Adiabatic spin-dependent momentum transfer in an SU(N) degenerate Fermi gas

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Strontium 87, nuclear spin 9/2: N = 10 spin states, to emulate the SU(10) Heisenberg model

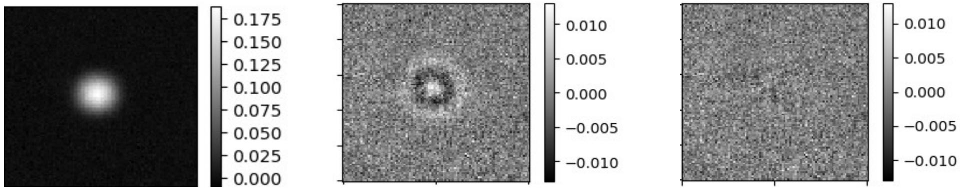
Effective Heisenberg model

From superexchange in an optical lattice

$$H_{\rm eff} = J \sum_{<i,j>} \vec{S}_i.\vec{S}_j$$

Hermele et al, PRL 2009
Gorshkov et al, Nat. Phys. 2010

T/Tf ~ 0.15 in bulk - Bataille et al, PRA 2020

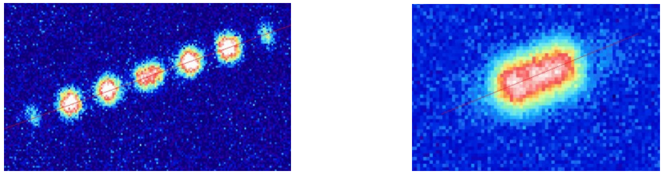


Momentum Boltzmann res. Fermi res.

Effectively tunable spin degree of freedom

Versatile optical pumping + spin-conserving [SU(N)] collisions
See e.g. experiments by Ozawa et. al., Phys. Rev. Lett. **121**, 225303

Lattice loading ongoing

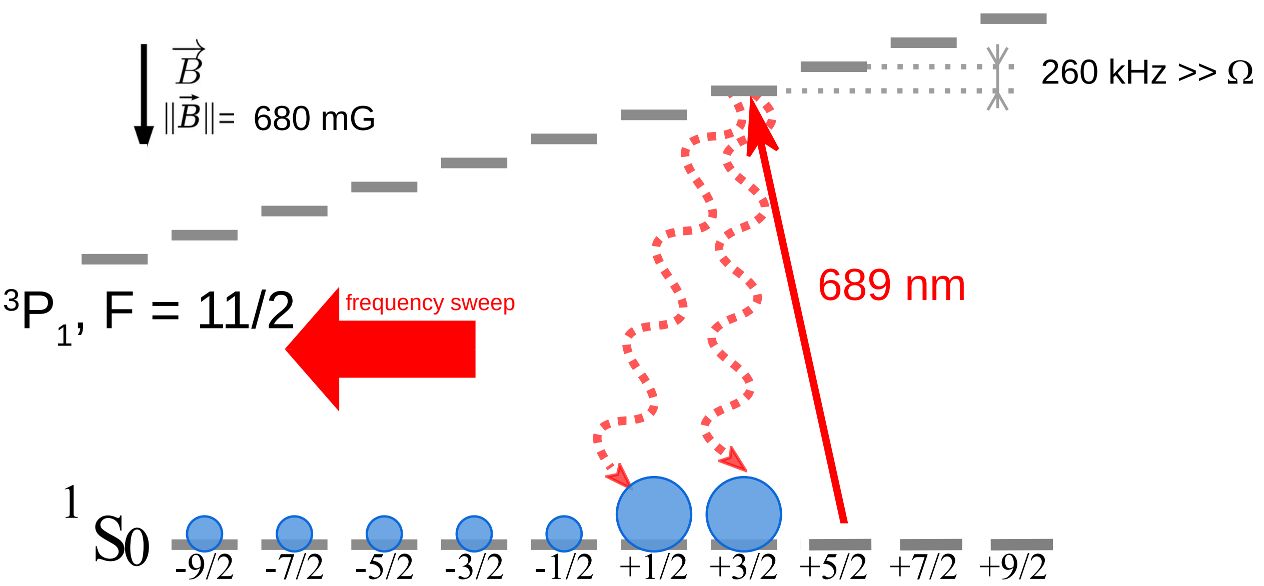


1-axis Diffraction 1D Band mapping

- Narrow inter-combination line:
new methods for spin preparation
and measurements

Shown on the right:
versatile spin preparation

<u>This poster: spin measurements</u>

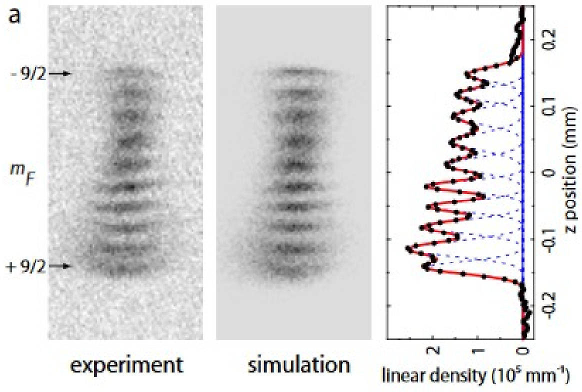


How to manipulate and probe a large, nuclear spin degree of freedom

Extremely small Lande factor of nucleons: magnetic field gradients have a negligible effect

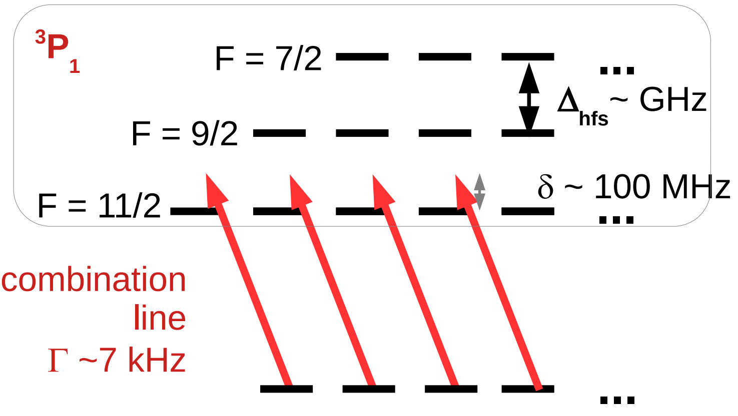
Nuclear-spin-dependent light shifts,
enabled by a narrow line with large hyperfine structure
$^1S_0 \rightarrow {}^3P_1$, F= {7/2, 9/2, 11/2} – Γ = 7kHz, Δ_{hfs} ~ GHz

Established tools based on
spin-dependent light shift gradients
→ Optical Stern-Gerlach separation
→ Singlet-Triplet Oscillation in optical lattices



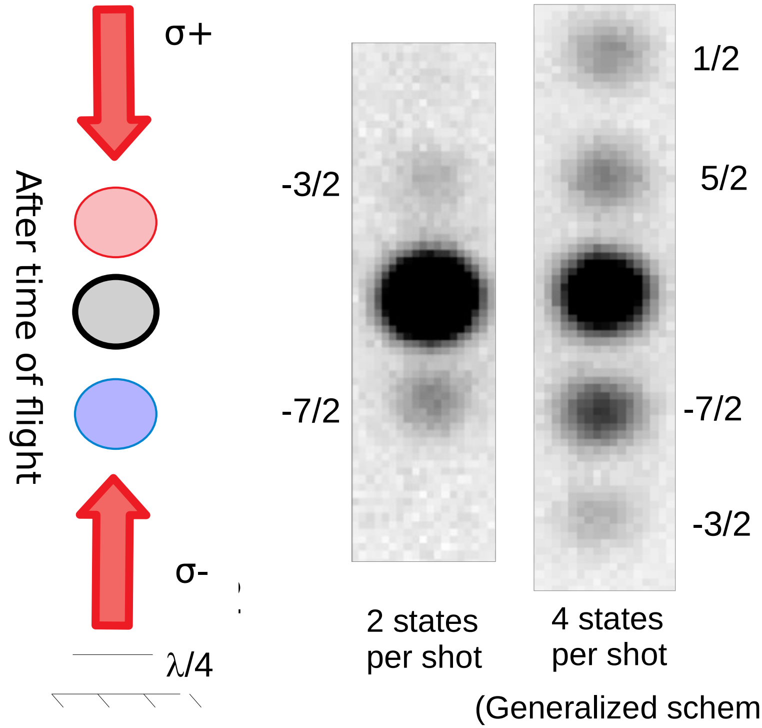
Sr: Stellmer et al,
Phys. Rev. A 84, 043611 (2011)

Yb: Taie et al,
Phys. Rev. Lett. 105, 190401 (2010)



Intercombination line
Γ ~7 kHz

Our work:
Spin-selective diffraction by a polarization lattice



(Generalized scheme)

Coherent process combining
spin-selective diffraction and spin swap

- Adiabatic procedure reminiscent of 1D Spin-orbit coupling
- Regular $\lambda/2$ spatial structure from opposing beams
  → minimal momentum distortion
  → good separation $2\hbar k$
- Coupling **resonant** with the excited state $^3P_1$, F = 11/2 enables excellent spin selectivity using polarized beams while a dark state inhibits spontaneous emission

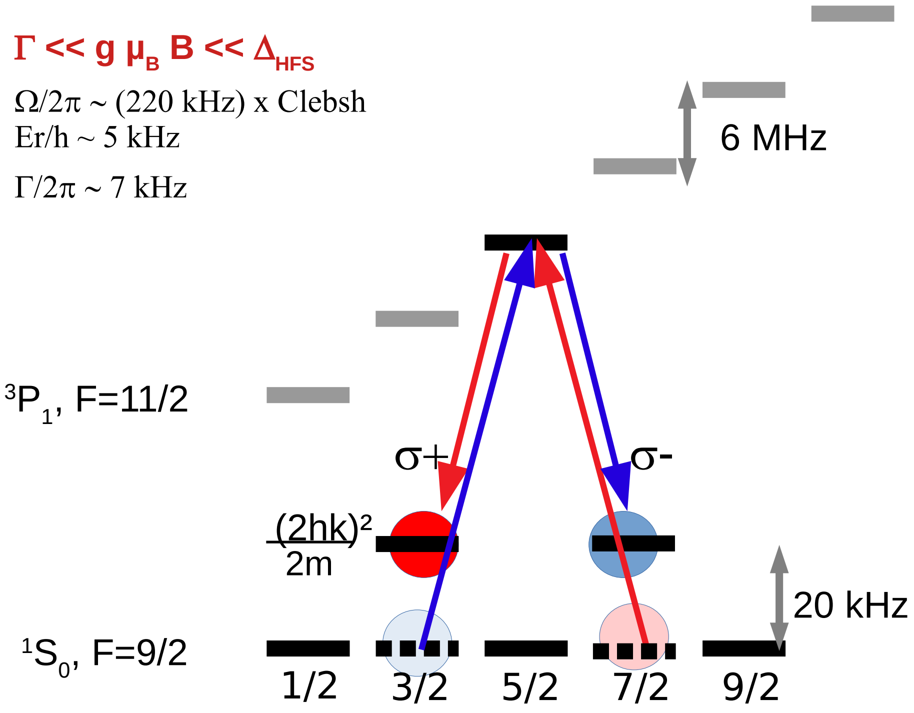
Momentum-resolved spin correlation measurements? (Bruun et al, PRA 2009)

Process description

$\Gamma << g\,\mu_B\,B << \Delta_{HFS}$

$\Omega/2\pi \sim$ (220 kHz) x Clebsh
$Er/h \sim$ 5 kHz

$\Gamma/2\pi \sim$ 7 kHz



$$\left.\begin{array}{l}\mathbf{|7/2,0\rangle \rightarrow |3/2,-2\,\hbar k\rangle}\\ \mathbf{|3/2,0\rangle \rightarrow |7/2,+2\,\hbar k\rangle}\end{array}\right\}\textbf{ in the same shot}$$

Accounting for the recoil energy in a manner that works for both processes simultaneously

→ **symmetric laser scheme:**
retroreflected beam with polarization optics

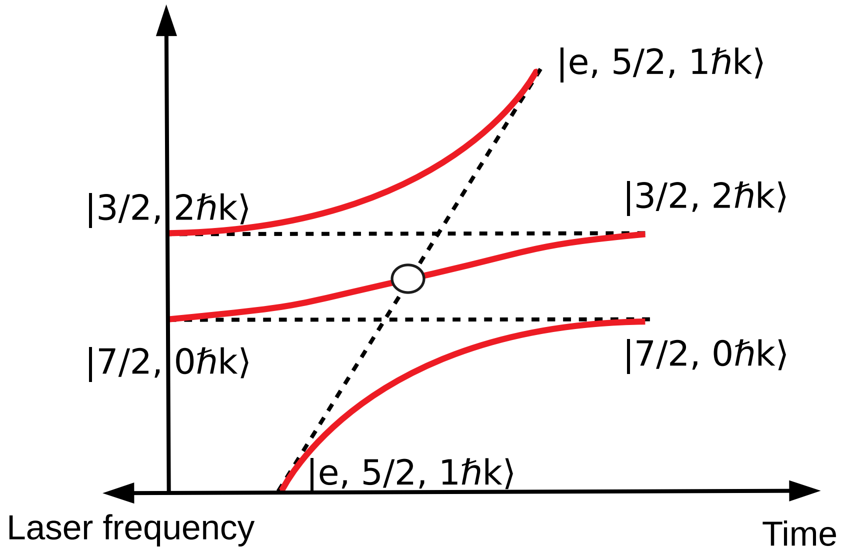
Recoil energy accounted for by a **time-dependent** laser frequency

- Dressed atomic states are followed adiabatically
They are "Dark"-states with low spontaneous emission

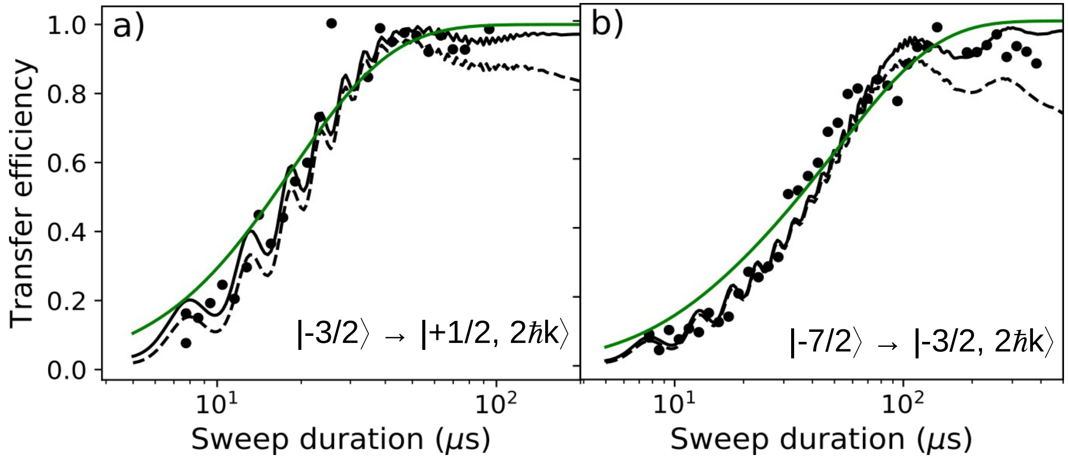
$$|\langle e|\psi\rangle|^2 \propto \frac{8\,Er^2}{\Omega^2}$$

$P(S.E.) \sim \Gamma\ Er\ /\ \Omega^2$

Dressed states energies

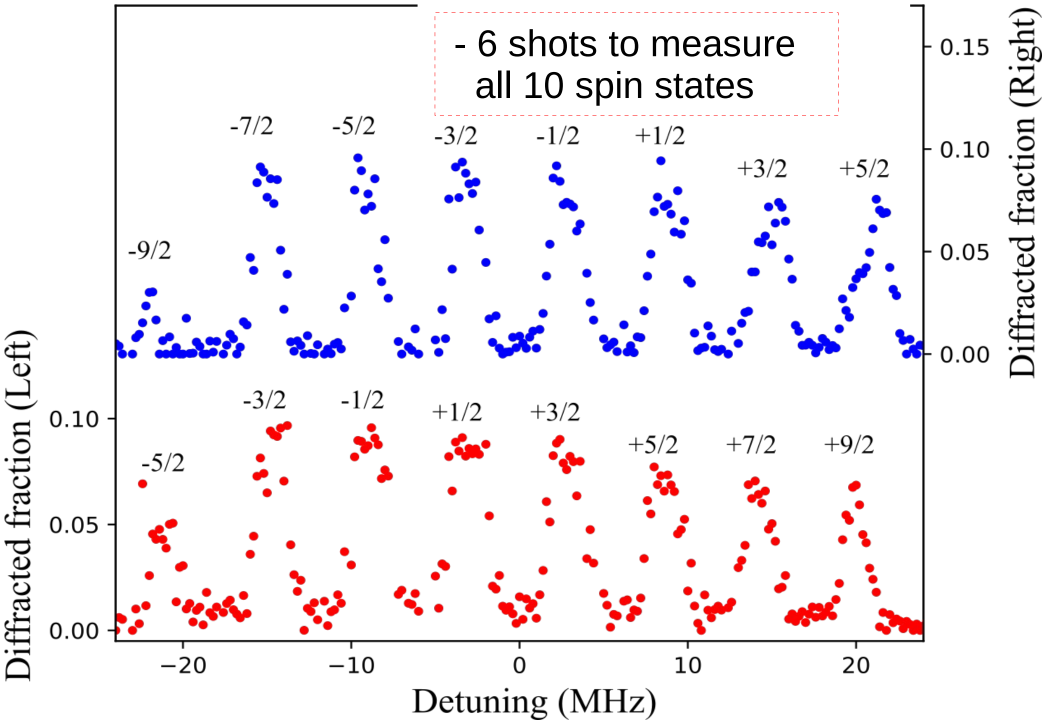


Adiabatic picture confirmation from temporal scaling



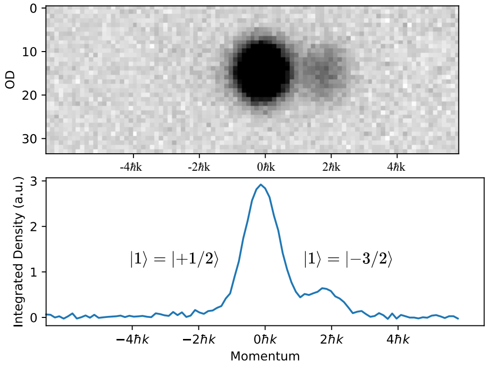
Model and Landau-Zener scaling: No adjustable parameter

Application



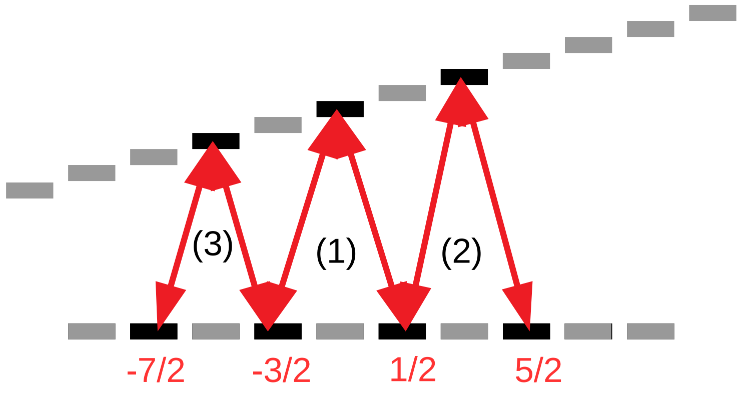
- Intensity-limited 80% transfer, 10% S. E., from target states. 95% transfer realistic with ~4x higher intensity.

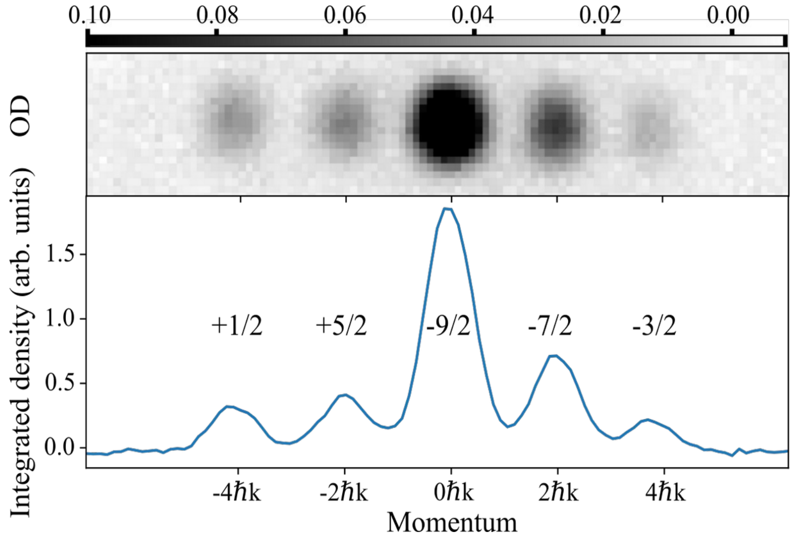
Optically pumped gas:
Demonstration that |+1/2> is empty
and that spin selectivity > 90%



- Population of the 10 spin states in 6 shots

- Generalisation to a 3-pulse scheme:
  4 diffracted states in one shot



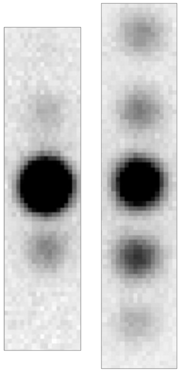


3-pulse experiment on an optically-pumped SU(5) cloud

- 8 states in two shots, still 10 states in 4 shots.

In a nutshell

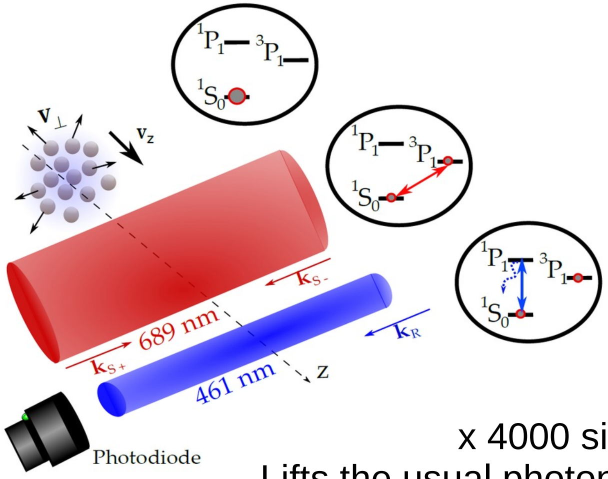
- Scheme based on **λ/2 structure** in uniform beams : large separation, minimal distortion
- **Coherent** process combining spin selective diffraction and spin swap
- **“Dark” state** enables coupling through the resonance, which comes with spin selectivity
- Population of the 10 spin states measured in 6 shots with the single-pulse protocol. Triple pulse protocol: 4 diffracted states in one shot, 8 in two shots, 10 in four shots.
- Large separation of spin components, and conservation of their momentum distribution
  → momentum-resolved spin correlation measurements could be foreseen (Bruun et al, PRA 2009)



Bataille et al, Adiabatic spin-dependent momentum transfer in an SU(N) degenerate Fermi gas, Phys. Rev. A **102**, 013317 (2020)

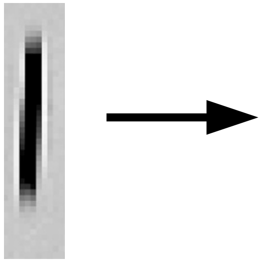
Other recent works:

- **I. Manai et al,** Shelving spectroscopy of the strontium intercombination line, J. Phys. B **53**, 085005 (2020)

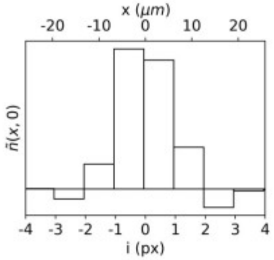


x 4000 signal
Lifts the usual photon shot noise limit in narrow-line saturated spectroscopy

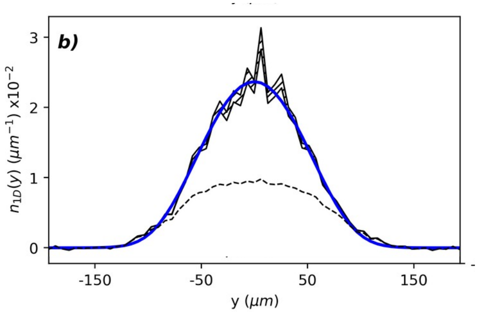
- **A. Litvinov et al**, Measuring densities of cold atomic clouds smaller than the resolution limit, Phys. Rev. A. **104**, 033309 (2021)



Here: elongated cloud. Applicable to other objects, e.g. solitons, vortices



Measuring the unresolved width



Getting the actual profile along the “resolved” dimension