# Coronal magnetic fields measurement using MIT method

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2022.09.19-23 Hinode-15/IRIS-12

## Collaborators:

**Atomic method, theory and calculations:**
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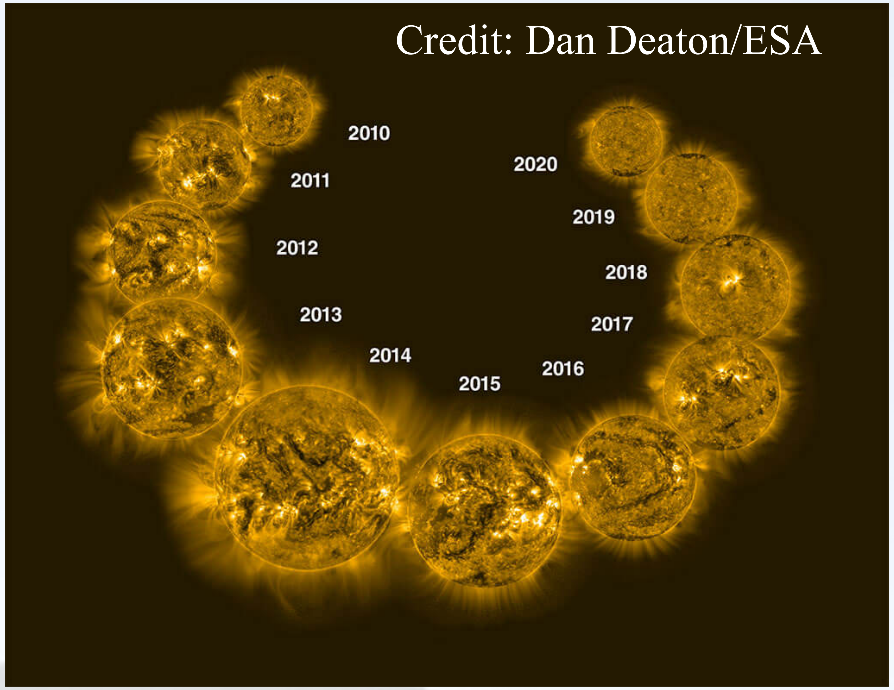
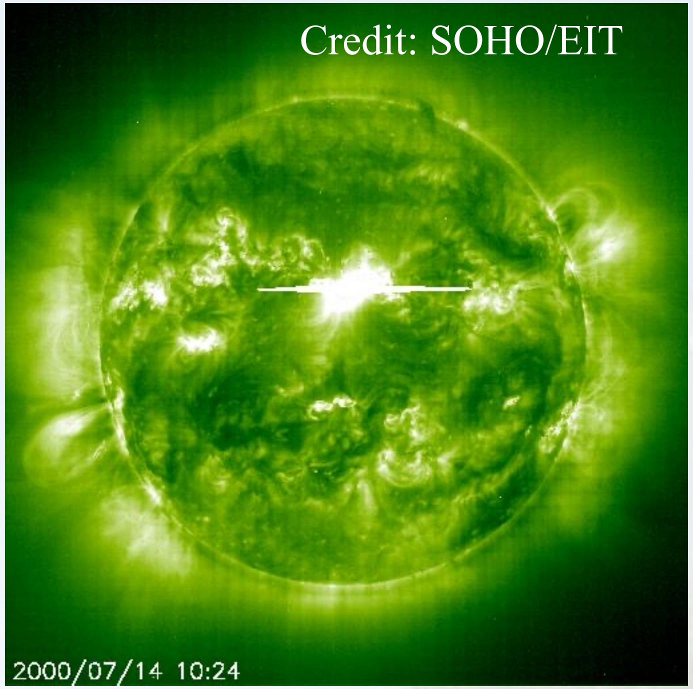
**Laboratory measurement:**
**Fudan University**: Shanghai-EBIT laboratory

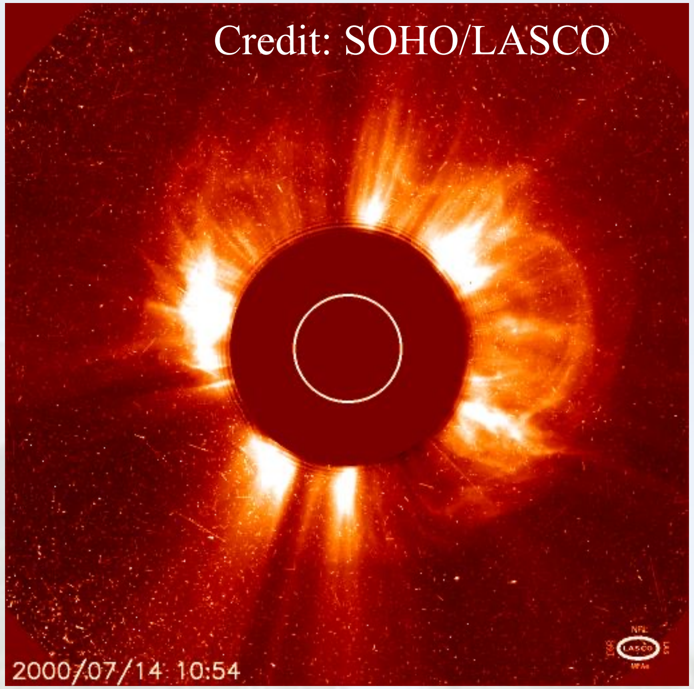
**Solar observations and applications:**
**High Altitude Observatory**: Philip G. Judge
**University of Michigan**: Enrico Landi
**Peking University**: Hui Tian group
**National Astronomical Observatories**: Huairou Solar Observing Station

# Why coronal magnetic field?

solar cycle, structuring, solar eruptions, coronal heating ……



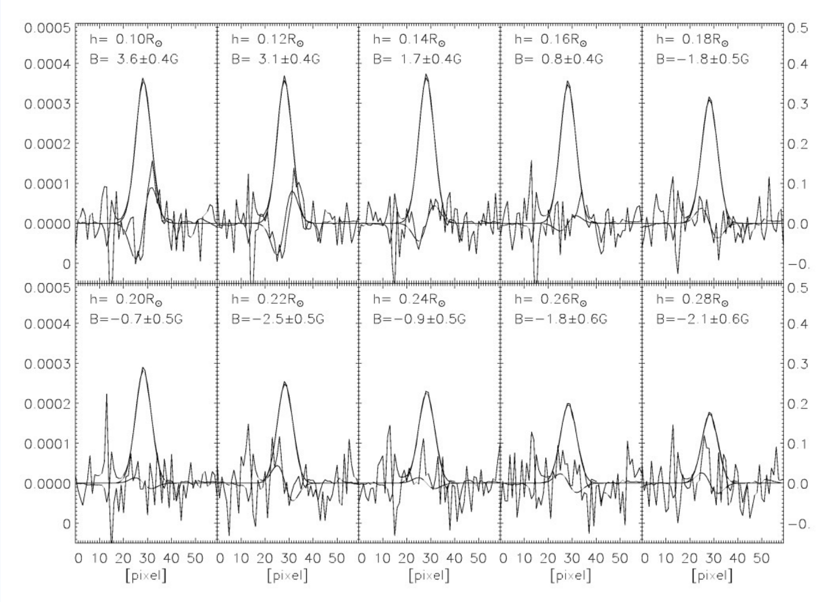




Coronal magnetic field measurement is still challenging

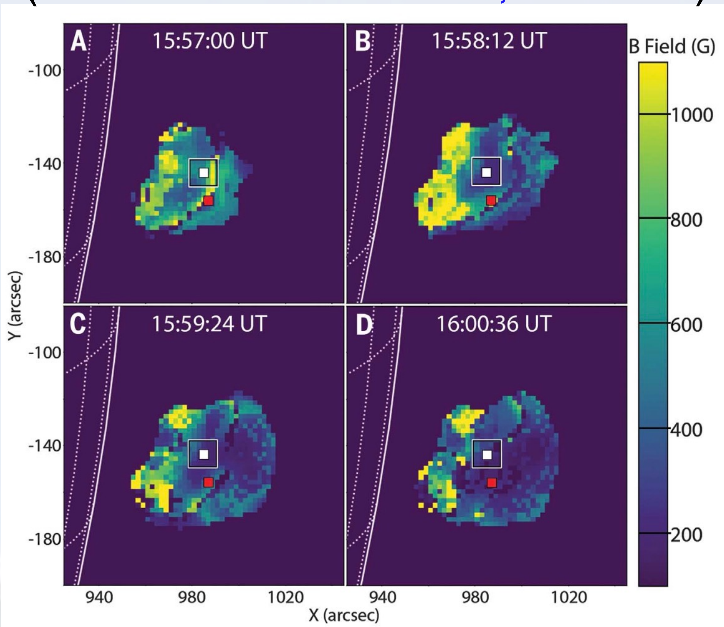
weaker field, higher temperature

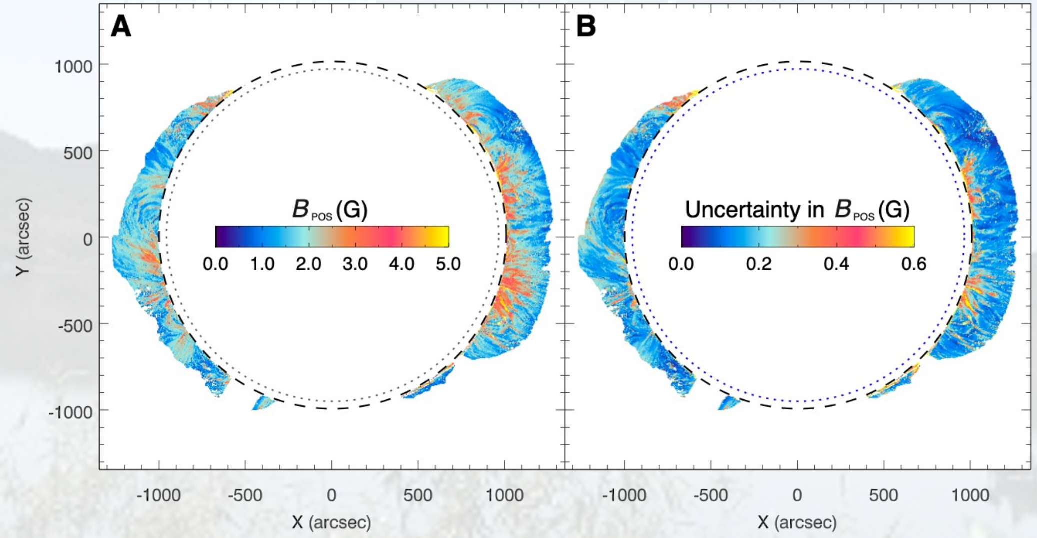
# How to measure the coronal magnetic field?

Spectropolarimetry of the visible and near-infrared coronal emission lines (Lin et al. 2004, ApJL)

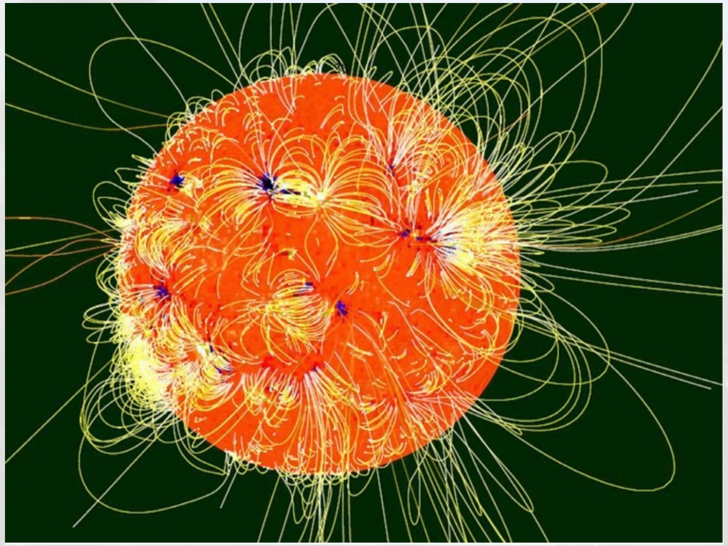



radio imaging observations (Fleishman et al. 2020, Science)




Extrapolation from photospheric magnetic field (Wiegelmann and Solanki 2004)⟶

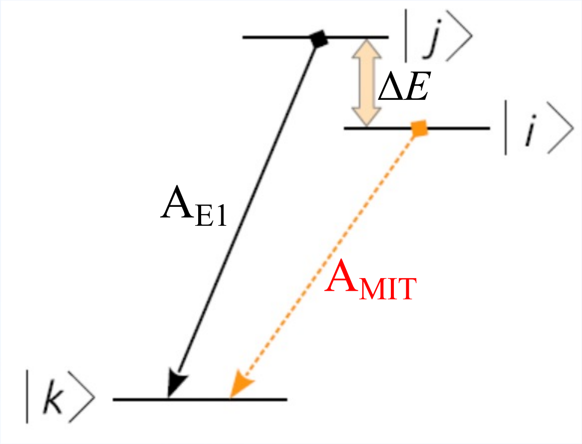


⟵ magnetoseismology (Yang et al. 2020, Science)

# Overview of magnetic-field induced transition, MIT

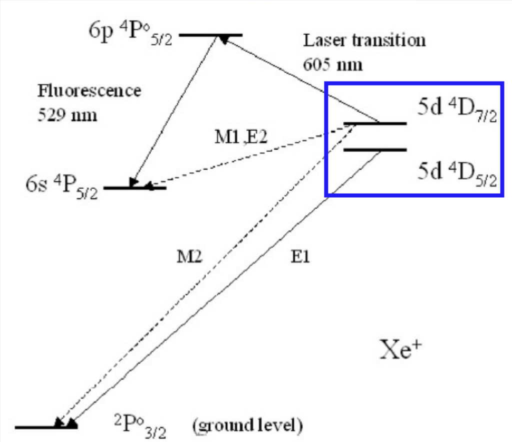
- External magnetic fields mix i and j and cause a new decay channel i → k: magnetic-field induced transition (MIT)

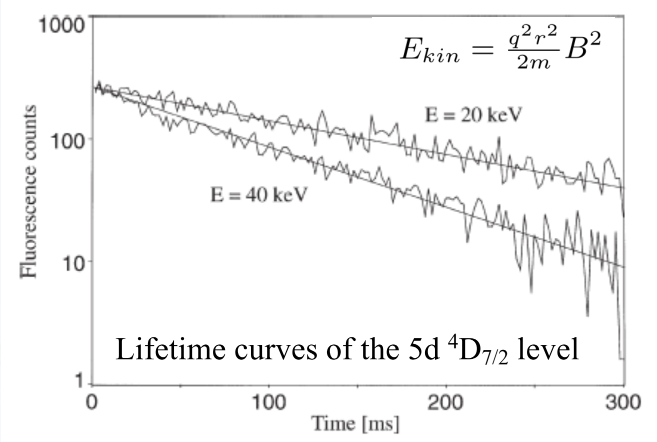
$$A_{\mathrm{MIT}} \propto A_{\mathrm{E1}} \frac{B^2}{\Delta E^2}$$



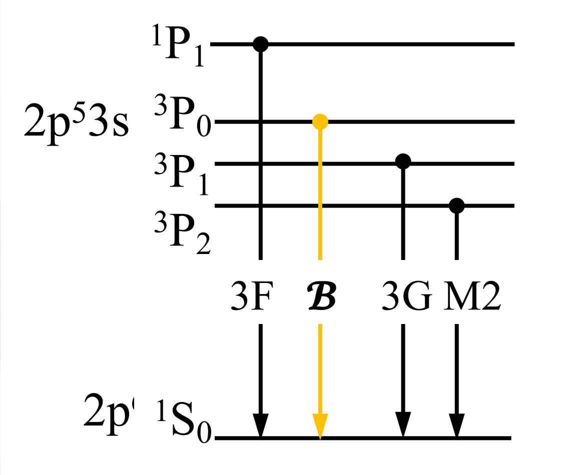

A simple three-level system

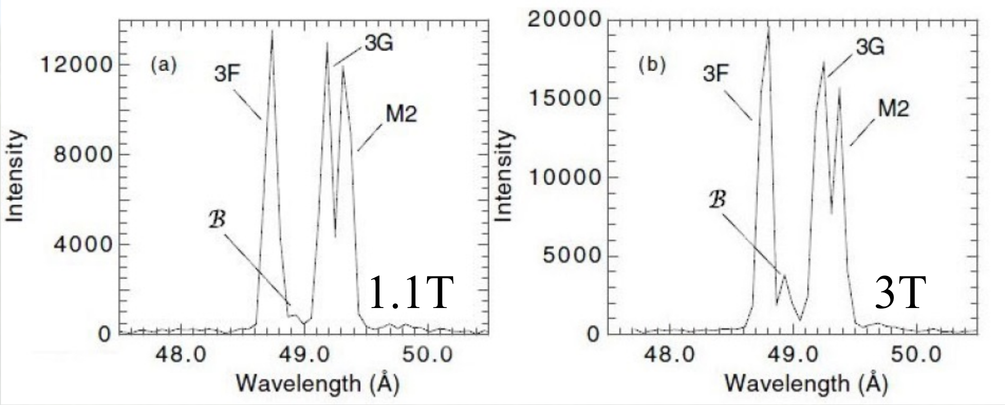
- Zeeman quenching: shorten the lifetime of levels (Schef et al. 2005, PRA)



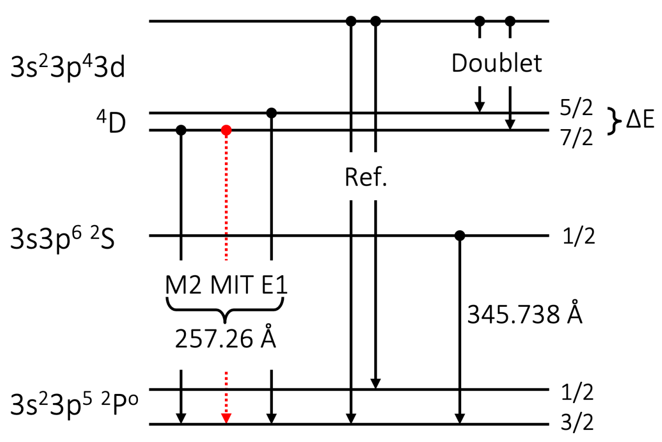

- MIT: spectroscopy measurement (Beiersdorfer et al. 2003, PRL)



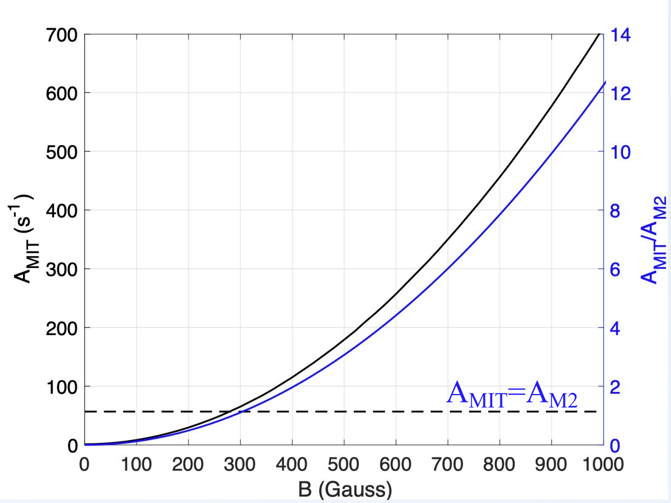
# Overview of MIT in Fe X

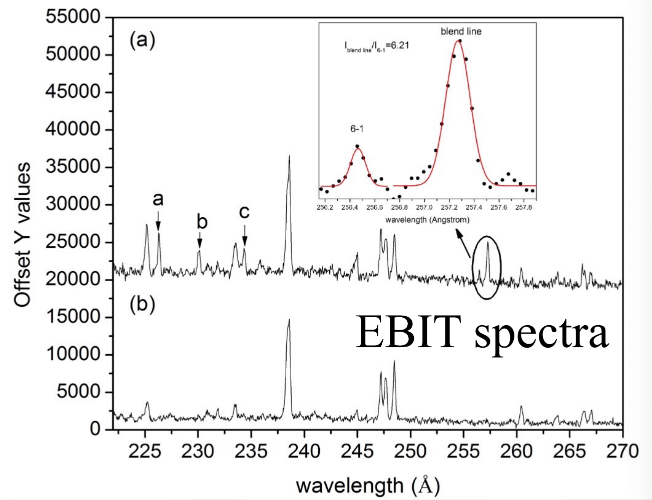
$$A_{\mathrm{MIT}} \propto A_{\mathrm{E1}} \frac{B^2}{\Delta E^2}$$

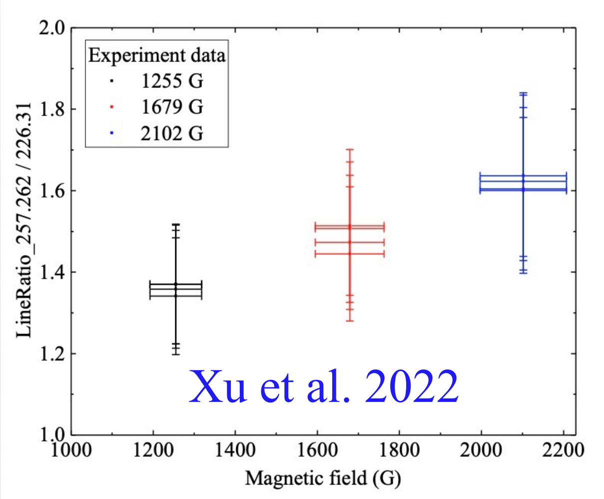



Schematic energy diagram of Fe X

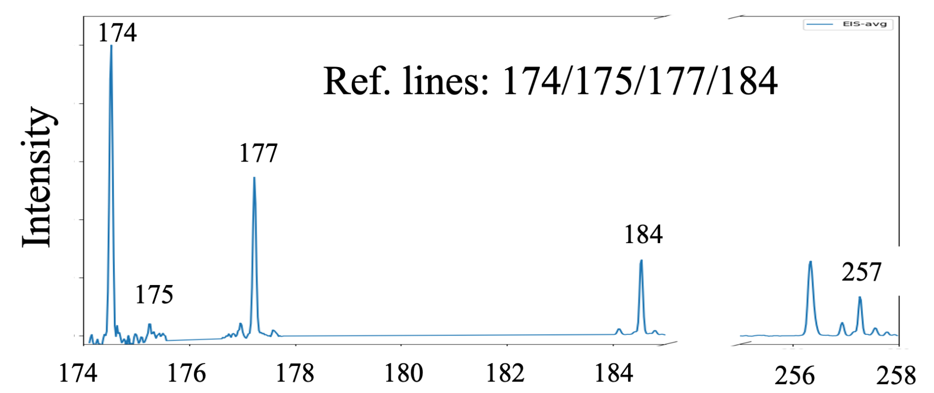
- MIT in Fe X: enhanced by the pseudo-degeneracy of $^4D_{7/2,5/2}$ (Li et al. 2015, 2016, 2021, ApJ)



# Methodology



Portion of Fe X spectrum from Hinode/EIS

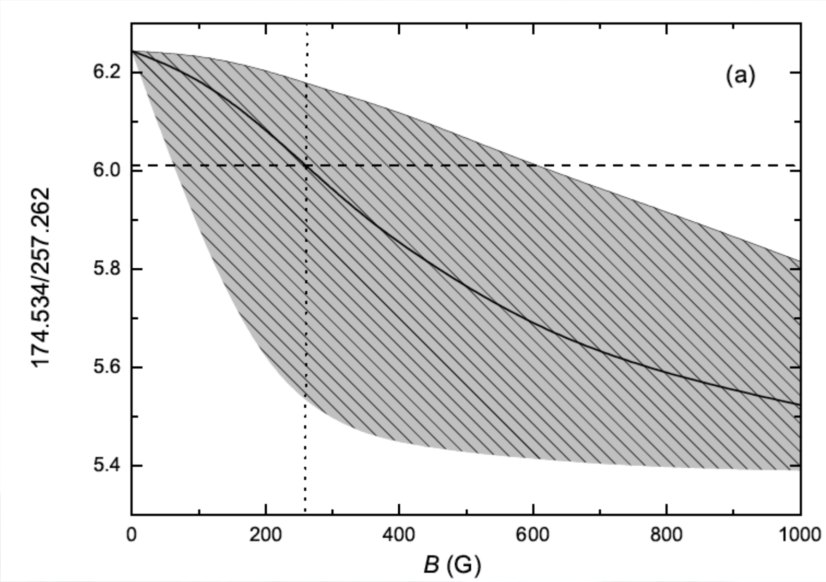

Hinode/EIS: solar corona and upper transition region emission lines in the wavelength ranges 170 – 210 Å (SW) and 250 – 290 Å (LW)

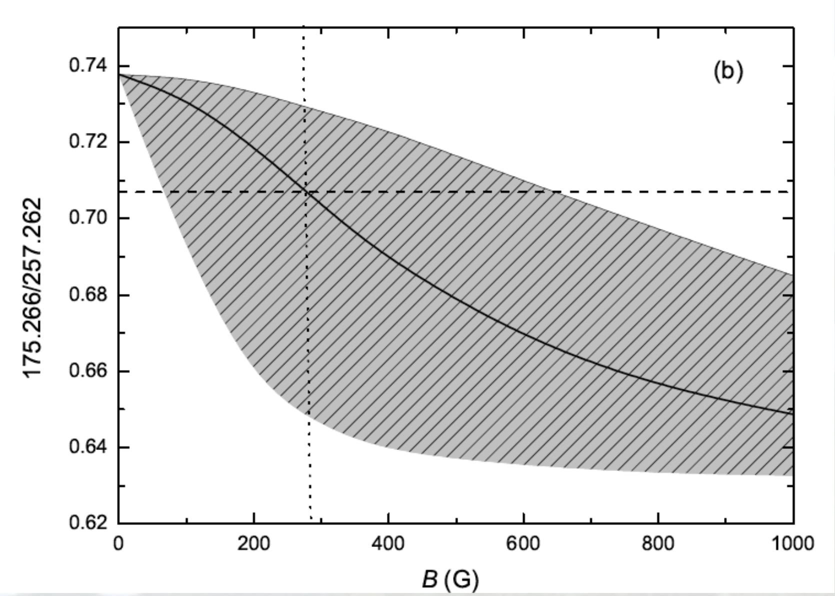
compare the observed 257/Ref. from EIS with theoretical predictions LR(T,N,B)

- Reference line: insensitive to B
- Density diagnostic: intensity ratio with Fe X 175
- Temperature diagnostic: intensity ratio with Fe X 345, DEM
- Spectral modelling: CHIANTI database, Int(T,N,B)

# coronal magnetic field measurement – example 1

- 174 and 175 as reference lines (Si et al., ApJL, 2020)
- 174/175 for density determination
- observed intensity ratios from Brown et al. ApJS, 2008, an active region observed on Nov. 4, 2006 on the solar disk from Hinode/EIS



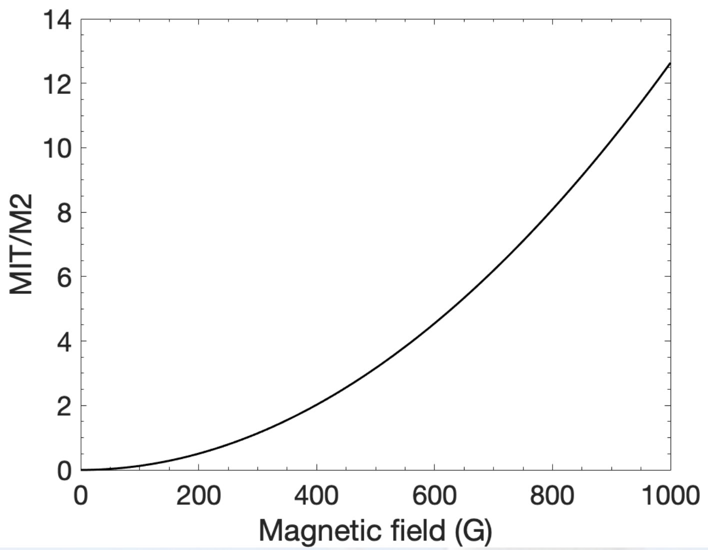

The field strength we determine is around 270 G.

# coronal magnetic field measurement – example 2

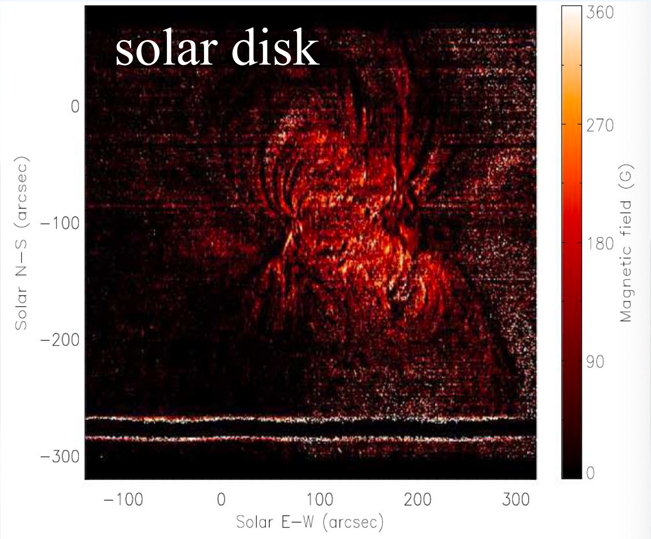
Landi et al. ApJ, 2020

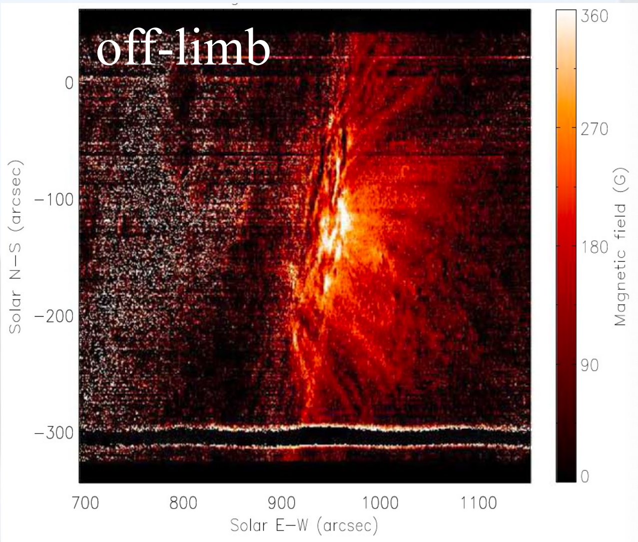
Assumption: $A_{MIT} < A_{M2}$, MIT transition does not affect the M2 intensity

$$\frac{I(\mathrm{MIT})}{I(\mathrm{M2})} = \frac{I(257)}{I(\mathrm{Ref.})} \cdot R(\frac{\mathrm{Ref.}}{\mathrm{M2}}) - R(\frac{\mathrm{E1+M2}}{\mathrm{M2}})$$




- reference line: 184 Å
- Density measurement: Fe X 174/175, Fe XI 182/188
- One example: AR10978 maps on 12 December(11:43:36 UT) 2007




Landi et al. 2020, 2021
Brooks & Yardley 2021
Brooks et al. 2021

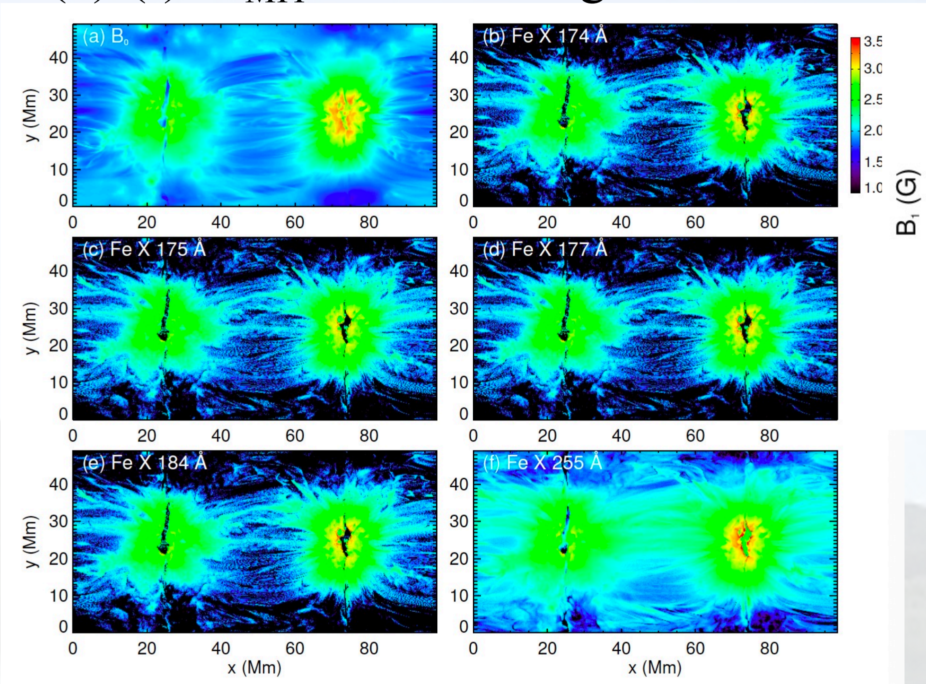
# Validation: Forward modeling with a 3D MHD model

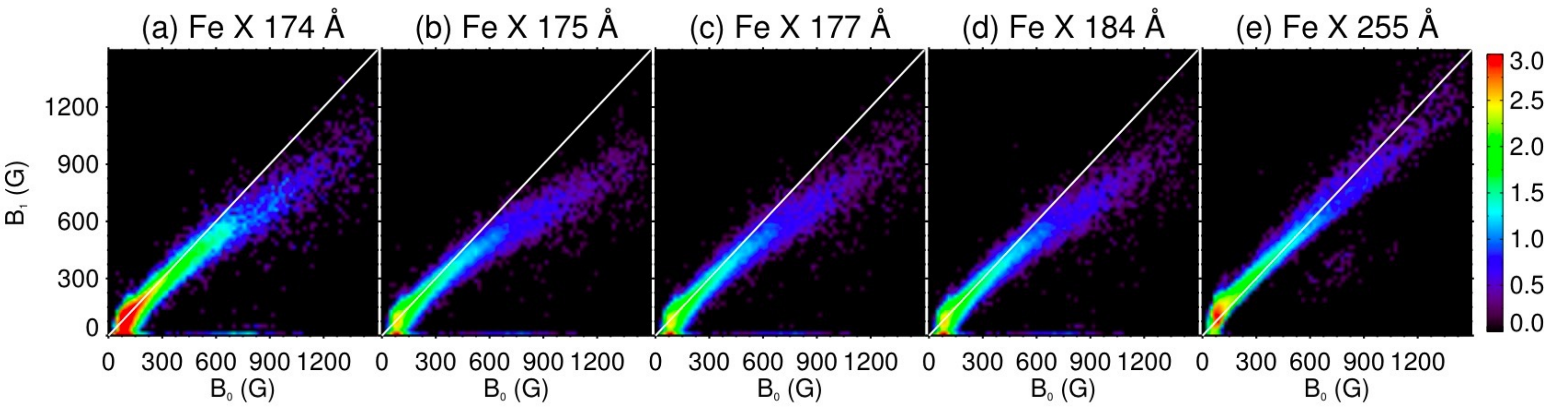
Chen et al. 2021a,b, Liu et al. 2022, ApJ

- Synthesize the Fe X line intensities from 3D MHD model
- Density diagnostics: Fe X 175/174 line ratio
- Temperature diagnostics: Fe X 184/345 line ratio

(a): $B_{model}$

(b)-(f): $B_{MIT}$ derived using different ref. lines




the MIT technique could provide reasonably accurate coronal magnetic field measurements in active region

# Limitations and uncertainties

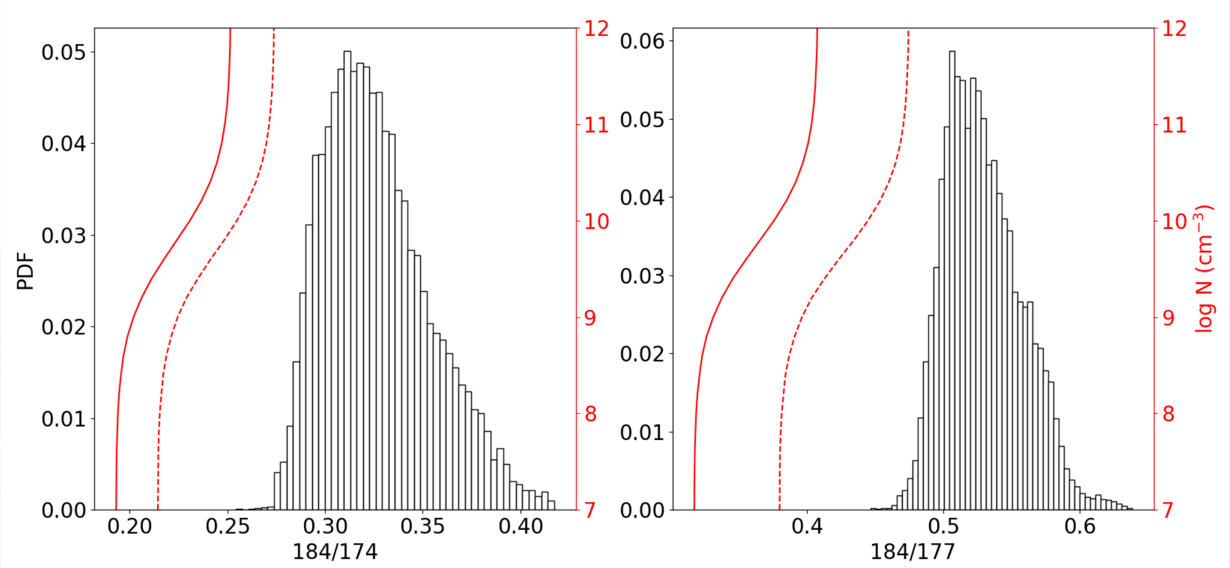
- Only field strength can be measured, but not the direction
- Uncertainty in atomic data:

  ΔE: 20% uncertainty from the recent SUMER measurements (Landi et al. 2020)

  CHIANTI v.10 – transition and collisional data from R-matrix (Del Zanna et al. 2012)
- Intensity calibration: short- and long-wavelength

Li et al. 2021, 2022:

- large-scale MCDHF calculations for energy levels and radiative data for states up to n=4
- Dirac Atomic R-matrix calculation for electron-impact collision strengths



# Summary

- The magnetic-field-induced transition method has been developed and was verified in the laboratory.
- The pseudo-degeneracy of two levels in Fe X causes the MIT@257 Å line to be sensitive to the relatively small magnetic fields expected in the solar corona.
- Forward modeling with 3D MHD models has verified that the MIT technique could provide reasonably accurate coronal magnetic field measurements in active regions.
- The MIT method has been applied to HINODE/EIS observations and illustrates the potential of a new diagnostic technique for coronal field strength measurement.
- Further efforts are necessary on both theoretical and observational side to provide a better estimation of magnetic field using the MIT method.
- It is also highly desirable to combine different magnetic field techniques to achieve a better understanding of coronal magnetism.

# Thanks for your attention!