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第四届生物医学光子学交叉融合学术论坛

面向原始数据域的生成式智能光声成像系统及应用

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南昌大学人工智能工业研究院
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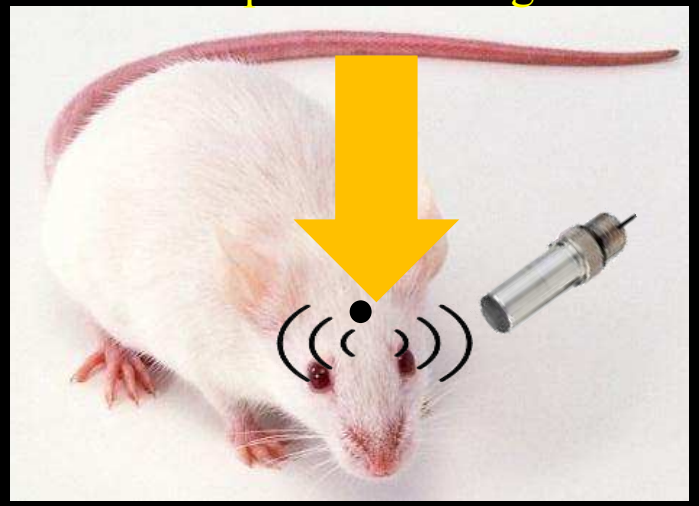
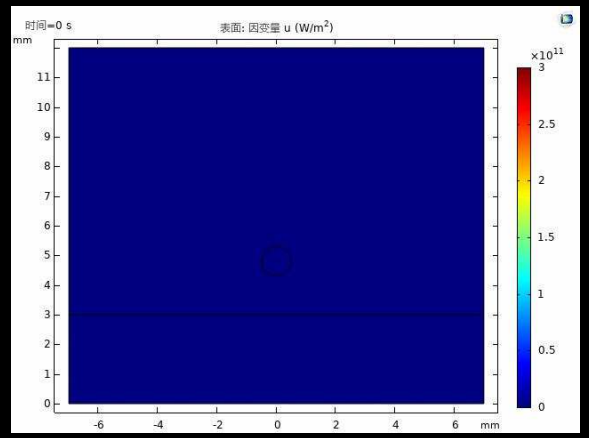
- **Photoacoustic imaging and artificial intelligence**
- Application of generative artificial intelligence in Photoacoustic imaging
- Summary and prospect

Photoacoustic imaging

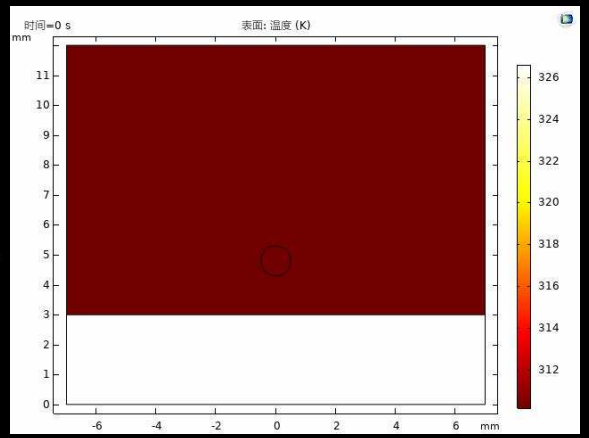
ns-pulsed laser light



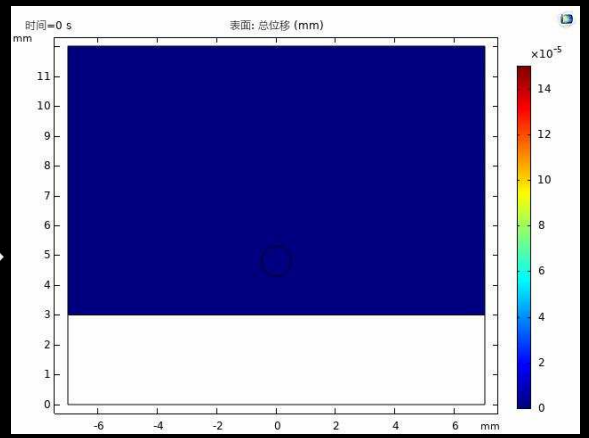
- Pulsed/modulated CW light irradiate biological tissues
- Transient temperature rise is induced by light energy absorption
- Thermoelastic expansion generates photoacoustic pressure
- Pressure rise results in ultrasonic waves emission



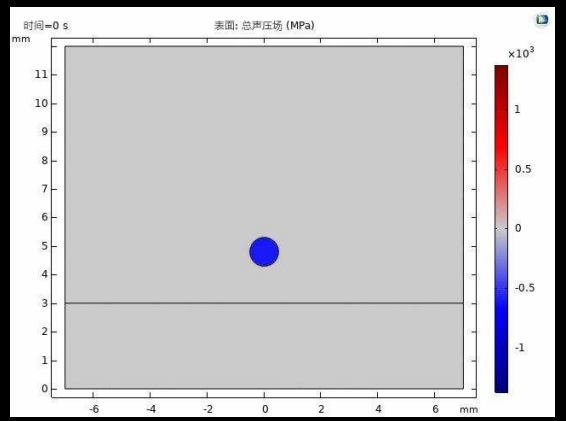
Optical transmission



Instantaneous temperature rise



Adiabatic expansion



Initial sound pressure is generated

Photoacoustic imaging

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Modality	Depth (mm)	Resolution (μm)	3D	Hb T	sO_2	contrast	invasive or radiative
CT	200	1000	Y			Exogenous	Y
MRI	100-200	1000	Y		Y	Endogenous	
PET/SPECT	200	1000	Y		Y	Exogenous	Y
US	100-200	500-1000	Y			Endogenous	
D-OCT	1-2	1-20	Y			Endogenous	
TPM	0.5-1	1-2	Y			Exogenous	
CM	0.2-0.5	1-2	Y			Exogenous	
IVM	0.2-0.5	1-2	N			Exogenous	Y
PAI	0.2-40	0.1-560	Y	Y	Y	Endogenous	

- ✓ **Multi-scale imaging: from cell to organ**
- ✓ **High resolution with large penetration**
- ✓ **Structural and functional imaging**
- ✓ **Non-invasive 3D imaging**

Yeqi Lao et al, Phys. Med. Biol, 2008.
Lihong Wang, Nature Photonics, 2009.

Photoacoustic imaging

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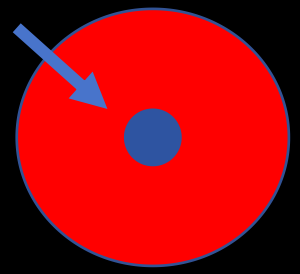
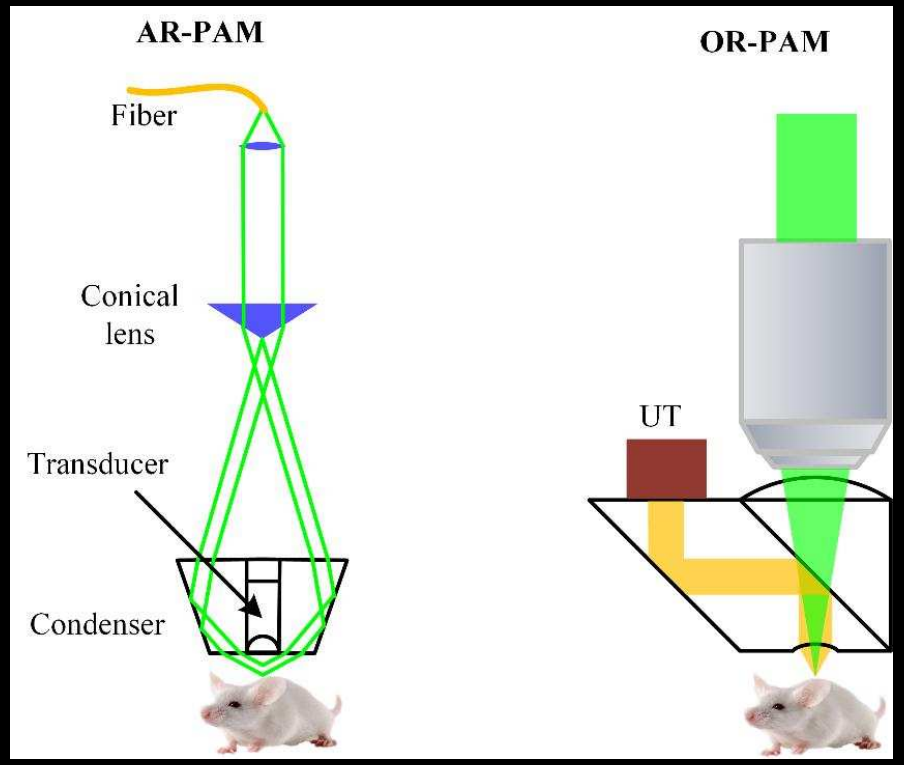
Photoacoustic mcroscopy:Micron-level spatial resolution

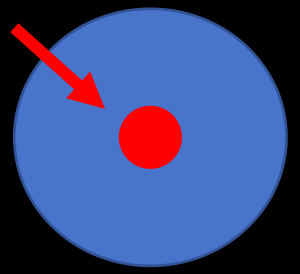
Ultrasonic focus



Optical focus



Optical focus



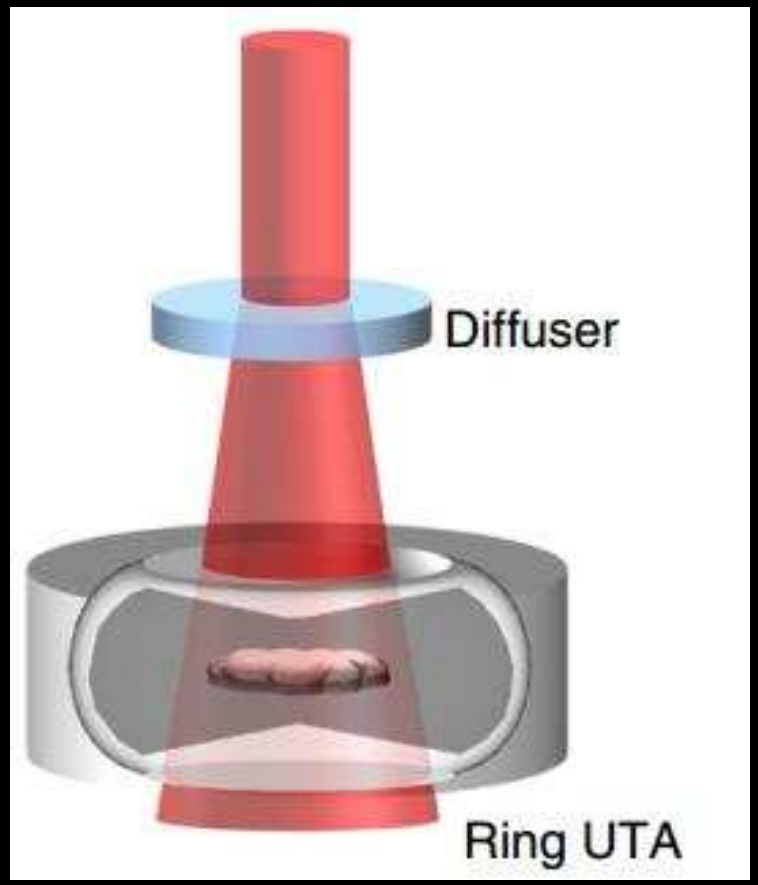
Ultrasonic focus

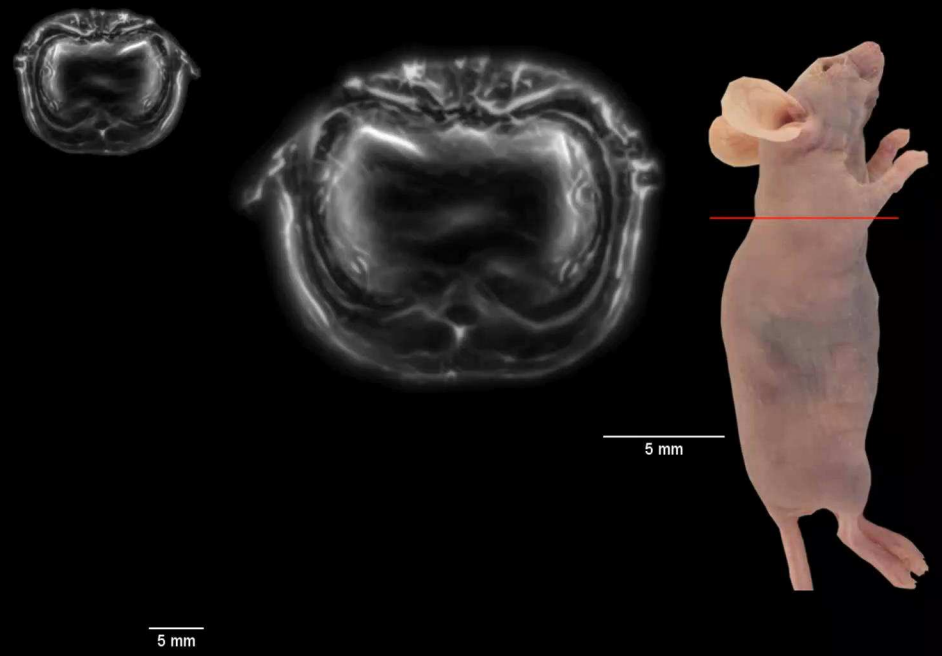
Acoustic-resolution photoacoustic microscopy (AR-PAM)

Optical-resolution photoacoustic microscopy (OR-PAM)

Photoacoustic imaging

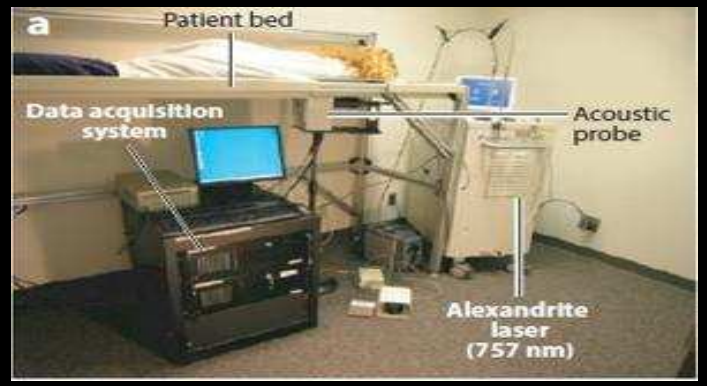
Photoacoustic tomography:Full-body, wide field of view



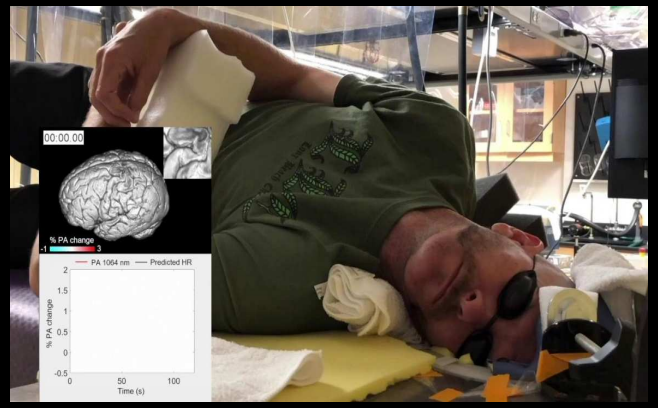


Wang, L. V., & Yao, J. (2016). A practical guide to photoacoustic tomography in the life sciences. *Nature methods*, *13*(8), 627-638.

Photoacoustic imaging

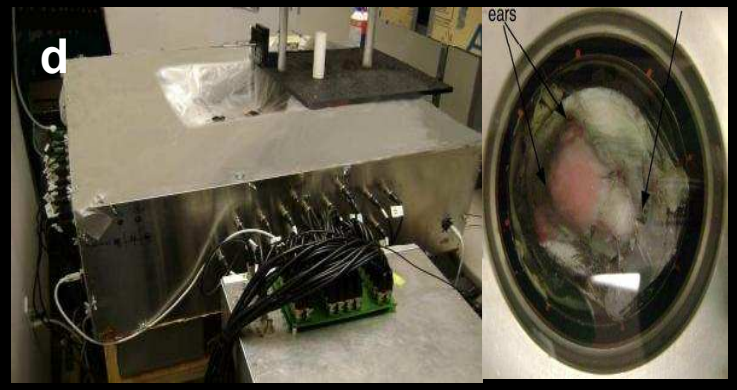


Breast cancer diagnosis

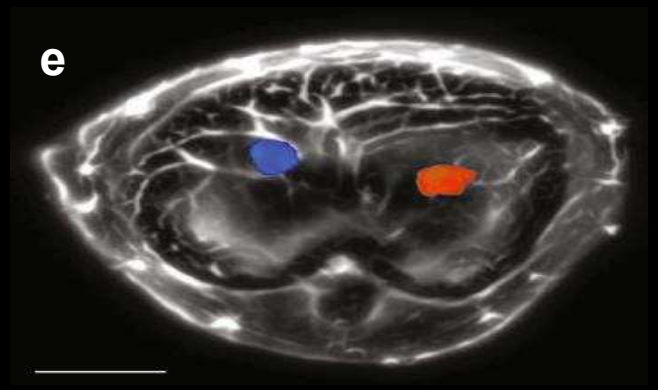


Functional tomography of human brain

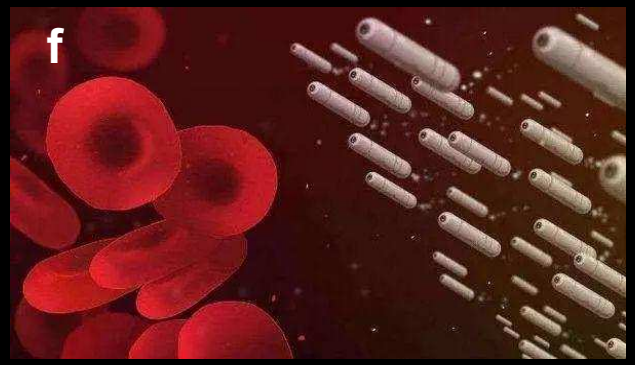
Vascular structure imaging



Real-time photoacoustic tomography for small animal



Tumor detection



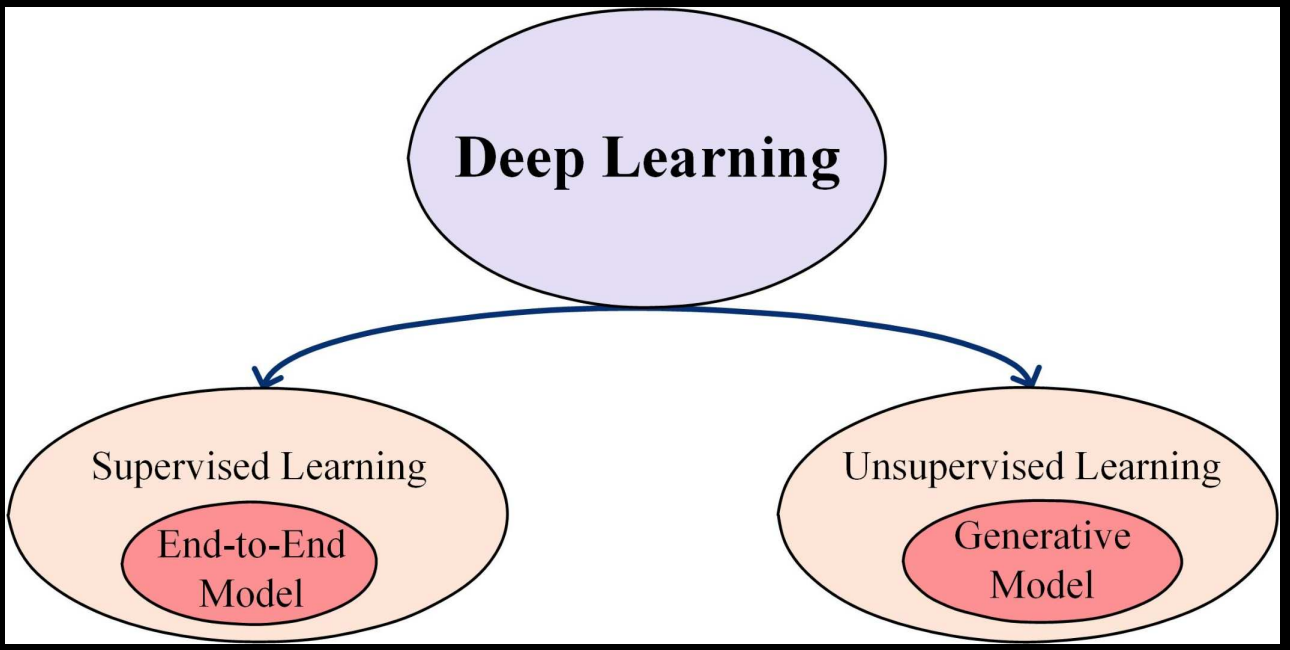
Control nanorobots in real time

Lin, Li, et al. "Single-breath-hold photoacoustic computed tomography of the breast." Nature communications 9.1 (2018): 1-9.

Anderson, Craig S., et al. "Intensive blood pressure reduction with intravenous thrombolysis therapy for acute ischaemic stroke (ENCHANTED)" The Lancet 393.10174 (2019): 877-888.

Gamelin, John, et al. "A real-time photoacoustic tomography system for small animals." Optics express 17.13 (2009): 10489-10498.

Generative artificial intelligence



Generative model

01 Denoising autoencoding(DAE)

02 Variational Autoencoders (VAE)

03 Generative Adversarial Network (GAN)

04 PixelCNN

05 Generative Flow (Glow)

Z. He, Q. Liu, et al., A comparative study of unsupervised deep learning methods in MRI reconstruction, *iMRI*, 2020.

Generative artificial intelligence

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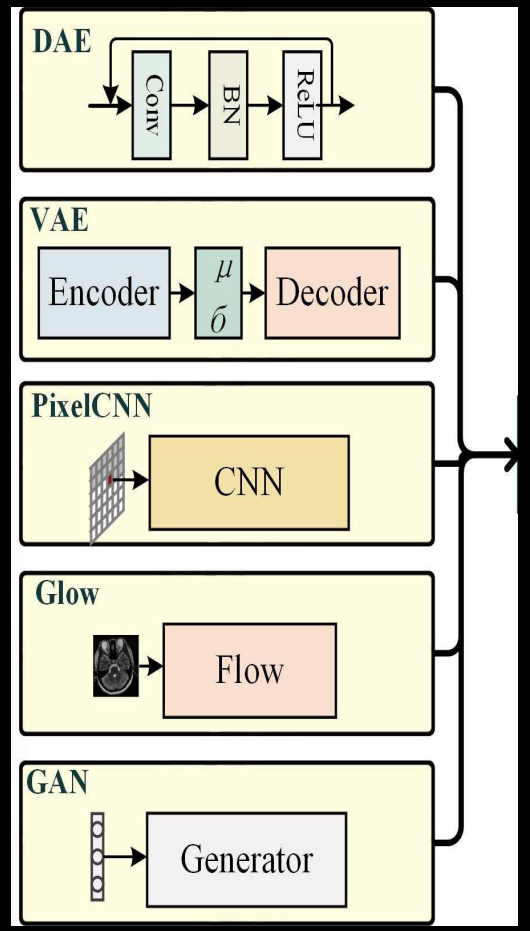
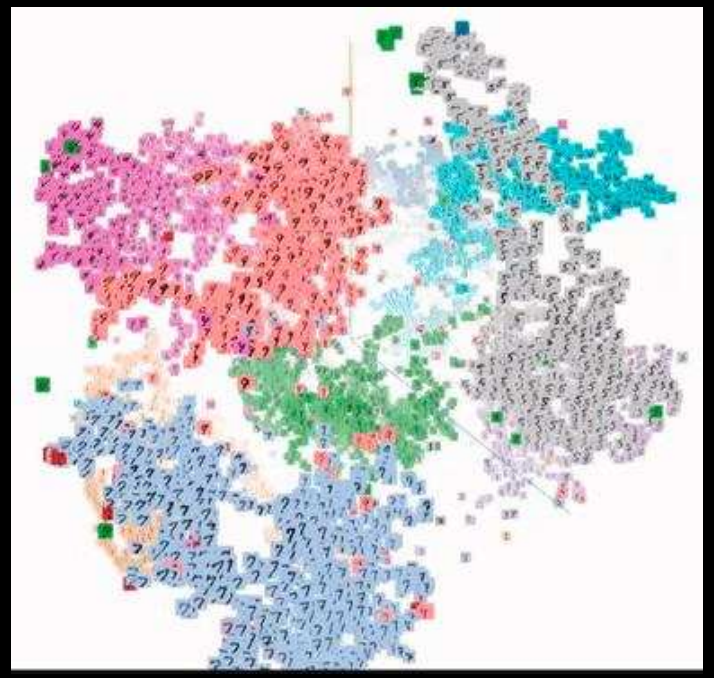
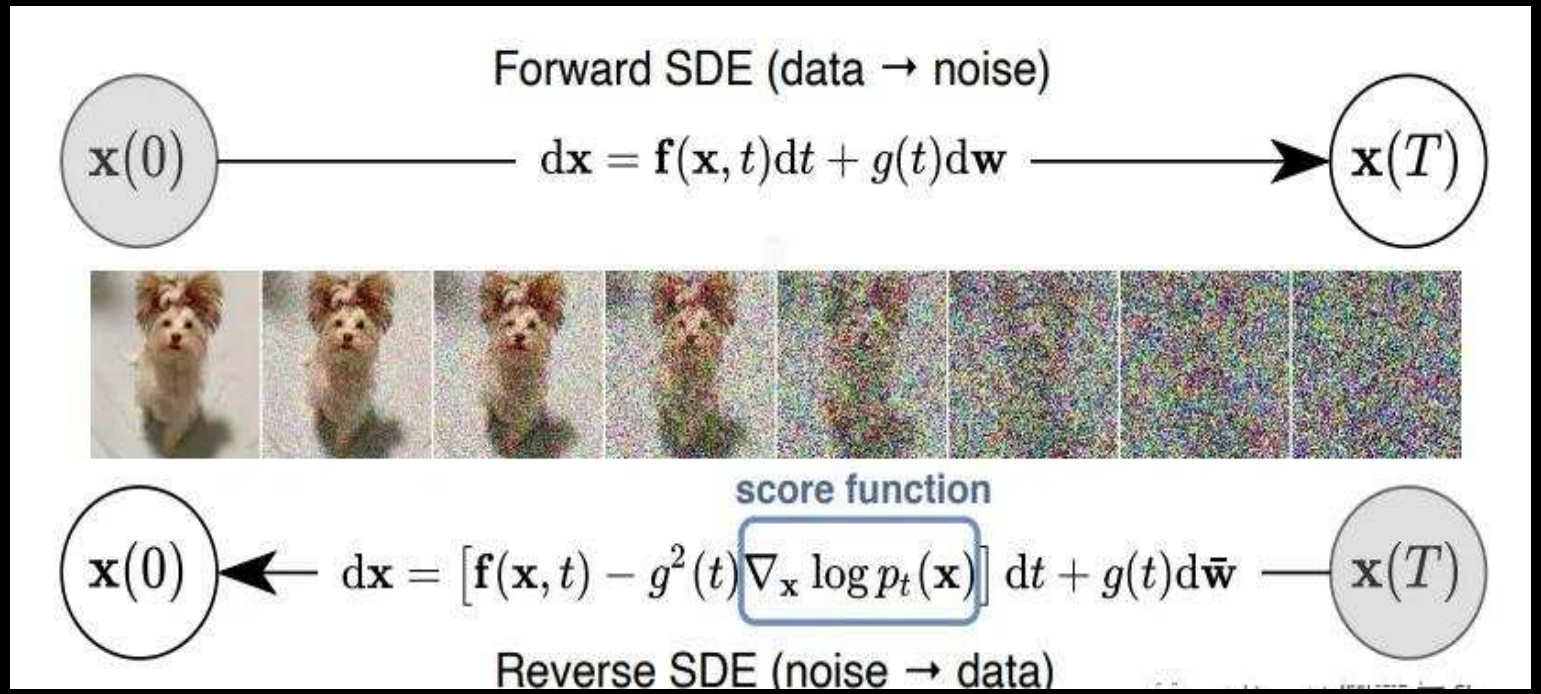


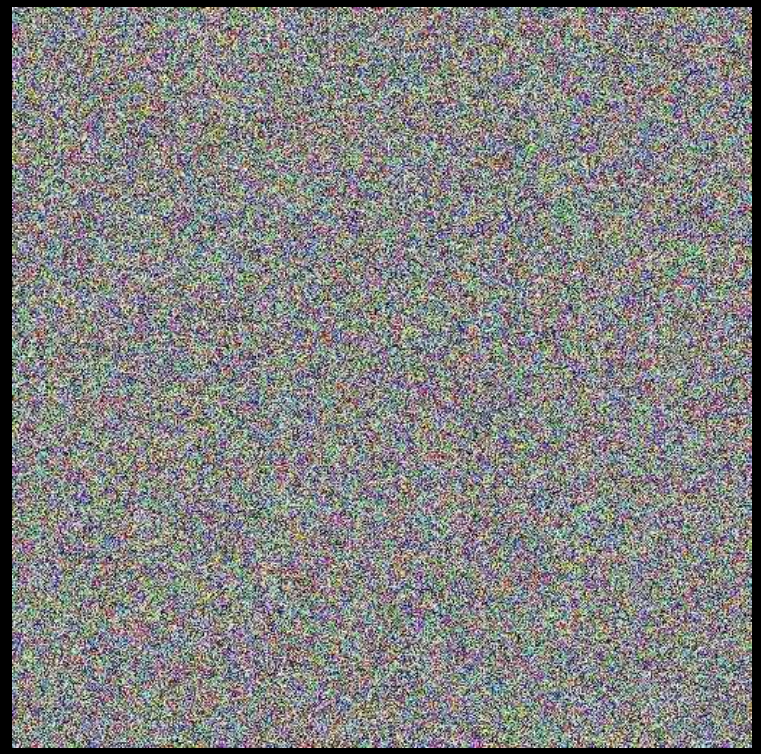
Data distribution

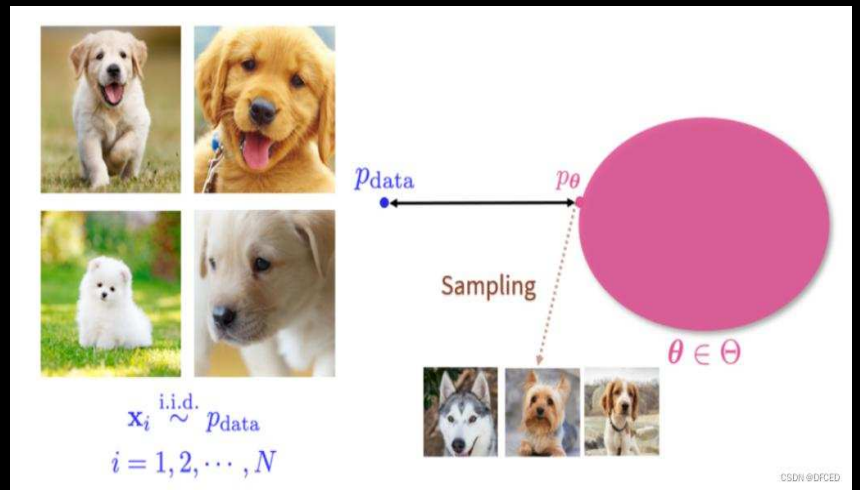


Z. He, Q. Liu, et al., A comparative study of unsupervised deep learning methods in MRI reconstruction, *iMRI*, 2020.

Diffusion model







USL from DAE to DSM

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Q. Liu, Q. Yang, H. Cheng, S. Wang, M. Zhang, D. Liang, Highly undersampled magnetic resonance imaging reconstruction using autoencoding priors, ***Magn. Reson. Med.***, vol. 83, no. 1, pp. 322-336, 2020.

DAEP

DAE

S. Wang, J. Lv, Z. He, D. Liang, Y. Chen, M. Zhang, Q. Liu, Denoising auto-encoding priors in undecimated wavelet domain for MR image reconstruction, ***Neurocomputing***, vol.437, pp.325-338, 2021.

DMSP

DSM

M. Zhang, M. Li, J. Zhou, Y, Zhu, S. Wang, D. Liang, Y. Chen, Q. Liu. High-dimensional embedding network derived prior for compressive sensing MRI reconstruction, ***Med. Image Anal.***, vol. 64, 101717, 2020.

C. Quan, J. Zhou, Y. Zhu, Y. Chen, S. Wang, D. Liang, Q. Liu, Homotopic gradients of generative density priors for MR image reconstruction, ***IEEE Trans. Med. Imag.***, 2021.

Generative model

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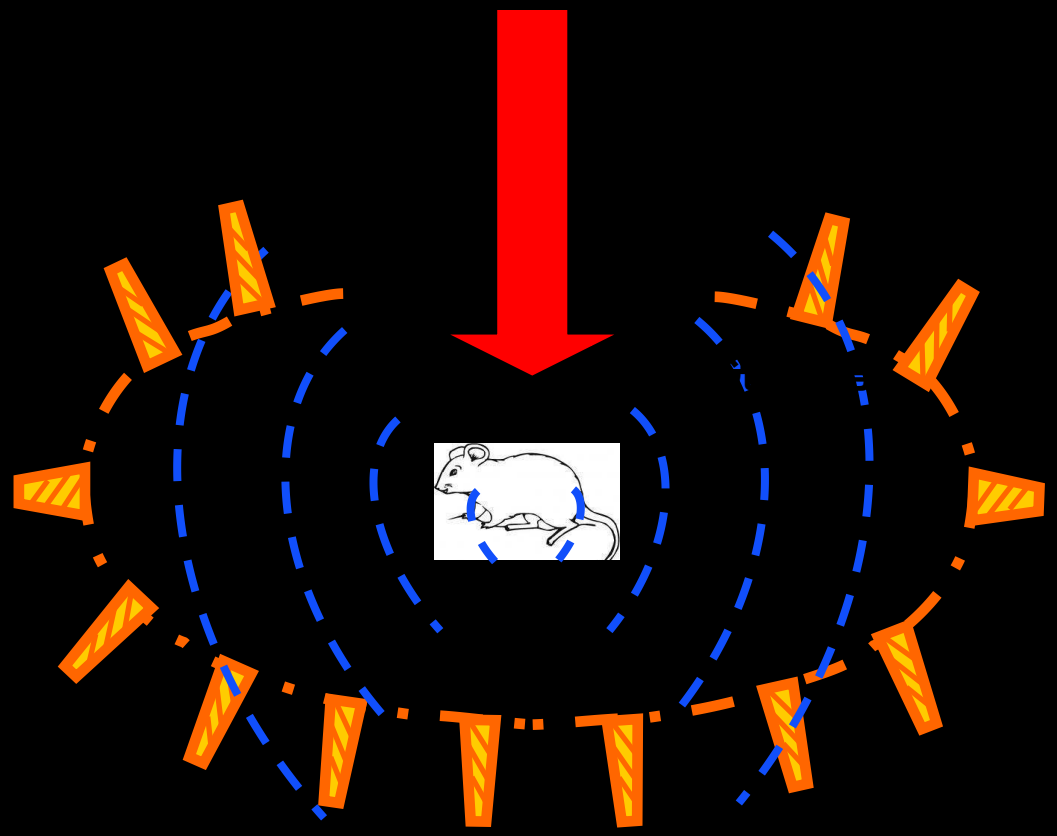
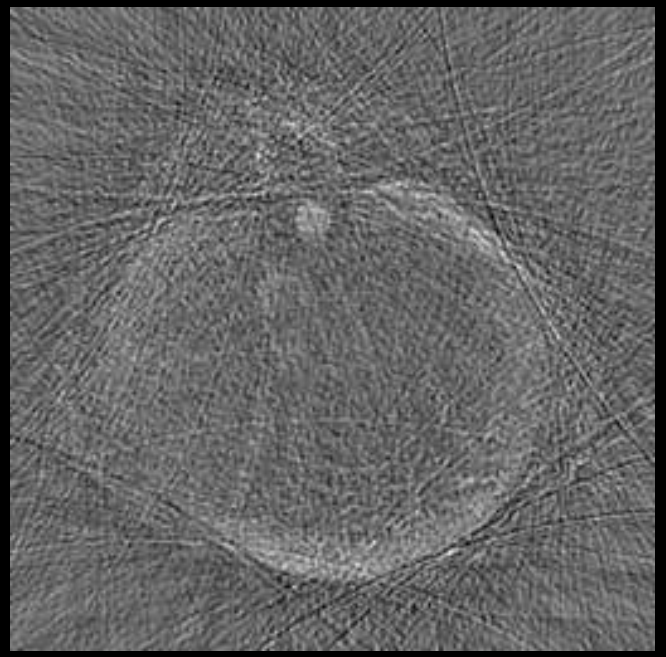
Photoacoustic tomography



Full View

Sparse view



Higher-speed imaging

Limited view、Sparse view

Limited bandwidth

Sacrificing image quality

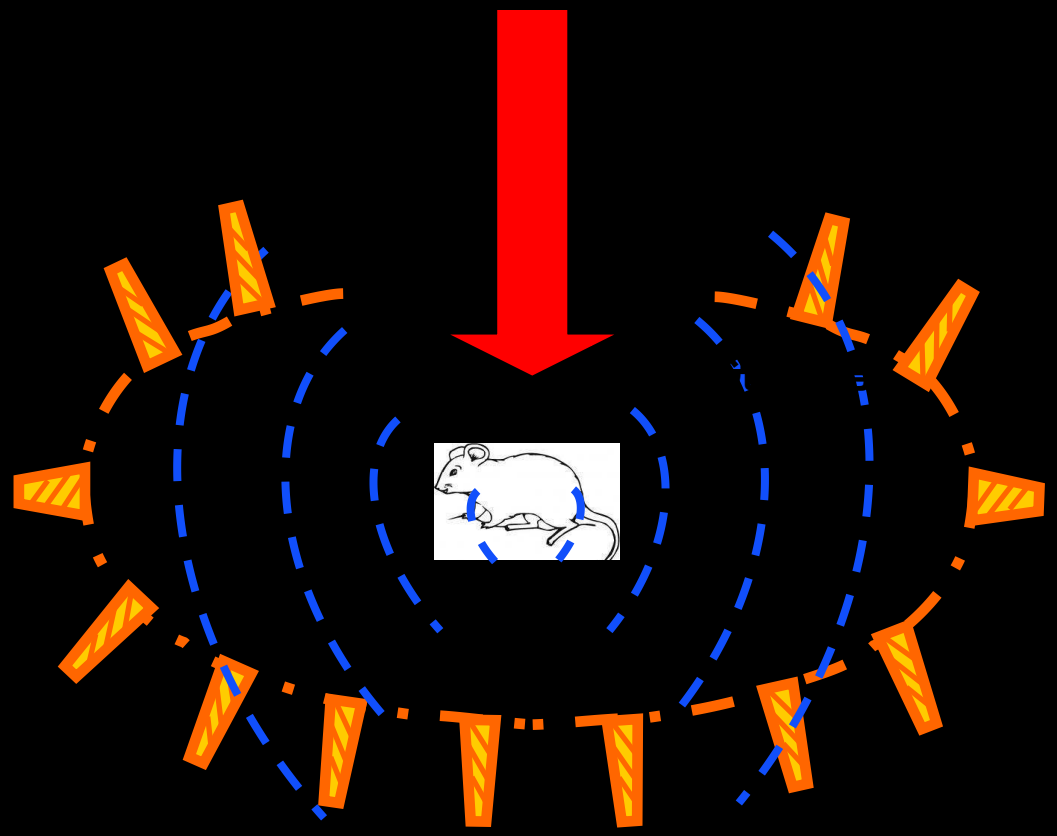
Missing Angle information: Artifacts

High-frequency information missing: fuzzy

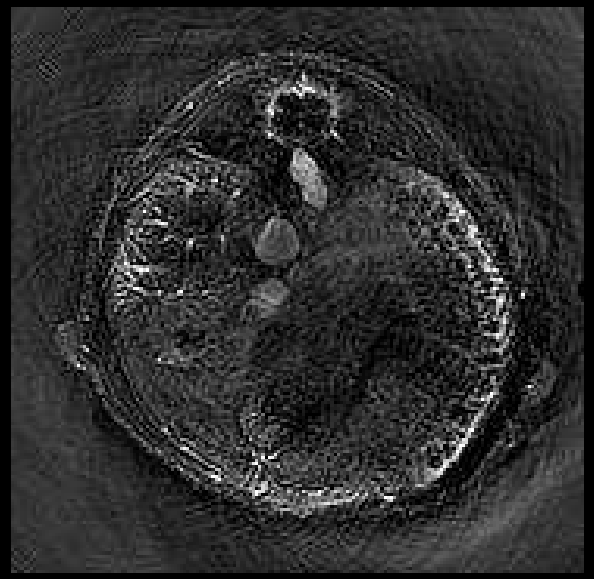
High speed High quality

Information recovery

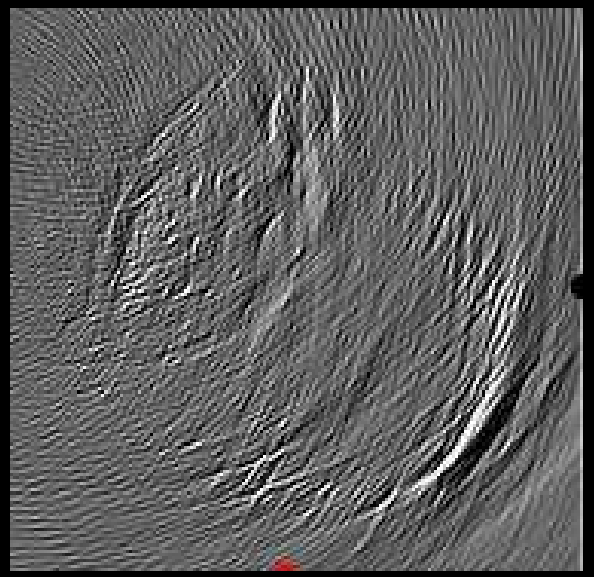
Photoacoustic tomography



Full View



Limited view



Higher-speed imaging

Limited view、Sparse view

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Information recovery

PAT-DM for sparse-view reconstruction

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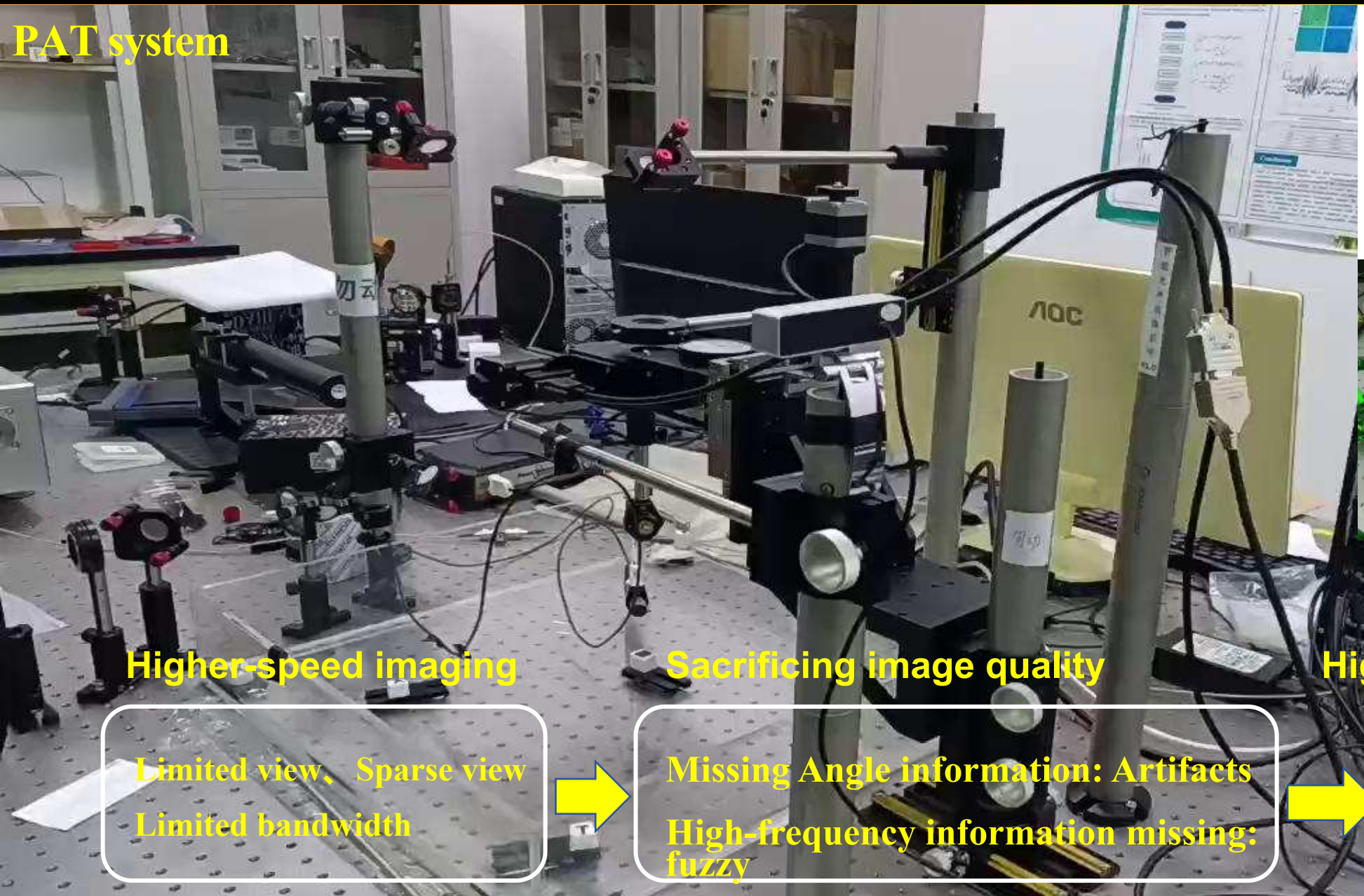

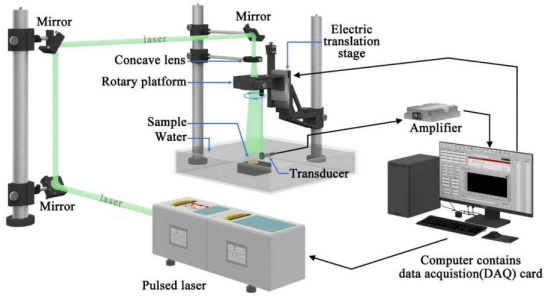

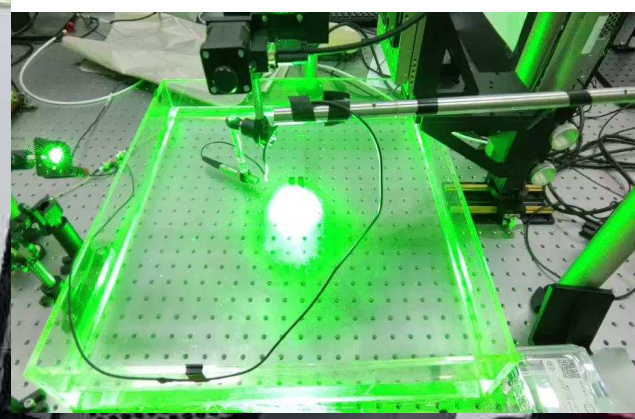

Higher-speed imaging

Limited view、Sparse view

Limited bandwidth

Sacrificing image quality

Missing Angle information: Artifacts

High-frequency information missing: fuzzy

High speed High quality

Information recovery

PAT + Generative artificial intelligence

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Mathematical expression model of photoacoustic tomography

$$p_0 = \Gamma \eta_{\text{th}} \mu_a \phi$$

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})p(r,t) = -\frac{\beta}{c_p}\frac{\partial H(r,t)}{\partial t}$$

$$p(r,t) = \frac{1}{4\pi c^2}\frac{\partial}{\partial t}\left[\frac{1}{ct}\int dr' p_0(r')\delta(t - \frac{|r-r'|}{c})\right]$$

$$y = Ax$$

Optimization problem

$$x = \arg\min_x \|Ax - y\|_2^2$$

The gradient descent method

$$x_{i-1} = x_i - \alpha A^*(Ax_i - y)$$

Regularization term

$$x = \arg\min_x \|Ax - y\|_2^2 + \boxed{\lambda R(x)}$$

PAT-DM for sparse-view reconstruction

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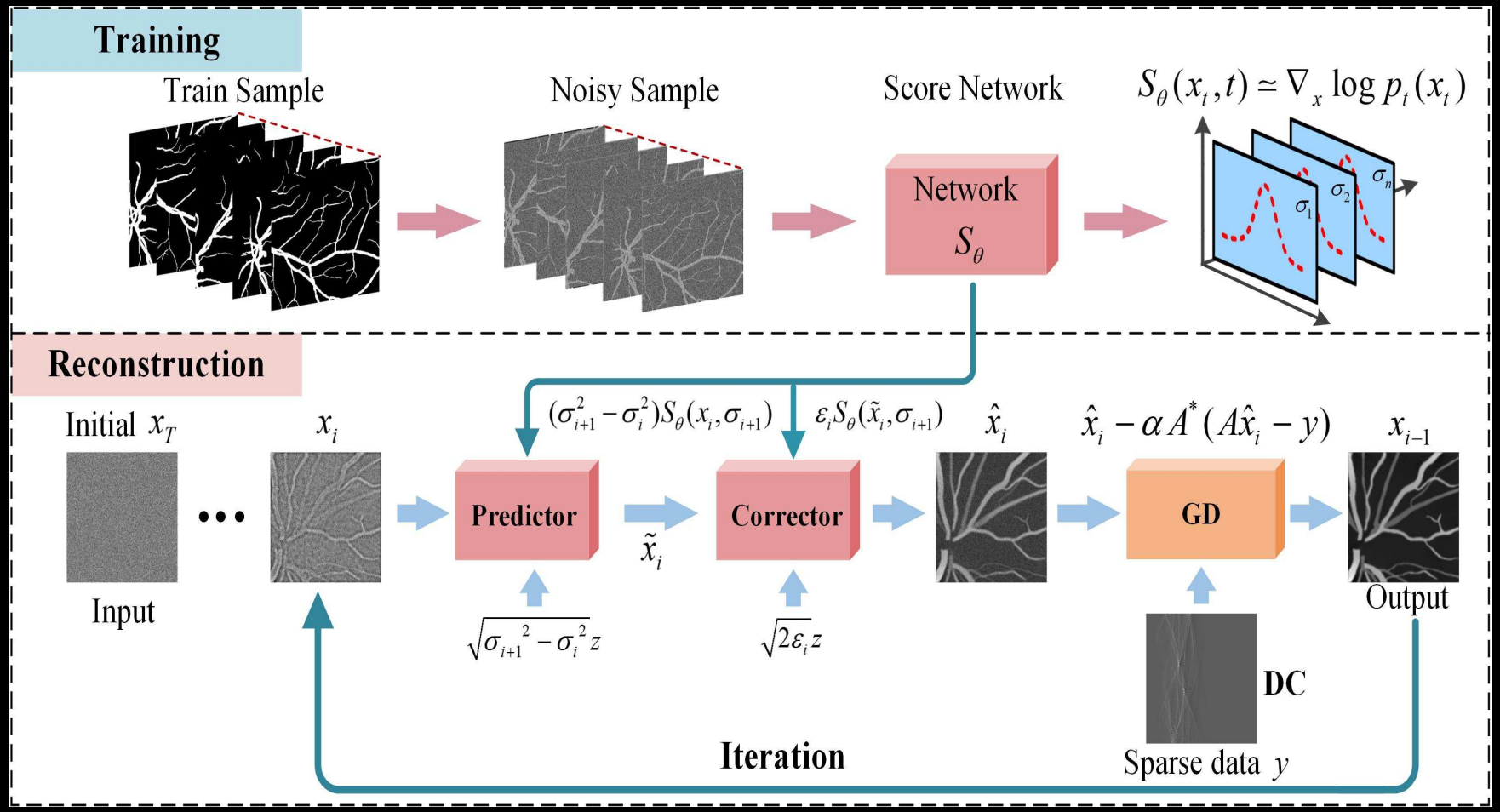
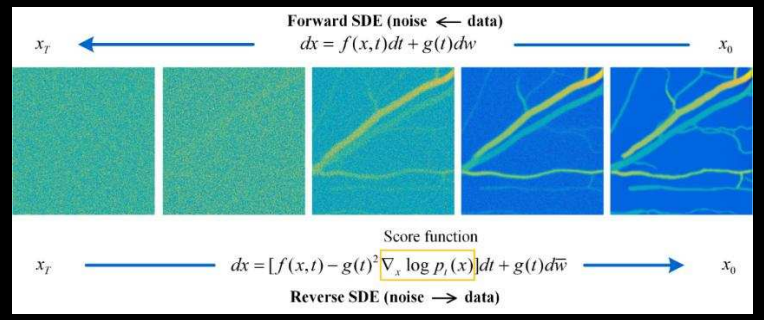
Diffusion model + model-based iteration





Algorithm 1

Training for prior learning

Dataset: Photoacoustic dataset: x

1: Training $S_\theta(x_t,t) \approx \nabla_x \log p_t(x_t)$

2: Output: Trained $S_\theta(x_t,t)$

Iterative reconstruction

Setting: Score network S_θ, Noise iteration step ε_i, Noise scale σ_i, Number of discretization steps for the reverse SDE N, Number of corrector steps M

1: $x_N \sim \mathcal{N}(0, \sigma_{max}^2 I)$

2: $z \sim \mathcal{N}(0,1)$

3: **For** $i = N$-1 to 0 **do (Outer loop)**

4: Update $\tilde{x}_i = x_i + (\sigma_{i+1}^2 - \sigma_i^2)S_\theta(x_i,\sigma_{i+1}) + \sqrt{\sigma_{i+1}^2 - \sigma_i^2}\,z$ **(Prediction)**

5: **For** $j = 1$ to M **do (Inner loop)**

6: Update $\hat{x}_i \leftarrow \tilde{x}_{i,j} + \varepsilon_i S_\theta(\tilde{x}_{i,j},\sigma_{i+1}) + \sqrt{2\varepsilon_i}\,z$ **(Correction)**

7: **End for**

8: Update $x_{i-1} = \hat{x}_i - \alpha A^*(A\hat{x}_i - y)$ **(Gradient descent)**

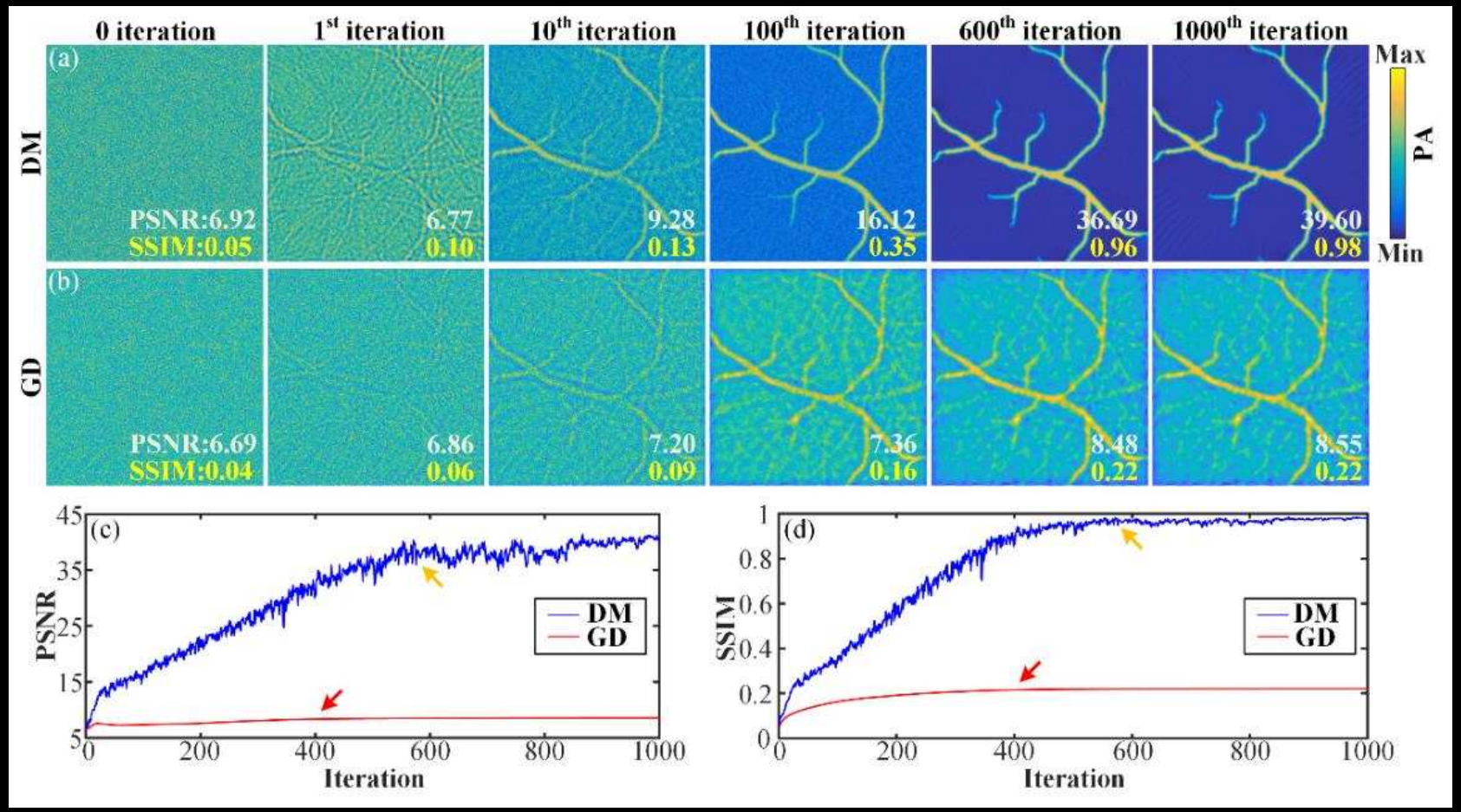
9: **End for**

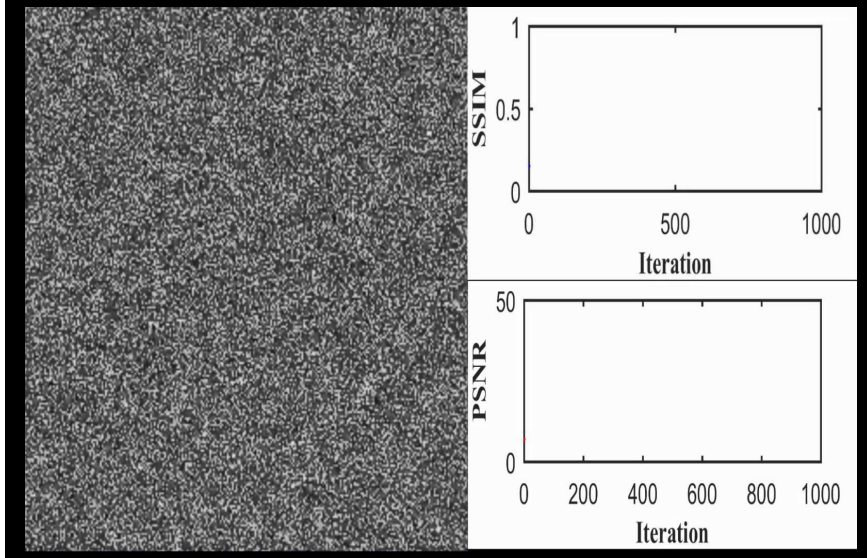
Return x_0

X.Song , G.Wang , W.Zhong, K.Guo, Z.Li, X.Liu, J.Dong, Q.Liu. Sparse-view reconstruction for photoacoustic tomography combining diffusion model with model-based iteration[J]. Photoacoustics, 2023, 33: 100558.

PAT-DM for sparse-view reconstruction

- The process of reconstruction of the simulated blood vessels
- Under 32 projections





PAT-DM for sparse-view reconstruction

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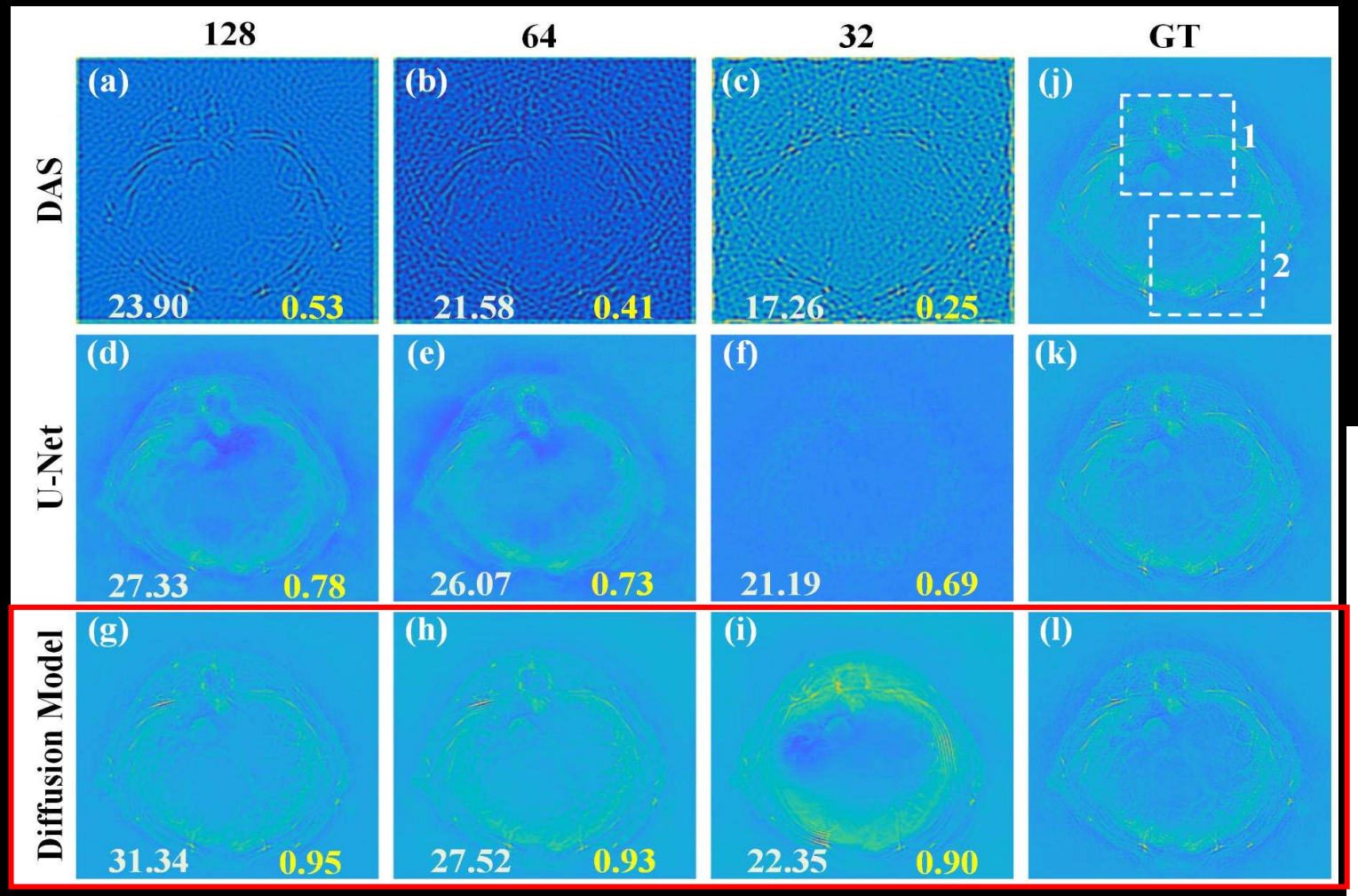
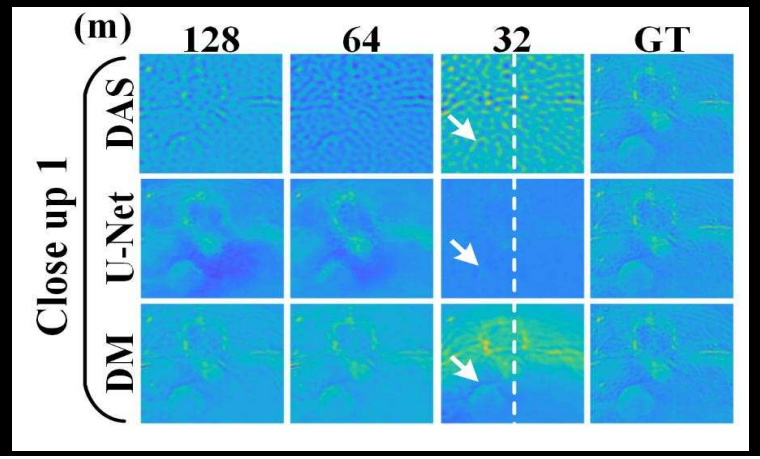
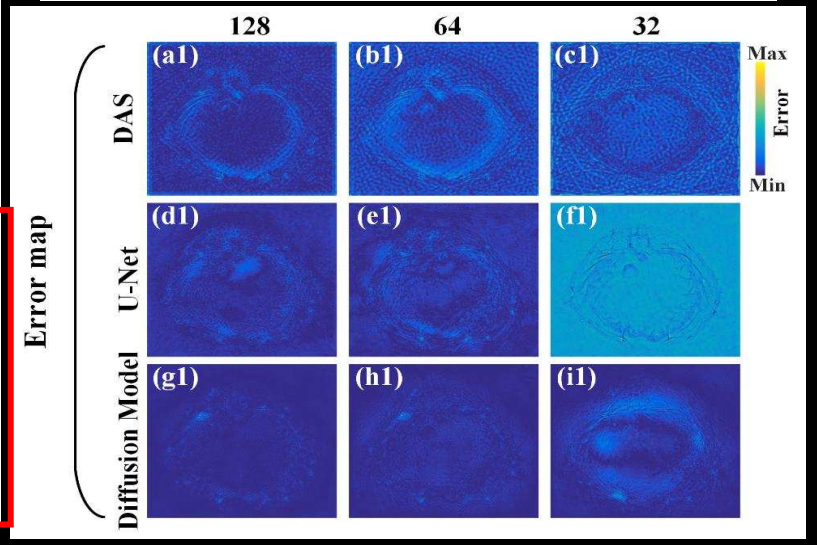
Experimental results The result of *in vivio* mouse abdomen







X.Song , G.Wang , W.Zhong, K.Guo, Z.Li, X.Liu, J.Dong, Q.Liu. Sparse-view reconstruction for photoacoustic tomography combining diffusion model with model-based iteration[J]. Photoacoustics, 2023, 33: 100558.

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June 2019
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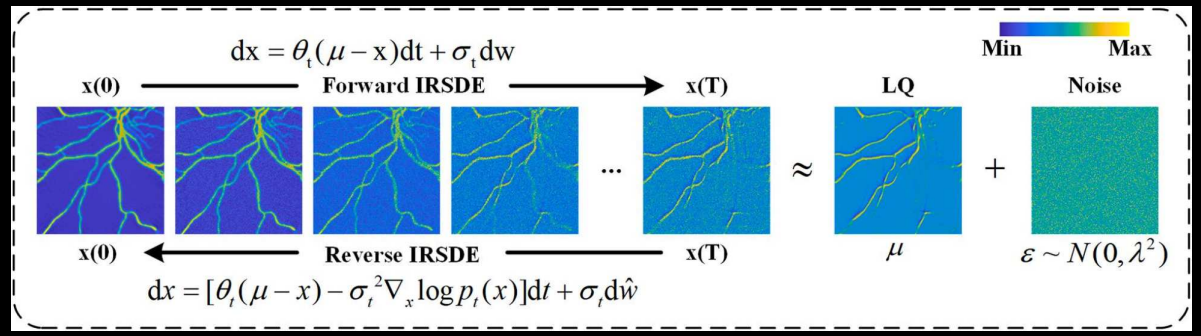
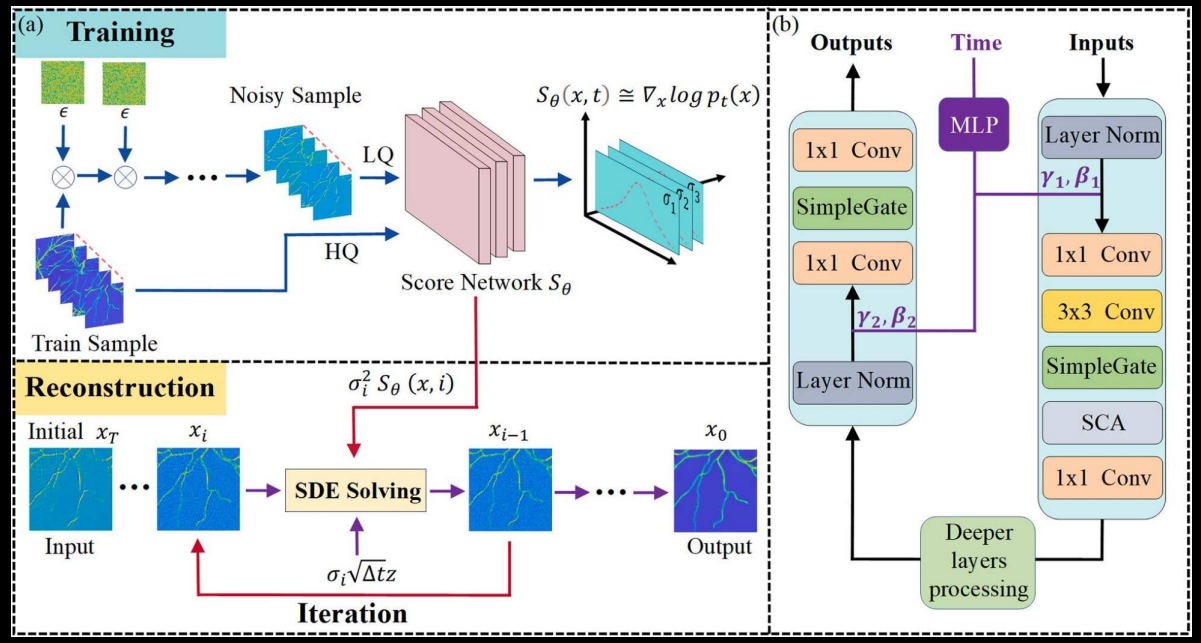
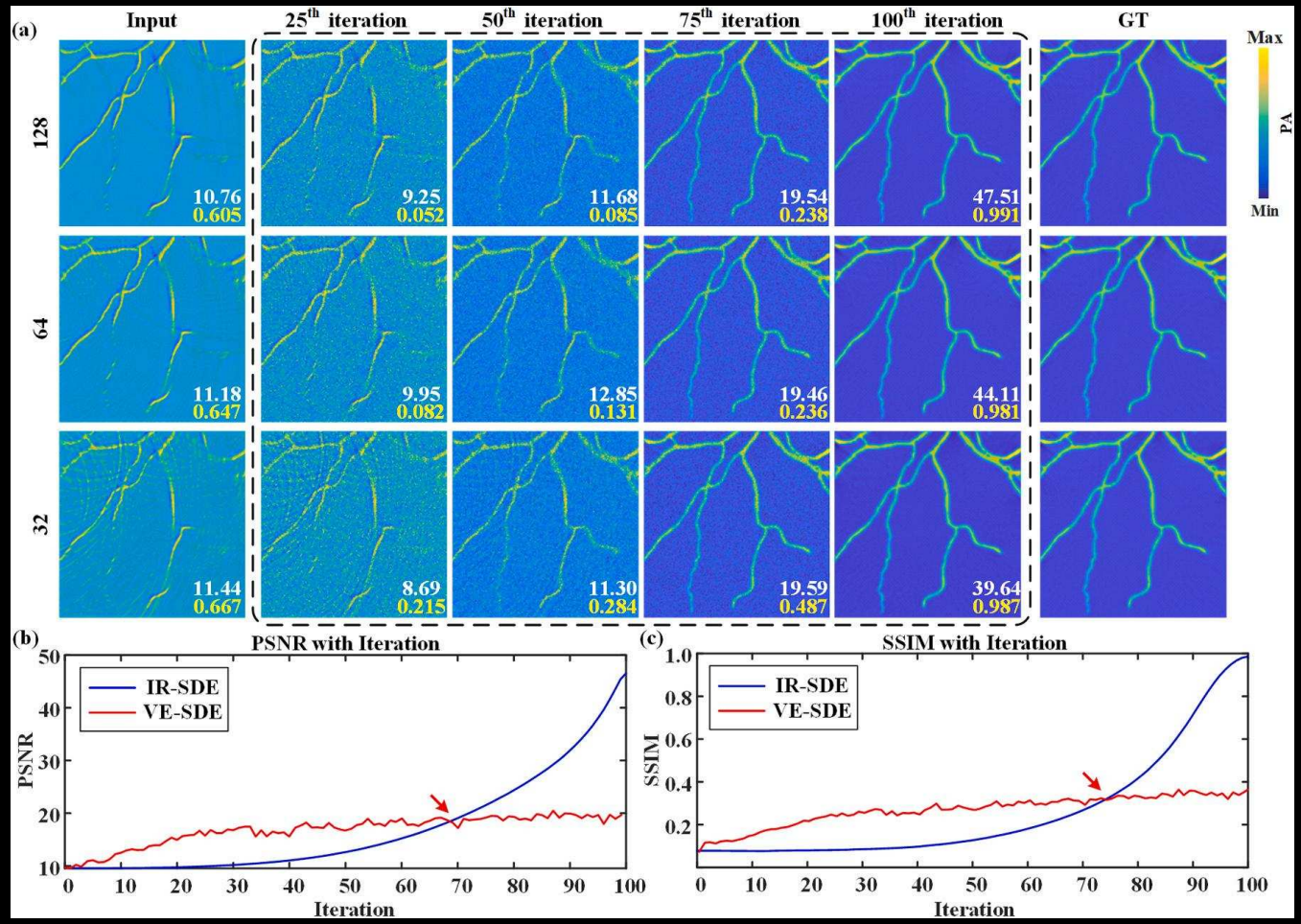
PAM-DM for resolution enhancement

- **Mean-reverting Diffusion model -enhanced photoacoustic tomography**
- **Towards 8 projection**







Lian, Teng, et al. "Generative priors-constraint accelerated iterative reconstruction for extremely sparse photoacoustic tomography boosted by mean-reverting diffusion model: Towards 8 projections." Photoacoustics 43 (2025): 100709.

PAM-DM for resolution enhancement

- **Mean-reverting Diffusion model -enhanced photoacoustic tomography**
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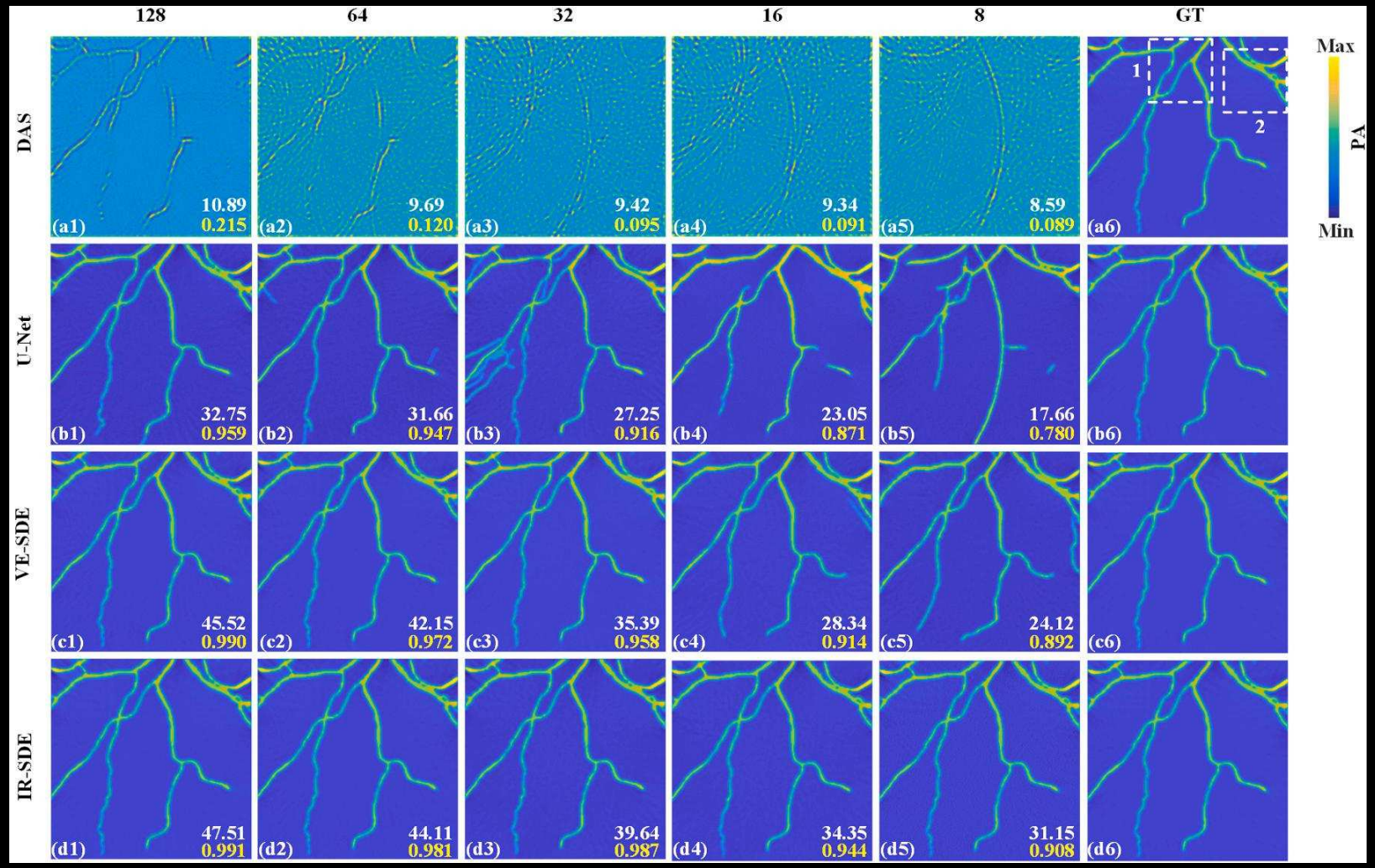
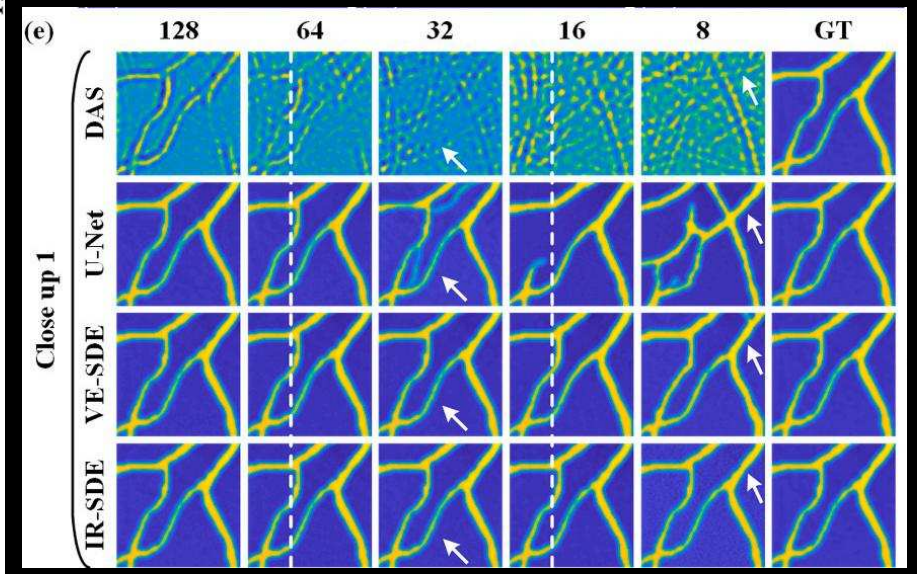
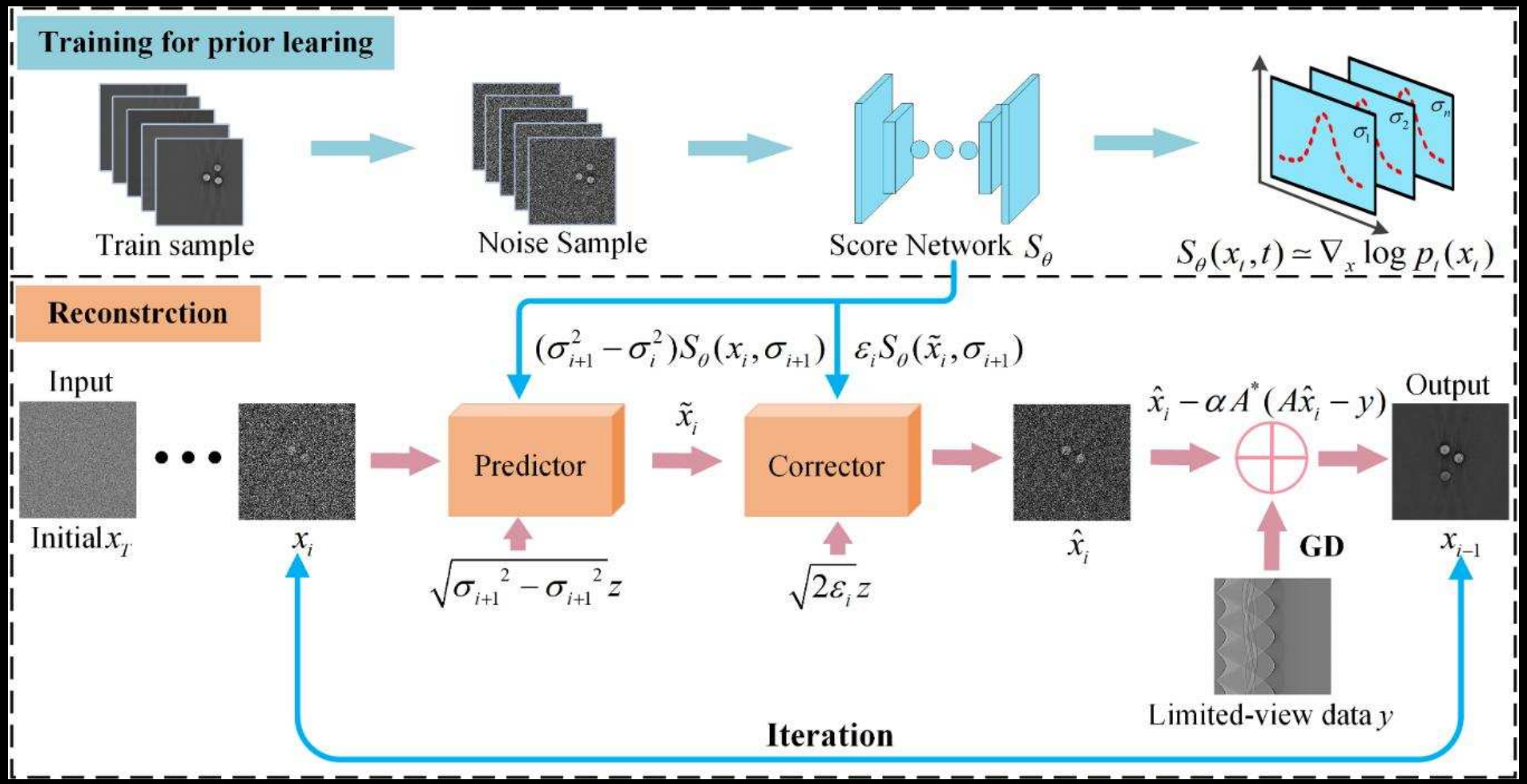


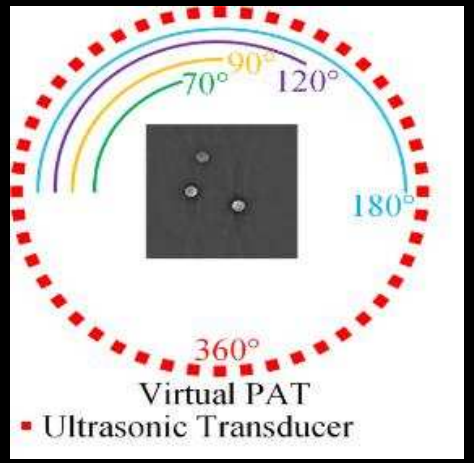


Lian, Teng, et al. "Generative priors-constraint accelerated iterative reconstruction for extremely sparse photoacoustic tomography boosted by mean-reverting diffusion model: Towards 8 projections." Photoacoustics 43 (2025): 100709.

PAT-DM for limited-view reconstruction

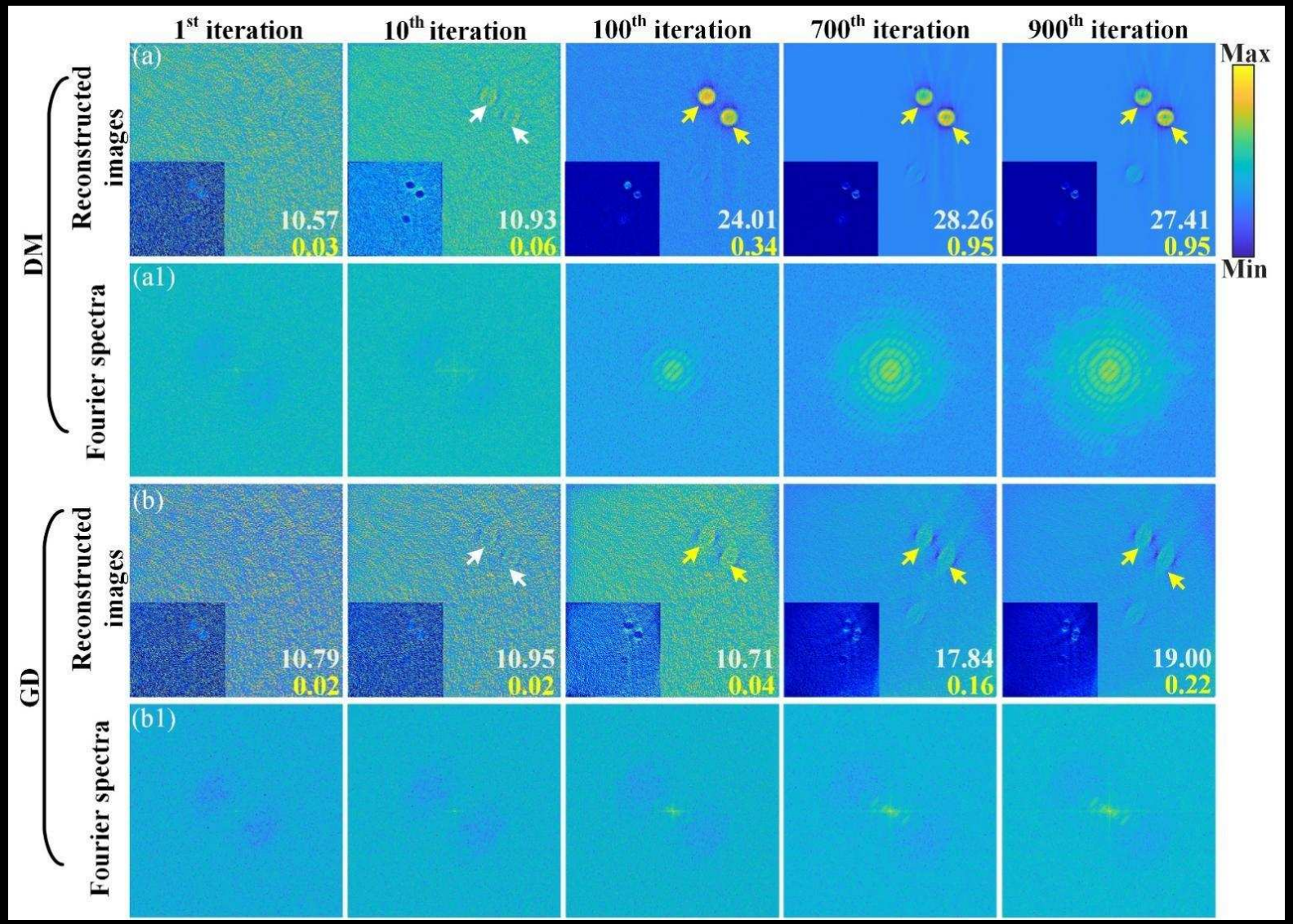
- Diffusion model + model-based iteration
- High-quality reconstruction with a limited 70-degree viewing Angle

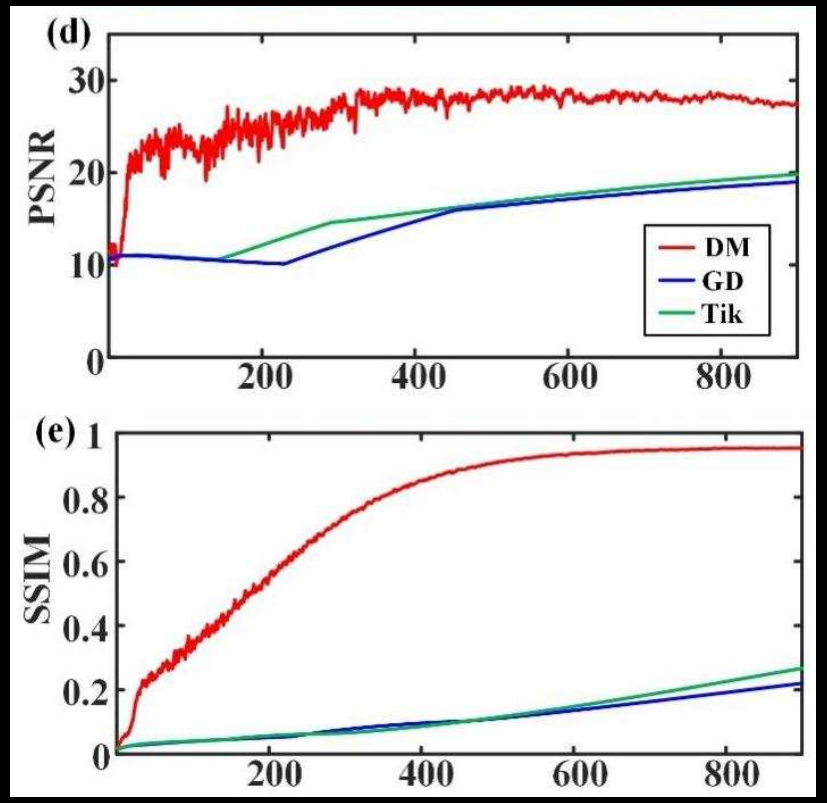




K. Guo, Z. Zheng, W. Zhong, Z. Li, G. Wang, J. Li, Y. Cao, Y. Wang, J. Lin, Q. Liu, X. Song. Score-based generative model-assisted information compensation for high-quality limited-view reconstruction in photoacoustic tomography. Photoacoustics, 2024, 38: 100623.

Results: circular phantom experimental data

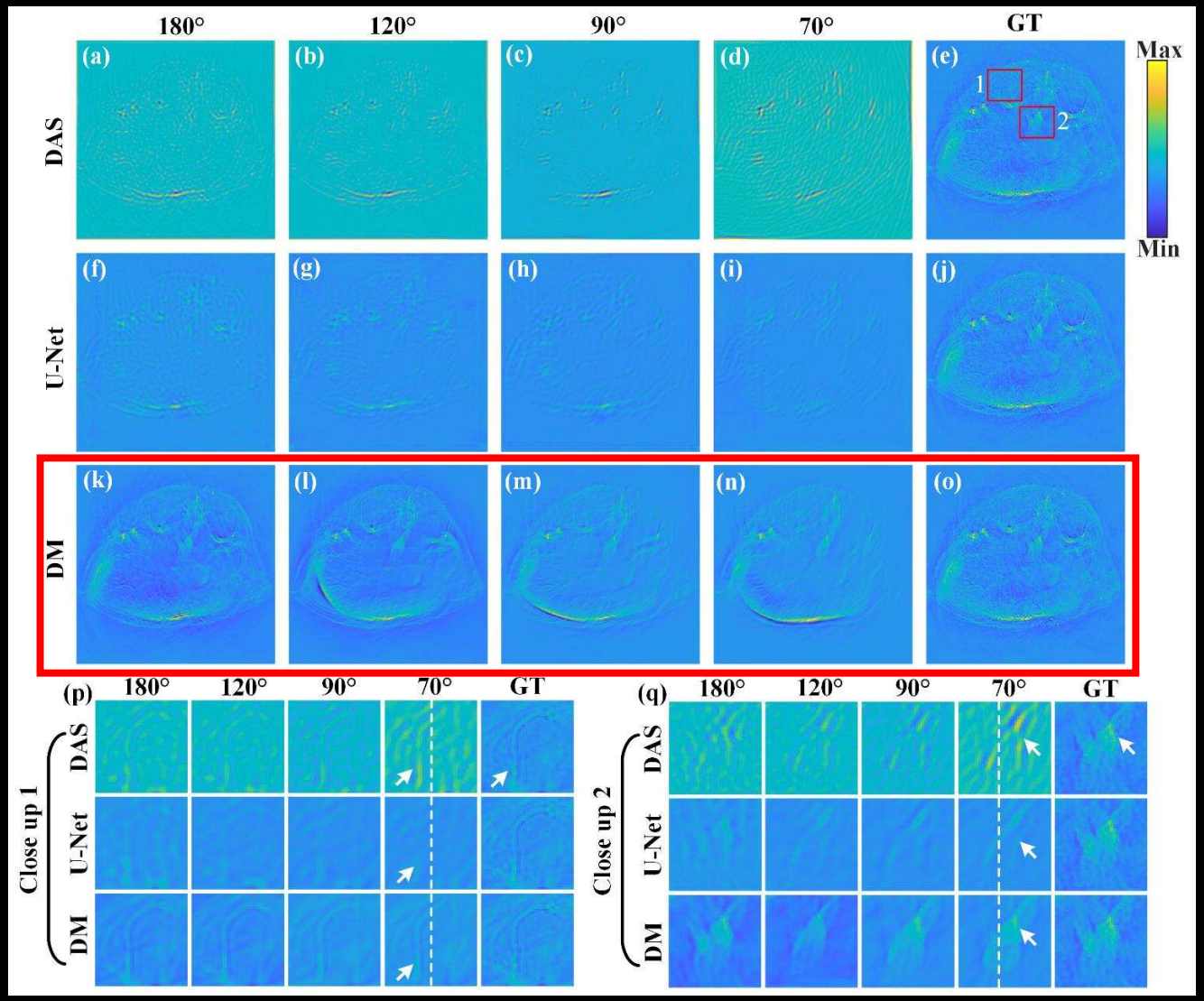


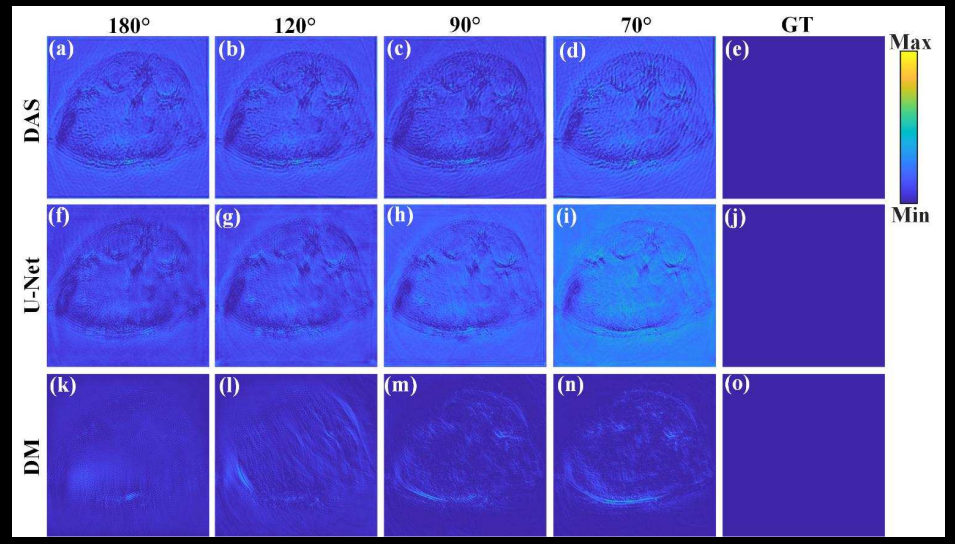


- **At the 700th iteration, the PSNR and SSIM of the results reach 28.26 dB and 0.95, respectively**

In limited-view case of 70°

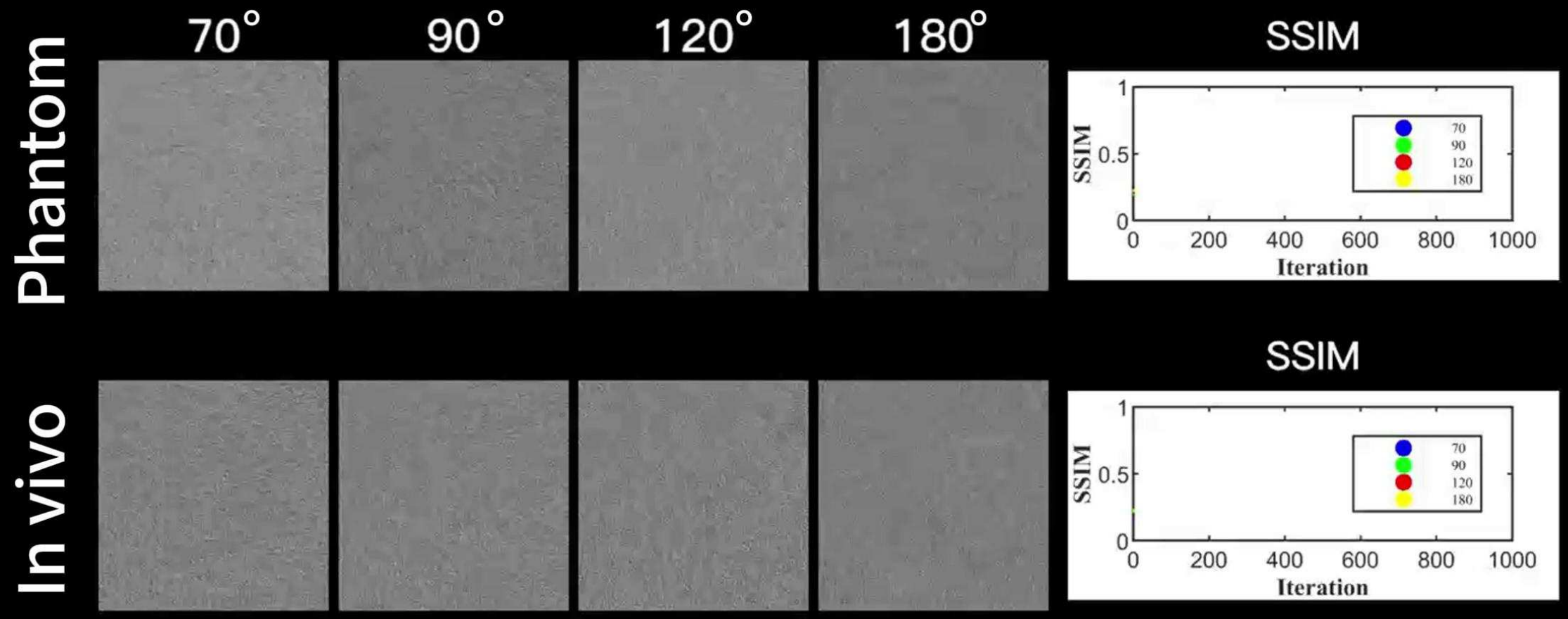
Results: in vivo experimental data





- Compared with the end-to-end U-net and GAN, the reconstruction method based on diffusion model has obvious advantages
- The proposed method surpasses the U-Net method even in exceedingly constrained limited-view cases (e.g., 70°-view)

Results: in vivo experimental data



PAM-DM for resolution enhancement

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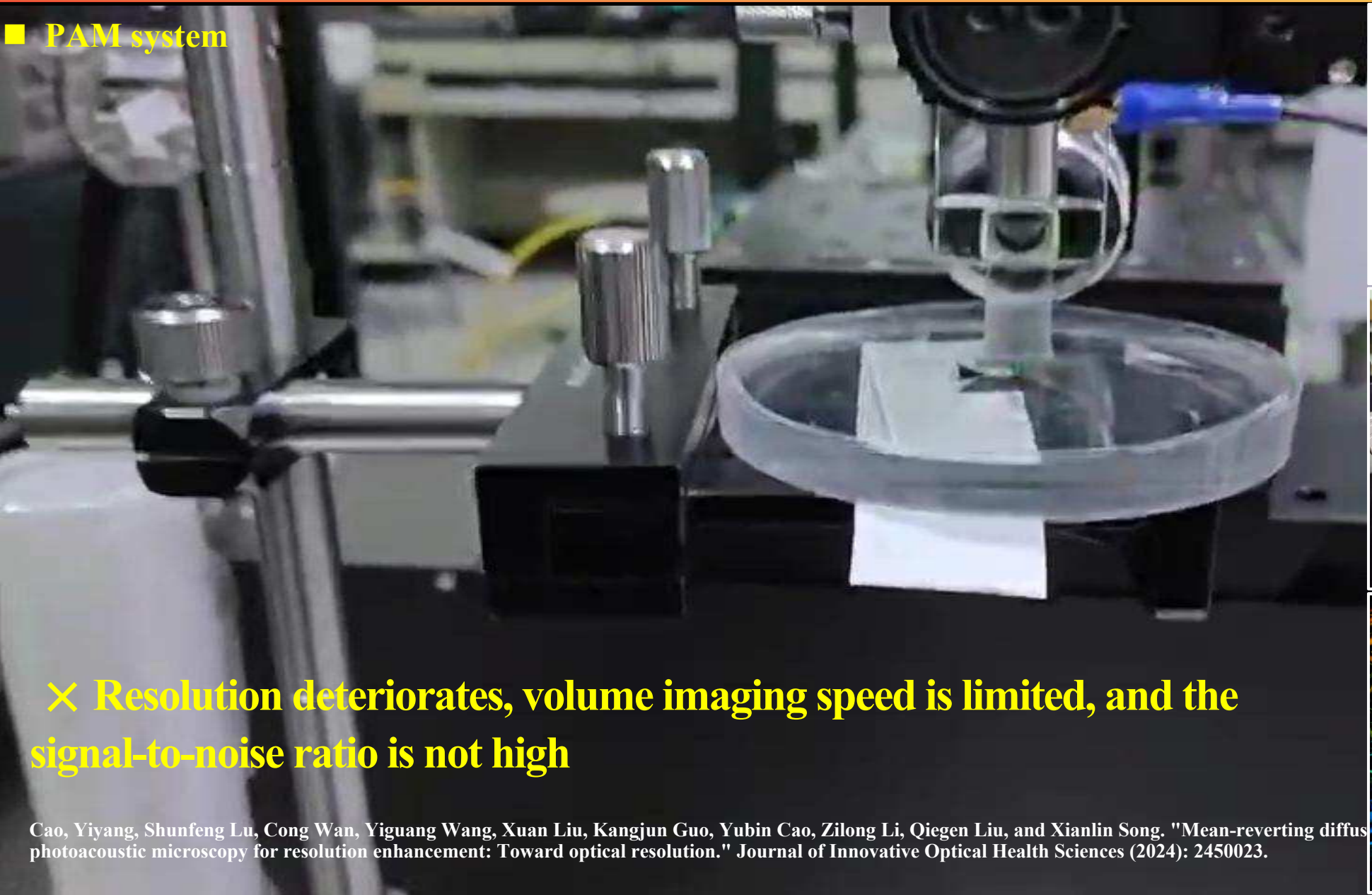
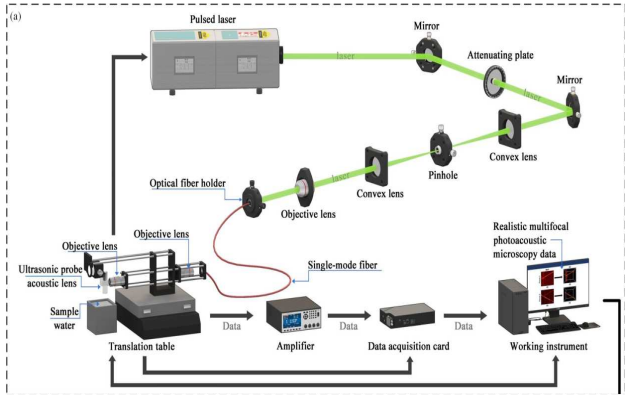
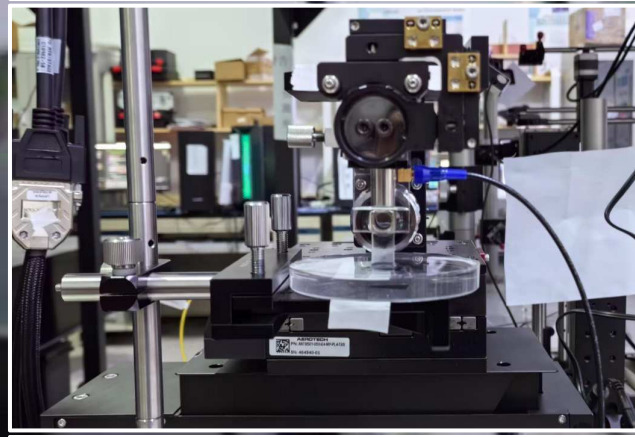
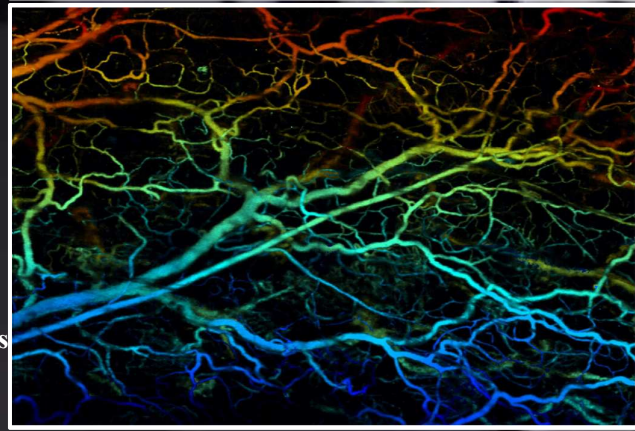
■ PAM system







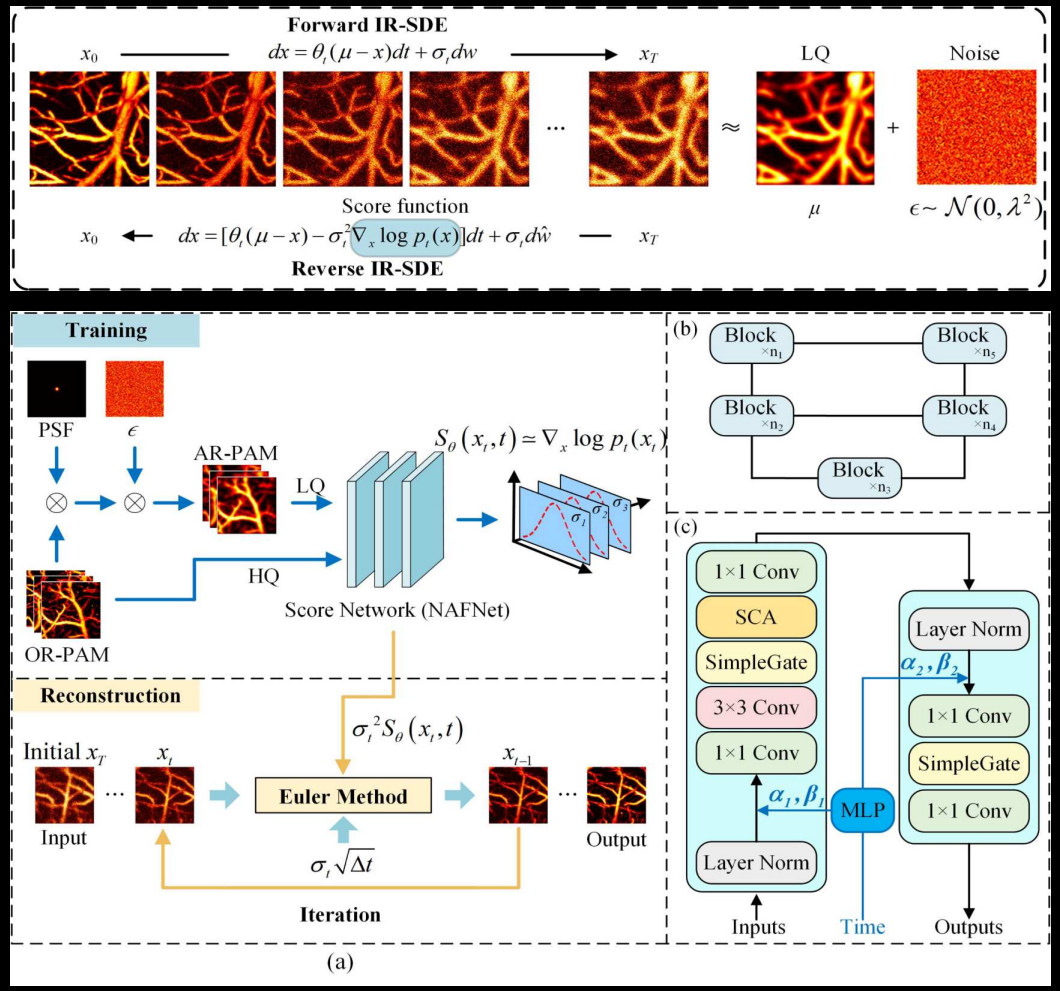


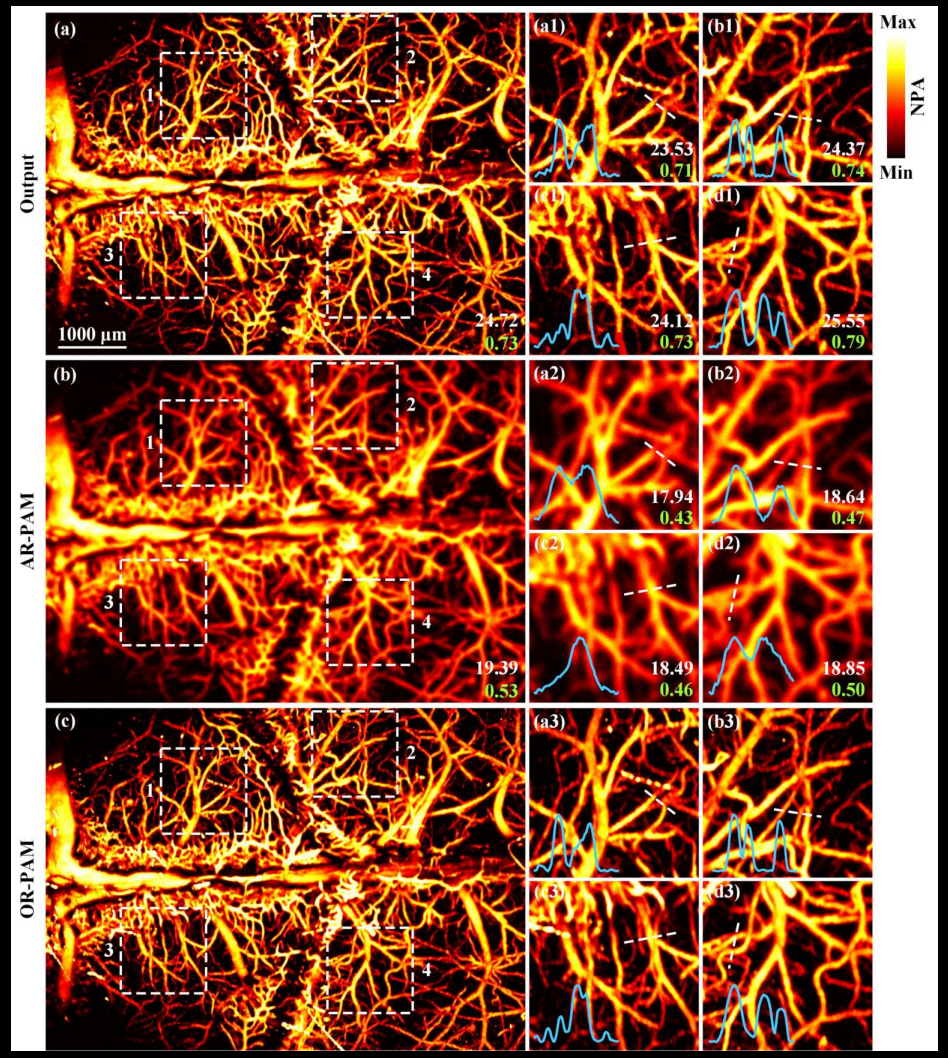
× Resolution deteriorates, volume imaging speed is limited, and the signal-to-noise ratio is not high

Cao, Yiyang, Shunfeng Lu, Cong Wan, Yiguang Wang, Xuan Liu, Kangjun Guo, Yubin Cao, Zilong Li, Qiegen Liu, and Xianlin Song. "Mean-reverting diffus photoacoustic microscopy for resolution enhancement: Toward optical resolution." Journal of Innovative Optical Health Sciences (2024): 2450023.

PAM-DM for resolution enhancement

- **Mean-reverting Diffusion model -enhanced acoustic-resolution photoacoustic microscopy**
- **Acoustic resolution to optical resolution**

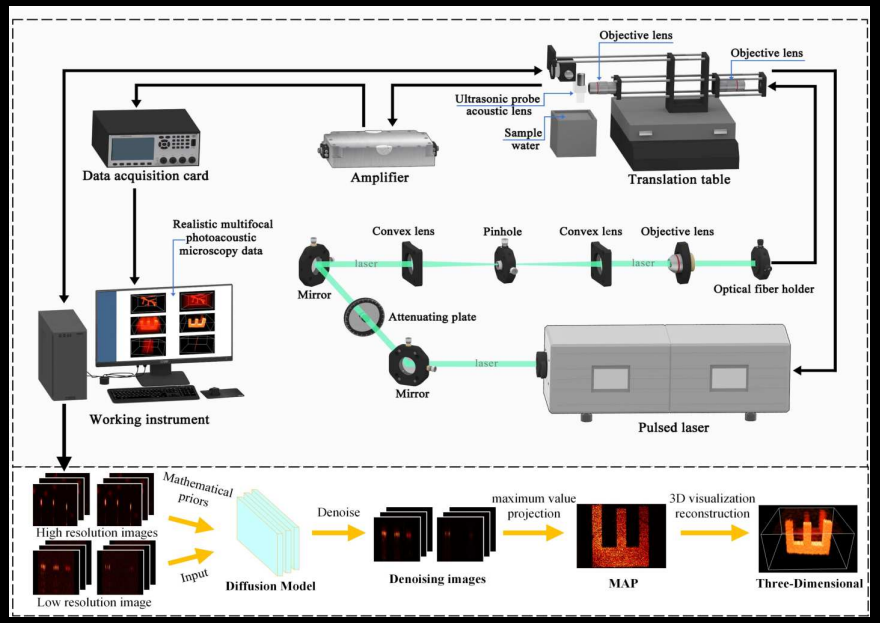


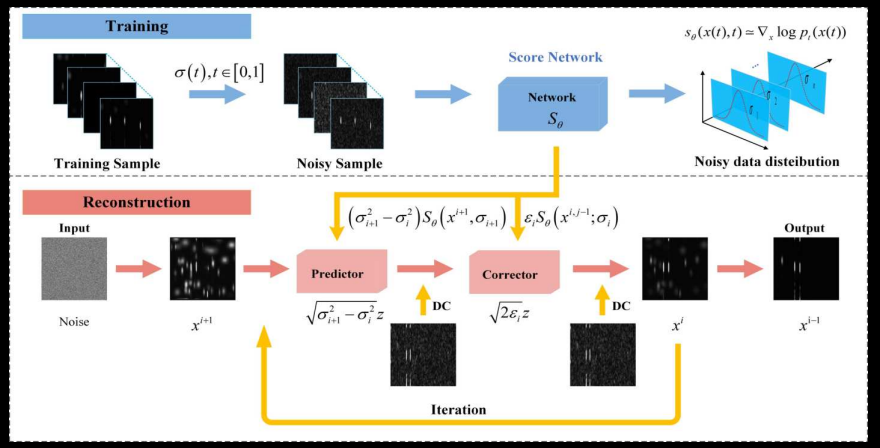


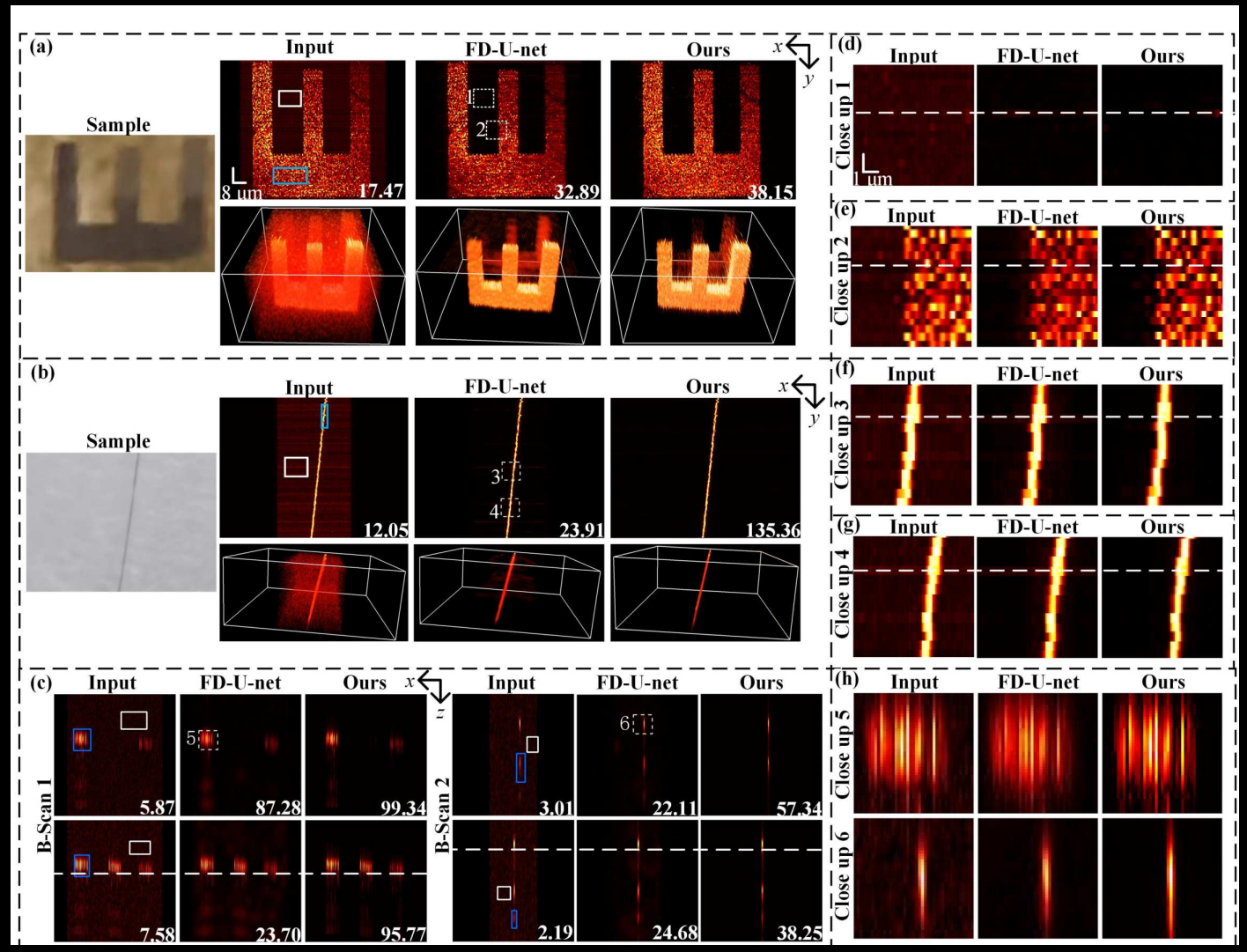
Cao, Yiyang, Shunfeng Lu, Cong Wan, Yiguang Wang, Xuan Liu, Kangjun Guo, Yubin Cao, Zilong Li, Qiegen Liu, and Xianlin Song. "Mean-reverting diffusion model-enhanced acoustic-resolution photoacoustic microscopy for resolution enhancement: Toward optical resolution." Journal of Innovative Optical Health Sciences (2024): 2450023.

PAM-DM for denoising

- **Diffusion model -enhanced optical-resolution photoacoustic microscopy**







Wang, Y., Liu, X., Cao, Y., Tang, C., Lei, Y., Fang, H., ... & Song, X. (2025). Score-based diffusion priors-guided generative deep learning for highly robust 3D denoising in photoacoustic microscopy. Optics & Laser Technology, 190, 113241.

PAM-DM for denoising

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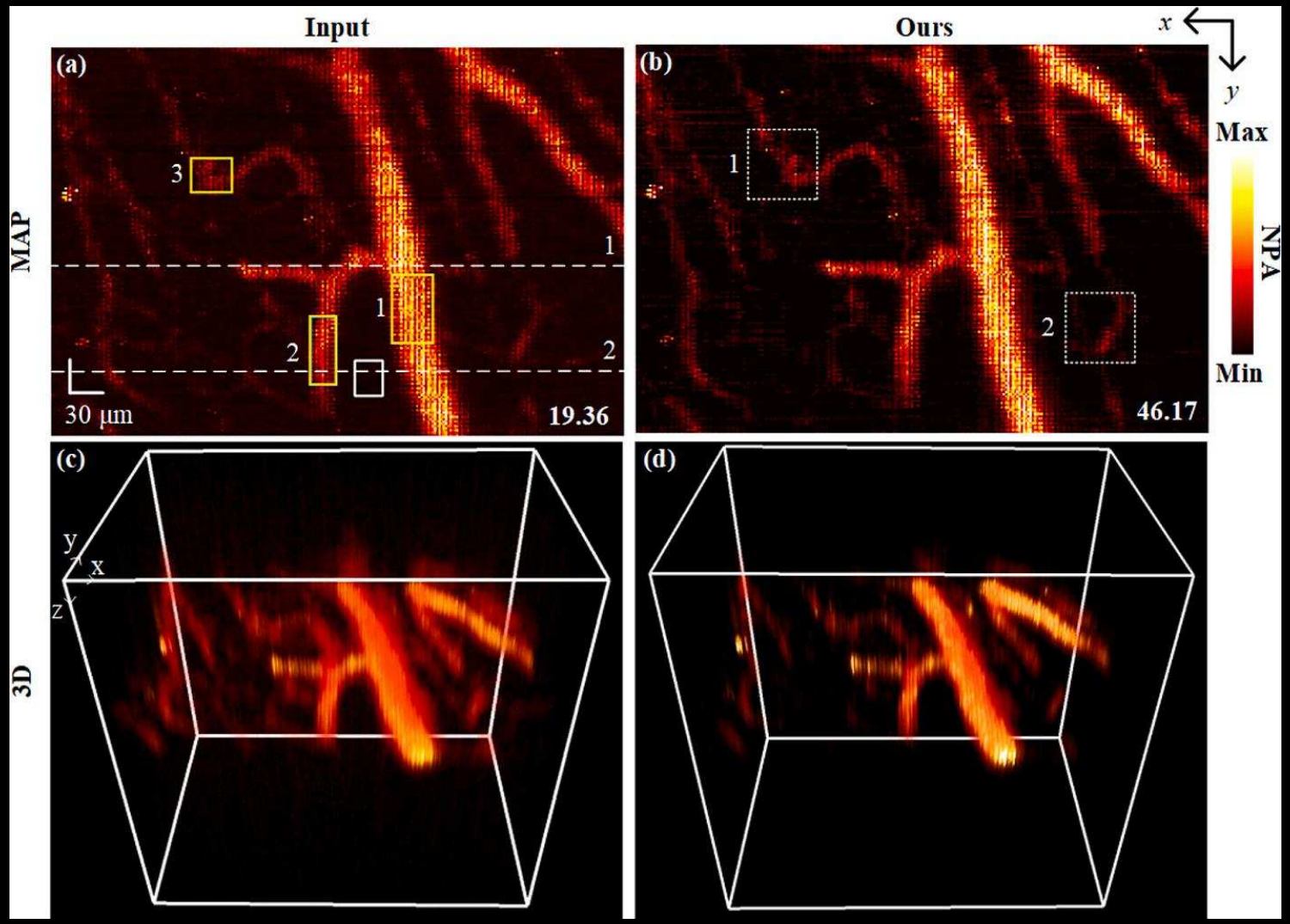
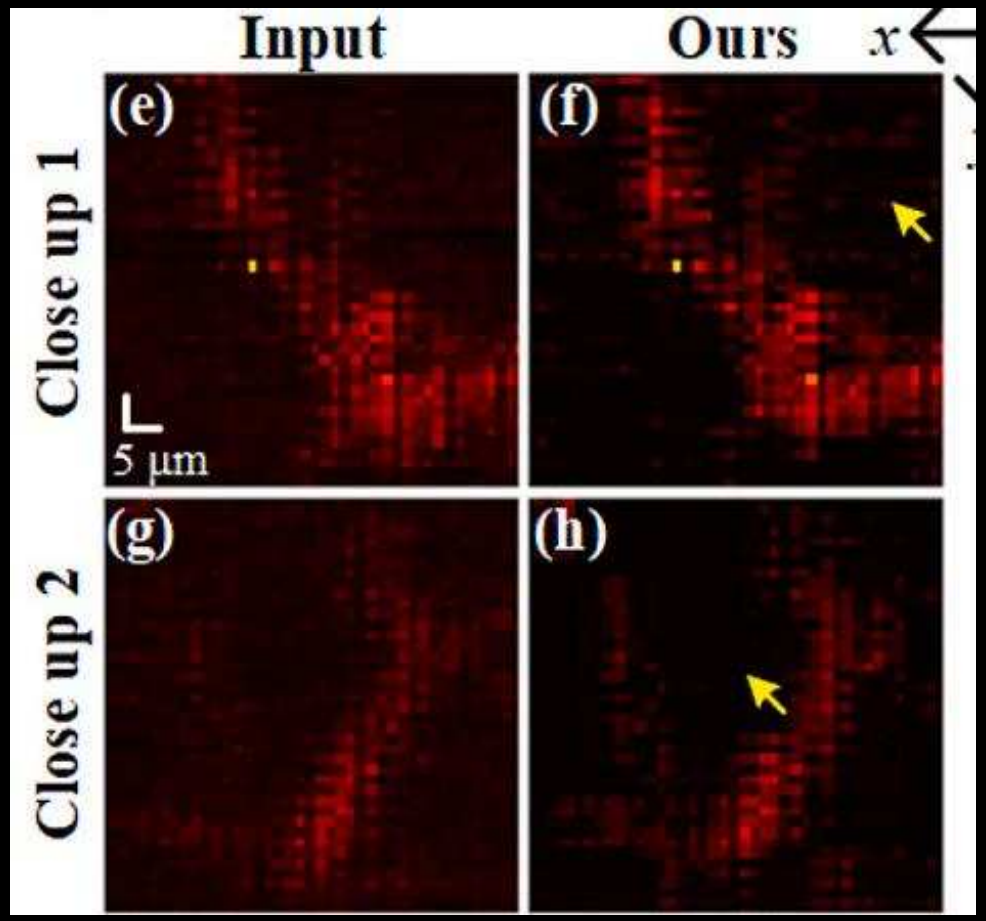
- **Diffusion model -enhanced optical-resolution photoacoustic microscopy**





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DSM from image domain to Projection domain

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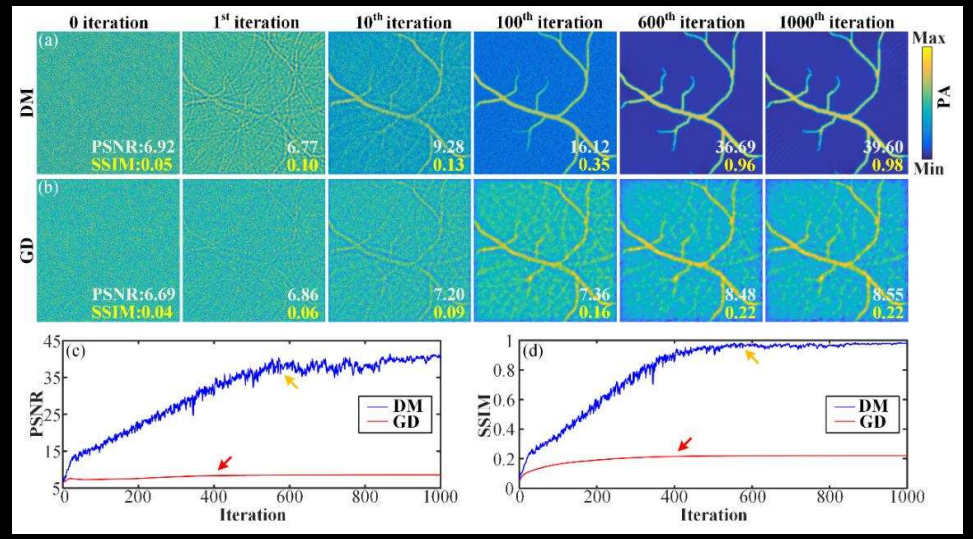
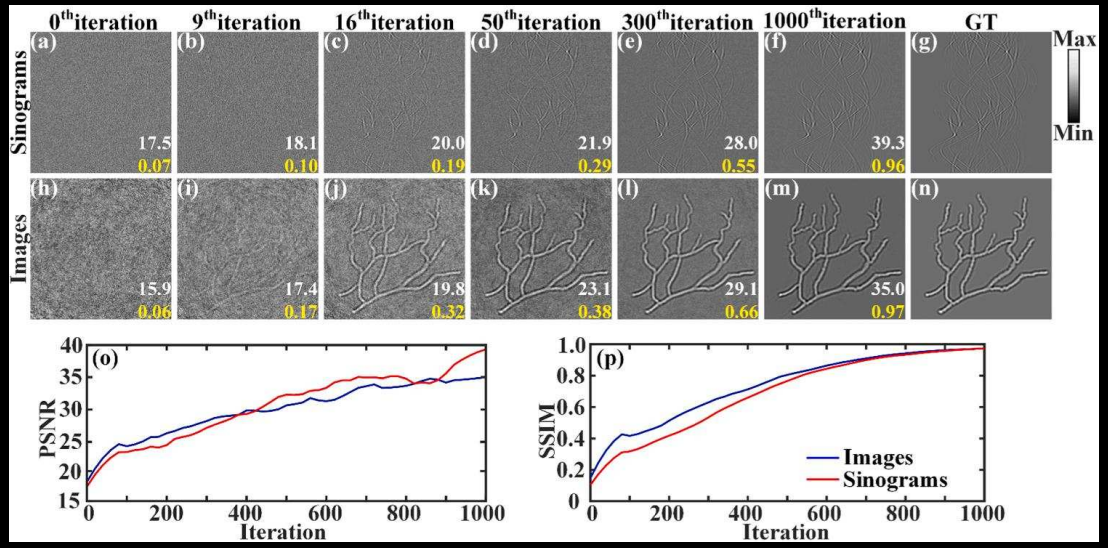
Generative model in image domain

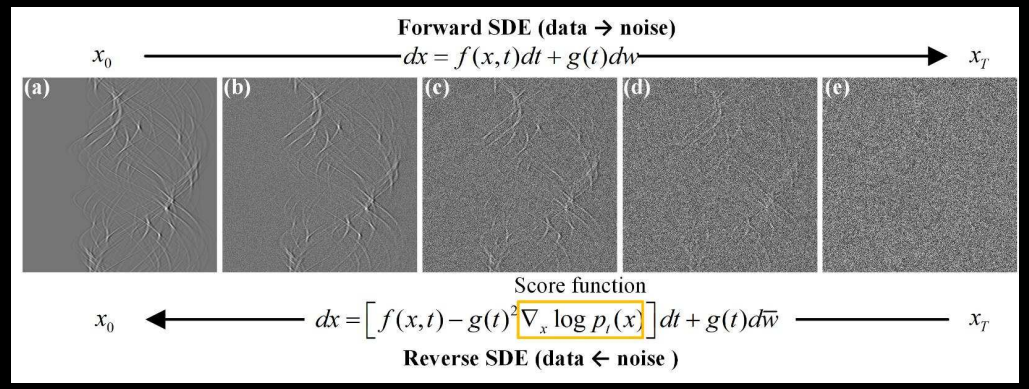


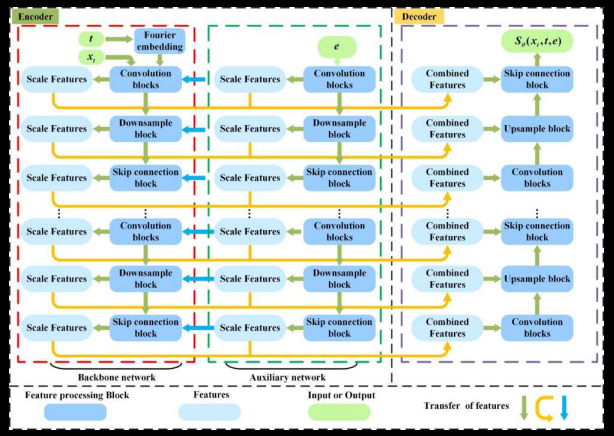


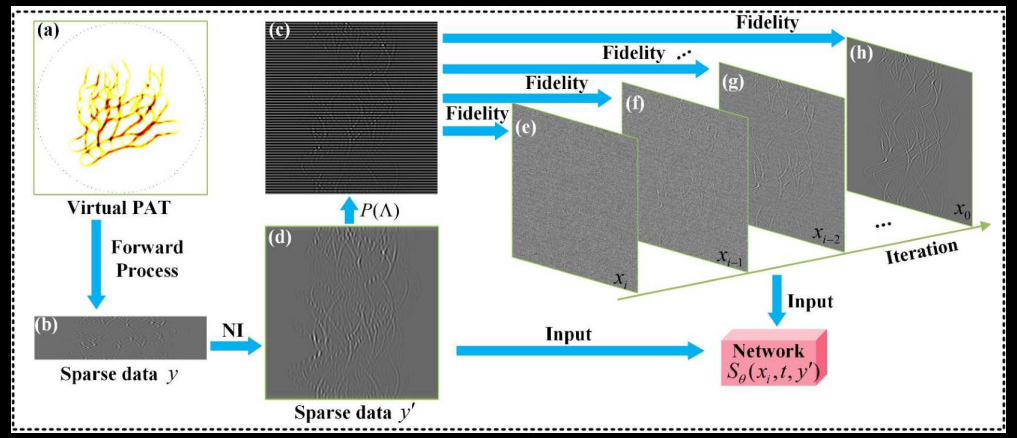
Generative model in Projection domain

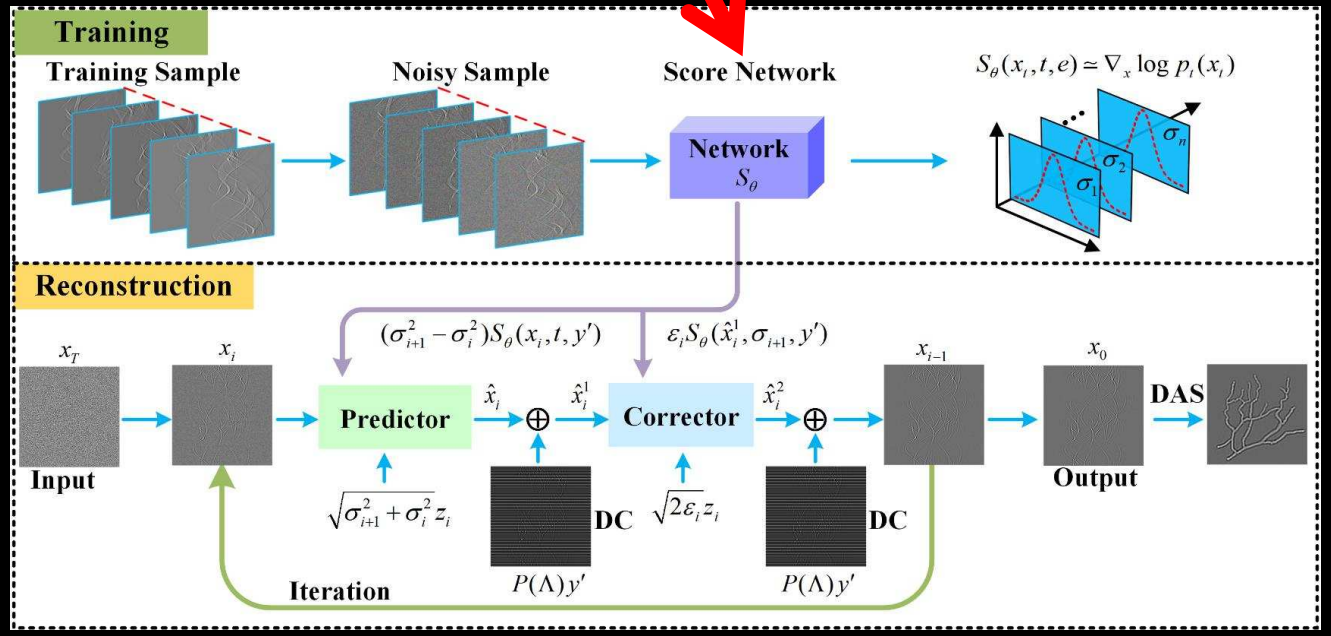
PAT-DM in projection domain

- **Diffusion model + sinogram domain prior**
- **Higher-quality reconstruction with 32 projections**



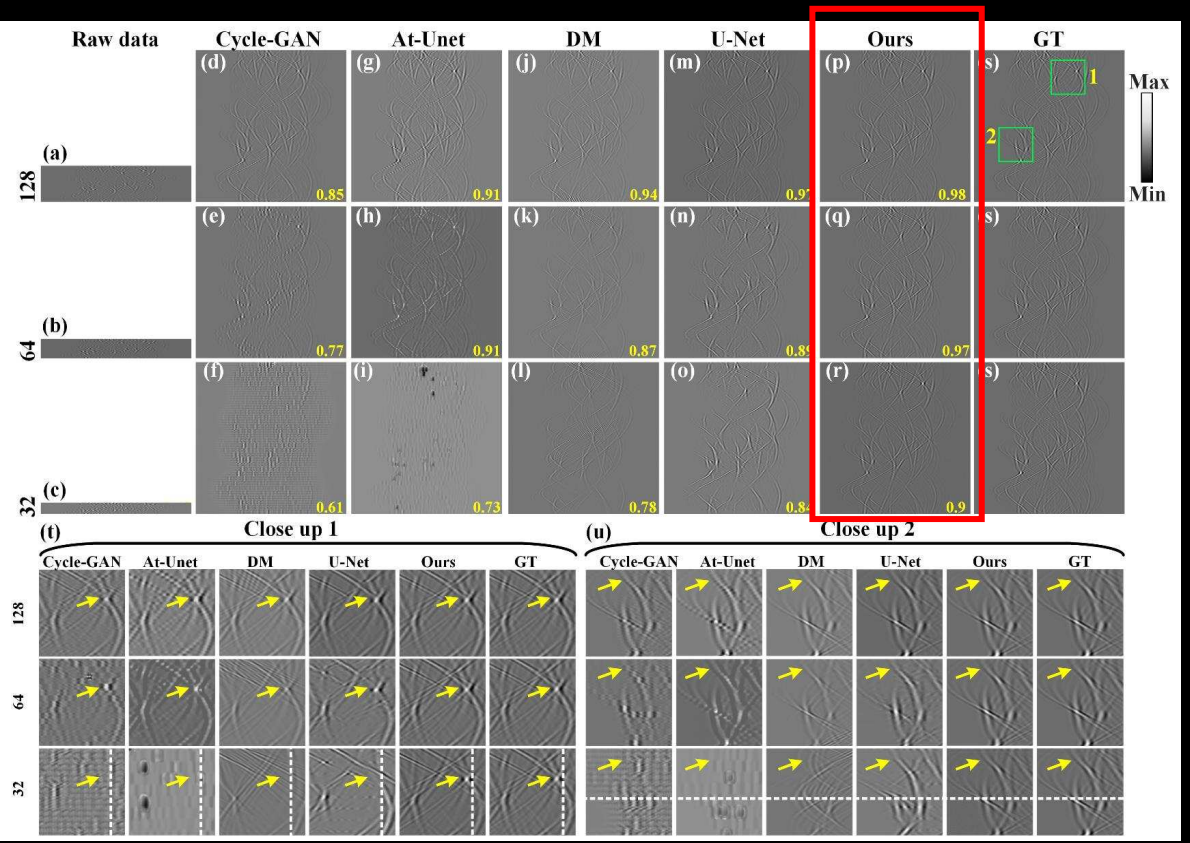






Li, Zilong, Jiabin Lin, Yiguang Wang, Jiahong Li, Yubin Cao, Xuan Liu, Wenbo Wan, Qiegen Liu, and Xianlin Song. "Ultra-sparse reconstruction for photoacoustic tomography: sinogram domain prior-guided method exploiting enhanced score-based diffusion model." Photoacoustics (2024): 100670.

PAT-DM in projection domain



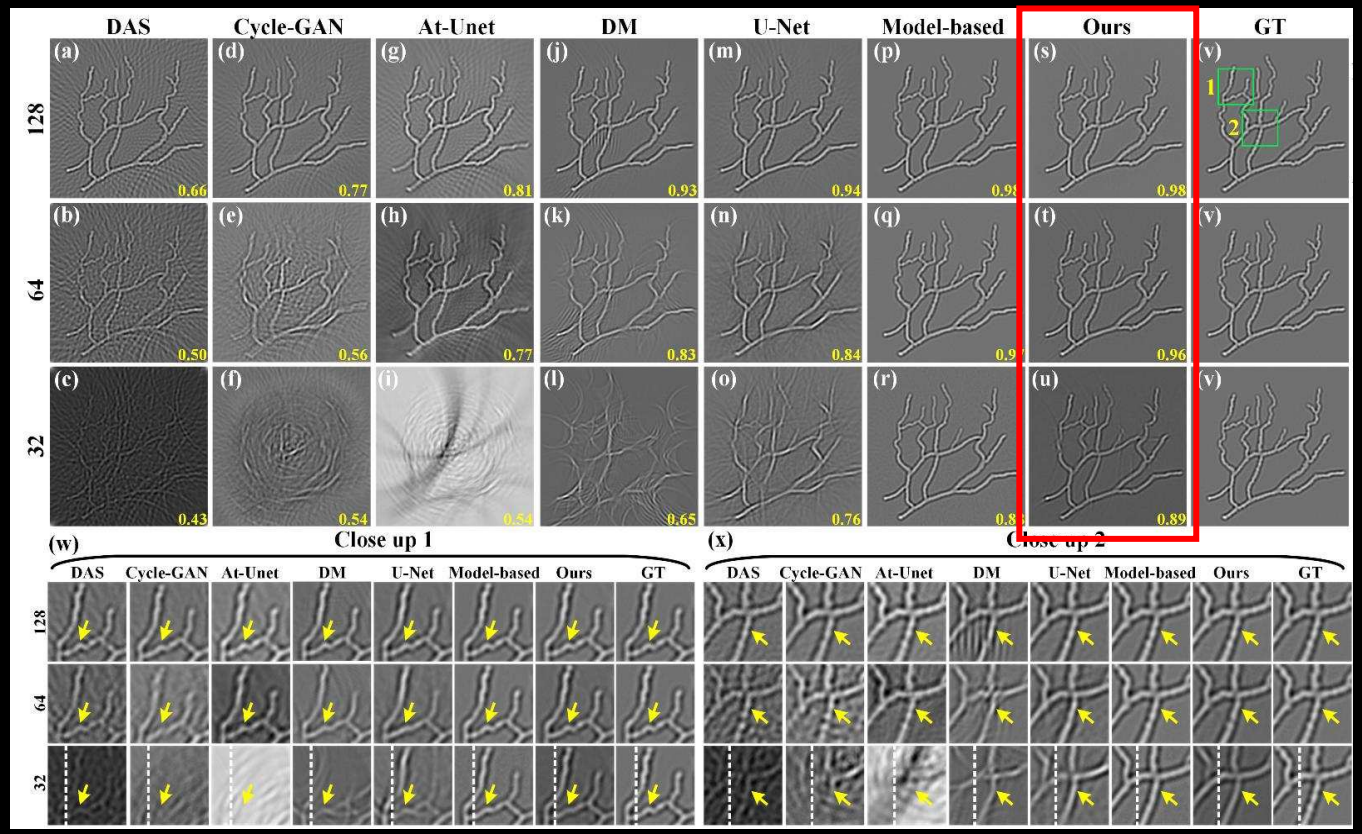


Table 1. The average SSIM and CC values for the reconstruction results of the simulated vascular sinograms.

Number of projections	32		64		128	
Method/Metric	SSIM	CC	SSIM	CC	SSIM	CC
Cycle-GAN	0.7584	0.2294	0.8090	0.4124	0.8803	0.6205
At-Unet	0.7591	0.2613	0.8078	0.4472	0.9315	0.6723
DM	0.7790	0.2911	0.9169	0.6153	0.9574	0.7029
U-Net	0.8829	0.5606	0.9198	0.6503	0.9792	0.8223
Ours	**0.9435**	**0.7127**	**0.9796**	**0.7777**	**0.9897**	**0.7895**

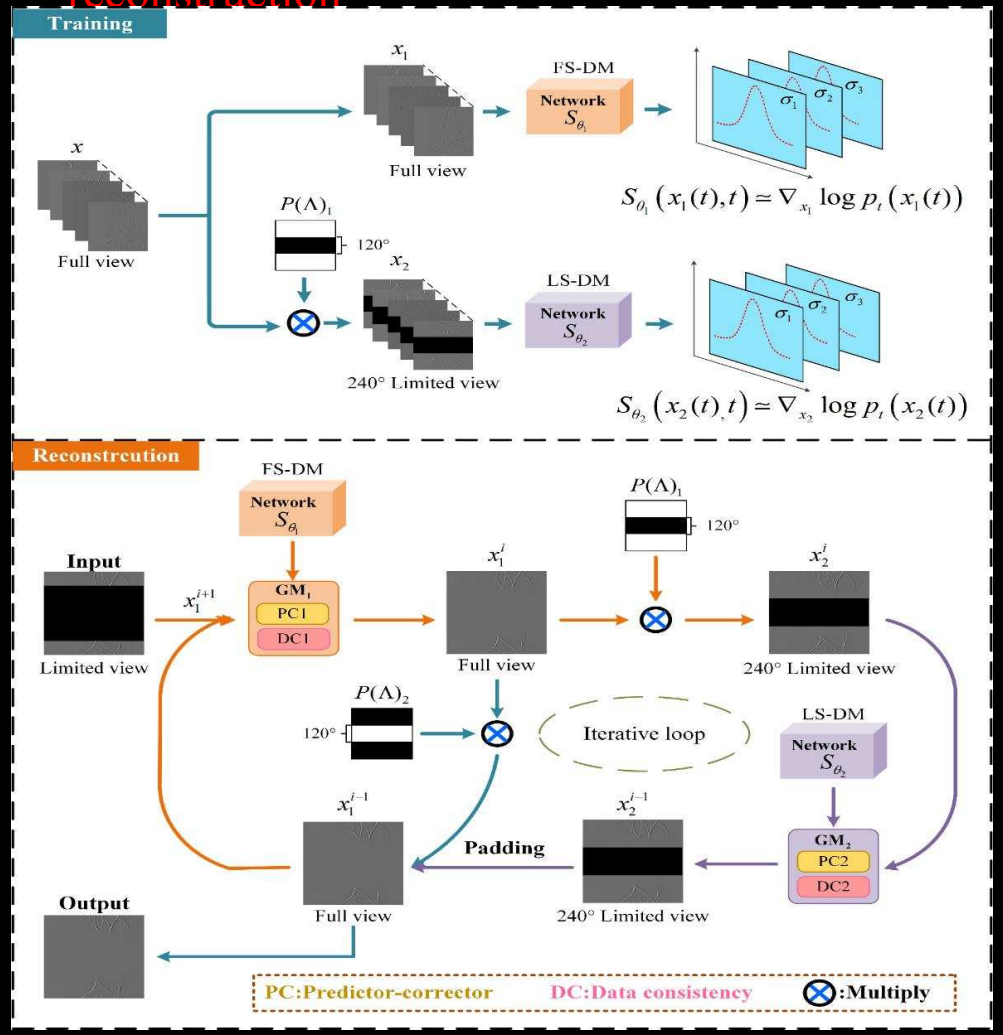
Table 2. The average SSIM and CC values for the reconstruction results of the simulated vascular images.

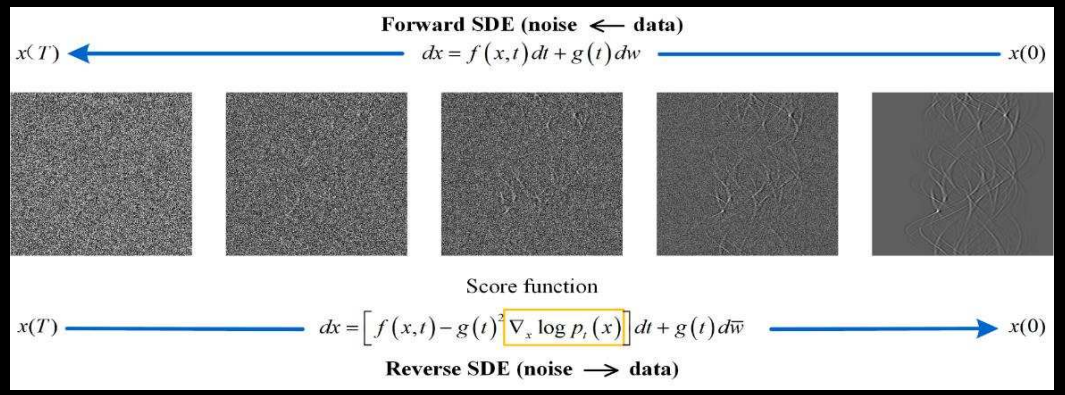
Number of projections	32		64		128	
Method/Metric	SSIM	CC	SSIM	CC	SSIM	CC
DAS	0.4388	0.4431	0.5242	0.6033	0.6599	0.7843
Cycle-GAN	0.5219	0.1148	0.5929	0.2627	0.7137	0.5652
At-Unet	0.6079	0.0742	0.6780	0.4359	0.8122	0.8064
DM	0.6776	0.4451	0.8917	0.8229	0.9559	0.9014
U-Net	0.8175	0.6794	0.8786	0.8233	0.9617	0.9294
Model-based DM	0.9308	**0.8943**	0.9714	0.9115	0.9801	0.9233
Ours	**0.9467**	0.8876	**0.9809**	**0.9443**	**0.9887**	**0.9563**

Li, Zilong, Jiabin Lin, Yiguang Wang, Jiahong Li, Yubin Cao, Xuan Liu, Wenbo Wan, Qiegen Liu, and Xianlin Song. "Ultra-sparse reconstruction for photoacoustic tomography: sinogram domain prior-guided method exploiting enhanced score-based diffusion model." Photoacoustics (2024): 100670.

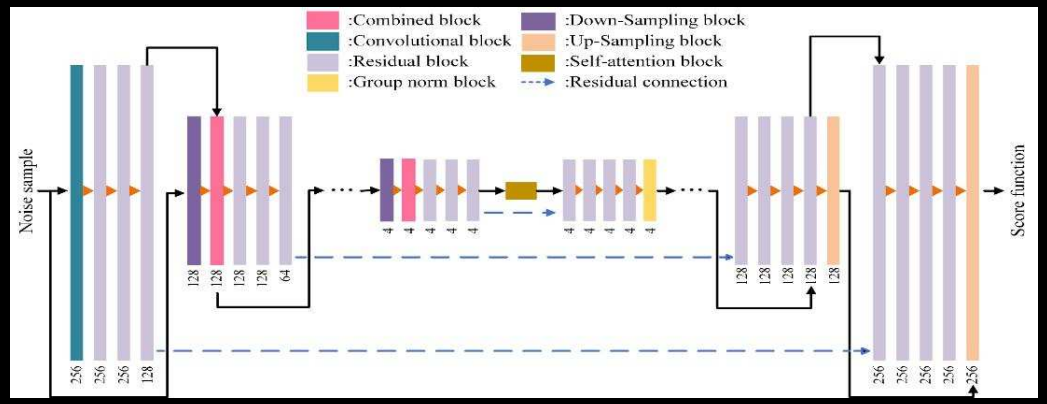
PAT+Multiple diffusion model

- Multiple diffusion models-enhanced extremely limited-view reconstruction: Multi-diffusion model + Rotational iterative reconstruction





Train in the projection domain



Score network

X. Song, X. Zou, K. Zeng, J. Li, S. Hou, Y. Wu, Z. Li, C. Ma, Z. Zheng, K. Guo, Q. Liu. Multiple diffusion models-enhanced extremely limited-view reconstruction strategy for photoacoustic tomography boosted by multi-scale priors[J]. Photoacoustics, 2024.

PAT+Multiple diffusion model

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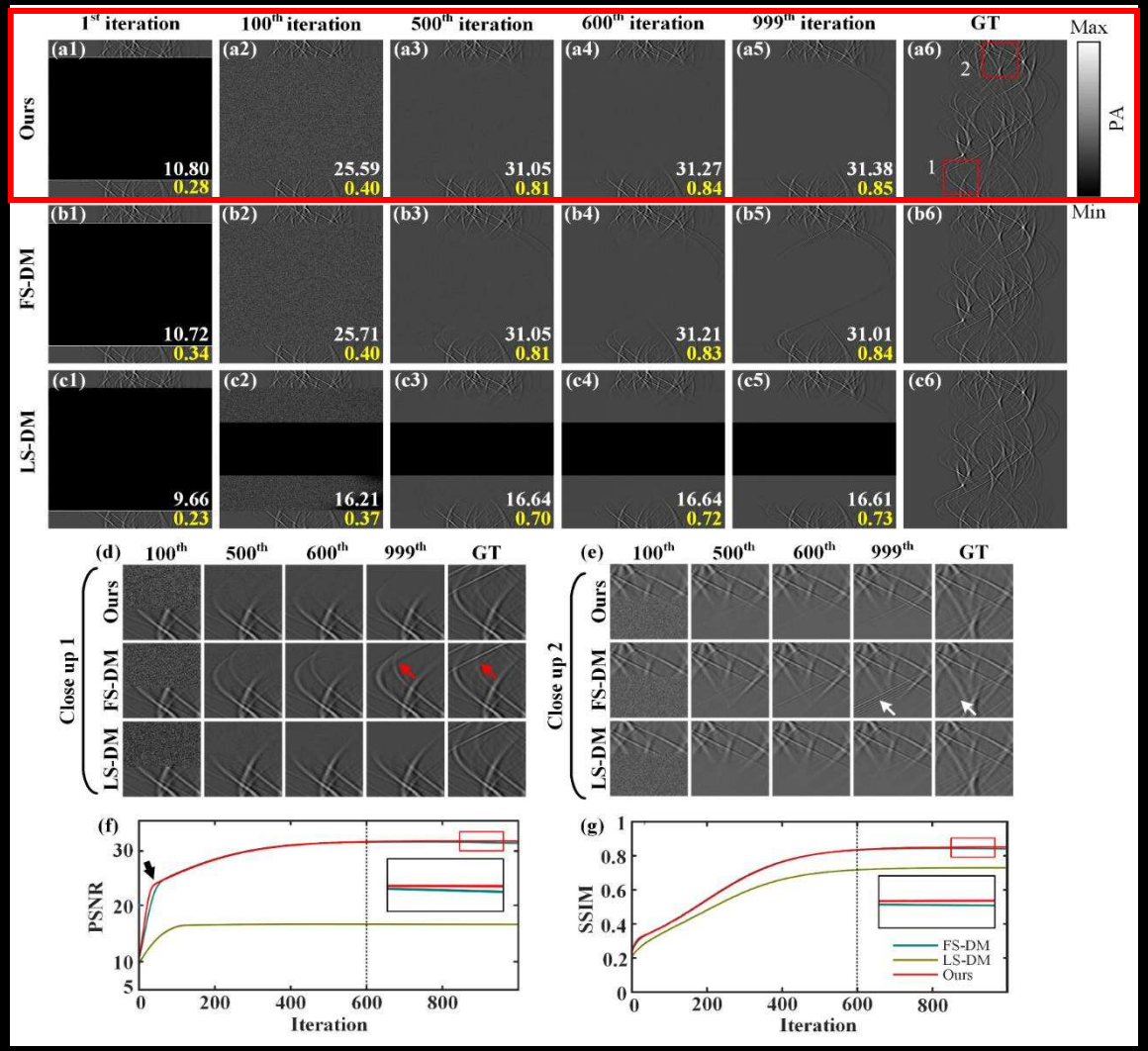
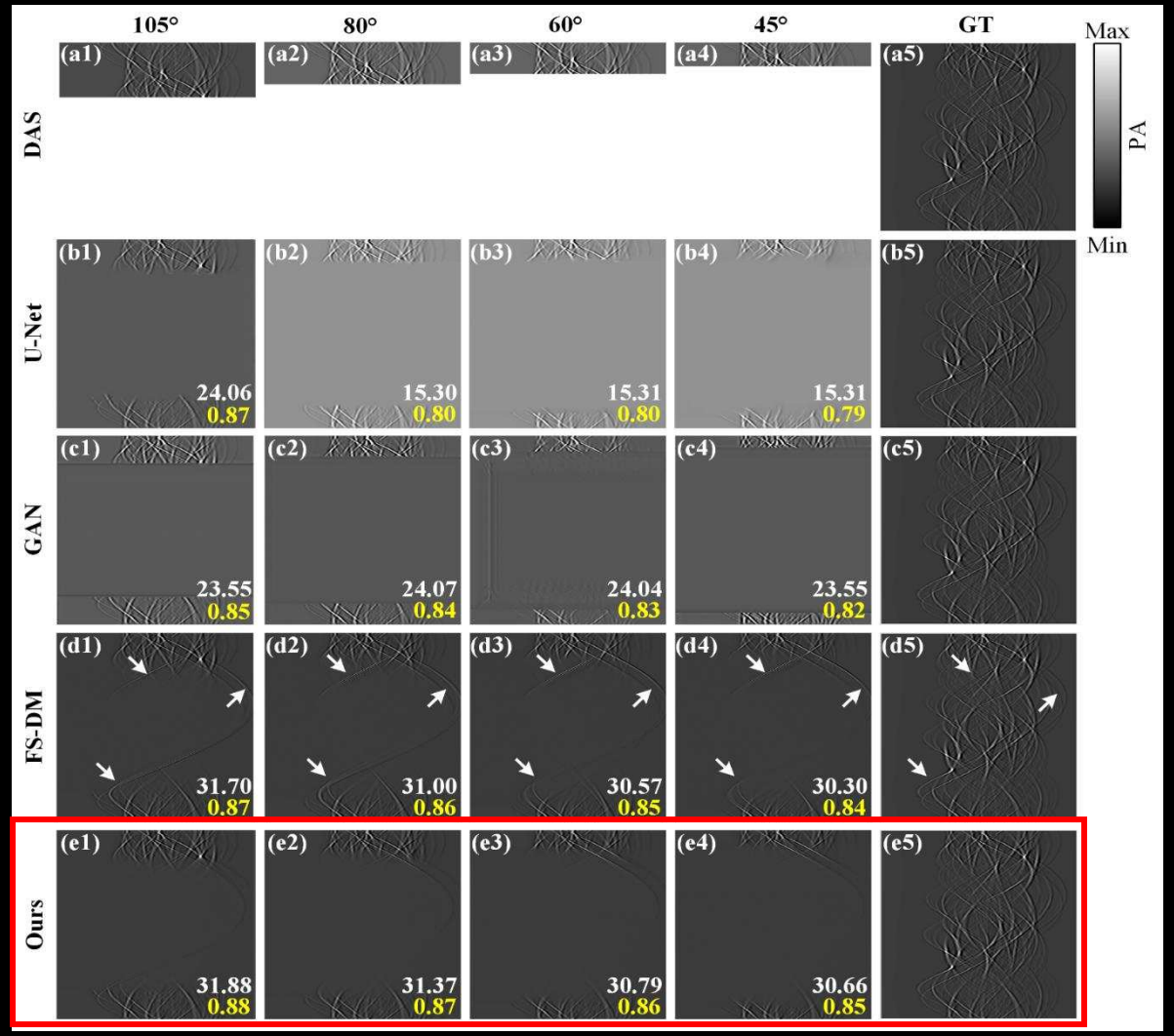
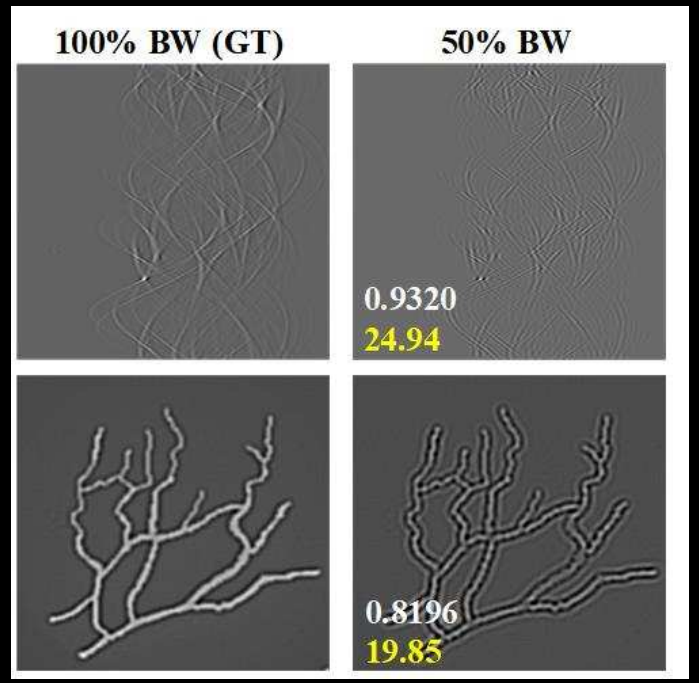




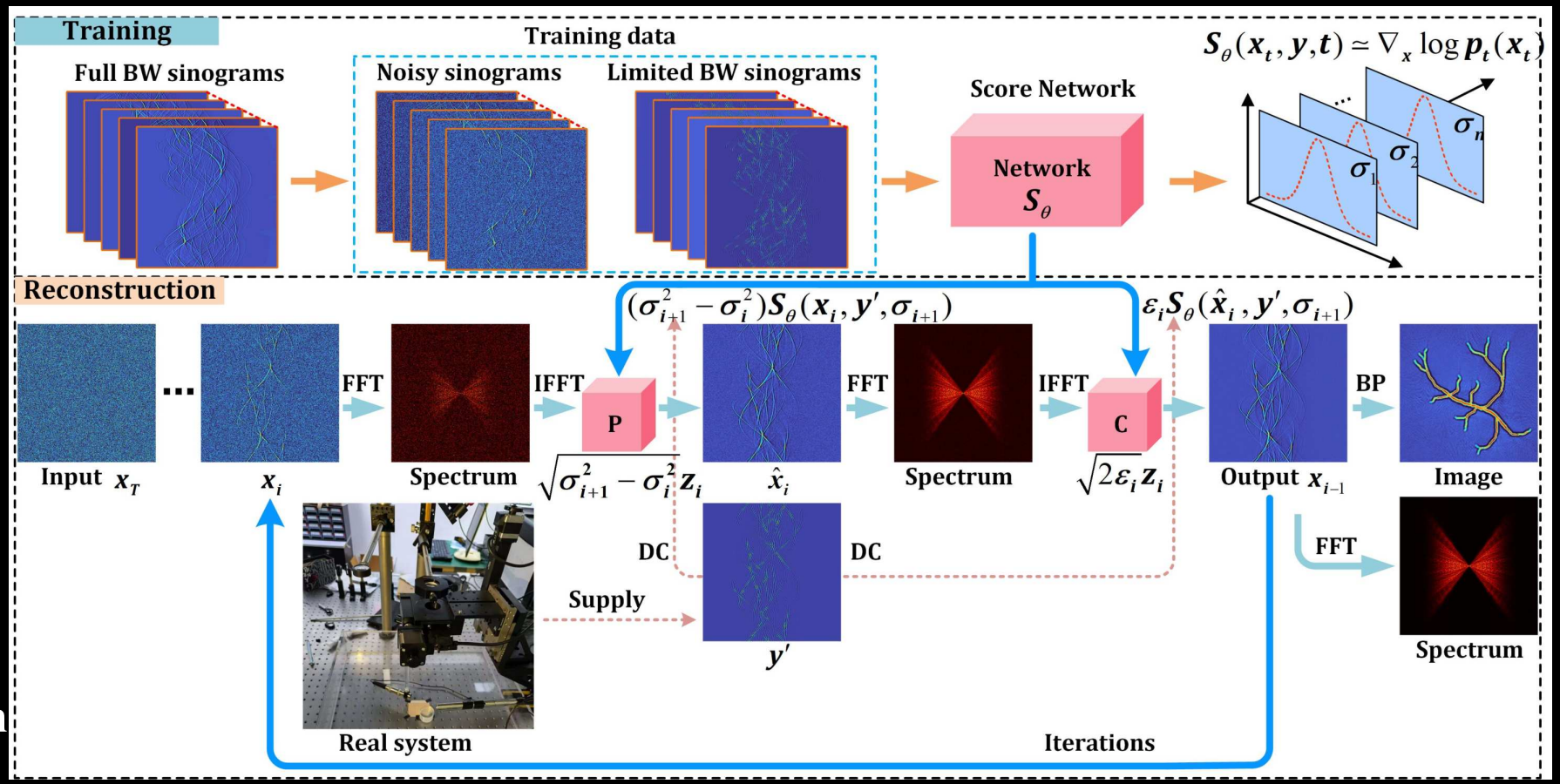
X. Song, X. Zou, K. Zeng, J. Li, S. Hou, Y. Wu, Z. Li, C. Ma, Z. Zheng, K. Guo, Q. Liu. Multiple diffusion models-enhanced extremely limited-view reconstruction strategy for photoacoustic tomography boosted by multi-scale priors[J]. Photoacoustics, 2024.

Bandwidth enhancement+diffusion model

- Enhanced score-based priors-boosted generative model for resolution breakthrough in photoacoustic tomography (ESDM)
- The resolution of the proposed method is about 1.66 times that of the limited bandwidth baseline



Images with different bandwidth



ESDM framework

Jiabin Lin, Zilong Li, Haoran Fang, Guolin Liu, Siyi Cao, Yubin Cao, Linxin Li, Jiahong Li, Yiguang Wang, Haipeng Wei, Shuhao Ma, Zhiyuan Zheng, Qiegen Liu, and Xianlin Song. Enhanced score-based priors-boosted generative model for resolution breakthrough in photoacoustic tomography[J]. Optics Letters, 2025.

Bandwidth enhancement+diffusion model

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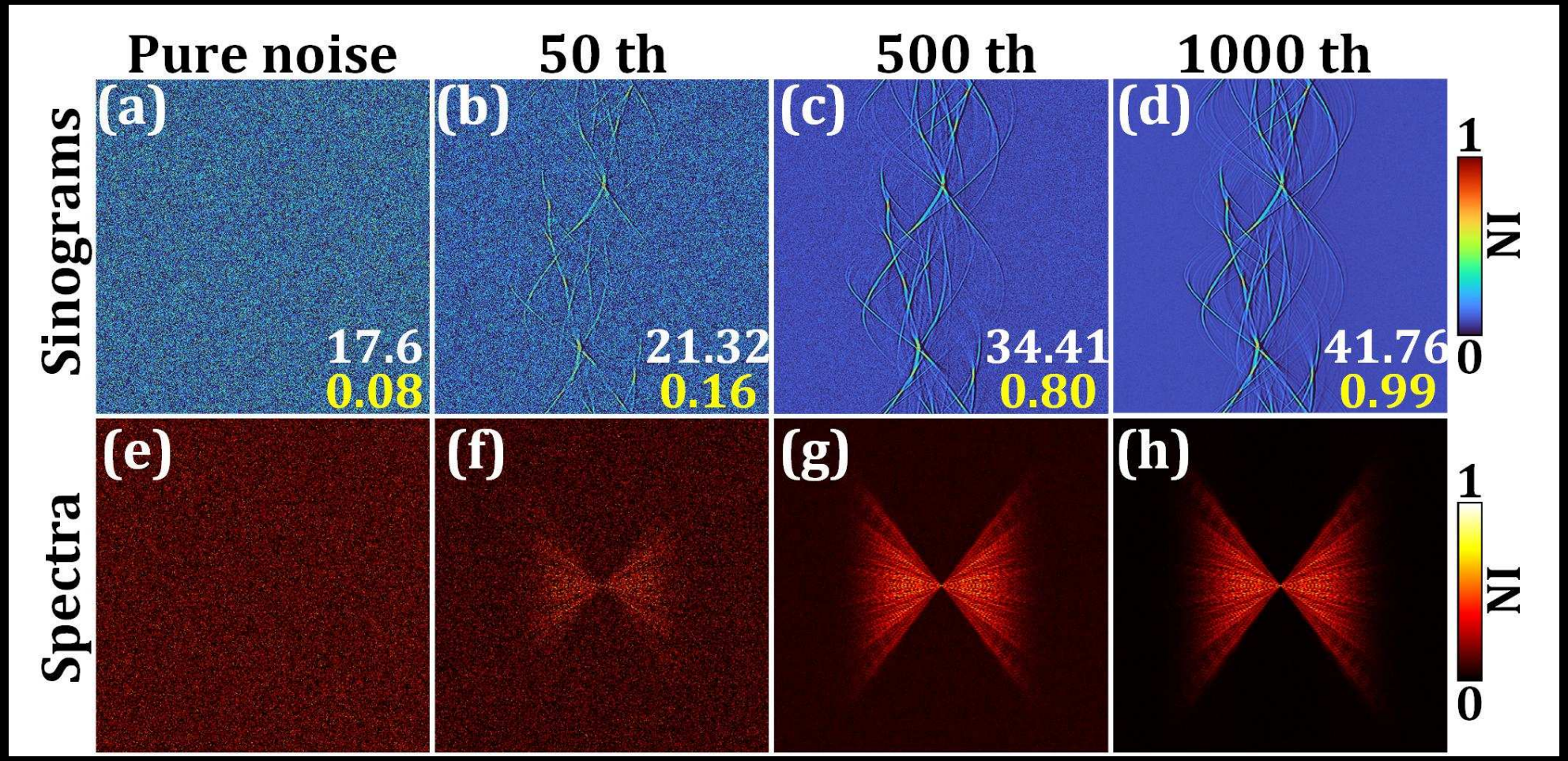
- **The resolution of the proposed method is about 1.66 times that of the limited bandwidth baseline**



Jiabin Lin, Zilong Li, Haoran Fang, Guolin Liu, Siyi Cao, Yubin Cao, Linxin Li, Jiahong Li, Yiguang Wang, Haipeng Wei, Shuhao Ma, Zhiyuan Zheng, Qiegen Liu, and Xianlin Song. Enhanced score-based priors-boosted generative model for resolution breakthrough in photoacoustic tomography[J]. Optics Letters, 2025.

Bandwidth enhancement+diffusion model

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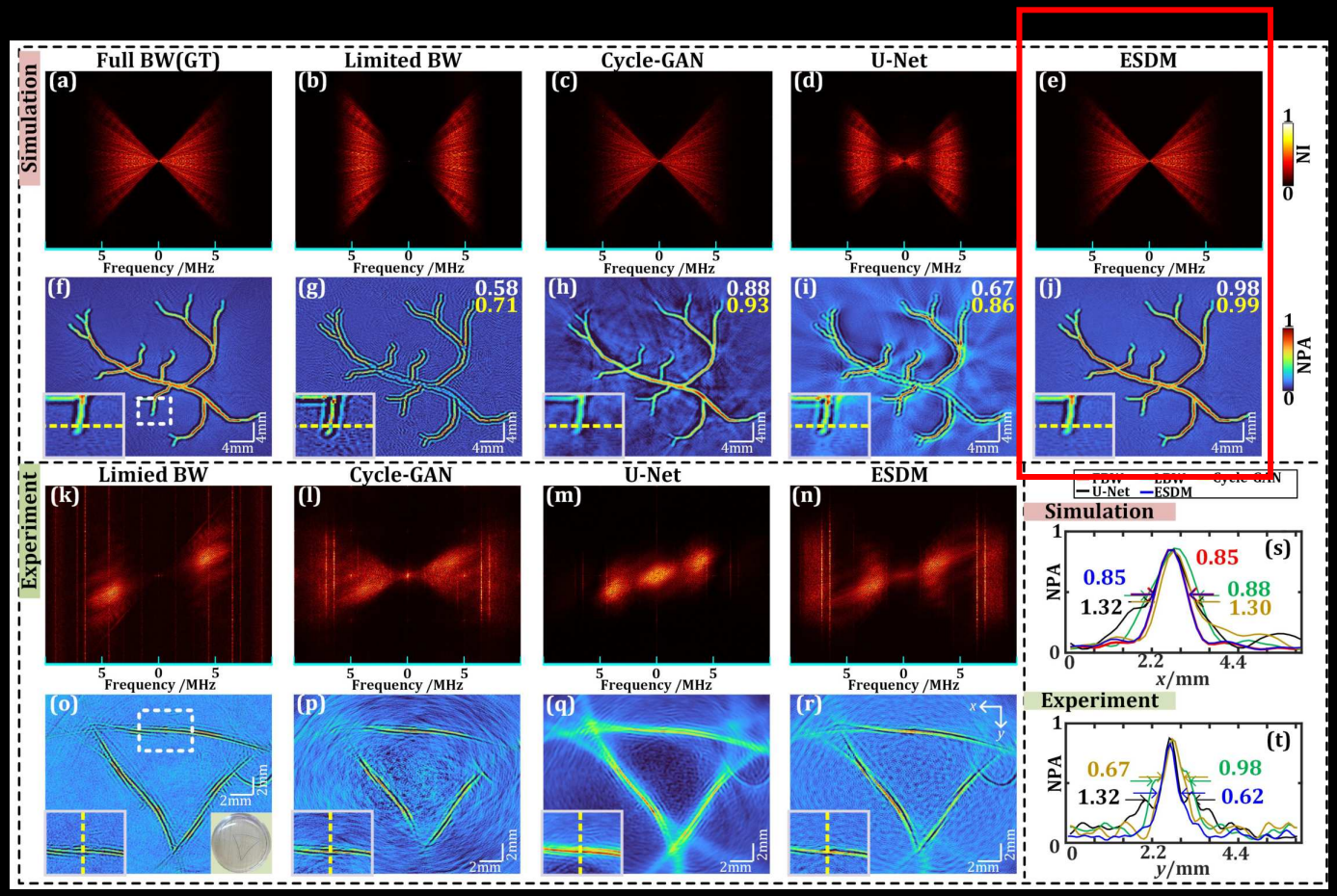

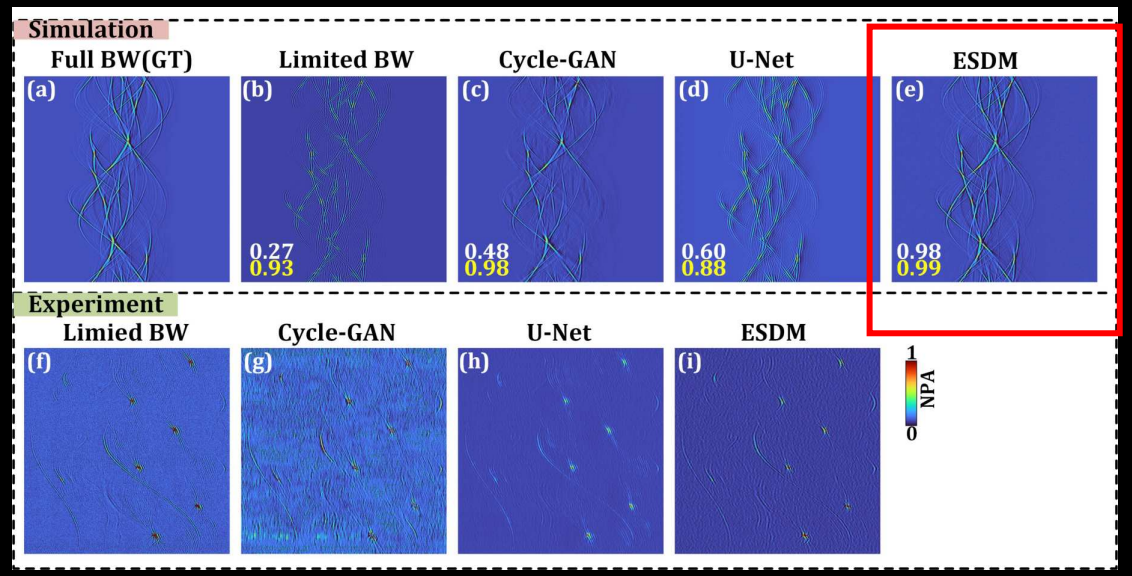

Jiabin Lin, Zilong Li, Haoran Fang, Guolin Liu, Siyi Cao, Yubin Cao, Linxin Li, Jiahong Li, Yiguang Wang, Haipeng Wei, Shuhao Ma, Zhiyuan Zheng, Qiegen Liu, and Xianlin Song. Enhanced score-based priors-boosted generative model for resolution breakthrough in photoacoustic tomography[J]. Optics Letters, 2025.

Summary

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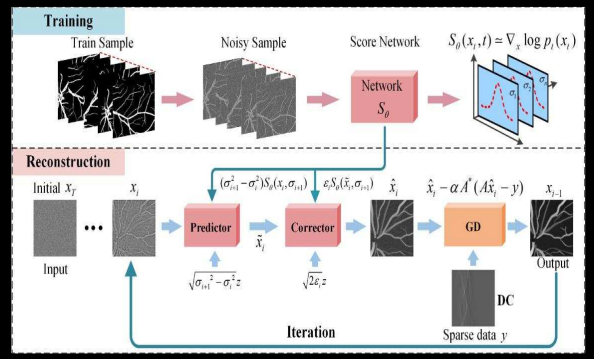
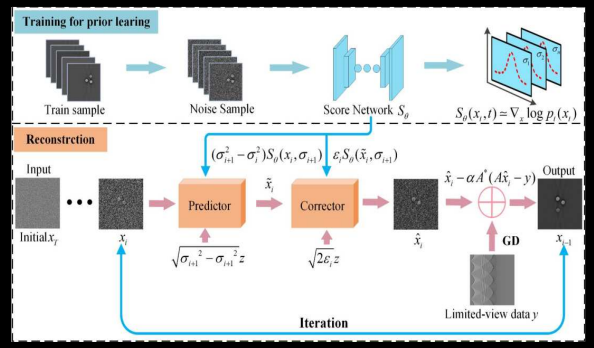
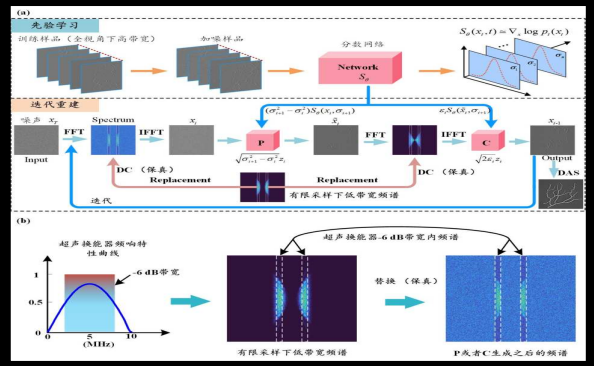
Diffusion model

- **Sparse-view reconstruction**
- **Limited-view reconstruction**
- **Bandwidth enhancement**







Multiple diffusion model

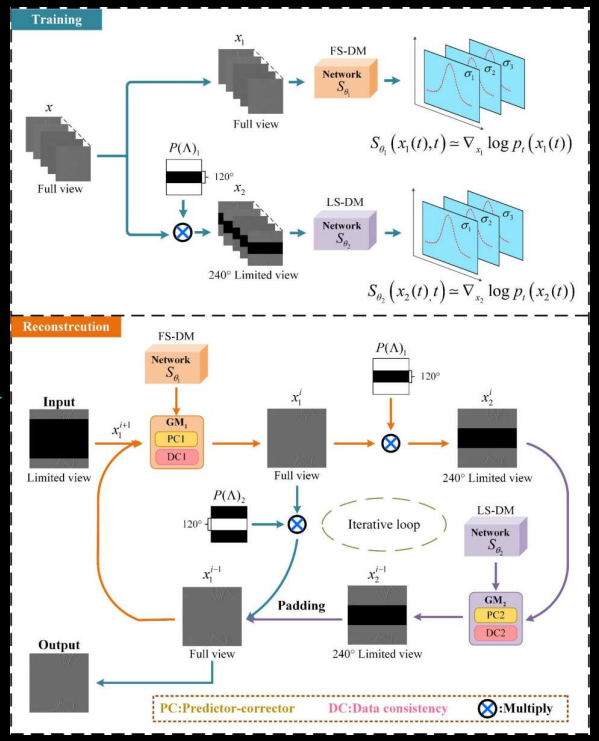


Image domain prior → **Data domain prior** → **Multi-scale priors**

成像与视觉表示实验室

研究领域： 智能成像系统与视觉显示的系统开发与算法研究

- 立足国家大健康战略需求和江西省电子信息产业发展
- 聚焦光电成像系统、软硬件嵌入式开发、信号及视觉处理等行业
- 围绕“传感成像-信号处理-增强显示”中的关键问题与技术瓶颈
- 实现关键技术突破与成果转化

刘且根 教授
国家优青
执行院长
政府津贴获得者

张明辉

徐晓玲

宋贤林

万文博

单文哲

胡嘉文

施柳

肖书源

刘婷婷

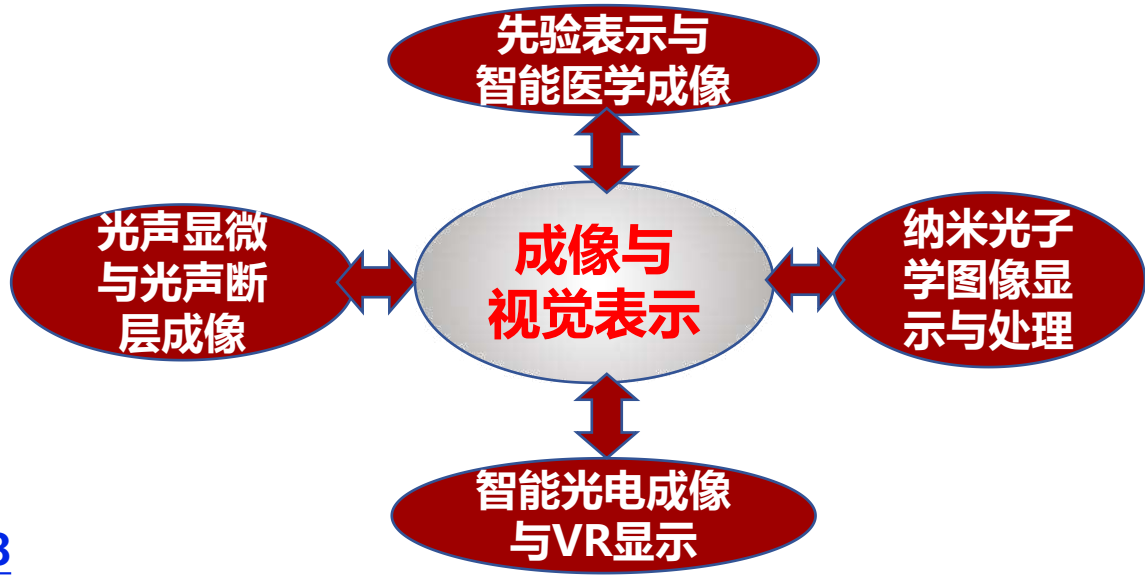
吴天涯

王少宇

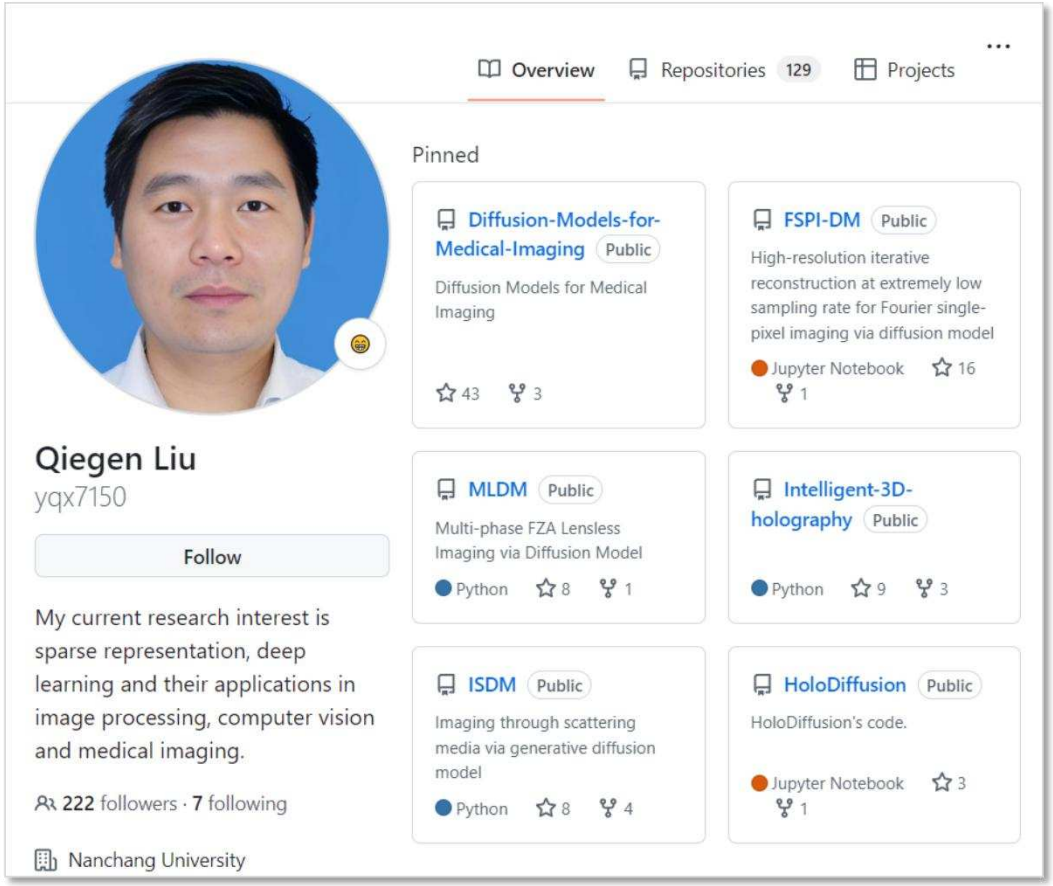
邹响红

实验室平台及网站：
江西省先进信号处理与智能通信重点实验室
江西省智能医学信息检测与物联工程研究中心
https://github.com/yqx7150; https://www.labxing.com/lab/1018

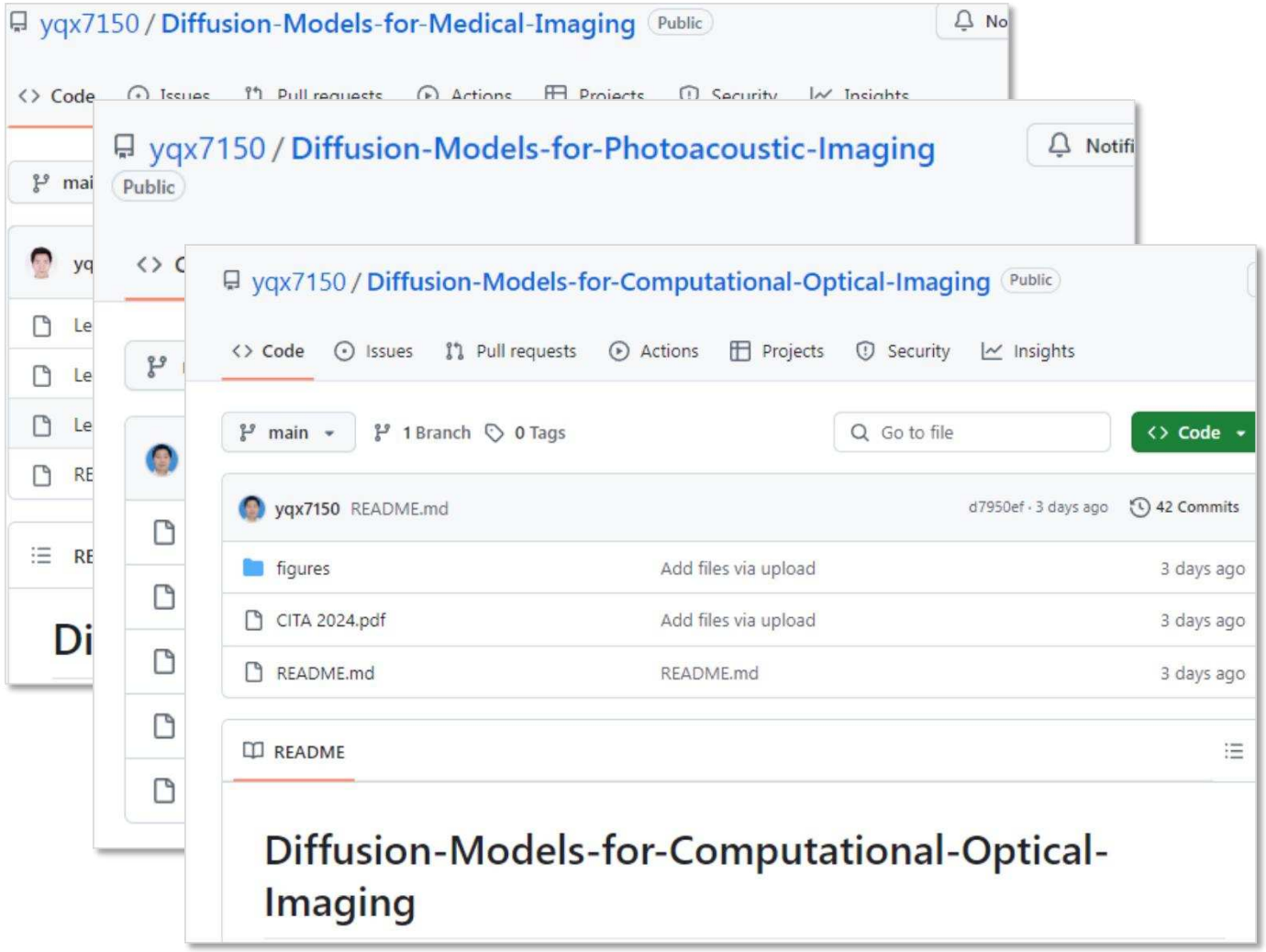
- 2024年吴文俊人工智能技术发明一等奖
- 2022年江西省自然科学一等奖
- 2023年江西省青年科学技术奖
- 2022年中国体视学学会青年科技奖
- 2020年中国体视学学会科技进步二等奖
- 第十届吴文俊人工智能科技进步二等奖
- 江西省省级示范研究生导师创新团队



成像与视觉表示实验室



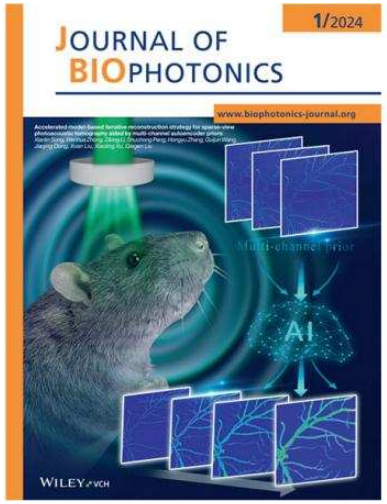
医学成像-光声成像-计算光学成像代表性工作

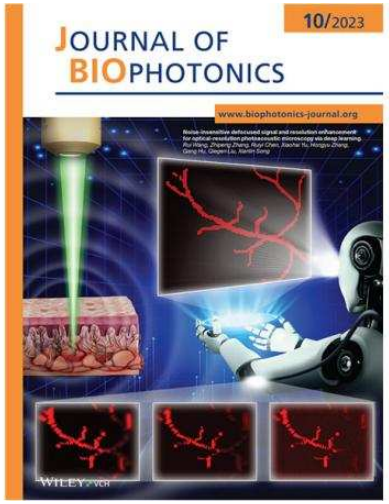


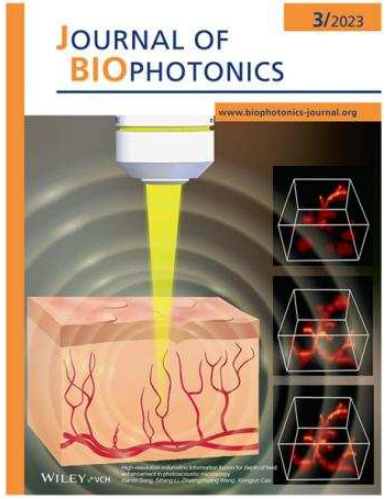
实验室代码公开超过100项：

https://github.com/yqx7150

4 成像与视觉表示实验室







第 34 卷 第 3 期 CT 理论与应用研究（中英文） Vol.34, No.3
2025 年 5 月（506-524） Computerized Tomography Theory and Applications May, 2025

刘且根, 官瑜, 伍伟文, 等. 基于扩散模型的医学成像研究综述[J]. CT 理论与应用研究（中英文）, 2025, 34(3): 506-524. DOI:10.15953/j.ctta.2024.316.
LIU Q G, GUAN Y, WU W W, et al. Diffusion Models in Medical Imaging: A Comprehensive Survey[J]. CT Theory and Applications, 2025, 34(3): 506-524. DOI:10.15953/j.ctta.2024.316. (in Chinese).

基于扩散模型的医学成像研究综述

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1.南昌大学 a）信息工程学院；b）数学与计算机学院，南昌 330031
2.中山大学生物医学工程学院，广东 深圳 518000
3.复旦大学类脑智能科学与技术研究院，上海 200433
4.中国科学院深圳先进技术研究院生物医学与健康工程研究所，广东 深圳 518055

摘要：以扩散模型为代表的生成式人工智能近年来在医学成像领域取得了迅猛的进展。为了帮助更多学者全面的了解扩散模型这一先进技术，本文旨在提供扩散模型在医学成像领域的详细概述。首先以扩散模型的起源演变为主线介绍扩散建模框架的基础理论和基本概念；其次根据扩散模型的特点提供其在医学成像领域的系统分类，并涵盖不同成像模态如磁共振成像、计算机断层扫描、正电子发射计算机断层显像和光声成像等的广泛应用；最后讨论目前扩散模型的局限性并展望未来研究的潜在发展方向，为研究者后续的探索提供了一个直观的起始点。部分代码开源在网址：https://github.com/yqx7150/Diffusion-Models-for-Medical-Imaging。

关键词：生成式人工智能；扩散模型；医学成像；图像重建

光电融合-前沿与工程, 年, 卷 (期): 页码范围 doi: xx.xxxxx/j.pxintegration.xxxxxxxx

基于扩散模型的光声成像研究综述

宋贤林[1]， 田超[2]，高飞[2,3,4], 李佳洪[1], 郑志远[1], 刘且根[1,*]

(1.南昌大学 信息工程学院，南昌，330031， 中国；
2. 中国科学技术大学 工程科学学院，合肥，230026，中国；
3. 中国科学技术大学 生物医学工程学院 生命科学与医学部，合肥，230026，中国；
4. 中国科学技术大学 苏州高等研究院，苏州，215123，中国)

摘要：近年来扩散模型在光声成像中的应用展现出显著潜力，为解决传统成像中的关键挑战提供了创新思路。为了使更多的学者全面了解扩散模型技术在光声成像上的应用，本文首先详细探究了光声断层成像 (Photoacoustic tomography, PAT) 和光声显微成像 (Photoacoustic microscopy, PAM) 在系统和算法的发展历程，引出了目前存在的一些问题，同时也引出了扩散模型在算法方面改进的巨大潜力。其次详细介绍了扩散模型在PAT和PAM上的具体应用，详细对比了扩散模型与其他一些深度学习方法在光声成像重建中的应用效果，展现了扩散模型在光声成像重建的创新性和优势性。最后探讨了扩散模型在光声成像及实际应用中所面临的挑战和亟待解决的问题，并进一步引出其未来的发展改进方向。部分代码开源在网址：https://github.com/yqx7150/Diffusion-Models-for-Photoacoustic-Imaging。

关键词：光声成像；图像重建；扩散模型；生成式人工智能

研究方向1：先验表示与智能医学成像

大型医疗器械国产化替代需求

全球/中国医疗器械市场规模 （千亿元）

医疗器械细分市场国产品牌占比

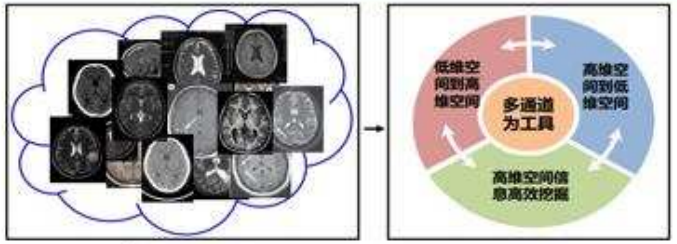
“企业-高校-医院”协同创新

医院

医疗器械

远程医疗

- 以高校为主要力量
- 联合企业力量为补充
- 结合医院提出目标任务
- 解决产业链痛点、难点、堵点



高维变量相关和多维空间分析新模式

优秀成果

✓ 转化应用

研究方向2：光声显微与光声层析成像

◆ **乳腺癌检测主要难点**

传统单模态成像精度低，仅实现解剖结构检测

- X光钼靶摄影有电离辐射，超声检测特异性低

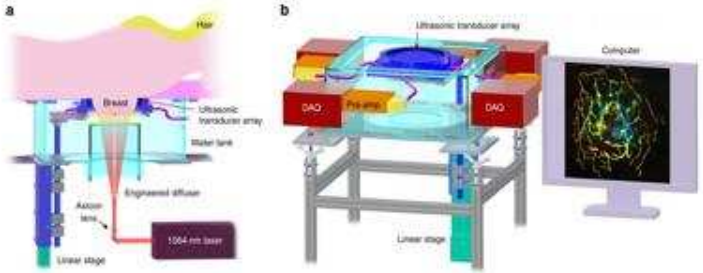
◆ **面向乳腺癌早期检测与诊断**

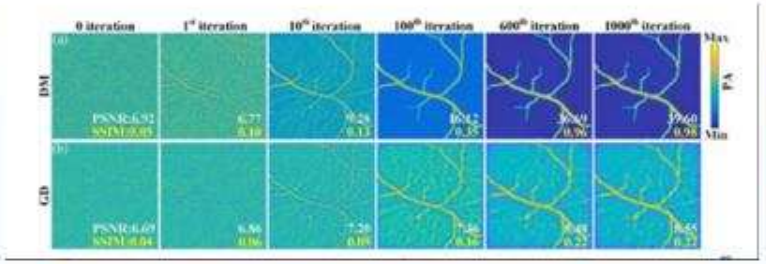
- 实现无损、高对比度、高分辨率深层智能成像
- 融合多模态信息，实现特异性诊断

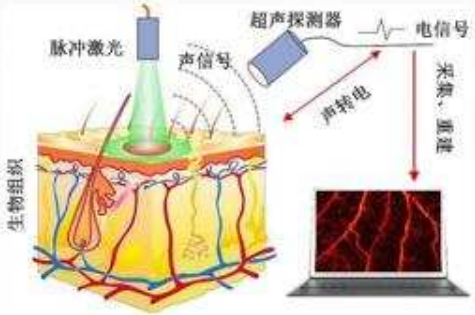
◆ **关键技术难题**

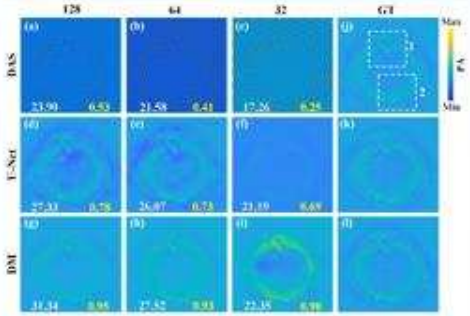
➢ 超声探测器数量有限、受到伪影干扰

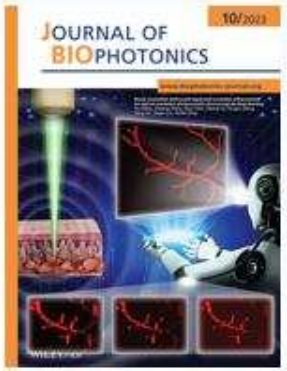
➢ 光学参数背景先验信息缺失

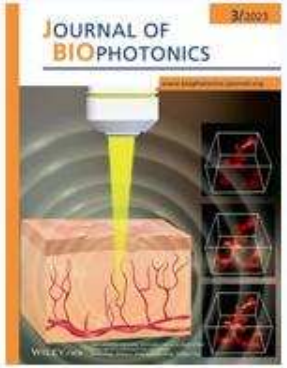












研究方向3：智能光电成像与VR显示

产业需求牵引

HUAWEI

OFILM 欧菲光

ZETTAVR 境

复杂场景智能光电成像

➢ 多相位菲涅尔孔径编码无透镜成像

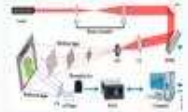
多相位FZA编码板

CMOS

光学计算重建

➢ 直接飞行时间激光雷达模组

➢ 高速追踪单像素探测系统

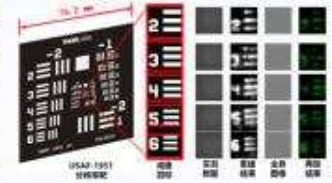


全息VR显示

➢ 三维场景快速采集与全息显示

- 极简系统结构
- 超快三维场景采集速度：~ 0.6 s

➢ 透过散射介质成像与全息显示

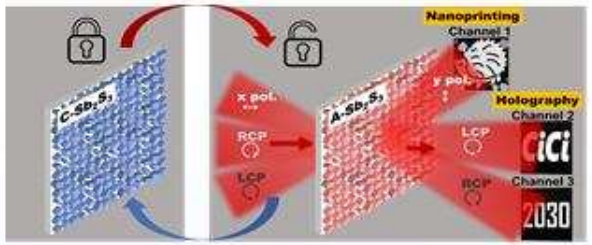


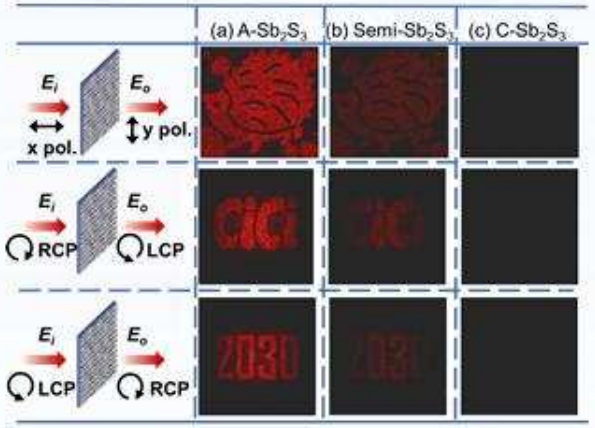
- 透过散射介质实现高分辨率成像
- 实现高质量全息显示

研究方向4：纳米光子学图像显示与信息处理

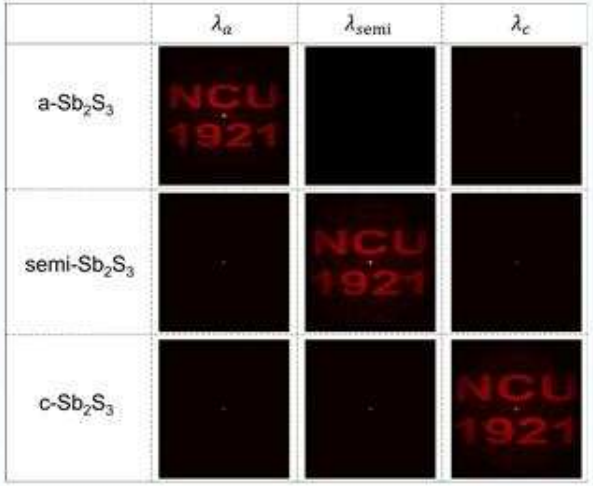
◆ 面向新一代信息技术产业的光学平面集成器件

光子取代电子作为信息载体和能源介质

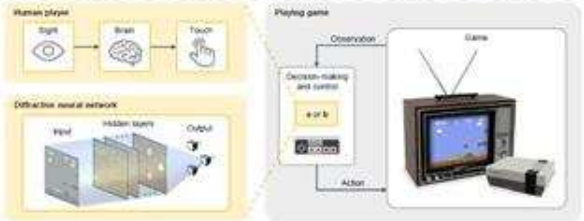




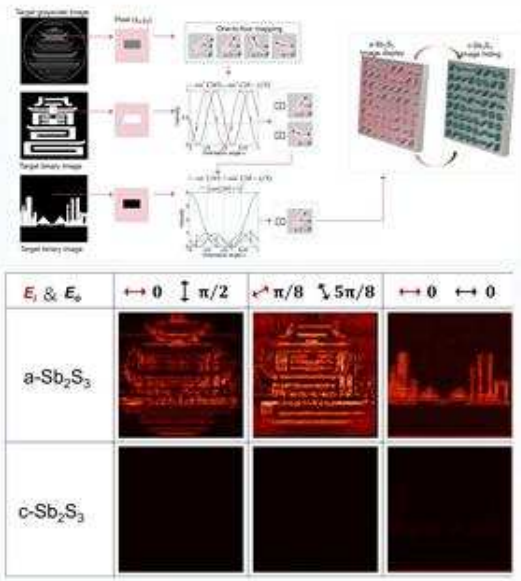
- ✓ 高容量、高集成度的片上信息存储
- ✓ 高空间分辨率的全息图像显示



- ✓ 光谱和空间调控的高自由度
- ✓ 可调谐波长的全息图像显示



- ✓ 高速度、大带宽、低功耗、高集成
- ✓ 模拟人类的感知能力与控制行为



- ✓ 信息复用超表面的极简设计
- ✓ 动态信息显示及加密编码

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