

A CPS1-Driven Market for the Frequency Control Contribution of Inadvertent Interchange

presented to

Inadvertent Interchange Payback Taskforce

North American Energy Standards Board

by Robert Blohm

Austin

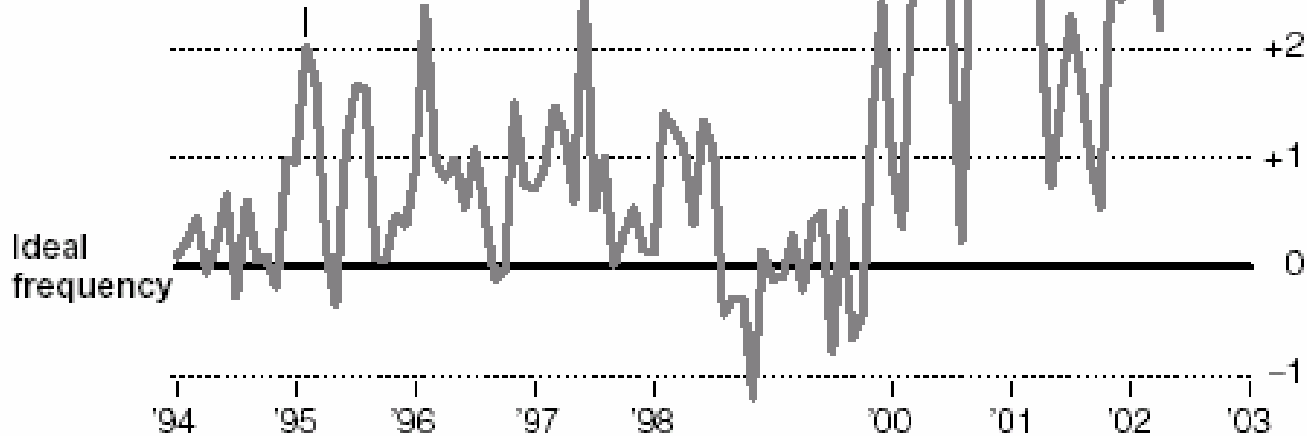
September 15/16, 2003

From *The New York Times*, August 19, 2003

Increased Grid Stress

An indicator of how well a grid is operating is the stability of the frequency at which it transmits energy — 60 cycles per second, or 60 hertz, is the norm. Since 1999 the average deviation from that frequency has been increasing in the East toward the danger threshold: 18 thousandths of a hertz above the norm. If this continues, the possibility of blackouts could increase as well.

Monthly average deviation from ideal frequency
in thousandths of a hertz

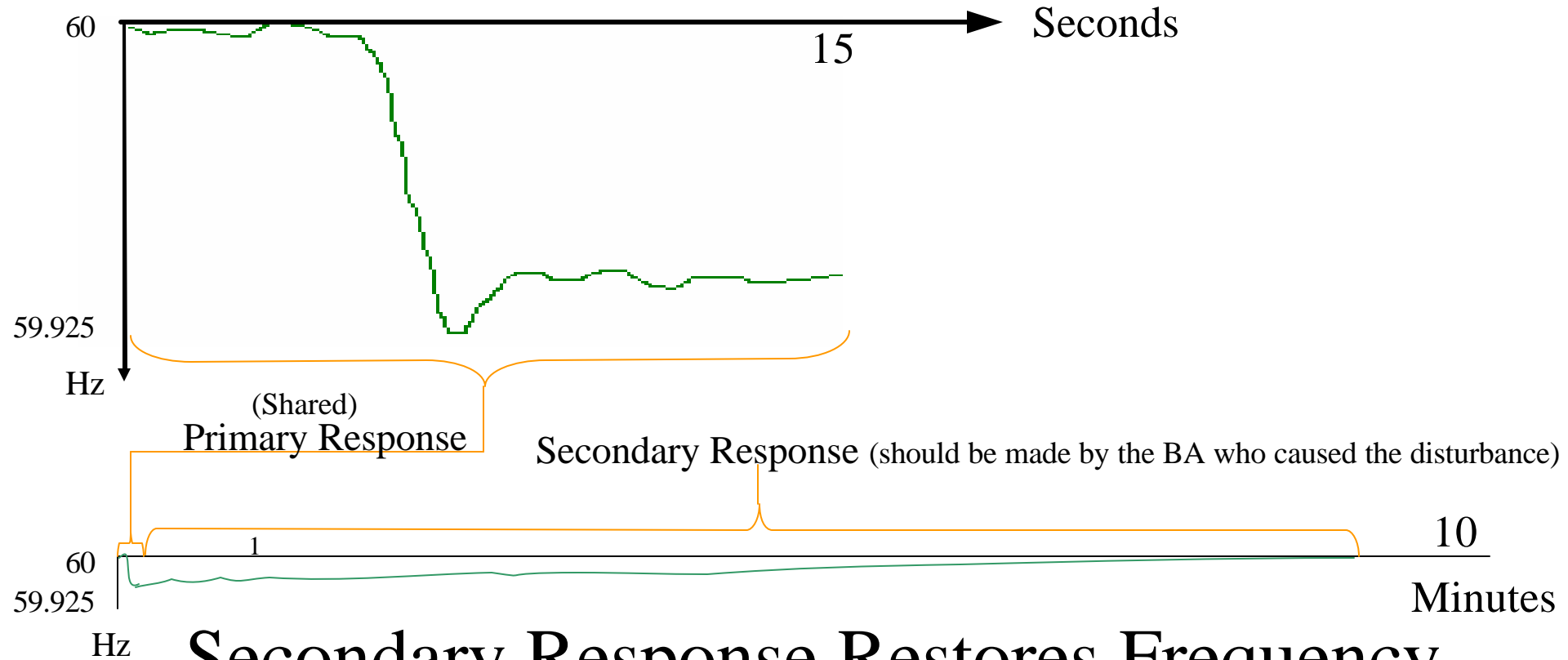


Source: Robert Blohm, energy consultant and adviser to the North American Electric Reliability Council

Managing
Inadvertent
or
Tie-Line Error:

Primary Response Stabilizes Frequency

Generator slows down while governor opens steam-control valve to stop the slow-down.
Interconnection's Overall Primary Response offsets Interconn.'s Overall Scheduling Error



Secondary Response Restores Frequency

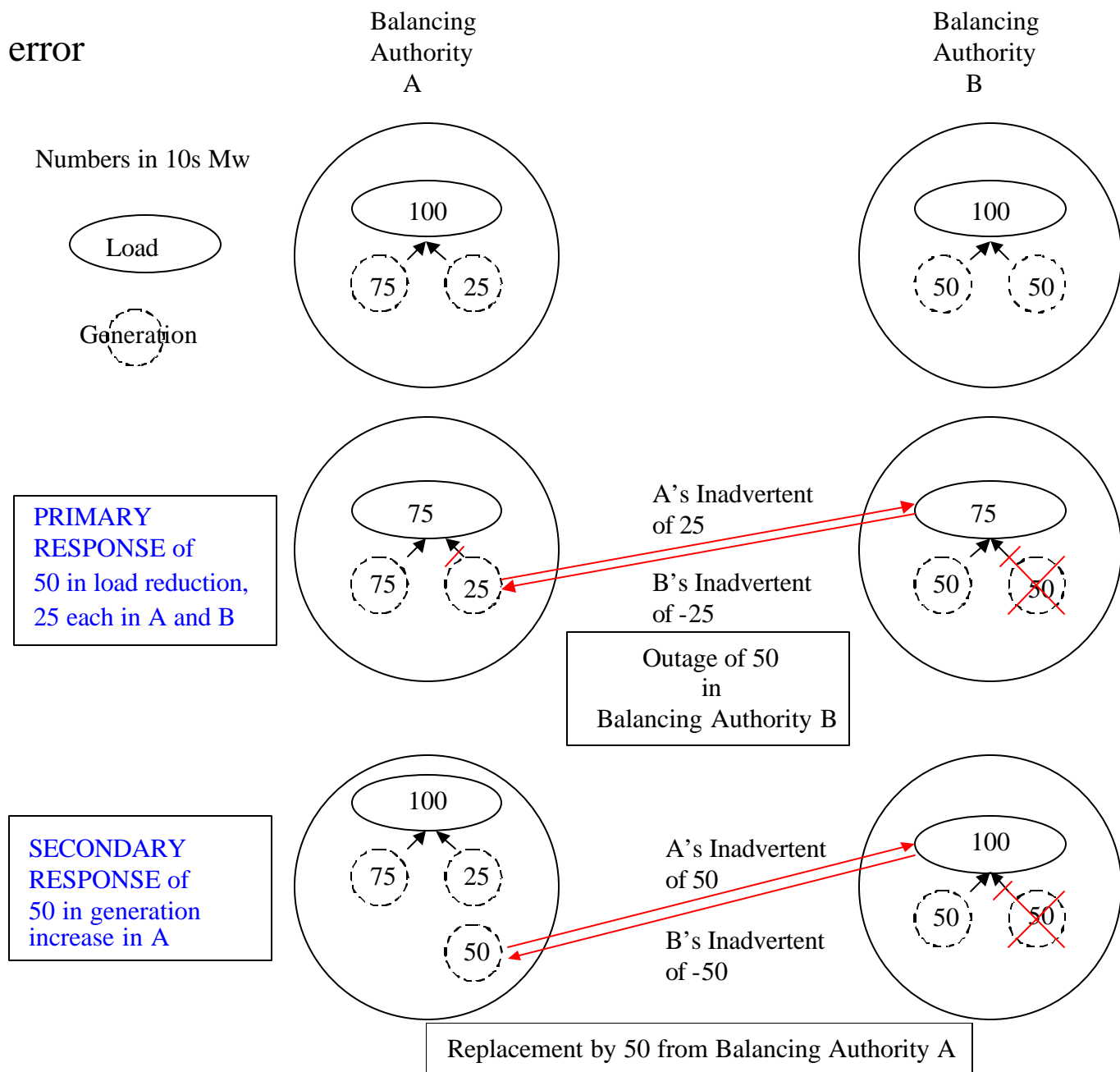
Operator raises steam-control valve set-point to increase the steam flow to speed up generator.

As generator speeds back up to normal, the governor closes-back steam-control valve.

Balancing Authority's Secondary Response to his own error replaces Interconnection's Shared Primary Response to that error.

A BA has Inadvertent* whenever the BA's share of the Interconnection's overall Scheduling Error doesn't match the BA's required share of the Interconnection's overall Primary Response to that Scheduling Error

* or tie-line error



Ancillary Service Dispatch Decision

- Three 500 MW Units with 5% Droop.

5 % Droop means

- 100 % of capacity needed to arrest freq. drop of 5 % of 60 Hz = 3 Hz
- Response Requirement of 10 % of capacity (= 150 MW = 50MW per gen.) to arrest .3 Hz freq. drop (= 0.5% of 60 Hz).

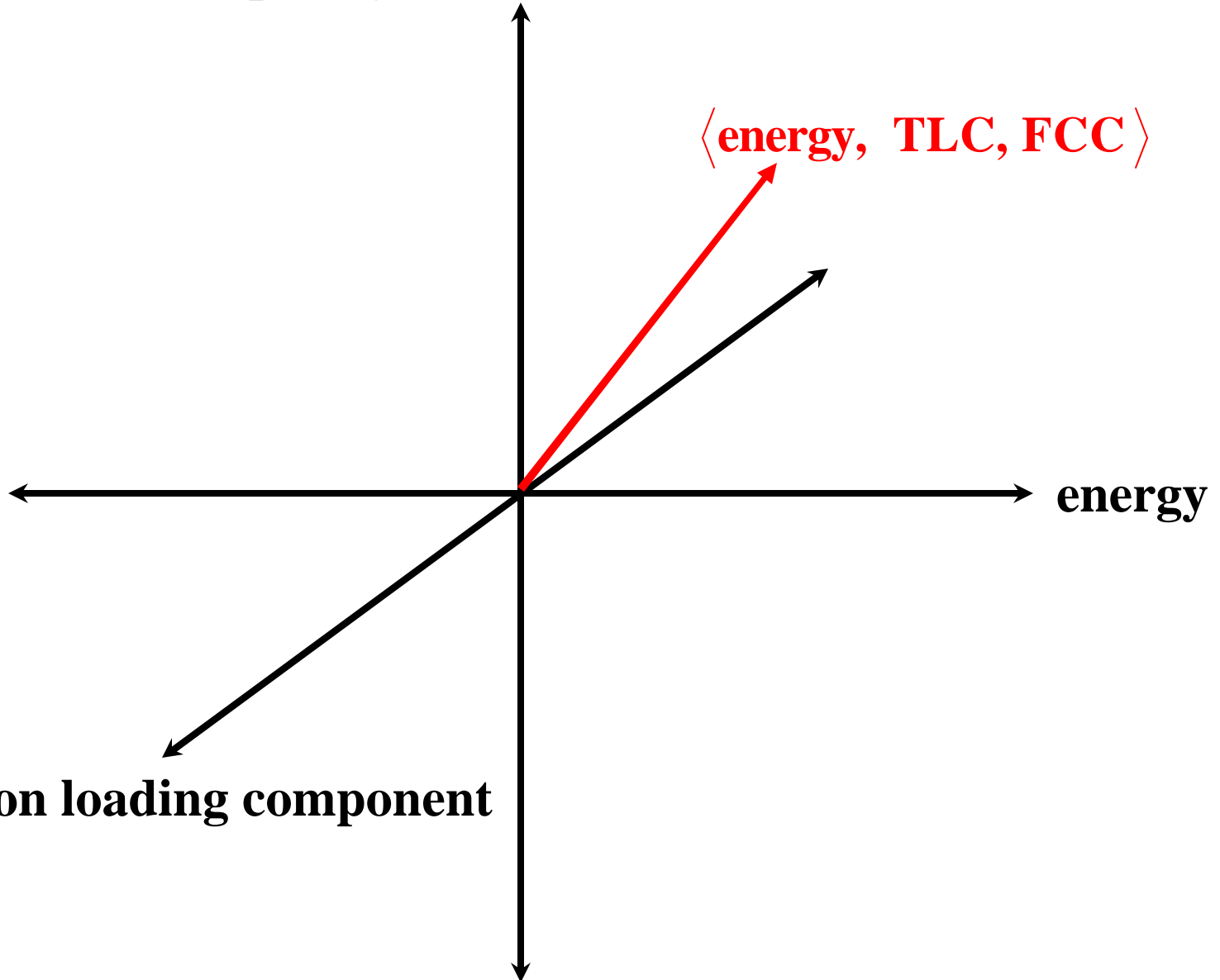
- Each Loaded to 425 MW
- Unit 1 – Incremental Price = \$30/MWh
- Unit 2 – Incremental Price = \$40/MWh
- Unit 3 – Incremental Price = \$50/MWh
- How should a 75 MW increase in balancing energy be delivered?

Marginal-Energy-Cost May Not be the Most Economic Basis for Reliability

- Alternative 1: Variable-cost Based Decision - load Unit 1 an additional 75 MW.
 - Cost \$ 2,250
 - Remaining resp. to next .3Hz drop: 100 MW \Rightarrow
 \Rightarrow only 2 available generators left @ 50 MW per generator = 1/3rd shortfall from response needed to arrest next frequency drop. Need to have bought 500 MW of new excess capacity to get the extra 50 MW of response
- Alternative 2: Capacity-cost Reliability Based Decision - load each unit an additional 25 MW.
 - Cost \$ 3,000
 - Remaining resp. to next .3Hz drop 150 MW \Rightarrow
 \Rightarrow all 3 generators available @ 50 MW per generator = No shortfall from the response needed to arrest next frequency drop

Inadvertent is a **vector** in a state space


frequency control contribution



Dual pricing of unscheduled energy
 Ambiguity along the diagonal

Revenue/Expense

		Unscheduled part $b > 0$	
		good	bad
energy part $U > 0$	sold	$p_e U + p_b 10b$	$p_e U - p_b 10b$
	bought	$-p_e U + p_b 10b$	$-p_e U - p_b 10b$

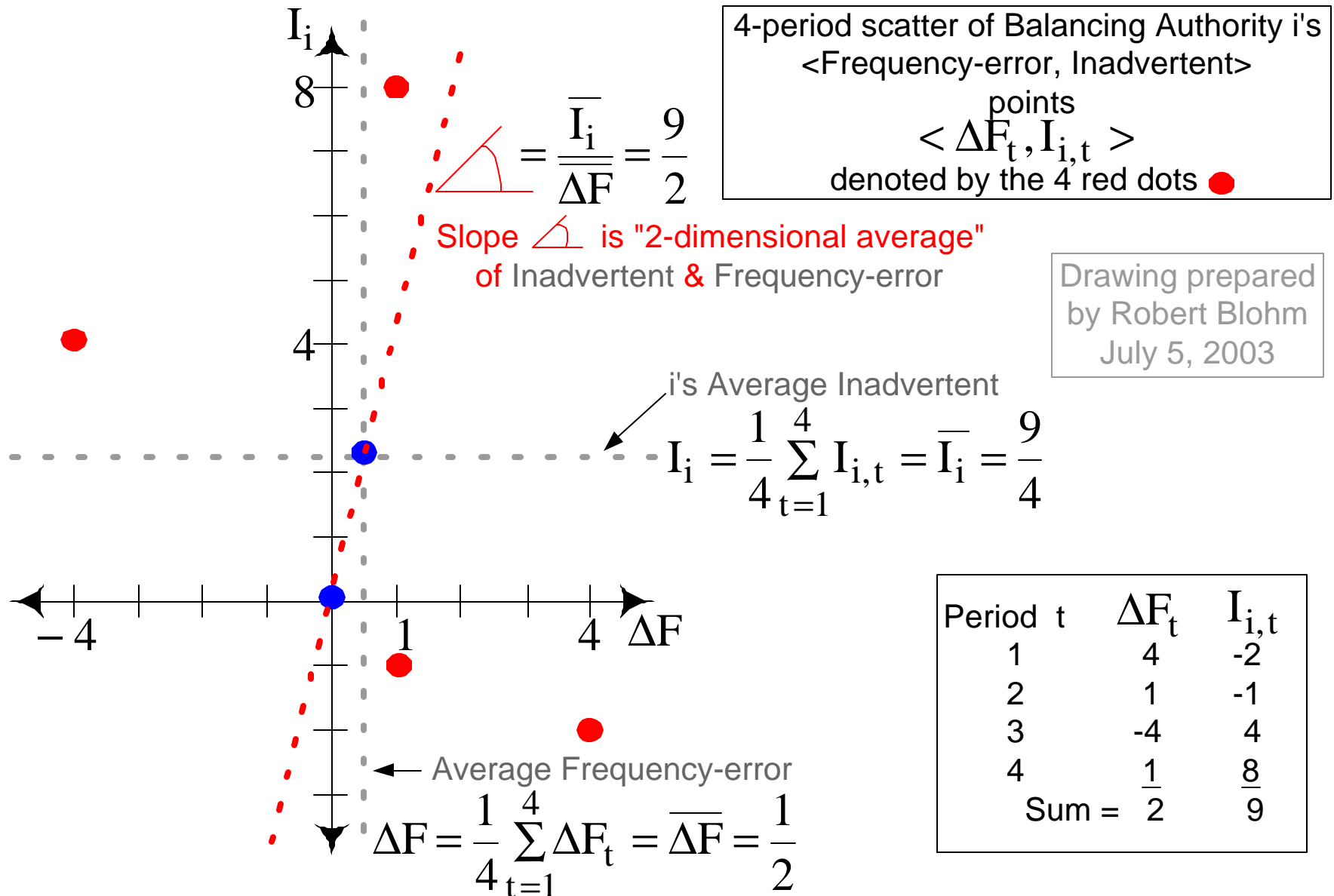
receive 

pay

Animation of the Mechanism for
Determining and Settling
Frequency Control Contribution:

A Balancing Authority i's Frequency Control Contribution is a frequency-error-weighted "2-dimensional average" of Inadvertent and Frequency-error.

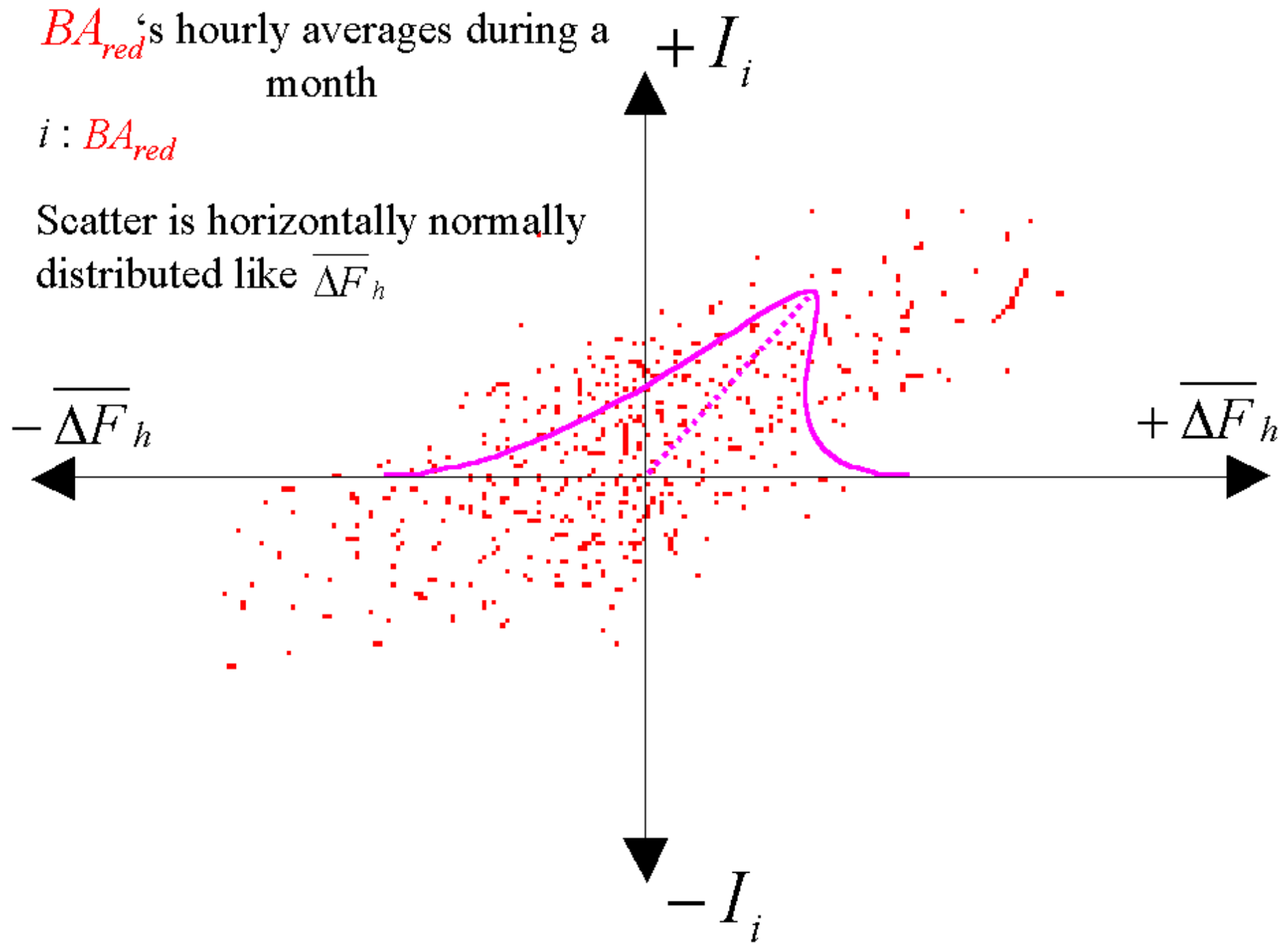
A "2-dimensional average" is the slope of a line from the origin ● through the intersection ● of the lines intercepting the two averages.



BA_{red} 's hourly averages during a month

$i : BA_{red}$

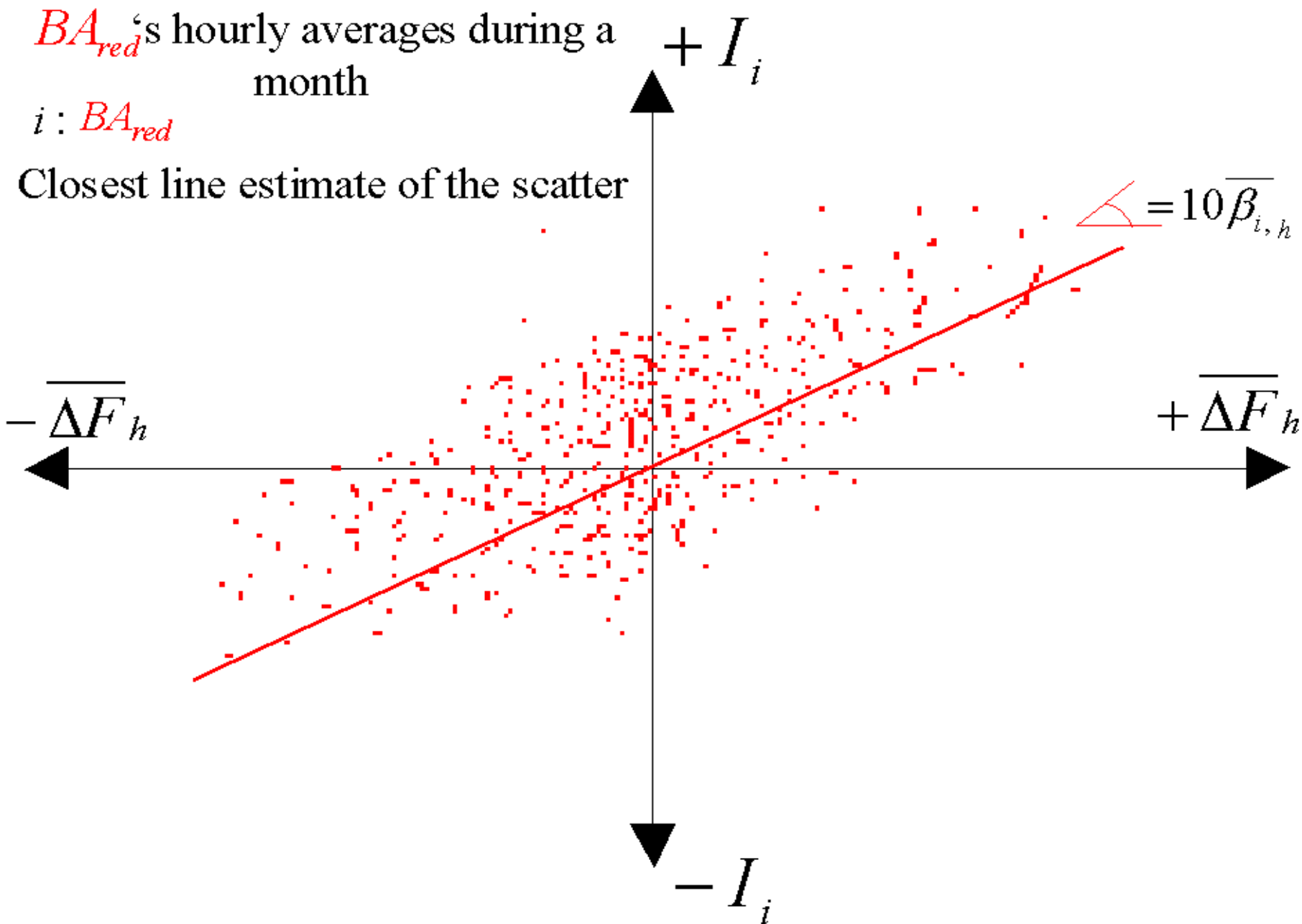
Scatter is horizontally normally distributed like $\overline{\Delta F_h}$



BA_{red} 's hourly averages during a month

$i : BA_{red}$

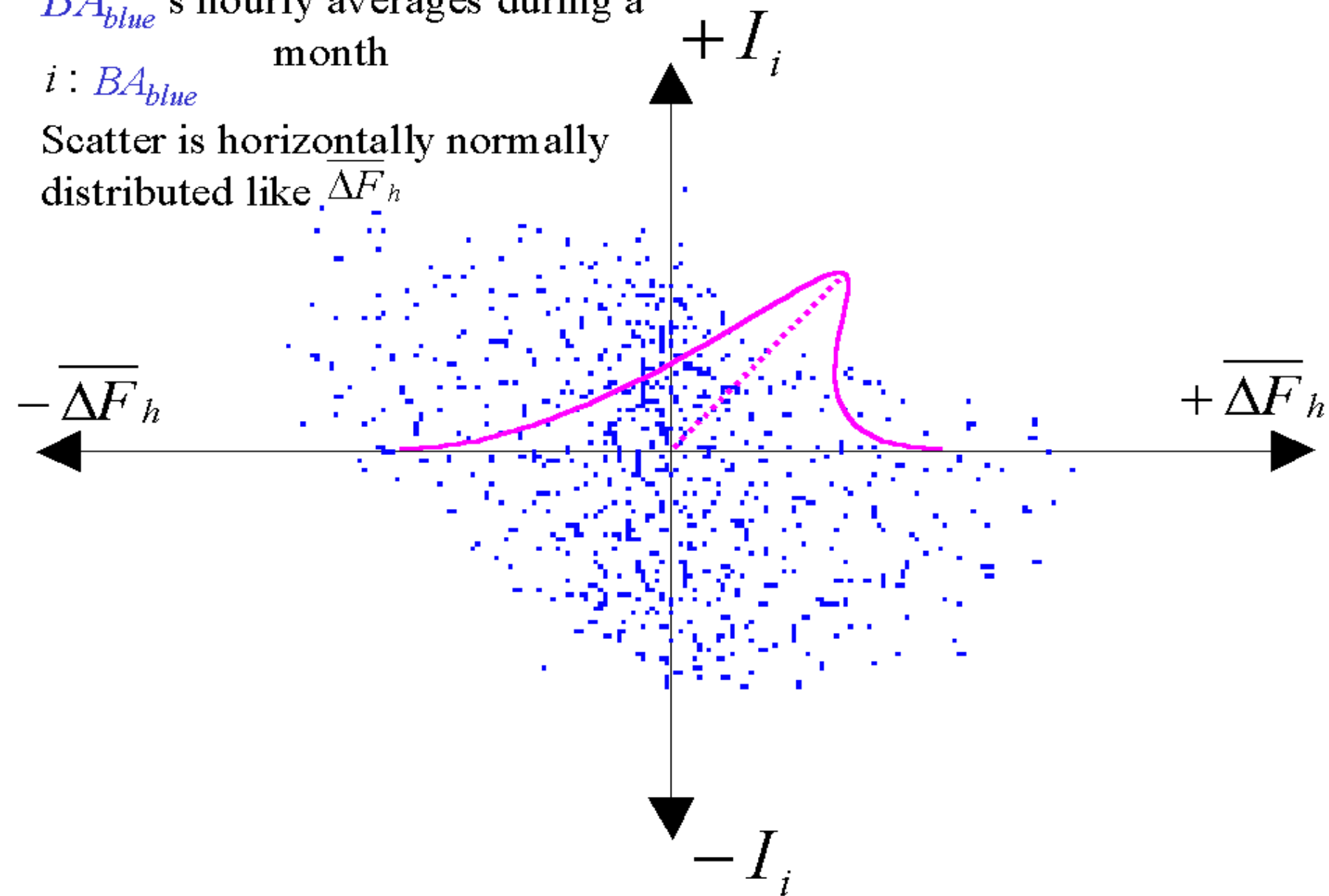
Closest line estimate of the scatter



BA_{blue} 's hourly averages during a month

$i : BA_{blue}$

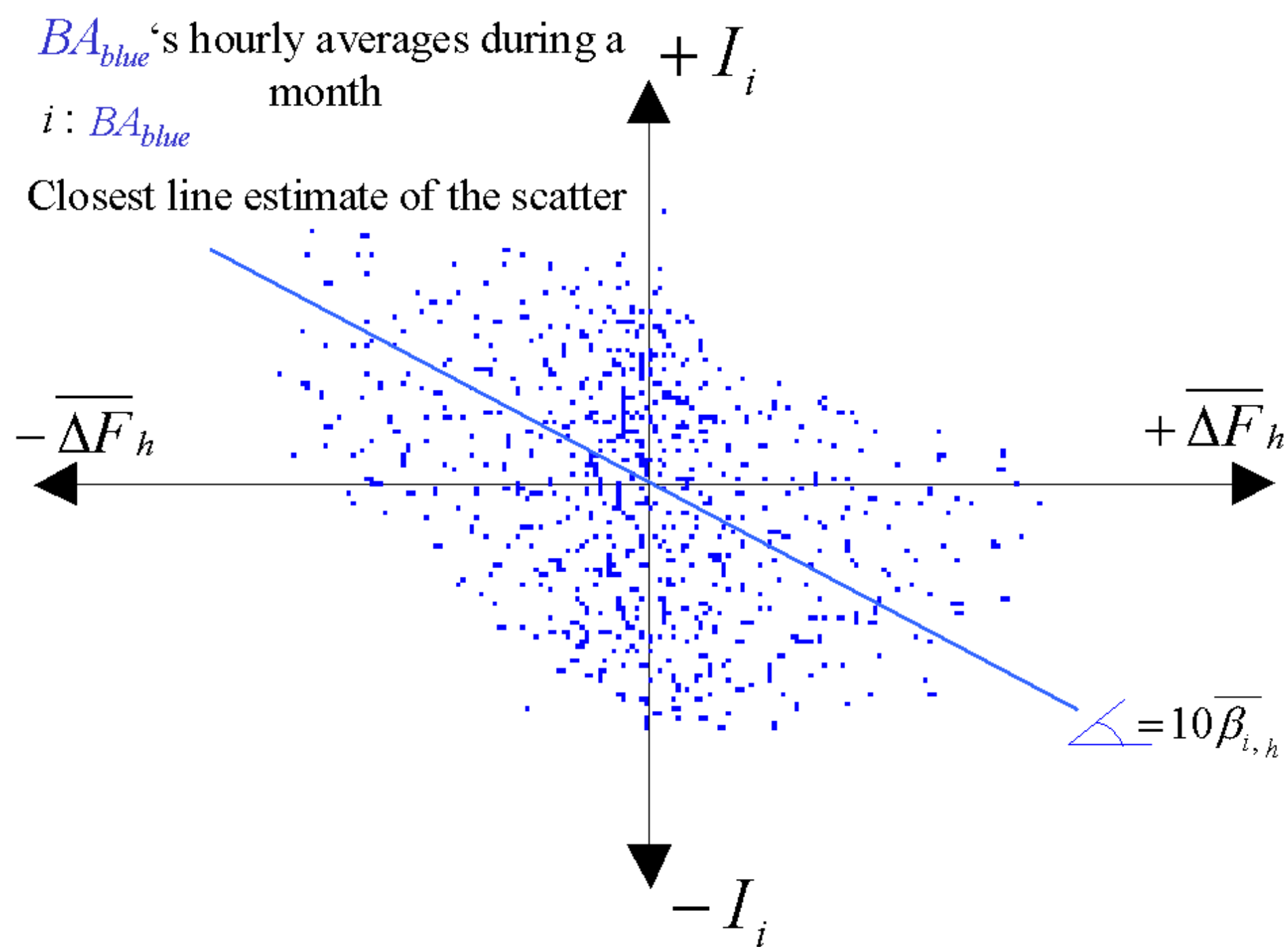
Scatter is horizontally normally distributed like $\overline{\Delta F}_h$



BA_{blue} 's hourly averages during a month

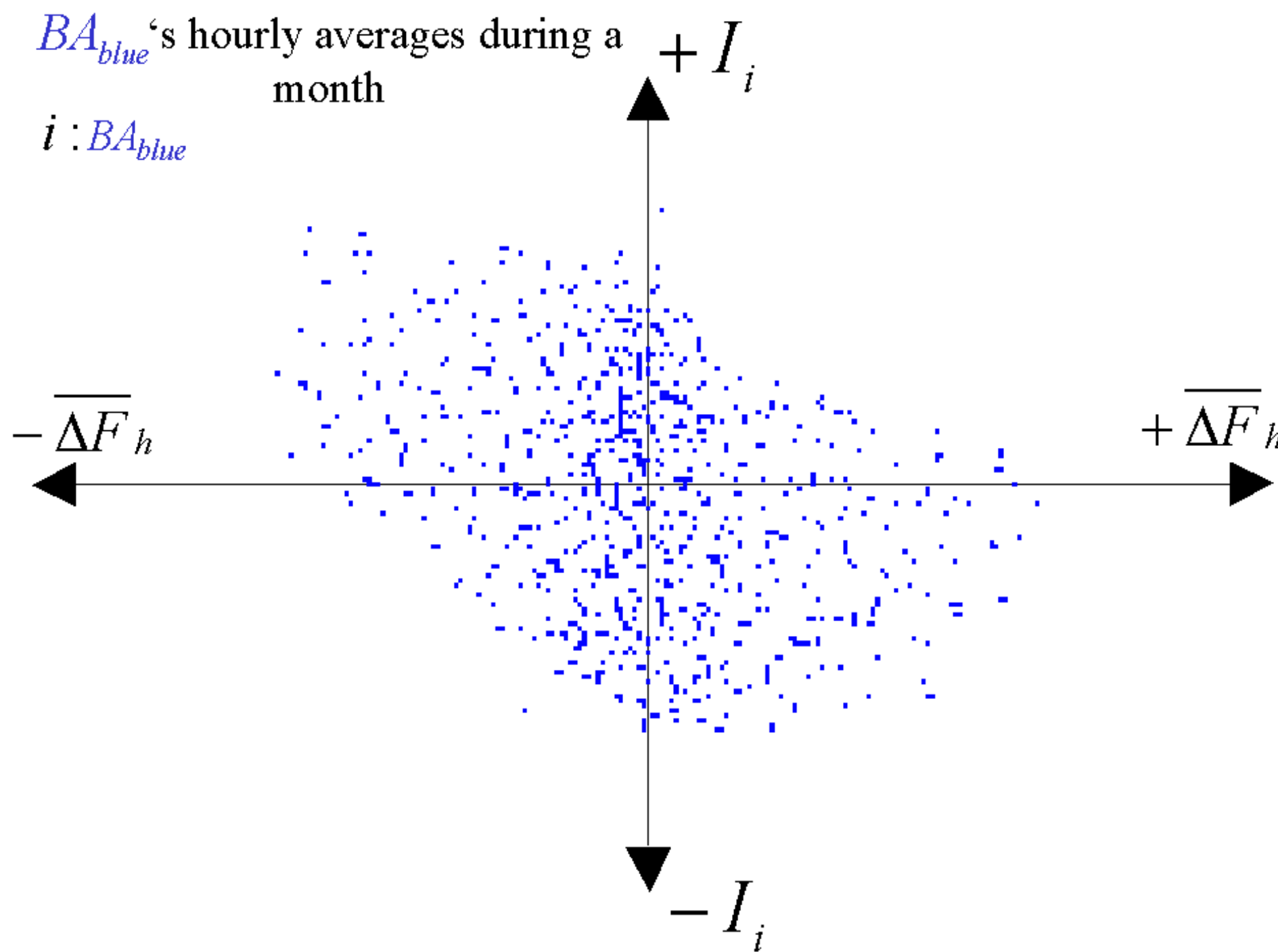
$i : BA_{blue}$

Closest line estimate of the scatter



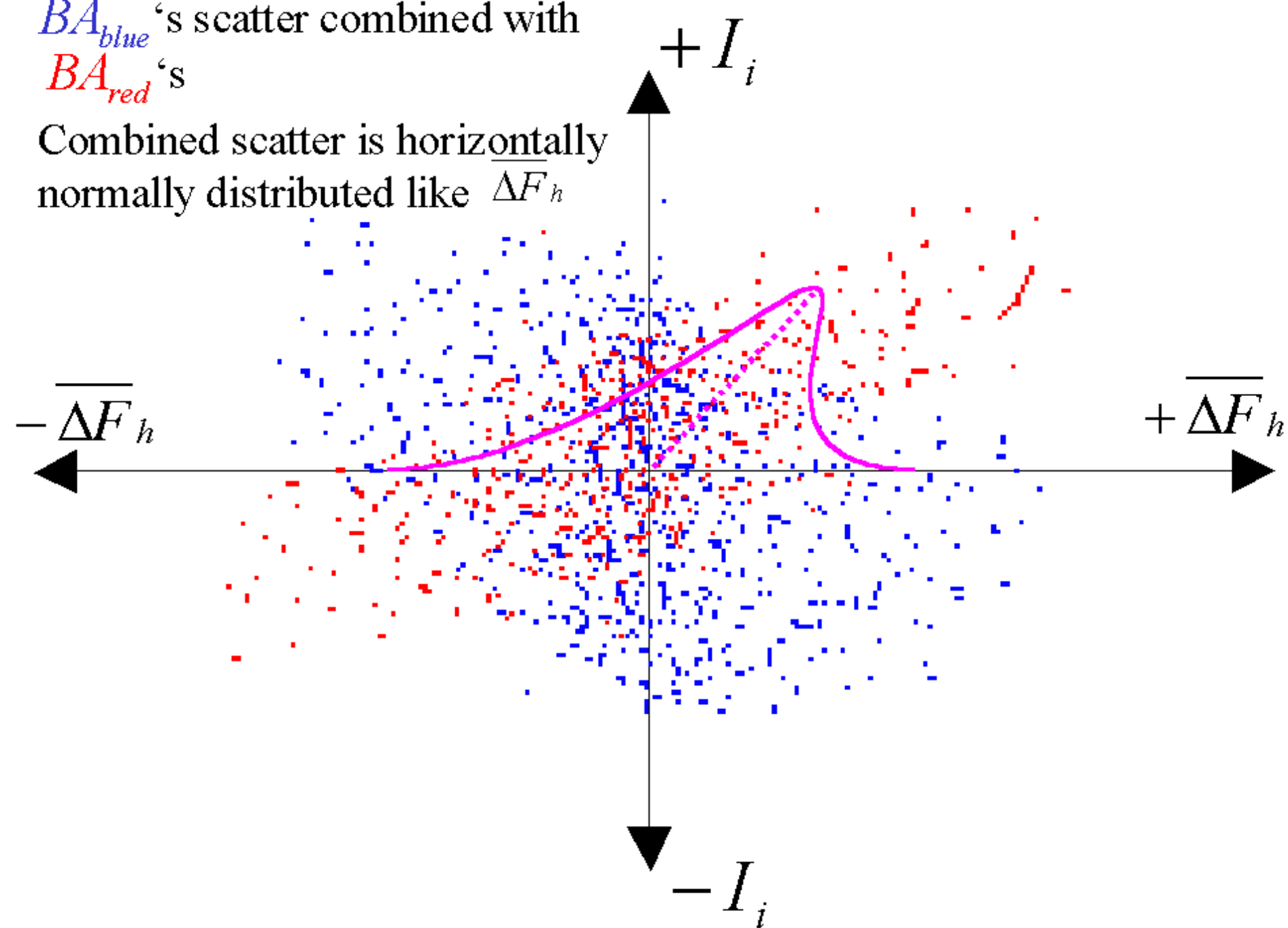
BA_{blue} 's hourly averages during a month

$i : BA_{blue}$



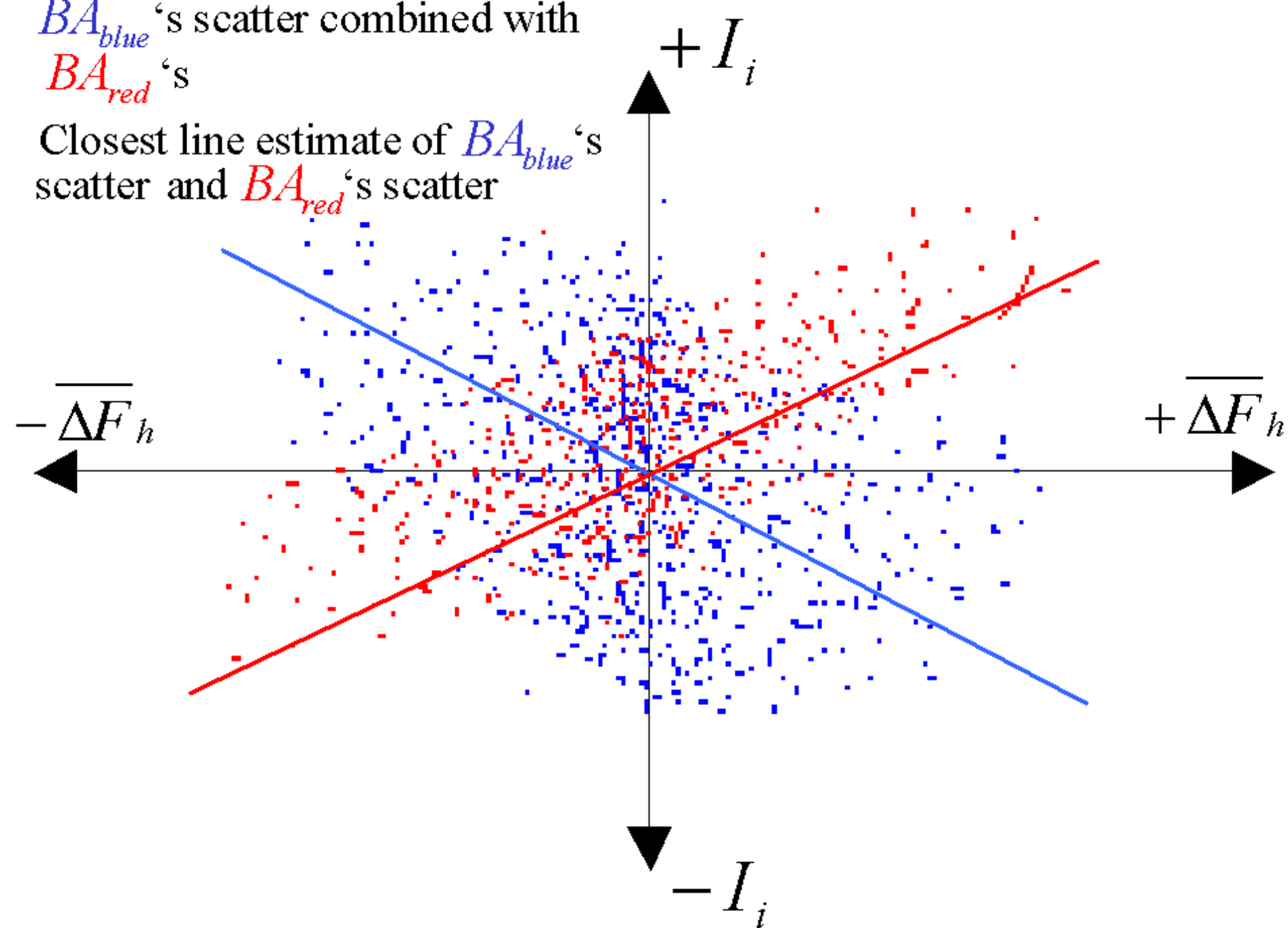
BA_{blue} 's scatter combined with
 BA_{red} 's

Combined scatter is horizontally
normally distributed like $\overline{\Delta F}_h$



BA_{blue} 's scatter combined with
 BA_{red} 's

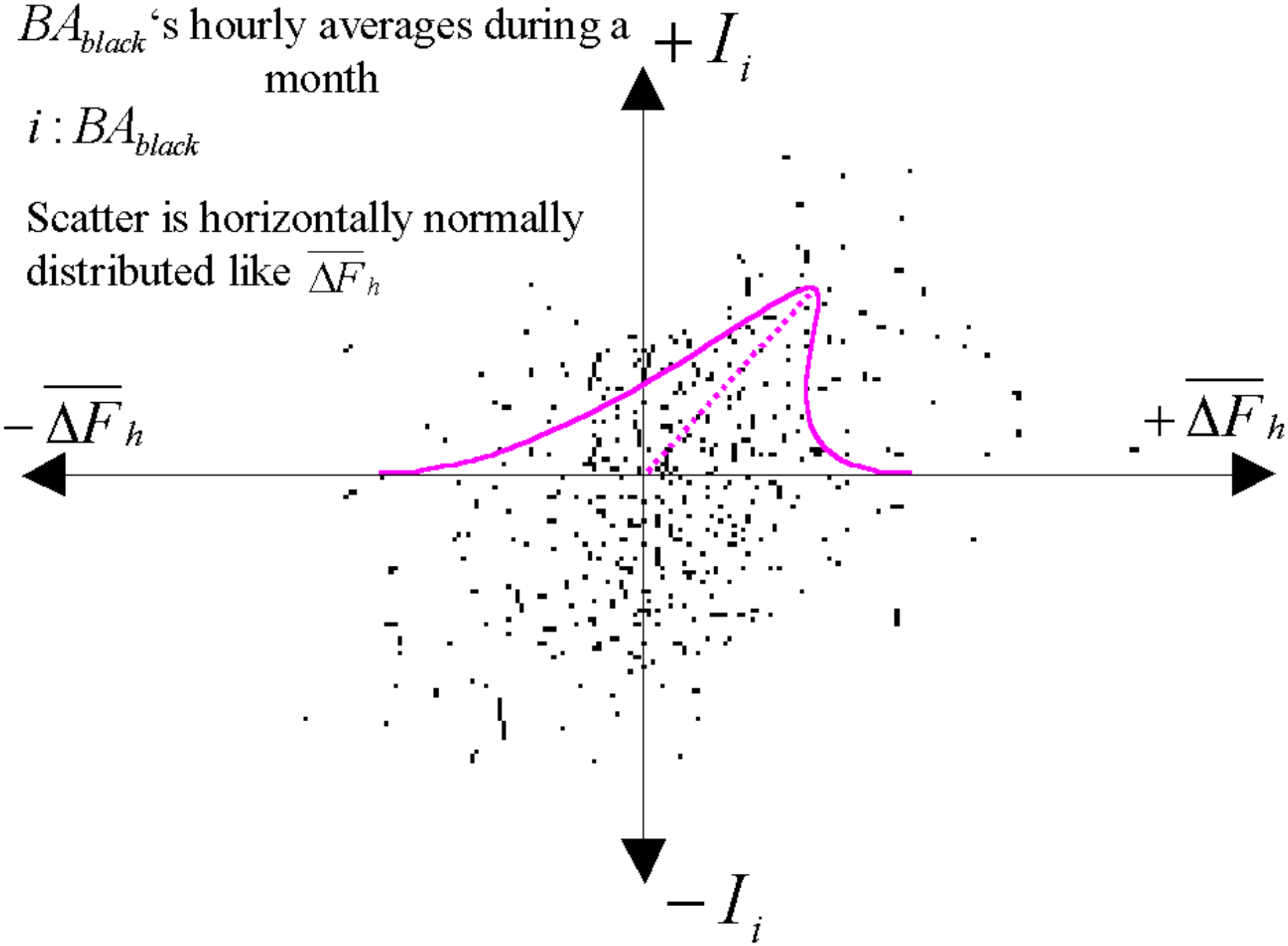
Closest line estimate of BA_{blue} 's
scatter and BA_{red} 's scatter



BA_{black} 's hourly averages during a month

$i : BA_{black}$

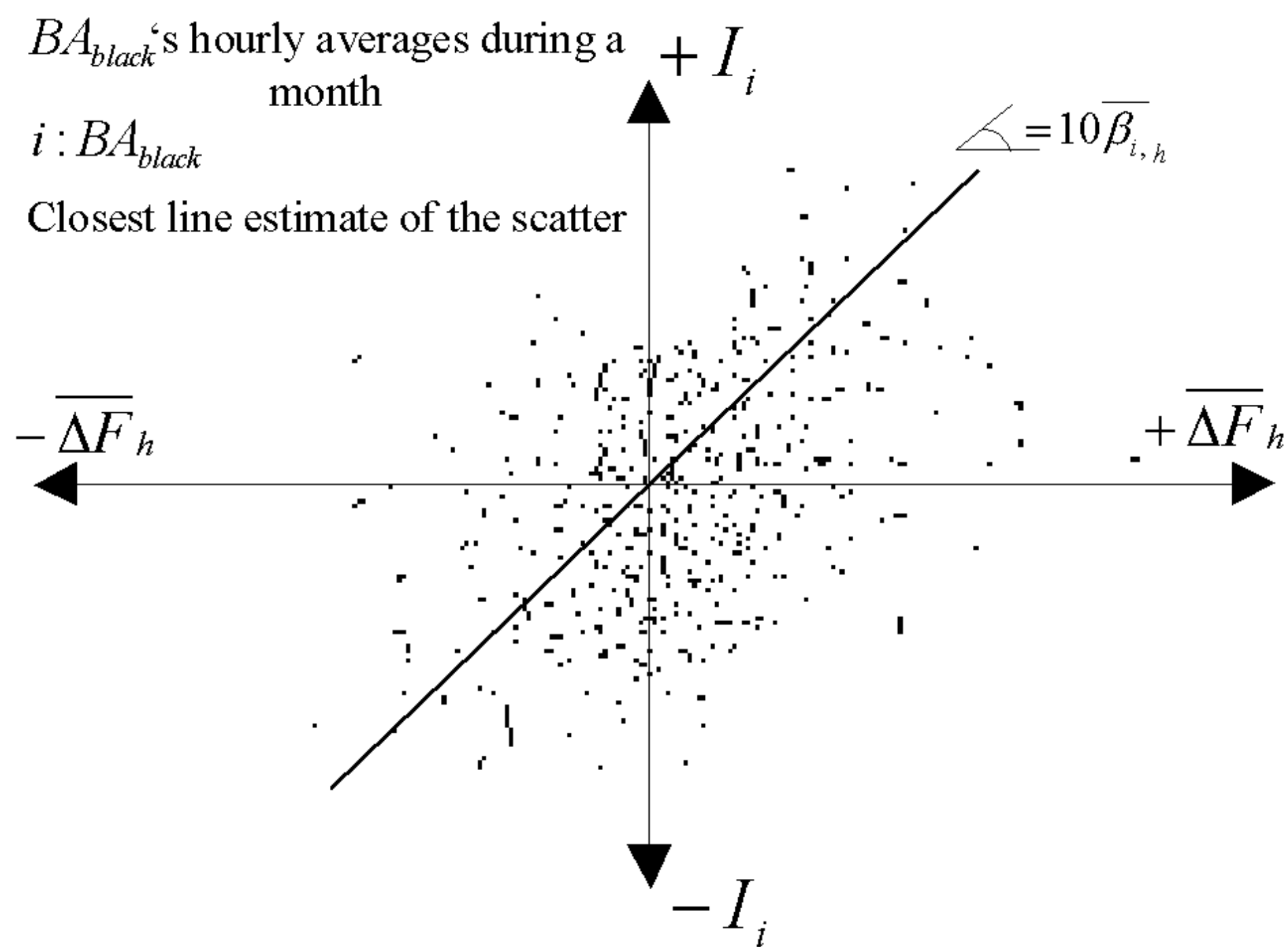
Scatter is horizontally normally distributed like $\overline{\Delta F_h}$



BA_{black} 's hourly averages during a month

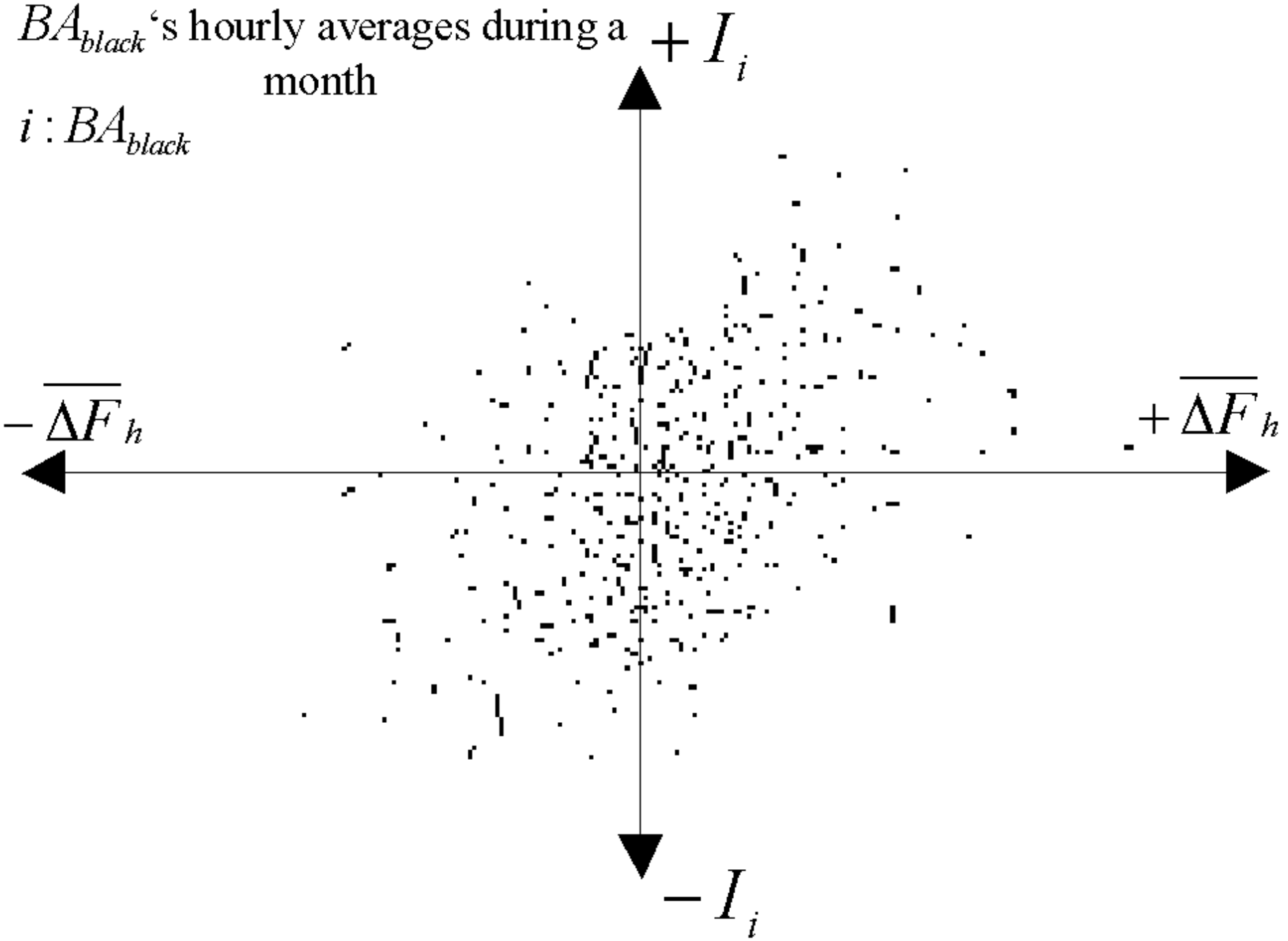
$i : BA_{black}$

Closest line estimate of the scatter

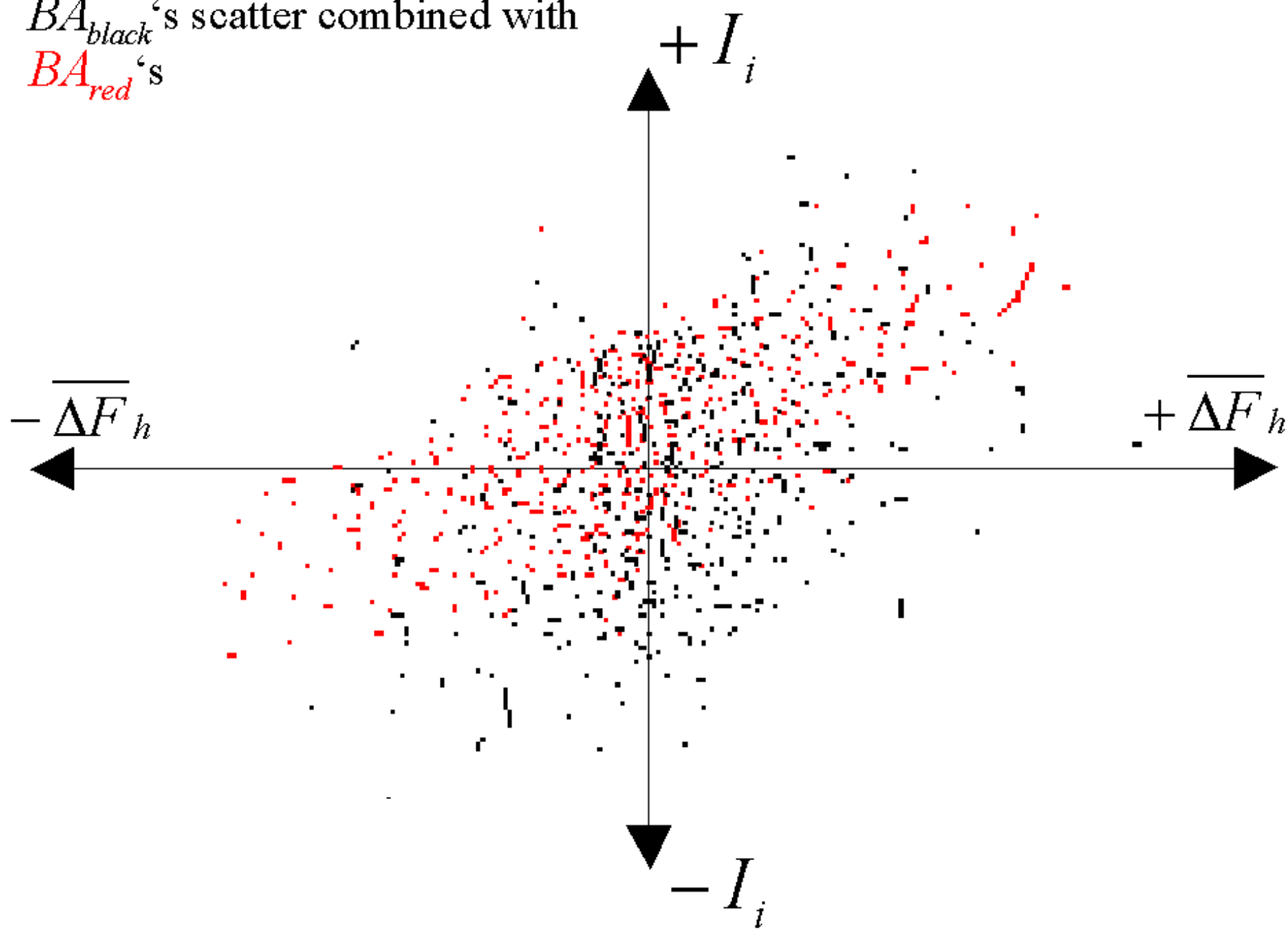


BA_{black} 's hourly averages during a month

$i : BA_{black}$

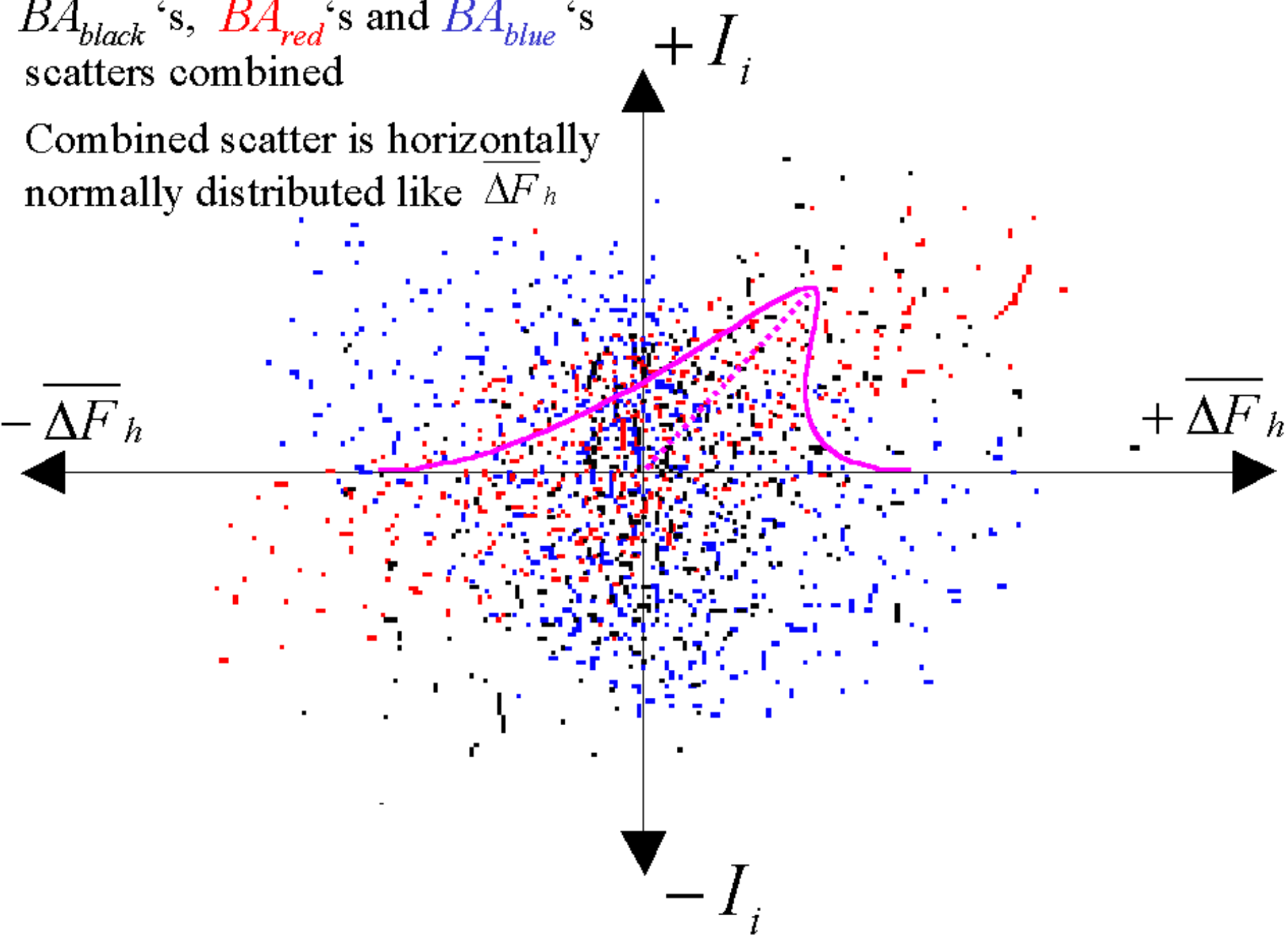


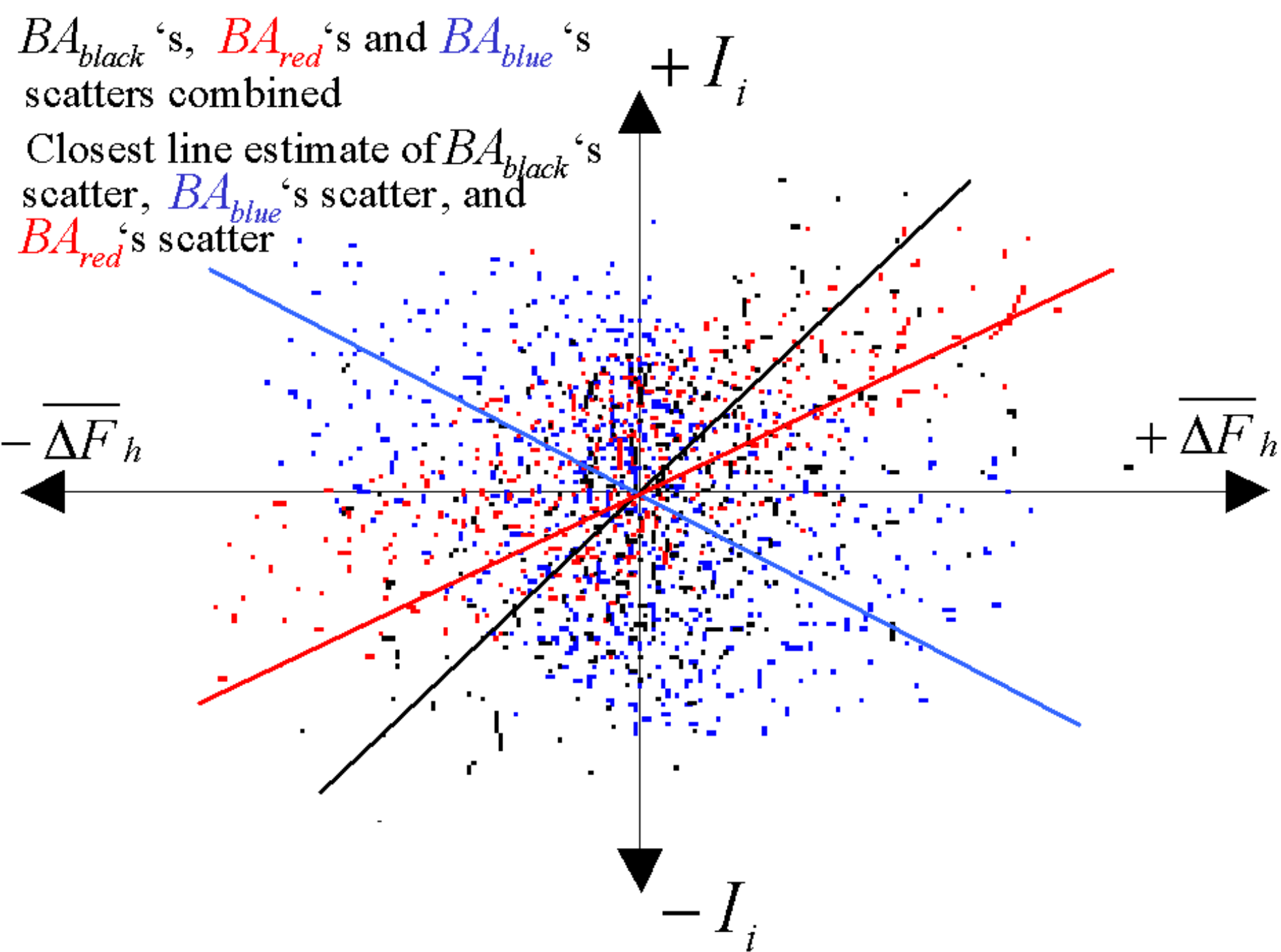
BA_{black} 's scatter combined with
 BA_{red} 's



BA_{black} 's, BA_{red} 's and BA_{blue} 's
scatters combined

Combined scatter is horizontally
normally distributed like $\overline{\Delta F}_h$

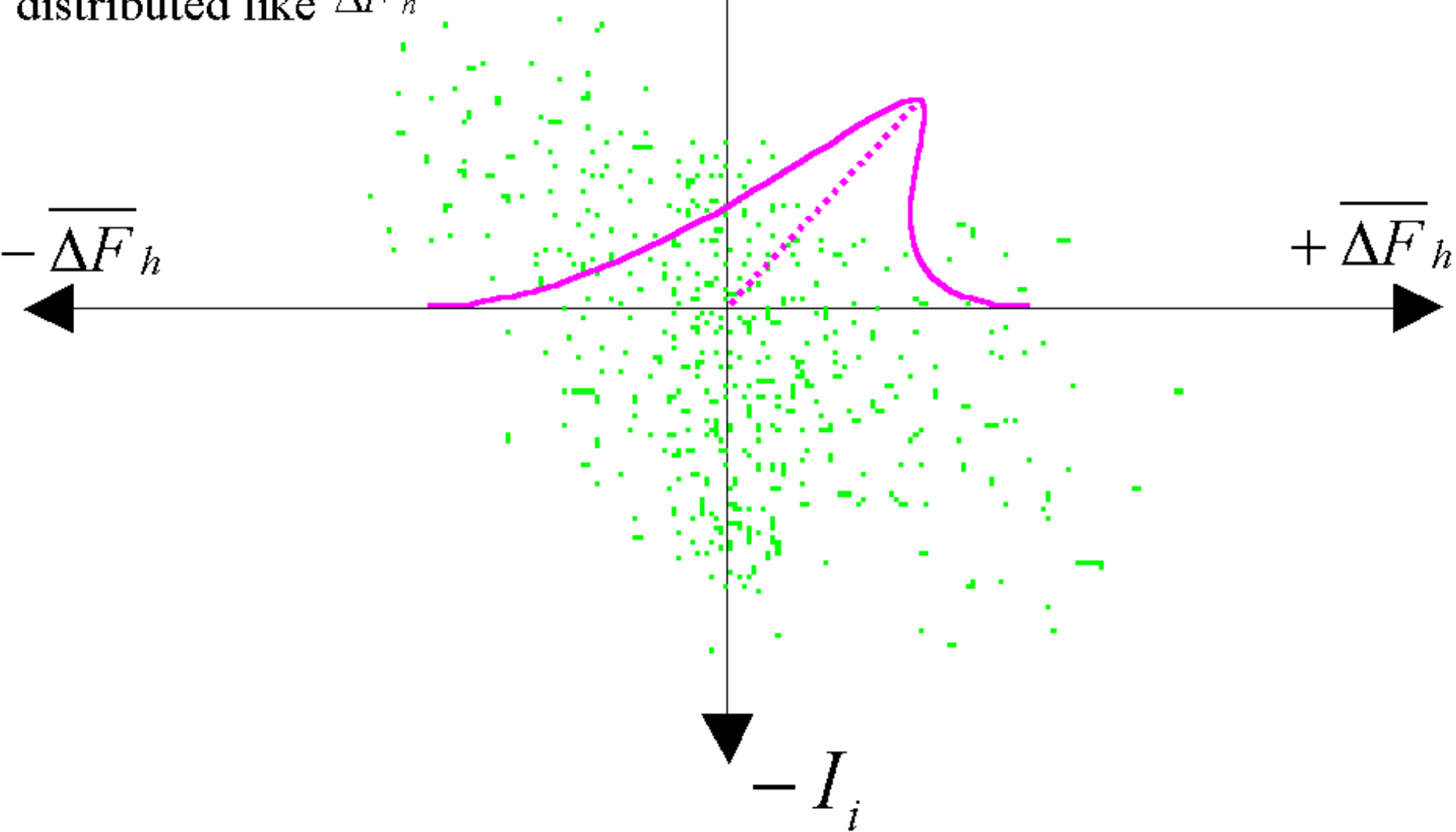




BA_{green}

$i : BA_{green}$

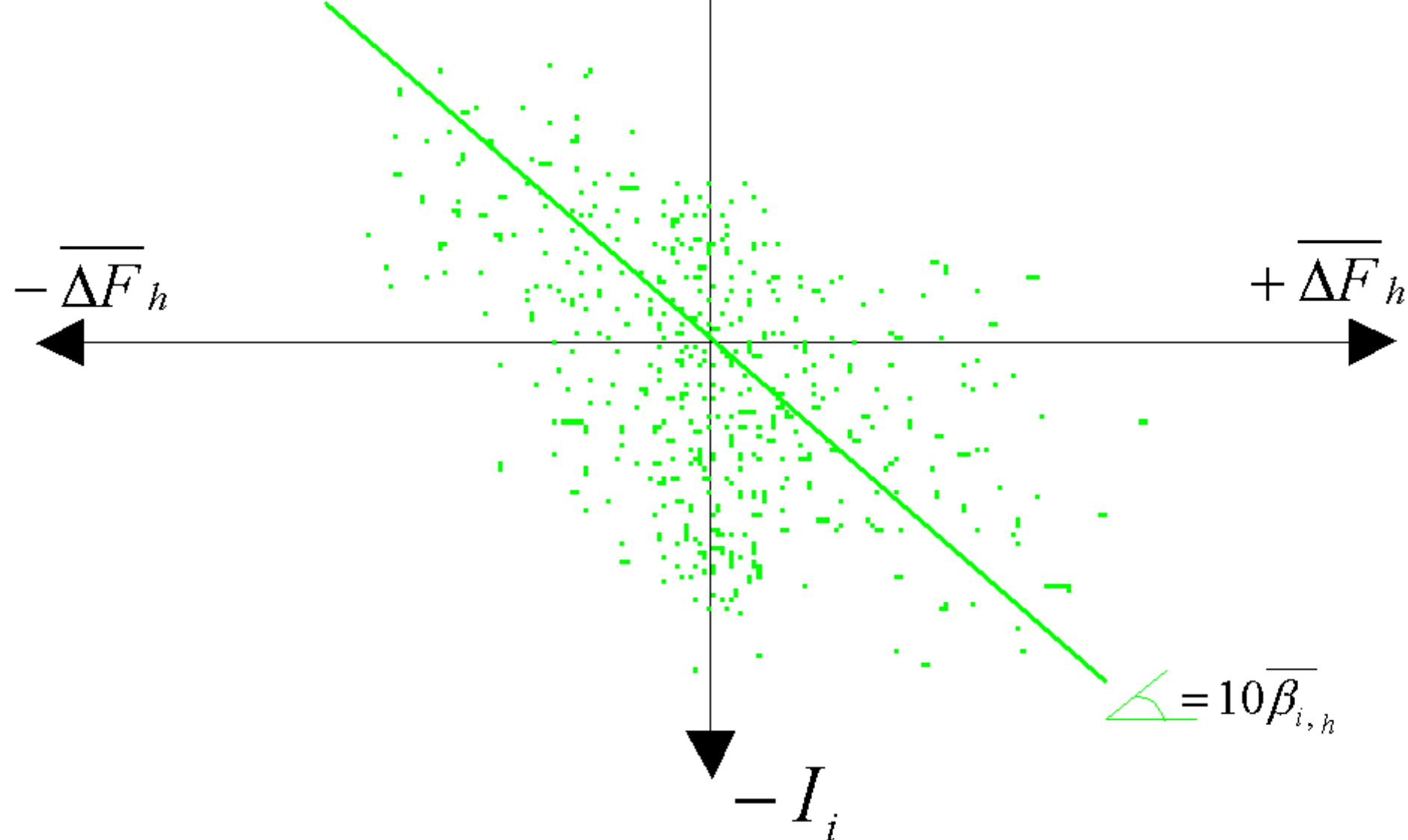
Scatter is horizontally normally distributed like $\overline{\Delta F}_h$



BA_{green} 's hourly averages during a month

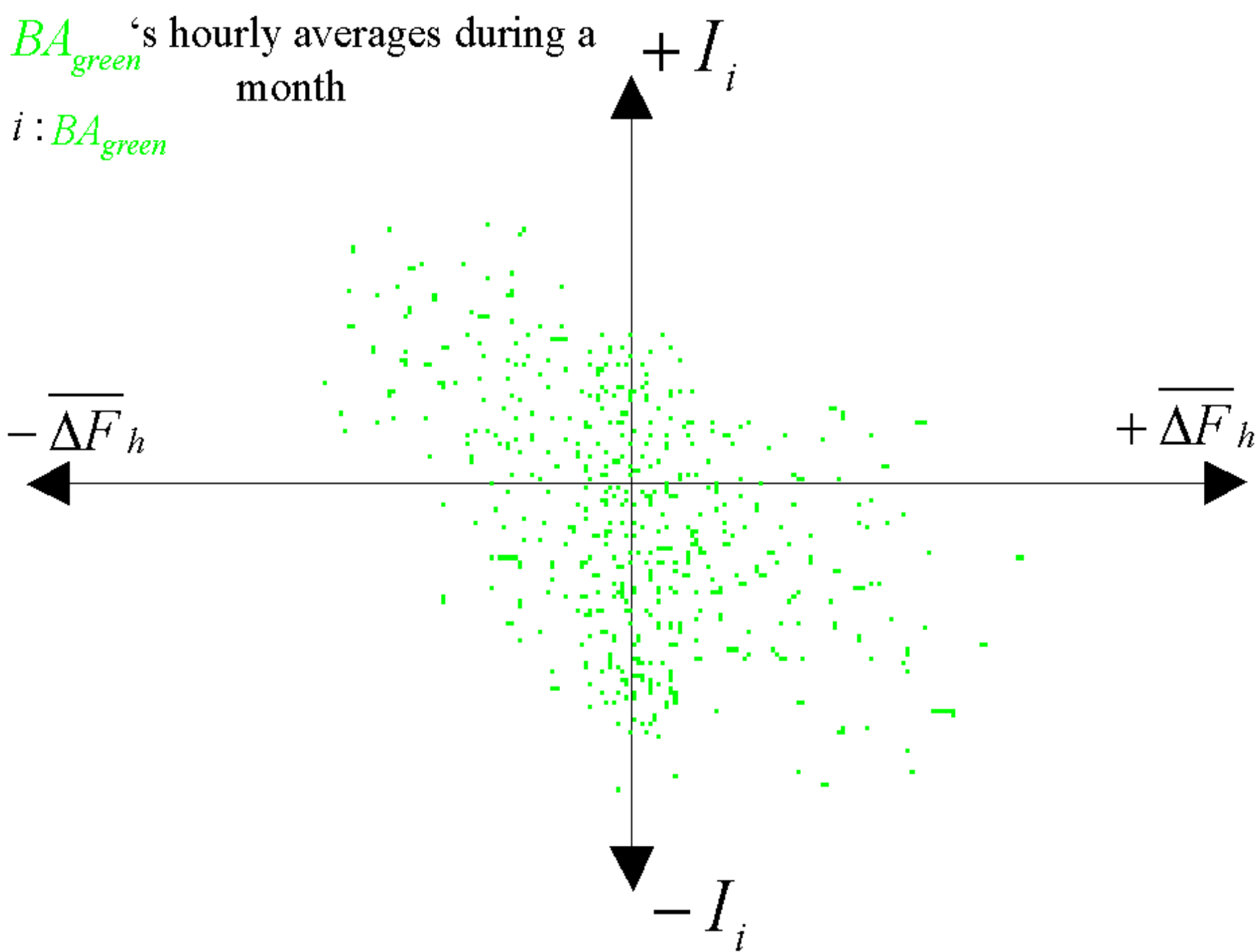
$i : BA_{green}$

Closest line estimate of the scatter

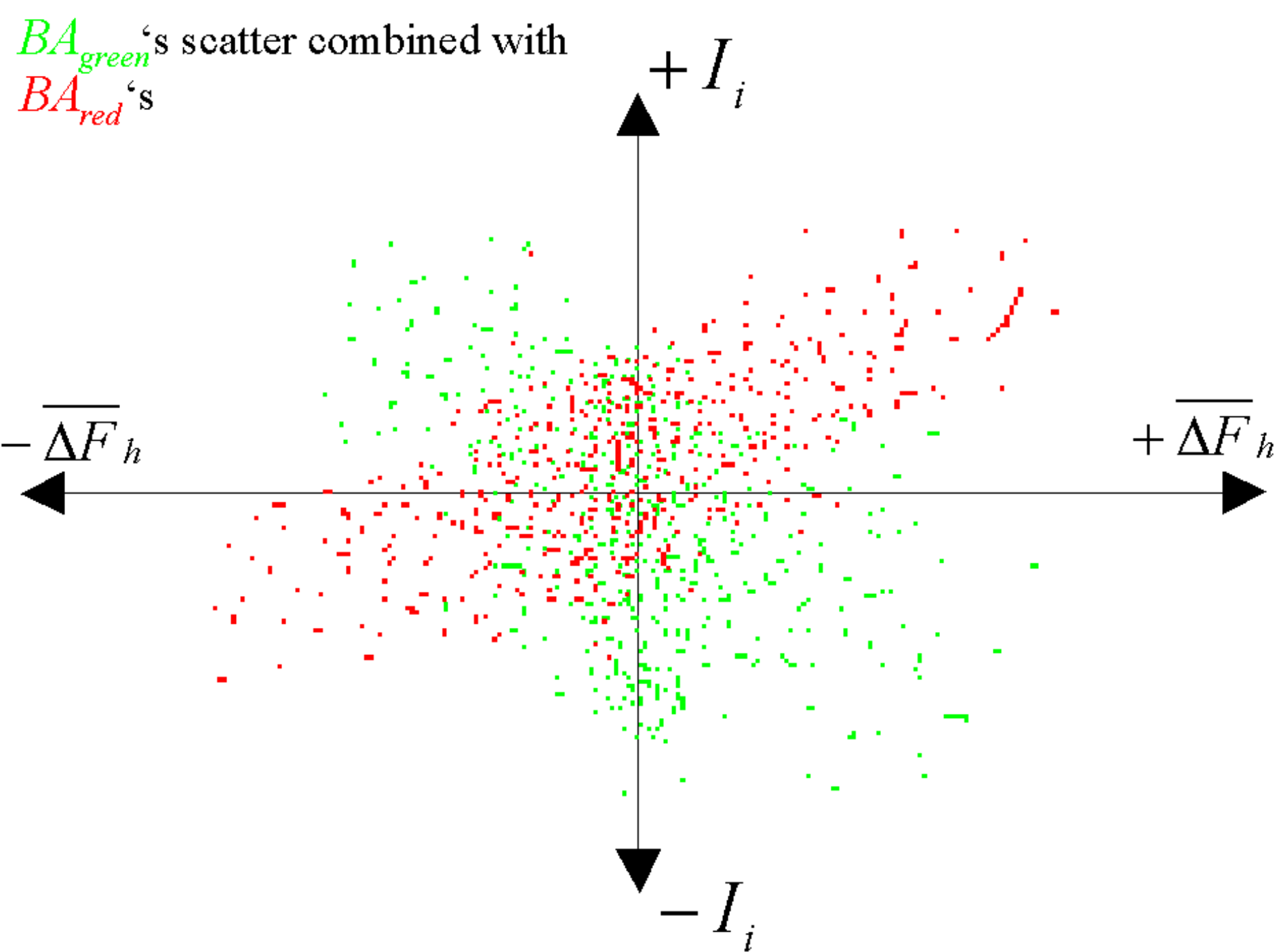


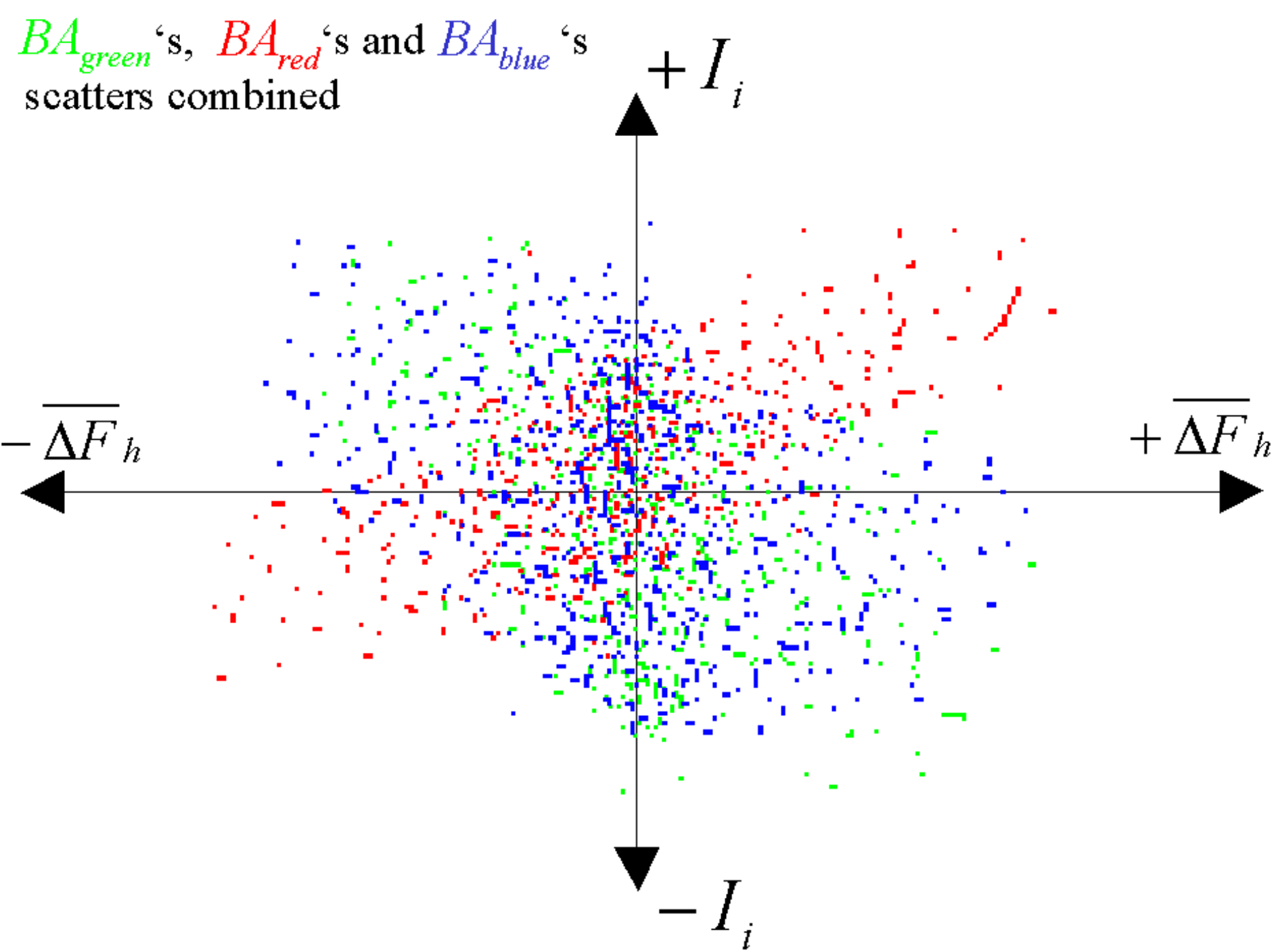
BA_{green} 's hourly averages during a month

$i : BA_{green}$



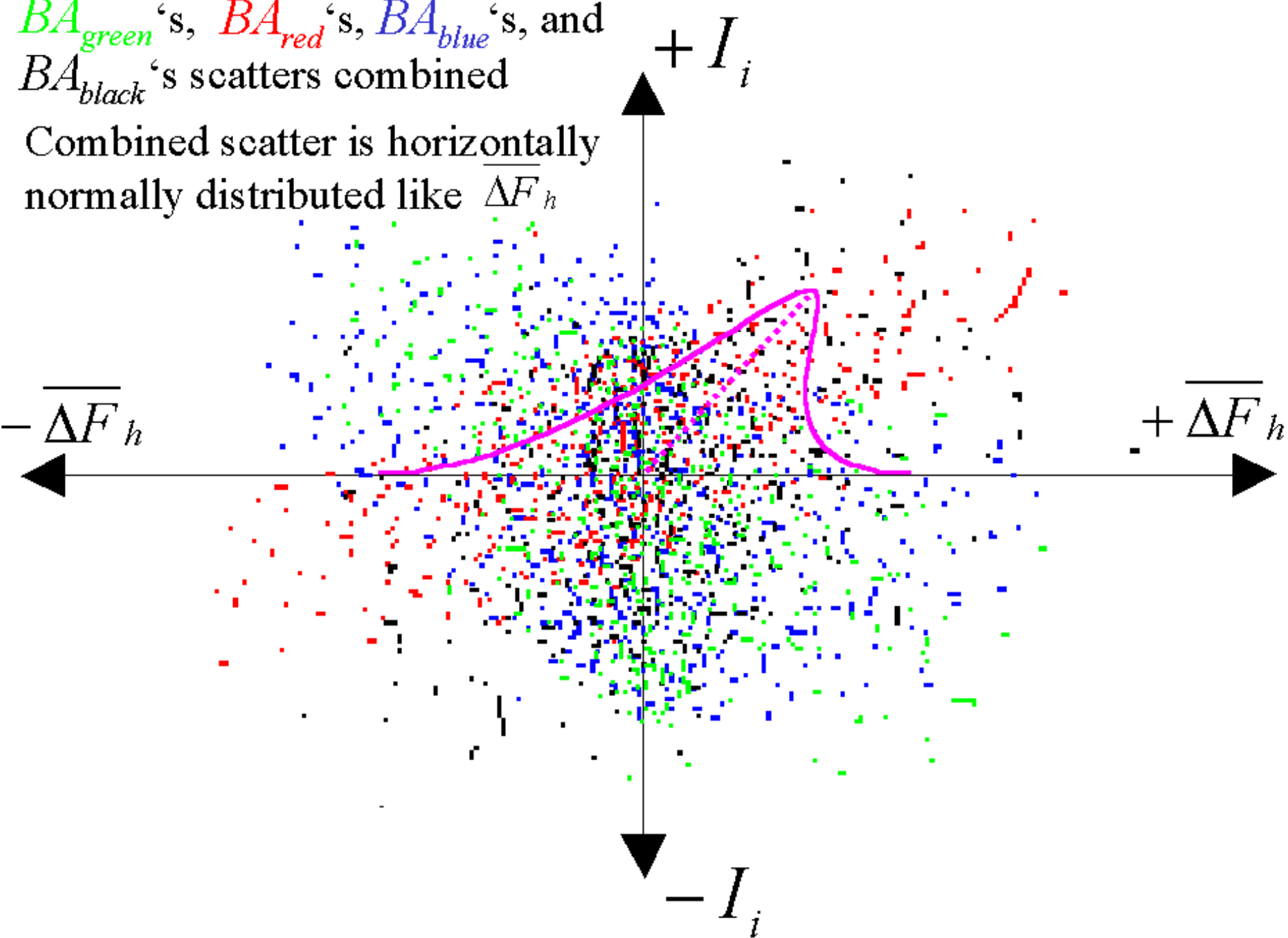
BA_{green} 's scatter combined with
 BA_{red} 's



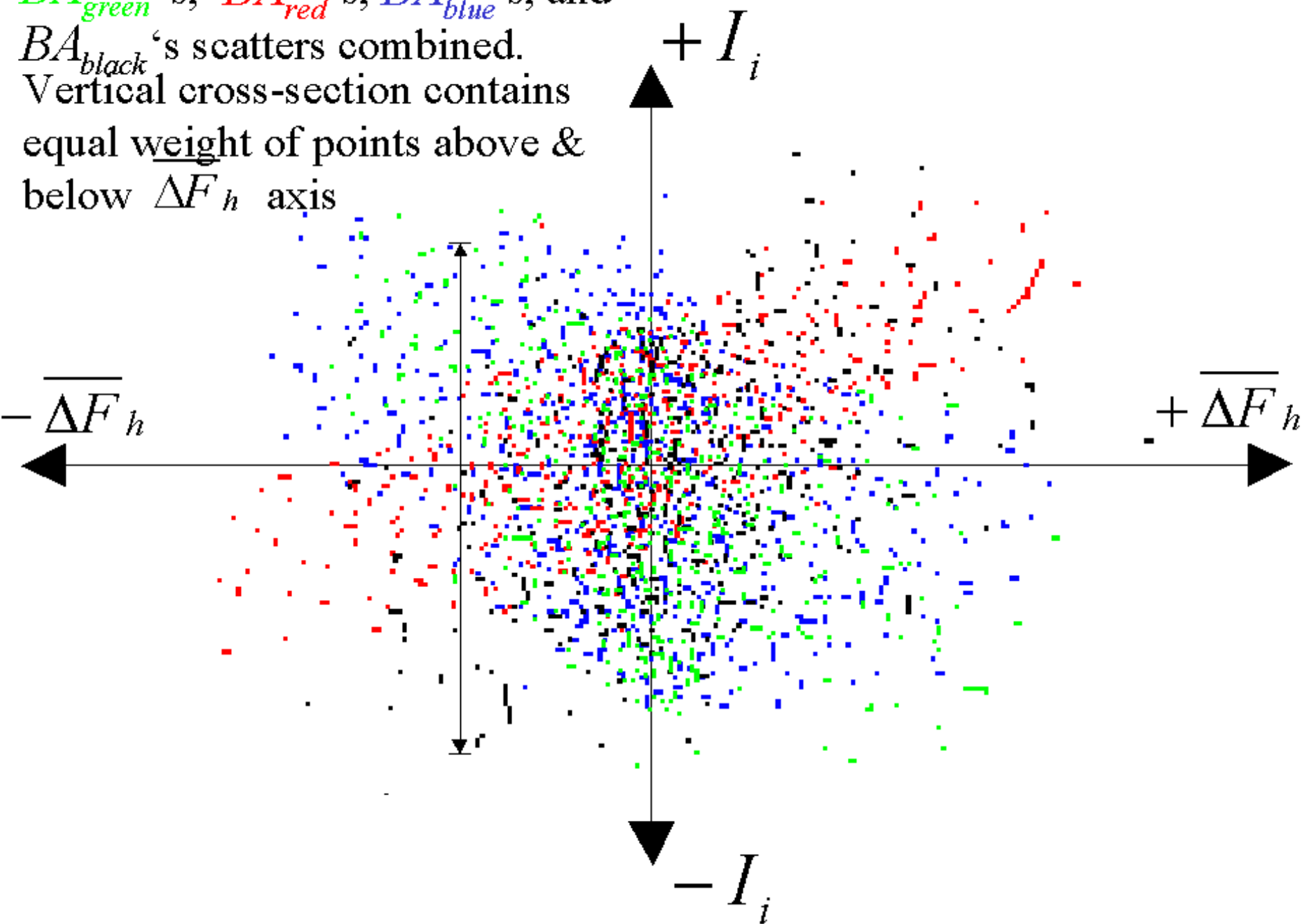


BA_{green} 's, BA_{red} 's, BA_{blue} 's, and BA_{black} 's scatters combined

Combined scatter is horizontally normally distributed like $\overline{\Delta F}_h$

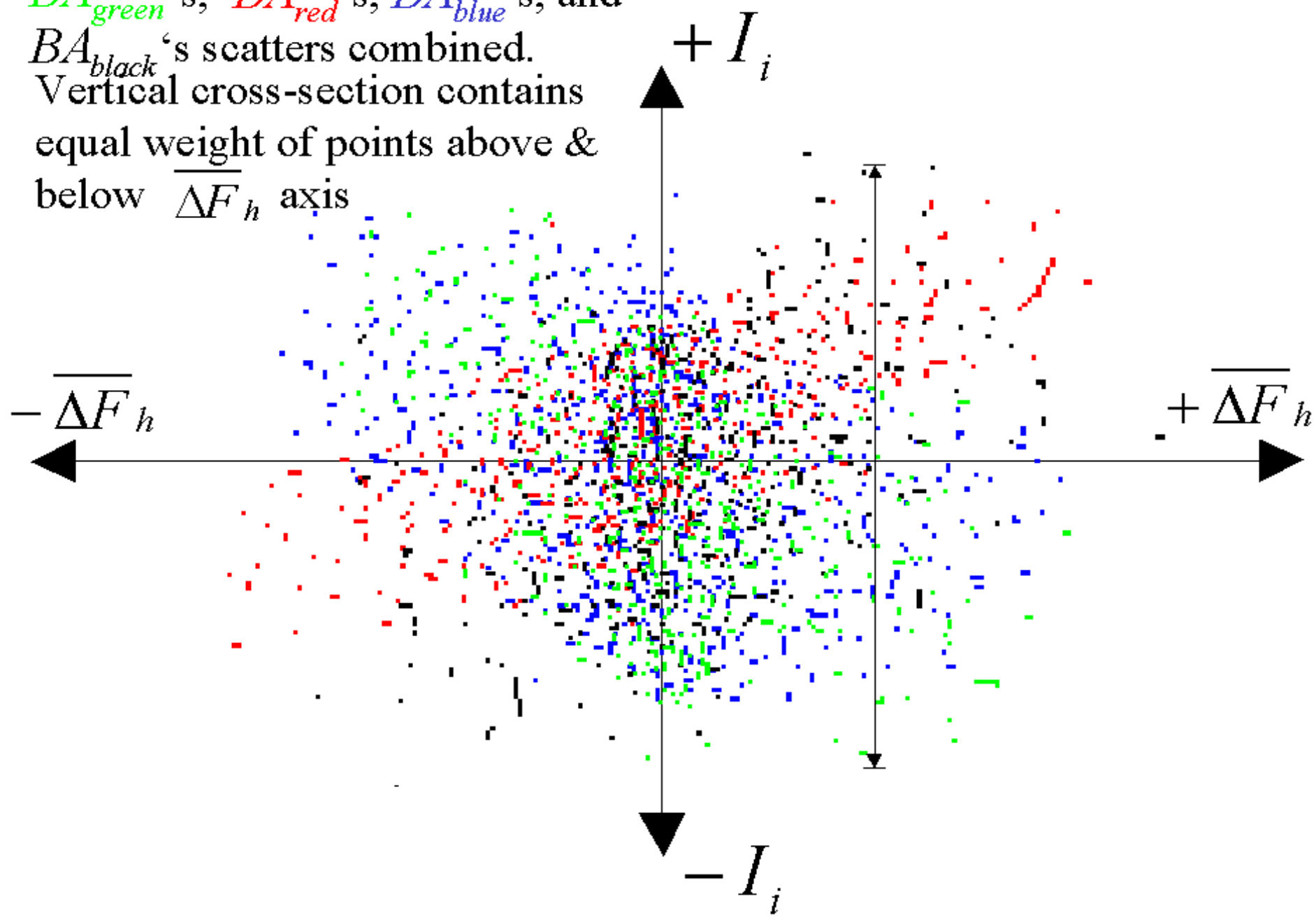


BA_{green} 's, BA_{red} 's, BA_{blue} 's, and
 BA_{black} 's scatters combined.
Vertical cross-section contains
equal weight of points above &
below $\overline{\Delta F}_h$ axis

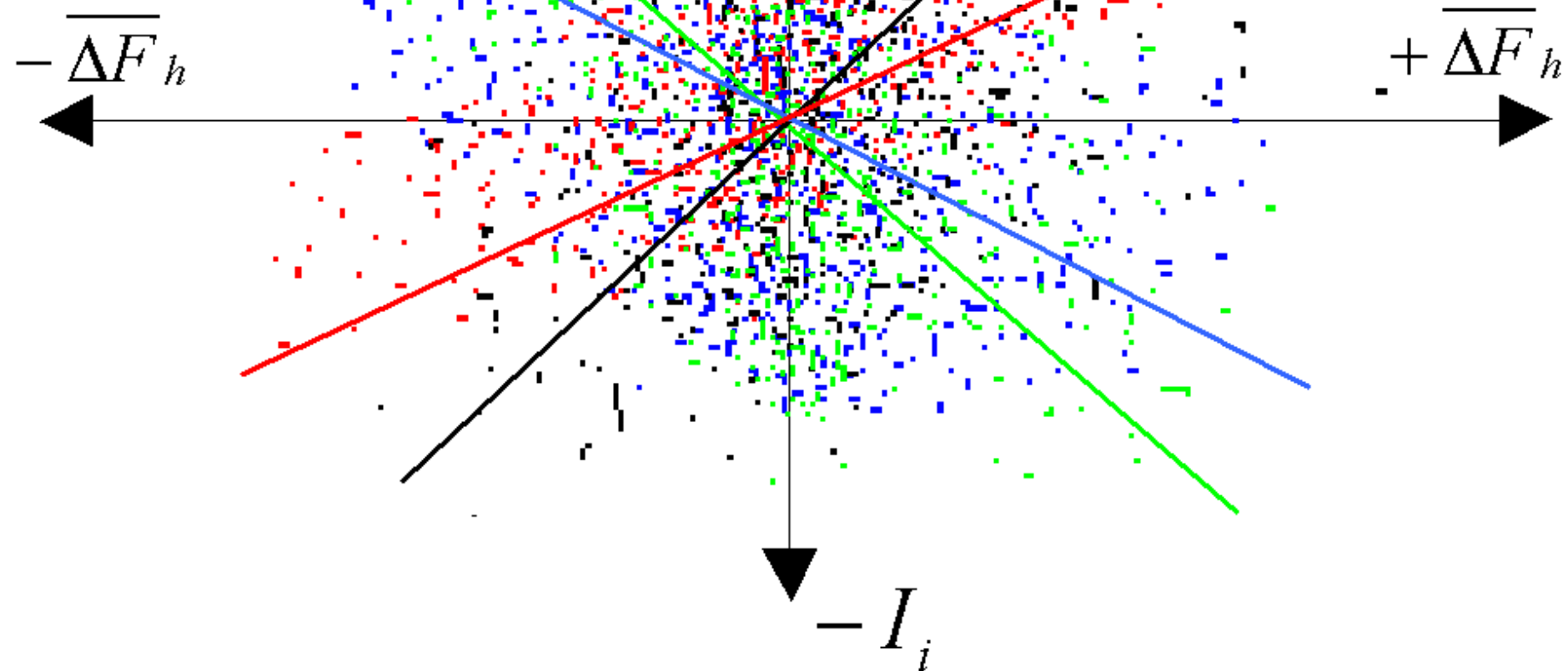


BA_{green} 's, BA_{red} 's, BA_{blue} 's, and BA_{black} 's scatters combined.

Vertical cross-section contains equal weight of points above & below $\overline{\Delta F_h}$ axis



BA_{green} 's, BA_{red} 's, BA_{blue} 's, and BA_{black} 's scatters combined.
Closest line estimate of BA_{green} 's scatter, BA_{black} 's scatter, BA_{blue} 's scatter, & BA_{red} 's scatter



BA_{green} 's, BA_{red} 's, BA_{blue} 's, and BA_{black} 's scatters combined

Line estimate of system's scatter is horizontal line on $\overline{\Delta F}_h$ axis. Zero system inadvertent.

$-\overline{\Delta F}_h$

$+\overline{\Delta F}_h$

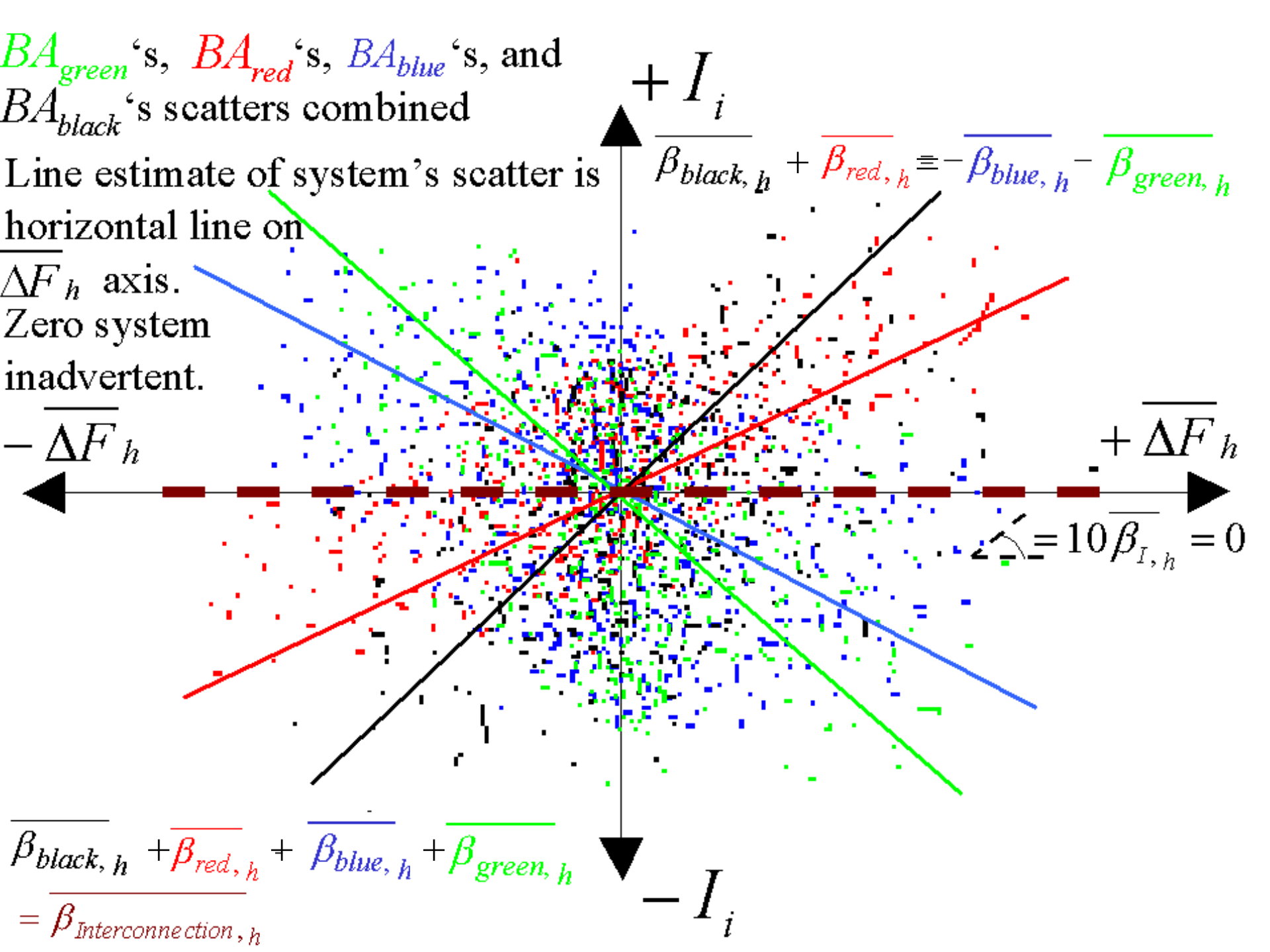
$+I_i$

$$\overline{\beta_{black, h}} + \overline{\beta_{red, h}} \equiv -\overline{\beta_{blue, h}} - \overline{\beta_{green, h}}$$

$$\overline{\beta_{black, h}} + \overline{\beta_{red, h}} + \overline{\beta_{blue, h}} + \overline{\beta_{green, h}} = \overline{\beta_{interconnection, h}}$$

$-I_i$

$$\angle = 10 \overline{\beta_{I, h}} = 0$$

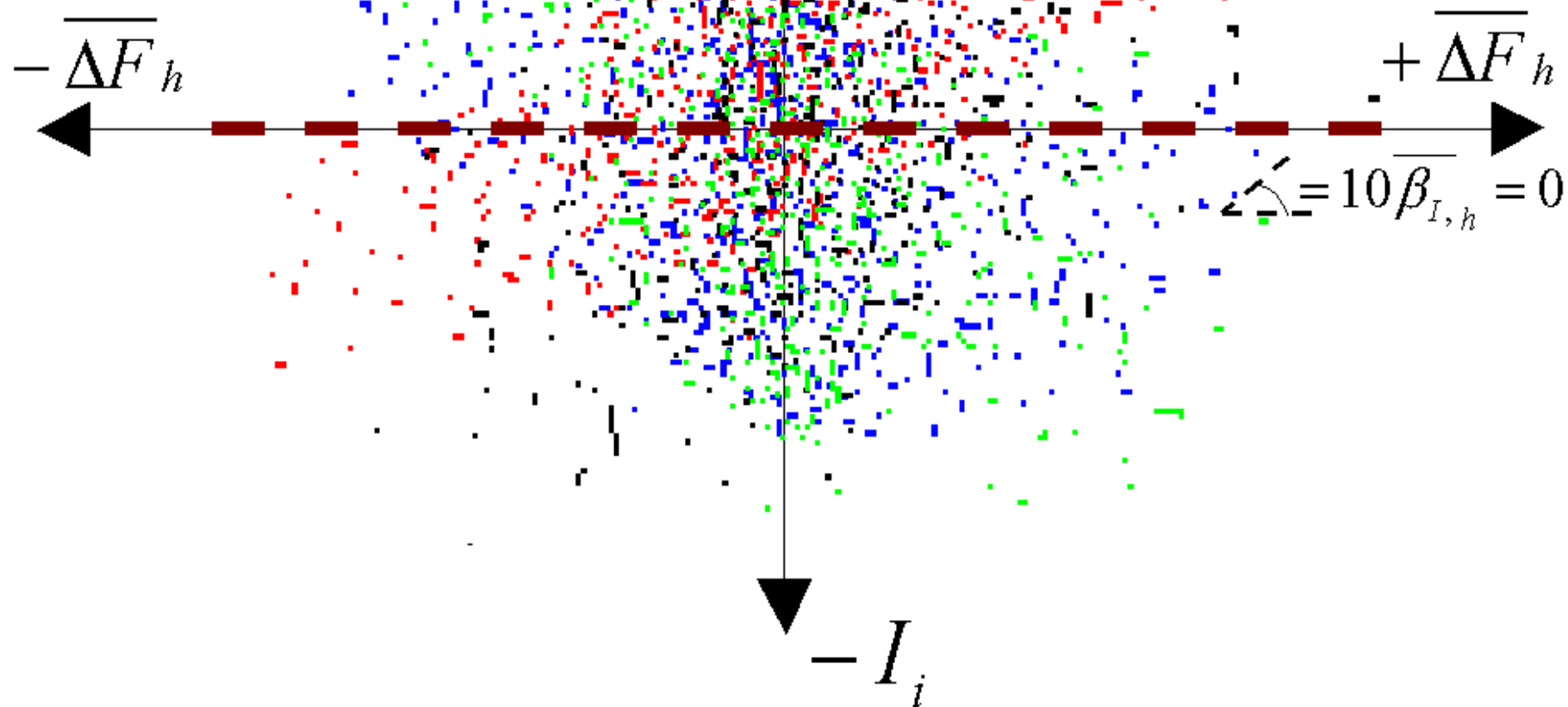


BA_{green} 's, BA_{red} 's, BA_{blue} 's, and BA_{black} 's scatters combined.

Line estimate of system's scatter is horizontal line on

$\overline{\Delta F_h}$ axis.

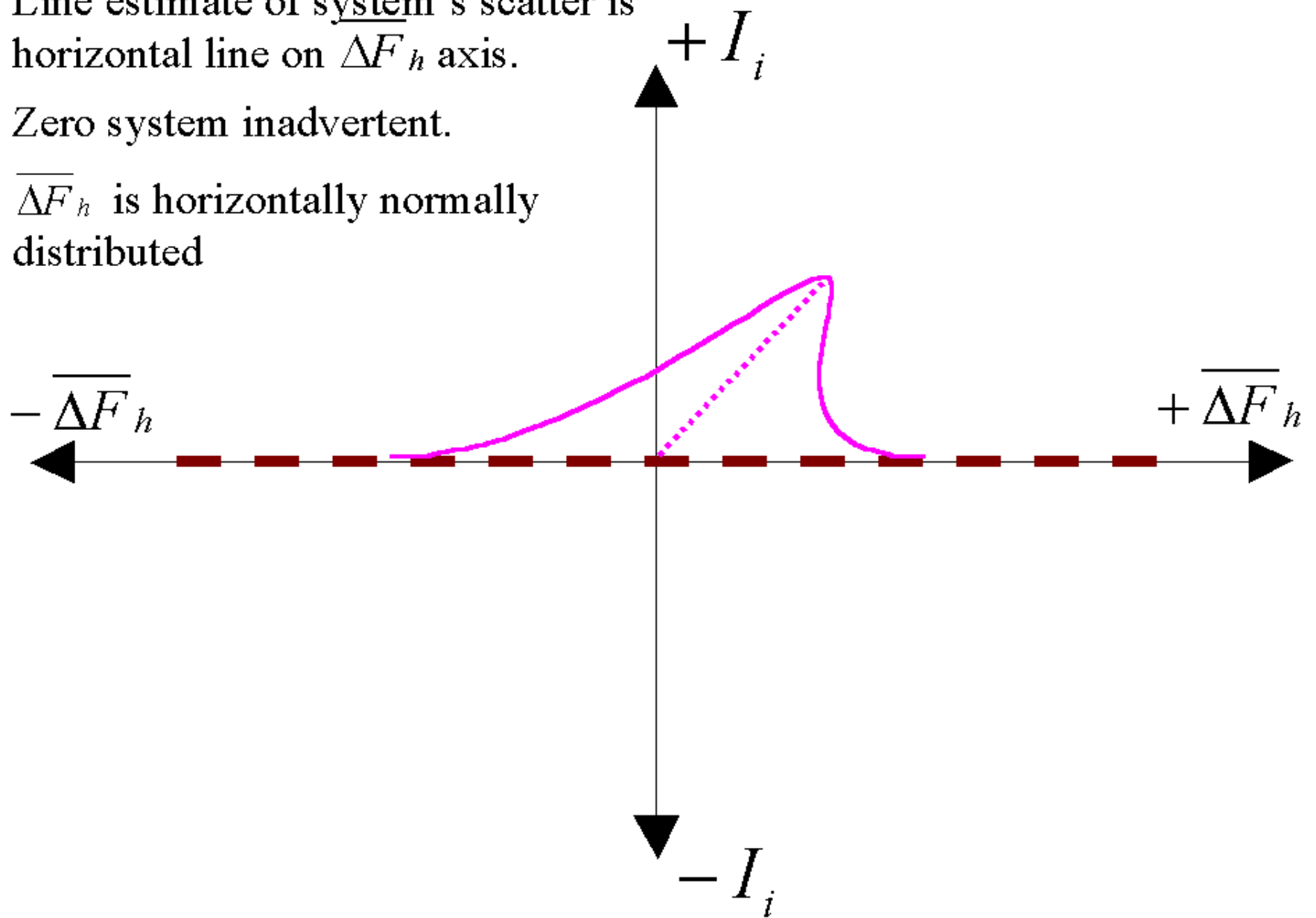
Zero system
inadvertent.



Line estimate of system's scatter is horizontal line on $\overline{\Delta F}_h$ axis.

Zero system inadvertent.

$\overline{\Delta F}_h$ is horizontally normally distributed



Market price of a distribution of points over time, not of a sharp point in time

- Real time transactions cannot be done moment-by-moment deterministically/deliberately
 - Time is too short
- Real time performance must be managed, measured and valued as a statistical distribution
 - Classical physics versus quantum mechanics
 - joint-indeterminacy of position and momentum
 - Joint-indeterminacy of time-quantity and reliability-pricing
 - reliability pricing of a time average

“Computational Equivalence” (Wolfram/Mathematica):
computational limitations in humans & physical nature

Tiered real-time market

- Three tiered market for frequency control
 - NERC, Balancing Authorities, local entities.
 - Frequency is a public good requiring an authority like NERC to drive the frequency-control markets by the threat of penalty.
 - This meets both a reliability and a markets objective
- Balancing Authorities must settle their FCC monthly
 - Since inadvertents sum to zero by definition, Balancing Authorities always clear

Tiered real-time market (cont.d)

- Balancing Authorities must also comply with CPS frequency targeting, acting as agents subject to NERC penalty
 - FCC does not target frequency
 - NERC CPS penalty will prompt Balancing Authorities to trade their CPS rights instead of paying the penalty, the way DOE pollution penalties prompted the market for pollution rights.
 - To meet their monthly CPS scores, Balancing Authorities will trade their frequency control contributions as an alternative to buying options on frequency support

Tiered real-time market (cont.d)

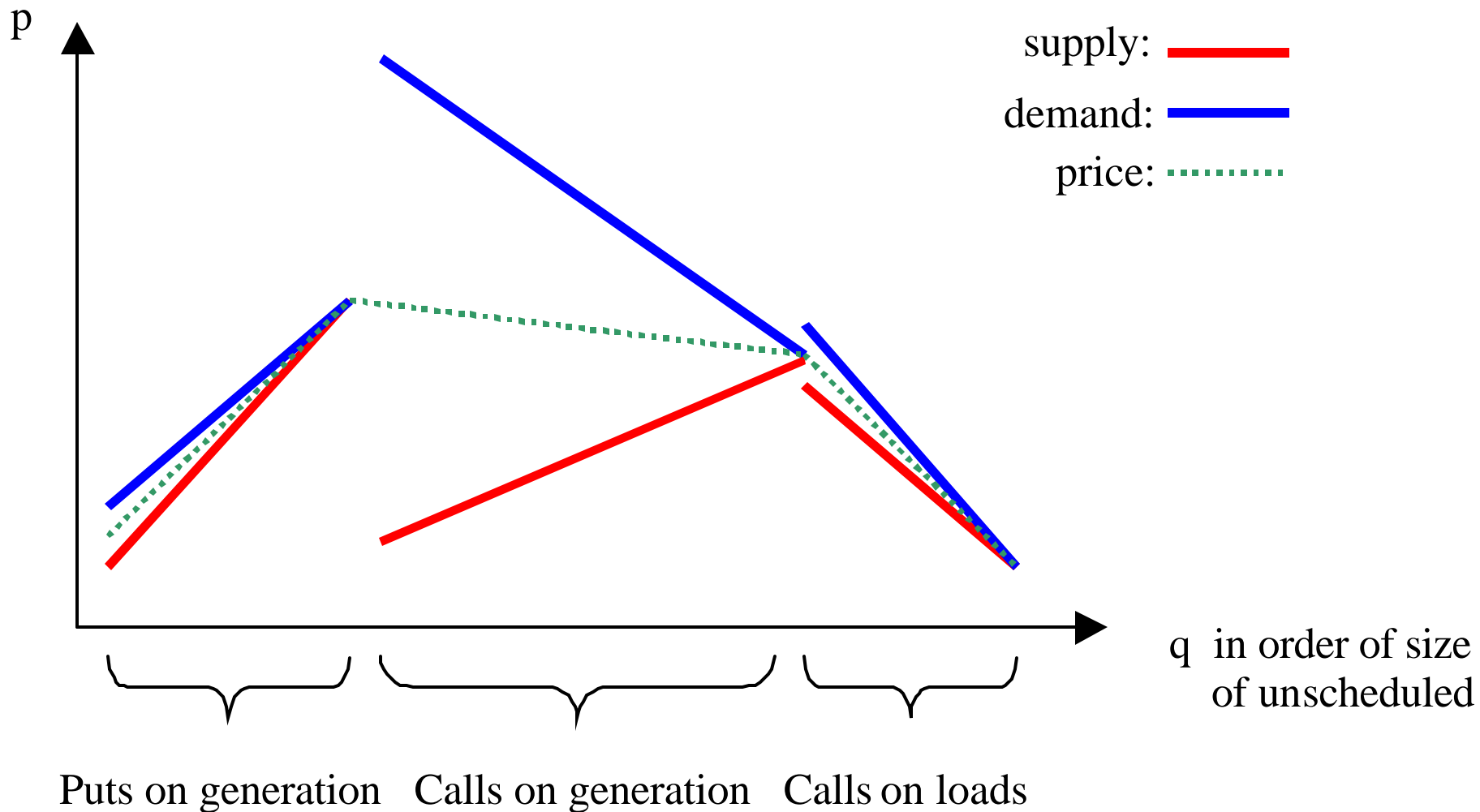
- FCC is open and scalable to a market below Balancing Authorities
 - Balancing Authorities can apply FCC to their constituent entities to incent entities' self-provision and good performance, thereby minimizing the Balancing Authority's own local intervention

Ancillary services markets

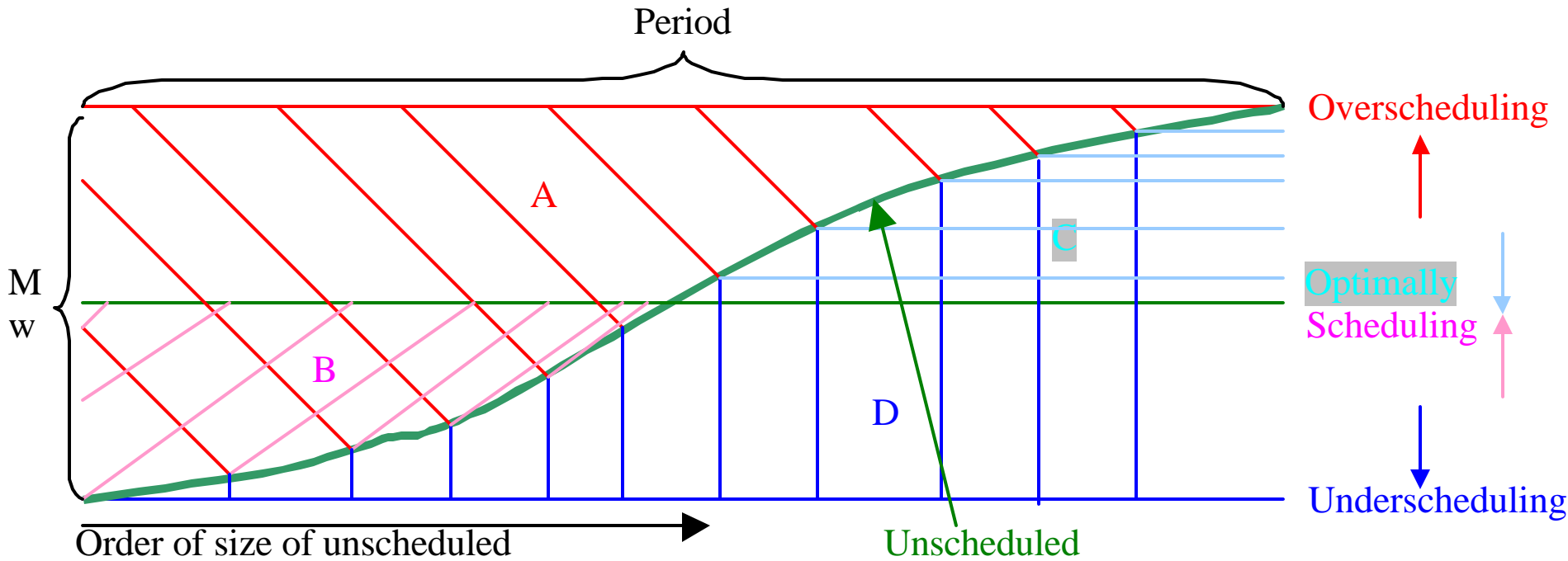
- Ancillary services markets need to be developed as robust options markets
 - The option price is driven by volatility which is another way to capture/express Frequency Control Contribution

Possible portfolio of options

Price should arbitrage buyer's avoided cost of b with supplier's opportunity cost



**In a complete options market for frequency response
the optimal scheduling point minimizes the cost of unscheduled B + C**



A ■
Overscheduled
due to overscheduling

B ■ + ■
Overscheduled + Underscheduled
due to optimally scheduling

D ■
Underscheduled
due to underscheduling

$$\boxed{\text{MinValue}(B + C) \leq \text{Min}[\text{Value}(A), \text{Value}(D)]}$$

Relation between CPS1

and

Frequency Control Contribution

FCC_p

FCC_{-p} extends to all inadvertent the price of the trading & procurement of residual inadvertent done to get compliant with $CPS1$.

The $CPS1$ tolerance band limits and drives FCC_{-p} .

CPS1 boils down to

$$\frac{\overline{\mathbf{b}}_{i, \Delta t} - \overline{b}_{i, \Delta t}}{-\overline{b}_{i, \Delta t}} \text{AVG} \left(\overline{\Delta F}_{\Delta t}^2 \right) \leq \mathbf{e}^2$$

$$\left(\overline{\mathbf{b}}_{i, \Delta t} - \overline{b}_{i, \Delta t} \right) \text{AVG} \left(\overline{\Delta F}_{\Delta t}^2 \right) \leq -\overline{b}_{i, \Delta t} \mathbf{e}^2$$

where $-\overline{b}_{i, \Delta t}$ is a least-squares estimator of bias $\overline{B}_{i, \Delta t}$

With bias $\overline{B}_{i, \Delta t} =_{set} 0$,
 tolerance band $-\overline{b}_{i, \Delta t} \mathbf{e}^2 = 0$ and
CPS1 becomes

$$\overline{\mathbf{b}}_{i, \Delta t} \text{AVG} \left(\overline{\Delta F}_{\Delta t}^2 \right) \leq 0$$

$$\frac{\text{AVG} \left(T_i \times \overline{\Delta F}_{\Delta t} \right)}{\text{AVG} \left(\overline{\Delta F}_{\Delta t}^2 \right)} \text{AVG} \left(\overline{\Delta F}_{\Delta t}^2 \right) \leq 0$$

$$\text{AVG} \left(T_i \times \overline{\Delta F}_{\Delta t} \right) \leq 0$$

$FCC_{\bar{p}}$ monetizes the part

$$AVG(T_i \times \overline{\Delta F}_{\Delta t}) \leq 0$$

of $CPS1$ not being subject to compliance enforcement

$$-k \times AVG(I_i \times \overline{\Delta F}_h) = FCC_{\bar{p}}$$

because

$$FCC_h \times p_{10\bar{b}} = -10 \overline{b_{i,h}} \times p_{10\bar{b}} = -\frac{\sum_n (I_i \times \overline{\Delta F}_h)}{\sum_n \overline{\Delta F}_h^2} \times p_{10\bar{b}} = FCC_{\bar{p}}$$

since

$$p_{10\bar{b}} \stackrel{?}{\approx} k \times AVG(\overline{\Delta F}_h^2)$$

Trading/procurement of $\overline{\mathbf{b}}_{i,h}$ to get within the *CPS1* tolerance band \mathbf{e}^2

$$\frac{\overline{\mathbf{b}}_{i,\Delta t} - \overline{\mathbf{b}}_{i,\Delta t}}{-\overline{\mathbf{b}}_{i,\Delta t}} \text{AVG} \left(\overline{\Delta F}_{\Delta t}^2 \right) \leq \mathbf{e}^2$$

drives the price $p_{10\overline{\mathbf{b}}}$ of all $\overline{\mathbf{b}}_{i,h}$ in

$$FCC_{p-} = p_{10\overline{\mathbf{b}}} \times FCC_h = p_{10\overline{\mathbf{b}}} \times (-10\overline{\mathbf{b}}_{i,h}).$$

- Marginal price of $\overline{\mathbf{b}}_{i,h}$ in terms of $\overline{\Delta F}_h$.
- When $\overline{\Delta F}_{\Delta t}^2 \leq \mathbf{e}^2$ it takes less response $-\overline{\mathbf{b}}_{i,\Delta t}$ than regulation $-\overline{\mathbf{b}}_{i,\Delta t}$ to avoid *CPS1* violation.

FCC provides a means for *BA s i* to decentralize *CPS1* frequency control to entities *j* by passing through the cost/benefit of *BA s i s'* *CPS1* compliance to the entities *j* necessitating/causing it.

- to alleviate *BA i*'s *CPS1* compliance, and
- to re-decentralize frequency control when *CPS1* compliance is centralized into fewer and bigger *BA s*

π : Instantaneous Approximate CPS1

— Probability **On average over the past year:**

e : Annual standard deviation of $\overline{\Delta F}$

Target RMS: $e = \sqrt{e^2 + m^2(\overline{\Delta F})}$

$m(\overline{\Delta F})$: Year's Mean of $\overline{\Delta F}$

$\overline{\Delta F}$: 1-minute average of Frequency error

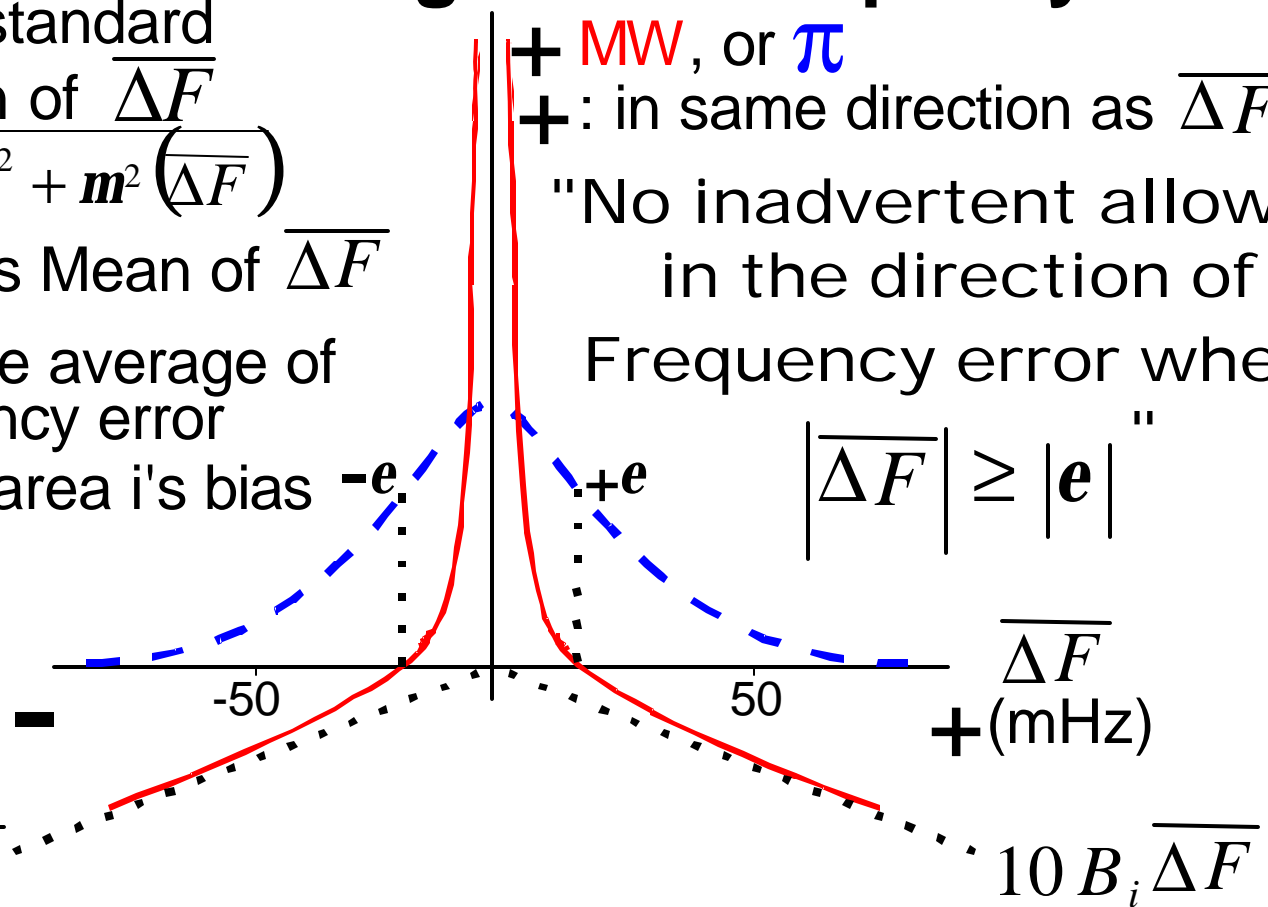
$B_i < 0$: Control area i's bias

+ MW, or π

+ : in same direction as $\overline{\Delta F}$

"No inadvertent allowed in the direction of Frequency error when

$$|\overline{\Delta F}| \geq |e|$$



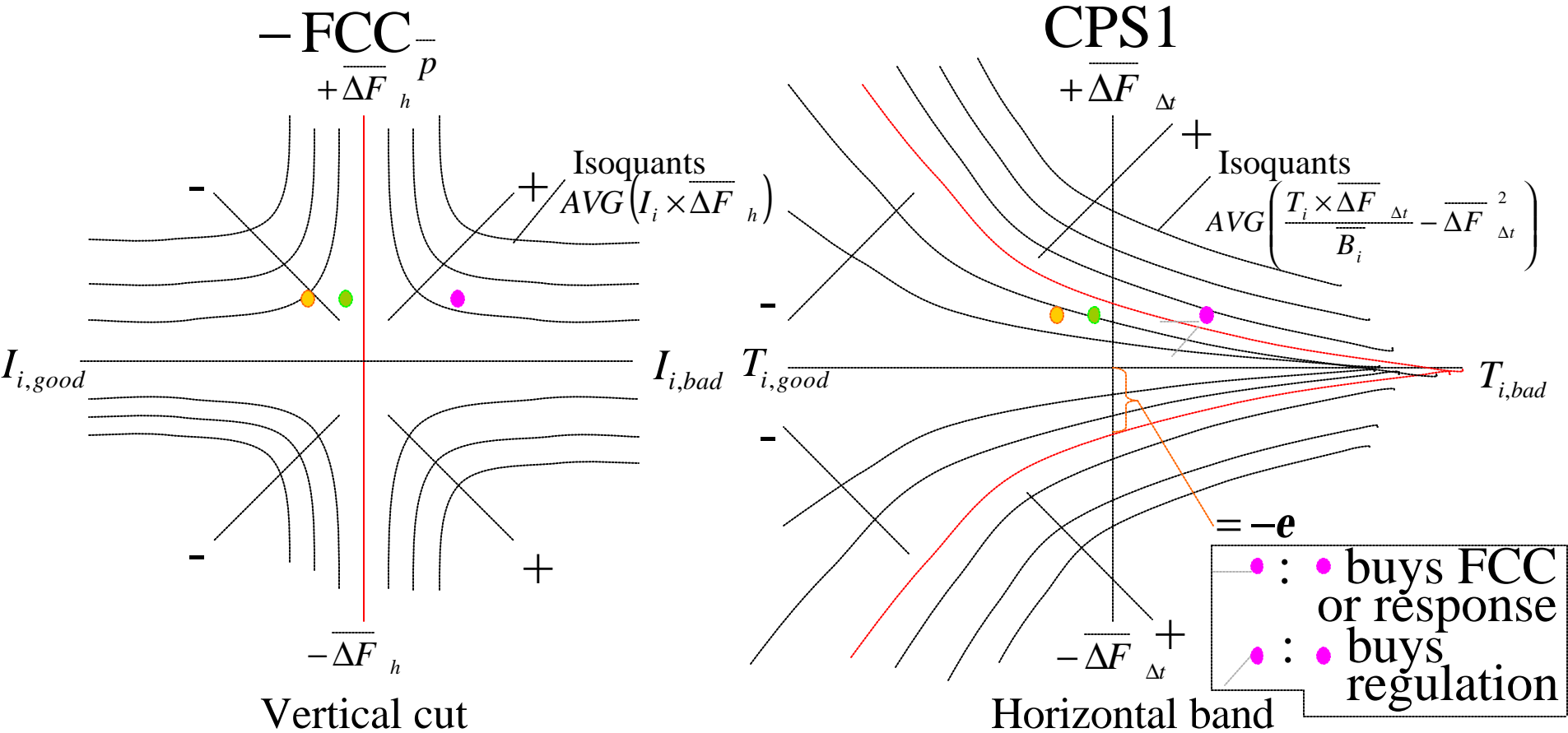
— : Control area i's maximum allowed 1-minute average tie-line error (plus response obligation) in direction of the frequency error:

$$\overline{\Delta T}_i = -10B_i \left(e \frac{e}{\overline{\Delta F}} - \overline{\Delta F} \right)$$

- - - : One-year target probability density of 1-minute averages of frequency error, adjusted for deviation of the mean from 0

FCC_p's **cut** is perpendicular to CPS1's **cut/band**.

Payments for traded FCC_hs would sum to zero around CPS1's **cut/band** when $|\overline{\Delta F}_{\Delta t}| \leq e$.
 There is excess demand for traded FCC_hs outside CPS1's cut/band when $|\overline{\Delta F}_{\Delta t}| > e$
 whence receipt of FCC_p reduces CPS1 penalty to incent BAs to get back inside.



FCC_p's vertical cut gets stretched right from the middle into CPS1's horizontal band.
 BA • outside his CPS1 cut/band buys enough FCC_h from BAs • & • to get inside his CPS1 cut/band & avoid CPS1 penalty, and thereby helps set the FCC_h settlement price $P_{10\bar{b}}$.

Tolerance band makes CPS1 control
proactive:
a Balancing Authority becomes non-compliant
before
the Interconnection becomes non-compliant.

CPS1 makes control economically more efficient by enabling:

- avoidance of expensive “overcontrolling”
to too-short deviations
that wears and tears generators.
- natural economic incentive to control
just as effectively and compliantly
but more cheaply
to a longer-term sample average.