太陽大気の輻射磁気流体シミュレーション

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アウトライン

- 太陽の大気構造を知るには
- フォワードモデリングによるアプローチ
- 今後の研究課題

アウトライン

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- フォワードモデリングによるアプローチ
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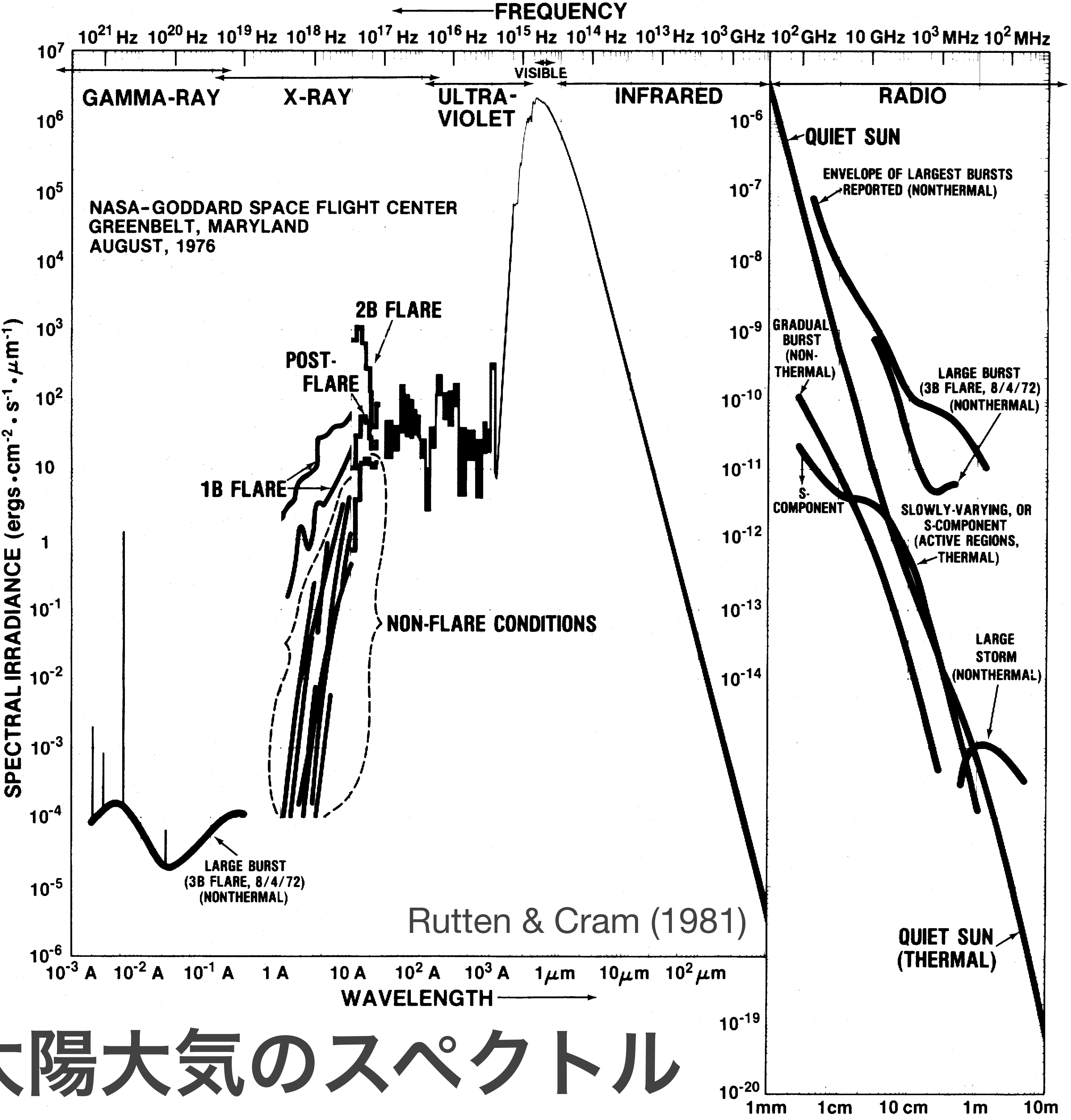
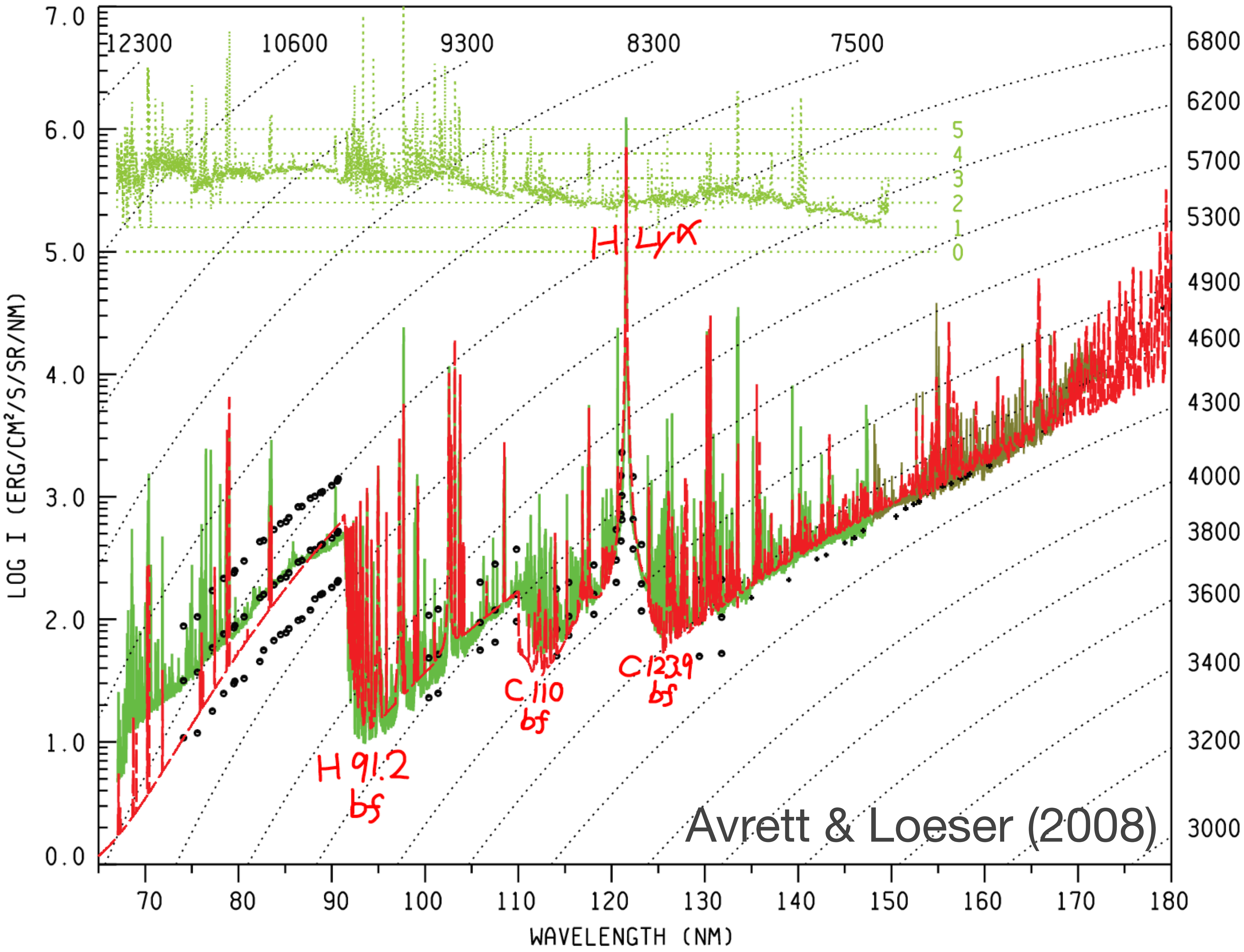


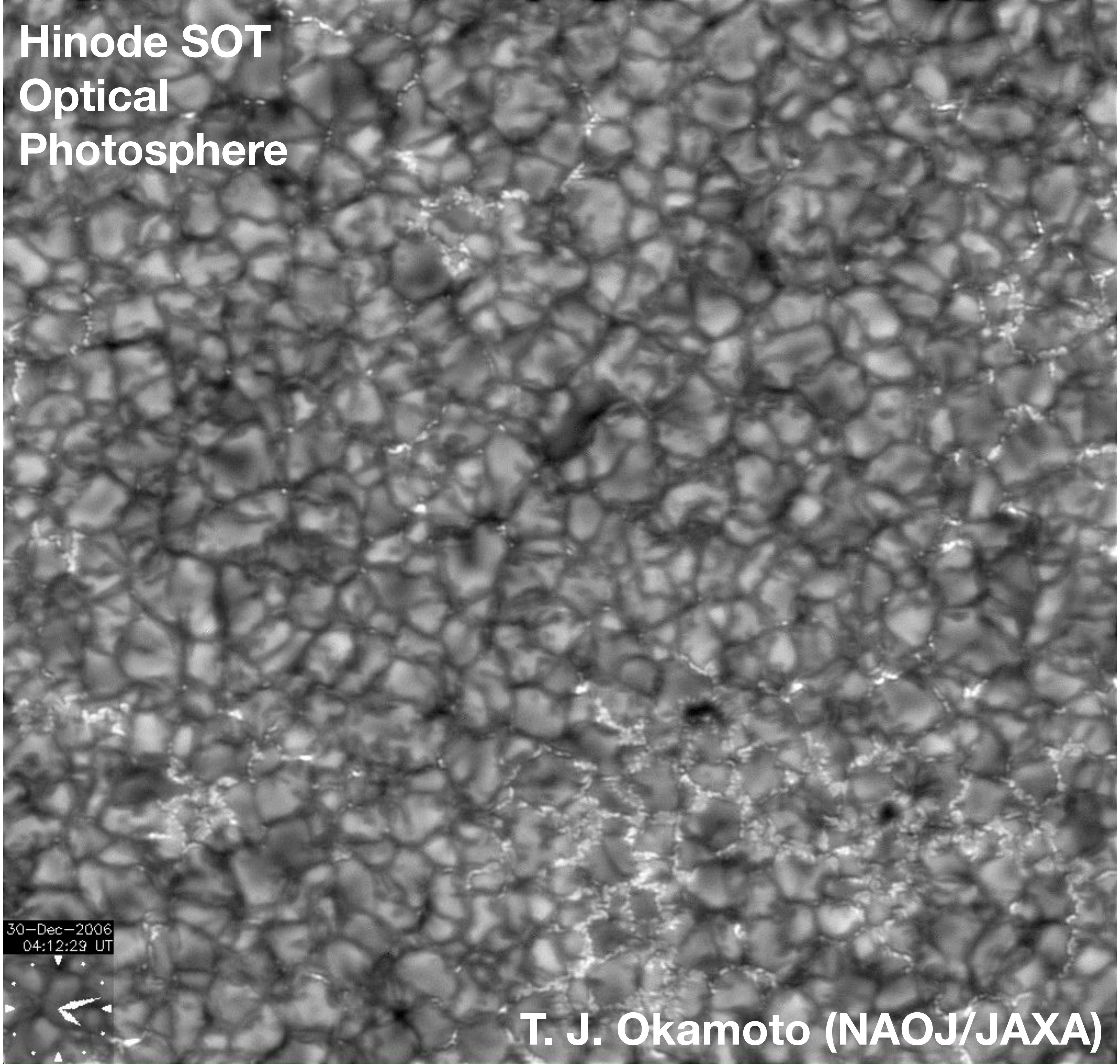
Rutten & Cram (1981)

太陽大気のスペクトル

紫外線のスペクトル例

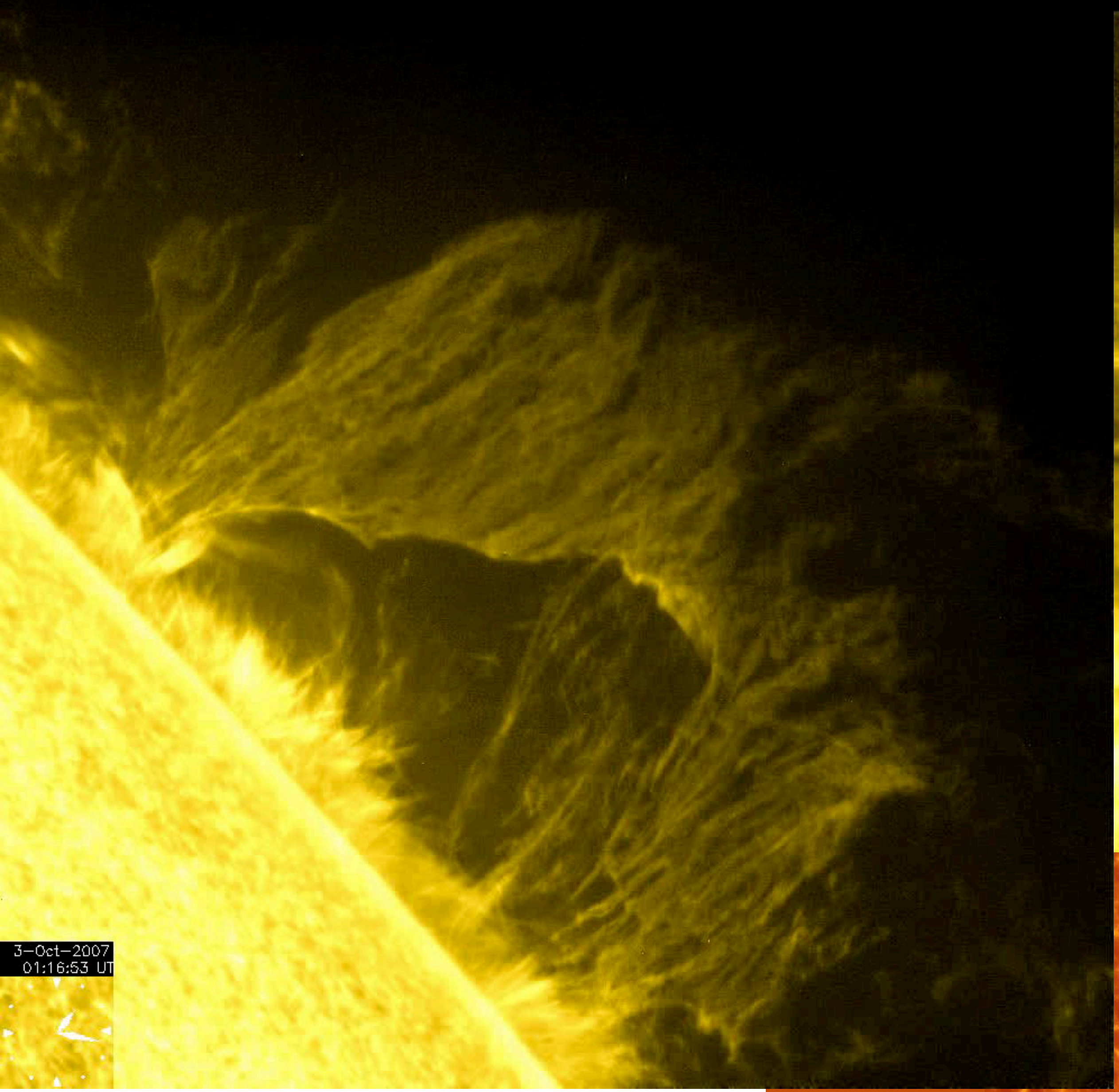


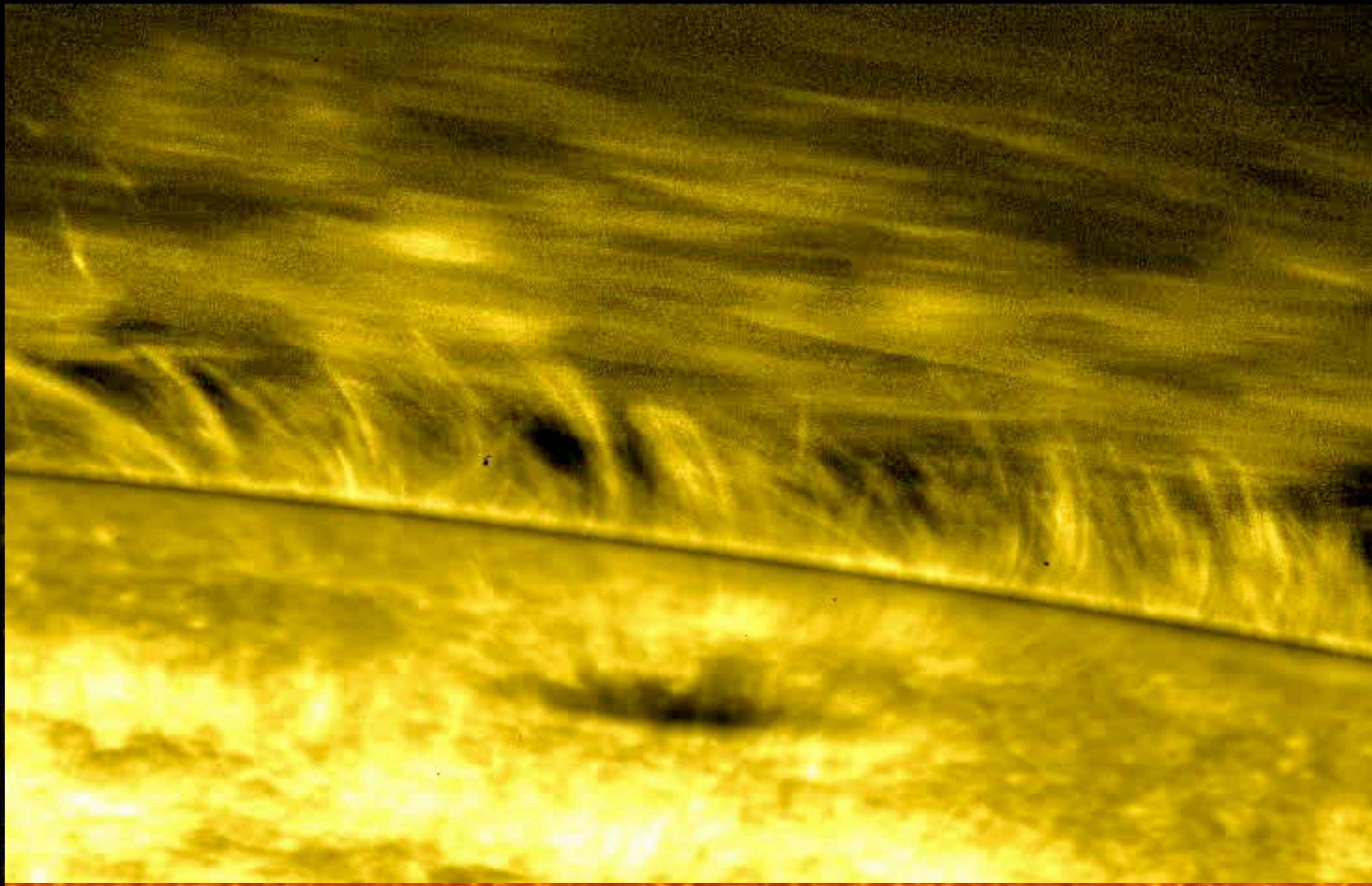
Avrett & Loeser (2008)

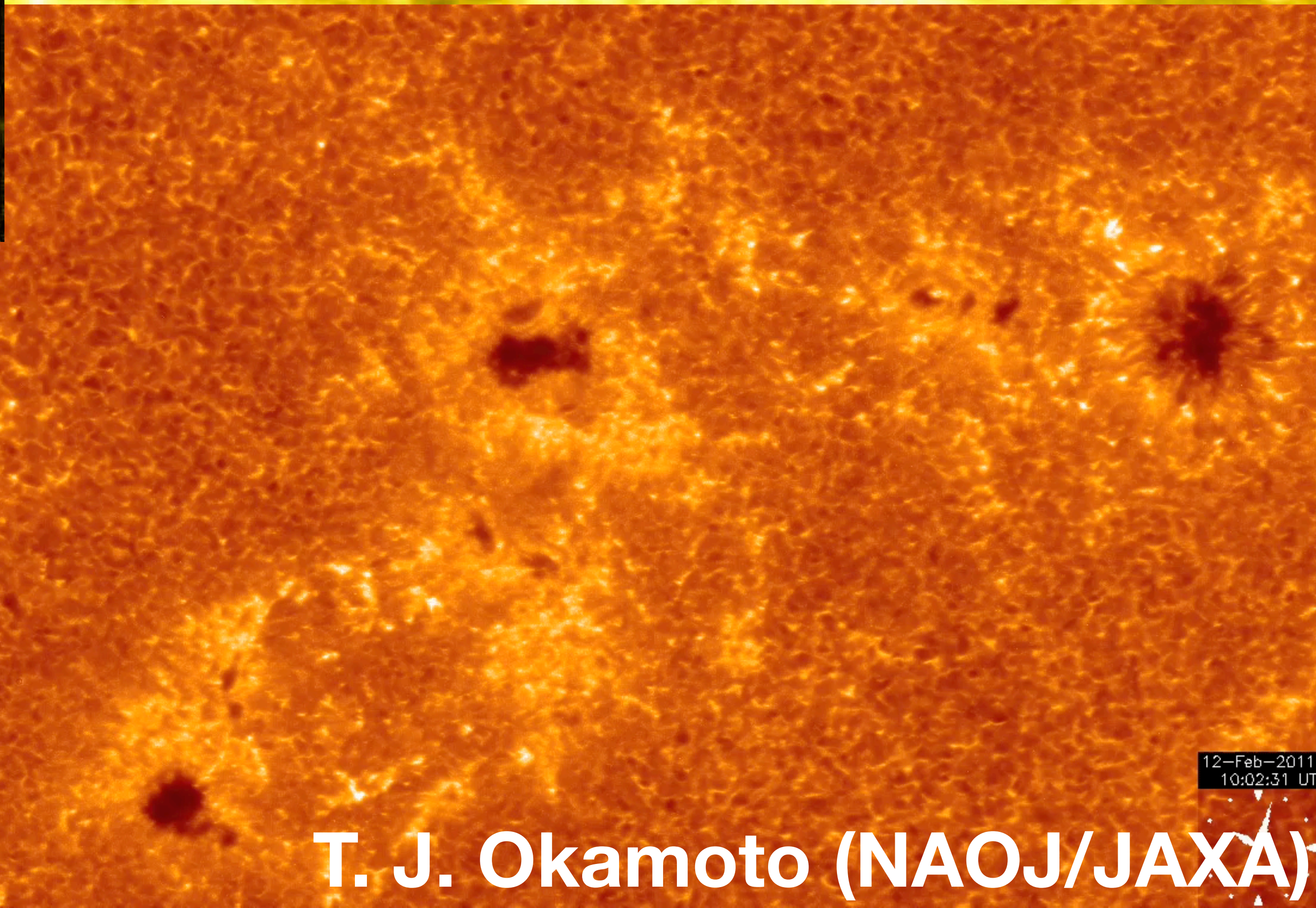


Hinode SOT
Optical
Photosphere

T. J. Okamoto (NAOJ/JAXA)

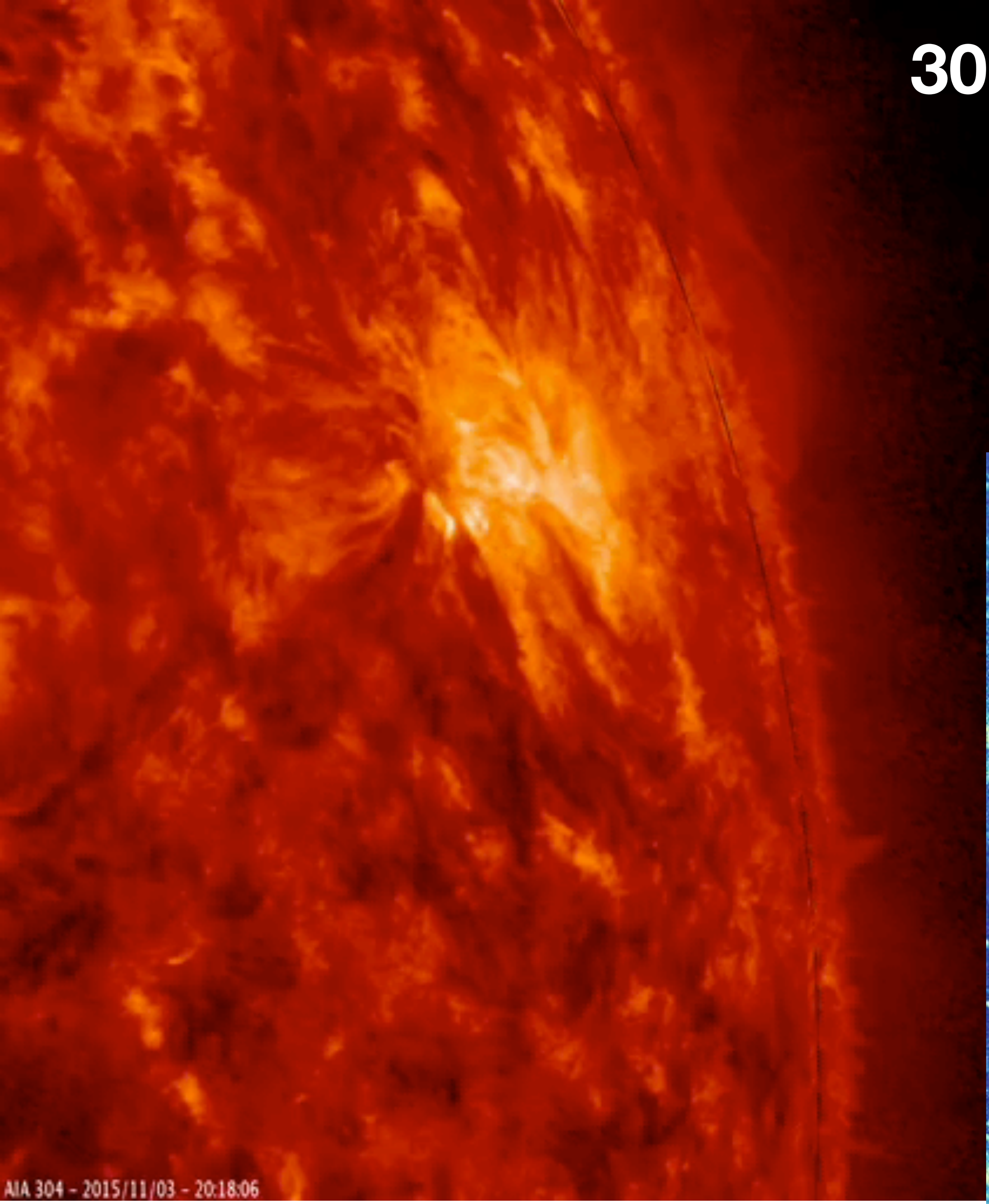




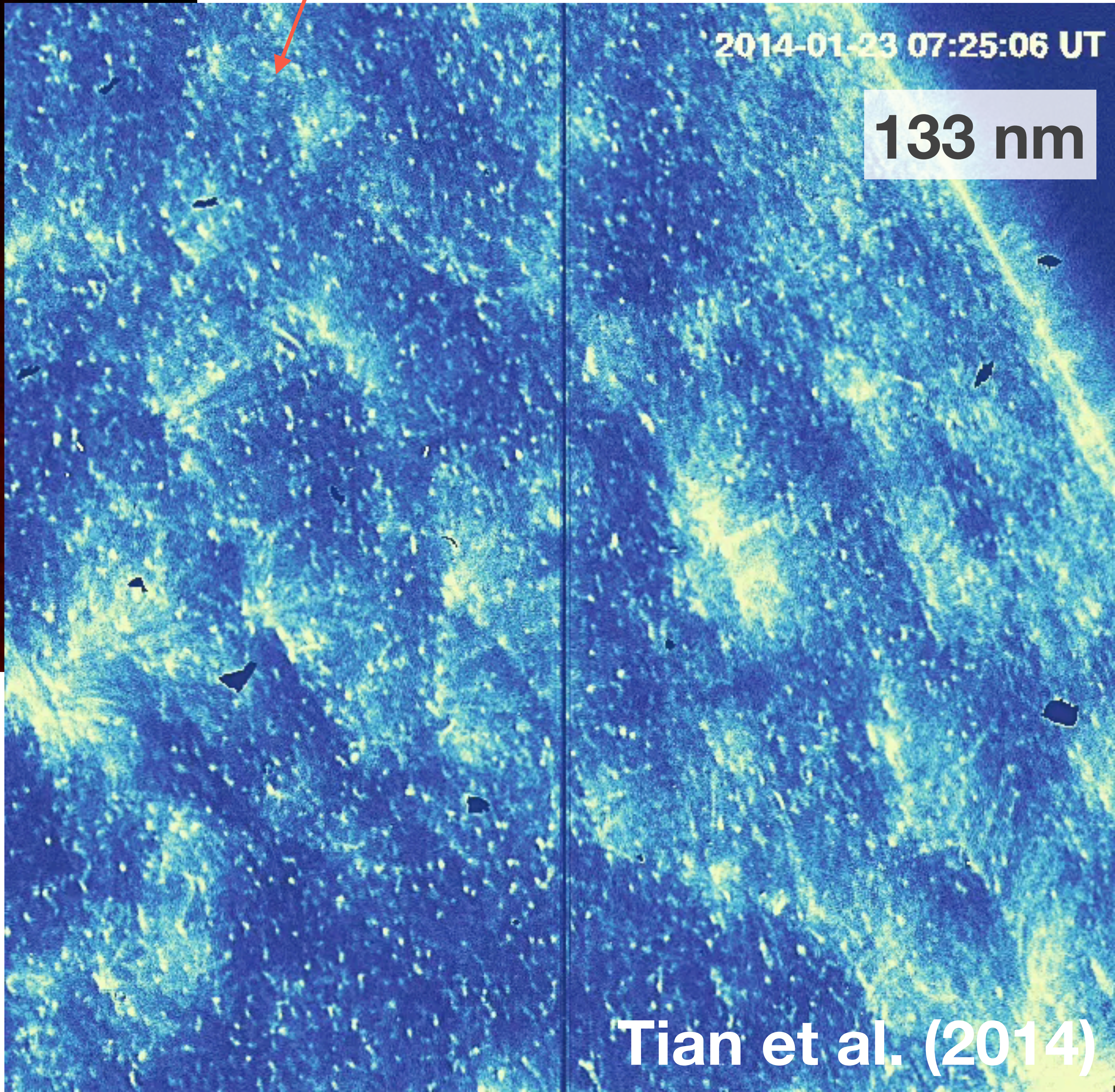


T. J. Okamoto (NAOJ/JAXA)

Hinode SOT
Ca II H filter
Optical (~ 395 nm)
Photo.-Chrom.



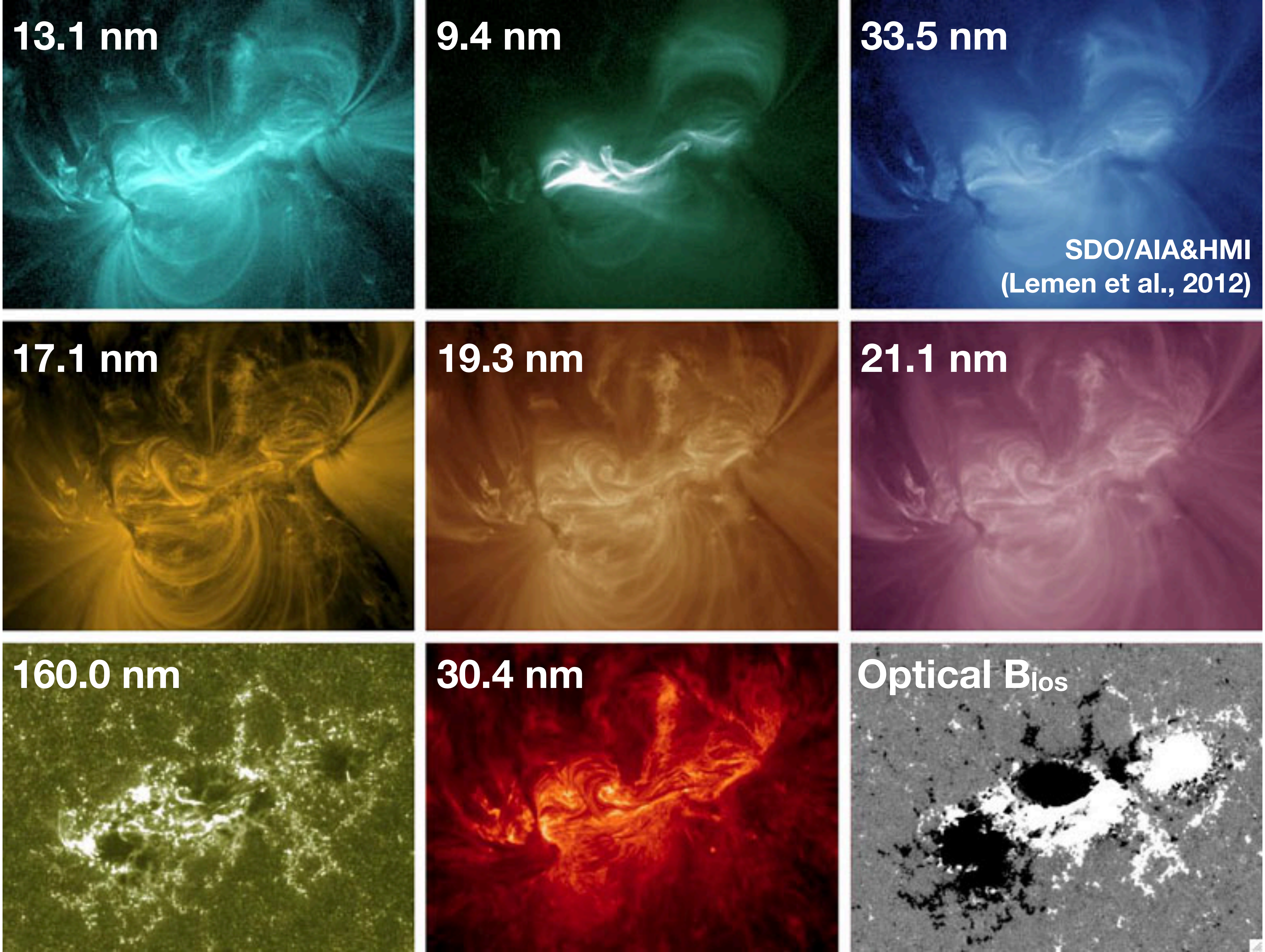
SDO/AIA
EUV (~30.4 nm)
Chrom. ~ TR



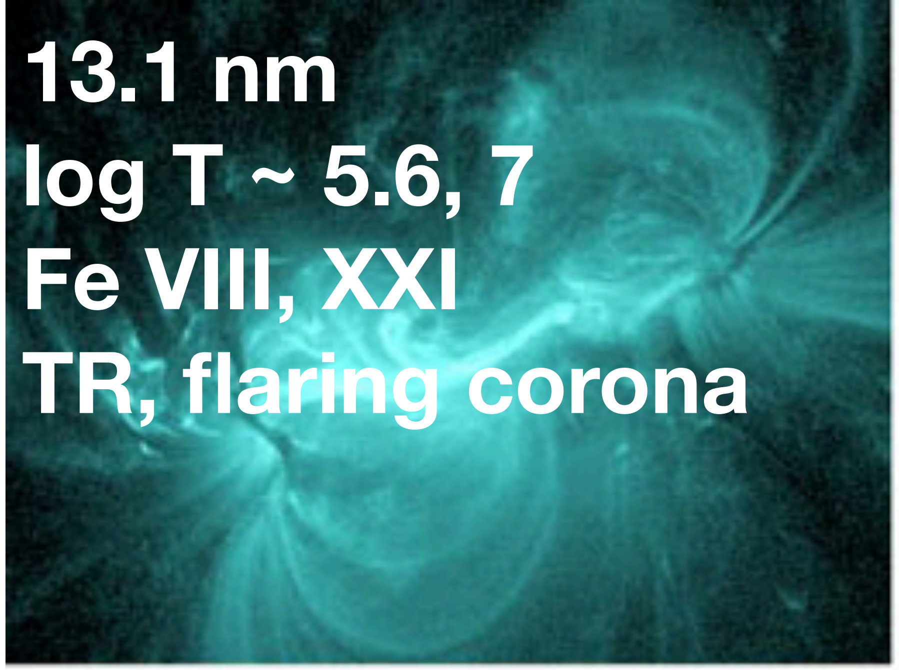
Supergranulation
Magnetic network

IRIS/Si IV SJ
FUV (~133 nm)
Chrom. ~ TR

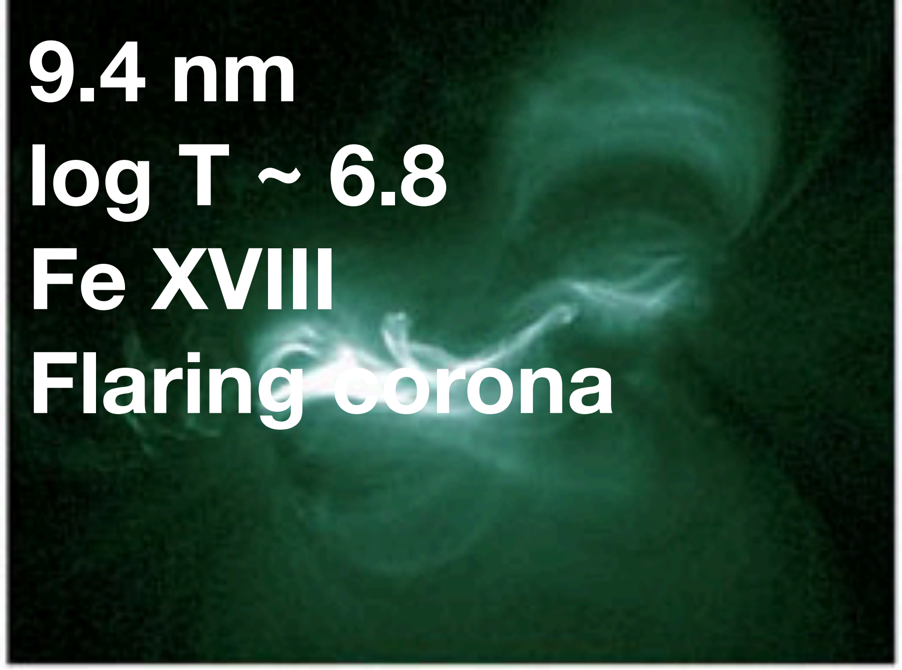
Tian et al. (2014)



SDO/AIA&HMI
(Lemen et al., 2012)



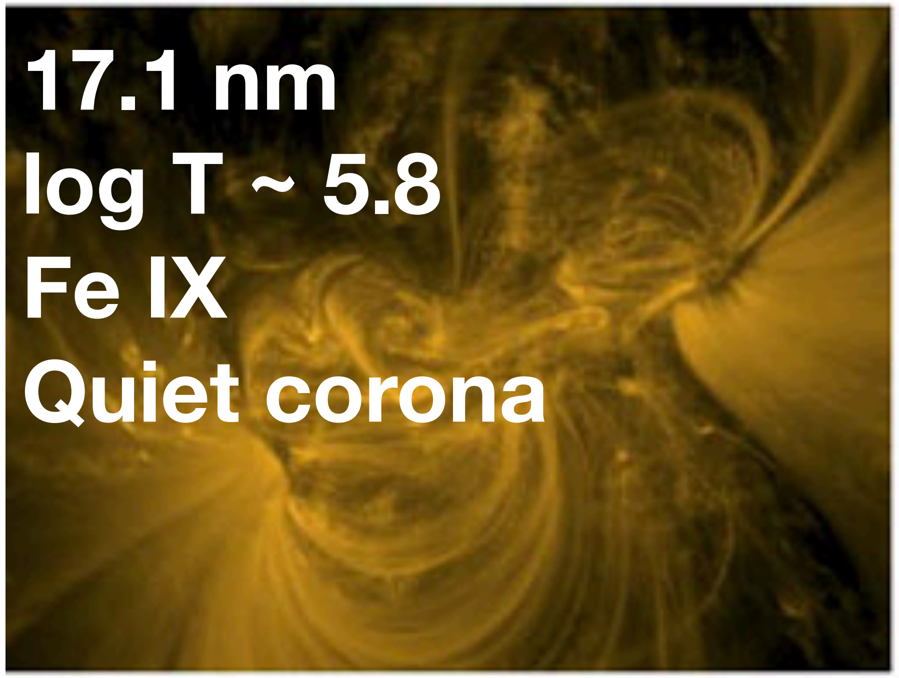
13.1 nm
log T ~ 5.6, 7
Fe VIII, XXI
TR, flaring corona



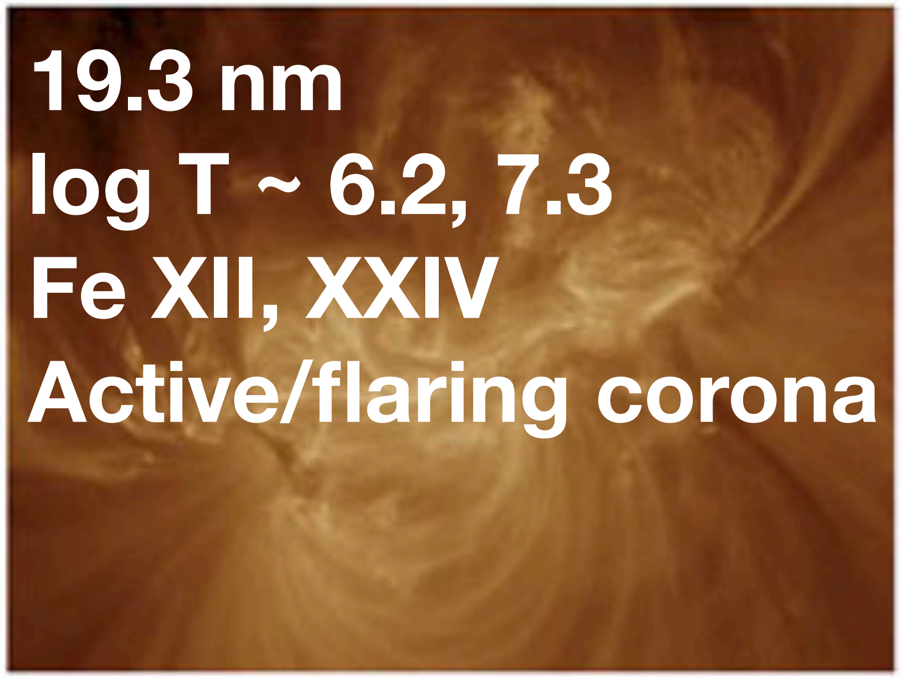
9.4 nm
log T ~ 6.8
Fe XVIII
Flaring corona

33.5 nm
log T ~ 6.4
Fe XVI
Active corona

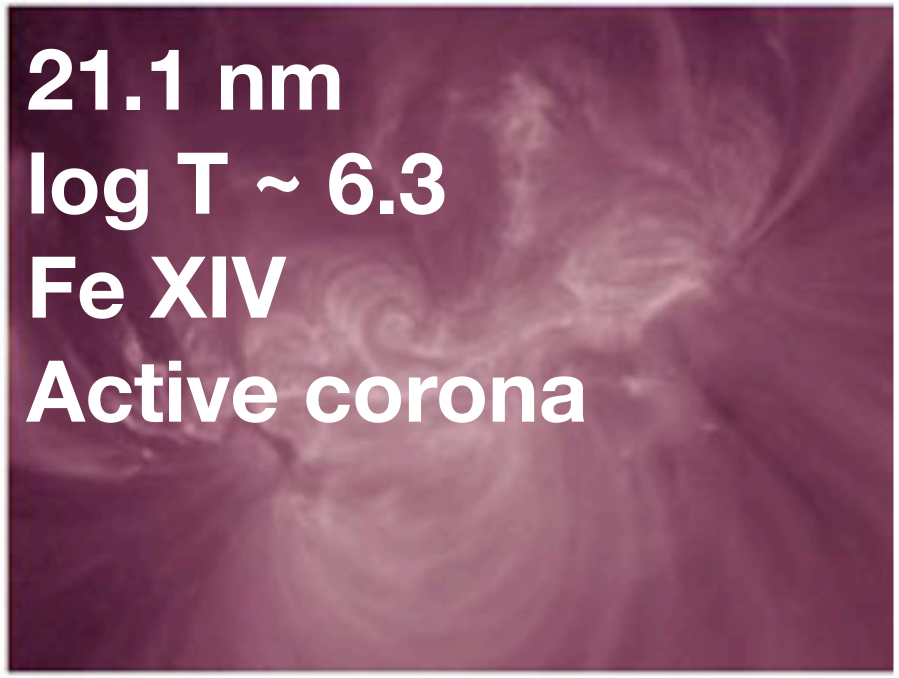
SDO/AIA&HMI
(Lemen et al., 2012)



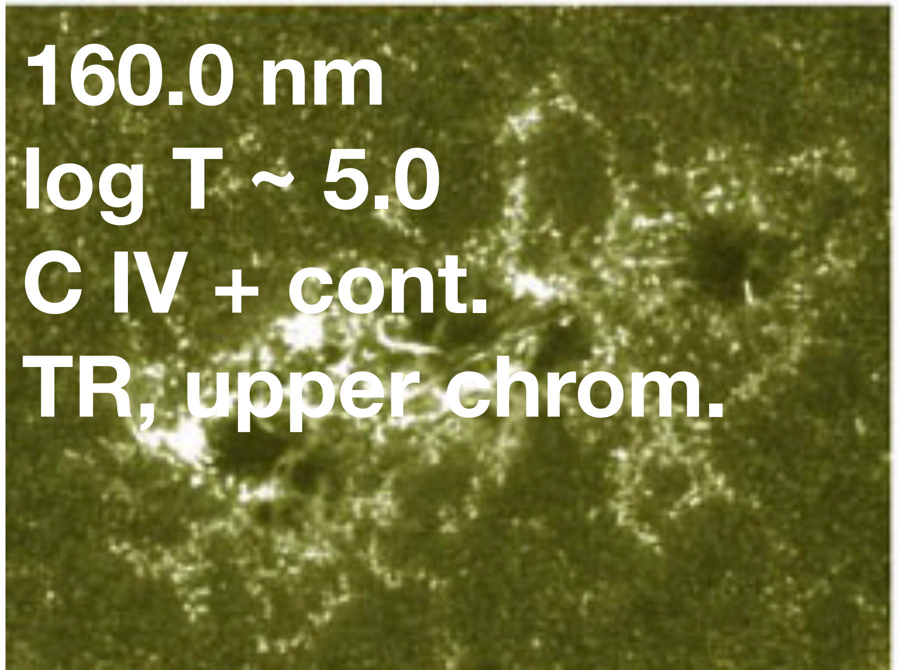
17.1 nm
log T ~ 5.8
Fe IX
Quiet corona



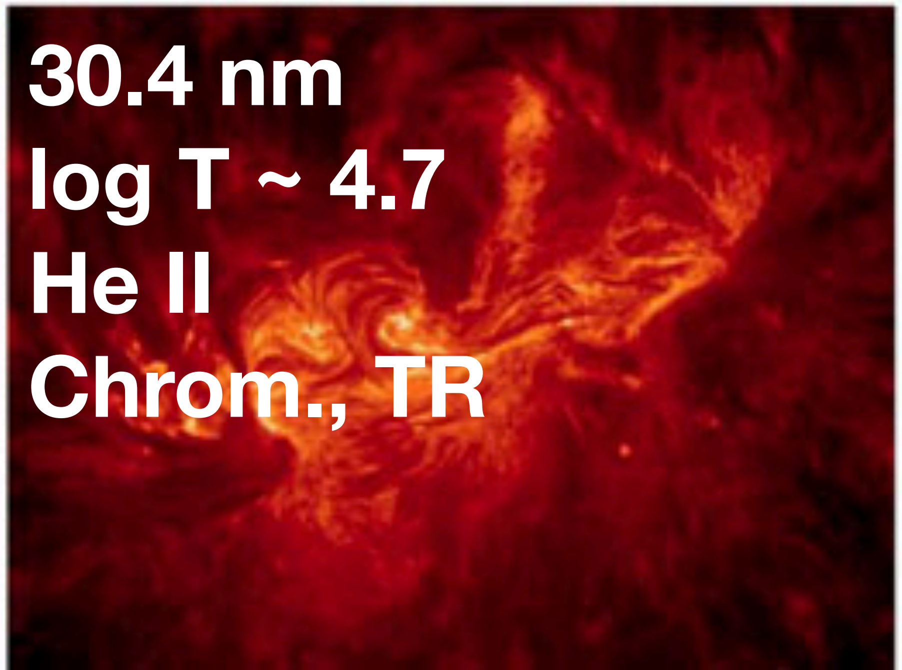
19.3 nm
log T ~ 6.2, 7.3
Fe XII, XXIV
Active/flaring corona



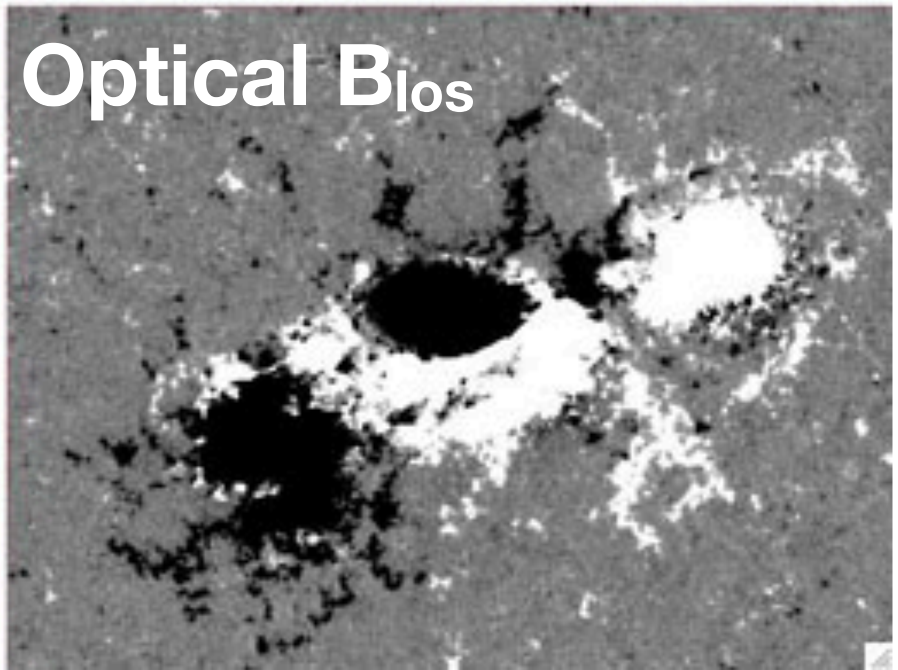
21.1 nm
log T ~ 6.3
Fe XIV
Active corona



160.0 nm
log T ~ 5.0
C IV + cont.
TR, upper chrom.

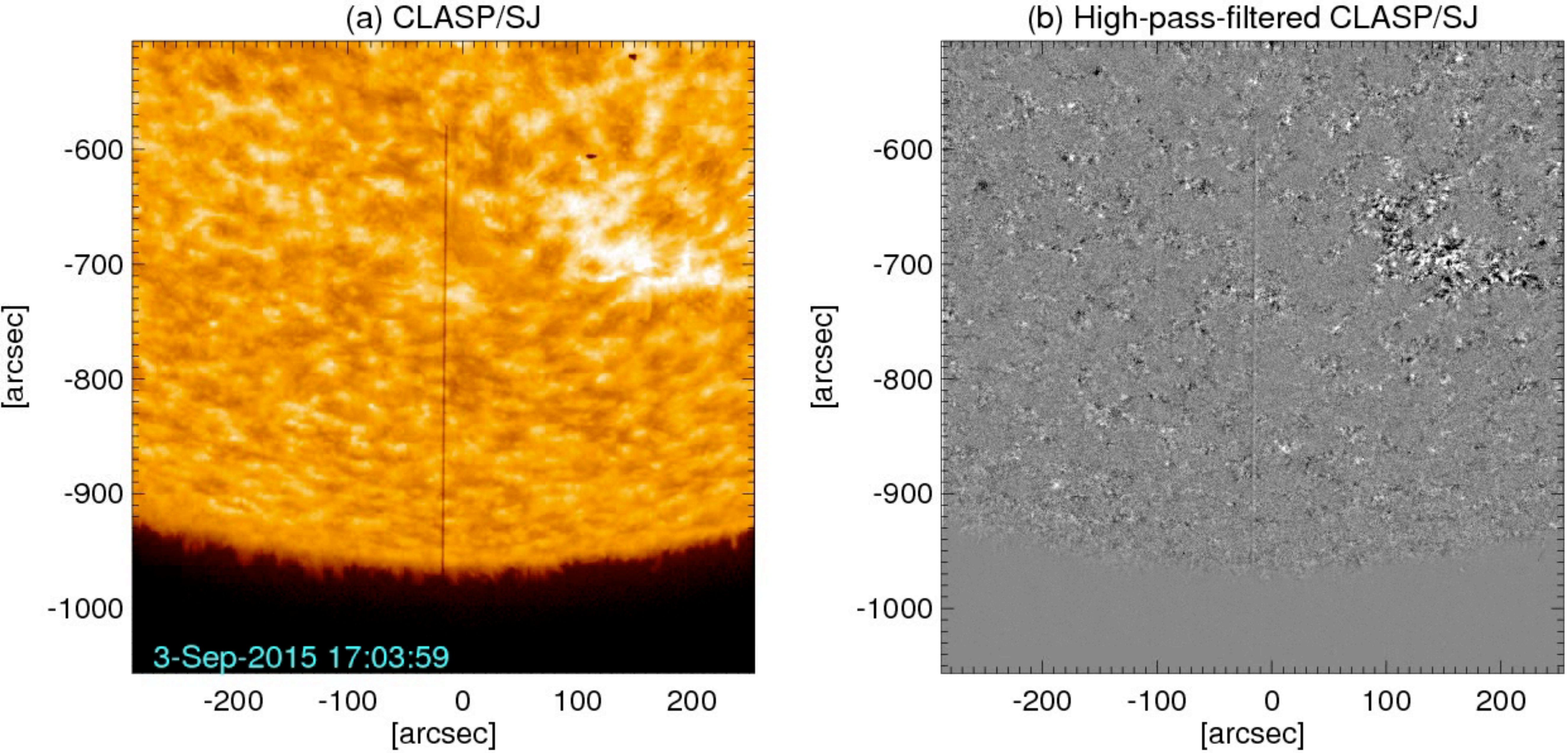


30.4 nm
log T ~ 4.7
He II
Chrom., TR



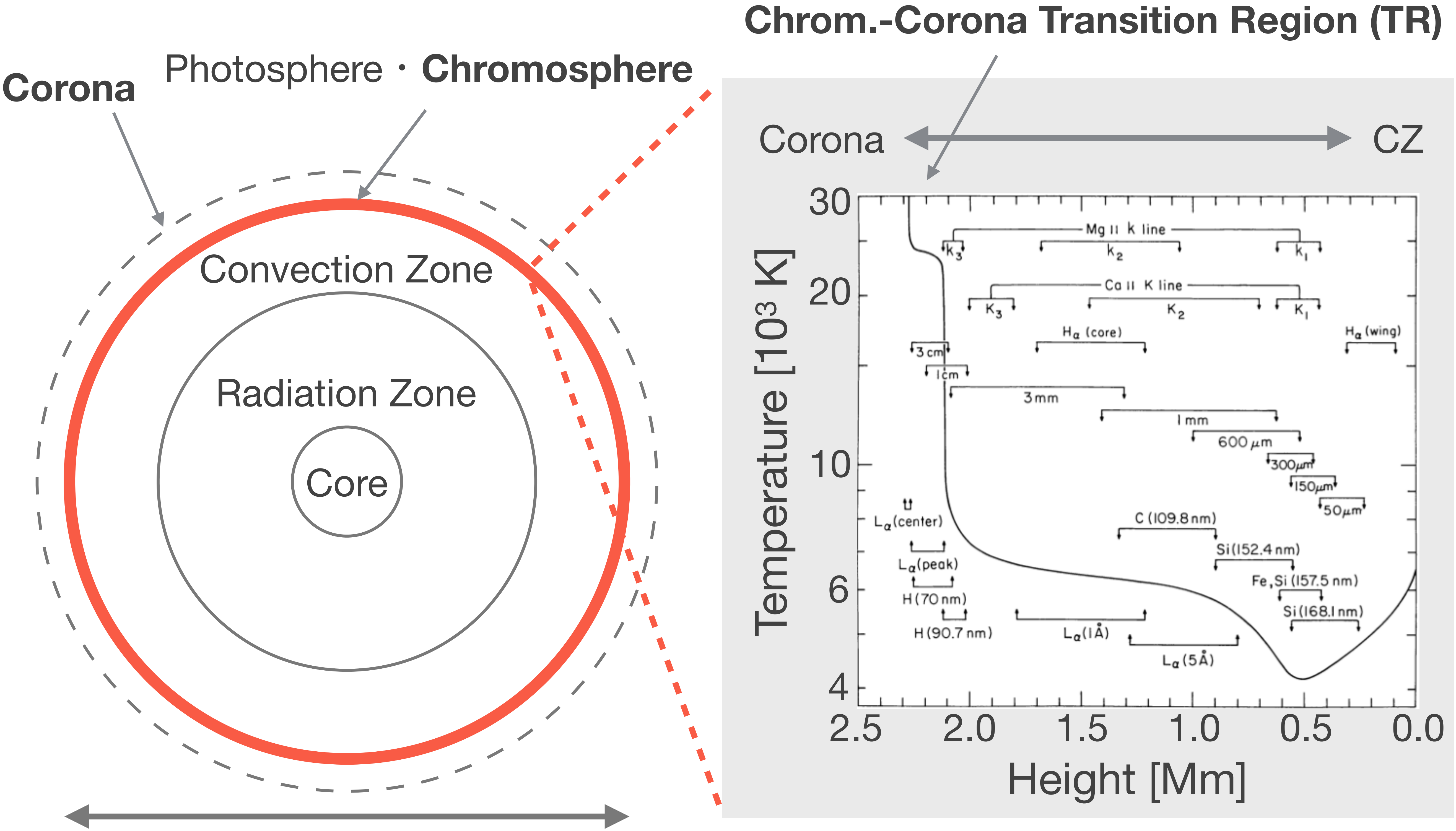
Optical B_{los}

Lyman-α (121 nm) from TR



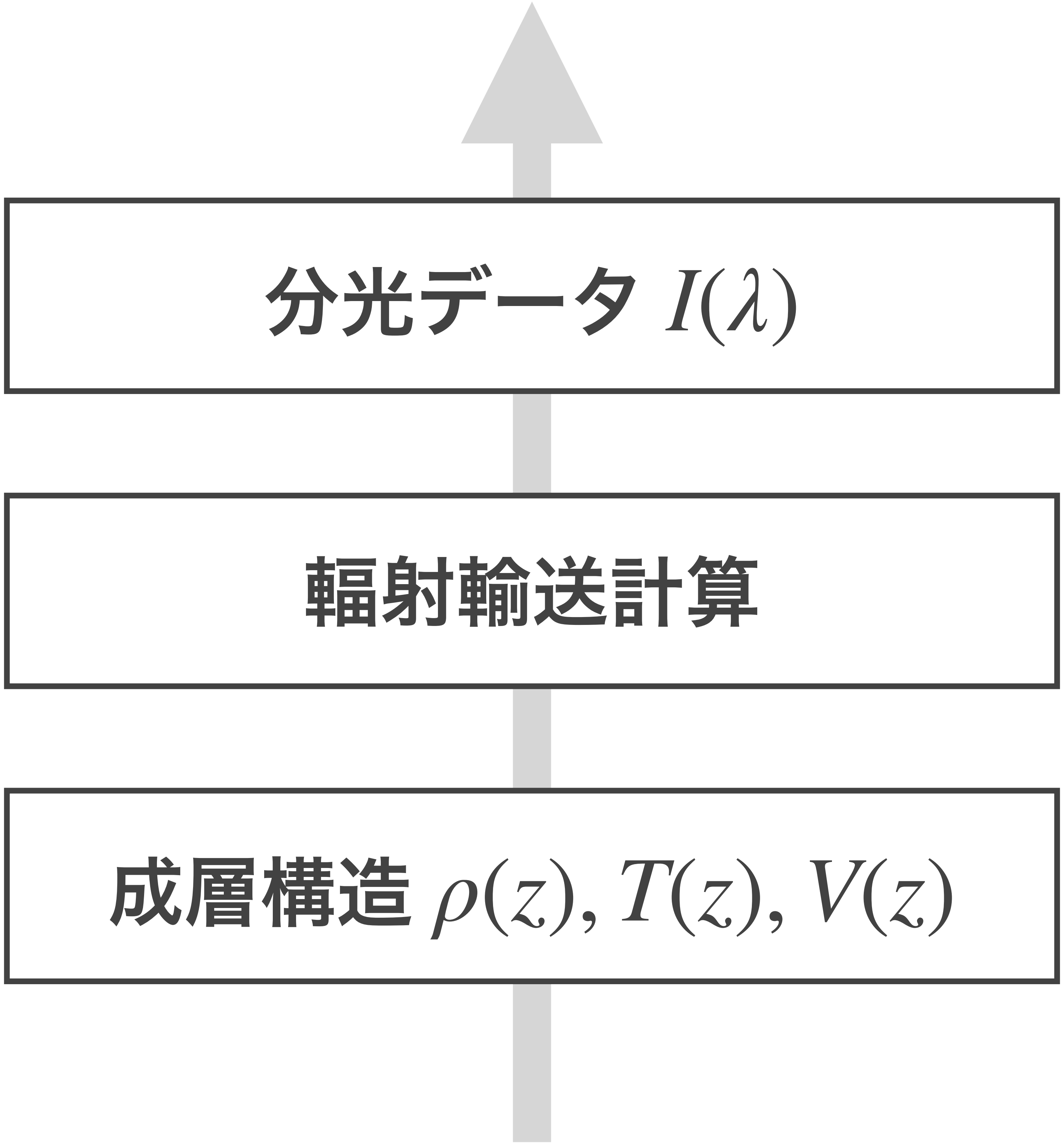
CLASP/SJ (Kubo et al., 2016)

太陽大気の鉛直構造



Vernazza et al. (1981)

輻射輸送計算の順問題

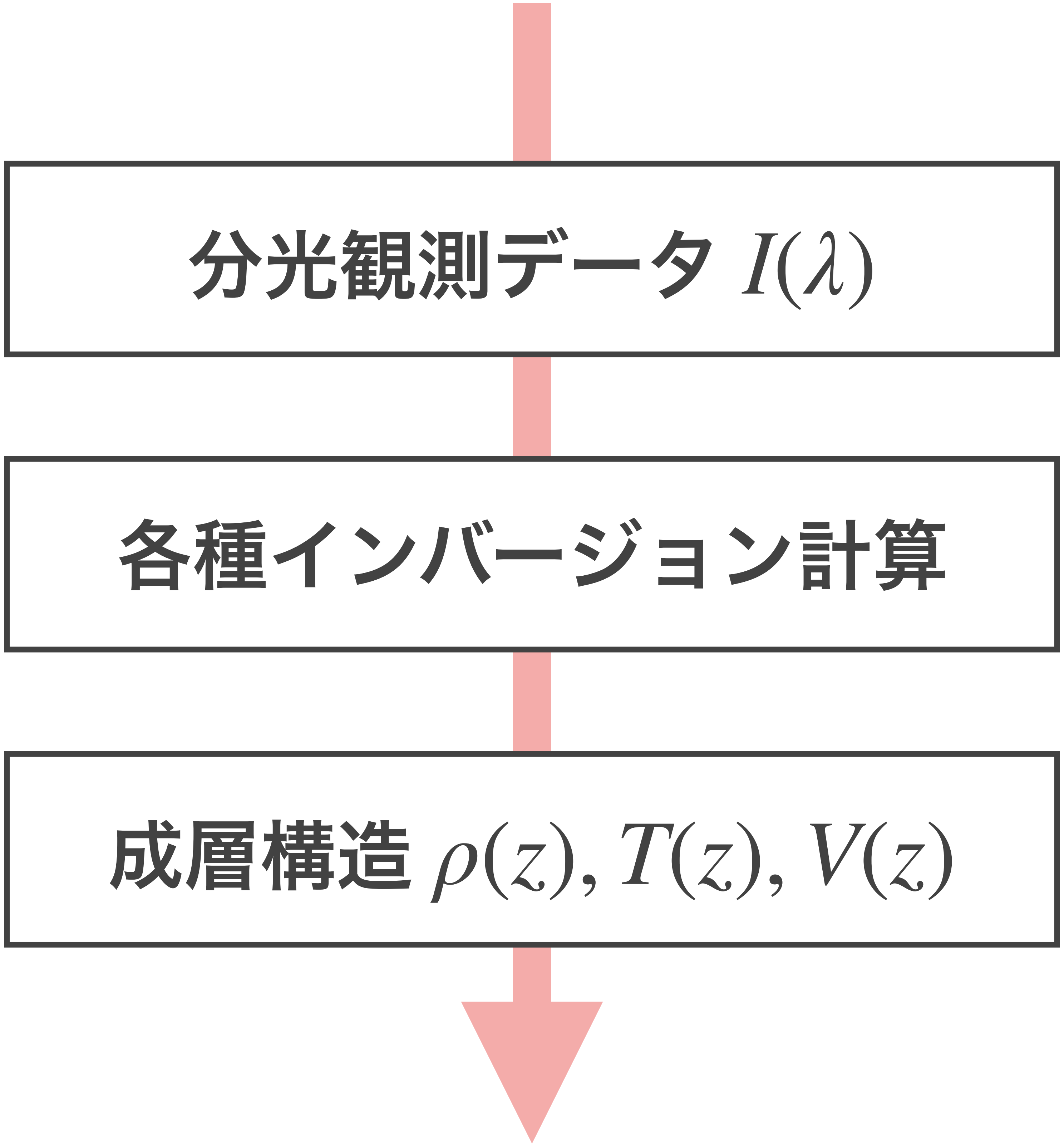


分光データ $I(\lambda)$

輻射輸送計算

成層構造 $\rho(z), T(z), V(z)$

太陽大気構造計算の逆問題

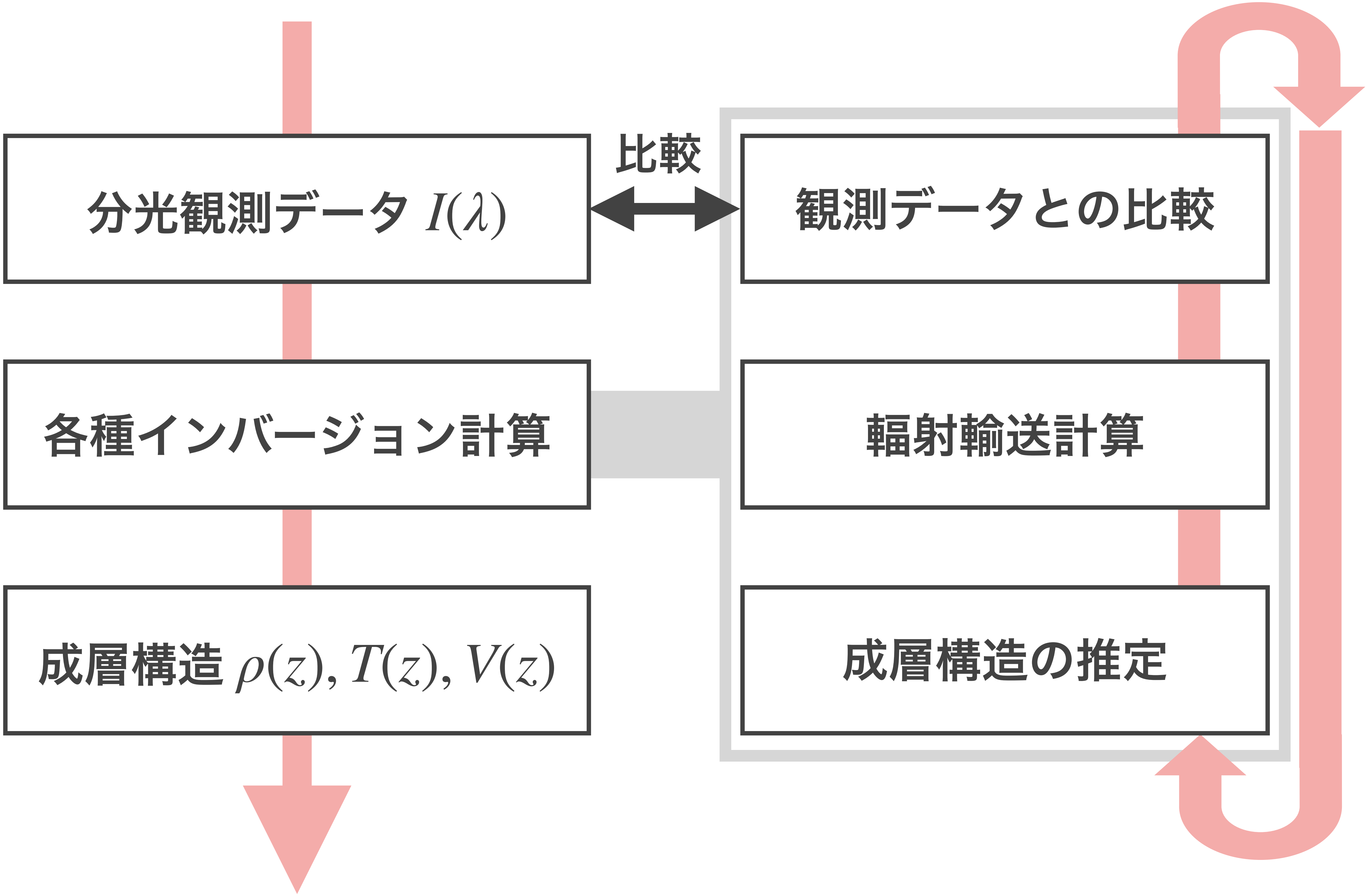


分光観測データ $I(\lambda)$

各種インバージョン計算

成層構造 $\rho(z), T(z), V(z)$

太陽大気構造計算の逆問題 | 単純な例



分光観測データ $I(\lambda)$

比較

観測データとの比較

各種インバージョン計算

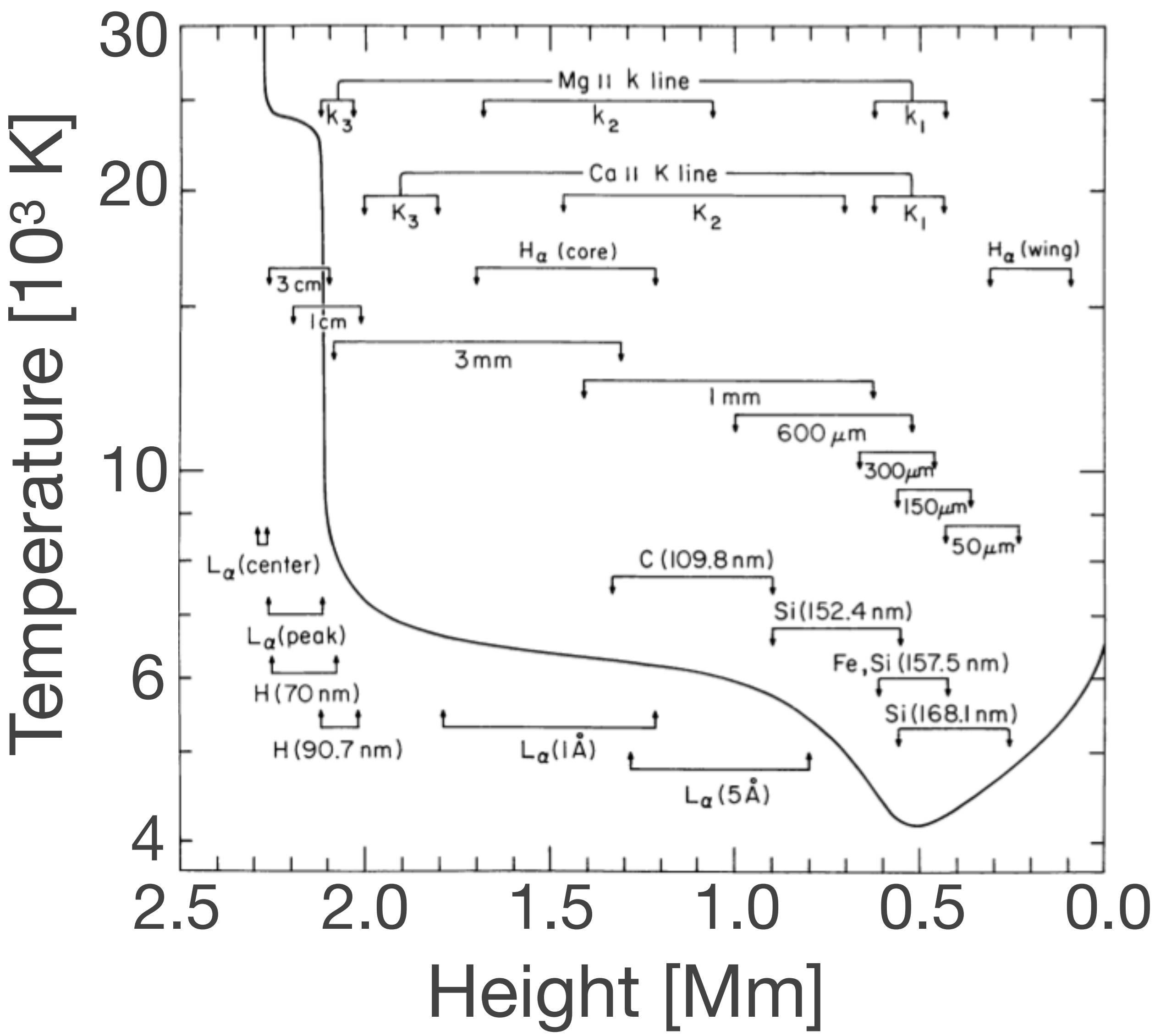
輻射輸送計算

成層構造 $\rho(z), T(z), V(z)$

成層構造の推定

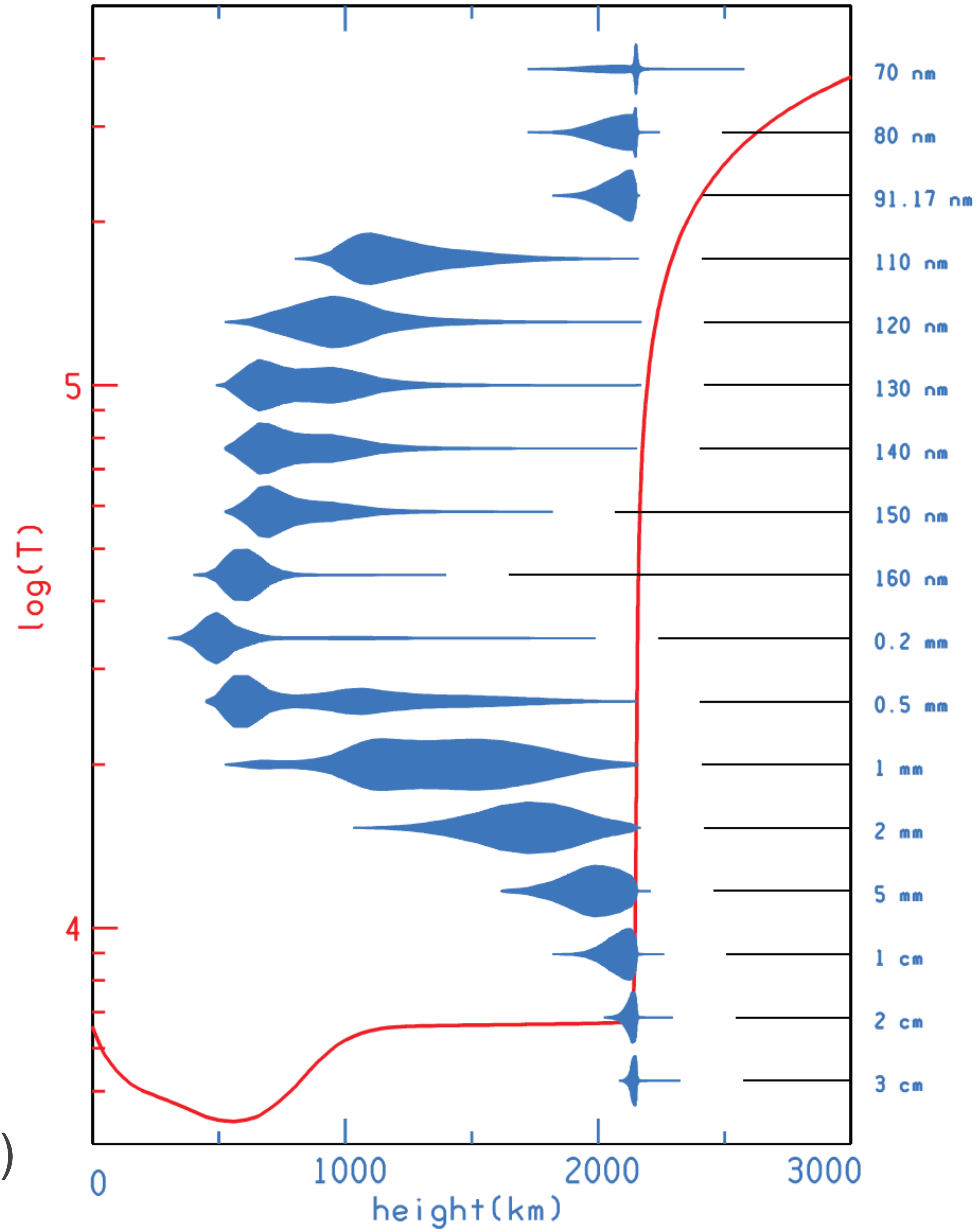
太陽からの光はどこを見ているのか

輝線の形成領域



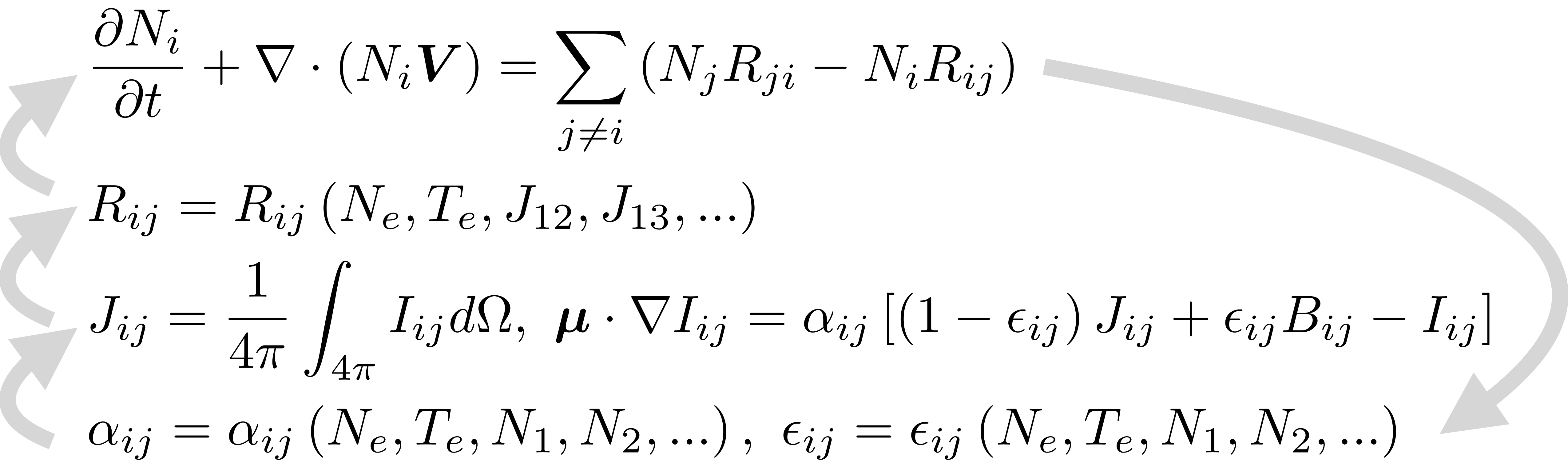
Vernazza et al. (1981)

連続光の形成領域



Avrett & Loeser (2008)

静的大気モデルの弱点 | 非平衡電離・励起



$$\frac{\partial N_i}{\partial t} + \nabla \cdot (N_i \boldsymbol{V}) = \sum_{j \neq i} (N_j R_{ji} - N_i R_{ij})$$

$$R_{ij} = R_{ij}\left(N_e, T_e, J_{12}, J_{13}, ...\right)$$

$$J_{ij} = \frac{1}{4\pi} \int_{4\pi} I_{ij} d\Omega,\ \boldsymbol{\mu} \cdot \nabla I_{ij} = \alpha_{ij}\left[\left(1 - \epsilon_{ij}\right) J_{ij} + \epsilon_{ij} B_{ij} - I_{ij}\right]$$

$$\alpha_{ij} = \alpha_{ij}\left(N_e, T_e, N_1, N_2, ...\right),\ \epsilon_{ij} = \epsilon_{ij}\left(N_e, T_e, N_1, N_2, ...\right)$$

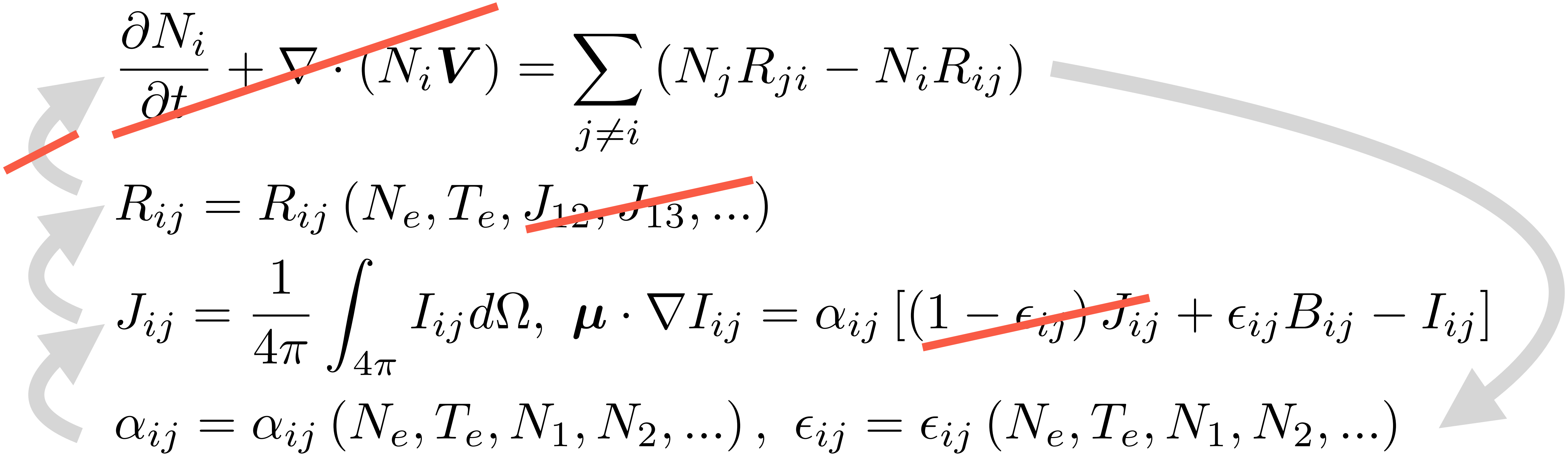
Corona (~EUV): optically thin, but weakly non-equilibrium ionization

Chrom. (~FUV): optically thick, non-equilibrium ionization

Hydrostatic/SE 1D model is available (e.g., Vernazza et al., 1981).
Dynamic/3D model will be available in next decade (hopefully).

静的大気モデルの弱点 | 非平衡電離・励起

LTE (Local Thermodynamic Equilibrium)



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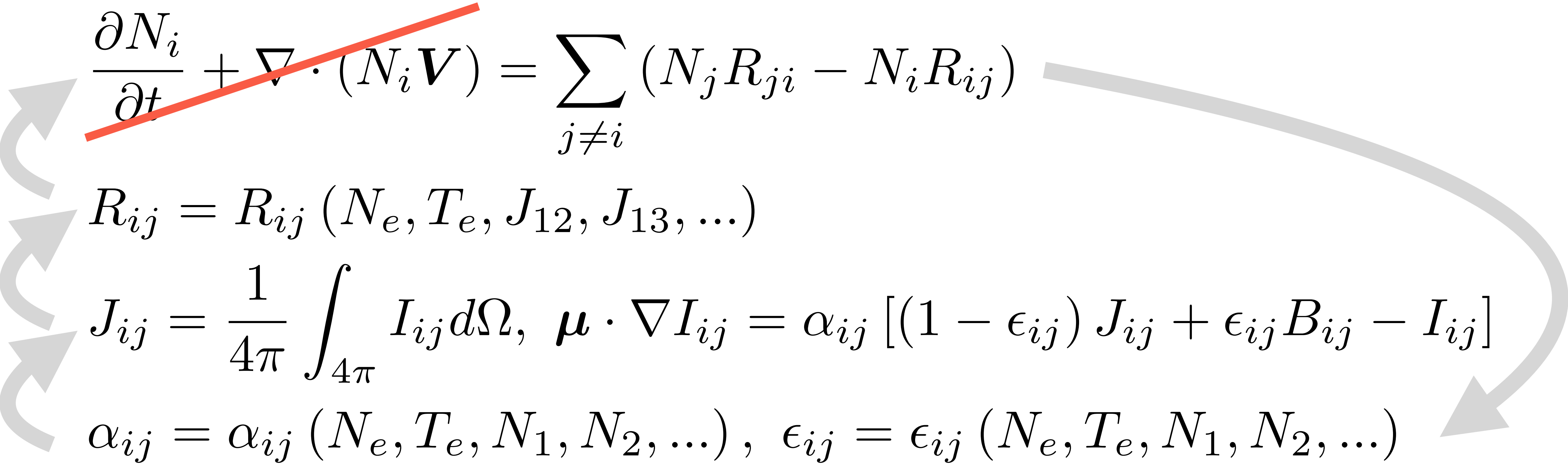
静的大気モデルの弱点 | 非平衡電離・励起

Statistical equilibrium



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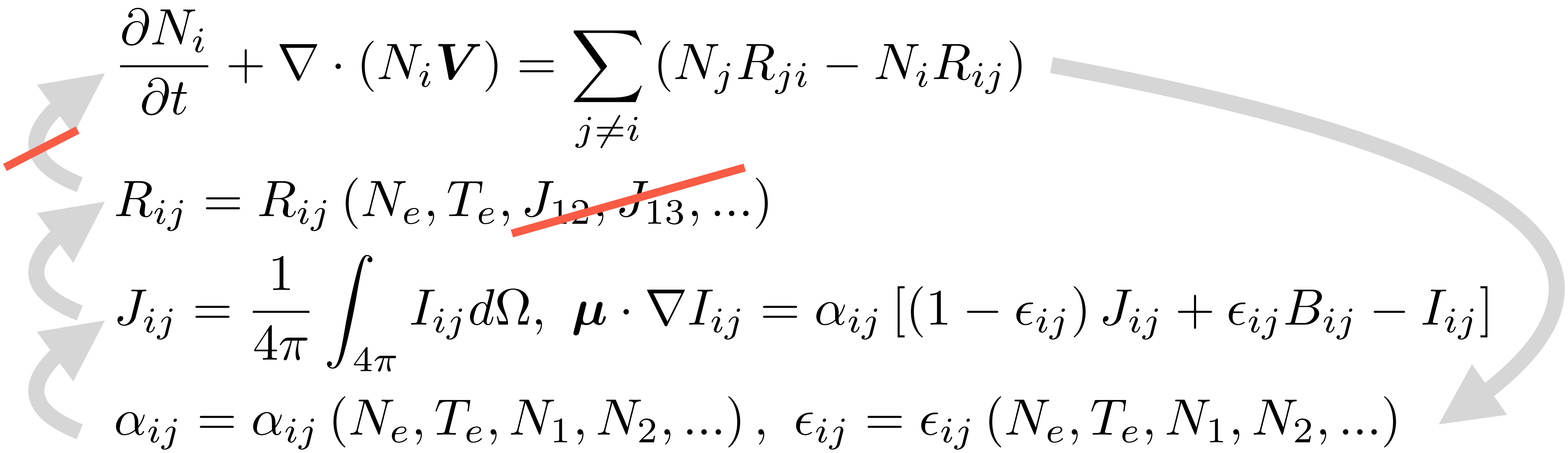
静的大気モデルの弱点 | 非平衡電離・励起

Non-equilibrium (optically thin; corona)



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Corona (~EUV): optically thin, but weakly non-equilibrium ionization

Chrom. (~FUV): optically thick, non-equilibrium ionization

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静的大気モデルの弱点 | 非平衡電離・励起

Non-equilibrium (optically thick; chromosphere~TR)

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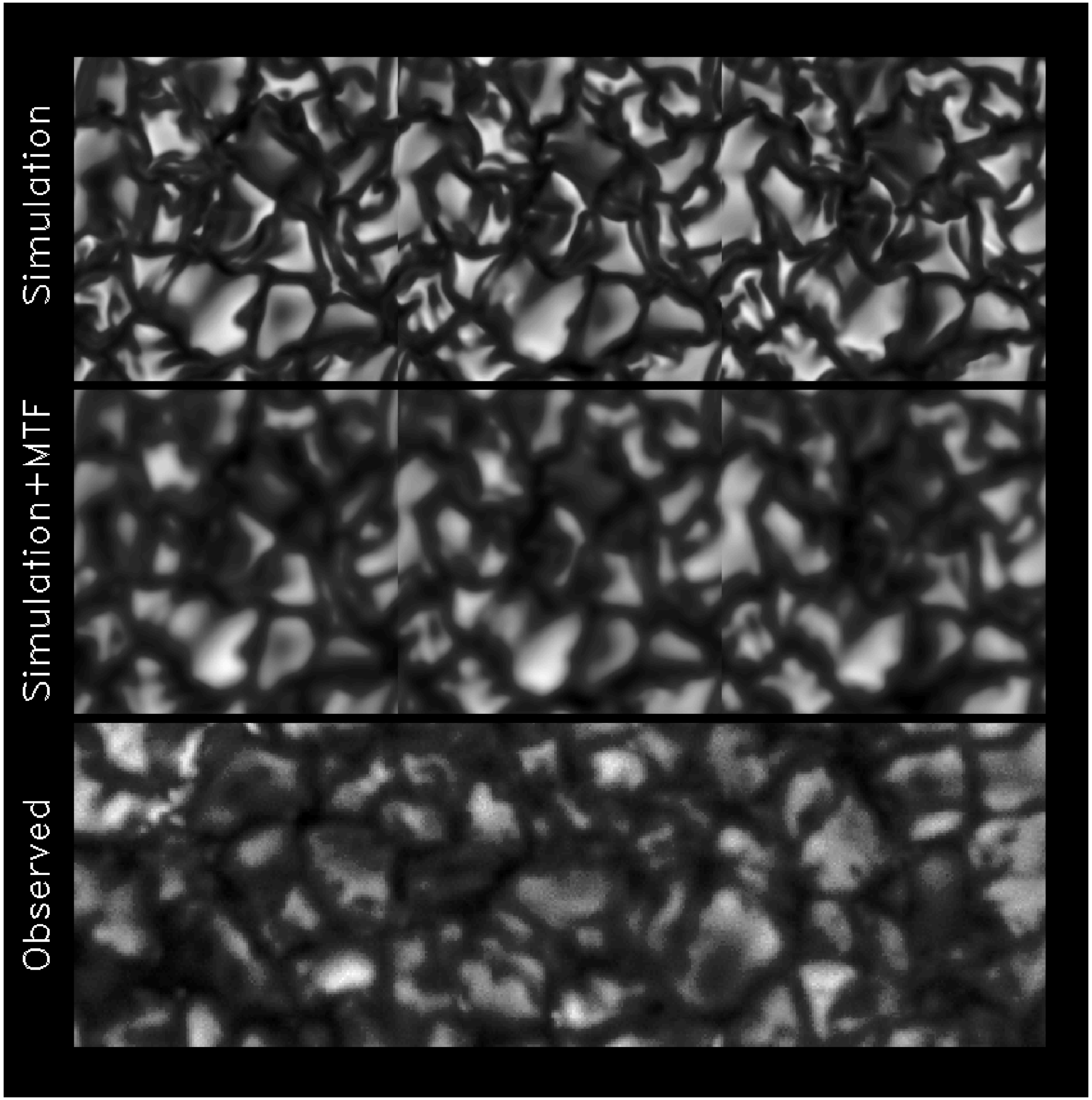
Radiation MagnetoHydroDynamic model of Sun



Photospheric RMHD model

=

MHD

+

LTE EOS

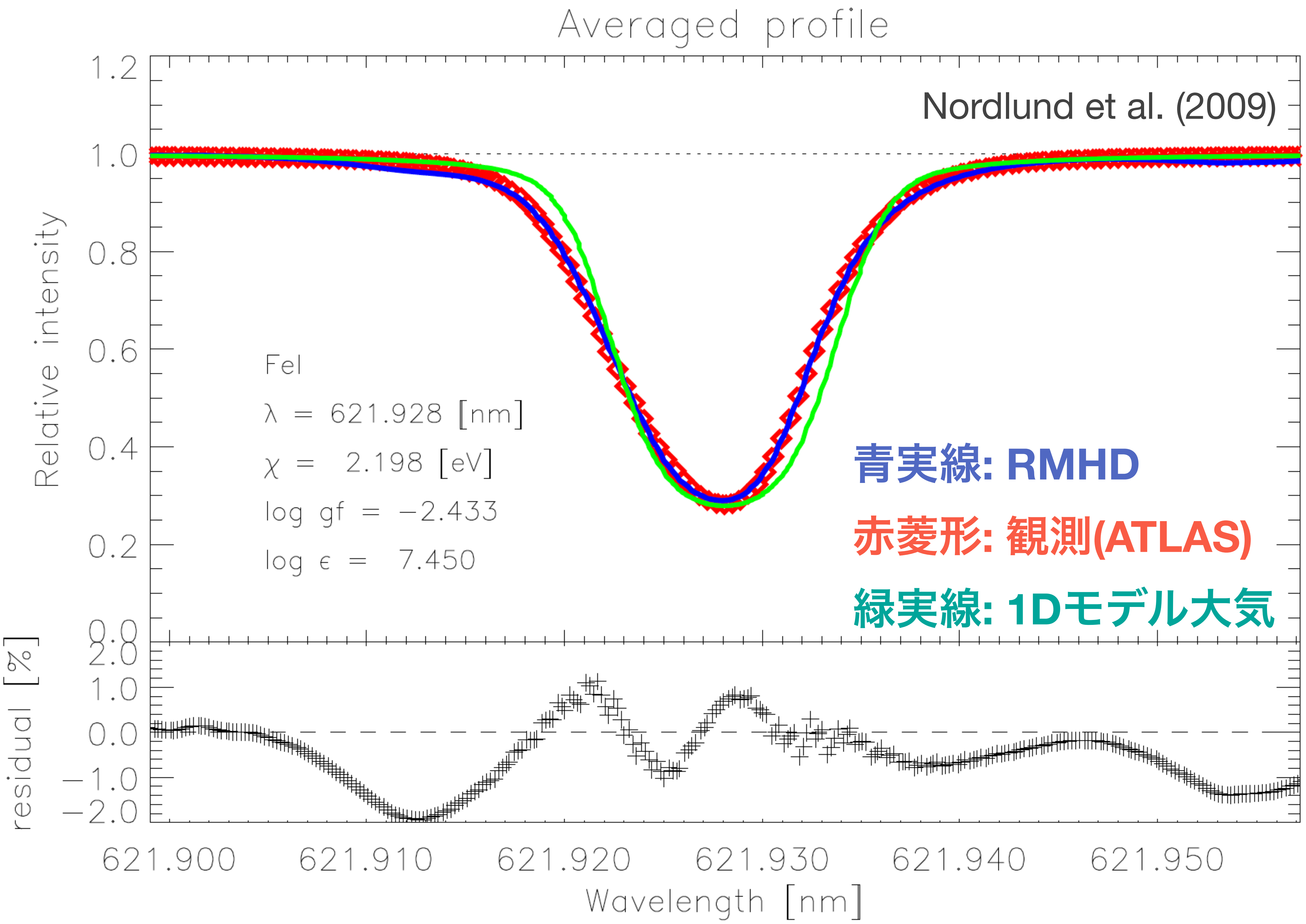
+

LTE radiation

Upper CZ to photosphere

Stein & Nordlund (1998)

光球RMHDの妥当性 | ライン形状

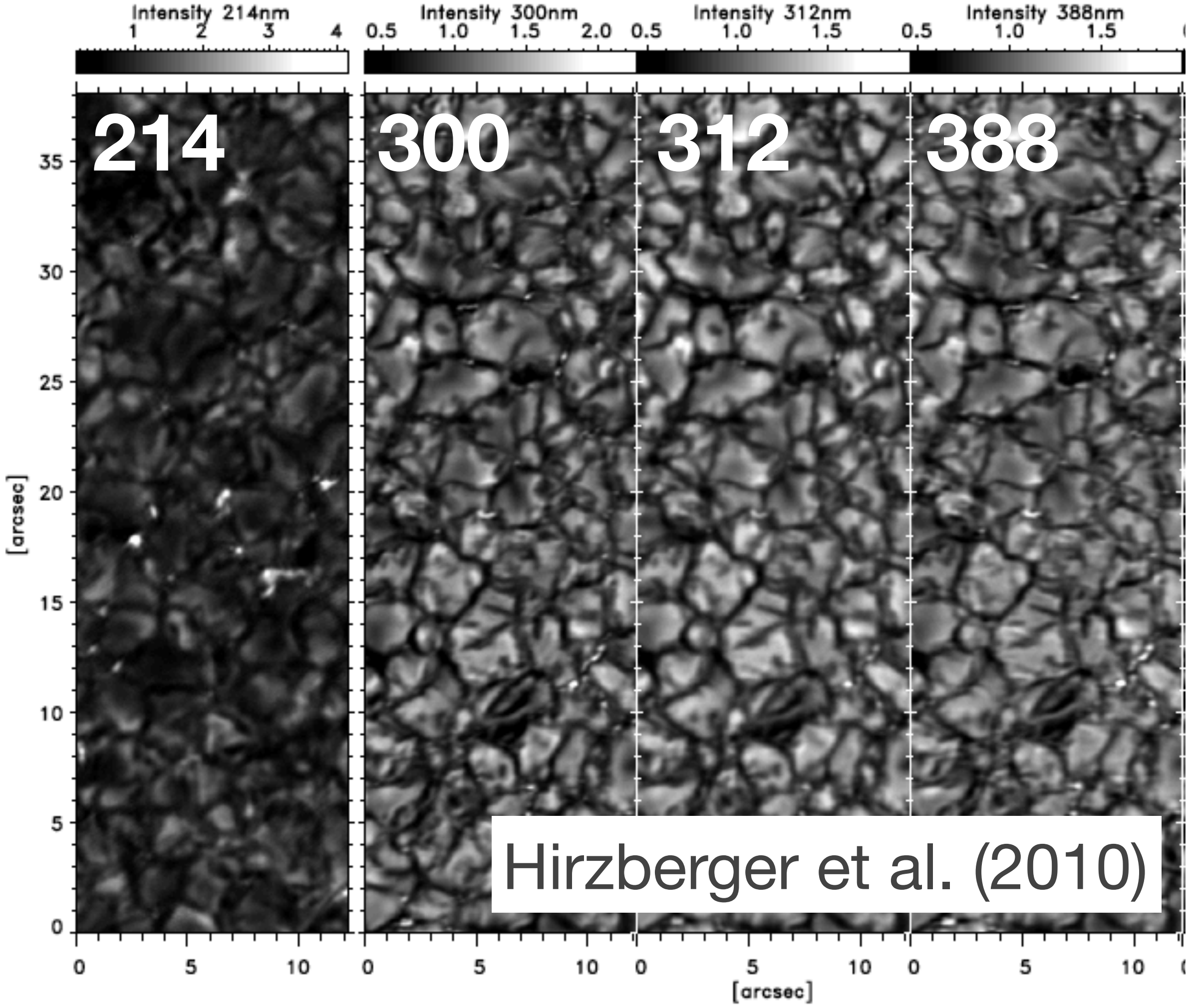


青実線: RMHD

赤菱形: 観測(ATLAS)

緑実線: 1Dモデル大気

光球RMHDの妥当性 | 粒状斑のコントラスト



Hirzberger et al. (2010)

RMHD: MURaM

Observation: Sunrise I SuFI

312, 388 nm slit: agree

300, 214 nm slit: disagree

Possible source of disagreement:
(1) Lack of physics in RMHD,

(2) NLTE effect, (3) Scattered light.

Similar study by Danilovic+08 for 630 nm using Hinode/SP (RMHD ~ 1.2 Observation).

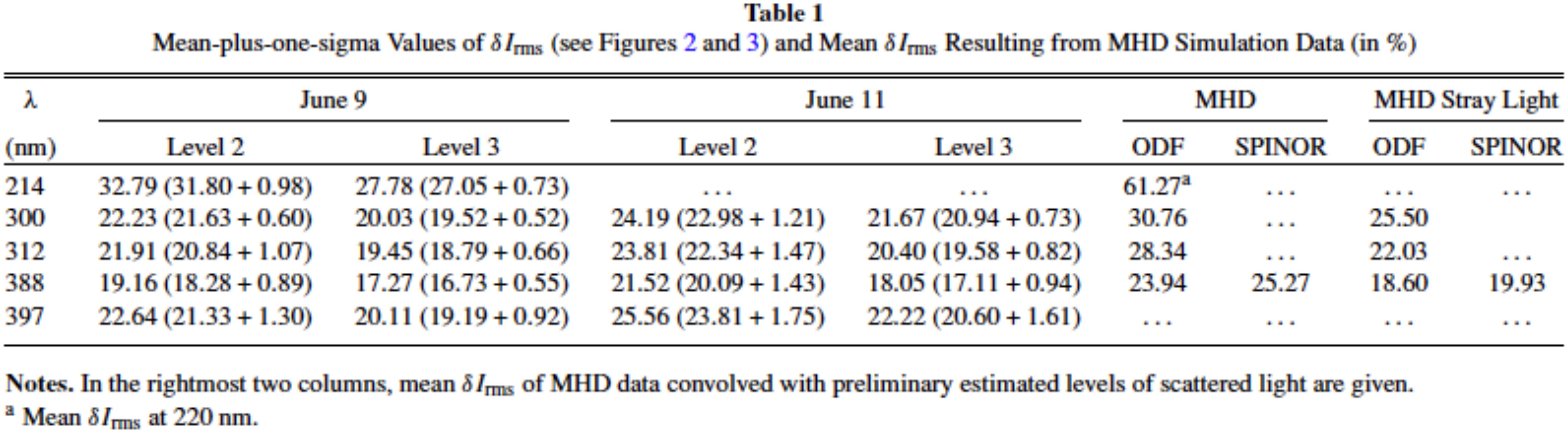


Table 1

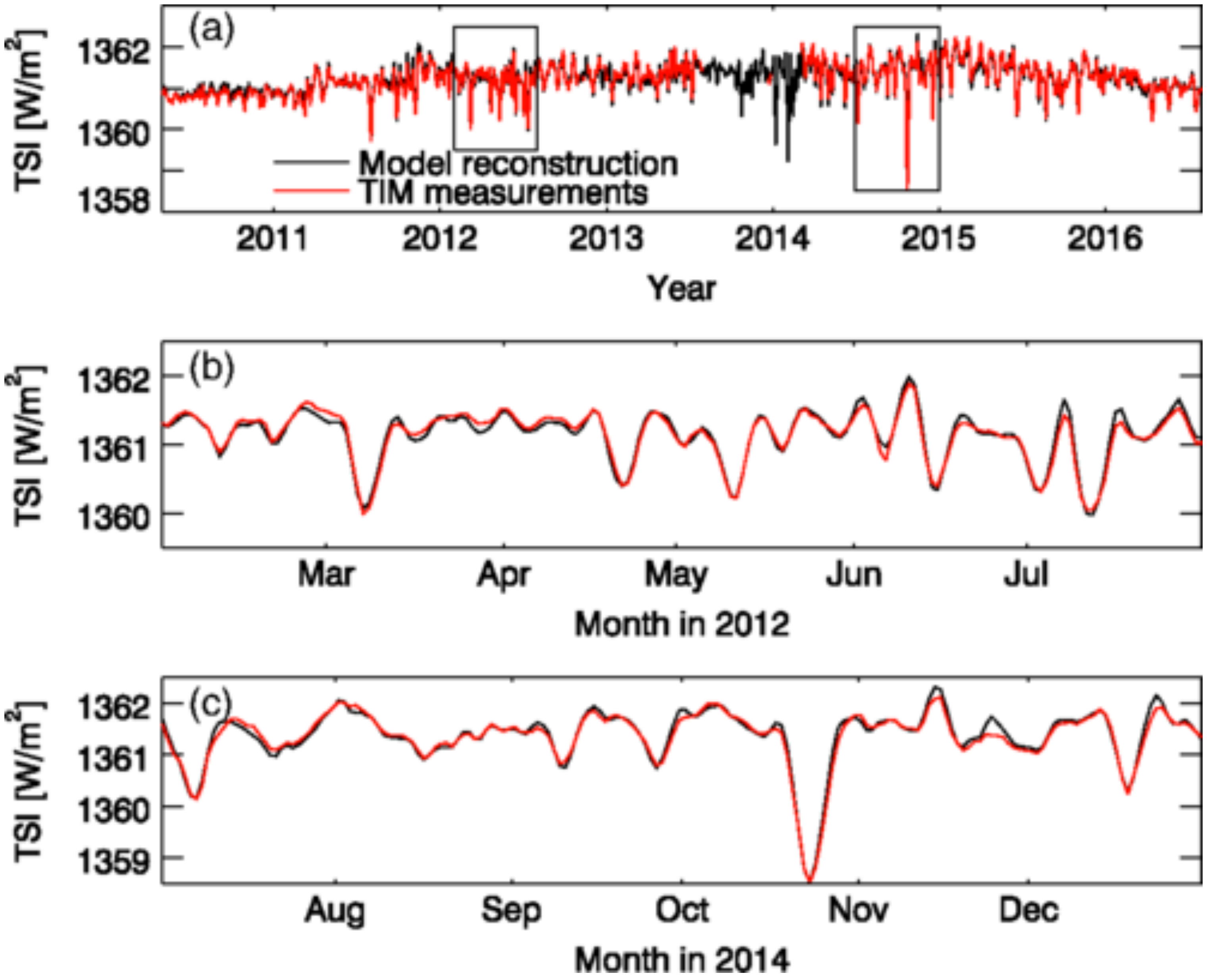
Mean-plus-one-sigma Values of $\delta I_{\rm rms}$ (see Figures 2 and 3) and Mean $\delta I_{\rm rms}$ Resulting from MHD Simulation Data (in %)

λ	June 9		June 11		MHD		MHD Stray Light	
(nm)	Level 2	Level 3	Level 2	Level 3	ODF	SPINOR	ODF	SPINOR
214	32.79 (31.80 + 0.98)	27.78 (27.05 + 0.73)	...	...	61.27[a]	...	...	...
300	22.23 (21.63 + 0.60)	20.03 (19.52 + 0.52)	24.19 (22.98 + 1.21)	21.67 (20.94 + 0.73)	30.76	...	25.50	
312	21.91 (20.84 + 1.07)	19.45 (18.79 + 0.66)	23.81 (22.34 + 1.47)	20.40 (19.58 + 0.82)	28.34	...	22.03	...
388	19.16 (18.28 + 0.89)	17.27 (16.73 + 0.55)	21.52 (20.09 + 1.43)	18.05 (17.11 + 0.94)	23.94	25.27	18.60	19.93
397	22.64 (21.33 + 1.30)	20.11 (19.19 + 0.92)	25.56 (23.81 + 1.75)	22.22 (20.60 + 1.61)	...	...	...	...

Notes. In the rightmost two columns, mean $\delta I_{\rm rms}$ of MHD data convolved with preliminary estimated levels of scattered light are given.

[a] Mean $\delta I_{\rm rms}$ at 220 nm.

光球RMHDの妥当性 | 総放射量



Time series	R	rms difference (W/m^2)
Model and TIM	0.976	0.0836
Model and VIRGO	0.968	0.0941
TIM and VIRGO	0.975	0.0865

Yeo et al. (2017)

RMHD: B_r -> Intensity

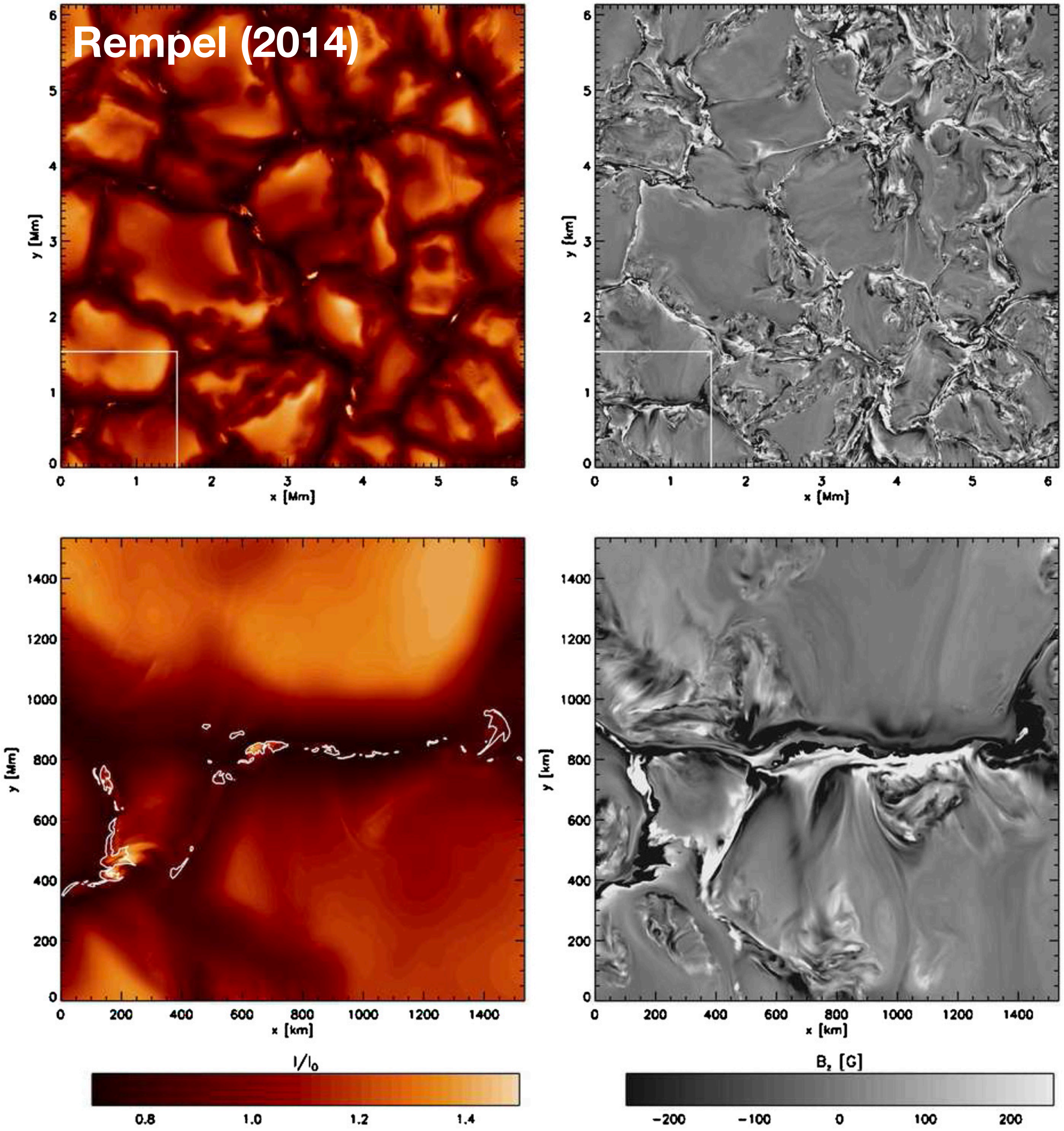
HMI: B_r

Pearson correlation coef.: **0.976** (indicating the model replicates **95%** of the apparent variability)

The **rms difference between the model and observation** (TIM or VIRGO) is **comparable to the difference from observational instruments**.

The direct evidence that the solar surface magnetic activity is the dominant driver of solar irradiance variability.

光球RMHDの妥当性 | 小スケールダイナモ


Rempel (2014)

Simulation: at τ=1

30 ≦ $<|B_z|>$ ≦ **85** G

$<B>$ ≦ **160** G

Observations

Danilovic+10:

$<|B_z|>$ = **84** G, $<B>$ = **170** G

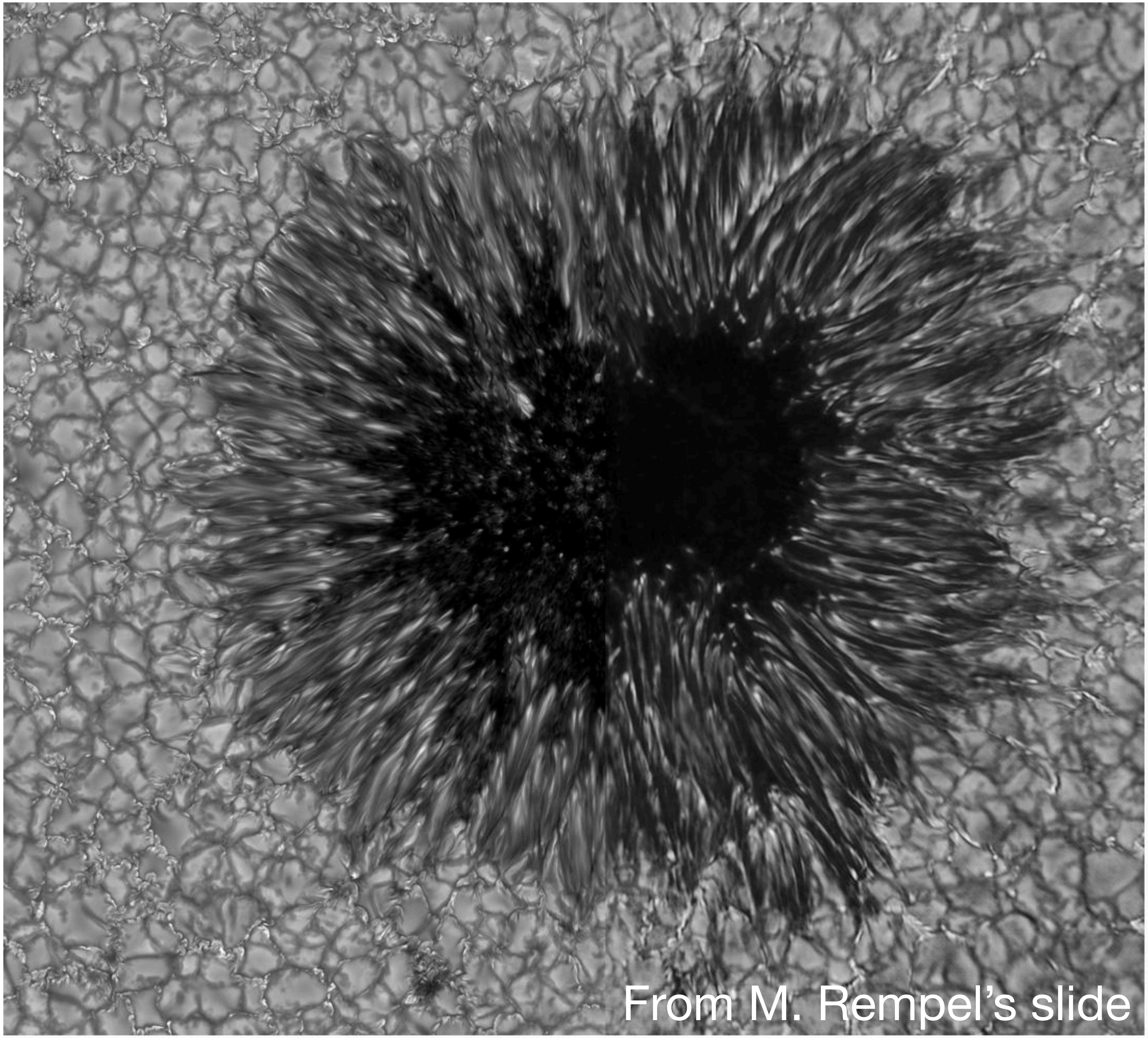
Orozco&Rubio12:

$<|B_z|>$ = **62** G, $<B>$ = **220** G

Trujillo Bueno04:

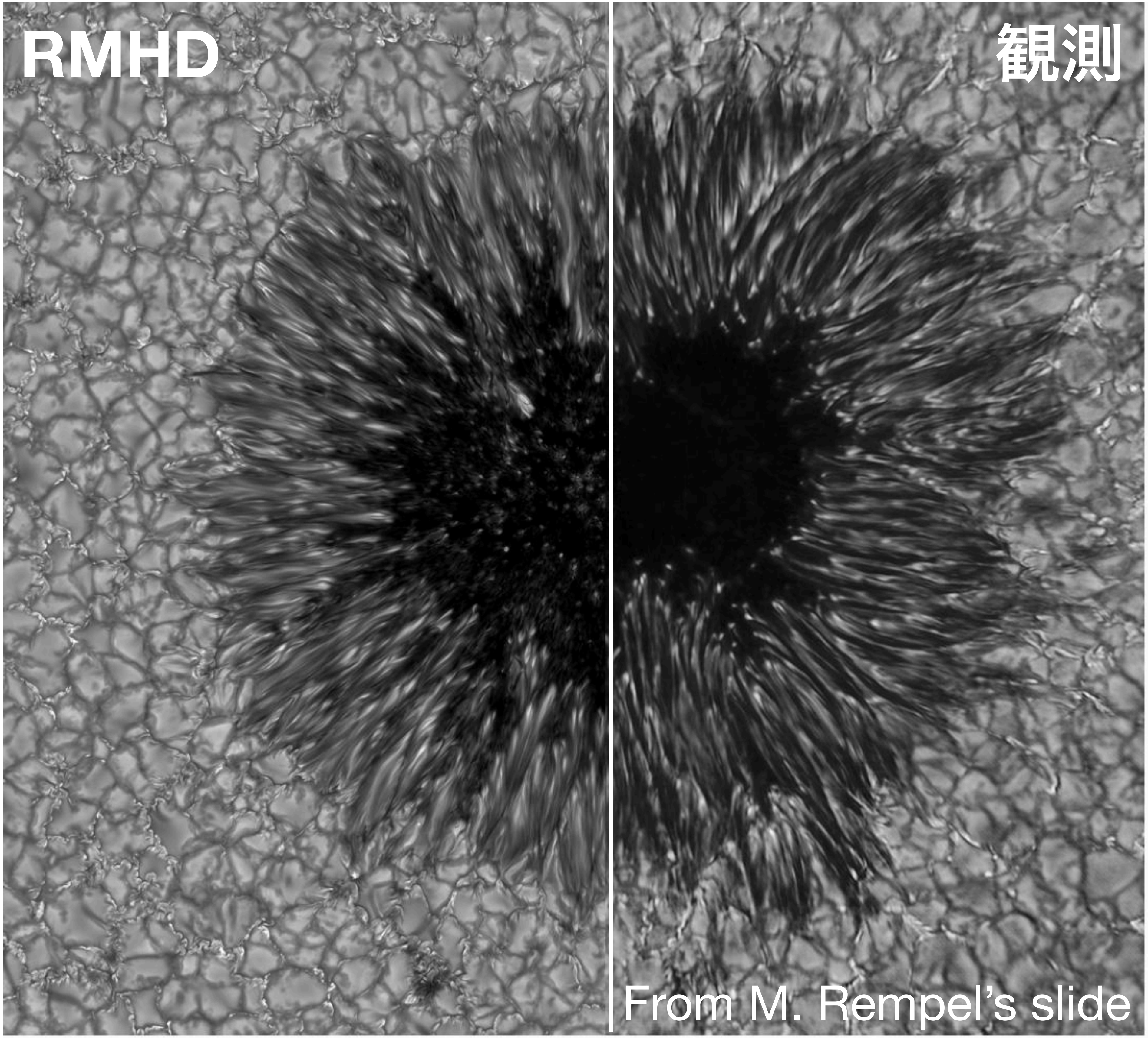
$<B>$ ~ **130** G at a few 100 km above τ=1 (del Pino Aleman+18 shows TB04 agrees well with R14 by synthetic 3D RT.)

Q. 左半分と右半分、どちらがシミュレーション？



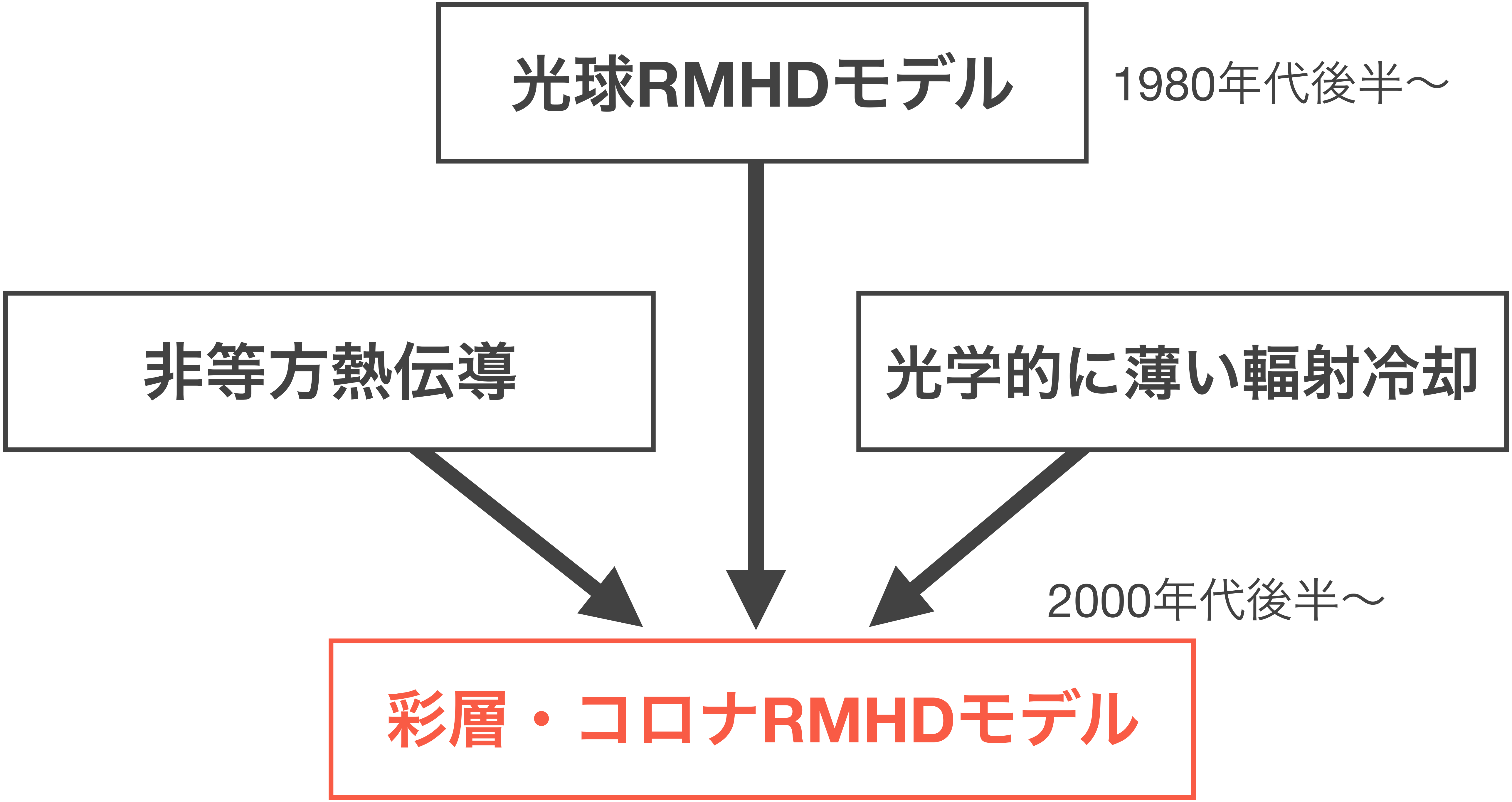
From M. Rempel’s slide

A. 左半分がシミュレーション



From M. Rempel's slide

彩層・コロナへの拡張



光球RMHDモデル

1980年代後半〜

非等方熱伝導

光学的に薄い輻射冷却

2000年代後半〜

彩層・コロナRMHDモデル

Magnetohydrodynamics

- CT scheme with multi-dimensional reconstruction
- Fifth-order WENO-Z reconstruction
- Third-order SSP Runge-Kutta method

Radiative Energy Transfer

- Short Characteristic method
- OPAL Rosseland mean Opacity
- Effectively optically thin radiative loss

Spitzer thermal conduction

- Flux limiter for preserving monotonicity
- Second-order Super TimeStepping method
- Second-order operator splitting

Equation of State

- LTE with hydrogen molecule formation
- 6 most abundant species
- Interpolation from numerical table

RAMENS

RAdiation Magnetohydrodynamics Extensive Numerical Solver

Magnetohydrodynamics

CT scheme with multi-dimensional reconstruction
Fifth-order WENO-Z reconstruction
Third-order SSP Runge-Kutta method

Radiative Energy Transfer

Short Characteristic method
OPAL Rosseland mean Opacity
Effectively optically thin radiative loss

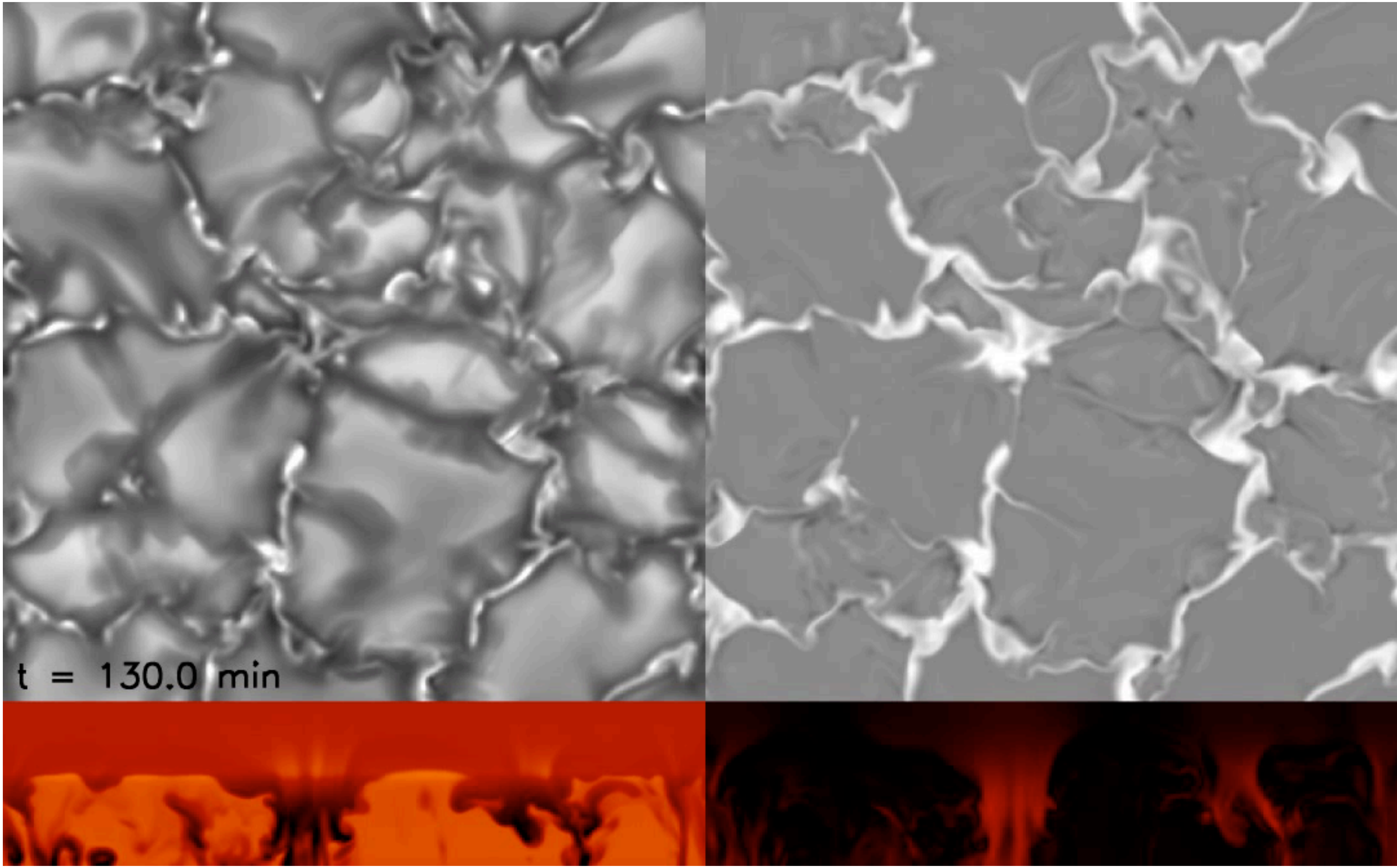
Spitzer thermal conduction

Flux limiter for preserving monotonicity
Second-order Super TimeStepping method
Second-order operator splitting

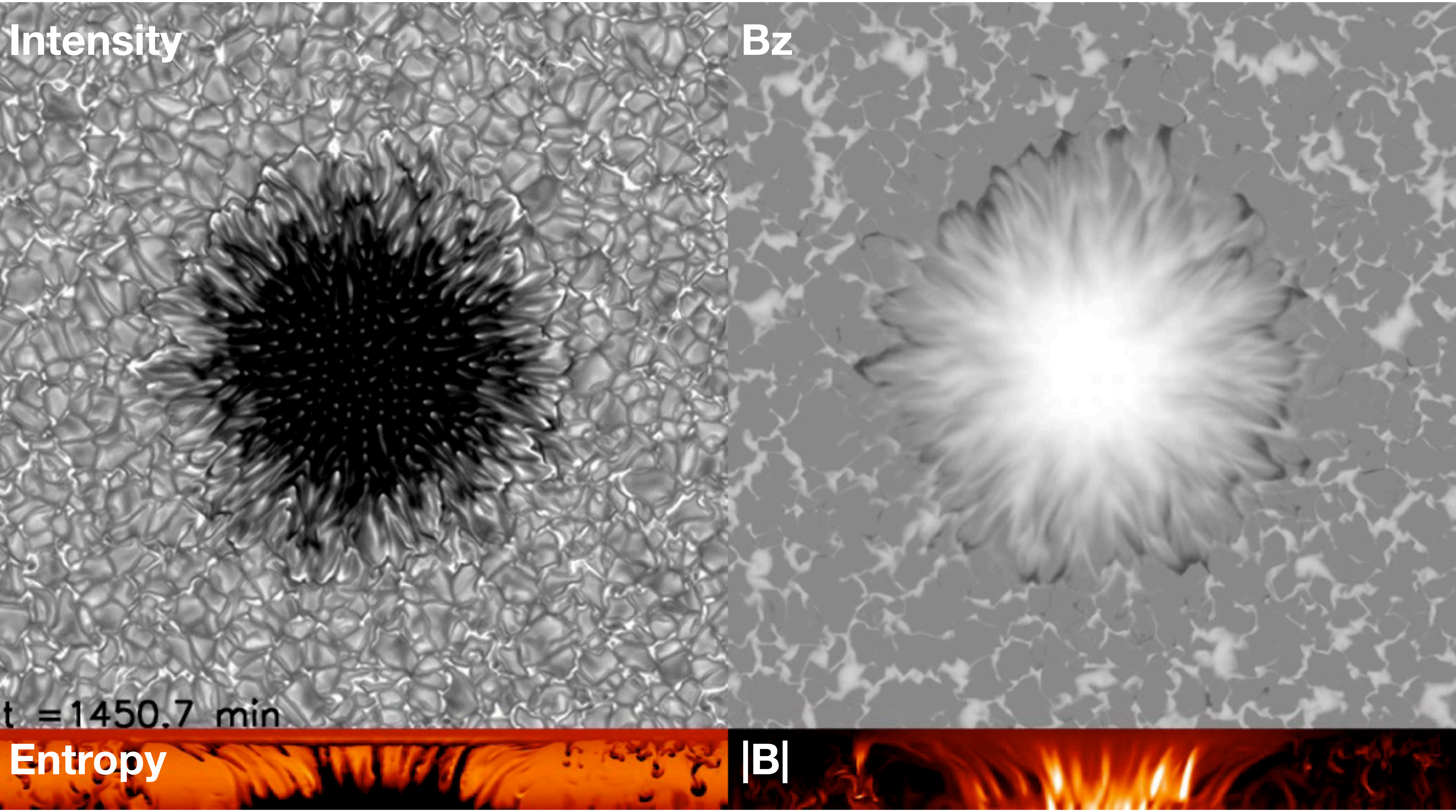
Equation of State

LTE with hydrogen molecule formation
6 most abundant species
Interpolation from numerical table

RAMENS | 表面対流



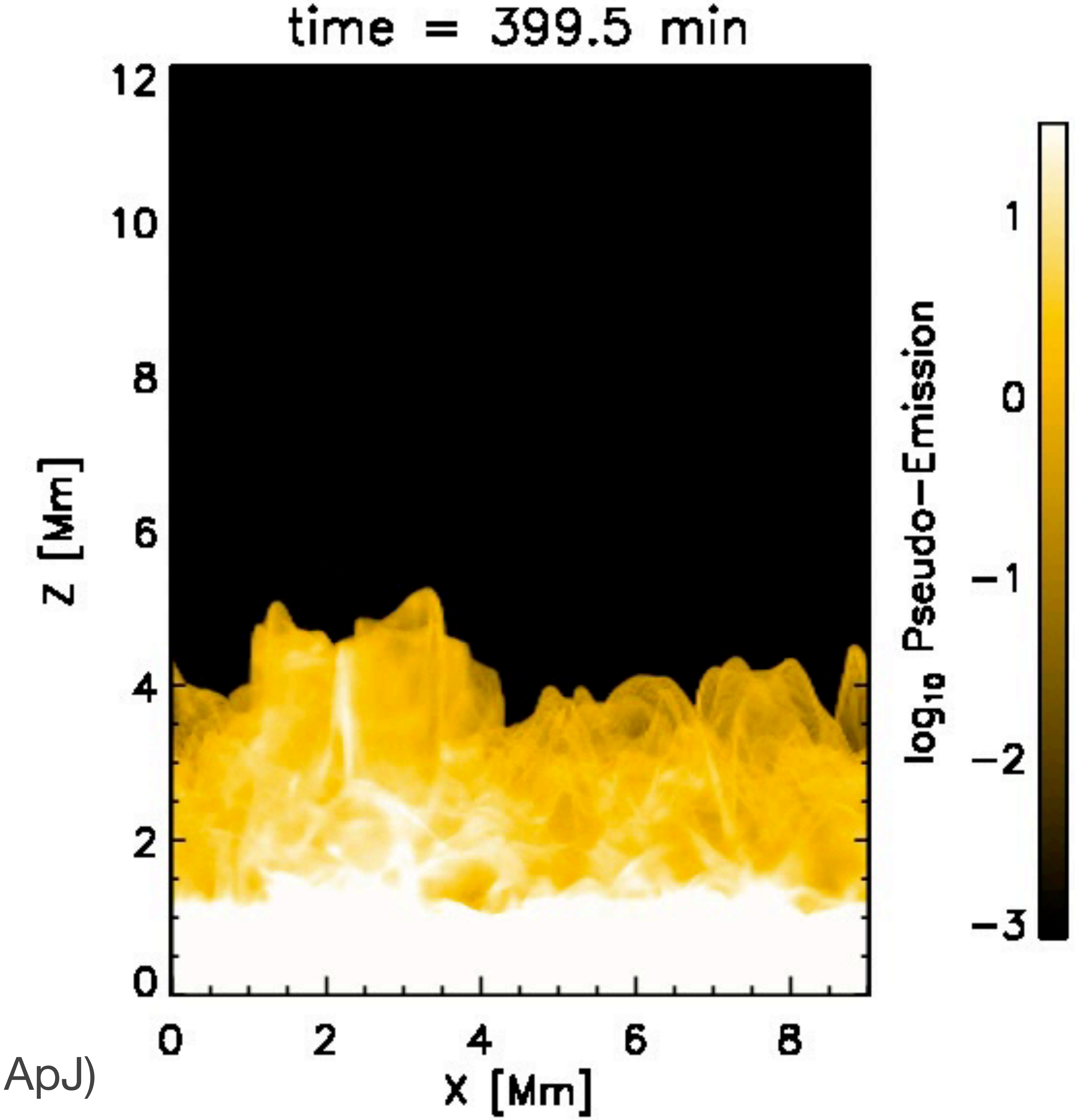
RAMENS | 黒点



RAMENS | 彩層ジェット

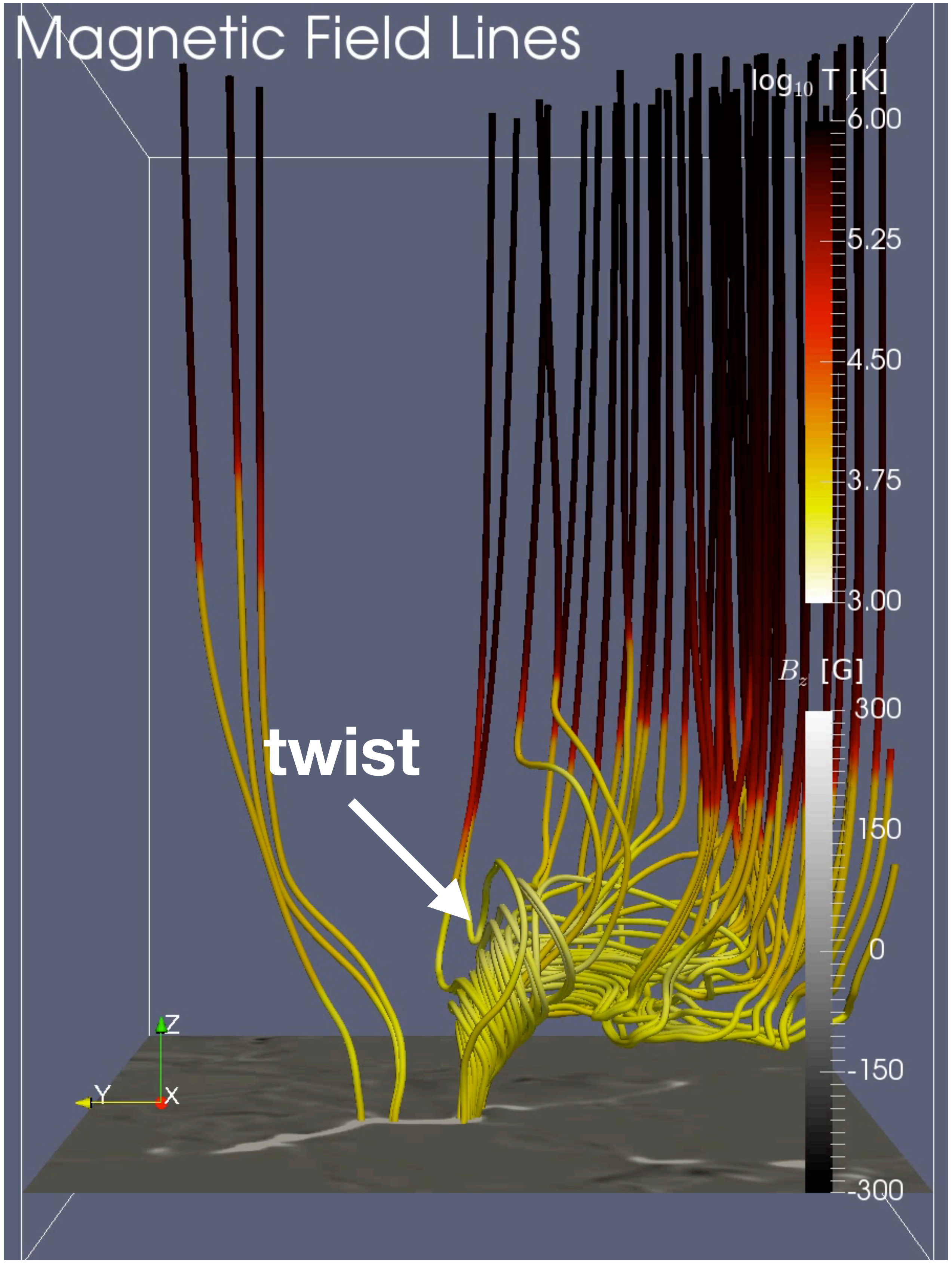
Right: optically thin emission with the Gaussian contribution function G(T) that mimics the chromospheric line emission (~ **10 kK**).

$$\epsilon = \int n_{\mathrm{e}} n_{\mathrm{H}} G(T) \mathrm{d}l$$

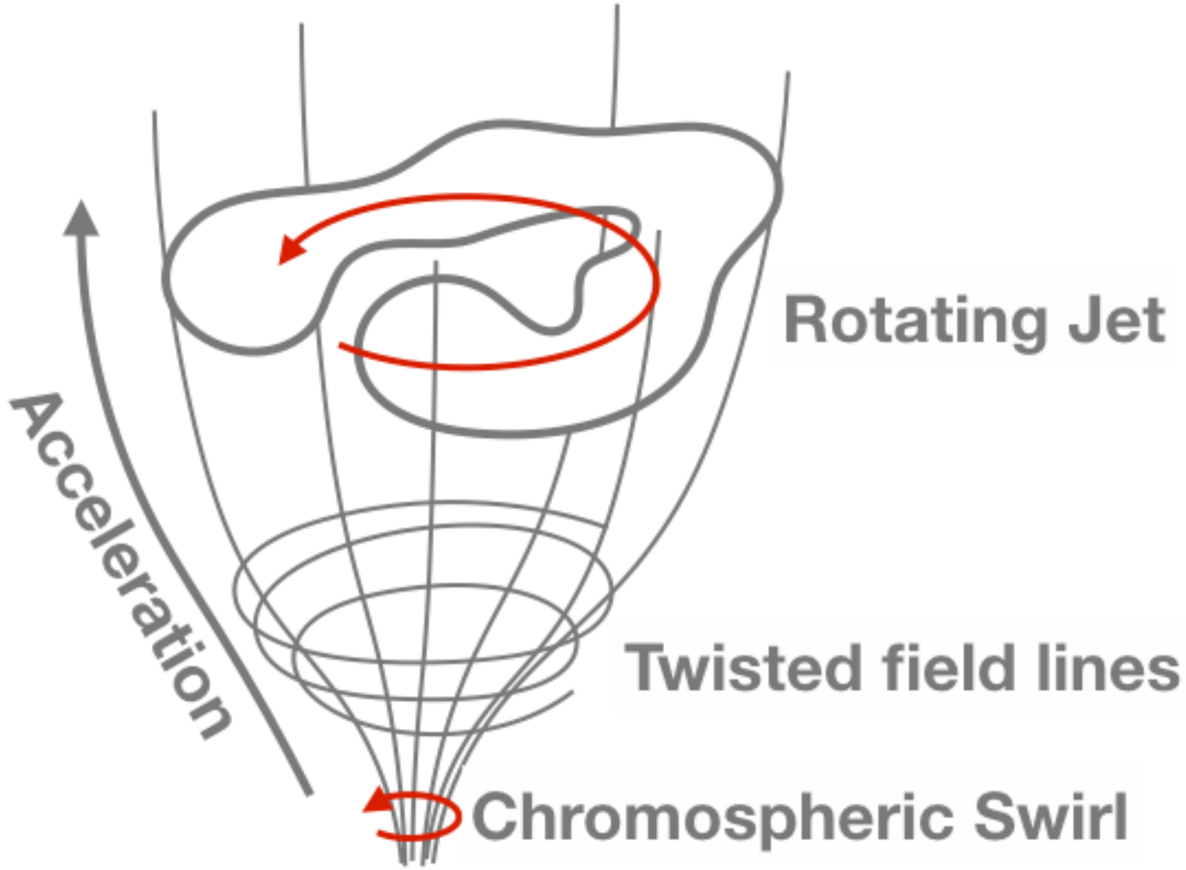


Iijima & Yokoyama (2017, ApJ)

RAMENS | 彩層ジェット

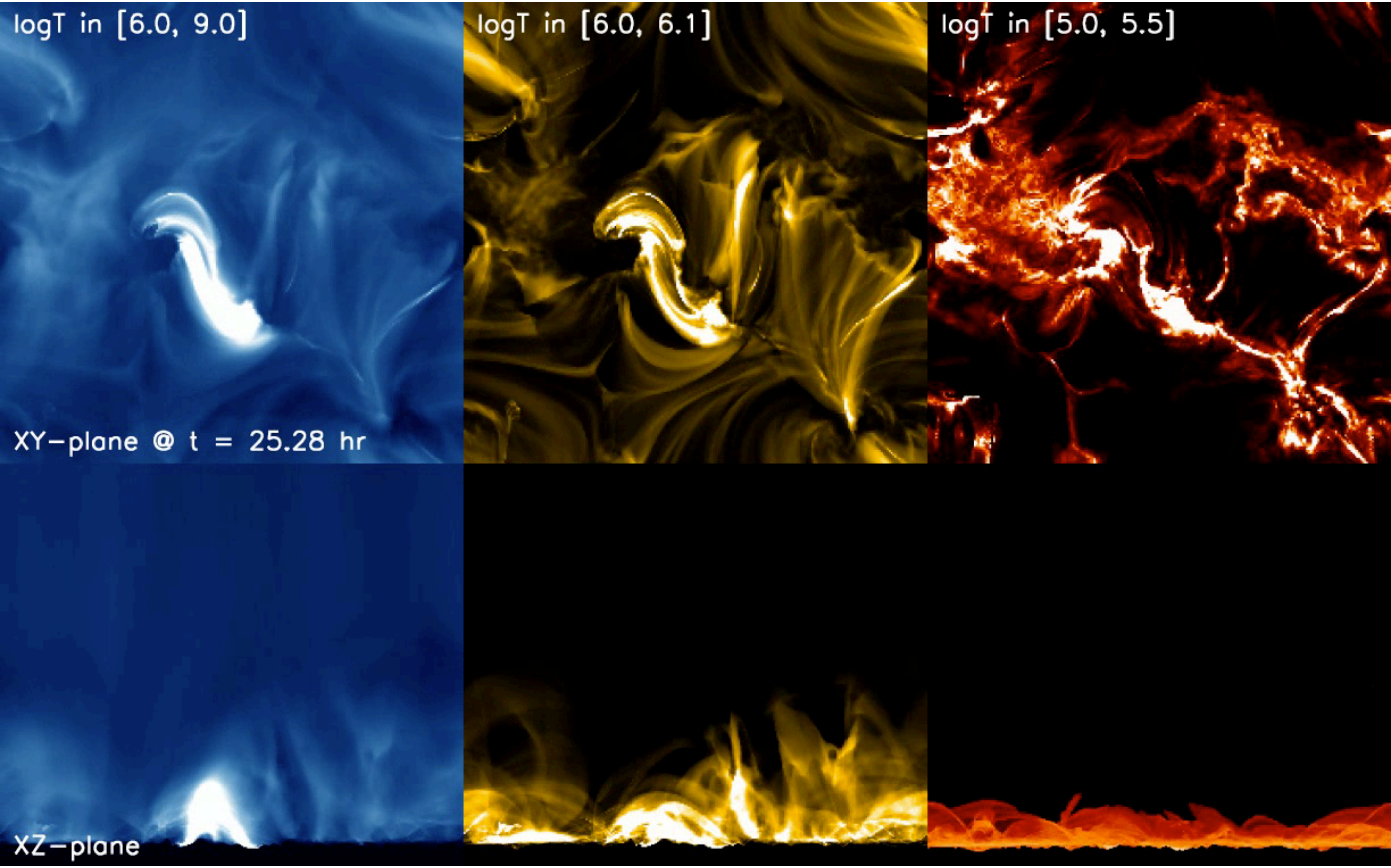


Torsional motion at the photosphere causes the twist in the chromosphere.
When twist becomes sufficiently strong, it releases the free energy and accelerate the plasma.



Iijima & Yokoyama (2017, ApJ)

RAMENS | コロナ


logT in [6.0, 9.0]
logT in [6.0, 6.1]
logT in [5.0, 5.5]
XY−plane @ t = 25.28 hr
XZ−plane

アウトライン

- 太陽の大気構造を知るには
- フォワードモデリングによるアプローチ
- **今後の研究課題**

今後の研究課題

- 標準的な彩層・コロナモデルの確立
- 超粒状斑の起源
- 他の恒星への応用・検証範囲拡大

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太陽大気の輻射磁気流体モデルの発展

1980年　1990　2000　2010　2020　20XX

- **三次元光球対流モデルの提案**
- 三次元光球対流モデルの発達
- 恒星の光球への適用
- 磁場の効果の考慮
- **彩層・コロナへの拡張**
- 水素非平衡電離の考慮
- 観測機器・診断手法の検証への利用
- 一般化オームの法則
- 各種高速化手法の発達
- ?

RMHDの課題 | 彩層の平均的輝線幅

Both brightness and Doppler width of Ca II 854.2 nm are smaller than observation.

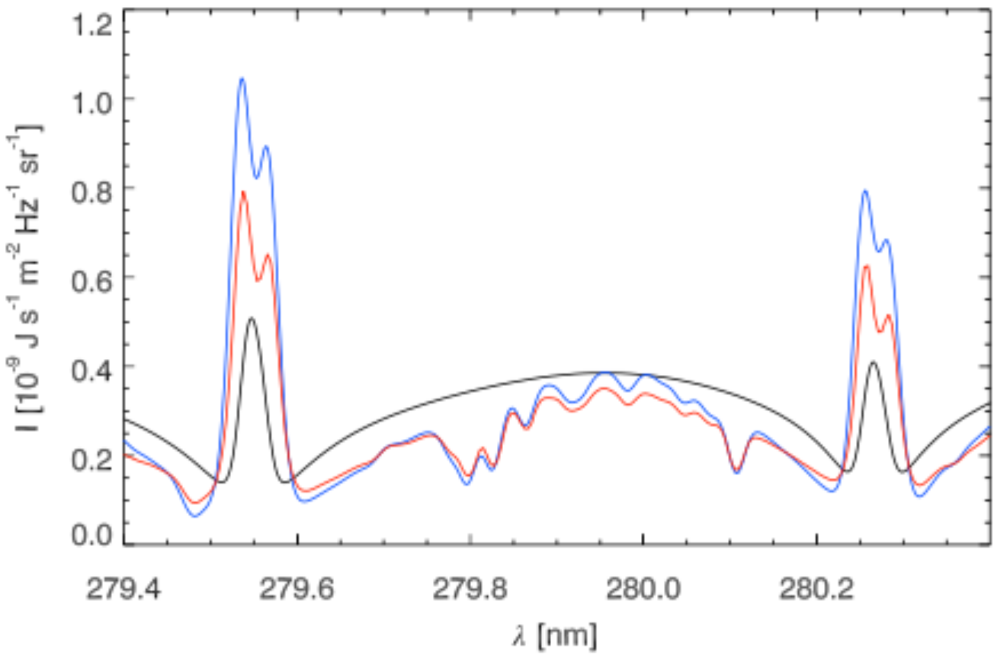
Possible sources of discrepancy:

(1) Lack of electron number density (EOS)

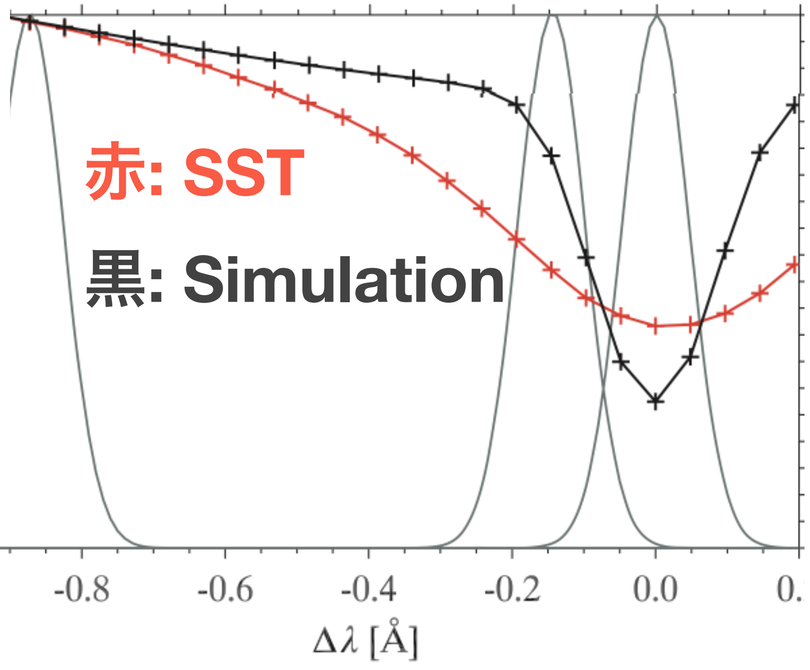
(2) Lack of velocity amplitude (radiative cooling)

(3) Lack of spatial resolution

(4) Lack of elemental process (e.g., ambipolar diffusion)



Mg II H/K
(Leenaarts et al., 2013)

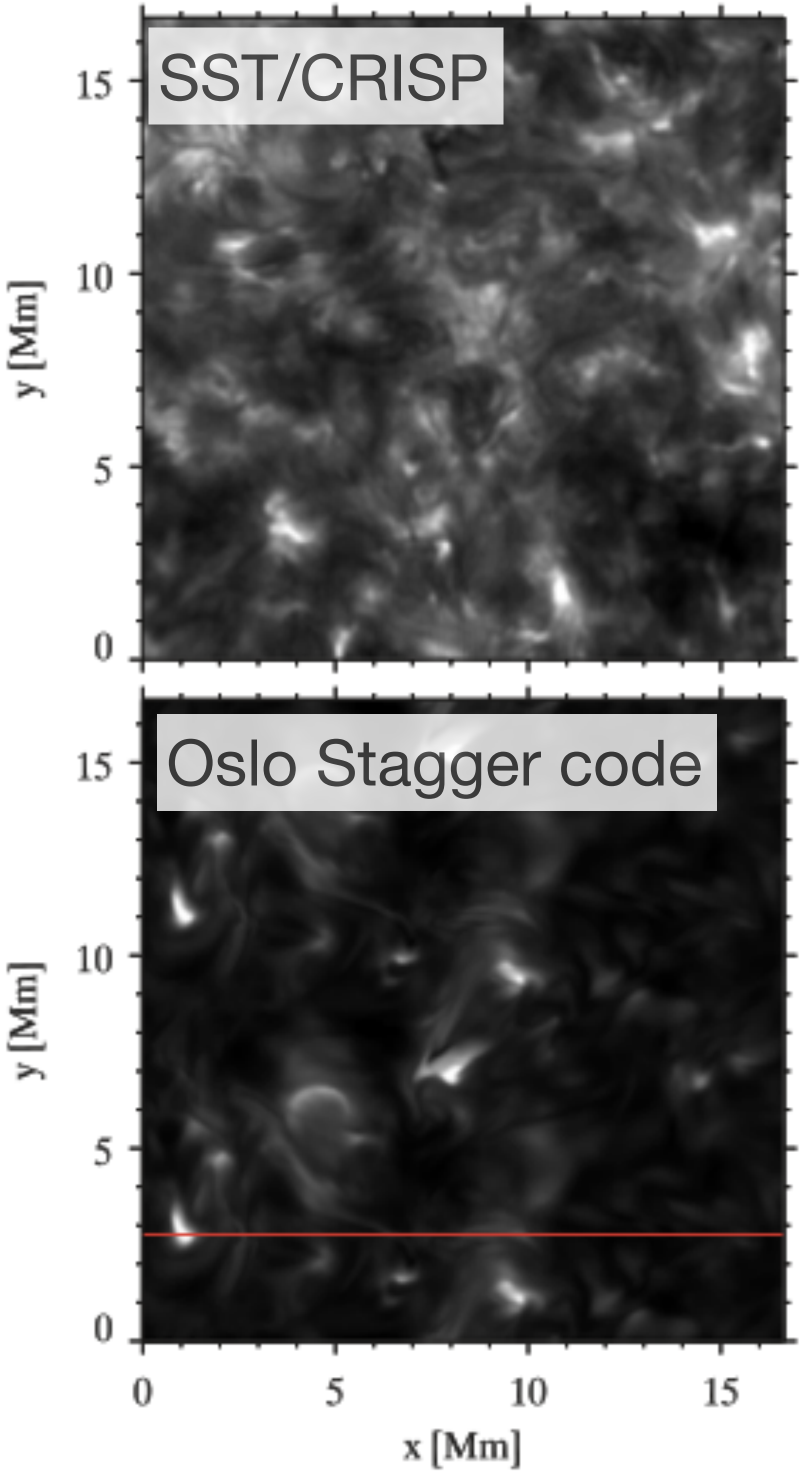


赤: SST

黒: Simulation

Ca II 854.2 nm
(Leenaarts et al., 2013)

Ca II 8542 Core
(Leenaarts et al., 2009)

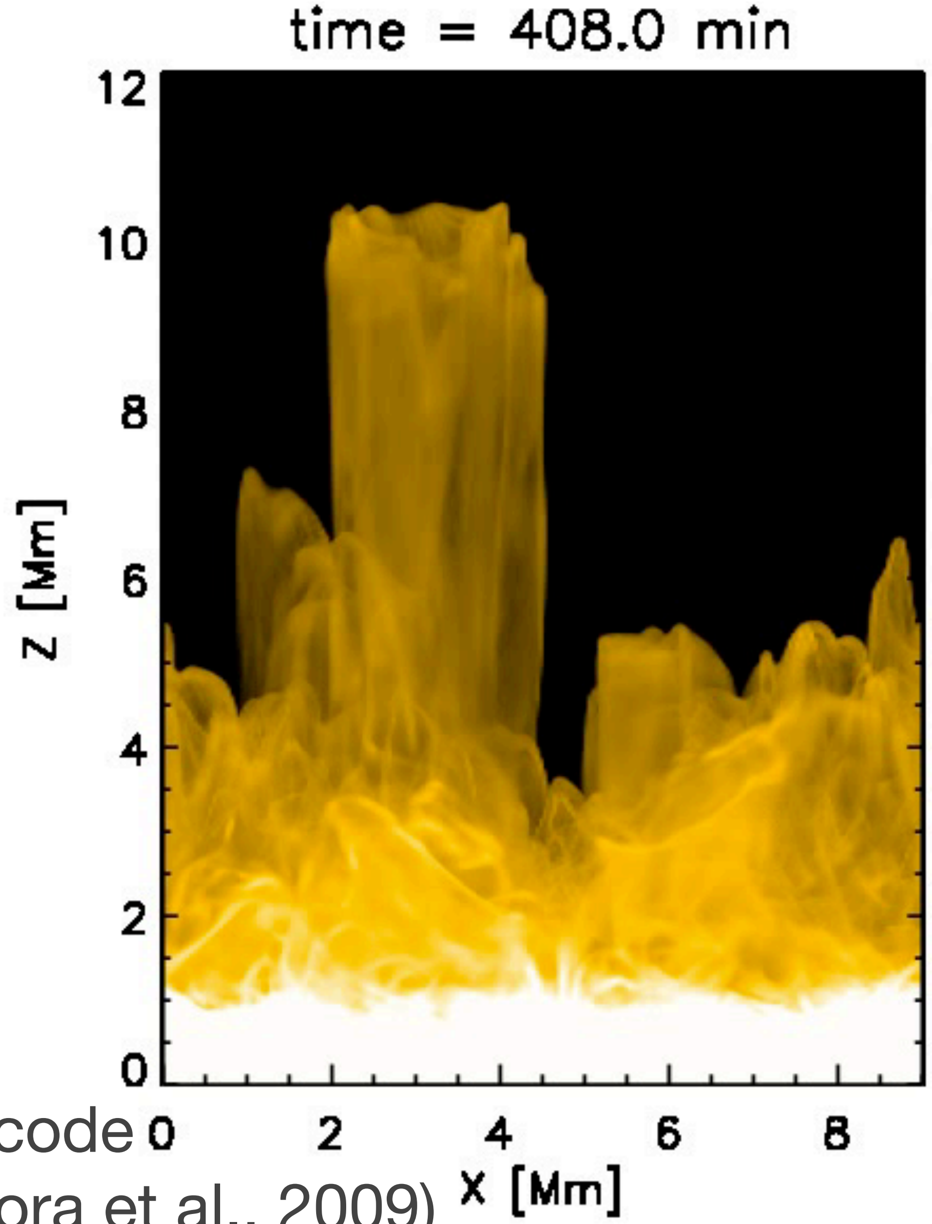


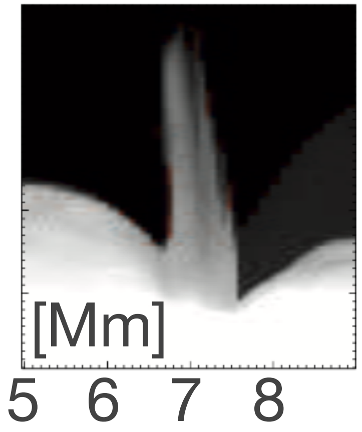
RMHDの課題 | 彩層ジェット

Spicule: need off-limb synthesis

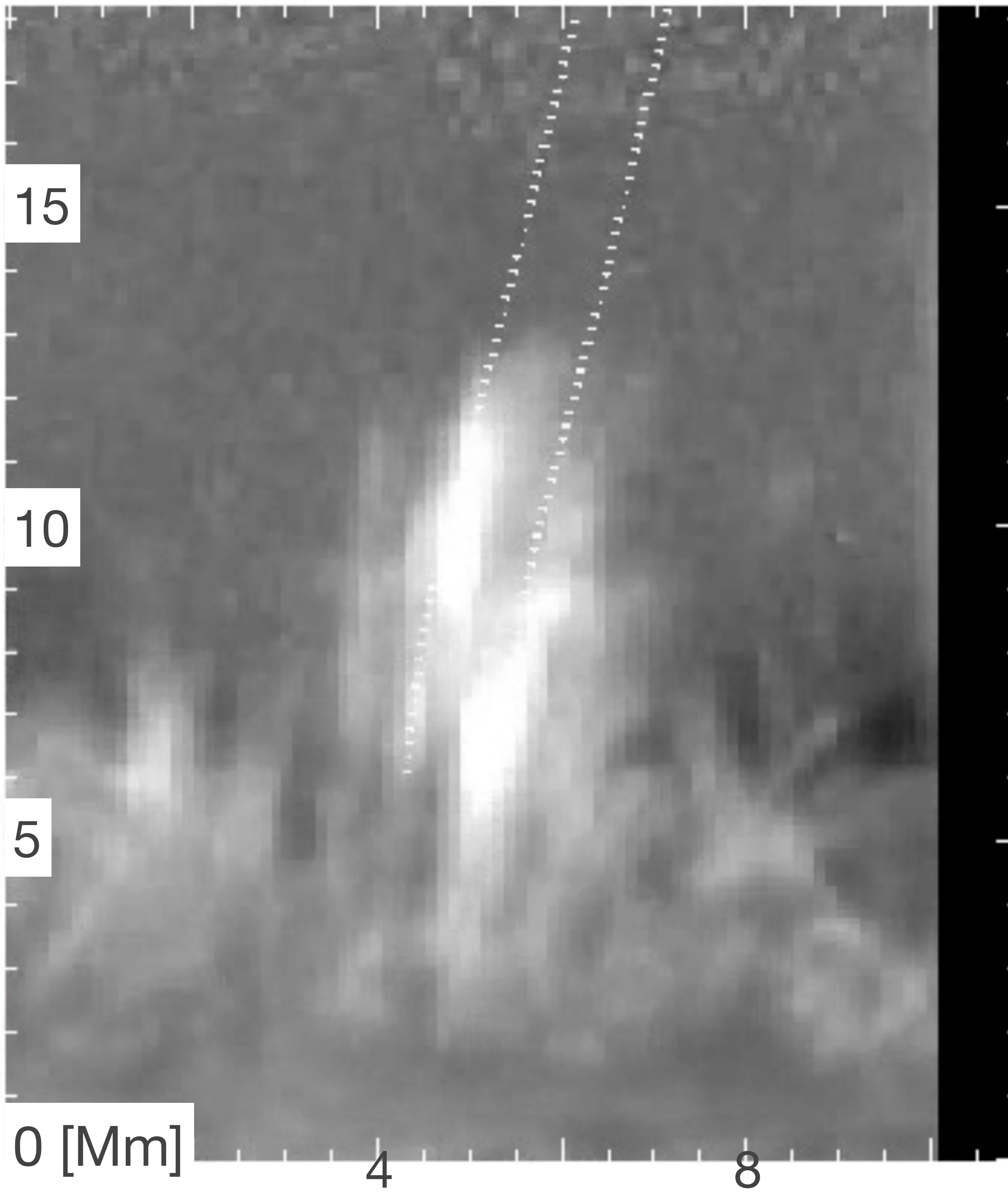
Fibrils: on-disk synthesis

RAMENS
(Iijima & Yokoyama, 2017)





Oslo Stagger code
(Martinez-Sykora et al., 2009)



Hinode/SOT Ca II H (Skogsrud et al., 2015)

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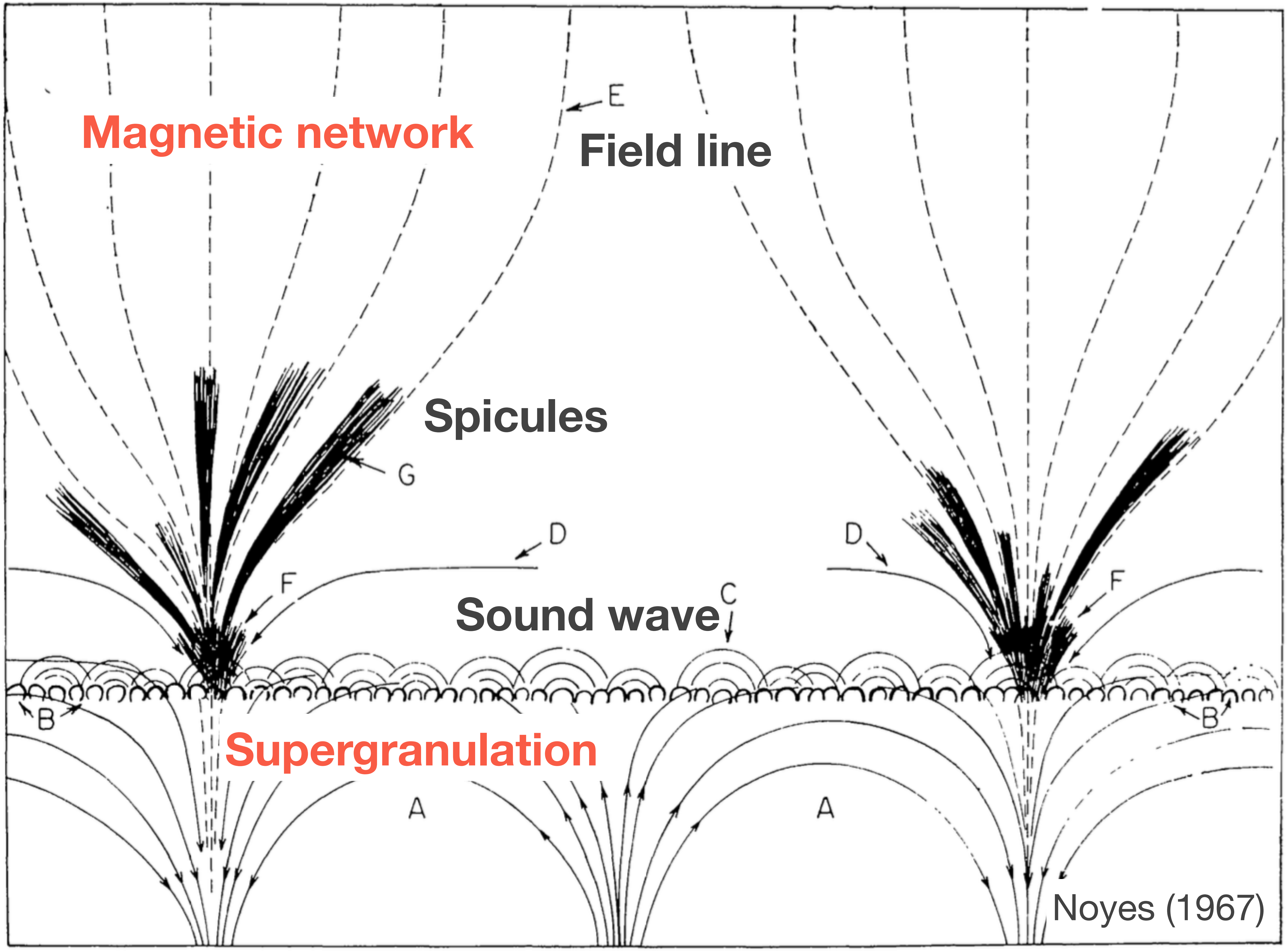
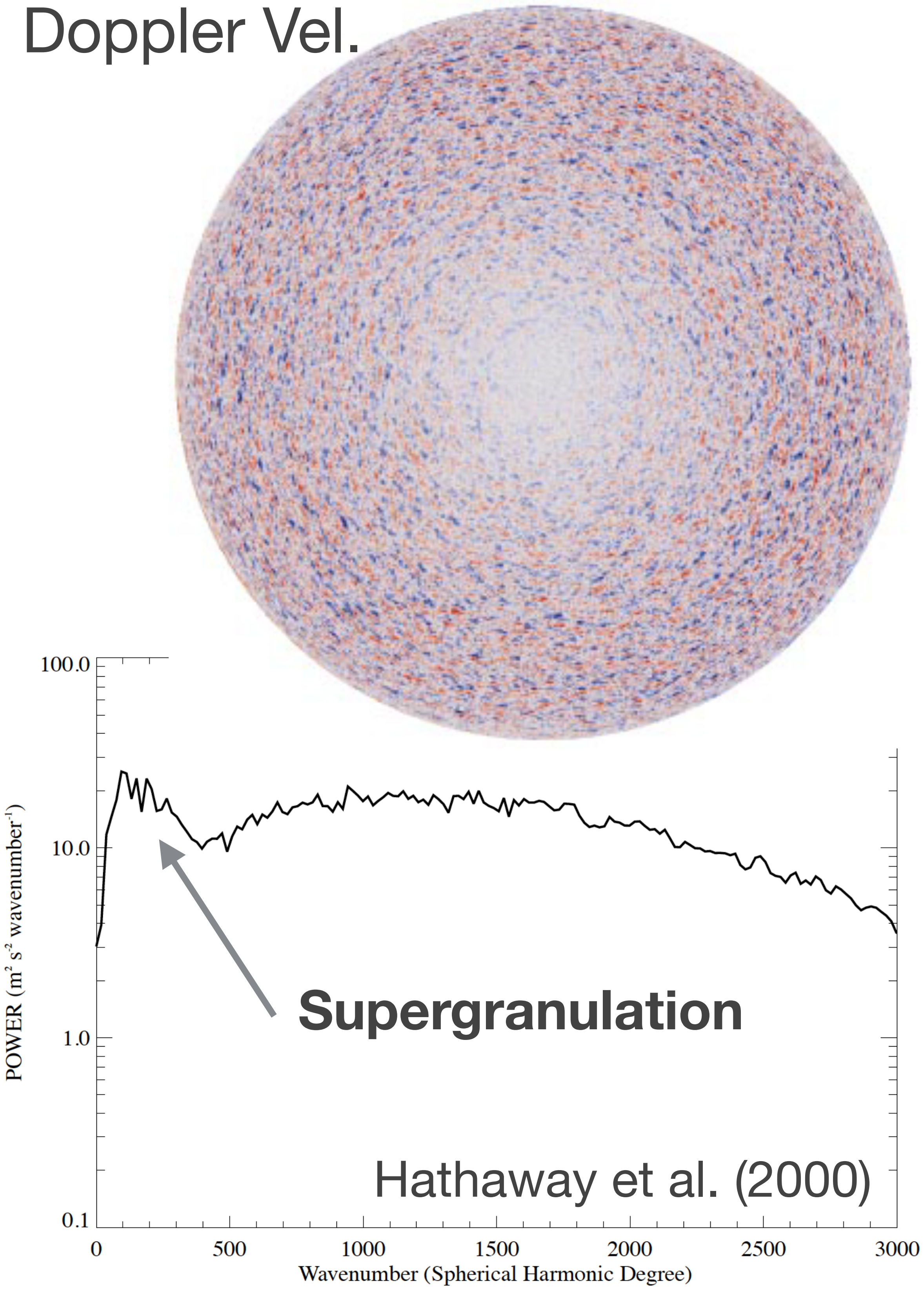
RMHDの課題 | 超粒状斑

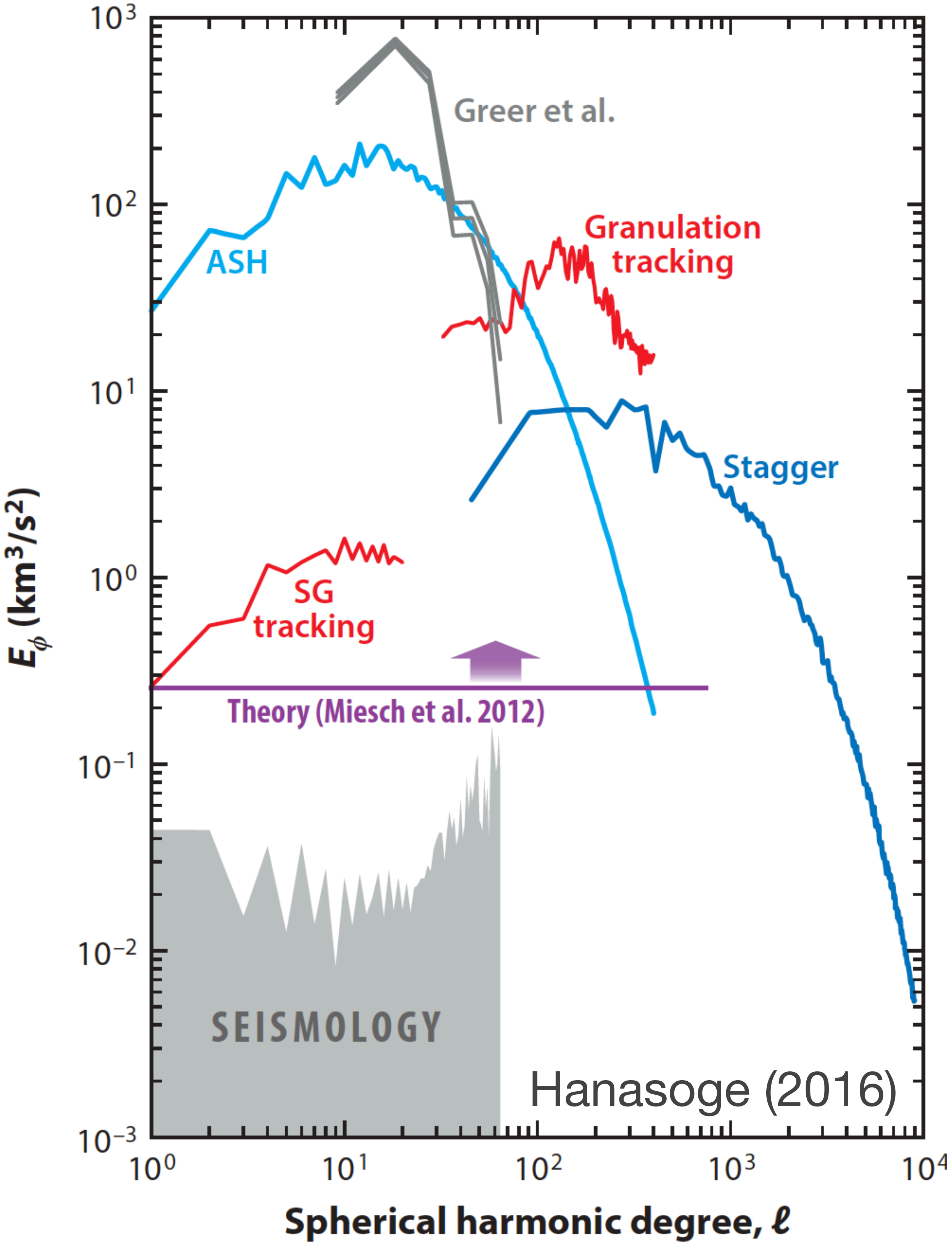


Noyes (1967)

RMHDの課題 | 超粒状斑

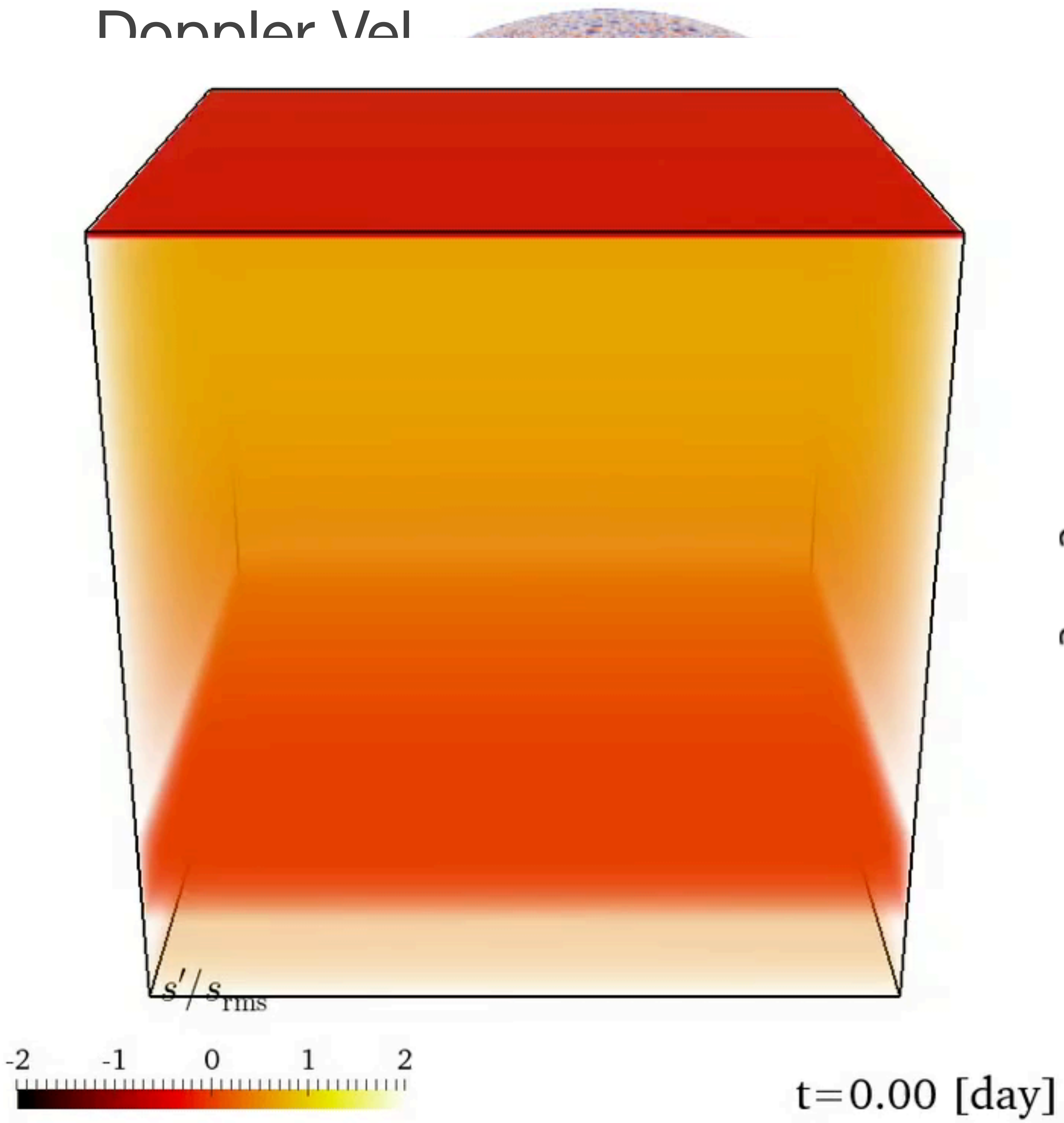


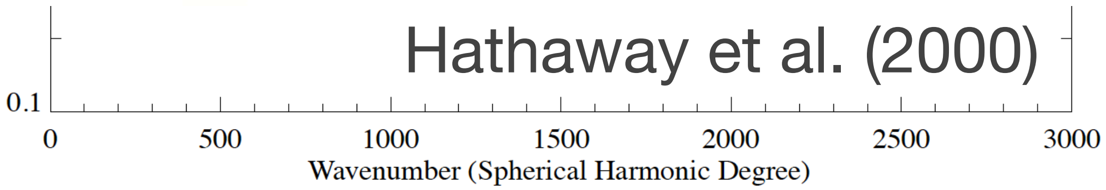
Hathaway et al. (2000)



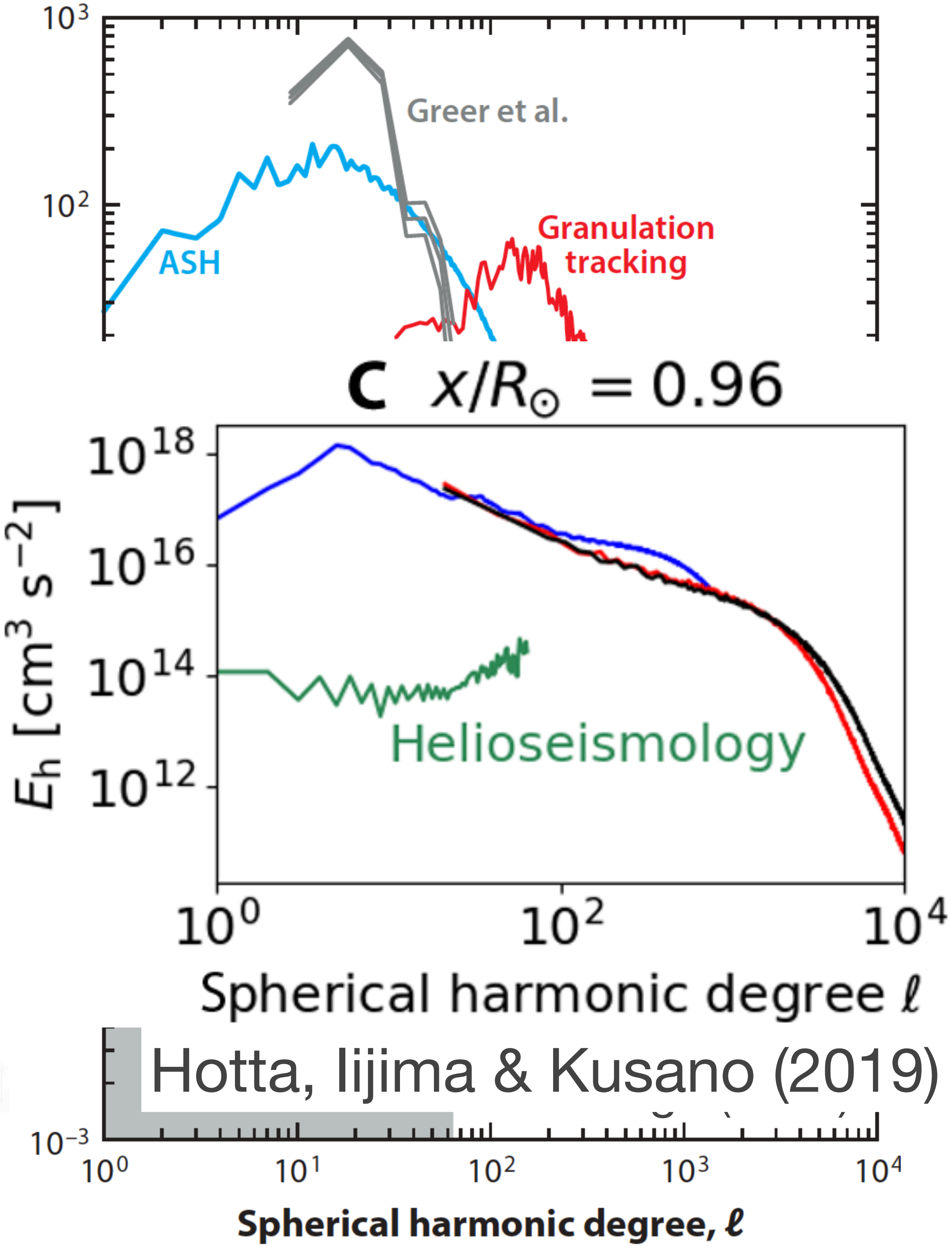
Hanasoge (2016)

RMHDの課題 | 超粒状斑





Hathaway et al. (2000)



Hotta, Iijima & Kusano (2019)

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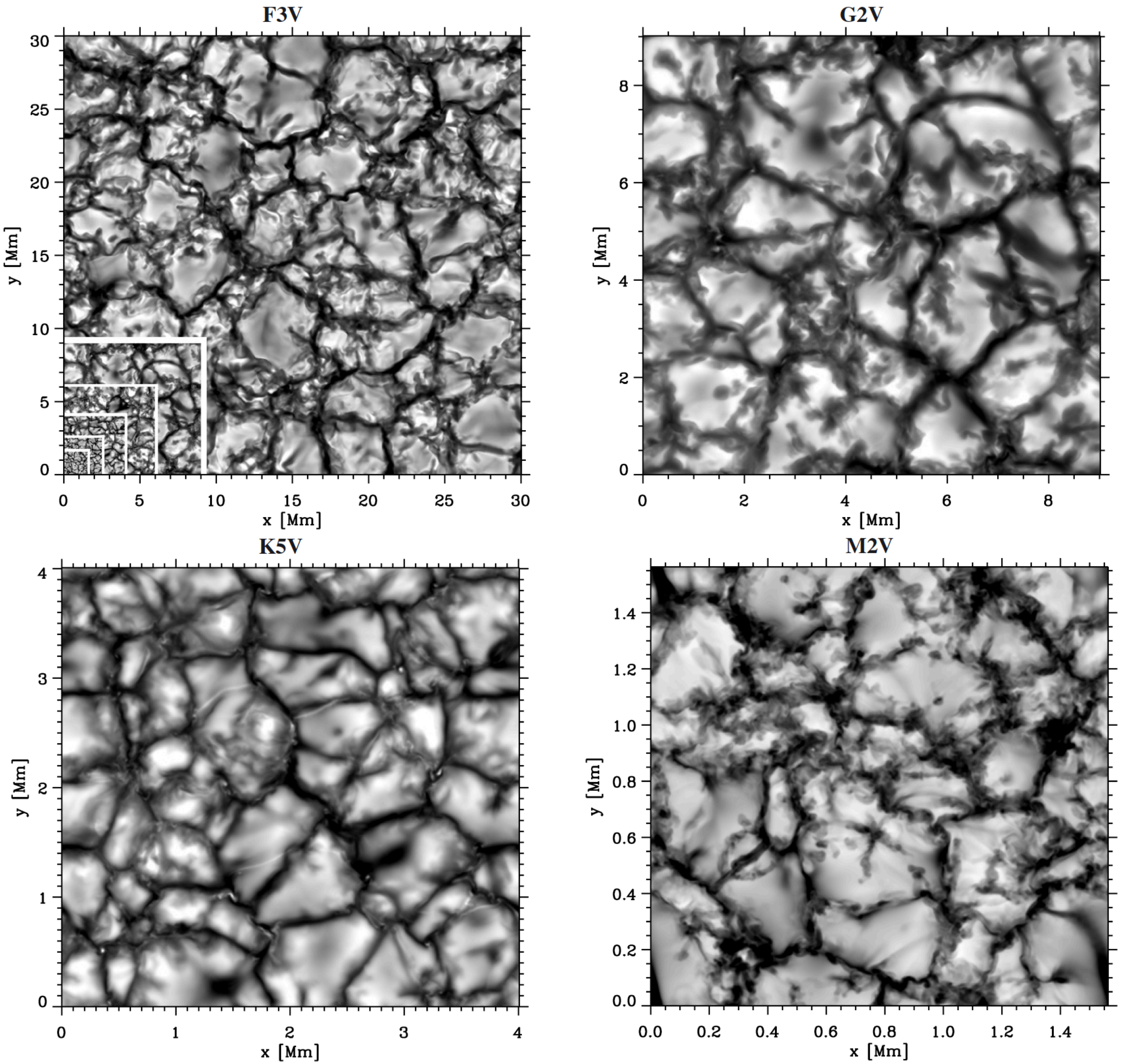
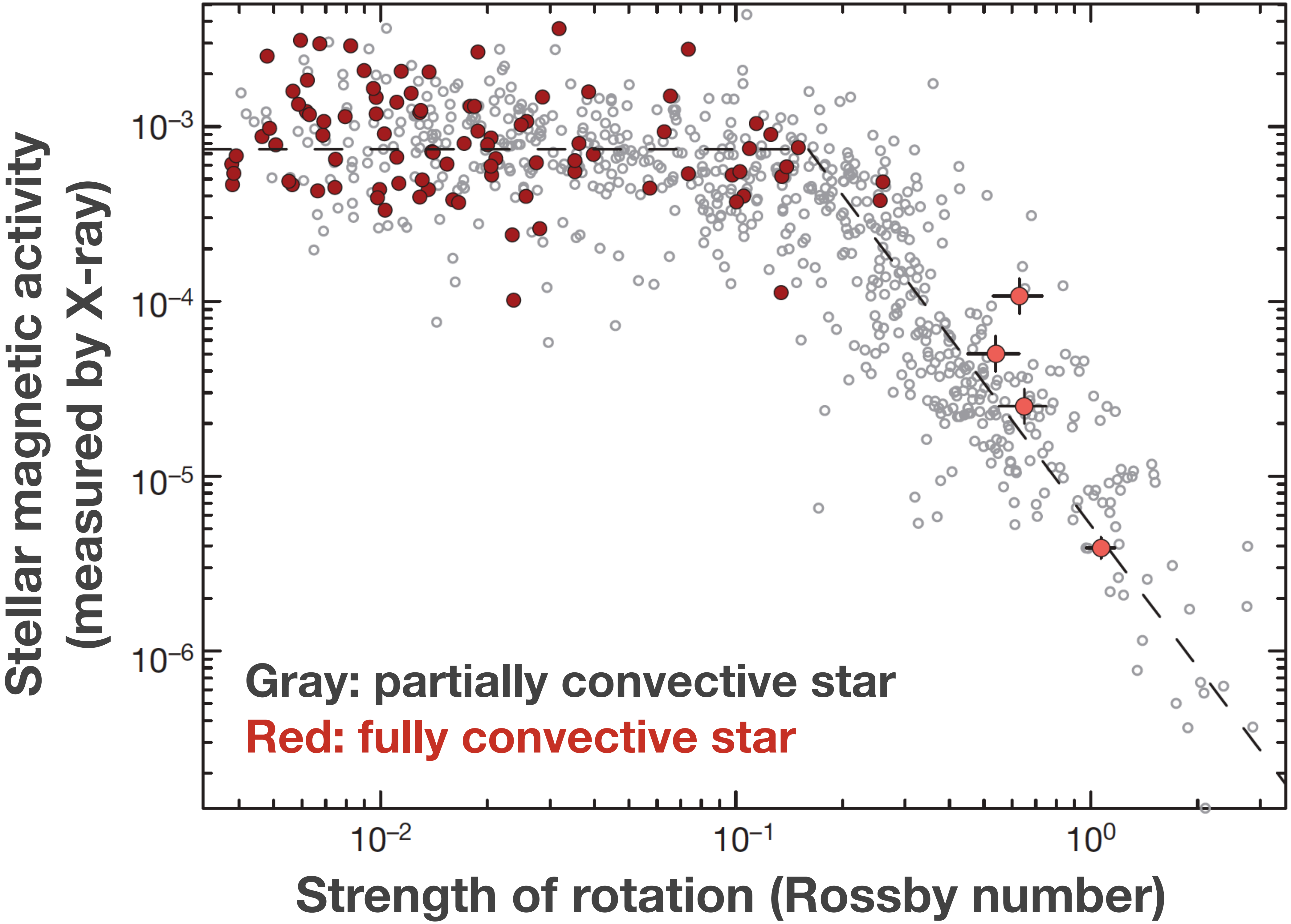
光球RMHD計算の他の恒星への適用



Beeck et al. (2013a)

恒星の自転とX線強度



Wright & Drake (2016)

RMHDの課題 | Ad-hocな取り扱いの除去

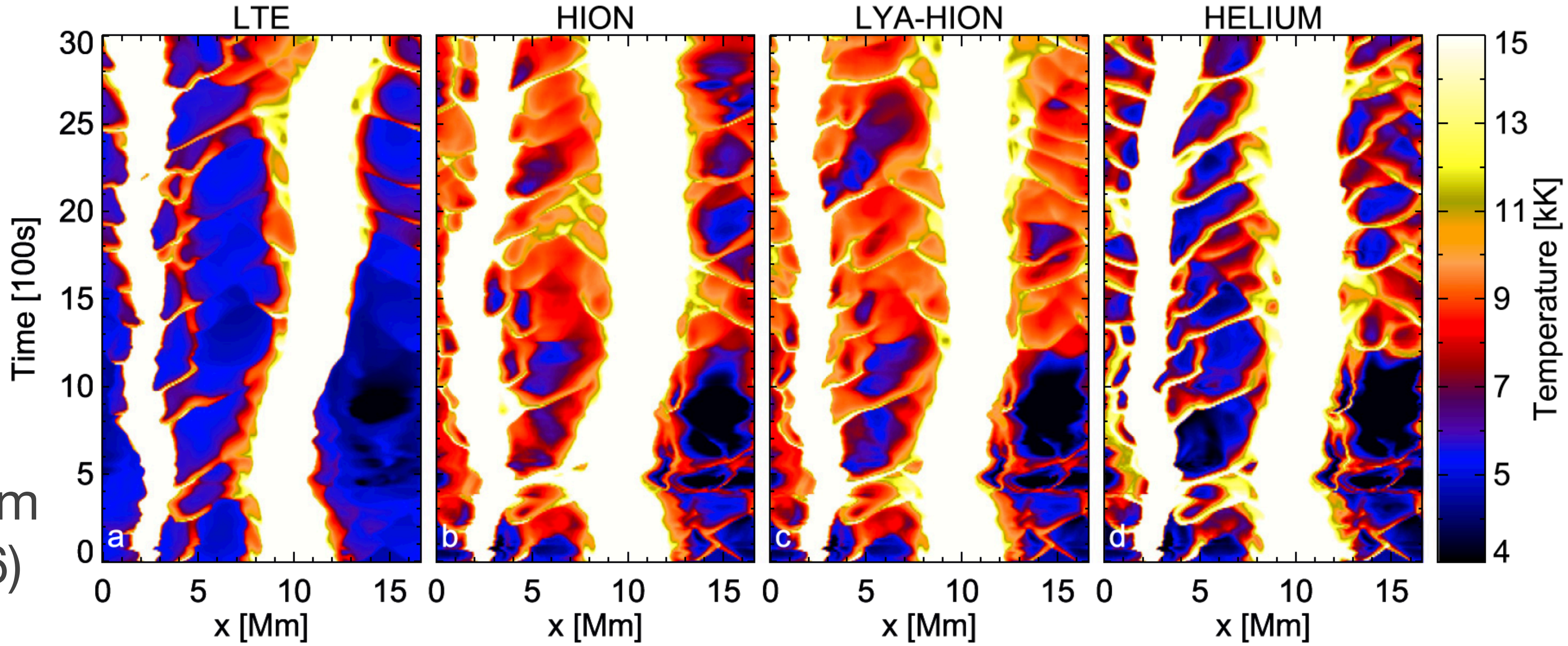
Ly-α case:

$$R_{21} = A_{21} E\left(\tau\right),$$

$$\eta_{\mathrm{L}\alpha} = \frac{h\nu_0}{4\pi} n_2 R_{21}, \quad \chi_{\mathrm{Ly}\alpha} = \frac{h\nu_0}{4\pi} n_1 B_{12} \phi,$$

Solve 3D RTE from *η* and *χ*

$$R_{12} = B_{12} J_{\mathrm{Ly}\alpha}. \quad Q_{\mathrm{Ly}\alpha} = h\nu_0 (n_1 R_{12} - n_2 R_{21}),$$



Temp. at Z = 2.6 Mm
Golding et al. (2016)

RMHDの課題 | Ad-hocな取り扱いの除去

Ly-α case:

Feedback is necessary.

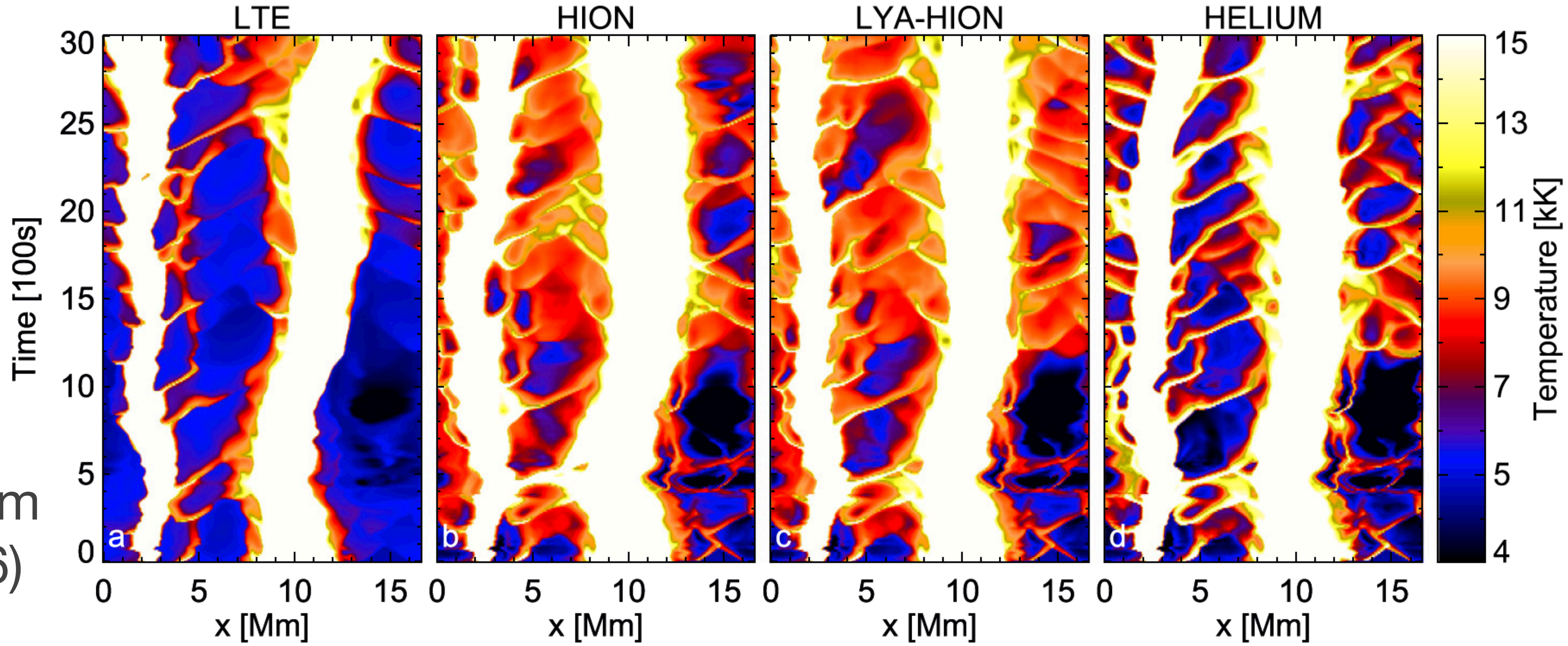
$$R_{21} = A_{21} E(\tau),$$

← 1D assumption.

$$\eta_{\mathrm{L}\alpha} = \frac{h\nu_0}{4\pi} n_2 R_{21}, \quad \chi_{\mathrm{Ly}\alpha} = \frac{h\nu_0}{4\pi} n_1 B_{12} \phi,$$

Solve 3D RTE from *η* and *χ*

$$R_{12} = B_{12} J_{\mathrm{Ly}\alpha}. \quad Q_{\mathrm{Ly}\alpha} = h\nu_0 (n_1 R_{12} - n_2 R_{21}),$$



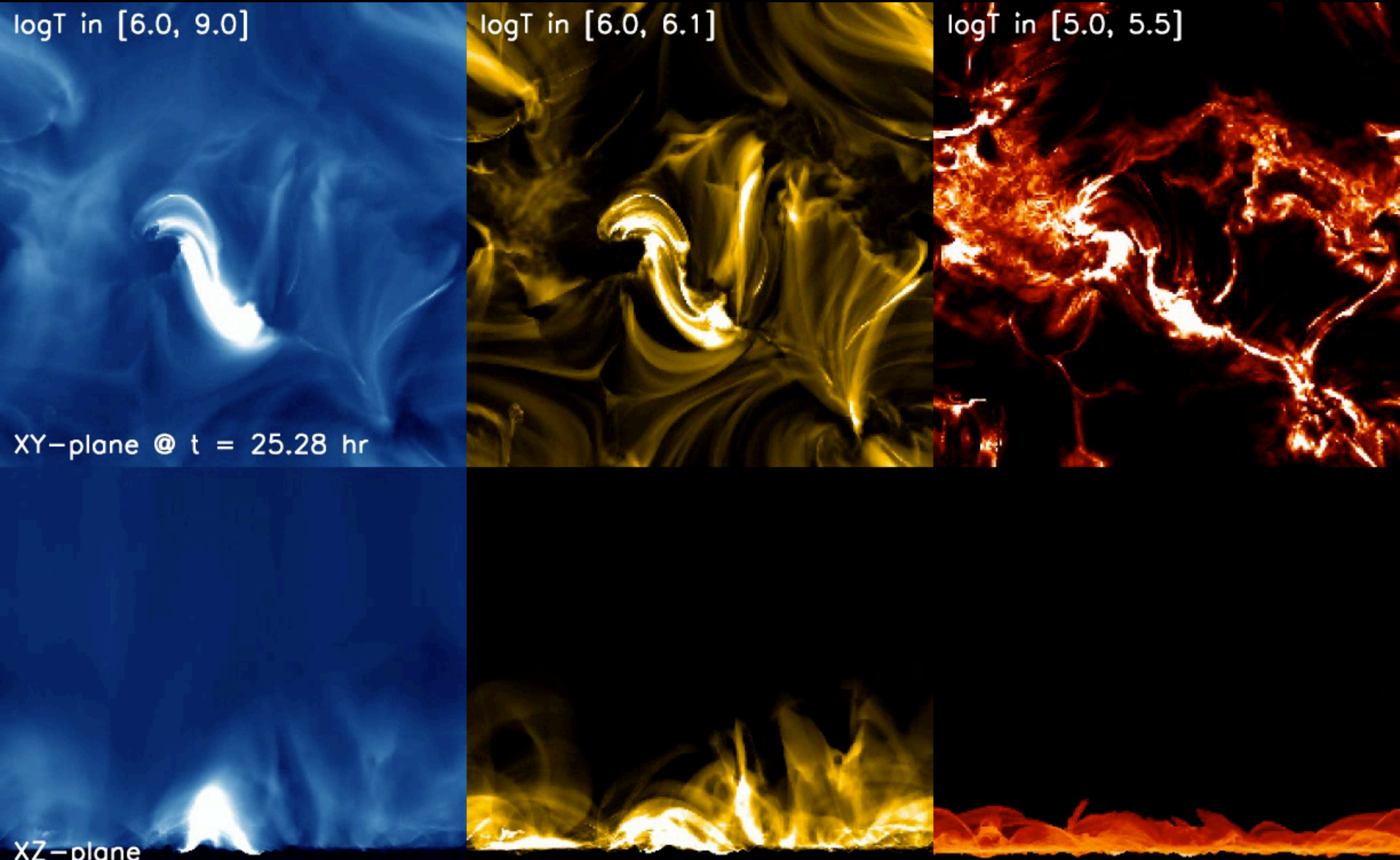
Temp. at Z = 2.6 Mm
Golding et al. (2016)

まとめ

- 太陽彩層・コロナの輻射磁気流体モデルはきれいな絵が出て楽しいです。

- きれいな絵が出るだけじゃなくて、いろいろ応用もあります。

- 課題もたくさんあります。



貴重なお時間ありがとうございました。研究楽しんで下さい。