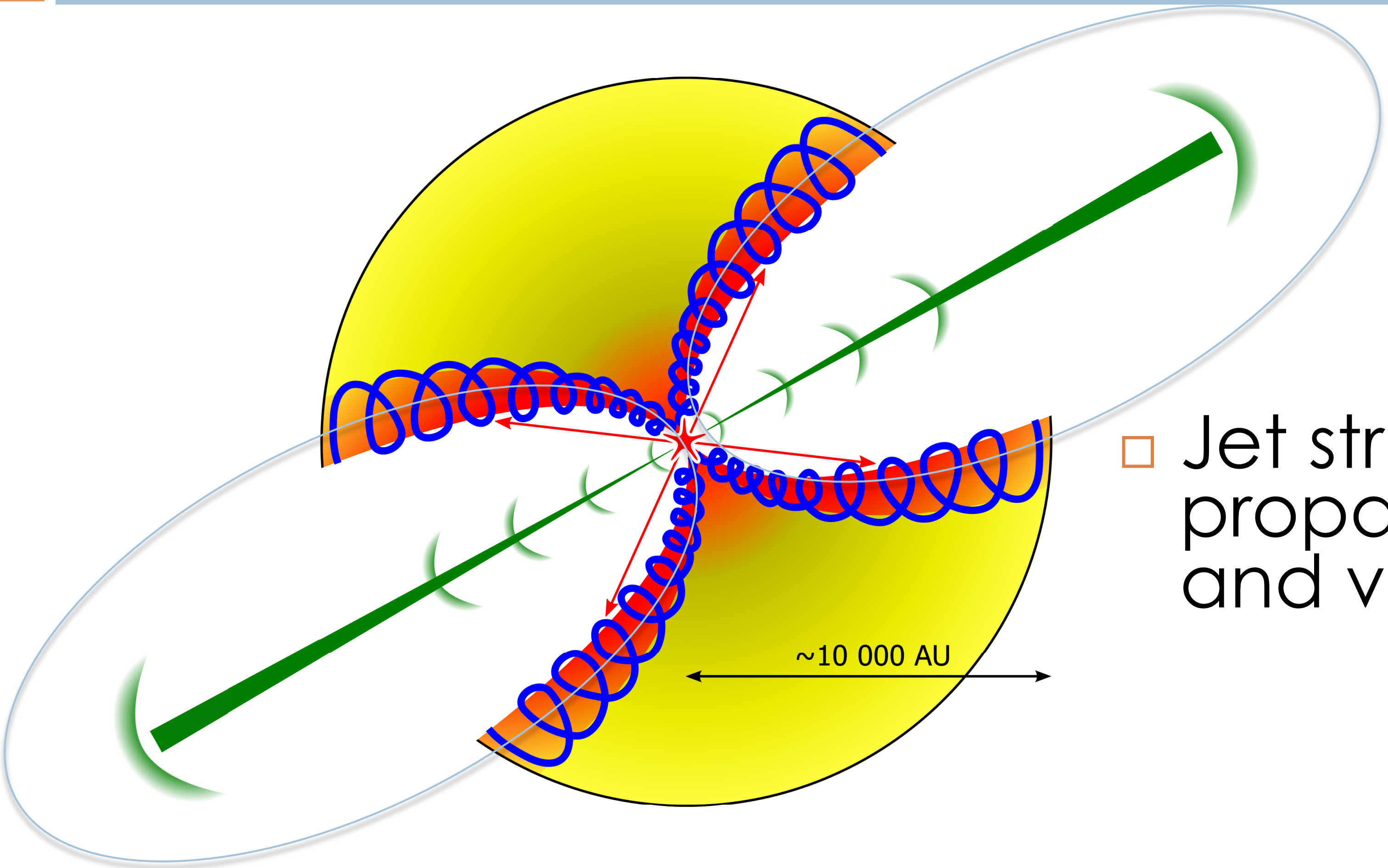
- Disk irradiation
  - X-rays/UV from collimation shock
  - Shielding by (dusty) disk wind
- MHD disk winds from 0.1-10 AU
  - radial transport at sonic speed
  - Lifting and melting of solids
  - Planet migration ? (eg. Terquem 2006)





Panoglou et al 2012, A&A

Intermediate scales 100 AU – 1 pc

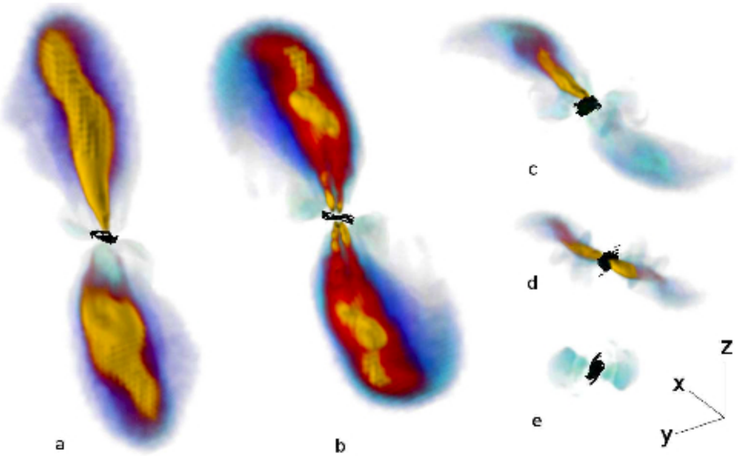


- Jet structure, propagation and variability

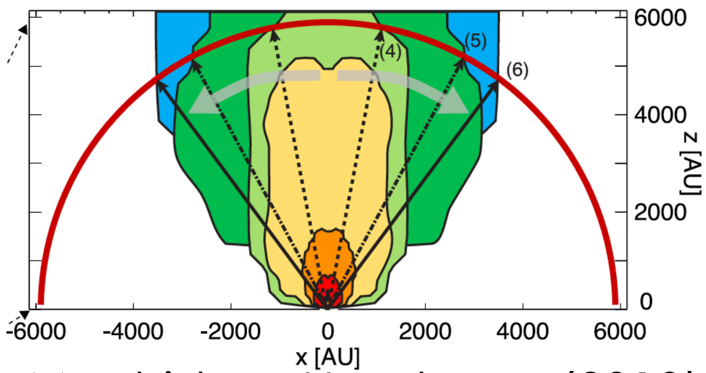
Visser et al 2012, A&A

Core to star efficiency

- 3D MHD collapse simulations
  - **Mstar ≈ 50% Mtot** for B-Ω angle up to 50°
  - Protostellar MHD ejections *determine final stellar mass?*
  - Outflow base broadens in time
    - See also Offner+2011



Ciardi & Hennebelle 2010, MNRAS

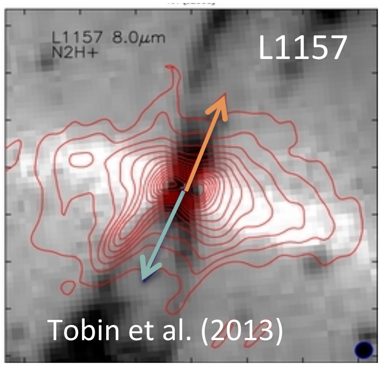


Machida & Hosokawa (2013)

Outflow-Envelope Interactions: widening of outflow cavity with time

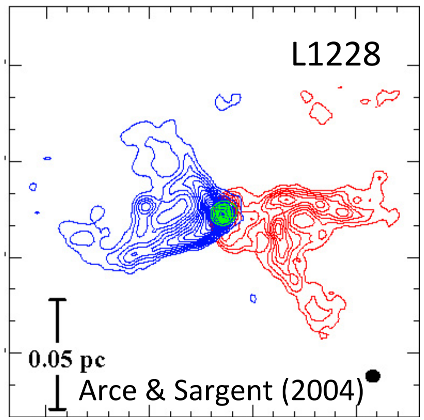
Time

Class 0



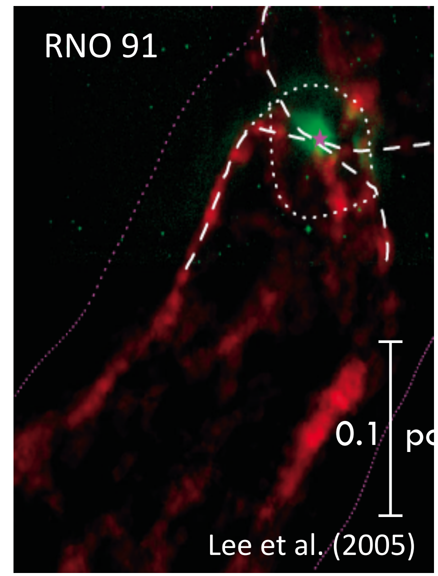
Cavity o.a. ~ 20-50º.
Outflow starts entraining dense envelope

Class I



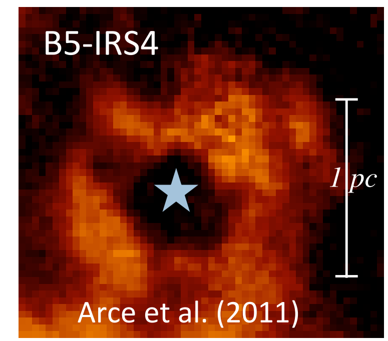
Cavity o.a. ~ 80-120º.

early Class II



Very wide cavity
o.a. > 100 -130 º.
Low-density (or no) envelope left

late Class II



Quasi-spherical shell
Not clear how common this is.

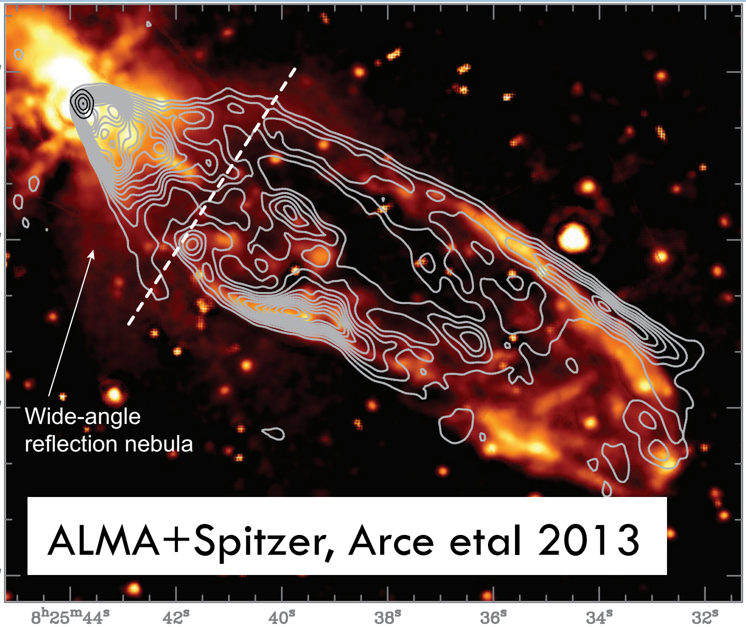
Wide-angle component(s)

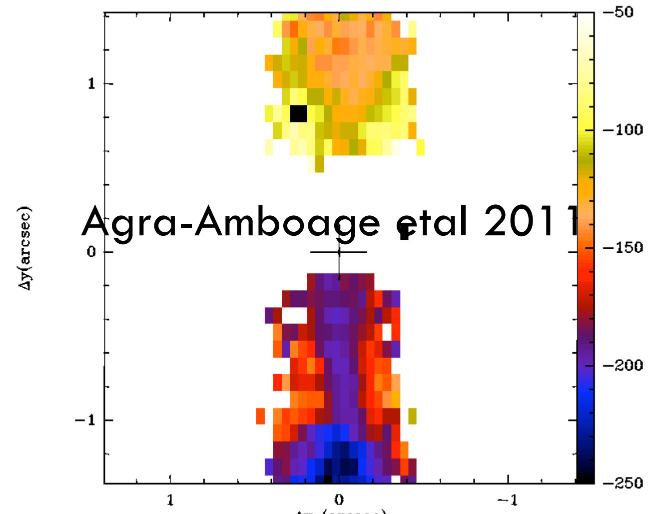
- Invoked for CO cavity expansion
  (cf. Arce et al 2007, PPV)

- Must be slower than jet
  - Highly curved bowshocks
  - Velocity decrease at jet edges

  (Bacciotti+2000, Coffey+2008, Agra-Amboage +2011)
  - *Not a « classical » X-wind*

- Possible origins
  - Slower disk wind ?
  - Outflow from 1st core phase ?

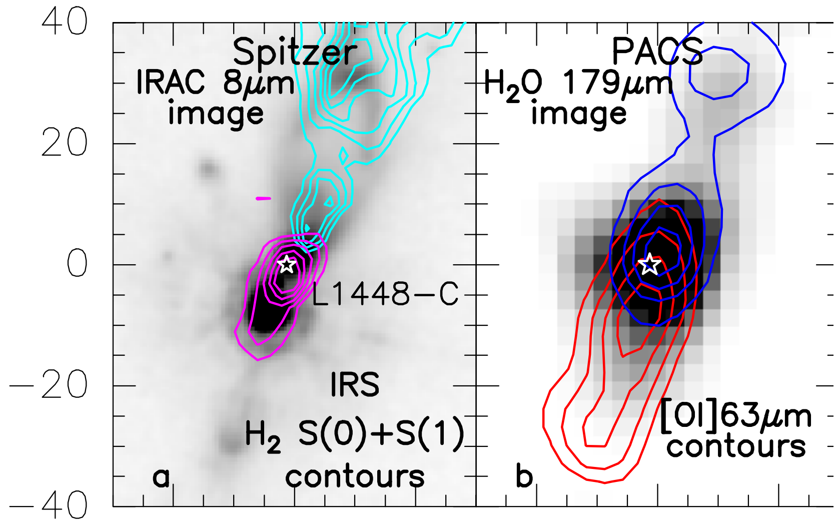




Multiple jet components

- *Spitzer & Herchel*: Jets often have both atomic & molecular components
- with range of V and T
  - Shocks
  - range of launch radii?
- Need to revisit mass fluxes
  - Outflow power vs Lacc !

Takami+2004,2007, Beck +2008, Garcia-Lopez+2008, Davis+2011,Giannini +2011,Nisini+2013…



Giannini+ 2011, Nisini+ 2013

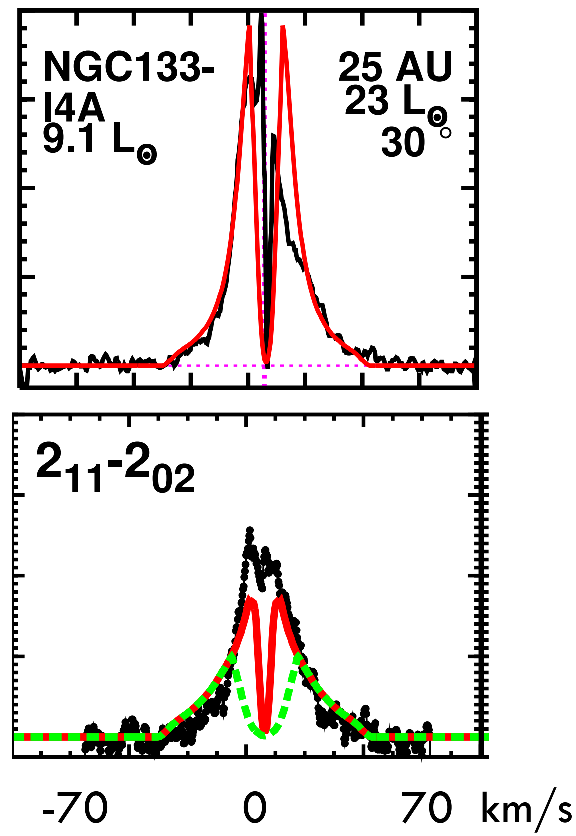
Class 0 jet L1448

Chemical diagnostics of R_{launch}

- Rlaunch > Rsub Fe, Si, Ca depletion at small z,V

  (Podio+2006,2011, Agra-Amboage +2011, poster by Giannini et al.)

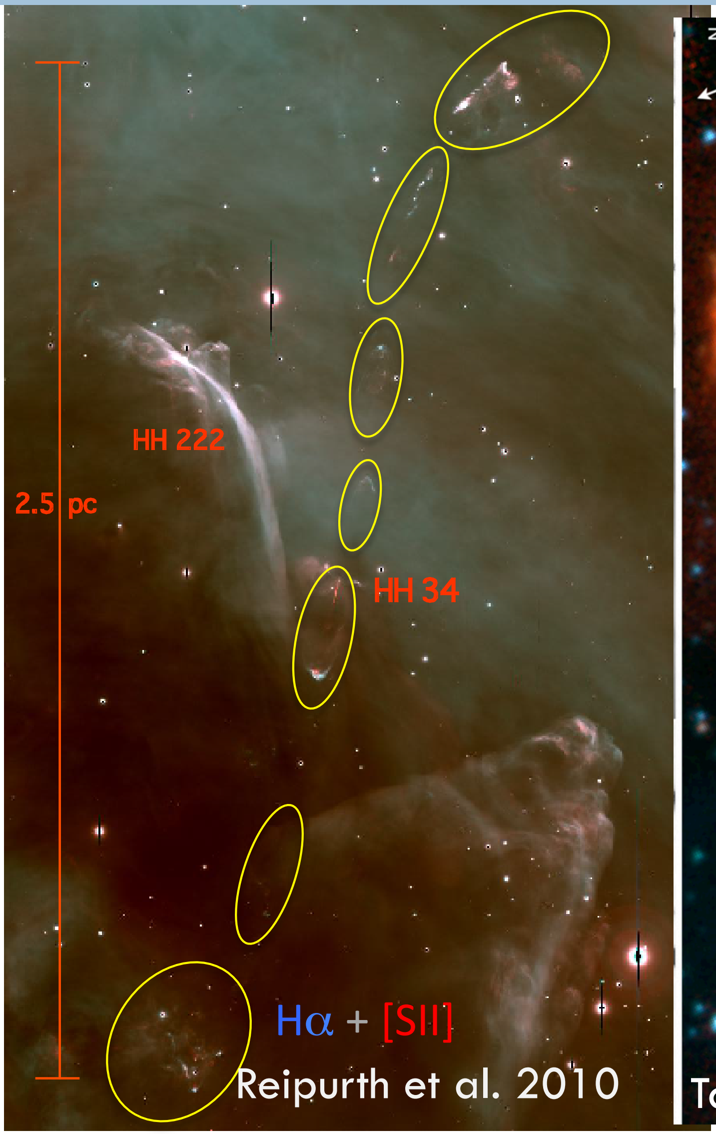
- Chemical models of dusty MHD disk winds (Panoglou et al 2012)
  - Molecules can survive !
  - Reproduce Herschel H_2O broad component in Class 0
- Next step: CO with ALMA, H_2 with AO



Models: Yvart et al. 2013
Data: Kristensen et al. 2012

Jet variability record

- Knots & Bows = internal shocks
  - Velocity and/or angle variations. **not pure Mdot var**
- Angle variations:
  - S-shaped precession 3000-50,000 yrs
  - **Orbital motion:** *HH211, P=43yrs; HH111, P=1800 yrs* Lee+2010, Noriega-Crespo+2011
    - constrain binary mass and separation



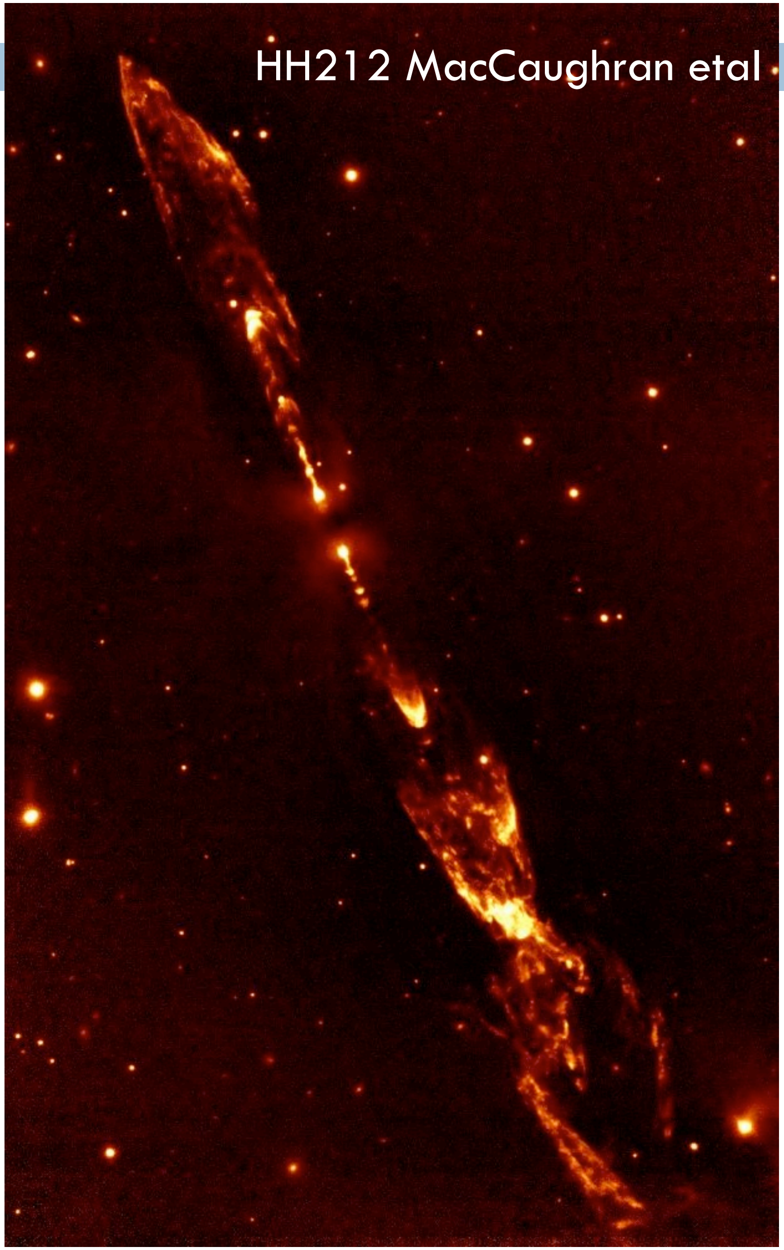
Velocity Variability

- 3 preferred time scales

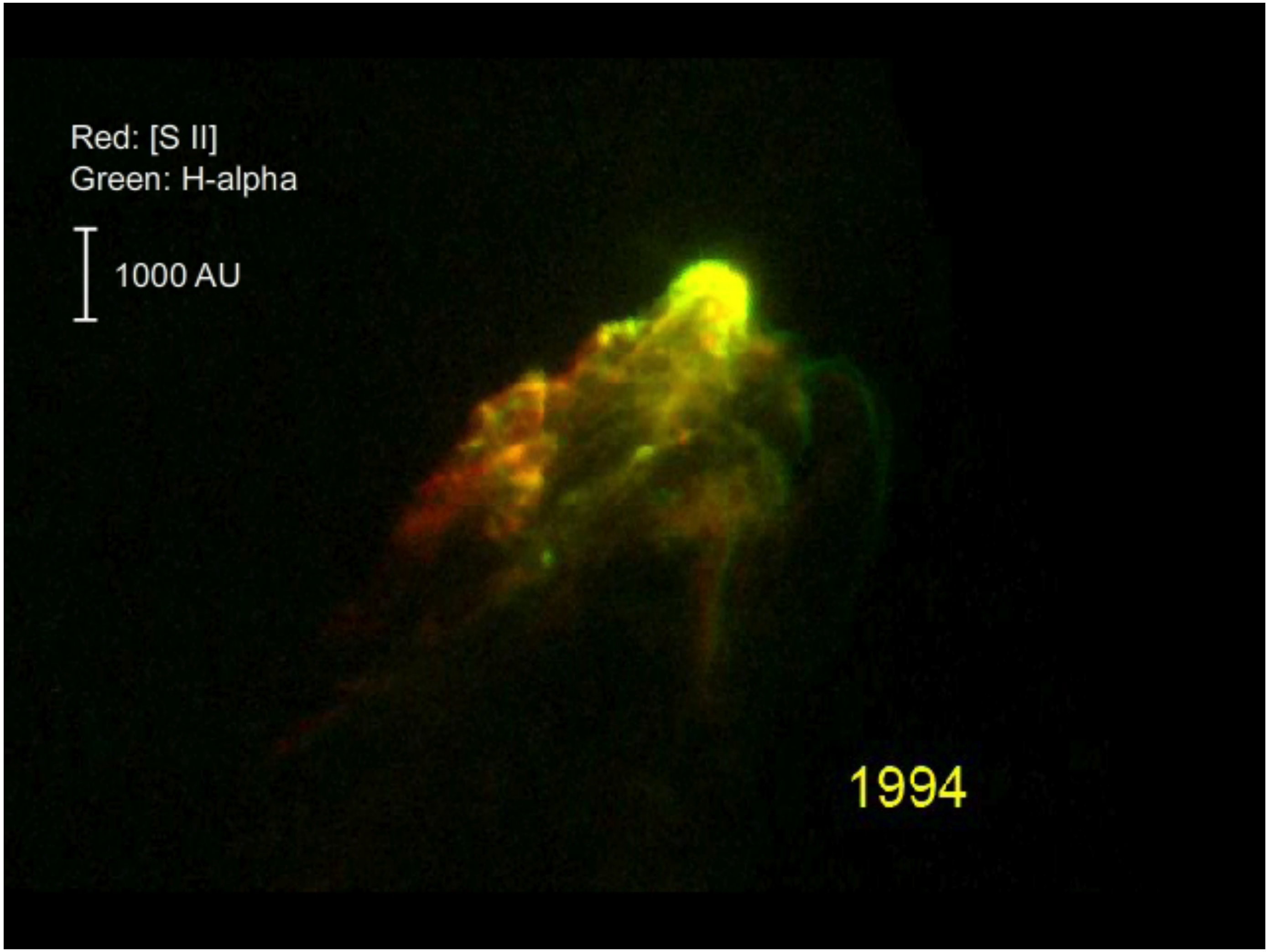
  ≈3-10yrs, ≈100yrs, ≈1000 yrs
  ΔV of 20-140 km/s

  Raga+2002,2011; Hartigan+2007; Agra-Amboage+2011…

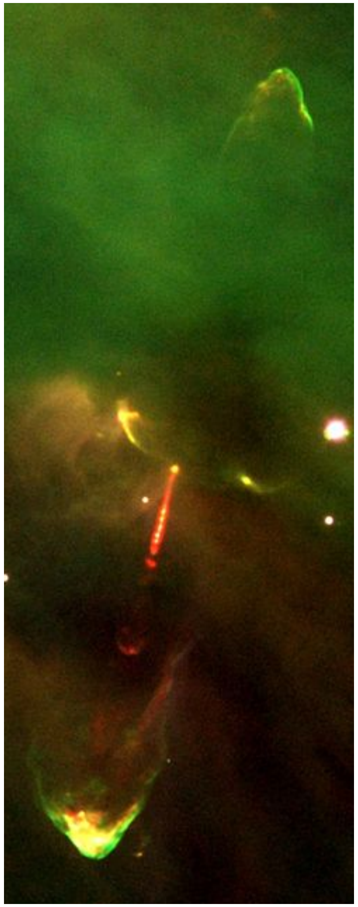
- May probe
  - Stellar magnetic cycles
  - perturbations by companion
  - link with EX Or / FU Or outbursts ? (cf. Audard etal. Chapter)

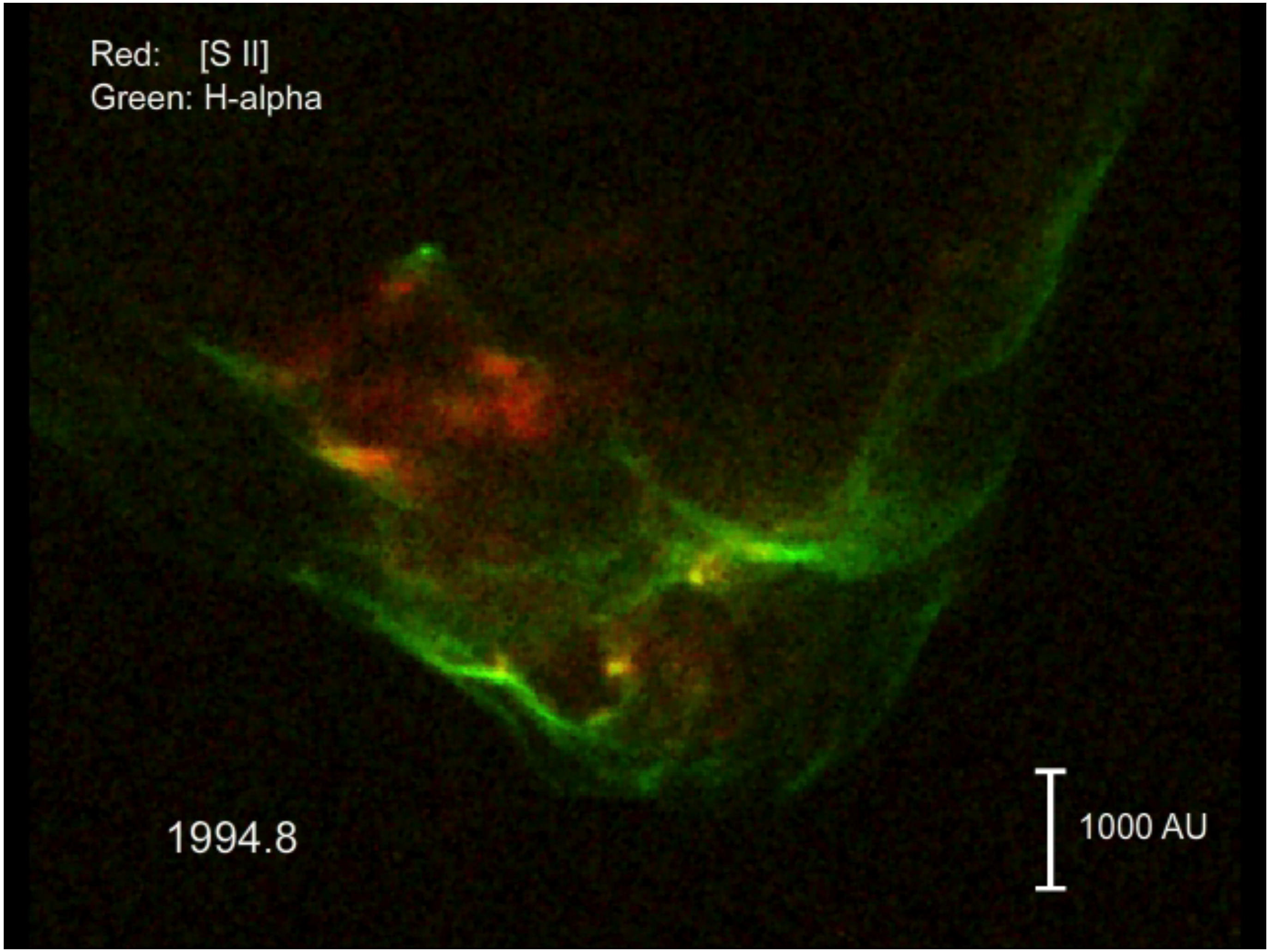


HH1: Clumps & Cloud Entrainment



HH37: Clumps & Mach Stems

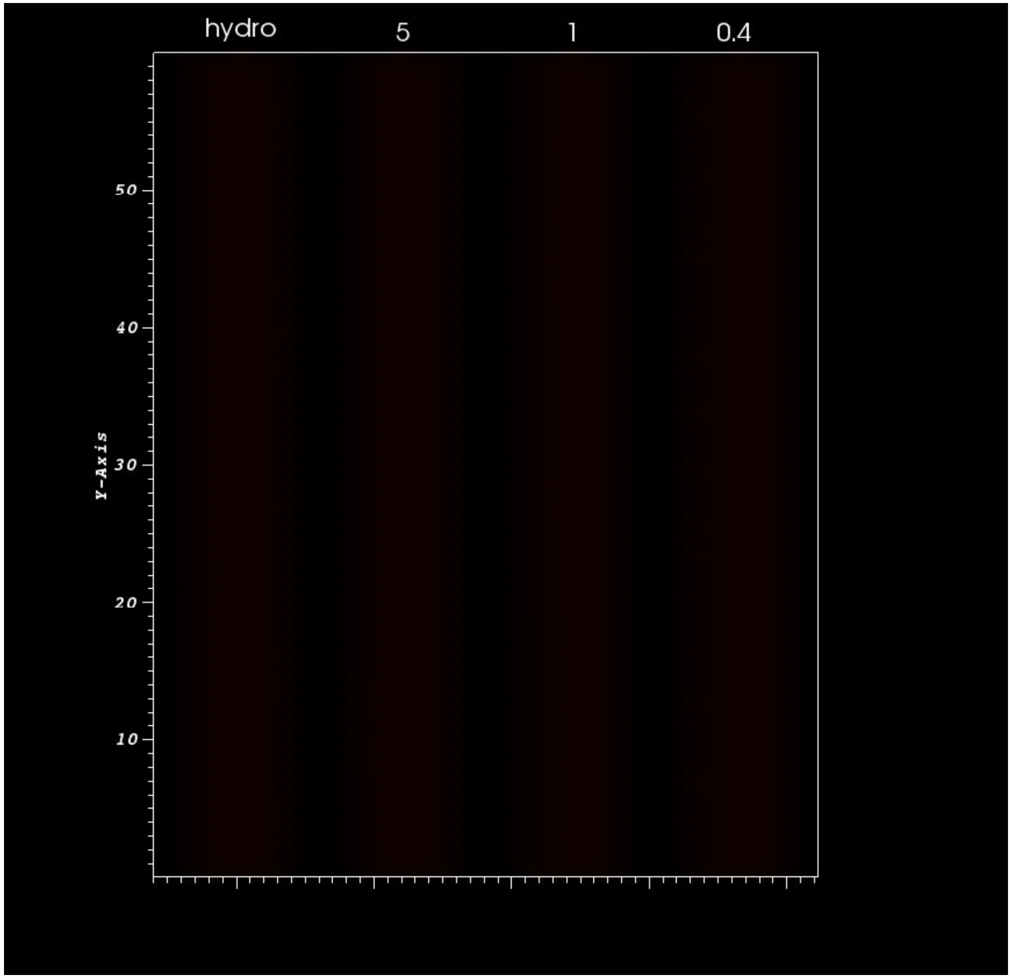




MHD Jet Synthetic Observations

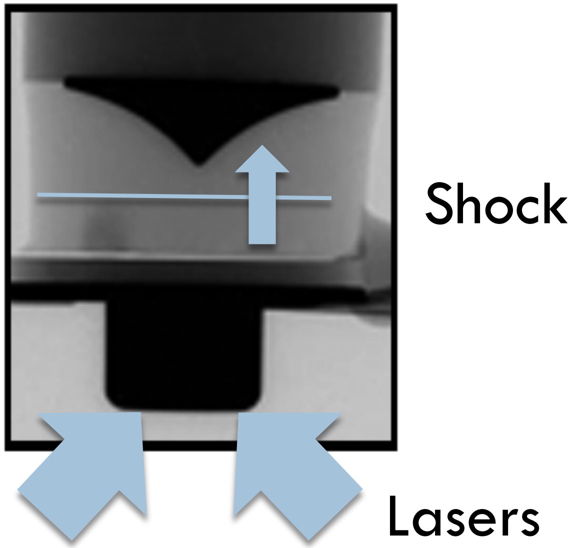
- Non-equilibrium ionization
- AMR resolves cooling zone
- Hα & [SII] maps

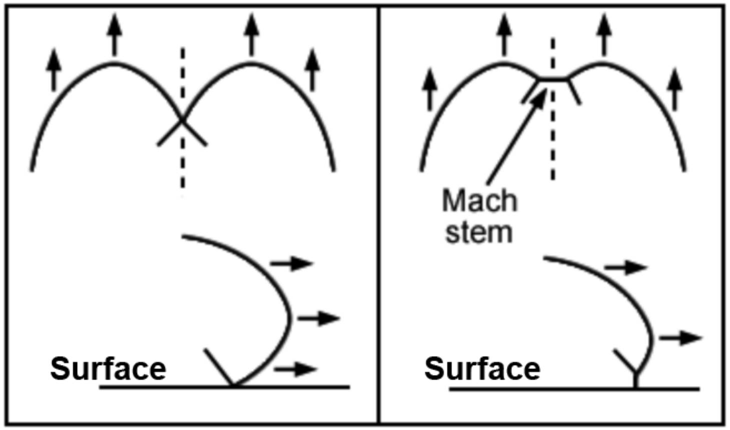
(Hansen et al13)

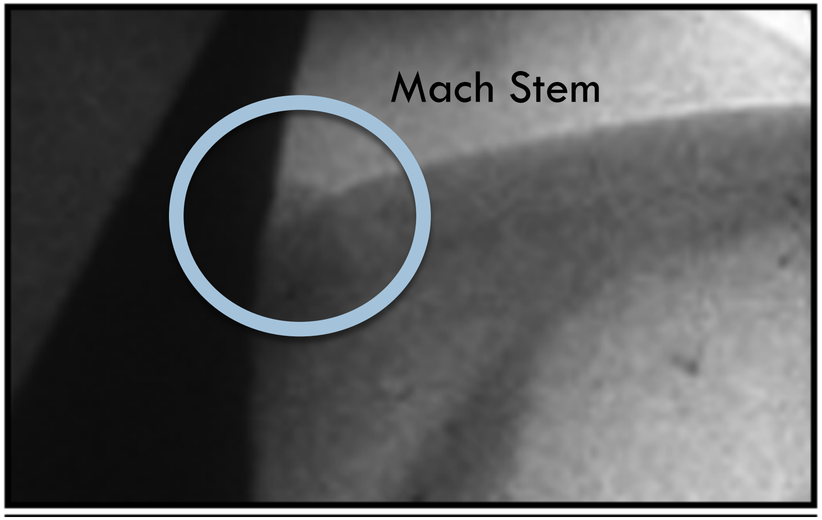


HEDLA Studies: Mach Stems

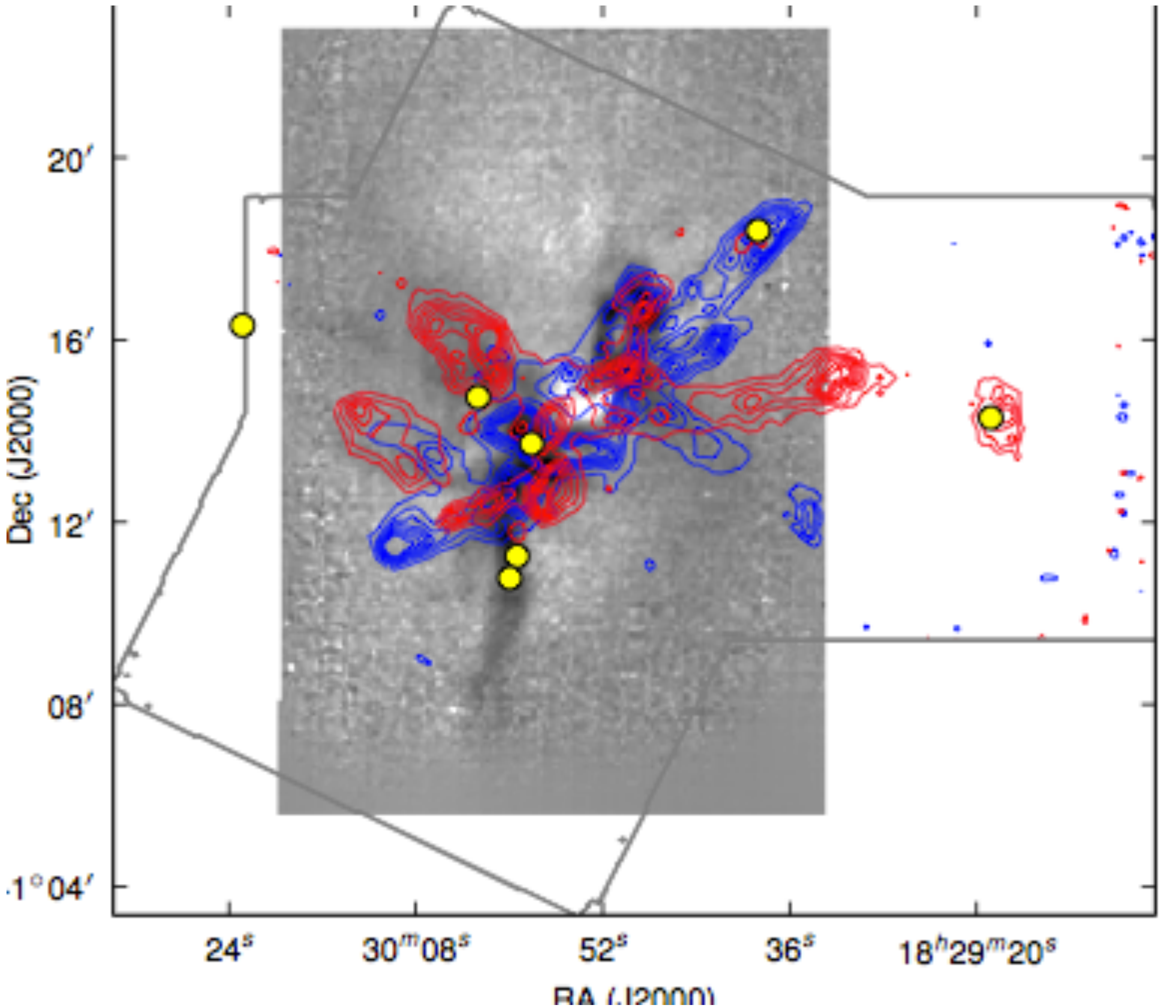
- Bright HH34 bright spots (Hartigan et al 14)
  - Clumps?
  - Shock intersections (Mach stems)?







Cluster/Cloud Scales > 1 pc



Outflow feeback

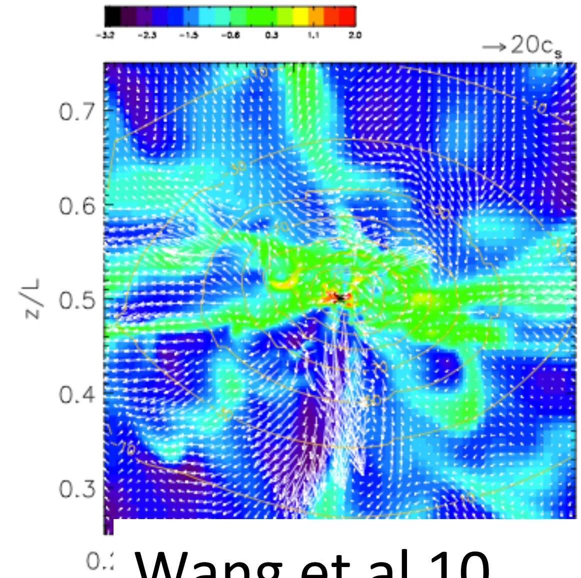
Overlapping Outflows In Serpens
Graves et al 2010

Outflow Feedback

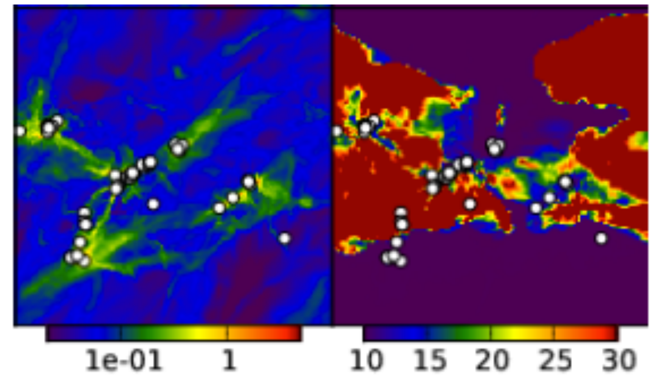
- Simulations: Outflow feedback needed?
  - Sustain turbulence
  - Reduce SFE
  - Reduce stellar masses

- Focus on processes observational connections

(see also: Li et al 10, Krumholtz et al 12)



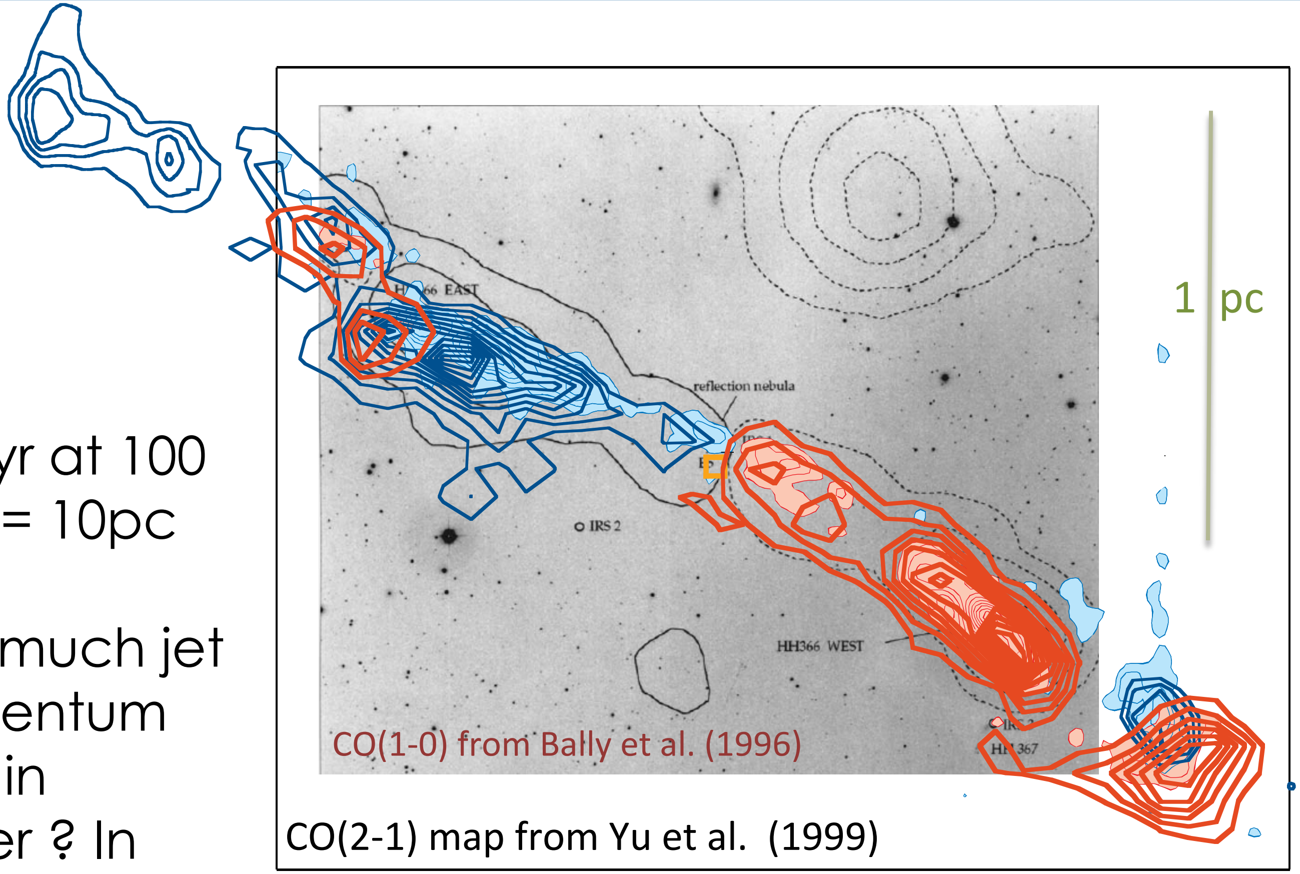
Wang et al 10



Hansen et al.12

Giant Outflows

- 0.1Myr at 100 km/s = 10pc
- How much jet momentum stays in cluster ? In cloud ?

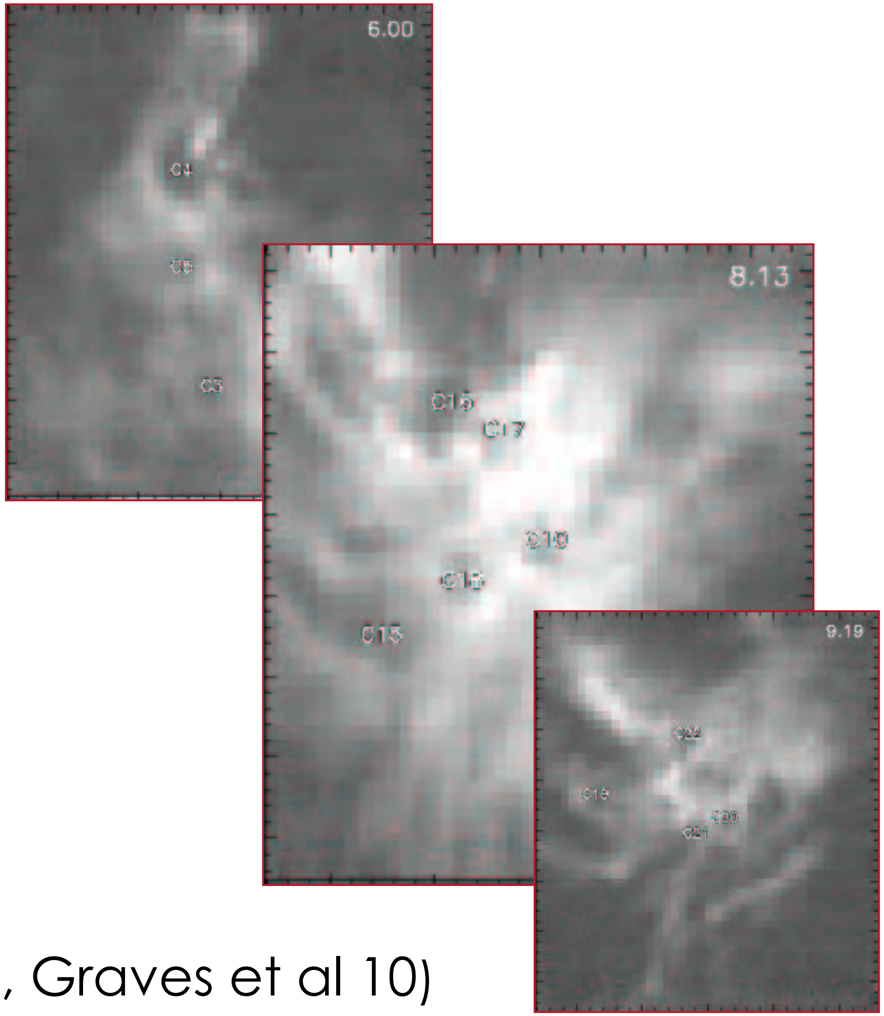


Example: B5 – IRS1 Molecular Outflow

CO (1-0) map from Arce et al. (2010)

Importance of Fossil Cavities

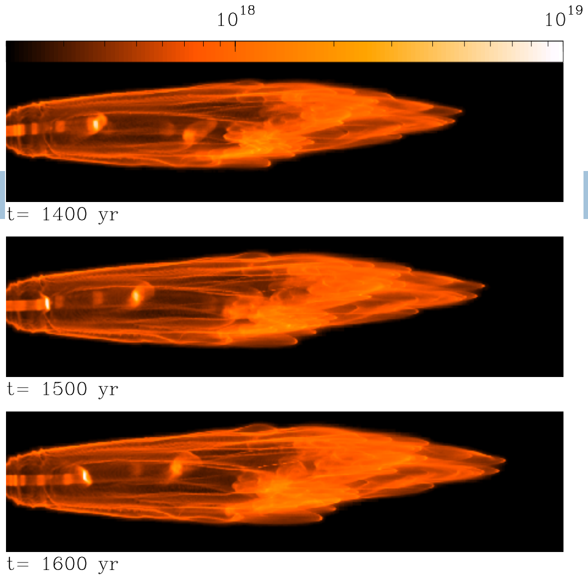
- Momentum rate balance is what counts
- Perseus: Outflow momentum rate 40% – 80% turbulence diss. rate
- Large contribution in low V *fossil shells*
  - Quillen (05), Arce (10,11)



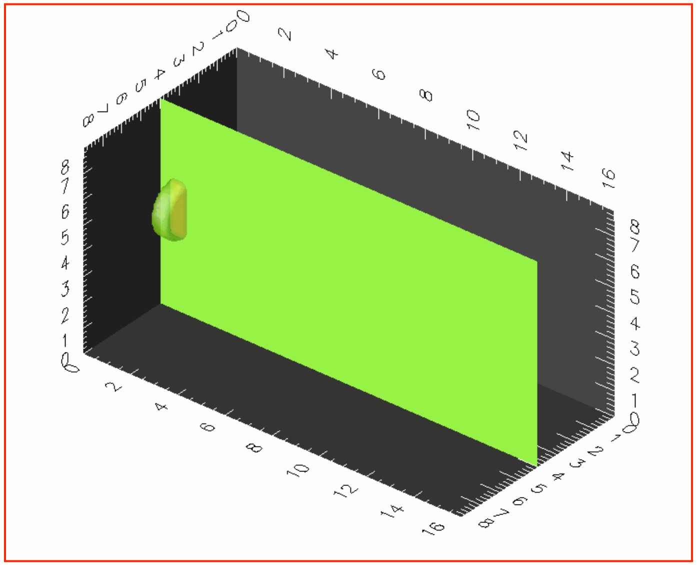
(see also: Nakmura et al 11, Aspen 03, Graves et al 10)

Outflows/Cloud Coupling

- Prompt Entrainment (Shocks)
  - Jet precession/Binary/ wandering; periodicity/ clumpiness
- Randomize bulk flow
  1. Interaction with existing turbulent flow
  2. interaction of multiple fossil shells.



Precession + Pulsing: Raga et al 09



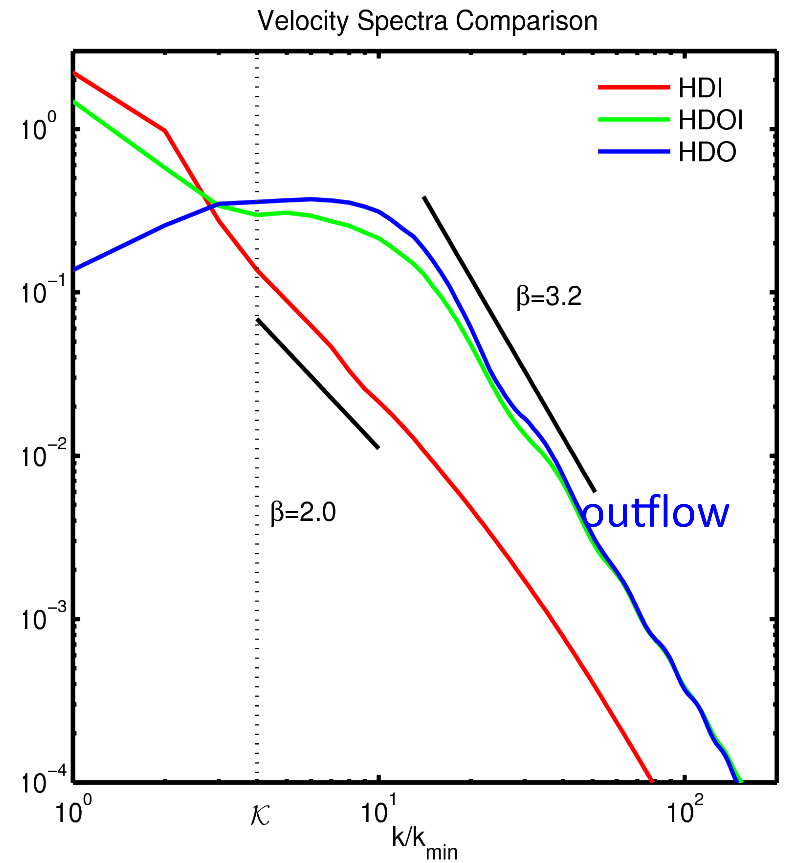
Outflows Re-energize Turbulence
Cunningham et al 09

Outflow Driven Turbulence

- Interaction of multiple fossil shells different from "Fourier" driving
  - Knee in spectra
  - Steeper power spectrum

$$E(k) \propto k^{-3}$$

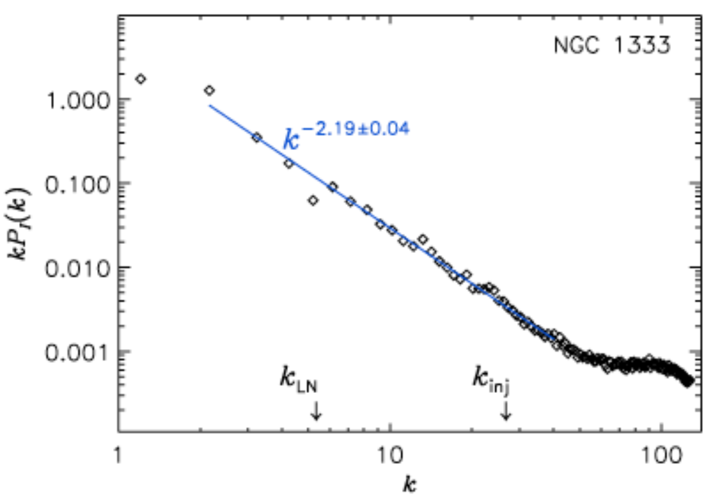
Carroll et al 09, 10
Nakamura & Li 07, 11



Energy spectra from 3 feedback simulations (Carrol et al 2010)

Observation vs. Theory

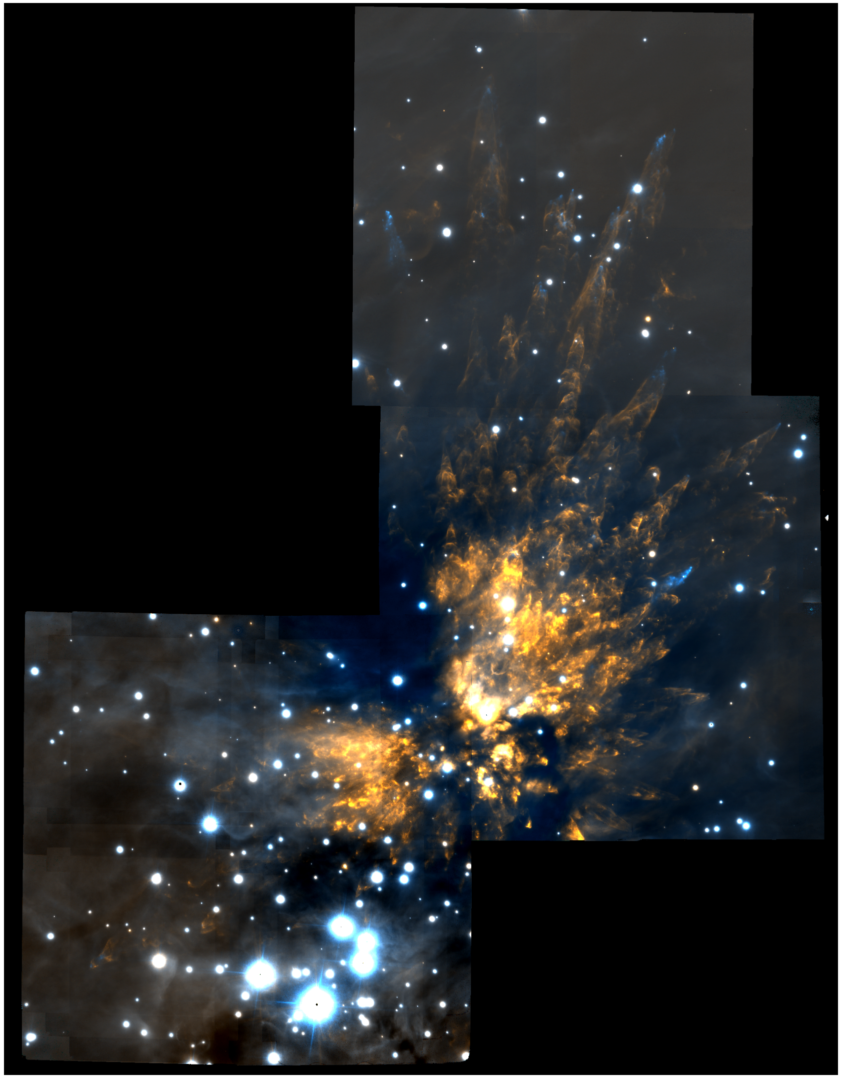
- No evidence for small scale injection?
  - Principle Component Analysis
    - Brunt et al. 09
  - Power Spectra (VCS method):
    - Padoan et al. 09
- PCA: Can't pick up outflow driving scale!!! (Carrol et al 2010)
- VCS Power Spectrum
  - Optical depth (?)
  - Multiple Interaction scales (?) (Arce 2010)



NGC 1333
Padoan et al

Wide winds and Outbursts

- Feedback: **Cloud scales (!)**
- Orion BN/KL outburst
  - E ~ 10^{47} erg
  - Triple star dynamical interaction
    - (Bally et al 2011)

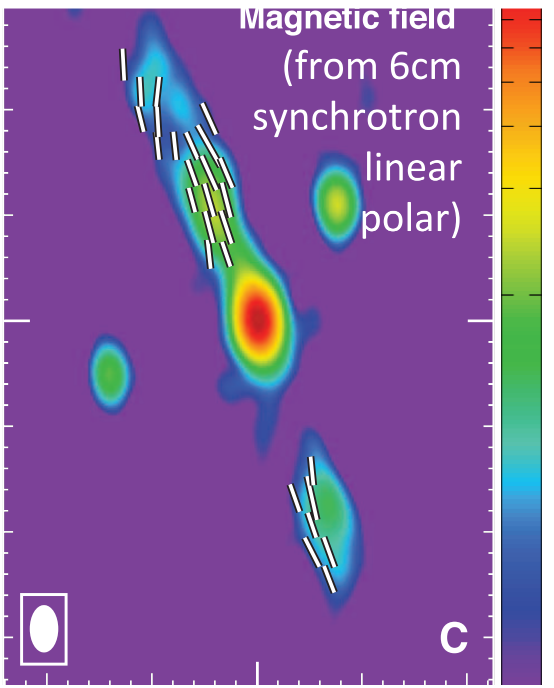


Conclusions

- Jets and outflows not only beautiful and dynamic; fundamental to understand star formation (SFE, IMF, turbulence)
- Jets could also impact planet formation through disk irradiation/shielding and MHD effects
- Multiple components: stellar winds / magnetospheric /disk winds seem present : need detailed analysis and modeling
- Laboratory Astrophysics (HEDLA) is new powerful tool to study and model RMHD jets

The next step

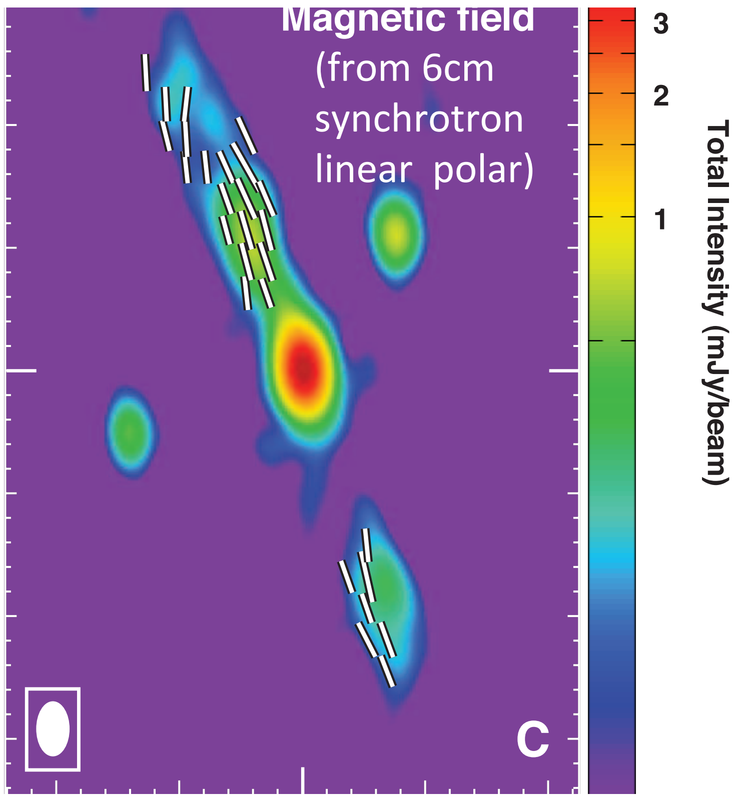
- ALMA + nIR IFUs : crucial to resolve jet rotation profile, shocks, chemical stratification in statistical jet sample
- nIR interferometry of CTTS (eg PIONEER): powerful test of atomic jet models
- Synchrotron with eVLA, LOFAR: jet B-field
- Monitoring of shortest quasi-period ≈3-15yr to clarify origin
- Identify observational diagnostics of outflow-driven turbulence
- Broaden Laboratory Astrophysics to other flows (eg. cometary globules, hot Jupiters)



Carrasco-Gonzalez et al 2010, *Science* **330**, 1209

Jet magnetic field

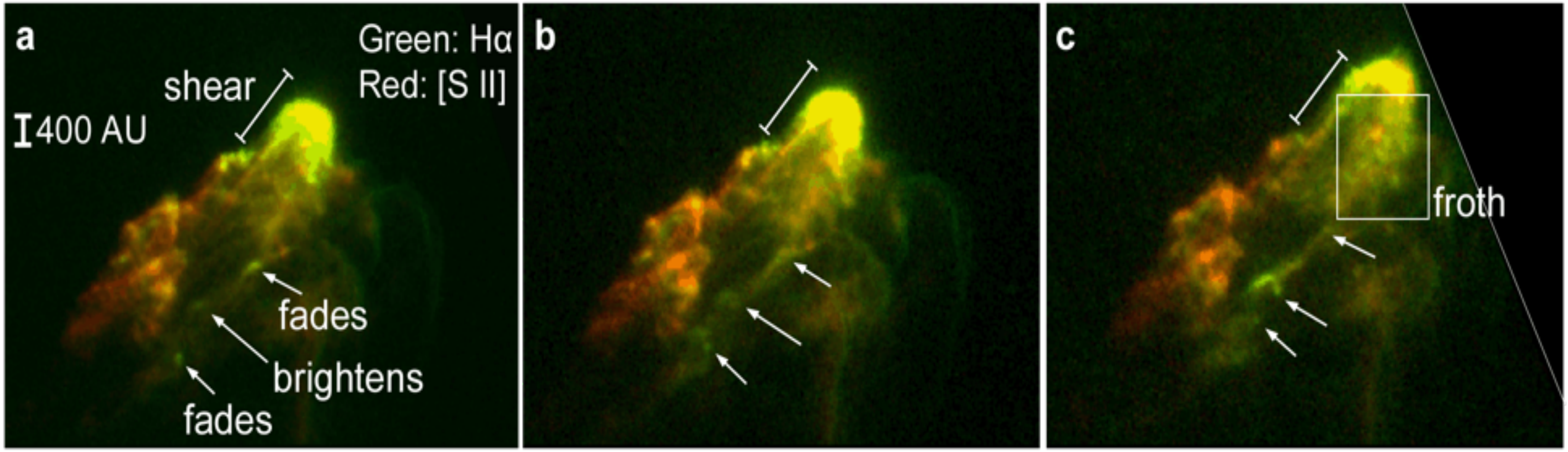
- Synchrotron linear polarisation:
  - B aligned with jet in HH80-81
- Synchrotron knot in DG Tau (see poster by Ainsworth et al.)
  - More to come with eVLA, LOFAR



Carrasco-Gonzalez et al 2010, *Science* **330**, 1209 (2010)

Multi-Epoch HST HH Jet Studies

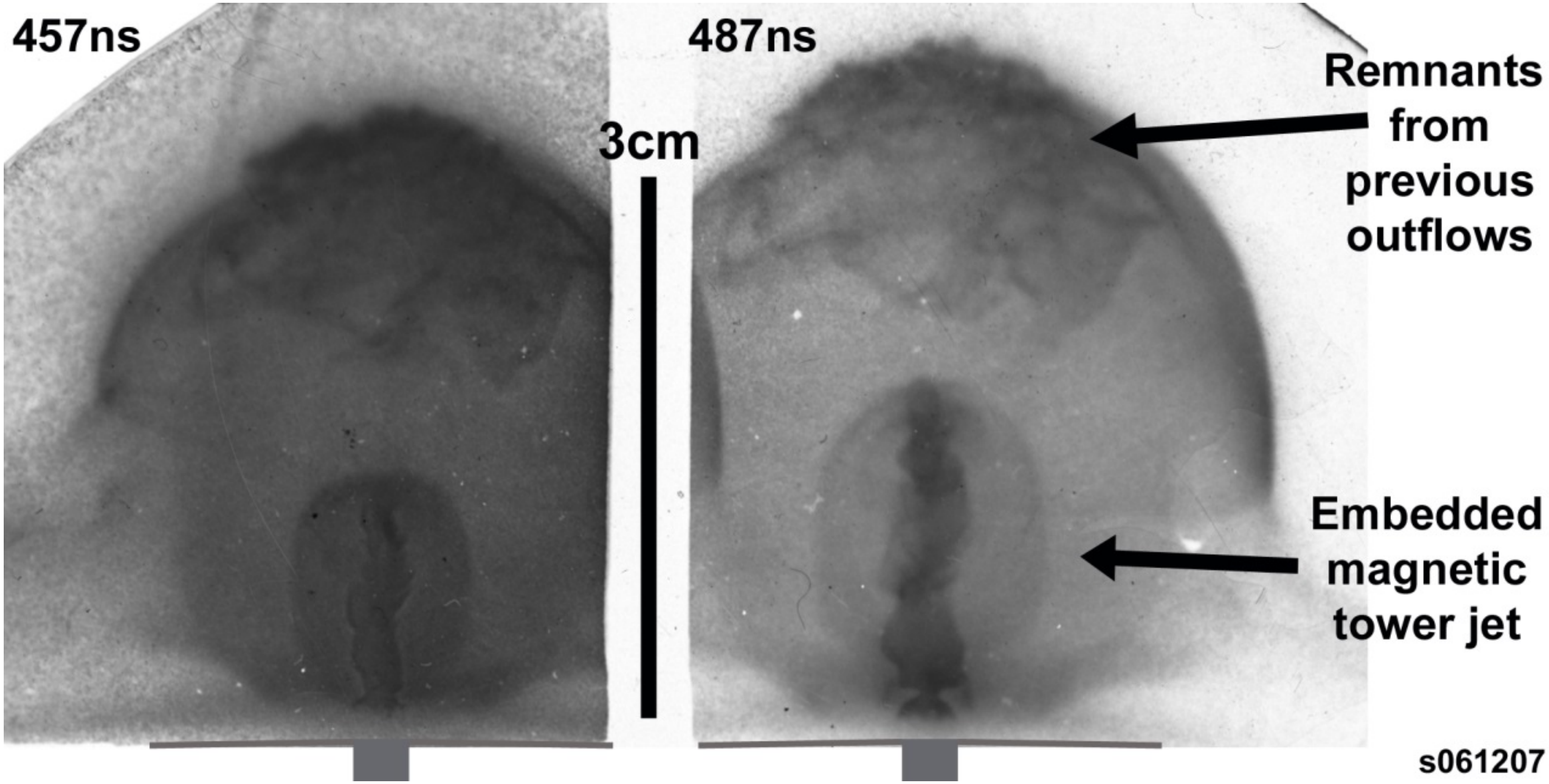
- Main Results (Hartigan et al 11, Bally)
  - Deflection shocks, Cavities, entrainment
  - Clumps!
  - Intersecting shocks, Mach Disks, sheets



1994.6 1997.6 2007.6

Episodic Ejections

Additional collimation by trapped magnetic fields



(Ciardi et al 09, Lebdev et al 10)