Instability of Walker Propagating Domain-Wall Mode in Magnetic Nanowires

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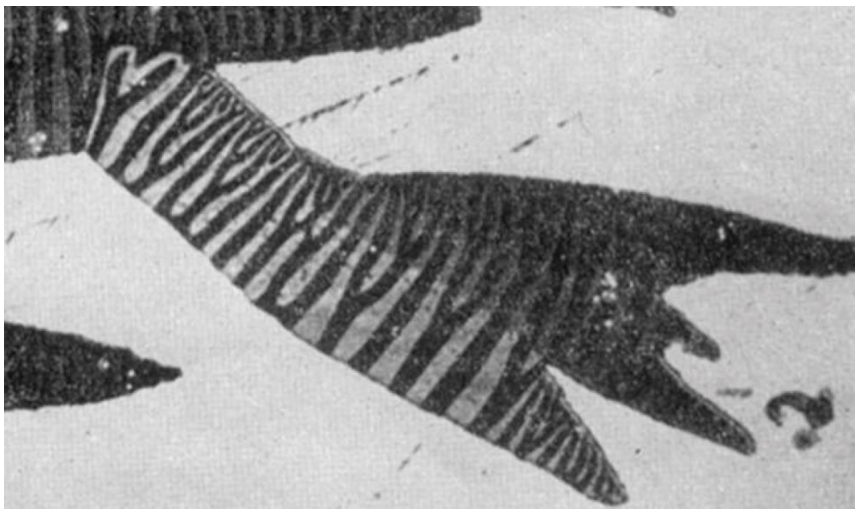
Concepts in Spintronics, KITP, Oct. 1, 2013

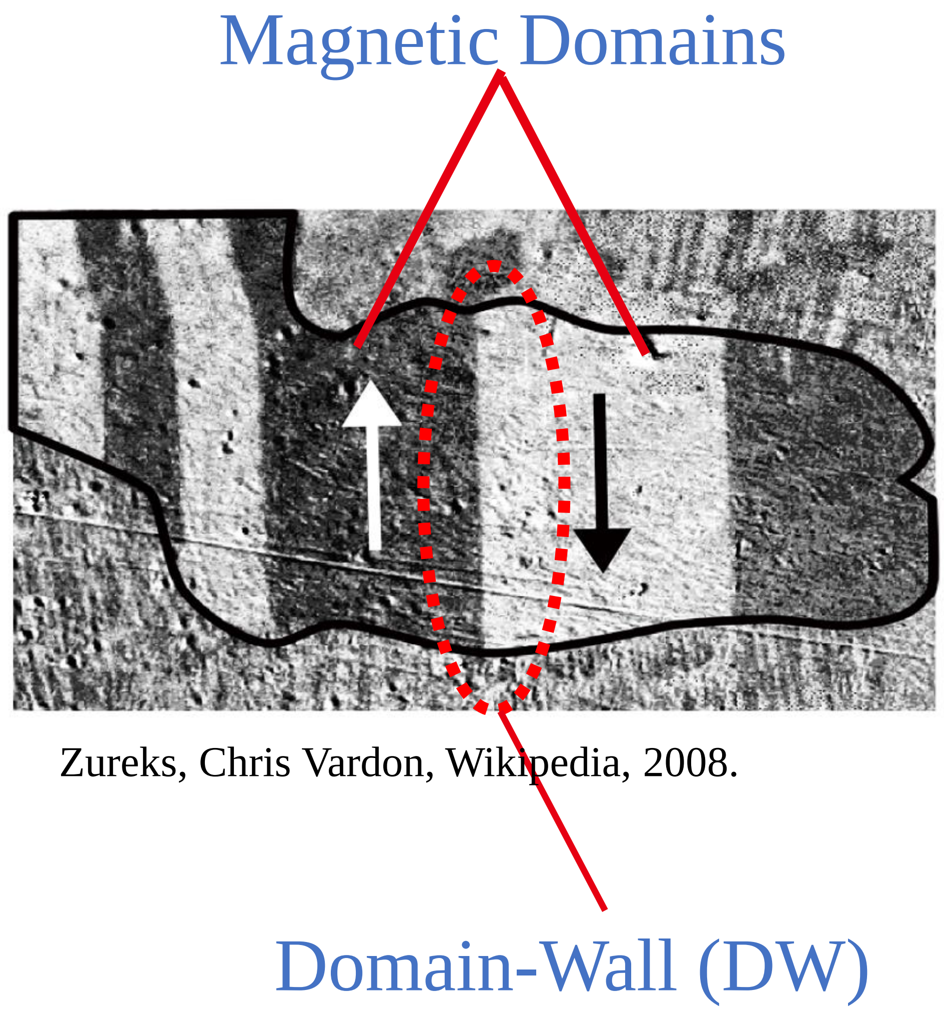
Outline

- Introduction
  - Magnetization Dynamics and Applications
  - Landau-Lifshitz-Gilbert Equation and Walker Solution
  - The Issue
- Instability of Walker Solution in Magnetic Nanowires
  - Essential Spectrum and Domain Instability
  - Absolute Spectrum and DW-Profile Instabilities
    - Transient Instability
    - Convective/Absolute Instability
- Conclusion

Magnetic Domain & Domain Wall

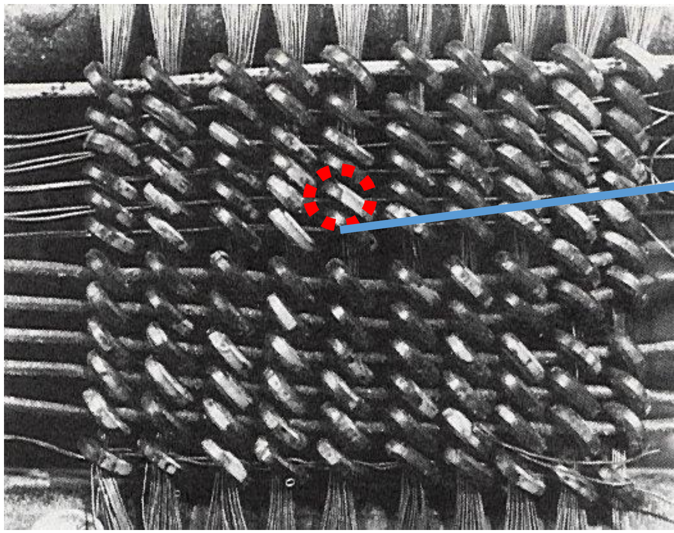


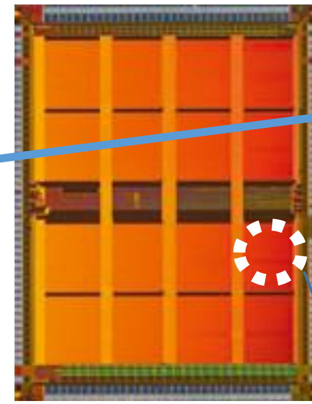
Roberts et al., Phys. Rev. 96, 1494 (1954).

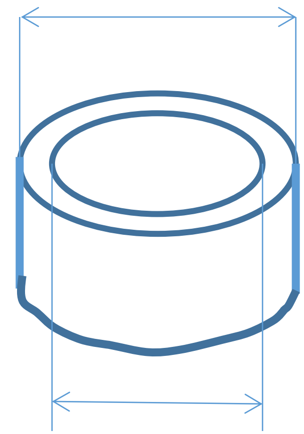


Zureks, Chris Vardon, Wikipedia, 2008.

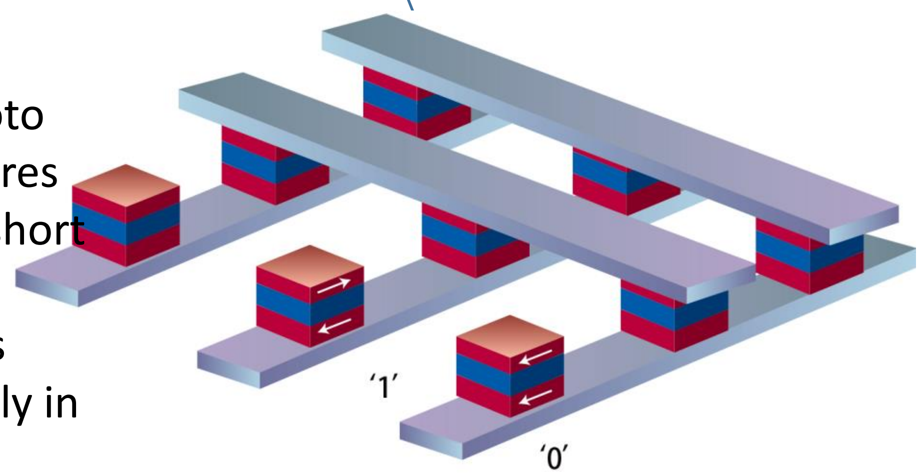
Domain Applications







Magnetoresistance Random Access Memory

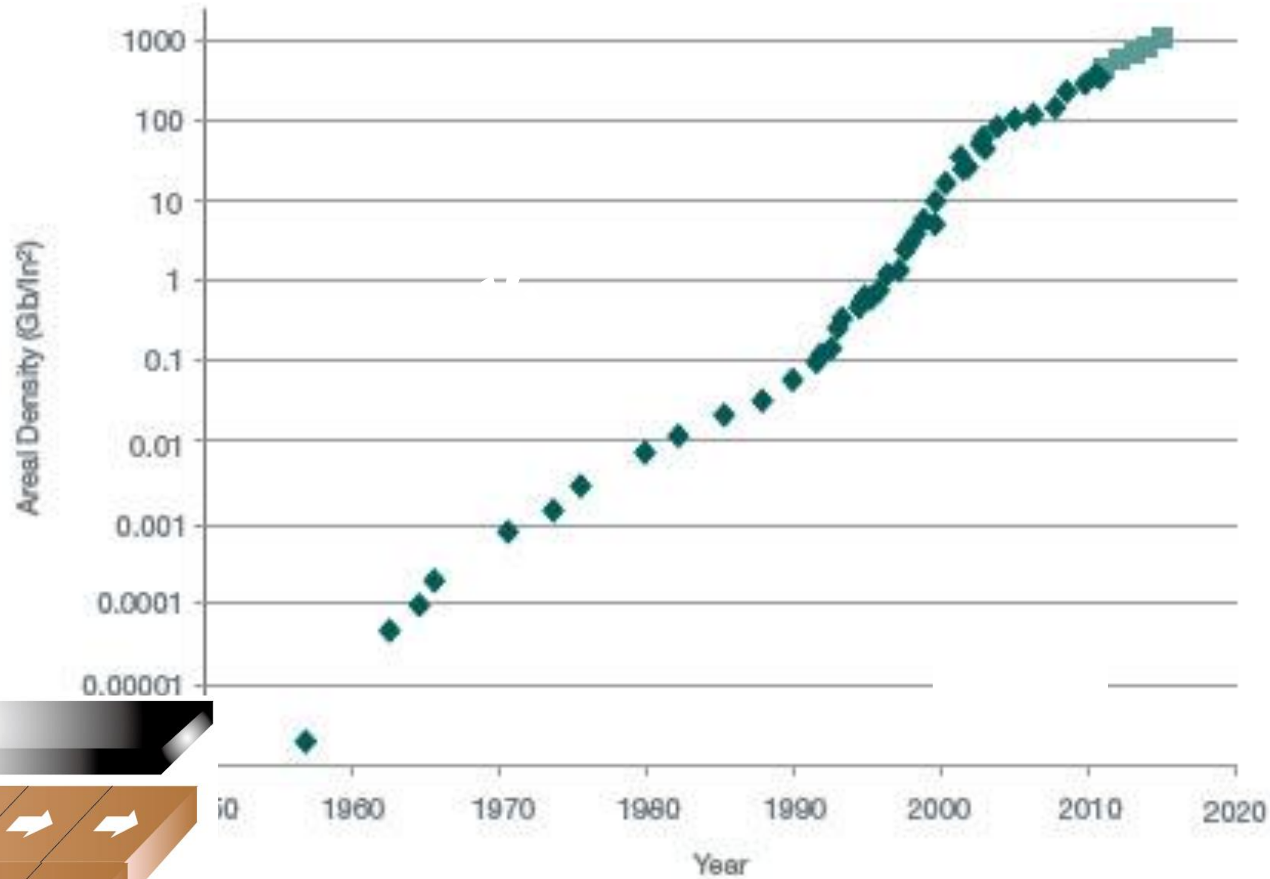


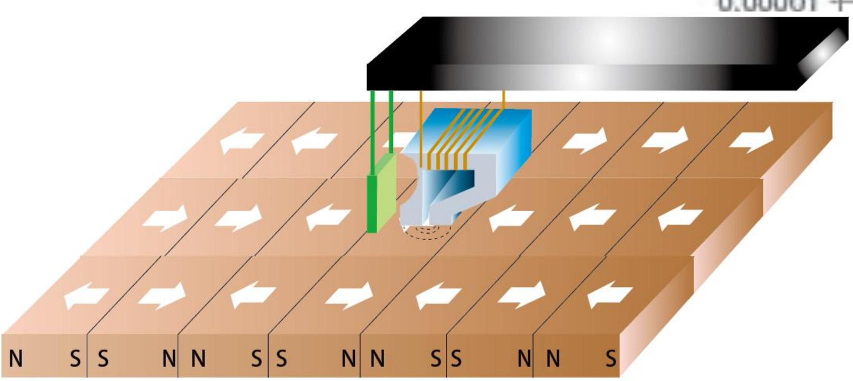
The 1st magnetic core memory, IBM 405 Alphabetical Accounting Machine. The photo shows the single drive lines through the cores in the long direction and fifty turns in the short direction. The cores are 150 mil inside diameter, 240 mil outside, 45 mil high. This experimental system was tested successfully in April 1952.

C. Chappert *et al*., Nat. Mater. **6**, 813 (2007).

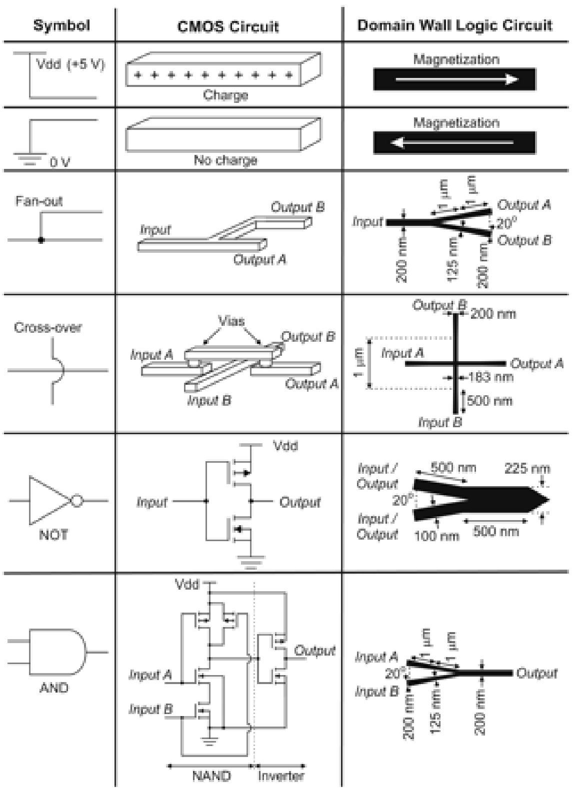
Applications

Hard Disk Drive



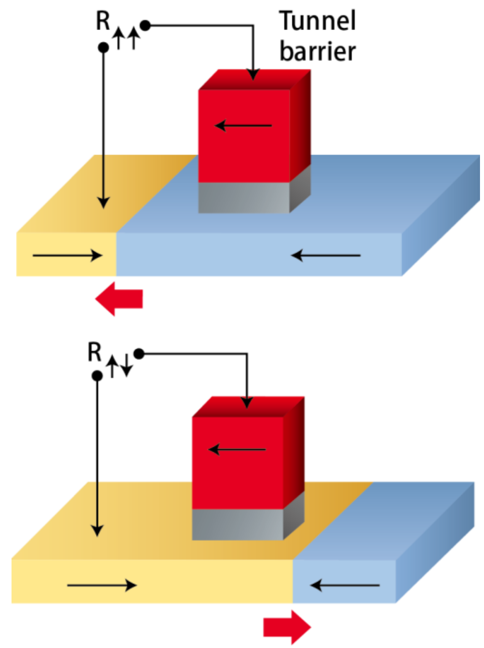


Domain Wall Propagation: Applications



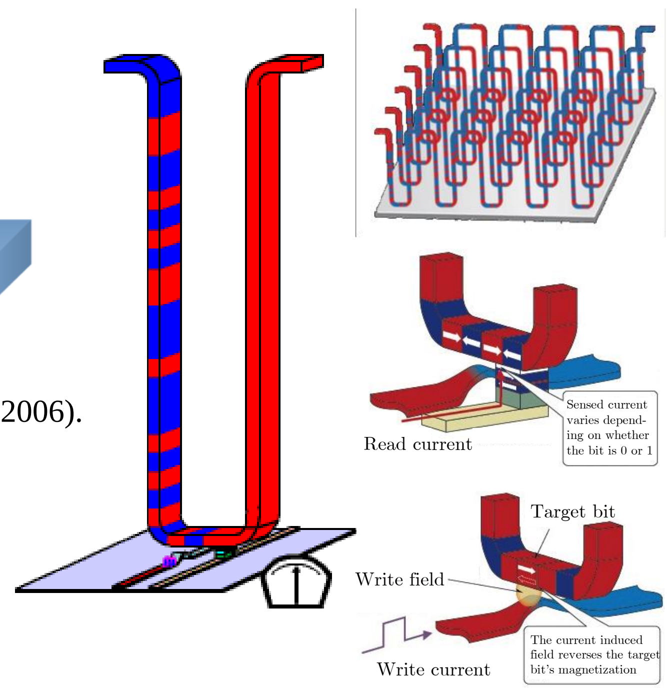
D. A. Allwood *et al.*, Science **309**, 1688 (2005).

DW Logic Circuit



Cros, V *et al.*, Patent WO, 064022 (2006).

DW-RAM



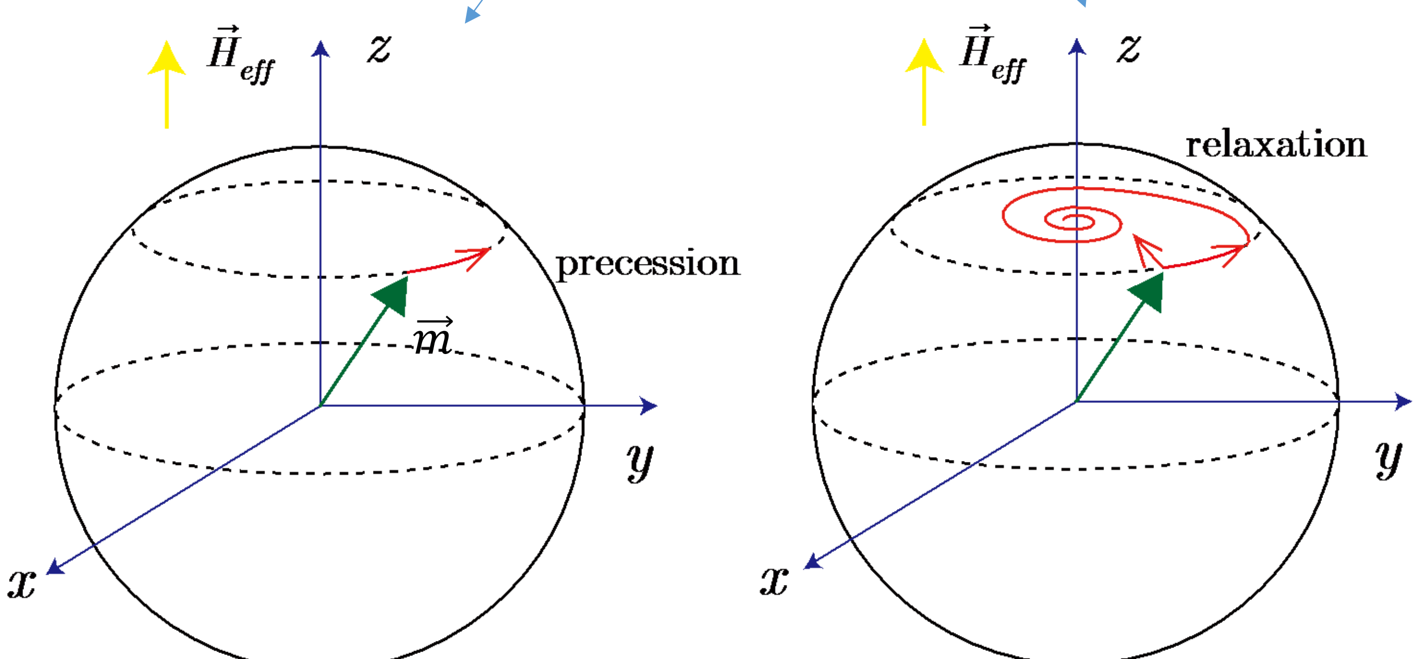
S. Parkin *et al.*, Science **320**, 190 (2008).

Racetrack Memory

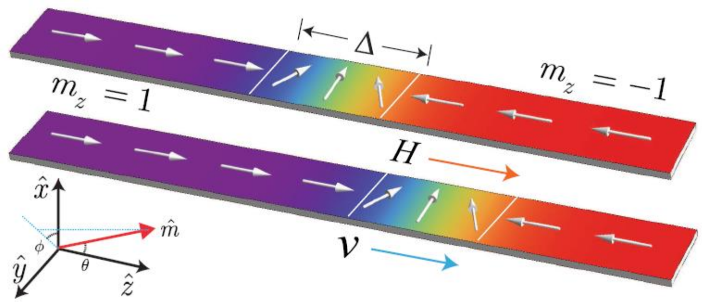
Landau-Lifshitz-Gilbert (LLG) Equation

$$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H}\Psi$$

$$\frac{\partial \vec{m}}{\partial t} = -\vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t}$$



Walker DW Solution of the LLG Eq.

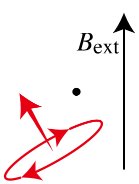


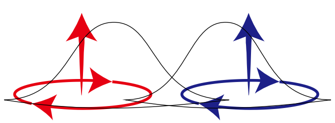
$$\frac{\partial \vec{m}}{\partial t} = -\vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t},$$

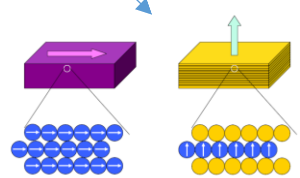
$$\theta\ \ z,t\ \ = 2\tan^{-1}\exp\left(\frac{z - vt}{\Delta}\right),$$

$$\phi = \pm\frac{\pi}{2} - \frac{1}{2}\sin^{-1}\frac{H}{H_c}.$$

$$\vec{H}_{eff} = H\,\hat{z} + A\frac{\partial^2}{\partial z^2}\vec{m} + K_{\|} m_z \hat{z} - K_{\perp} m_x \hat{x}$$

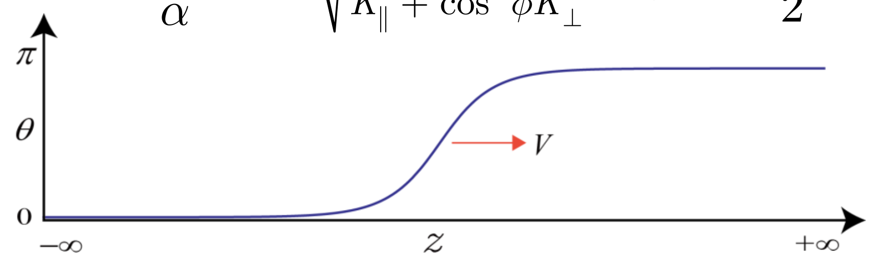






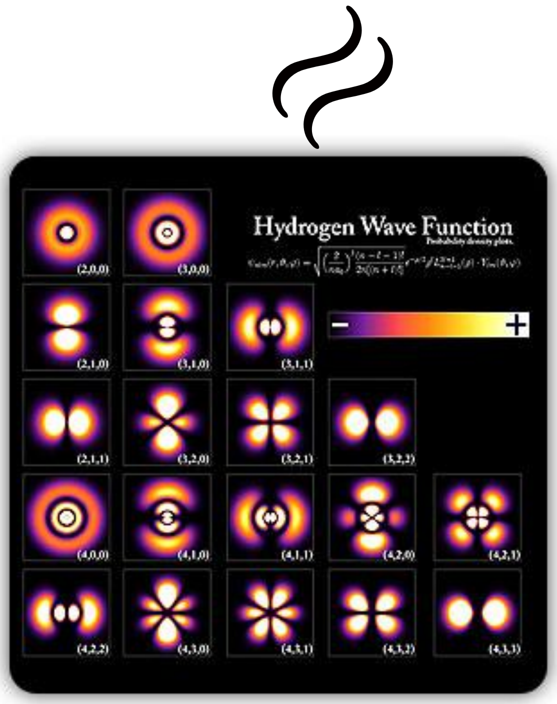
$\mathcal{E}_z$ $\mathcal{E}_e$ $\mathcal{E}_a$

$$v = \frac{\Delta H}{\alpha}, \Delta = \sqrt{\frac{A}{K_{\|} + \cos^2\phi K_{\perp}}}, H_c = \frac{\alpha K_{\perp}}{2}$$



L. R. Walker *et al.*, J. Appl. Phys. **45**, 5406 (1974).

The Walker DW Solution-A Starting Point!



Hydrogen Wave function

S. Zhang and Z. Li, "Roles of nonequilibrium conduction electrons on the magnetization dynamics of ferromagnets," *Physical Review Letters, vol. **93**, p. 127204, 2004.*

K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, *et al.*, *"Electrical switching of the vortex core in a magnetic disk," Nature materials, vol. **6**, pp. 270-273, 2007.*

D. Ralph and M. D. Stiles, "Spin transfer torques," *Journal of Magnetism and Magnetic Materials, vol. **320**, pp. 1190-1216, 2008.*

Z. Li and S. Zhang, "Domain-wall dynamics and spin-wave excitations with spin-transfer torques," *Physical review letters, vol. **92**, p. 207203, 2004.*

M. Hayashi, L. Thomas, C. Rettner, R. Moriya, and S. S. Parkin, "Direct observation of the coherent precession of magnetic domain walls propagating along permalloy nanowires," *Nature Physics, vol. **3**, pp. 21-25, 2006.*

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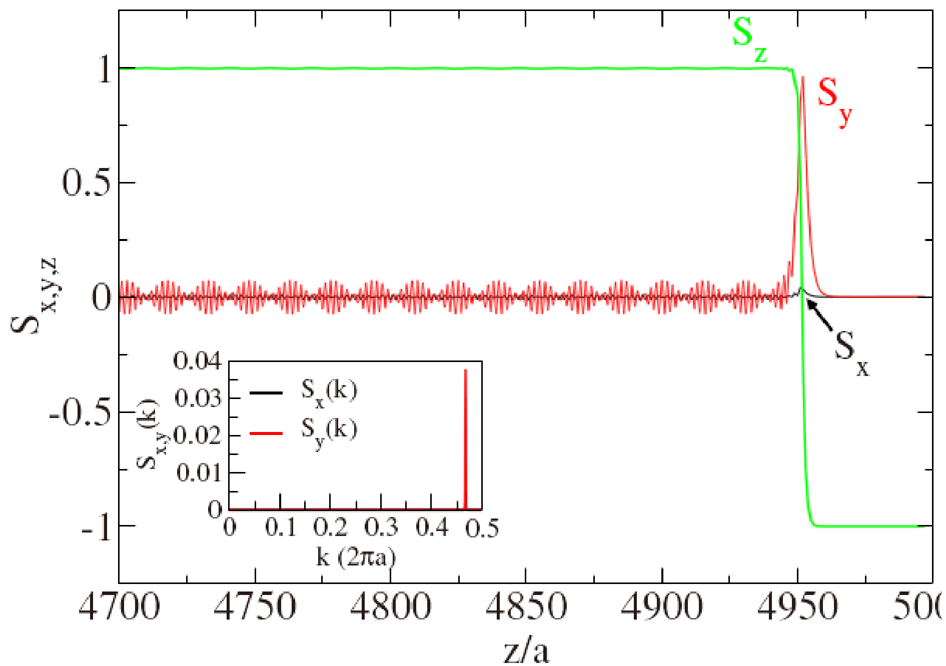
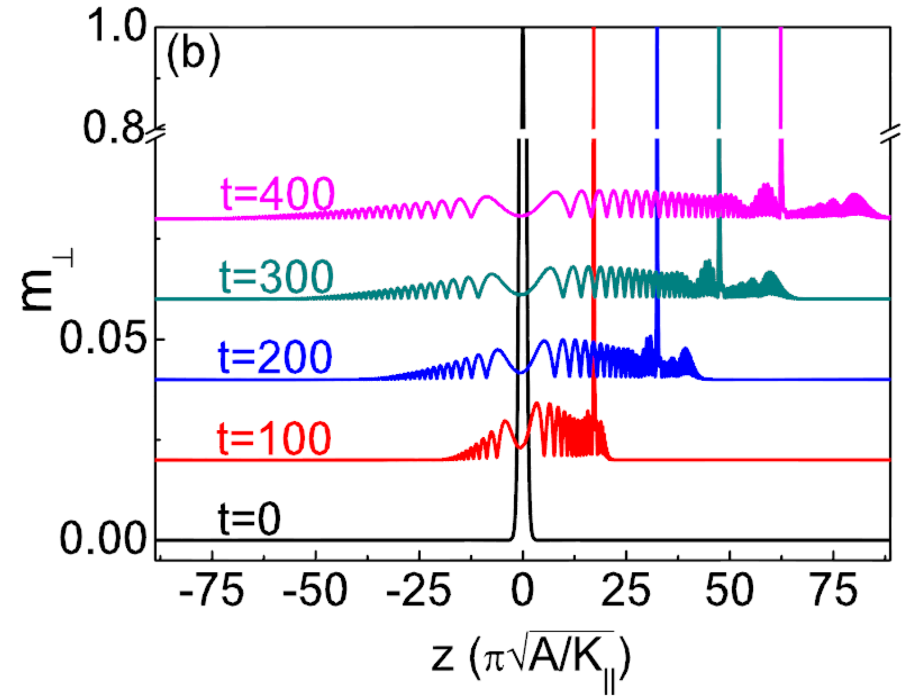
Issue:

Is the Walker Solution Stable?

Signs of Instability of Walker DW Mode



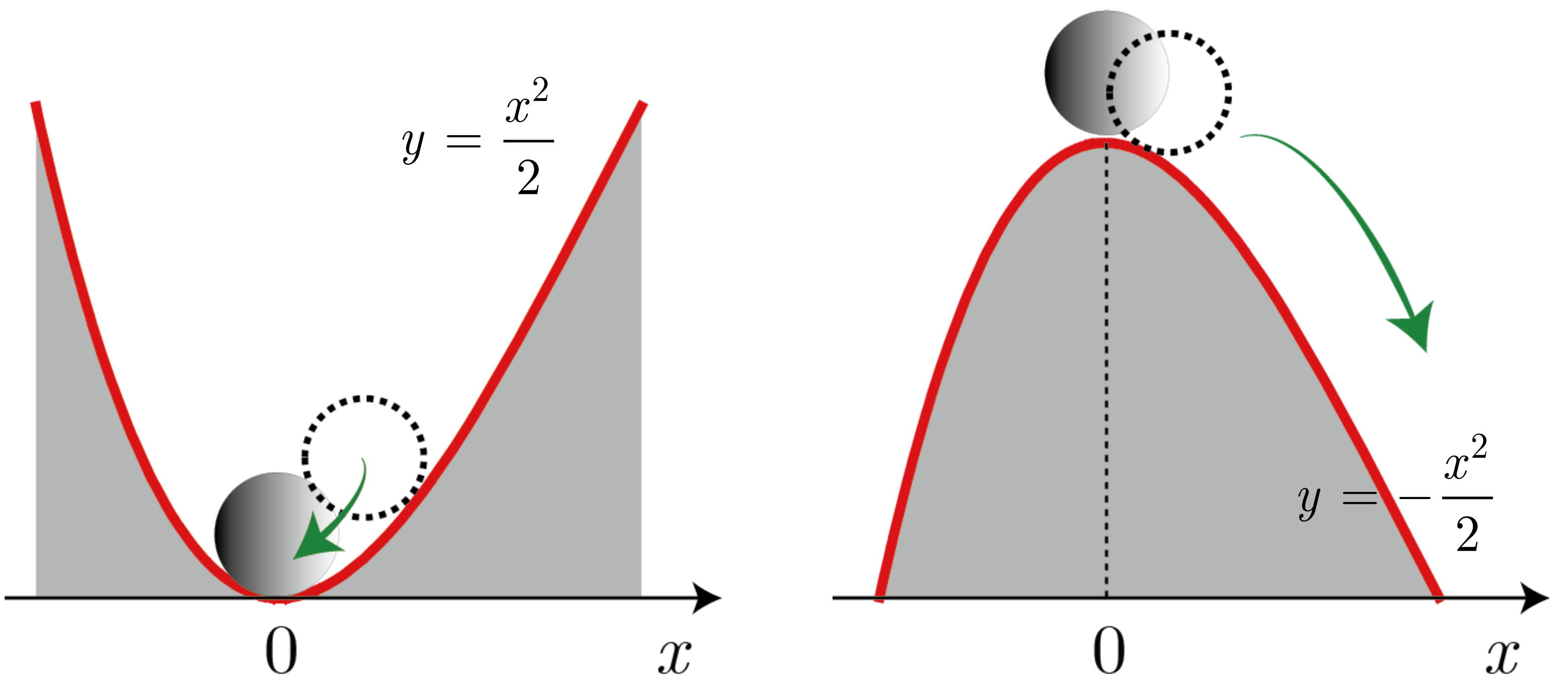
R. Wieser, et al. ,
Phys. Rev. B **81**, 024405 (2010).



X. S. Wang, *et al.*,
Phys. Rev. Lett. **109**, 167209 (2012).

Overlooked！ Attributed to Quasi-1D Nature

Issue: Instability of a Walker DW mode?



$$\ddot{x} = -x - \eta\dot{x},$$
$$x_0 = 0.$$

Stable

$$\ddot{x} = x - \eta\dot{x},$$
$$x_0 = 0.$$

Unstable

Stability Analysis Revisit

Linear ODE

$\dot{x} = Ax,$

$x \in R^n,\ A \in R^n \times R^n.$

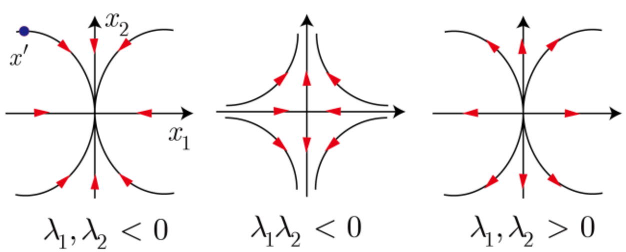
$\dot{x} = 0 \Rightarrow x_0 = 0$

eigenvalues of A

example:

$$A = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix},$$

$$x(\mathrm{t}) = \begin{pmatrix} e^{\lambda_1 t} & 0 \\ 0 & e^{\lambda_1 t} \end{pmatrix} x',\ x(0) = x'.$$



Stable Unstable

Nonlinear ODE

$\dot{x} = f(x),$

$x \in R^n,$

$\dot{x} = 0 \Rightarrow f(x_0) = 0,$

$\Downarrow \quad x \to x + \delta$

$\dot{\delta} = A' \cdot \delta,$

$A' = \nabla f(x)\,|_{x=x_0}\ .$

eigenvalues of A'

Nonlinear PDE ?

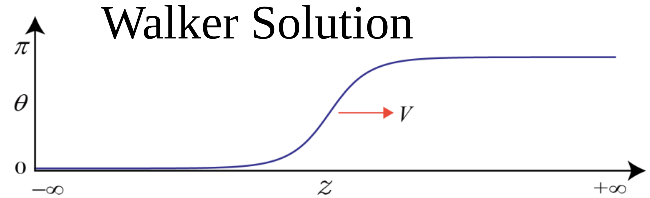
$LLG : \vec{m}(\mathrm{z}, \mathrm{t})$

$$\frac{\partial \vec{m}}{\partial t} = -\vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t},$$

$$\vec{H}_{eff} = H\,\hat{z} + A\frac{\partial^2}{\partial z^2}\vec{m} + K_{\parallel} m_z \hat{z} - K_{\perp} m_x \hat{x}$$

Recent Progress (2001) of Stability Analysis of Traveling Front

Walker Solution



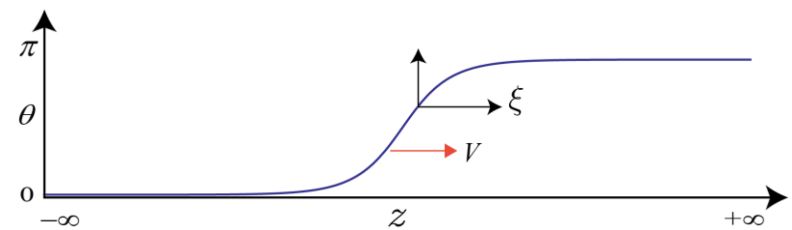
Lyapunov analysis

Modus Operandi: Linearization

$$\frac{\partial \vec{m}}{\partial t} = -\vec{m}\times\vec{H}_{eff} + \alpha\vec{m}\times\frac{\partial \vec{m}}{\partial t}, \quad \longleftrightarrow$$

$$\begin{aligned}\dot{\theta} - \alpha\sin\theta\dot{\varphi} &= -2K_{\perp}\sin\theta\sin\varphi\cos\varphi + 4A\theta'\varphi' \\ &\quad +2A\sin\theta\varphi'', \\ \sin\theta\dot{\varphi} + \alpha\dot{\theta} &= -2K_{\perp}\sin\theta\cos\theta\cos^2\varphi + 2K_{//}\sin\theta\cos\theta \\ &\quad + H\sin\theta + 2A\sin\theta\cos\theta\varphi'^2 - 2A\theta'',\end{aligned}$$

$$\sin 2\varphi_w = \frac{H}{H_c}, \quad \ln\tan\frac{\theta_w(z,t)}{2} = \frac{z-vt}{\Delta}. \quad \xrightarrow{\xi = z - vt} \quad \sin 2\varphi_w = \frac{H}{H_c}, \quad \ln\tan\frac{\theta_w(\xi)}{2} = \frac{\xi}{\Delta}.$$



$$\theta_w + \theta$$

$$\varphi_w + \varphi \quad \xrightarrow{\text{substitute with } \theta_w, \varphi_w} \quad LLG$$

$$|\,\theta\,|, |\,\varphi\,| \ll 1$$

expand w.r.t. θ, φ

keep only 1st terms

$$\frac{d\Lambda}{dt} = L_0\Lambda + L_1\frac{\partial\Lambda}{\partial\xi} + L_2\frac{\partial^2\Lambda}{\partial\xi^2}$$

$$\Lambda \equiv (\theta, \varphi)^T, \; L_{0,1,2}(\theta_w)$$

$$L_{0,11} = \frac{1}{1+\alpha^2}$$ [redacted]

$$L_{0,12} = \frac{K_\perp \sinh\xi}{1+\alpha^2}\left(-\sqrt{1-\rho^2} + \alpha\rho\tanh\xi\right)$$

$$L_{0,21} = \frac{1}{1+\alpha^2}$$ [redacted]

$$L_{0,22} = \frac{K_\perp}{1+\alpha^2}\left(\alpha\sqrt{1-\rho^2} + \rho\tanh\xi\right)$$

$G(\xi)$ is the Gudermannian function; $\rho = \frac{H}{H_c}$.

$$L_1 = \begin{pmatrix} v & -\dfrac{2A}{(1+\alpha^2)\cosh\xi} \\ 0 & v + \dfrac{2A\alpha}{1+\alpha^2} \end{pmatrix}$$

$$L_2 = \frac{1}{1+\alpha^2}\begin{pmatrix} A\alpha & -\dfrac{A}{\cosh\xi} \\ A\cosh\xi & A\alpha \end{pmatrix}$$

$$\frac{d\Lambda}{dt} = L_0\Lambda + L_1\frac{\partial\Lambda}{\partial\xi} + L_2\frac{\partial^2\Lambda}{\partial\xi^2},$$

$$\Lambda(\xi,\mathrm{t}) = \sum_i \mathrm{e}^{\lambda_i t}\,\Lambda_i(\xi).$$

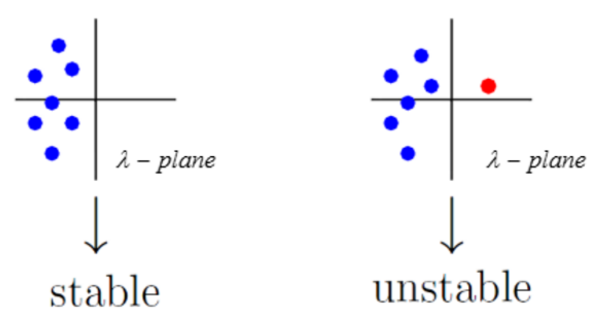
$$(L-\lambda_i)\Lambda_i = 0, \qquad *$$

$$L := L_0 + L_1\frac{\partial}{\partial\xi} + L_2\frac{\partial^2}{\partial\xi^2}.$$

Spectrum: any λ_i such that the equation (*) has nontrivial solution Λ_i

$$\text{iff}.\ \forall\lambda_i,\ \mathrm{Re}(\lambda) < 0:\ \textit{all}\ \Lambda \text{ exponentially decay} \rightarrow \text{stable}$$

$$\text{iff}.\ \exists\lambda_i,\ \mathrm{Re}(\lambda_i) > 0:\ \textit{some}\ \Lambda \text{ exponentially grows} \rightarrow \text{unstable}$$



In the 1st Order ODEs form:

$$(L - \lambda_i)\Lambda_i = 0, \quad *$$
$$L := L_0 + L_1 \frac{\partial}{\partial \xi} + L_2 \frac{\partial^2}{\partial \xi^2}.$$

$$\Rightarrow \quad \frac{d}{d\xi}\Lambda' = \Gamma(\lambda, \theta_w)\Lambda',$$

$$\Gamma(\lambda, \theta_w) = \begin{pmatrix} 0 & I \\ {L_2}^{-1}(\lambda - L_0) & -{L_2}^{-1}L_1 \end{pmatrix},$$

$$\Lambda' = (\theta, \varphi, \frac{\partial \theta}{\partial \xi}, \frac{\partial \varphi}{\partial \xi})^T$$

$$\mathrm{Spec}(\mathrm{L} - \lambda) \overset{iden.}{\Longleftrightarrow} \mathrm{Spec}[\frac{d}{d\xi} - \Gamma(\lambda, \theta_w)]$$

How to find (λ, Λ') for $\frac{d}{d\xi}\Lambda' = \Gamma(\lambda, \theta_w)\Lambda'$?

[redacted]

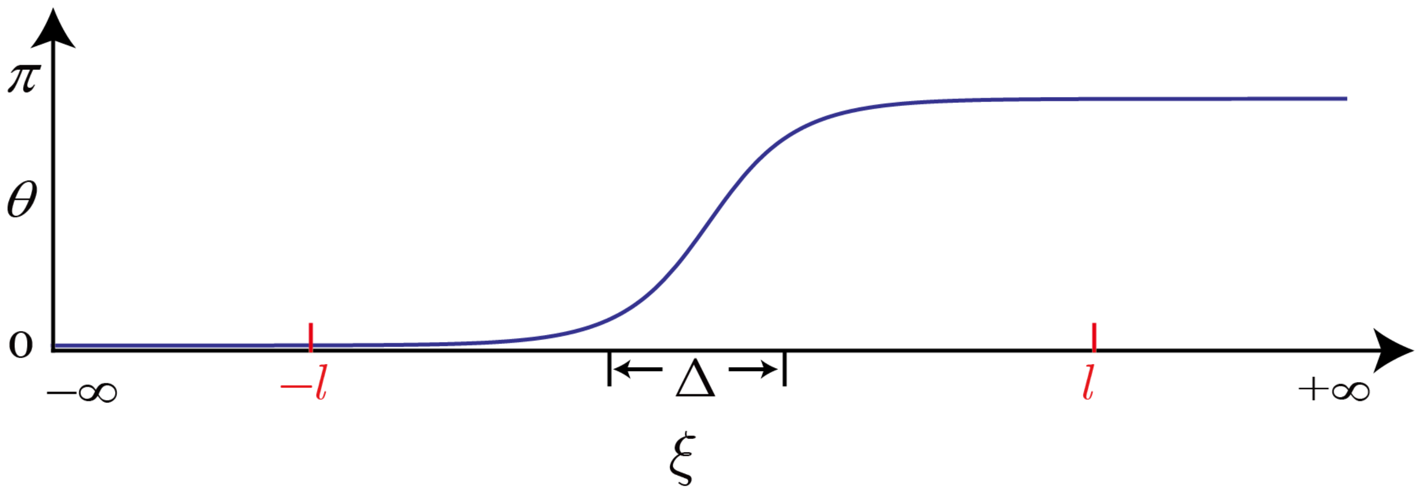
$$\Gamma = \begin{vmatrix} 0 & 0 & 0 & 1 \\ \Gamma_{31} & \dfrac{\lambda - K_{\perp}\rho\tanh\xi}{A\cosh\xi} & -\dfrac{v\alpha}{A} & -\dfrac{v}{A\cosh\xi} \end{vmatrix}$$

[redacted]

$$\Gamma_{31} = \frac{\alpha\lambda - H\tanh\xi}{A} - \frac{1}{2A}\;\; K_{\perp} - 2K_{\parallel} - K_{\perp}\sqrt{1-\rho^2}\;\; \cos\left[2G(\xi)\right]$$

$G(\xi)$ is the Gudermannian function; $\rho = \dfrac{H}{H_c}$.

Utilize the Property of a Front:



$$\theta_w(\xi) = 2\arctan e^{\frac{\xi}{\Delta}}.$$

$$\lim_{\xi\to\pm\infty}\theta_w = 0,\ \pi, \quad \Rightarrow \quad \lim_{\xi\to\pm\infty}\Gamma(\lambda,\theta_w) = \Gamma^{\pm}$$

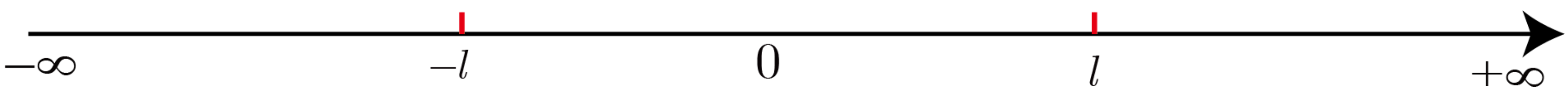
$$\Downarrow$$

$$\exists\, l \gg 1,\ \frac{d\Lambda'}{d\xi} = \Gamma\Lambda' \ \ is\ \frac{d\Lambda'}{d\xi} = \Gamma^{\pm}\Lambda' \ \ \text{for } |\xi| > l$$

Solve for Λ' (in principle)

Denote ([redacted]

λ can be classified by two inegers $n_+^{\pm}$ ($n_-^{\pm}$), denoting the number of $\kappa_i^{\pm}$ whose real part is positive (negative).



$\xi \in (-\infty, -l)$,

$$\frac{d\Lambda'}{d\xi} = \Gamma^- \Lambda',$$

$\& \ \Lambda' \ -l \ = \mu_i^-$,

$\Downarrow$

$$\Lambda_i'^- = \mu_i^- e^{\kappa_i^-(\xi + l)}.$$

$\xi \in (-l, 0)$,

$$\frac{d\Lambda'}{d\xi} = \Gamma \Lambda',$$

$\& \ \Lambda_i' \ -l \ = \mu_i^-$,

$\xi \in (0, l)$,

$$\frac{d\Lambda'}{d\xi} = \Gamma \Lambda',$$

$\& \ \Lambda_j' \ l \ = \mu_j^+$,

$\xi \in (l, \infty)$,

$$\frac{d\Lambda'}{d\xi} = \Gamma^+ \Lambda',$$

$\& \ \Lambda' \ l \ = \mu_j^+$,

$\Downarrow$

$$\Lambda_j'^+ = \mu_j^+ e^{\kappa_j^+(\xi - l)}.$$

for $|\xi| < l$, shoot towards 0 from $\xi = \pm l$,

with $\Lambda_i' \ \pm l \ = \mu_i^{\pm}$, denoted as $\widehat{\Lambda}_i^{\pm} \ \xi$.

Solve for Λ' (in principle)

$\Lambda'_{\mu_i^-}(\xi) = \mu_i^- e^{\kappa_i^-(\xi+l)}$, $\widehat{\Lambda}_i^-(\xi)$, $\widehat{\Lambda}_i^+(\xi)$, $\Lambda'_{\mu_i^+}(\xi) = \mu_i^+ e^{\kappa_i^+(\xi-l)}$,

$-\infty$ $\quad -l \quad 0 \quad l \quad$ $+\infty$

ξ

$$\lambda \in spec \Leftrightarrow \text{for } \lambda, \exists\, (a_i, b_j),\ s.t.$$

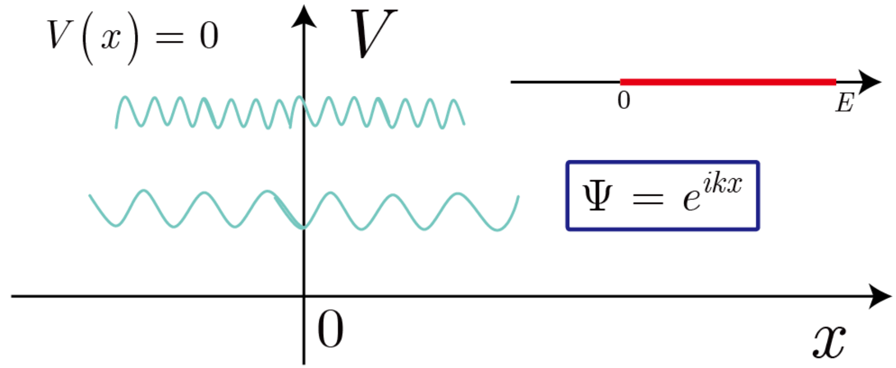
$$\sum_i a_i \widehat{\Lambda}_i^+(0) = \sum_j b_j \widehat{\Lambda}_j^-(0).$$

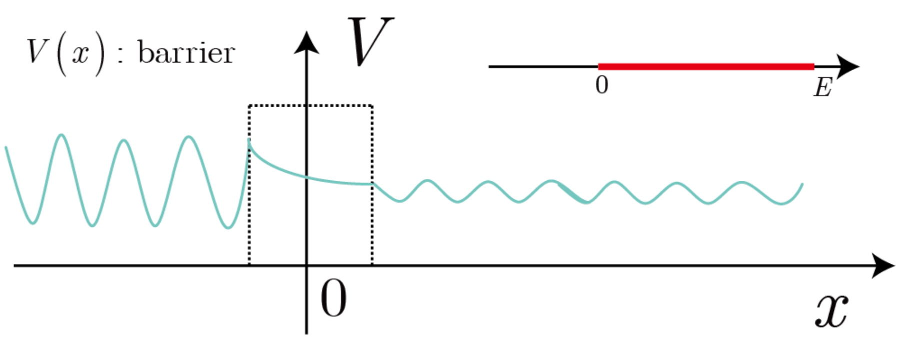
for each (a_i, b_j), $\Lambda'(\xi) = \begin{cases} \sum_i a_i \varsigma \widehat{\Lambda}_i^+(\xi) + \sum_i a_i (1-\varsigma)\Lambda_i'(\xi), & \xi \geq 0 \\ \sum_j b_j \varsigma \widehat{\Lambda}_i^-(\xi) + \sum_j b_j (1-\varsigma)\Lambda_j'^-(\xi). & \xi \leq 0 \end{cases}$ $\quad \varsigma = \begin{cases} 1, & |\xi| < l, \\ 0, & |\xi| > l. \end{cases}$

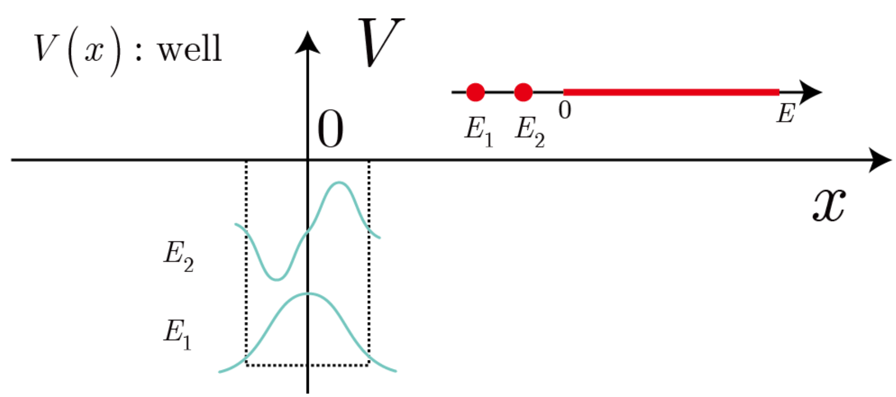
How to dodge the heavy workload in finding $\widehat{\Lambda}$?

A Clue from the Schrödinger Eq.

$$\left(-\frac{d^2}{dx^2}+V\left(x\right)\right)\Psi = E\Psi$$



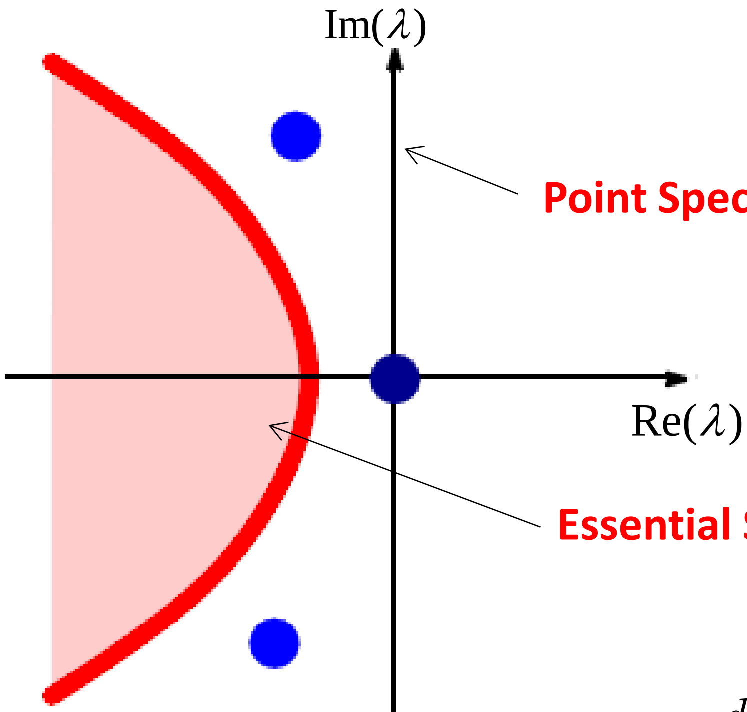




1 Spectrum can be decomposed into continum and discrete.

2 Local purterbation does not change the continum spectrum.

Decomposition of the Spectrum

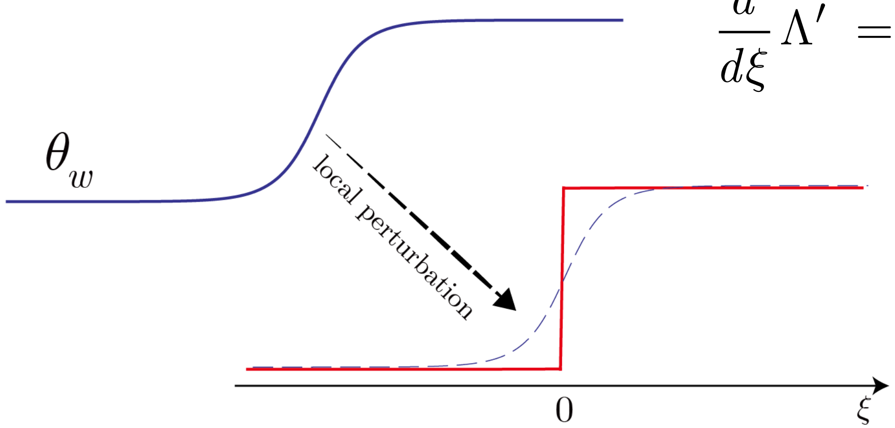


Point Spectrum: all Λ' for each λ, *s.t.* $\left\| L(\lambda)\Lambda' \right\| < \varepsilon$

expand finite dimensional space

Essential Spectrum: all Λ' for each λ, *s.t.* $\left\| L(\lambda)\Lambda' \right\| < \varepsilon$

expand infinite dimensional space



$$\frac{d}{d\xi}\Lambda' = \Gamma(\lambda,\theta_w)\Lambda', \xrightleftharpoons{\text{id. } \lambda_{ess}} \boxed{\begin{array}{l} \dfrac{d}{d\xi}\Lambda' = \Gamma^{\infty}\Lambda', \\ \Gamma^{\infty}\begin{cases} \Gamma^{+}, \xi > 0, \\ \Gamma^{-}, \xi < 0. \end{cases} \end{array}}$$

$$\lim_{\xi \to \pm\infty} \Gamma(\lambda,\theta_w) = \Gamma^{\pm}$$

Essential Spectrum of $d\Lambda' \,/\, d\xi = \Gamma^{\infty}\Lambda'$

$$\frac{d}{d\xi}\Lambda' = \Gamma(\lambda,\theta_w)\Lambda', \quad \overset{\text{identical } \lambda_{ess}}{\rightleftharpoons} \quad \frac{d}{d\xi}\Lambda' = \Gamma^{\infty}\Lambda'$$

$$\Downarrow \qquad\qquad\qquad \Downarrow$$

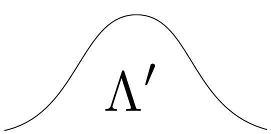
$$\sum_i a_i \widehat{\Lambda}_{\mu_i^+}(0) = \sum_j b_j \widehat{\Lambda}_{\mu_j^-}(0)$$

$$\boxed{\sum_i a_i \mu_i^+ = \sum_j b_j \mu_j^-}$$

n_-^+: number of κ^+ with $\mathrm{Re}(\kappa^+) < 0$,

n_+^-: number of κ^- with $\mathrm{Re}(\kappa^-) > 0$.

Example: $\sum_{i=1}^{n_-^+} a_i \mu_i^+ = \sum_{j=1}^{n_+^-} b_j \mu_j^-$,



$$a_1 \begin{pmatrix} \square \\ \square \\ \square \\ \square \end{pmatrix} + \dots + a_{n_-^+} \begin{pmatrix} \square \\ \square \\ \square \\ \square \end{pmatrix} = b_1 \begin{pmatrix} \square \\ \square \\ \square \\ \square \end{pmatrix} + \dots + b_{n_+^-} \begin{pmatrix} \square \\ \square \\ \square \\ \square \end{pmatrix}$$

$n_-^+ + n_+^- \Rightarrow$ number of variables

$4 \Rightarrow$ number of equations

$$n_-^+ + n_+^- \begin{cases} > 4 & \text{many solutions} \\ = 4 & \text{unique solution} \\ < 4 & \textit{no} \text{ solution} \end{cases}$$

Is λ_{ess} related with n_-^+ & n_+^- ?

Conclusion: $\lambda \in \lambda_{ess}$

$\Downarrow$

closed region on complex plane

$\Downarrow$

boundaries+inner area

two curves

$\lambda_{1,2}(\mathrm{k}) := \det[\Gamma^{\pm}(\lambda) - \mathrm{ik}] = 0$

$\Downarrow$

$\Lambda' \propto e^{ik\xi}$, plane wave

$$v_{1,2} = \mathrm{Im}\left(\frac{d\lambda_{1,2}(\mathrm{k})}{dk}\right)$$

$v > 0$ bow wave

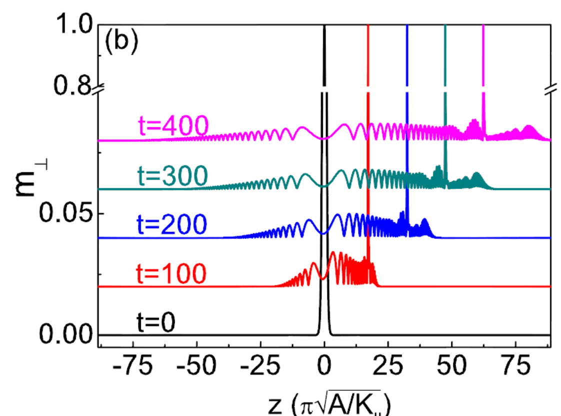
$v < 0$ stern wave

all λ, $s.t.\ n_-^+ + n_+^- \neq 4.$

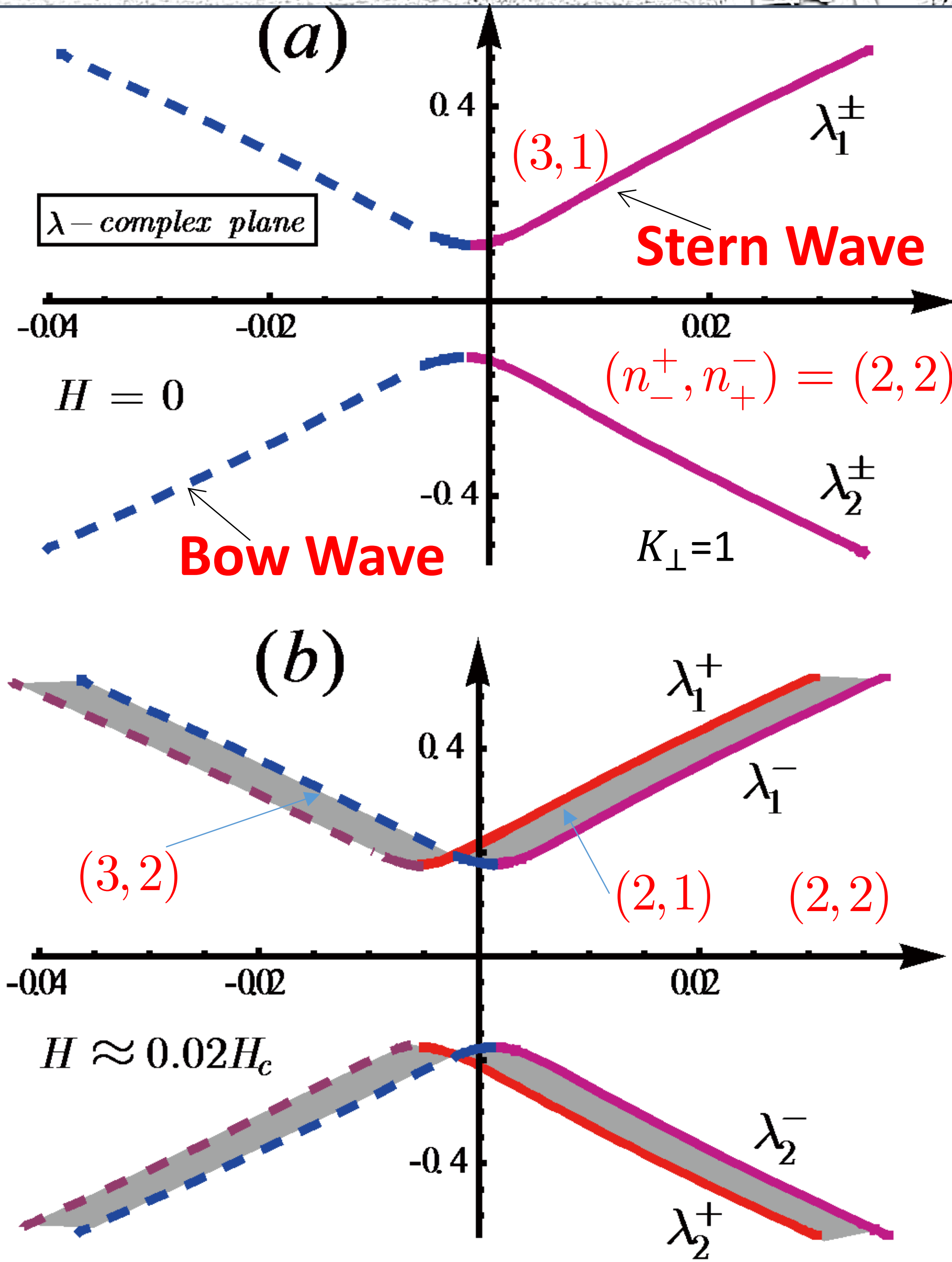
$\Downarrow$

a group of Λ', wave packet

YIG Parameter	
Damping	α =0.001
Exchange	A=3.84 $\times 10^{-12} J/m$
Saturation Magnetization	$M_s = 1.94 \times 10^5$ A/m
Gyromagnetic Ratio	γ=3.51 /kHz/(A/m)
Easy Axis Anisotropy	$K_{\parallel} = 2 \times 10^3 J/m^3$
Hard Axis Anisotropy	$K_{\perp} = 1$



X. S. Wang et al., Phys Rev Lett 109 167209 (2012).



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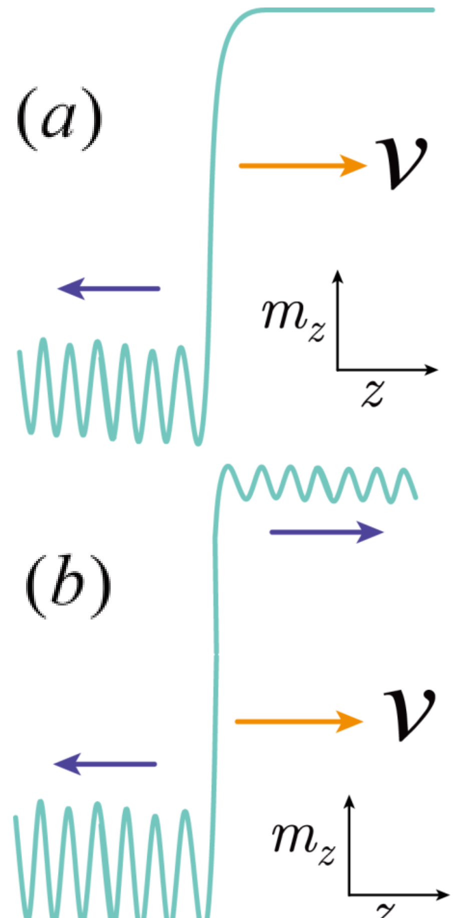
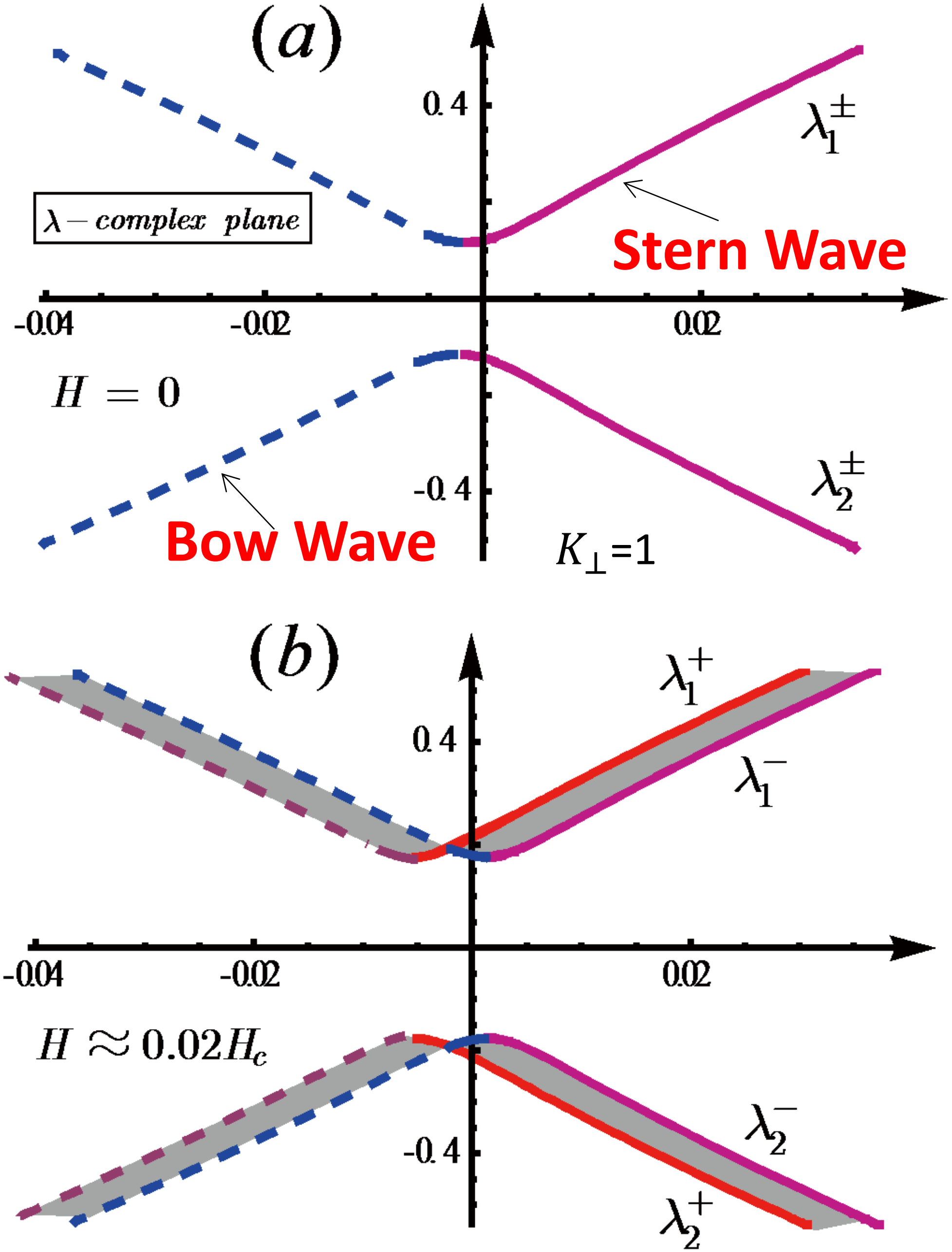
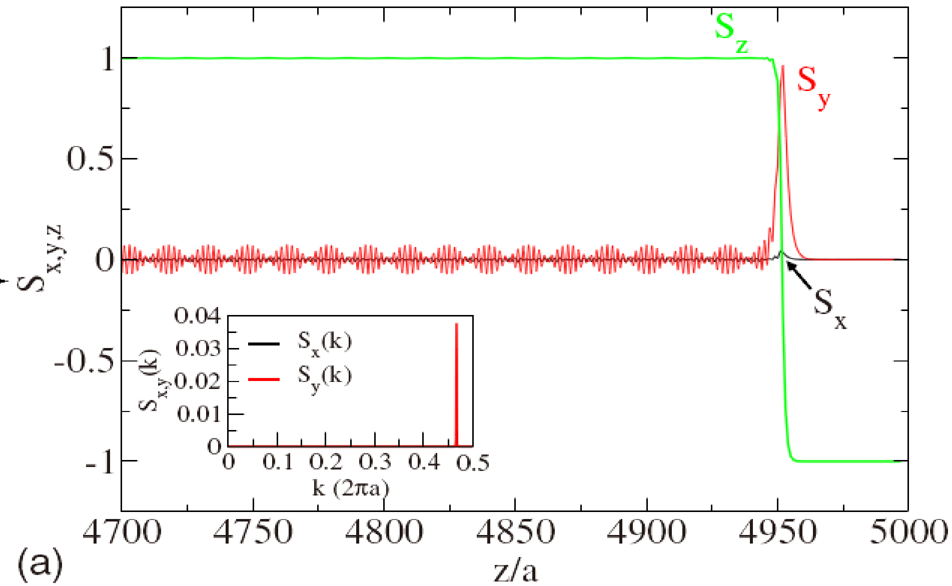
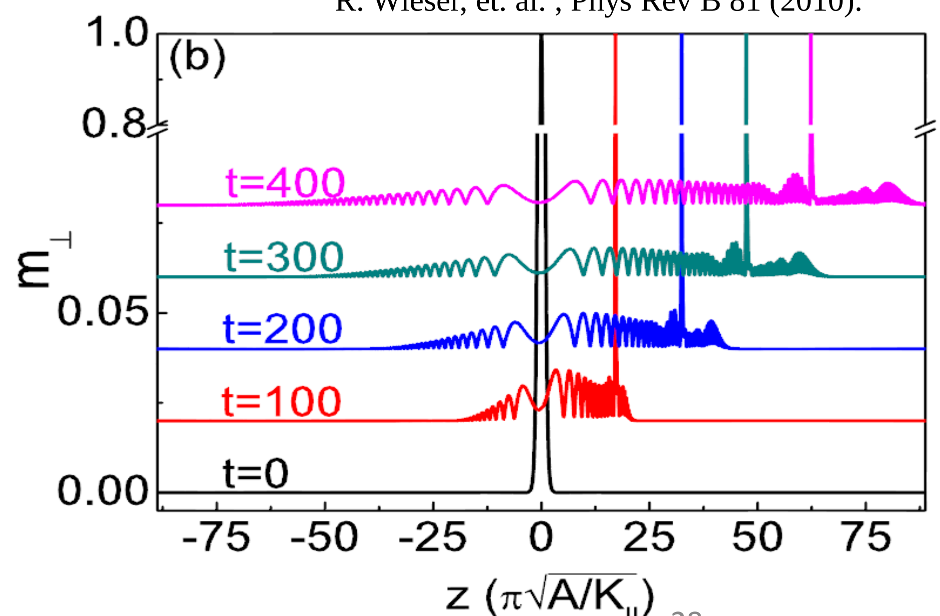




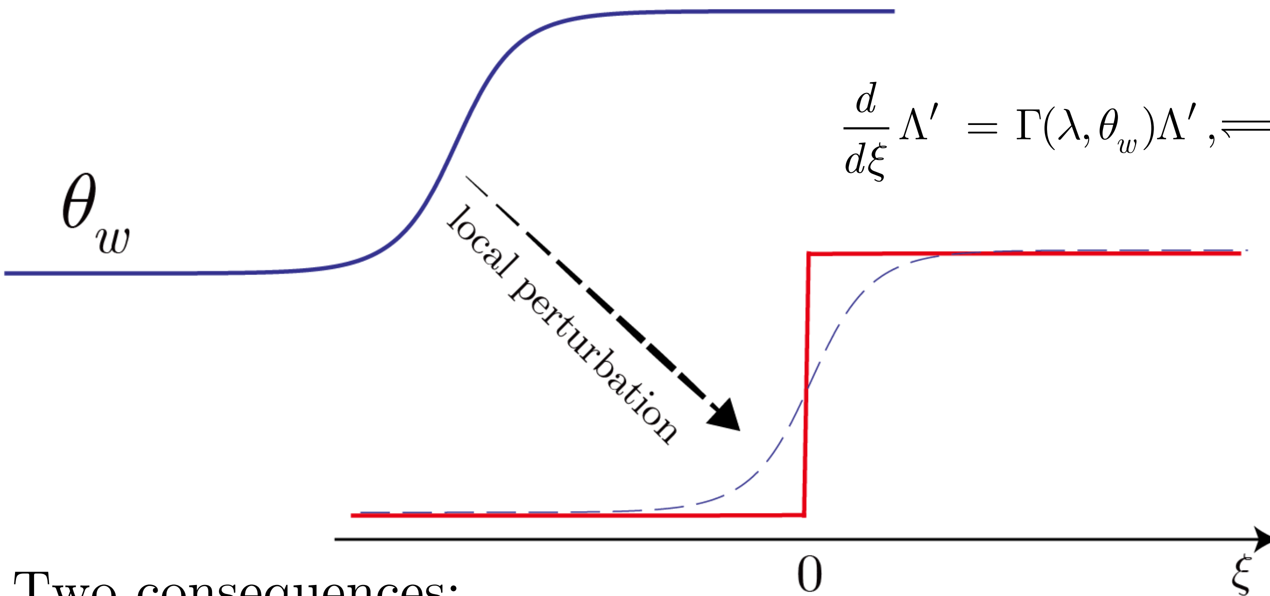


R. Wieser, et. al. , Phys Rev B 81 (2010).



X. S. Wang et al., Phys Rev Lett 109 167209 (2012).

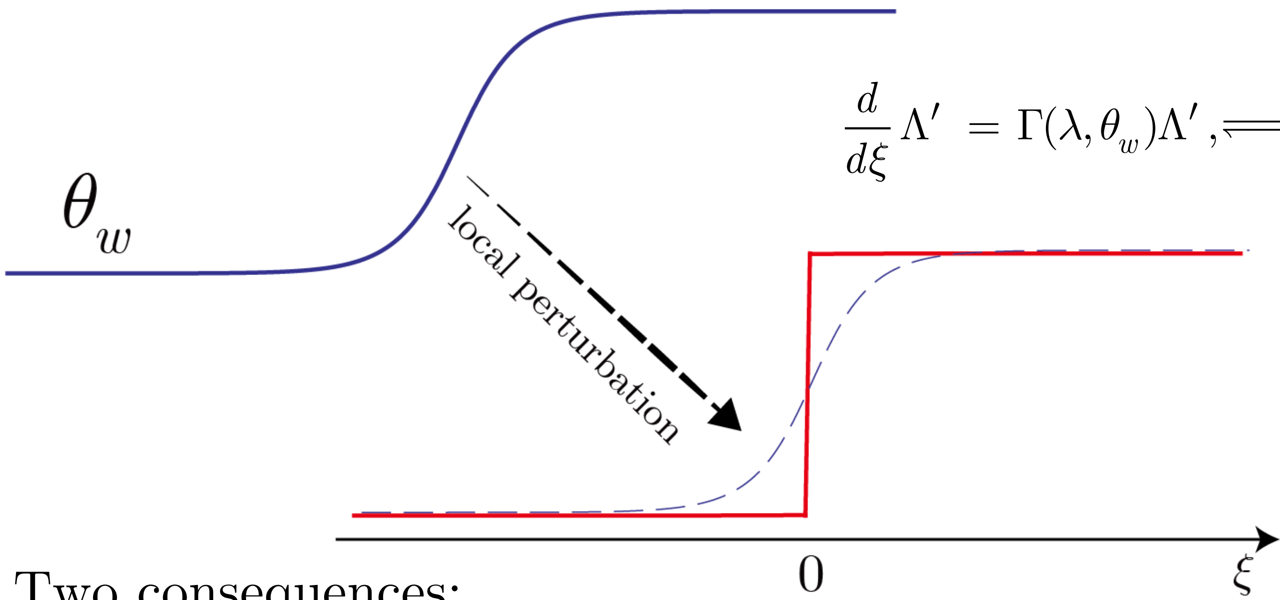
$$\frac{d}{d\xi}\Lambda' = \Gamma(\lambda,\theta_w)\Lambda', \xRightarrow{\text{id. } \lambda_{ess}} \frac{d}{d\xi}\Lambda' = \Gamma^{\infty}\Lambda',$$



Two consequences:

1 Spin wave emission is not sensitive to local deformation of DW profile.

2 Essential spectrum cannot capture instability of DW profile.



$$\frac{d}{d\xi}\Lambda' = \Gamma(\lambda,\theta_w)\Lambda' \,, \xrightarrow{\text{id. } \lambda_{ess}} \frac{d}{d\xi}\Lambda' = \Gamma^{\infty}\Lambda' \,,$$

Two consequences:

1 Spin wave emission is not sensitive to local deformation of DW profile.

2 Essential spectrum cannot capture instability of DW profile.

Why and how to capture DW's instability?

Many quantities, e.g. DW speed, are sensitive to profile deformation

growth rate λ ($e^{\lambda t}$), group velocity V, wave packet profile.

Absolute Spectrum

$$\lambda \in \lambda_{abs} \quad iff. \quad \mathrm{Re}(\kappa_2^+) = \mathrm{Re}(\kappa_3^+) \ or \ \mathrm{Re}(\kappa_2^-) = \mathrm{Re}(\kappa_3^-)$$

Consider: $\lambda \in$ branching set λ_{sd} $iff.$ $\kappa_2^+ = \kappa_3^+ \ or \ \kappa_2^- = \kappa_3^-$

branching set: λ_{sd}

$\Updownarrow$

nontraveling modes

Proof : $v = \mathrm{Im}[\frac{d\lambda(\kappa)}{d\kappa}]$

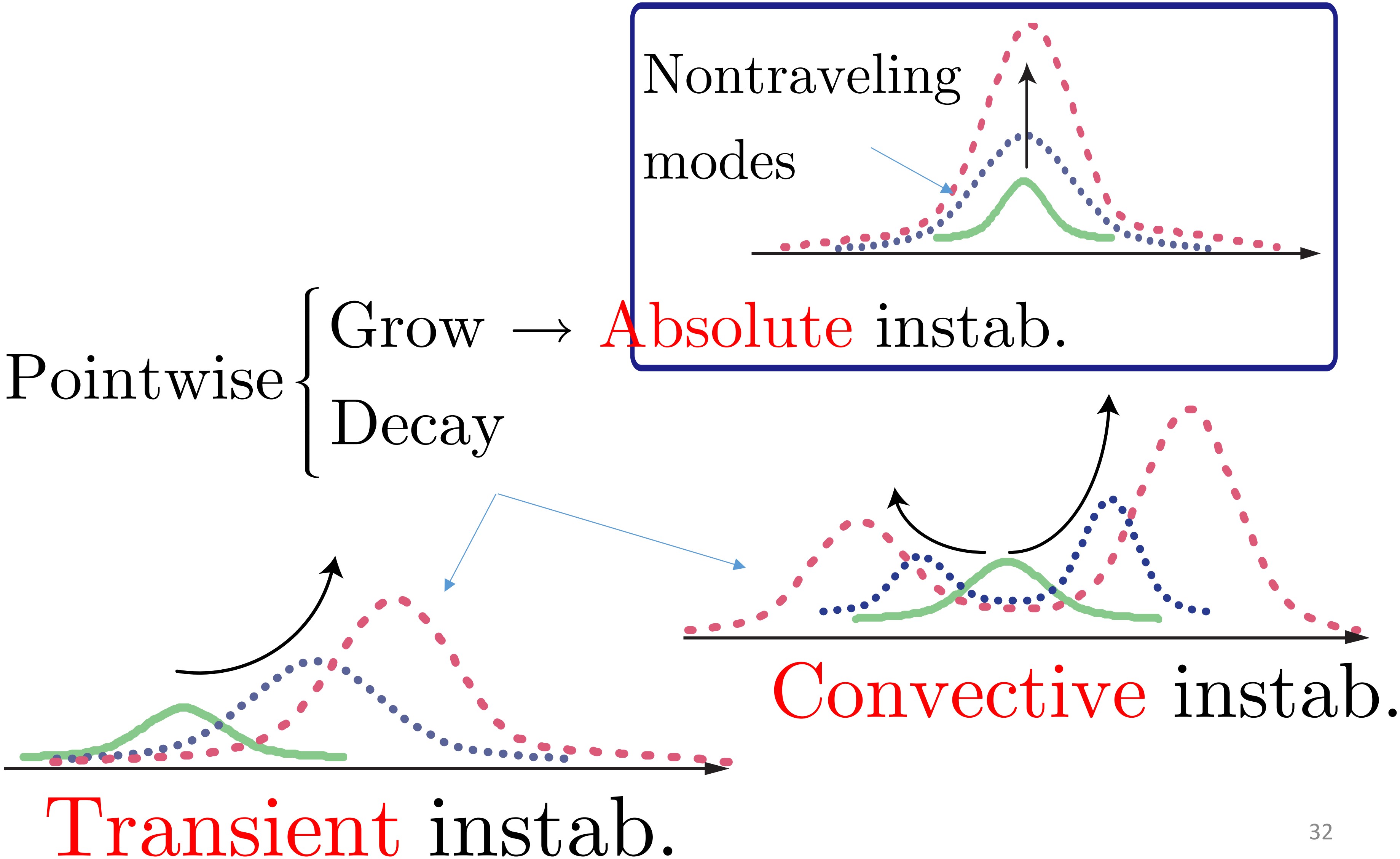
$$\frac{d\lambda}{d\kappa} = -\frac{\partial F(\lambda,\kappa)}{\partial \kappa} \Big/ \frac{\partial F(\lambda,\kappa)}{\partial \lambda}$$

$$\lambda \in Sd \Leftrightarrow \kappa_2 = \kappa_3 = \bar{\kappa}$$

$$F(\lambda,\kappa) \equiv \det(\Gamma(\lambda) - \kappa\,\mathrm{I})$$

$$F(\lambda_{sd},\kappa) = (\kappa - \bar{\kappa})^2(\kappa - \kappa_1)(\kappa - \kappa_4) \Rightarrow \frac{\partial F(\lambda,\kappa)}{\partial \kappa}\Big|_{\kappa=\bar{\kappa},\ \lambda=\lambda_{sd}} = 0 = v!$$

Classifications of Instabilities with Unstable λ_{ess}

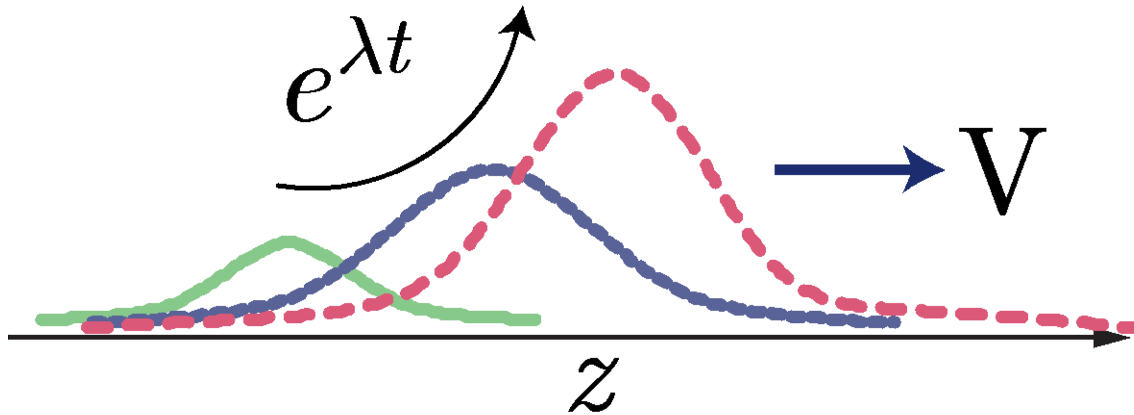


An Example:

growth rate λ ($e^{\lambda t}$),

group velocity V,

wave packet profile.



$$\Lambda(z,t) = e^{\lambda t} sech(z - vt)$$

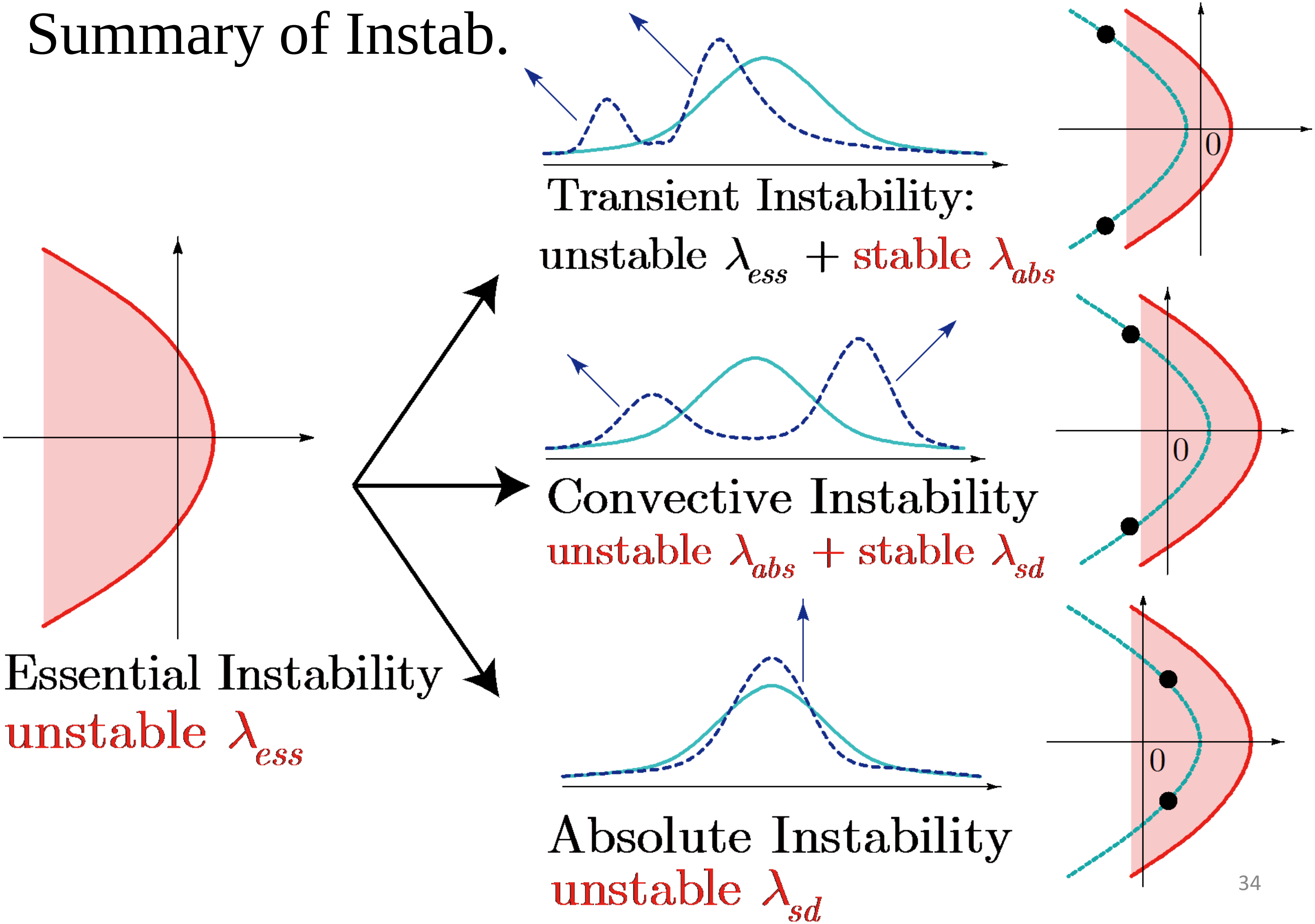
$\forall$ fixed z_0,

$$\lim_{t \to \infty} \Lambda(z_0) = \begin{cases} 0, & \text{if V} > \text{Re}(\lambda) \to p.w. \text{ decay} \\ \infty. & \text{if V} < \text{Re}(\lambda) \end{cases}$$

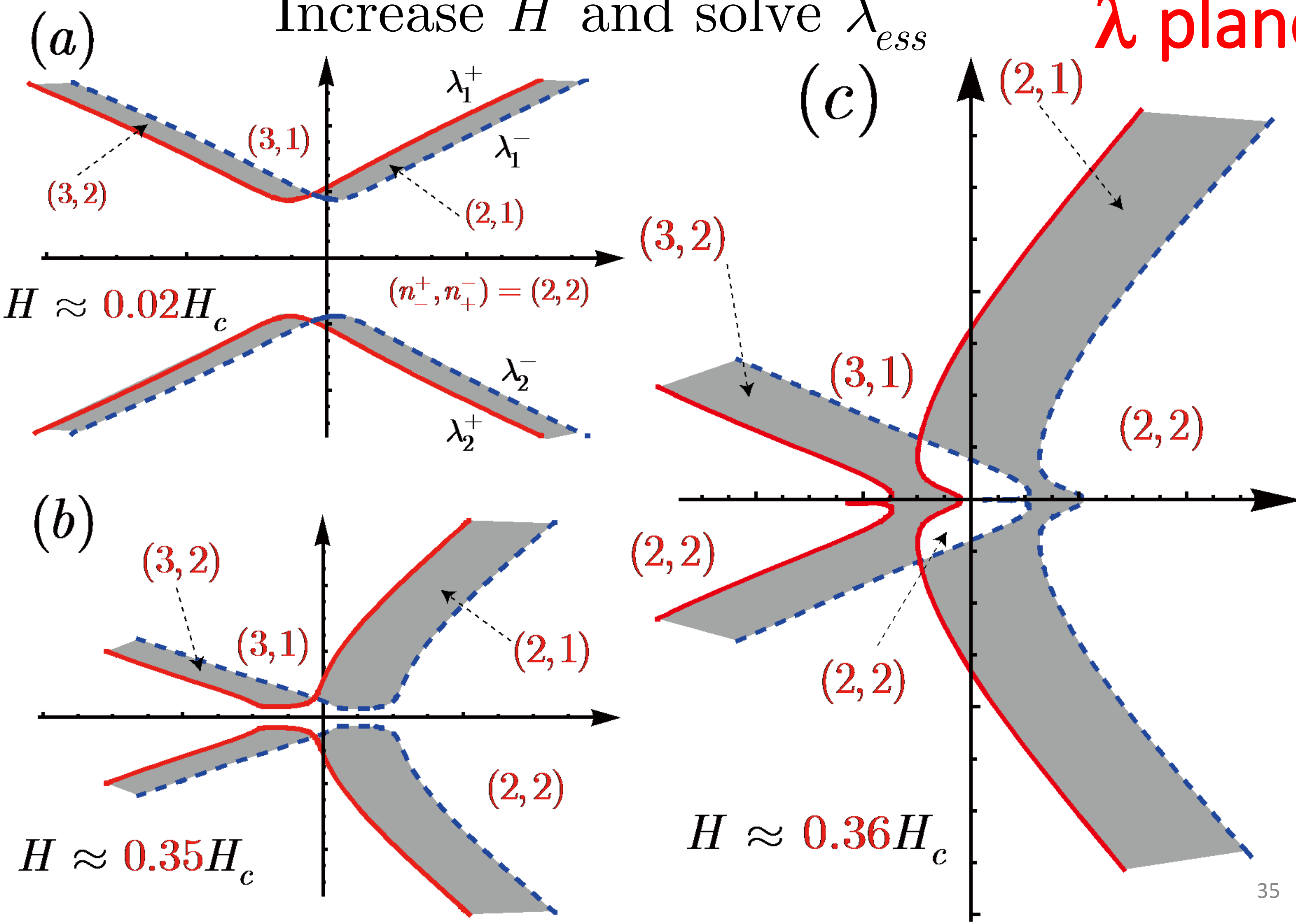
$$\downarrow$$

$p.w.$ growth

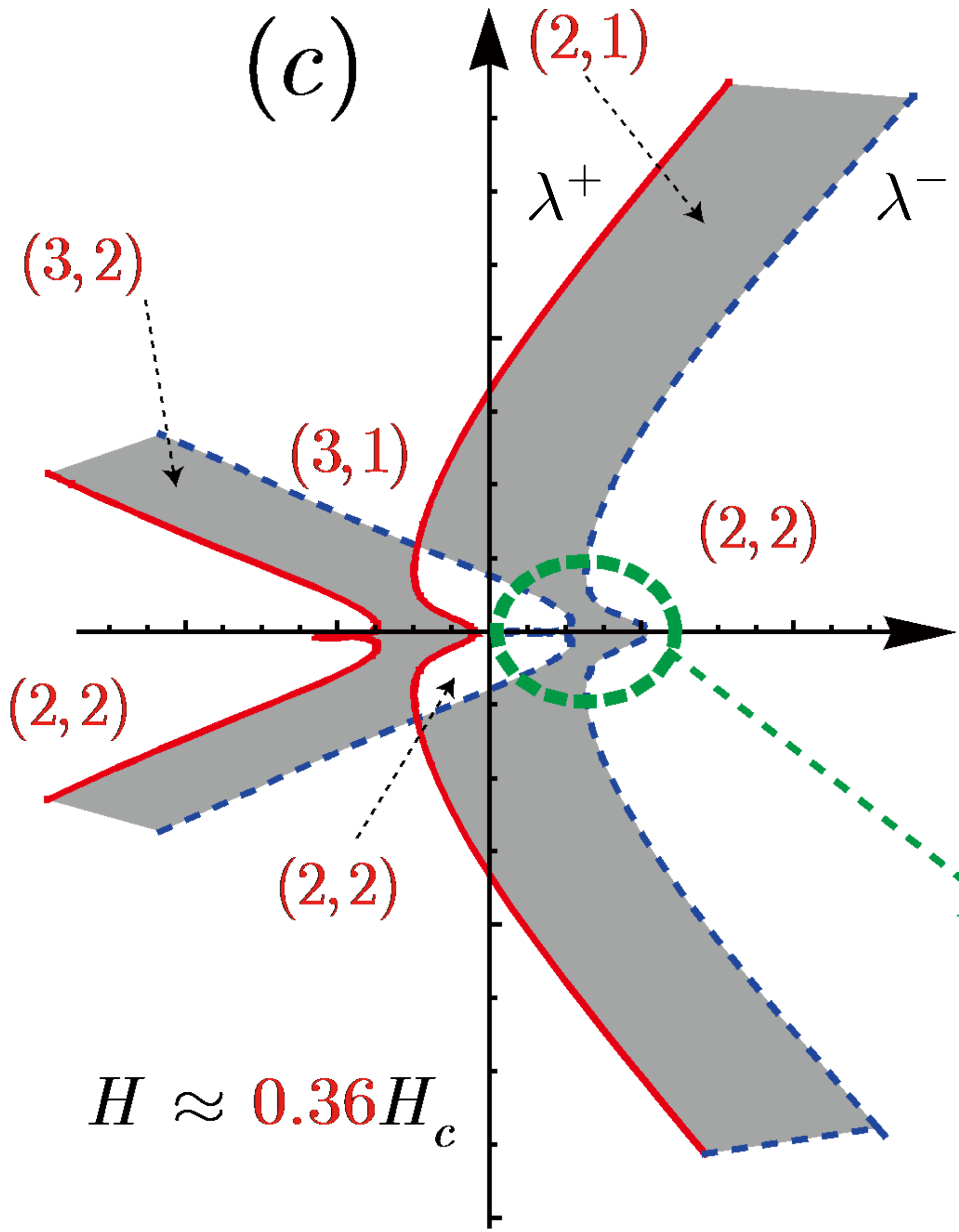
Summary of Instab.



Increase H and solve λ_{ess} **λ plane**

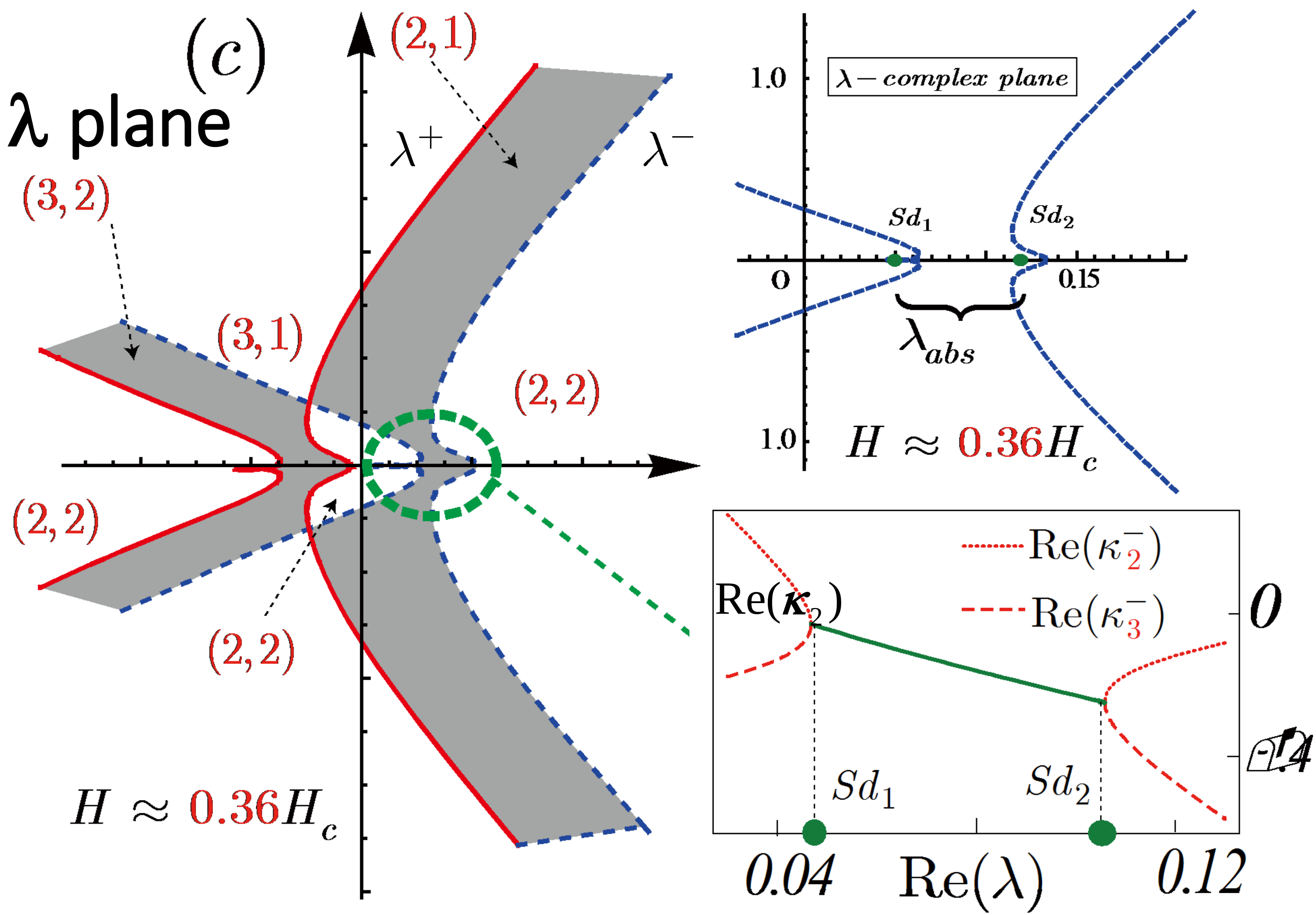


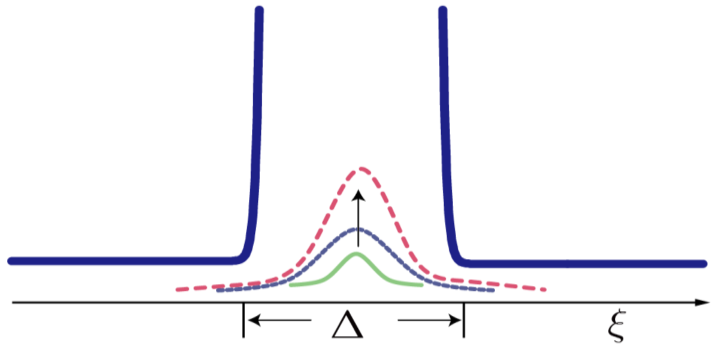
λ plane



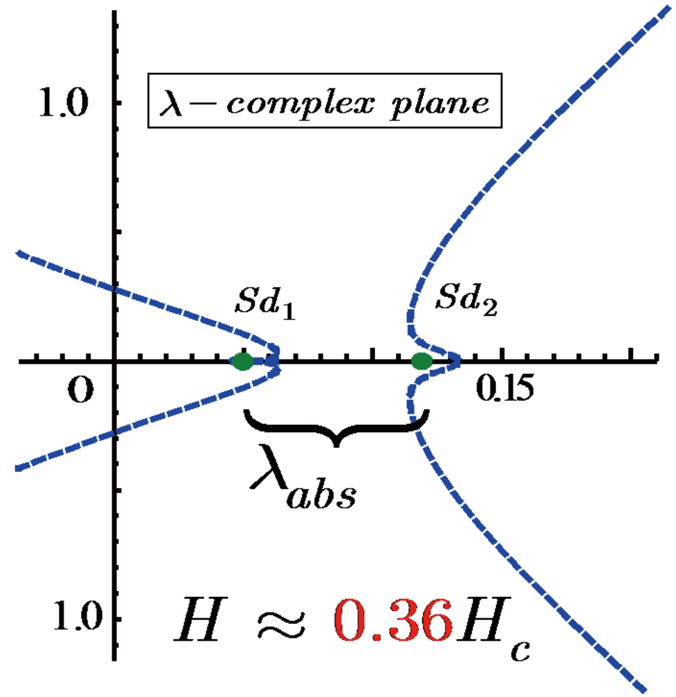
No λ_{abs} found for H<H$_a$ $\approx 0.36H_c$, Transient Ins.

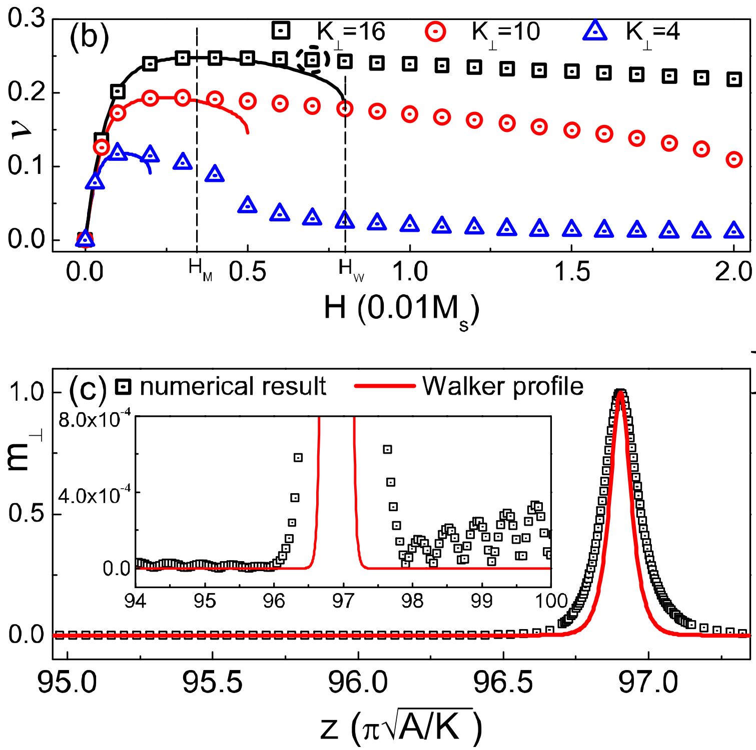
λ_{abs} emerges if H>H$_a$ $\approx 0.36H_c$

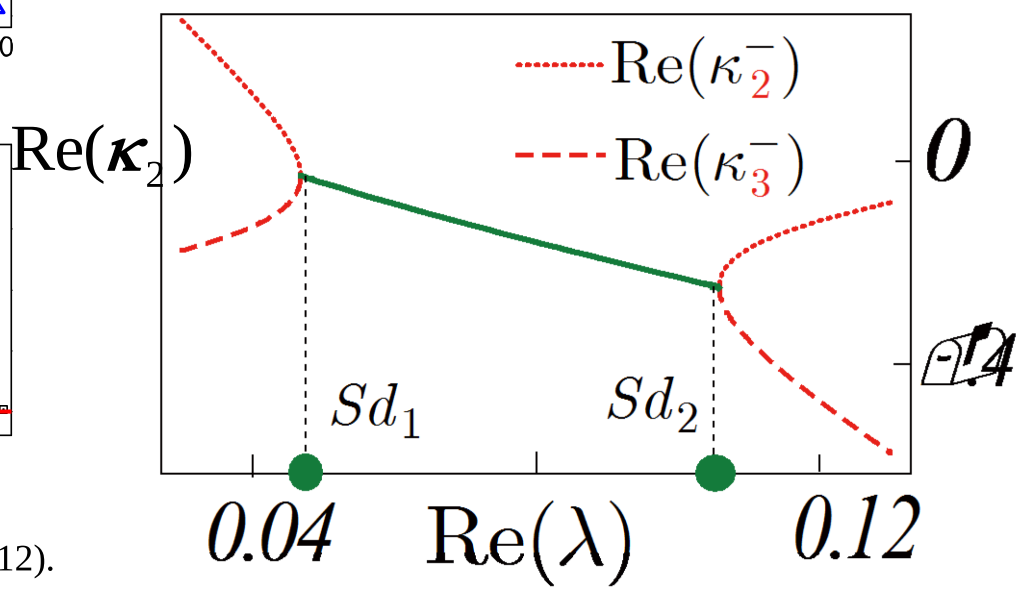

(c)
λ plane
(2,1)
λ+
λ−
(3,2)
(3,1)
(2,2)
(2,2)
(2,2)
H ≈ 0.36Hc
λ− complex plane
1.0
Sd1
Sd2
0
0.15
λabs
1.0
H ≈ 0.36Hc
Re(κ2−)
Re(κ3−)
Re(κ2)
0
Sd1
Sd2
0.04
Re(λ)
0.12



AI/CI occurs at H_a







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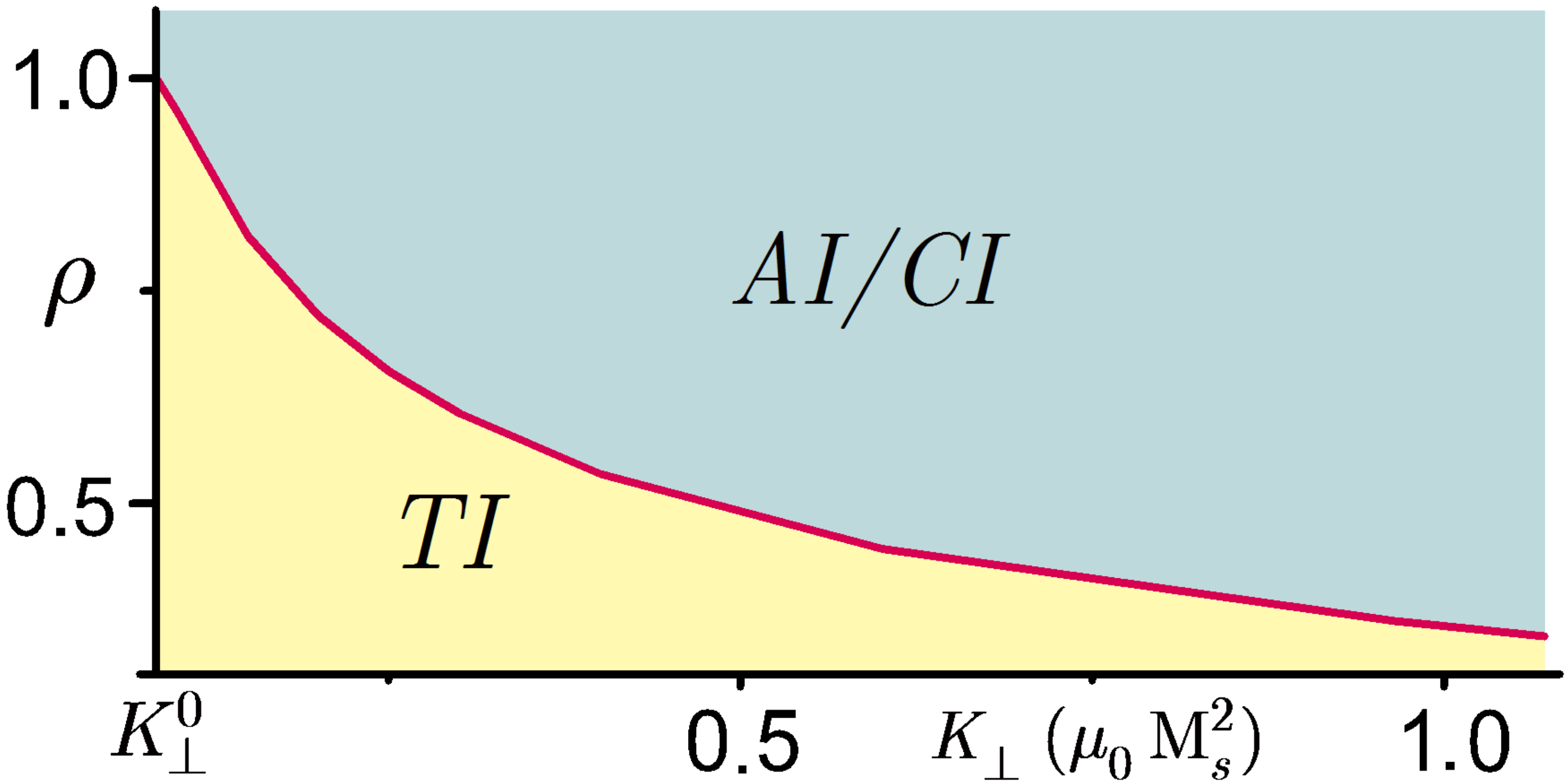
Gyromagnetic Ratio	γ=3.51 /kHz/(A/m)
Easy Axis Anisotropy	$K_{\parallel} = 2 \times 10^3\, J/m^3$
Hard Axis Anisotropy	$K_{\perp}$: Varying

$$\rho = H_a \,/\, H_c,$$
$$\rho = 1\ at,$$
$$K_{\perp}^0 \approx 0.085$$



Conclusion

- It is shown that a Walker propagating DW will always emit stern waves in a low field, and both stern and bow waves in a higher field.
- The true propagating DW is always dressed with spin waves.
- For a realistic wire with its transverse magnetic anisotropy larger than a critical value and when the applied external field is large enough, a propagating DW may undergo simultaneous convective and absolute instabilities, leading to DW deformation and velocity deviation.