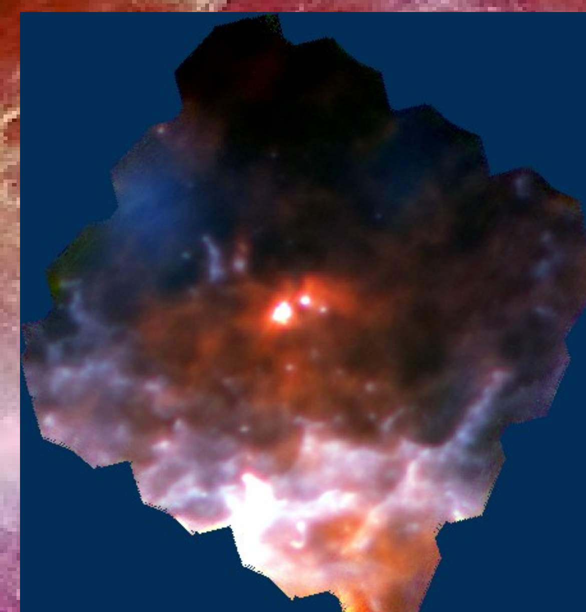
Cold Cores of Molecular Clouds



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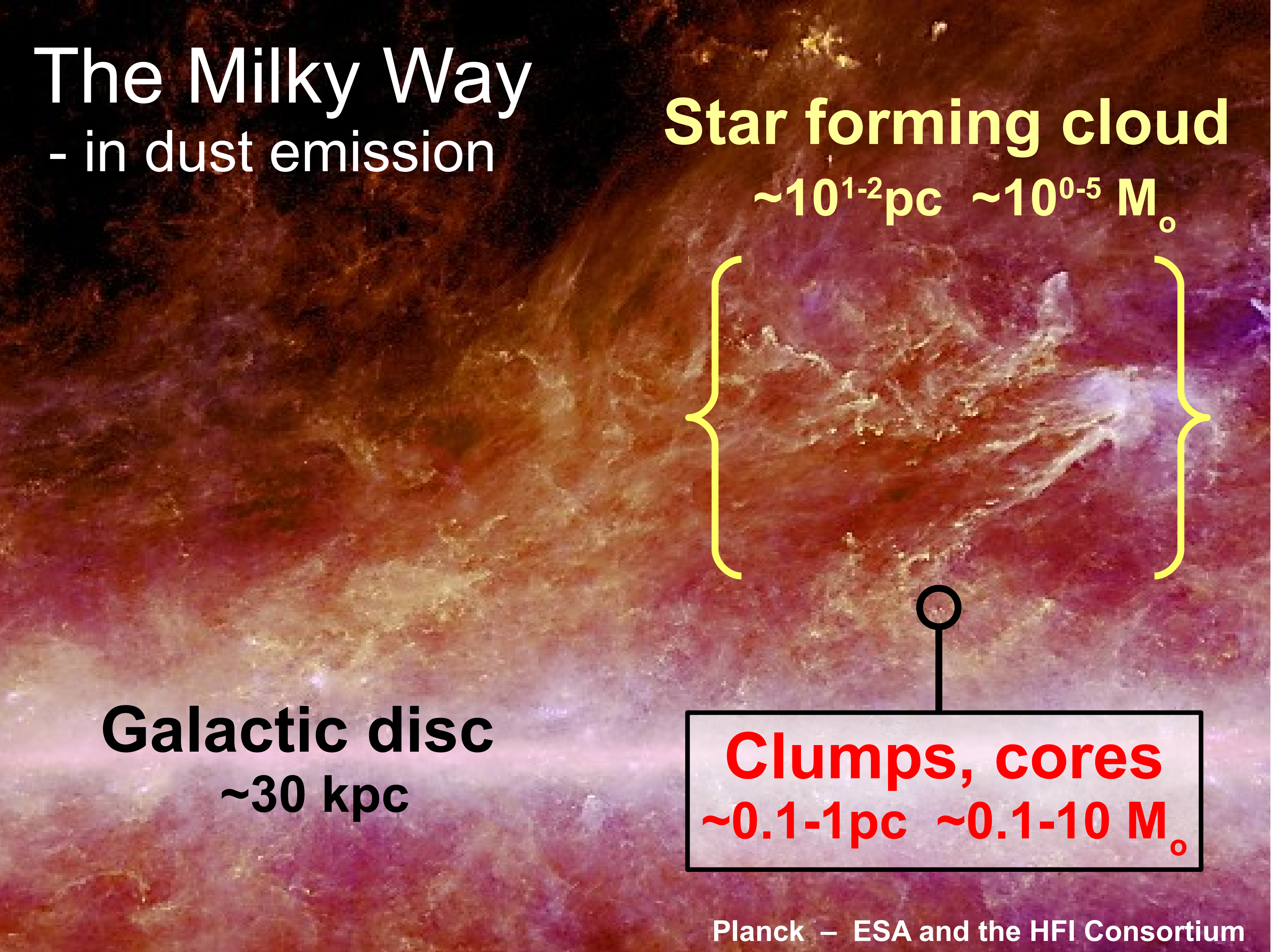
On behalf of the Planck and Herschel projects on cold cores

Content

- Molecular clouds and star formation

- **Cold Cores**
  - Observations and interpretation
  - Project Galactic Cold Cores → Planck & Herschel

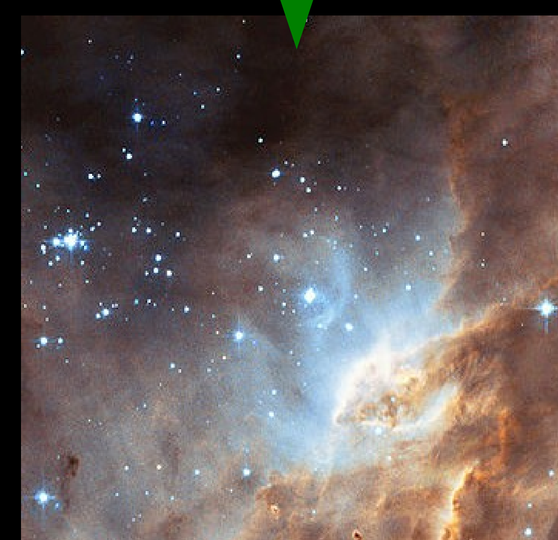
- Some notes on modelling – moderating the interpretation of observations


The Milky Way
- in dust emission
Star forming cloud
~10^{1-2}pc ~10^{0-5} M_{o}
Galactic disc
~30 kpc
Clumps, cores
~0.1-1pc ~0.1-10 M_{o}
Planck – ESA and the HFI Consortium

Galactic Cold Cores & **dust**

- Far-infrared and sub-millimetre dust emission probes dense molecular clouds, especially the **cold** phase
- A tracer of the **pre-stellar phase**
  - The initial conditions for the birth of **stars** and **planetary** systems
  - The **density** and the **temperature**
    - … only estimates of the **column density** and **colour temperature**
  - How does dust itself evolve?
    - κ and β change because of grain growth, ice mantles... probably also as function of ν and $\boldsymbol{T}$
    - Stepnik et al. 2003, Boudet et al. 2005, Köhler et al. 2012, Paradis et al. 2012

Alves (2001)

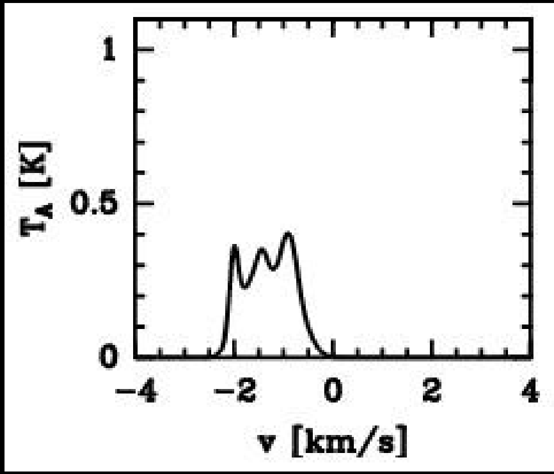


The objects

- **Cold** cloud cores, where the stars are born
  - *T* down to 6K? (Evans et al.2001, Galli et al. 2002; Pagani et al. 2003; Crapsi et al. 2007; Harju et al. 2008)
- We want to **understand** the physics
  - Density → the origin of the density field
  - Temperature → factors affecting thermal balance
  - Velocity field → core formation and evolution

The tools

- Observations of **spectral lines** →
- Observations of **dust**
  - **thermal dust emission**
  - light scattered by dust
  - light extinction



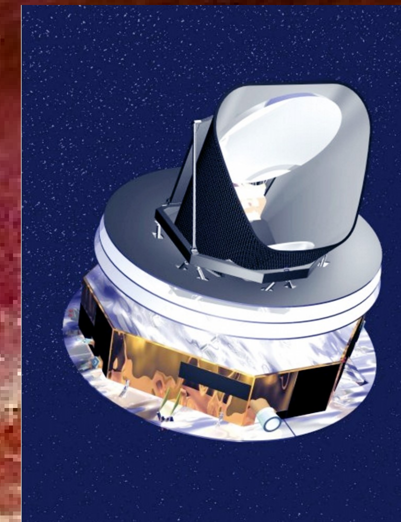
- **Space-borne far-infrared** surveys: Estimates of T_{dust}, *not* very sensitive to cold dust (IRAS, ISO, AKARI, Spitzer)
  - Boulanger et al. 1996, Abergel et al. 1996, Laureijs et al. 1998, Juvela et al. 2002, Lehtinen et al. 2004, Kirk et al. 2009, Rebull et al. 2007, Padgett et al. 2008, Nutter et al. 2009
- **Ground based (sub-)mm** observations: Often no T_{dust} data, better resolution (Scuba, LABOCA, Bolocam, MAMBO)
  - Motte et al. 1998, Hill et al. 2006, Enoch et al. 2006, 2008, Sadavoy et al. 2012, Belloche et al. 2011, etc.
- **Balloon-borne (sub-mm)** observations: Large area, multi-wavelength surveys (PRONAOS, Archeops, BLAST, etc.)
  - Dupac et al. 2003, Desert et al. 2008, Olmi et al. 2009, Martin et al. 2012
- **Space-borne sub-millimetre and radio** observations: Several frequencies, large areas, high sensitivity → **Planck**, **Herschel**

Cold Cores & **Planck**

The Planck satellite mapped the sky at nine sub-millimetre and radio wavelengths

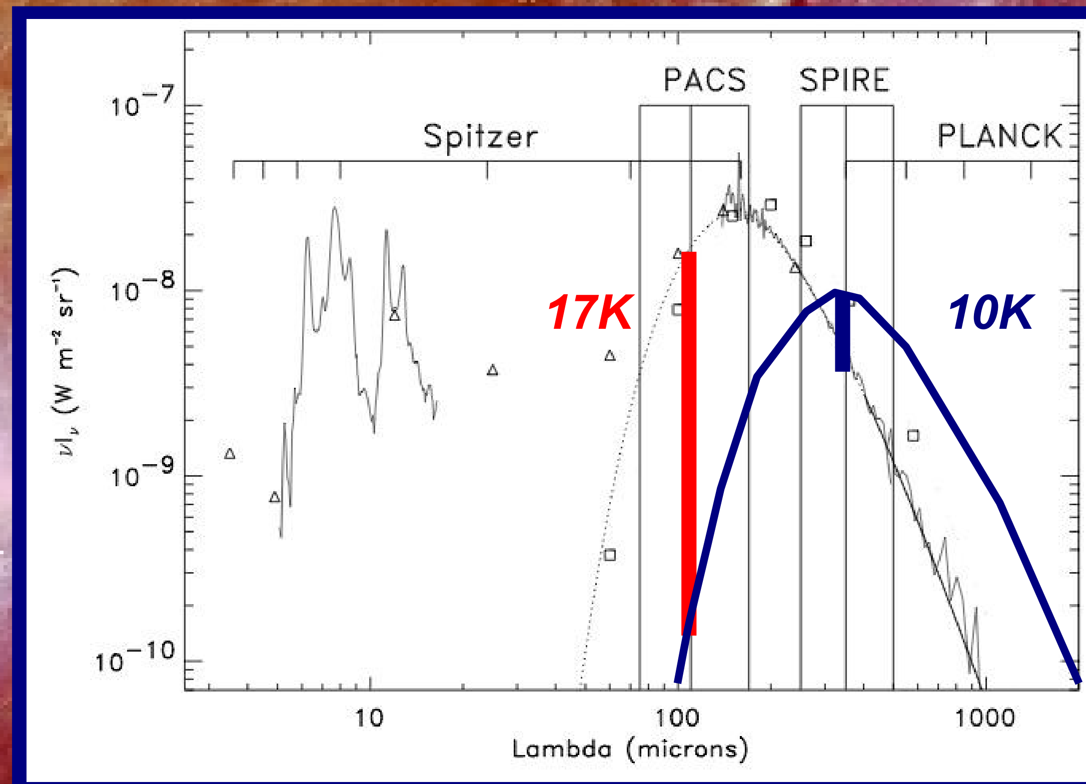
- **350μm, 550μm, 850μm**, ...,1cm
- **better than 5'** resolution in the sub-mm

This enables the **detection of cold clumps**!



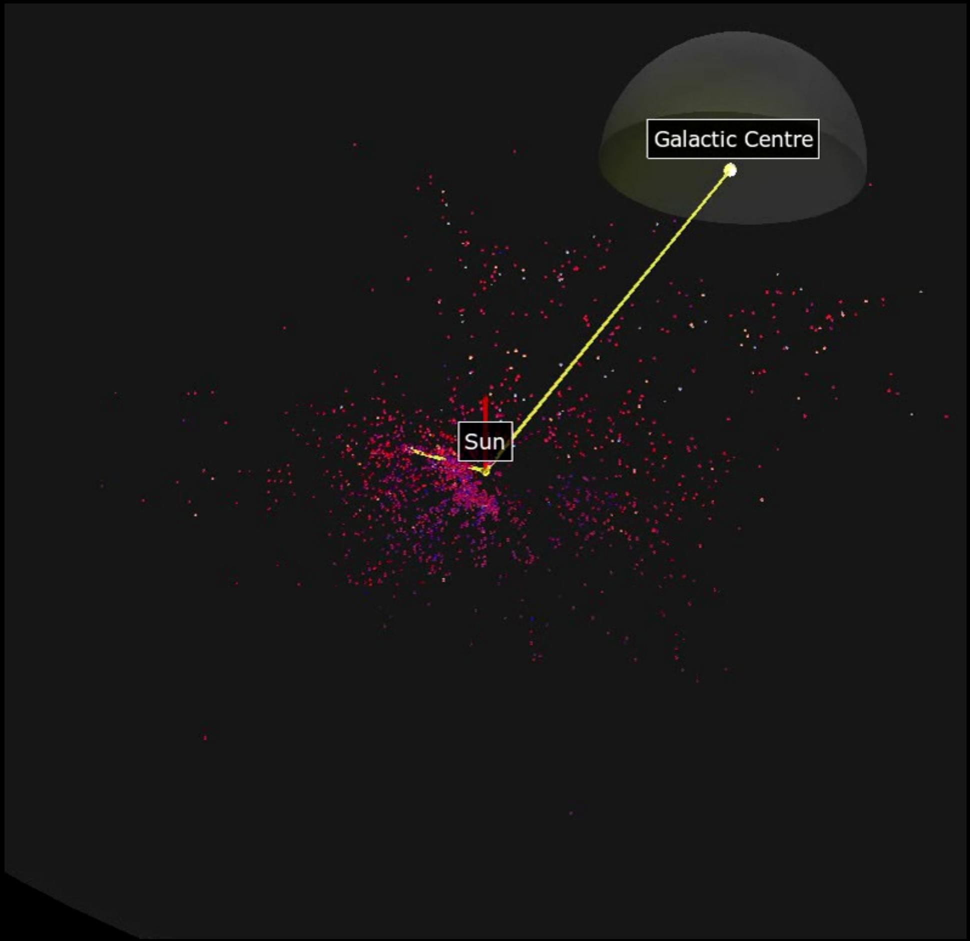
Planck is also **the first** mission capable of a full survey

- full sky coverage
- sub-millimetre bands
- sufficient resolution
- excellent sensitivity

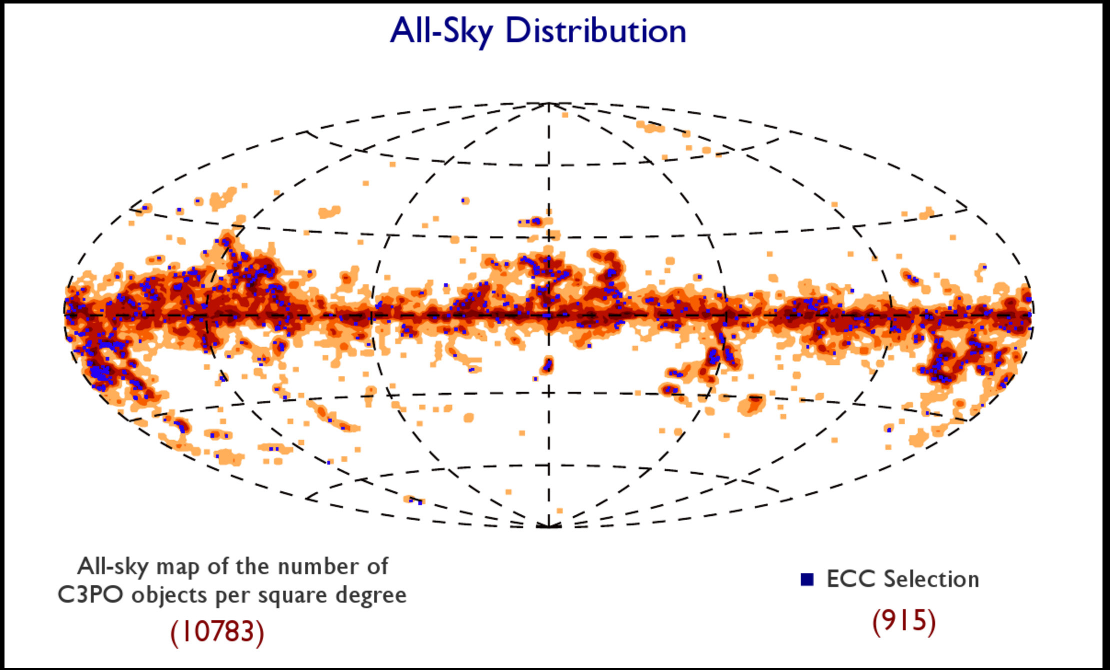


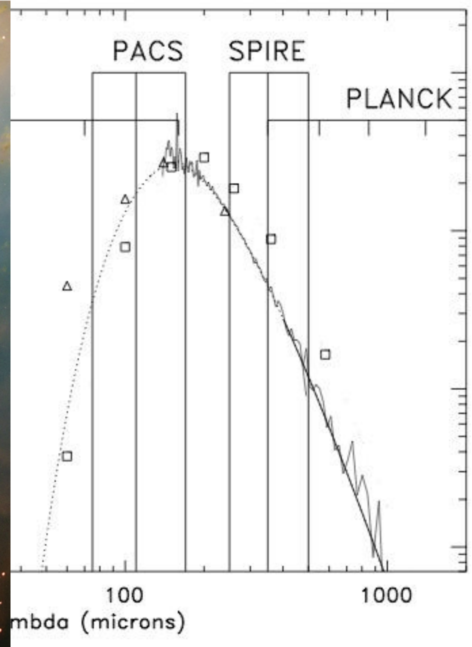
Preliminary catalog contained over 10000 sources, some 900 of which were included in the Early Cold Clumps catalogue (Planck collaboration 2011)

- distances from 100pc to 8kpc, Galactic heights up to ± 400pc



Planck Collaboration (2011)
Planck early results XXIII, A&A 536, A23



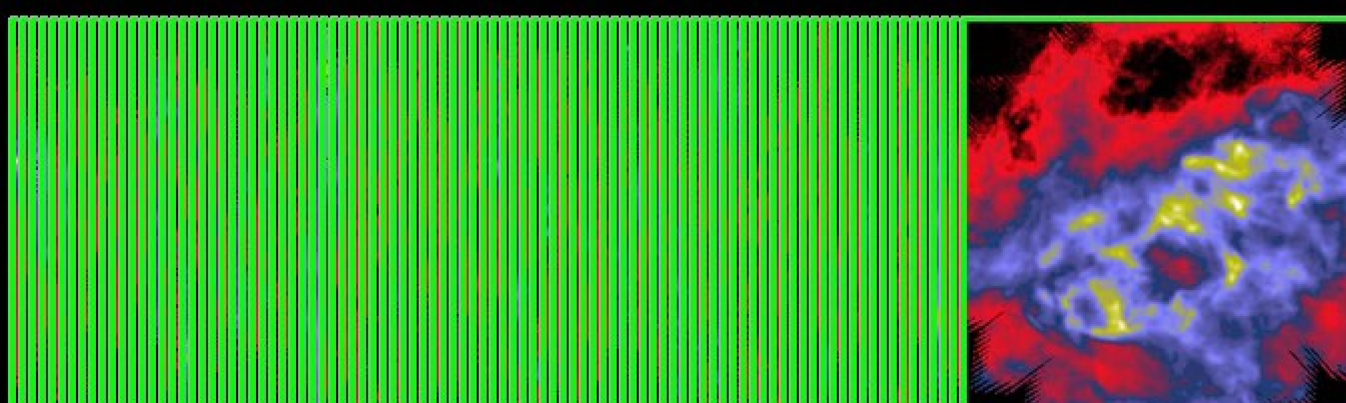


Cold Cores & **Herschel**

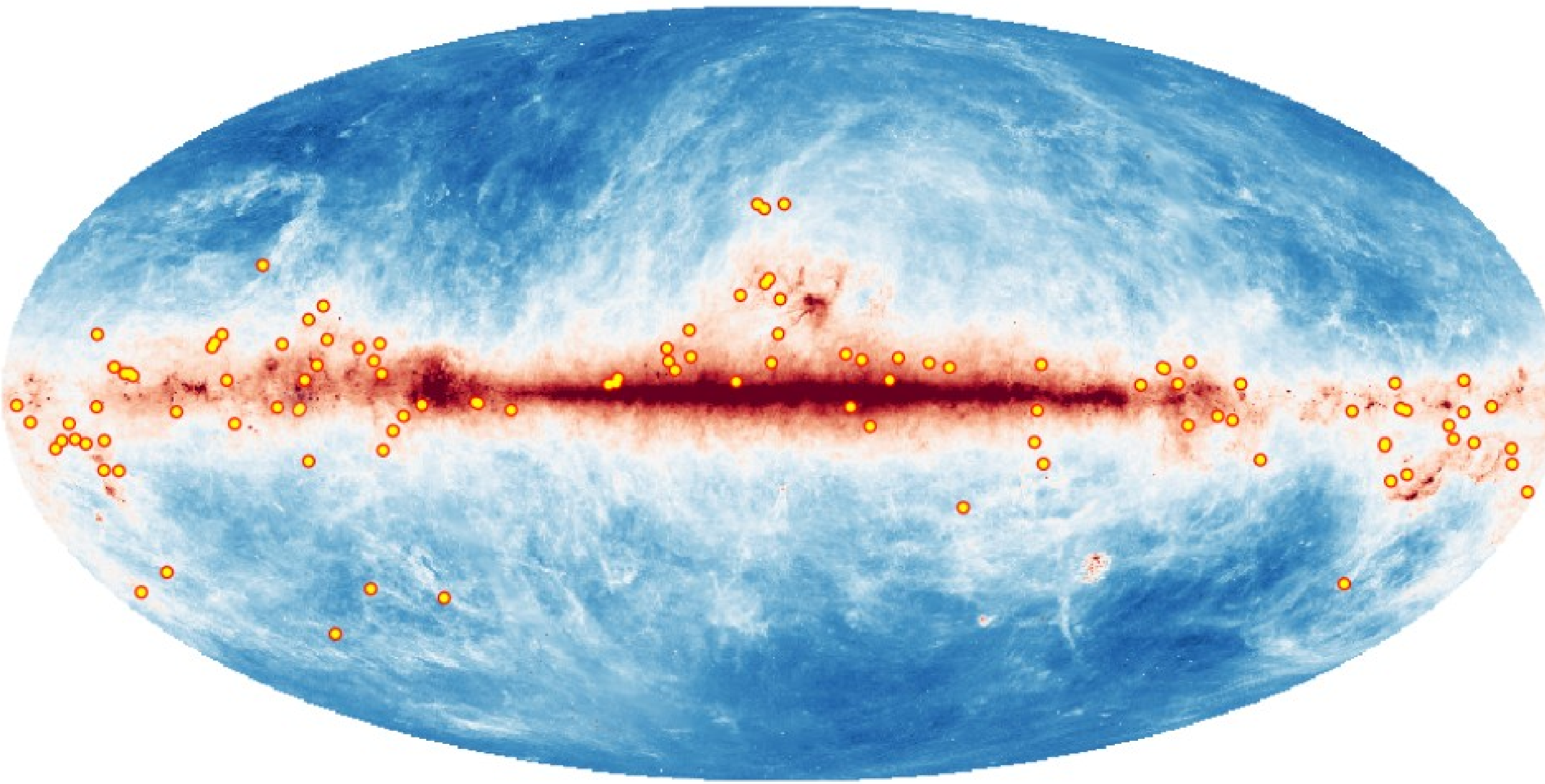
Key Programme ***Galactic Cold Cores***

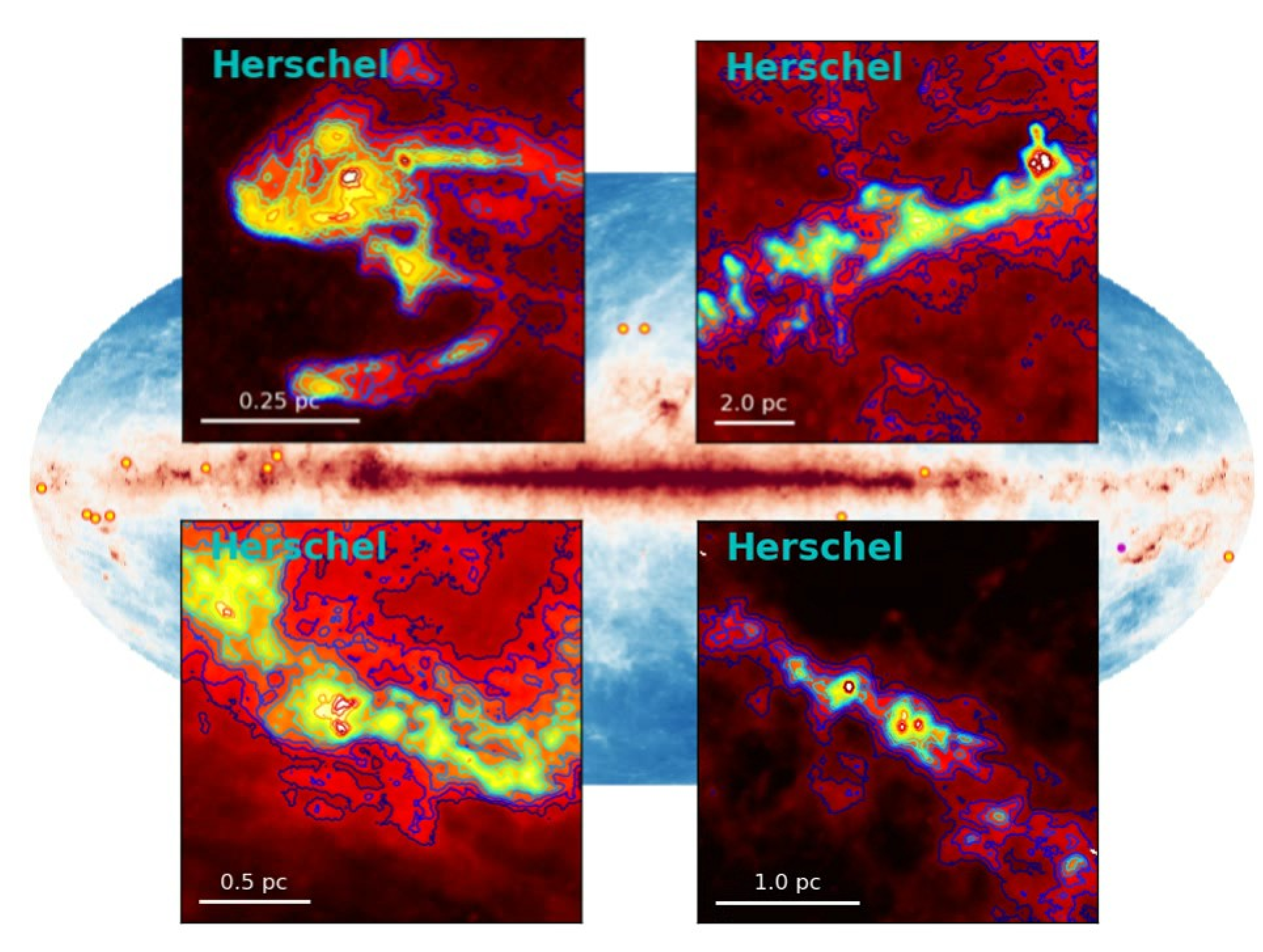
- to map ~120 fields containing cold Planck clumps
- a **cross-section** of the full population (T, M, n, R, l, b etc.)

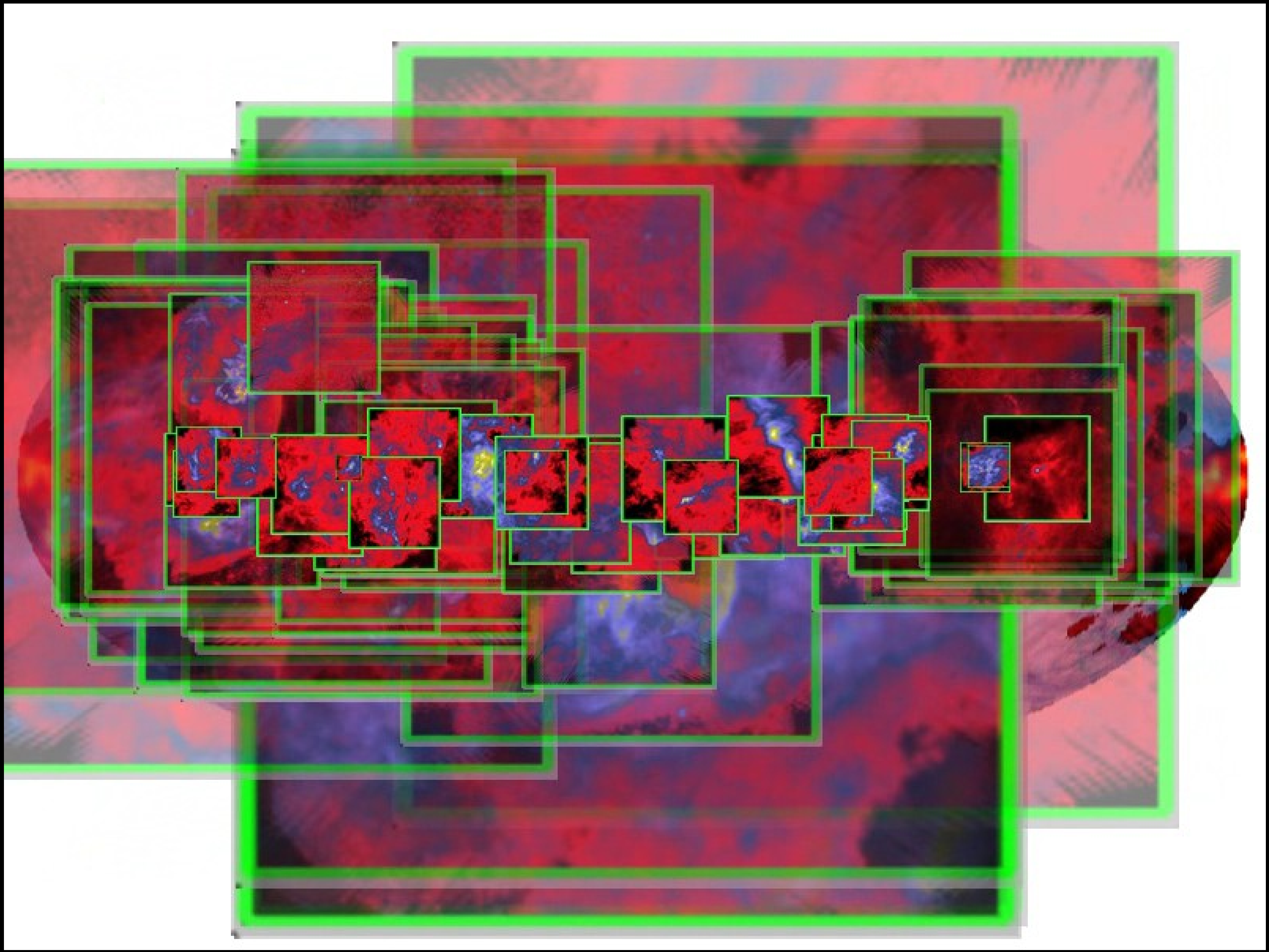
- complementary to other programmes → includes high latitudes, outer regions of molecular cloud complexes, large distances
  - cf. **Gould Belt Survey** (Andre), **HIGAL** (Molinari), **EPOS** (Krause), and many other key programmes and normal programmes

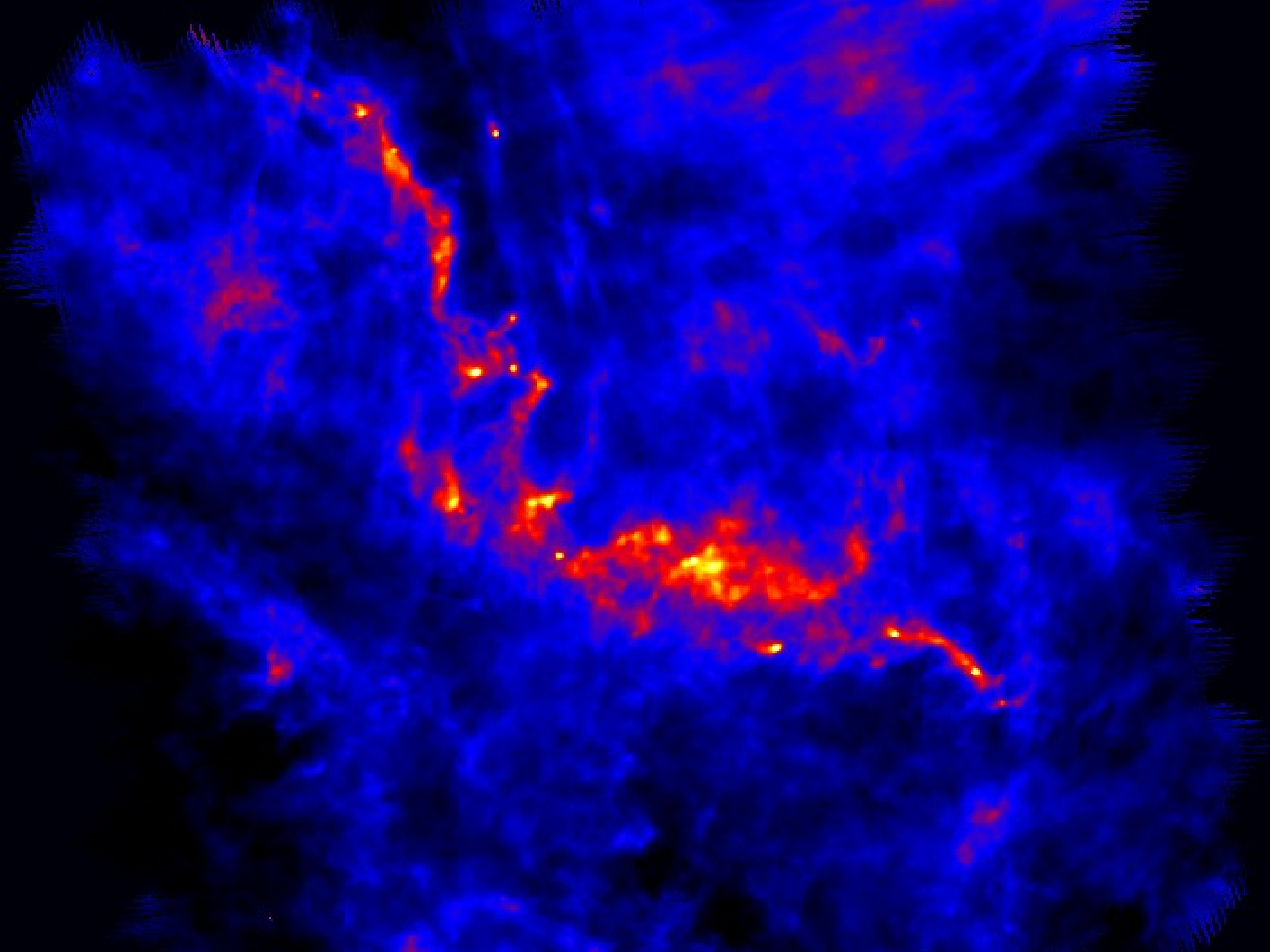


Distribution of the ~120 Herschel target fields
that include over 350 Planck-detected cold clumps



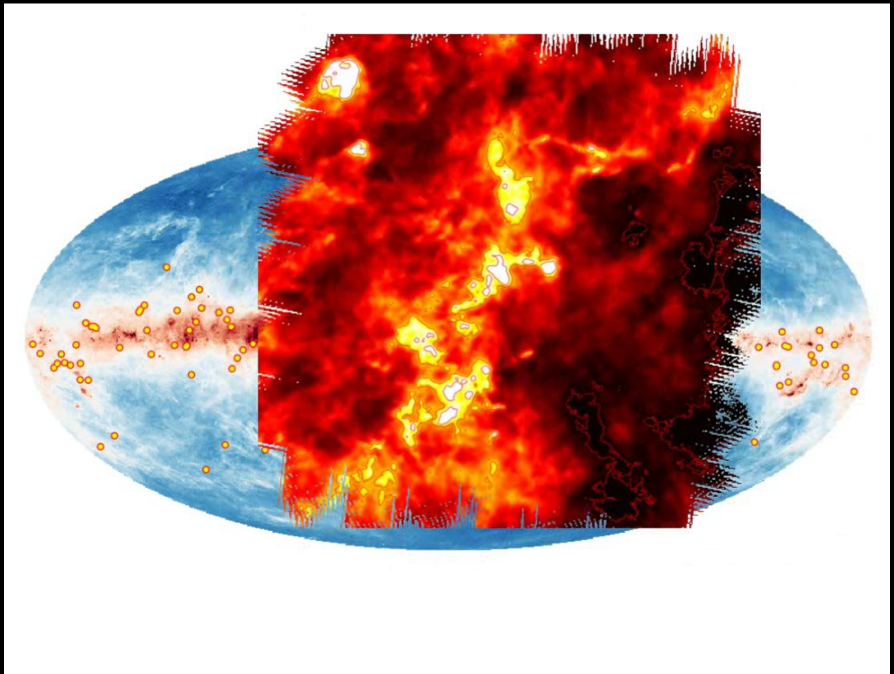

Herschel
0.25 pc
Herschel
2.0 pc
Herschel
0.5 pc
Herschel
1.0 pc





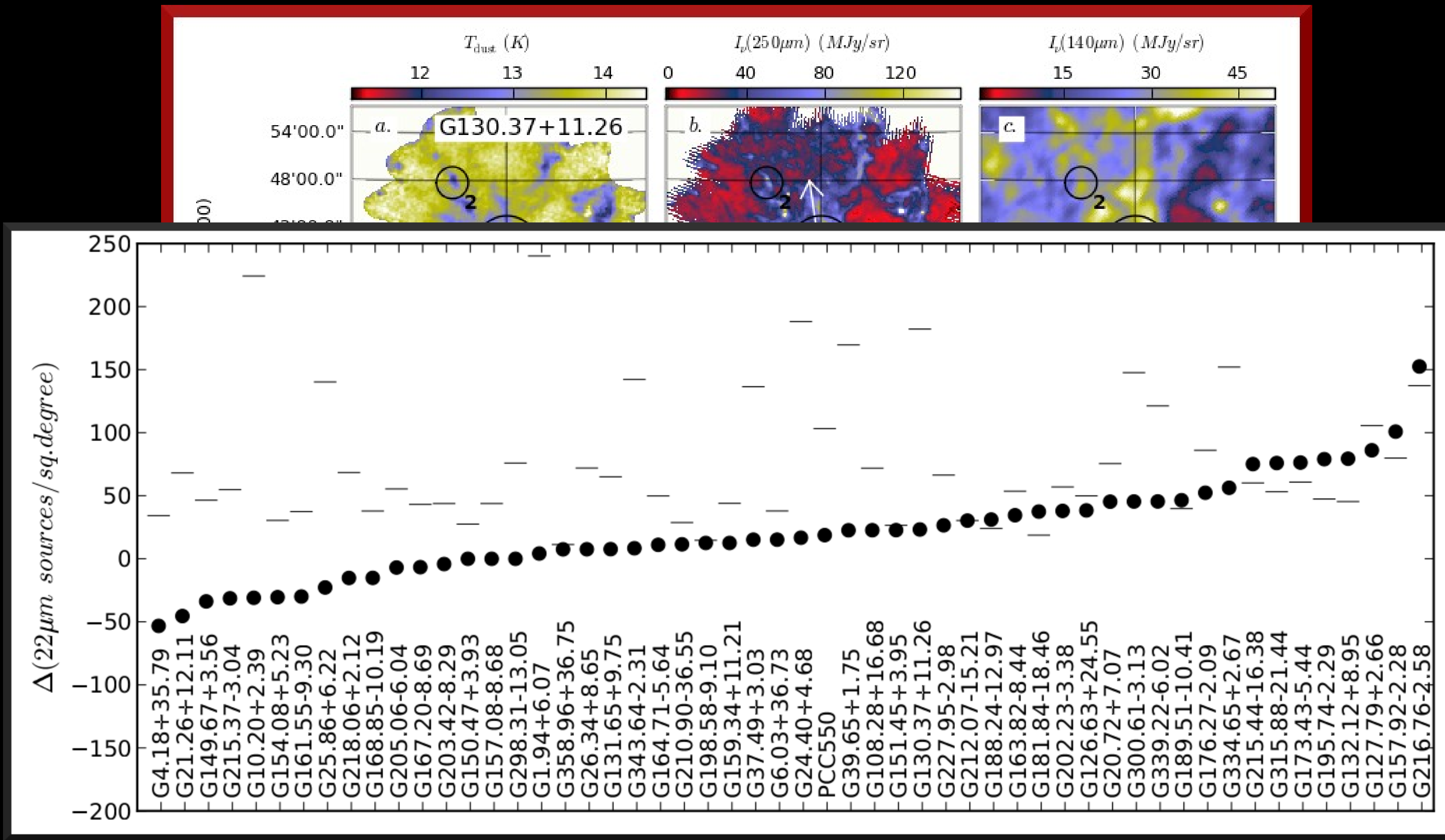
Morphology

- Isolated, cometary, filamentary, etc.
- Occasionally indications of dynamic **interaction**
- Further quantitative analysis
  - Clump mass spectra, P(D) analysis, filament extraction



Star formation

- WISE data show that a many cold sub-millimetre clumps are **already** associated with **star formation**

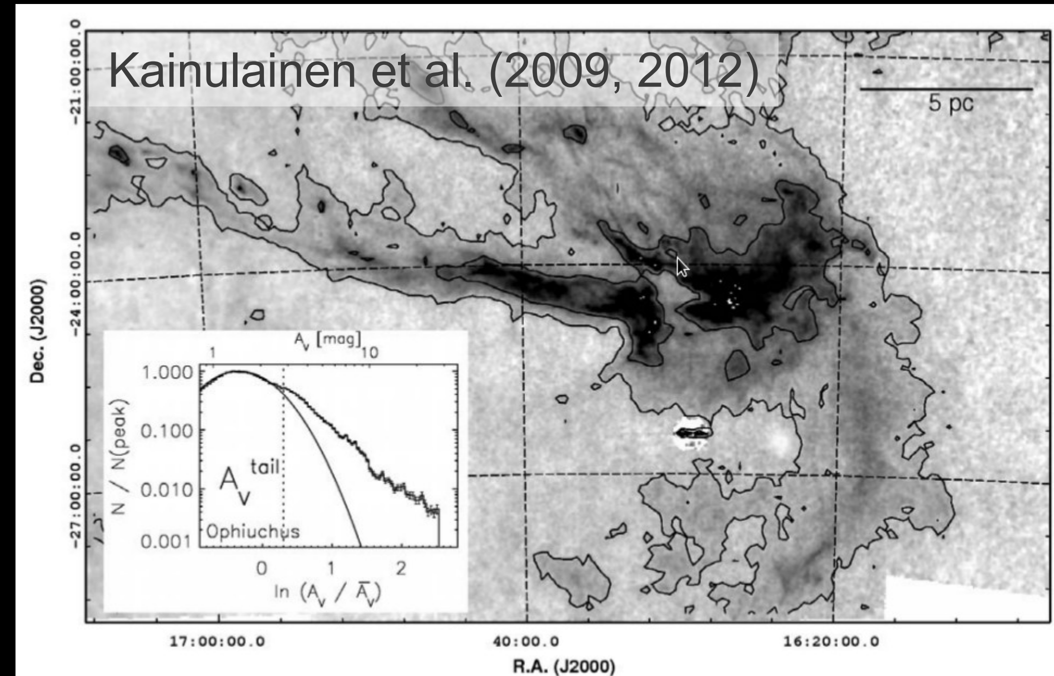


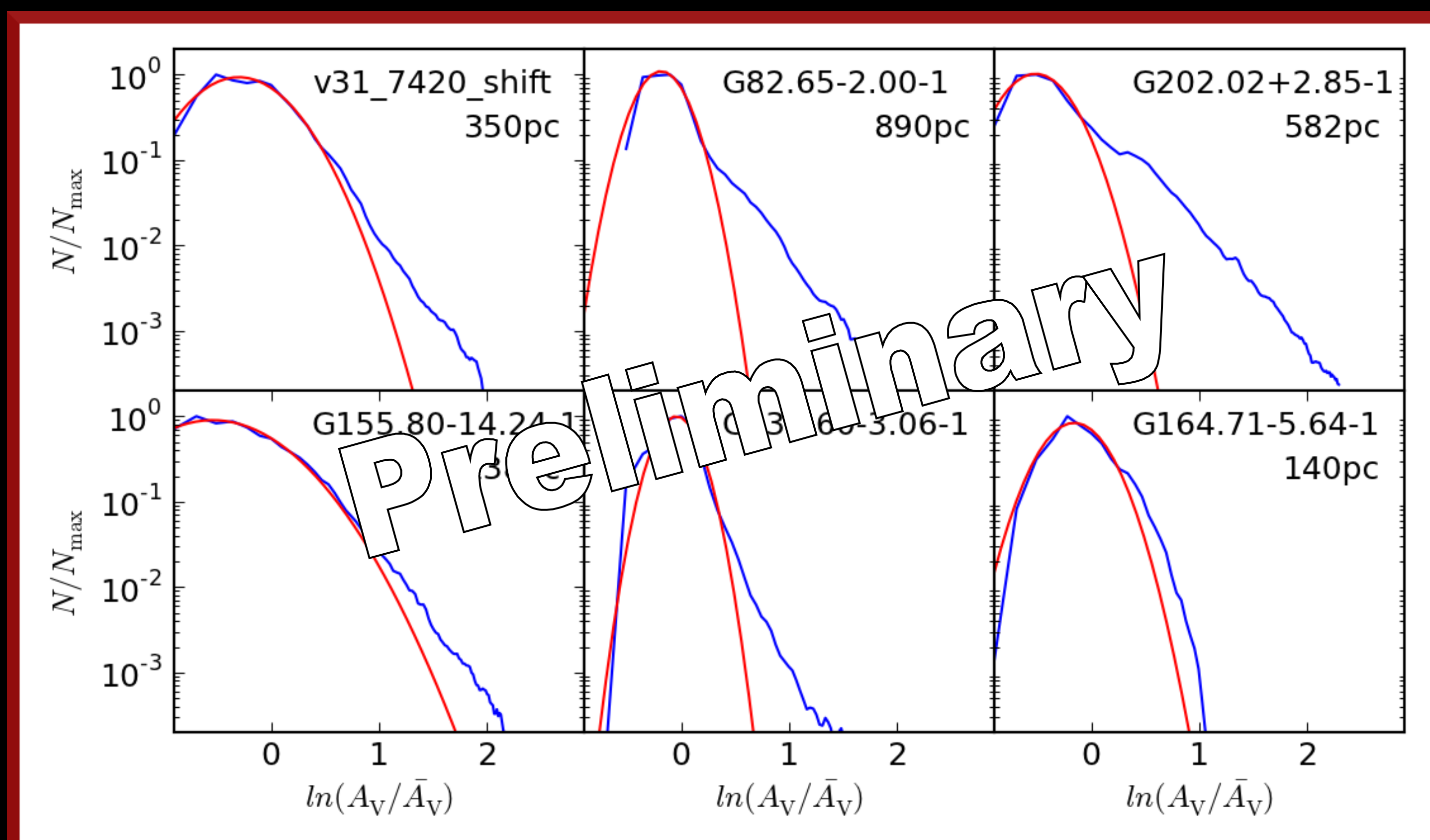
CMF – Clump/core mass function (work in progress)

- can CMF be described with a unique power-law; what is the connection with the IMF
  - Motte et al. (1998)... Könyves et al. (2010) – talk by Ph. Andre
- in case of GCC, no more than ~100 c's per field → distance scatter make a joint study more challenging
- another goal: correlation of clumps and YSOs
  - J.Montillaud (in preparation)
- eventually: the internal structure of individual cores
  - *n*, *T* – requires radiative transfer modelling of the data
  - e.g., Sadavoy et al. 2012; Nielbock et al. (?) B68 etc.

P(A_V) analysis

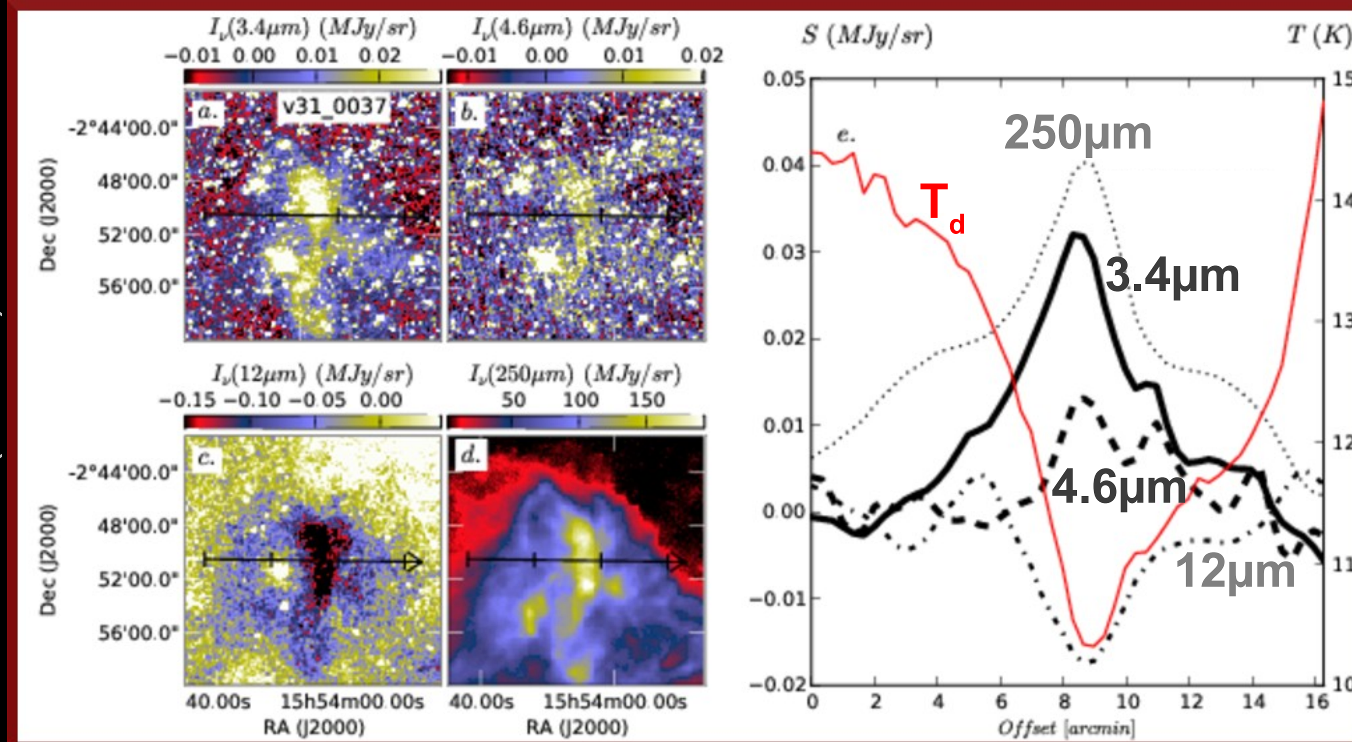
- tail above the log-normal distribution is related to star formation? (Kainulainen et al. 2009, 2011)
- the analysis can be done now using Herschel column densities





Dust physics

Juvela et al. (2012d)



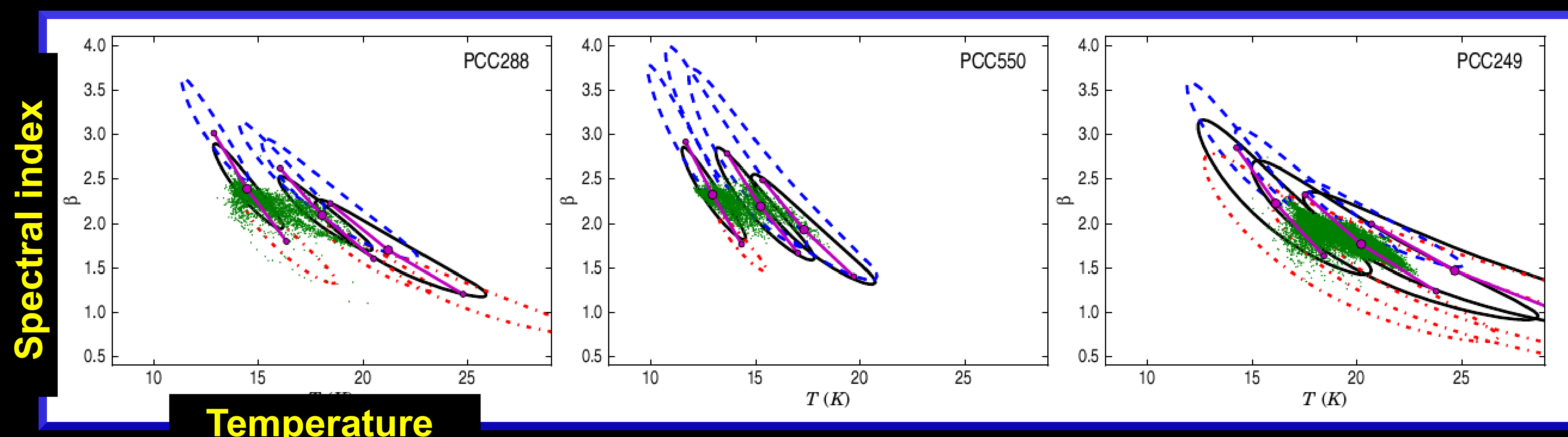
Coreshine?

- In dense cloud cores **scattered light** has been detected as surprisingly long wavelengths
  - **~3.5μm** signal caused by the growth of dust particles? (Steinacker et al. 2010, Pagani et al. 2010)
- In WISE data of 56 fields, four detections, six tentative det.
  - there is a follow-up Spitzer programme on 90 Planck clumps, PI **R. Paladini**

β(*T*) relation?

- The spectral index β **appears** to decrease with temperature, as suggested by laboratory data.... but
  - also **the noise** can produce an apparent anticorrelation
  - **temperature variations** decrease the apparent β

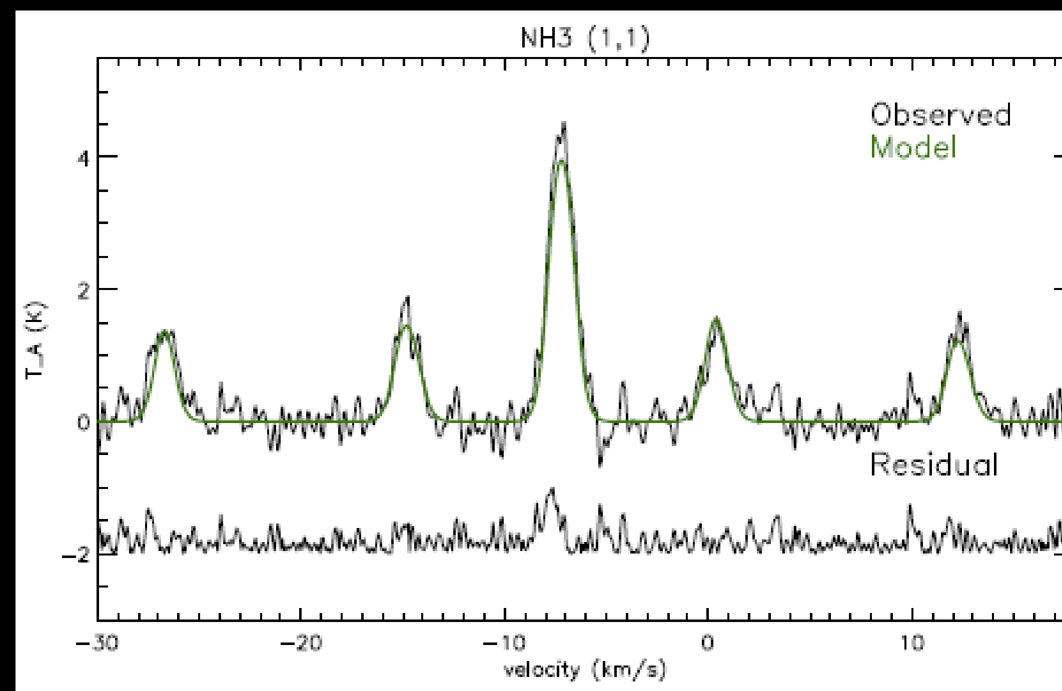
  → need Monte Carlo and/or (hierarchical) statistical modelling to find the (~) un-biased truth
    - Planck Early Results XXIII; Kelly et al. 2012; Veneziani et al. 2012 (submitted); Juvela et al. (in prep.)



Juvela et al. (2011)

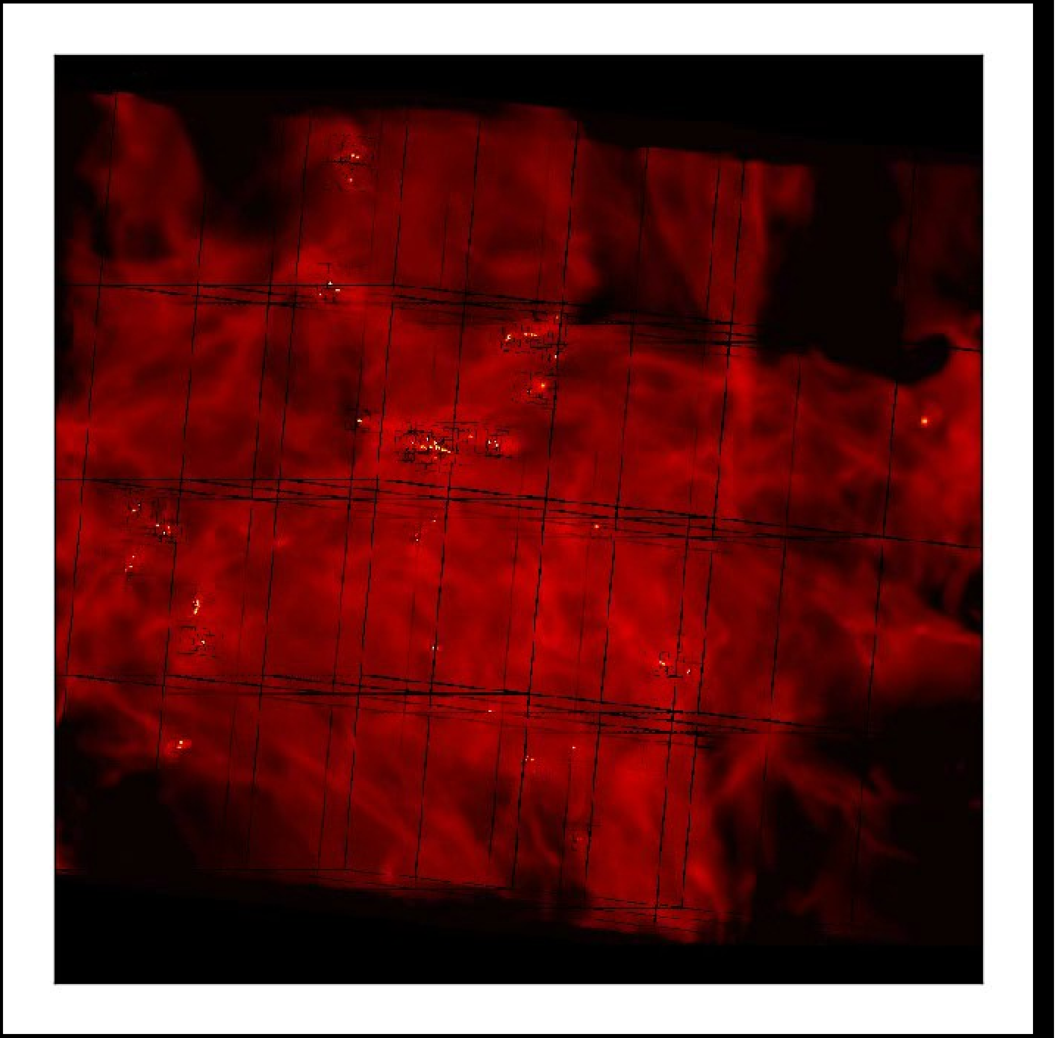
Molecular lines

- Velocity-resolved line data **essential**
  - kinematic distances, separation of kinematic components, estimates of turbulent support
  - internal kinematics
    - rotation, infall, outflows
  - main gas parameters
    - density, temperature
  - chemistry
    - age, deuteration, depletion
- Observations ongoing
    - APEX, Onsala 20m,
      IRAM 30m, Effelsberg, CSO;
      see also Wu et al. (2012), Liu et al. (2012)



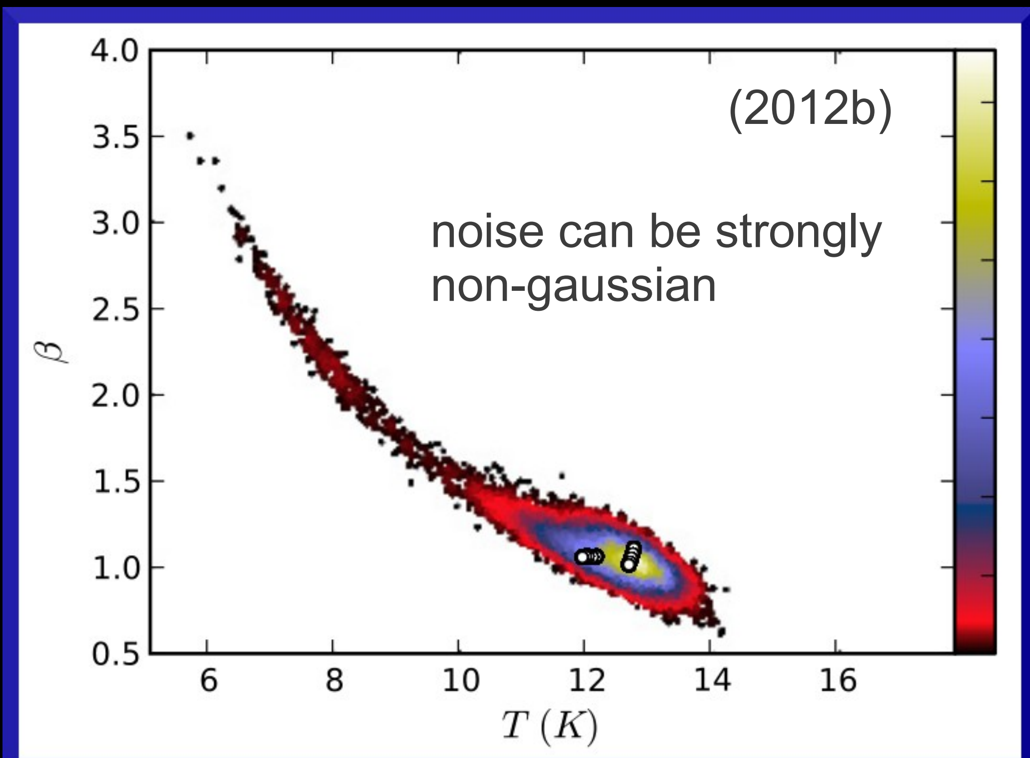
Modelling

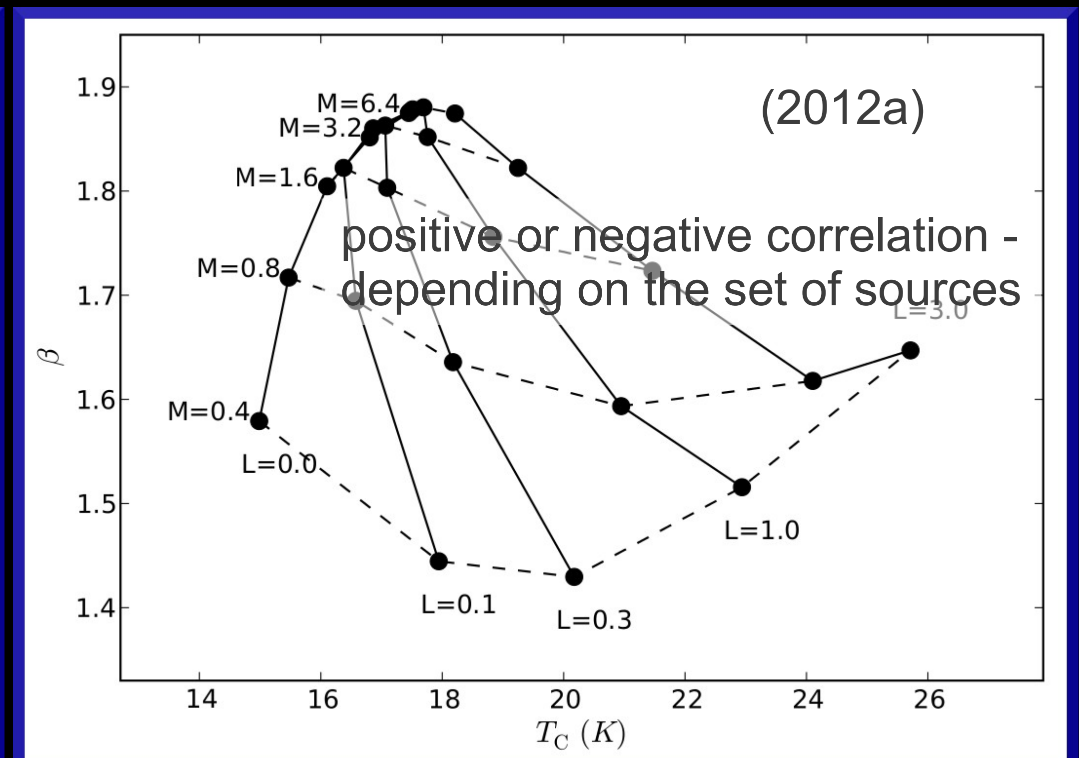
- to **understand** the limitations of the observations
  - to show uncertainties and biases, still usually under idealised conditions
- to **extract** the most information from the data
  - e.g., to estimate the temperature and density structure of a core when only projected surface brightness data are available; to separate dust properties from radiation field effects etc.



β (*T*) relation

- We *know* the observed spectral index is affected by
  - observational noise → artificial (β, *T*) anticorrelation
    - Shetty et al. (2009b); Juvela & Ysard (2012b); Kelly et al. (2012); Veneziani et al. (2012)
  - mixing of temperatures → lower apparent β values
    - Shetty et al. (2009a); Juvela & Ysard (2012a)

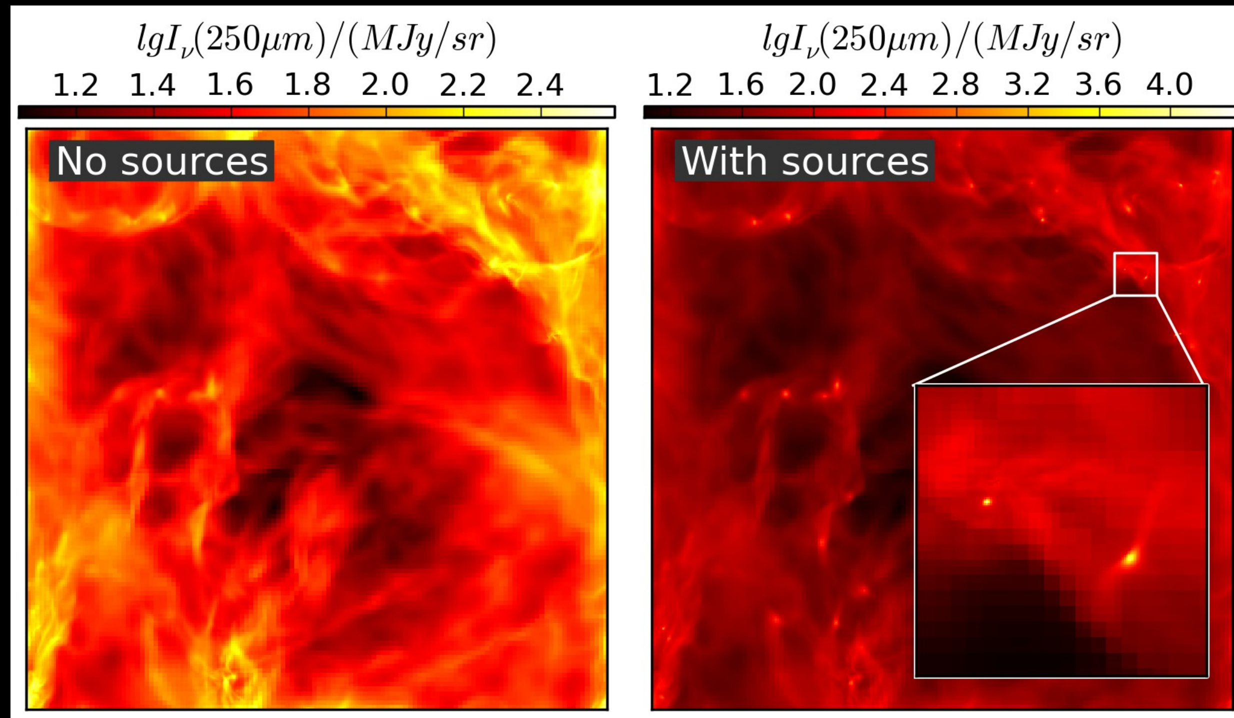




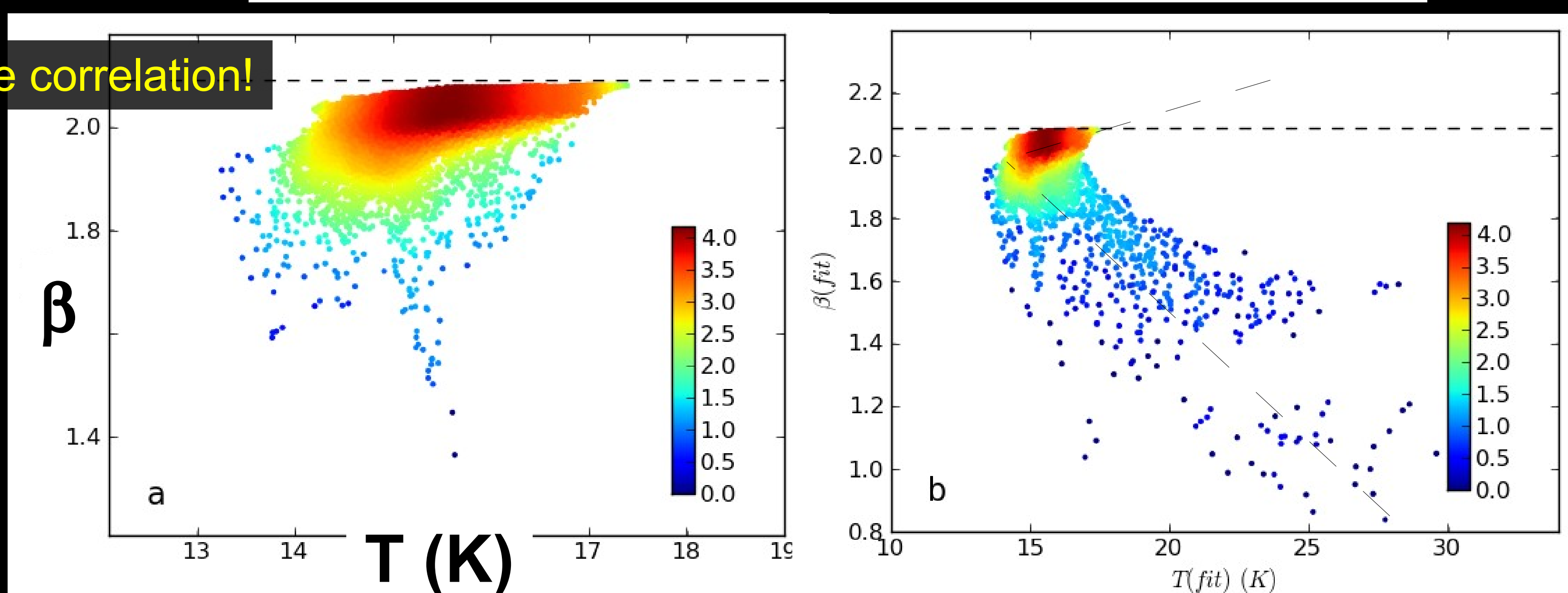
The difference between cores that are heated

externally by ISRF or **by embedded protostars**?

High resolution AMR MHD + radiative transfer modelling (see Lunttila et al. 2012)



Malinen et al. (2011)

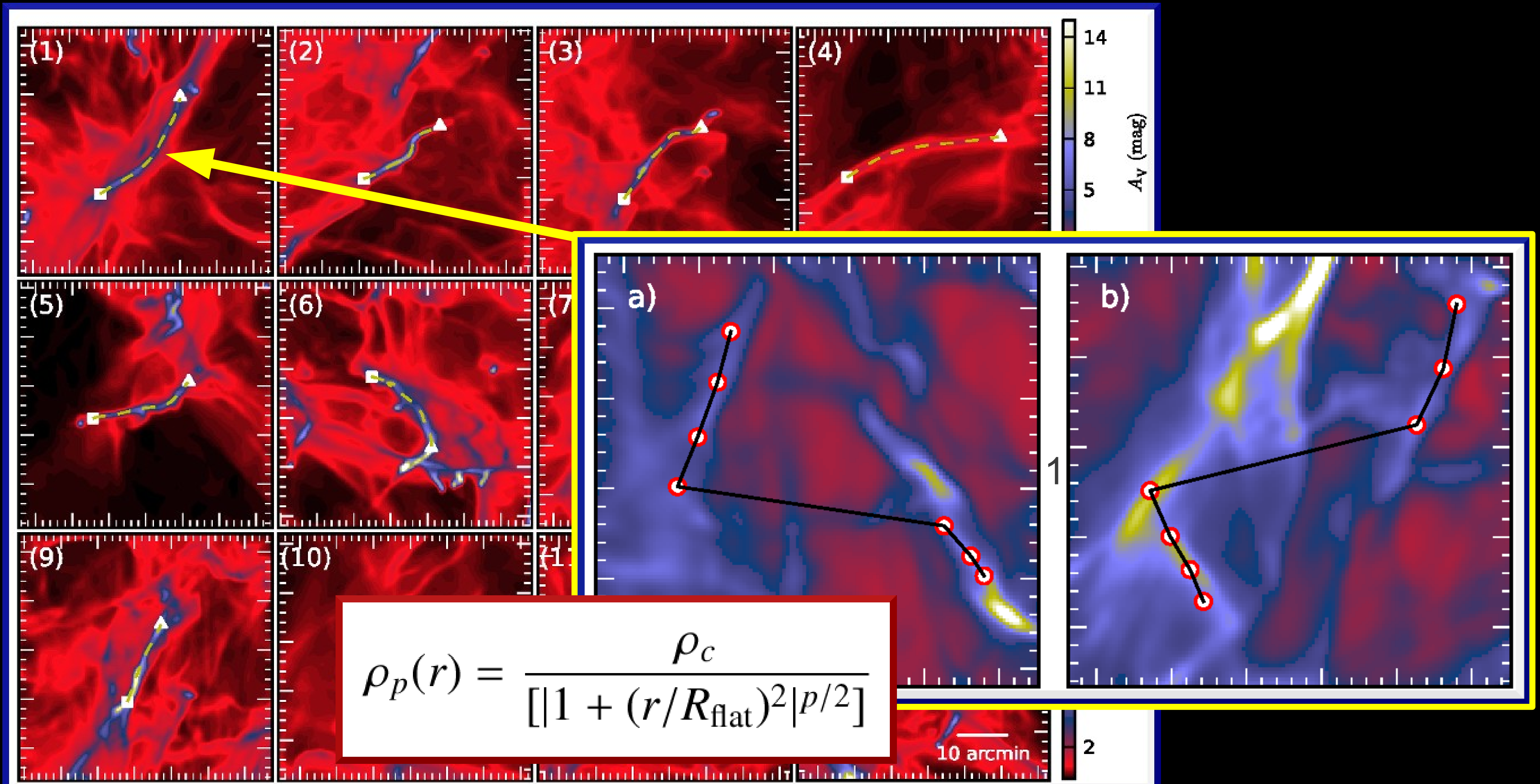


Filaments

Arzoumanian et al. (2011), Hill et al. (2011), Nguyen Luong et al. (2011), Hennemann et al. (2012), Peretto et al. (2012), Schneider et al. (2012), ...

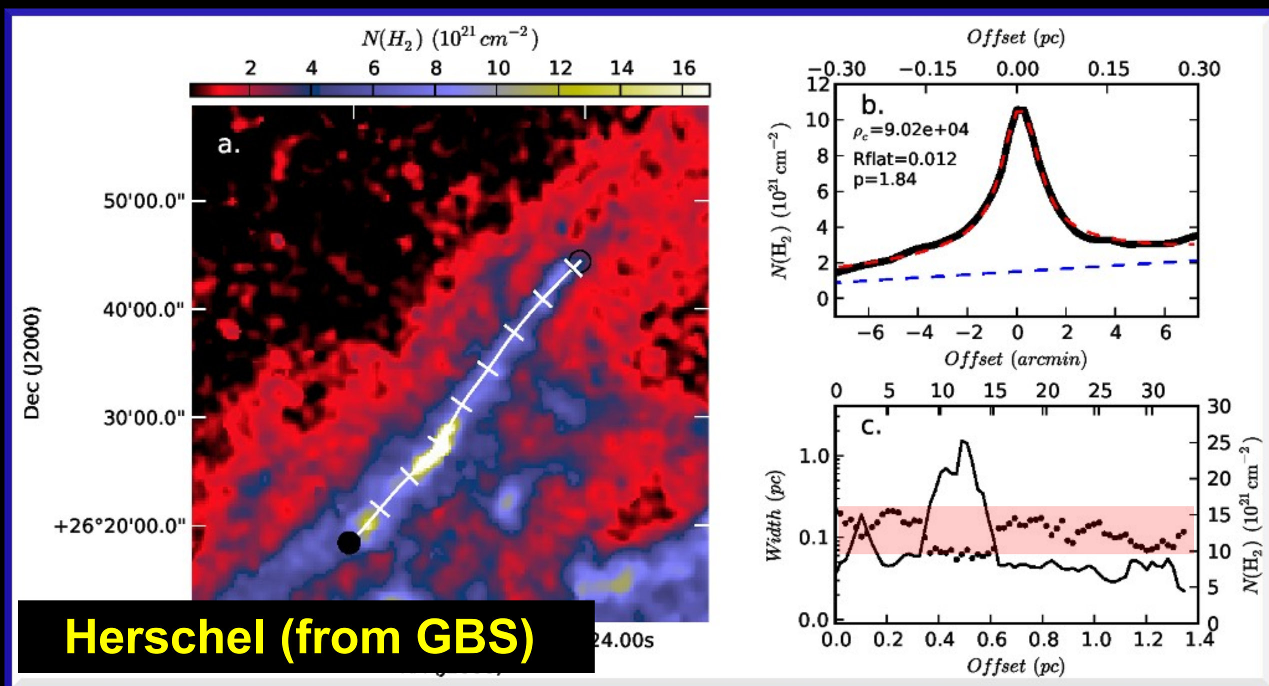
- Can we measure the filament profiles?
  - Up to a point. With Herschel the limit is at a few 100 pc
- Are some 'filaments' formed by a chance alignment
  - Possibly. This should apply more to clumps/cores (CMS!)

Juvela et al. (2012f)

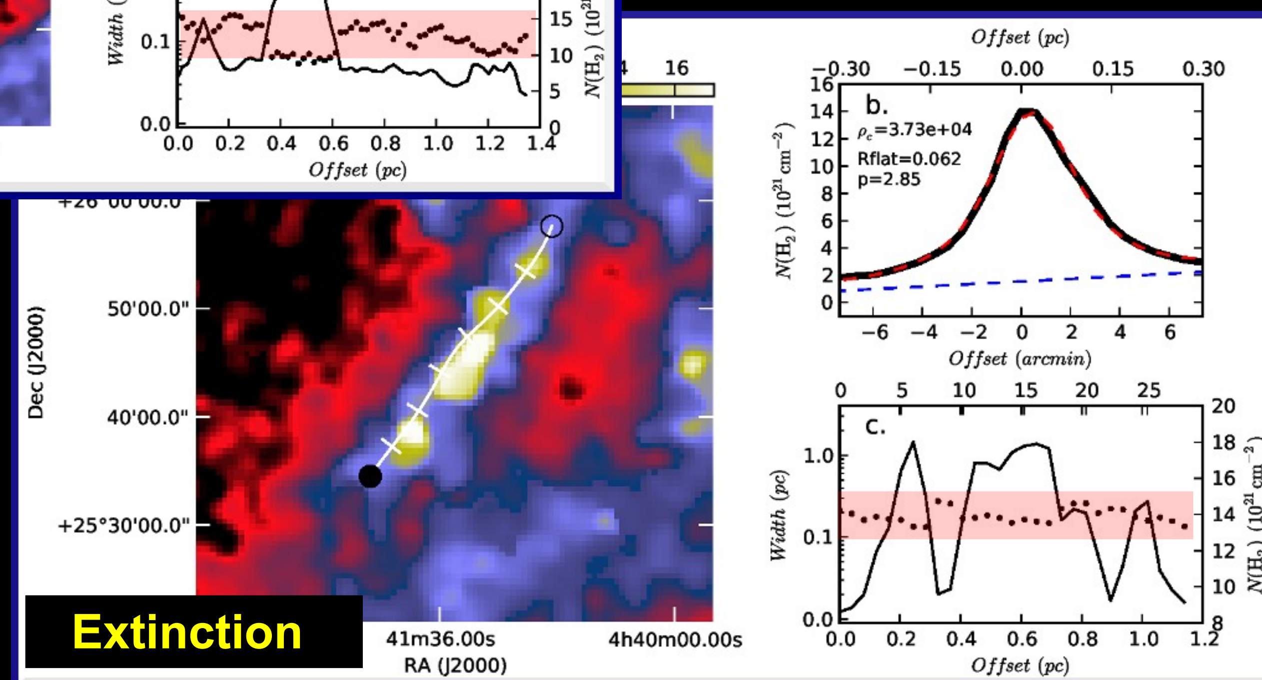


$$\rho_p(r) = \frac{\rho_c}{[|1 + (r/R_{\rm flat})^2|^{p/2}]}$$

- For nearby filaments, even 2MASS stellar colour excesses are enough to constrain filament properties
  - … the average profile



Malinen et al. (2012)



Summary

- **Sub-millimetre** observations **locate** pre-stellar clumps
  - The **Planck** survey is resulting in a catalogue of more than 10000 cold clumps in the Milky Way
- High resolution data from the **Herschel** satellite reveal the **structure** of the clumps and their environment
  - Often fragmented, many already containing young stars
- Data must be complemented with **other wavelengths**
  - mid-infrared to trace young stellar objects, molecular lines to measure gas temperature and to map cloud kinematics
- Numerical **modelling** help us to understand what we see
  - … or reveals things we cannot see or do not yet understand

- The first summary of the Herschel project **Galactic Cold Cores** is to be expected within a year

References

- Andre et al. (2010), A&A 518, L102
- Andre et al. (2011), IAUS S270, Vol. 6, 255
- Arzoumanian et al. (2011), A&A 529, L6
- Belloche et al. (2011), A&A 535, A2; A&A 527, A145
- Boudet et al. (2005), A&A 633, 272
- Crapsi et al. (2007), A&A 470, 221
- Enoch et al.(2006), ApJ 638, 293; (2007), ApJ 666, 982; (2008), ApJ 684, 1240
- Giannini et al. (2012), A&A 539, A156
- **Harju** et al. (2008), A&A 482, 535
- Henneman et al. (2012), A&A 543, L2
- Hill et al. (2011), A&A 533, A94
- Kainulainen et al.(2009), A&A, 508, L35
- Kainulainen et al. (2011),A&A 530, A64
- Kelly et al. (2012), ApJ 752, 55
- Könyves et al. (2010), A&A 518, L106
- Köhler et al. (2012), submitted
- Liu et al. (2012), arXiv-1207.0881
- **Lunttila** et al. (2012), A&A 544, A52
- **Juvela** et al. (2010), A&A 518: GCC-I
- **Juvela** et al. (2011), A&A 527, A111: GCC-II
- **Juvela** & Ysard (2011), ApJ 739, 63: on the temperature of cloud cores
- **Juvela** & Ysard (2012a), A&A 539, A71: the effect of T mixing on $\beta(T)$
- **Juvela** & Ysard (2012b), A&A 541, A33: $\beta(T)$ and noise
- **Juvela** et al. (2012c), A&A 538, A133: measuring T_{gas} with NH_3 lines
- **Juvela** et al. (2012d), A&A 541, A12: GCC-III
- **Juvela** et al. (2012e), A&A 544, A14: modelling of dust emission and scattering
- **Juvela** et al. (2012f), A&A 544, A141: measuring filament profiles with dust emission
- **Malinen** et al. (2011), A&A 530, A101: radiative transfer models of cores
- **Malinen** et al. (2012), A&A 544, A50: profiling filaments with extinction
- Martin et al. (2012), ApJ 751, 28

- Maury et al. (2011), A&A 535, A77
- Motte et al. (1998), A&A 336, 150
- Nguyen Luong et al. (2011), A&A 535, A76
- Nutter et al. (2009), MNRAS 396, 1851
- Pagani et al. (2010), Science 329, 1622
- Paradis et al. (2012), A&A 537, A113
- Peretto et al. (2012), A&A 541, A63
- Planck Collaboration, Planck early results VII (2011) A&A 536, A7
- Planck Collaboration, Planck early results XXII (2011) A&A 536, A22
- Planck Collaboration, Planck early results XXIII (2011) A&A 536, A23
- Ragan et al. (2012), arXiv-1207-6518
- Sadavoy et al. (2012), A&A 540, A10
- Schnee et al. (2012), ApJ 745, 18
- Schneider et al. (2012), A&A 540, L11
- Shetty et al. (2009a) ApJ 696, 2234
- Shetty et al. (2009b) ApJ 696, 676
- **Sipilä** (2012), A&A 543, A38
- Stamatellos et al. (2003) A&A 407, 941
- Steinacker et al. (2010) A&A 511, A9
- Stepnik et al. (2003) A&A 398, 551
- Veneziani et al. (2012), submitted
- Wilcock et al. (2011), A&A 526, A159
- Wu et al. (2012), arXiv-1206.7027
- **Ysard** et al. (2012), A&A 542, A21