Traffic Flow:
From experimemts to Modeling

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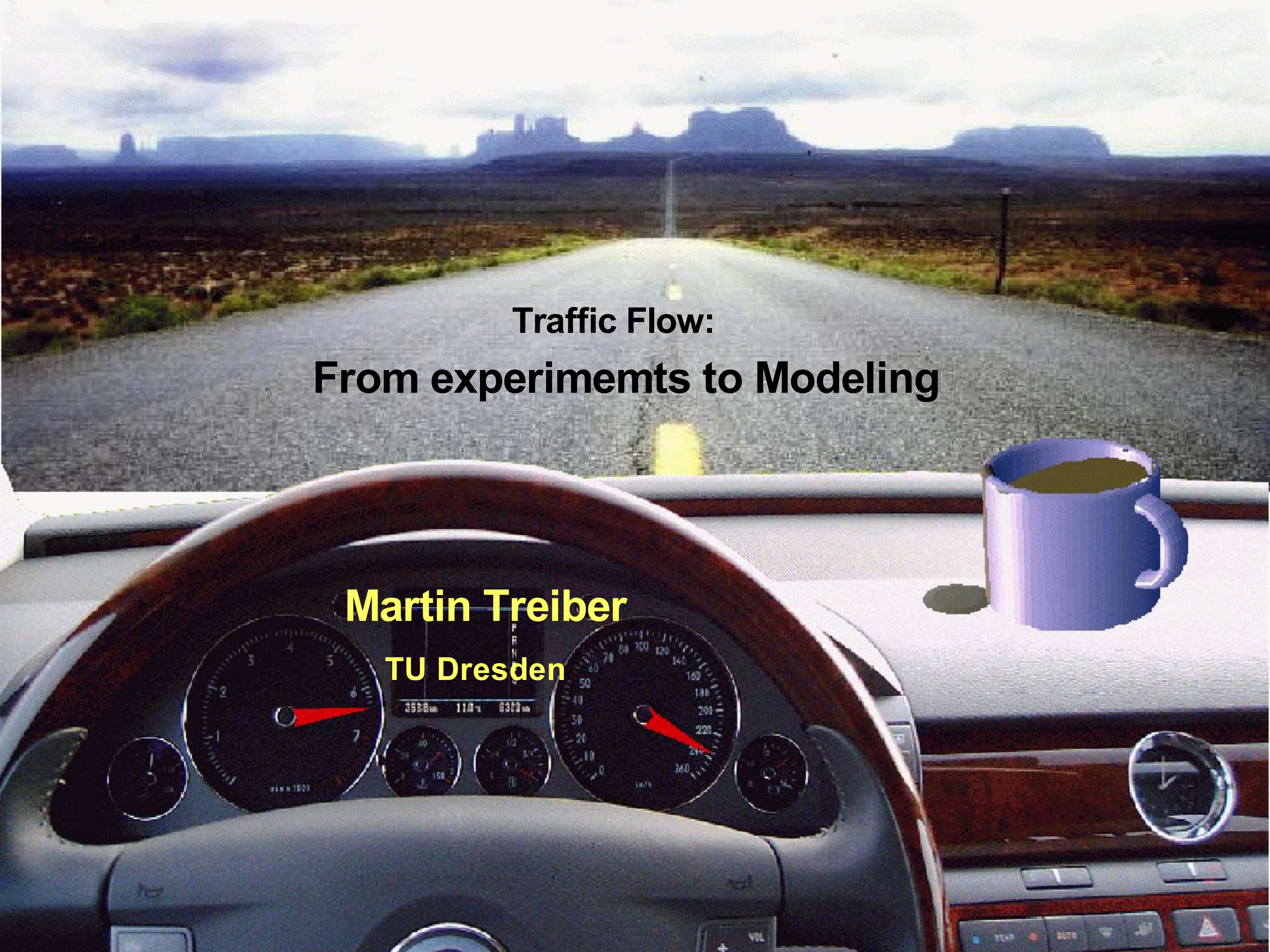


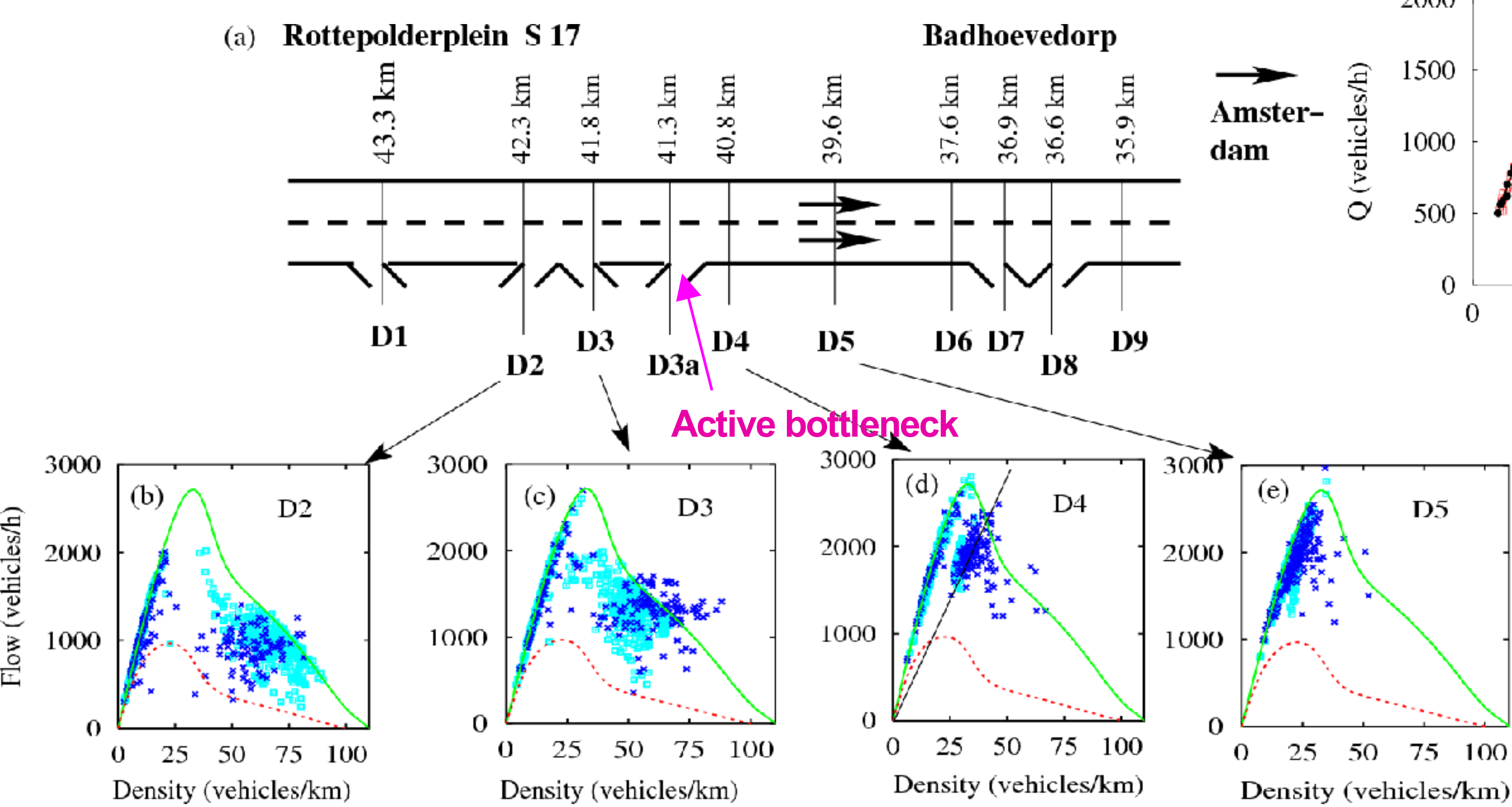
Overview

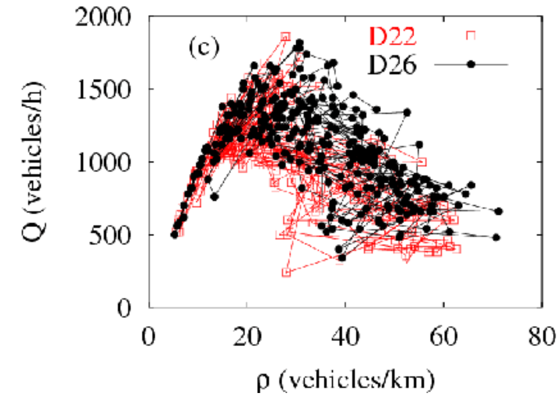
- Empirics: Stylized facts
- Microscopic and macroscopic models: typical examples:
- Linear stability: Which concepts are relevant for describing traffic flow?
- From the stability diagram to the “dynamic state diagram”: Mechanisms for generating the observed spatiotemporal and local phenomena
- Numerical examples: Car-following, CA and macroscopic models with one, two, or three phases …
- Conclusion: How many traffic “phases” are necessary?

Stylized facts relating to local aspects: scattered flow-density data

Dutch A9 Haarlem-Amsterdam

German A9-South



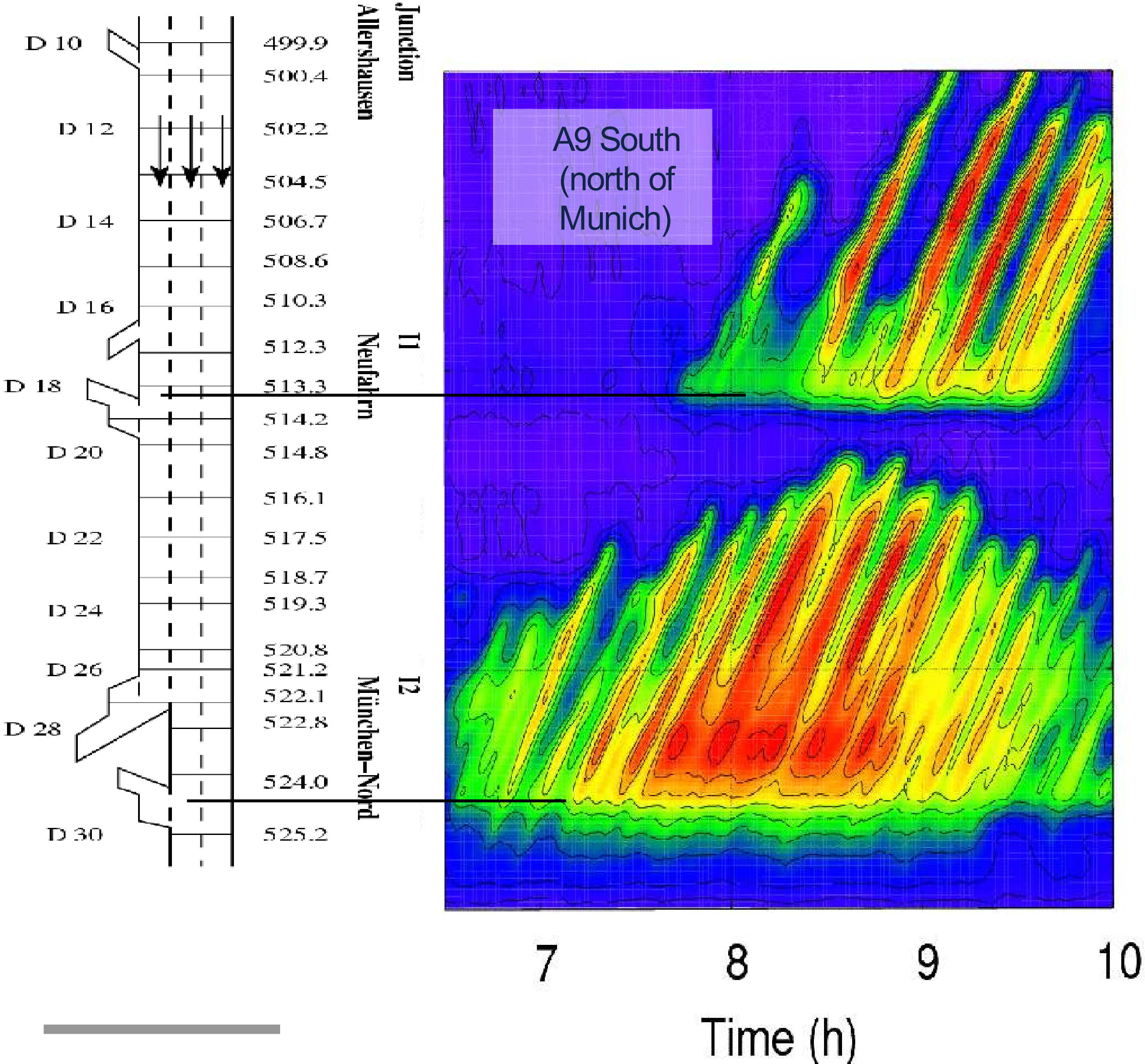


Nonhomogeneous-instationary

Homogeneous-stationary

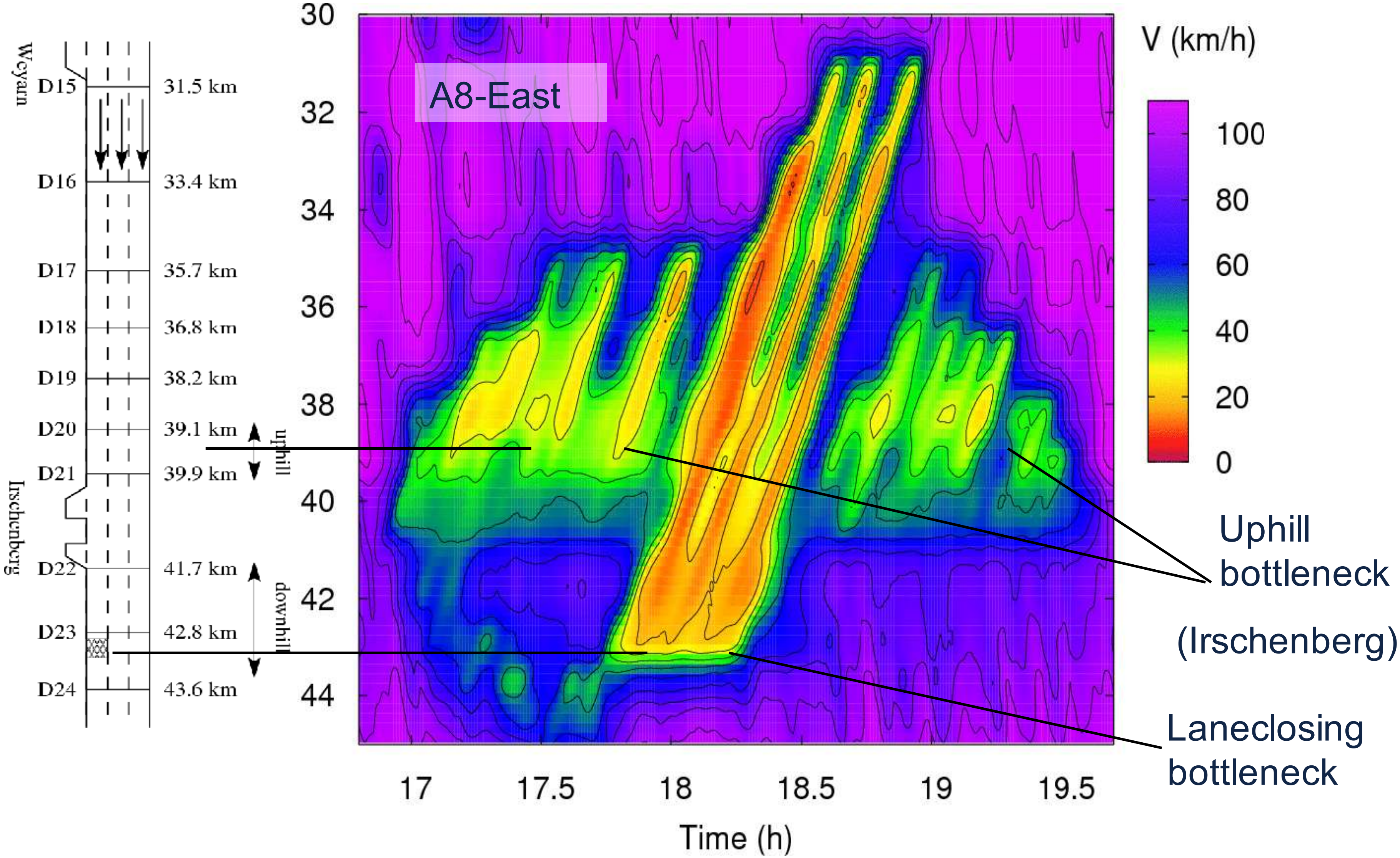
Homogeneous-in speed

2. Stylized facts relating to spatiotemporal data

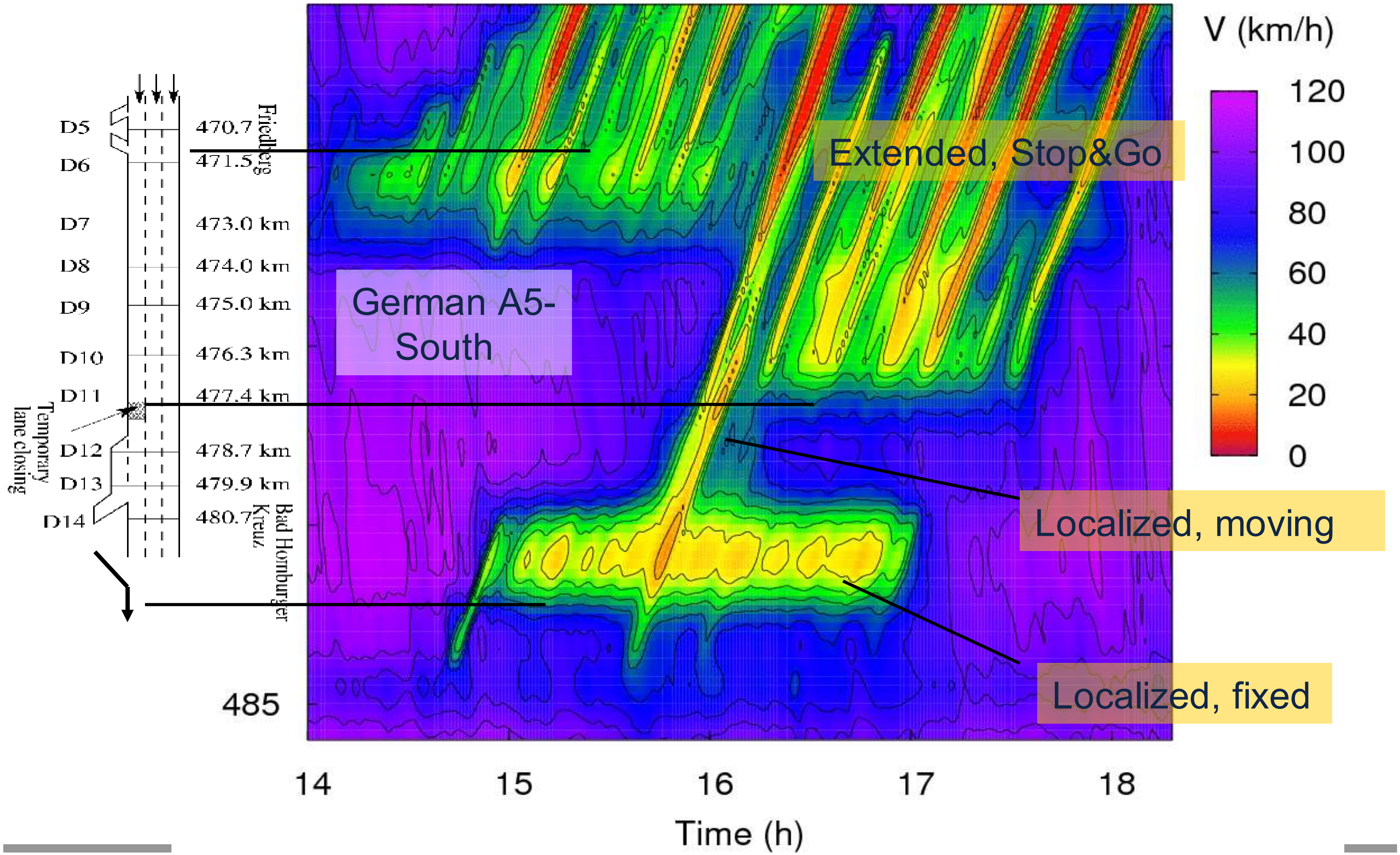


- **Downstream front:** Fixed or moving upstream with velocity vg
- **Upstream front:** Non-characteristic (pos/neg.) velocity
- **Internal structures:** Moving all with vg
- **Amplitude** of internal structures grows when moving upstream
- **Frequency** grows with severety of bottleneck

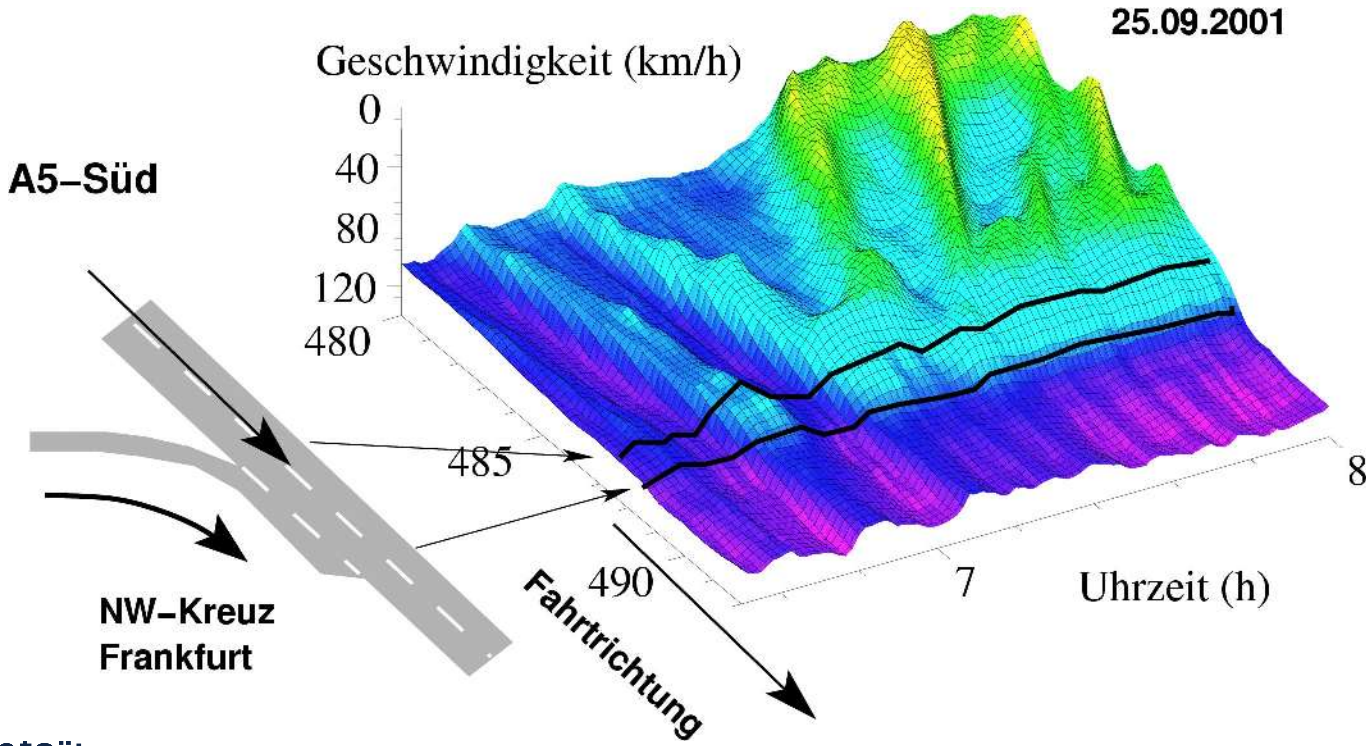
2(a) The bottlenecks may be diffeent in nature



2(b): The patterns may form composite structures



2(c): To “make a jam”, one needs three ingredients …

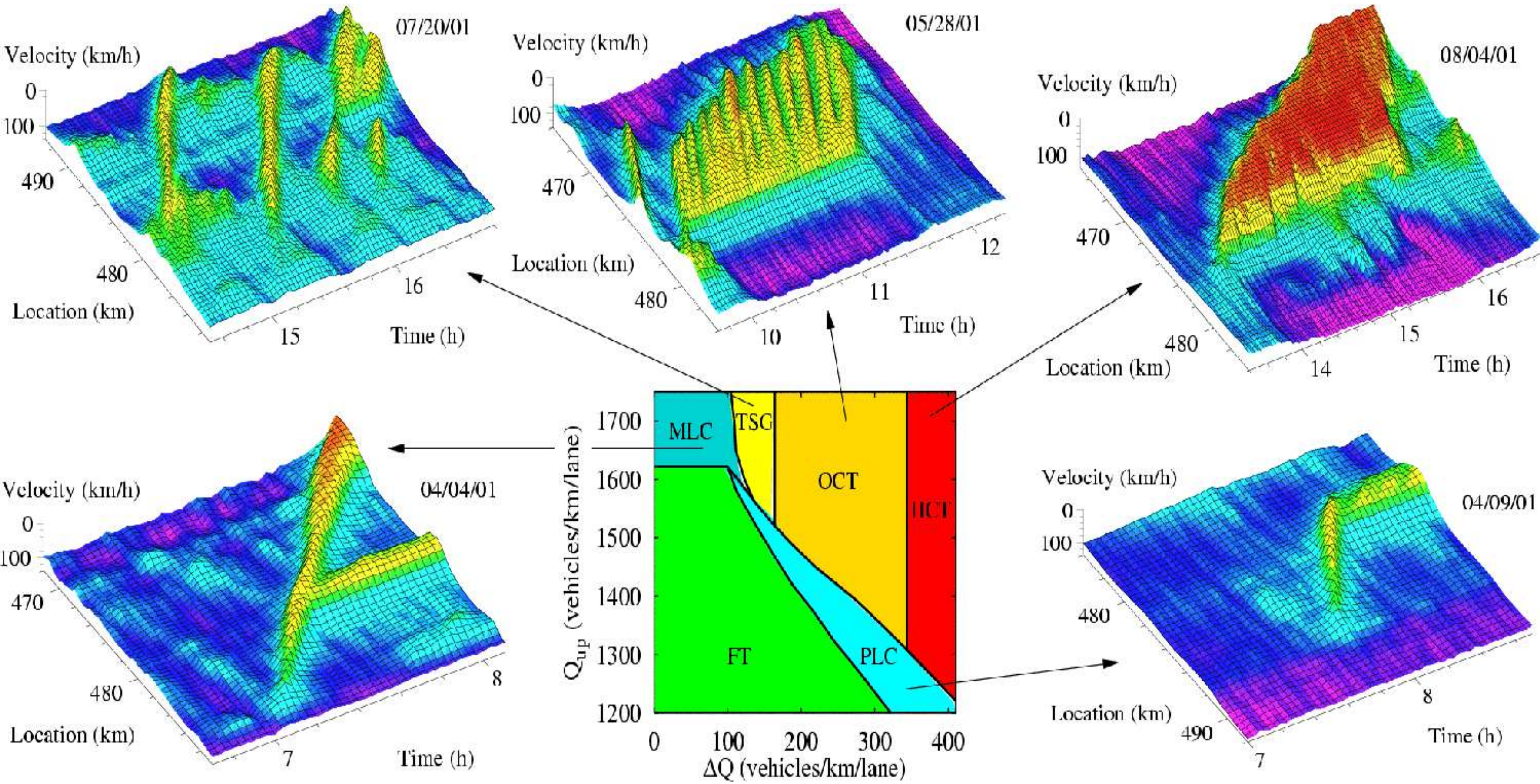


- Three „ingredients¨:

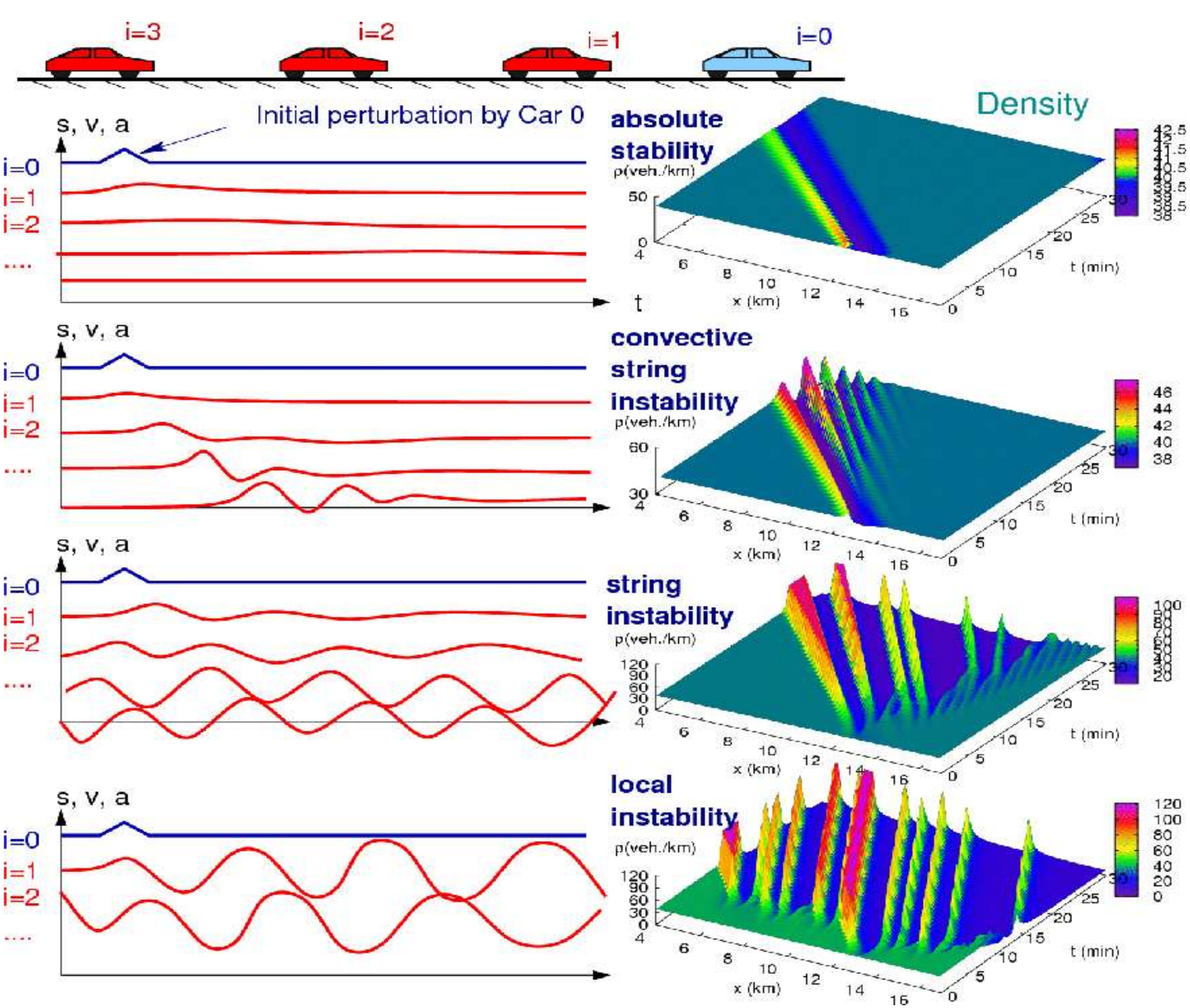
2. **High traffic demand (inflow)**
3. **Spatial inhomogeneity (“bottleneck”)**
4. **Perturbation in traffic flow**

Summary: Typical spatiotemporal patterns

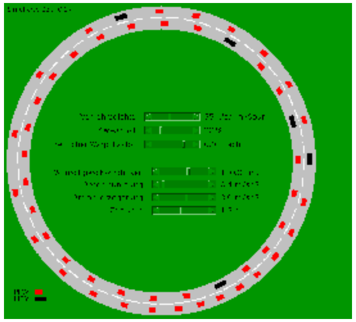
German A5 near Frankfurt



II Stability: 1. Which types are relevant for traffic flow?



- Three kinds of linear instabilities:
  - convective string instability,
  - Absolute string instability,
  - Absolute local instability.
- Additional nonlinear instabilities (metastability, hysteresis)



► Simulate …

(s1=14 m, a=0.6 m/s^2)

2. Collective instabilities: Mathematical and numerical definitions

Linear modes: $A_k(x,t) = e^{ikx} e^{\lambda(k)t}$

Localized perturbation: $A(x,0) = \begin{cases} \epsilon & |x - x_c| < \frac{1}{2\rho_0} \\ 0 & \text{otherwise.} \end{cases}$

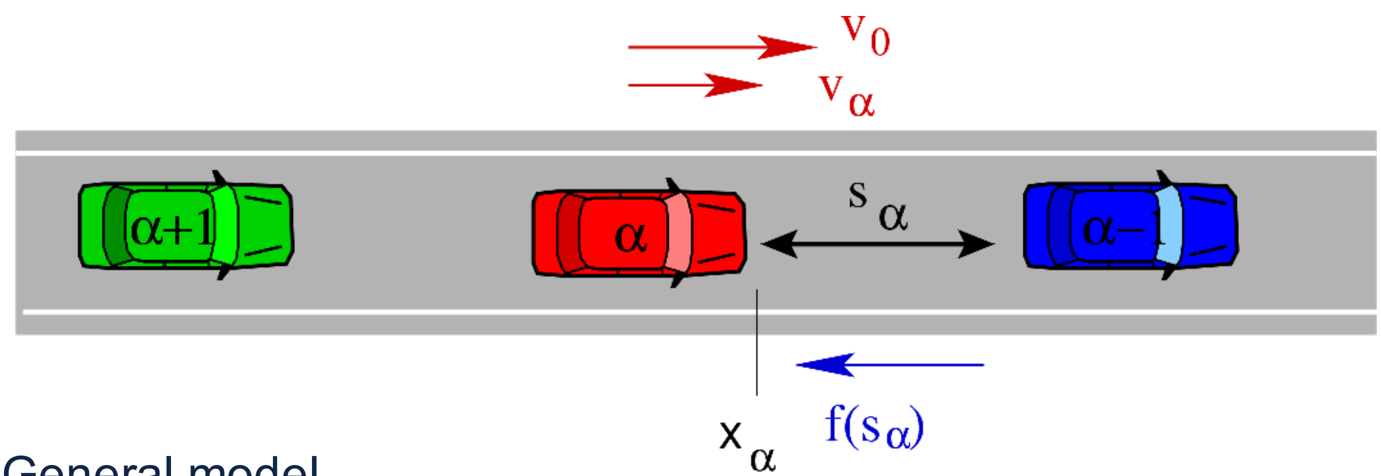
- Linear string instability:

  Re(λ(k))>0 for some k, or $\lim_{t\to\infty} \int \mathrm{d}x |A(x,t)| > 0$

- Nonlinear instability (metastability): $\lim_{t\to\infty} \int \mathrm{d}x |A(x,t)| = 0 \quad \forall \epsilon < \epsilon_{\text{nl}}$ for some $\varepsilon_{nl} > 0$

- Convective (meta-)stability: Linearly (meta-)stable, and $\lim_{t\to\infty} |A(x,t)| = 0$ For any fixed x

Derivation of the criterion for linear string instability



- General model

$$\frac{\mathrm{d}x_\alpha}{\mathrm{d}t} = v_\alpha,$$

$$\frac{\mathrm{d}v_\alpha}{\mathrm{d}t} = a_{\mathrm{mic}}\Big(s_\alpha(t-T_r), v_\alpha(t-T_r), s_{\alpha-1}(t-T_r), v_{\alpha-1}(t-T_r), \ldots\Big)$$

- Local and instantaneous model

$$\frac{\mathrm{d}v_\alpha}{\mathrm{d}t} = a_{\mathrm{mic}}\Big(s_\alpha(t), v_\alpha(t), \Delta v_\alpha(t)\Big)$$

Example: The Intelligent-Driver Model (IDM)

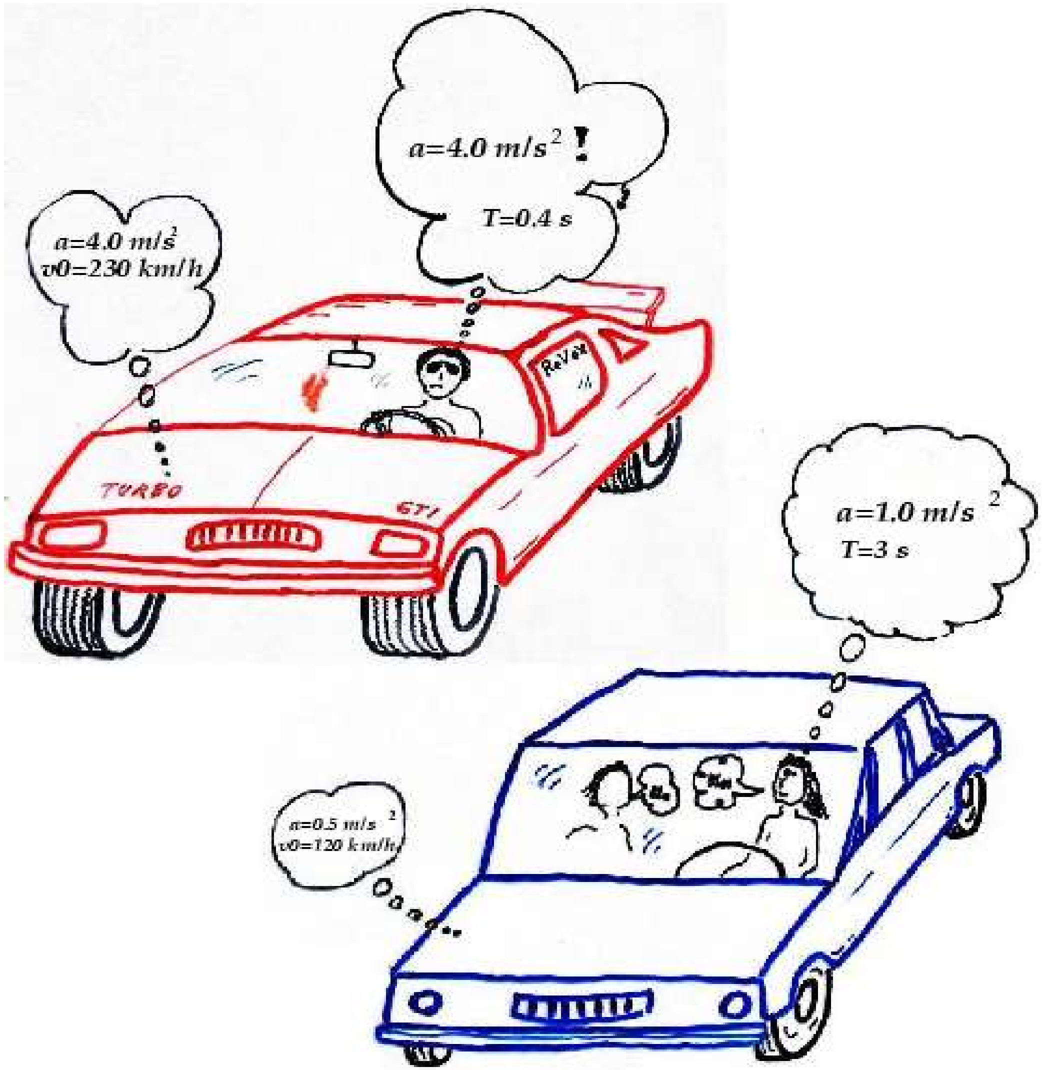
- Equations of motion:

$$\begin{aligned}\dot{x}_\alpha &= v_\alpha, \\ \dot{v}_\alpha &= a\underbrace{\left[1-\left(\frac{v_\alpha}{v_0}\right)^\delta\right.}_{\text{Beschleunigung}}\underbrace{\left.-\left(\frac{s^*(v_\alpha,\Delta v_\alpha)}{s_\alpha}\right)^2\right]}_{\text{Bremsverzögerung}}\end{aligned}$$

- Dynamic desired distance

$$s^*(v,\Delta v) = \underbrace{s_0}_{\substack{\text{Mindest-}\\ \text{abstand}}} + \underbrace{vT}_{\substack{\text{“Sicherheits”-}\\ \text{abstand}}} + \underbrace{\frac{v\Delta v}{2\sqrt{ab}}}_{\substack{\text{dynamischer}\\ \text{Teil}}}$$

IDM Model Parameters



Parameter	Typical value
v_0	120 km/h
T	1.5 s
a	0.3-2.5 m/s²
b	2.0 m/s²
s_0	2 m
Reaction time T’	1-2 s
Number of observed vehicles	1-4

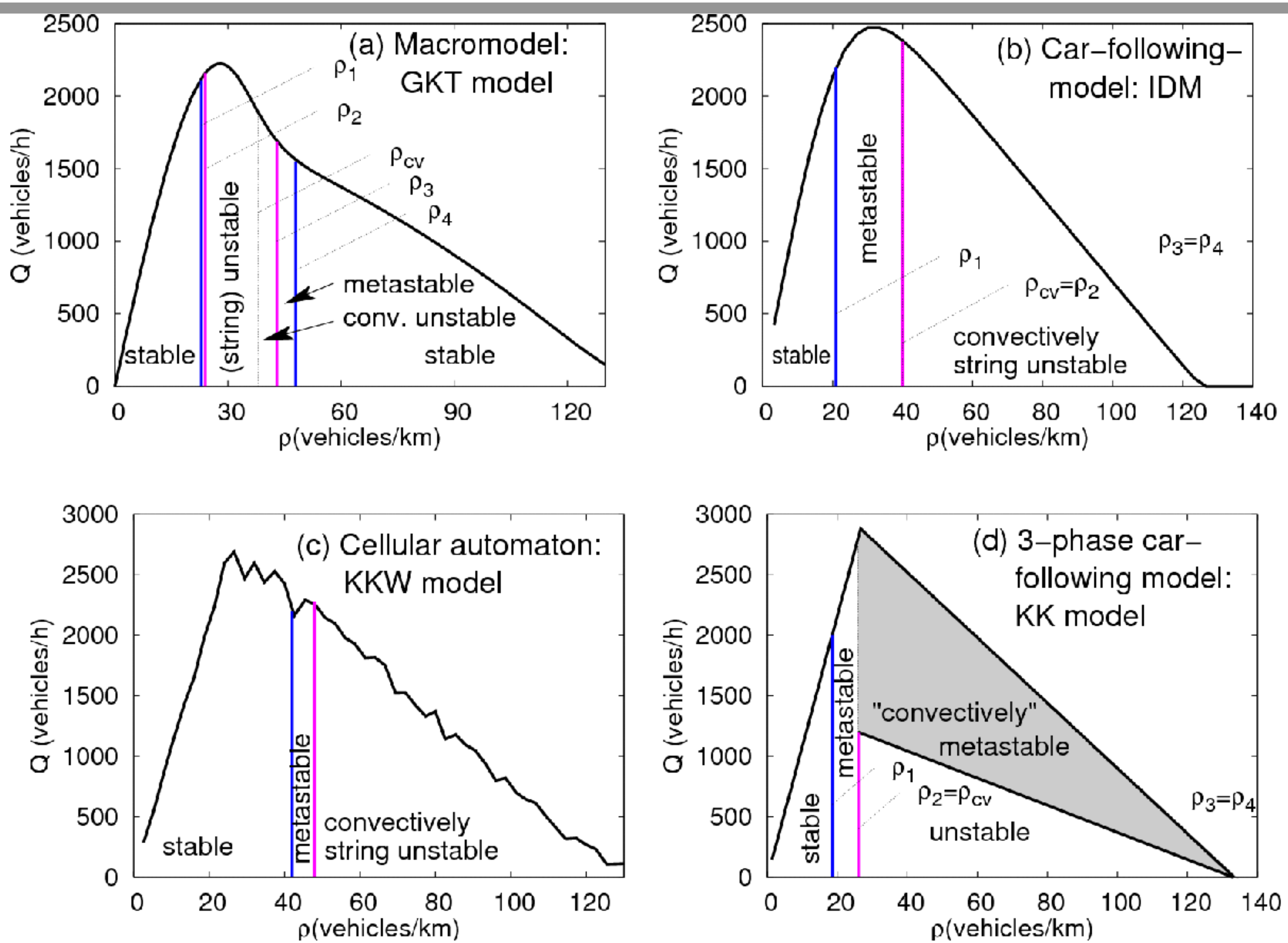
Example: General macroscopic model

$$\frac{\partial \rho}{\partial t} + V\frac{\partial \rho}{\partial x} = -\rho\frac{\partial V}{\partial x} + D\frac{\partial^2 \rho}{\partial x^2},$$

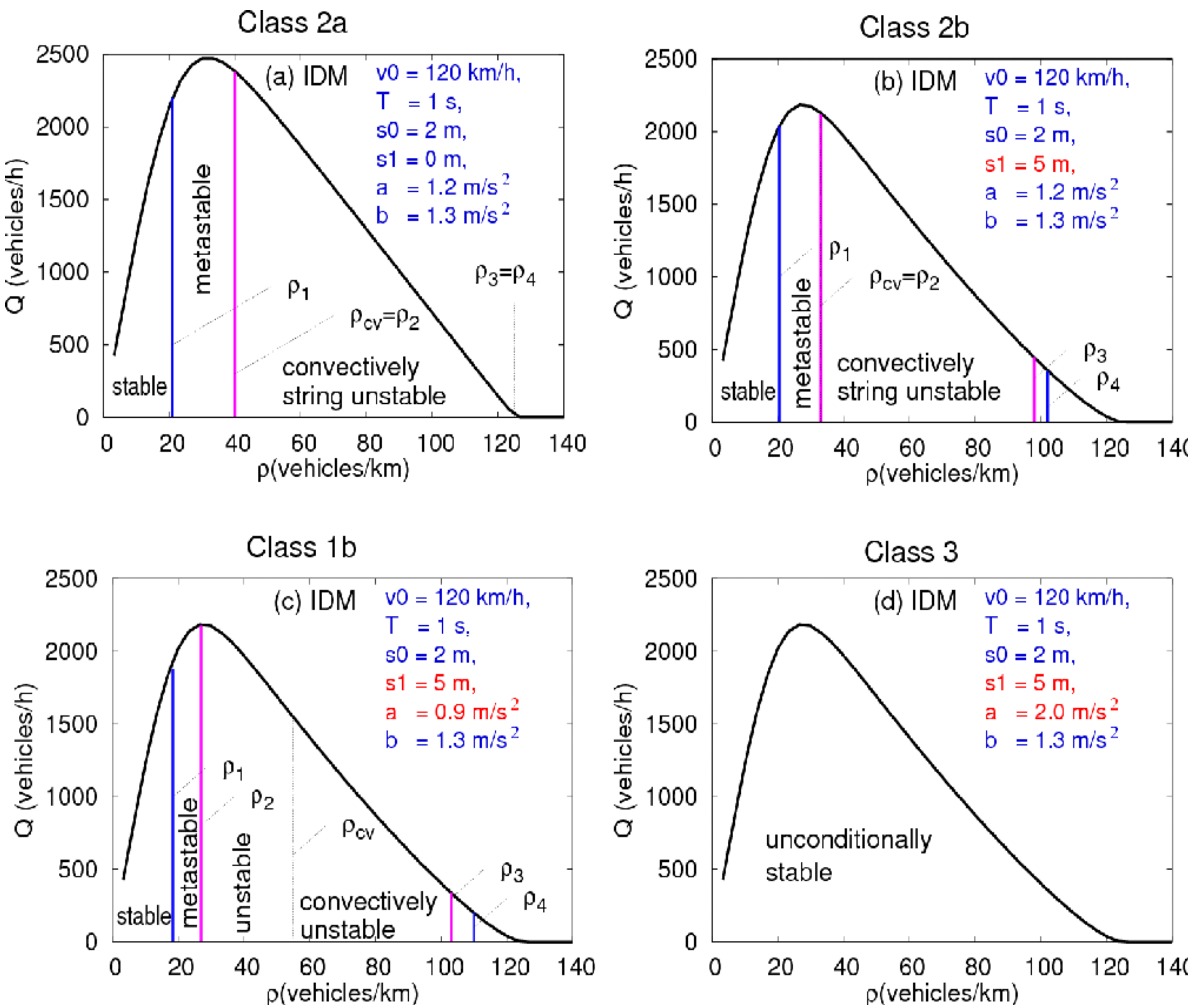
$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = \frac{V_\mathrm{e}(\rho)-V}{\tau} - \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}x} + \nu\frac{\partial^2 V}{\partial x^2}$$

- Stability conditions for both micro and macro models: Blackboard …

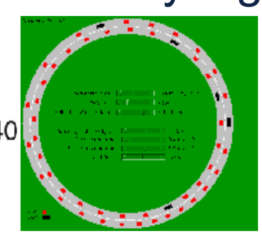
Stability diagram for several models …



One and the same model can adopt several stability classes!



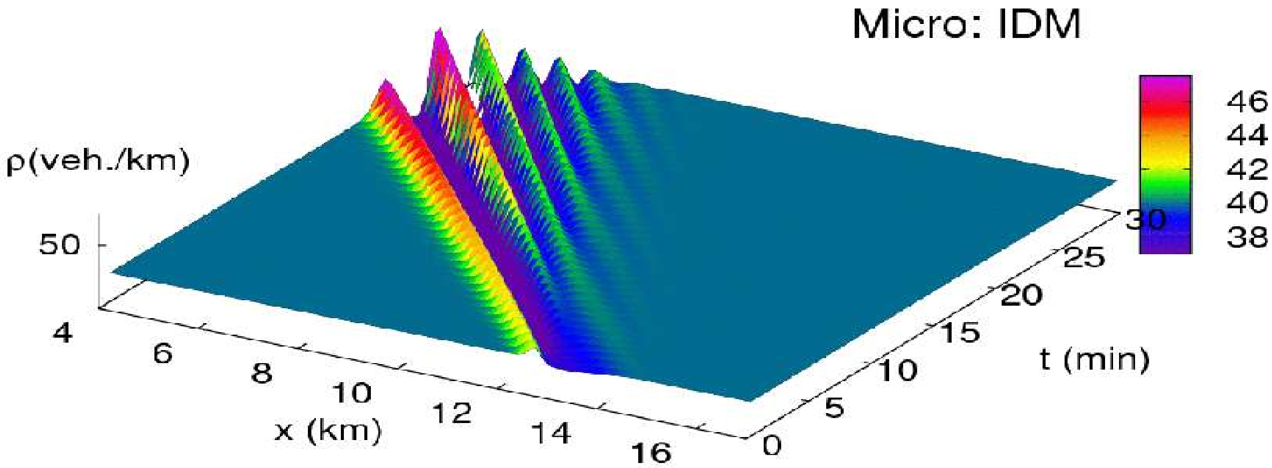
- **Class 1:** Maximum flow unstable
- **Class 2:** Maximum flow (meta-)stable, (convectively) unstable for higher densities
- **Class 3:** Unconditionally stable
- **Subclasses a/b:** No restabilization/ restabilization for very high densities

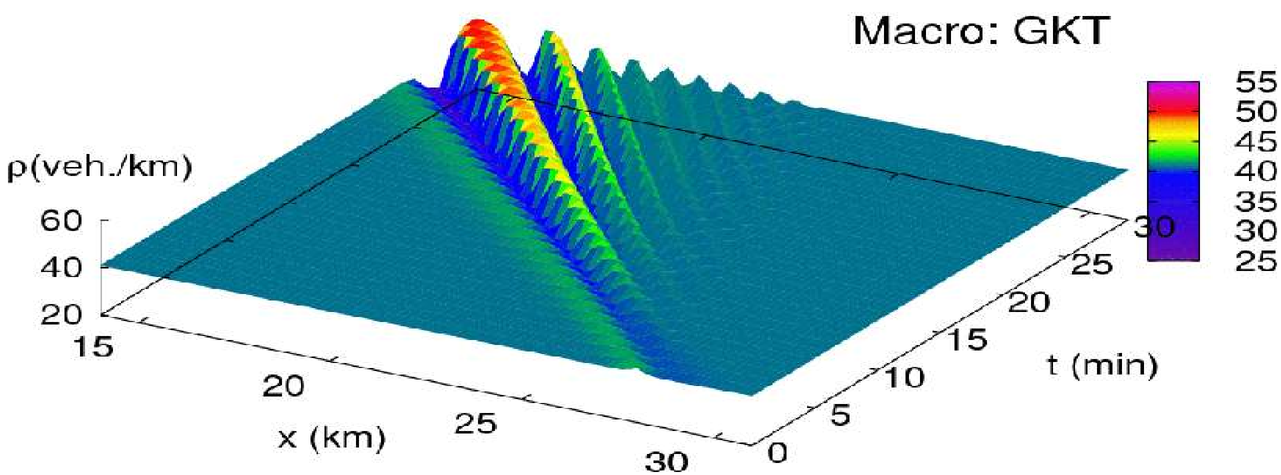


Class 1/2/3: a=0.3/0.6/2

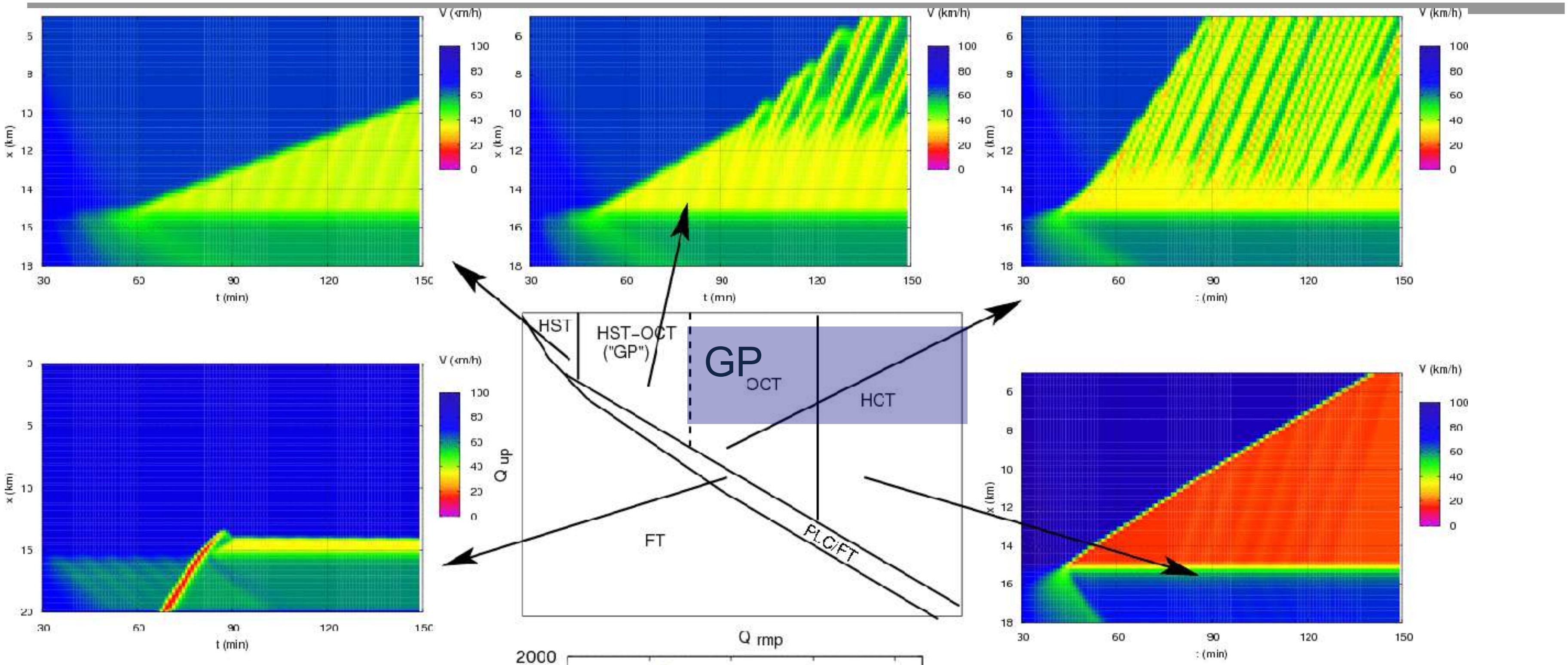
Class a-b:s1=0/14

3a: Convective instability is really universal!

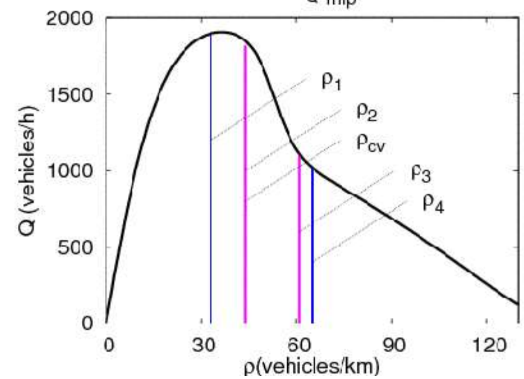


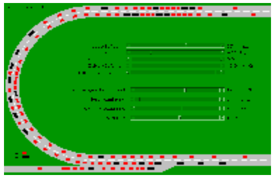


3c: States for a stability class 2b macroscopic model



GKT model



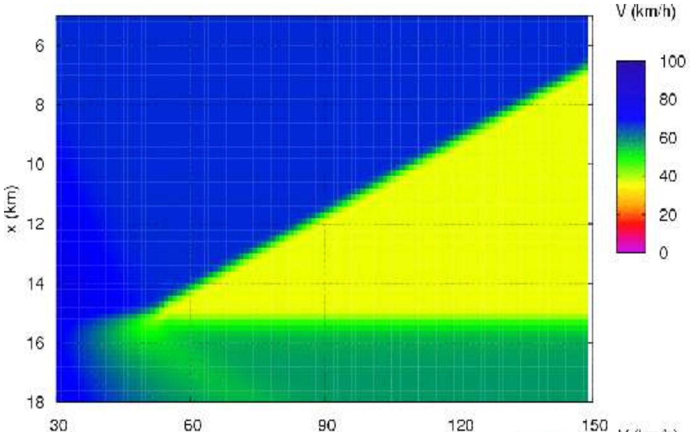


Class 2b: a=0.6 m/s^2,s1=14 m

Class 2a: s1=0

3d: Effect of Instationarities at the bottleneck

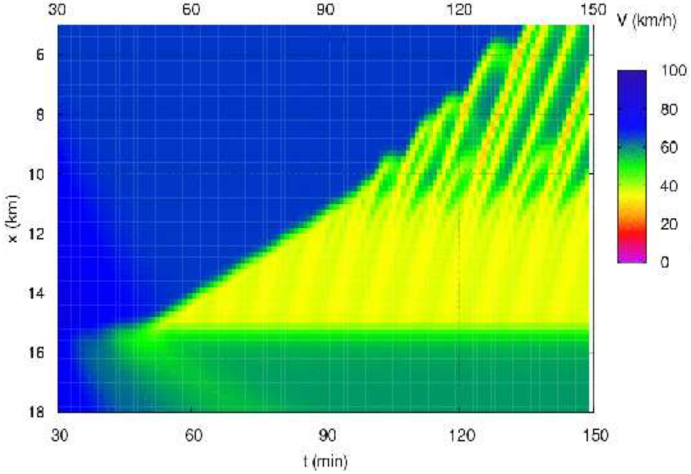
GKT model



Onramp bottleneck:

Stationary

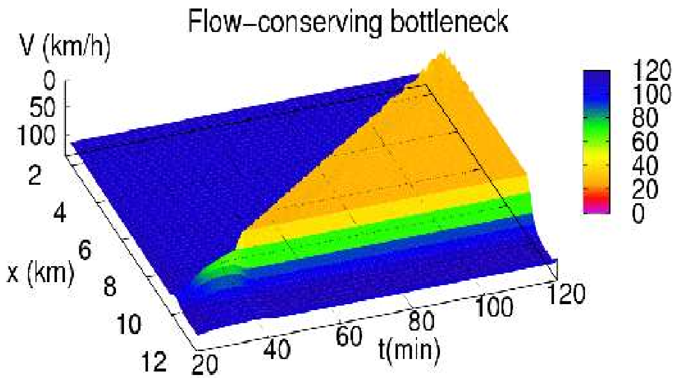
+Variable part

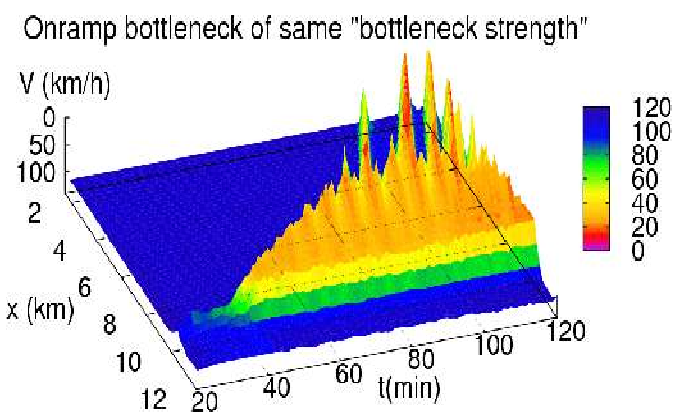


Onramp bottleneck

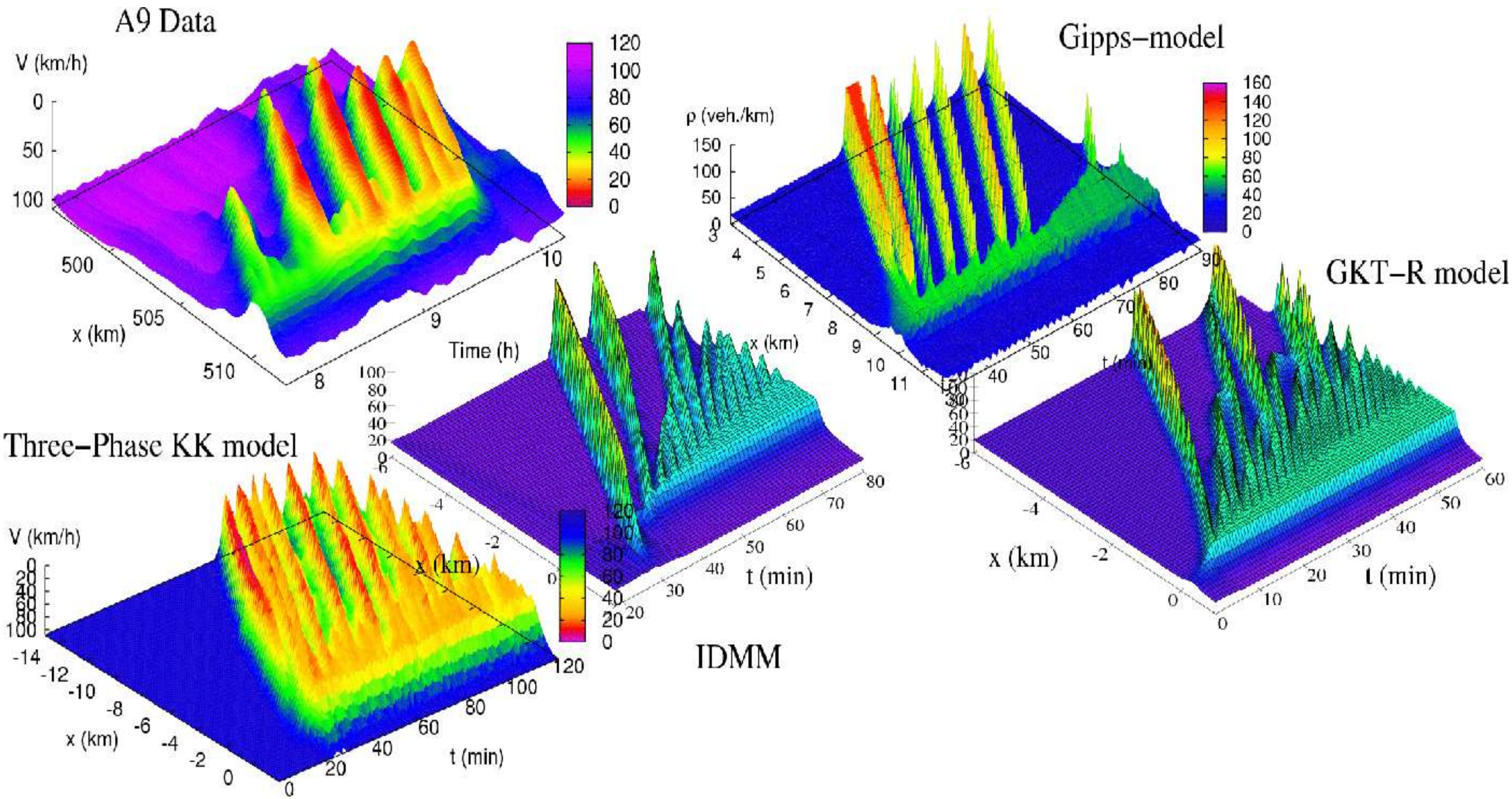
No variable part

IDM

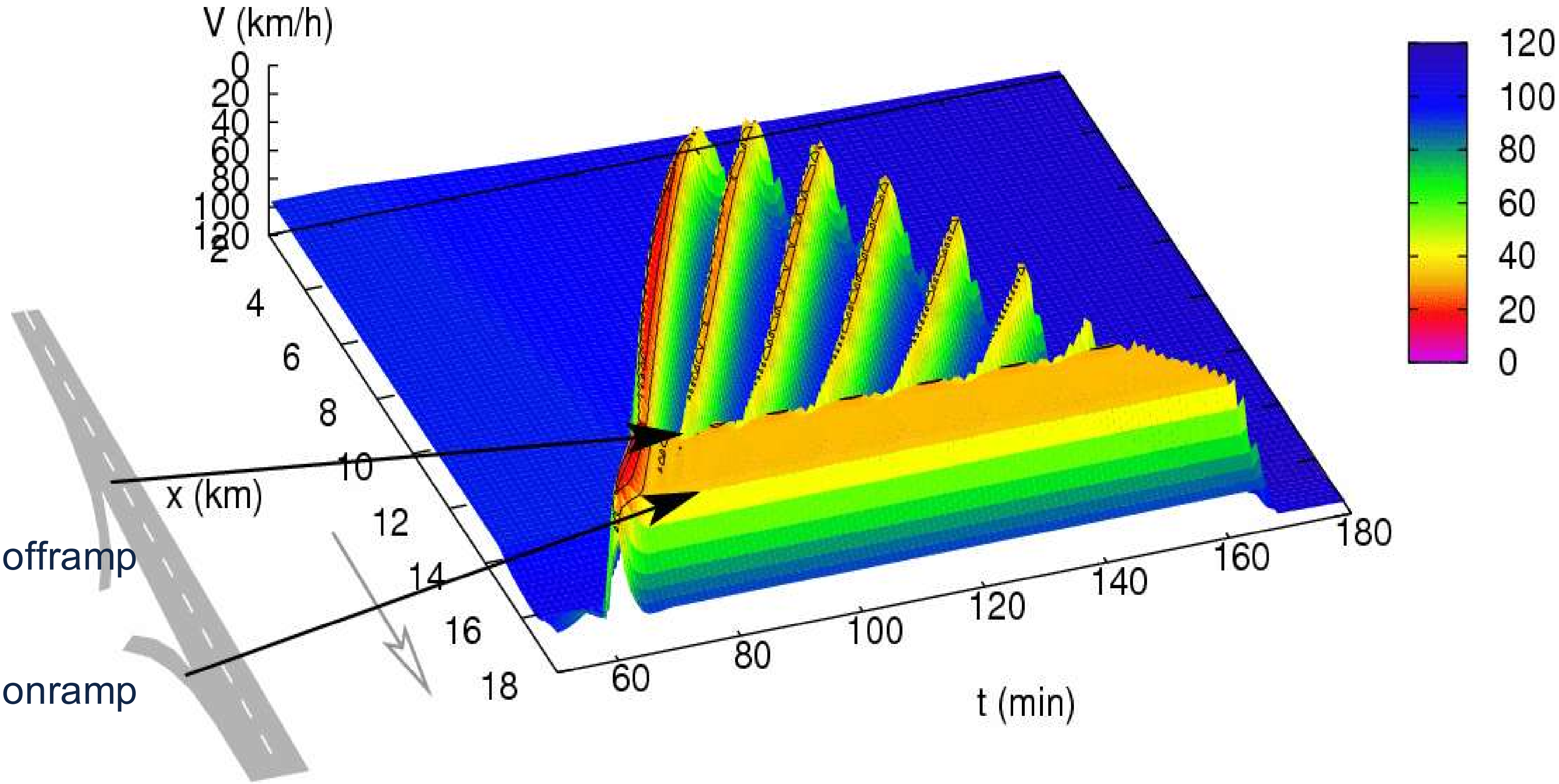




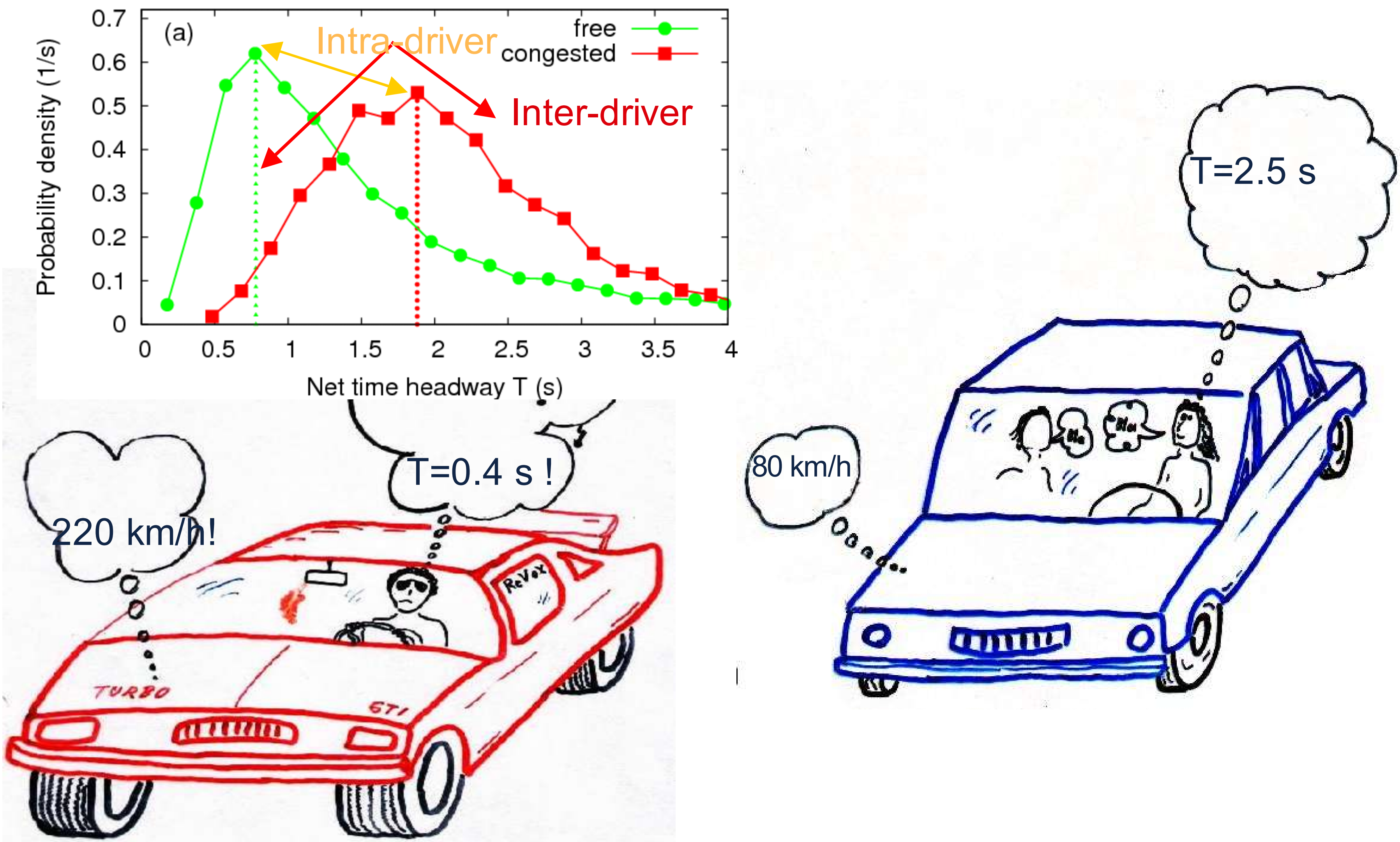
Again, this mechanism is universal …



Alternative mechanism 2 to GP/pinch effect: Offramp - onramp combinations create this phenomenon as well …



Alternative explanation 1 for the fundamental diagram: Inter-driver heterogeneity

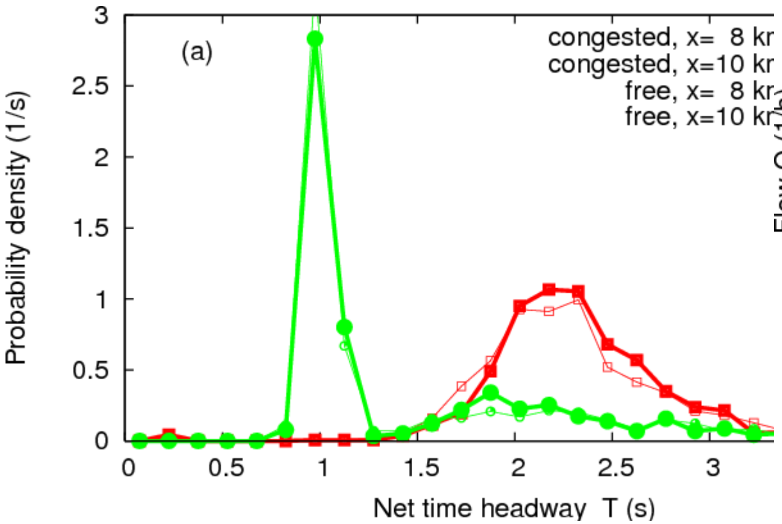


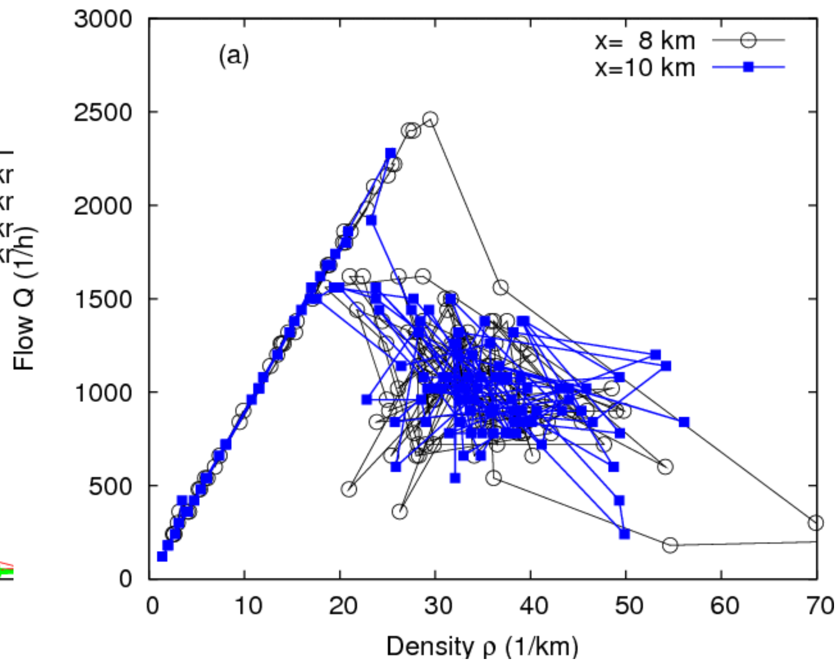
Variance-Driven Time headways (VDT)

$$T = T_{free} \left(1 + \gamma \, \sigma_v / \langle V \rangle\right)$$

+2 types

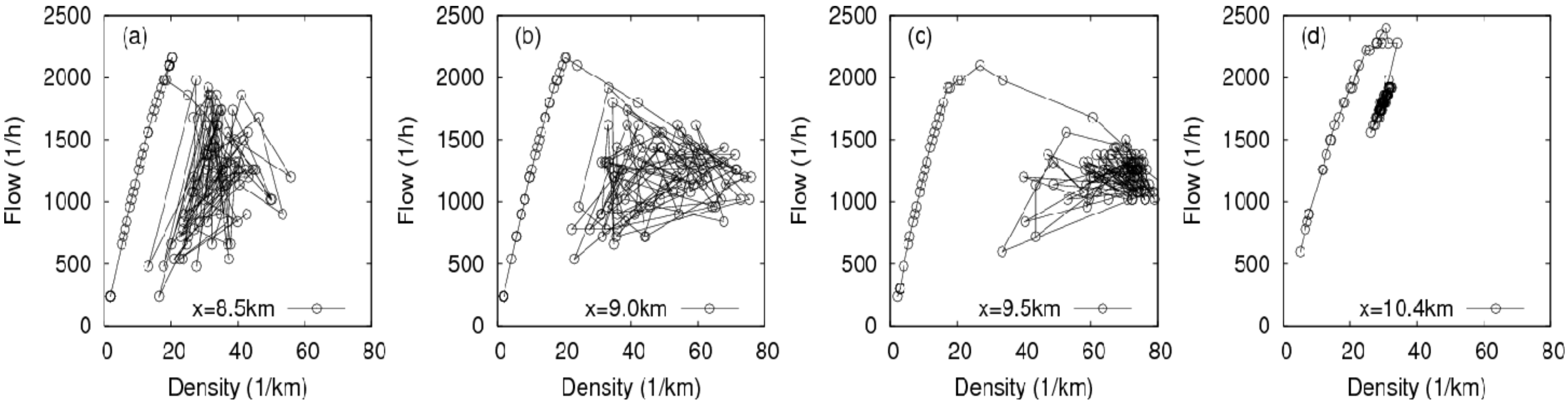
+acceleration fluctuations





2D fundamental diagram:
Alternative explanation 3: Dynamical instability

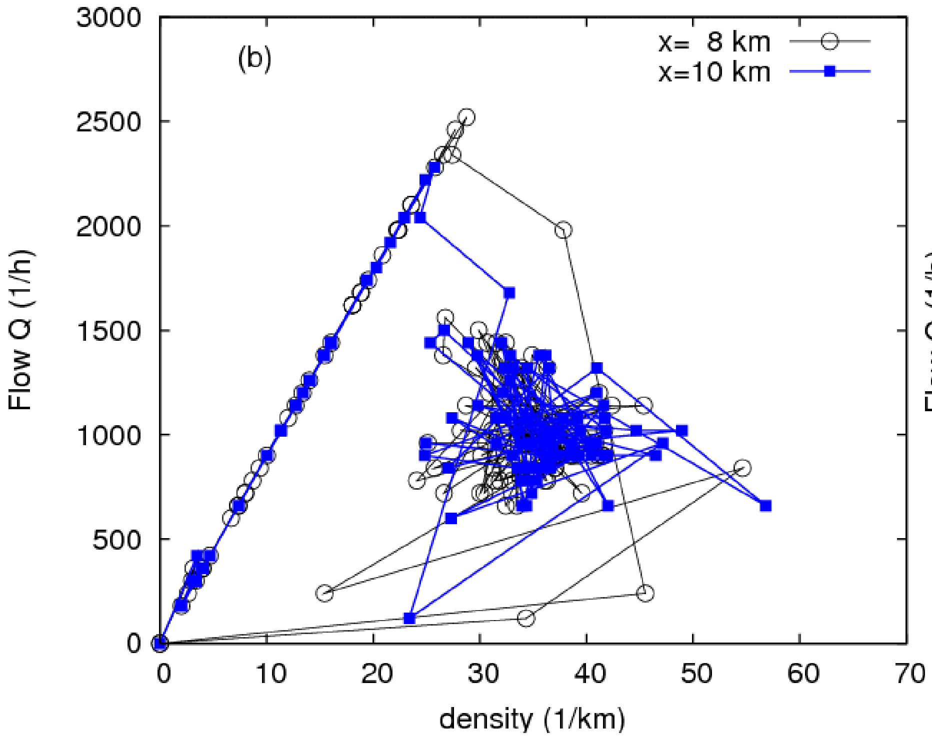
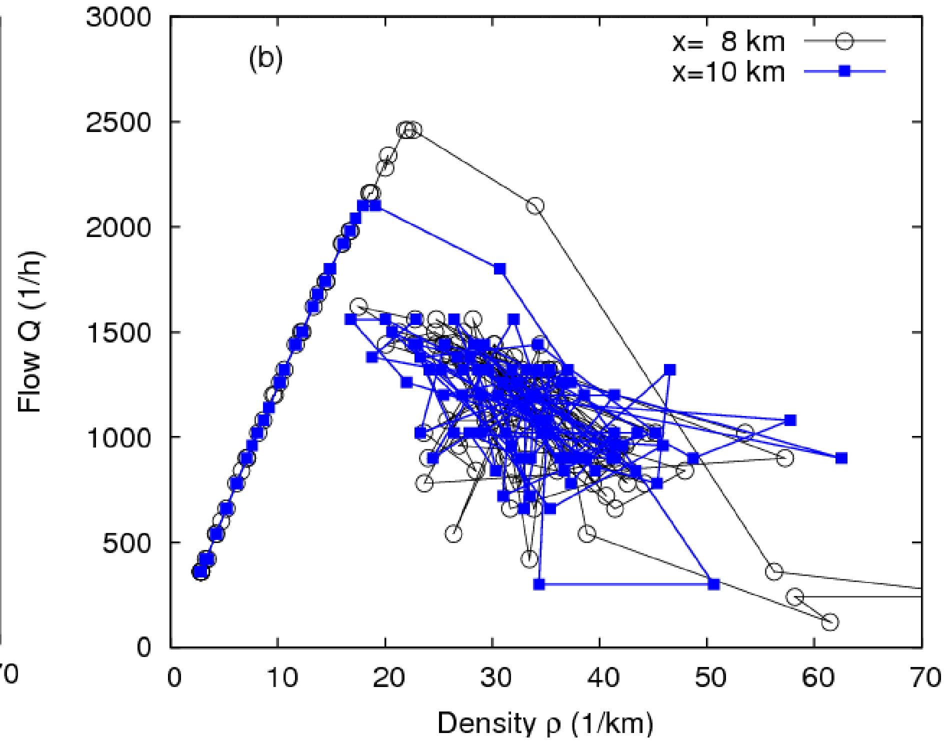
Plain IDM (parameters for stability class 2a)



Upstream of on-ramp bottleneck

At bottleneck

Summary : All three alternative factors for the “2D” nature of the fundamental diagram

Deterministic, 2 types, VDT	Stochastic, 1 type, VDT
	

Conclusions

- The question whether three or five dynamic phases is essentially one of the definition of a “dynamic phase”.
- There are several mechanisms to explain the observed spatiotemporal features and the 2D fundamental diagrams with “two-phase” models featuring a unique equilibrium relation.
- In many aspects, the discrepancies between Kerner’s approaches and ours are just a result of interpreting things differently.